Caches II

CSE 351 Spring 2022

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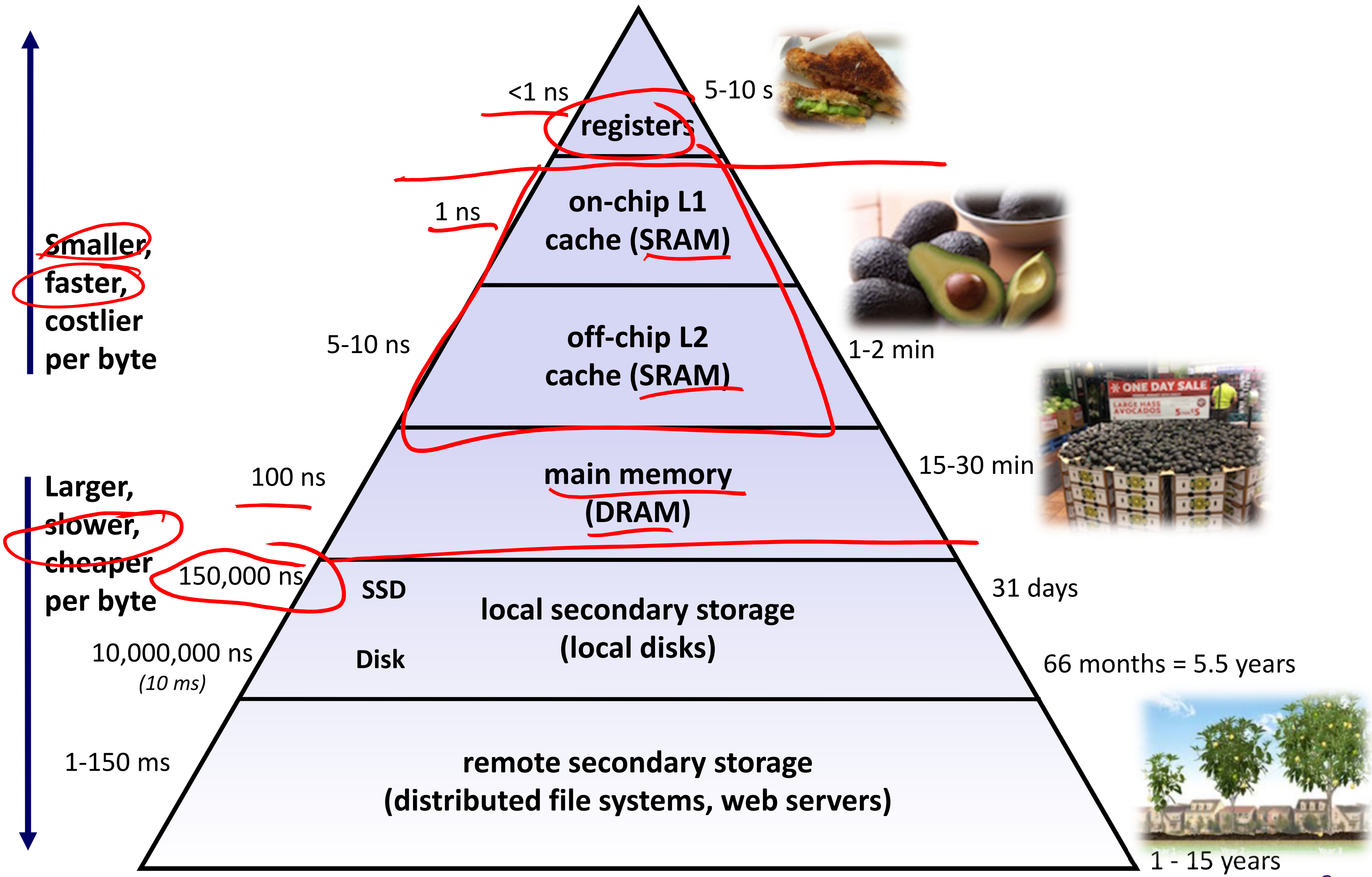
Relevant Course Information

- **Midterm due TONIGHT** Wednesday 5/04 11:59pm
- hw15 due Friday (5/06)
- Mid-quarter Survey due Saturday (5/07)

- hw16 due Monday (5/09)
- Lab 3 due Wednesday (5/11)
  - You will have everything you need for this now!
  - Some discussion in section this week
  - Last part of hw15 (due Fri 5/06) is useful for Lab 3
- hw17 due *next* Friday (5/13)
  - Don't wait too long, this is a BIG hw

An Example Memory Hierarchy

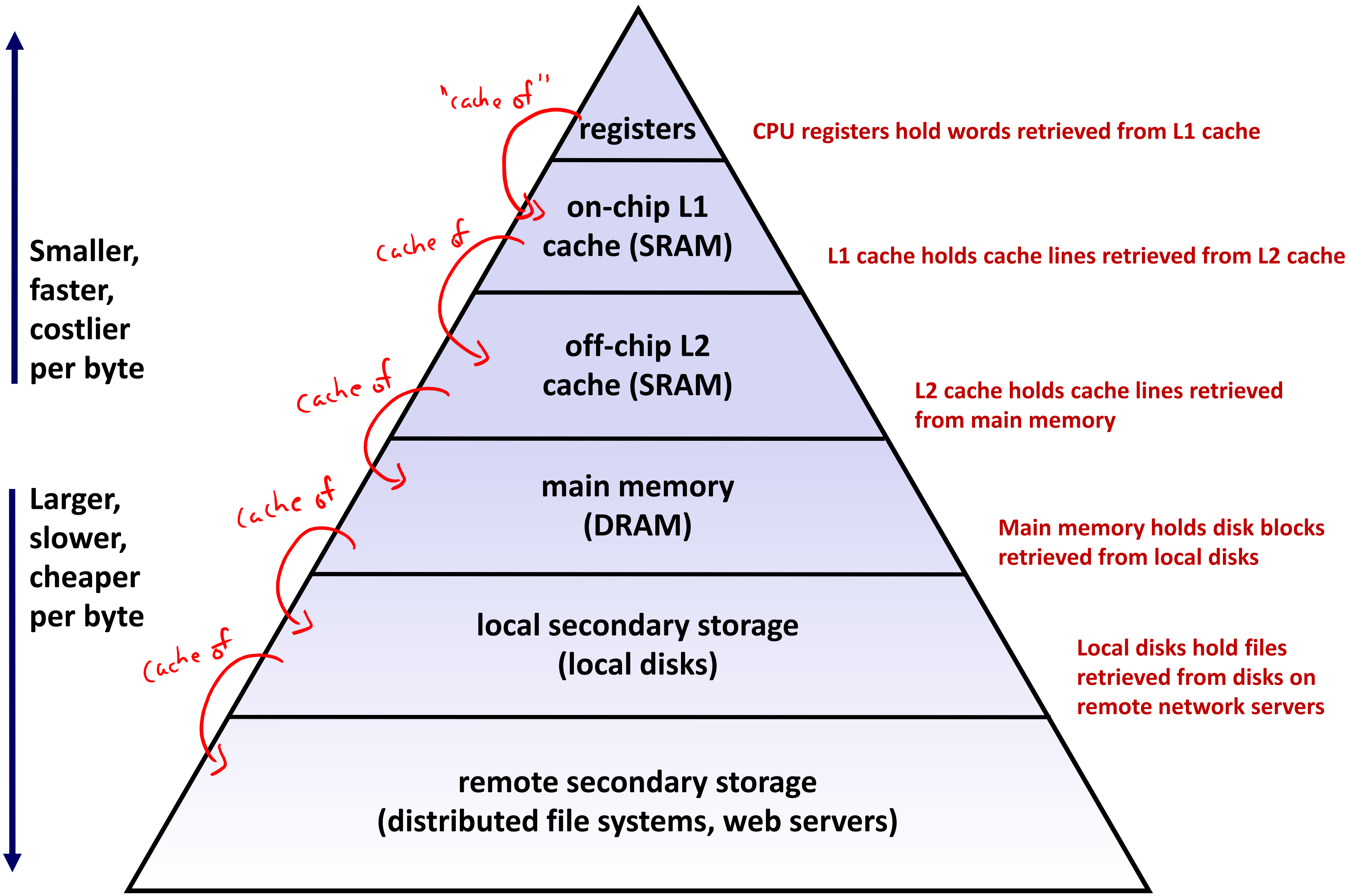


Memory Hierarchies (Review)

- Some fundamental and enduring properties of hardware and software systems:
  - Faster storage technologies almost always cost more per byte and have lower capacity
  - The gaps between memory technology speeds are widening
    - True for: registers ↔ cache, cache ↔ DRAM, DRAM ↔ disk, etc.
  - Well-written programs tend to exhibit good locality

- These properties complement each other beautifully
  - They suggest an approach for organizing memory and storage systems known as a memory hierarchy
    - For each level k, the faster, smaller device at level k serves as a cache for the larger, slower device at level k+1

An Example Memory Hierarchy



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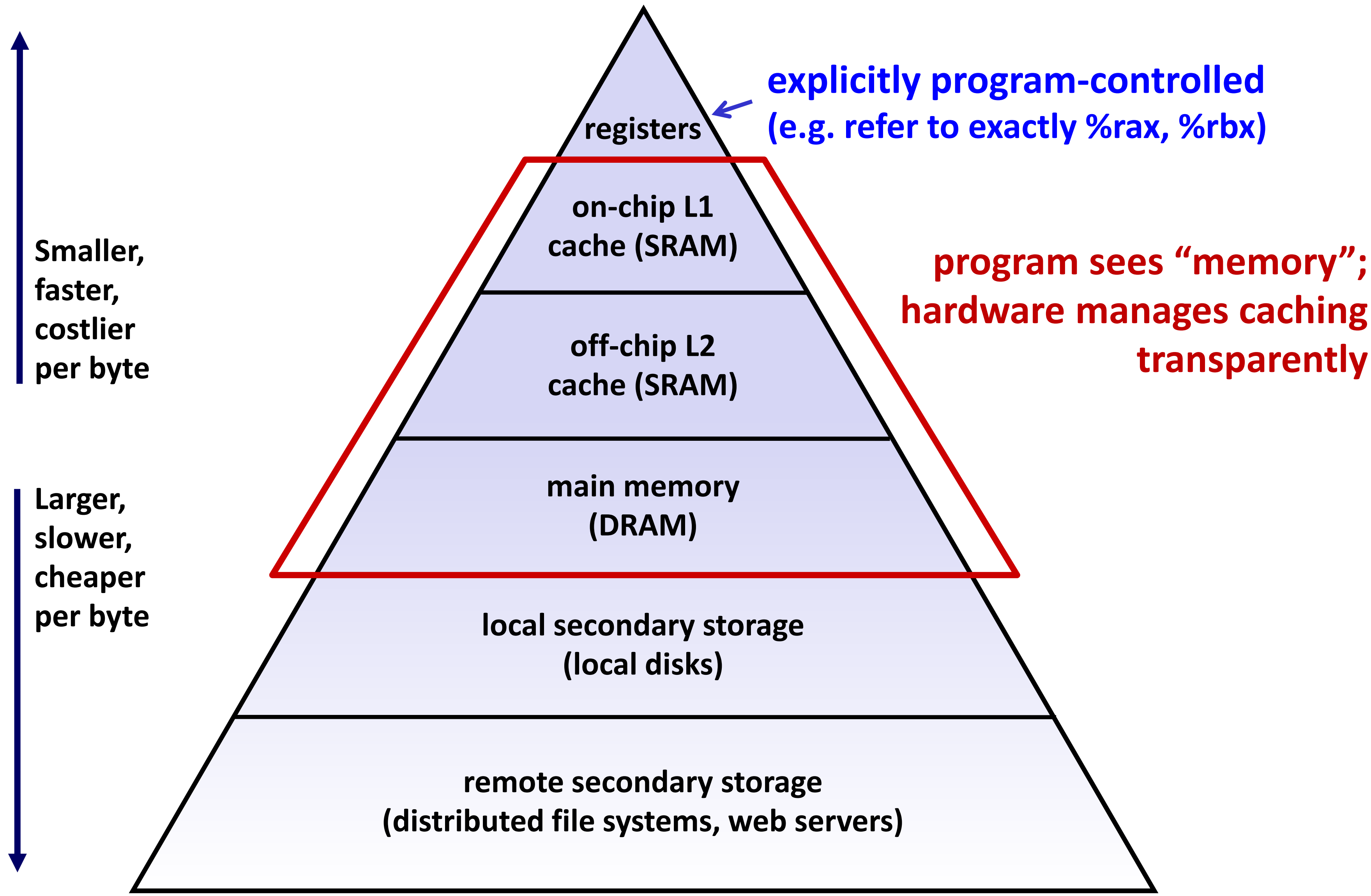
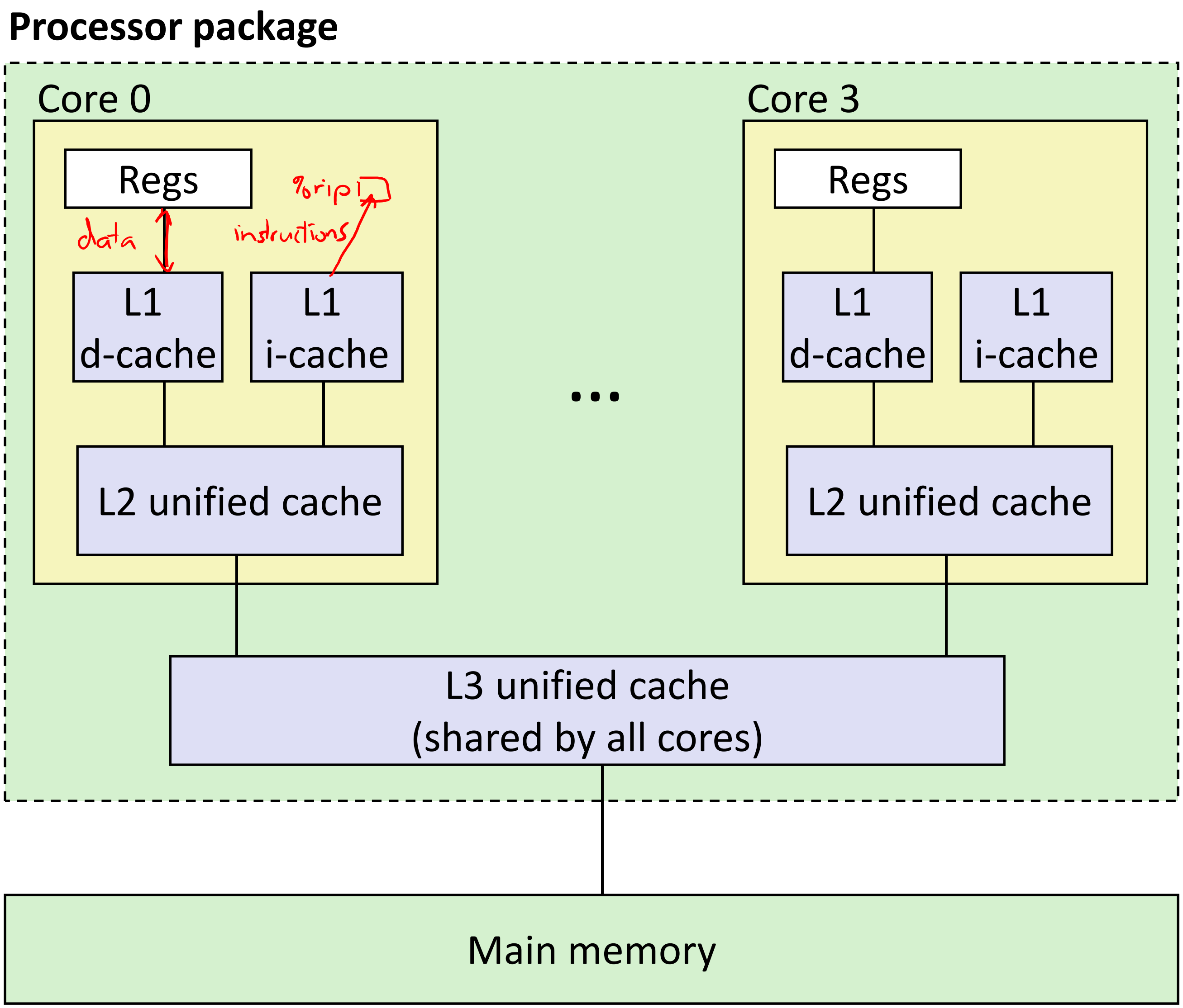


Intel Core i7 Cache Hierarchy



Block size:
64 bytes for all caches

L1 i-cache and d-cache:
32 KiB, 8-way,
Access: 4 cycles

L2 unified cache:
256 KiB, 8-way,
Access: 11 cycles

L3 unified cache:
8 MiB, 16-way,
Access: 30-40 cycles

Making memory accesses fast!

- Cache basics
- Principle of locality
- Memory hierarchies
- **Cache organization**
  - **Direct-mapped (*sets*; index + tag)**
  - Associativity (ways)
  - Replacement policy
  - Handling writes
- Program optimizations that consider caches

Reading Review

- Terminology:
  - Memory hierarchy
  - Cache parameters: block size (K), cache size (C)
  - Addresses: block offset field (k bits wide)
  - Cache organization: direct-mapped cache, index field

Review Questions

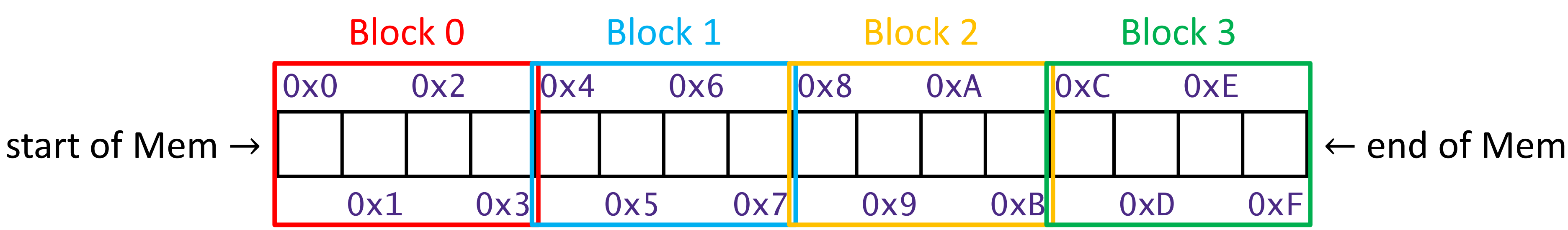
- We have a direct-mapped cache with the following parameters:
  - Block size of 8 bytes $K = 2^3$ B
  - Cache size of 4 KiB $C = 2^{12}$ B (2^2, 2^{10})
- How many blocks can the cache hold? $C/K = \frac{2^{12}}{2^3} = 2^9 = 512$ blocks
- How many bits wide is the block offset field? $\log_2 K = 3$ bits
- Which of the following addresses would fall under block number 3?

A. 0x3	B. 0x1F	C. 0x30	D. 0x38
⌊3/8⌋ = 0	⌊31/8⌋ = 3	⌊48/8⌋ = 6	⌊56/8⌋ = 7
0b...000|011	0b...011|111	0b...0110|000	0b...0111|000
block 0	block 3	block 6	block 7

Cache Organization (1)

Note: The textbook uses "B" for block size

- Block Size (K): unit of transfer between $ and Mem
  - Given in bytes and always a power of 2 (*e.g.*, 64 B)
  - Blocks consist of adjacent bytes (differ in address by 1)
    - Spatial locality!
  - Small example ($K = 4$ B):



Cache Organization (1)

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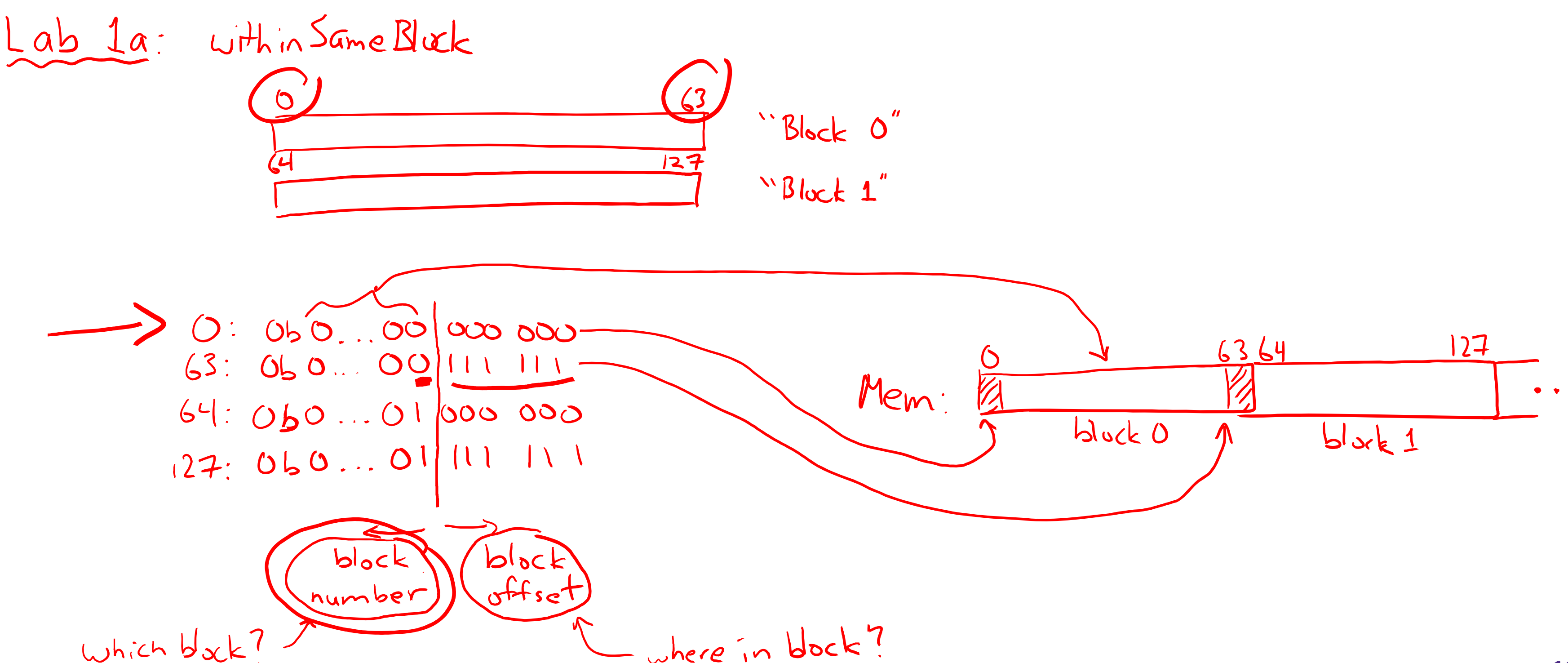


Cache Organization (1)

Note: The textbook uses "b" for offset bits

- Block Size (K): unit of transfer between $ and Mem
  - Given in bytes and always a power of 2 (*e.g.* 64 B)
  - Blocks consist of adjacent bytes (differ in address by 1)
    - Spatial locality!
- Offset field
  - Low-order $\log_2(K) = k$ bits of address tell you which byte within a block
    - (address) mod 2^n = n lowest bits of address
  - (address) modulo (# of bytes in a block)

$m - k$ bits	k bits
Block Number	Block Offset

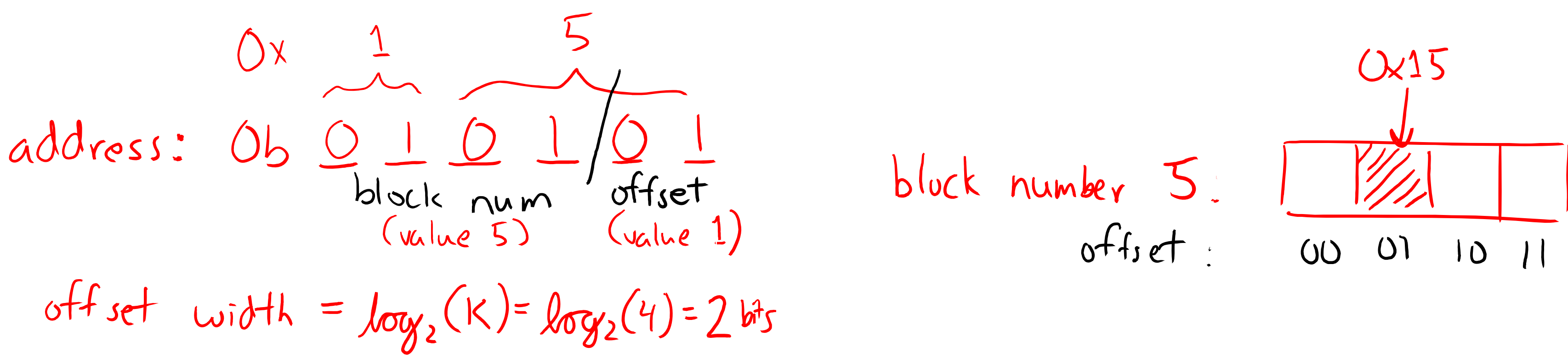
m-bit address:
(refers to byte in memory)

Cache Organization (1)

Note: The textbook uses "b" for offset bits

- Block Size (K): unit of transfer between \$ and Mem
  - Given in bytes and always a power of 2 (*e.g.*, 64 B)
  - Blocks consist of adjacent bytes (differ in address by 1)
    - Spatial locality!

- Example:
  - If we have 6-bit addresses and block size K = 4 B, which block and byte does 0x15 refer to?



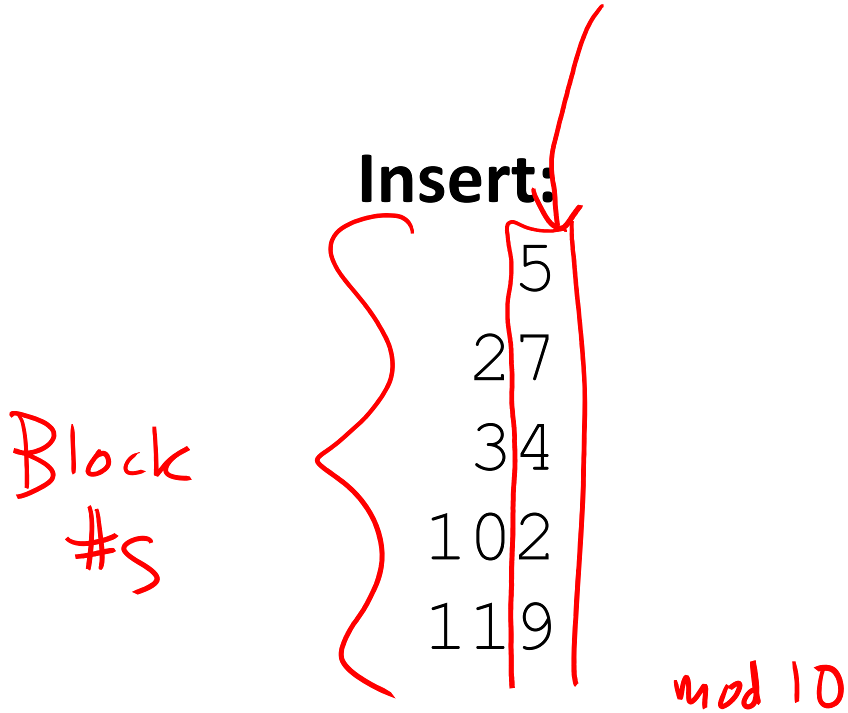
Cache Organization (2)

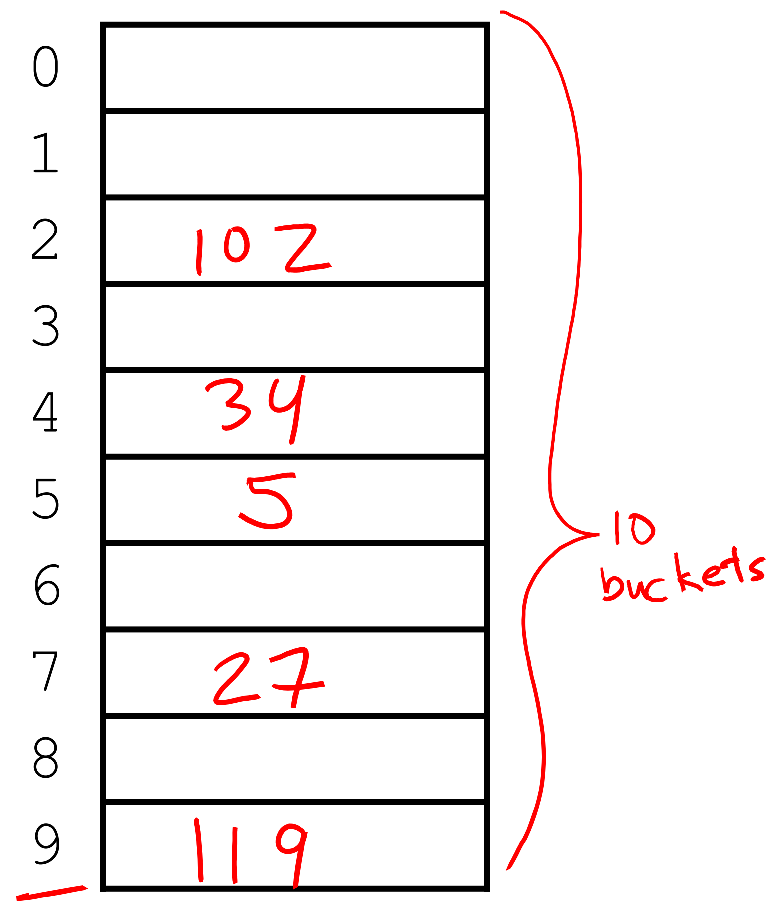
- Cache Size (C): amount of *data* the $ can store
  - Cache can only hold so much data (subset of next level)
  - Given in bytes (C) or number of blocks (C/K)
  - Example: C = 32 KiB = 512 blocks if using 64-B blocks

$2^5 \times 2^{10} = 2^{15}$ B $\times \frac{1 \text{ block}}{2^6 \text{ B}} = 2^9$ blocks

- Where should data go in the cache?
  - We need a mapping from memory addresses to specific locations in the cache to make checking the cache for an address **fast**
- What is a data structure that provides fast lookup?
  - Hash table!

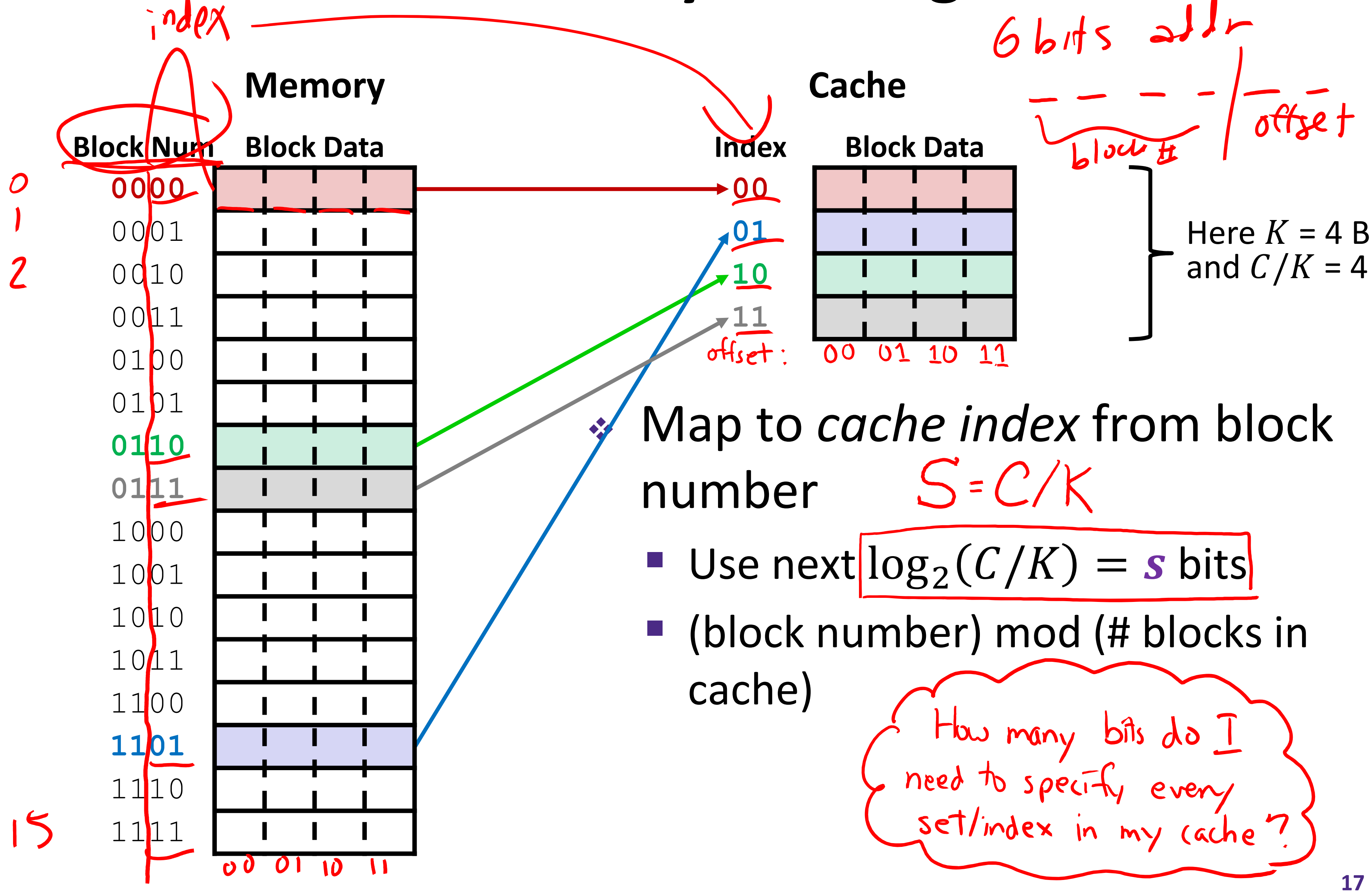
Hash Tables for Fast Lookup





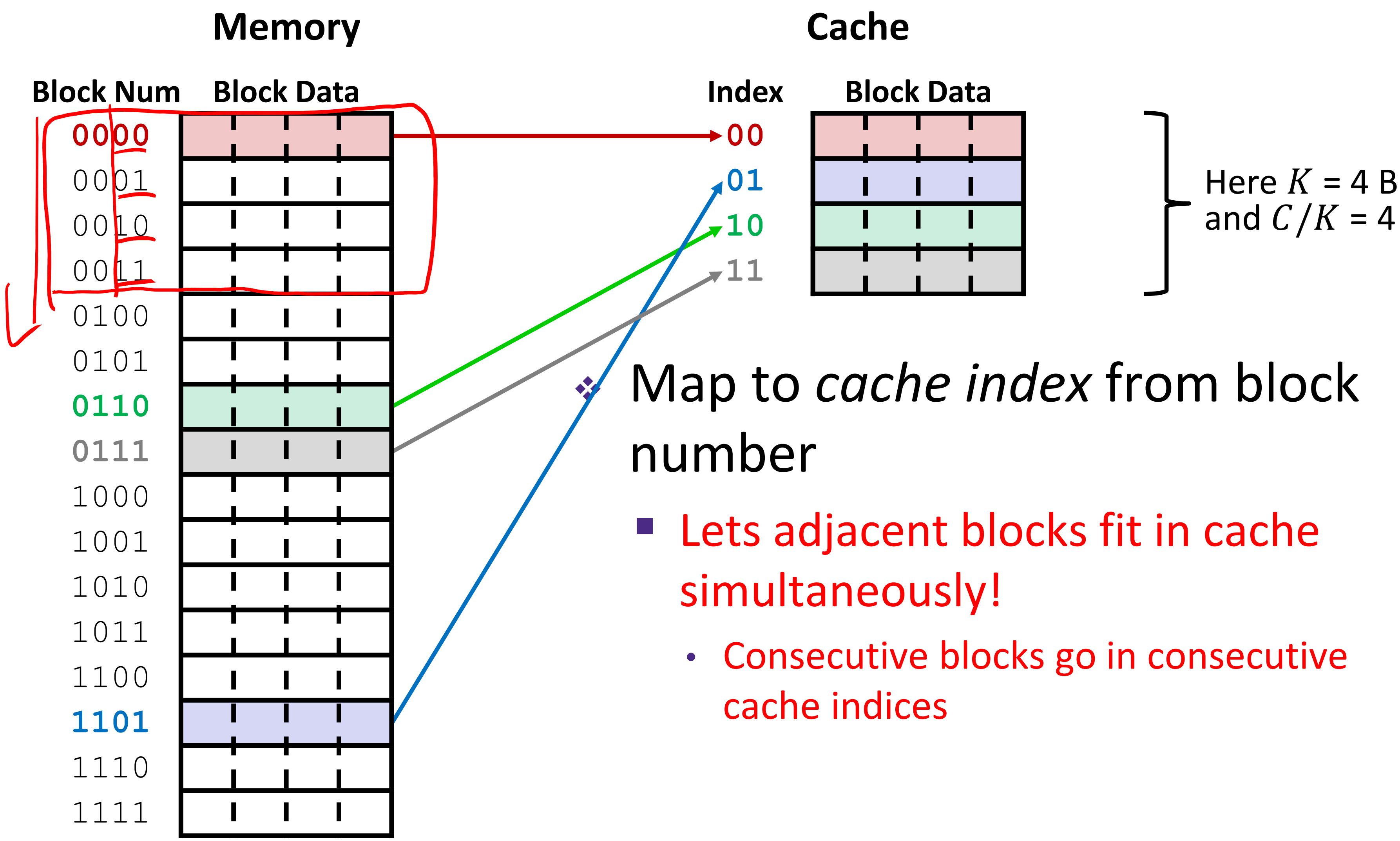
Apply hash function to map data to "buckets"

Place Data in Cache by Hashing Address



- Map to *cache index* from block number
  - Use next $\log_2(C/K) = s$ bits
  - (block number) mod (# blocks in cache)

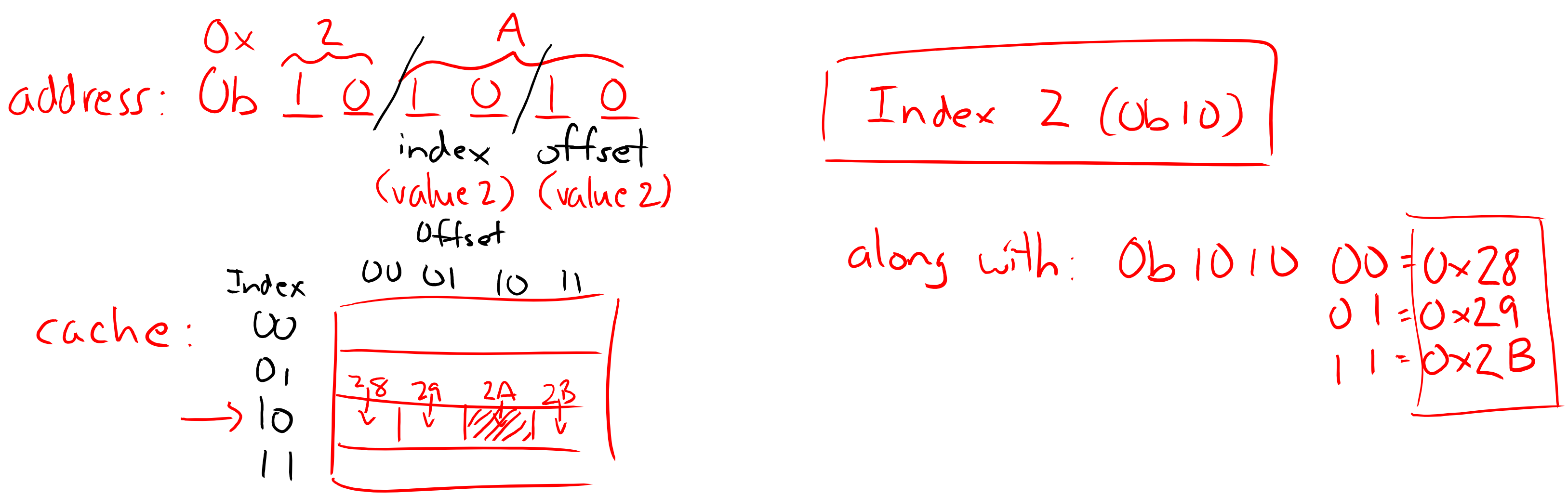
Place Data in Cache by Hashing Address



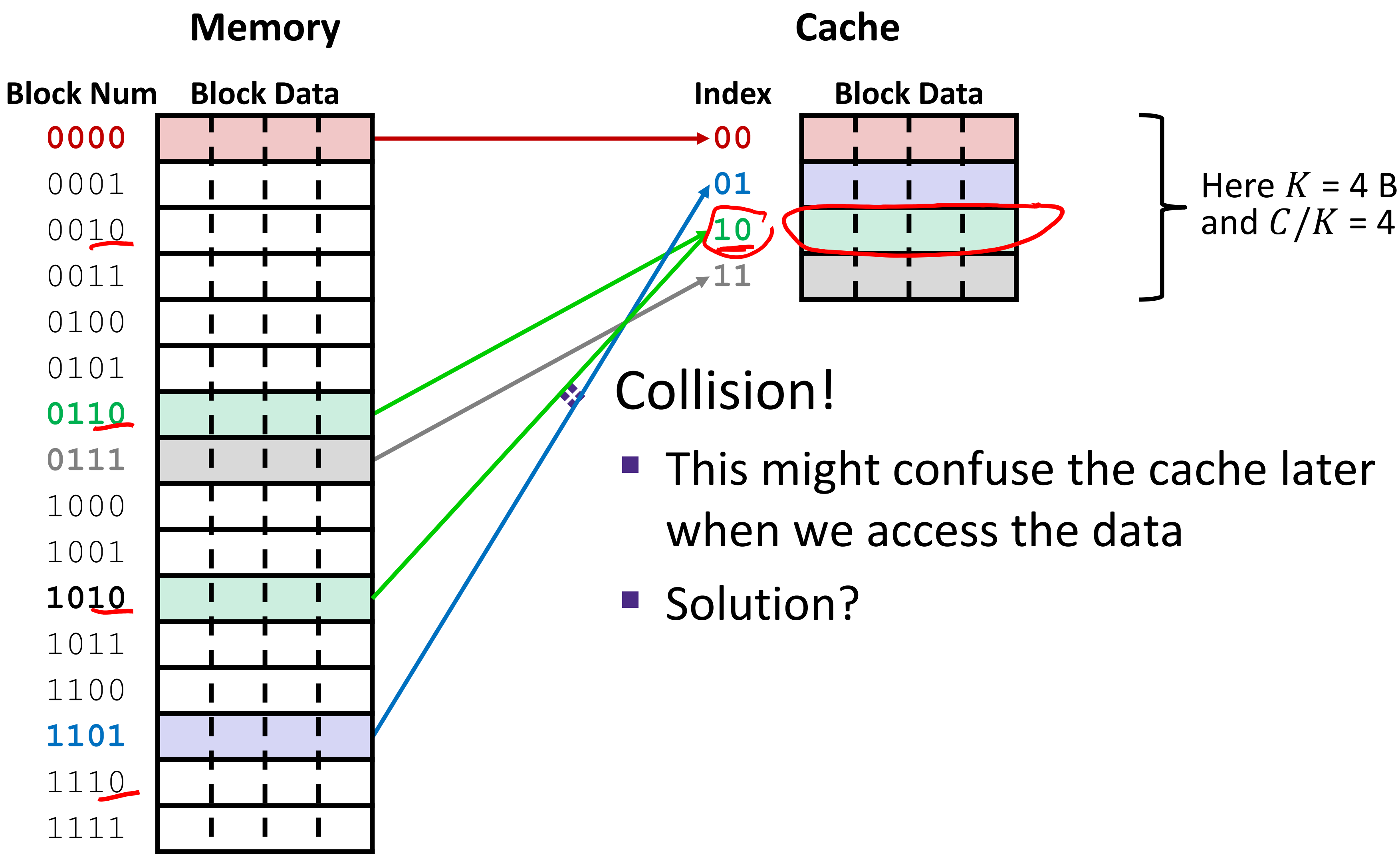
- Map to *cache index* from block number
  - Lets adjacent blocks fit in cache simultaneously!
    - Consecutive blocks go in consecutive cache indices

Polling Question

- 6-bit addresses, block size K = 4 B, and our cache holds S = 4 blocks.
- A request for address **0x2A** results in a cache miss. Which index does this block get loaded into and which 3 other addresses are loaded along with it?
  - Vote on Ed Lessons



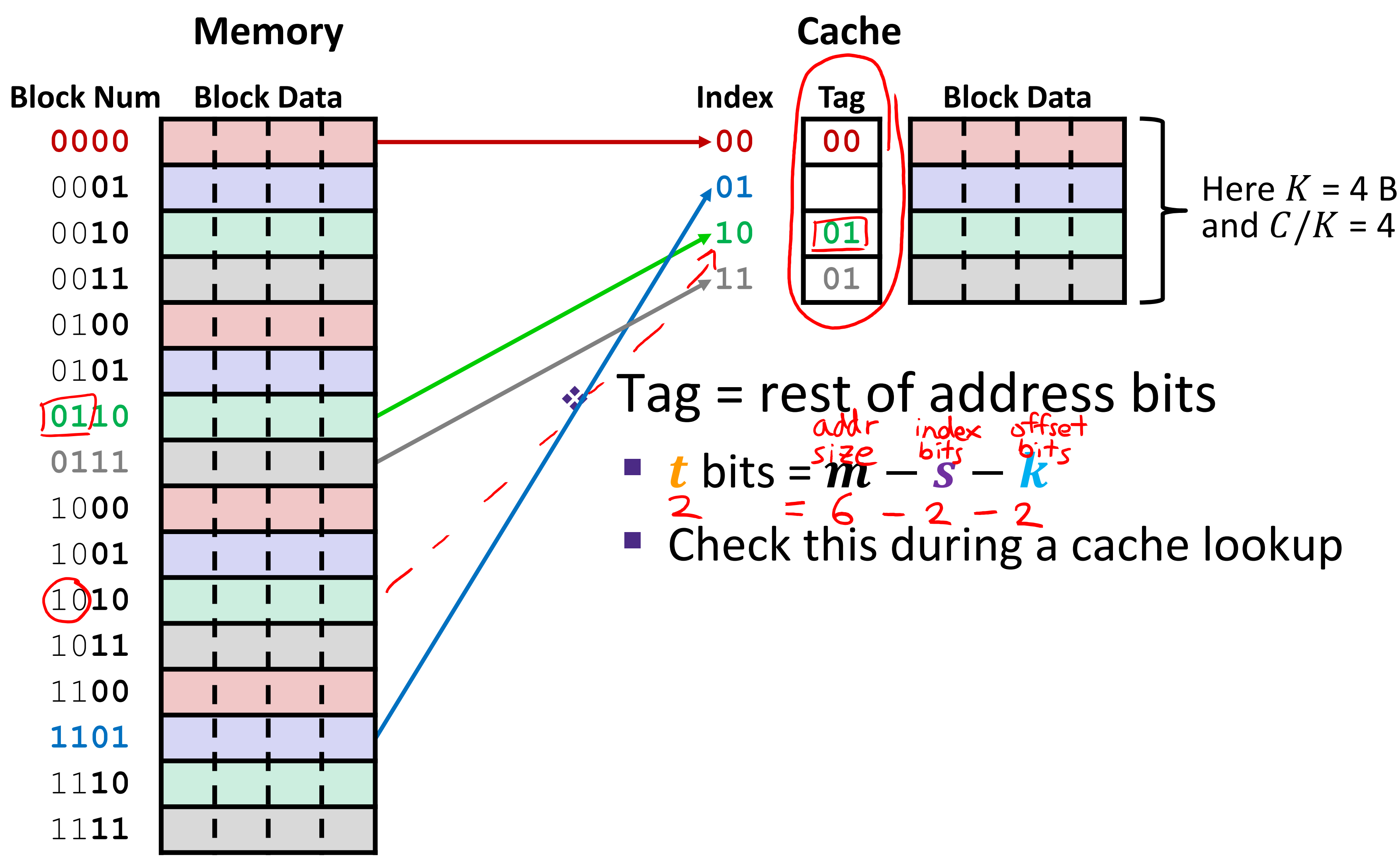
Place Data in Cache by Hashing Address



Collision!

- This might confuse the cache later when we access the data
- Solution?

Tags Differentiate Blocks in Same Index

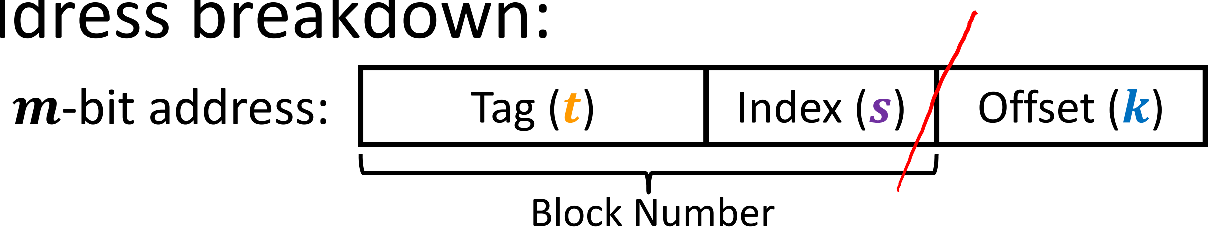


- Tag = rest of address bits
  - t bits = $m - s - k$
  - Check this during a cache lookup

Checking for a Requested Address

- CPU sends address request for chunk of data
  - Address and requested data are not the same thing!
    - Analogy: your friend ≠ their phone number

- TIO address breakdown:



  - **Index** field tells you where to look in cache
  - **Tag** field lets you check that data is the block you want
  - **Offset** field selects specified start byte within block

  - **Note:** t and s sizes will change based on hash function

Cache Puzzle

- Based on the following behavior, which of the following block sizes is NOT possible for our cache?
  - Cache starts *empty*, also known as a *cold cache*
  - Access (addr: hit/miss) stream:
    - (14: miss), (15: hit), (16: miss)

hit: block with data already in \$
miss: data not in \$, pulls block containing data from Mem

(3) 16 is in a different block
(2) 14 & 15 are in the same block
(1) pulls block containg 14 into \$

- [Not in Ed Lessons]

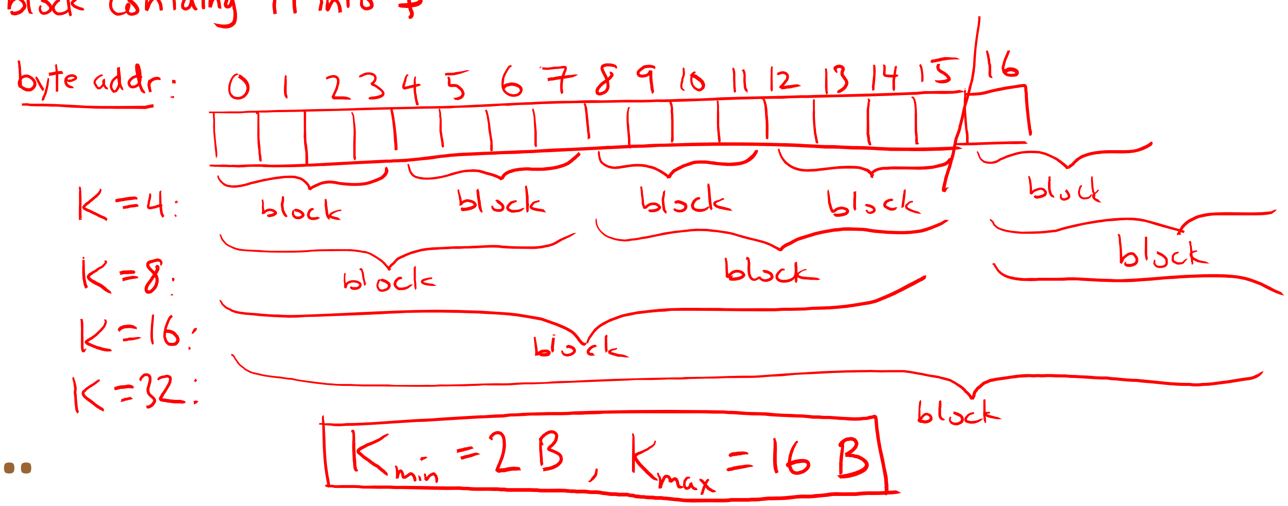
A. 4 bytes

B. 8 bytes

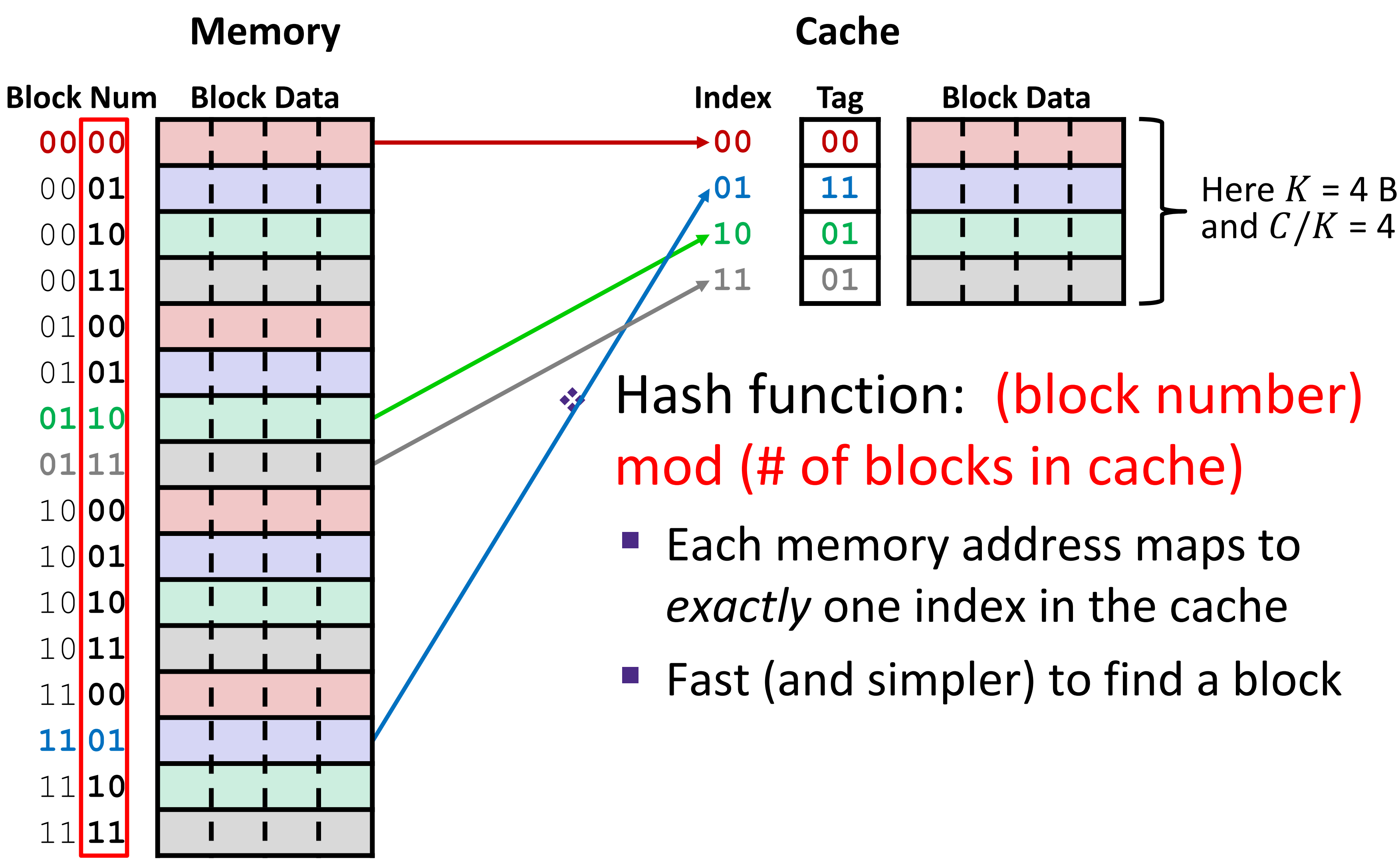
C. 16 bytes

D. 32 bytes

E. We're lost…



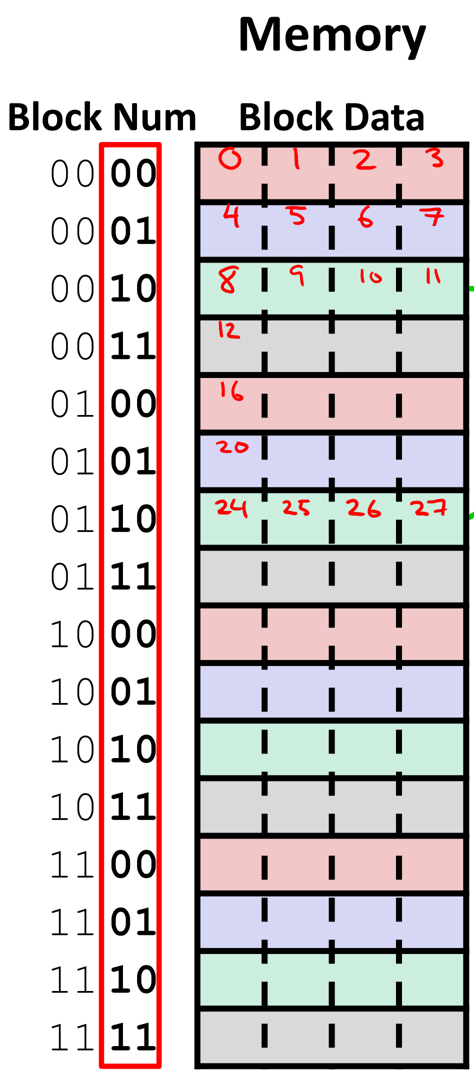
Summary: Direct-Mapped Cache

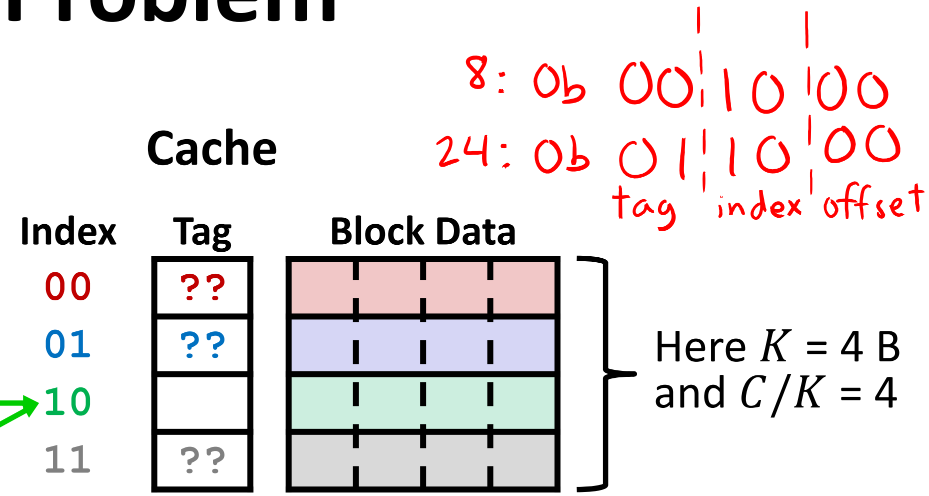


Hash function: (block number) mod (# of blocks in cache)

- Each memory address maps to *exactly* one index in the cache
- Fast (and simpler) to find a block

Direct-Mapped Cache Problem





- What happens if we access the following addresses?
  - 8, 24, 8, 24, 8, …? (Miss Miss Miss Miss Miss …)
  - Conflict in cache (misses!)
  - Rest of cache goes *unused*
- Solution?