Caches II

CSE 351 Winter 2018

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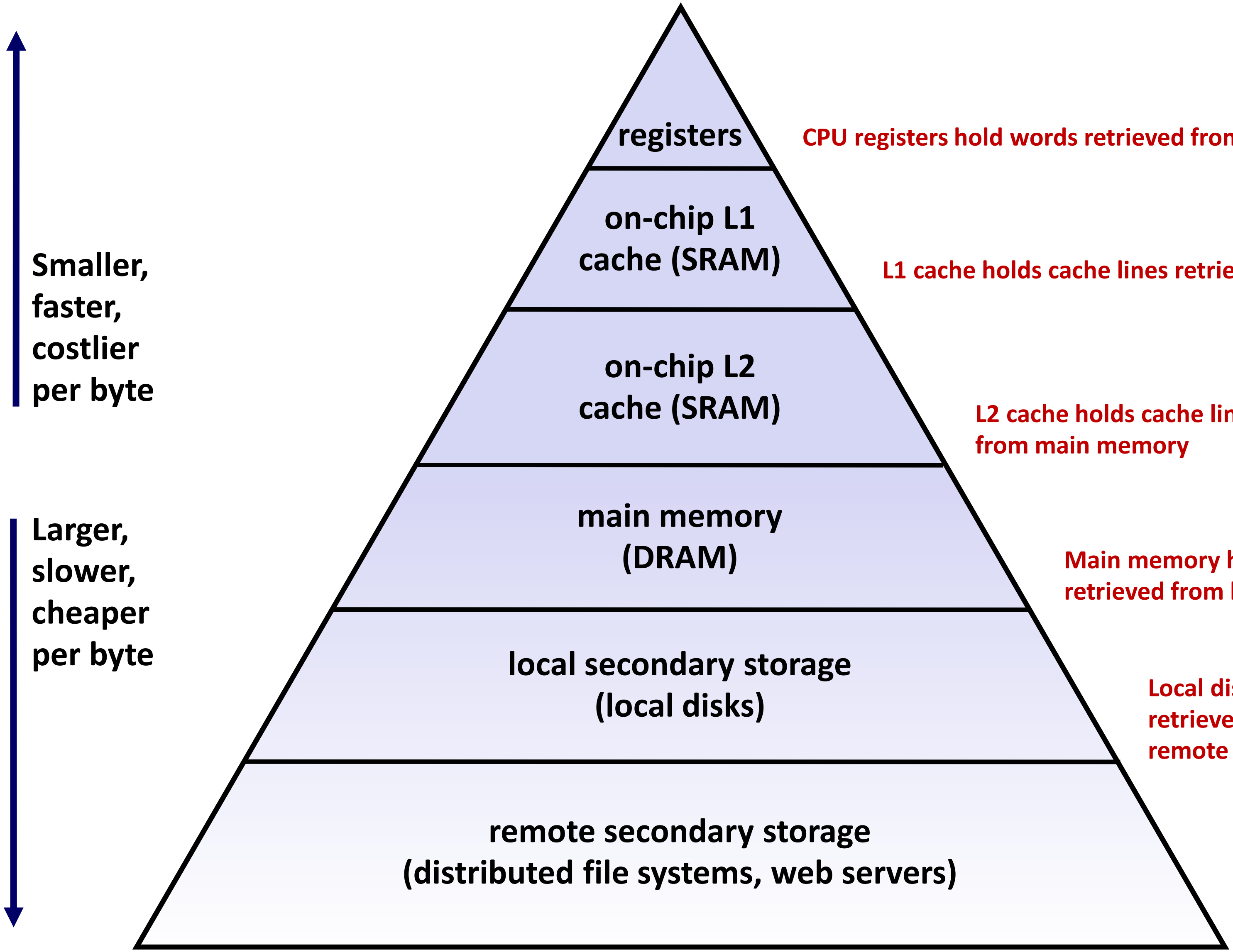
Administrative

- Lab 3 due *Friday* (2/16)
- Homework 4 released today (Structs, Caches)
- Midterm Regrade Requests due Friday (2/16)

An Example Memory Hierarchy



CPU registers hold words retrieved from L1 cache

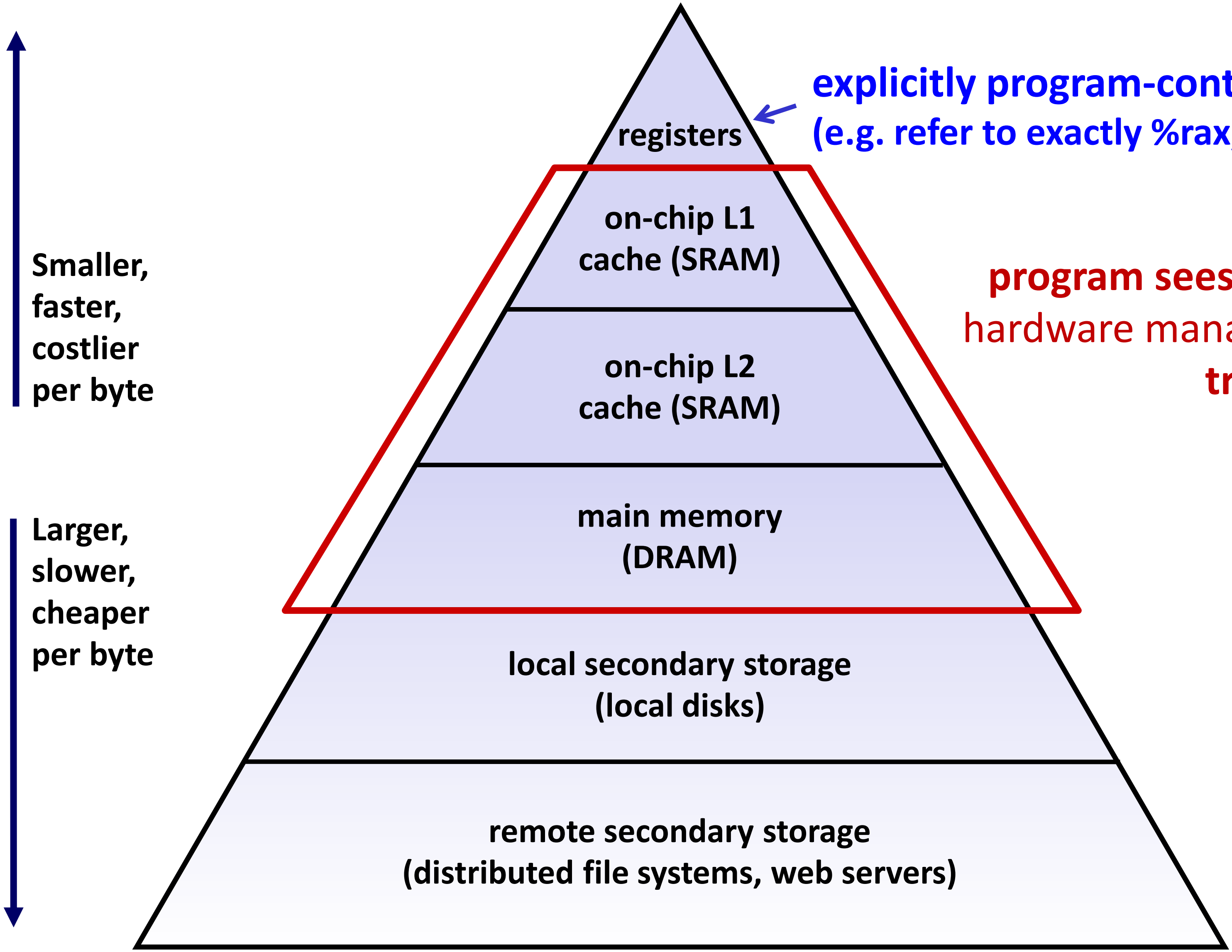
L1 cache holds cache lines retrieved from L2 cache

L2 cache holds cache lines retrieved from main memory

Main memory holds disk blocks retrieved from local disks

Local disks hold files retrieved from disks on remote network servers

An Example Memory Hierarchy



explicitly program-controlled (e.g. refer to exactly %rax, %rbx)

program sees “memory”; hardware manages caching **transparently**

Memory Hierarchies

- Fundamental idea of 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
- Why do memory hierarchies work?
  - Because of locality, programs tend to access the data at level k more often than they access the data at level k+1
  - Thus, the storage at level k+1 can be slower, and thus larger and cheaper per bit
- *Big Idea:* 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

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

Cache Organization

- Fundamental Equation: $C = S * E * B$

- Cache Size (C): total capacity (Bytes) of cache
- Block Size (B): unit of transfer between $ and Mem
- Sets (S): collection of blocks
  - Cache can be thought of as an “array of sets”
- Associativity (E): number of cache blocks per set
- Address Bits (m): number of bits in address

Cache Organization (1)

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

- Offset field
  - Low-order $\log_2(B) = \boldsymbol{b}$ 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)

	$\boldsymbol{m} - \boldsymbol{b}$ bits	$\boldsymbol{b}$ bits
$\boldsymbol{m}$-bit address: (refers to byte in memory)	Block Number	Block Offset

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/B)
  - Example: C = 32 KB = 512 blocks if using 64-Byte blocks

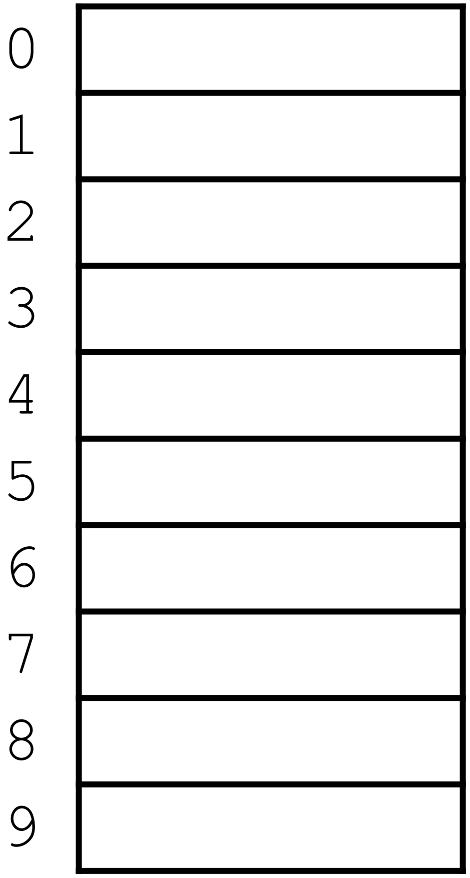
- Where should data go in the cache?
  - We need a mapping from memory addresses to specific locations in the cache to make checking the cache for an address **fast**

- What is a data structure that provides fast lookup?
  - Hash table!

Review: Hash Tables for Fast Lookup

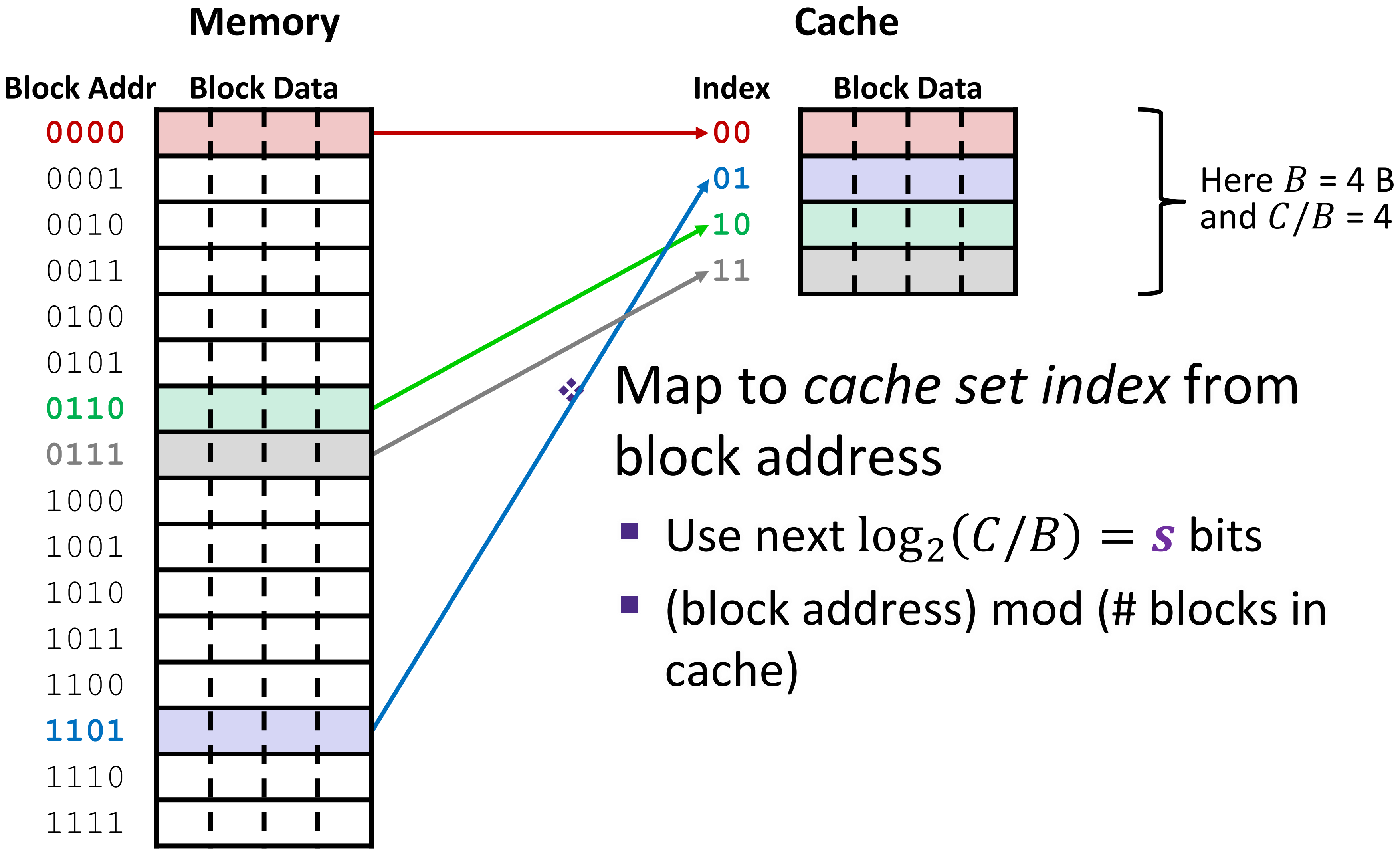
Insert:
5
27
34
102
119

Apply hash function to map data to “buckets”



0
1
2
3
4
5
6
7
8
9

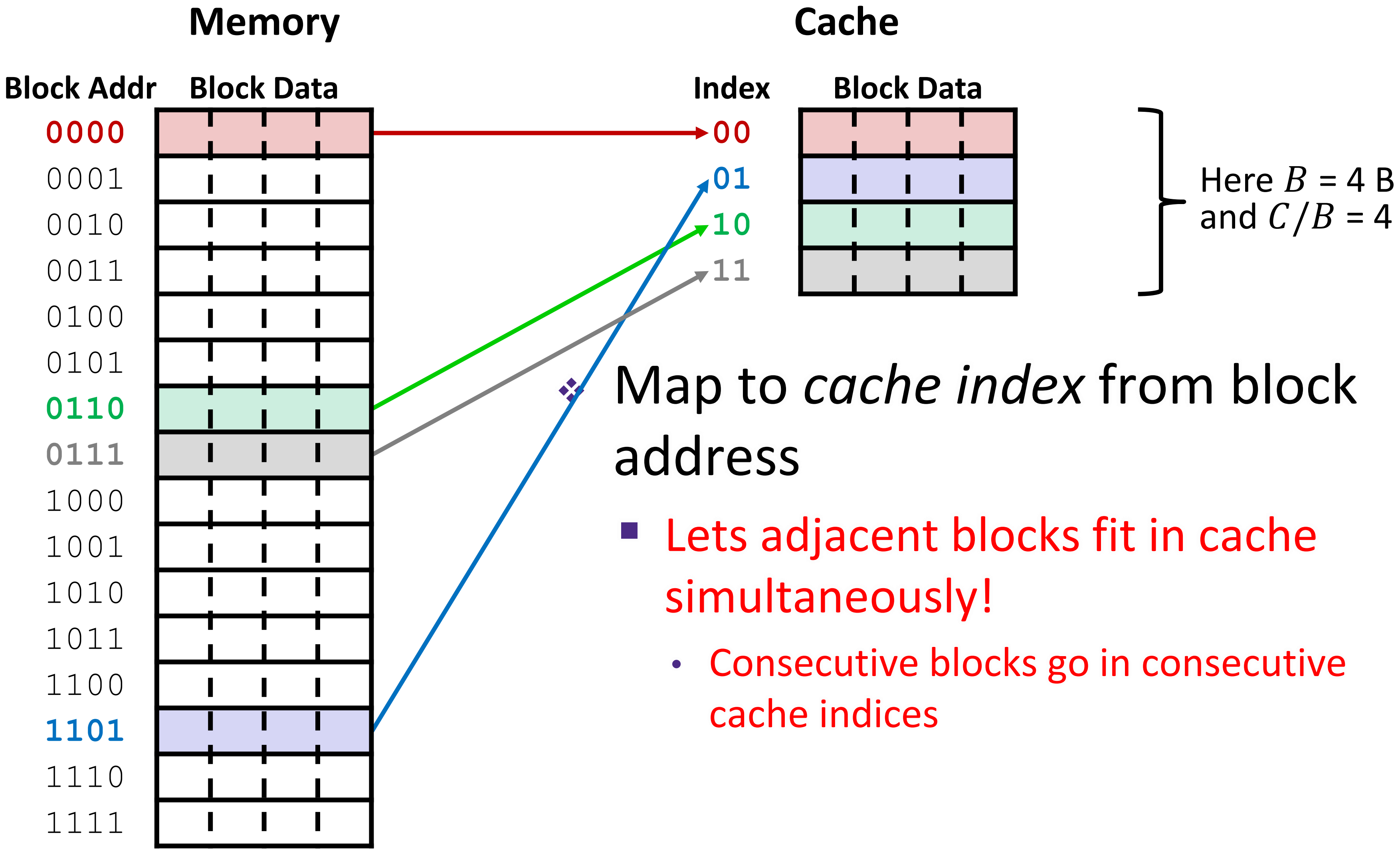
Place Data in Cache by Hashing Address



Here B = 4 B and C/B = 4

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

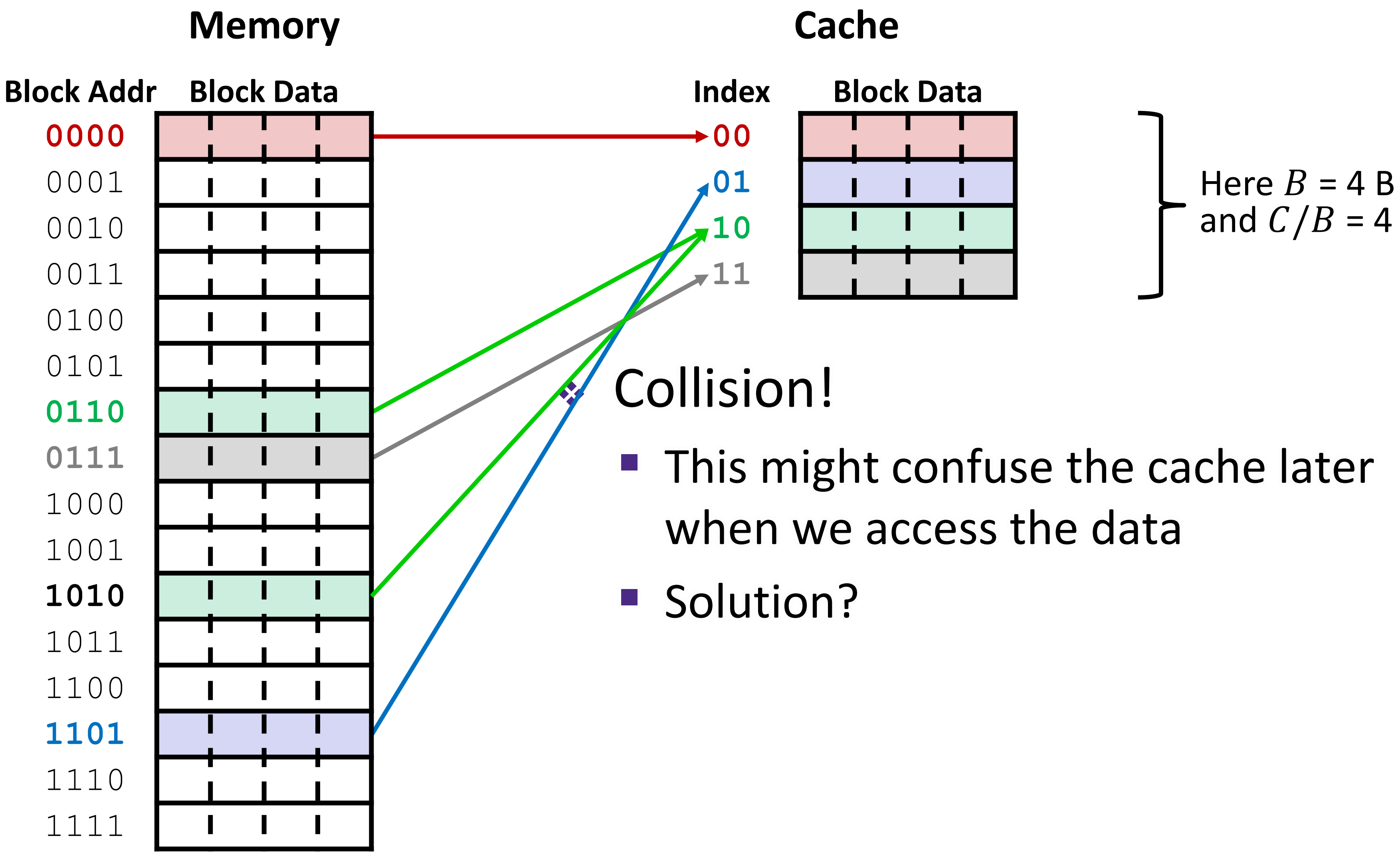
Place Data in Cache by Hashing Address



Map to *cache index* from block address

- Lets adjacent blocks fit in cache simultaneously!
  - Consecutive blocks go in consecutive cache indices

Place Data in Cache by Hashing Address

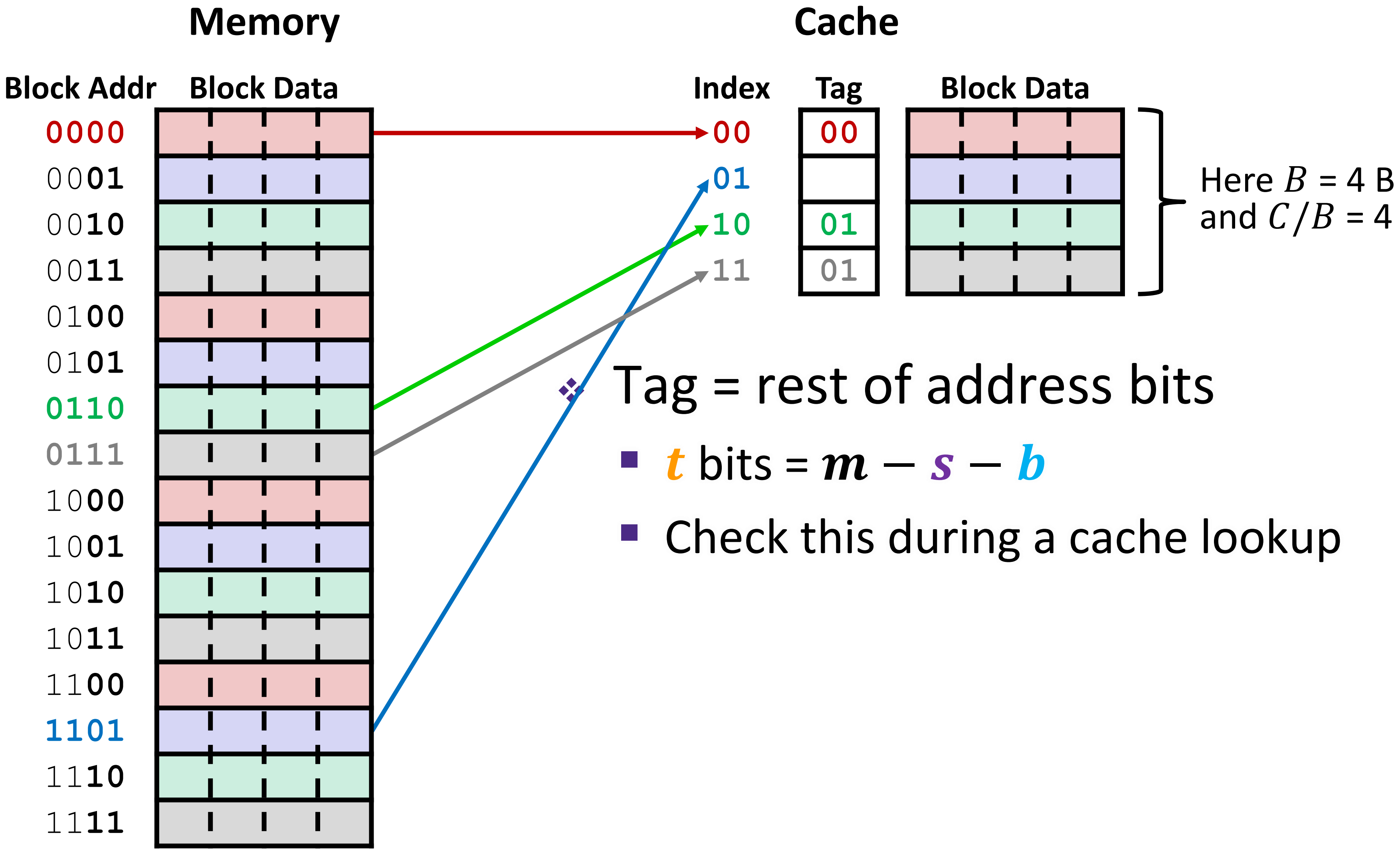


Here B = 4 B and C/B = 4

Collision!

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

Tags Differentiate Blocks in Same Index

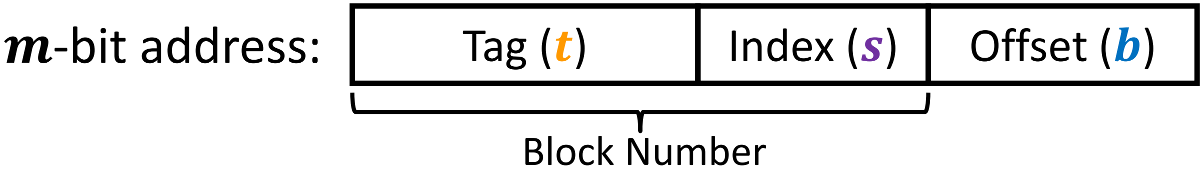


- Tag = rest of address bits
  - t bits = $m - s - b$
  - Check this during a cache lookup

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 ≠ his or her phone number

- TIO address breakdown:



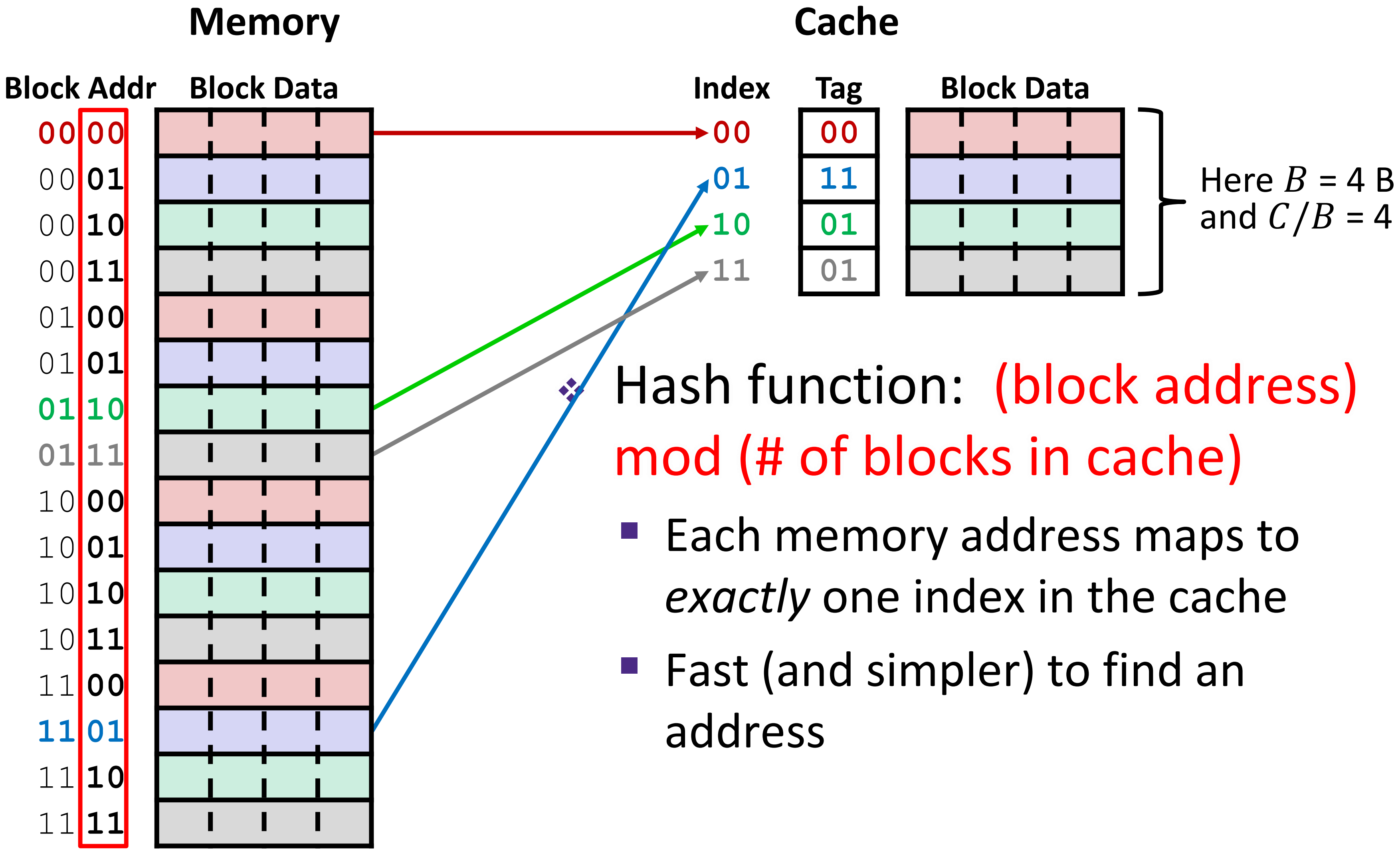
m-bit address: Tag (t) Index (s) Offset (b)

Block Number

  - **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

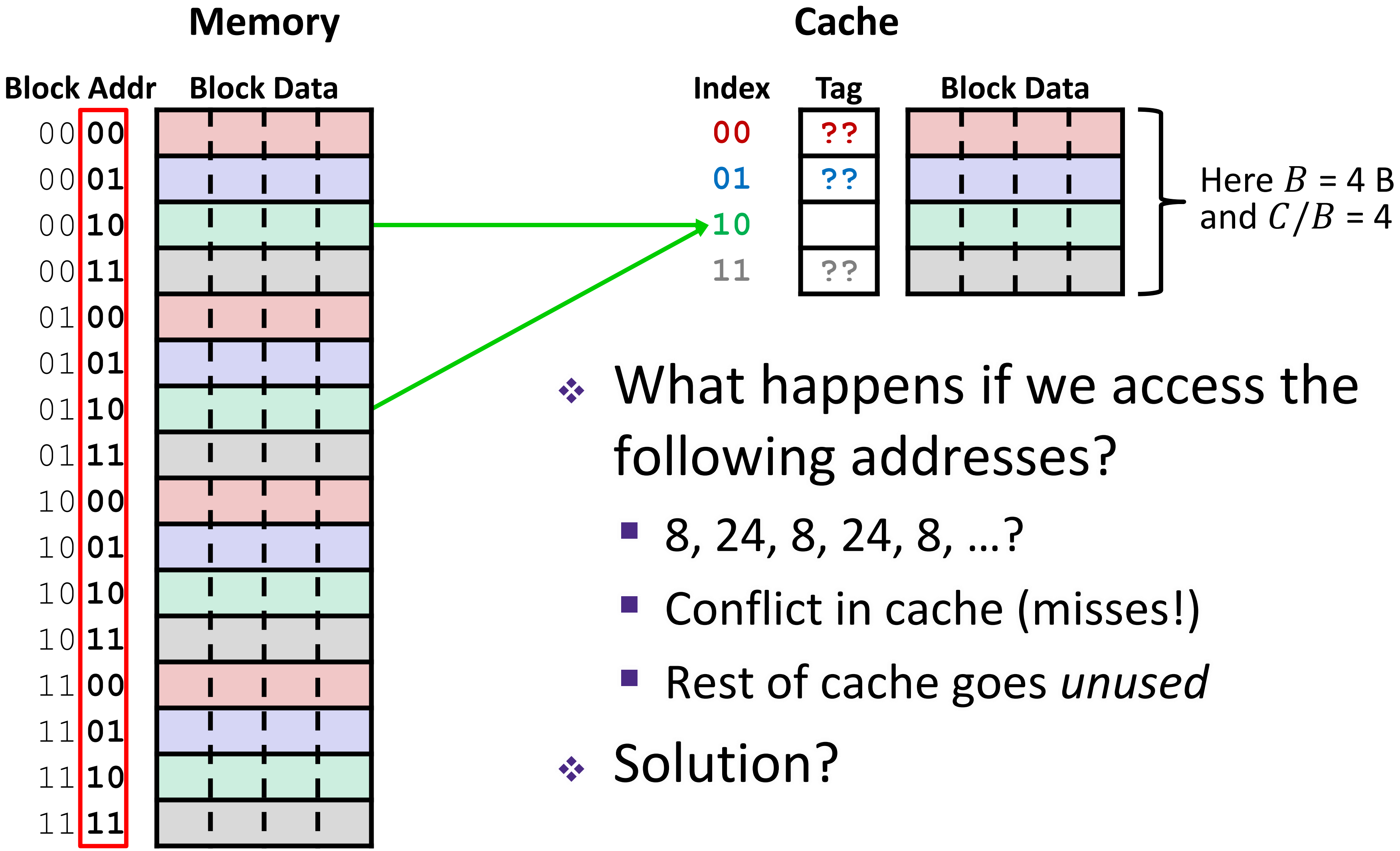
Direct-Mapped Cache



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

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

Direct-Mapped Cache Problem

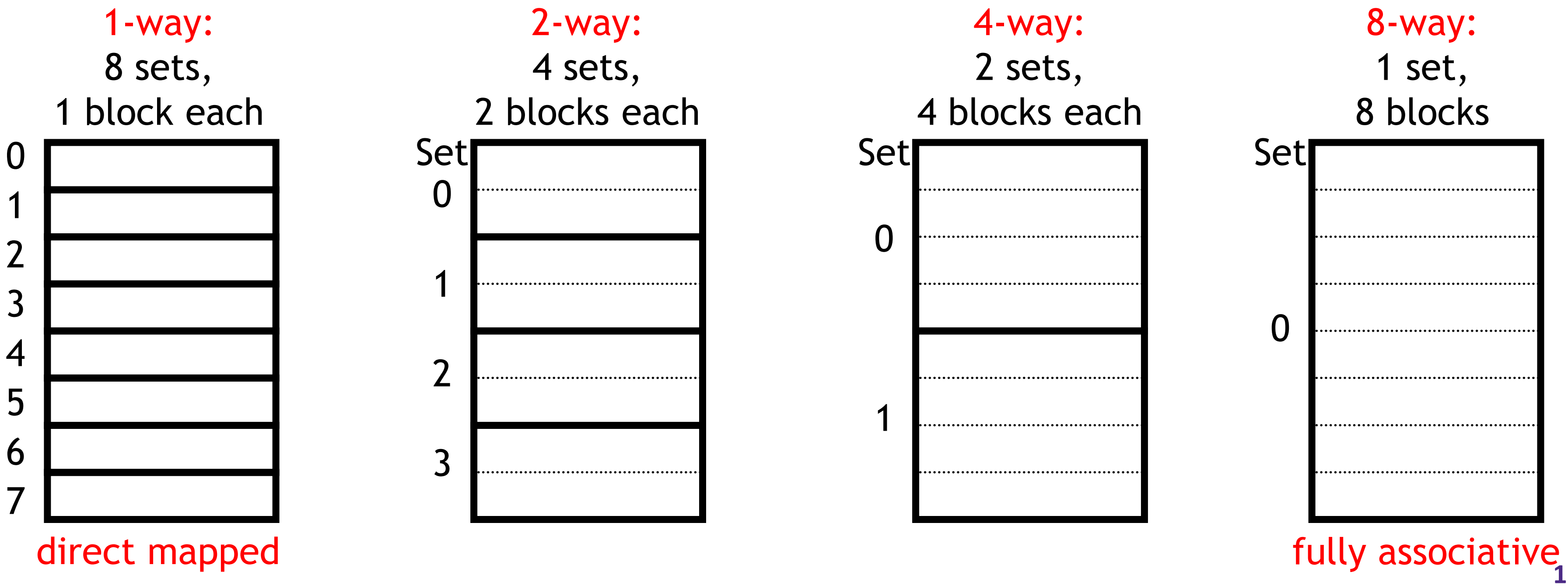


Here B = 4 B and C/B = 4

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

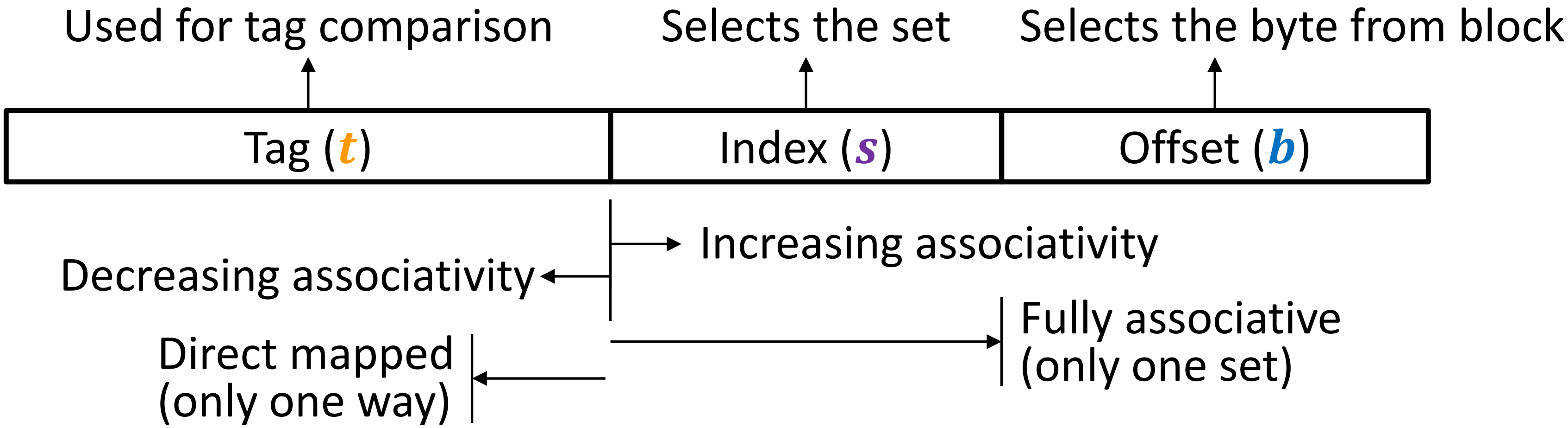
Associativity

- What if we could store data in any place in the cache?
  - More complicated hardware = more power consumed, slower
- So we *combine* the two ideas:
  - Each address maps to exactly one **set**
  - Each set can store block in more than one **way**



Cache Organization (3)

- Associativity (E): # of ways for each set
  - Such a cache is called an “*E-way set associative cache*”
  - We now index into cache *sets*, of which there are $C/B/E$
  - Use lowest $\log_2(C/B/E)$ = $\boldsymbol{s}$ bits of block address
    - Direct-mapped: E = 1, so $\boldsymbol{s}$ = $\log_2(C/B)$ as we saw previously
    - Fully associative: E = C/B, so $\boldsymbol{s}$ = 0 bits



Example Placement

block size:	16 B
capacity:	8 blocks
address:	16 bits

- Where would data from address `0x1833` be placed?
  - Binary: `0b 0001 1000 0011 0011`

$t = m - s - b$ $s = \log_2(C/B/E)$ $b = \log_2(B)$

m-bit address:

Tag (t)	Index (s)	Offset (b)

s = ?

Direct-mapped

Set	Tag	Data
0		
1		
2		
3		
4		
5		
6		
7		

s = ?

2-way set associative

Set	Tag	Data
0		
1		
2		
3		

s = ?

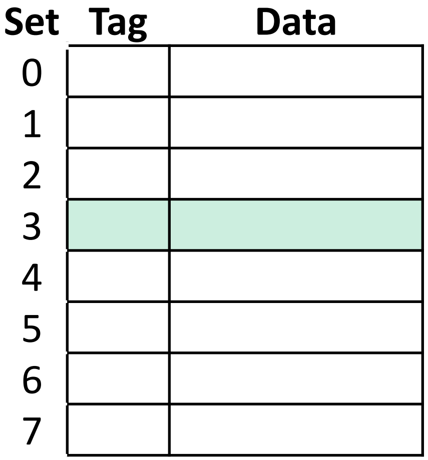
4-way set associative

Set	Tag	Data
0		
1		

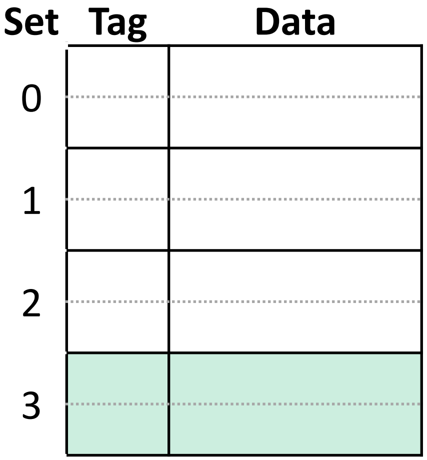
Block Replacement

- *Any* empty block in the correct set may be used to store block
- If there are no empty blocks, which one should we replace?
  - No choice for direct-mapped caches
  - Caches typically use something close to ***least recently used (LRU)*** (hardware usually implements "*not most recently used*")

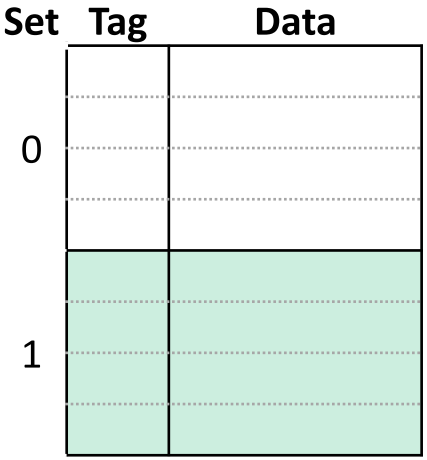
Direct-mapped



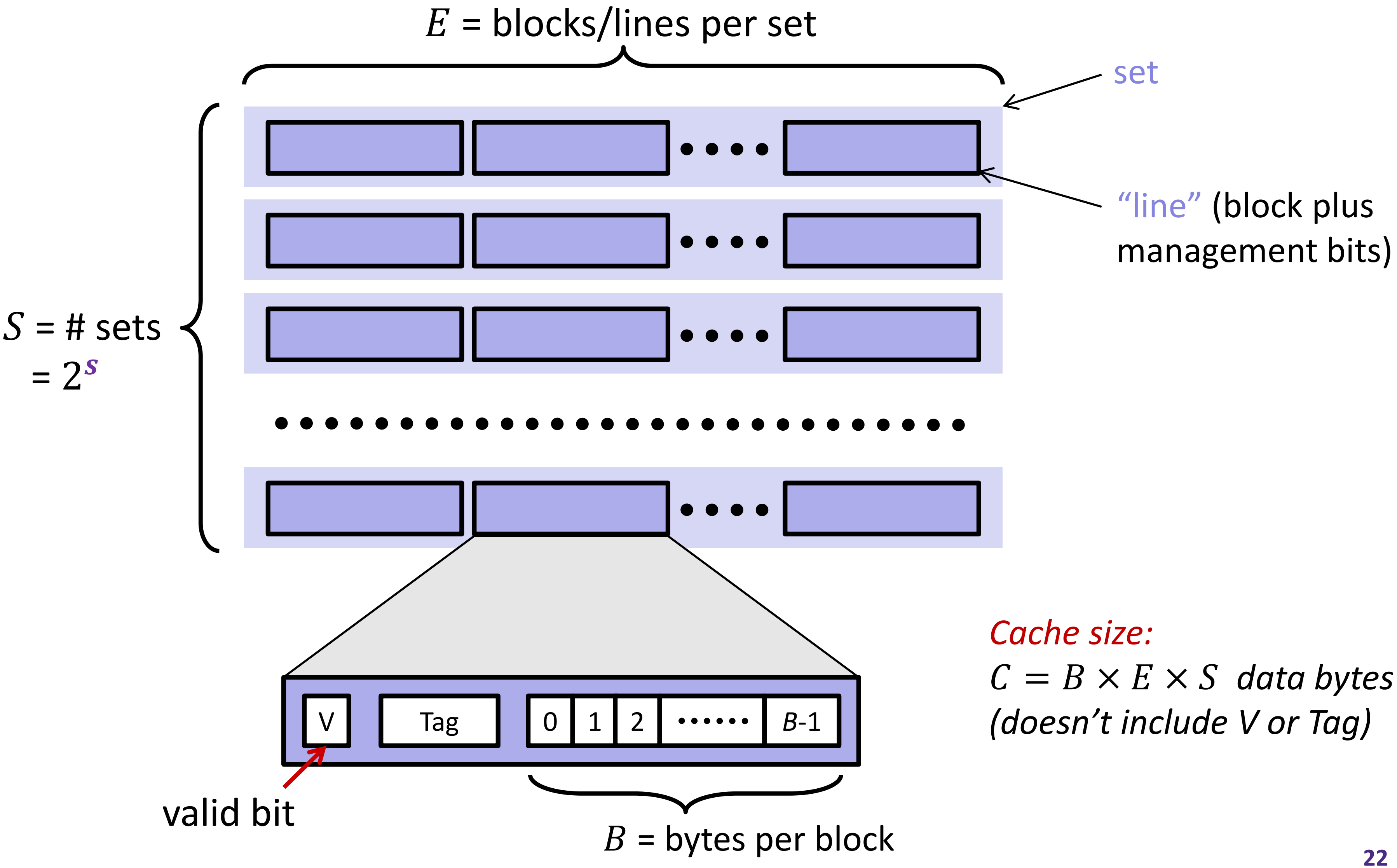
2-way set associative



4-way set associative



General Cache Organization (S, E, B)



Cache size:

$C = B \times E \times S$ data bytes

(doesn't include V or Tag)

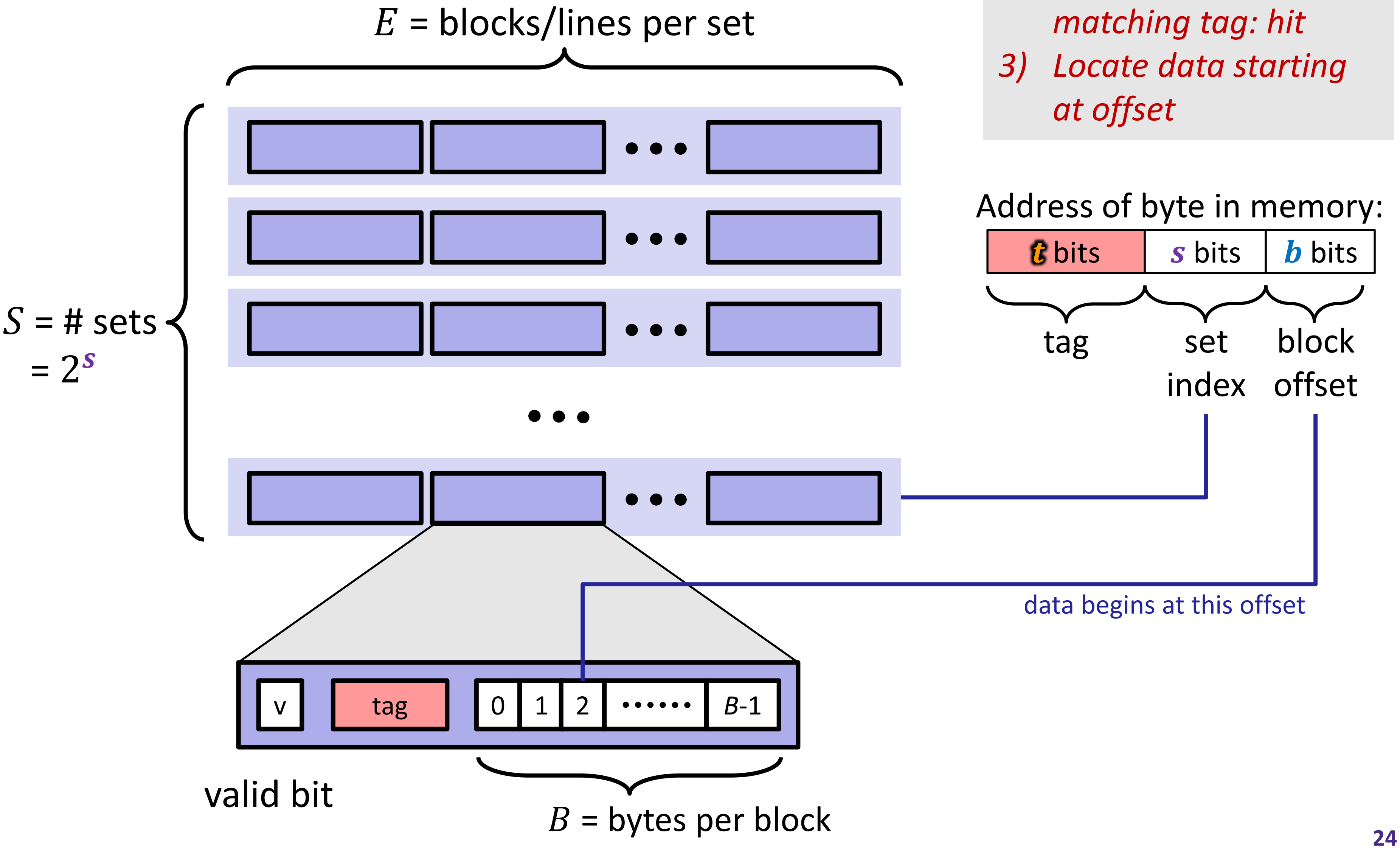
Notation Review

- We just introduced a lot of new variable names!
  - Please be mindful of block size notation when you look at past exam questions or are watching videos

Variable	This Quarter	Formulas
Block size	B	$M = 2^{\boldsymbol{m}} \leftrightarrow \boldsymbol{m} = \log_2 M$ $S = 2^{\boldsymbol{s}} \leftrightarrow \boldsymbol{s} = \log_2 S$ $B = 2^{\boldsymbol{b}} \leftrightarrow \boldsymbol{b} = \log_2 B$ $C = B \times E \times S$ $\boldsymbol{s} = \log_2(C/B/E)$ $\boldsymbol{m} = \boldsymbol{t} + \boldsymbol{s} + \boldsymbol{b}$
Cache size	C	
Associativity	E	
Number of Sets	S	
Address space	M	
Address width	$\boldsymbol{m}$	
Tag field width	$\boldsymbol{t}$	
Index field width	$\boldsymbol{s}$	
Offset field width	$\boldsymbol{b}$	

Cache Read

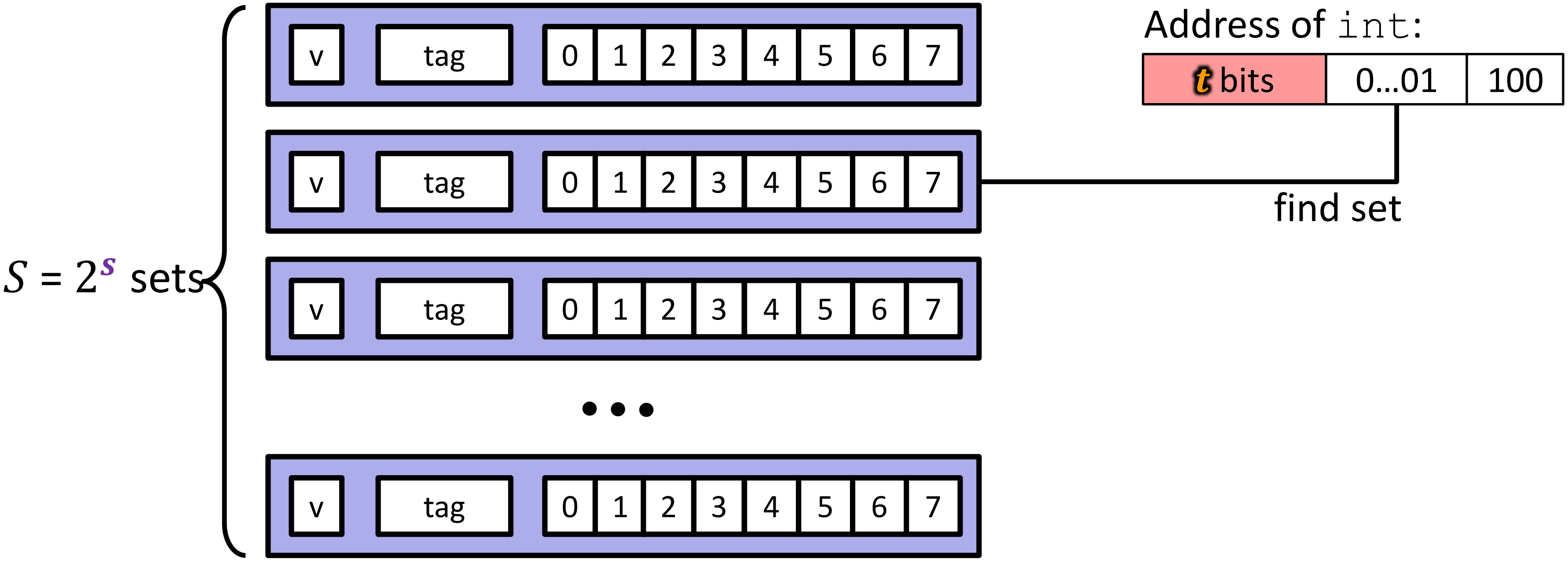
1) *Locate set*
2) *Check if any line in set is valid and has matching tag: hit*
3) *Locate data starting at offset*



Example: Direct-Mapped Cache (E = 1)

Direct-mapped: One line per set

Block Size B = 8 Bytes



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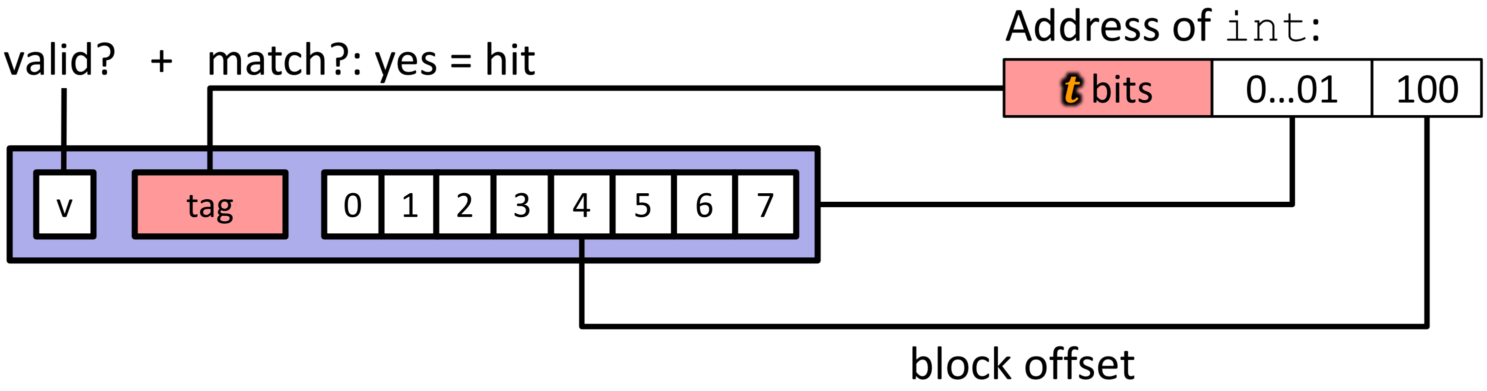
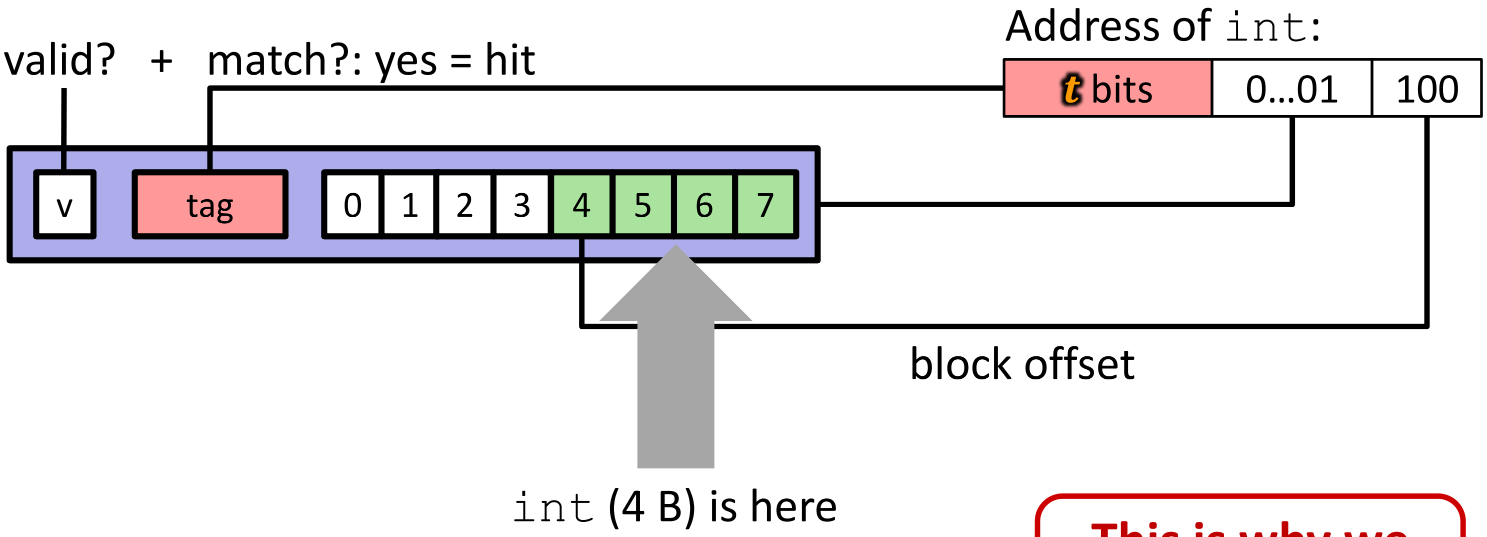


Example: Direct-Mapped Cache (E = 1)

Direct-mapped: One line per set
Block Size B = 8 Bytes



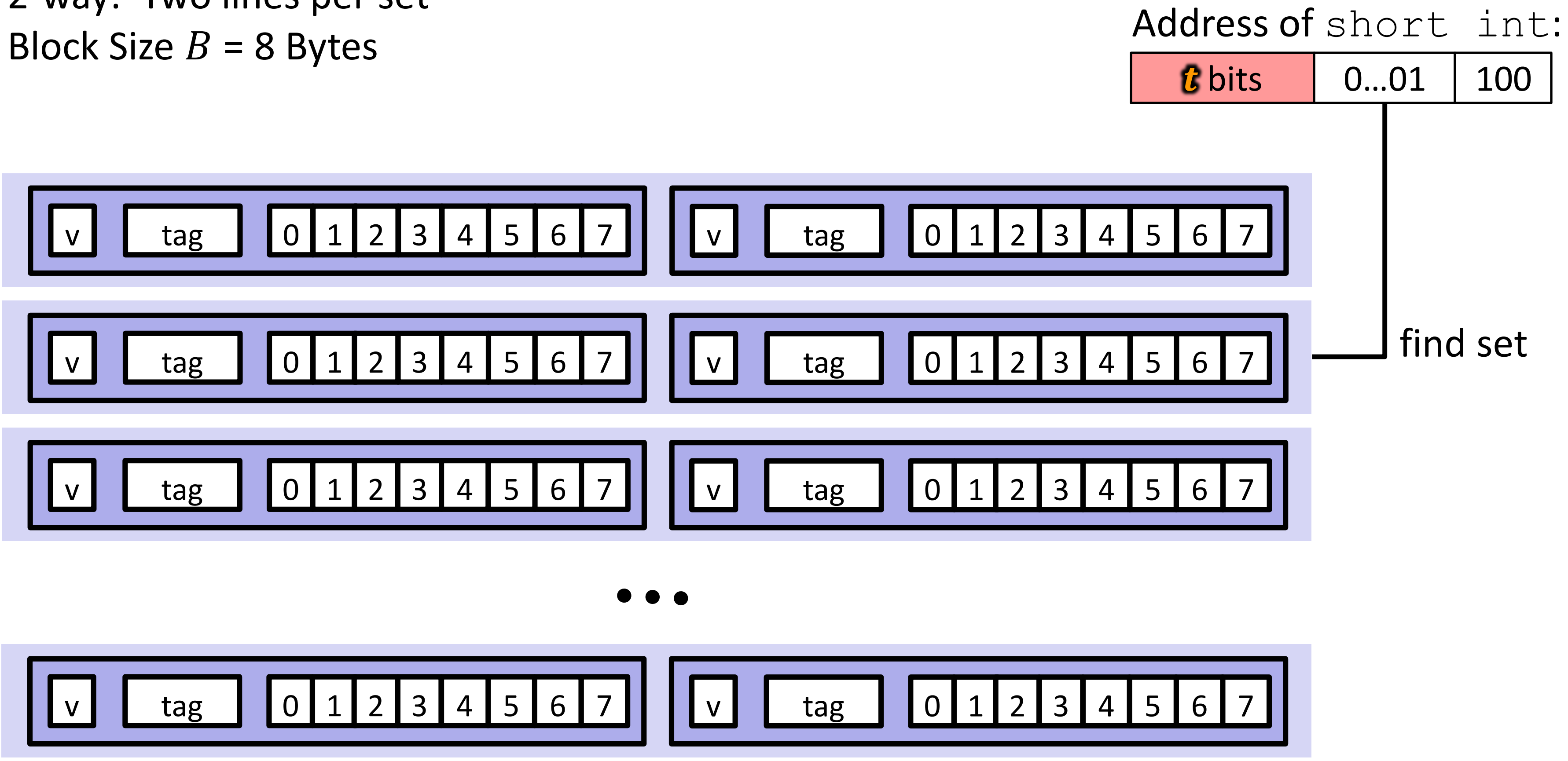
This is why we want alignment!

No match? Then old line gets evicted and replaced

Example: Set-Associative Cache (E = 2)

2-way: Two lines per set

Block Size B = 8 Bytes



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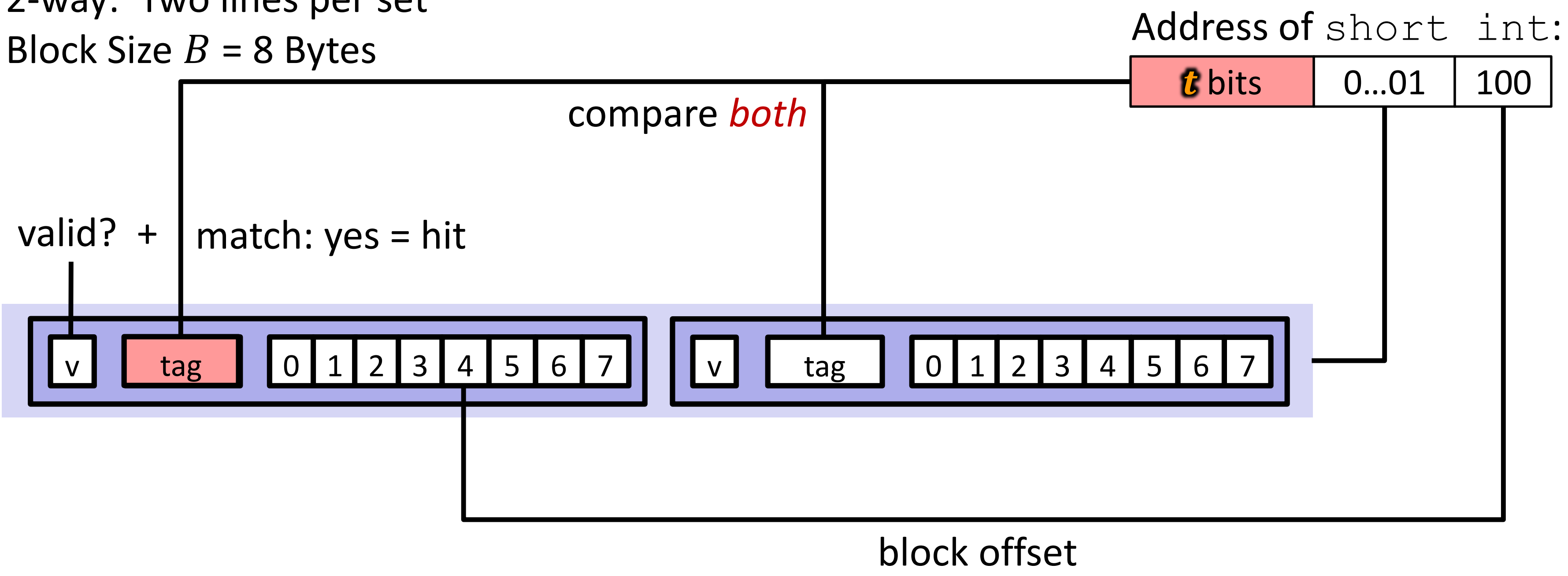
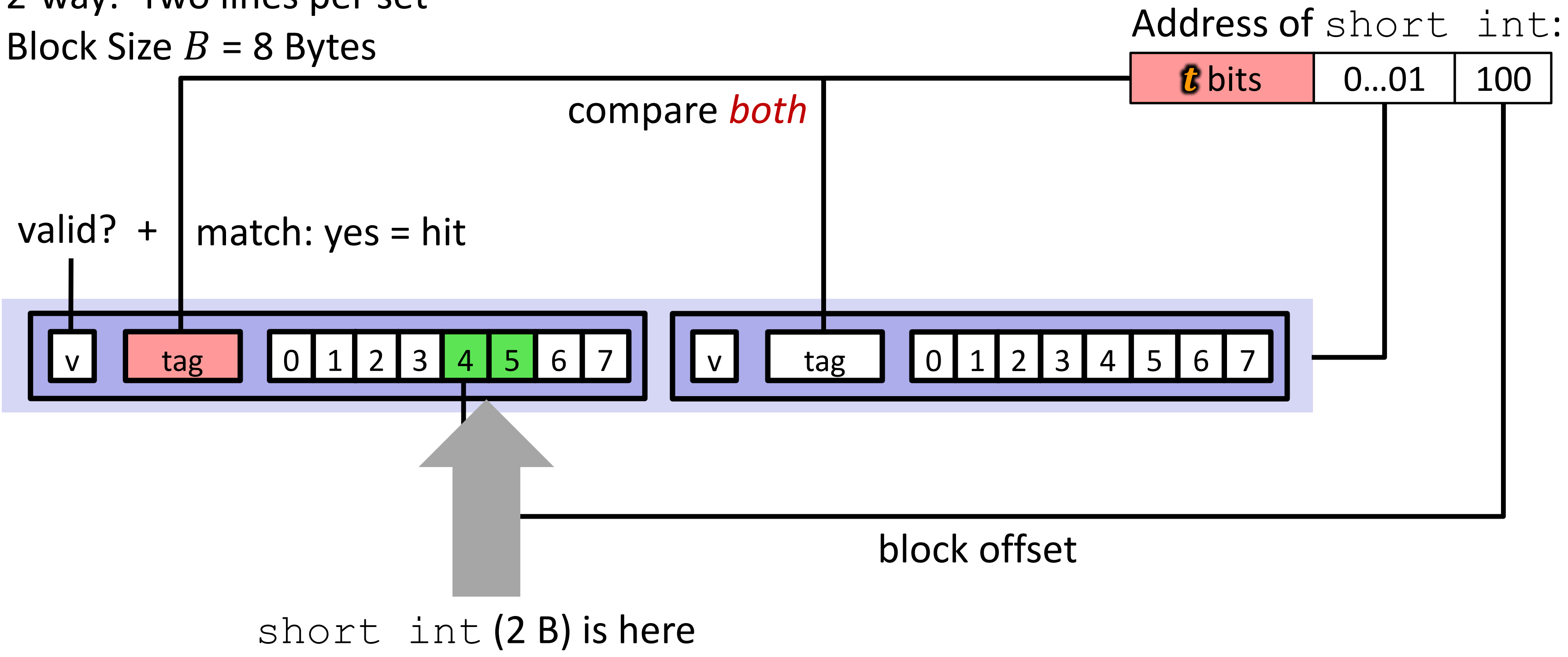


Example: Set-Associative Cache (E = 2)

2-way: Two lines per set

Block Size B = 8 Bytes



No match?

- One line in set is selected for eviction and replacement
- Replacement policies: random, least recently used (LRU), …