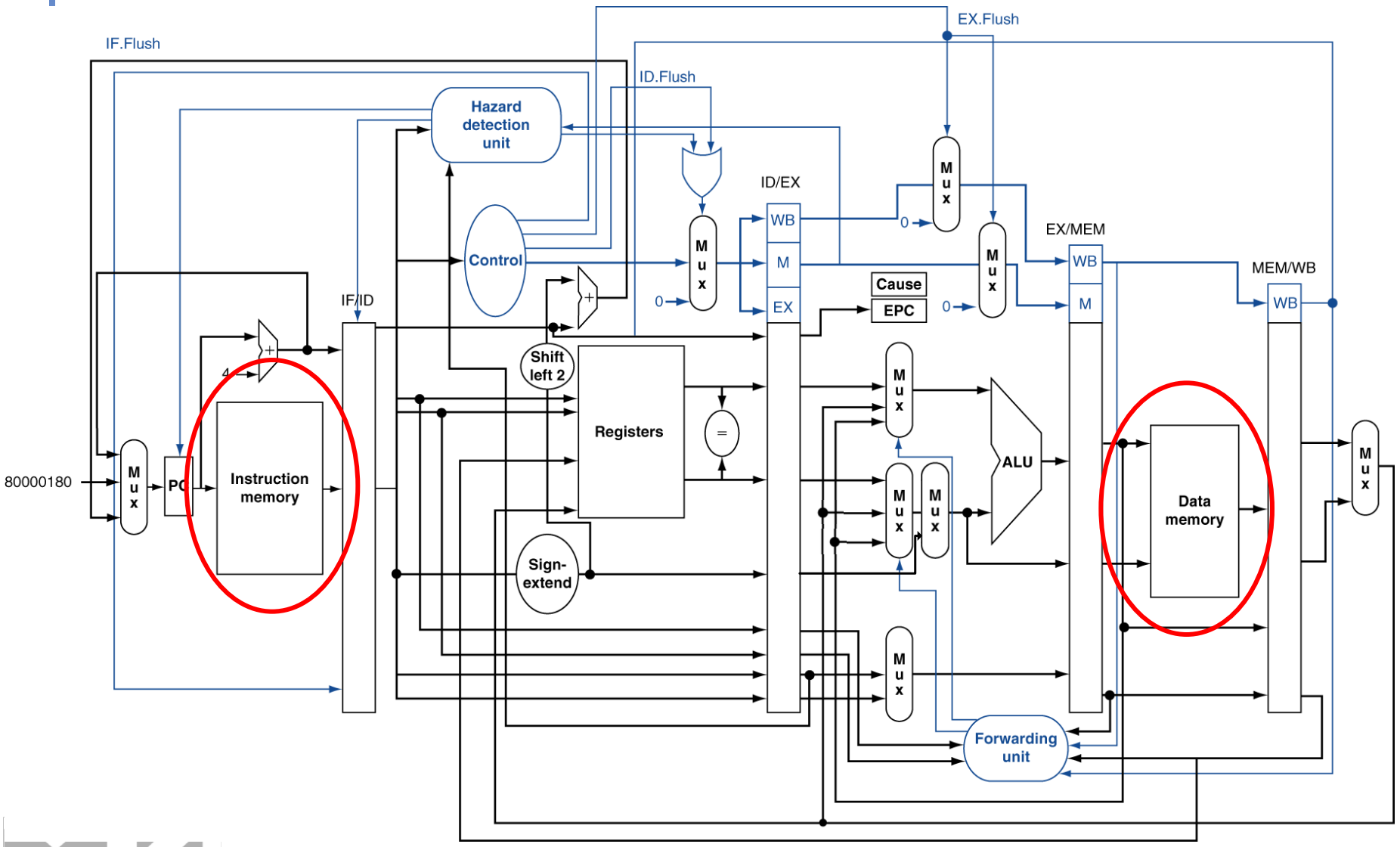
Topic 11

Memory Hierarchy

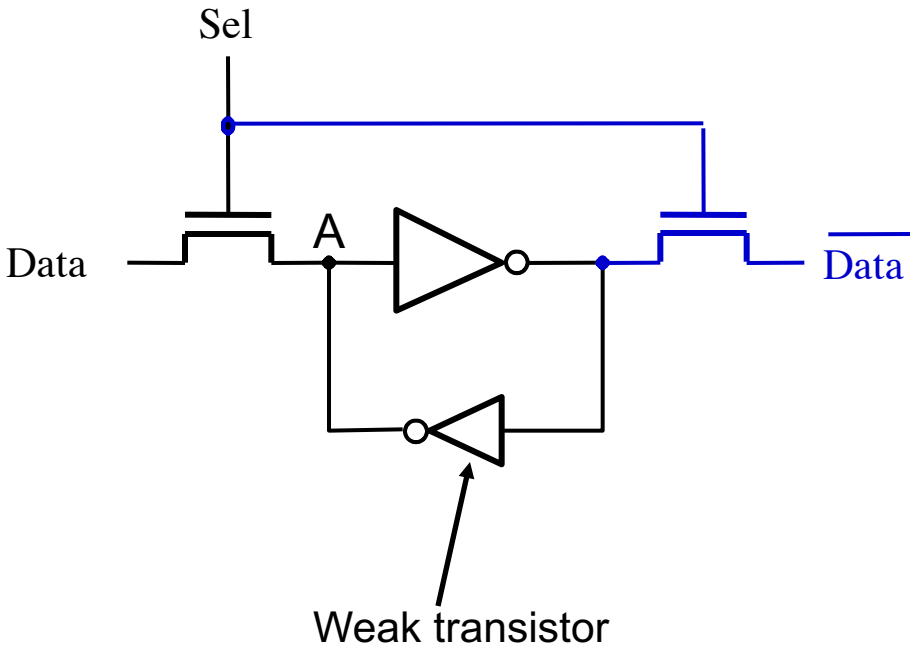
- Cache

MIPS Pipeline Architecture



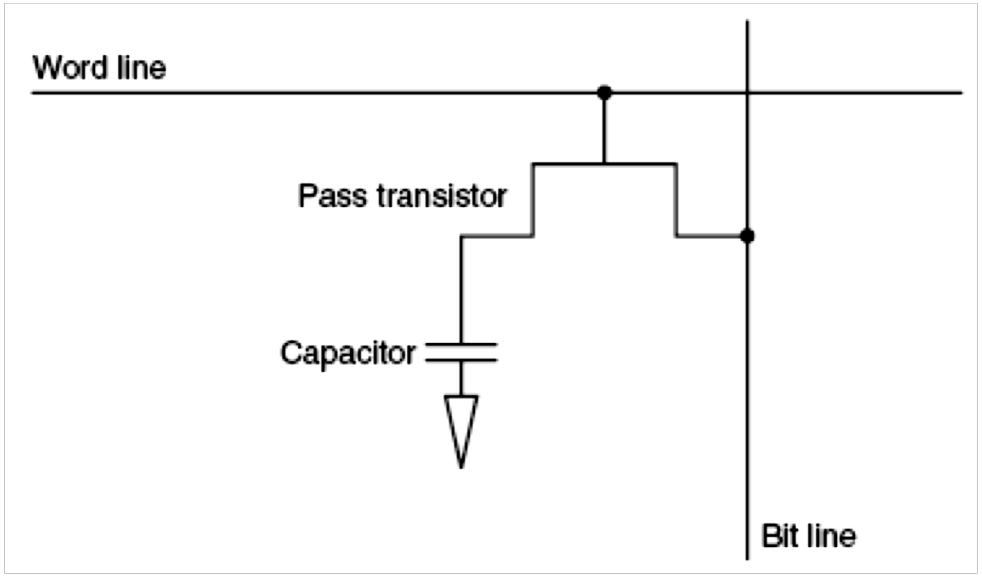
Static RAM (SRAM)

- When Sel = 1, Data is stored and retained in the SRAM cell by the feedback loop
- When Sel = 1, Data can be read out on the same port
- Point A is driven by both the Data transistor and the smaller inverter, but the Data transistor wins because the inverter is implemented using a weak transistor



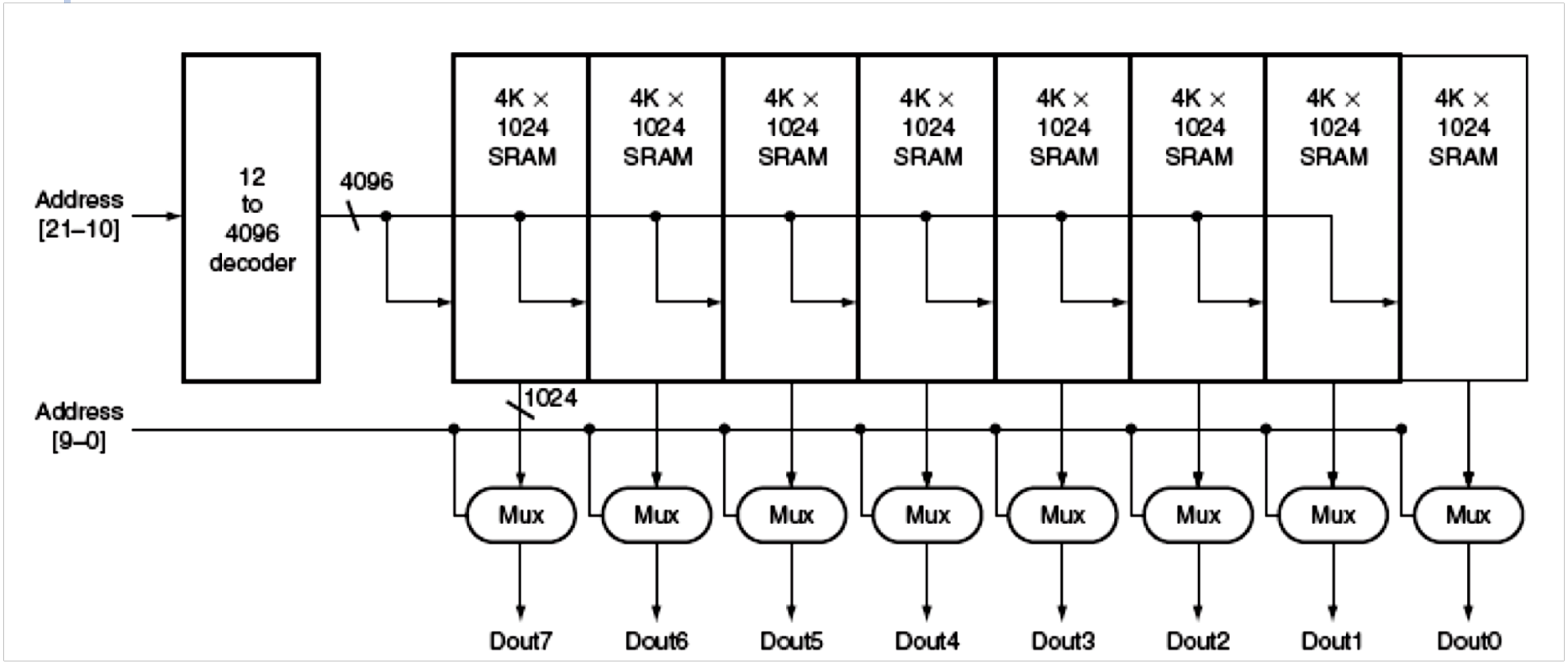
Dynamic RAM (DRAM)

- Write: turn on word line, charge capacitor through pass transistor by bit line
- Read: charge bit line halfway between high and low, turn on word line, then sense the voltage change on bit line
  - 1 if voltage increases
  - 0 if voltage decreases



Memory

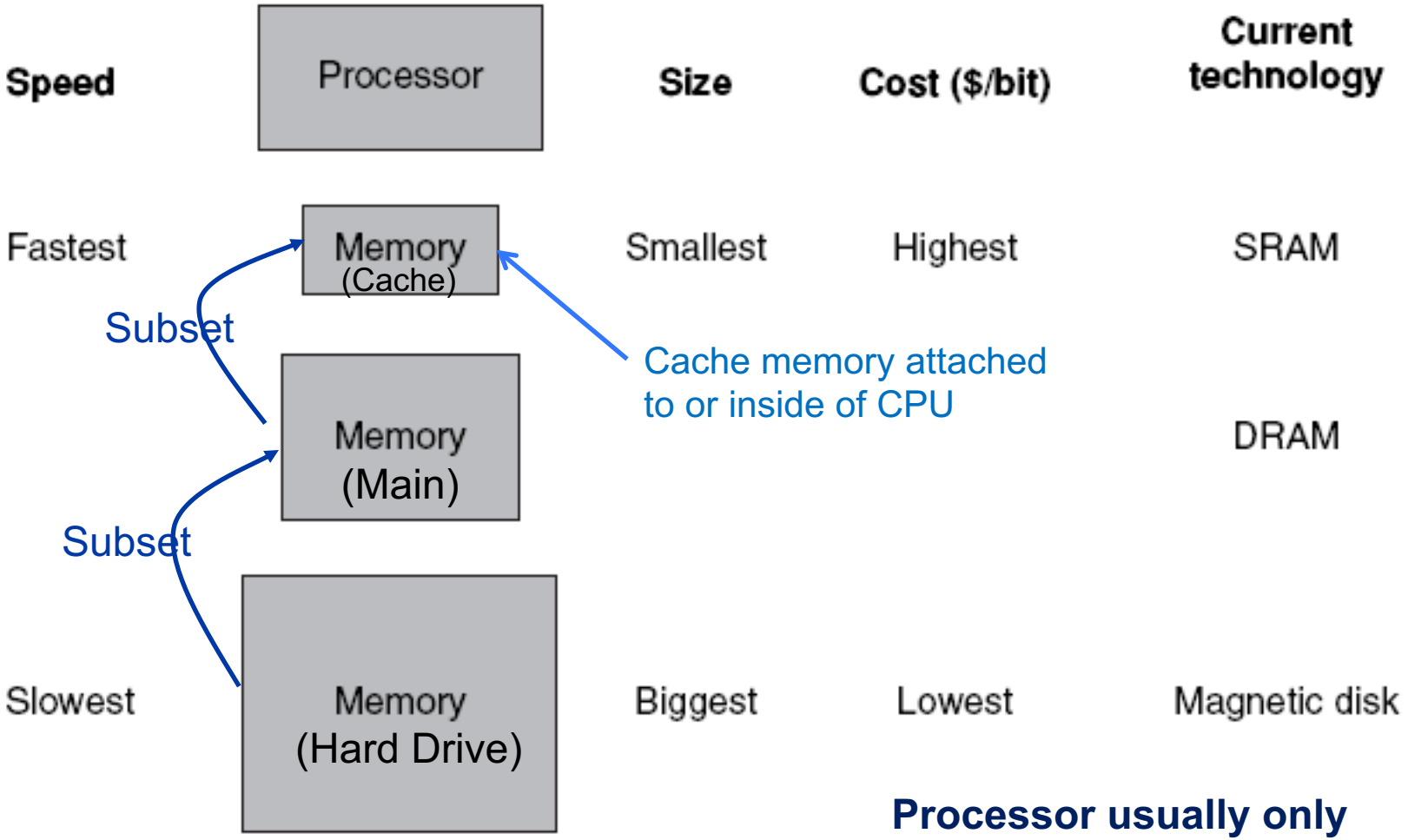
- Typical memory organization



Memory Technology

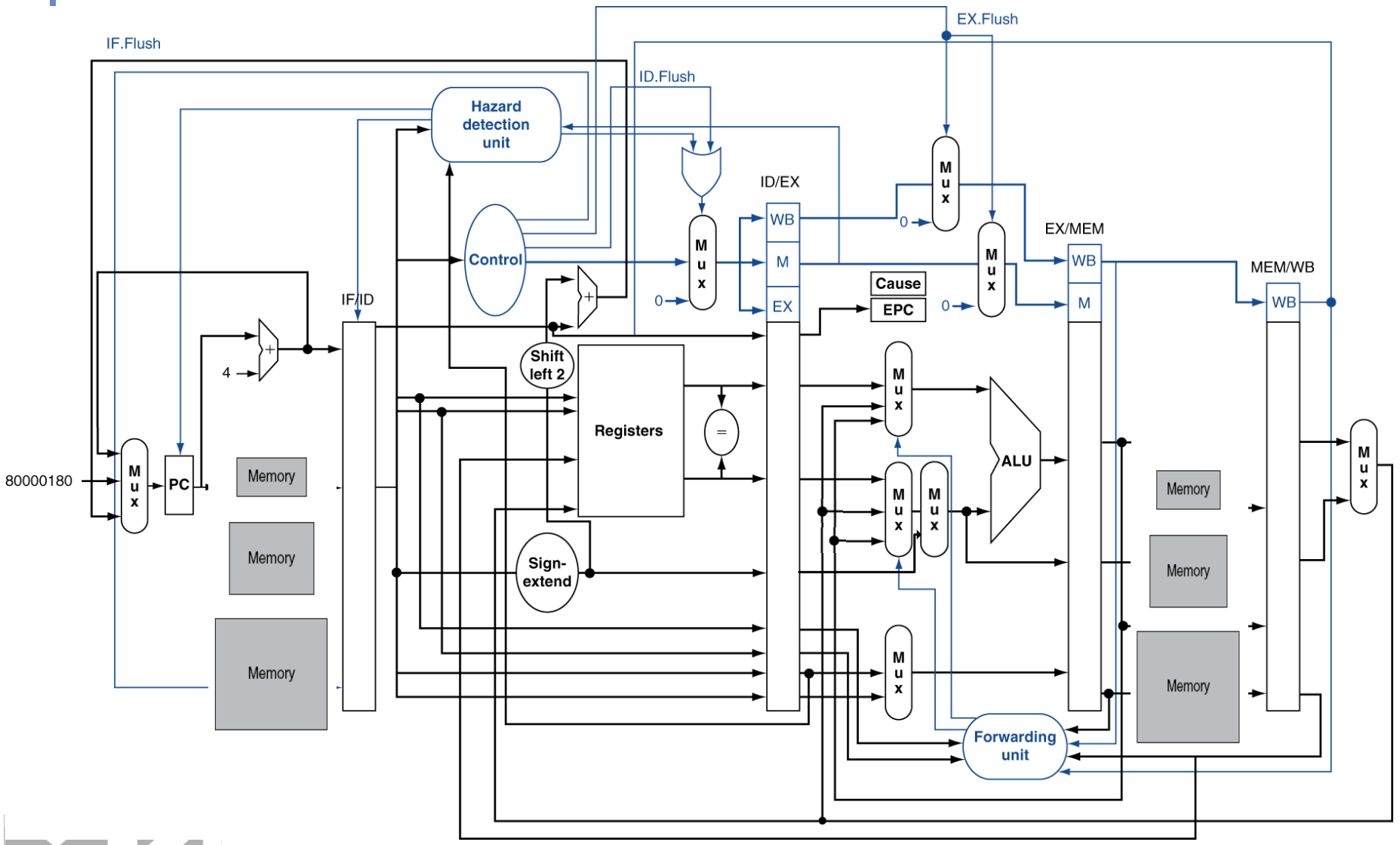
- Static RAM (SRAM)
  - 0.5ns – 2.5ns, $2000 – $5000 per GB
- Dynamic RAM (DRAM)
  - 50ns – 70ns, $20 – $75 per GB
- Magnetic disk
  - 5ms – 20ms, $0.20 – $2 per GB
- Ideal memory
  - Access time of SRAM
  - Capacity and cost of disk

Memory Hierarchy



Processor usually only talks to Cache

MIPS Pipeline Architecture



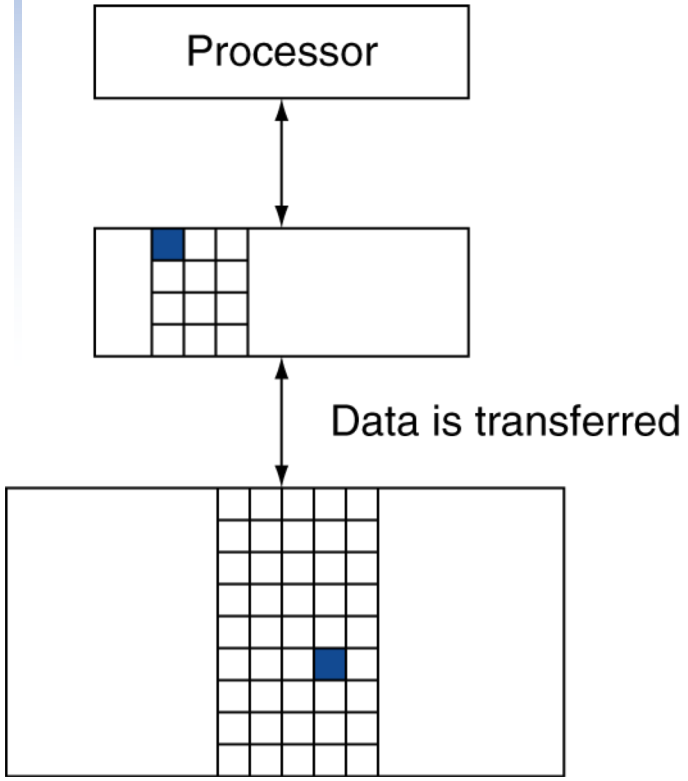
Principle of Locality

- Programs access a small proportion of their address space at any time
- Temporal locality
  - Items that are accessed recently are likely to be accessed again soon
  - e.g., instructions in a loop
- Spatial locality
  - Items near those that are accessed recently are likely to be accessed soon
  - E.g., sequential instruction access, array data

Principle of Memory Access

- Taking Advantage of Locality
- If a word of data/instruction is referenced
  - Copy this recently accessed word (temporal locality) and nearby items (spatial locality) together as a block from lower level memory to higher level memory (Hard Drive to Main memory or Main memory to Cache)

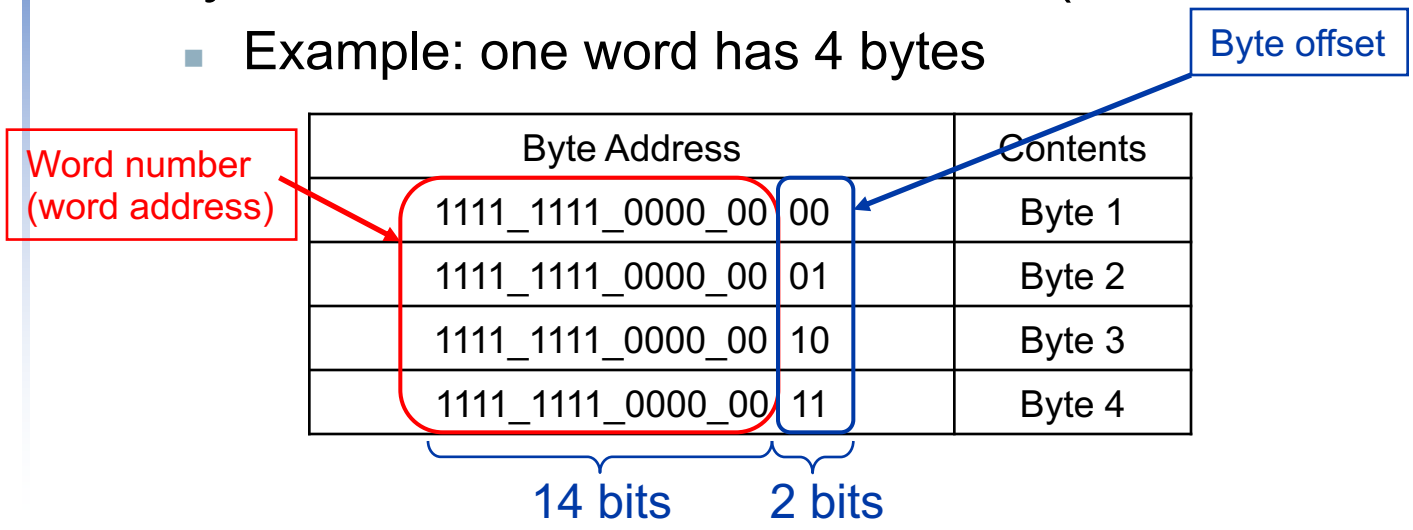
Memory Hierarchy Levels



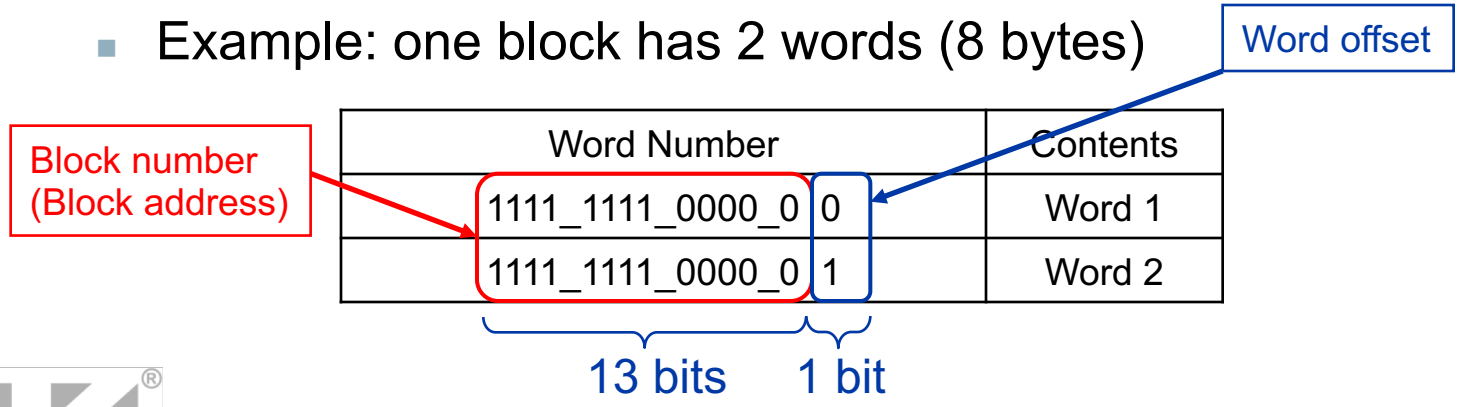
- Concepts:
  - Block (aka line)
    - Unit of data referencing to take advantage of temporal and spatial locality
    - May be one or multiple words
    - Block also has an address
  - Hit
    - If accessed data is present in upper level, access satisfied by upper level
    - Hit rate: hits/accesses
  - Miss
    - If accessed data is absent
    - Block copied from lower to higher level
    - Then accessed data supplied from upper level
    - Time taken: miss penalty
    - Miss rate: misses/accesses = 1 – hit rate

Block, Word, Byte Addresses

- Byte address vs. word address (assume 16-bit address)
  - Example: one word has 4 bytes



- Word address vs. block address (block number)
  - Example: one block has 2 words (8 bytes)

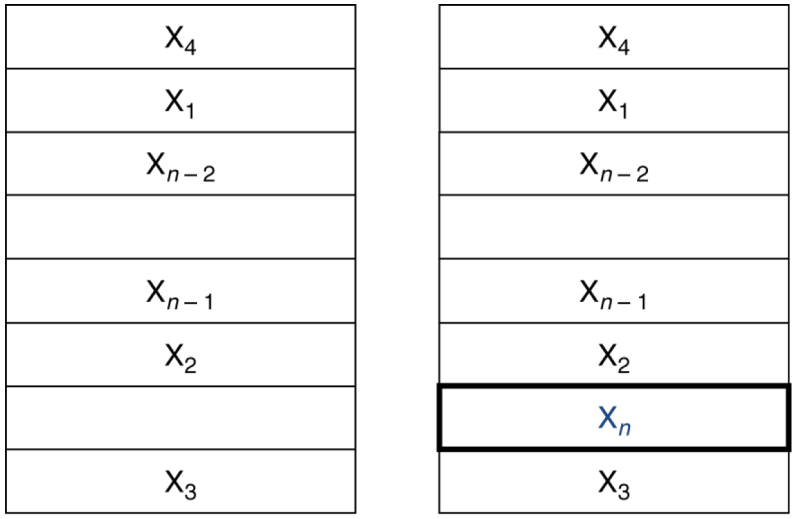


Hit Time and Miss Penalty

- Hit time
  - Time to access a memory including
    - Time to determine whether a hit or miss
    - Time to pass block to requestor
- Miss (time) penalty
  - Time to fetch a block from lower level upon a miss including
    - Time to access the block
    - Time to transfer it between levels
    - Time to overwrite the higher level block
    - Time to pass block to requestor

Cache Memory

- Cache memory
  - The level of the memory hierarchy closest to the CPU
- Example: assume a cache with 1-word blocks X_1, …, Xn–1 (word address = block address). Now CPU requests X_n

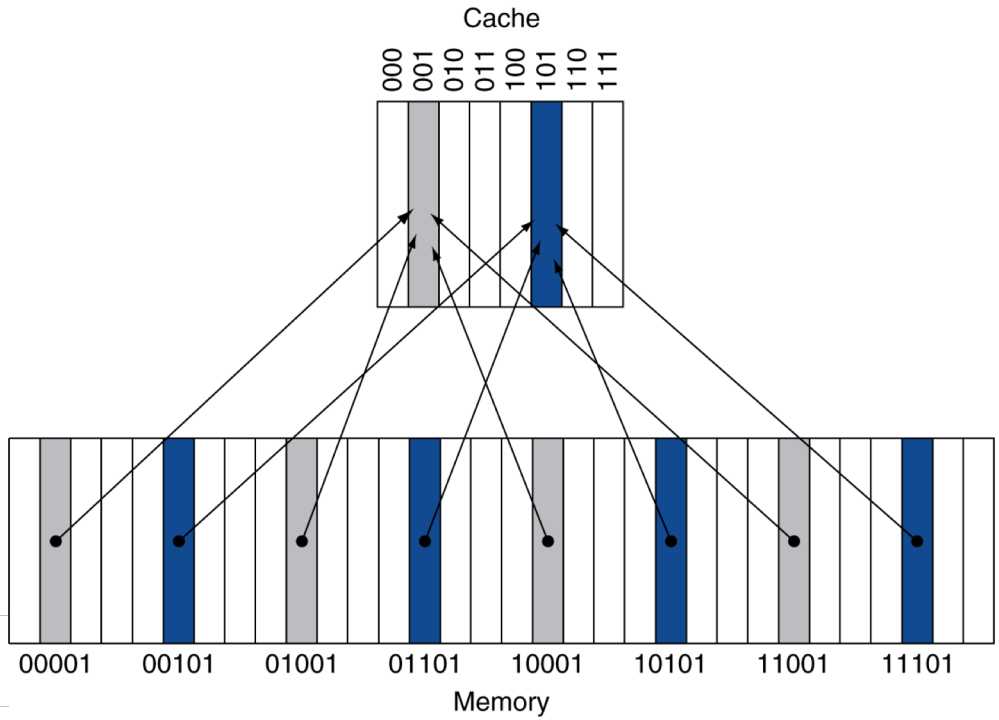


a. Before the reference to X_n b. After the reference to X_n

- Miss: X_n is brought in from lower level
- But
  - How do we know if there is a hit or miss?
  - Where do we look?

Direct Mapped Cache

- Location of a block in cache is determined by address of the requested word
- Direct mapped cache: each memory location corresponds to one choice in cache
  - Cache location (or cache index) =
    (Block address in memory) modulo (Number of blocks in cache)
  - Direct mapped memory uses an n-to-1 mapping



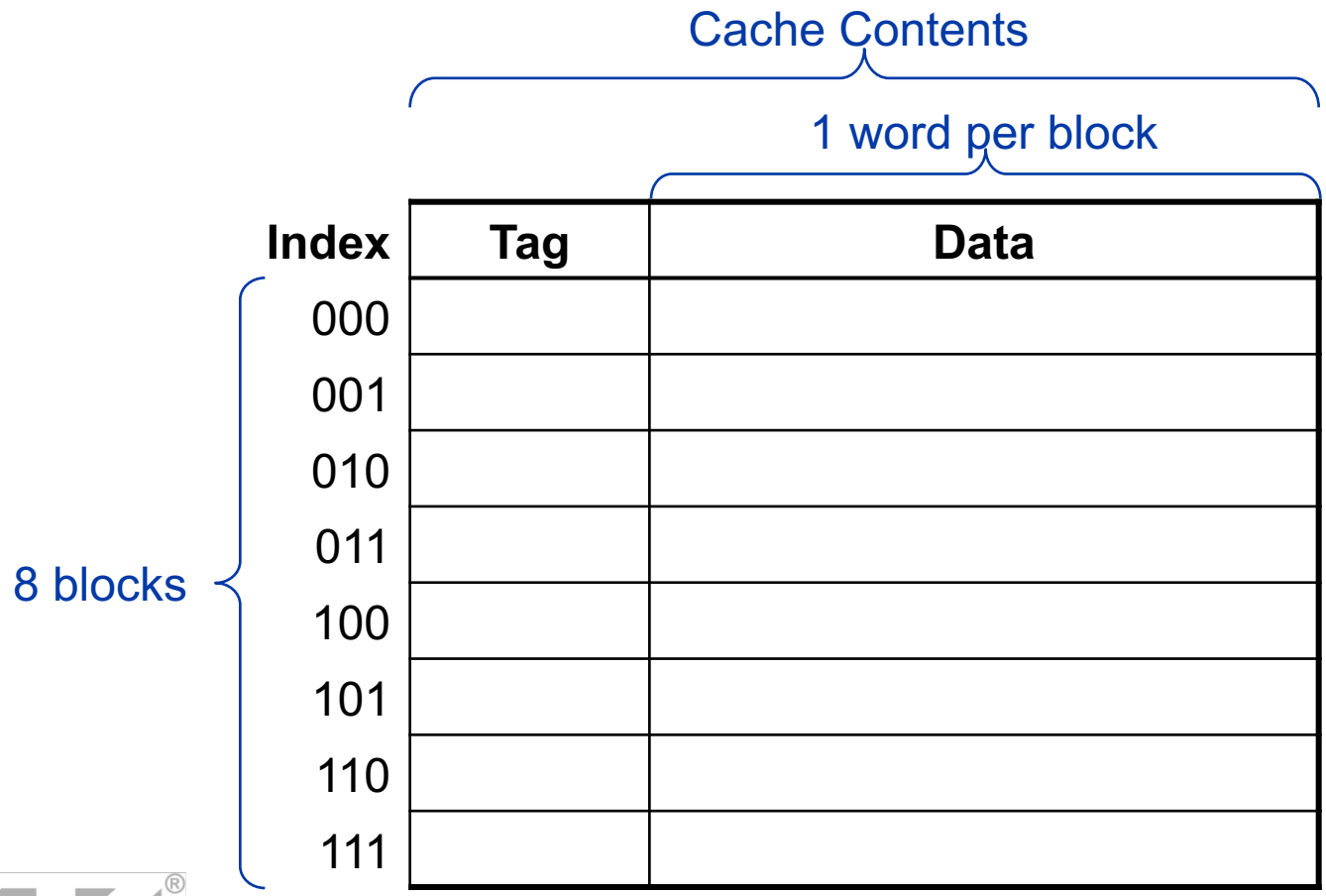
- Number of blocks in a cache is a power of 2
- Low-order bits of block address in memory = cache index

Tags in Cache

- How do we know which block of data is present in cache since it's n-to-1 mapping?
  - Store part of block address together with the data when the data is copied to higher level
    - Only need to store the high-order bits of memory block address
    - Called ***tag***

Direct Mapped Cache Example

- 8-block cache
- 1 word per block (word address = block address)

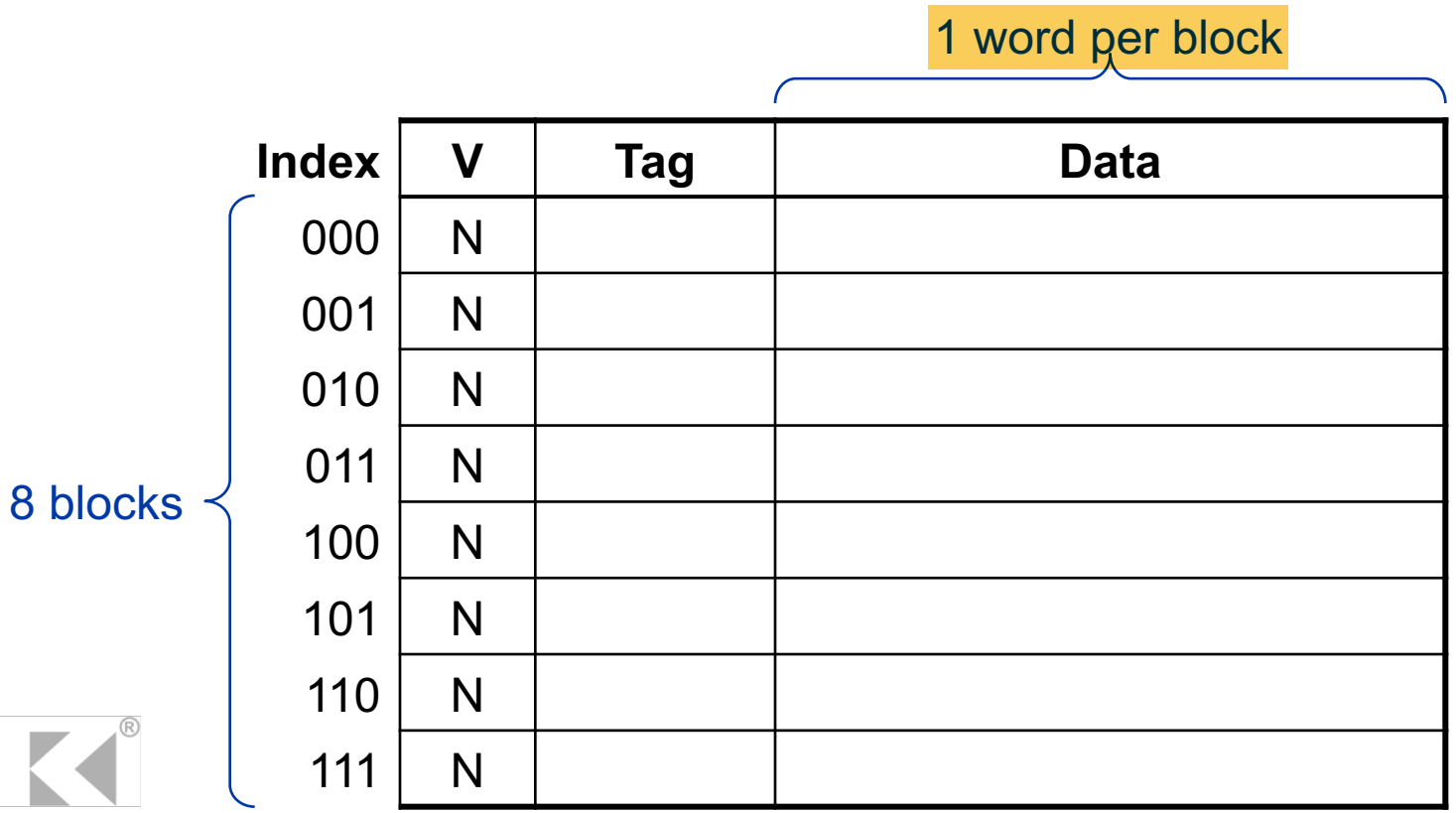


Valid Bits in Cache

- Waste searching time if there is no valid data in a location
  - Valid bit: 1 = present, 0 = not present
  - Initially 0 (N), to improve search speed

Cache Example 1

- 8-block cache
- 1 word per block (word address = block address)
- direct mapped
- Assuming 5-bit word addresses



Index	V	Tag	Data
000	N		
001	N		
010	N		
011	N		
100	N		
101	N		
110	N		
111	N		

Cache Example 1 (cont.)

Requested word (also block) addr	Binary addr	Hit/miss	Cache block
22 (decimal)	10 110	Miss	110

Index	V	Tag	Data
000	N		
001	N		
010	N		
011	N		
100	N		
101	N		
110	Y	10	Mem[22]
111	N		

Cache Example 1 (cont.)

Requested word addr	Binary addr	Hit/miss	Cache block
26	11 010	Miss	010

Index	V	Tag	Data
000	N		
001	N		
010	Y	11	Mem[26]
011	N		
100	N		
101	N		
110	Y	10	Mem[22]
111	N		

Cache Example 1 (cont.)

Requested word addr	Binary addr	Hit/miss	Cache block
22	10 110	Hit	110
26	11 010	Hit	010

Index	V	Tag	Data
000	N		
001	N		
010	Y	11	Mem[26]
011	N		
100	N		
101	N		
110	Y	10	Mem[22]
111	N		

Hit due to temporal locality

Cache Example 1 (cont.)

Req. word addr	Binary addr	Hit/miss	Cache block
16	10 000	Miss	000
3	00 011	Miss	011
16	10 000	Hit	000

Index	V	Tag	Data
000	Y	10	Mem[16]
001	N		
010	Y	11	Mem[26]
011	Y	00	Mem[3]
100	N		
101	N		
110	Y	10	Mem[22]
111	N		

Cache Example 1 (cont.)

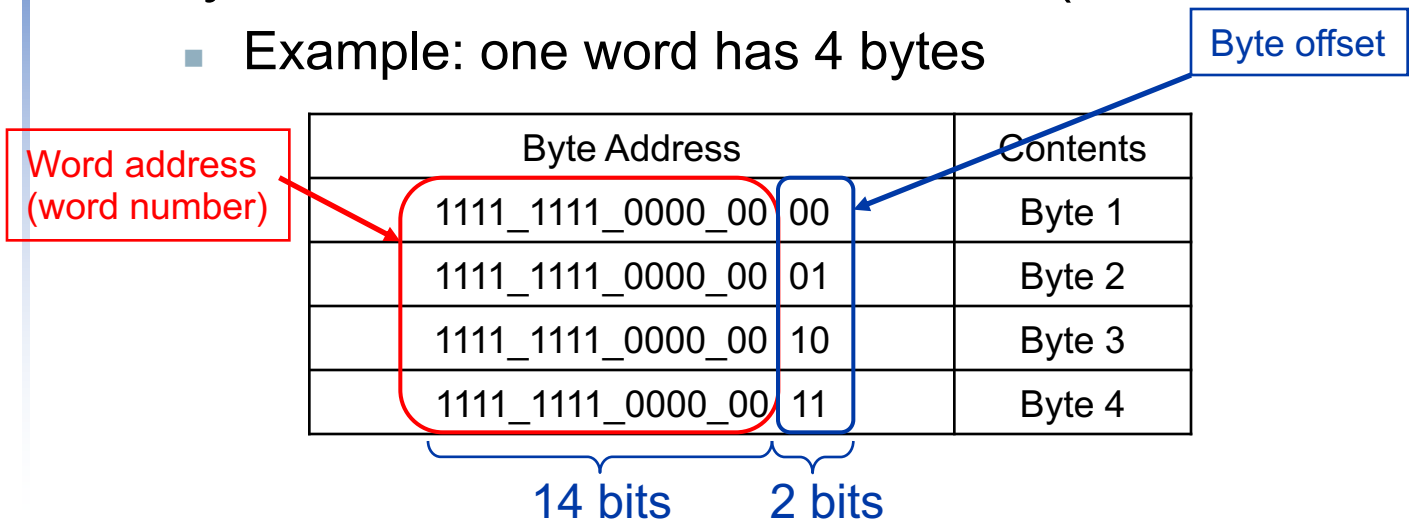
Req. word addr	Binary addr	Hit/miss	Cache block
18	10 010	Miss	010

Currently occupied by Mem[26]

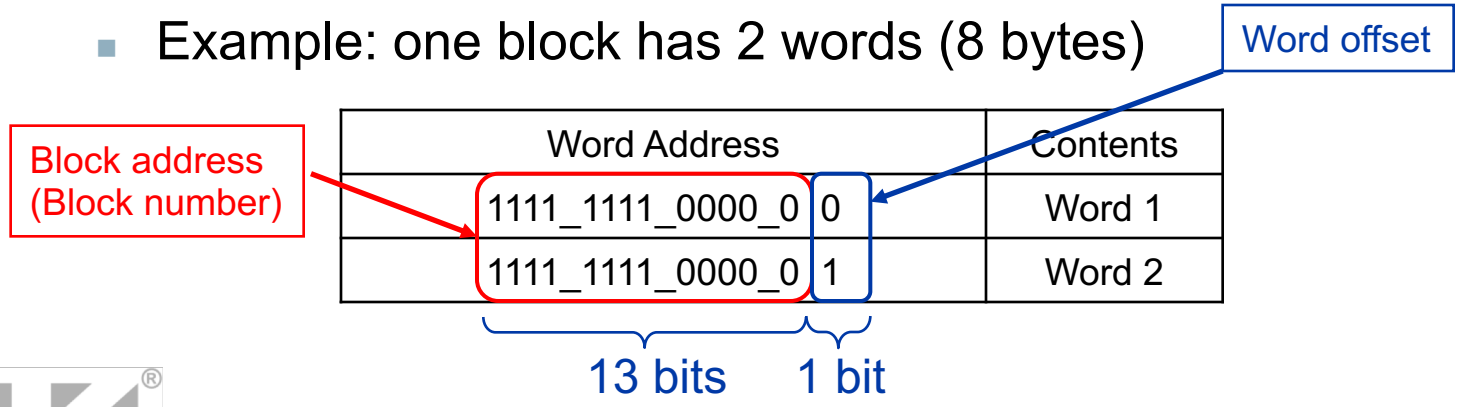
Index	V	Tag	Data
000	Y	10	Mem[16]
001	N		
010	**Y**	**10**	**Mem[18]**
011	Y	00	Mem[3]
100	N		
101	N		
110	Y	10	Mem[22]
111	N		

Block, Word, Byte Addresses

- Byte address vs. word address (assume 16-bit address)
  - Example: one word has 4 bytes

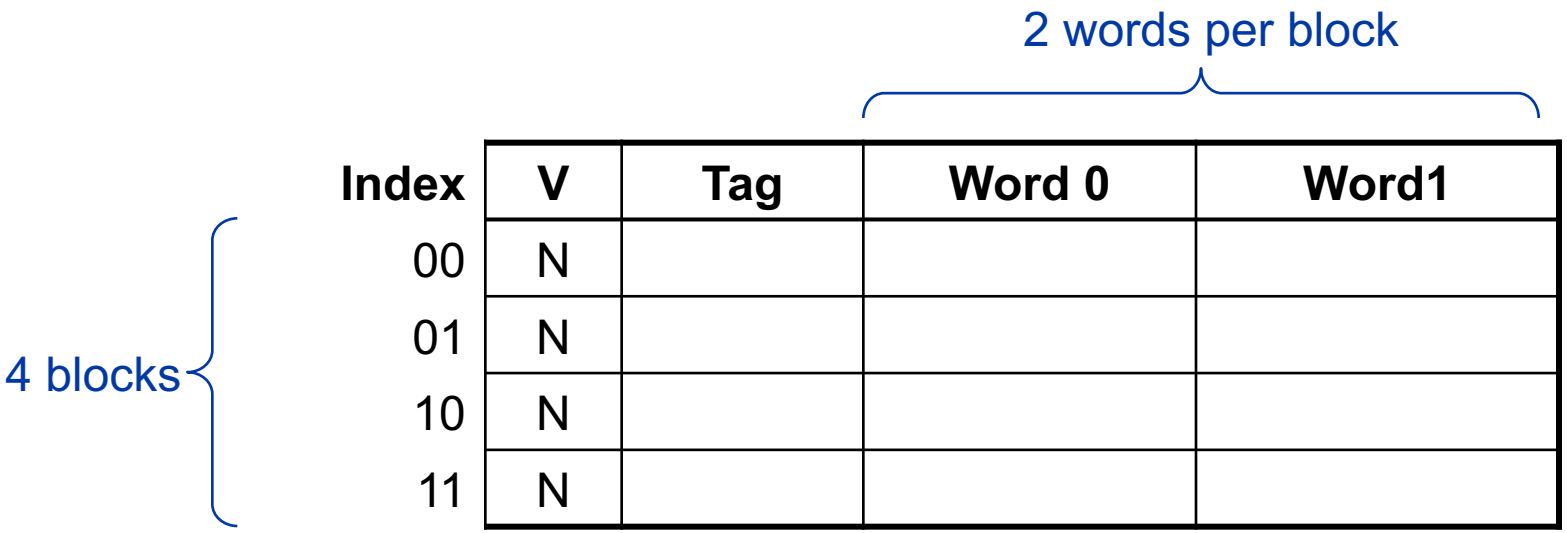


- Word address vs. block address (block number)
  - Example: one block has 2 words (8 bytes)



Cache Example 2

- 4-block cache
- 2 words per block
- direct mapped
- Assuming 5-bit word addresses



Index	V	Tag	Word 0	Word1
00	N			
01	N			
10	N			
11	N			

Cache Example 2 (cont.)

Req. word addr	Binary addr	Hit/miss	Cache block
22 (decimal)	10 **11** 0	Miss	11

Index	V	Tag	Word 0	Word1
00	N			
01	N			
10	N			
11	Y	10	Mem[22]	Mem[23]

Cache Example 2 (cont.)

Req. word addr	Binary addr	Hit/miss	Cache block
23	10 11 1	Hit	11
27	11 01 1	Miss	01

Index	V	Tag	Word 0	Word1
00	N			
01	Y	11	Mem[26]	Mem[27]
10	N			
11	Y	10	Mem[22]	**Mem[23]**

Hit due to spatial locality

Cache Example 2 (cont.)

Word addr	Binary addr	Hit/miss	Cache block
6	00110	Miss	11

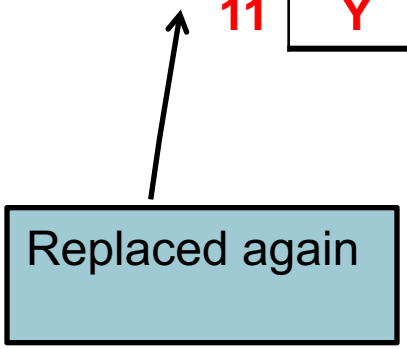
Index	V	Tag	Word 0	Word1
00	N			
01	Y	11	Mem[26]	Mem[27]
10	N			
11	Y	00	Mem[6]	Mem[7]

N-to-1 mapping causes competition, original block was replaced

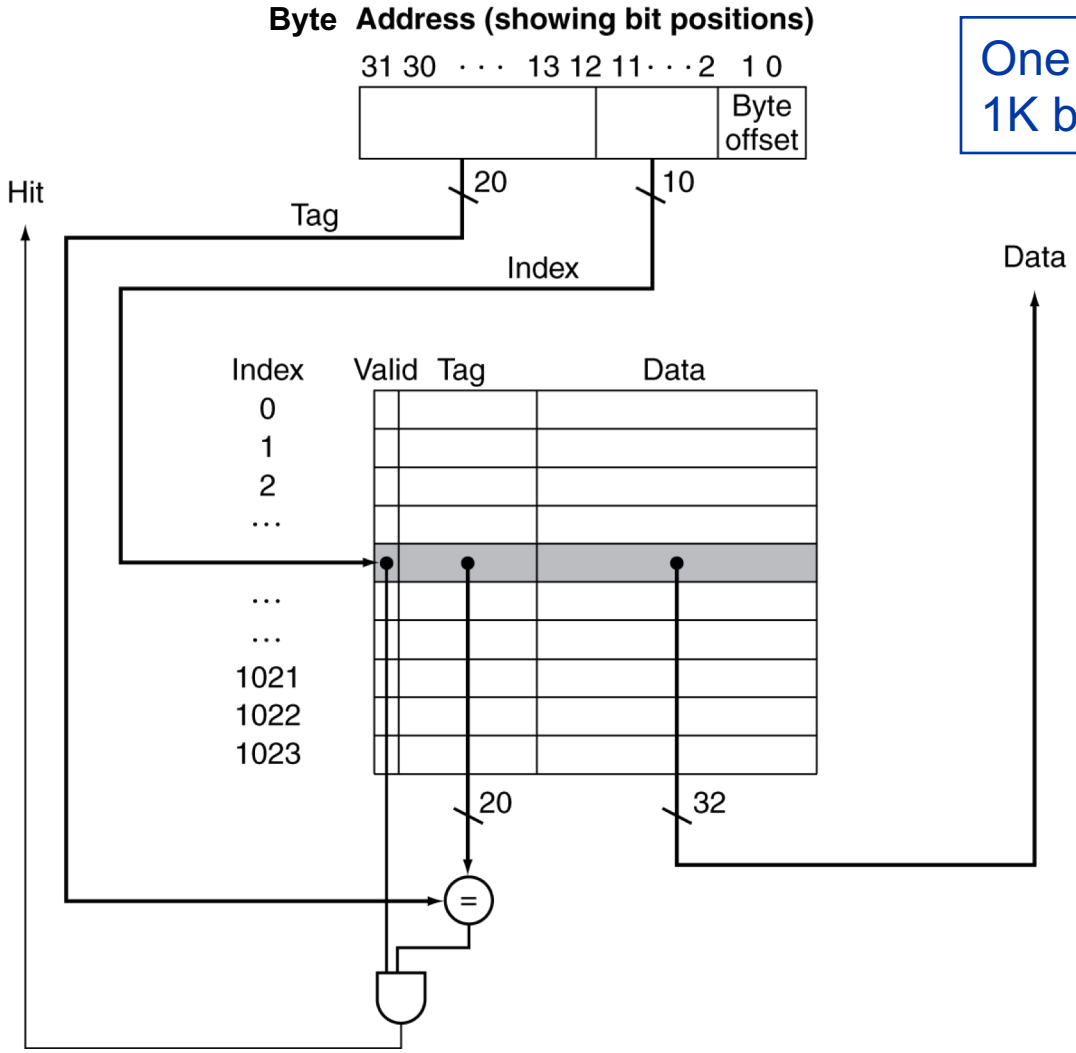
Cache Example 2 (cont.)

Word addr	Binary addr	Hit/miss	Cache block
22	10110	Miss	11

Index	V	Tag	Word 0	Word1
00	N			
01	Y	11	Mem[26]	Mem[27]
10	N			
11	Y	10	Mem[22]	Mem[23]



Search Block in Cache



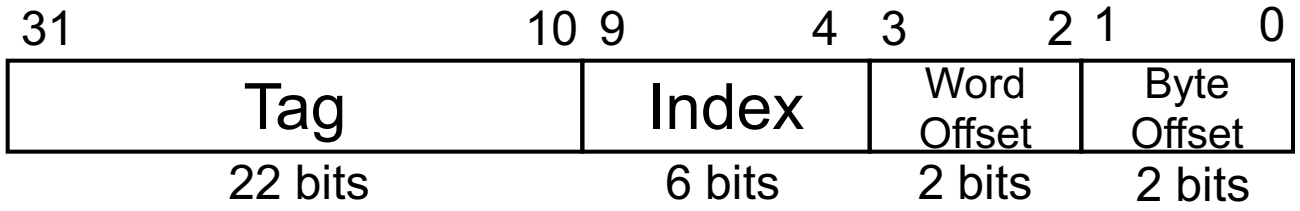
One word per block
1K blocks

Cache Size in Bits

- Given
  - 32-bit byte address
  - 2^n blocks in cache
  - 2^m words per block, 2^{m+2} bytes
- Size of tag field = 32 – (n + m + 2)
  - n bits to index blocks in cache
  - m bits used to select words in a block
  - 2 bits used to select the 4 bytes in a word
  - Tag field decreases when n and m increase
- Cache size = $2^n \times$ (block size + tag size + valid field size)

Example: Larger Block Size

- 64 blocks, 4 words/block
  - What cache block number does byte address 1200 map to?
  - Word number = 1200/4 = 300
  - Block (address) number = 300/4 = 75
- Block index in cache = 75 modulo 64 = 11



Class Exercise

- Given
  - 1K blocks in cache
  - 16 words in each block
  - 32-bit byte address 0x81002345 requested by CPU
- Show address and organization of the target cache block

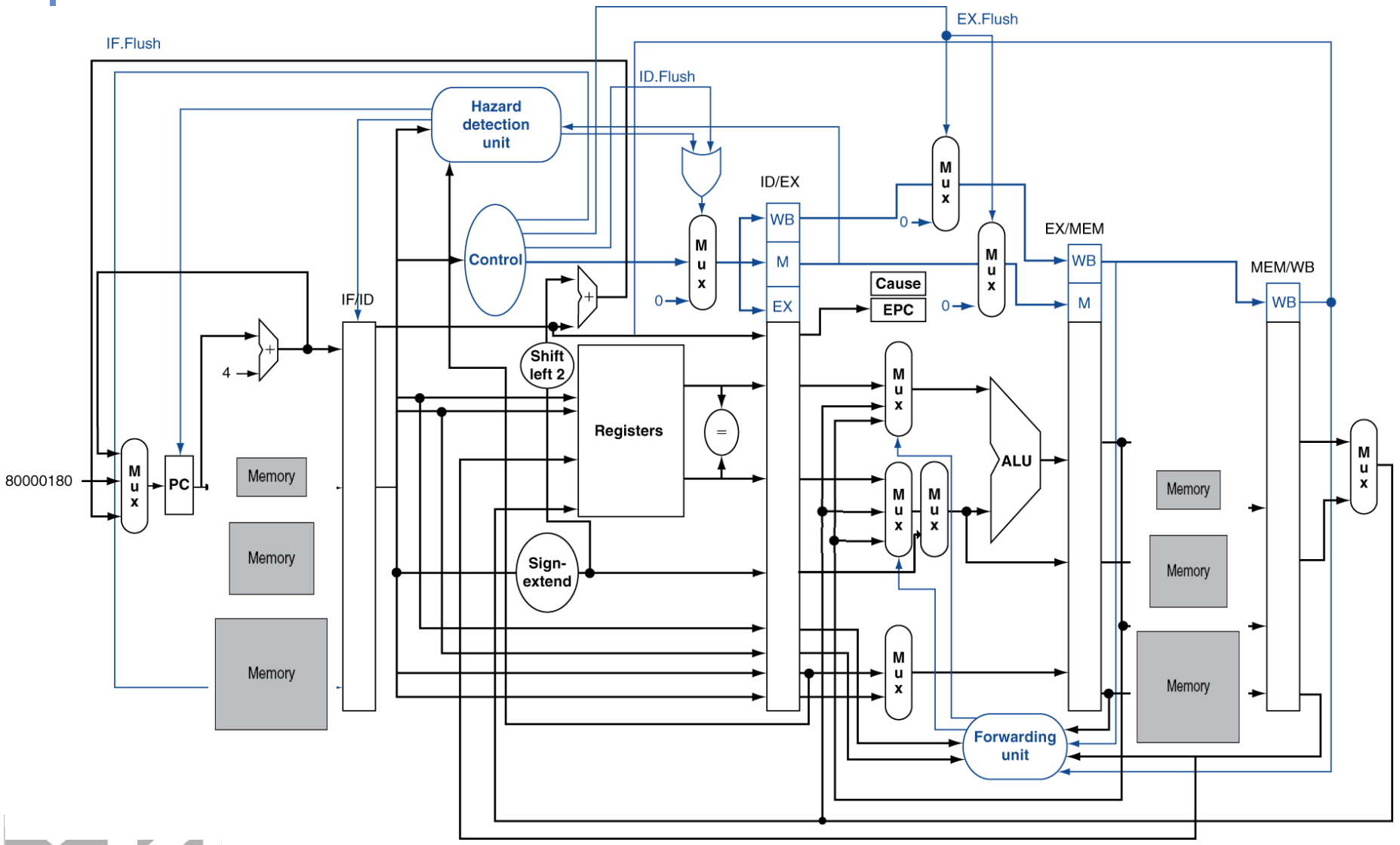
Block Size Considerations

- ***Larger blocks should reduce miss rate***
  - Due to spatial locality
- But in a fixed-sized cache
  - Larger blocks ⇒ fewer of them
    - More competition ⇒ increased miss rate
- Larger miss penalty
  - Primarily result of longer time to fetch block
    - Latency to first word
    - Transfer time for the rest of the block
  - Can override benefit of reduced miss rate
  - Early restart and critical-word-first can help

Reducing Miss Penalty

- Early restart
  - Restart execution as soon as the requested word if available, instead of waiting for the entire block
  - More effective for instruction memory because instructions are accessed sequentially
- Critical word first
  - Requires specially organized memory
  - Transfer the requested words first

MIPS Pipeline Architecture



Cache Miss

- On cache hit, CPU proceeds normally
- On cache miss
  - Stall the CPU pipeline
    - Using processor control unit and a cache controller
    - Freezes registers and waits for memory
  - Fetch block from next level of hierarchy
  - Instruction cache miss
    - Restart instruction fetch with address = PC – 4
  - Data cache miss
    - Stall pipeline until complete data access

Handling Instruction Miss

1. Send original PC (PC – 4) to memory
   - From the Adder
2. Read main (lower level) memory and wait for data
3. Write data into cache data field from main memory, write upper bits of address into cache tag field, set valid field
4. Restart the missing instruction

Handling Data Miss – Reads

1. Hold the MEM to IF stages
2. Read main (lower level) memory and wait for data
3. Write data into cache data field from main memory, write upper bits of address into cache tag field, set valid field
4. Read cache again, proceed

Handling Data Writes – Write Through

- On data-write (e.g. sw) hit, could just update the block in cache
  - But then cache and memory would be inconsistent
- Write through: also update the word in memory
- But makes writes take longer time
  - Must wait till the update finishes
  - e.g., if base CPI = 1, 10% of instructions are stores, write to memory takes 100 cycles
    - Effective CPI = base CPI + write time (cycles) per instruction
    - Effective CPI = 1 + 0.1×100 = 11
- Even worse for write miss
  - Detect a miss on target address
  - Fetch the block from main memory to cache
  - Overwrite the word in cache
  - Write the block back to main memory

Write Buffer

- Solution to time consuming write through technique (for both hit and miss)
  - Buffer stores data to be written to memory
    - May have one or more entries
  - CPU proceeds to next step, while letting buffer to complete write through
  - Frees buffer when completing write to memory
  - CPU stalls if buffer is full

Handling Data Writes – Write Back

- Alternative of write through: On data-write hit, just update the block in cache
  - CPU keeps track of whether each block is dirty (updated with new values)
- Write a block back to memory
  - Only when a dirty block has to be replaced (on miss)
  - More complex than write through

Write Through/Back Sequences

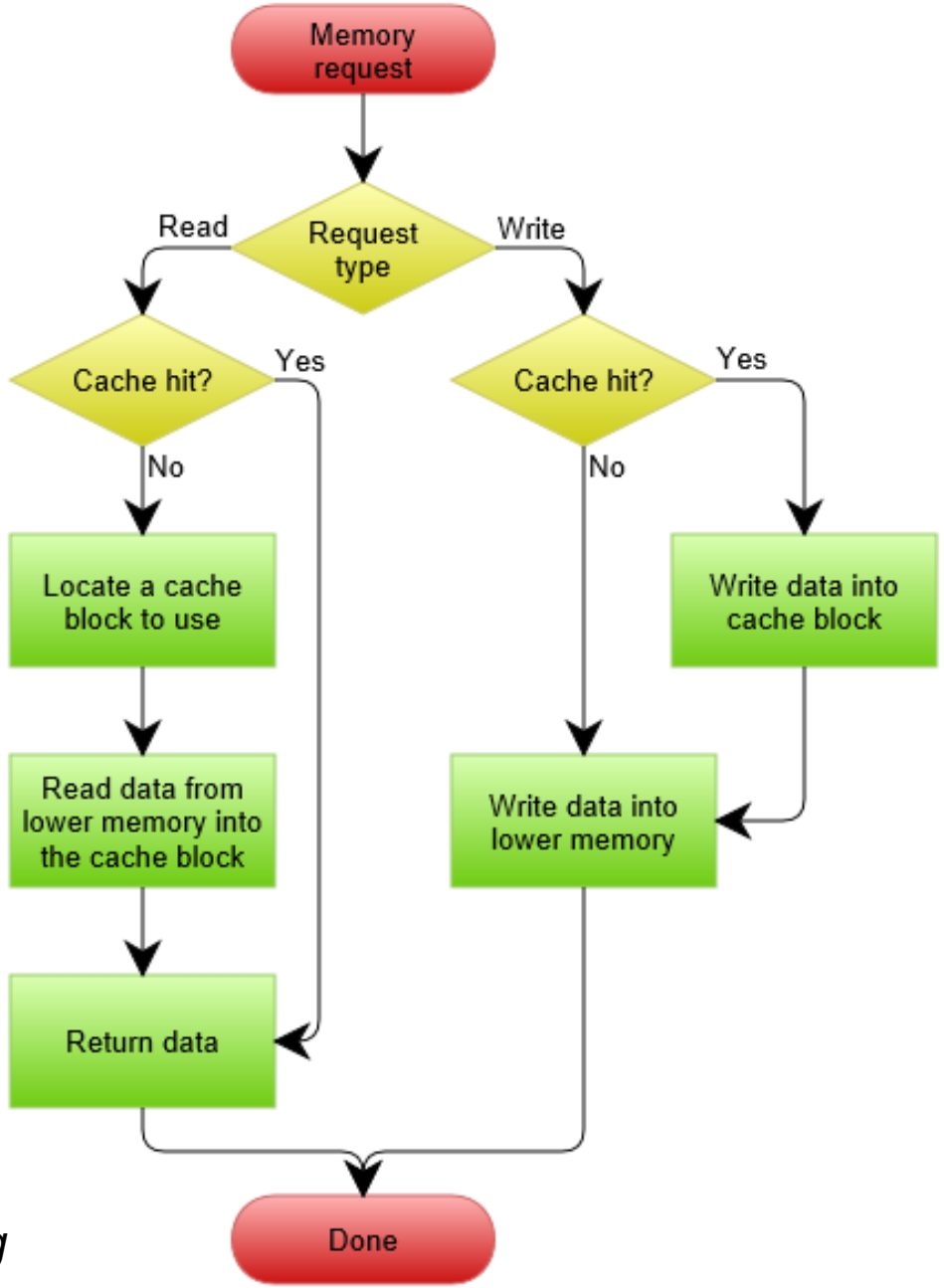
- Write back sequence
  - Two steps: 1. check match, 2. write data
  - Otherwise, will destroy the mismatch block, and there is no backup copy
  - May use write buffer
    - Writing buffer and checking match simultaneously
- Write through sequence
  - Write data
  - Check for match

  } ***Simultaneously in one step***
  - Mismatch doesn't matter
    - Because the mismatch block to be replaced anyway
  - For hit, saves a step, less time for write through

Write Allocation on Miss

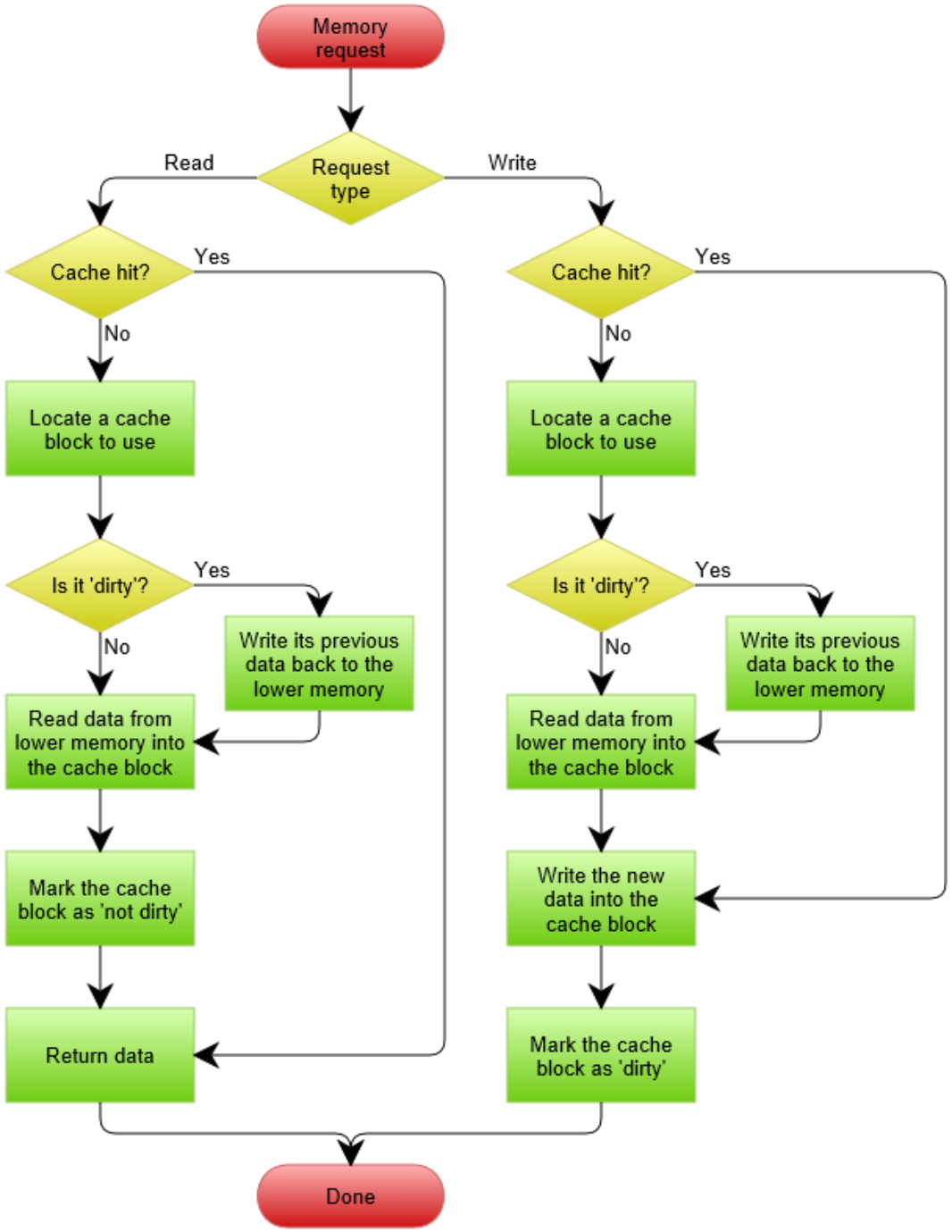
- Ways of cache handlings for write-through
  - Write Allocate
    - Allocate cache block on miss by fetching corresponding memory block
    - Update cache block
    - Update memory block
  - No Write Allocate
    - Write around: write directly to memory
    - Then fetch from memory to cache
- For write-back
  - Usually fetch the block (write allocate)

Write Through with no Write Allocation



Source: Wikipedia.org

Write Back with Write Allocation

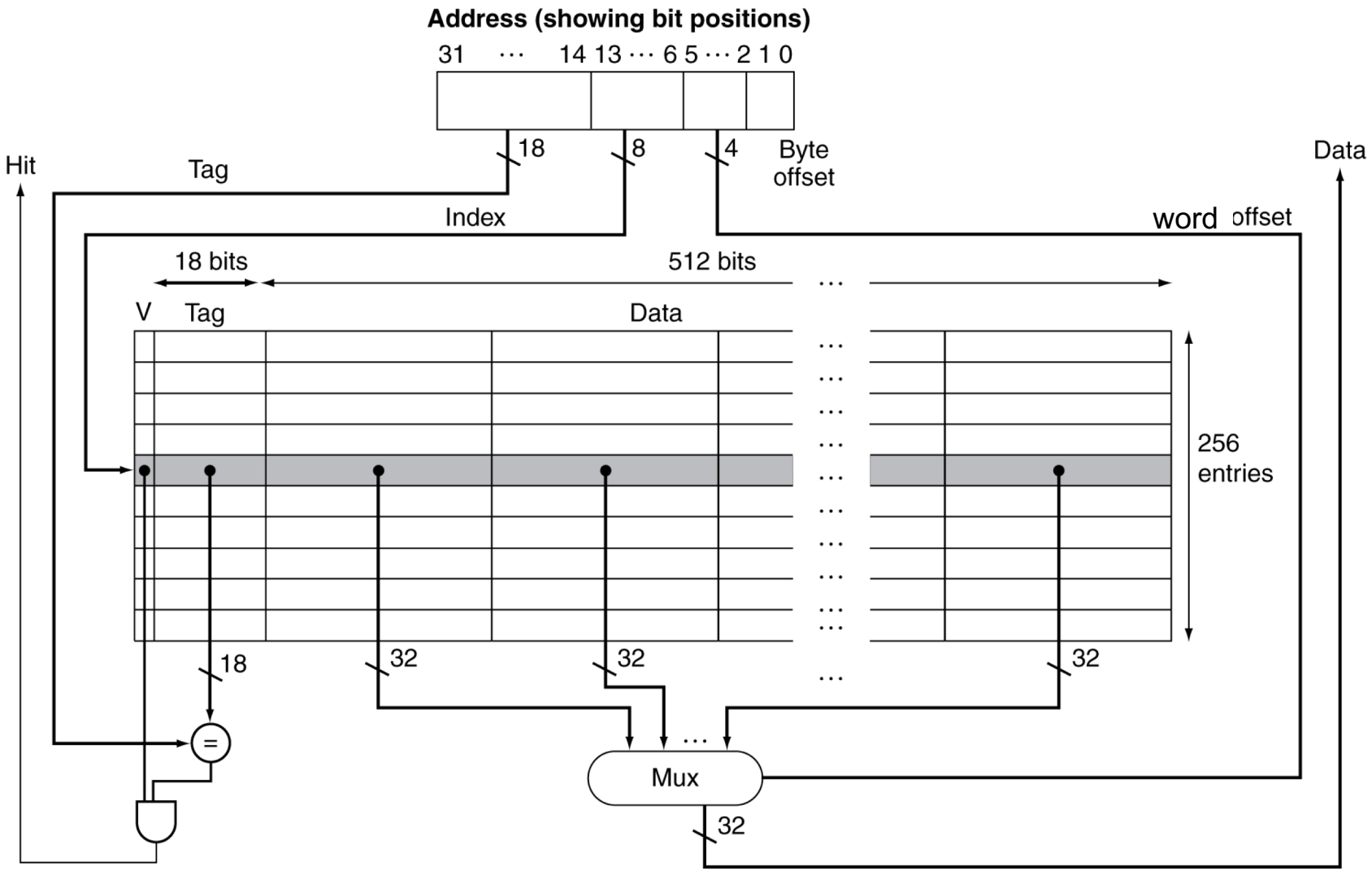


Source: Wikipedia.org

Example: Intrinsity FastMATH

- Intrinsity
  - Fabless microprocessor company
  - Acquired by Apple in 2010
- 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%

Example: Intrinsity FastMATH

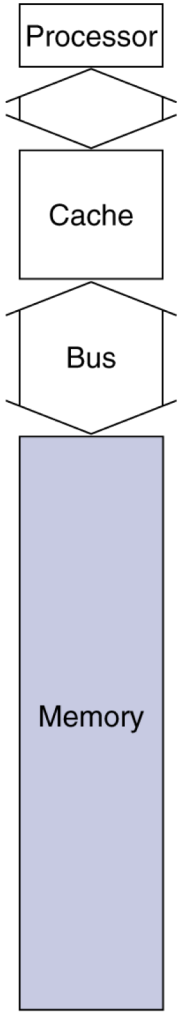


Main Memory Supporting Caches

- Use DRAMs for main memory
  - Fixed width (e.g., 1 word)
  - Connected by fixed-width bus
    - Bus clock is typically slower than CPU clock
- Example cache block read
  - 1 bus cycle for address transfer
  - 15 bus cycles per DRAM access
  - 1 bus cycle per data transfer

Reducing Miss Penalty

by Increasing Memory Bandwidth

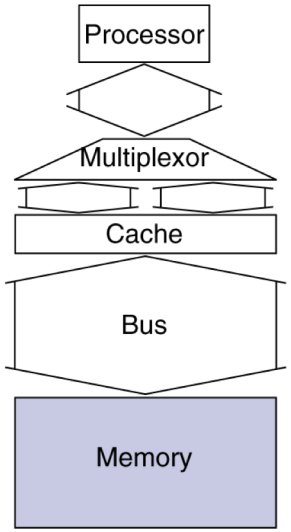


a. One-word-wide memory organization

- For 4-word block, 1-word-wide DRAM
  - Miss penalty = 1 + 4×15 + 4×1 = 65 bus cycles
  - Bandwidth = 16 bytes / 65 cycles = 0.25 B/cycle

Reducing Miss Penalty

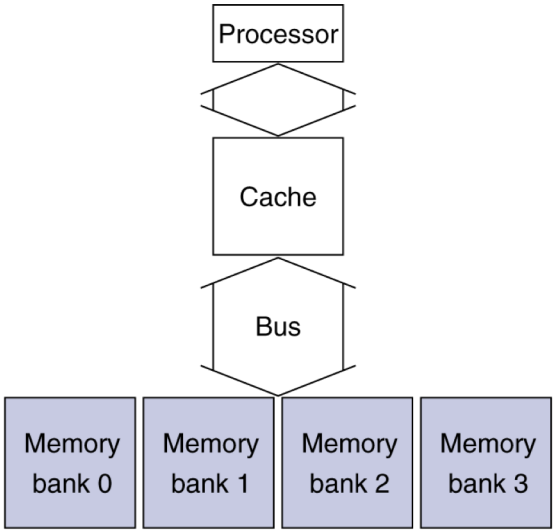
by Increasing Memory Bandwidth



b. Wider memory organization

- 2-word wide memory
  - Miss penalty = 1 + 2×15 + 2×1 = 33 bus cycles
  - Bandwidth = 16 bytes / 33 cycles = 0.48 B/cycle

- 4-bank ***interleaved memory***
  - Miss penalty = 1 + 15 + 4×1 = 20 bus cycles
  - Bandwidth = 16 bytes / 20 cycles = 0.8 B/cycle



c. Interleaved memory organization

Measuring Cache Performance

- Components of CPU time
  - Program execution cycles
    - Include cache hit time
  - Memory stall (miss) cycles
    - Mainly from cache misses
- With simplified 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

- Given
  - I-cache miss rate = 2% (2 misses per 100 instructions)
  - D-cache miss rate = 4% (4 misses per 100 memory access instructions)
  - Miss penalty = 100 cycles
  - Base CPI (ideal cache) = 2
  - Load & stores are 36% of instructions
- Miss cycles per instruction
  - I-cache: 100% × 2% × 100 = 2
  - D-cache: 36% × 4% × 100 = 1.44
- Total CPI = base CPI + Miss (stall) cycles per instruction
  - Actual CPI = 2 + 2 + 1.44 = 5.44
  - Ideal CPU is 5.44/2 =2.72 times faster

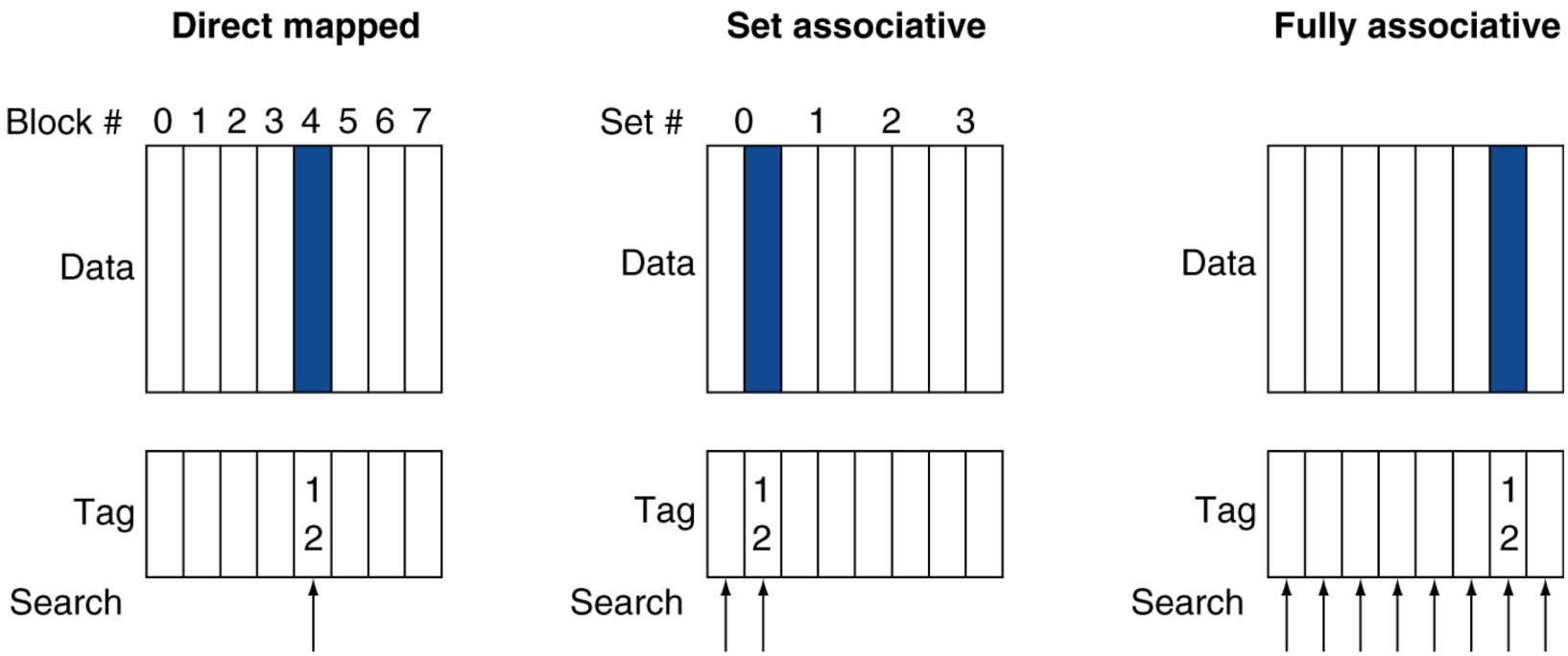
Average Memory Access Time

- Hit time is important to 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

Improve Performance – Associative Caches

- *n*-way **set associative** cache
  - Each set contains *n* blocks
  - Each address maps to a unique set
    - Set address = (Block address) modulo (number of sets in cache)
  - A mem block maps to any block within the corresponding set
  - However, to locate a block in a set, need to compare *n* times
    - all *n* tags in a set must be checked and compared
    - *n* comparators (more effective - faster)
- Fully associative – opposite extreme of direct mapped
  - Allow a given block to go in any cache entry
  - Must search all entries to find a hit
  - One comparator each block (expensive)
    - # of comparator = cache size (block number)

Associative Cache Example



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

- Compare caches of 4 one-word blocks
  - Direct mapped, 2-way set associative, fully associative
  - Block access sequence: 0, 8, 0, 6, 8
- Direct mapped
  - Cache index: 0 for block 0 & 8, 2 for block 6

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
  - Cache index: set 0 for all blocks
  - Replace least recently used block in a set

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]		

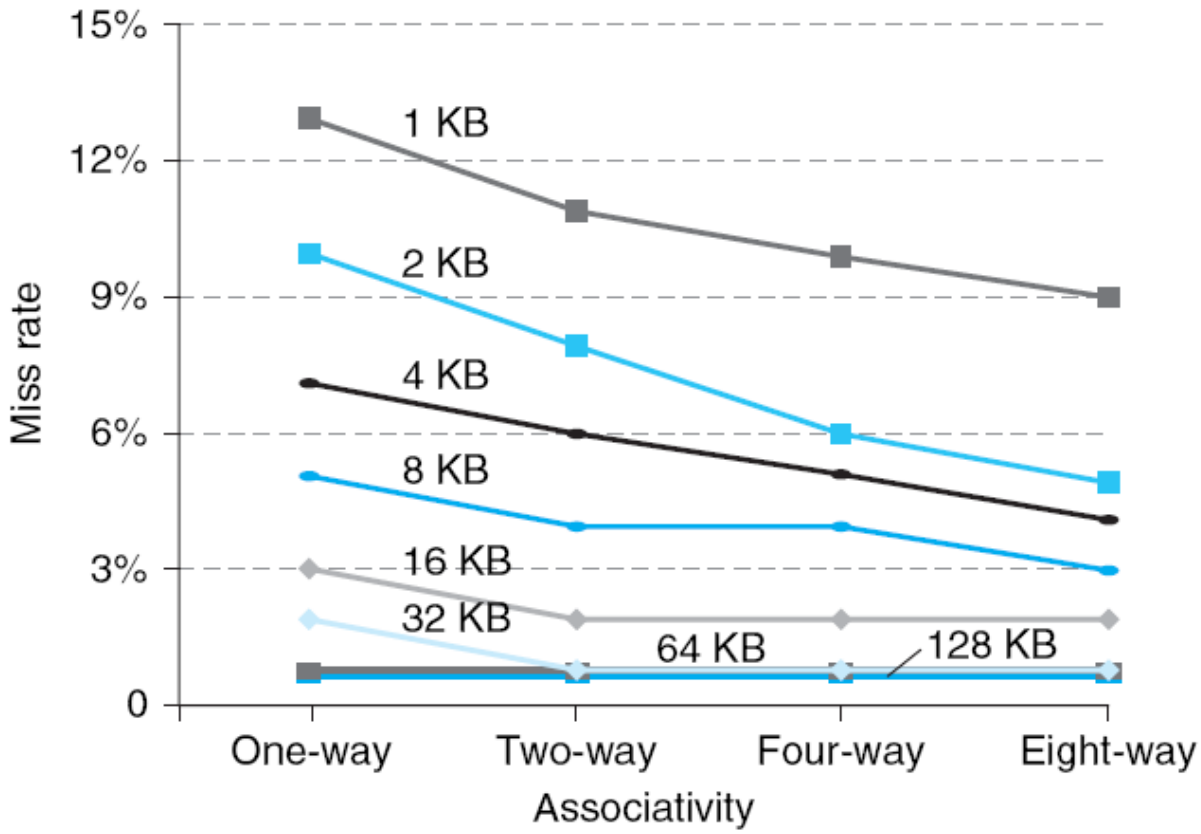
- Fully associative

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]	

How Much Associativity

- ***Increased associativity decreases miss rate***
  - But with diminishing improvement
- 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%

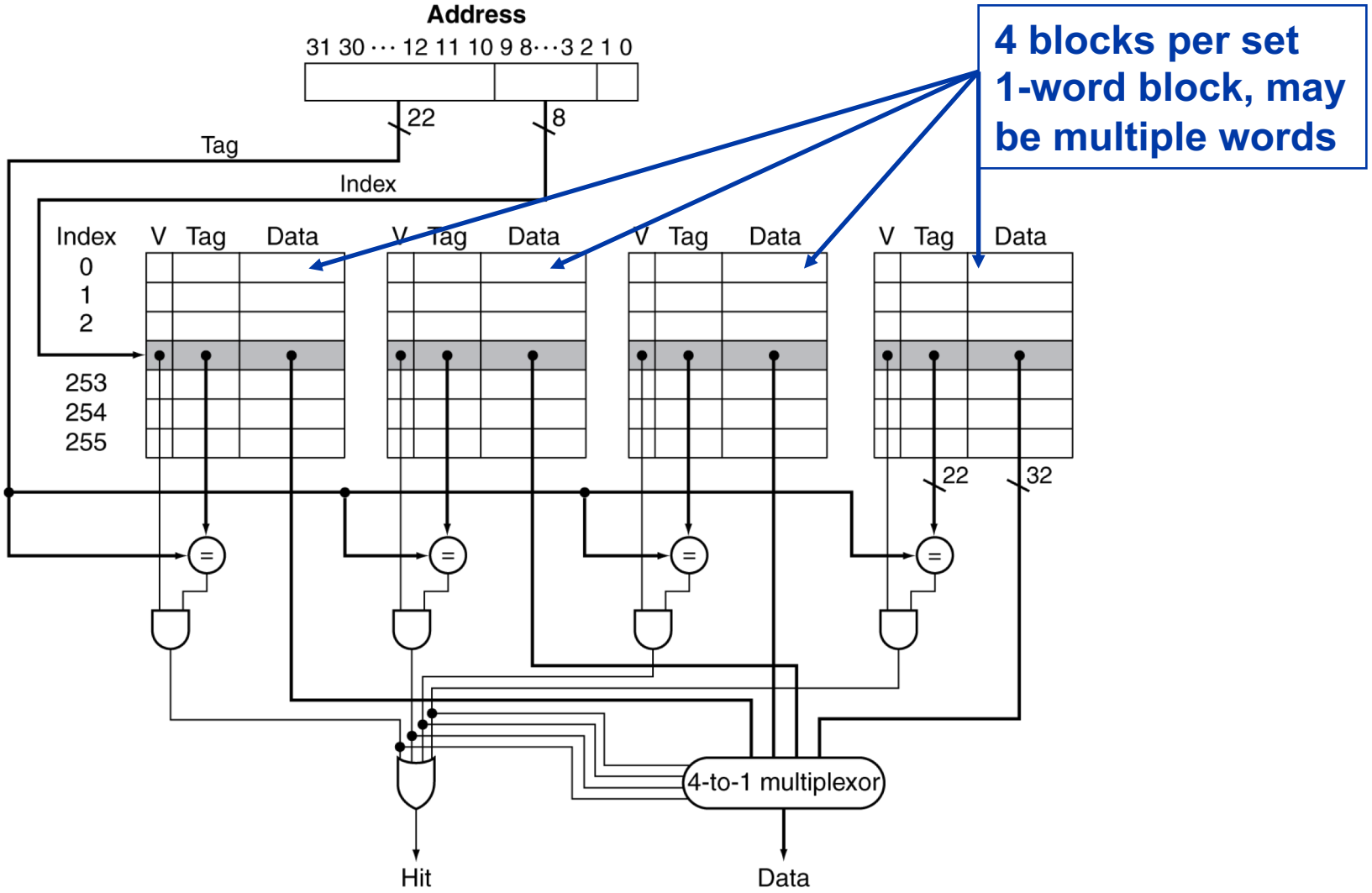
How Much Associativity



Locating a Block

- Memory address decomposition
  - Index – locate a set in cache
  - Tag – upper address bits to locate block
  - Word/Byte offset – to locate a word/byte in a block
- Size of index field
  - Increasing degree of associativity decreases the number of sets, decreases number of bits for index, increases tag field
    - Doubling # of blocks by 2 halves # of set by 2
    - Reduce index bits by 1
    - Increase tag bits by 1
- All blocks in a set must be searched
  - Tag field compared in parallel
  - Extra hardware and **extra access (hit) time**

Set Associative Cache Organization



Replacement Policy

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

Improve Performance – Multilevel Caches

- ***Multilevel cache decreases miss penalty***
- Primary (L-1) cache attached to CPU
  - Small, but fast
- Level-2 (secondary) cache services misses from primary 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 (misses/instruction) = 2%
  - Main memory access time = 100ns
    - As miss penalty, ignoring other times
- With one-level cache
  - Miss penalty = 100ns/0.25ns = 400 cycles
  - Effective CPI = 1 + 0.02 × 400 = 9

Example (cont.)

- Now add L-2 cache
  - Access time = 5ns (L-1 miss penalty)
  - Miss rate for L-2 = 25% of L1 misses (have to access main memory)
    - L-1 cache miss have a miss on L-2
- Primary (L-1) cache miss with L-2 hit
  - Miss penalty = 5ns/0.25ns = 20 cycles
- Primary cache miss with L-2 miss main & memory hit
  - Extra penalty = 400 cycles
- CPI = base CPI + L-1 miss L-2 hit (cycles per instruction)
  + L-1 miss L-2 miss (cycles per instruction)
  - CPI = 1 + 0.02 × 75% × 20 + 0.02 × 25% × (20+400) = 3.4
- Performance ratio = 9/3.4 = 2.6

Multilevel Cache Considerations

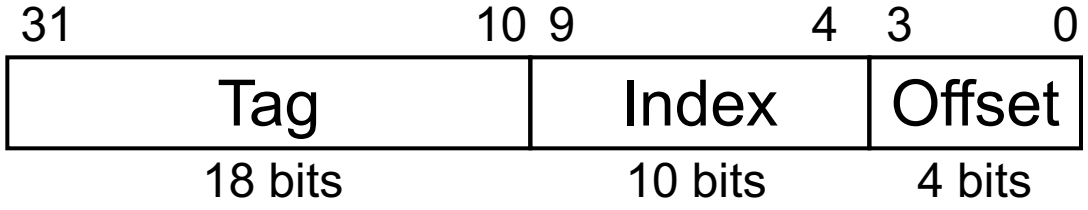
- Primary cache
  - Focus on minimal hit time because miss penalty is smaller
  - And to reduce CPU clock cycle
- Secondary cache
  - Focus on low miss rate to avoid main memory access
  - Hit time has less overall impact
- Comparison with single level cache
  - L-1
    - Cache size usually smaller than a single level cache
    - Block size smaller than single level cache organization due to
      - Smaller total cache size
      - Reduced search time -> reduced hit time
      - Reduced miss penalty -> less time to fetch
  - L-2
    - Cache and block size much larger than single level cache
      - because of less critical hit time
    - Higher associativity and block size to reduce miss rates
      - Because miss penalty is more severe

Advanced CPUs

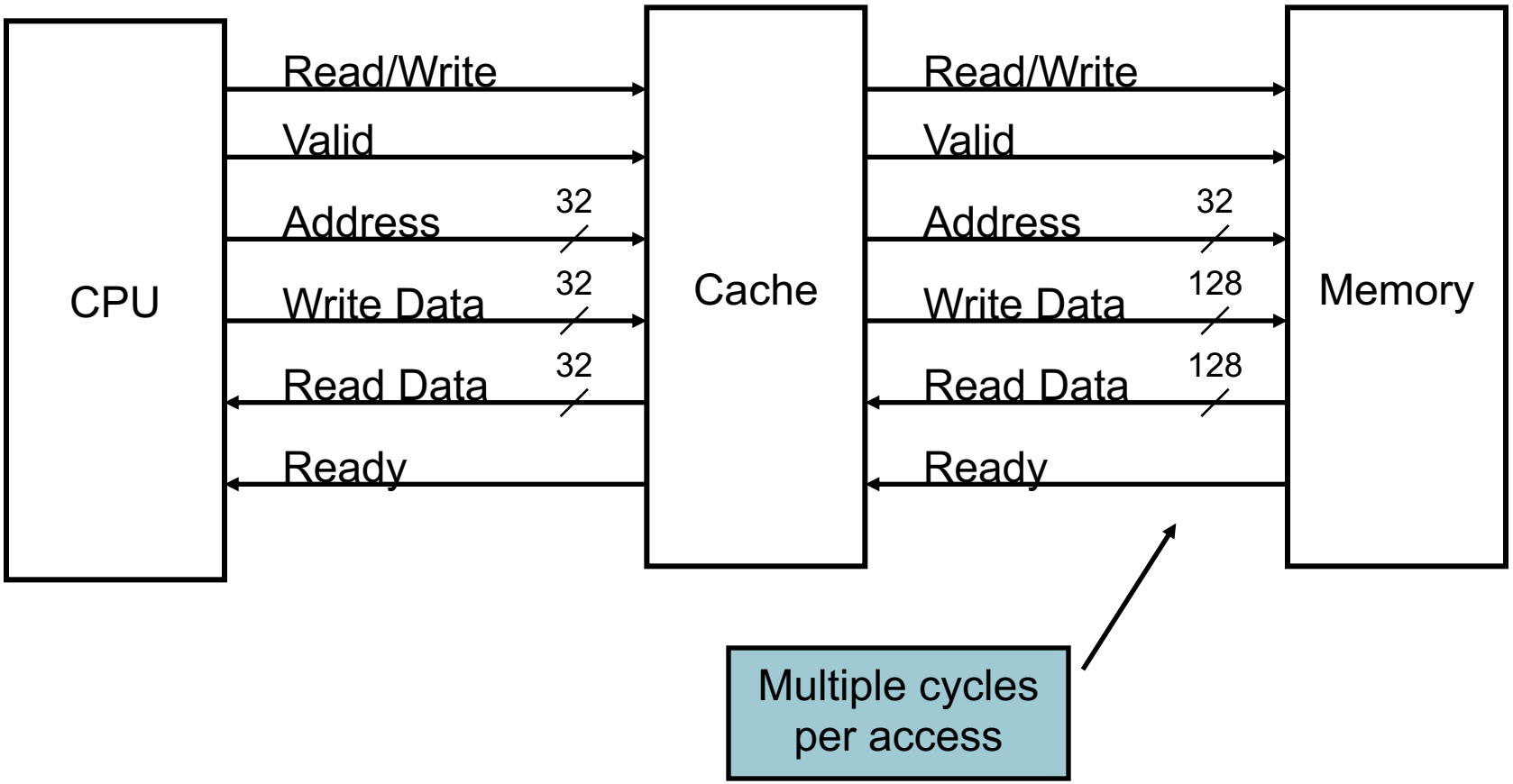
- Out-of-order CPUs can execute instructions during cache miss
  - Dependent instructions wait in reservation stations
  - Independent instructions continue
  - Might work only for small miss penalties
    - So the independent instructions don't go too far
      - Harder arrangement for part of a program to go too far alone
  - Effect of miss depends on program data flow
    - Much harder to analyze
    - Use system simulation
- Autotuning ability

Cache Controller

- Example cache characteristics
  - Direct-mapped, write-back, write allocate
  - Block size: 4 words (16 bytes)
  - Cache size: 16 KB (1024 blocks)
  - 32-bit byte addresses
  - Valid bit and dirty bit per block
  - Blocking cache
    - CPU waits until access is complete

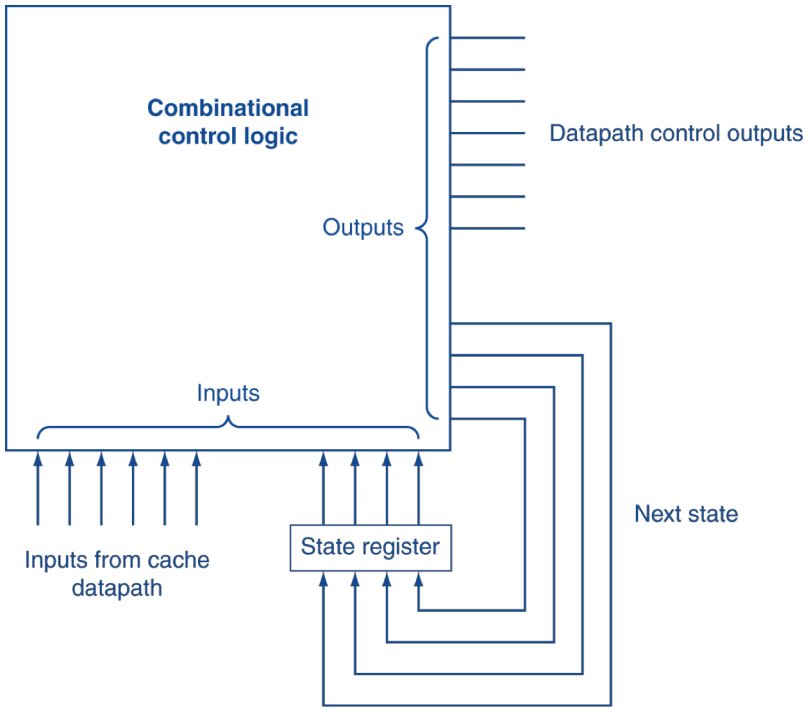


Interface Signals



Finite State Machines

- Use an FSM for sequence control steps
- Set of states, transition on each clock edge
  - State values are binary encoded
  - Current state stored in a register
  - Next state = f_n (current state, current inputs)
- Control output signals = f_o (current state)



Cache Controller FSM