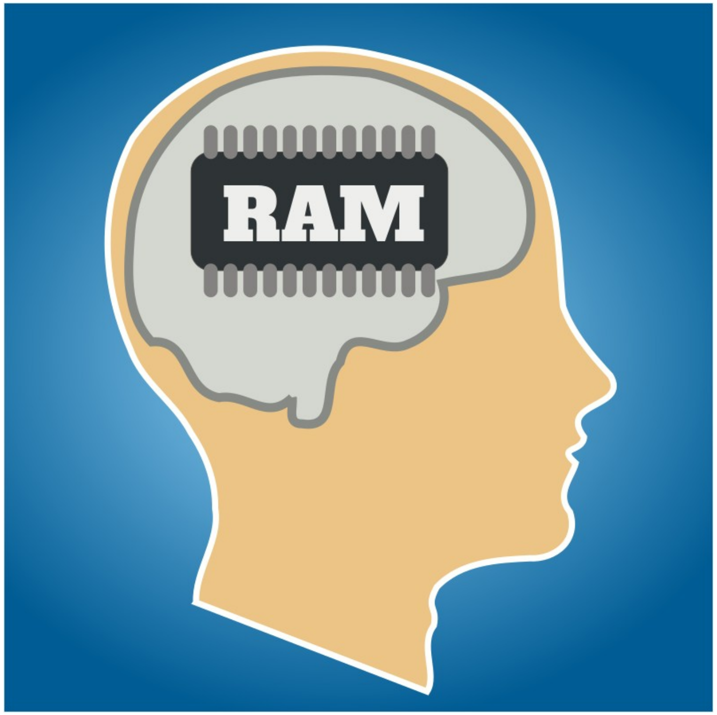
CS 261
Spring 2024

Mike Lam, Professor



Memory

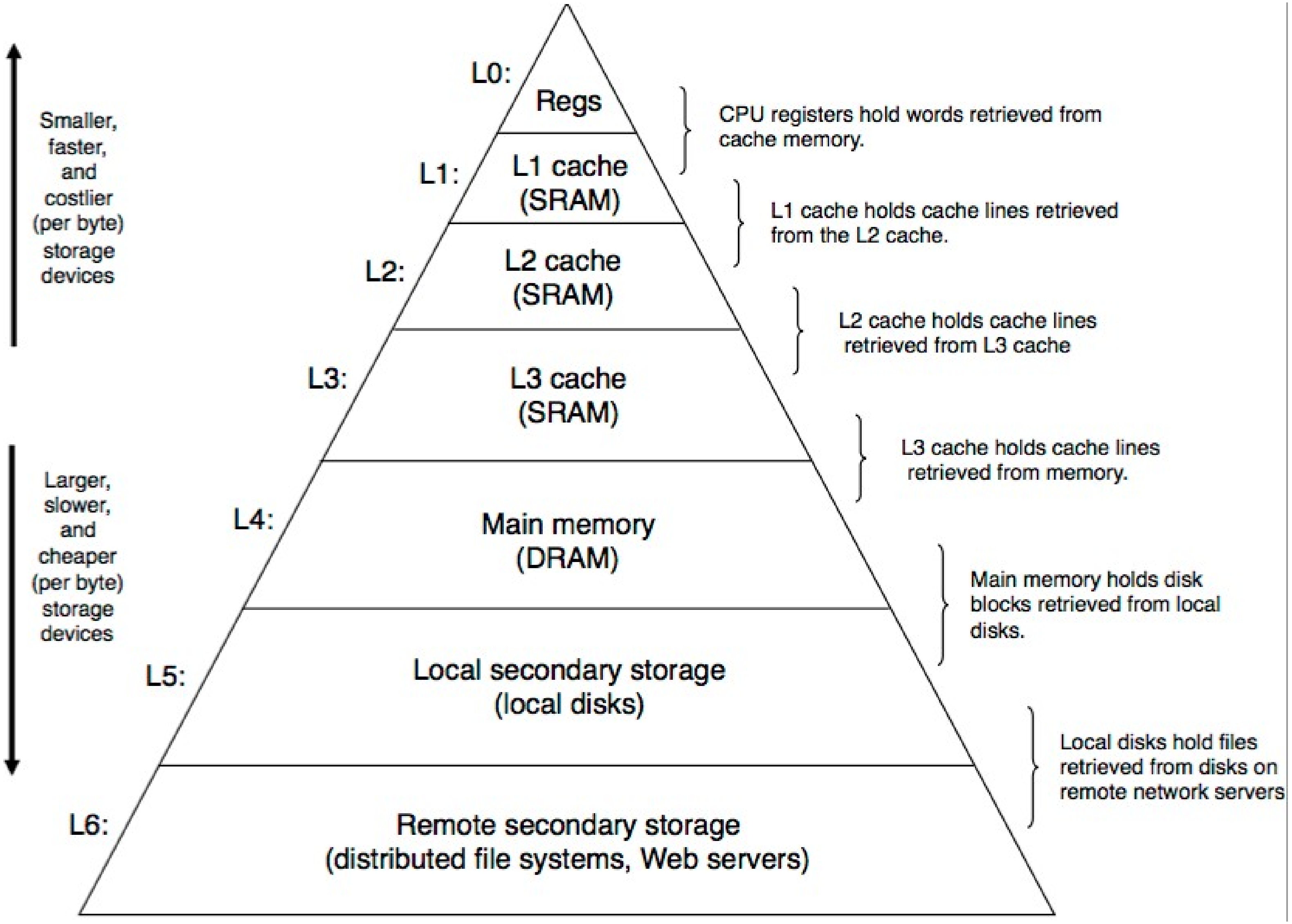
Topics

- Memory hierarchy overview
- Storage technologies
- I/O architecture
- Latency comparisons
- Locality
- Storage trends

Memory

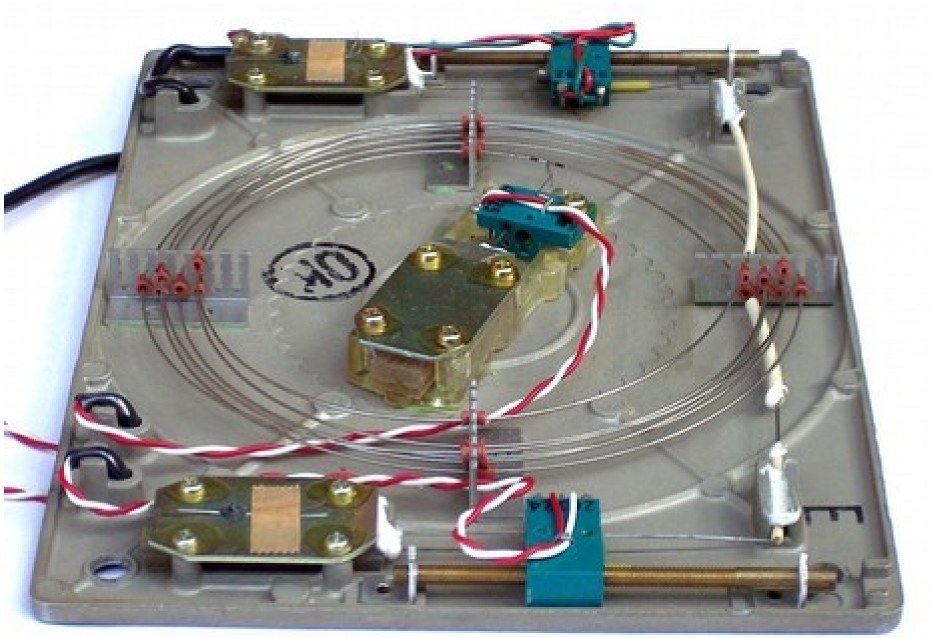
- Until now, we've referred to “memory” as a black box
- Modern systems actually have a variety of memory types called a memory hierarchy
  - Frequently-accessed data in faster memory
  - Each level caches data from the next lower level
- Goal: large general pool of memory that performs *almost* as well as if it was **all** made of the fastest memory
- Key concept: locality of time and space
- Other useful distinctions:
  - Volatile vs. non-volatile
  - Random access vs sequential access

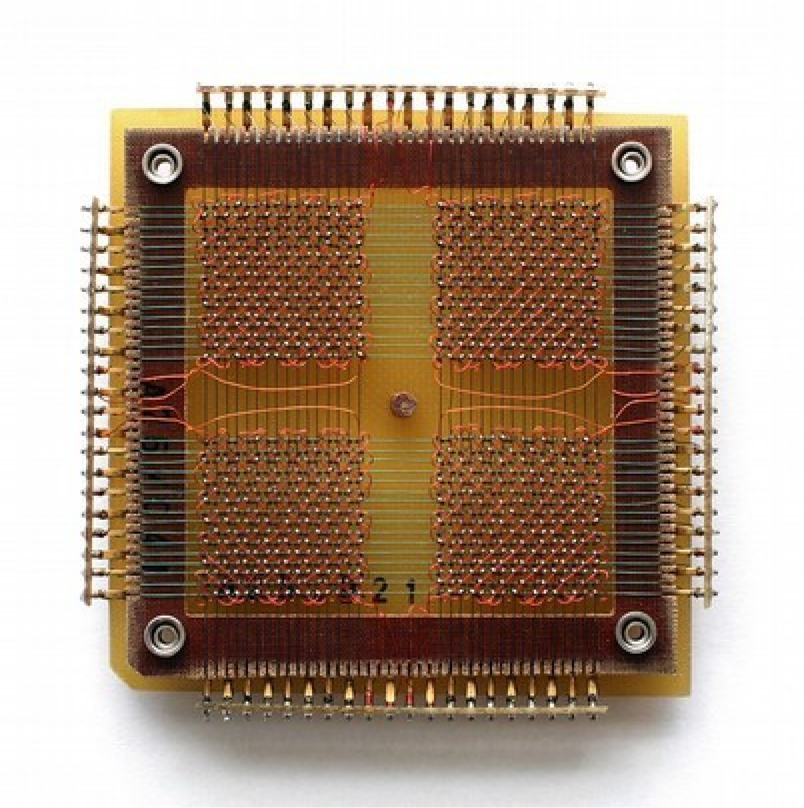
Memory hierarchy



History

- Delay-line memory (volatile, sequential)
- Magnetic core memory (non-volatile, random-access)





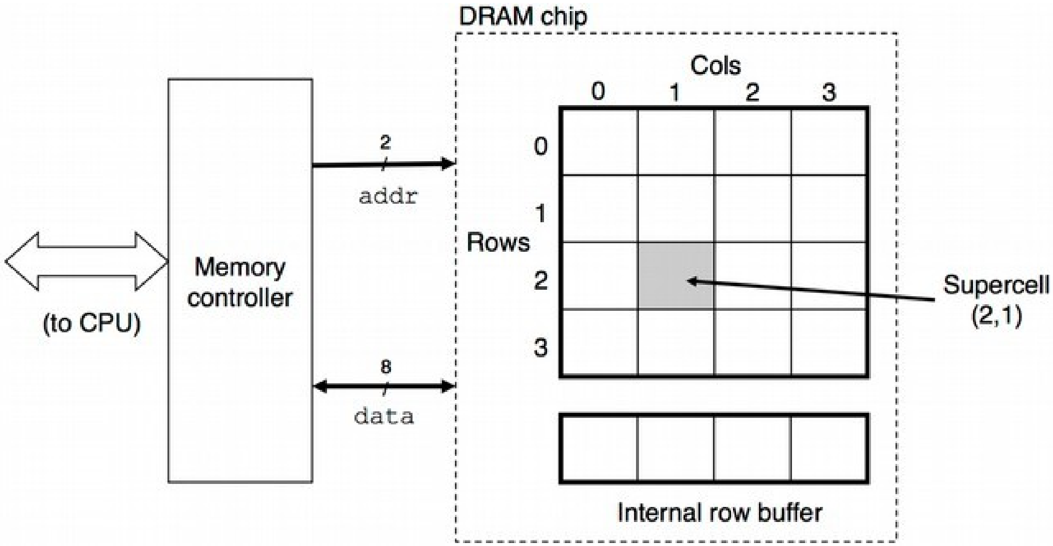
Images from Wikpedia

RAM

- Random Access Memory
  - Smaller pools of fast memory, closer to the CPU
  - Volatile: eventually lose data if the supply voltage is turned off
  - Static RAM (SRAM)
    - Six transistors per bit in a circuit w/ feedback loops
    - Essentially the same as discussed in Ch. 4
    - Used for CPU caches; usually <1GB
  - Dynamic RAM (DRAM)
    - One capacitor per bit with a single access transistor
    - Must be refreshed periodically
    - Used for main memory and graphics memory
    - Usually <64 GB

DRAM

- DRAM chips store data in a grid of supercells
- Memory controller used to access data
  - Connected to CPU via memory bus
  - Row access strobe (RAS) request loads a row into a buffer
  - Column access strobe (CAS) request reads a particular supercell



Enhanced DRAM

- Fast page mode DRAM (FPM DRAM)
  - Serve same-row accesses from the row buffer
- Extended data out DRAM (EDO DRAM)
  - Allow CAS signals to be more closely spaced
- Synchronous DRAM (SDRAM)
  - Use a clock to synchronize and speed accesses
- Double data-rate SDRAM (DDR SDRAM)
  - Use both rising and falling edges of clock signal
- Video RAM (VRAM)
  - Shift an entire buffer's contents in a single operation
  - Allow simultaneous reads and writes

Question

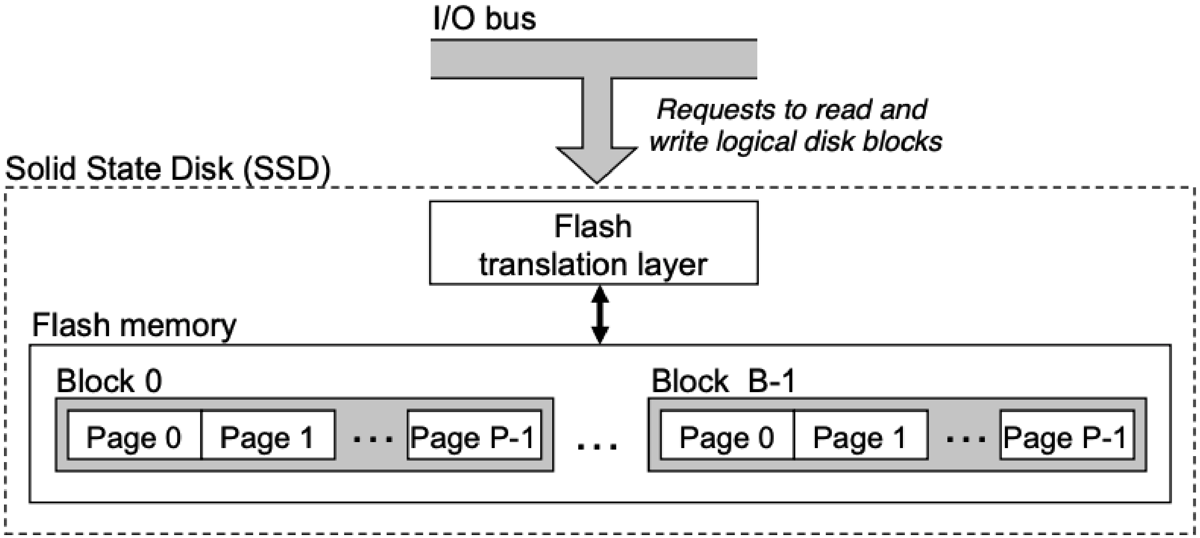
- What do all the previously-discussed DRAM technologies have in common?
  - A) They all have equally-spaced CAS signals
  - B) They all use both edges of a clock signal for synchronization
  - C) They all allow simultaneous reads and writes
  - D) They all lose data when the supply voltage is turned off
  - E) They all have identical access times

Nonvolatile memory

- Nonvolatile memory retains data if the supply voltage is turned off
  - Historically referred to as read-only memory (ROM)
  - Newer forms of nonvolatile memory can be written
- Programmable ROM (PROM)
  - Programmed only once by blowing fuses
- Erasable PROM (EPROM)
  - Re-programmed using ultraviolet light

Nonvolatile memory

- Electrically-erasable PROM (EEPROM)
  - Re-programmed using electric signals
  - Basis for flash memory storage devices
  - Examples: USB thumb drives, solid-state disks (SSDs)



Non-volatile SRAM

- Battery-backed SRAM (BBSRAM)
  - External battery maintains value when power is off
- Non-volatile SRAM (nvSRAM)
  - Handles reads and writes the same as SRAM
  - Non-volatile component for permanent storage
  - Capacitor provides energy to store if current is lost

Disk storage

- Disk storage systems hold large amounts of data
  - More cost effective than SRAM or DRAM
  - Usually order of magnitudes slower
- Solid-state drives (SSDs)
  - Flash memory organized into blocks
- Traditional magnetic hard disk drives (HDDs)
  - Multiple platters with surfaces coated with magnetic material
  - Accessed using a physical arm with a magnetic head
  - Data stored on surface in tracks partitioned into sectors

Hard disk drives

- Capacity is based on areal density
  - Product of recording density and track density
- Operation requires mechanical motion
  - Magnetic read/write head on an actuator arm
- Speed is based on average access time
  - Sum of seek time, rotational latency, and transfer time
  - Platters spin at standard rate in one direction
- Disk controller coordinates accesses
  - Maps logical blocks to (surface, track, sector) numbers

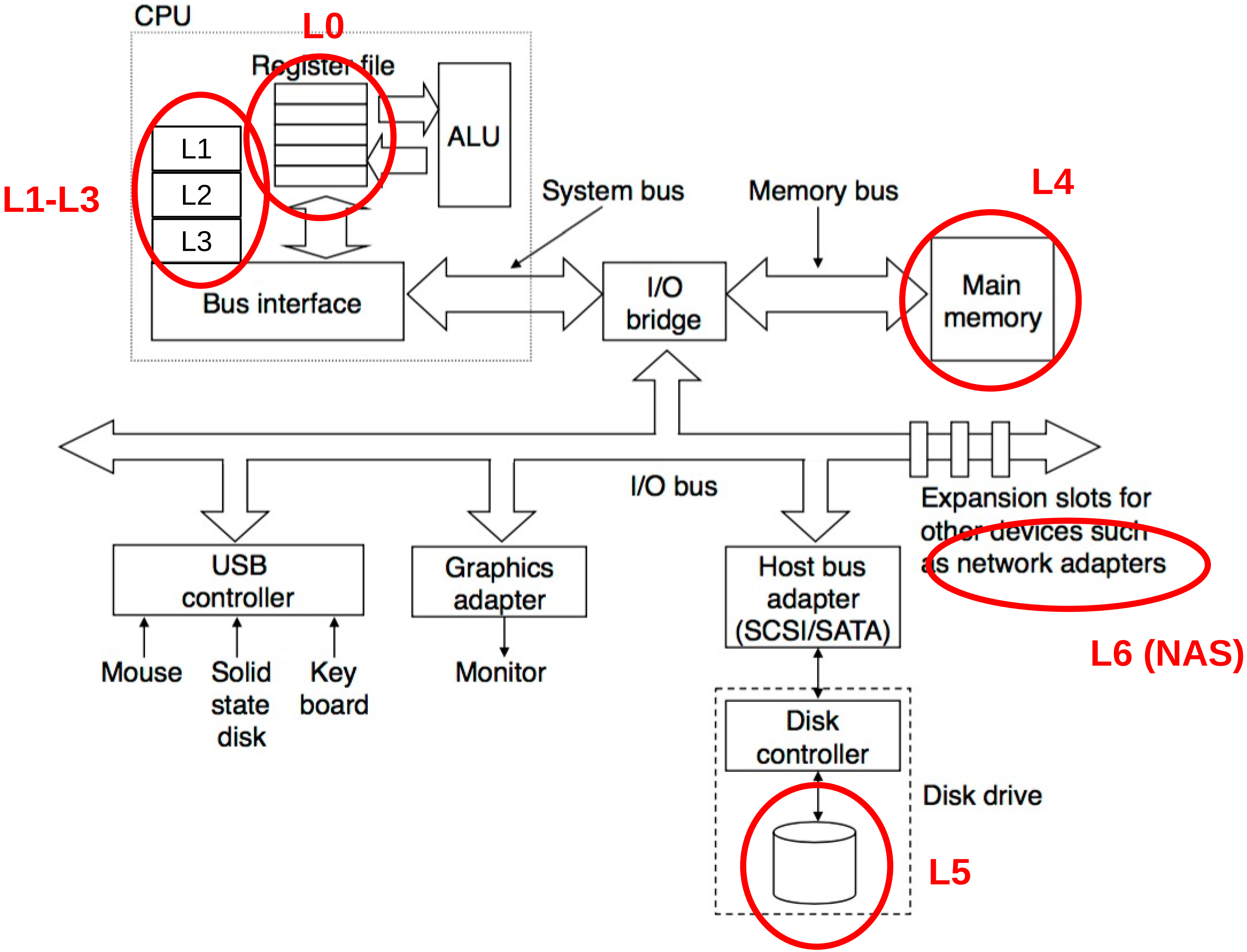
Question

- Which data access pattern will give the highest performance with a magnetic hard disk drive?
  - A) Sequential
  - B) Every other byte
  - C) Reverse sequential
  - D) Random
  - E) It doesn’t matter; they are all the same

Tape and network storage

- Archival storage systems provide large-scale data storage
  - Lowest cost per byte, but slowest access
- Tape drives store data on magnetic tape
  - Often in an off-site location for added redundancy
- Network-attached storage (NAS) systems
  - Dedicated data storage server
  - Often uses redundant disks for reliability (RAID)
  - Communicate over a network via a file sharing protocol
  - Examples: NFS, Samba, AFS
  - *More about this in CS 361 and CS 470!*

Memory architecture



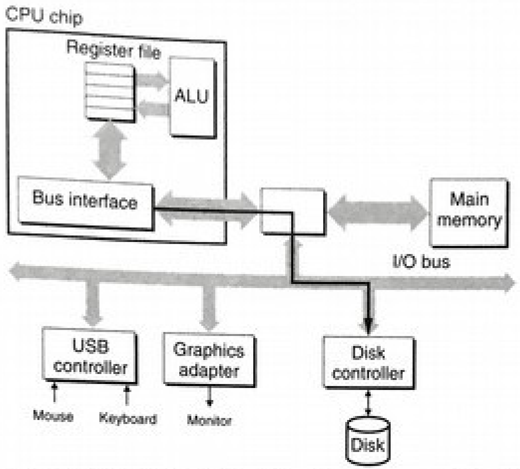
Memory architecture

- Registers and cache memory (SRAM)
  - Access via direct connection to CPU (or on-die)
- Main memory (DRAM)
  - Bus transactions via I/O bridge on motherboard
- Disk drives (magnetic disk & SSD)
  - Connected to I/O bridge via I/O bus
  - Requires a device controller for communication
  - Memory transactions w/o CPU via direct memory access (DMA)
  - Technologies: USB, SATA, SCSI
- Other memory (graphics, network storage)
  - Connected to I/O bus using expansion slots on motherboard

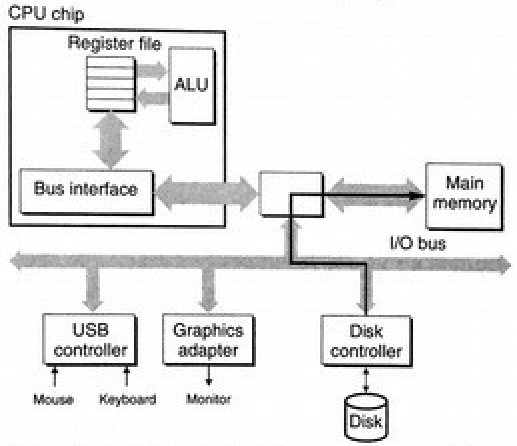
DMA

1) CPU initiates disk read
2) Disk reads data
3) Disk writes RAM via DMA
4) Disk notifies CPU

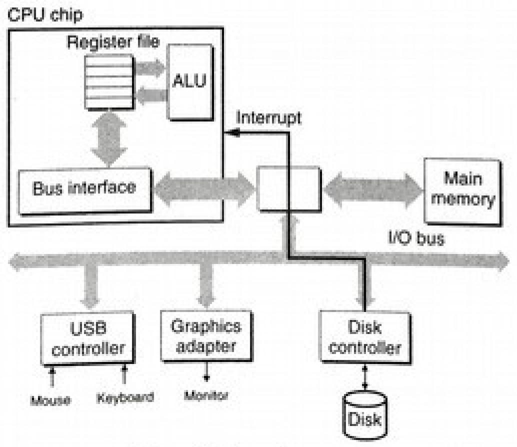
This is much faster than reading data from disk into registers then storing it in memory, and the CPU can do other tasks while this happens



(a) The CPU initiates a disk read by writing a command, logical block number, and destination memory address to the memory-mapped address associated with the disk.

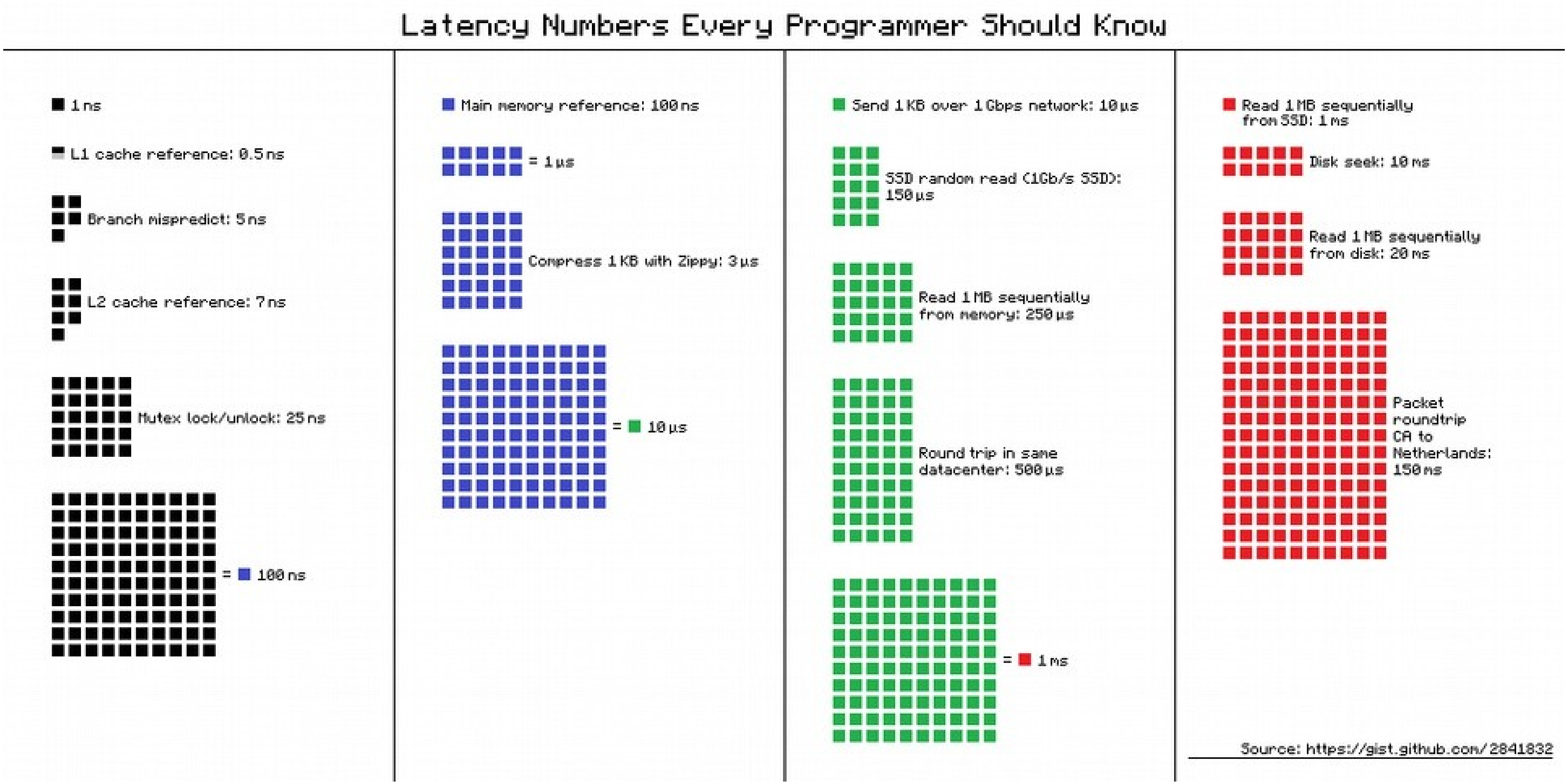


(b) The disk controller reads the sector and performs a DMA transfer into main memory.



(c) When the DMA transfer is complete, the disk controller notifies the CPU with an interrupt.

Latency comparison


Latency Numbers Every Programmer Should Know

Source: https://gist.github.com/2841832

Latency comparison

Lets multiply all these durations by a billion: (originally from https://dzone.com/articles/every-programmer-should-know)

Seconds:
- L1 cache reference (0.5s) - *One heart beat*
- L2 cache reference (7s) - *Long yawn*

Minutes:
- Main memory reference (100s) - *Brushing your teeth*

Hours:
- Send 2K bytes over 1 Gbps network (5.5 hr) - *From lunch to end of work day*

Days:
- SSD random read (1.7 days) - *A normal weekend*
- Read 1 MB sequentially from memory (2.9 days) - *A long weekend*
- Read 1 MB sequentially from SSD (11.6 days) - *Waiting for almost 2 weeks for a delivery*

Weeks:
- Disk seek (16.5 weeks) - *A semester in university*
- Read 1 MB sequentially from disk (7.8 months) – *Two semesters in university*
- The above 2 together (1 year)

Years:
- Send packet CA->Netherlands->CA (4.8 years) - *Completing a bachelor's degree*

“Nanoseconds”

- Admiral Grace Hopper on the importance of being aware of limits on latency
  - https://www.youtube.com/watch?v=9eyFDBPk4Yw

Locality

- Temporal locality: frequently-accessed items will continue to be accessed in the future
  - Theme: **repetition is common**
- Spatial locality: nearby addresses are more likely to be accessed soon
  - Theme: **sequential access is common**
- Why do we care?
  - *Programs with good locality run faster than programs with poor locality*

Question

- Assume the last three memory locations accessed were 0x438, 0x43C, and 0x440 (in that order). What is the address (in hex) that is most likely to be accessed next?

Data locality

- Using predictable access patterns exhibits *spatial* locality
  - Stride-1 reference pattern (sequential access)
  - Stride-k reference pattern (every k elements)
  - Arrays: row-major vs. column-major
  - Allows for prefetching (predicting the next needed element and preloading it)
- Re-using values many times exhibits *temporal* locality
  - Can keep them in a high level of the memory hierarchy

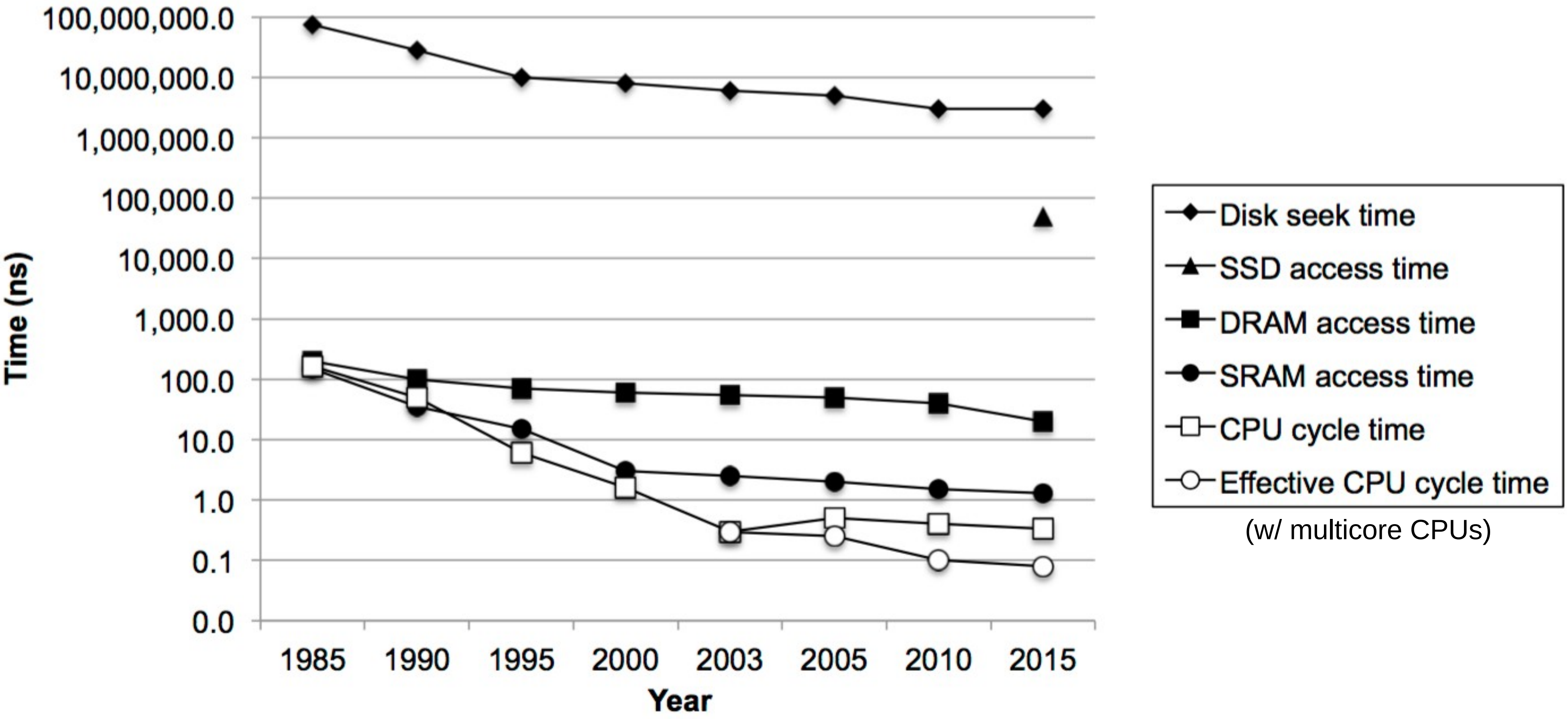
Question

- Which of the following will generally exhibit good locality in machine code? (choose all that apply)
  - A) Normal instruction execution
  - B) Long jumps
  - C) Short loops
  - D) Function calls

Instruction locality

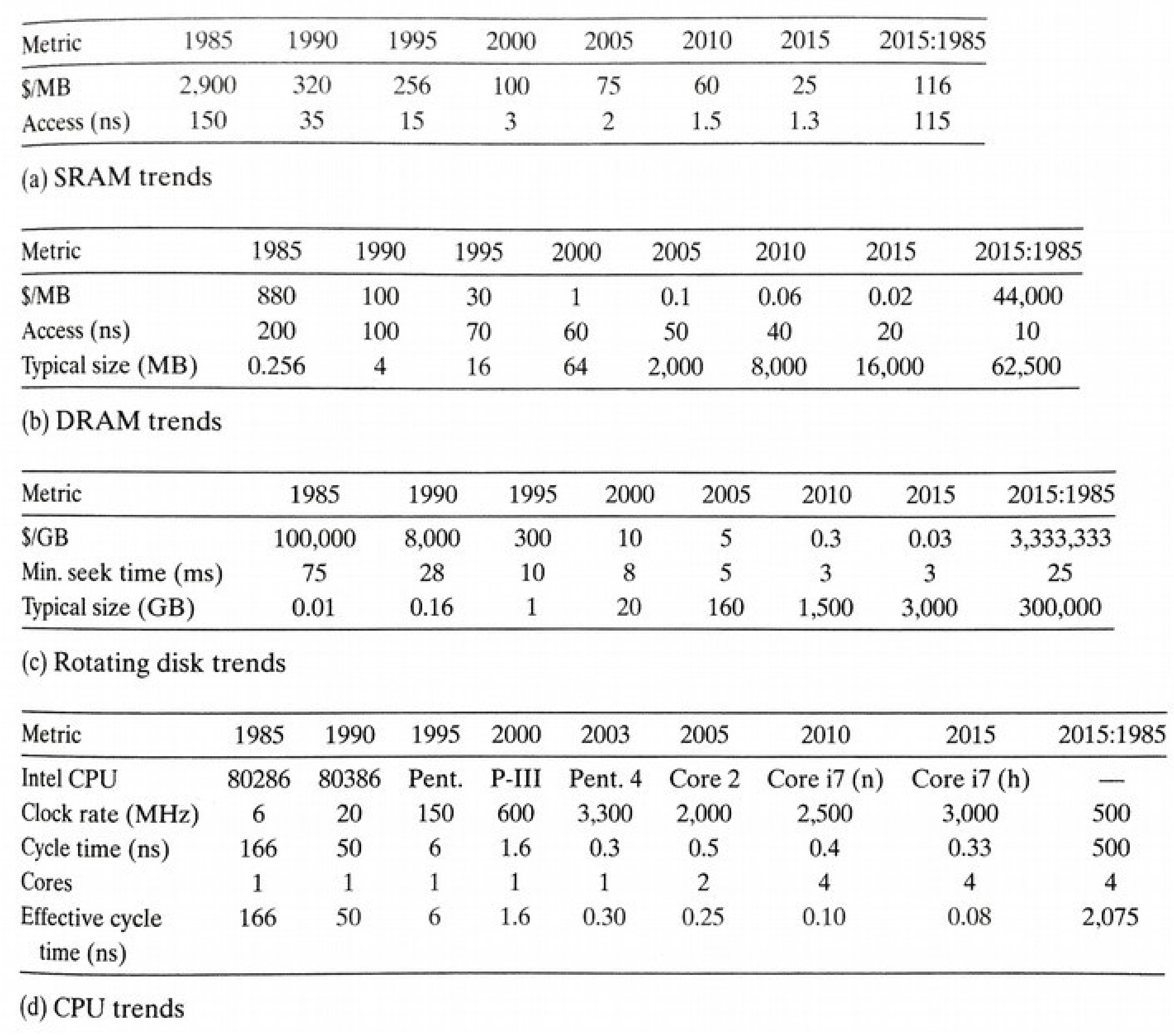
- Normal execution exhibits *spatial* locality
  - Instructions execute **in sequence**
  - Long jumps exhibit poor locality (this includes function calls)
- Loops exhibit both *temporal* and *spatial* locality
  - The body statements execute **repeatedly** (temporal locality) and **in sequence** (spatial locality)
  - Short loops are better

Technology comparison



(w/ multicore CPUs)

Storage trends



Metric	1985	1990	1995	2000	2005	2010	2015	2015:1985
$/MB	2,900	320	256	100	75	60	25	116
Access (ns)	150	35	15	3	2	1.5	1.3	115

(a) SRAM trends

Metric	1985	1990	1995	2000	2005	2010	2015	2015:1985
$/MB	880	100	30	1	0.1	0.06	0.02	44,000
Access (ns)	200	100	70	60	50	40	20	10
Typical size (MB)	0.256	4	16	64	2,000	8,000	16,000	62,500

(b) DRAM trends

Metric	1985	1990	1995	2000	2005	2010	2015	2015:1985
$/GB	100,000	8,000	300	10	5	0.3	0.03	3,333,333
Min. seek time (ms)	75	28	10	8	5	3	3	25
Typical size (GB)	0.01	0.16	1	20	160	1,500	3,000	300,000

(c) Rotating disk trends

Metric	1985	1990	1995	2000	2003	2005	2010	2015	2015:1985
Intel CPU	80286	80386	Pent.	P-III	Pent. 4	Core 2	Core i7 (n)	Core i7 (h)	—
Clock rate (MHz)	6	20	150	600	3,300	2,000	2,500	3,000	500
Cycle time (ns)	166	50	6	1.6	0.3	0.5	0.4	0.33	500
Cores	1	1	1	1	1	2	4	4	4
Effective cycle time (ns)	166	50	6	1.6	0.30	0.25	0.10	0.08	2,075

(d) CPU trends

Faster and cheaper

Clock rates and cycle times have stalled, but effective cycle times continue to decrease

NVM Express

- Non-Volatile Memory Express (NVMe)
  - Newer flash memory technology that uses the PCI Express bus (direct connection to the main board)
  - Commonly used to support M.2 form factor SSDs
  - Building block of burst buffer storage in early 2020’s supercomputers (e.g., Sierra, Summit, and 富岳 Fugaku)
    - Essentially a cache between main memory and HDDs

https://en.wikipedia.org/wiki/NVM_Express
https://en.wikipedia.org/wiki/M.2

Core themes

- **Systems design involves tradeoffs**
  - Memory: price vs. performance (e.g., DRAM vs. SRAM)
- **The details matter!**
  - Knowledge of the underlying system enables you to exploit latency inequalities for better performance
- Key concepts: locality and caching
  - Store and access related things together
  - Keep copies of things you’ll need again soon
  - We’ll look at these more next time