CS 110
Computer Architecture
Lecture 16:
Caches Part I

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https://toast-lab.sist.shanghaitech.edu.cn/courses/CS110@ShanghaiTech/Spring-2023/index.html
School of Information Science and Technology SIST

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Slides based on UC Berkeley's CS61C

About Me

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  - OH: 9am – 11am, every Friday except holidays
  - Also instructor for CA II (CS211)
    - Advanced Computer Architecture, in Fall semester
    - As interesting as CA I, in my opinion
    - Why not try?

Cache Agenda

- Cache Lecture I
  - Caches Introduction
  - Principle of Locality
  - Simple Cache
  - Direct Mapped & Set-Associative Caches
- Cache Lecture II
  - Stores to Caches
  - Cache Performance
  - Cache Misses
- Cache Lecture III
  - Multi-Level Caches
  - Cache Configurations
  - Cache Examples
- …
- Lecture: Cache Coherence (Caches for multi-core computers)
- Lecture: Advanced Caches

New-School Machine Structures (It’s a bit more complicated!)

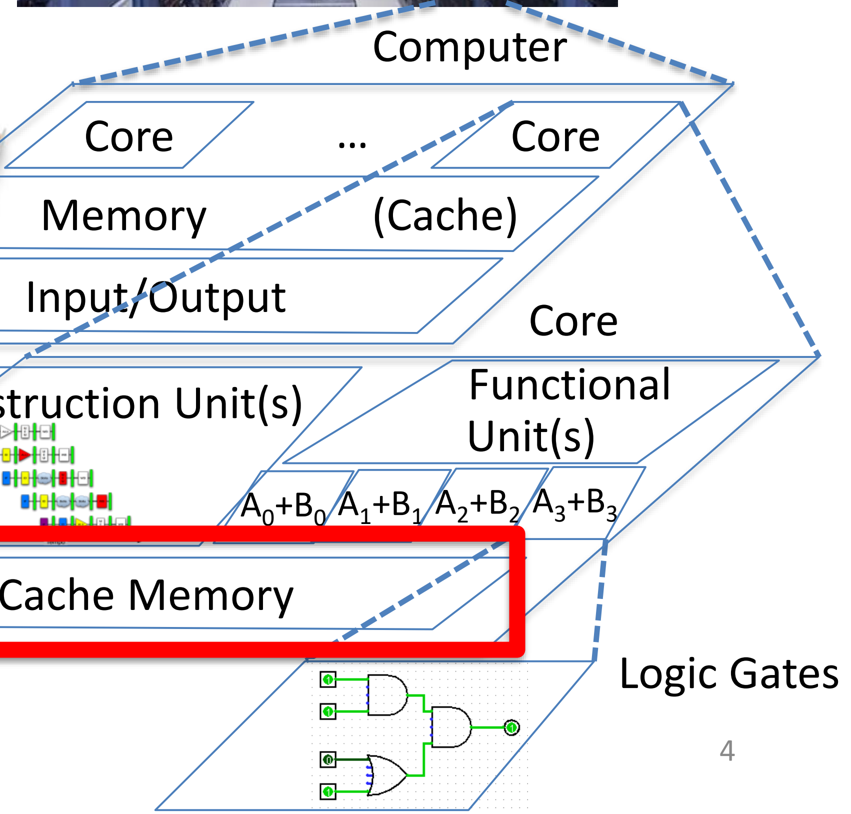
Software | *Hardware*

- Parallel Requests
  Assigned to computer
  e.g., Search “Katz”
- Parallel Threads
  Assigned to core
  e.g., Lookup, Ads
- Parallel Instructions
  >1 instruction @ one time
  e.g., 5 pipelined instructions
- Parallel Data
  >1 data item @ one time
  e.g., Add of 4 pairs of words
- Hardware descriptions
  All gates @ one time
- Programming Languages

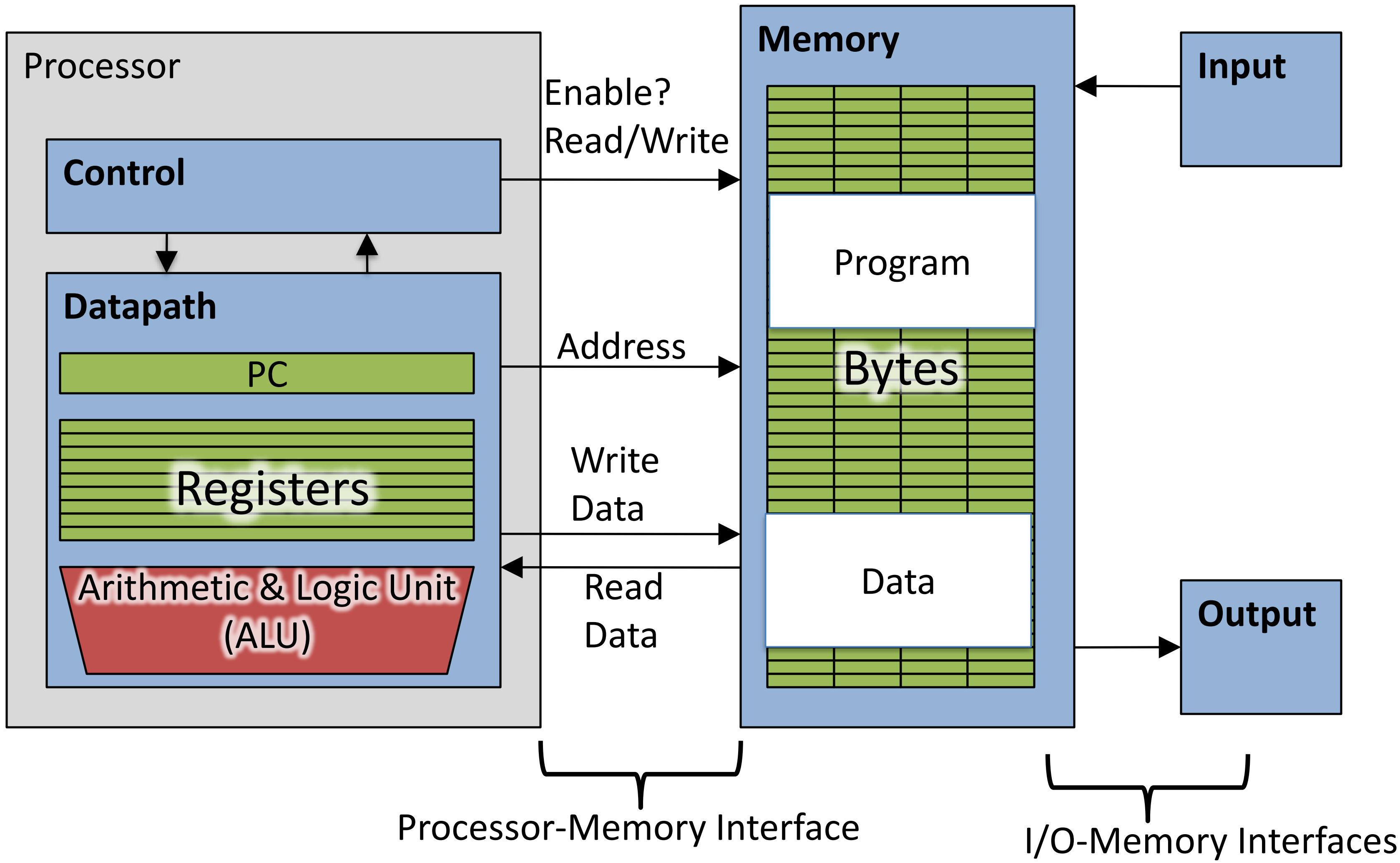
Harness Parallelism & Achieve High Performance

Warehouse Scale Computer

Smart Phone



Components of a Computer

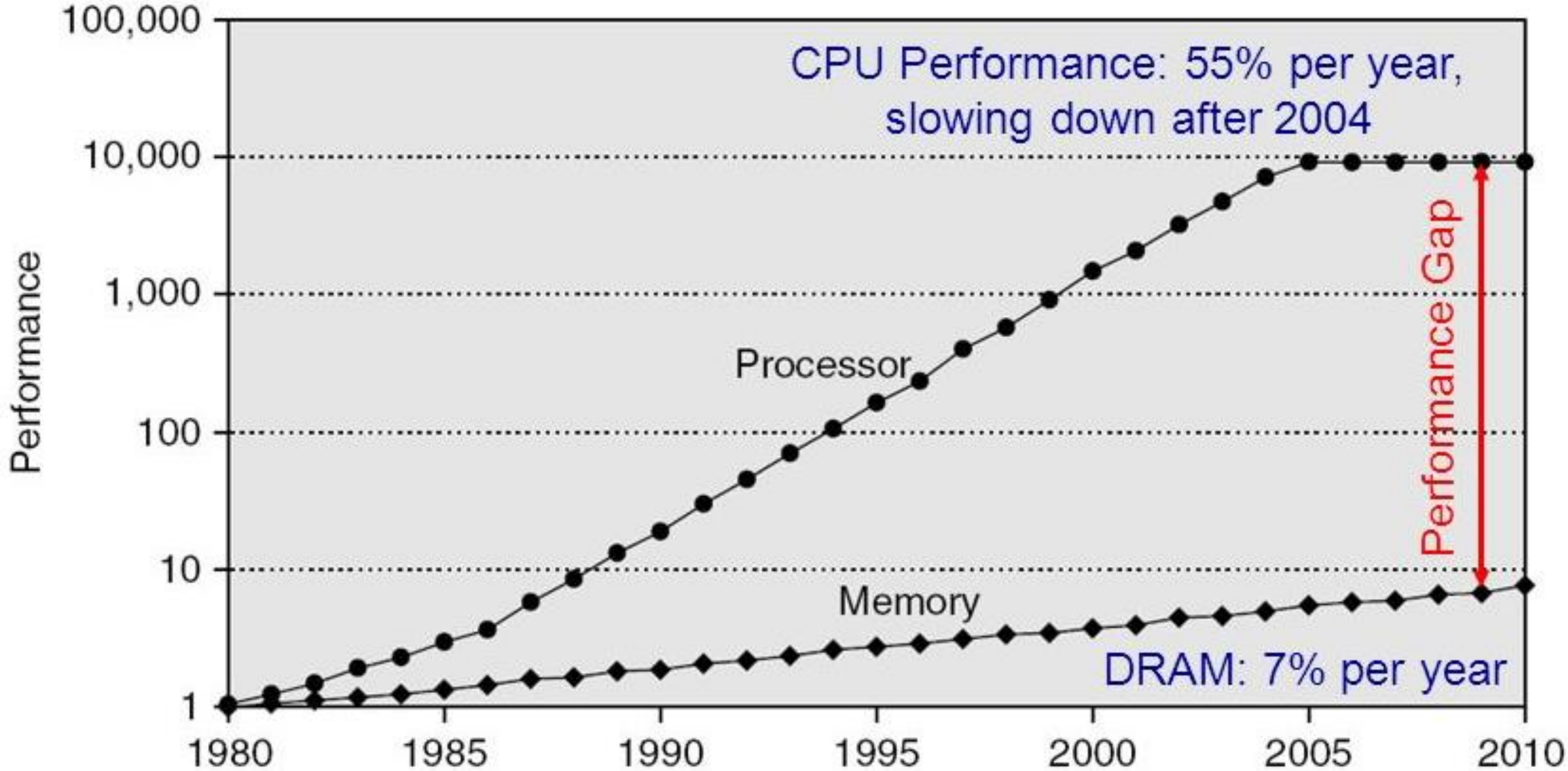


Problem: Large memories slow? Library Analogy

- Finding a book in a large library takes time
  - Takes time to search a large card catalog – (mapping title/author to index number)
  - Round-trip time to walk to the stacks and retrieve the desired book.
- Larger libraries makes both delays worse
- Electronic memories have the same issue, *plus* the technologies that we use to store an individual bit get slower as we increase density (SRAM versus DRAM versus Magnetic Disk)

However what we want is a large yet fast memory!

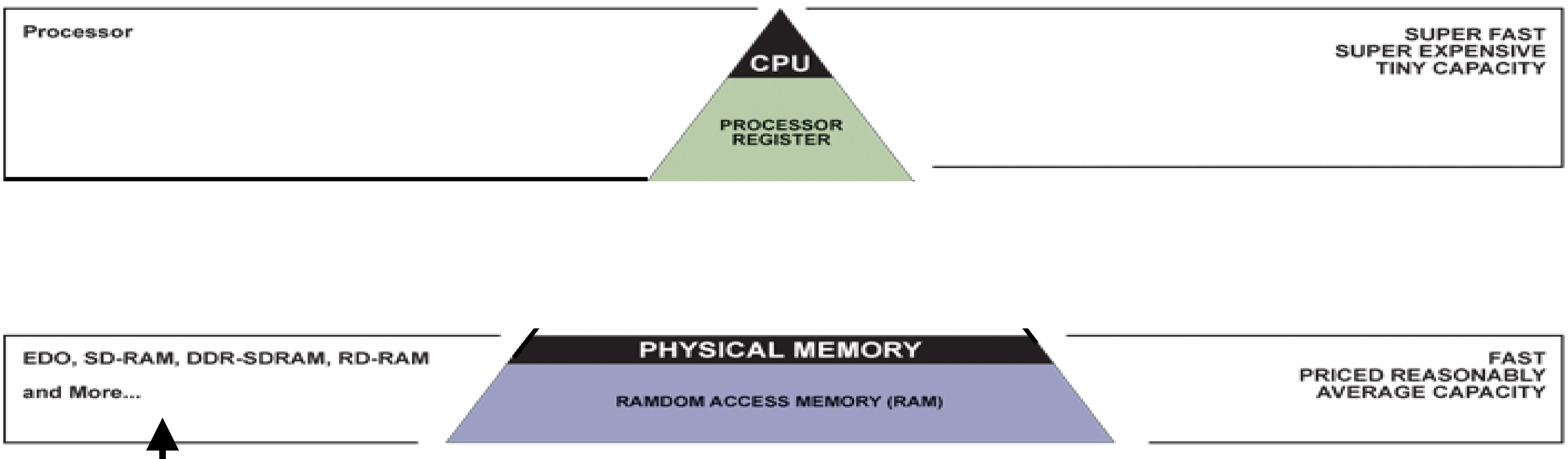
Processor-DRAM Gap (Latency)



1980 microprocessor executes **~one instruction** in same time as DRAM access
2017 microprocessor executes **~1000 instructions** in same time as DRAM access

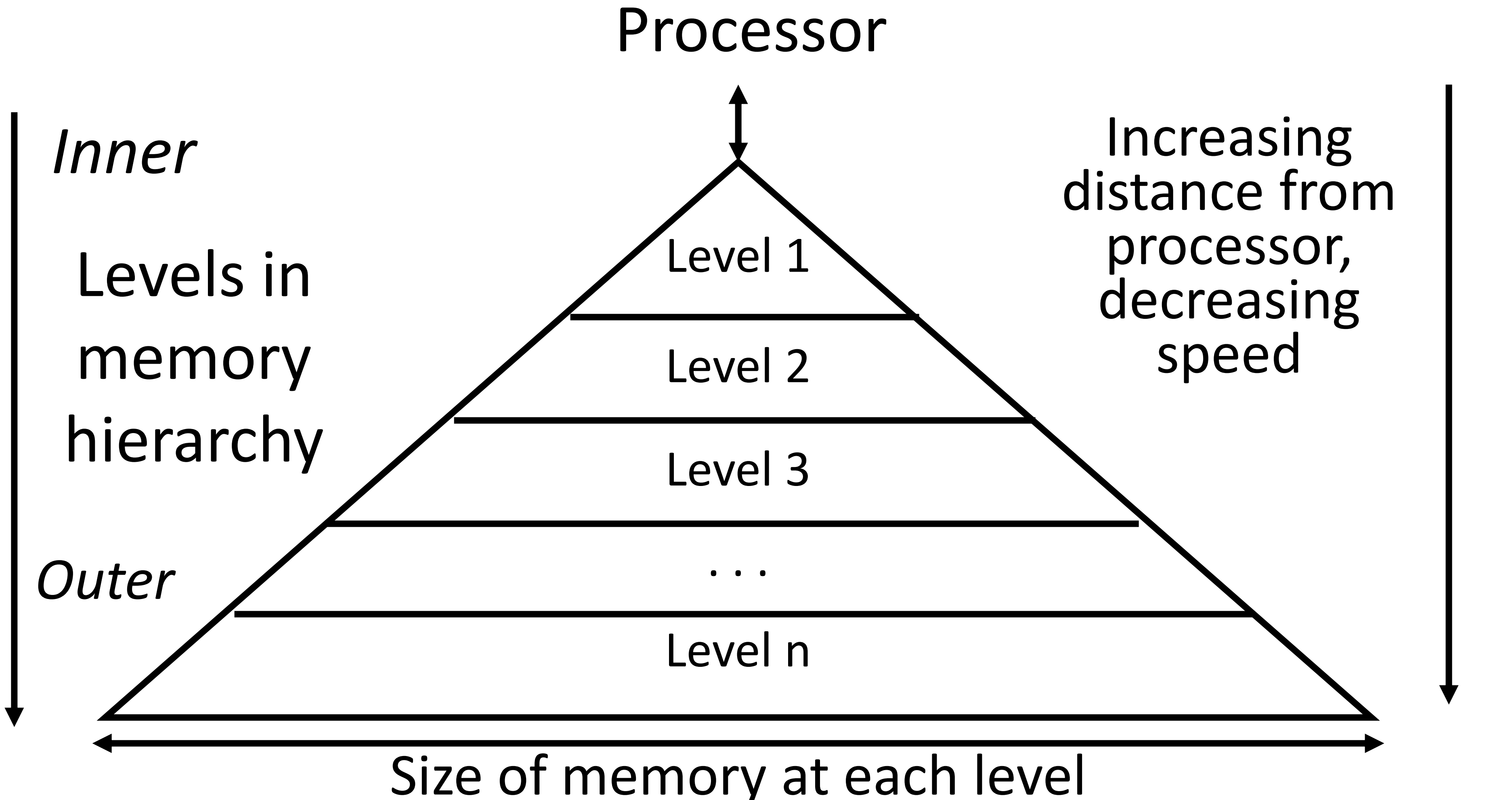
Slow DRAM access has disastrous impact on CPU performance!

Great Idea #3: Principle of Locality / Memory Hierarchy



Note: These names are a bit dated

Big Idea: Memory Hierarchy

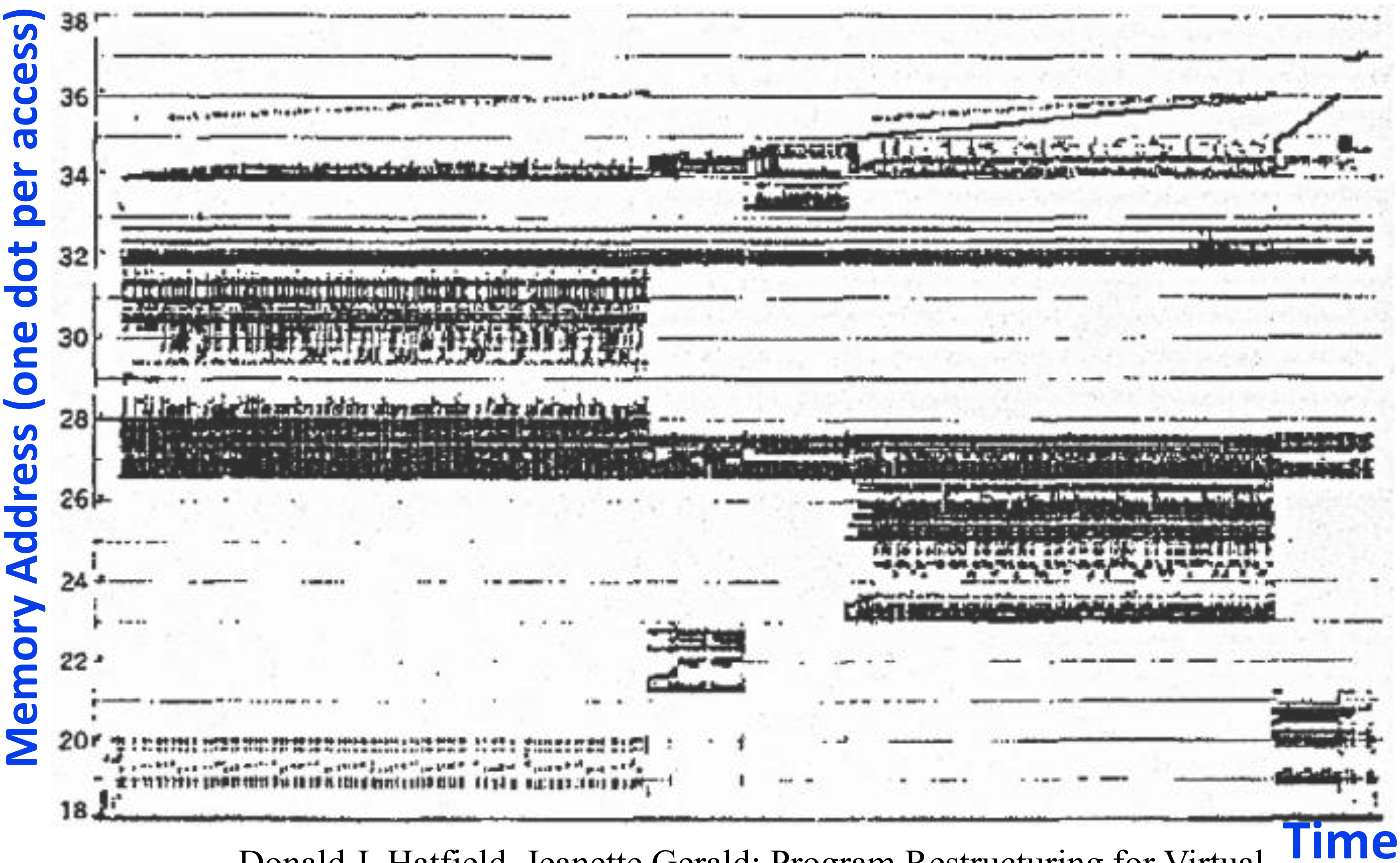


As we move to outer levels the latency goes up and price per bit goes down.

What to do: Library Analogy

- Want to write a report using library books
- Go to library, look up relevant books, fetch from stacks, and place on desk in library
- If need more, check them out and keep on desk
  – But don't return earlier books since might need them
- You hope this collection of ~10 books on desk enough to write report, despite 10 being only a tiny fraction of books available

Real Memory Reference Patterns



Donald J. Hatfield, Jeanette Gerald: Program Restructuring for Virtual Memory. IBM Systems Journal 10(3): 168-192 (1971)

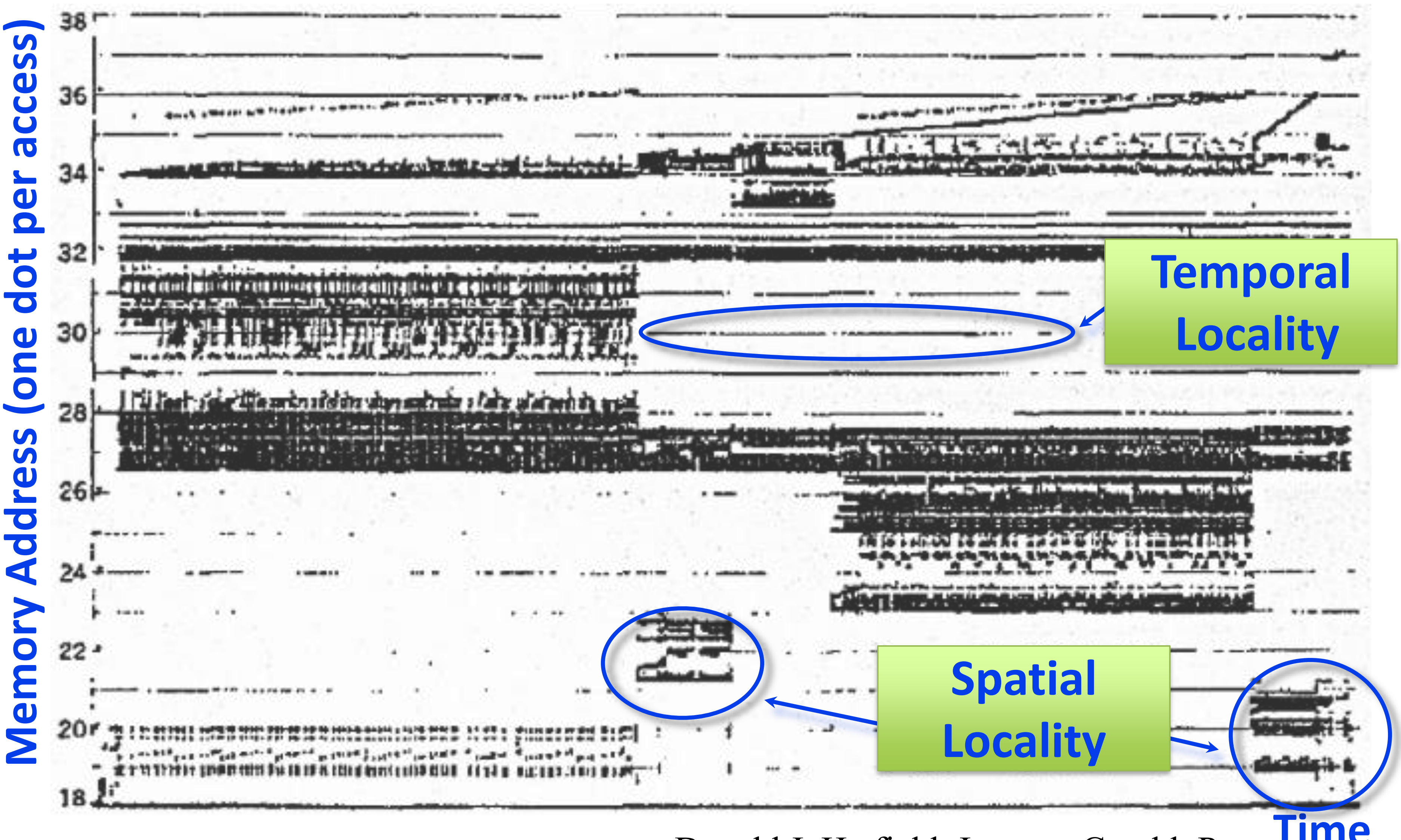
Big Idea: Locality

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

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

```
// Sample code for CS110@Spring 2023 -- Chundong
for (i = 0, sum = 0; i < n; sum += a[i], ++i);
```

Memory Reference Patterns



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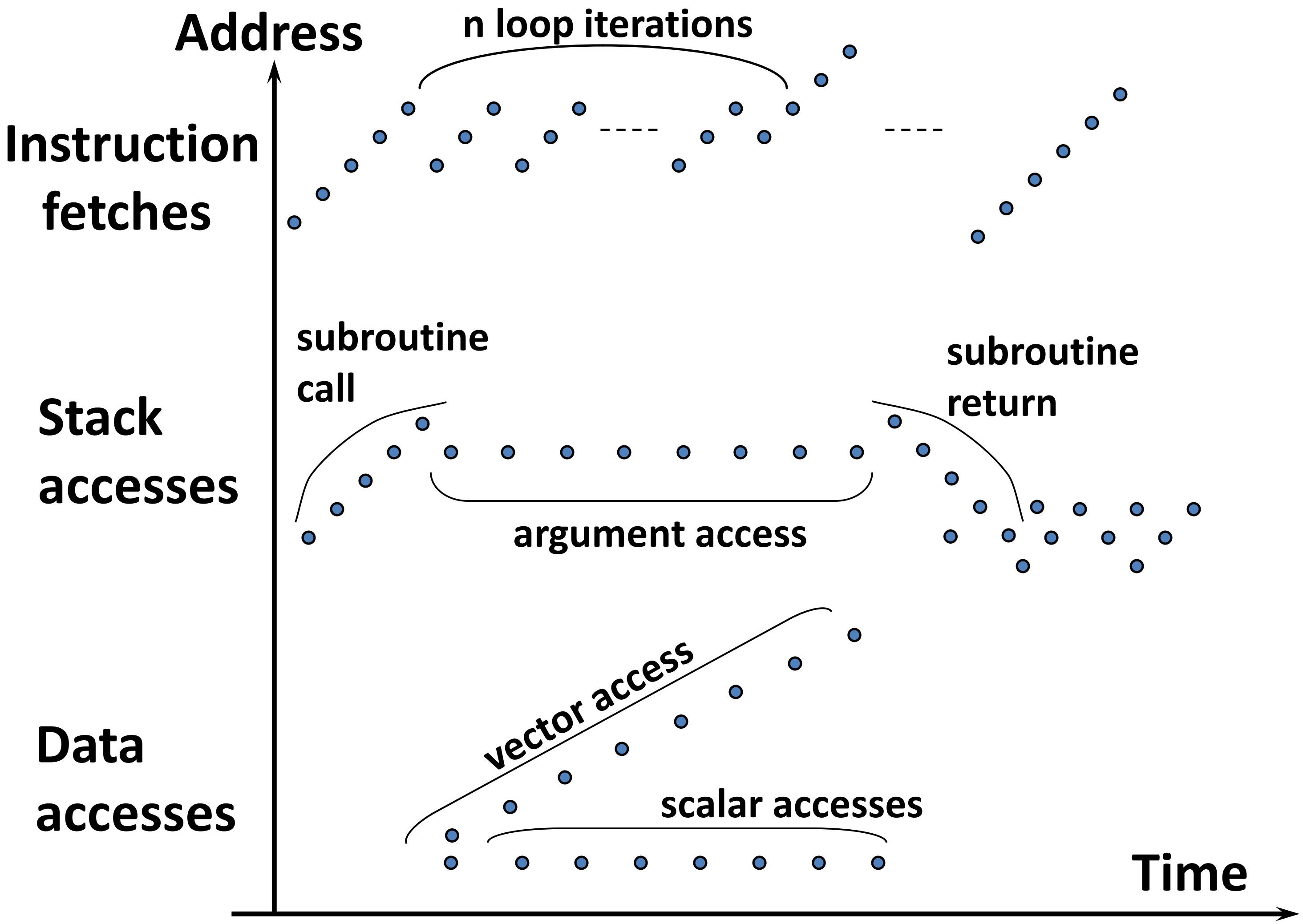
Principle of Locality

- *Principle of Locality*: Programs access small portion of address space at any instant of time (spatial locality) and repeatedly access that portion (temporal locality)
- What program structures lead to temporal and spatial locality in **instruction** accesses?
- In **data** accesses?

Memory Reference Patterns



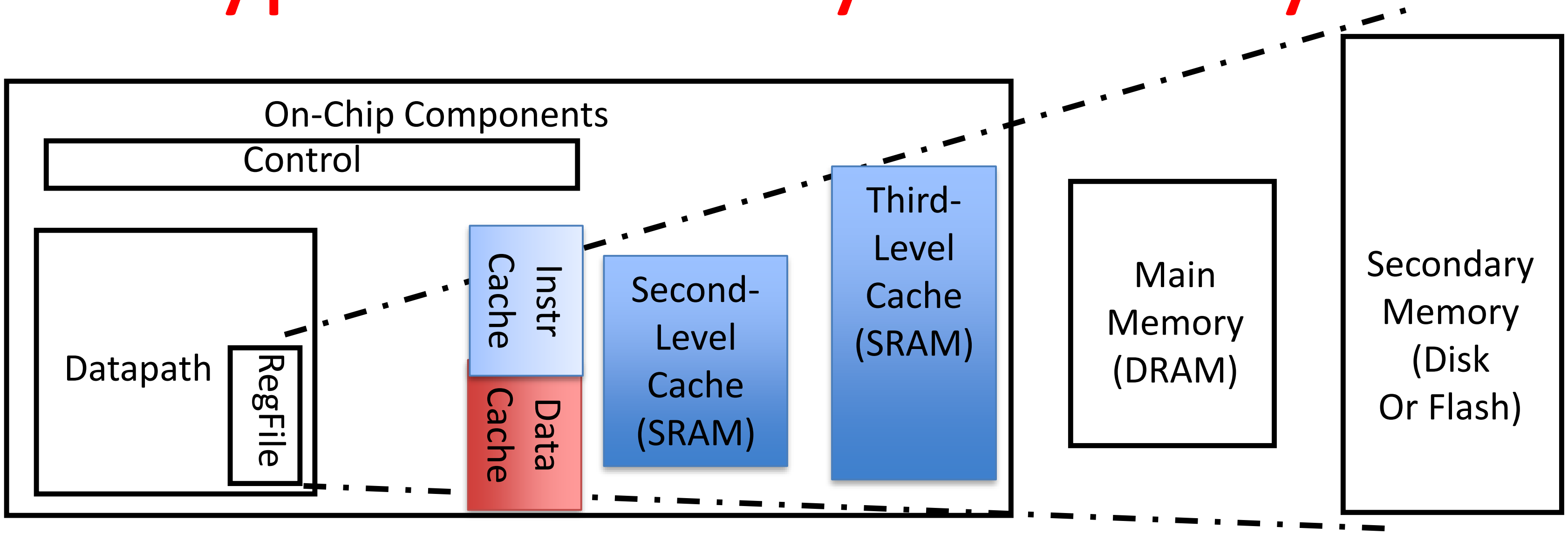
And the Bane of Locality: Pointer Chasing...

- We all love linked lists, trees, etc...
  - Easy to append onto and manipulate...
- But they have ***horrid*** locality preferences
  - Every time you follow a pointer it is to an unrelated location: No spacial reuse from previous pointers
  - And if you don't chase the pointers again you don't get temporal reuse either
- Why modern languages tend to do things a bit differently. For example, ***go*** has "slices" and "maps":
  - Slice, easy to append to array
    - Only copies on append when you overwhelm the size
  - Map, a hash table implementation
    - But without nearly so much pointer chasing

Cache Philosophy

- Programmer-invisible hardware mechanism to give illusion of speed of fastest memory with size of largest memory
  - Works fine even if programmer has no idea what a cache is
  - However, performance-oriented programmers today sometimes “reverse engineer” cache design to design data structures to match cache
  - And modern programming languages try to provide storage abstractions that provide flexibility while still caching well
- Does have limits: When you overwhelm the cache your performance may drop off a cliff...

Typical Memory Hierarchy



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

- Principle of locality + memory hierarchy presents programmer with ≈ as much memory as is available in the *cheapest* technology at the ≈ speed offered by the *fastest* technology

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 (‘translation lookaside buffer’ or TLB)
  - By the programmer (files)

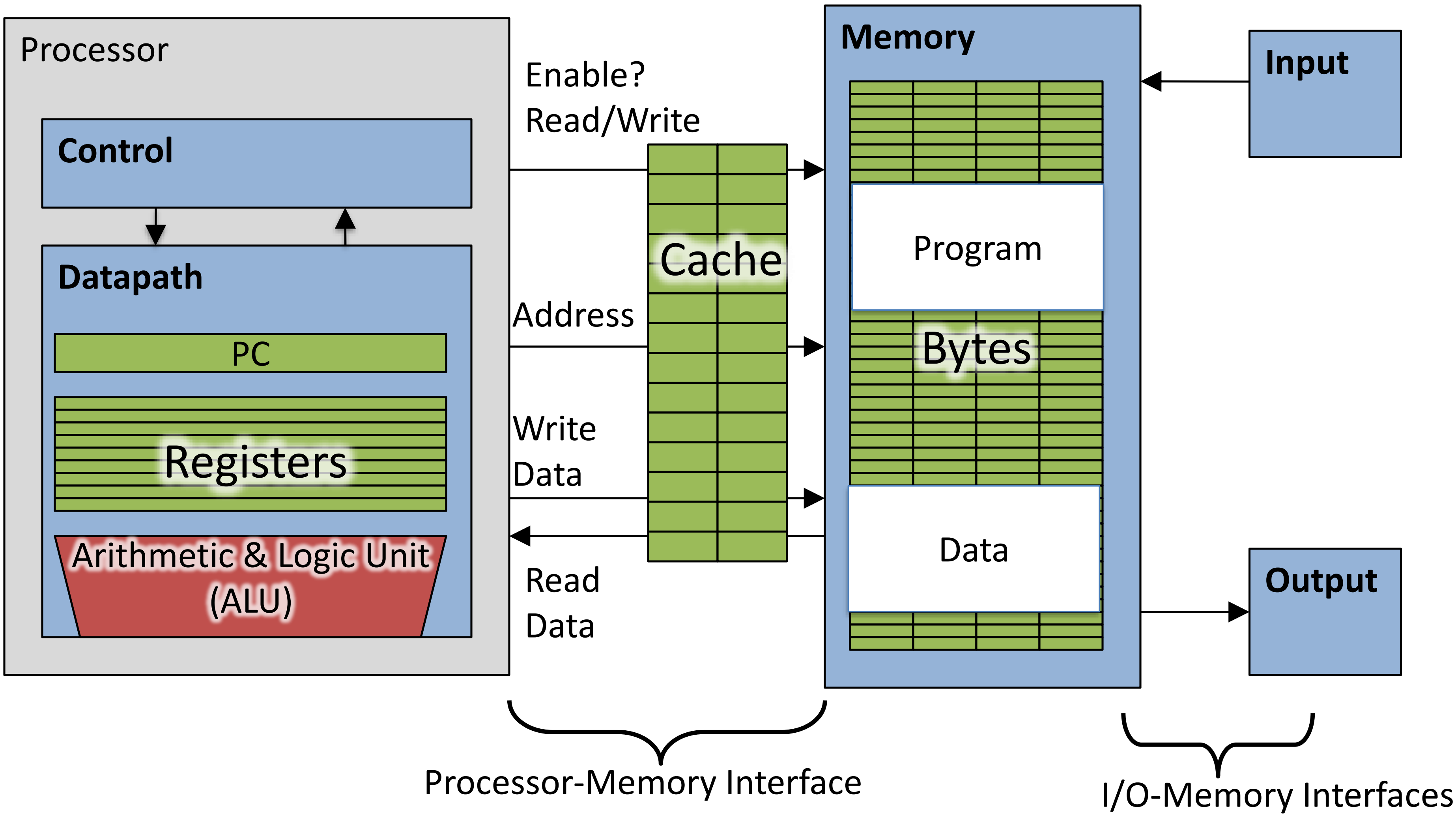
Also a type of cache

Memory Access without Cache

- Load word instruction: `lw t0,0(t1)`
- t1 contains $1022_{ten,}$ Memory[1022] = 99

1. Processor issues address 1022_{ten} to Memory
2. Memory reads word at address 1022_{ten} (99)
3. Memory sends 99 to Processor
4. Processor loads 99 into register t0

Adding Cache to Computer



Memory Access with Cache

- Load word instruction: `lw t0,0(t1)`
- t1 contains $1022_{ten,}$ Memory[1022] = 99
- With cache: Processor issues address 1022_{ten} to Cache
  1. Cache checks to see if has copy of data at address 1022_{ten}

     2a. If finds a match (Hit): cache reads 99, sends to processor

     2b. No match (Miss): cache sends address 1022 to Memory

     I. Memory reads 99 at address 1022_{ten}

     II. Memory sends 99 to Cache

     III. Cache replaces some word with new 99

     IV. Cache sends 99 to processor
  2. Processor loads 99 into register t0

Cache "Tags"

- Need way to tell if have copy of location in memory so that can decide on hit or miss
- On cache miss, put memory address of block in "tag address" of cache block

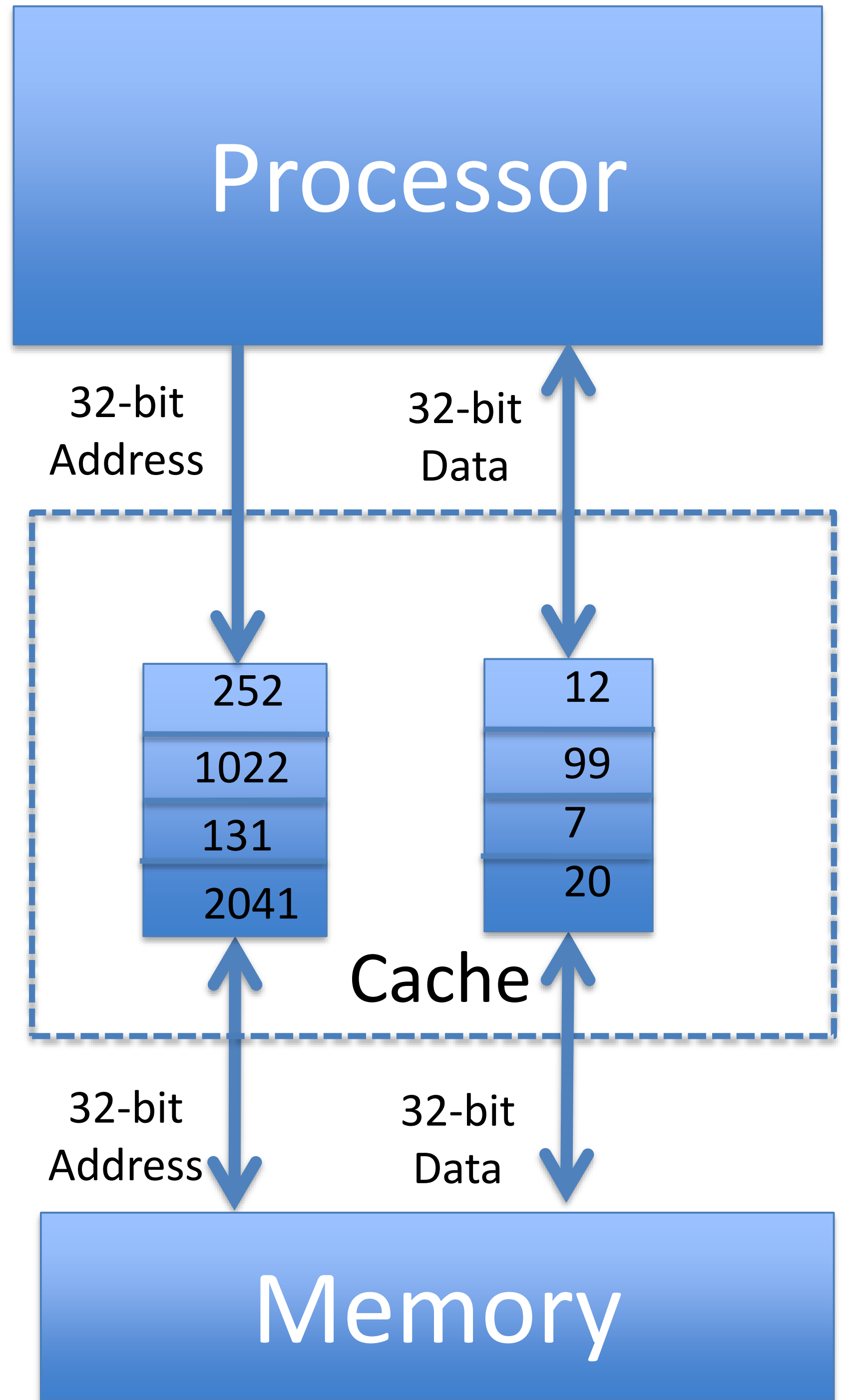
1022 placed in tag next to data from memory (99)

Tag (= Address in this simple example)	Data
252	12
1022	99
131	7
2041	20

From earlier instructions

Anatomy of a 16 Byte Cache, 4 Byte Block

- Operations:
  1. Cache Hit
  2. Cache Miss
  3. Refill cache from memory
- Cache needs Address Tags to decide if Processor Address is a Cache Hit or Cache Miss
  – Compares all 4 tags



Cache Replacement

- Suppose processor now requests location 511, which contains 11?
- Doesn't match any cache block, so must "evict" one resident block to make room
  - Which block to evict?
- Replace "victim" with new memory block at address 511

Tag	Data
252	12
1022	99
511	11
2041	20

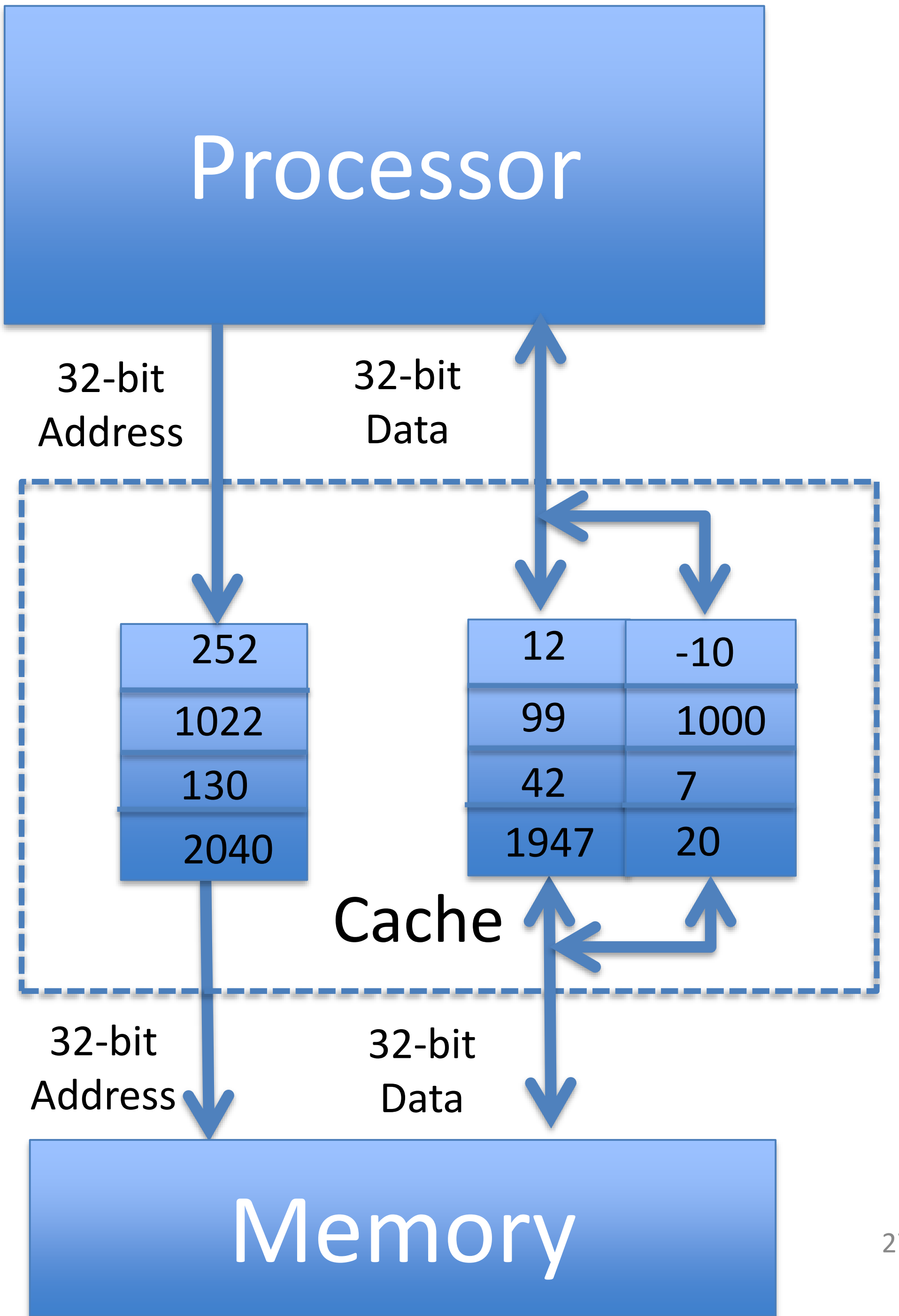
Block Must be Aligned in Memory

- Word blocks are aligned, so binary address of all words in cache always ends in 00_{two}
- How to take advantage of this to save hardware and energy?
- Don't need to compare last 2 bits of 32-bit byte address (comparator can be narrower)

=> Don't need to store last 2 bits of 32-bit byte address in Cache Tag (Tag can be narrower)

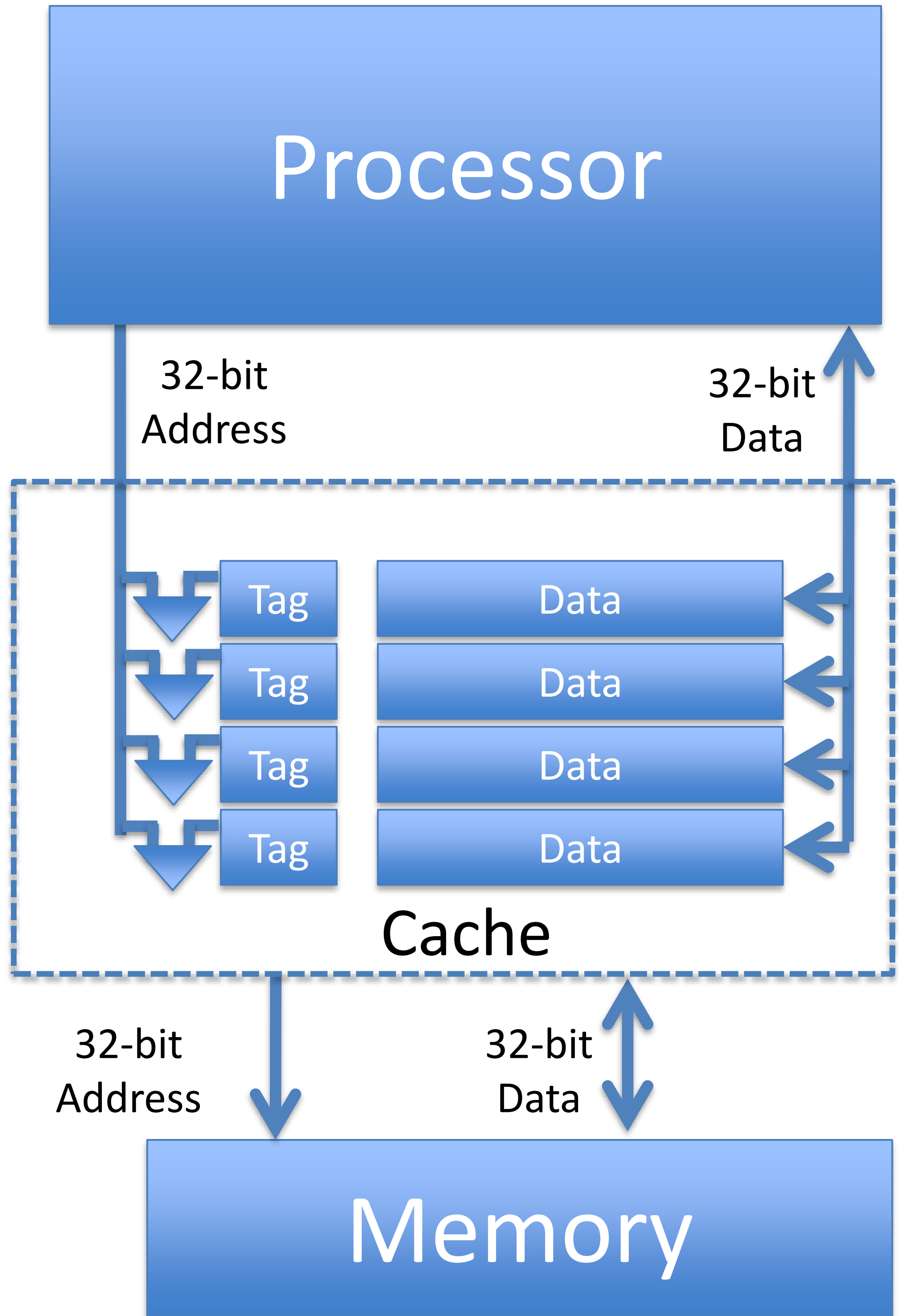
Anatomy of a 32B Cache, 8B Block

- Blocks must be aligned in pairs, otherwise could get same word twice in cache
  - ➢ Tags only have even-numbered words
  - ➢ Last 3 bits of address always 000_{two}
  - ➢ Tags, comparators can be narrower
- Can get hit for either word in block



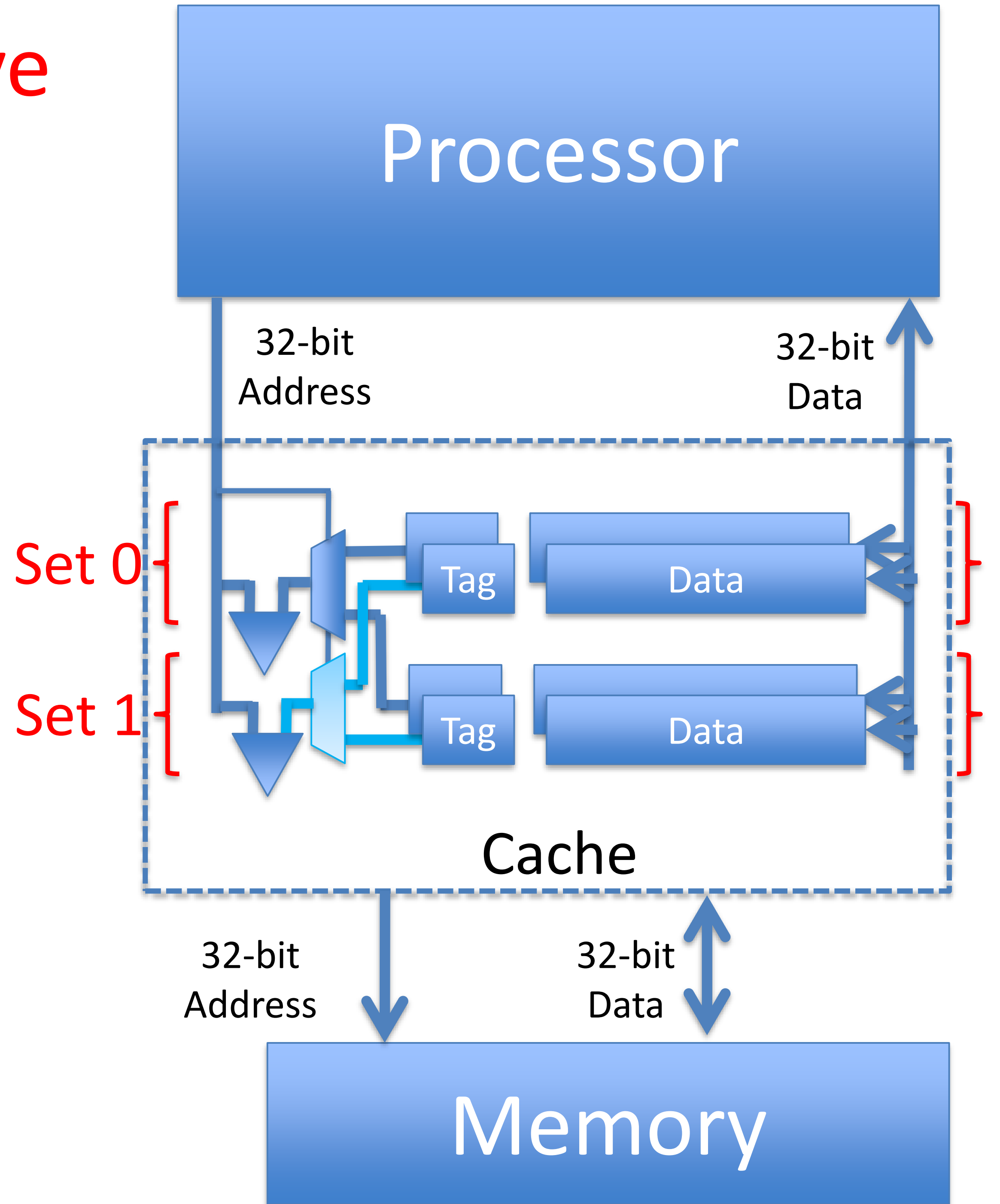
Hardware Cost of Cache

- Need to compare every tag to the Processor address
- Comparators are expensive



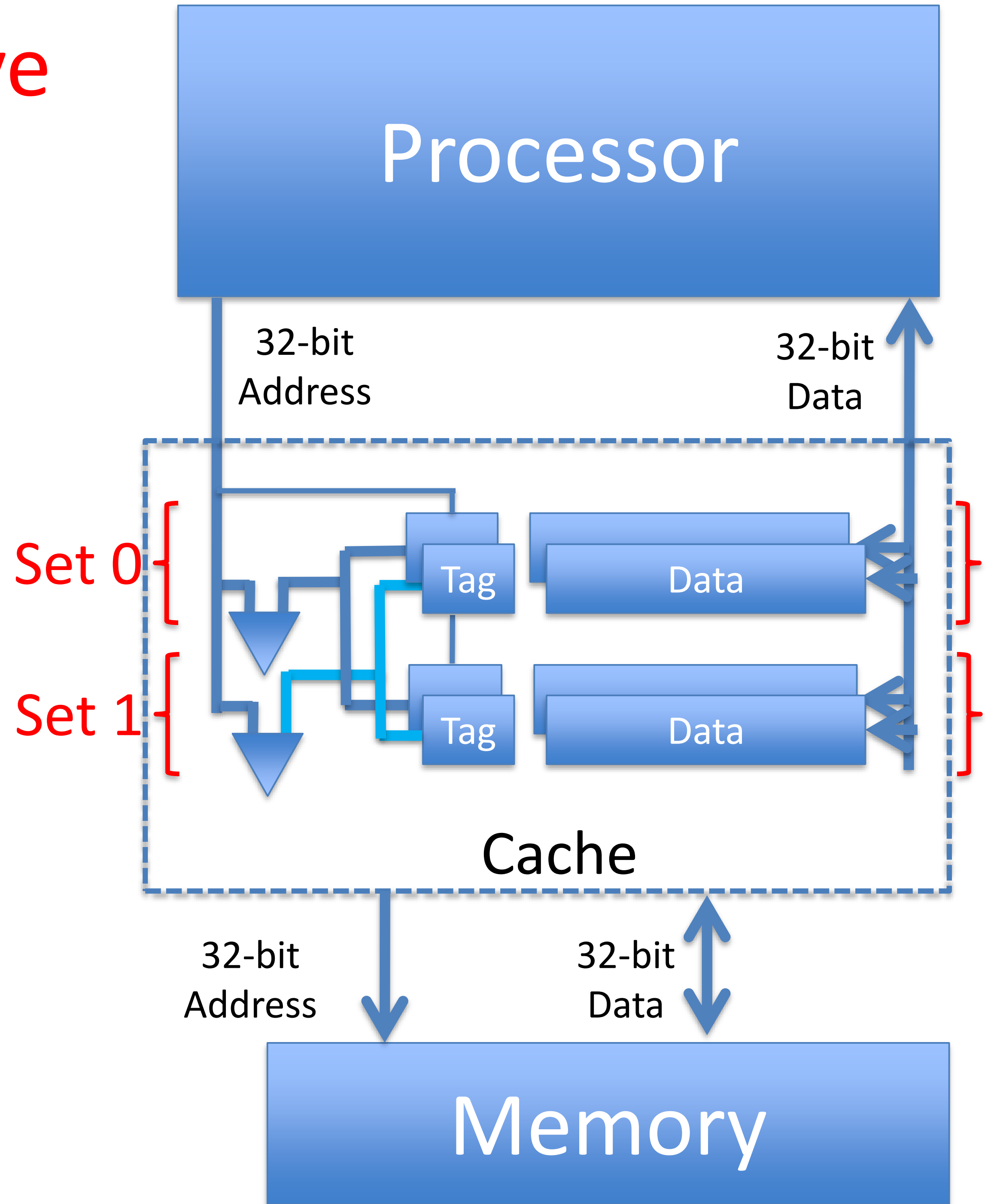
Set Associative Cache

- Optimization: use 2 "sets" => ½ comparators
- 1 Address bit selects which set
- Compare only tags from selected set
- Generalize to more sets:
  - Need as many comparators as tags in a set



Set Associative Cache

- Optimization: use 2 “sets” => ½ comparators
- 1 Address bit selects which set
- Compare only tags from selected set
- Generalize to more sets:
  - Need as many comparators as tags in a set
  - Don’t need extra mux per comparators – tags and data are memory – have mux inside!



Processor Address Fields used by Cache Controller

- Block Offset: Byte address within block
- Set Index: Selects which set
- Tag: Remaining portion of processor address

Processor Address (32-bits total)

Tag	Set Index	Block offset

- Size of Index = log2 (number of sets)
- Size of Tag = Address size – Size of Index – log2 (number of bytes/block)

What is limit to number of sets?

- For a given total number of blocks, we can save more comparators if have more than 2 sets
- Limit: As Many Sets as Cache Blocks => only one block per set – only needs one comparator!
- Called “Direct-Mapped” Design

Tag	Index	Block offset

Direct Mapped Cache Ex: Mapping a 6-bit Memory Address

5 4	3 2	1 0
Tag	*Index*	*Byte Offset*
Mem Block Within $ Block	Block Within $	Byte Within Block

- In example, block size is 4 bytes/1 word
- Memory and cache blocks always the same size, unit of transfer between memory and cache
- # Memory blocks >> # Cache blocks
  - 16 Memory blocks = 16 words = 64 bytes => 6 bits to address all bytes
  - 4 Cache blocks, 4 bytes (1 word) per block
  - 4 Memory blocks map to each cache block
- Memory block to cache block, aka *index*: middle two bits
- Which memory block is in a given cache block, aka *tag*: top two bits

One More Detail: Valid Bit

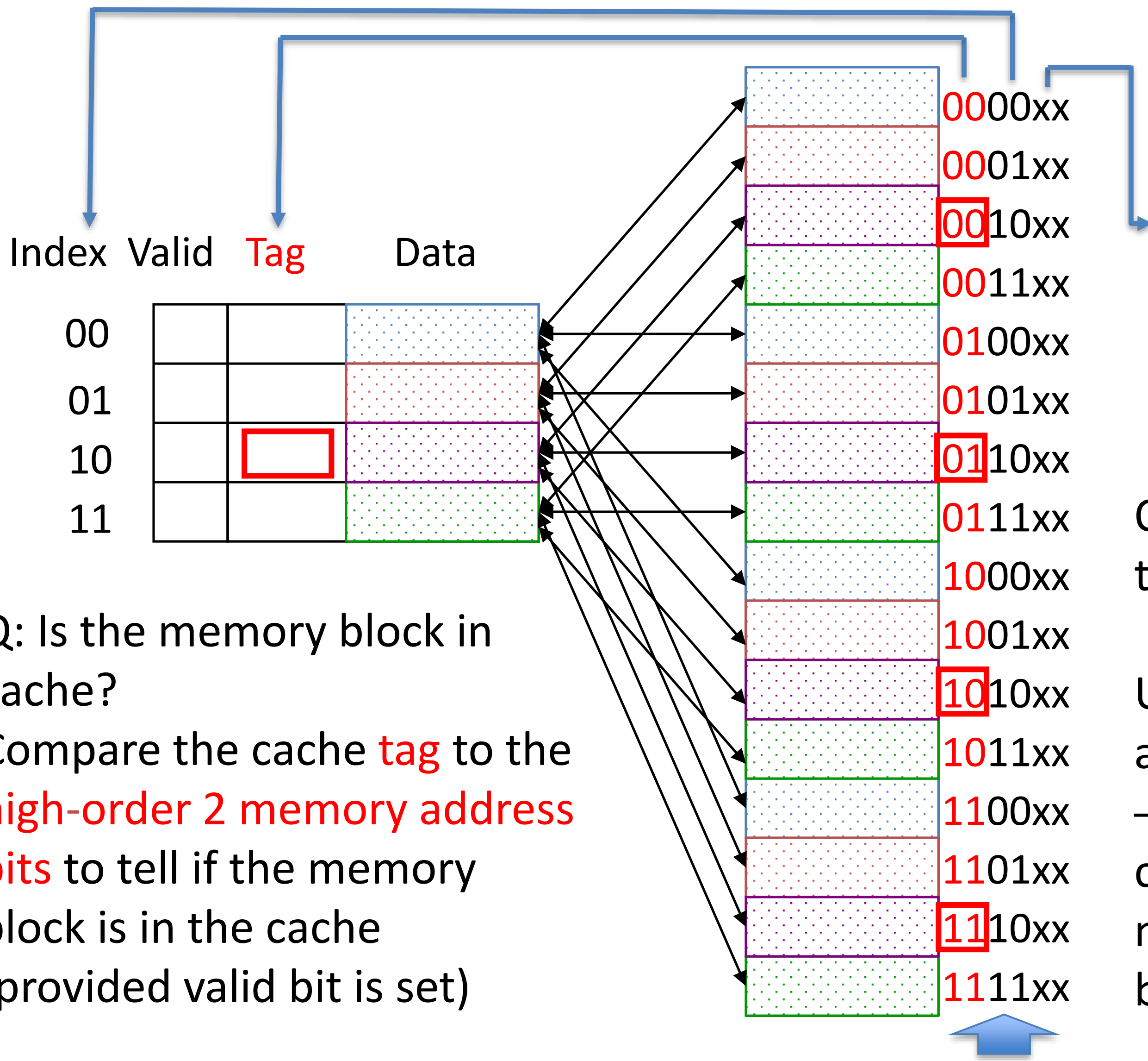
- When start a new program, cache does not have valid information for this program
- Need an indicator whether this tag entry is valid for this program
- Add a “valid bit” to the cache tag entry

  0 => cache miss, even if by chance, address = tag

  1 => cache hit, if processor address = tag

Caching: A Simple First Example

Cache **Main Memory**



6bit Memory Address

One word blocks
Two low order bits (xx) define the byte in the block (32b words)

Q: Where in the cache is the mem block?

Use 2 middle memory address bits – the index – to determine which cache block (i.e., modulo the number of blocks in the cache)

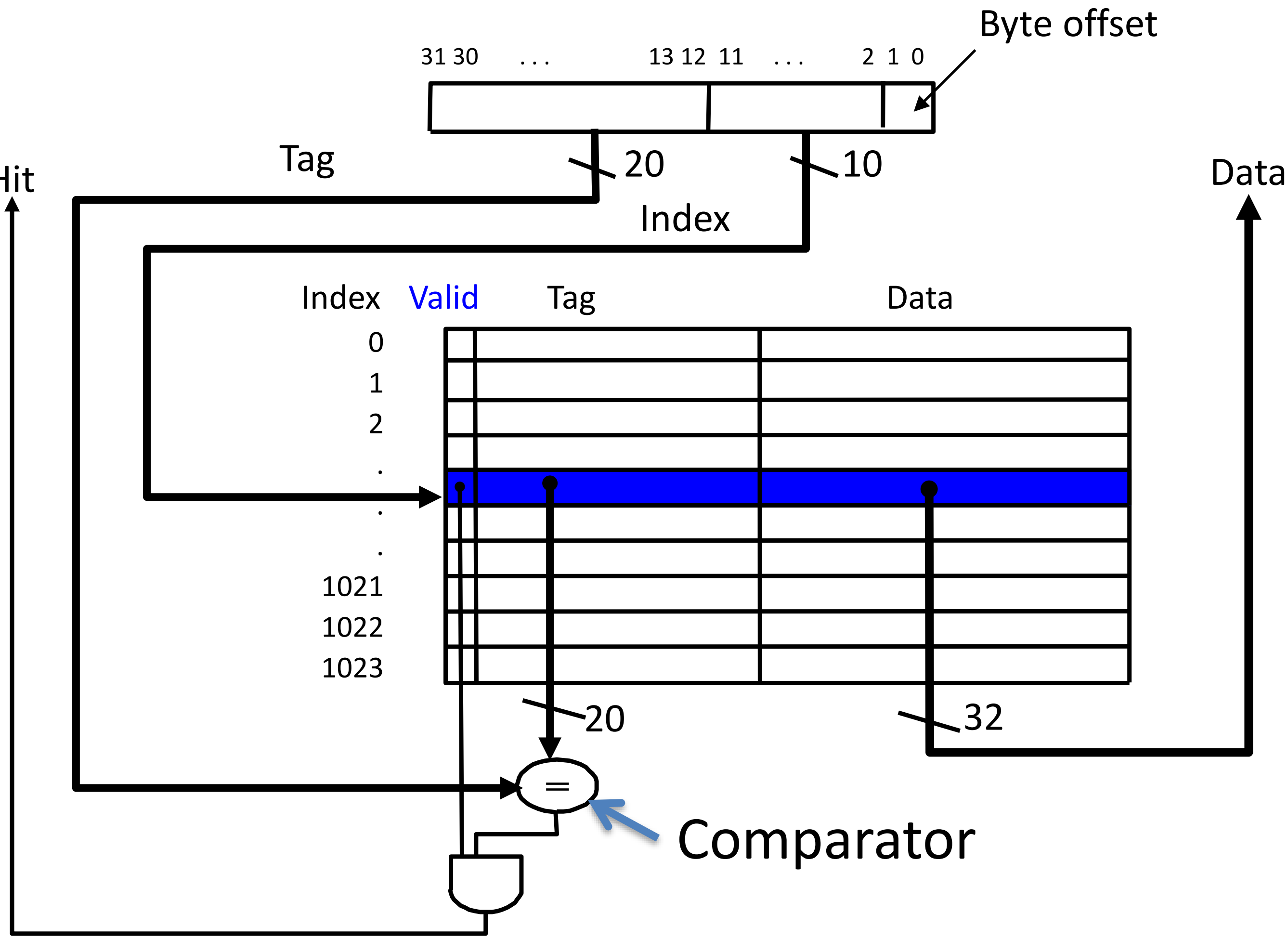
Q: Is the memory block in cache?
Compare the cache tag to the high-order 2 memory address bits to tell if the memory block is in the cache (provided valid bit is set)

Direct-Mapped Cache Example

- One word blocks, cache size = 1K words (or 4KB)

Valid bit ensures something useful in cache for this index

Compare Tag with upper part of Address to see if a Hit

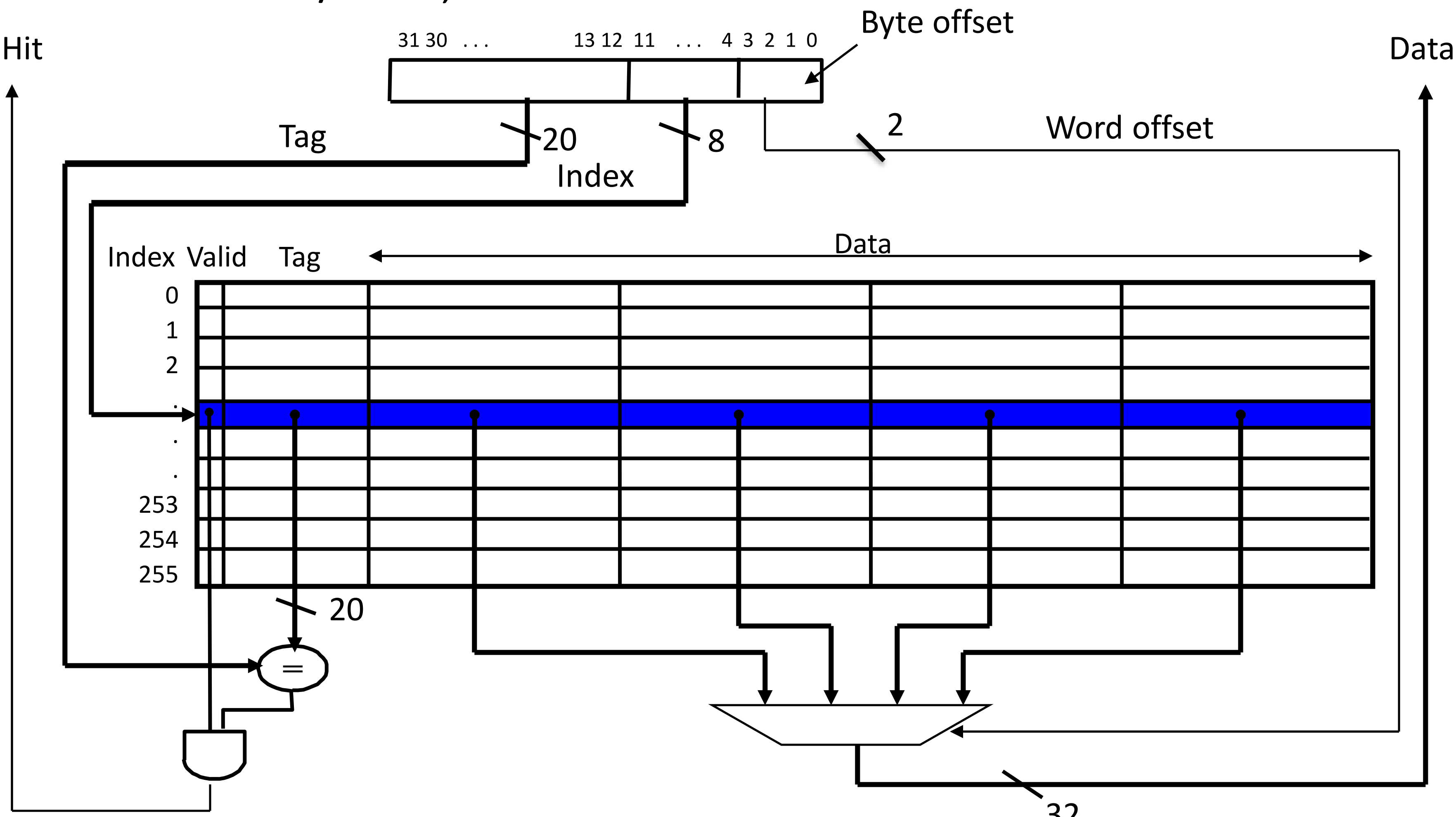


Read data from cache instead of memory if a Hit

What kind of locality are we taking advantage of?

Multiword-Block Direct-Mapped Cache

- Four words/block, cache size = 1K words



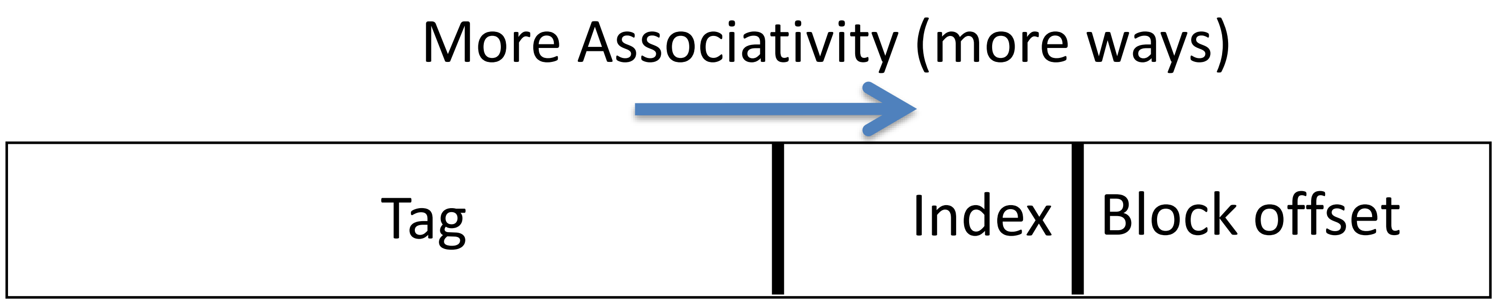
What kind of locality are we taking advantage of?

Cache Names for Each Organization

- "Fully Associative": Line can go anywhere
  - First design in lecture
  - Note: No Index field, but 1 comparator/ line
- "Direct Mapped": Line goes one place
  - Note: Only 1 comparator
  - Number of sets = number blocks
- "N-way Set Associative": N places for a line
  - Number of sets = number of lines/ N
  - N comparators
  - ***Fully Associative: N = number of lines***
  - ***Direct Mapped: N = 1***

Range of Set-Associative Caches

- For a fixed-size cache, and a given block size, each increase by a factor of 2 in associativity doubles the number of blocks per set (i.e., the number of "ways") and halves the number of sets –
  - decreases the size of the index by 1 bit and increases the size of the tag by 1 bit



Total Cache Capacity =

Associativity * # of sets * block_size

*Bytes = blocks/set * sets * Bytes/block*

$$C = N * S * B$$

Tag	*Index*	*Byte Offset*

address_size = tag_size + index_size + offset_size
= tag_size + log2(S) + log2(B)

And In Conclusion, …

- Principle of Locality for Libraries /Computer Memory
- Hierarchy of Memories (speed/size/cost per bit) to Exploit Locality
- Cache – copy of data lower level in memory hierarchy
- Direct Mapped to find block in cache using Tag field and Valid bit for Hit