Chapter 5

Large and Fast: Exploiting Memory Hierarchy

Recap

- Memory hierarchy
- Storage technologies
- Direct mapped cache
- Write policies

Direct mapped

# of blocks ⇒ index bit

block size ⇒ offset bit

other ⇒ tag bit

set-associated

# of sets ⇒ index bit

Write Policies Summary

- If that memory location is in the cache?
  - Send it to the cache
  - Should we also send it to memory right away?

    (write-through policy)
  - Wait until we kick the block out (write-back policy)
- If it is not in the cache?
  - Allocate the line (put it in the cache)?

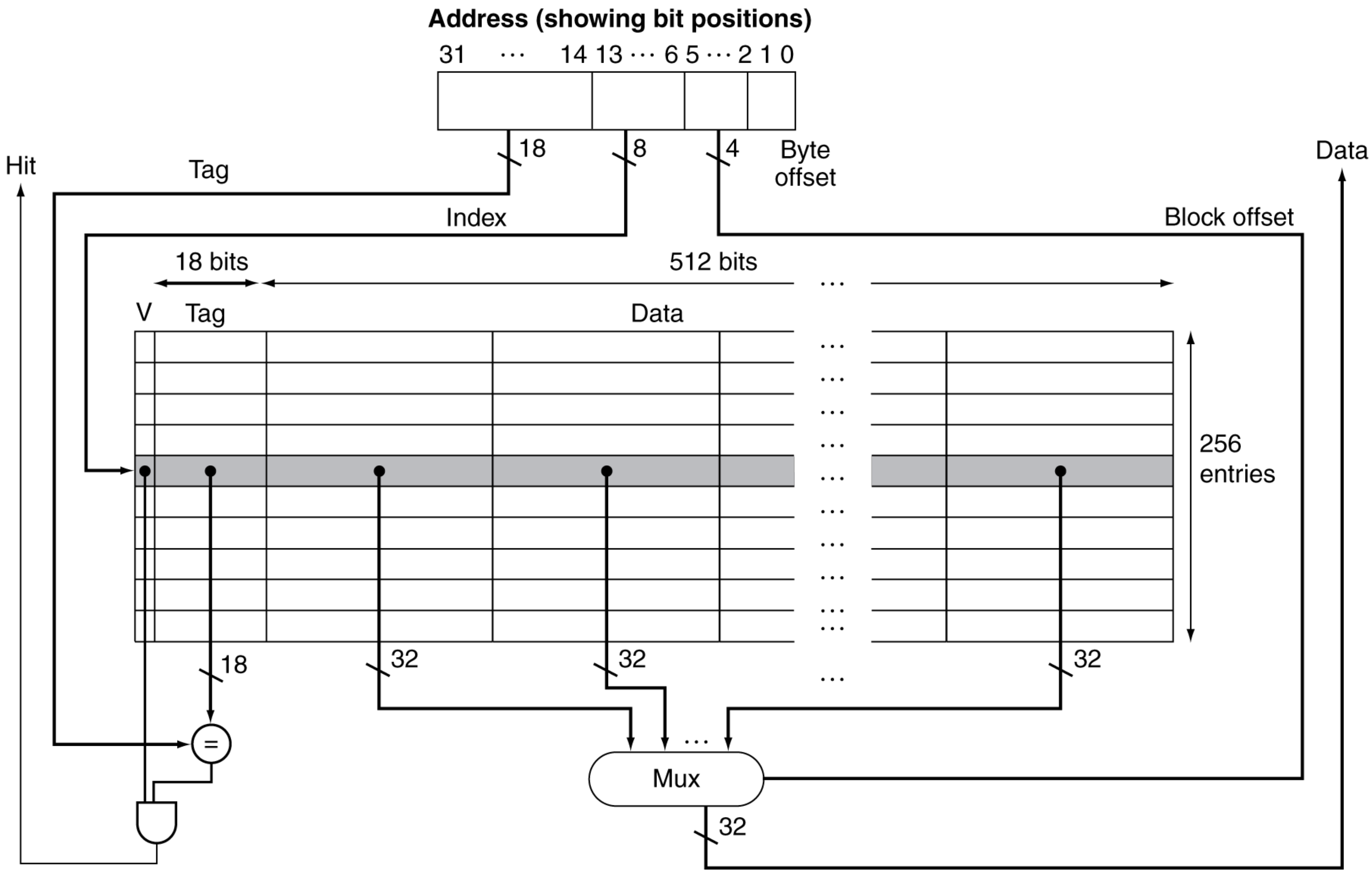
    (write allocate policy)
  - Write it directly to memory without allocation?

    (no write allocate policy)

Example: Intrinsity FastMATH

- Embedded MIPS processor
  - 12-stage pipeline
  - Instruction and data access on each cycle
- Split cache: separate I-cache and D-cache
  - Each 16KB: 256 blocks × 16 words/block
  - D-cache: write-through or write-back
- SPEC2000 miss rates
  - I-cache: 0.4%
  - D-cache: 11.4%
  - Weighted average: 3.2%

Example: Intrinsity FastMATH



Measuring Cache Performance

- Components of CPU time
  - Program execution cycles
    - Includes cache hit time
  - Memory stall cycles
    - Mainly from cache misses
- With simplifying assumptions:

$$\text{Memory stall cycles}$$

$$= \frac{\text{Memory accesses}}{\text{Program}} \times \text{Miss rate} \times \text{Miss penalty}$$

$$= \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Misses}}{\text{Instruction}} \times \text{Miss penalty}$$

Cache Performance Example

- Calculate actual CPI, given that
  - I-cache miss rate = 2%
  - D-cache miss rate = 4%
  - Miss penalty = 100 cycles
  - Base CPI (ideal cache) = 2
  - Load & stores are 36% of instructions
- Miss cycles per instruction (assume *N* ins. In total)
  - I-cache: $N \times 0.02 \times 100/N = 2$
  - D-cache: $N \times 0.36 \times 0.04 \times 100/N = 1.44$
- Actual CPI = 2 + 2 + 1.44 = 5.44
  - Ideal CPU is 5.44/2 =2.72 times faster

Average Access Time

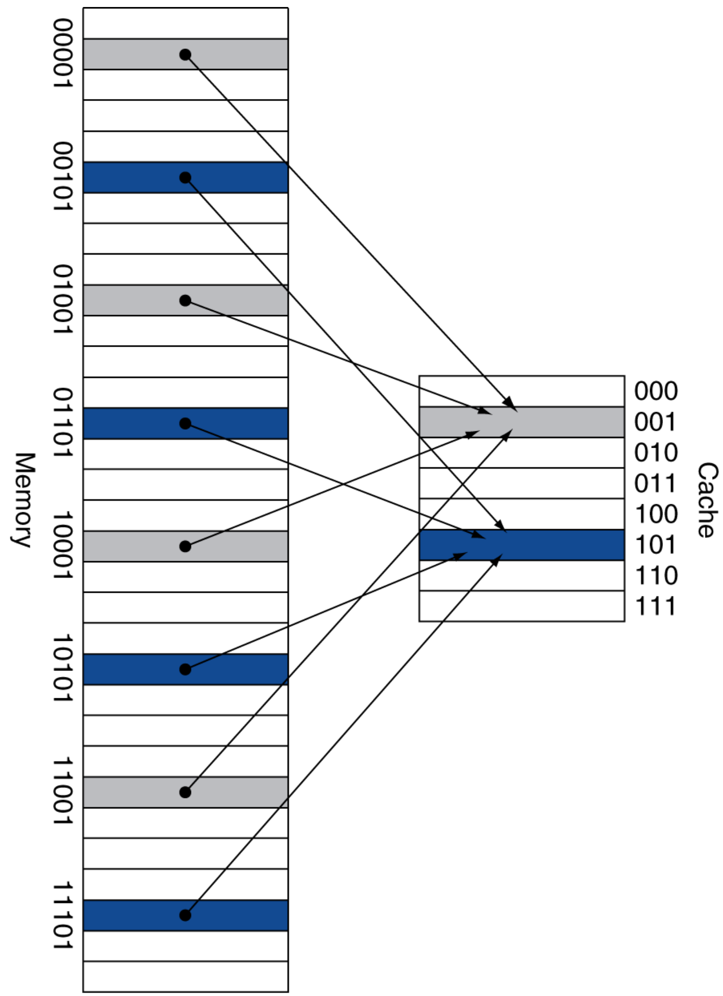
- Hit time is also important for performance
- Average memory access time (AMAT)
  - AMAT = Hit time + Miss rate × Miss penalty
- Example
  - CPU with 1ns clock, hit time = 1 cycle, miss penalty = 20 cycles, I-cache miss rate = 5%
  - AMAT = 1 + 0.05 × 20 = 2ns
    - 2 cycles per instruction

Performance Summary

- When CPU performance increased
  - Miss penalty becomes more significant
  - CPI=2, Miss=3.44, % of memory stall: 3.44/5.44=63%
  - CPI=1, Miss=3.44, % of memory stall: 3.44/4.44=77%
- Decreasing base CPI
  - Greater proportion of time spent on memory stalls
- Increasing clock rate
  - Memory stalls account for more CPU cycles
- Can't neglect cache behavior when evaluating system performance

Recall: Direct Mapped Cache

- Location determined by address
- Direct mapped: only one choice
  - Capacity of cache is not fully exploited
  - Miss rate is high



Cache Example

Word addr	Binary addr	Hit/miss	Cache block
18	10 010	Miss	010
26	11 010	Miss	010
18	10 010	Miss	010

Index	V	Tag	Data
000	Y	10	Mem[10000]
001	N		
010	**Y**	**10**	**Mem[10010]**
011	Y	00	Mem[00011]
100	N		
101	N		
110	Y	10	Mem[10110]
111	N		

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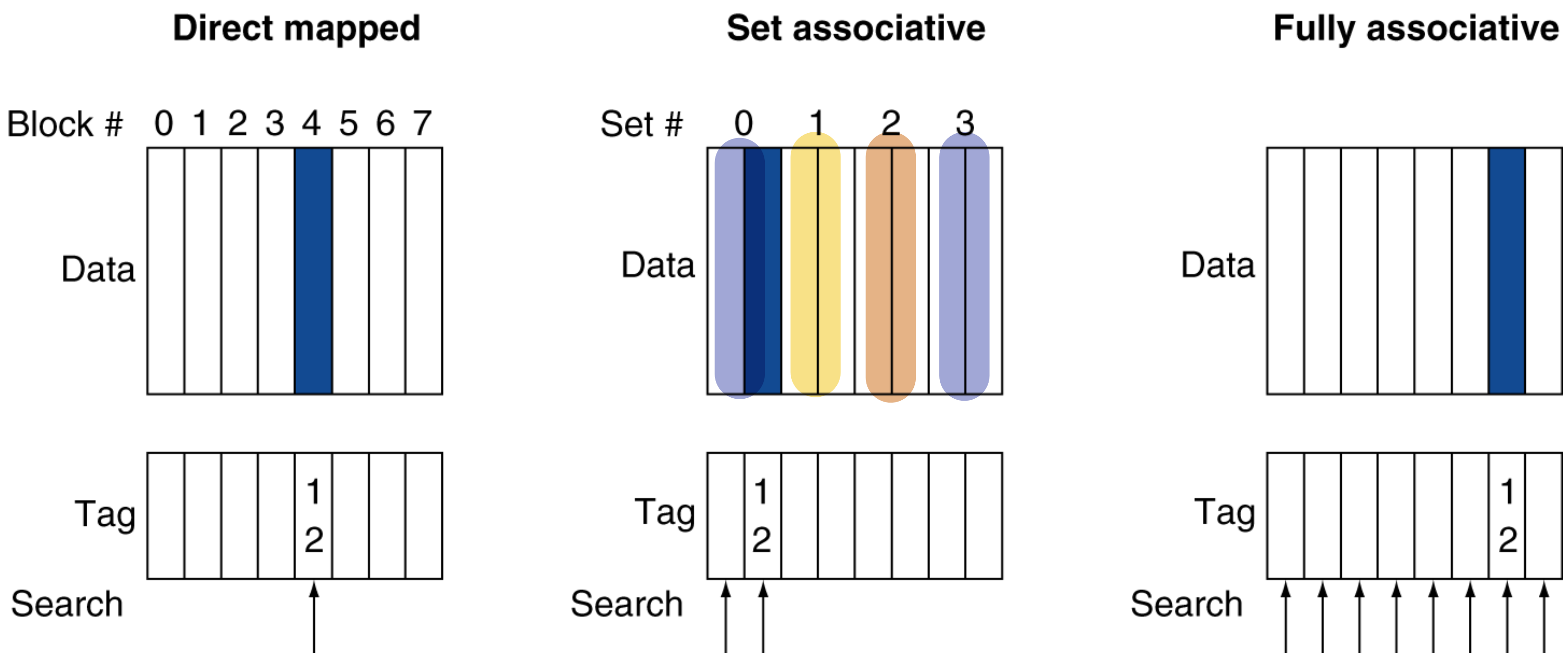
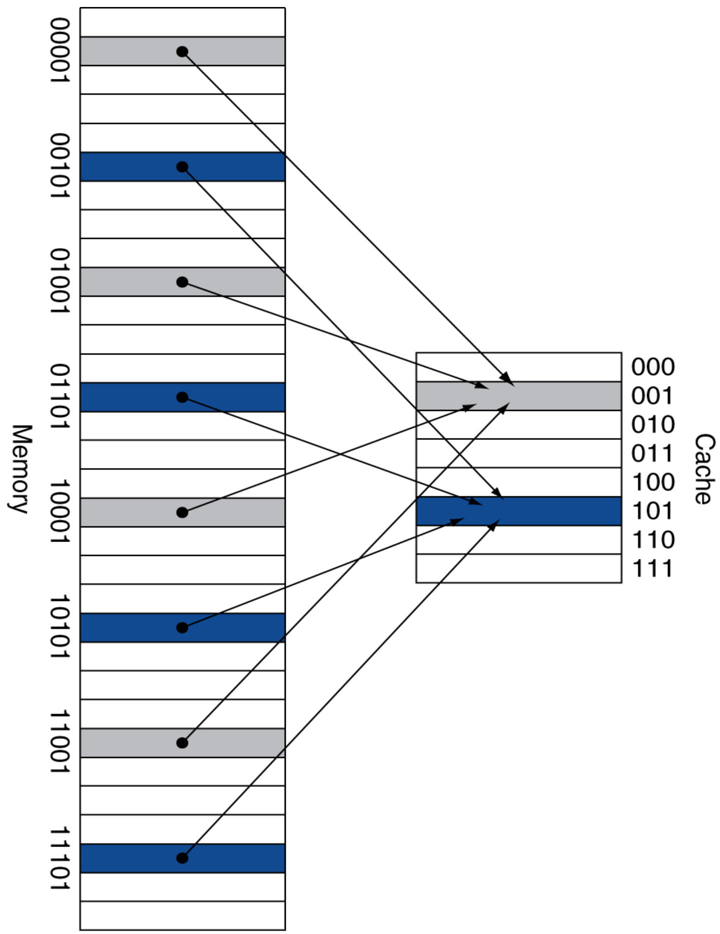
Associative Cache Example

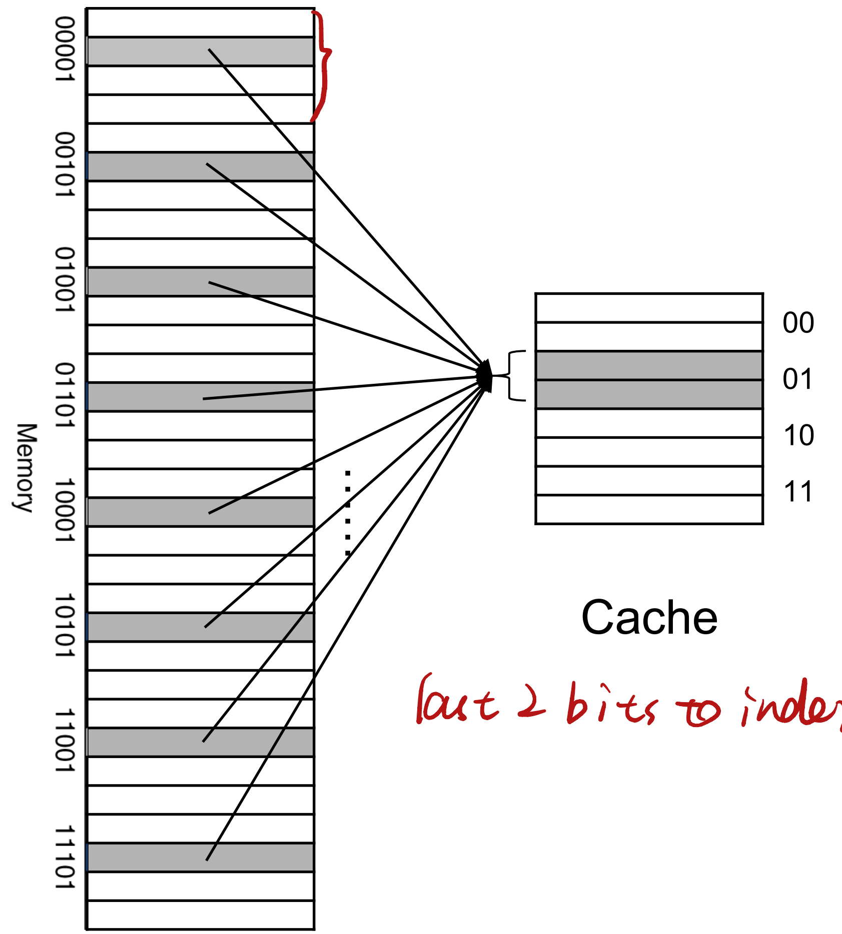


2-Way Set Associative Cache

Direct mapped cache



2-way set associative cache



last 2 bits to index.

Associative Caches

- Fully associative
  - Allow a given block to go in any cache entry
  - Requires all entries to be searched at once
  - Comparator per entry (expensive)
- *n*-way set associative
  - Each set contains *n* entries
  - Block number determines which set
    - (Block number) modulo (#Sets in cache)
  - Search all entries in a given set at once
  - *n* comparators (less expensive)

Spectrum of Associativity

- For a cache with 8 blocks

One-way set associative
(direct mapped)

Block	Tag	Data
0		
1		
2		
3		
4		
5		
6		
7		

Two-way set associative

Set	Tag	Data	Tag	Data
0				
1				
2				
3				

Four-way set associative

Set	Tag	Data	Tag	Data	Tag	Data	Tag	Data
0								
1								

Eight-way set associative (fully associative)

Tag	Data	Tag	Data	Tag	Data	Tag	Data	Tag	Data	Tag	Data	Tag	Data	Tag	Data

Associativity Example

- Assume a cache has 4 blocks
  - Compare three kinds of cache: Direct mapped, 2-way set associative, fully associative
  - Assume block size is 8 bytes, we access address 0, 64, 0, 48, 64 sequentially, then, the block sequence we accessed should be: 0, 8, 0, 6, 8
- Direct mapped

Tag: 27 bits	Index: 2 bits	Offset: 3 bits

  - Index: 2-bit (because the cache has 4 blocks)

Block address	Cache index	Hit/miss	Cache content after access			
			0	1	2	3
0	0	miss	**Mem[0]**			
8	0	miss	**Mem[8]**			
0	0	miss	**Mem[0]**			
6	2	miss	Mem[0]		**Mem[6]**	
8	0	miss	**Mem[8]**		Mem[6]	

Associativity Example

- 2-way set associative

Tag: 28 bits	Index: 1 bits	Offset: 3 bits

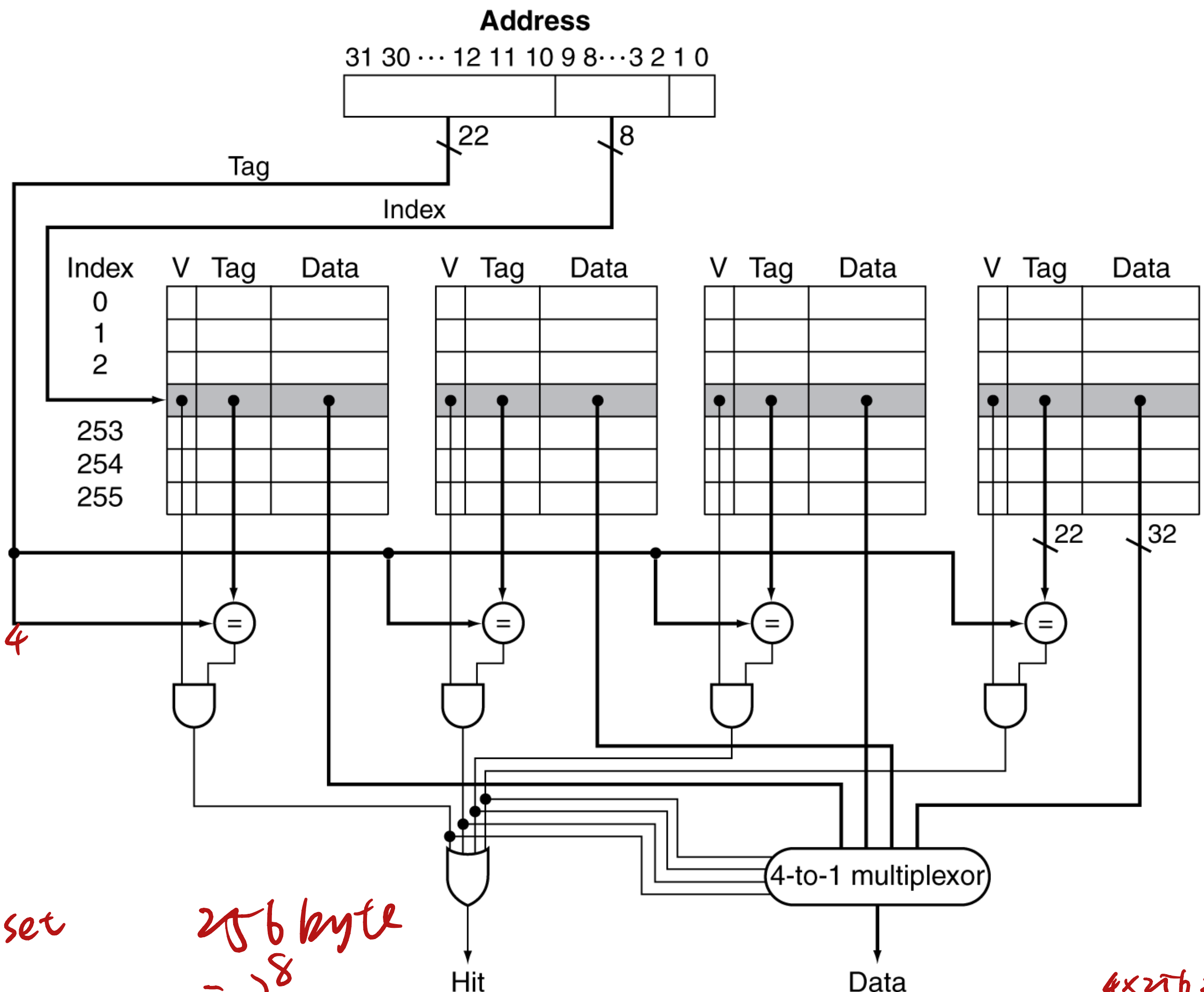
Block address	Cache index	Hit/miss	Cache content after access			
			Set 0		Set 1	
0	0	miss	**Mem[0]**			
8	0	miss	Mem[0]	**Mem[8]**		
0	0	hit	**Mem[0]**	Mem[8]		
6	0	miss	Mem[0]	**Mem[6]**		
8	0	miss	**Mem[8]**	Mem[6]		

- Fully associative

Tag: 29 bits	Index: 0 bits	Offset: 3 bits

Block address		Hit/miss	Cache content after access			
0		miss	**Mem[0]**			
8		miss	Mem[0]	**Mem[8]**		
0		hit	**Mem[0]**	Mem[8]		
6		miss	Mem[0]	Mem[8]	**Mem[6]**	
8		hit	Mem[0]	**Mem[8]**	Mem[6]	

Set Associative Cache Organization



16 4+4

$\times 16$

96

16

256

一行一个set

4

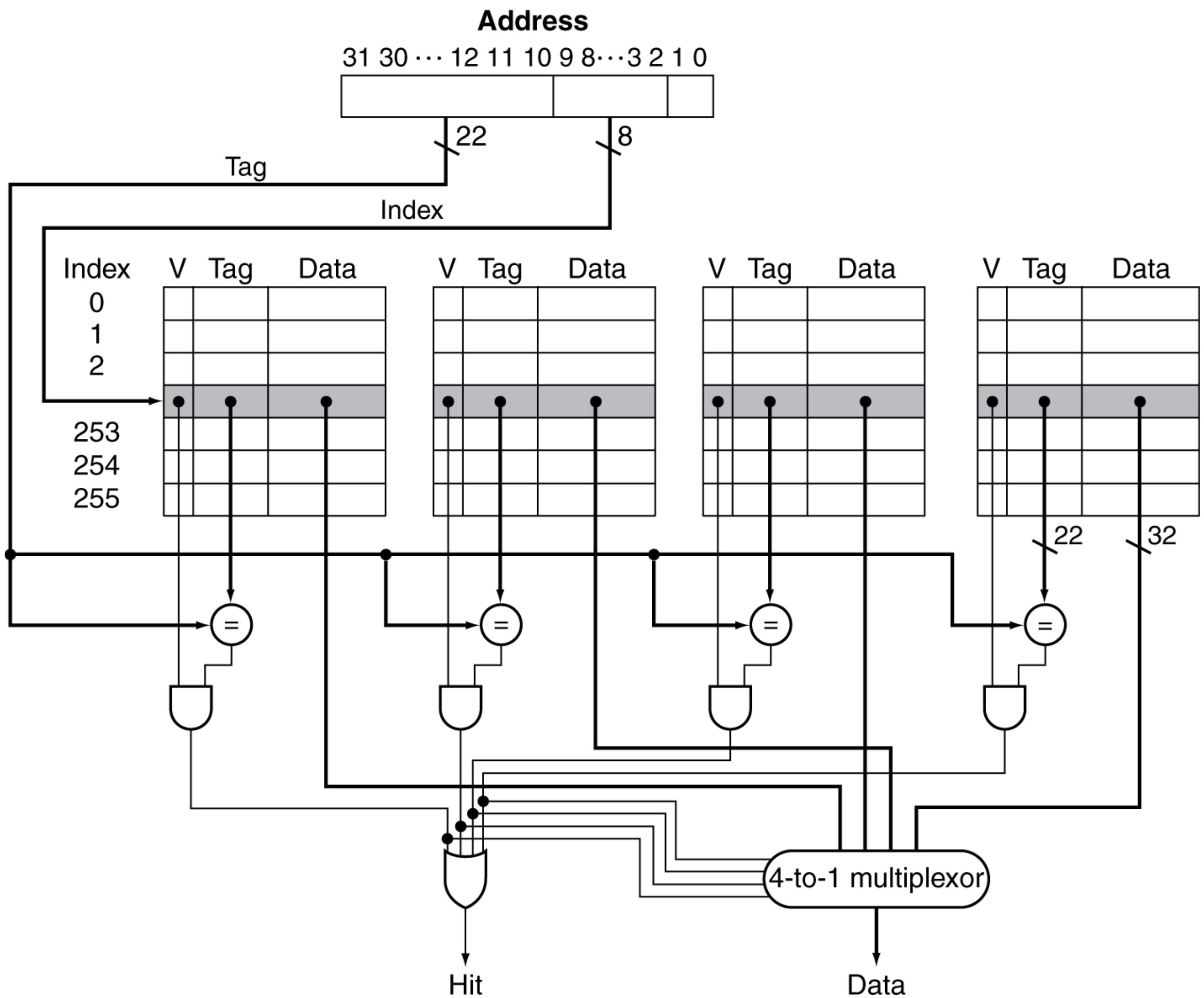
256 byte $= 2^8$

$4\times256=1024$

?-way set associative? Block size? How many sets in cache? How many tags?

2bit , $2^2=4$byte 256行 $=2^8$ bit index

Set Associative Cache Organization



4-way set associative. Block size: 4 bytes. 256 sets. 1024 tags.

How Much Associativity

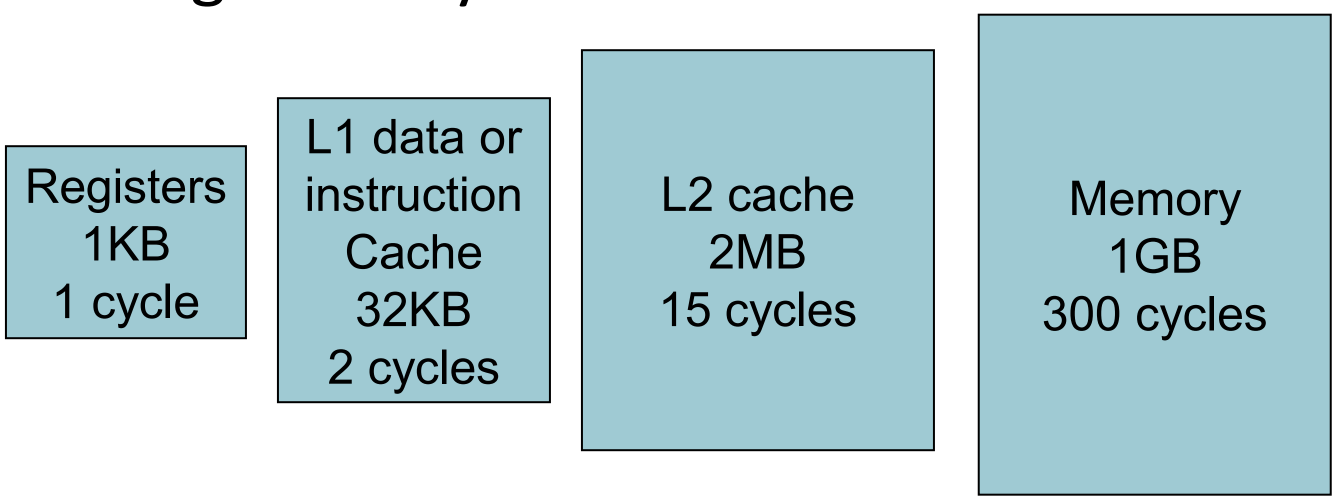
- Increased associativity decreases miss rate
  - But with diminishing returns
- Simulation of a system with 64KB D-cache, 16-word blocks, SPEC2000
  - 1-way: 10.3%
  - 2-way: 8.6%
  - 4-way: 8.3%
  - 8-way: 8.1%

Replacement Policy

- Direct mapped: no choice, no replacement policy needed
- Set associative
  - Prefer non-valid entry, if there is one
  - Otherwise, choose among entries in the set
- Least-recently used (LRU)
  - Choose the one unused for the longest time
    - Simple for 2-way, manageable for 4-way, too hard beyond that
- Random
  - Gives approximately the same performance as LRU for high associativity

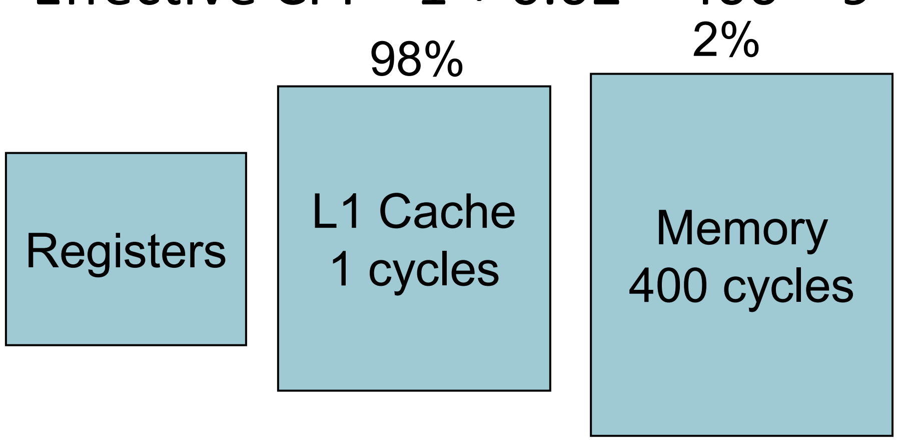
Multilevel Caches

- Primary cache (level-1 cache) attached to CPU
  - Small, but fast
- Level-2 cache services misses from level-1 cache
  - Larger, slower, but still faster than main memory
- Main memory services L-2 cache misses
- Some high-end systems include L-3 cache



Multilevel Cache Example

- Given
  - CPU base CPI = 1, clock rate = 4GHz
  - Miss rate/instruction = 2%
  - Main memory access time = 100ns
- With only L1 cache
  - Miss penalty = 100ns/0.25ns = 400 cycles
  - Effective CPI = 1 + 0.02 × 400 = 9

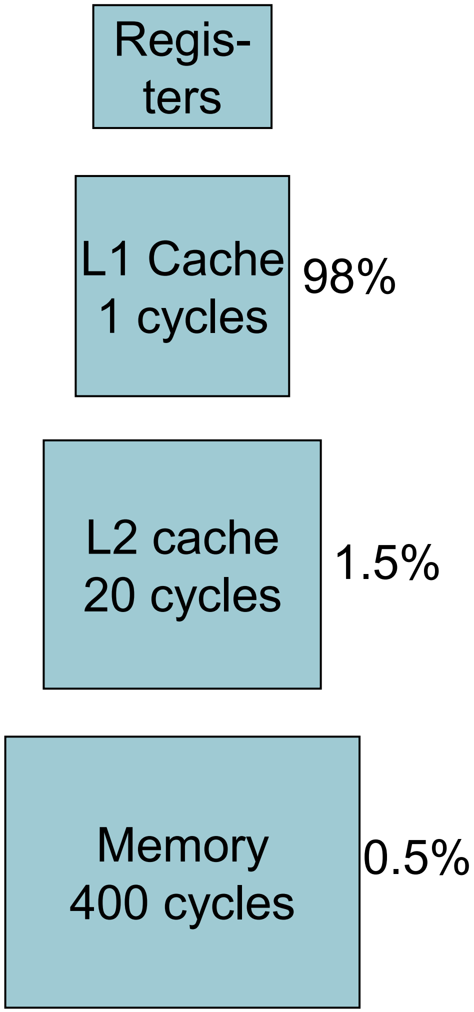


Example (cont.)

- Now add L-2 cache, calculate the new CPI, given
  - Access time = 5ns
  - Global miss ratio of L2 cache = 0.5%

    (Local miss ratio of L2 = 0.5%/2% = 25%)
- L-1 miss with L-2 hit
  - Penalty = 5ns/0.25ns = 20 cycles
- L-1 miss with L-2 miss
  - Extra penalty = 400 cycles
- CPI = $0.98 \times 1 + 0.015 \times 21$

  $+ 0.005 \times 421 = 3.4$
- Performance ratio = 9/3.4 = 2.6



Multilevel Cache Considerations

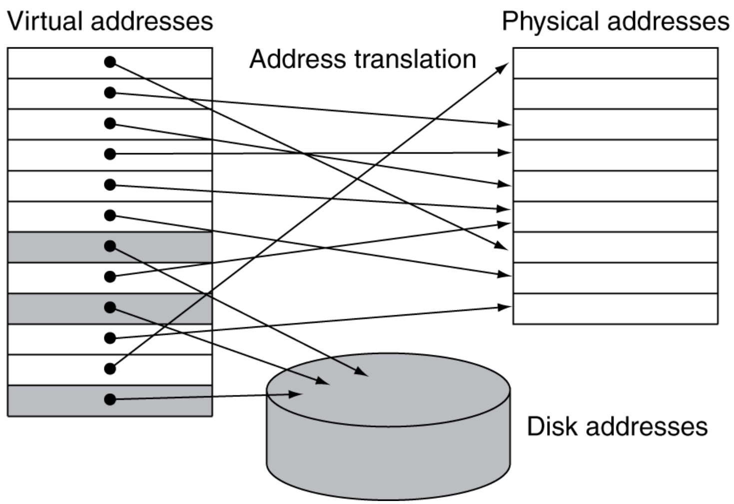
- L-1 cache
  - Focus on minimal hit time
- L-2 cache
  - Focus on low miss rate to avoid main memory access
  - Hit time has less overall impact
- Results
  - L-1 cache usually smaller than a single cache
  - L-1 block size smaller than L-2 block size

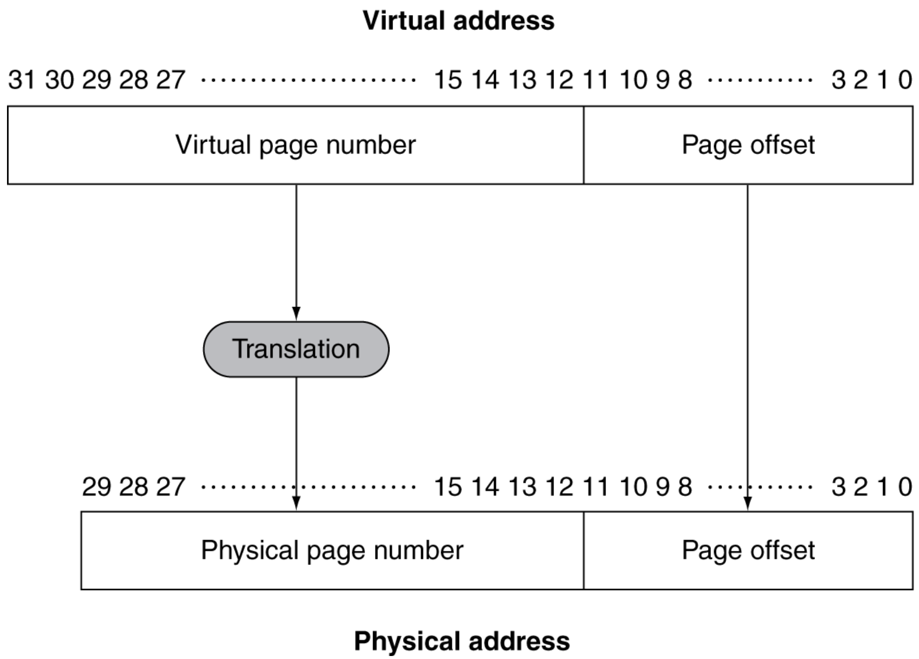
Virtual Memory

- Use main memory as a "cache" for secondary (disk) storage
  - Managed jointly by CPU hardware and the operating system (OS)
- Programs share main memory
  - Each gets a private virtual address space holding its frequently used code and data
  - Protected from other programs
- CPU and OS translate virtual addresses to physical addresses
  - VM "block" is called a page
  - VM "miss" is called a page fault

Address Translation

- Fixed-size pages (e.g., 4K)





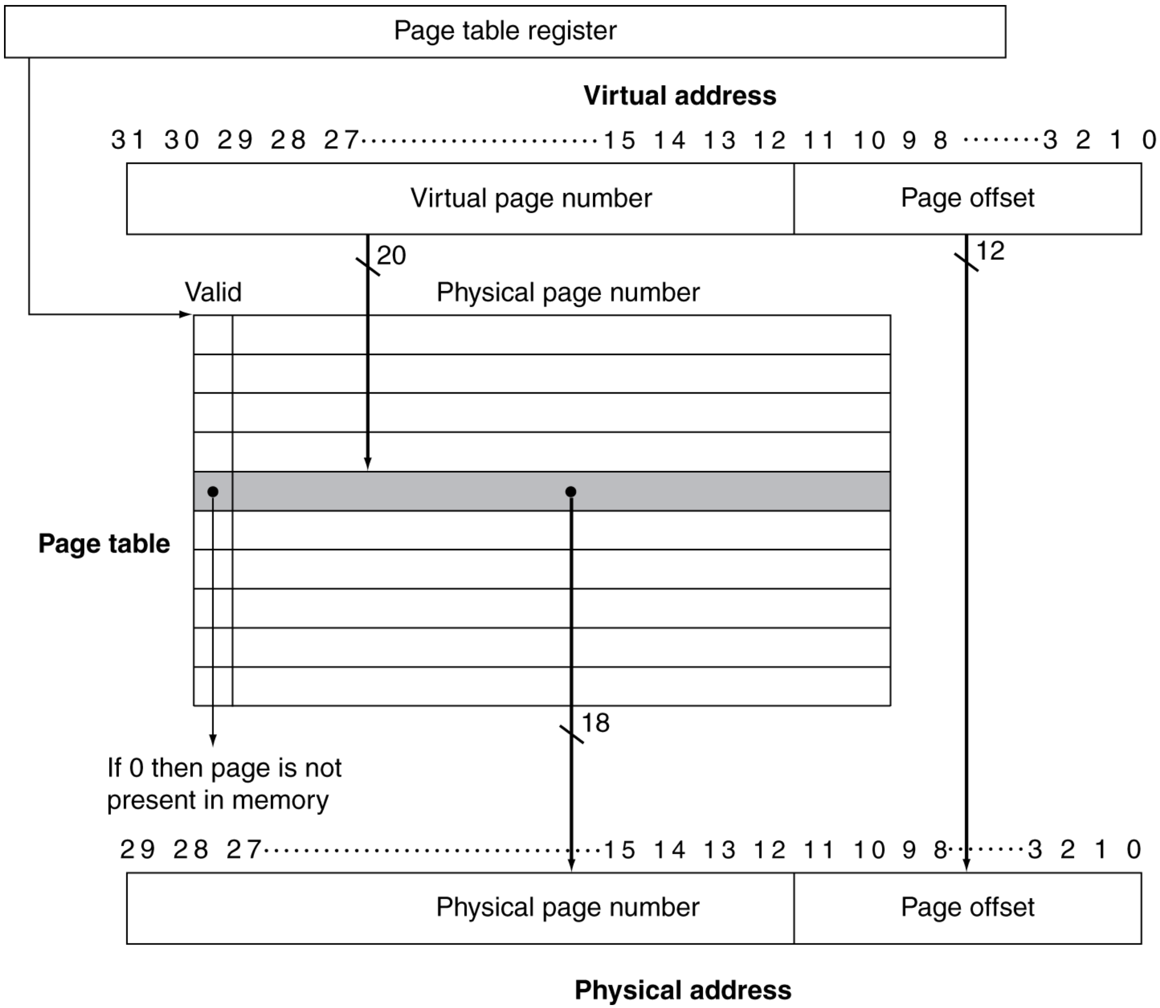
Page Fault Penalty

- On page fault, the page must be fetched from disk
  - Takes millions of clock cycles
  - Handled by OS code
- Try to minimize page fault rate
  - Fully associative placement
  - Smart replacement algorithms

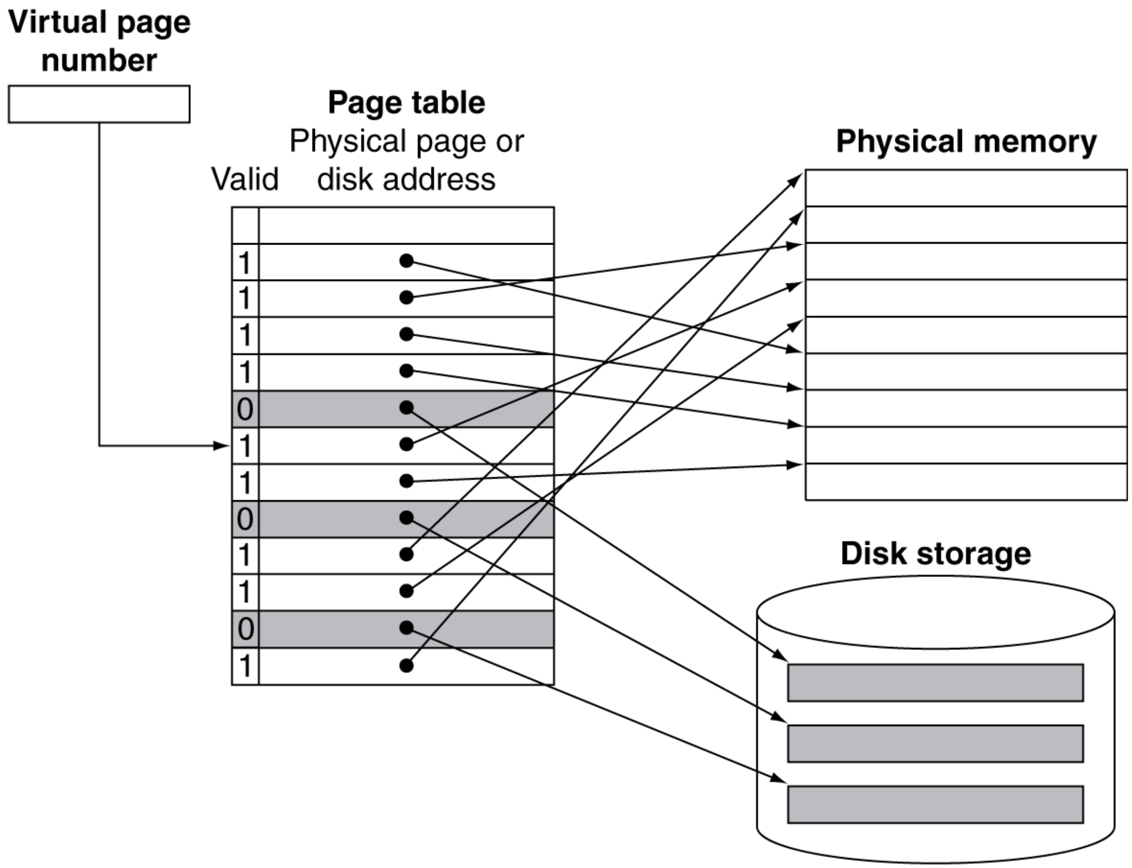
Page Tables

- Where is the placement information? Page Table
  - Array of page table entries (PTE), indexed by virtual page number 只是index，不用存
  - Page table register in CPU points to page table in physical memory
- Each program has its page table. Page table is in memory
- If page is present in memory
  - PTE stores the physical page number
  - Plus other status bits (referenced, dirty, …)
- If page is not present
  - PTE can refer to location in swap space on disk

Translation Using a Page Table



Mapping Pages to Storage



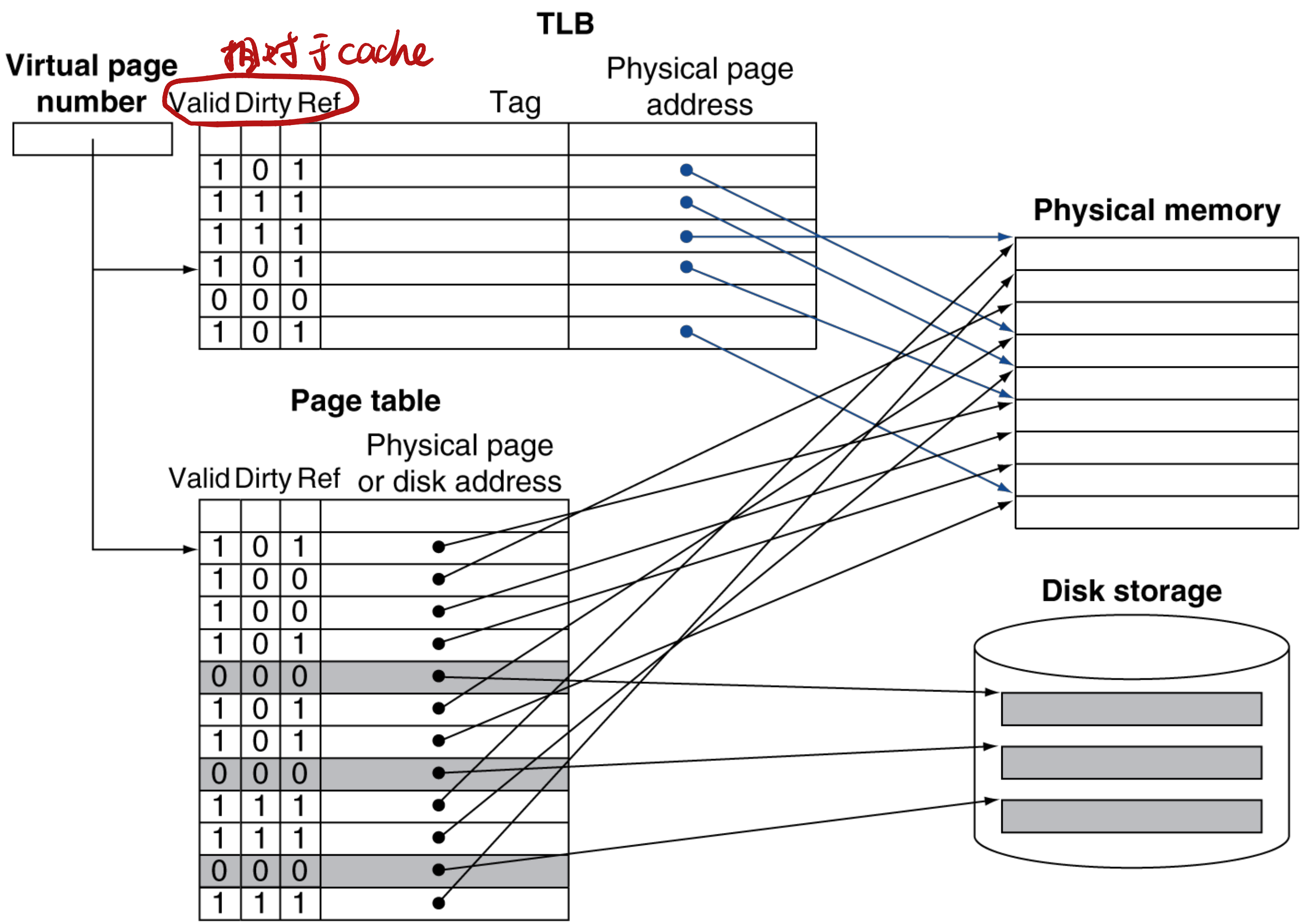
Replacement and Writes

- To reduce page fault rate, prefer least-recently used (LRU) replacement
  - Reference bit (aka use bit) in PTE set to 1 on access to page
  - Periodically cleared to 0 by OS
  - A page with reference bit = 0 has not been used recently
- Disk writes take millions of cycles
  - Block at once, not individual locations
  - Use write-back, because write through is impractical
    × write-through
  - Dirty bit in PTE set when page is written

Fast Translation Using a TLB

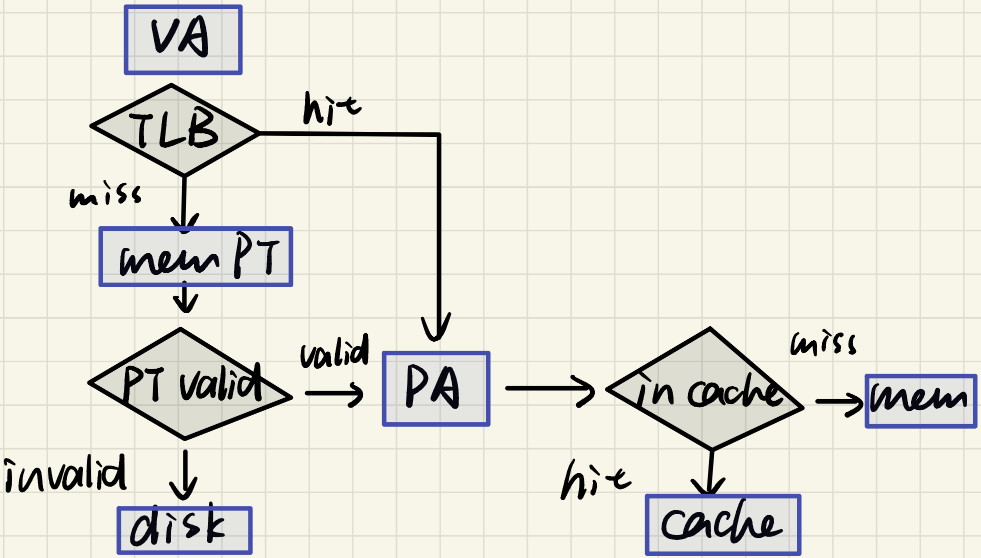
- Since page table is in memory, every memory access by a program requires two memory accesses
  - One to access the page table entry
  - Then the actual memory access
- Can we move the page table to CPU?
  - Yes, use a fast cache in CPU to store recently used PTEs, because access to page tables has good locality
  - Called a Translation Look-aside Buffer (TLB)
  - Typical: 16–512 PTEs, 0.5–1 cycle for hit, 10–100 cycles for miss, 0.01%–1% miss rate
  - Misses could be handled by hardware or software

Fast Translation Using a TLB



TLB Misses

- If page is in memory
  - Load the PTE from memory and retry
  - Could be handled in hardware
    - Can get complex for more complicated page table structures
  - Or in software
    - Raise a special exception, with optimized handler
- If page is not in memory (page fault)
  - OS handles fetching the page and updating the page table
  - Then restart the faulting instruction

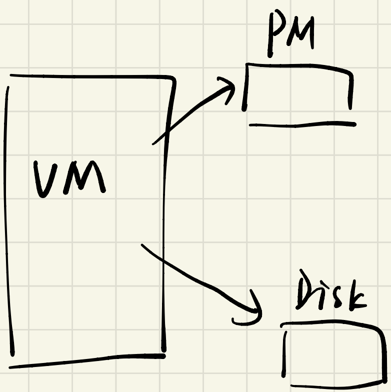

VA
TLB
hit
miss
mem PT
PT valid
valid
invalid
disk
PA
in cache
miss
mem
hit
cache

VPN → TLB → PTE → PPN → Cache

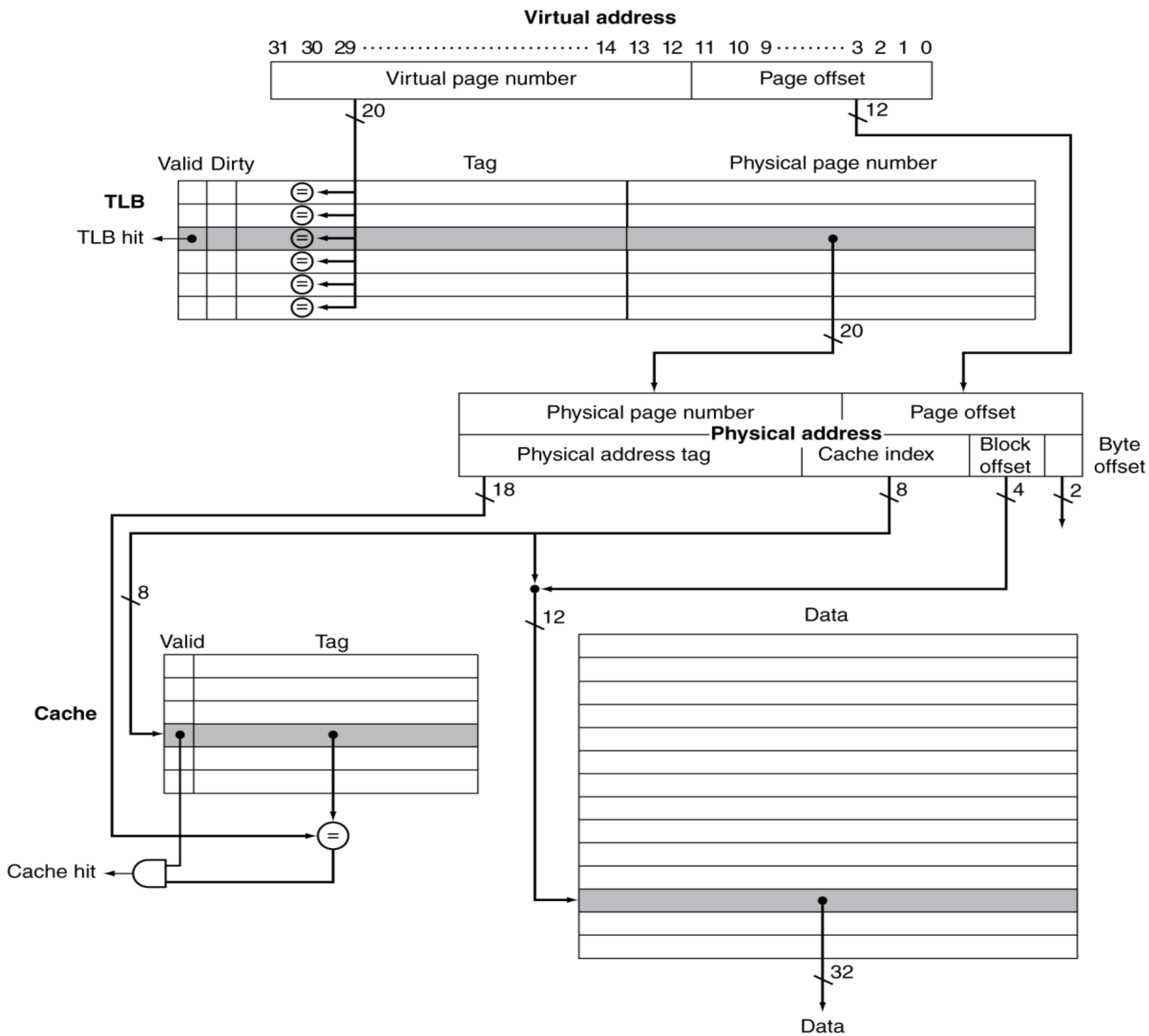
$\boxed{\text{VM}}$

block = page

miss = fault



TLB and Cache Interaction



Memory Protection

- Different tasks can share parts of their virtual address spaces
  - But need to protect against errant access
  - Requires OS assistance
- Hardware support for OS protection
  - Privileged supervisor mode (aka kernel mode)
  - Privileged instructions
  - Page tables and other state information only accessible in supervisor mode
  - System call exception (e.g., syscall in MIPS)

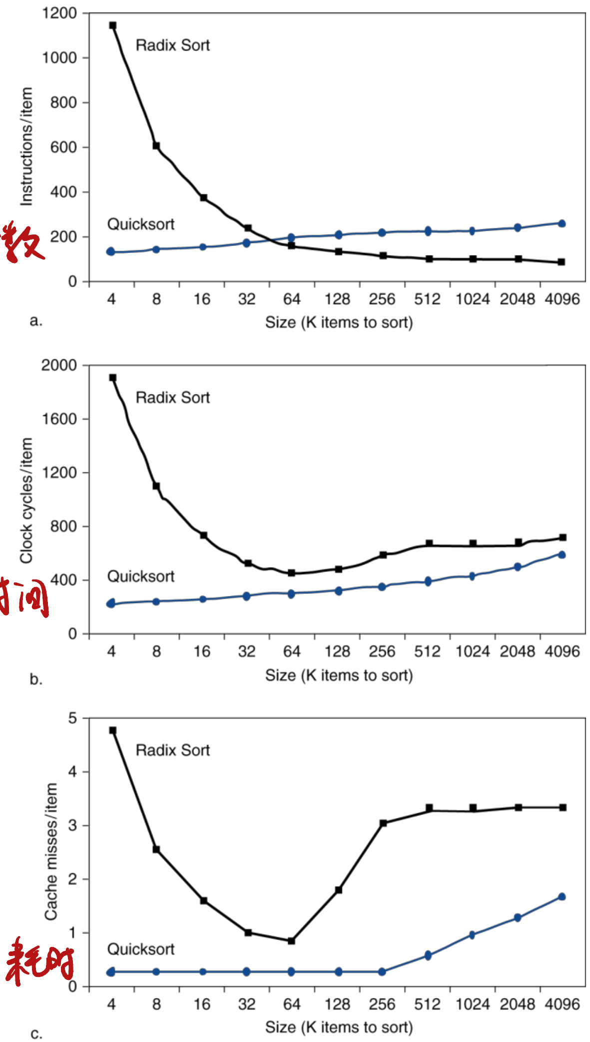
Check Yourself

- Match the definitions between left and right

L1 cache	A cache for a cache
L2 cache	A cache for disks
Main memory	A cache for a main memory
TLB	A cache for page table entries

Interactions with Software

- Compare two algorithms: Radix sort & Quicksort
- When size is large,
  - Radix sort has less instructions
  - But quicksort has less clock cycles
  - Because miss rate of radix sort is higher



指令数

耗时间

cache miss耗时

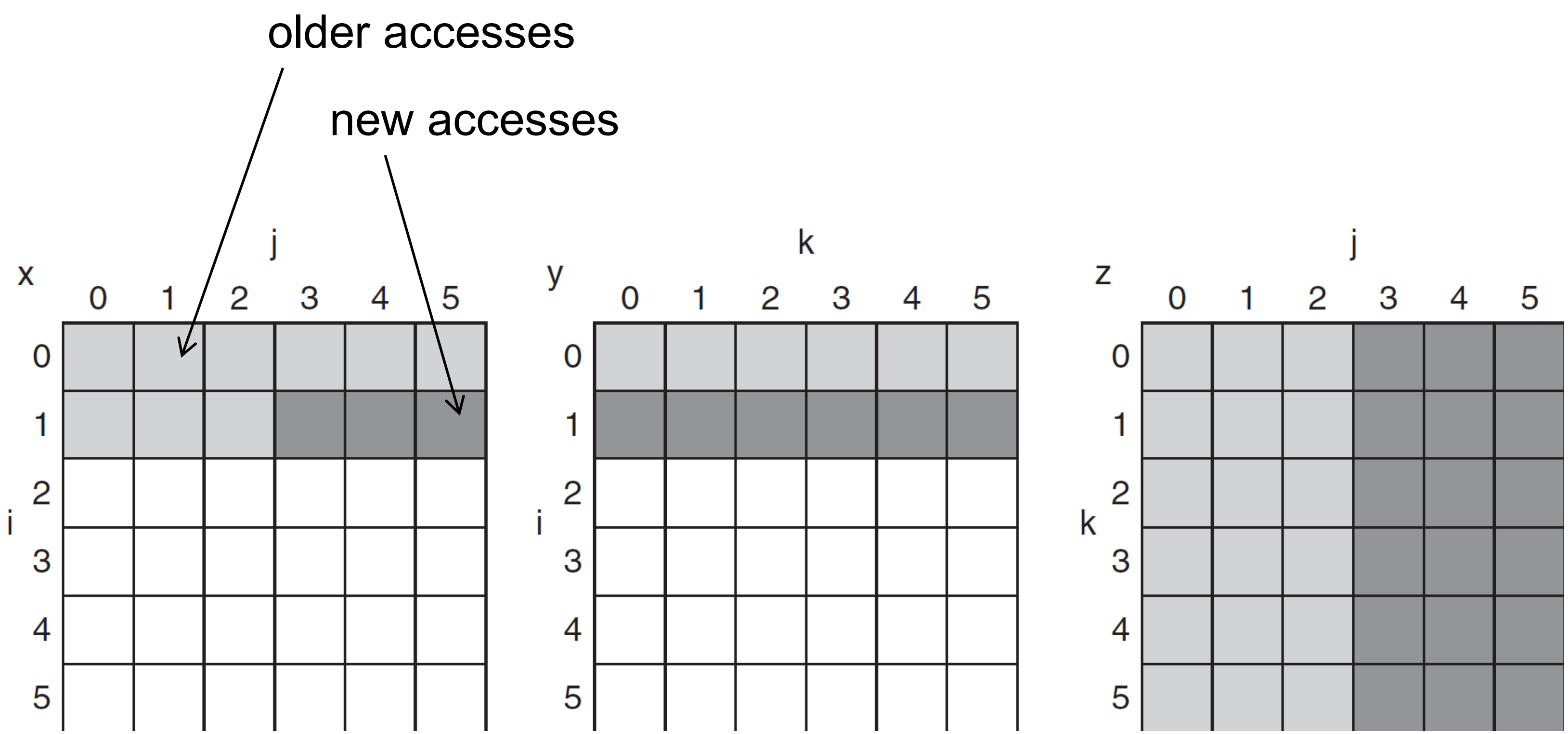
Software Optimization via Blocking

- Goal: maximize accesses to data before it is replaced
- Consider inner loops of DGEMM:

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

DGEMM Access Pattern

- C, A, and B arrays



Blocked DGEMM Access Pattern