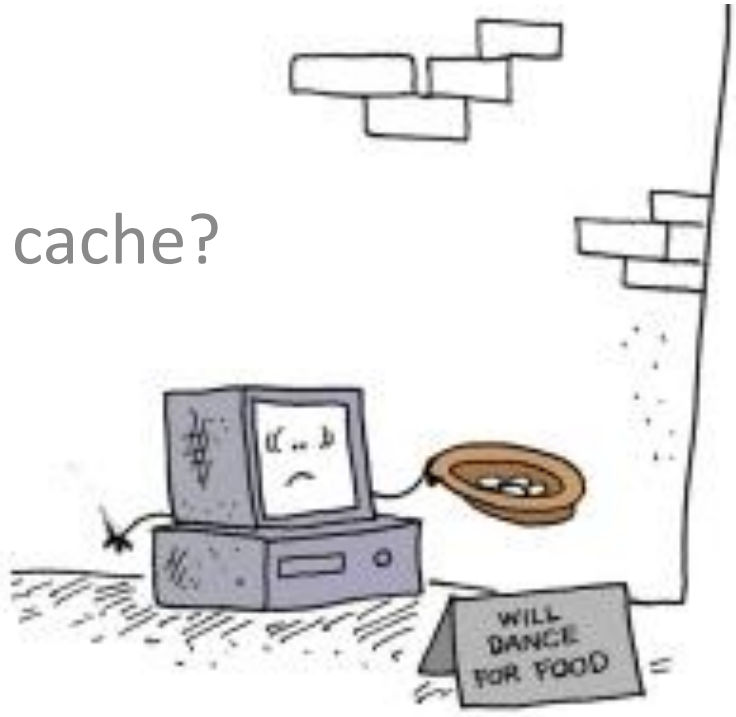
Low on cache?

Caches, Part I



Outline

- Memory Hierarchy
- Direct-Mapped Cache
- Types of Cache Misses
- A (long) detailed example

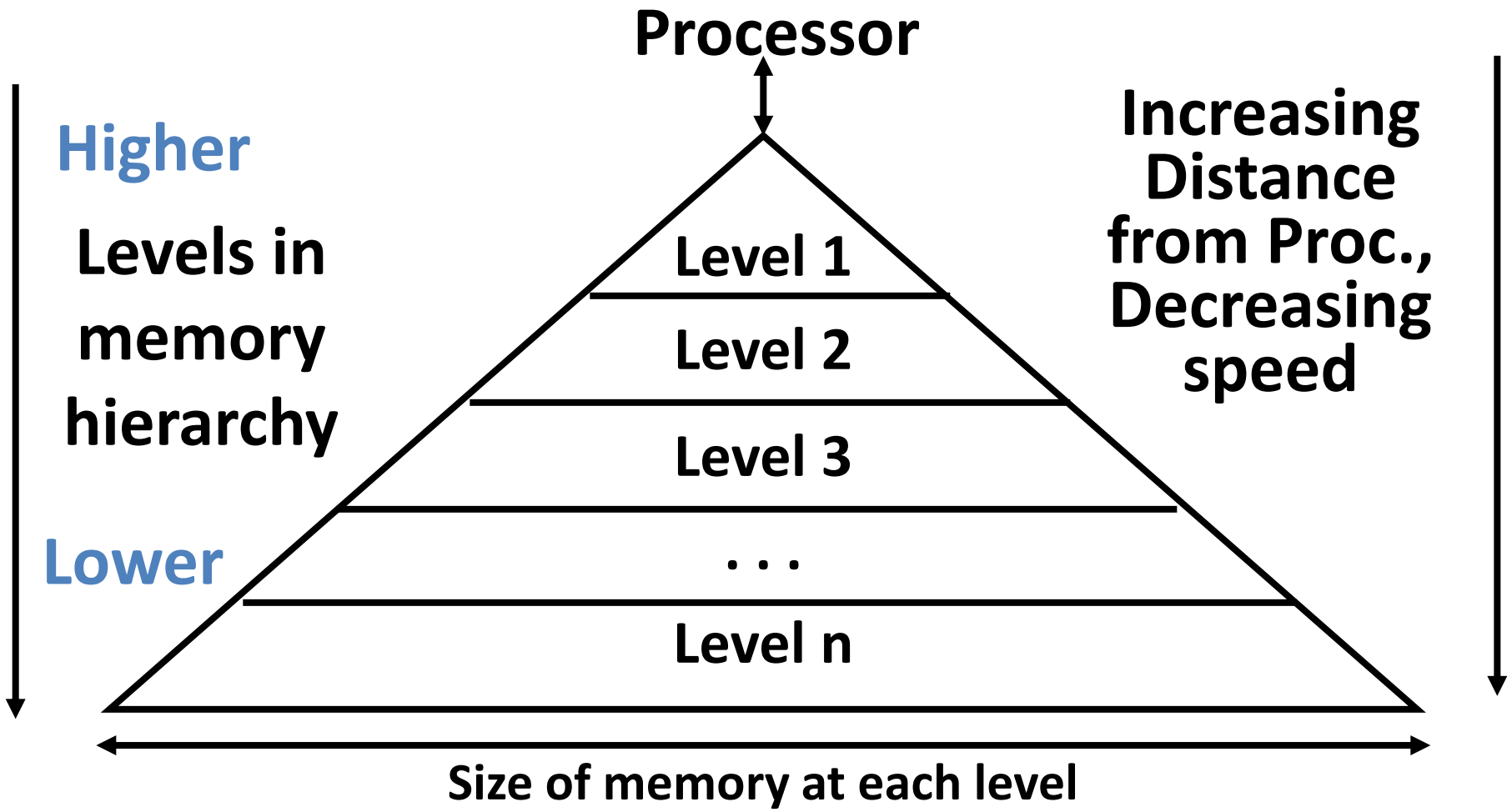
Memory Hierarchy (1/4)

- Processor
  - executes programs
  - runs on order of nanoseconds to picoseconds
  - needs to access code and data for programs: where are these?
- Disk
  - HUGE capacity (virtually limitless)
  - VERY slow: runs on order of milliseconds
  - so how do we account for this gap?

Memory Hierarchy (2/4)

- Memory (DRAM)
  - smaller than disk (not limitless capacity)
  - contains subset of data on disk: basically portions of programs that are currently being run
  - much faster than disk: memory accesses don't slow down processor quite as much
  - Problem: memory is still too slow (hundreds of nanoseconds)
  - Solution: add more layers (caches)

Memory Hierarchy (3/4)

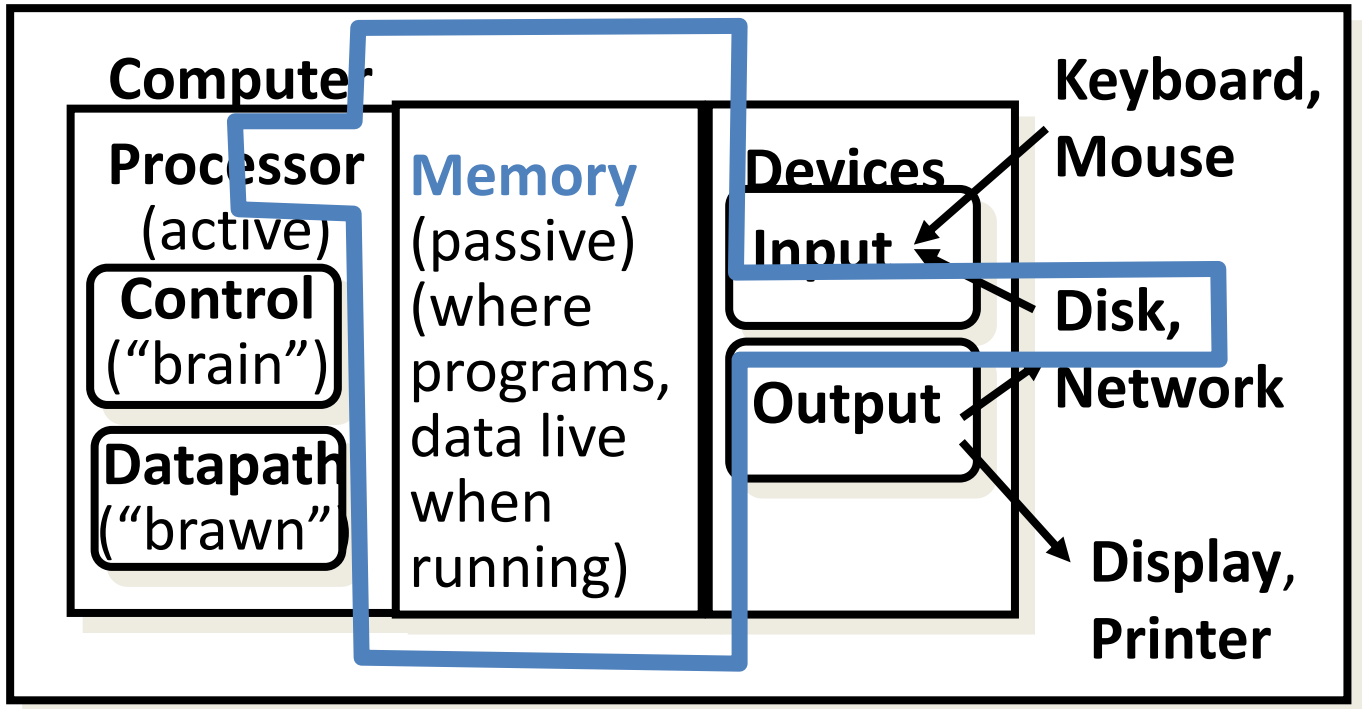


As we move to deeper levels the latency goes up and price per bit goes down.

Memory Hierarchy (4/4)

- If level is closer to Processor, it must…
  - Be smaller
  - Be faster
  - Contain a subset (most recently used data) of lower levels beneath it (i.e., levels farther from processor)
  - Contain all the data in higher levels above it (i.e., levels closer to processor)
- Lowest Level (usually disk) contains all available data
- Is there another level lower than disk?

Memory Hierarchy



- Purpose:
  - Faster access to large memory from processor

Memory Hierarchy Analogy: Library (1/2)

- You (the processor) are writing a term paper at a table in Schulich
- Schulich Library is equivalent to disk
  - essentially limitless capacity
  - very slow to retrieve a book
- Table is memory
  - smaller capacity: means you must return book when table fills up
  - easier and faster to find a book there once you've already retrieved it

Memory Hierarchy Analogy: Library (2/2)

- Open books on table are cache
  - smaller capacity: can have very few open books fit on table; again, when table fills up, you must close a book
  - much, much faster to retrieve data
- Illusion created: whole library open on the tabletop
  - Keep as many recently used books open on table as possible since likely to use again
  - Also keep as many books on table as possible, since faster than going to library

Memory Hierarchy Basis

- Disk contains everything
- When Processor needs something, bring it into to all upper levels of memory
- Cache contains copies of data in memory that are being used
- Memory contains copies of data on disk that are being used
- Entire idea is based on ***Temporal Locality***: if we use it now, we'll want to use it again soon (a Big Idea)

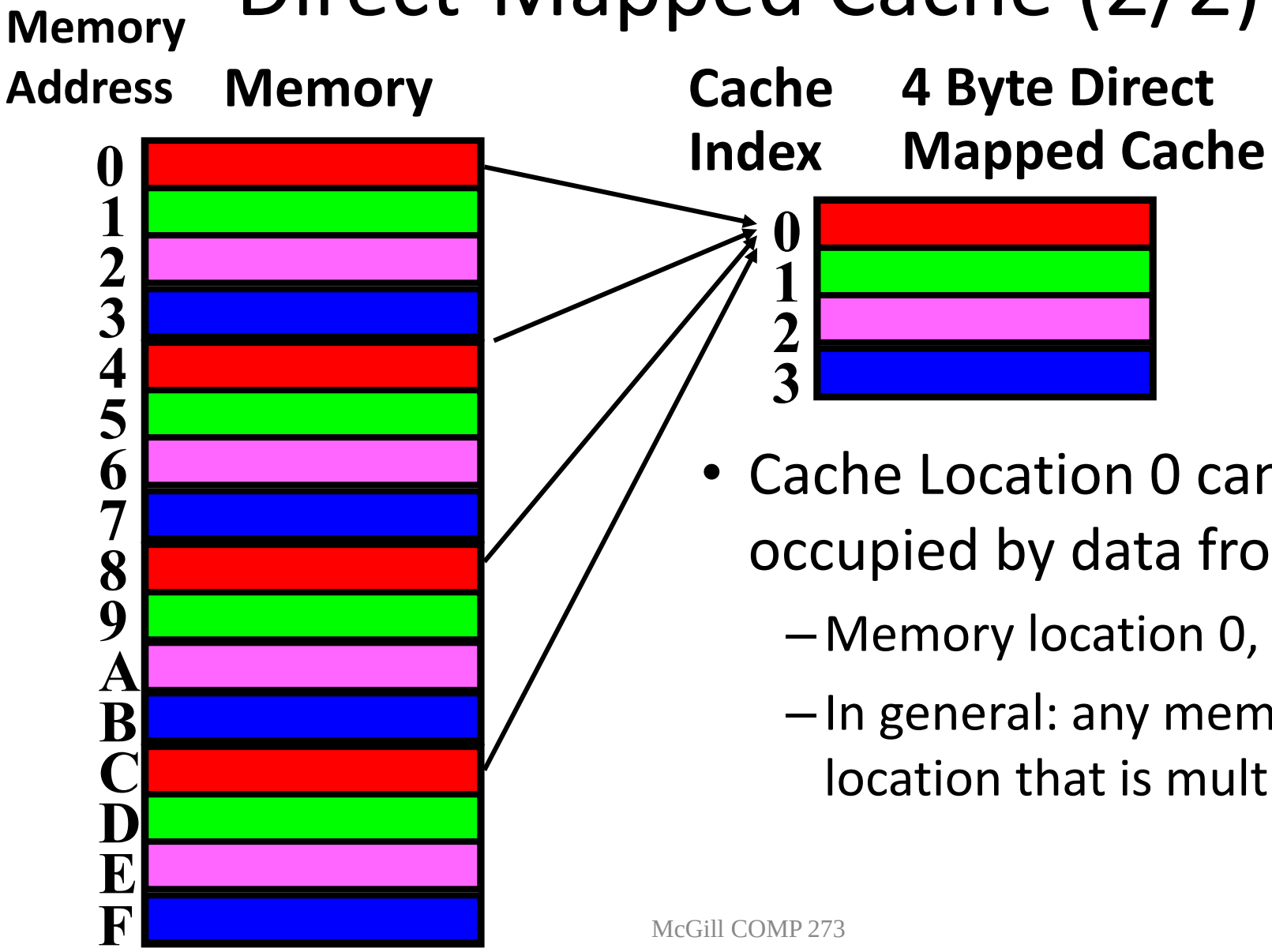
Cache Design

- How do we organize cache?
- Where does each memory address map to?
  - Remember that cache is subset of memory, so multiple memory addresses map to the same cache location.
- How do we know which elements are in cache?
- How do we quickly locate them?

Direct-Mapped Cache (1/2)

- In a ***direct-mapped cache***, each memory address is associated with one possible ***block*** within the cache
  - Therefore, we only need to look in a single location in the cache to see if the data exists in the cache
  - A *block* is the unit of transfer between cache and memory

Direct-Mapped Cache (2/2)



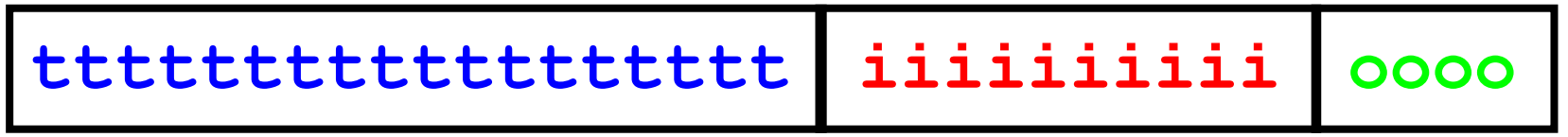
- Cache Location 0 can be occupied by data from:
  - Memory location 0, 4, 8, ...
  - In general: any memory location that is multiple of 4

Issues with Direct-Mapped

1 Since multiple memory addresses map to same cache index, how do we tell which one is in there?

2 What if we have a block size > 1 byte?

- **Solution**: divide memory address into three fields



tag	index	offset
to check if have correct block	to select block	byte within block

Direct-Mapped Cache Terminology

- All fields are read as unsigned integers.
- The ***Index***: specifies the cache index (which "row" of the cache we should look in)
- The ***Offset***: once we've found correct block, specifies which byte within the block we want
- The ***Tag***: the remaining bits after offset and index are determined; these are used to distinguish between all the memory addresses that map to the same location

Direct-Mapped Cache Example

- Suppose we have a direct-mapped **16KB cache** with **4 word blocks**.
- Determine the size of the tag, index and offset fields if we're using a 32-bit architecture.

Direct-Mapped Cache Example

- Offset
  - need to specify correct byte within a block
  - block contains

    4 words = 16 bytes = 2^4 bytes
  - need **4 bits** to specify correct byte

Direct-Mapped Cache Example

- Index
  - need to specify correct row in cache
  - cache contains 16 KB = 2^4 2^{10} = 2^{14} bytes
    block contains 2^4 bytes (4 words)

rows/cache = # blocks/cache (there's one block/row)

$$= \frac{\text{bytes/cache}}{\text{bytes/row}}$$

$$= \frac{2^{14}\ \text{bytes/cache}}{2^4\ \text{bytes/row}}$$

$$= 2^{10}\ \text{rows/cache}$$

  - need ***10 bits*** to specify this many rows

Direct-Mapped Cache Example

- Tag
  - used remaining bits as tag
  - tag length = memory address bits minus offset bits minus index bits
    = 32 - 4 - 10 bits
    = 18 bits
  - so the tag is leftmost ***18 bits*** of memory address

Accessing data in a direct mapped cache

- Example: 16KB, direct-mapped, 4 word blocks
- Read 4 addresses

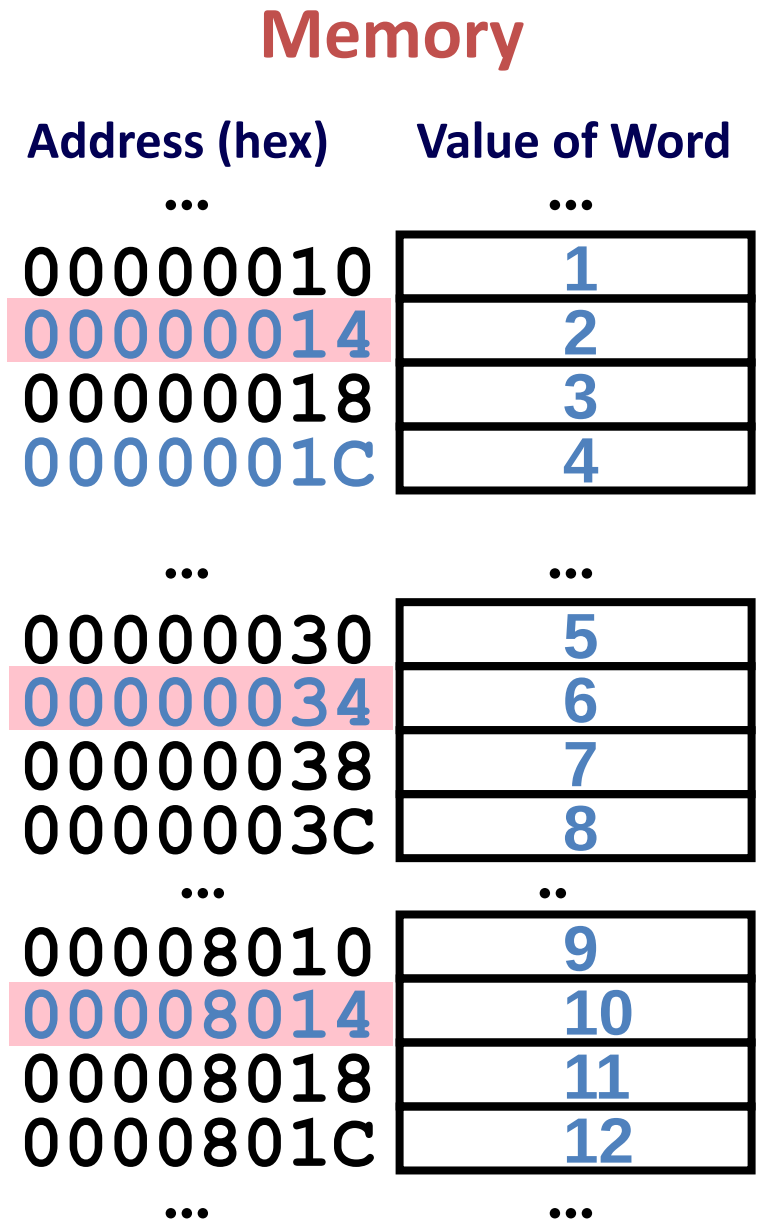
  0x00000014

  0x0000001C

  0x00000034

  0x00008014

- Memory values on right:
  - Let us only consider cache and memory levels of hierarchy



Accessing data in a direct mapped cache

- 4 Addresses:

  0x00000014, 0x0000001C, 0x00000034, 0x00008014

- 4 Addresses divided (for convenience) into Tag, Index, Byte Offset fields

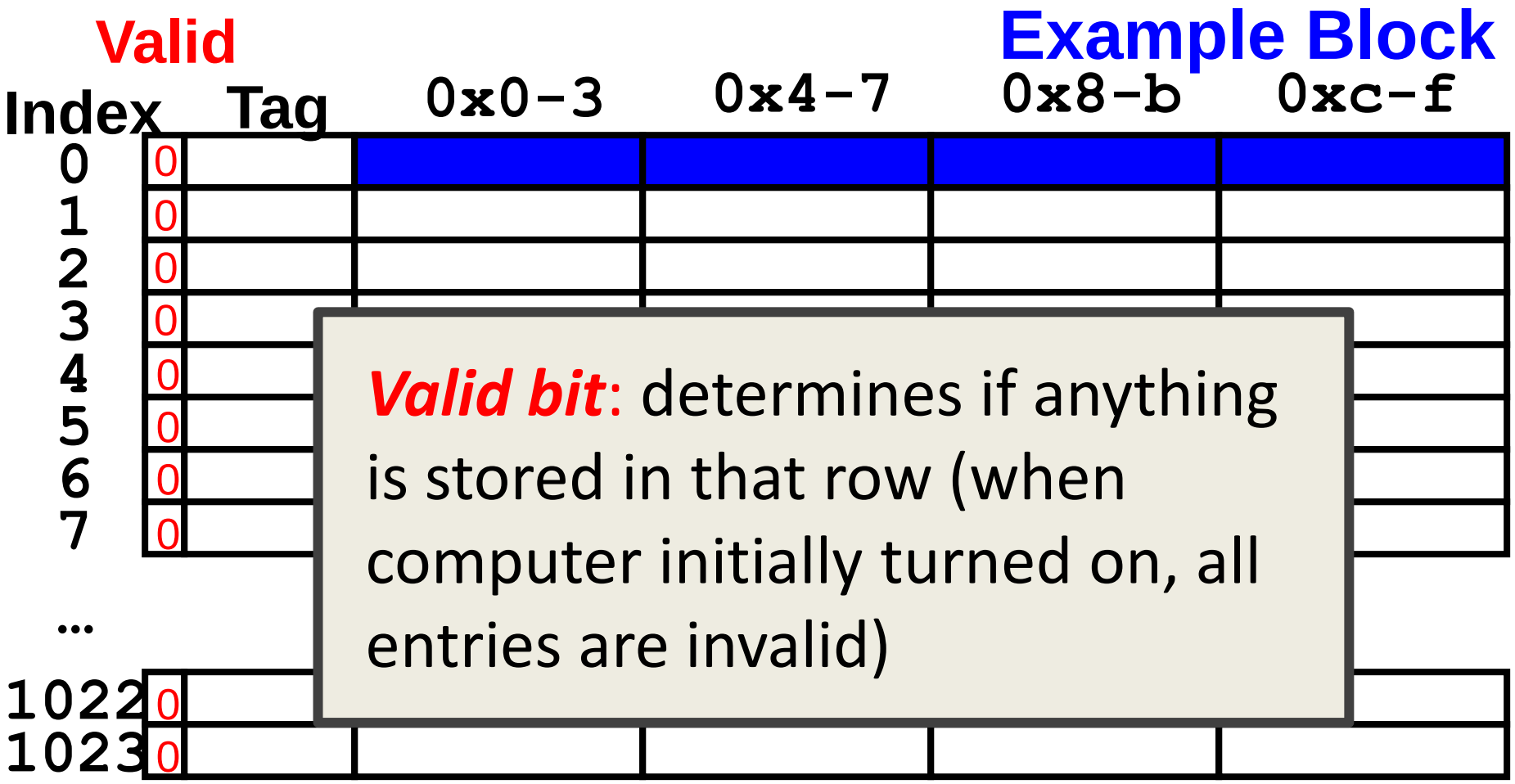
```
0000000000000000 0000000001 0100
0000000000000000 0000000001 1100
0000000000000000 0000000011 0100
0000000000000010 0000000001 0100
```

Tag **Index** **Offset**

Accessing data in a direct mapped cache

- Lets go through accessing some data in this cache
  - 16KB, direct-mapped, 4 word blocks
- Will see 3 types of events:
- cache miss: nothing in cache in appropriate block, so fetch from memory
- cache hit: cache block is valid and contains proper address, so read desired word
- cache miss, block replacement: wrong data is in cache at appropriate block, so discard it and fetch desired data from memory

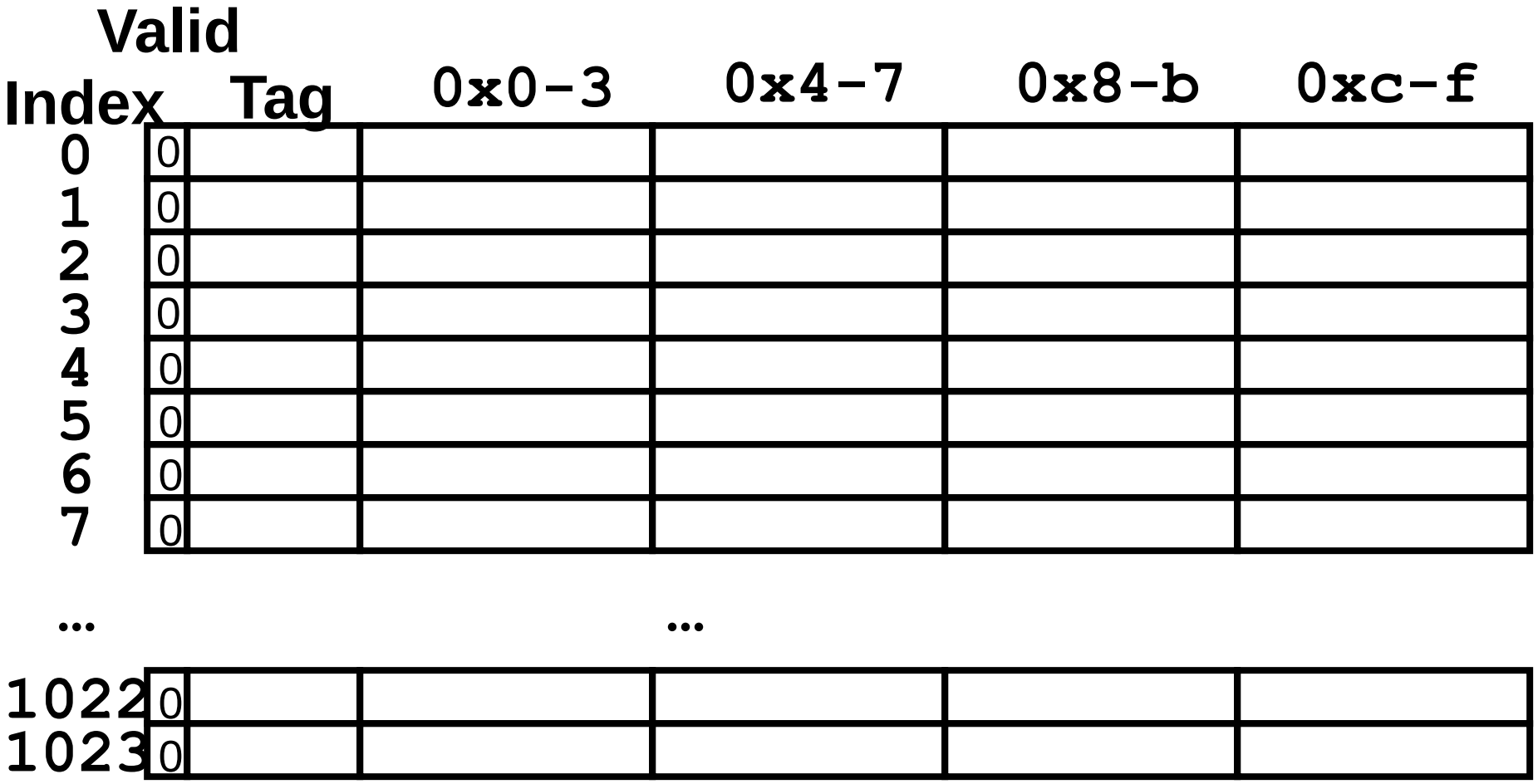
16 KB Direct Mapped Cache, 16B blocks



Read 0x00000014

00000000000000000000 0000000001 0100

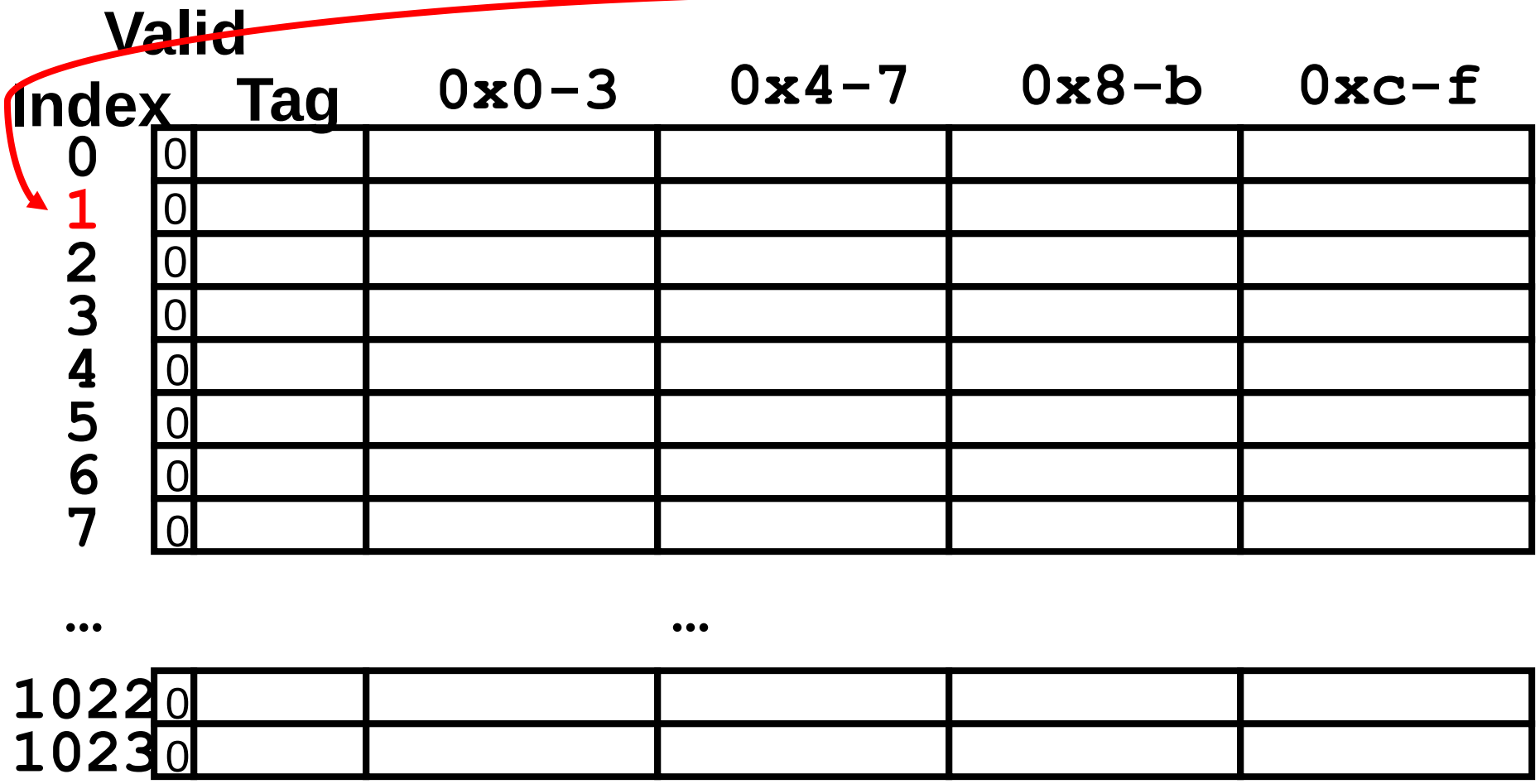
Tag field **Index field** **Offset**



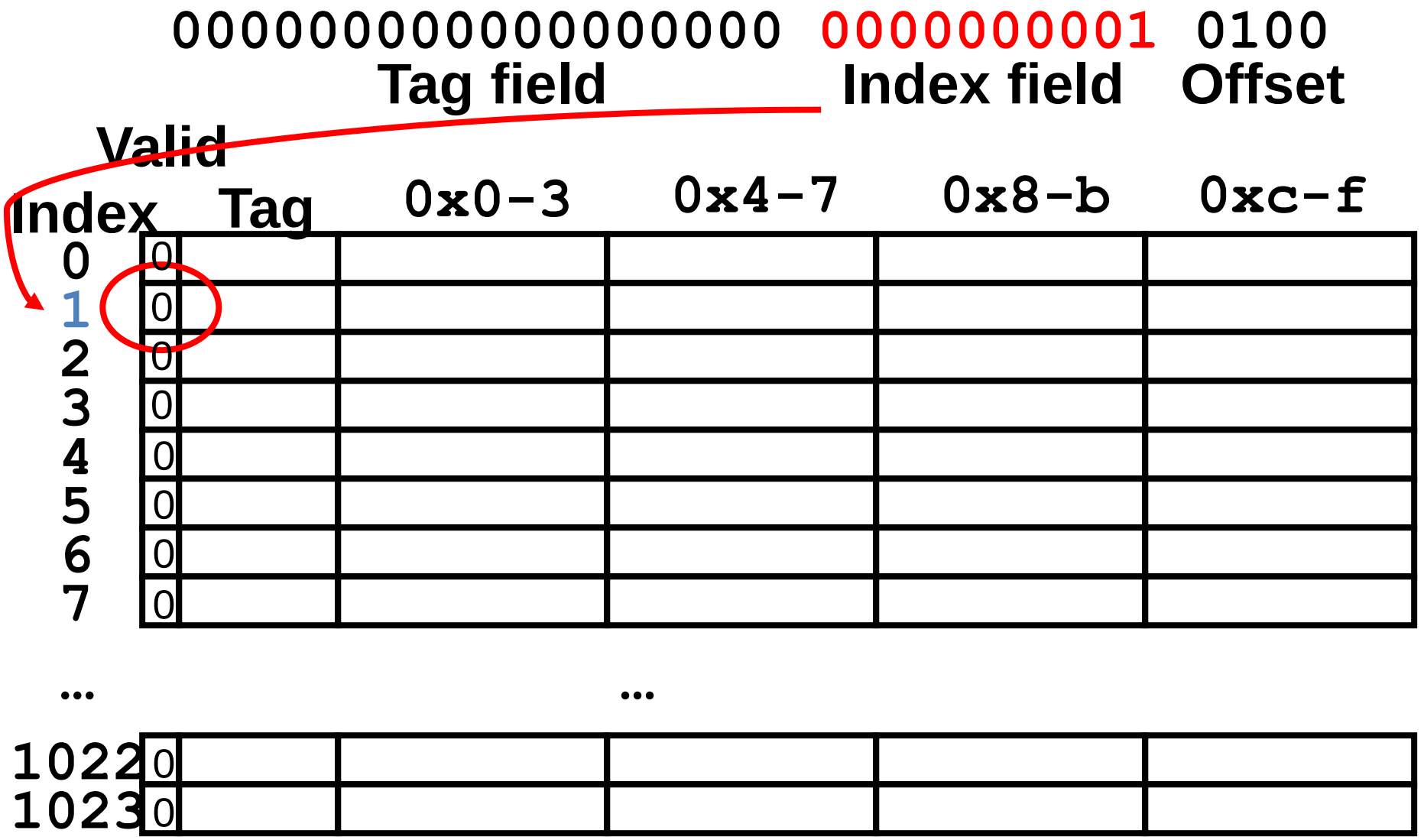
So we read block 1 (0000000001)

0000000000000000 0000000001 0100

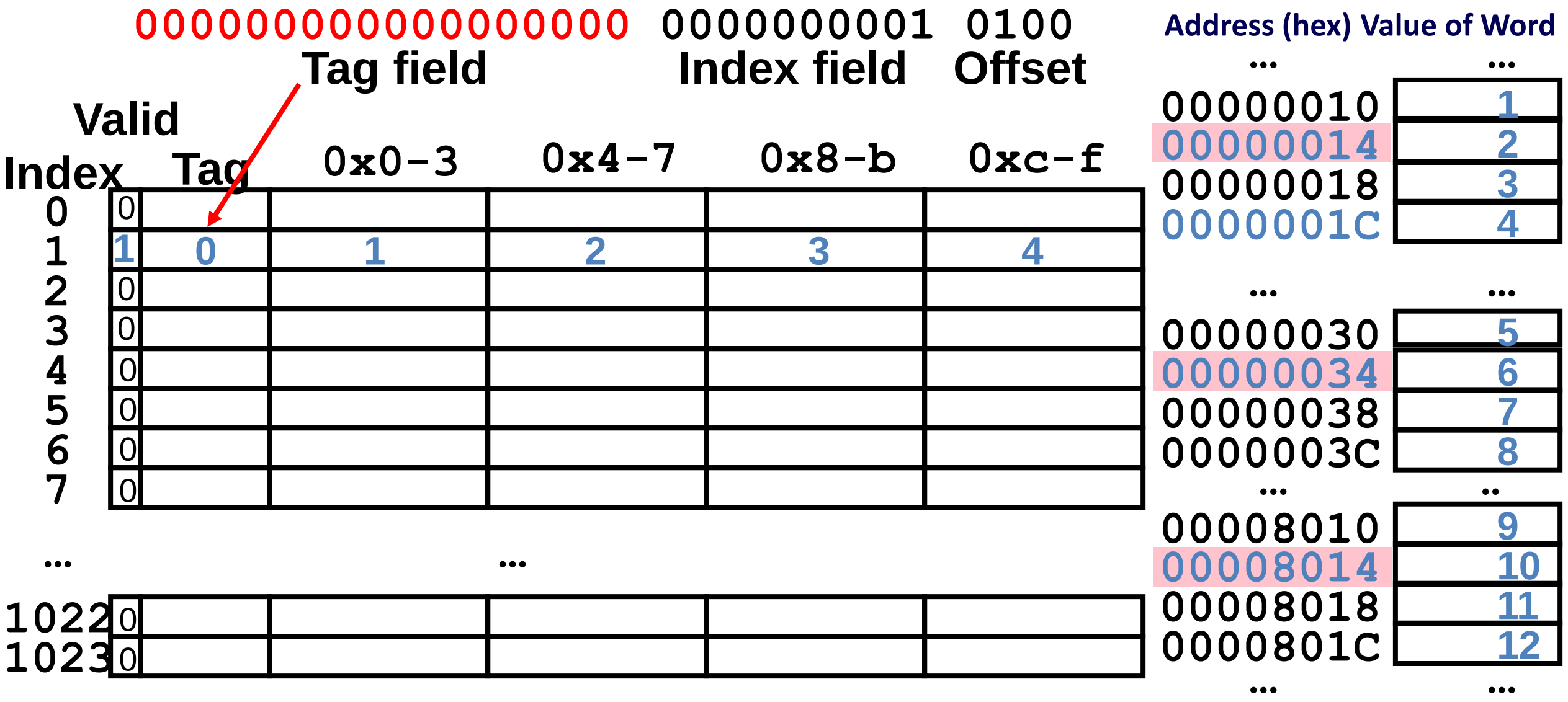
Tag field Index field Offset



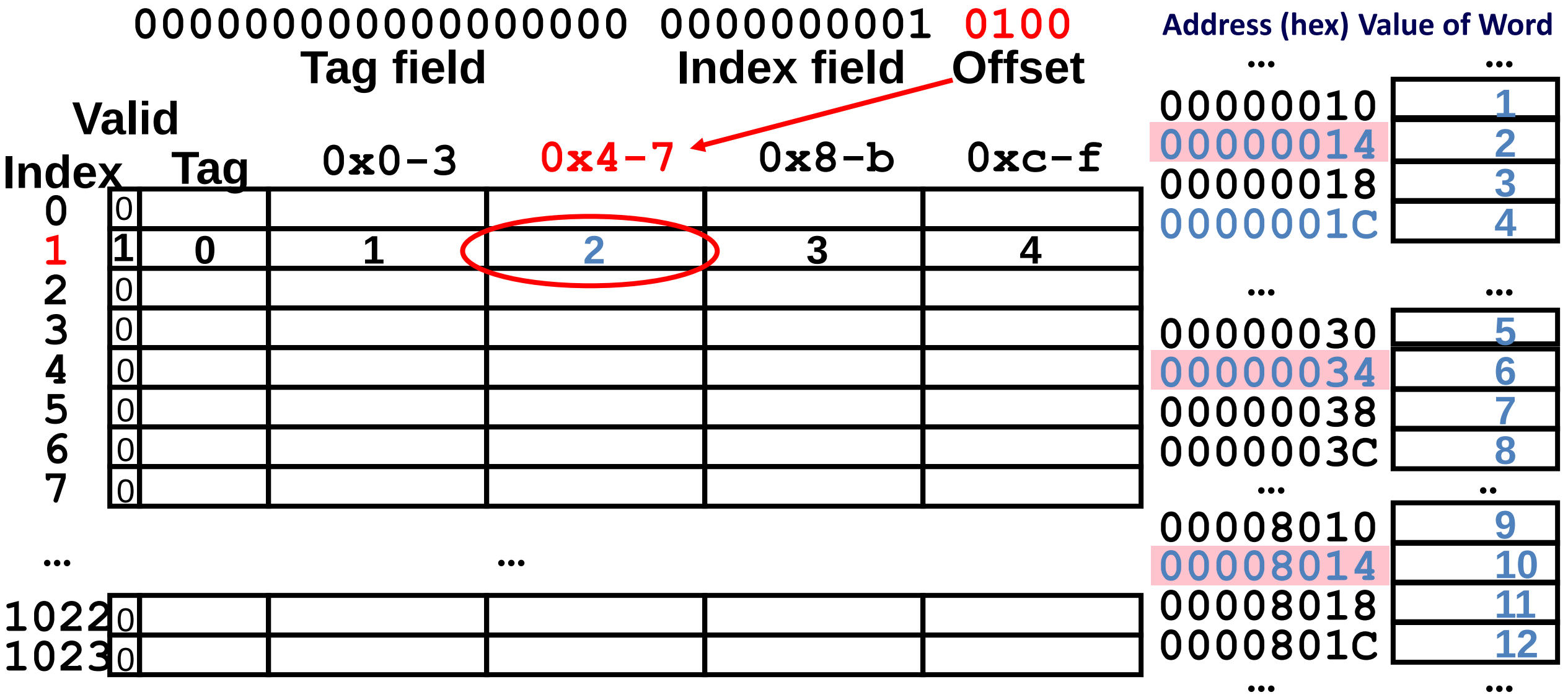
No valid data



So load that data into cache, setting tag, valid



Read from cache at offset, return word 2

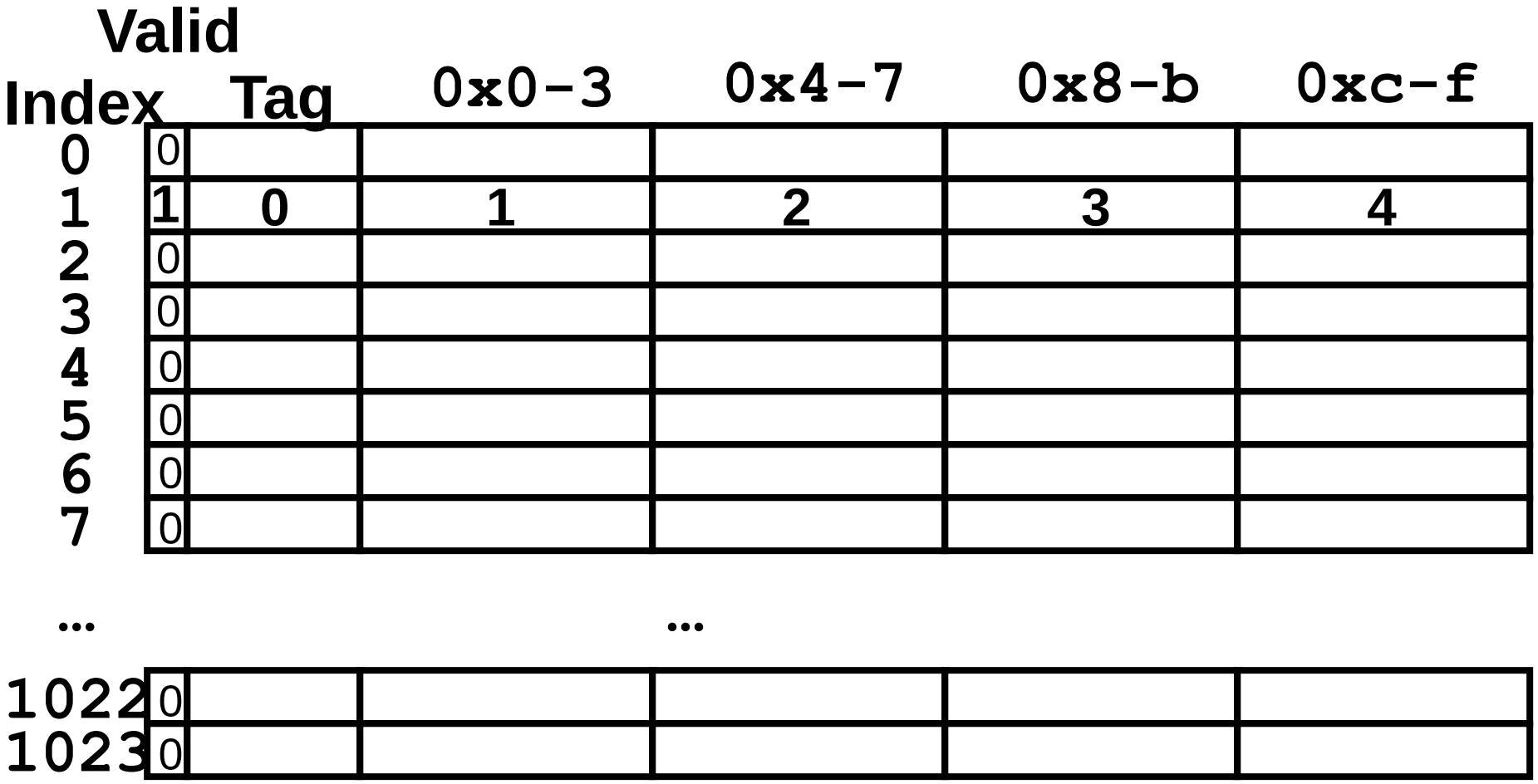


Slides from Patterson's 61C, Fall 2001

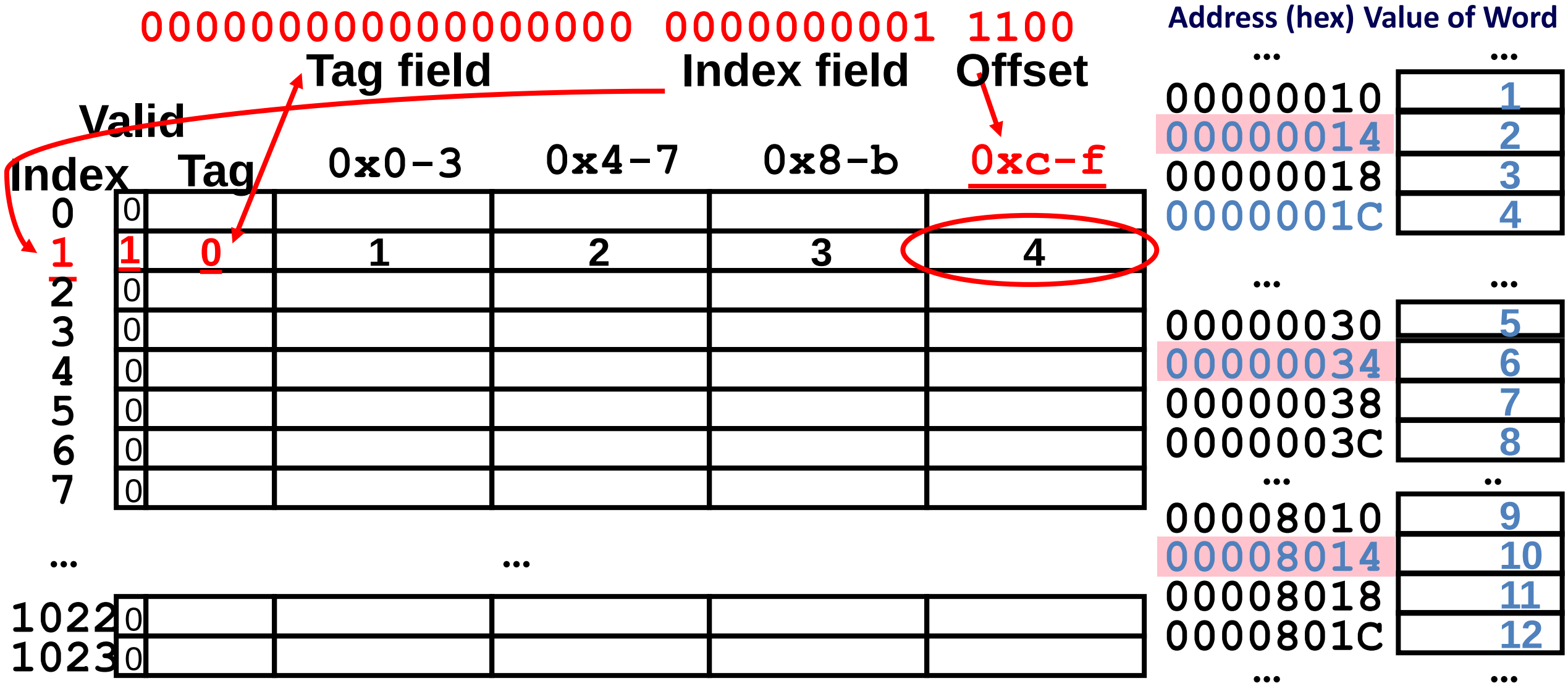
Read 0x0000001C

0000000000000000 0000000001 1100

Tag field | Index field | Offset



Data valid, tag OK, so read offset return word 4

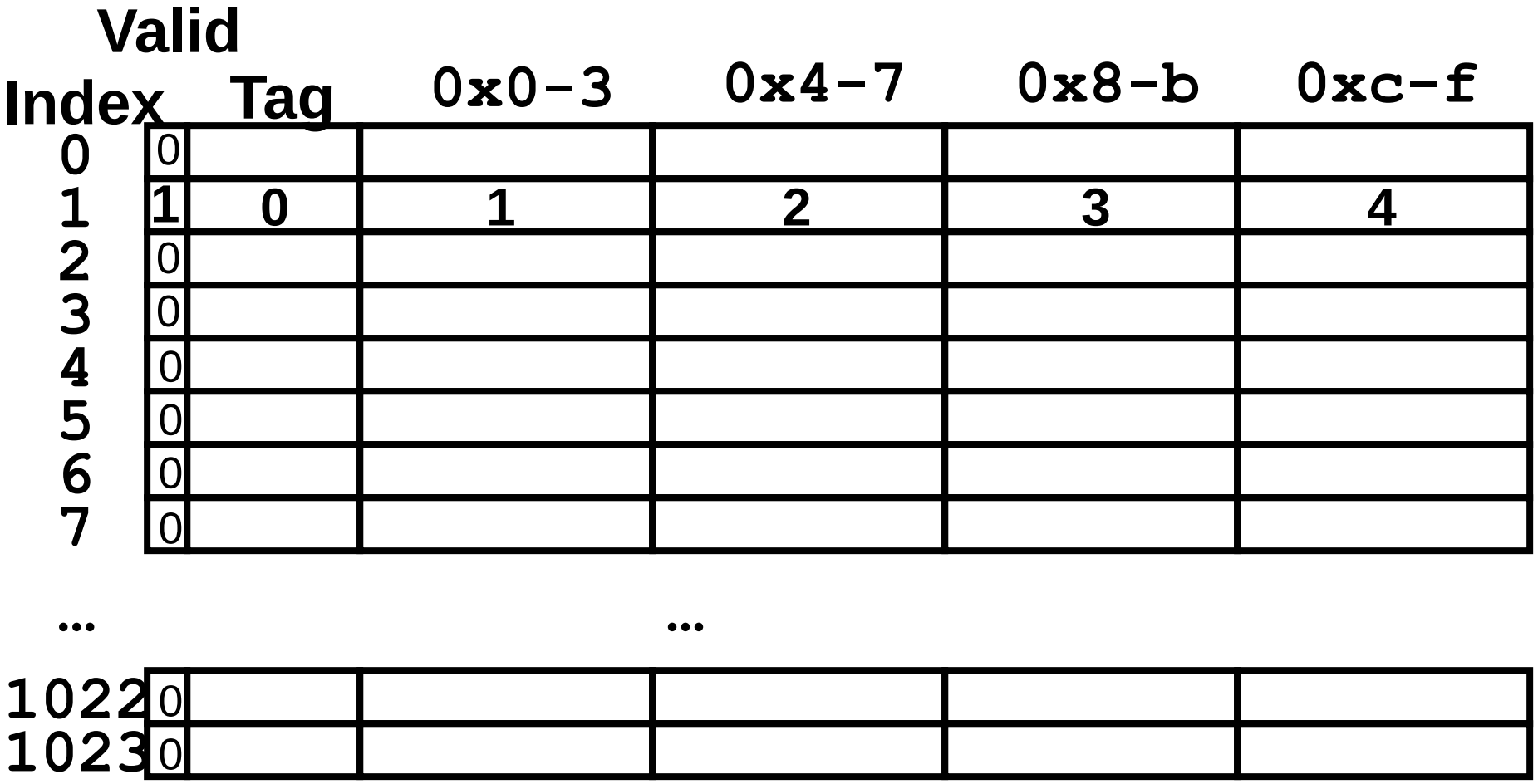


Slides from Patterson's 61C, Fall 2001

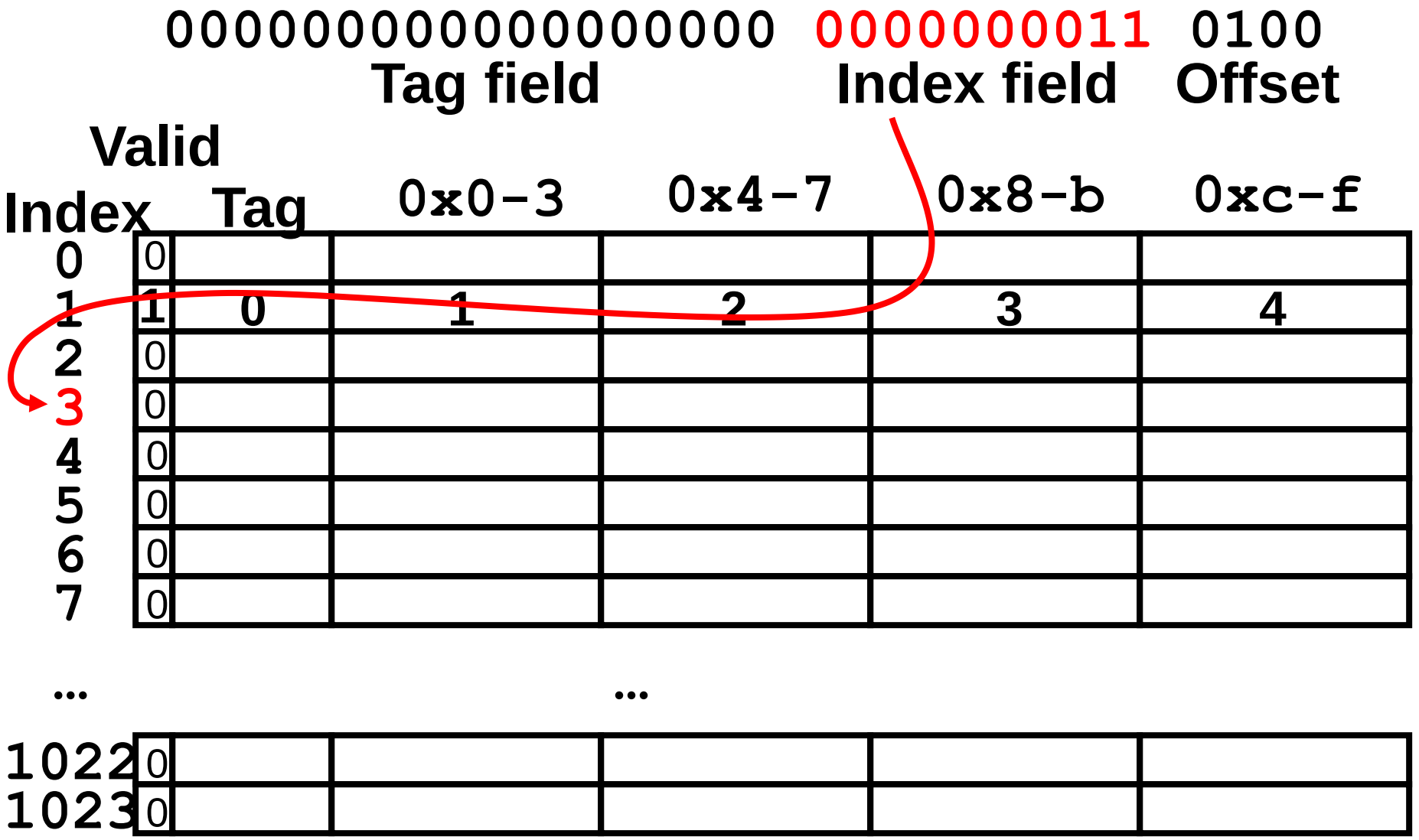
Read 0x00000034

00000000000000000000 0000000011 0100

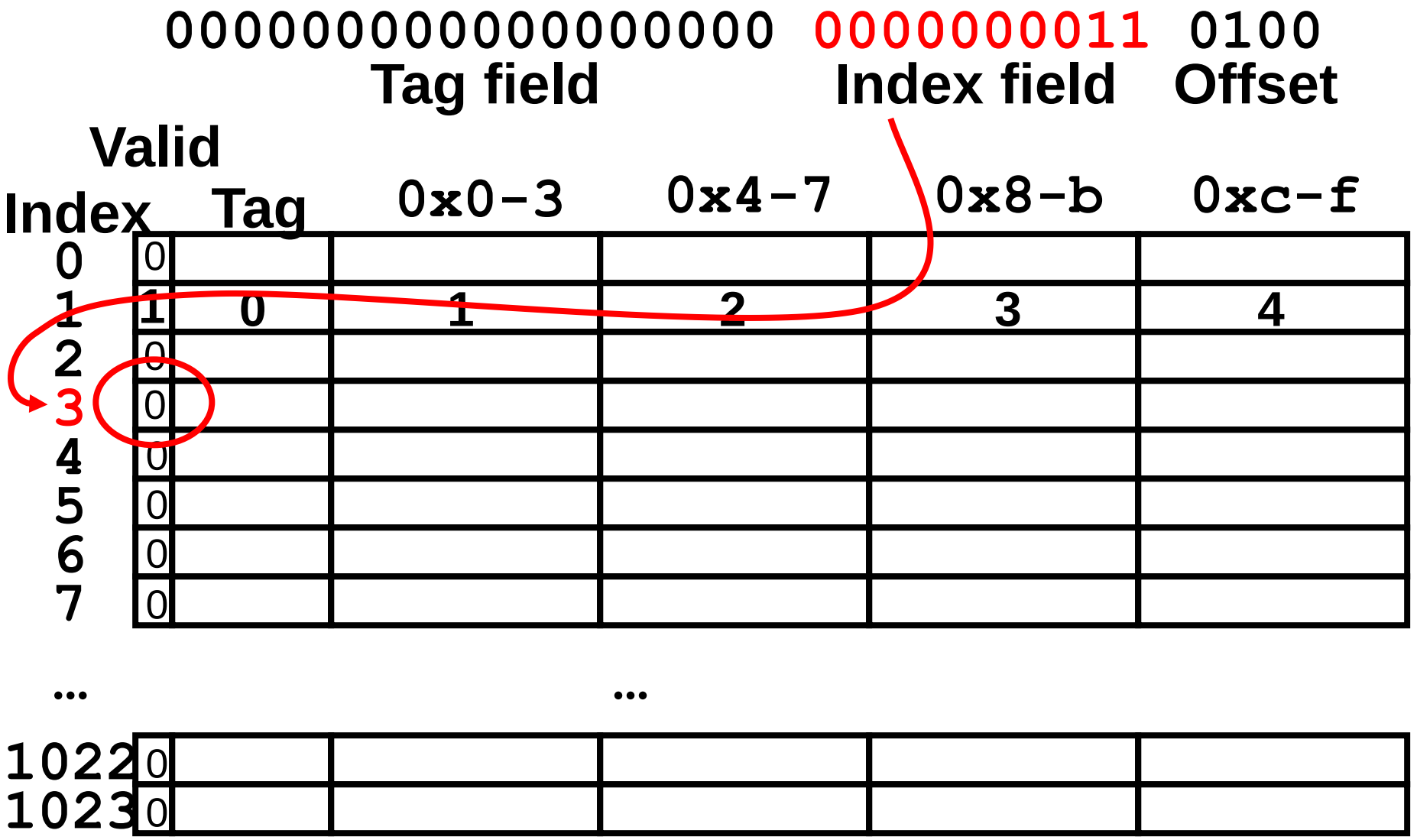
Tag field | Index field | Offset



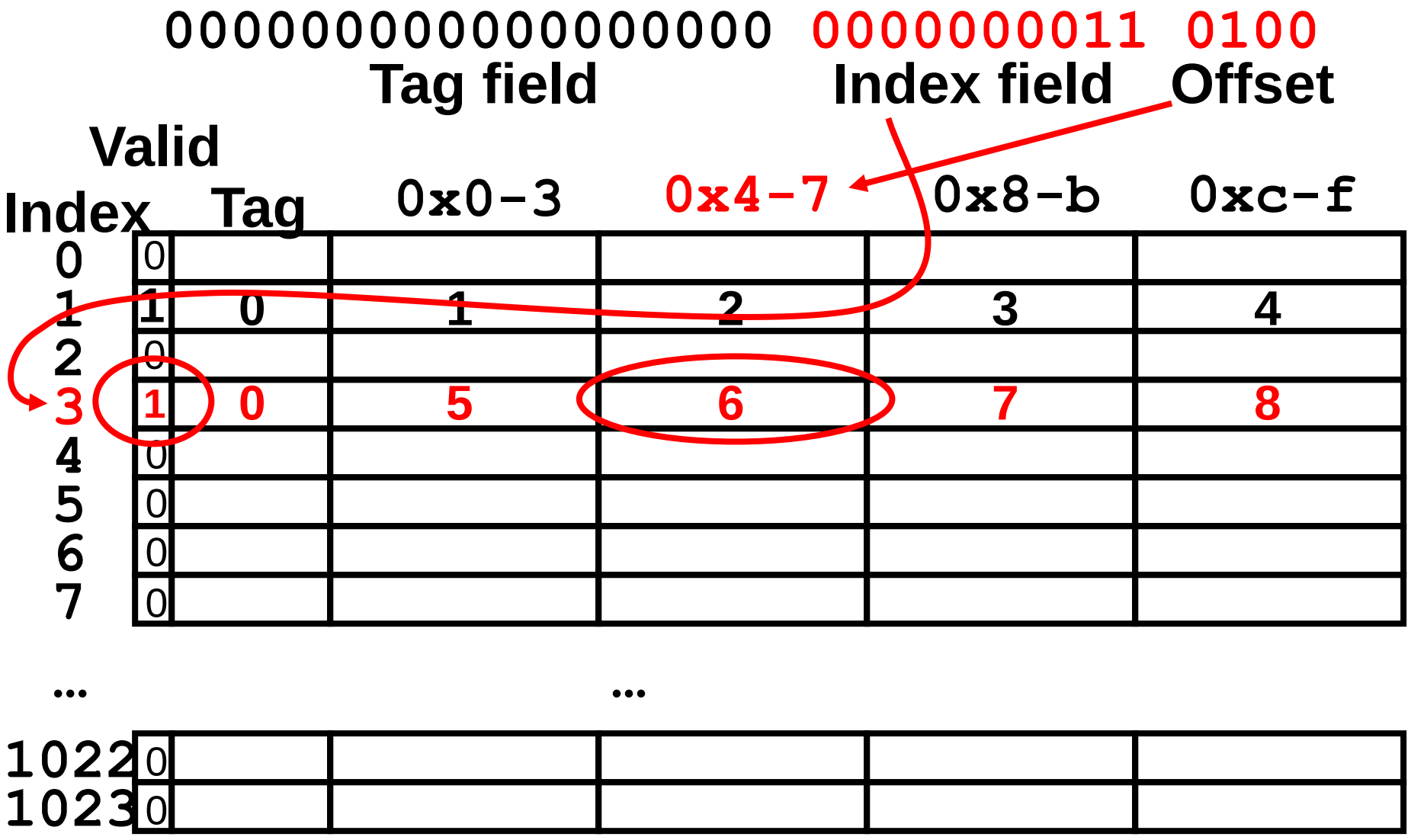
So read block 3



No valid data



Load that cache block, return word 6



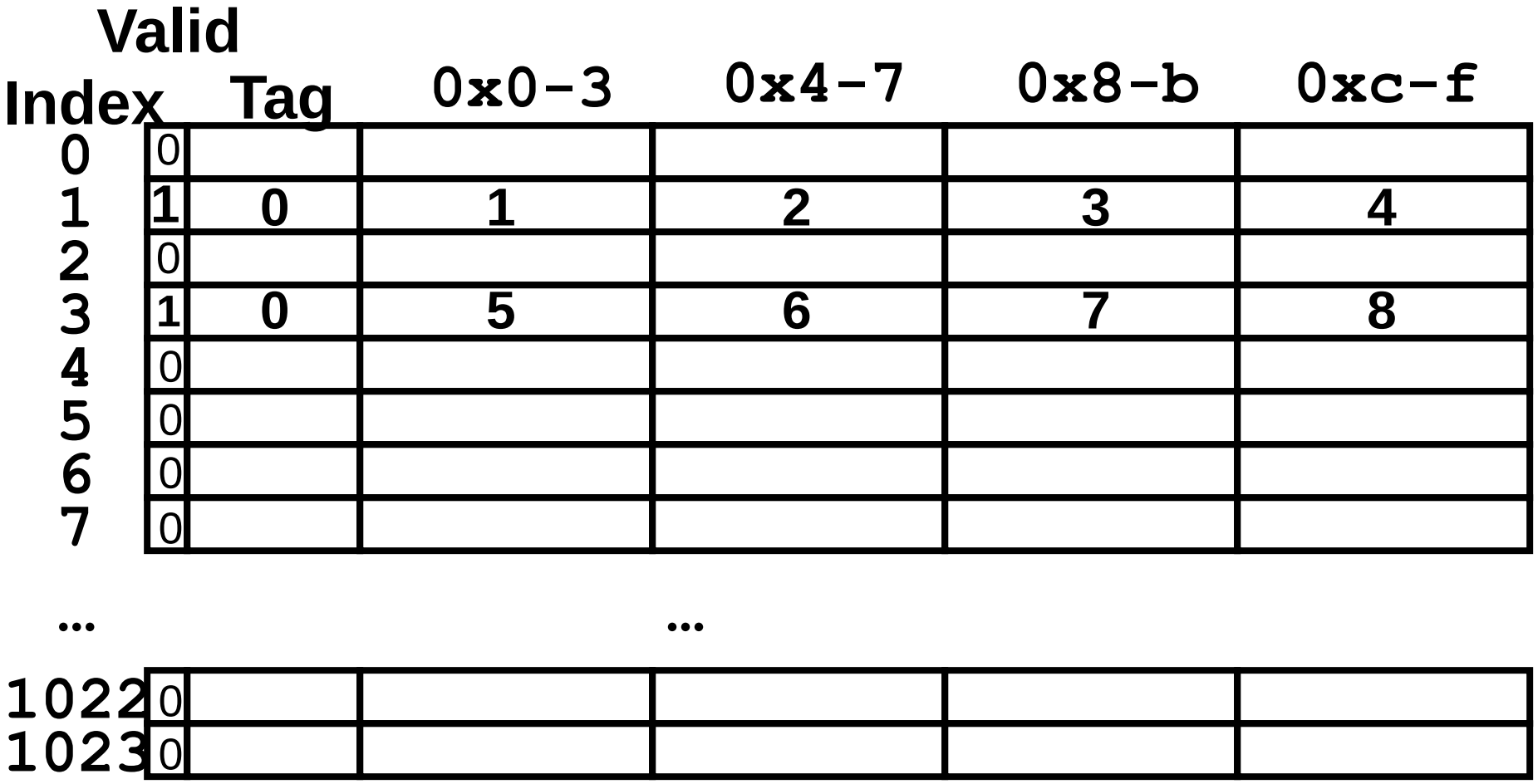
Address (hex)	Value of Word
…	…
00000010	1
00000014	2
00000018	3
0000001C	4
…	…
00000030	5
00000034	6
00000038	7
0000003C	8
…	..
00008010	9
00008014	10
00008018	11
0000801C	12
…	…

Slides from Patterson's 61C, Fall 2001

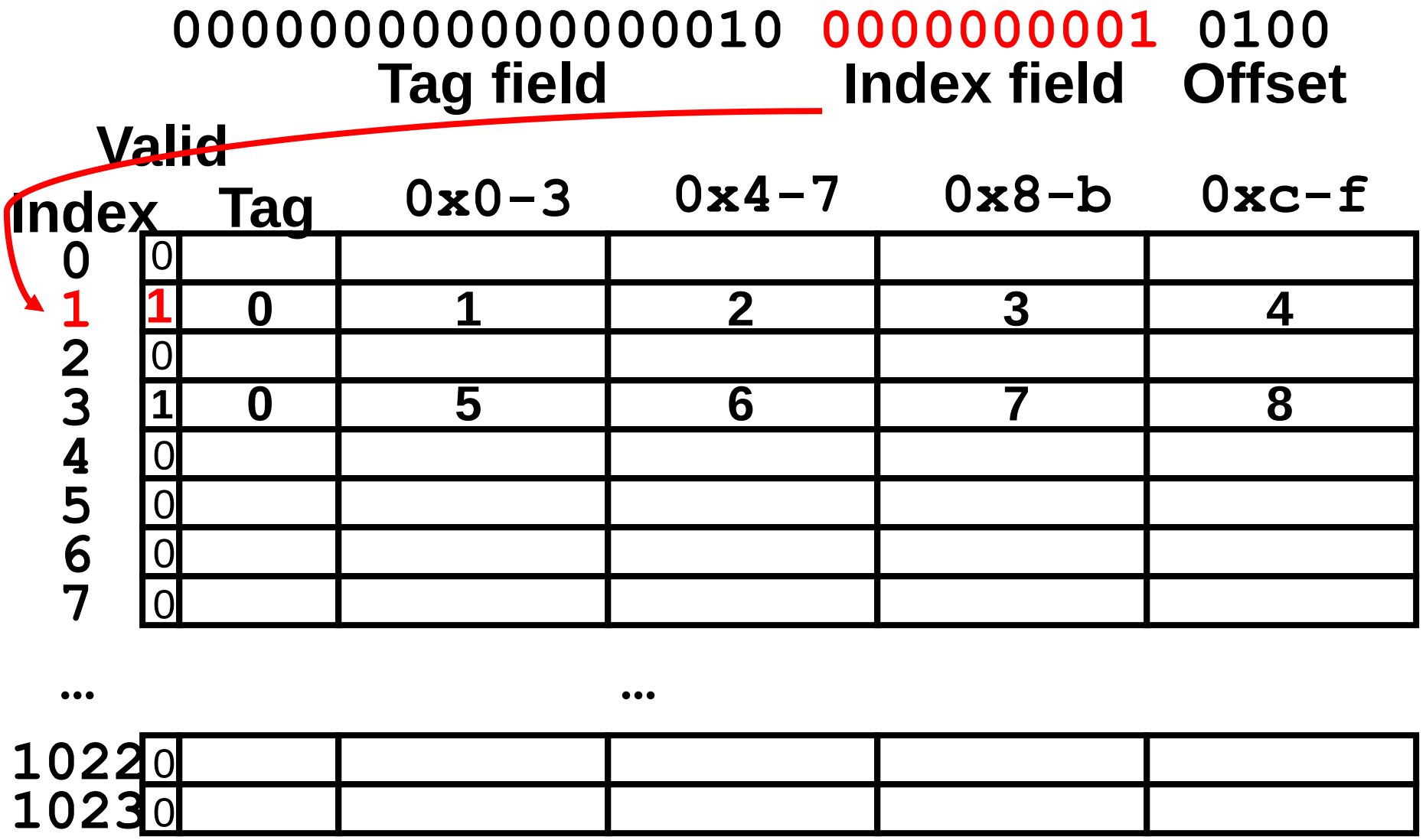
Read 0x00008014

0000000000000010 0000000001 0100

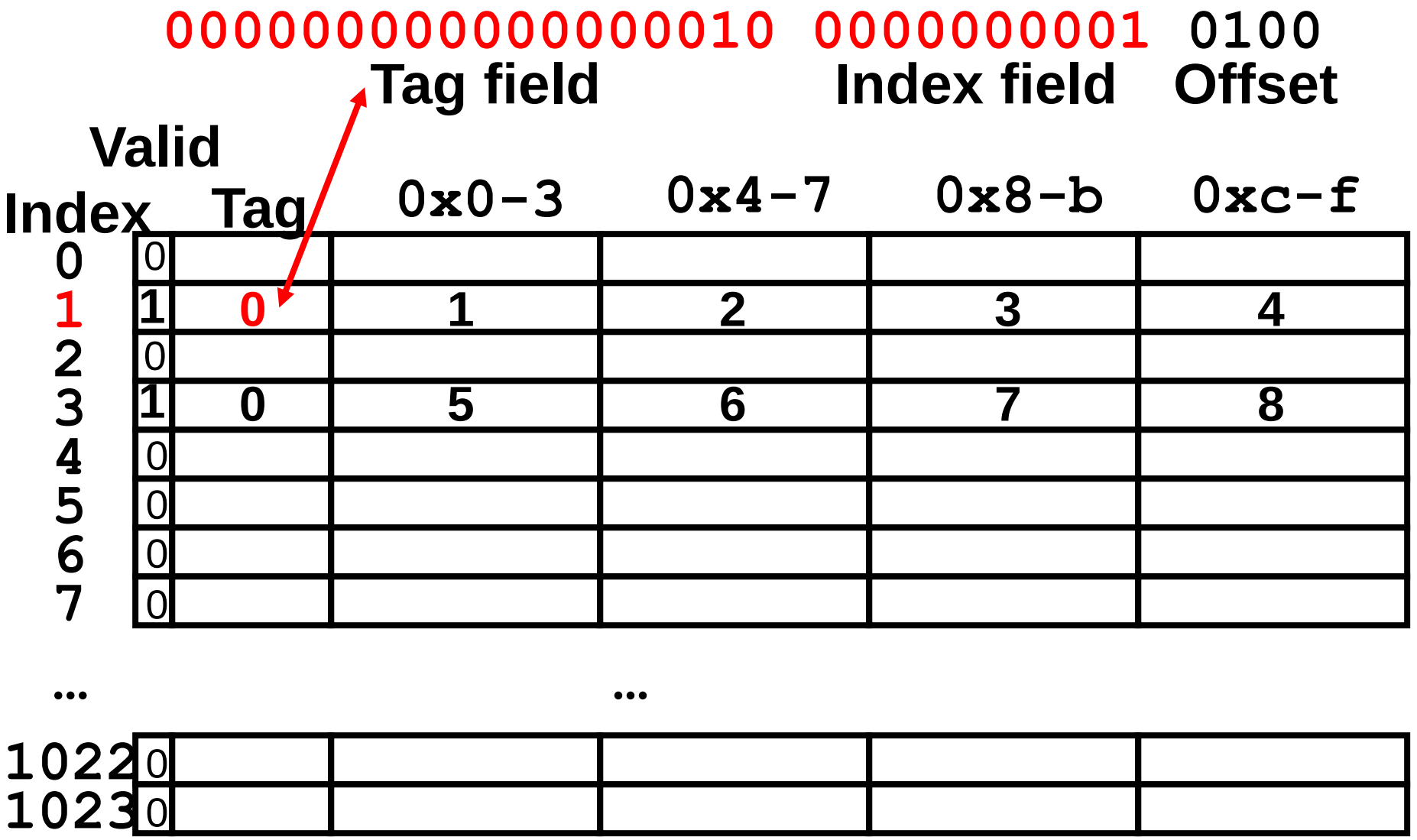
Tag field | Index field | Offset



So we read block 1, Data is Valid



Cache Block 1 Tag does not match (0 != 2)



Miss, replace block 1 with new data & tag

0000000000000010 0000000001 0100

Tag field | Index field | Offset

Index	Valid	Tag	0x0-3	0x4-7	0x8-b	0xc-f
0	0					
1	1	2	9	10	11	12
2	0					
3	1	0	5	6	7	8
4	0					
5	0					
6	0					
7	0					
…			…			
1022	0					
1023	0					

Address (hex)	Value of Word
…	…
00000010	1
00000014	2
00000018	3
0000001C	4
…	…
00000030	5
00000034	6
00000038	7
0000003C	8
…	..
00008010	9
00008014	10
00008018	11
0000801C	12
…	…

And return word 10

0000000000000010 0000000001 0100

Tag field | Index field | Offset

Index	Valid	Tag	0x0-3	0x4-7	0x8-b	0xc-f
0	0					
1	1	2	9	10	11	12
2	0					
3	1	0	5	6	7	h8
4	0					
5	0					
6	0					
7	0					
…			…			
1022	0					
1023	0					

Address (hex)	Value of Word
…	…
00000010	1
00000014	2
00000018	3
0000001C	4
…	…
00000030	5
00000034	6
00000038	7
0000003C	8
…	..
00008010	9
00008014	10
00008018	11
0000801C	12
…	…

Do an example yourself. What happens?

- Cache: Hit, Miss, Miss with replace ?
  Values returned: 1 ,2, 3, 4, 5, …, 11, 12 ?
- Read address 0x00000030 ?
  `0000000000000000 0000000011 0000`
- Read address 0x0000001c ?
  `0000000000000000 0000000001 1100`

Cache

Index	Valid	Tag	0x0-3	0x4-7	0x8-b	0xc-f
0	0					
1	1	2	9	10	11	12
2	0					
3	1	0	5	6	7	8
4	0					
5	0					
6	0					
7	0					
…				…		

Answers

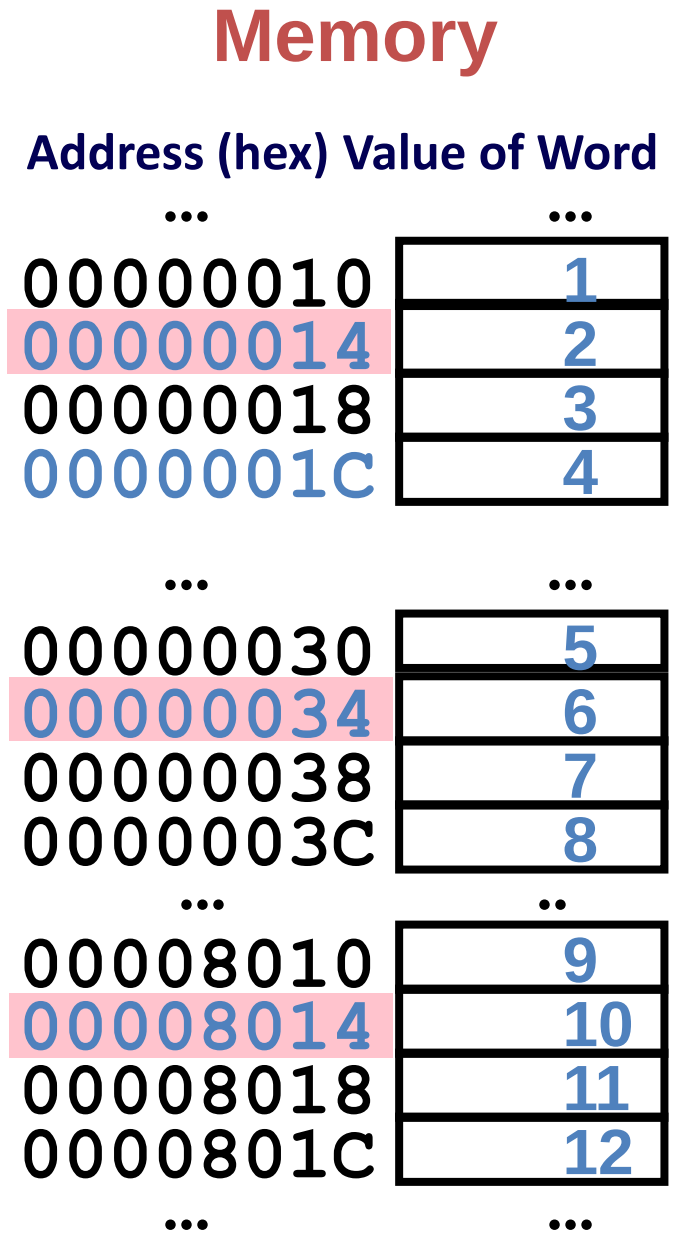
- 0x00000030 a hit

  Index = 3, Tag matches,
  Offset = 0, value = 5

- 0x0000001c a miss

  Index = 1, Tag mismatch, so replace from memory,
  Offset = 0xc, value = 4

- Therefore, returned values are:
  - 0x00000030 = 5
  - 0x0000001c = 4



“And in Conclusion…”

- We would like to have the capacity of disk at the speed of the processor: unfortunately this is not feasible.
- So we create a memory hierarchy:
  - each successively higher level contains “most used” data from next lower level
  - exploits temporal locality and spatial locality
- Locality of reference is a Big Idea

Review and More Information

- Sections 5.1 - 5.3 of textbook