`inst.eecs.berkeley.edu/~cs61c`

CS61C : Machine Structures

Lecture 32
Caches I

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Is this the beginning of the end for our beloved… Google?!

`http://beta.search.msn.com/`

Review : Pipelining

- Pipeline challenge is hazards
  - Forwarding helps w/many data hazards
  - Delayed branch helps with control hazard in our 5 stage pipeline
  - Data hazards w/Loads ⇒ Load Delay Slot
    - Interlock ⇒ “smart” CPU has HW to detect if conflict with inst following load, if so it stalls
- More aggressive performance:
  - Superscalar (parallelism)
  - Out-of-order execution

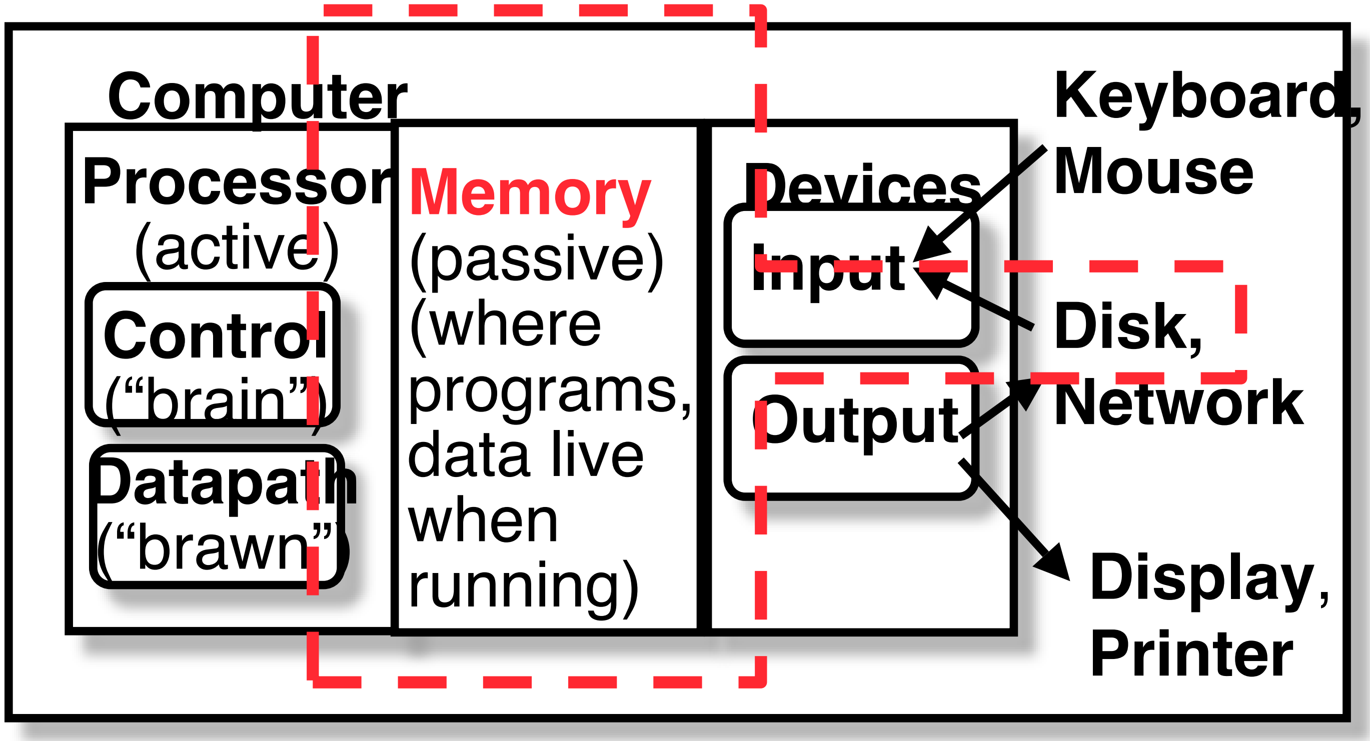
Big Ideas so far

- 15 weeks to learn big ideas in CS&E
  - Principle of abstraction, used to build systems as layers
  - Pliable Data: a program determines what it is
  - Stored program concept: instructions just data
  - Compilation v. interpretation to move down layers of system
  - Greater performance by exploiting parallelism (pipeline)
  - Principle of Locality, exploited via a memory hierarchy (cache)
  - Principles/Pitfalls of Performance Measurement

Where are we now in 61C?

- Architecture! (aka “Systems”)
  - CPU Organization
  - Pipelining
  - Caches
  - Virtual Memory
  - I / O
  - Networks
  - Performance

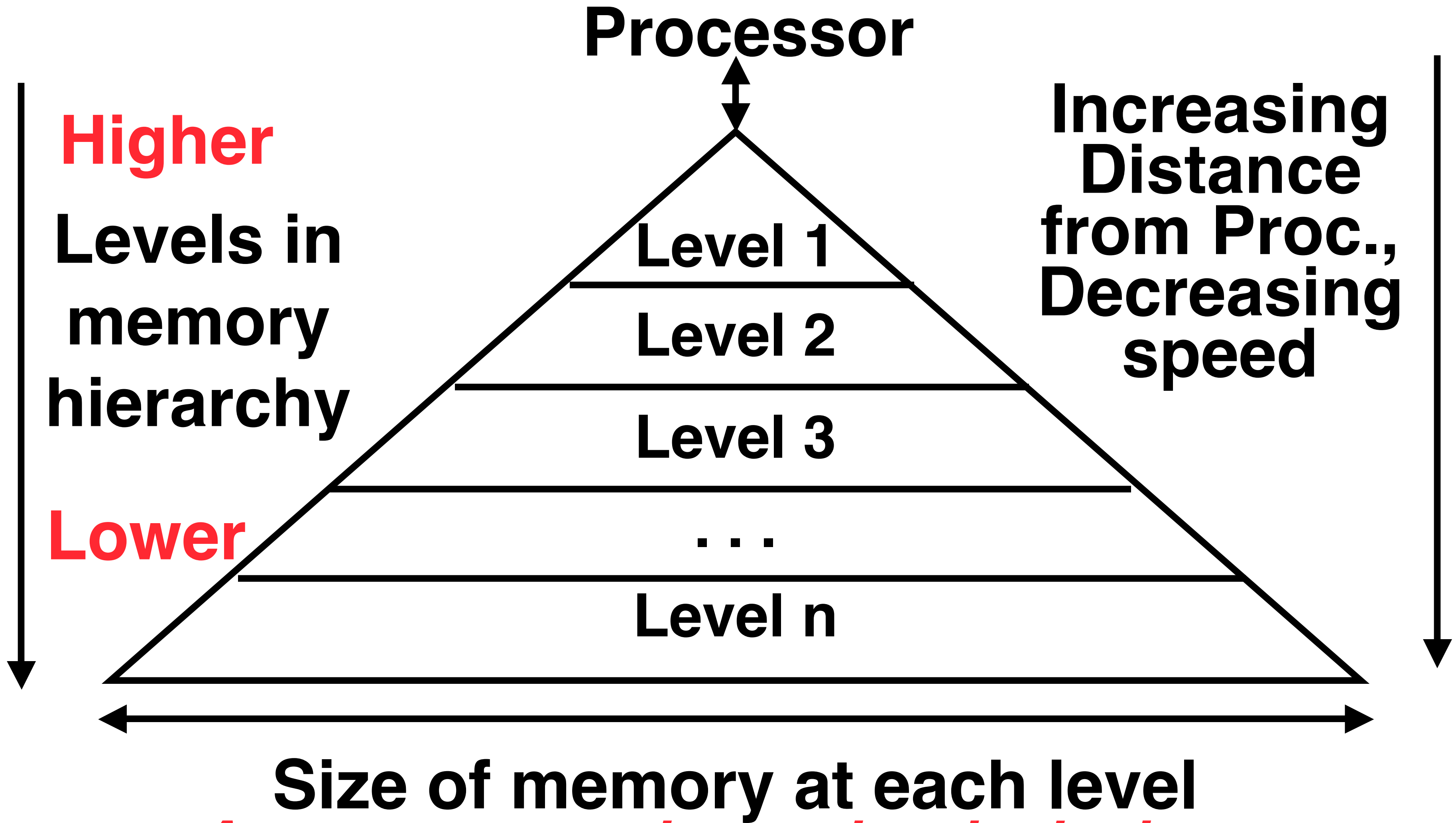
The Big Picture



Memory Hierarchy (1/3)

- Processor
  - executes instructions on order of nanoseconds to picoseconds
  - holds a small amount of code and data in registers
- Memory
  - More capacity than registers, still limited
  - Access time ~50-100 ns
- Disk
  - HUGE capacity (virtually limitless)
  - VERY slow: runs ~milliseconds

Memory Hierarchy (2/3)



Processor
Higher
Levels in memory hierarchy
Lower
Level 1
Level 2
Level 3
. . .
Level n
Increasing Distance from Proc., Decreasing speed
Size of memory at each level

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

Q: Can $/bit go up as move deeper?

Memory Hierarchy (3/3)

- If level closer to Processor, it must be:
  - smaller
  - faster
  - subset of lower levels (contains most recently used data)
- Lowest Level (usually disk) contains all available data
- Other levels?

Memory Caching

- **We've discussed three levels in the hierarchy: processor, memory, disk**
- **Mismatch between processor and memory speeds leads us to add a new level: a memory cache**
- **Implemented with SRAM technology: faster but more expensive than DRAM memory.**
    - **"S" = Static, no need to refresh, ~60ns**
    - **"D" = Dynamic, need to refresh, ~10ns**
    - `arstechnica.com/paedia/r/ram_guide/ram_guide.part1-1.html`

Memory Hierarchy Analogy: Library (1/2)

- 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 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

Memory Hierarchy Analogy: Library (2/2)

- 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: whole library open on the tabletop
  - 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

- Disk contains everything.
- When Processor needs something, bring it into to all higher levels of memory.
- Cache contains copies of data in memory that are being used.
- Memory contains copies of data on disk that are being used.
- Entire idea is based on Temporal Locality: if we use it now, we'll want to use it again soon (a Big Idea)

Cache Design

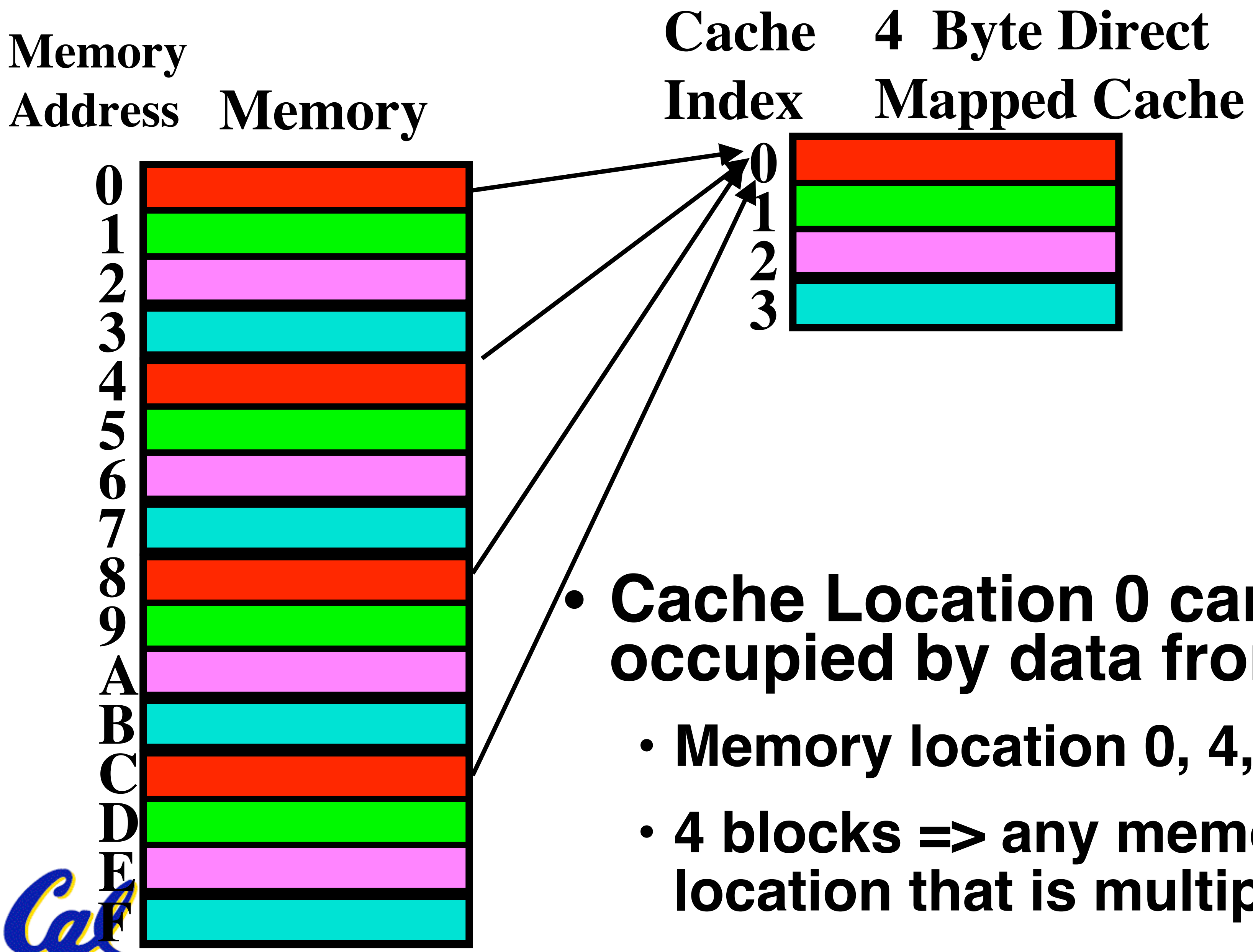
- How do we organize cache?
- Where does each memory address map to?

  (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?

Direct-Mapped Cache (1/2)

- 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

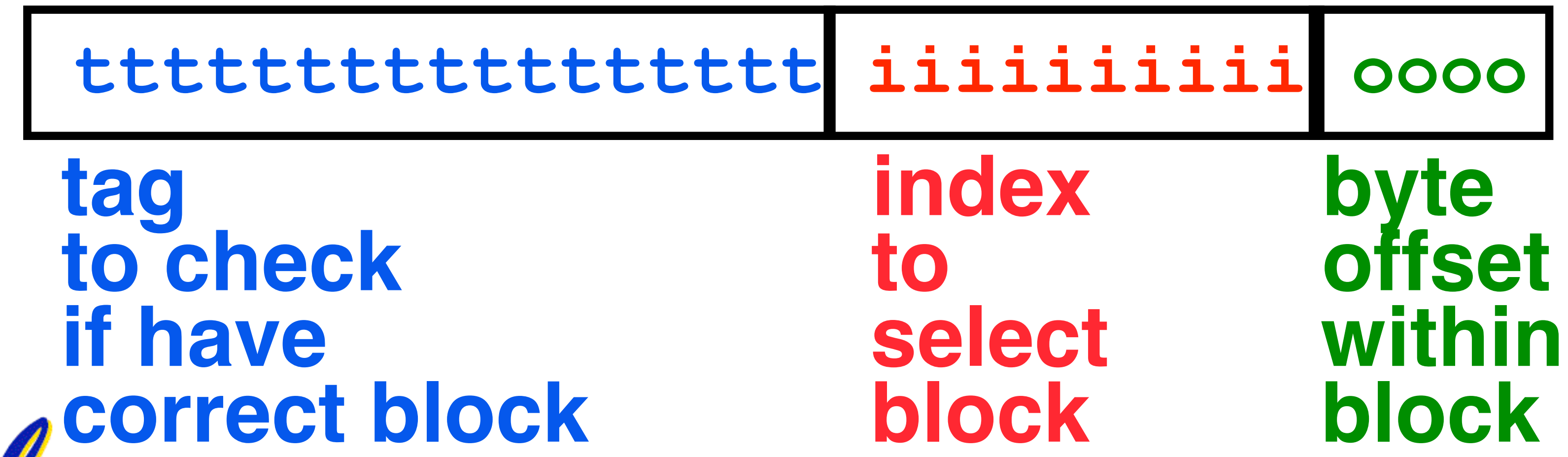
Direct-Mapped Cache (2/2)



- Cache Location 0 can be occupied by data from:
  - Memory location 0, 4, 8, ...
  - 4 blocks => any memory location that is multiple of 4

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 unsigned integers.
- Index: specifies the cache index (which "row" 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 location

Caching Terminology

- When we try to read memory,
  3 things can happen:

1. cache hit:
   cache block is valid and contains proper address, so read desired word
2. cache miss:
   nothing in cache in appropriate block, so fetch from memory
3. cache miss, block replacement:
   wrong data is in cache at appropriate block, so discard it and fetch desired data from memory (cache always copy)

Direct-Mapped Cache Example (1/3)

- **Suppose we have a 16KB of data in a direct-mapped cache with 4 word blocks**
- **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 4 words**

    = 16 bytes

    = 2^4 bytes
  - **need 4 bits to specify correct byte**

Direct-Mapped Cache Example (2/3)

- **Index: (~index into an "array of blocks")**
  - need to specify correct row in cache
  - cache contains 16 KB = 2^{14} bytes
  - block contains 2^4 bytes (4 words)
  - # blocks/cache

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

$$= \frac{2^{14}\text{ bytes/cache}}{2^{4}\text{ bytes/block}}$$

$$= 2^{10}\text{ blocks/cache}$$

  - need 10 bits to specify this many rows

Direct-Mapped Cache Example (3/3)

- Tag: use remaining bits as tag
  - tag length = addr length – offset - index
    = 32 - 4 - 10 bits
    = 18 bits
  - so tag is leftmost 18 bits of memory address
- 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. Mem hierarchies were invented before 1950. (UNIVAC I wasn't delivered 'til 1951)

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
2:	FFT
3:	FTF
4:	FTT
5:	TFF
6:	TFT
7:	TTF
8:	TTT

Peer Instruction Answer

A. "We are…forced to recognize the possibility of constructing a hierarchy of memories, each of which has greater capacity than the preceding but which is less accessible." – von Neumann, 1946

B. Certainly! That's call "tuning"

C. "Most Recent" items ⇒ Temporal locality

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6:	TFT
7:	[✓ TTF]
8:	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 locality
  - do the common case fast, worry less about the exceptions (design principle of MIPS)
- Locality of reference is a Big Idea