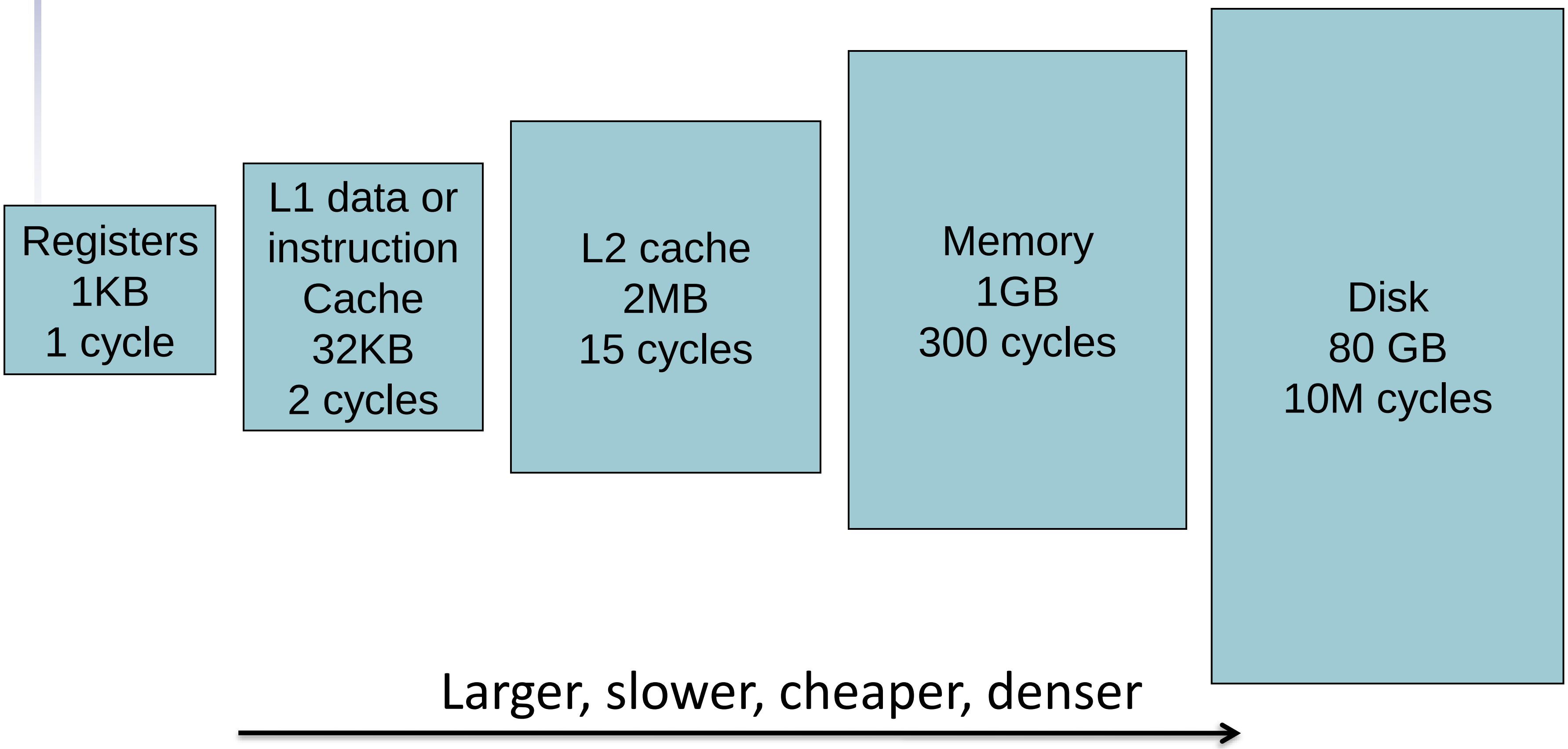
Chapter 5

Large and Fast: Exploiting Memory Hierarchy

Memory Hierarchy

- Various storage devices in computers:



Memory Technology

- Access time and price per bit vary widely among different technologies

Memory technology	Typical access time	$ per GiB in 2012
SRAM semiconductor memory	0.5–2.5 ns	$500–$1000
DRAM semiconductor memory	50–70 ns	$10–$20
Flash semiconductor memory	5,000–50,000 ns	$0.75–$1.00
Magnetic disk	5,000,000–20,000,000 ns	$0.05–$0.10

Data in 2012

- Ideal memory
  - Access time of Cache
  - Capacity and cost/GB of disk

Outline

- Cache (CPU←→memory)
  - Direct mapped cache
  - Set associative cache
  - Multi-level cache
- Virtual memory (memory←→disk)
- Dependable memory
- Real examples

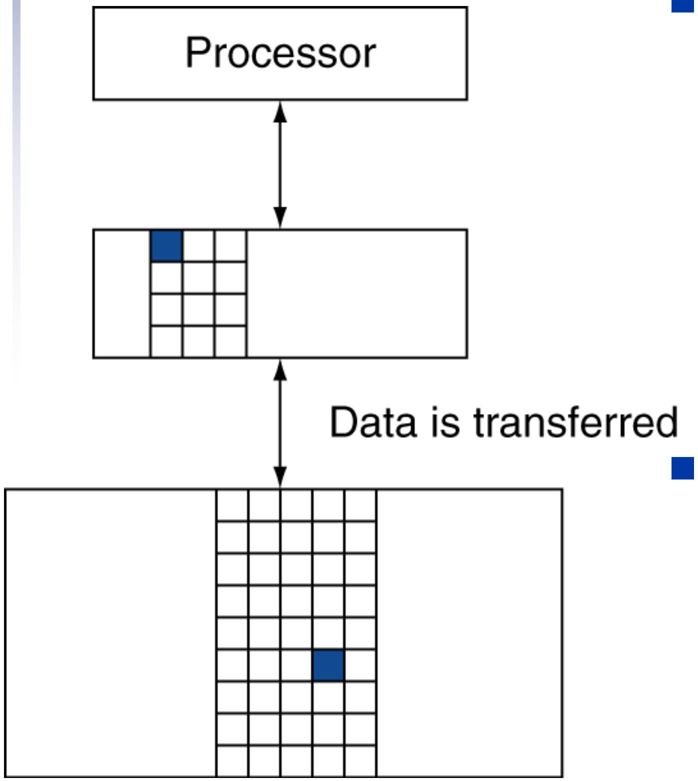
Cache Hierarchies

- Data and instructions are stored on DRAM chips
  - DRAM is a technology that has high bit density, but relatively poor latency
  - an access to data in memory can take as many as 300 cycles!
- Hence, some data is stored on the processor in a structure called the cache
  - caches employ SRAM technology, which is faster, but has lower bit density
- Internet browsers also cache web pages – same concept

Memory hierarchy

- Store everything on disk
- Copy recently accessed (and nearby) items from disk to smaller DRAM memory
  - Main memory
- Copy more recently accessed (and nearby) items from DRAM to smaller SRAM memory
  - Cache memory attached to CPU

Memory Hierarchy Levels



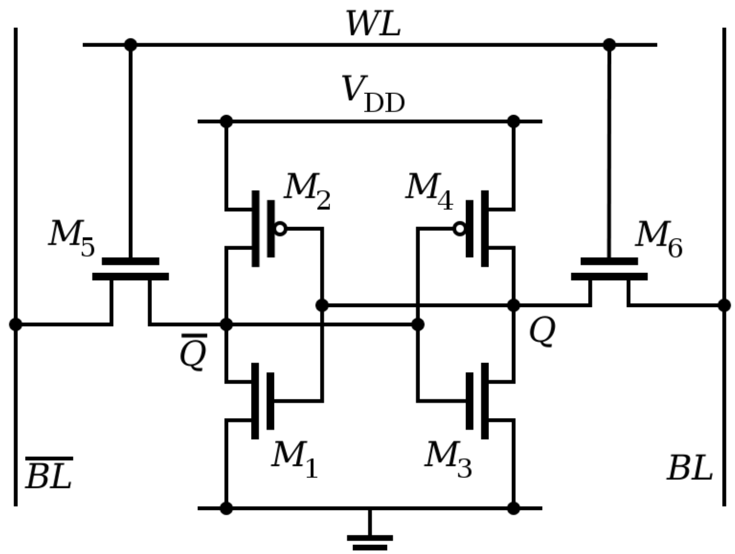
- The memory in upper level is originally empty
- If accessed data is absent
  - Miss: block copied from lower level
    - Time taken: miss penalty
    - Miss ratio: misses/accesses
  - Block (also called line): unit of copying
    - May be multiple words
- If accessed data is present in upper level
  - Hit: access satisfied by upper level
    - Hit ratio: hits/accesses = 1 – miss ratio
  - Then accessed data supplied from upper level

Locality

- Why do caches work?
  - Temporal locality: if you used some data recently, you will likely use it again
  - Spatial locality: if you used some data recently, you will likely access its neighbors
- No hierarchy:
  - average access time for data = 300 cycles
- 32KB 1-cycle L1 cache that has a hit rate of 95%:
  - average access time = 0.95 x 1 + 0.05 x (301) = 16 cycles

SRAM Technology

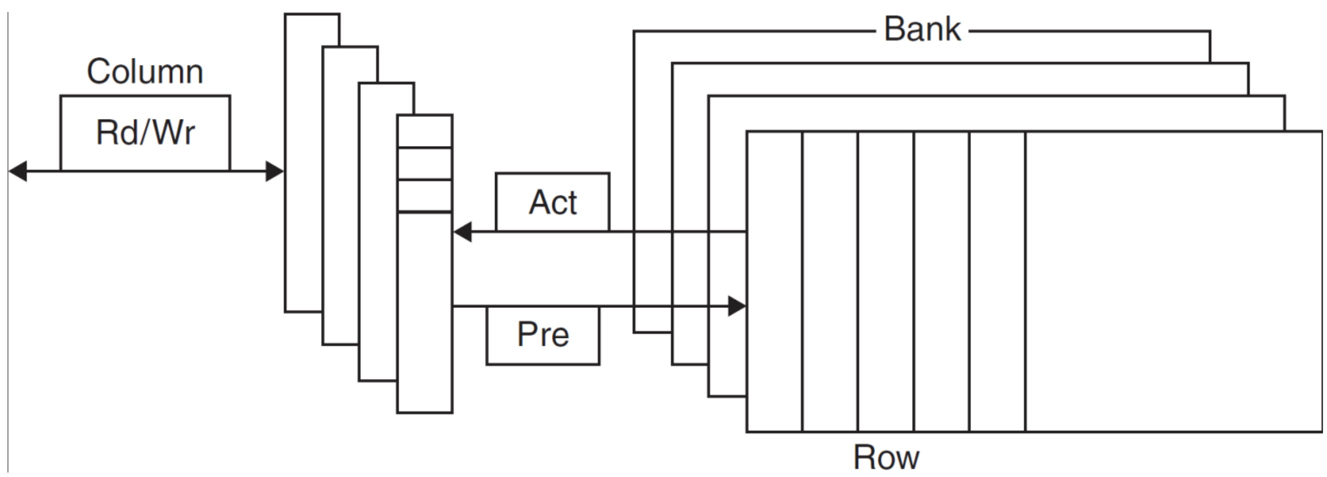
- Static RAM
  - Memory arrays with a single read/write port
- It's Volatile
  - The data will lost when SRAM is not powered



- Compared with DRAM
  - Don't need to refresh, use 6-8 transistors to install a bit
- Used in CPU cache, integrated onto the processor chip

DRAM Technology

- Data stored as a charge in a capacitor
  - Single transistor used to access the charge
  - Must periodically be refreshed
    - Read contents and write back
    - Performed on a DRAM “row”



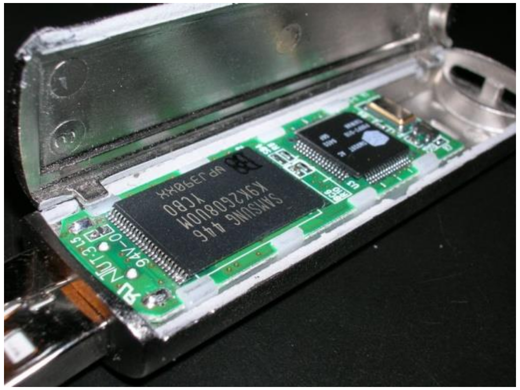
Advanced DRAM Organization

- Bits in a DRAM are organized as a rectangular array
  - DRAM accesses an entire row
  - Burst mode: supply successive words from a row with reduced latency
- Synchronous DRAM
  - A clock is added, the memory and processor are synchronized
  - Allows for consecutive accesses in bursts without needing to send each address
  - Improves bandwidth
- Double data rate (DDR) DRAM
  - Transfer on rising and falling clock edges
  - DDR4-3200 DRAM: 3200M times of transfer per second

Flash Storage

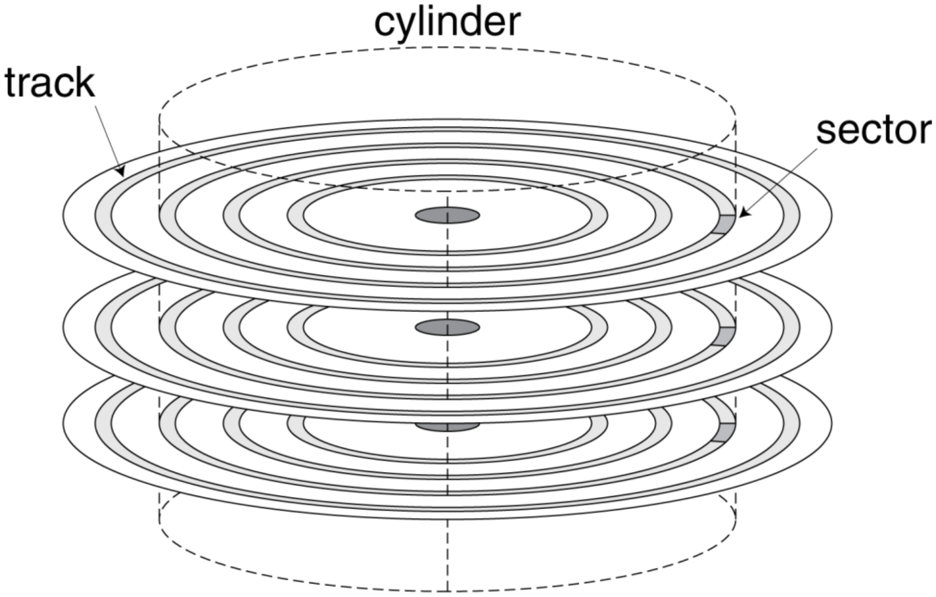
- Nonvolatile semiconductor storage
  - 100× – 1000× faster than disk
  - Smaller, lower power, more robust
  - But more $/GB (between disk and DRAM)

- Flash bits wears out after 1000's of accesses
  - Not suitable for direct RAM or disk replacement
  - Wear leveling: remap data to less used blocks



Disk Storage

- Nonvolatile, rotating magnetic storage

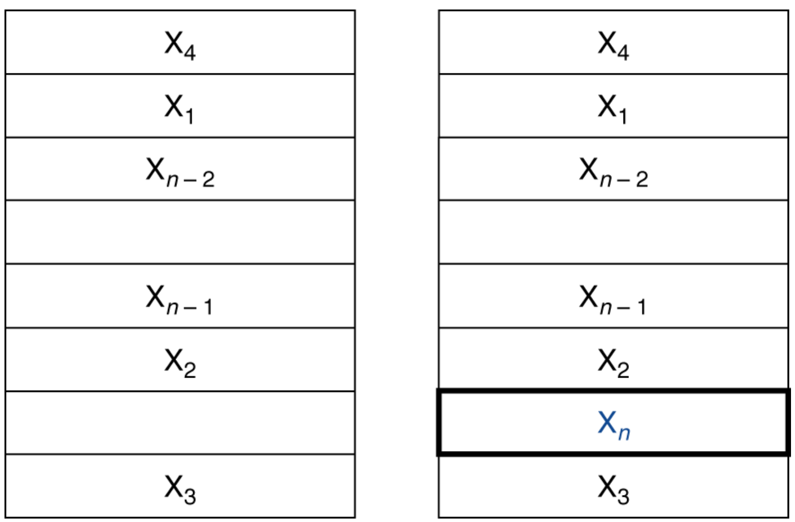


Disk Sectors and Access

- Each sector records
  - Sector ID
  - Data (512 bytes, 4096 bytes proposed)
  - Error correcting code (ECC)
    - Used to hide defects and recording errors
- Access to a sector involves
  - Queuing delay if other accesses are pending
  - Seek: move the heads
  - Rotational latency
  - Data transfer
  - Controller overhead

Cache Memory

- Cache memory
  - The level of the memory hierarchy closest to the CPU
- Given accesses $X_1, \ldots, X_{n-1}, X_n$



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

- How do we know if the data is present?
- Where do we look?

Memory Structure

- Address and data
  - Address is the index, are not stored in memory
    - Address can be in unit of byte or in unit of word
  - Only data is stored in memory

address	data
000	Byte 1
001	Byte 2
010	Byte 3
011	…
100	
101	
110	
111	

Word1

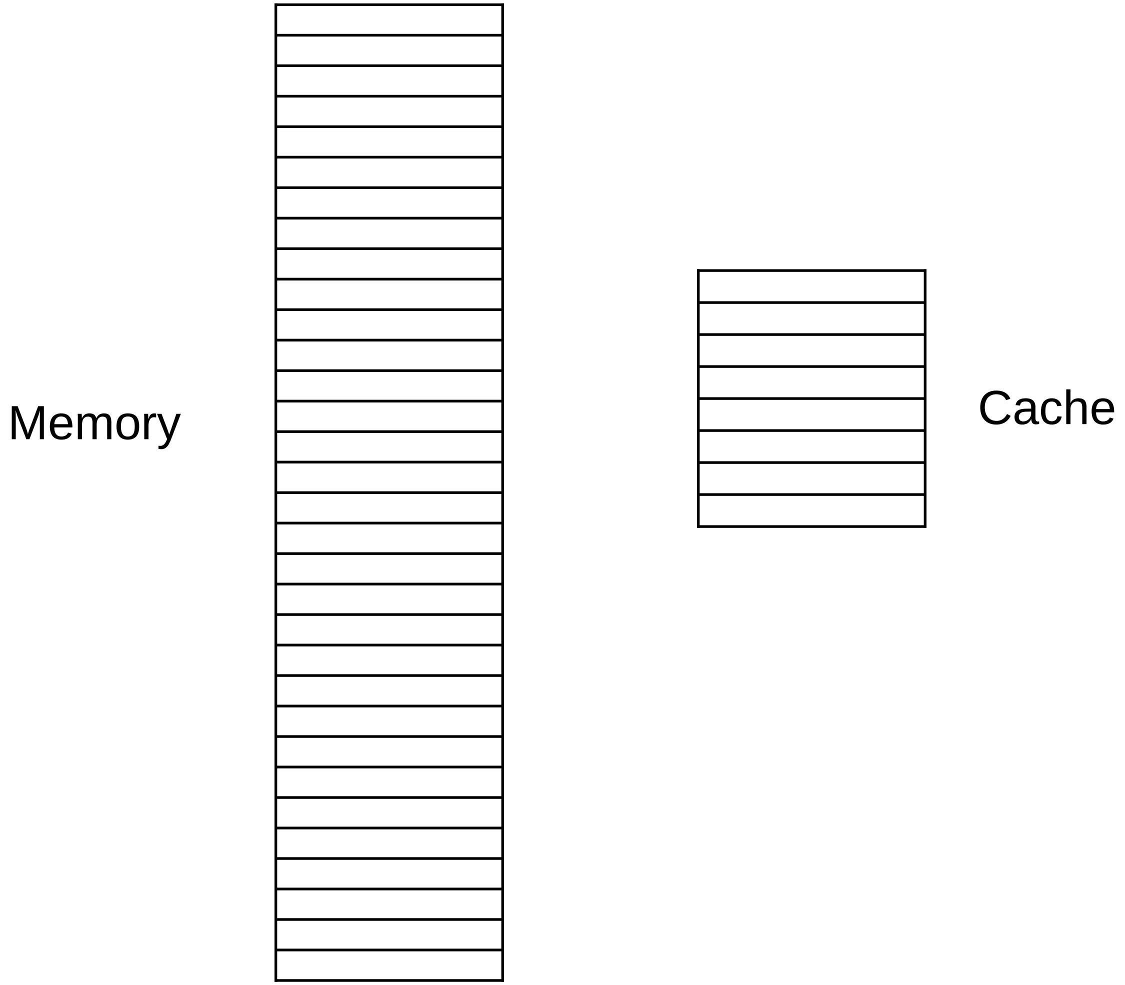
in unit of byte

address	data
000	Word1
001	Word2
010	Word3
011	Word4
100	…
101	
110	
111	

in unit of word

Direct Mapped Cache

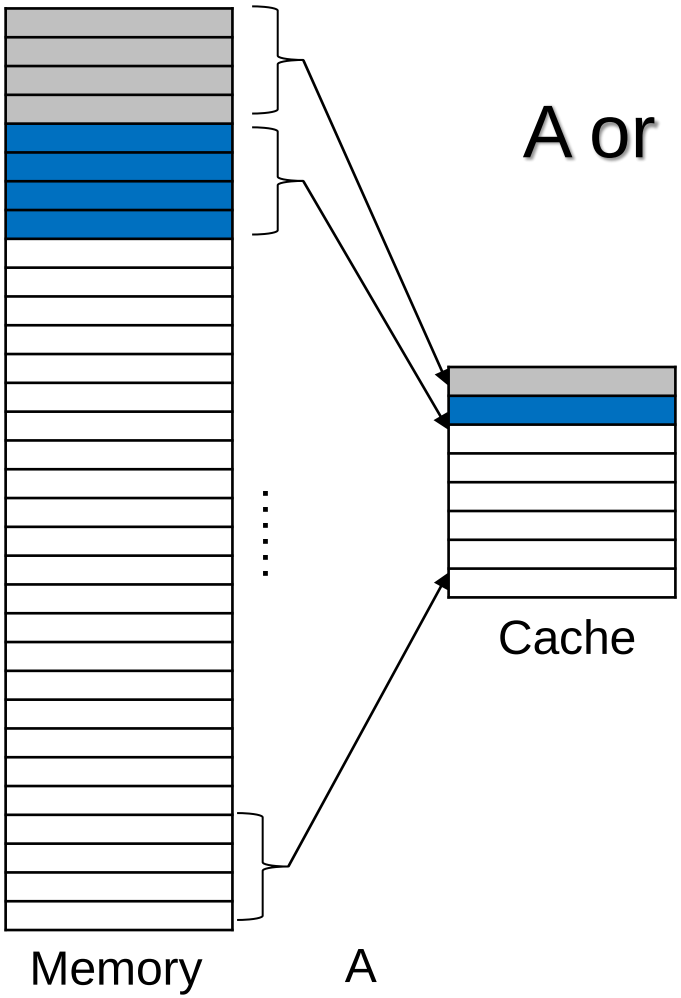
- Memory size: 32 words, cache size: 8 words, block size: 1 word
- The address is in unit of word



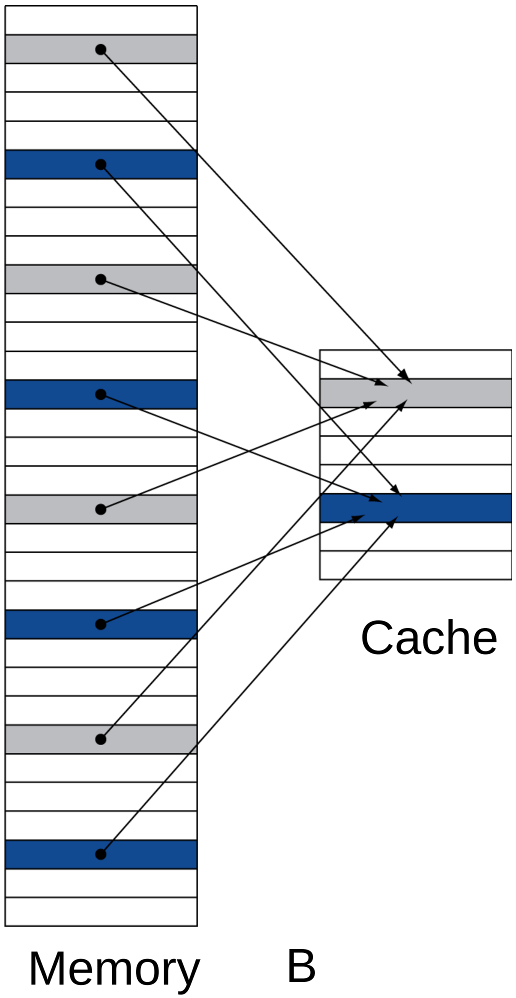
Direct Mapped Cache

- Memory size: 32 words, cache size: 8 words, block size: 1 word
- The address is in unit of word

A or B?



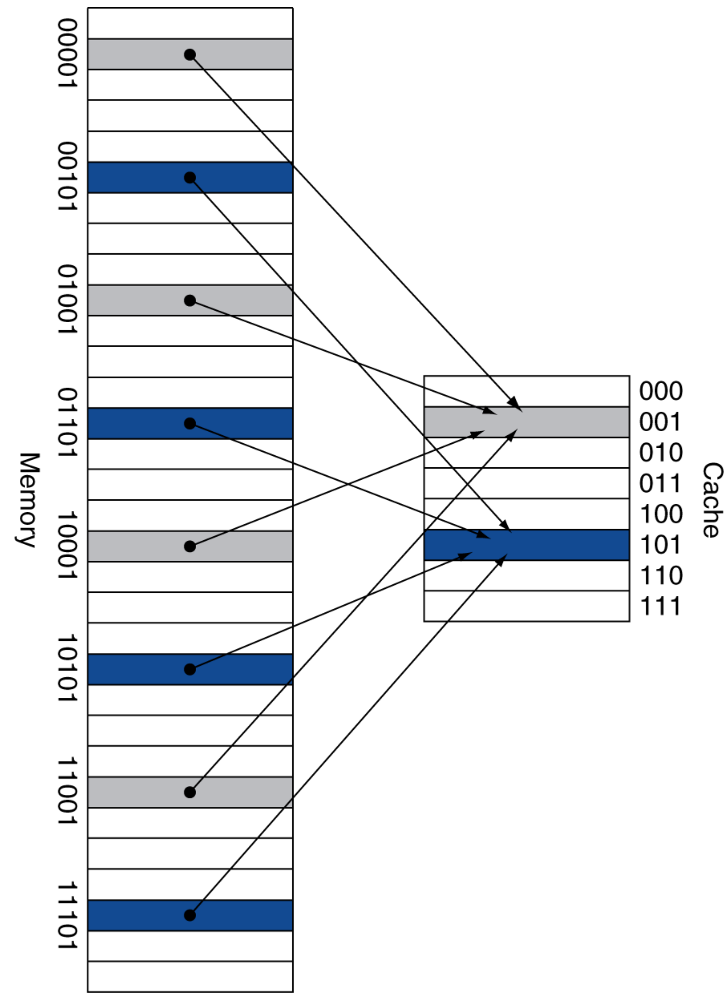
A



B

Direct Mapped Cache

- Memory size: 32 words, cache size: 8 words, block size: 1 word
- The address is in unit of word
- Direct mapped cache:
  - Location determined by address
  - One data in memory is mapped to only one location in cache
  - Use low-order address bits or high-order bits?
  - The lower bits defines the address of the cache
  - Index: which block to select



Tags and Valid Bits

- How do we know which particular block is stored in a cache location?
  - Store block address as well as the data
  - Actually, only need the high-order bits
  - Called the tag
- What if there is no data in a location?
  - Valid bit: 1 = present, 0 = not present
  - Initially 0

Cache Example

- 8-blocks, 1 word/block, direct mapped
- Initial state

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

Cache Example

Word addr	Binary addr	Hit/miss	Cache block
22	10 110	Miss	110

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

Cache Example

Word addr	Binary addr	Hit/miss	Cache block
22	10 110	Miss	110

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

Cache Example

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

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

Cache Example

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[11010]**
011	N		
100	N		
101	N		
110	Y	10	Mem[10110]
111	N		

Cache Example

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[11010]
011	N		
100	N		
101	N		
110	Y	10	Mem[10110]
111	N		

Cache Example

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	**N**		
001	N		
010	Y	11	Mem[11010]
011	**N**		
100	N		
101	N		
110	Y	10	Mem[10110]
111	N		

Cache Example

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[10000]**
001	N		
010	Y	11	Mem[11010]
011	**Y**	**00**	**Mem[00011]**
100	N		
101	N		
110	Y	10	Mem[10110]
111	N		

Cache Example

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

Index	V	Tag	Data
000	Y	10	Mem[10000]
001	N		
010	Y	11	Mem[11010]
011	Y	00	Mem[00011]
100	N		
101	N		
110	Y	10	Mem[10110]
111	N		

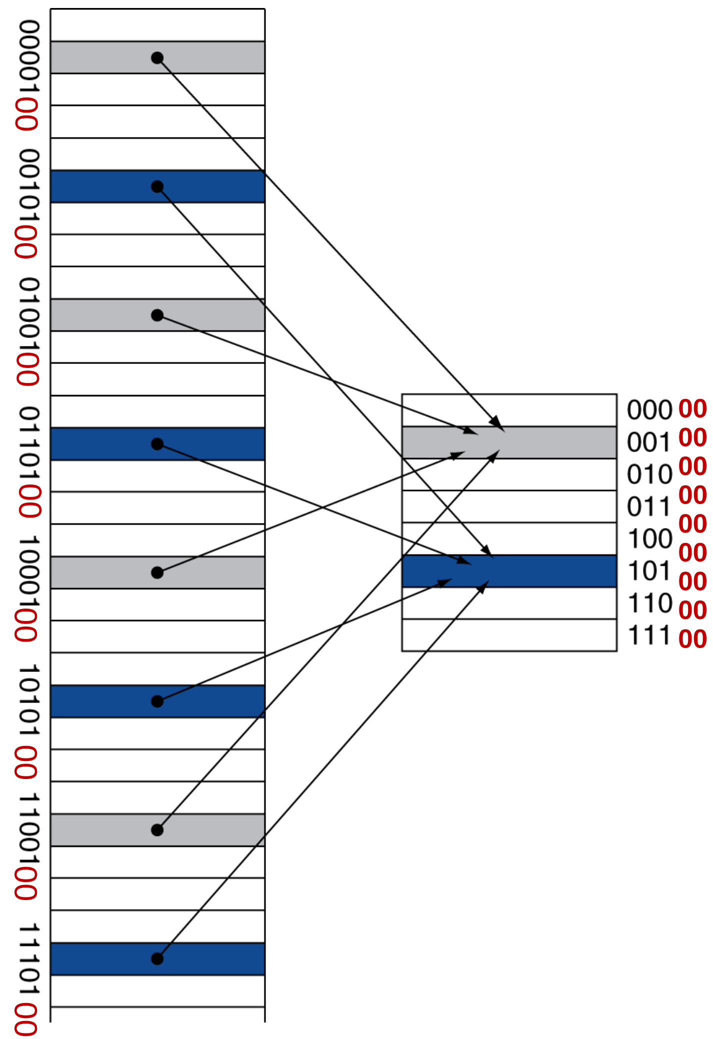
Cache Example

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

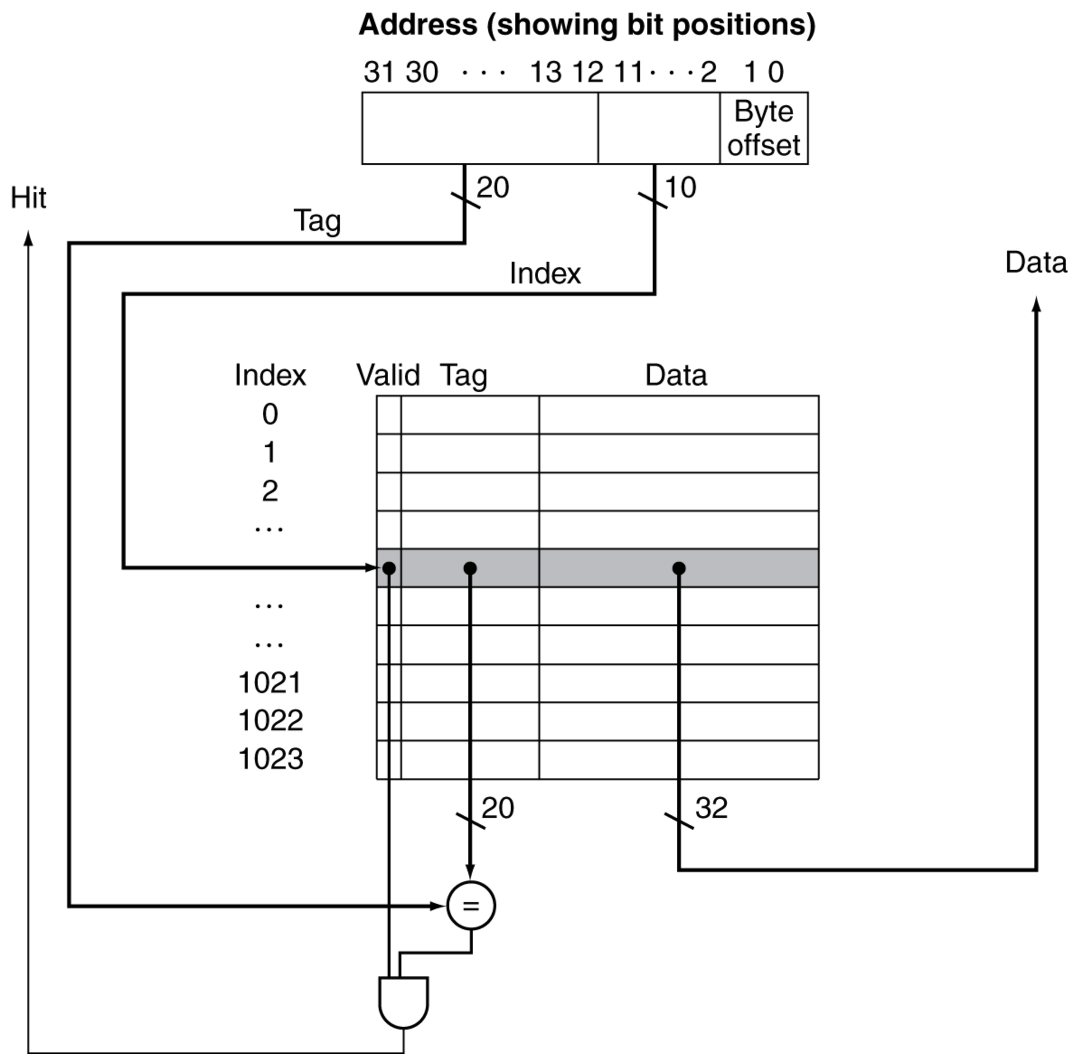
Index	V	Tag	Data
000	Y	10	Mem[10000]
001	N		
010	**Y**	**10**	**Mem[10010]**
011	Y	00	Mem[00011]
100	N		
101	N		
110	Y	10	Mem[10110]
111	N		

Memory in unit of byte

- How about the memory is in unit of byte? Assume:
- Memory size:
  - 32 words = 128 bytes
- Cache size:
  - 8 words = 32 bytes
- Block size:
  - 1 word = 4 bytes
- How to determine cache index and tag?

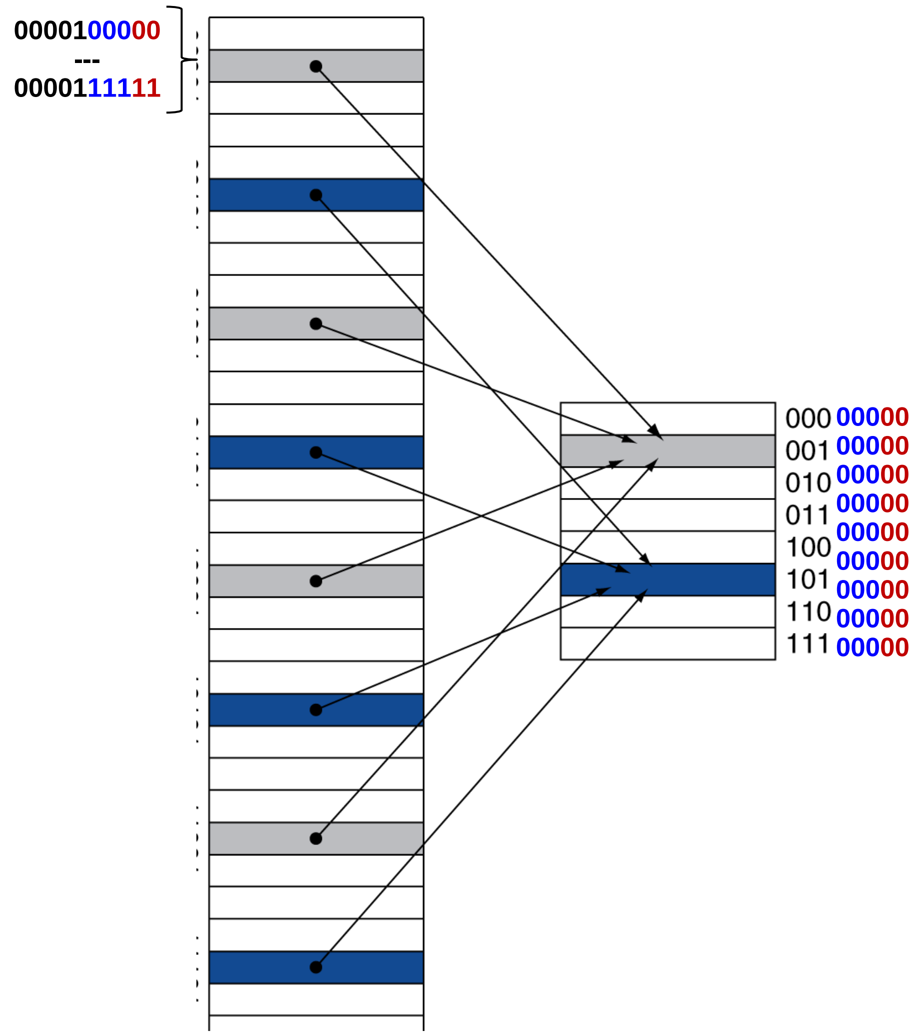


Address Subdivision



Larger Block Size

- How about the block size is larger? Assume:
- Memory size:
  - 256 words = 1024 bytes
- Cache size:
  - 64 words = 256 bytes
- Block size:
  - 8 word = 32 bytes
- How to determine cache index and tag?



Larger Block Size

- Assume:
  - 32-bit address
  - Direct mapped cache
  - 2^n number of blocks, so n bit for index
  - Block size: 2^m words, so m bit for the word within the block
- Calculate:
  - Size of tag field: 32-(n+m+2)
  - Size of cache: 2^n*(block size + tag size +valid field size)

    $=2^n*(2^m*32+(32-n-m-2)+1)$

Example: Larger Block Size

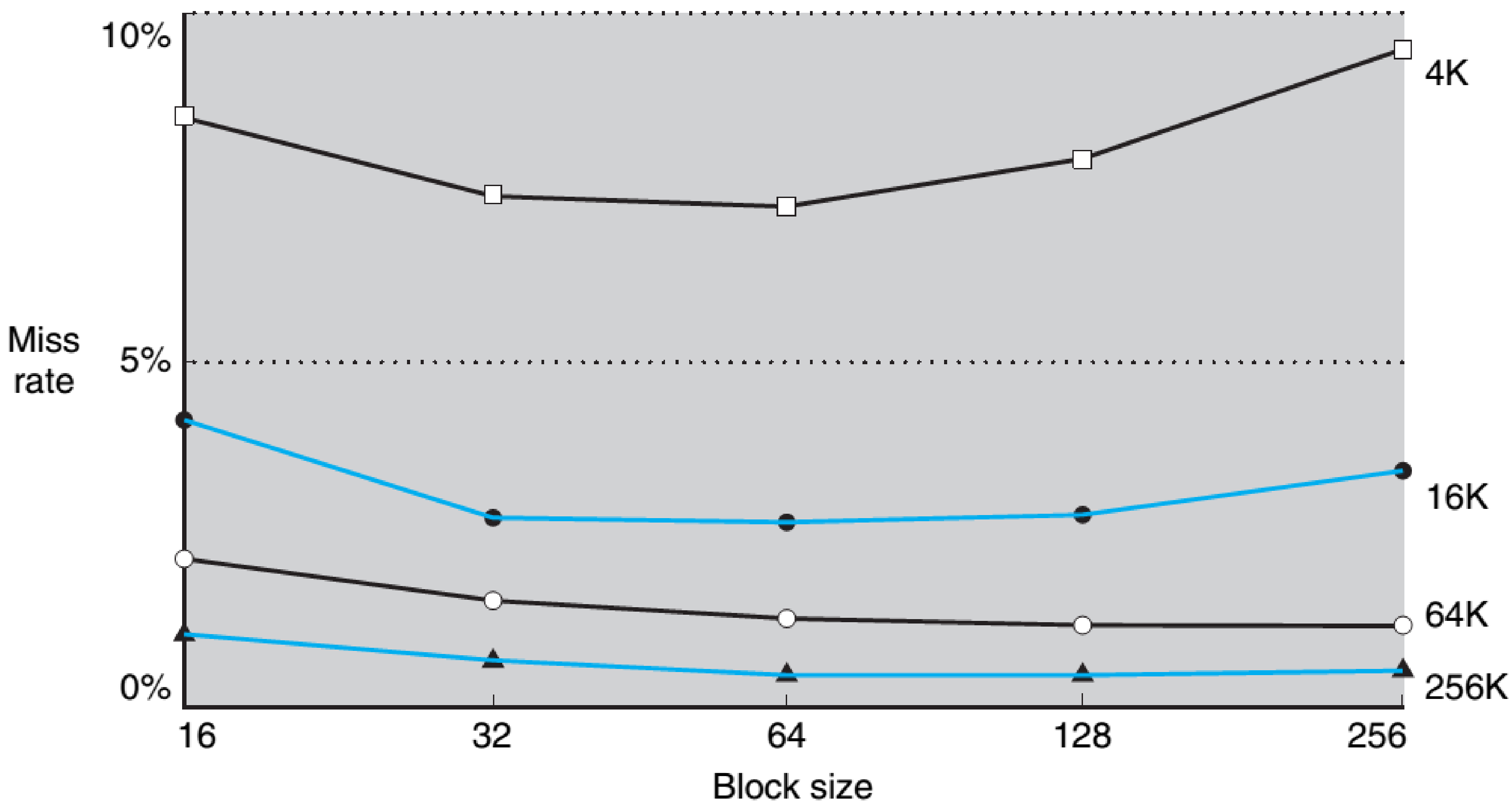
- 64 blocks, 16 bytes/block
  - To what block number does address 1200 map?
- Block address = $\lfloor 1200/16 \rfloor = 75$
- Block number = 75 modulo 64 = 11

31 10	9 4	3 0
Tag	Index	Offset
22 bits	6 bits	4 bits

Block Size Considerations

- Larger blocks should reduce miss rate
  - Due to spatial locality
- But in a fixed-sized cache
  - Larger blocks $\Rightarrow$ fewer of blocks
    - More competition $\Rightarrow$ increased miss rate
  - Larger blocks $\Rightarrow$ more transfer time upon missing $\Rightarrow$ Larger miss penalty
    - *Early restart* and *critical-word-first* can help
- We should find a suitable block size to achieve a good trade-off between miss rate and miss penalty

Block Size Considerations



Cache Misses

- On cache hit, CPU proceeds normally
- On cache miss
  - Read miss vs. write miss
  - Stall the CPU pipeline
  - Fetch block from next level of hierarchy
  - Instruction cache miss
    - Restart instruction fetch
  - Data cache miss
    - Complete data access

Write-Through

- On data-write hit, could just update the block in cache
  - But then cache and memory would be inconsistent
- Write through: also update memory
- But makes writes take longer
  - e.g., if base CPI = 1, 10% of instructions are stores, write to memory takes 100 cycles
    - Effective CPI = $1 + 0.1 \times 100 = 11$
- Solution: write buffer
  - Holds data waiting to be written to memory
  - CPU continues immediately
    - Only stalls on write if write buffer is already full

Write-Back

- Alternative: On data-write hit, just update the block in cache
  - Keep track of whether each block is dirty
- When a dirty block is replaced
  - Write it back to memory
  - Can use a write buffer to allow replacing block to be read first

Write Allocation

- What should happen on a write miss?
- Alternatives for write-through
  - Allocate on miss: fetch the block
  - Write around: don’t fetch the block
    - Since programs often write a whole block before reading it (e.g., initialization)
- For write-back
  - Usually fetch the block

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