# Machine Structures

# Caches, Part I

# Outline

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

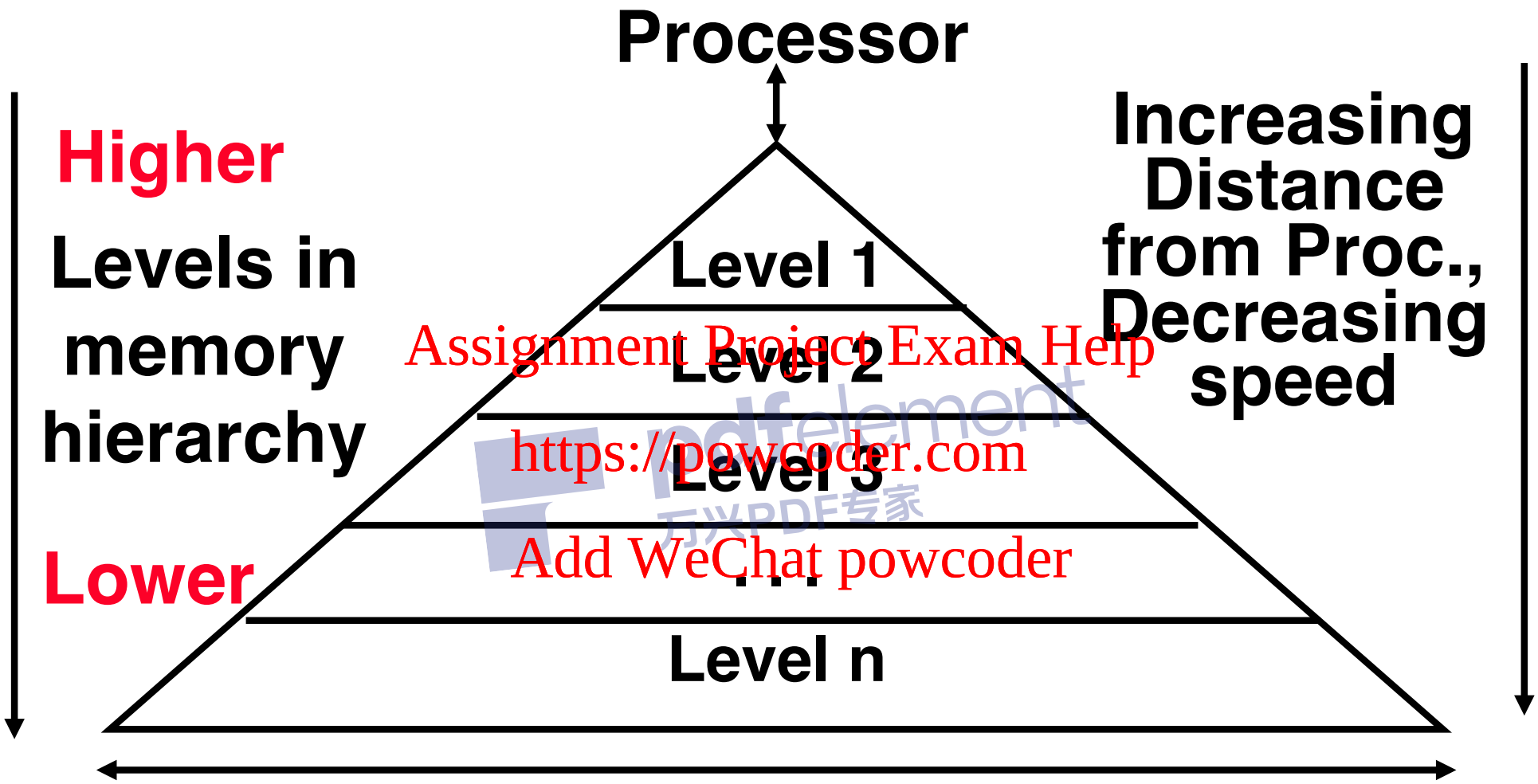
# Memory Hierarchy (1/4)

- 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)



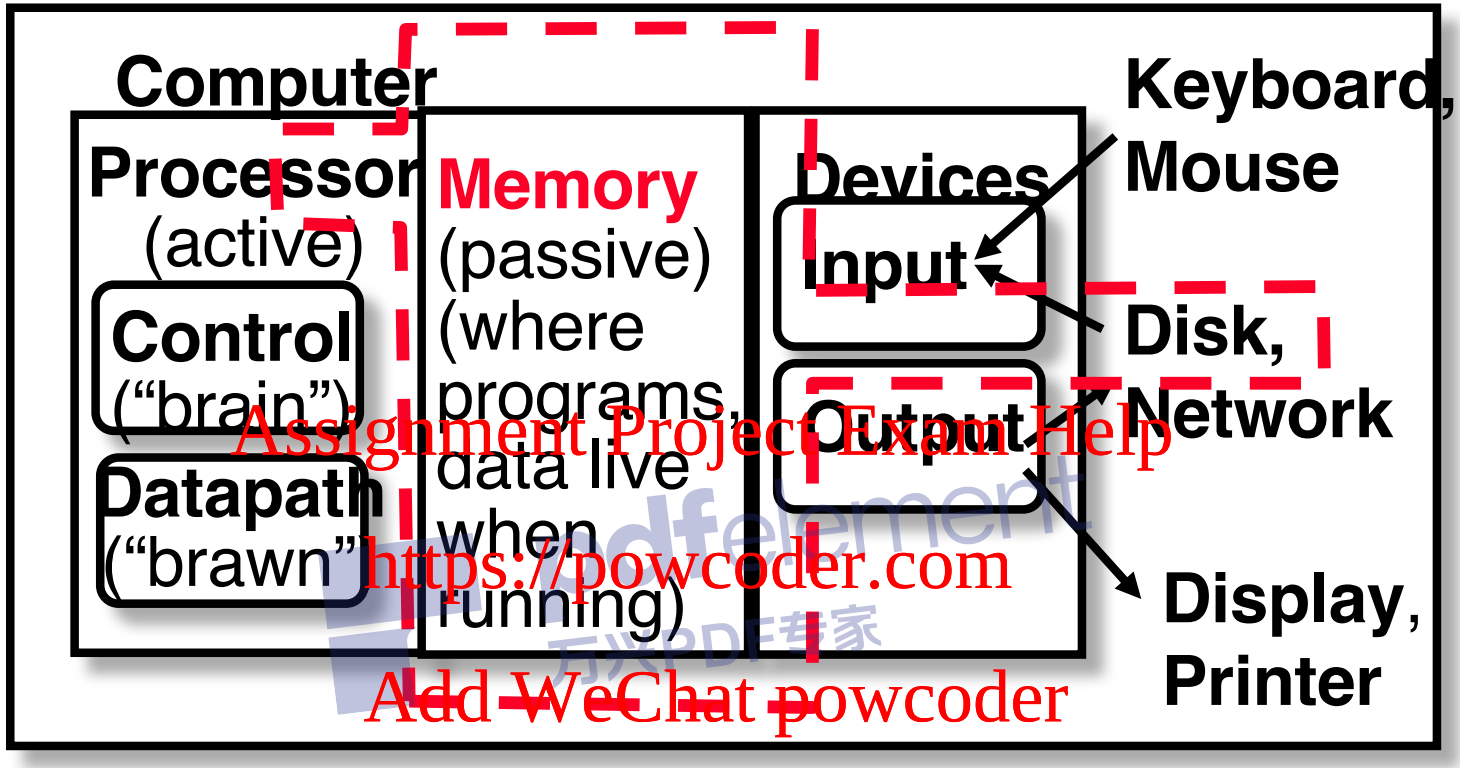



***As we move to deeper levels the latency goes up and price per bit goes down.***

# 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
  - Contain all the data in higher levels above it
- 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're writing a term paper (processor) 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 all lower 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

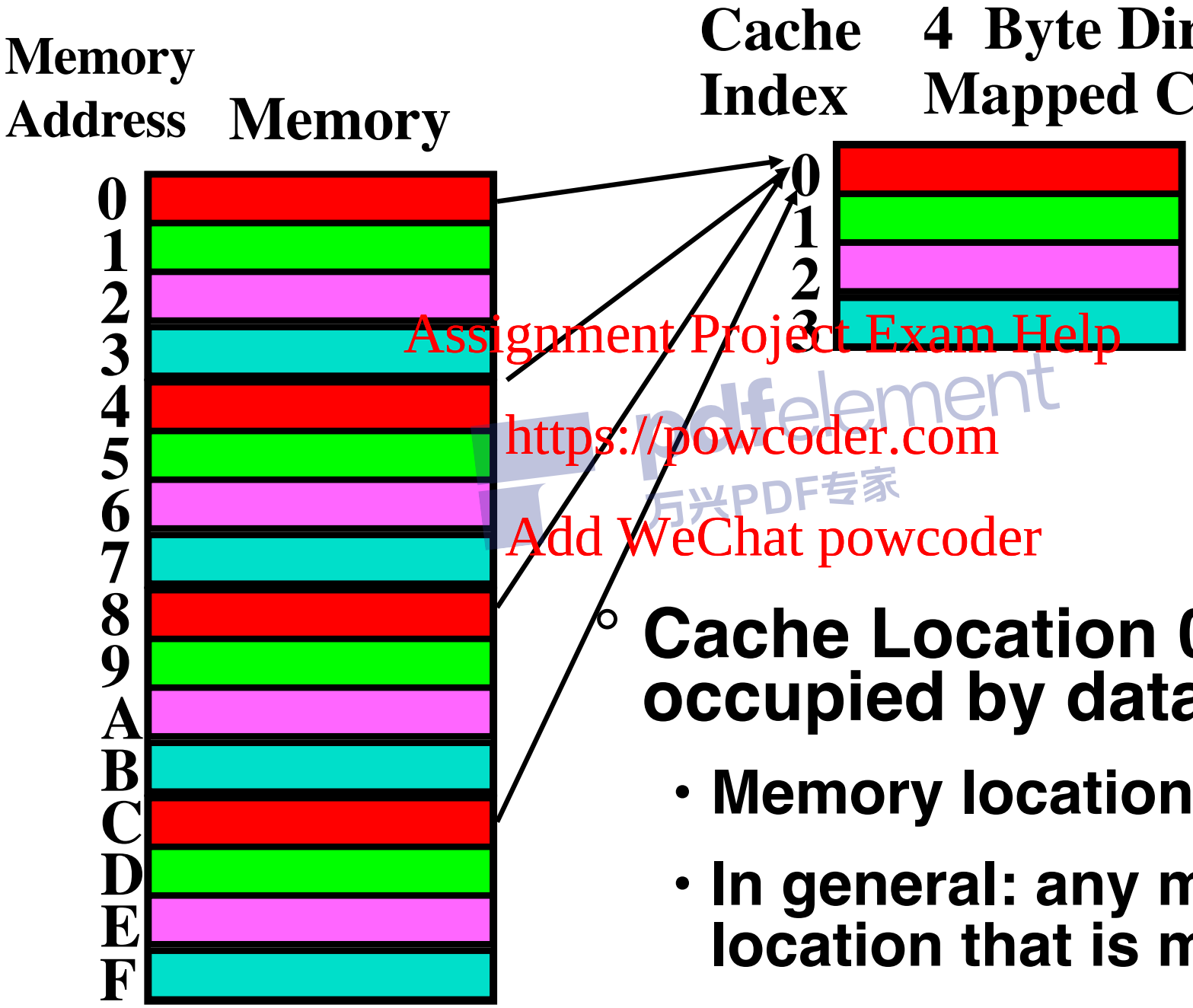
# Cache Design

- 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 for the data if it exists in the cache
  - 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

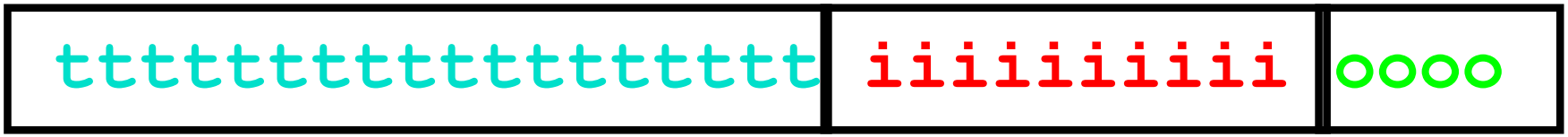
# Issues with Direct-Mapped

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.
- **Index**: specifies the cache index (which "row" of the cache we should look in)
- **Offset**: once we've found correct block, specifies which byte within the block we want
- **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 (1/3)

- Suppose we have a 16KB direct-mapped cache with 4 word blocks.
- Determine the size of the tag, index and offset fields if we're using a 32-bit architecture.
- 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 (2/3)

- 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 (since there's one block/row)

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

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

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

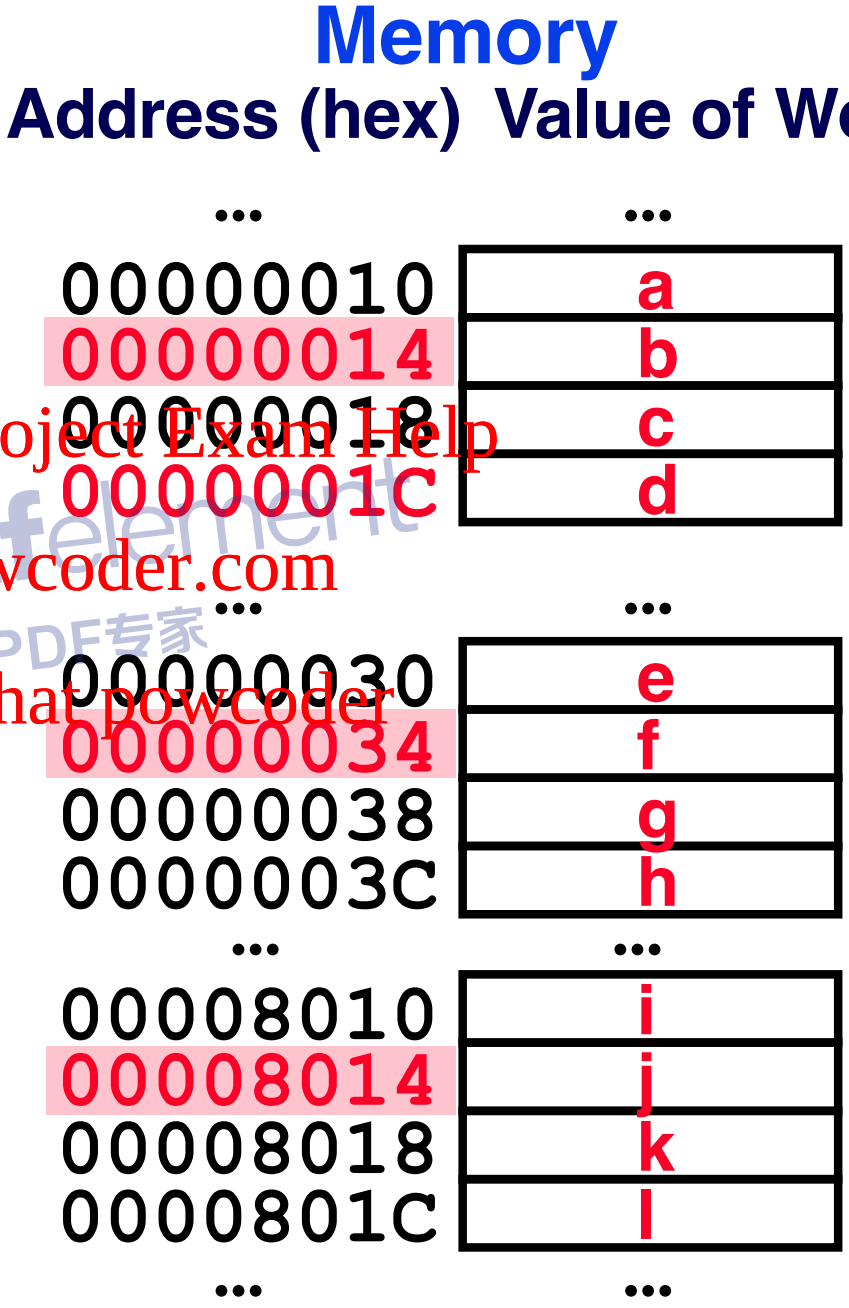
  - need 10 bits to specify this many rows

# Direct-Mapped Cache Example (3/3)

- Tag
  - used remaining bits as tag
  - tag length = mem addr length
    - offset
    - index
    - = 32 - 4 - 10 bits
    - = 18 bits
  - so 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:
  - only cache/memory level 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



```
00000000000000000 0000000001 0100
00000000000000000 0000000001 1100
00000000000000000 0000000011 0100
00000000000000010 0000000001 0100
```

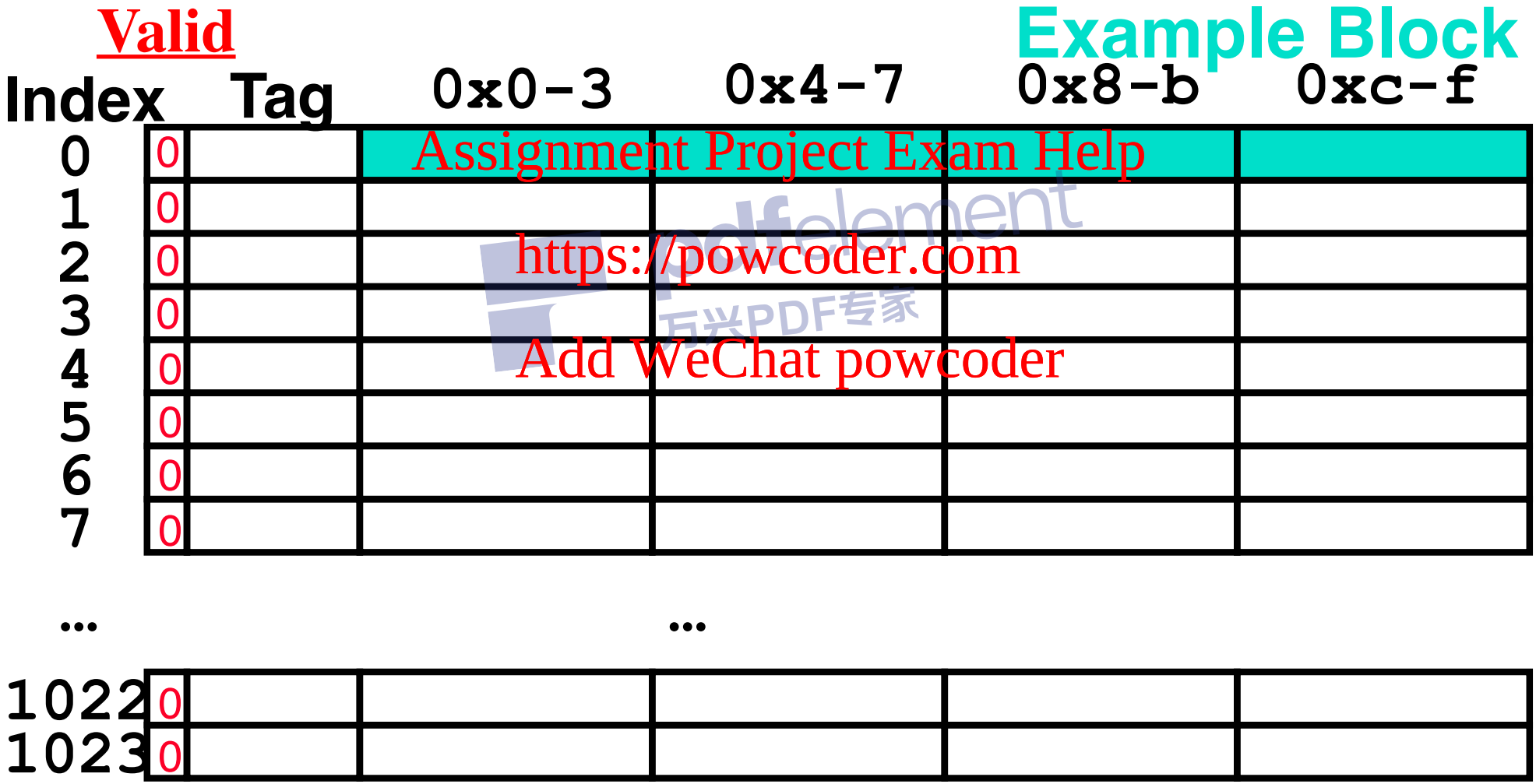
Tag Index Offset

# Accessing data in a direct mapped cache

- So 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

- **Valid bit:** determines whether anything is stored in that row (when computer initially turned on, all entries are invalid)



# Read 0x00000014 = 0…00 0..001 0100

° 00000000000000000000 0000000001 0100

Tag field | Index field | Offset

| Index | Valid | Tag | 0x0-3 | 0x4-7 | 0x8-b | 0xc-f |
|---|---|---|---|---|---|---|
| 0 | 0 | | | | | |
| 1 | 0 | | | | | |
| 2 | 0 | | | | | |
| 3 | 0 | | | | | |
| 4 | 0 | | | | | |
| 5 | 0 | | | | | |
| 6 | 0 | | | | | |
| 7 | 0 | | | | | |
| … | | | | … | | |
| 1022 | 0 | | | | | |
| 1023 | 0 | | | | | |

# So we read block 1 (0000000001)

° 00000000000000000 0000000001 0100

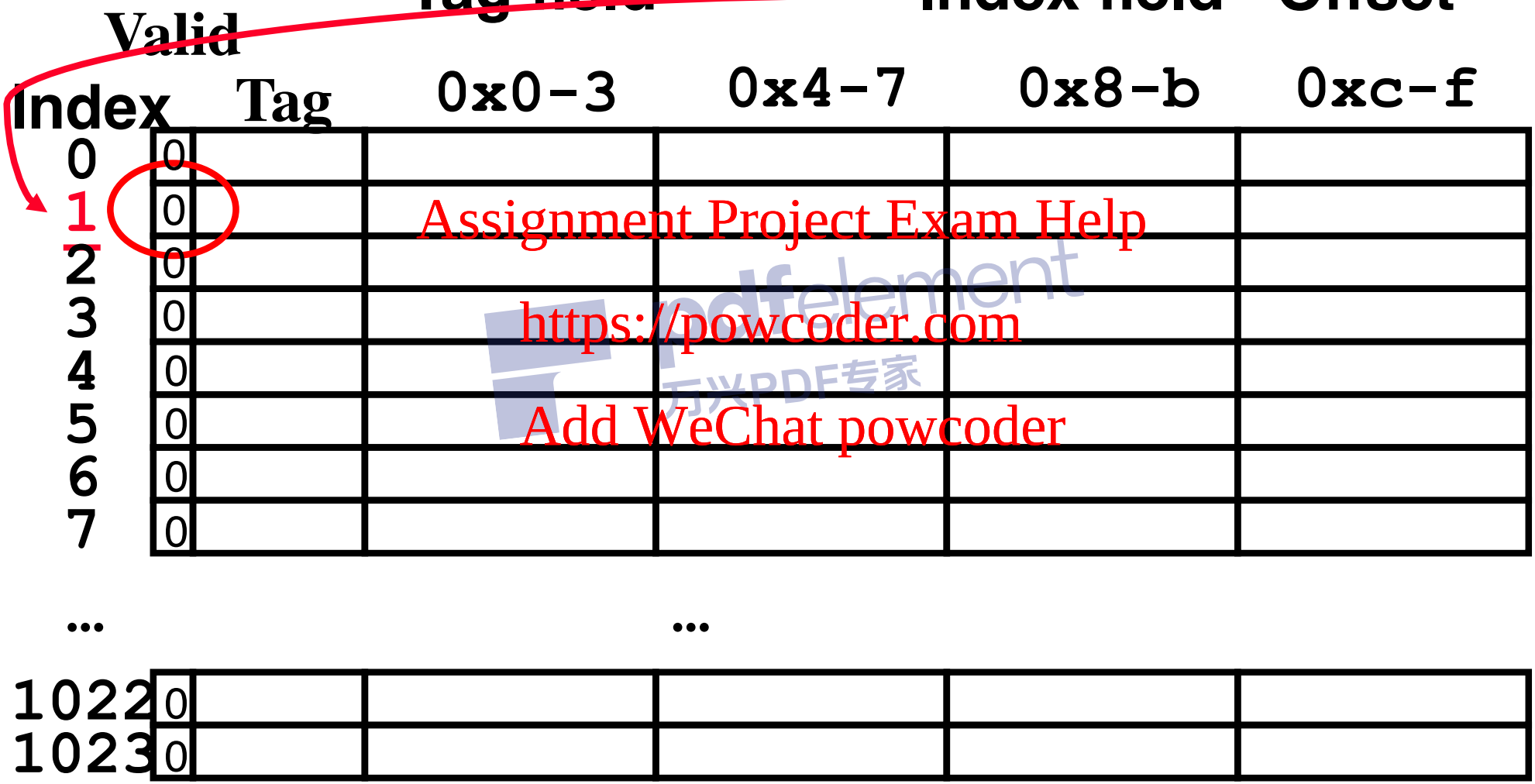
Tag field | Index field | Offset

| Index | Valid | Tag | 0x0-3 | 0x4-7 | 0x8-b | 0xc-f |
|---|---|---|---|---|---|---|
| 0 | 0 | | | | | |
| 1 | 0 | | | | | |
| 2 | 0 | | | | | |
| 3 | 0 | | | | | |
| 4 | 0 | | | | | |
| 5 | 0 | | | | | |
| 6 | 0 | | | | | |
| 7 | 0 | | | | | |
| … | | | … | | | |
| 1022 | 0 | | | | | |
| 1023 | 0 | | | | | |

# No valid data

° 00000000000000000000 0000000001 0100

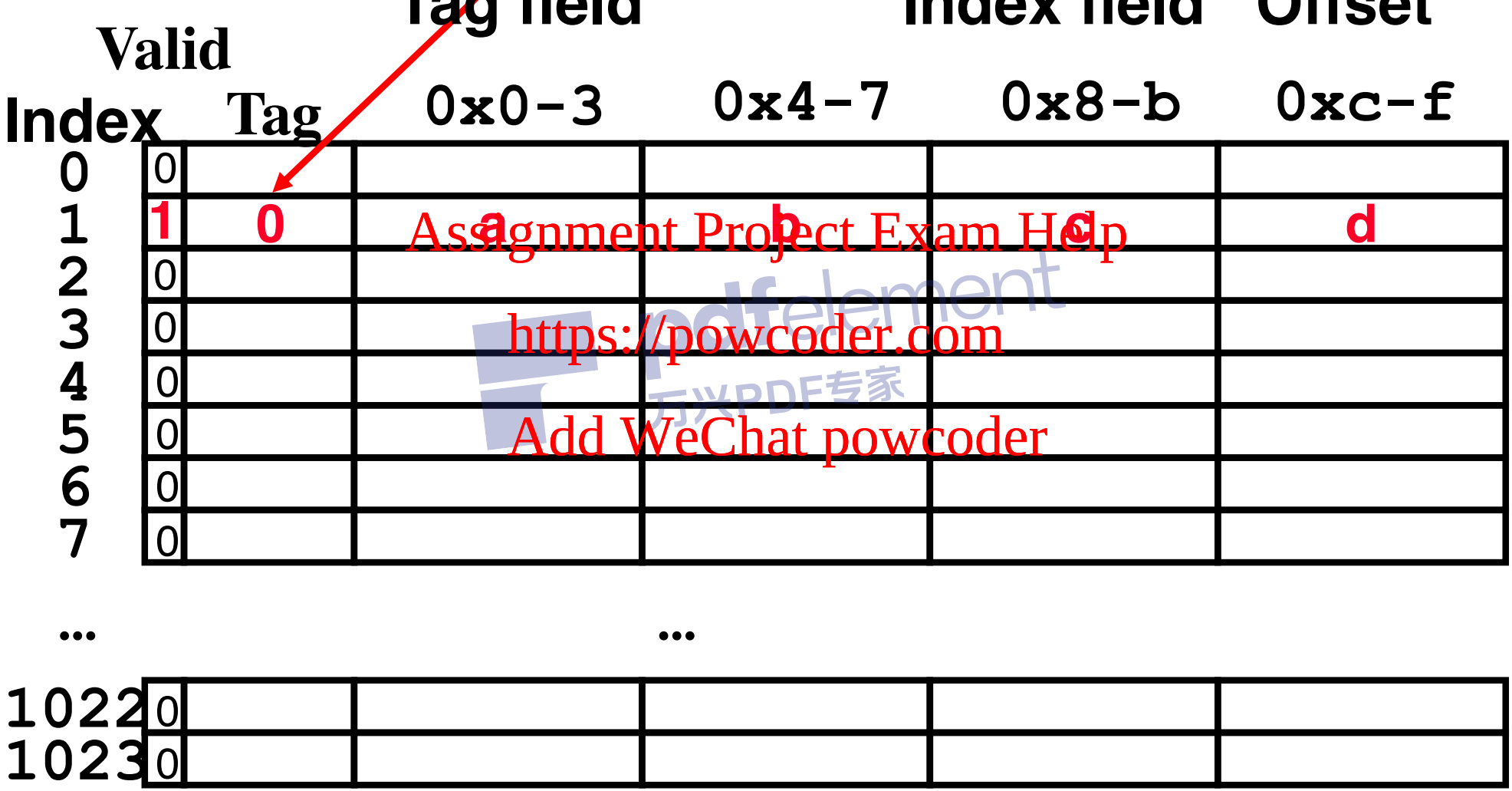
Tag field | Index field | Offset



# So load that data into cache, setting tag, valid

° 00000000000000000000 0000000001 0100

Tag field Index field Offset



# Read from cache at offset, return word

° 0000000000000000 0000000001 0100

Tag field | Index field | Offset

| Index | Valid | Tag | 0x0-3 | 0x4-7 | 0x8-b | 0xc-f |
|---|---|---|---|---|---|---|
| 0 | 0 | | | | | |
| 1 | 1 | 0 | a | b | c | d |
| 2 | 0 | | | | | |
| 3 | 0 | | | | | |
| 4 | 0 | | | | | |
| 5 | 0 | | | | | |
| 6 | 0 | | | | | |
| 7 | 0 | | | | | |
| … | | | | … | | |
| 1022 | 0 | | | | | |
| 1023 | 0 | | | | | |

# Read 0x0000001C = 0…00 0..001 1100

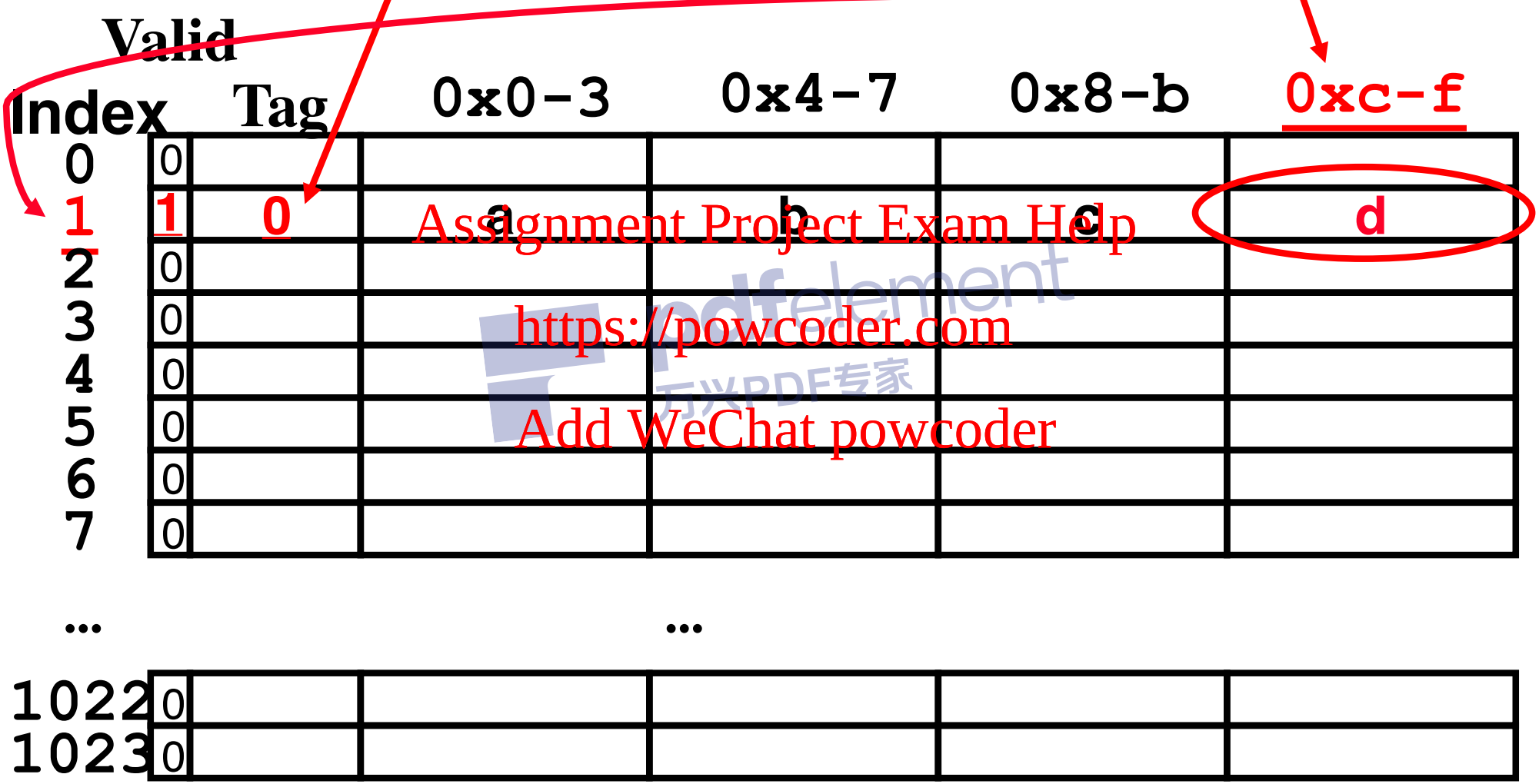
° 00000000000000000000 0000000001 1100

Tag field | Index field | Offset

| Index | Valid | Tag | 0x0-3 | 0x4-7 | 0x8-b | 0xc-f |
|---|---|---|---|---|---|---|
| 0 | 0 | | | | | |
| 1 | 1 | 0 | a | b | c | d |
| 2 | 0 | | | | | |
| 3 | 0 | | | | | |
| 4 | 0 | | | | | |
| 5 | 0 | | | | | |
| 6 | 0 | | | | | |
| 7 | 0 | | | | | |
| … | | | | … | | |
| 1022 | 0 | | | | | |
| 1023 | 0 | | | | | |

# Data valid, tag OK, so read offset return word d

° 00000000000000000000 0000000001 1100



# Read 0x00000034 = 0…00 0..011 0100

° 00000000000000000000 0000000011 0100

Tag field | Index field | Offset

| Index | Valid | Tag | 0x0-3 | 0x4-7 | 0x8-b | 0xc-f |
|---|---|---|---|---|---|---|
| 0 | 0 | | | | | |
| 1 | 1 | 0 | a | b | c | d |
| 2 | 0 | | | | | |
| 3 | 0 | | | | | |
| 4 | 0 | | | | | |
| 5 | 0 | | | | | |
| 6 | 0 | | | | | |
| 7 | 0 | | | | | |
| … | | | | … | | |
| 1022 | 0 | | | | | |
| 1023 | 0 | | | | | |

# So read block 3

° 00000000000000000000 0000000011 0100

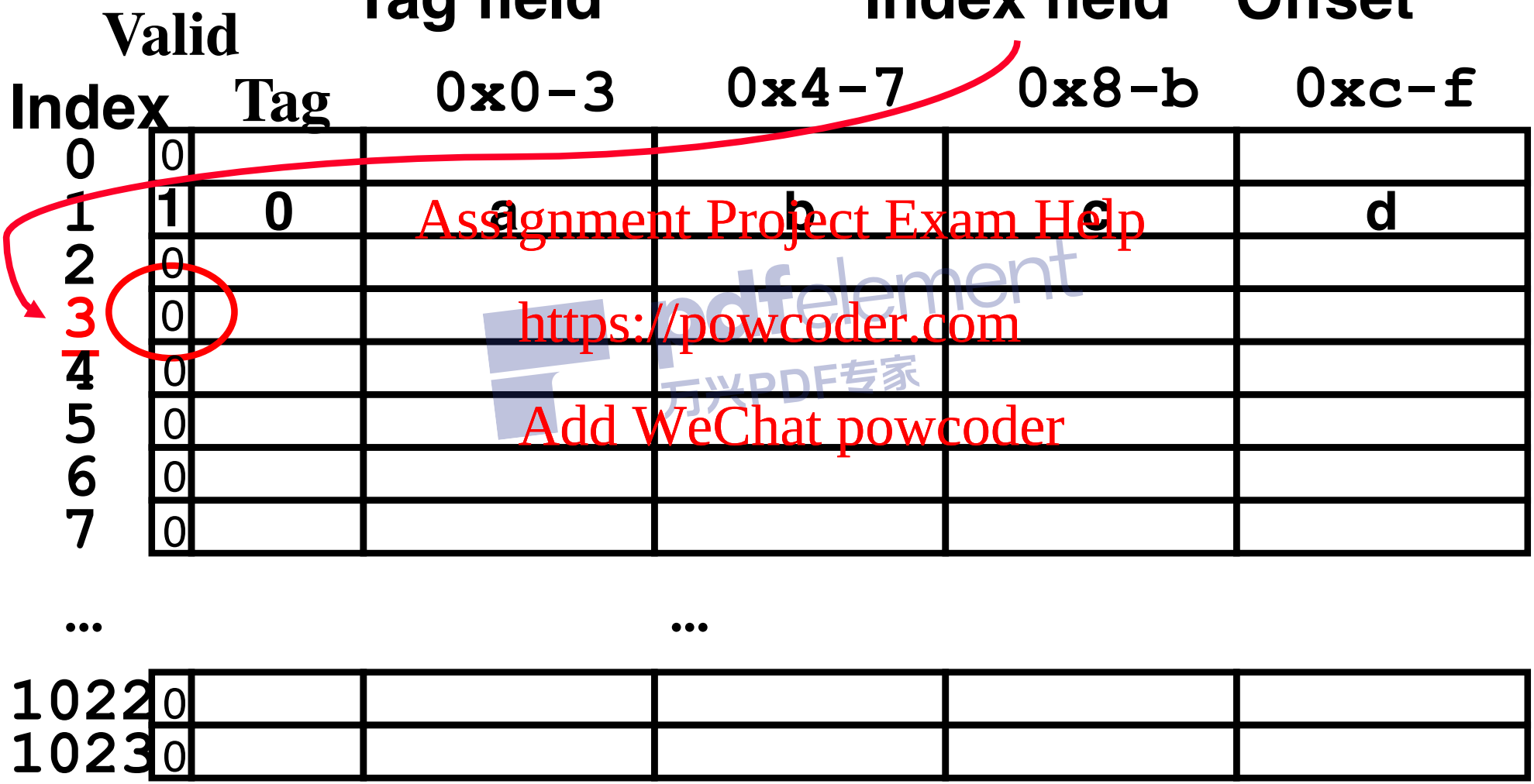
Tag field | Index field | Offset

| Index | Valid | Tag | 0x0-3 | 0x4-7 | 0x8-b | 0xc-f |
|---|---|---|---|---|---|---|
| 0 | 0 | | | | | |
| 1 | 1 | 0 | a | b | c | d |
| 2 | 0 | | | | | |
| 3 | 0 | | | | | |
| 4 | 0 | | | | | |
| 5 | 0 | | | | | |
| 6 | 0 | | | | | |
| 7 | 0 | | | | | |
| ... | | | | ... | | |
| 1022 | 0 | | | | | |
| 1023 | 0 | | | | | |

# No valid data

° 00000000000000000000 0000000011 0100

Tag field | Index field | Offset



# Load that cache block, return word

° 0000000000000000 0000000011 0100

Tag field | Index field | Offset

| Index | Valid | Tag | 0x0-3 | 0x4-7 | 0x8-b | 0xc-f |
|---|---|---|---|---|---|---|
| 0 | 0 | | | | | |
| 1 | 1 | 0 | a | b | c | d |
| 2 | 0 | | | | | |
| 3 | 1 | 0 | e | f | g | h |
| 4 | 0 | | | | | |
| 5 | 0 | | | | | |
| 6 | 0 | | | | | |
| 7 | 0 | | | | | |
| … | | | | … | | |
| 1022 | 0 | | | | | |
| 1023 | 0 | | | | | |

# Read 0x00008014 = 0…10 0..001 0100

° 0000000000000010 0000000001 0100

Tag field | Index field | Offset

| Index | Valid | Tag | 0x0-3 | 0x4-7 | 0x8-b | 0xc-f |
|---|---|---|---|---|---|---|
| 0 | 0 | | | | | |
| 1 | 1 | 0 | a | b | c | d |
| 2 | 0 | | | | | |
| 3 | 1 | 0 | e | f | g | h |
| 4 | 0 | | | | | |
| 5 | 0 | | | | | |
| 6 | 0 | | | | | |
| 7 | 0 | | | | | |
| … | | | | … | | |
| 1022 | 0 | | | | | |
| 1023 | 0 | | | | | |

# So read Cache Block 1, Data is Valid

° 0000000000000010 0000000001 0100

Tag field | Index field | Offset

| Index | Valid | Tag | 0x0-3 | 0x4-7 | 0x8-b | 0xc-f |
|---|---|---|---|---|---|---|
| 0 | 0 | | | | | |
| 1 | 1 | 0 | a | b | c | d |
| 2 | 0 | | | | | |
| 3 | 1 | 0 | e | f | g | h |
| 4 | 0 | | | | | |
| 5 | 0 | | | | | |
| 6 | 0 | | | | | |
| 7 | 0 | | | | | |
| … | | | | … | | |
| 1022 | 0 | | | | | |
| 1023 | 0 | | | | | |

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

° 0000000000000010 0000000001 0100

Tag field | Index field | Offset

| Index | Valid | Tag | 0x0-3 | 0x4-7 | 0x8-b | 0xc-f |
|---|---|---|---|---|---|---|
| 0 | 0 | | | | | |
| 1 | 1 | 0 | a | b | c | d |
| 2 | 0 | | | | | |
| 3 | 1 | 0 | e | f | g | h |
| 4 | 0 | | | | | |
| 5 | 0 | | | | | |
| 6 | 0 | | | | | |
| 7 | 0 | | | | | |
| ... | | | ... | | | |
| 1022 | 0 | | | | | |
| 1023 | 0 | | | | | |

# Miss, so 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 | i | j | k | l |
| 2 | 0 | | | | | |
| 3 | 1 | 0 | e | f | g | h |
| 4 | 0 | | | | | |
| 5 | 0 | | | | | |
| 6 | 0 | | | | | |
| 7 | 0 | | | | | |
| … | | | | … | | |
| 1022 | 0 | | | | | |
| 1023 | 0 | | | | | |

# And return word

° 0000000000000010 0000000001 0100

Tag field | index field | Offset

| Index | Valid | Tag | 0x0-3 | 0x4-7 | 0x8-b | 0xc-f |
|---|---|---|---|---|---|---|
| 0 | 0 | | | | | |
| 1 | 1 | 2 | i | j | k | l |
| 2 | 0 | | | | | |
| 3 | 1 | 0 | e | f | g | h |
| 4 | 0 | | | | | |
| 5 | 0 | | | | | |
| 6 | 0 | | | | | |
| 7 | 0 | | | | | |
| … | | | | … | | |
| 1022 | 0 | | | | | |
| 1023 | 0 | | | | | |

# Do an example yourself. What happens?

- Chose from: Cache:Hit, Miss, Miss w. replace
  Values returned: a ,b, c, d, e, ..., k, l
- 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 | i | j | k | l |
| 2 | 0 | | | | | |
| 3 | 1 | 0 | e | f | g | h |
| 4 | 0 | | | | | |
| 5 | 0 | | | | | |
| 6 | 0 | | | | | |
| 7 | 0 | | | | | |
| … | | | | … | | |

# Answers

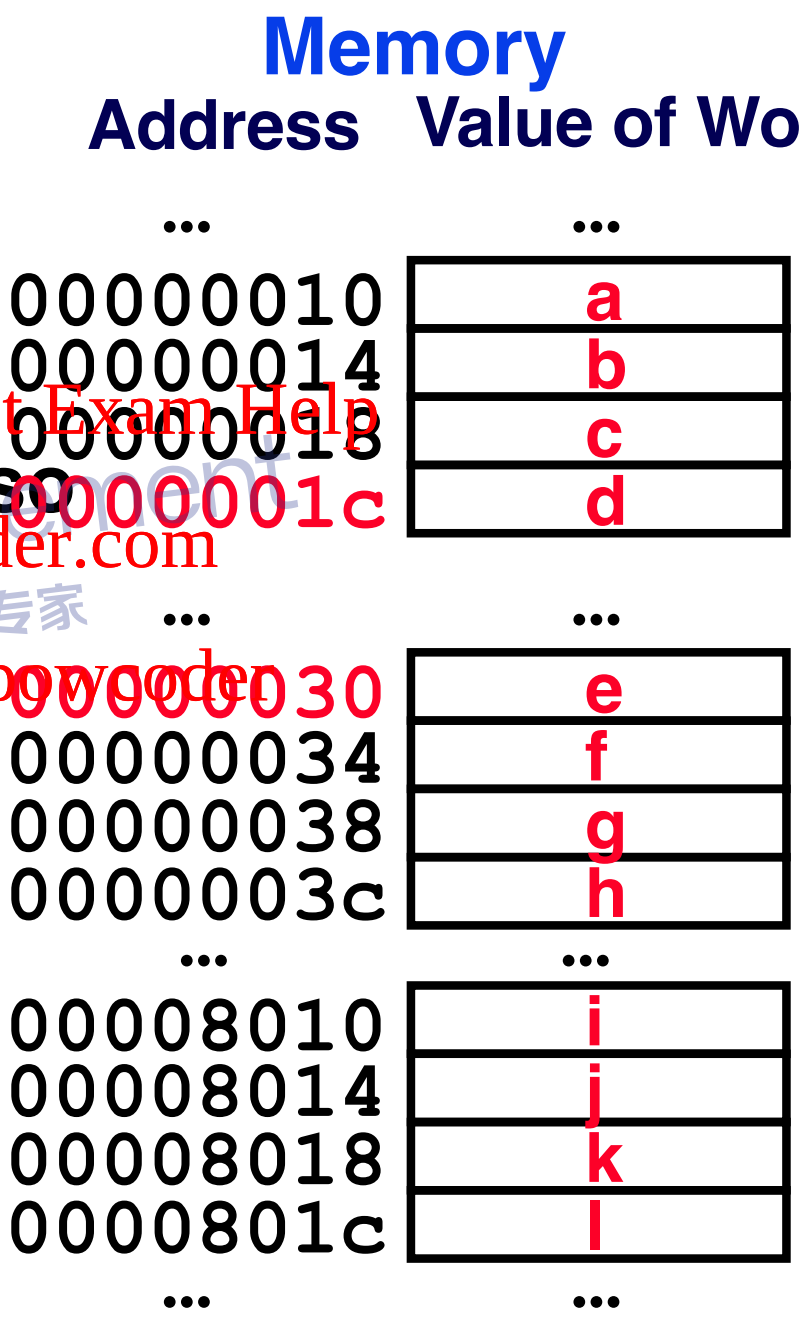
- 0x00000030 a hit

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

- 0x0000001c a miss

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

- Therefore, returned values are:
  - 0x00000030 = e
  - 0x0000001c = d



# “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
  - do the common case fast, worry less about the exceptions (design principle of MIPS)
- Locality of reference is a Big Idea