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CS61C : Machine Structures

Lecture 12 – Caches I

2014-09-26

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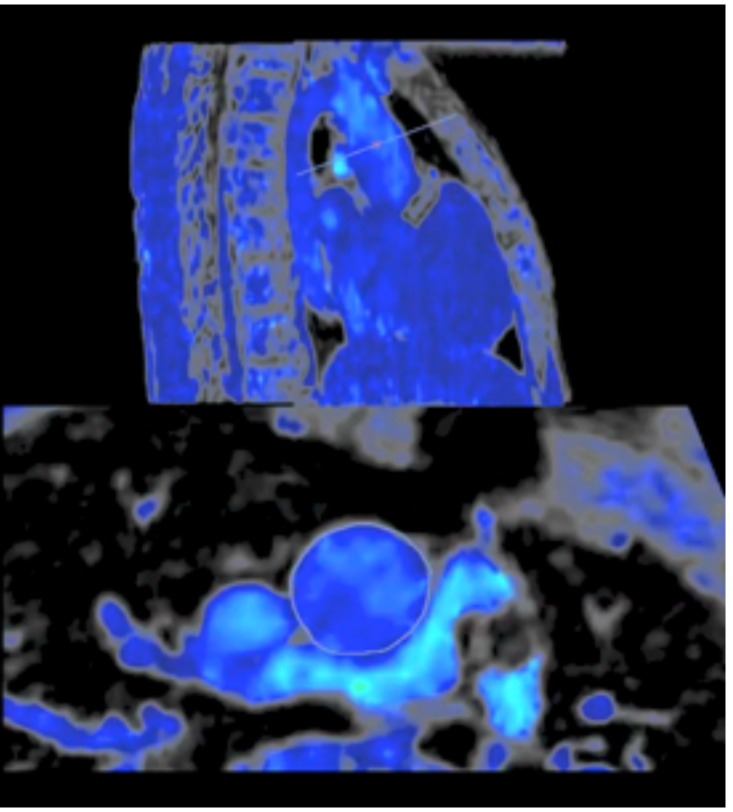


September 23: Another type of Cache

PayPal Integrates Bitcoin Processors BitPay, Coinbase and GoCoin
The eBay-owned company wants to help digital goods merchants accept Bitcoin payments, ...The company envisions anything that can be obtained digitally, such as video games and music, being sold in Bitcoin

http://news.slashdot.org/story/14/09/23/227251/paypal-integrates-bitcoin-processors-bitpay-coinbase-and-gocoin

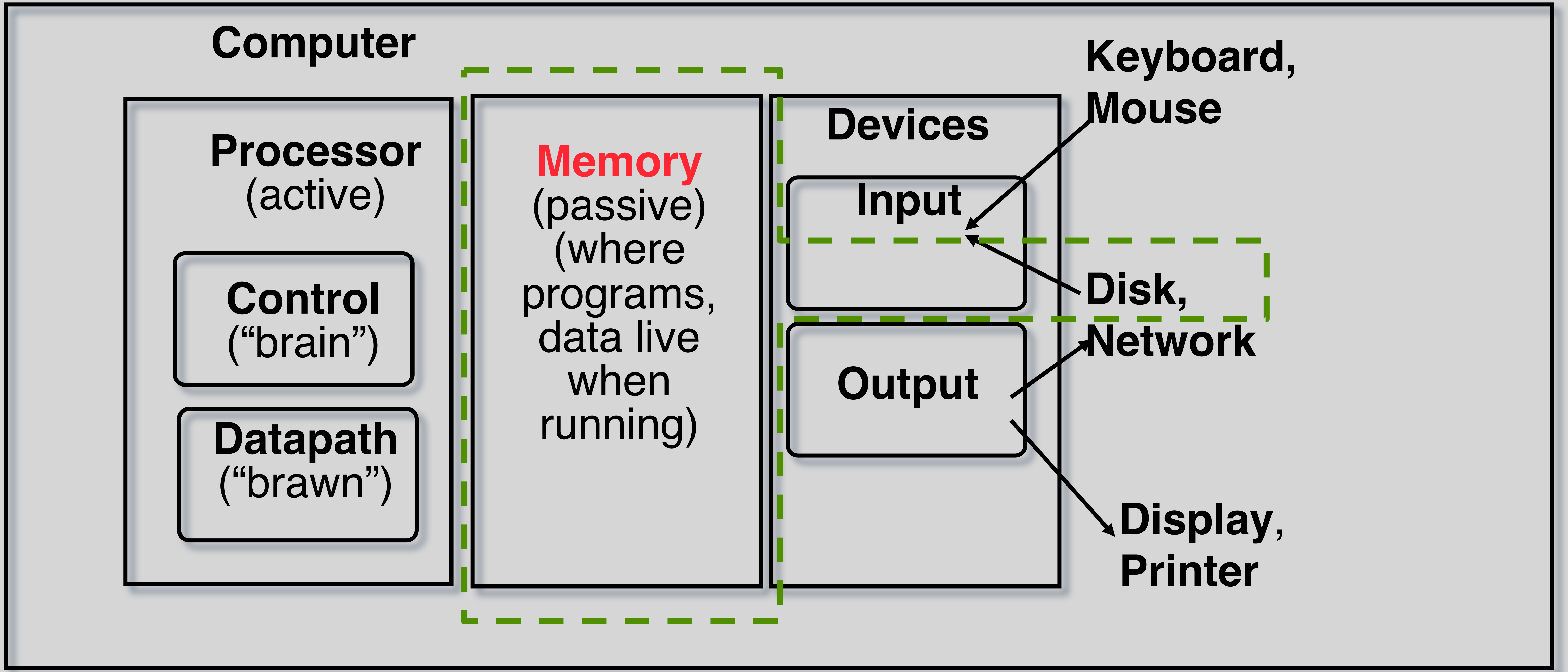
Review

- Register Conventions: Each register has a purpose and limits to its usage. Learn these and follow them, even if you're writing all the code yourself.
- Logical and Shift Instructions
  - Operate on bits individually, unlike arithmetic, which operate on entire word.
  - Use to isolate fields, either by masking or by shifting back and forth.
  - Use shift left logical, `sll`, for multiplication by powers of 2
  - Use shift right logical, `srl`, for division by powers of 2 of unsigned numbers (`unsigned int`)
  - Use shift right arithmetic, `sra`, for division by powers of 2 of signed numbers (`int`)
- New Instructions:
  `and, andi, or, ori, sll, srl, sra`

6 Great Ideas in Computer Architecture

1. Layers of Representation/Interpretation
2. Moore's Law
3. Principle of Locality/Memory Hierarchy
4. Parallelism
5. Performance Measurement & Improvement
6. Dependability via Redundancy

The Big Picture



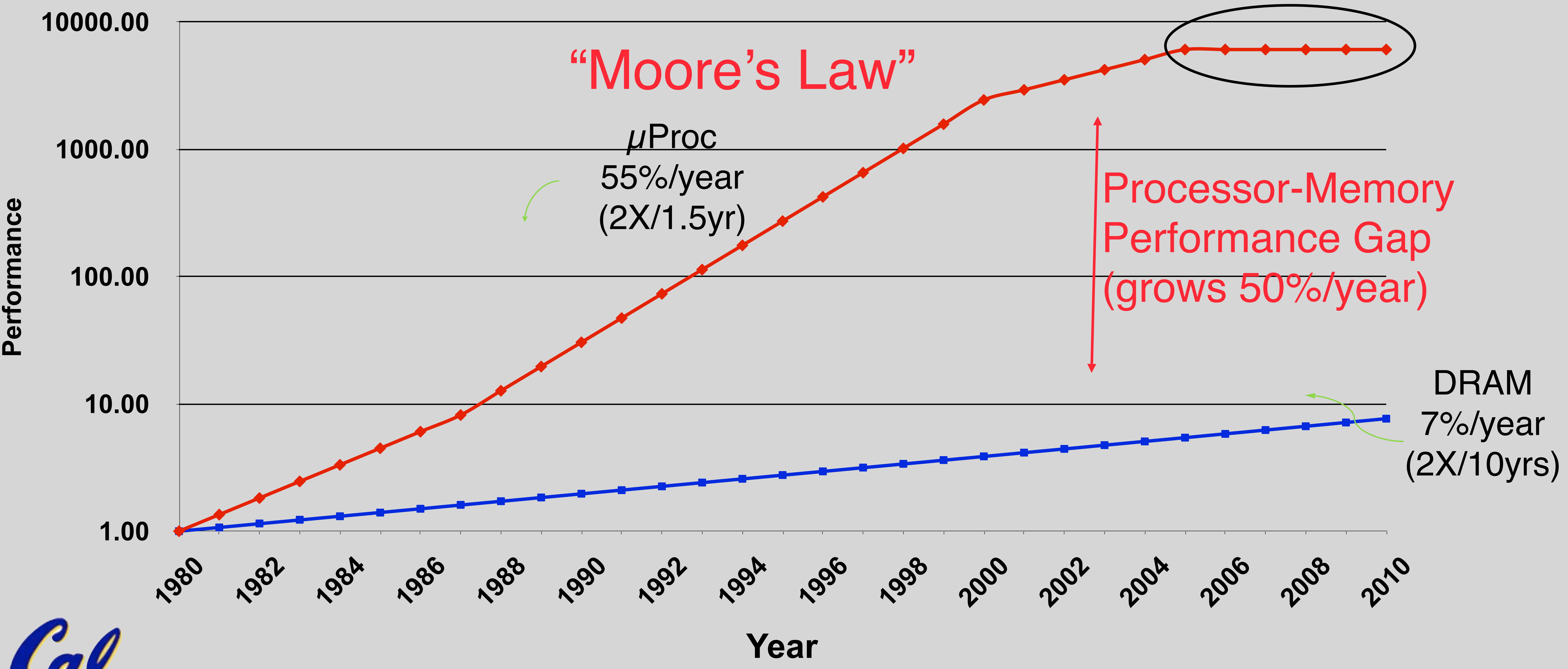
Memory Hierarchy

I.e., storage in computer systems

- Processor
  - holds data in register file (~100 Bytes)
  - Registers accessed on nanosecond timescale
- Memory (we'll call "main memory")
  - More capacity than registers (~Gbytes)
  - Access time ~50-100 ns
  - Hundreds of clock cycles per memory access?!
- Disk
  - HUGE capacity (virtually limitless)
  - VERY slow: runs ~milliseconds

Motivation : Processor-Memory Gap

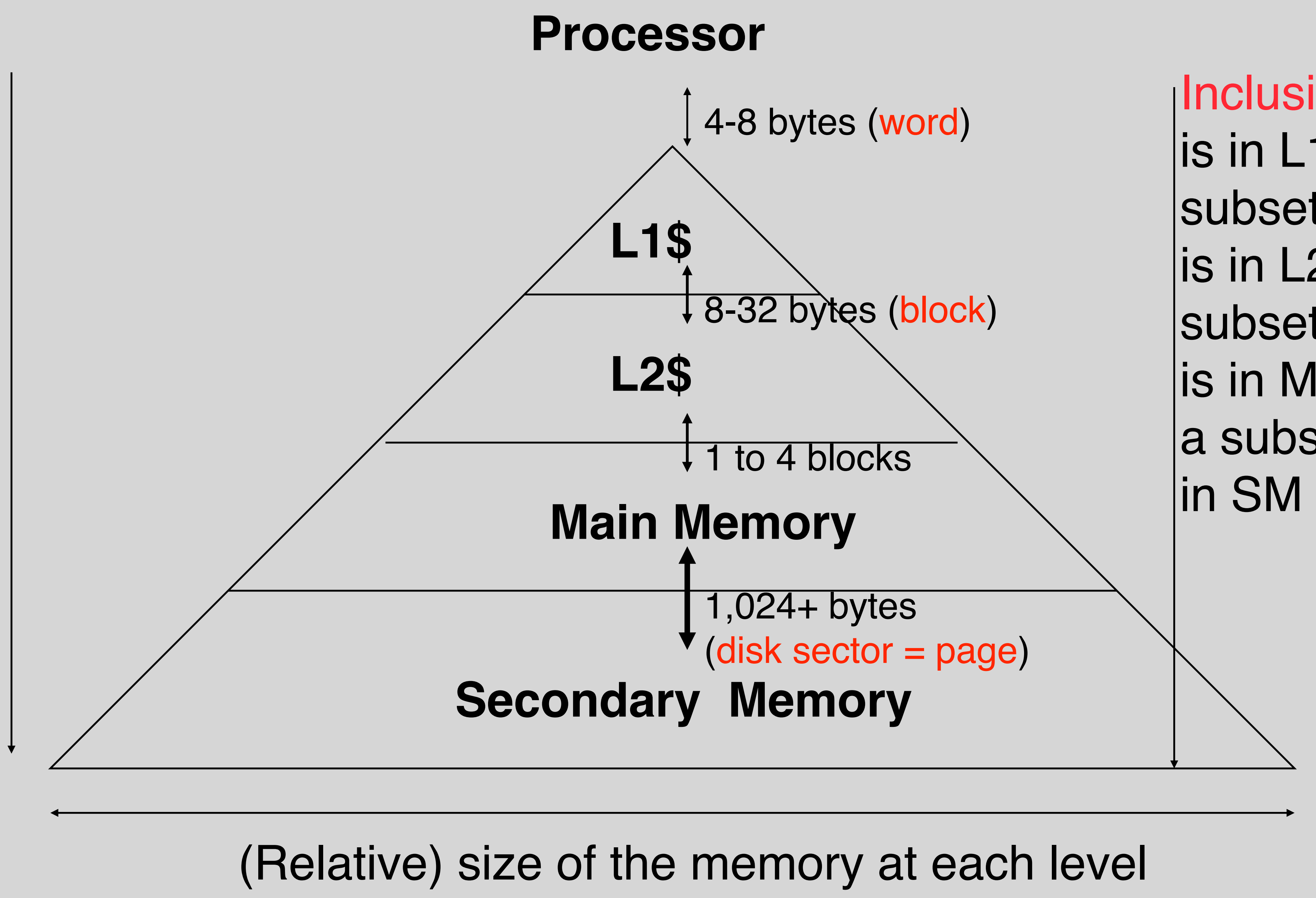
1989 first Intel CPU with cache on chip
1998 Pentium III has two cache levels on chip



Memory Caching

- Mismatch between processor and memory speeds leads us to add a new level: a memory cache
- Implemented with same IC processing technology as the CPU (usually integrated on same chip): faster but more expensive than DRAM memory.
- Cache is a copy of a subset of main memory.
- Most processors have separate caches for instructions and data.

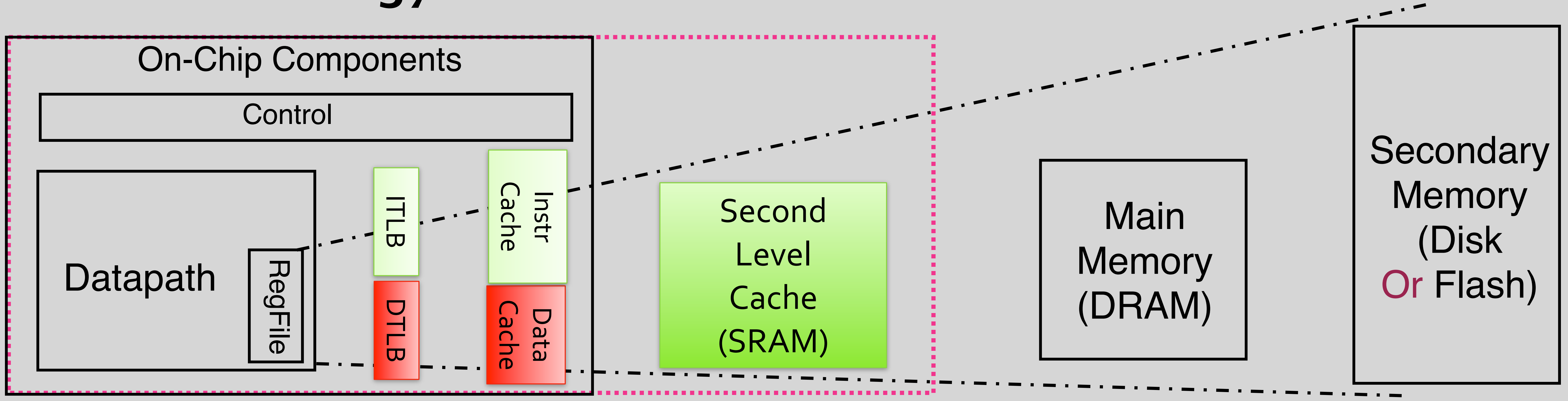
Characteristics of the Memory Hierarchy



Inclusive– what is in L1$ is a subset of what is in L2$ is a subset of what is in MM that is a subset of is in SM

Typical Memory Hierarchy

- **The Trick: present processor with as much memory as is available in the cheapest technology at the speed offered by the fastest technology**



Speed (#cycles):	½'s	1's	10's	100's	10,000's
Size (bytes):	100's	10K's	M's	G's	T's
Cost:	highest				lowest

Memory Hierarchy

- If level closer to Processor, it is:
  - Smaller
  - Faster
  - More expensive
  - subset of lower levels (contains most recently used data)
- Lowest Level (usually disk) contains all available data (does it go beyond the disk?)
- Memory Hierarchy presents the processor with the illusion of a very large & fast memory

Memory Hierarchy Analogy: Library

- You're writing a term paper (Processor) at a table in Doe
- Doe Library is equivalent to disk
  - essentially limitless capacity, very slow to retrieve a book
- Table is main memory
  - smaller capacity: means you must return book when table fills up
  - easier and faster to find a book there once you've already retrieved it
- Open books on table are cache
  - smaller capacity: can have very few open books fit on table; again, when table fills up, you must close a book
  - much, much faster to retrieve data
- Illusion created: <u>whole library open on the tabletop</u>
  - Keep as many recently used books open on table as possible since likely to use again
  - Also keep as many books on table as possible, since faster than going to library

Memory Hierarchy Basis

- Cache contains copies of data in memory that are being used.
- Memory contains copies of data on disk that are being used.
- Caches work on the principles of temporal and spatial locality.
    - Temporal Locality: if we use it now, chances are we'll want to use it again soon.
    - Spatial Locality: if we use a piece of memory, chances are we'll use the neighboring pieces soon.

Two Types of Locality

- Temporal Locality (locality in time)
  - If a memory location is referenced then it will tend to be referenced again soon

  ⇒ Keep most recently accessed data items closer to the processor

- Spatial Locality (locality in space)
  - If a memory location is referenced, the locations with nearby addresses will tend to be referenced soon

  ⇒ Move blocks consisting of contiguous words closer to the processor

Cache Design (for ANY cache)

- How do we organize cache?
- Where does each memory address map to?
  - (Remember that cache is subset of memory, so multiple memory addresses map to the same cache location.)
- How do we know which elements are in cache?
- How do we quickly locate them?

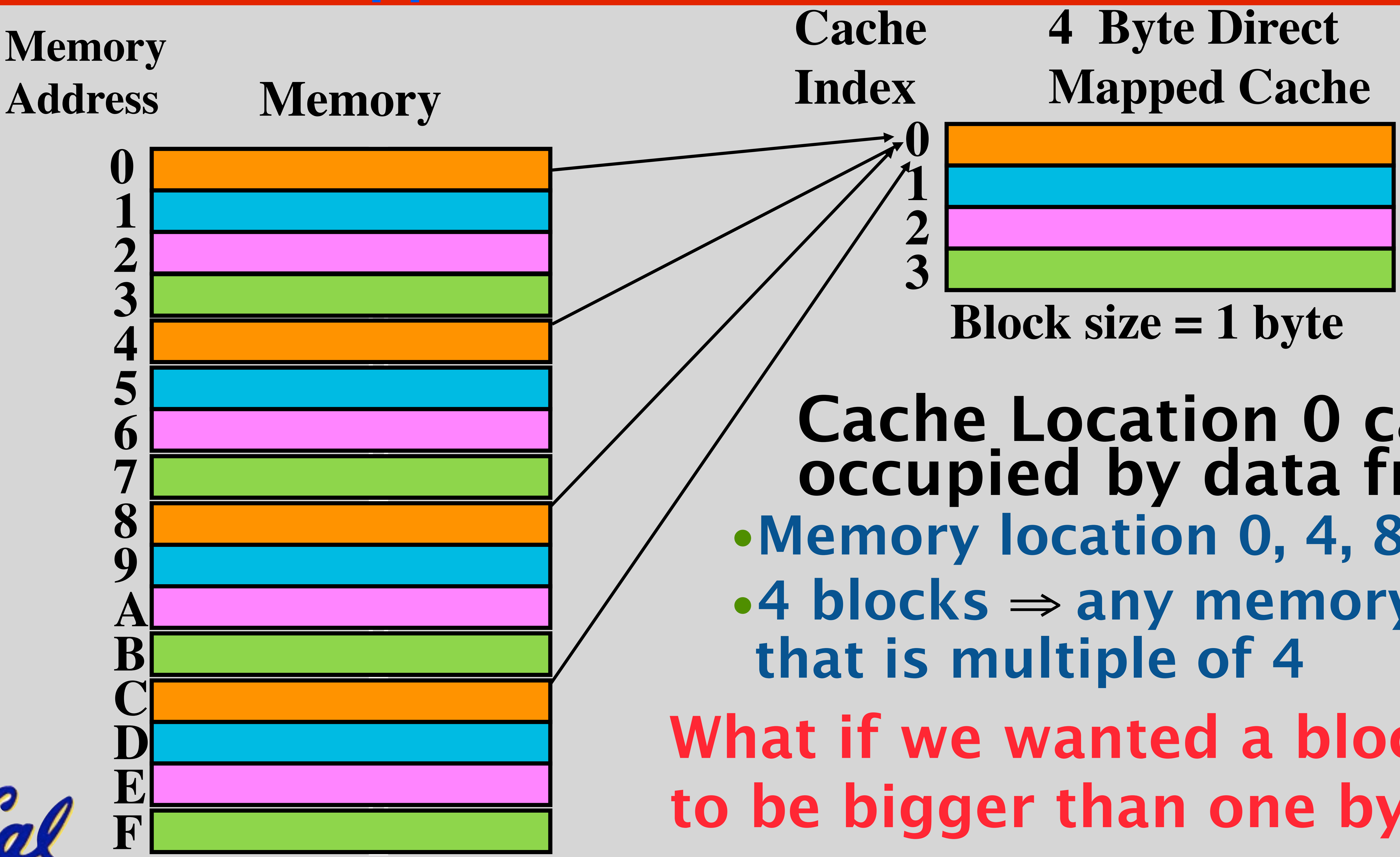
How is the Hierarchy Managed?

- registers ↔ memory
  - By compiler (or assembly level programmer)
- cache ↔ main memory
  - By the cache controller hardware
- main memory ↔ disks (secondary storage)
  - By the operating system (virtual memory)
  - Virtual to physical address mapping assisted by the hardware (TLB)
  - By the programmer (files)

Direct-Mapped Cache (1/4)

- In a direct-mapped cache, each memory address is associated with one possible block within the cache
  - Therefore, we only need to look in a single location in the cache for the data if it exists in the cache
  - Block is the unit of transfer between cache and memory

Direct-Mapped Cache (2/4)

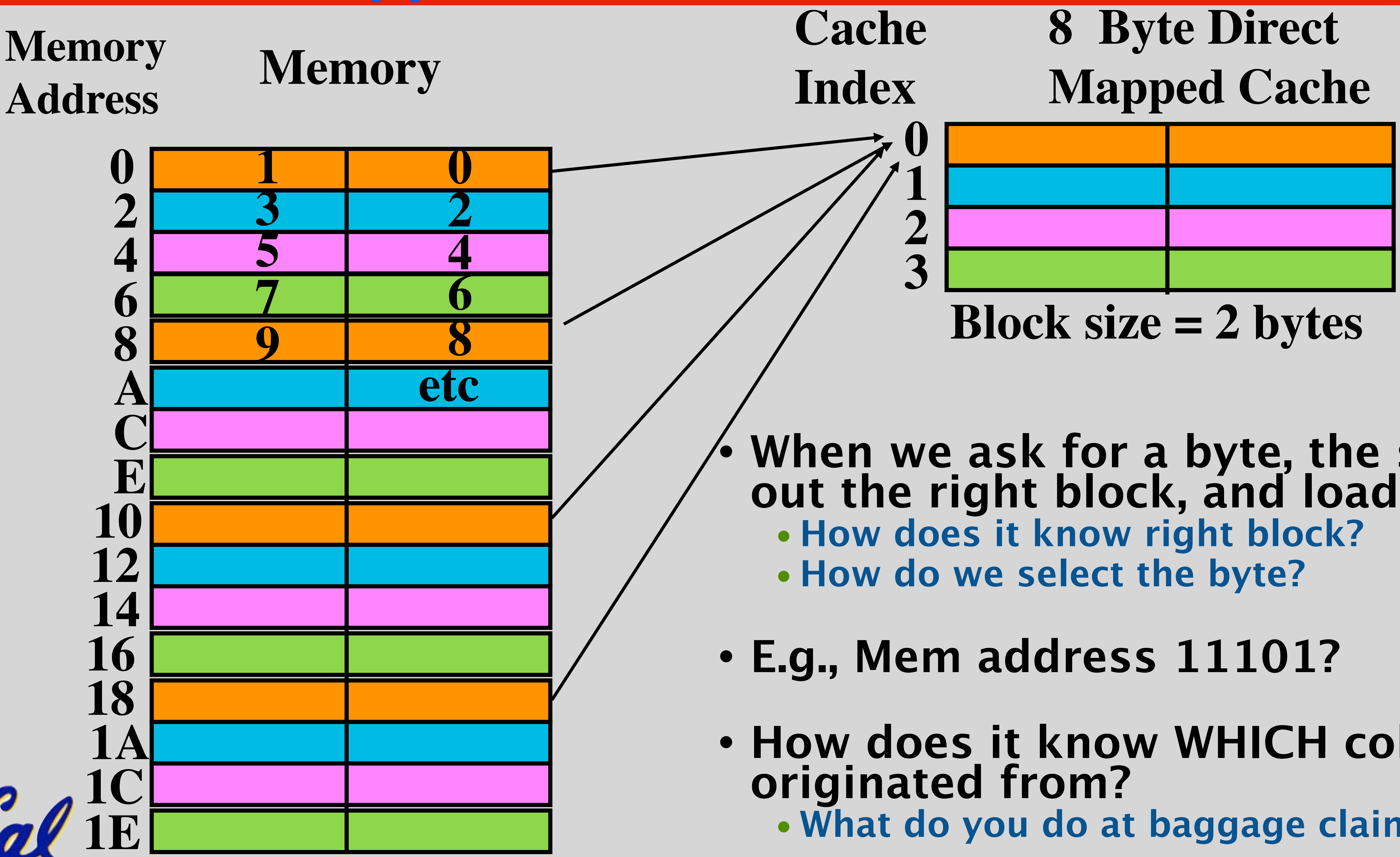


Cache Location 0 can be occupied by data from:

- Memory location 0, 4, 8, ...
- 4 blocks ⇒ any memory location that is multiple of 4

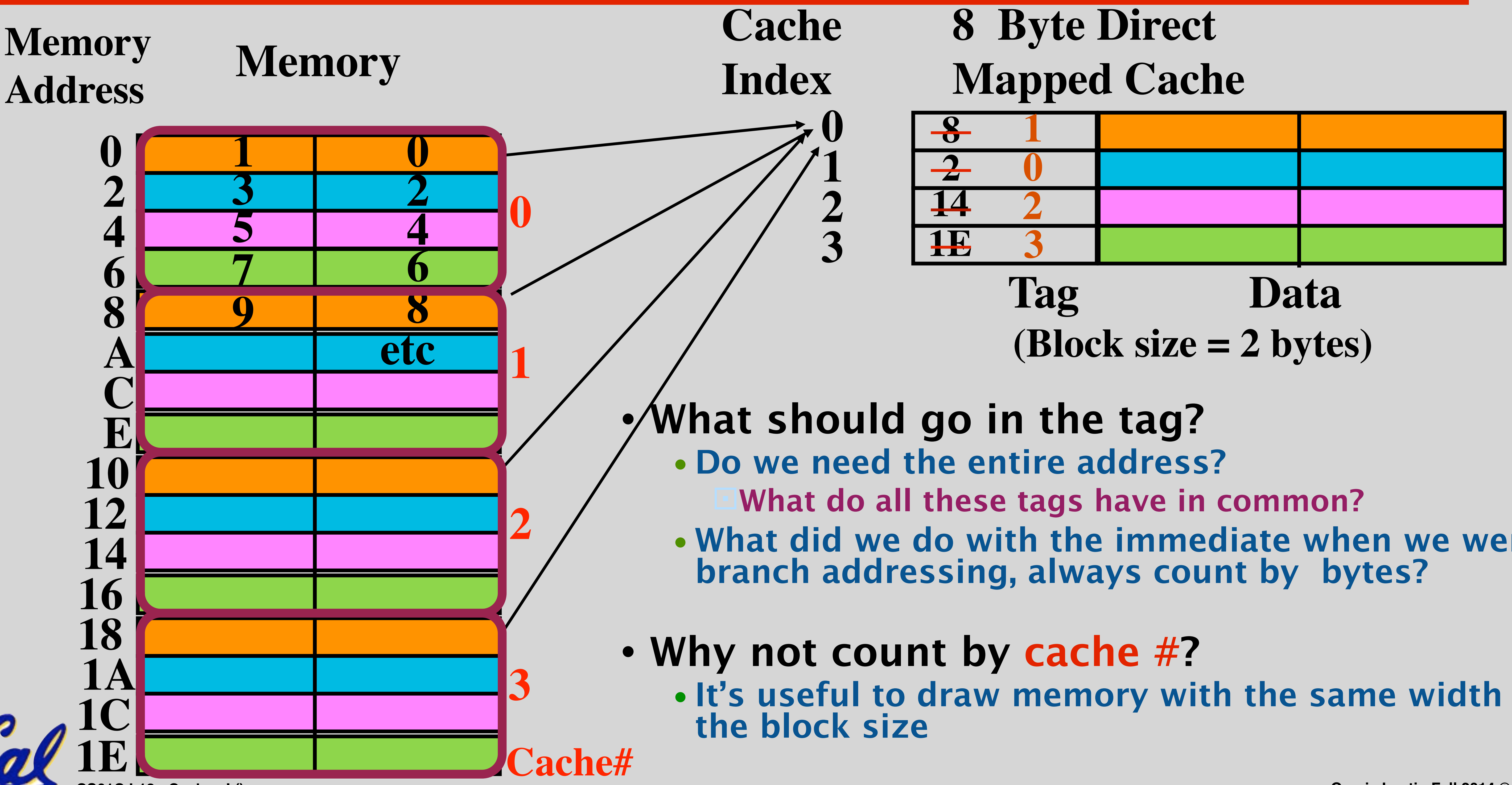
What if we wanted a block to be bigger than one byte?

Direct-Mapped Cache (3/4)



- When we ask for a byte, the system finds out the right block, and loads it all!
  - How does it know right block?
  - How do we select the byte?
- E.g., Mem address 11101?
- How does it know WHICH colored block it originated from?
  - What do you do at baggage claim?

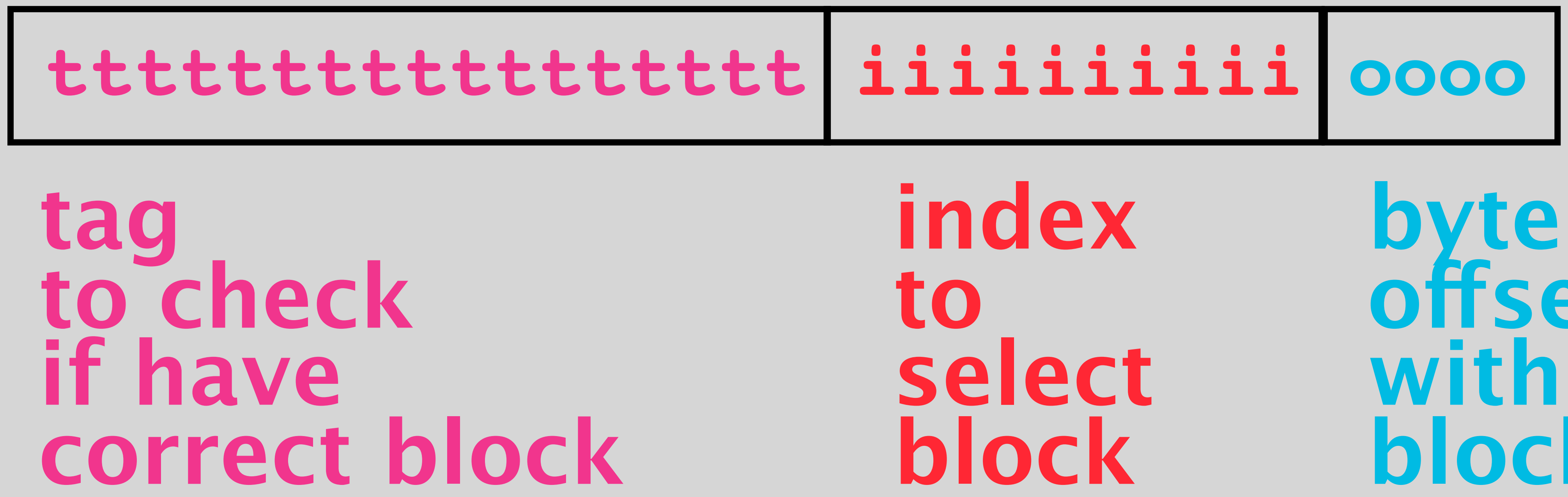
Direct-Mapped Cache (4/4)



- What should go in the tag?
  - Do we need the entire address?
    - What do all these tags have in common?
  - What did we do with the immediate when we were branch addressing, always count by bytes?
- Why not count by cache #?
  - It's useful to draw memory with the same width as the block size

Issues with Direct-Mapped

- Since multiple memory addresses map to same cache index, how do we tell which one is in there?
- What if we have a block size > 1 byte?
- Answer: divide memory address into three fields



Direct-Mapped Cache Terminology

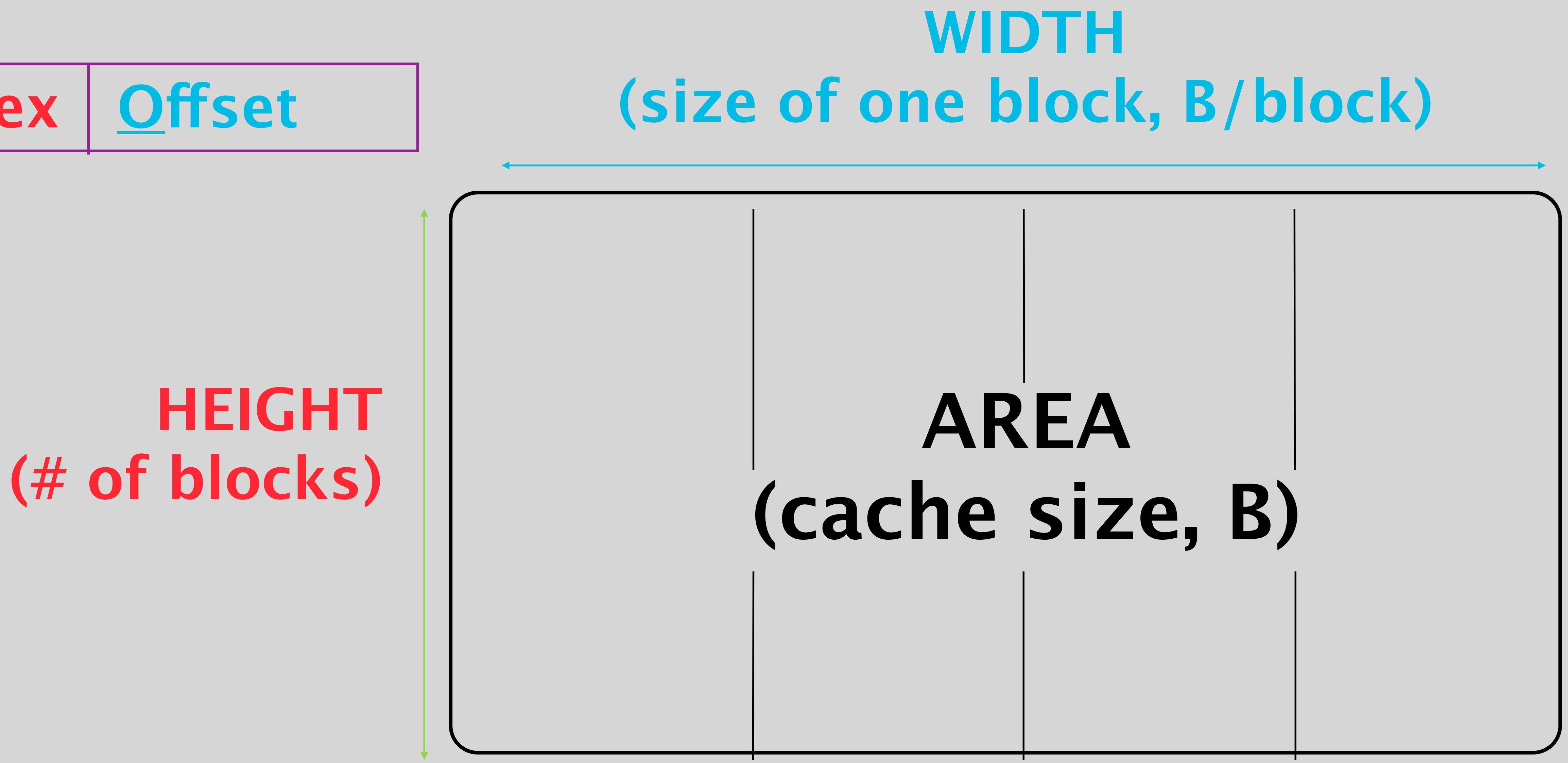
- All fields are read as <u>unsigned</u> integers.
- Index
  - specifies the cache index (which "row"/block of the cache we should look in)
- Offset
  - once we've found correct block, specifies which byte within the block we want
- Tag
  - the remaining bits after offset and index are determined; these are used to distinguish between all the memory addresses that map to the same

TIO Dan's great cache mnemonic

AREA (cache size, B)
= HEIGHT (# of blocks)
* WIDTH (size of one block, B/block)

$$\boxed{2^{(H+W)} = 2^H * 2^W}$$

Tag	Index	Offset



Direct-Mapped Cache Example (1/3)

- Suppose we have a 8B of data in a direct-mapped cache with 2 byte blocks
  - Sound familiar?
- Determine the size of the tag, index and offset fields if we're using a 32-bit architecture
- Offset
  - need to specify correct byte within a block
  - block contains 2 bytes

    = 2^1 bytes
  - need 1 bit to specify correct byte

Direct-Mapped Cache Example (2/3)

- Index: (~index into an "array of blocks")
  - need to specify correct block in cache
  - cache contains 8 B = 2^3 bytes
  - block contains 2 B = 2^1 bytes
  - # blocks/cache

$$= \frac{\text{bytes/cache}}{\text{bytes/block}}$$

$$= \frac{2^3 \text{ bytes/cache}}{2^1 \text{ bytes/block}}$$

$$= 2^2 \text{ blocks/cache}$$

  - need 2 bits to specify this many blocks

Direct-Mapped Cache Example (3/3)

- Tag: use remaining bits as tag
  - tag length = addr length – offset – index
    = 32 – 1 – 2 bits
    = 29 bits
  - so tag is leftmost 29 bits of memory address
  - Tag can be thought of as "cache number"
- Why not full 32 bit address as tag?
  - All bytes within block need same address (4b)
  - Index must be same for every address within a block, so it's redundant in tag check, thus can leave off to save memory (here 10 bits)

Peer Instruction

A. For a given cache size: a larger block size can cause a lower hit rate than a smaller one.

B. If you know your computer's cache size, you can often make your code run faster.

C. Memory hierarchies take advantage of spatial locality by keeping the most recent data items closer to the processor.

	ABC
1:	FFF
1:	FFT
2:	FTF
2:	FTT
3:	TFF
3:	TFT
4:	TTF
5:	TTT

And in Conclusion…

- We would like to have the capacity of disk at the speed of the processor: unfortunately this is not feasible.
- So we create a memory hierarchy:
  - each successively lower level contains “most used” data from next higher level
  - exploits temporal & spatial locality
  - do the common case fast, worry less about the exceptions (design principle of MIPS)
- Locality of reference is a Big Idea