The Memory Hierarchy

Today

- Storage technologies and trends
- Locality of reference
- Caching in the memory hierarchy

Next time

- Cache memory

Random-Access Memory (RAM)

- Computer technology success due in big part to progress in storage technology
- Random-Access Memory
  - Packaged as a chip
  - Basic storage unit is a cell (one bit per cell).
  - Multiple RAM chips form a memory
  - Comes in two flavors *static* and *dynamic*

IBM PC 5150
August 1981
16KB Main memory
36kbit DRAM chips

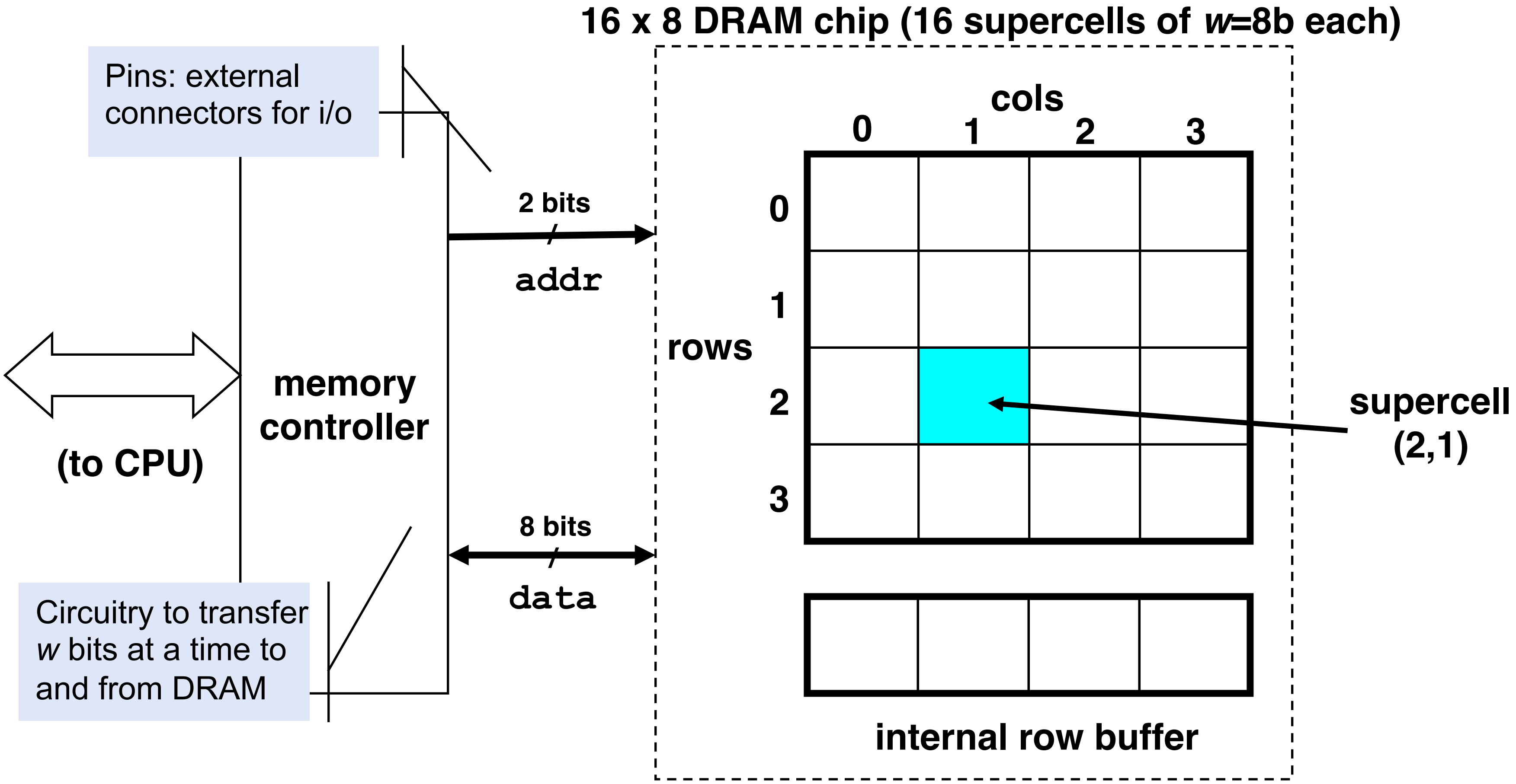
Static and Dynamic RAMs

- Static RAM (SRAM)
  - Static – no need for periodic refreshed; keeps data while powered
  - Each cell stores bit in a bistable cell, a six-transistor circuit
  - Relatively insensitive to disturbances such as electrical noise
  - *Faster and more expensive* than DRAM
- Dynamic RAM (DRAM)
  - Each cell stores bit as a charge in a capacitor, cell is a capacitor and a single access transistor
  - Value must be refreshed every 10-100 ms
  - Sensitive to disturbances
  - *Slower and cheaper* than SRAM

	Transistors/bit	**Acc time**	**Persist?**	**Sensitive?**	**Cost**	**Applications**
SRAM	6	1X	Yes	No	100X	Cache mem.
DRAM	1	10X	No	Yes	1X	Main mem., frame buffers

Conventional DRAM organization

- Cell in a DRAM chip partitioned into supercells
  - Supercells organized as arrays of *r* rows and *c* cols (*r*c=d*)
  - Each of *w* DRAM cells; a *(d* x *w)* DRAM stores *(d*w)* bits



16 x 8 DRAM chip (16 supercells of *w*=8b each)

Pins: external connectors for i/o

Circuitry to transfer *w* bits at a time to and from DRAM

(to CPU)

memory controller

2 bits

addr

8 bits

data

cols

0

1

2

3

rows

0

1

2

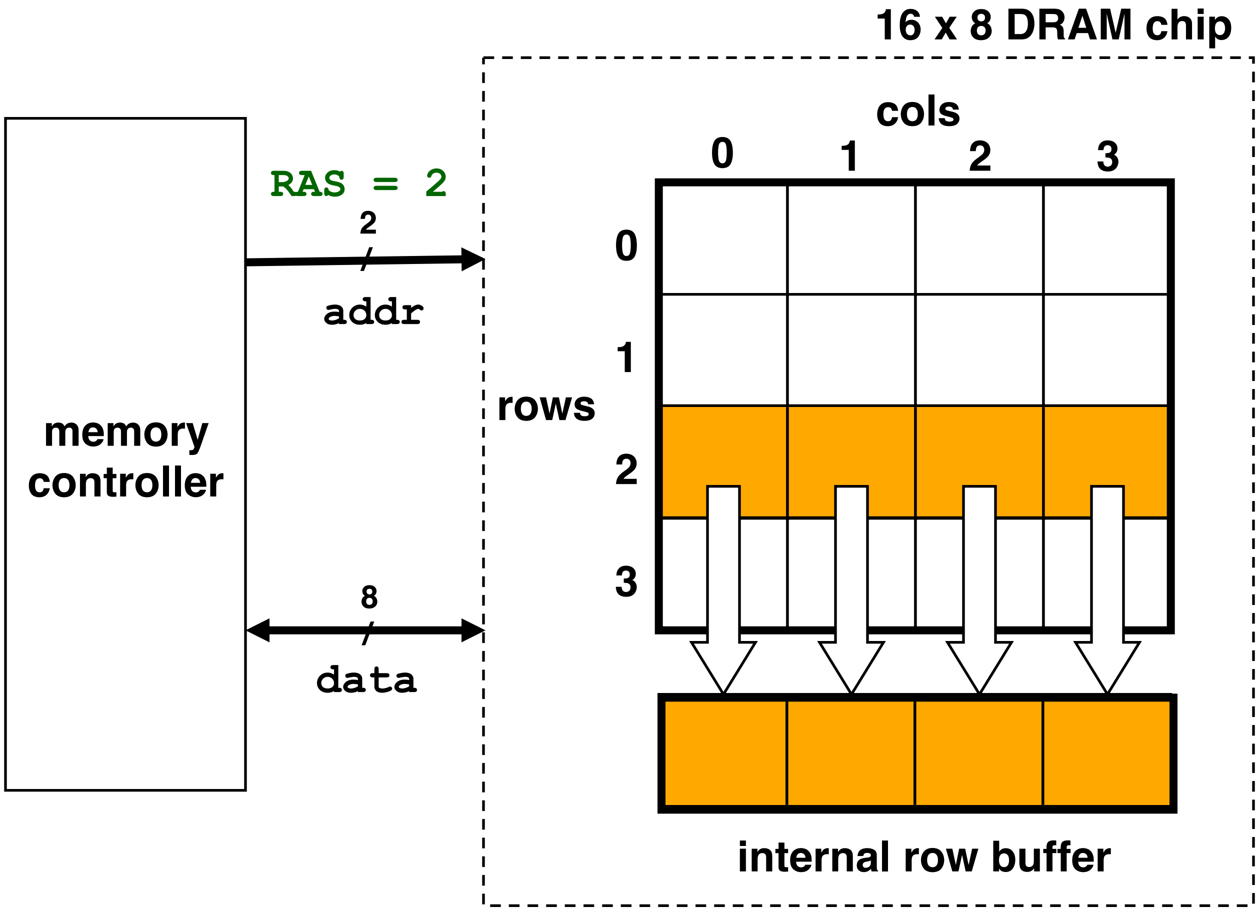
3

supercell (2,1)

internal row buffer

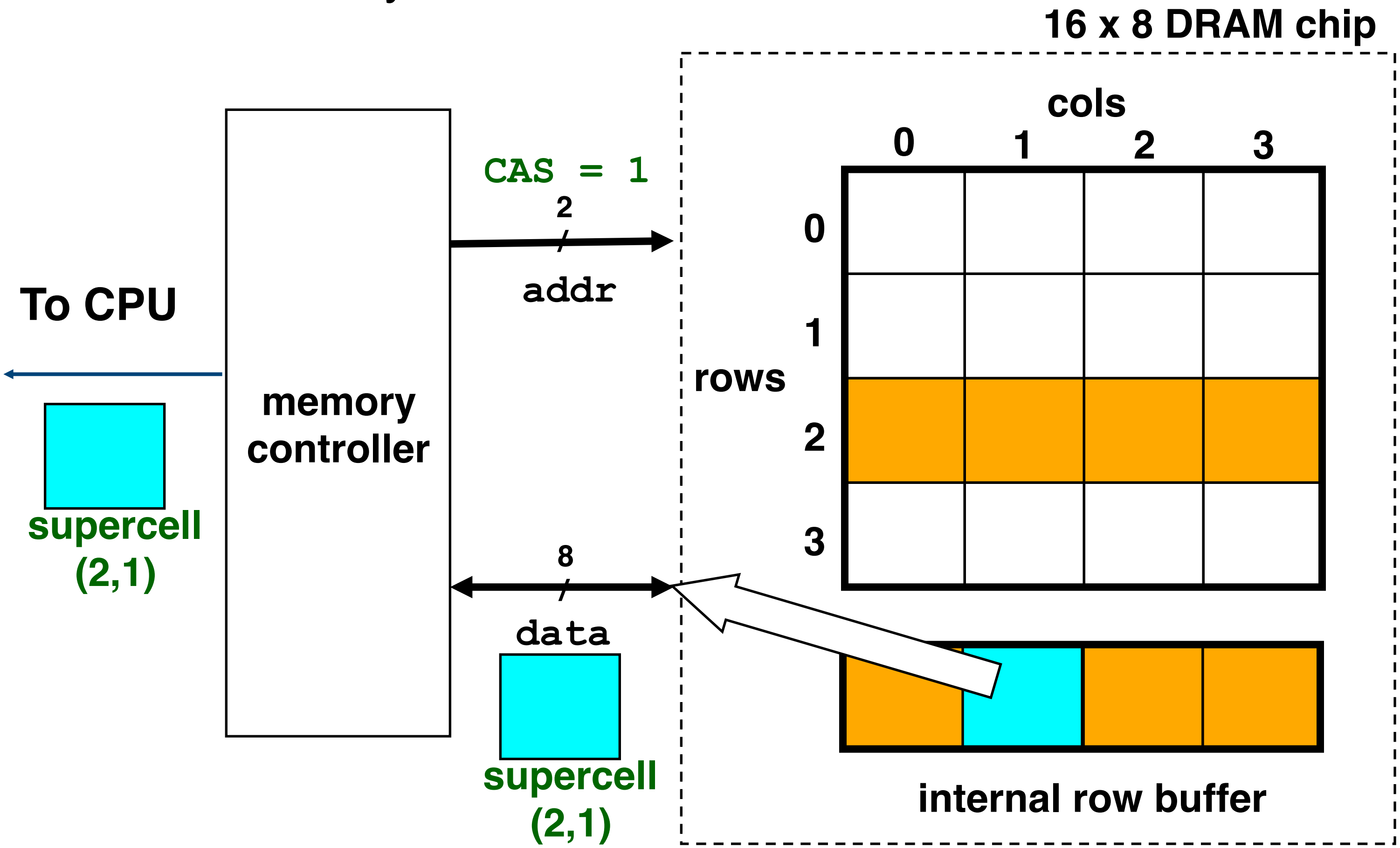
Reading DRAM supercell (2,1)

- Access done in two steps
  - Step 1(a): Row access strobe (RAS) selects row 2.
  - Step 1(b): Row 2 copied from DRAM array to row buffer.



Reading DRAM supercell (2,1)

- …
  - Step 2(a): Column access strobe (CAS) selects col 1.
  - Step 2(b): Supercell (2,1) copy row buffer to data lines, and eventually back to the CPU.

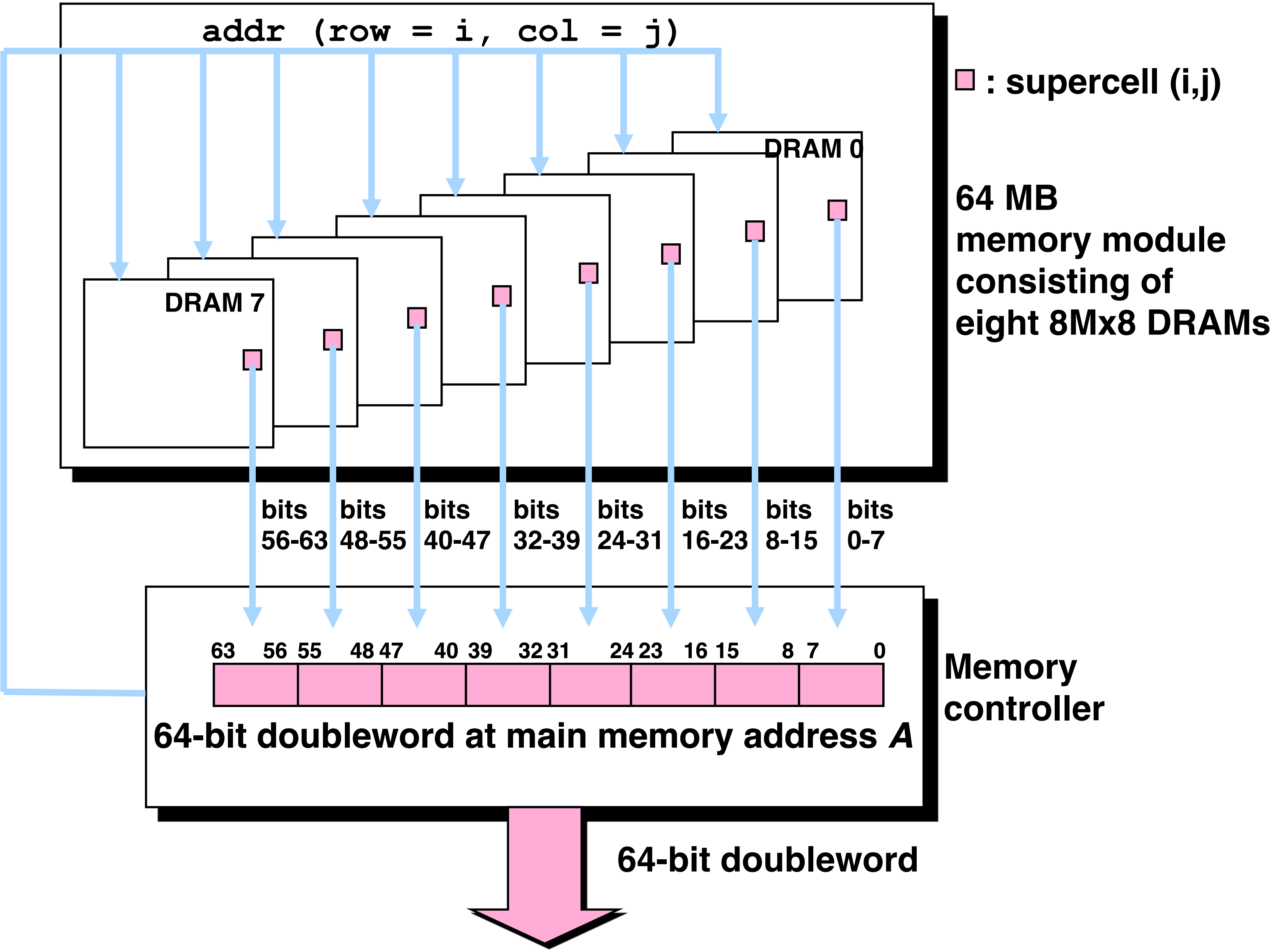


Memory modules

- DRAM chips are packaged in memory modules
- Mem. modules plug into expansion slots on main system board
  - Examples
    - 168-pin Dual Inline Memory Module (DIMM) – transfer data in 64-bit chunks

    - 72-pin Single Inline Memory Module (SIMM) – transfer data in 32-bit chunks

Memory module basic idea



Enhanced DRAMs

- Basic cell has not changed since 1966
- Enhanced DRAMs are built around conventional core
  - Synchronous DRAM (SDRAM)
    - Driven with rising clock edge instead of asynchronous control signals.
    - Allows reuse of the row address [RAS, CAS, CAS, CAS, CAS]
  - Double data-rate synchronous DRAM (DDR SDRAM)
    - Enhancement of SDRAM that uses both clock edges as control signals.
    - Different types with different sizes for small prefetch buffer
      - DDR (2b), DDR2 (4b), DDR4 (8b)
    - Standard for most servers and desktops (2010)

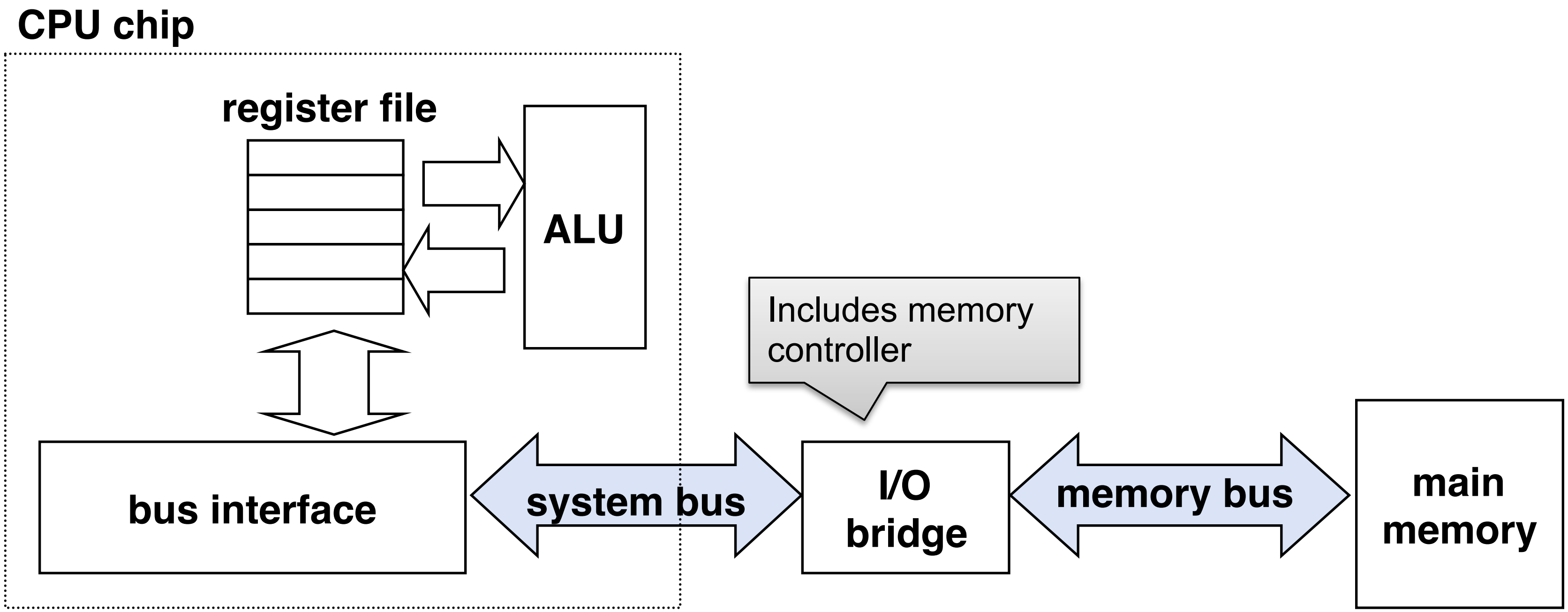
Nonvolatile memories

- DRAM and SRAM are volatile memories
  - Lose information if powered off
- Nonvolatile memories retain value even if powered off
  - Generic name is read-only memory (ROM)
  - Misleading because some ROMs can be read and modified.
- Types of ROMs
  - Programmable ROM (PROM)
  - Eraseable Programmable ROM (EPROM)
  - Electrically Eraseable PROM (EEPROM)
  - Flash memory (based on EEPROM)
- Firmware
  - Program stored in a ROM
    - Boot time code, BIOS (basic input/output system)
    - graphics cards, disk controllers.

Accessing main memory

- Data flows bet/ main memory and CPU over buses
  – A collection of parallel wires that carry address, data, and control signals
  – Typically shared by multiple devices

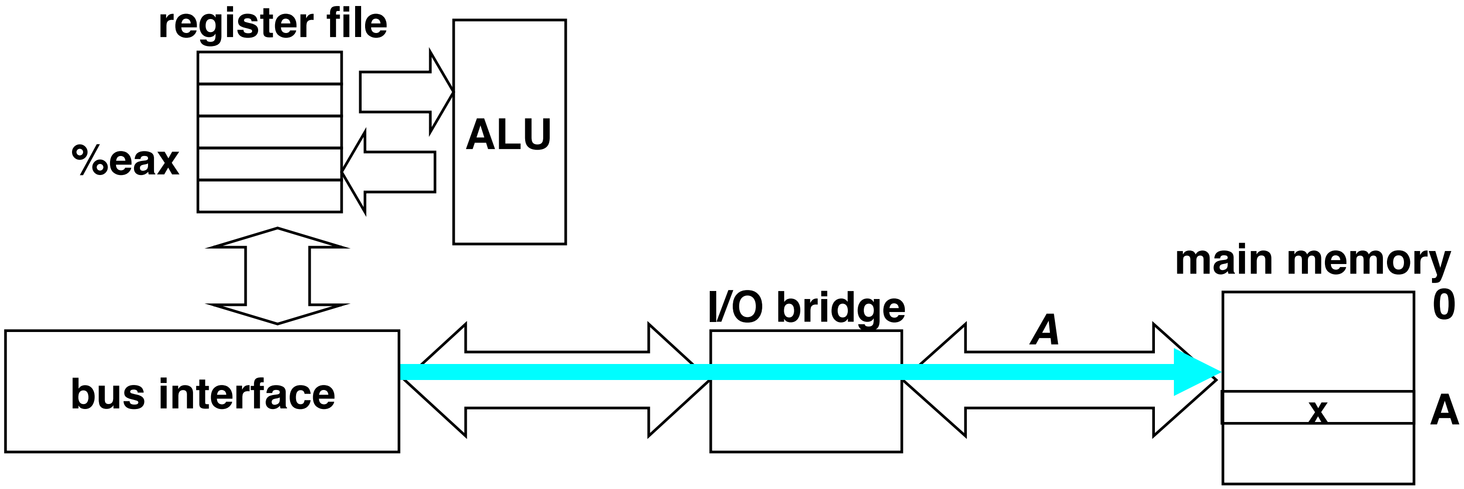
Example configuration



Memory read transaction (1)

- Load content of address A into a register
- CPU places address A on the system bus, I/O bridge passes it on to the memory bus

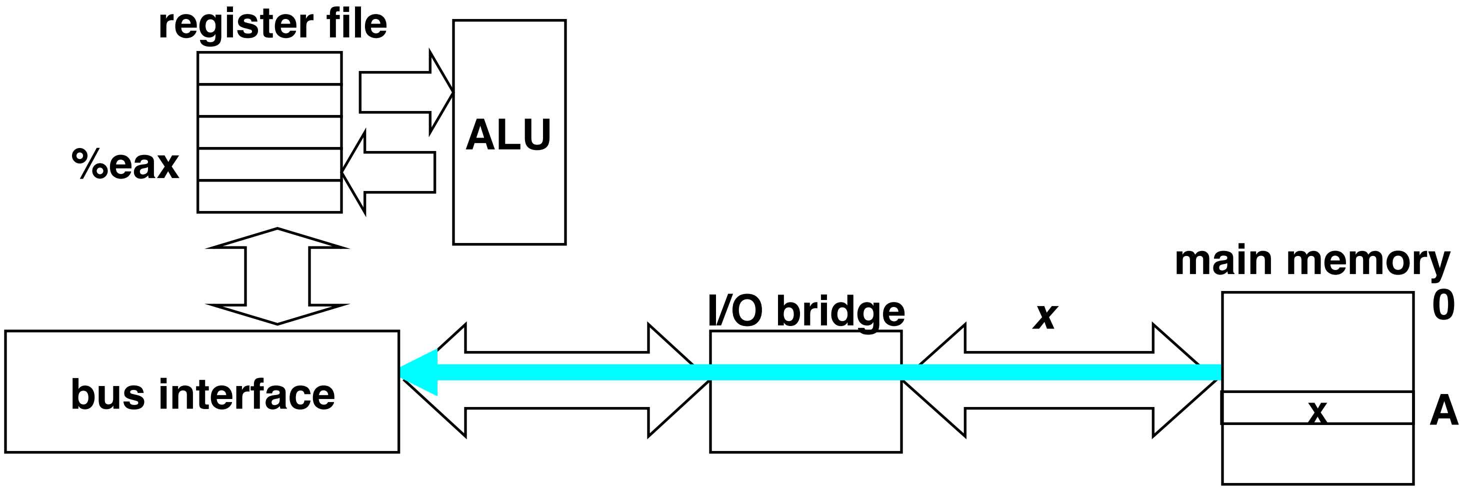
Load operation: `movl A, %eax`



Memory read transaction (2)

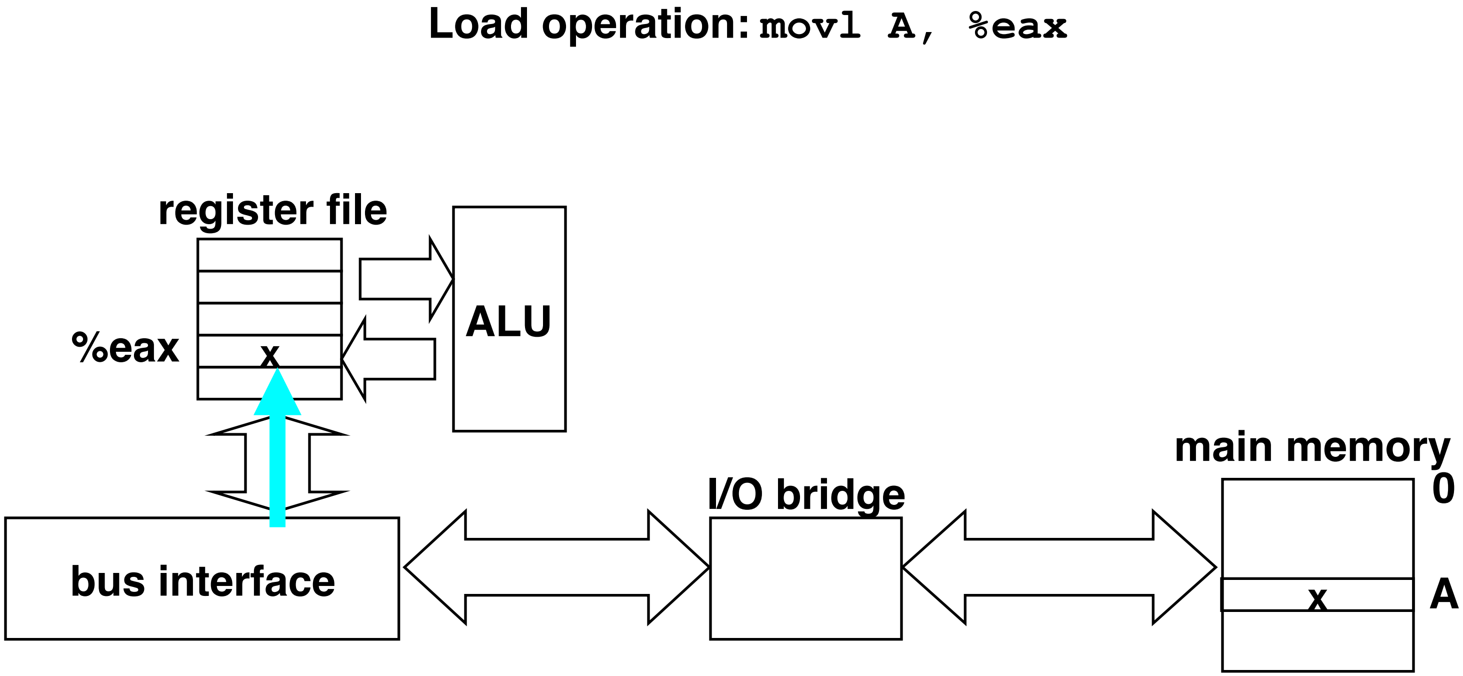
- Main memory reads A from the memory bus, retrieves word x, and places it on the bus; I/O bridge passes it along to the system bus

Load operation: `movl A, %eax`



Memory read transaction (3)

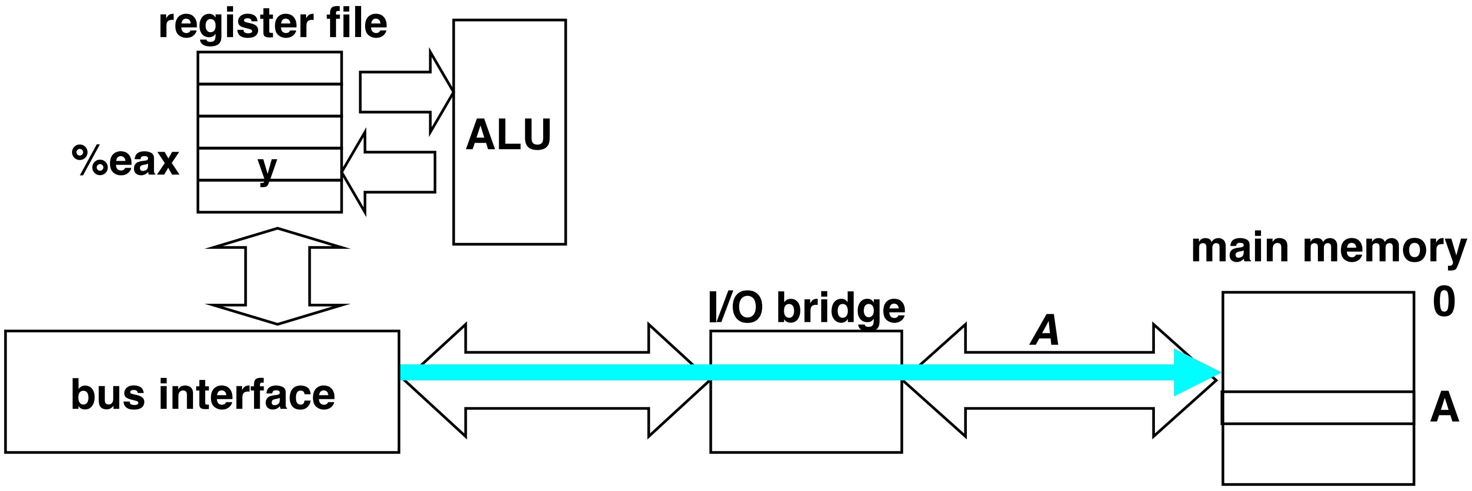
- CPU read word x from the bus and copies it into register %eax.



Memory write transaction (1)

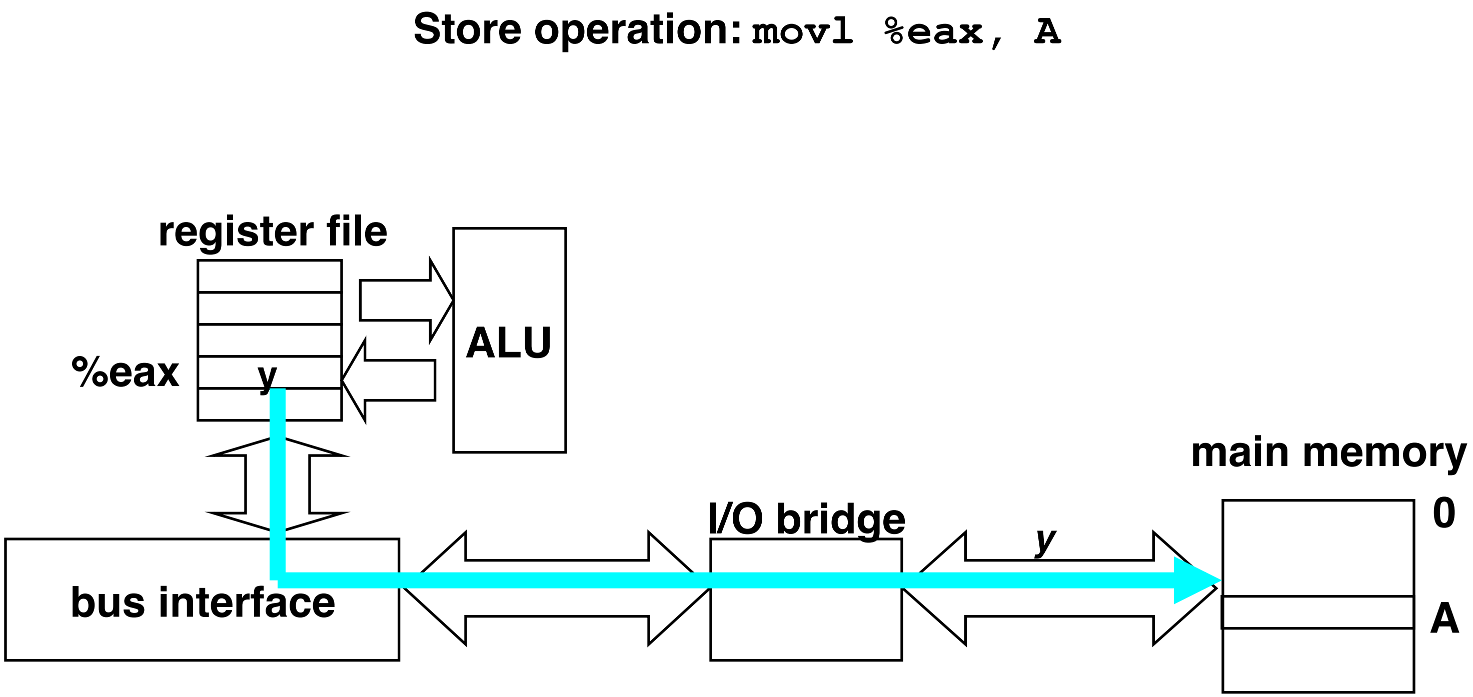
- Similar for store; CPU places address A on bus. Main memory reads it and waits for the corresponding data word to arrive.

Store operation: `movl %eax, A`



Memory write transaction (2)

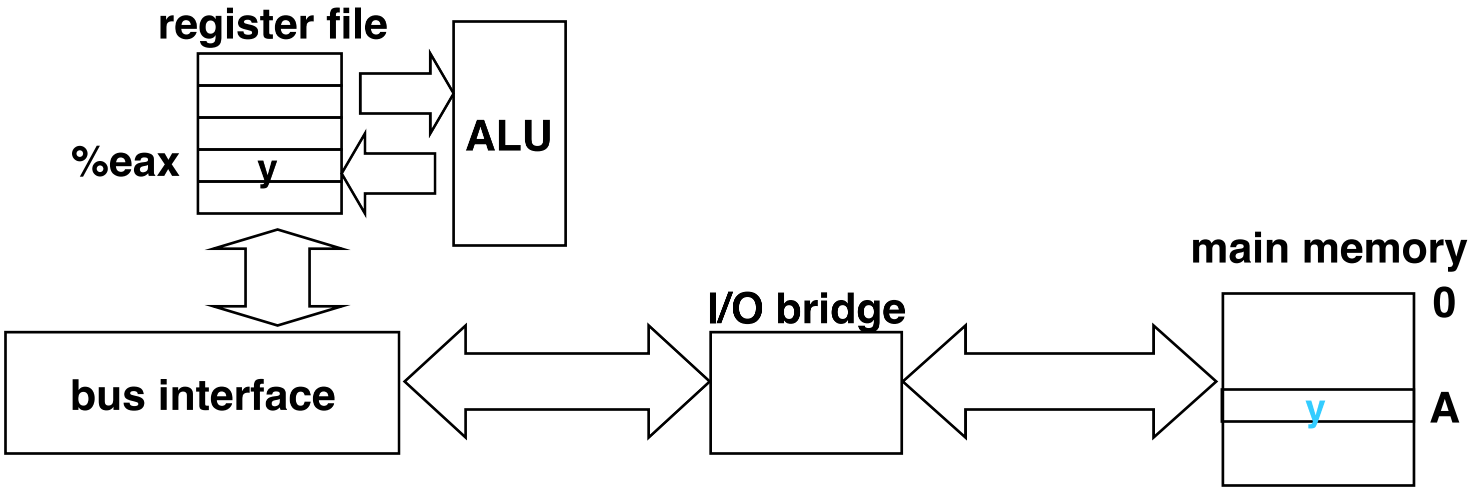
- CPU places data word y on the bus.



Memory write transaction (3)

- Main memory read data word y from the bus and stores it at address A.

Store operation: `movl %eax, A`



Disk storage

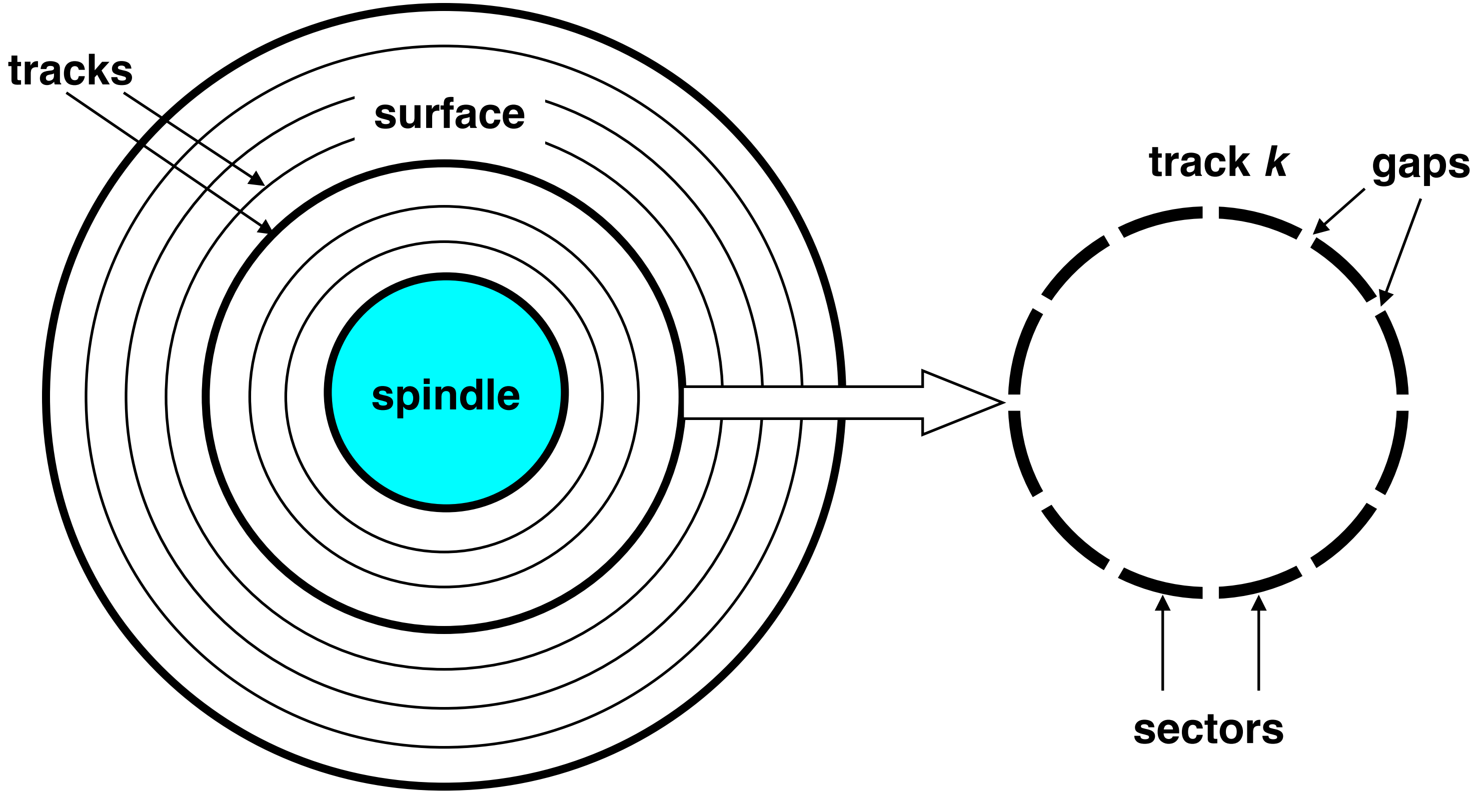
- Workhorse storage devices
  - 100-1,000x GB
  - Milliseconds to read (100,000x longer than from DRAM, 1,000,000x longer than from SRAM)

IBM 350 Disk Storage Unit
Announced Sep. 4, 1956
5MB

Seagate Barracuda XT
2TB, 2010

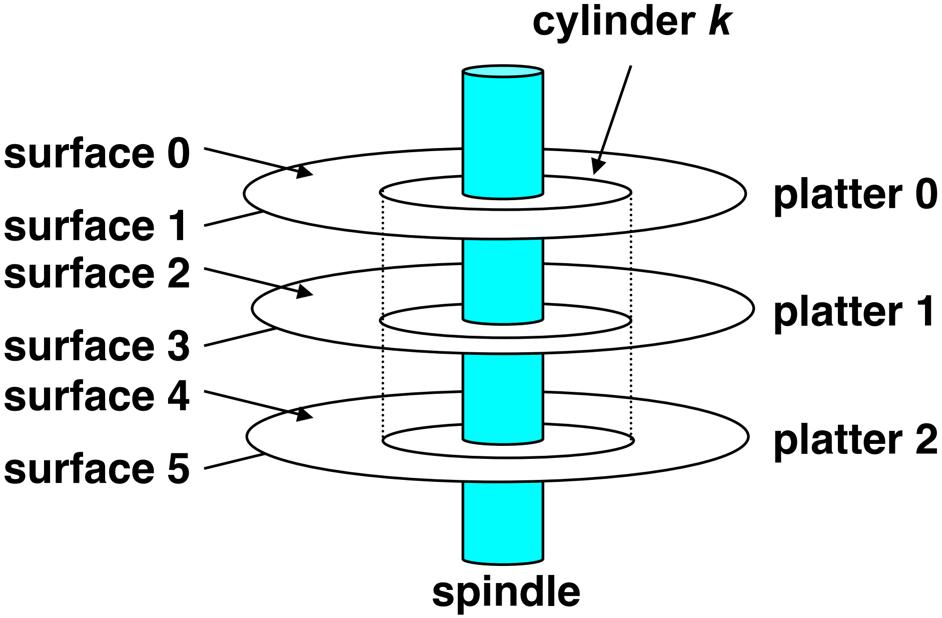
Disk geometry

- Disks consist of platters, each with two surfaces
- Each surface consists of concentric rings called tracks
- Each track consists of sectors separated by gaps
- Sectors contain equal # of data bits (typically 512B)



Disk geometry (Muliple-platter view)

- Aligned tracks form a cylinder



Disk capacity

- *Capacity*: maximum number of bits that can be stored.
  - Vendors express capacity in units of gigabytes (GB), where 1 GB = 10^9
- Capacity is determined by these technology factors:
  - *Recording density* (bits/in): # bits that fit into a 1 inch of a track
  - *Track density* (tracks/in): # of tracks that fit into a 1 inch radial segment
  - *Areal density* (bits/in^2): recording density * track density\
- Modern disks partition tracks into disjoint subsets called recording zones
  - Each track in a zone has the same number of sectors, determined by the circumference of innermost track
  - Each zone has a different number of sectors/track

Computing disk capacity

- Capacity =

  (# bytes/sector)
  x (avg. # sectors/track)
  x (# tracks/surface)
  x (# surfaces/platter)
  x (# platters/disk)

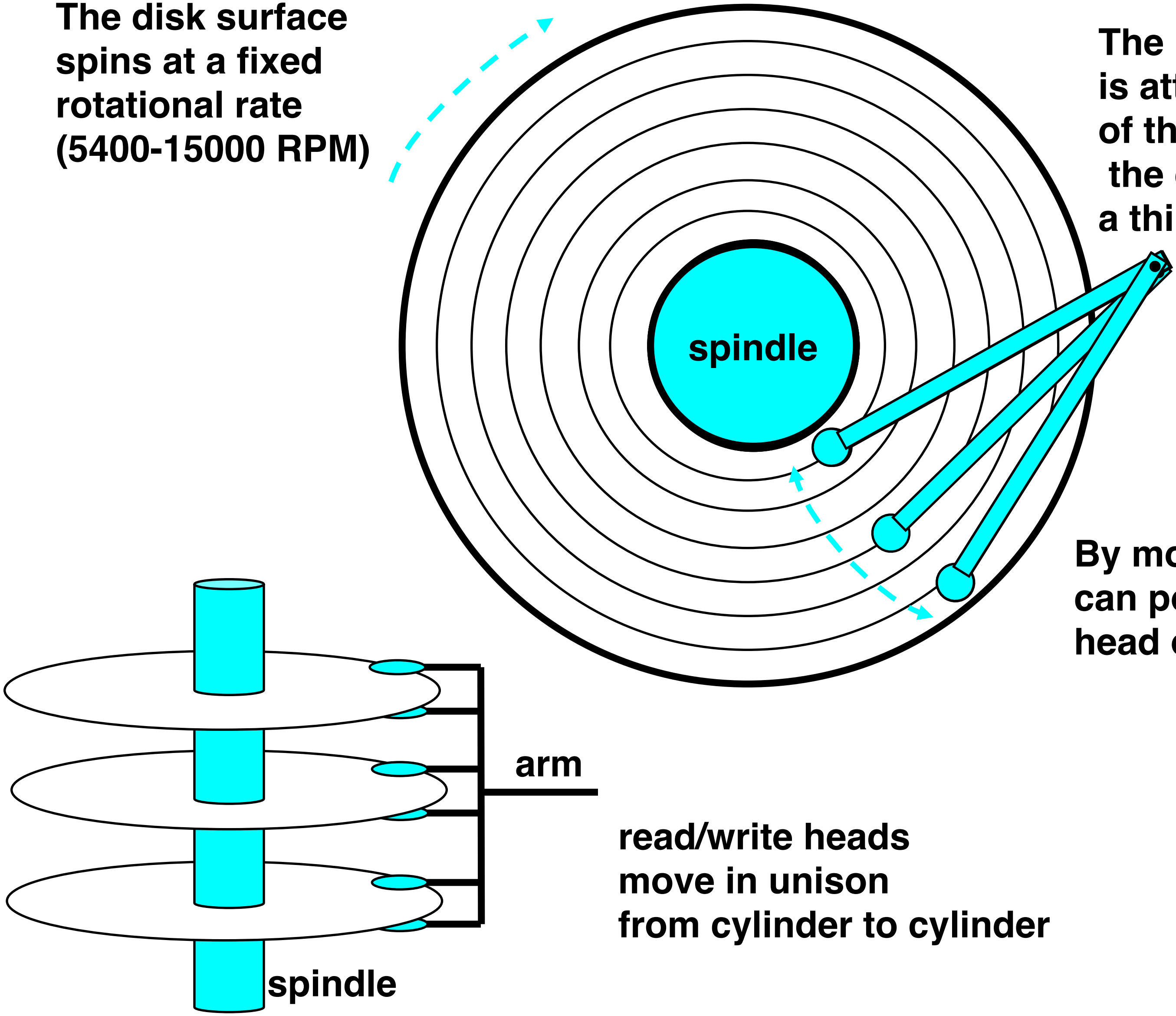
- Example:
  - 512 bytes/sector
  - 300 sectors/track (on average)
  - 20,000 tracks/surface
  - 2 surfaces/platter
  - 5 platters/disk

- Capacity = 512 x 300 x 20000 x 2 x 5 = 30,720,000,000 = 30.72 GB

Disk operation (Single-platter view)

The disk surface spins at a fixed rotational rate (5400-15000 RPM)

The read/write *head* is attached to the end of the *arm* and flies over the disk surface on a thin cushion of air.



By moving radially, the arm can position the read/write head over any track.

read/write heads move in unison from cylinder to cylinder

Disk access time

- Avg time to access target sector approximated by
  - $T_{access} = T_{avg\ seek} + T_{avg\ rotation} + T_{avg\ transfer}$

- Seek time ($T_{avg\ seek}$)
  - Time to position heads over cylinder containing target sector.
  - Typical $T_{avg\ seek}$ = 9 ms
- Rotational latency ($T_{avg\ rotation}$)
  - Time waiting for first bit of sector to pass under r/w head.
  - $T_{avg\ rotation} = T_{max\ rotation}/2 =$ 1/RPMs x 60 sec/1 min x 1/2
- Transfer time ($T_{avg\ transfer}$)
  - Time to read the bits in the target sector.
  - $T_{avg\ transfer}$ = 1/RPM x 1/(avg # sectors/track) x 60 secs/1 min.

Disk access time example

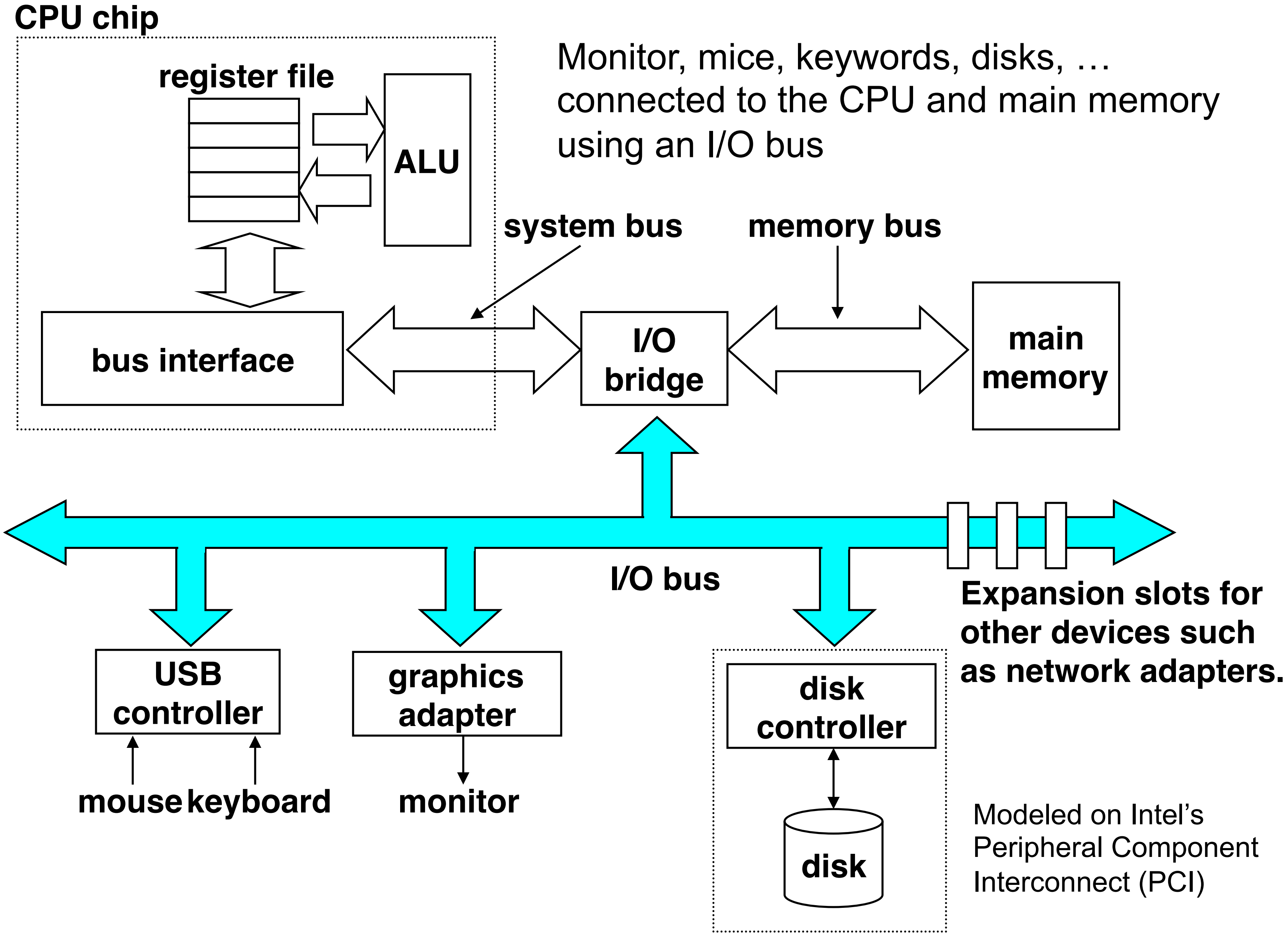
- Given:
  - Rotational rate = 7,200 RPM
  - Average seek time = 9 ms.
  - Avg # sectors/track = 400.
- Derived:
  - $T_{\text{avg rotation}}$ = 1/2 x (60 secs/7200 RPM) x 1000 ms/sec = 4 ms.
  - $T_{\text{avg transfer}}$ = 60/7200 RPM x 1/400 sec/track x 1000 ms/sec = 0.02 ms
  - $T_{\text{access}} = T_{\text{avg seek}} + T_{\text{avg rotation}} + T_{\text{avg transfer}}$ = 9 ms + 4 ms + 0.02 ms
- Important points:
  - *Access time dominated by seek time and rotational latency*
  - First bit in a sector is the most expensive, the rest are free
  - SRAM access time ~4 ns/doubleword, DRAM ~60 ns
    - Disk is about 40,000 times slower than SRAM,
    - 2,500 times slower than DRAM

Logical disk blocks

- Disks present a simpler abstract view of the complex sector geometry
  - Set of available sectors modeled as a sequence of b-sized logical blocks (0, 1, 2, ...)
- Mapping between logical blocks and physical sectors
  - Maintained by hw/firmware device called disk controller.
  - Converts requests for logical blocks into (surface, track, sector) triples
- Allows controller to set aside spare cylinders per zone
  - Accounts for the difference in “formatted capacity” and “maximum capacity”

Connecting I/O devices – I/O Bus

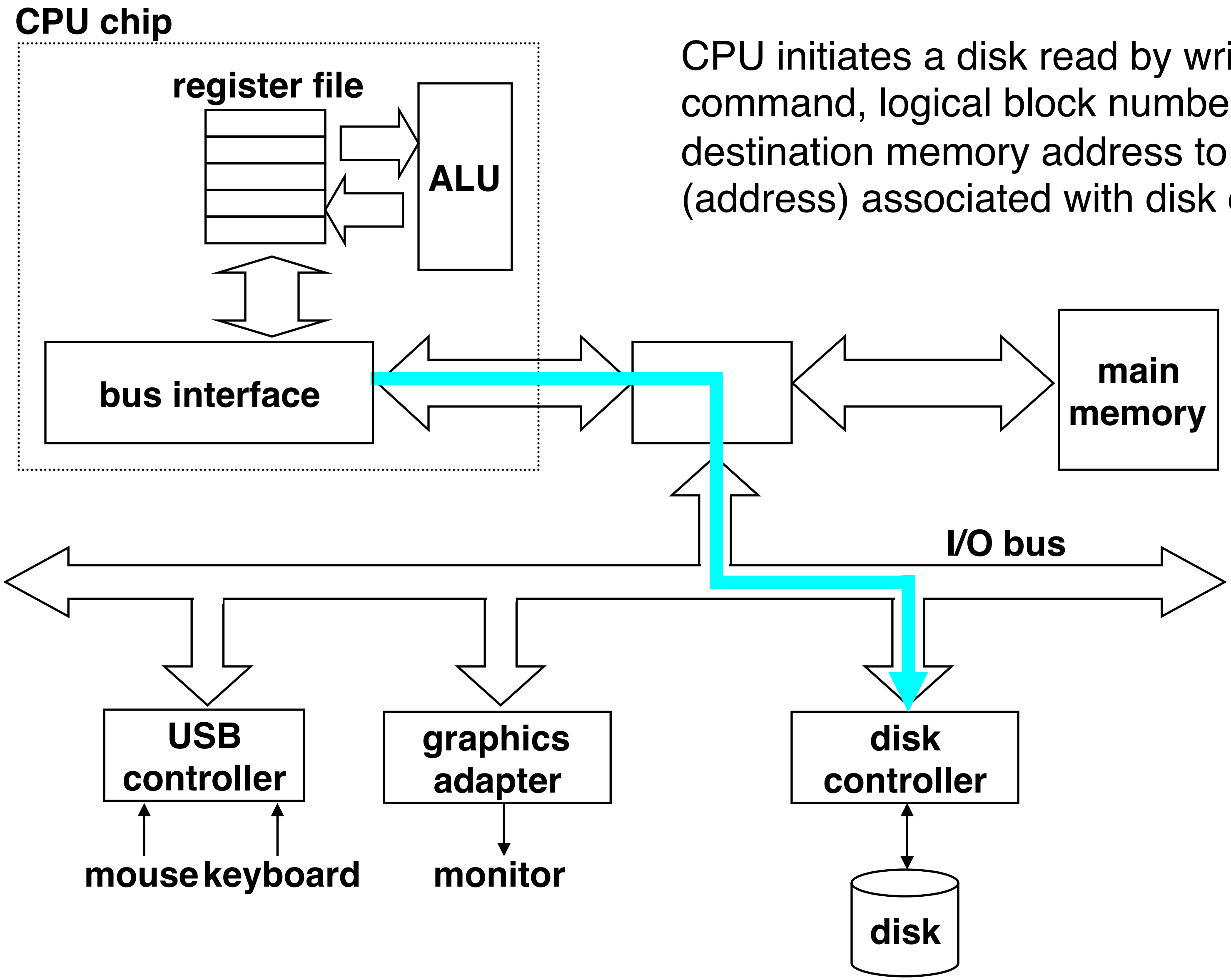
Monitor, mice, keywords, disks, … connected to the CPU and main memory using an I/O bus



Expansion slots for other devices such as network adapters.

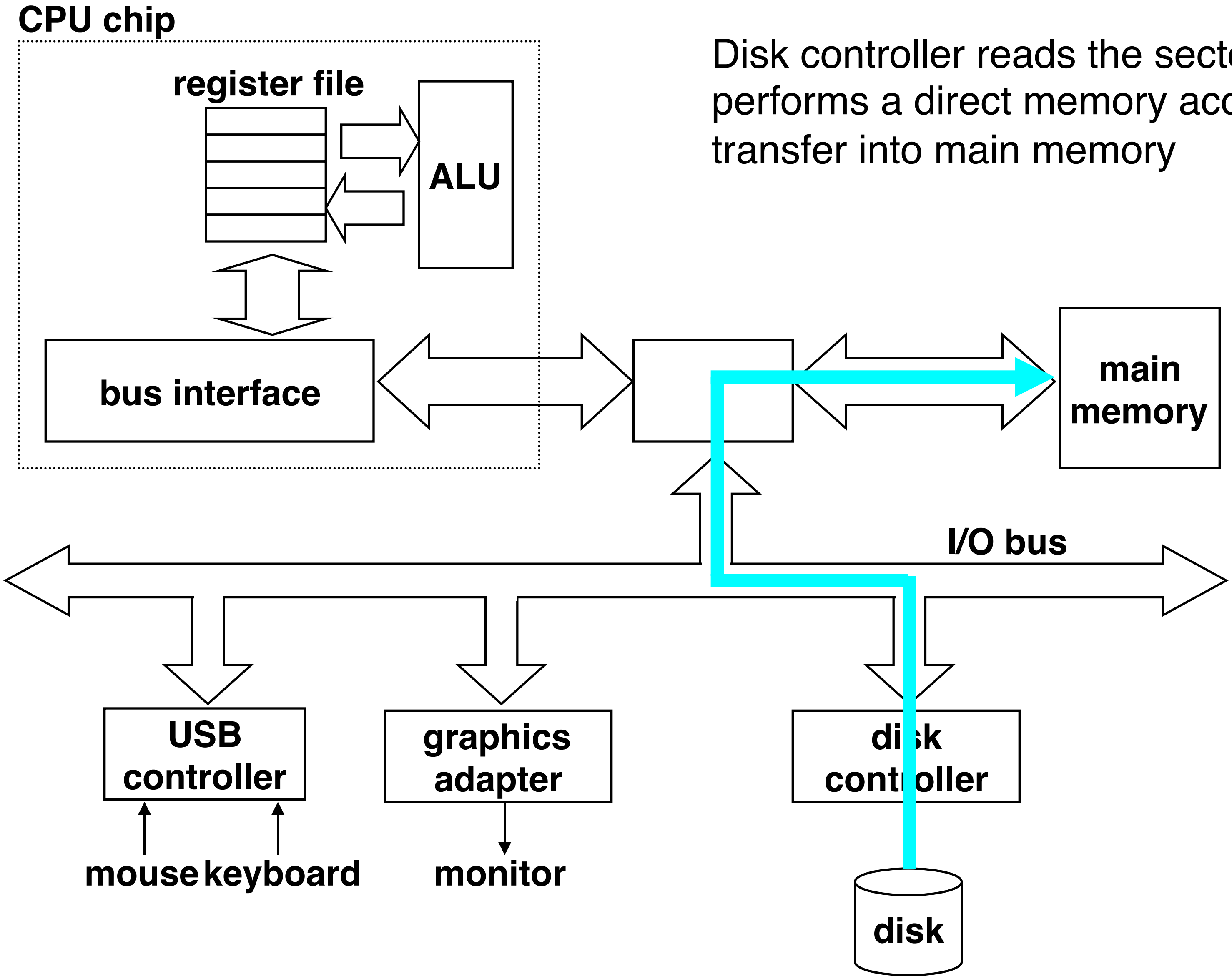
Modeled on Intel's Peripheral Component Interconnect (PCI)

Reading a disk sector (1)



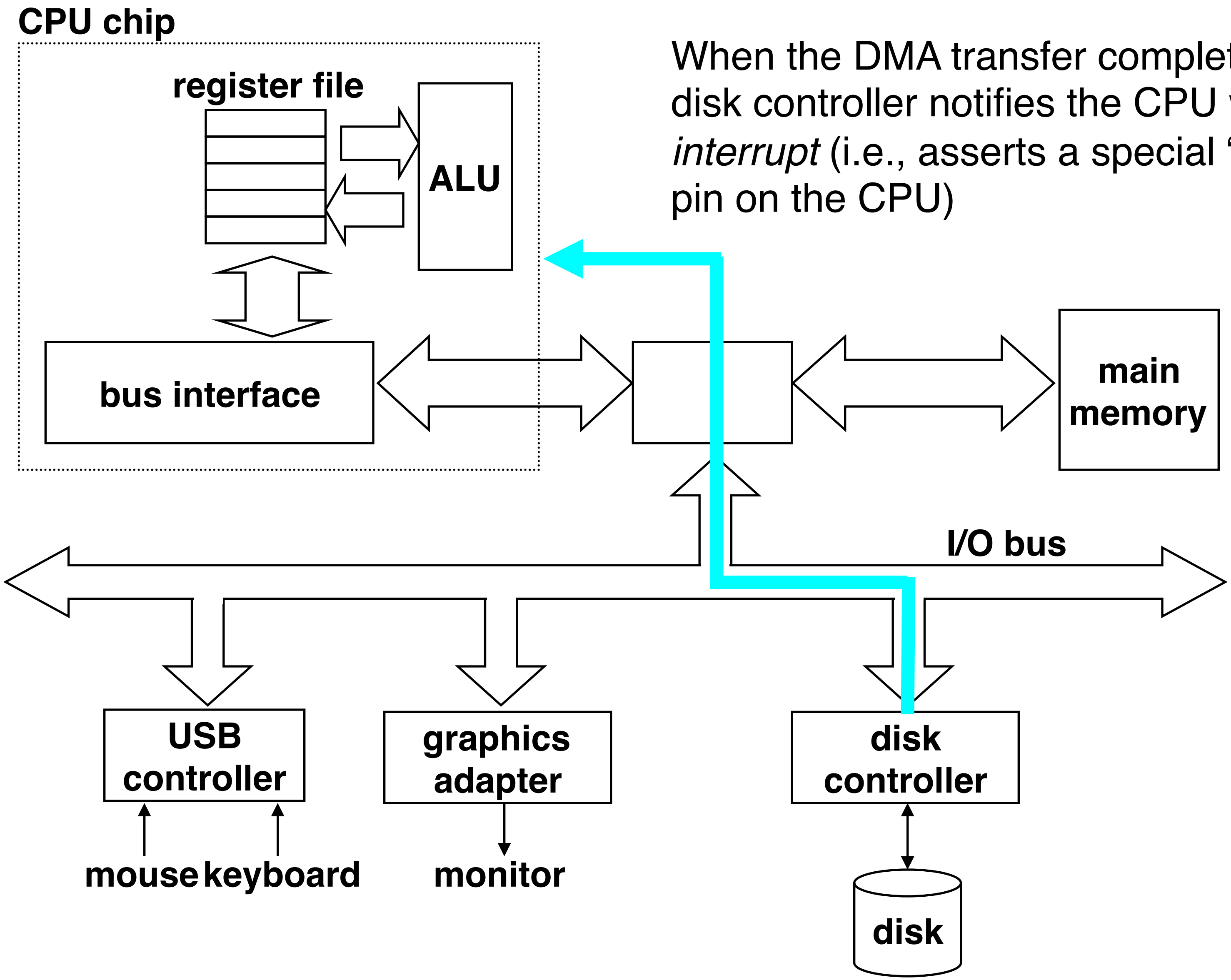
CPU initiates a disk read by writing a command, logical block number, and destination memory address to a *port* (address) associated with disk controller

Reading a disk sector (2)



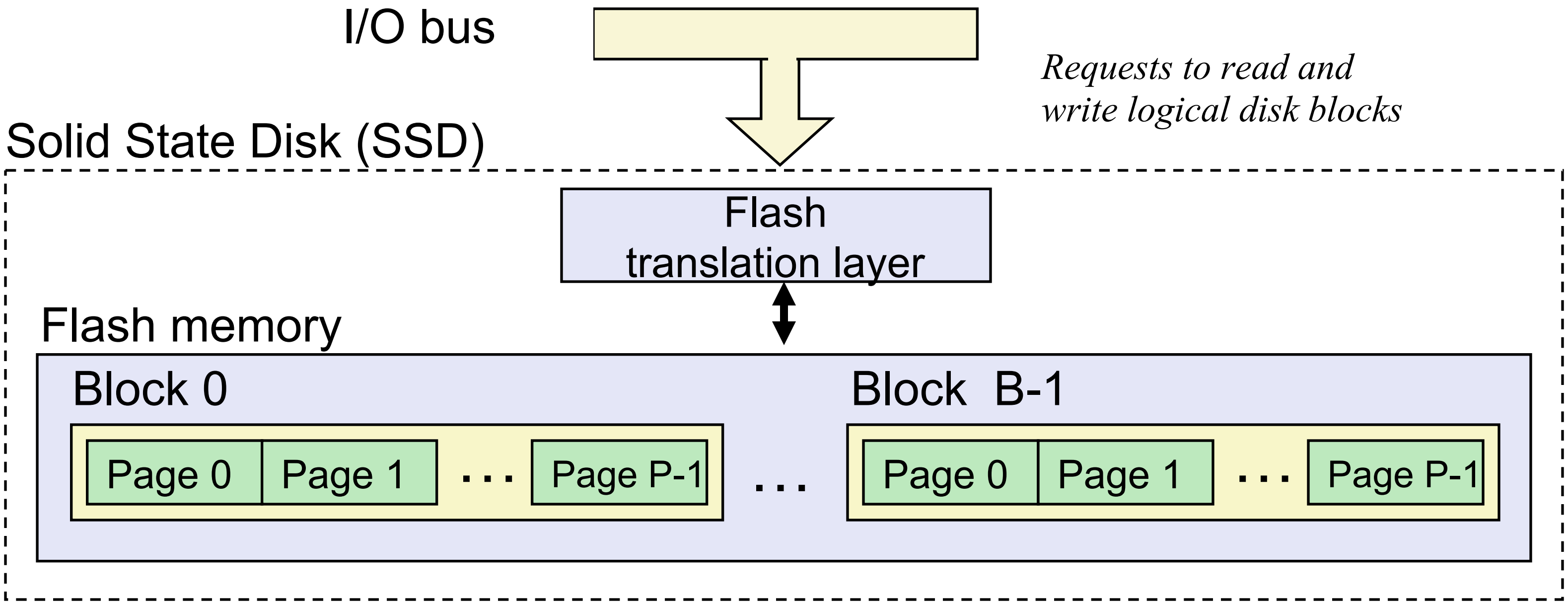
Disk controller reads the sector and performs a direct memory access (*DMA*) transfer into main memory

Reading a disk sector (3)



When the DMA transfer completes, the disk controller notifies the CPU with an *interrupt* (i.e., asserts a special “interrupt” pin on the CPU)

Solid State Disks (SSDs)



- Pages: 512KB to 4KB, Blocks: 32 to 128 pages
- Data read/written in units of pages.
- Page can be written only after its block has been erased
- A block wears out after ~100,000 repeated writes

SSD Performance Characteristics

Reads		Writes	
Sequential read tput	250MB/s	Sequential write tput	170MB/s
Random read tput	140MB/s	Random write tput	14MB/s
Random read access	30us	Random write access	300us

- Why are random writes so slow?
  - Erasing a block is slow (around 1 ms)
  - Write to a page triggers a copy of all useful pages in the block
    - Find an used block (new block) and erase it
    - Write the page into the new block
    - Copy other pages from old block to the new block

SSD Tradeoffs vs Rotating Disks

- Advantages
  - No moving parts → faster, less power, more rugged
- Disadvantages
  - Have the potential to wear out
    - Mitigated by “wear leveling logic” in flash translation layer
    - E.g. Intel X25 guarantees 1 petabyte (10^{15} bytes) of random writes before they wear out
  - In 2010, about 100 times more expensive per byte
- Applications
  - MP3 players, smart phones, laptops
  - Beginning to appear in desktops and servers

Storage trends

Cost decreased by a factor of ~200

SRAM

Metric	1980	1985	1990	1995	2000	2005	2010	2010:1980
$/MB	19,200	2900	320	256	100	75	60	320
Access (ns)	300	150	35	15	3	2	1.5	200

Access times decreased by a factor of ~300

DRAM

Metric	1980	1985	1990	1995	[illegible]	[illegible]	[illegible]	2010:1980
$/MB	800	880	100	30	1	.1	0.06	130,000
Access (ns)	375	200	100	70	60	50	40	9
Typical size (MB)	0.064	0.256	4	16	64	2000	8000	125,000

Different trends for DRAM and disks

Rotating disks

Metric	1980	1985	1990	1995	2000	2005	2010	2010:1980
$/MB	500	100	8	0.30	0.01	0.005	0.0003	1,600,000
Access (ns)	87	75	28	10	8	5	3	29
Typical size (MB)	1	10	16	1000	20,000	160,000	1,500,000	1,500,000

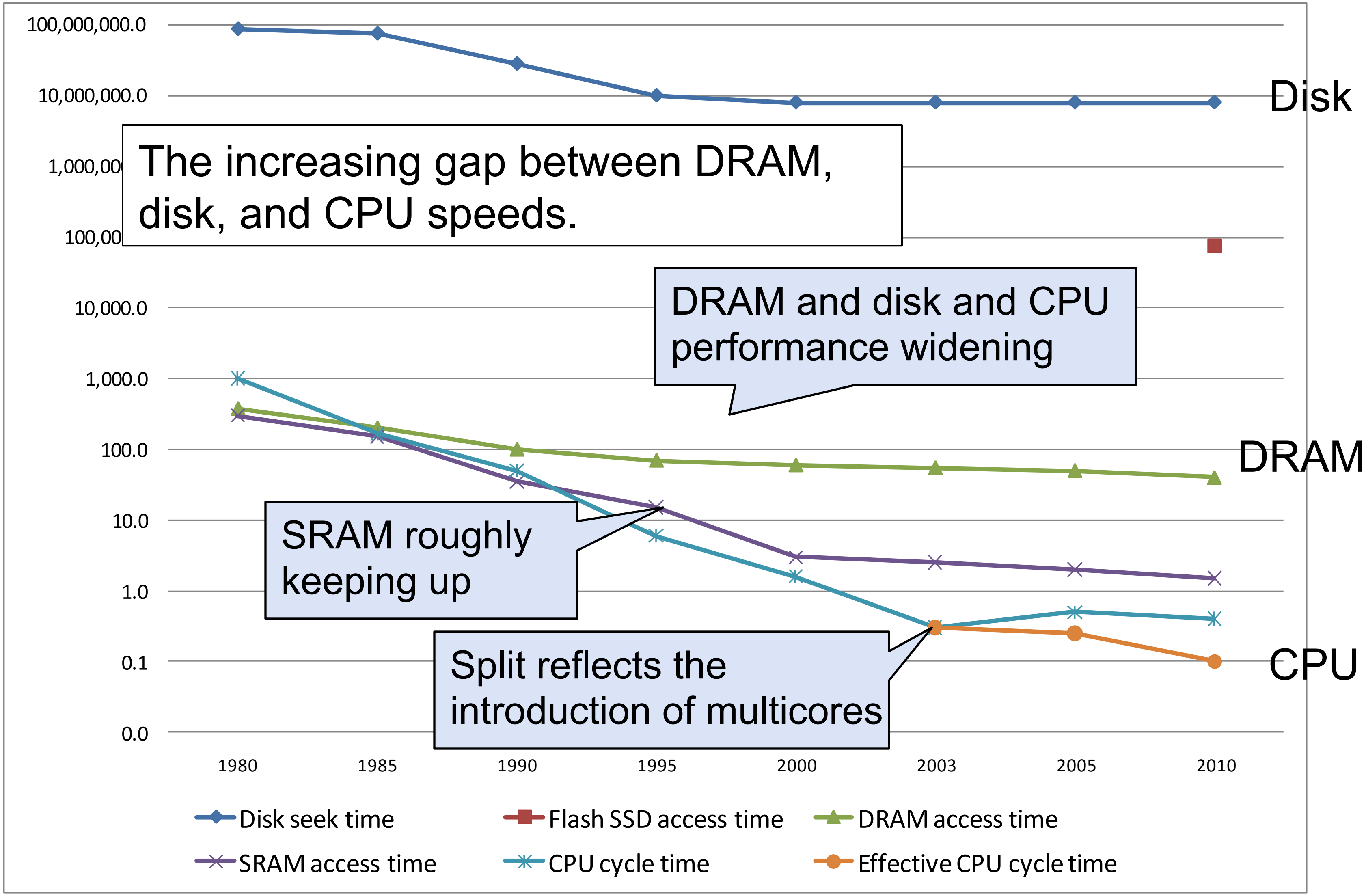
(Culled from back issues of Byte and PC Magazine)

CPU trends

Metric	1980	1985	1990	1995	2000	2003	2005	2010	2010:1980
Intel CPU	**8080**	**80286**	**80386**	**Pent**	**P-III**	**Pent. 4**	**Core 2**	**Core i7**	
Clock rate (MHz)	1	6	20	150	600	3300	2000	2500	2500
Cycle time (ns)	1000	166	50	6	1.6	0.30	0.50	0.4	2500
Cores	1	1	1	1	1	1	2	4	4
Eff. cycle times (ms)	1000	166	50	6	1.6	0.30	0.25	0.10	10,000

Cycle time divided by number of cores

The CPU-Memory gap



The increasing gap between DRAM, disk, and CPU speeds.

DRAM and disk and CPU performance widening

SRAM roughly keeping up

Split reflects the introduction of multicores

Locality

- Principle of Locality:
  - Programs tend to reuse/use data items recently used or nearby those recently used
  - Temporal locality: Recently referenced items are likely to be referenced in the near future
  - Spatial locality: Items with nearby addresses tend to be referenced close together in time

```
sum = 0;
for (i = 0; i < n; i++)
    sum += a[i];
return sum;
```

Locality Example:

- **Data**
  - Reference array elements in succession (stride-1 reference pattern): **Spatial locality**
  - Reference `sum` each iteration: **Temporal locality**
- **Instructions**
  - Reference instructions in sequence: **Spatial locality**
  - Cycle through loop repeatedly: **Temporal locality**

Locality example

- To look at code and get a qualitative sense of its locality is a key skill for a professional programmer
- *Does this function have good locality?*

```
int sumarrayrows(int a[M][N])
{
    int i, j, sum = 0;

    for (i = 0; i < M; i++)
        for (j = 0; j < N; j++)
            sum += a[i][j];
    return sum
}
```

Temporal or spatial locality?

- *Yes!* Array is accessed in same row-major order in which it is stored in memory

Locality example

- *Does this function have good locality?*

```
int sumarraycols(int a[M][N])
{
    int i, j, sum = 0;

    for (j = 0; j < N; j++)
        for (i = 0; i < M; i++)
            sum += a[i][j];
    return sum
}
```

- *No!* Scans array column-wise instead of row-wise

Locality example

- Can you permute the loops so that the function scans the 3-d array `a[]` with a stride-1 reference pattern (and thus has good spatial locality)?

```
int sumarray3d(int a[M][N][N])
{
    int i, j, k, sum = 0;

    for (i = 0; i < M; i++)
        for (j = 0; j < N; j++)
            for (k = 0; k < N; k++)
                sum += a[k][i][j];
    return sum
}
```

Visiting every k-element of a contiguous vector is called a stride-k reference pattern

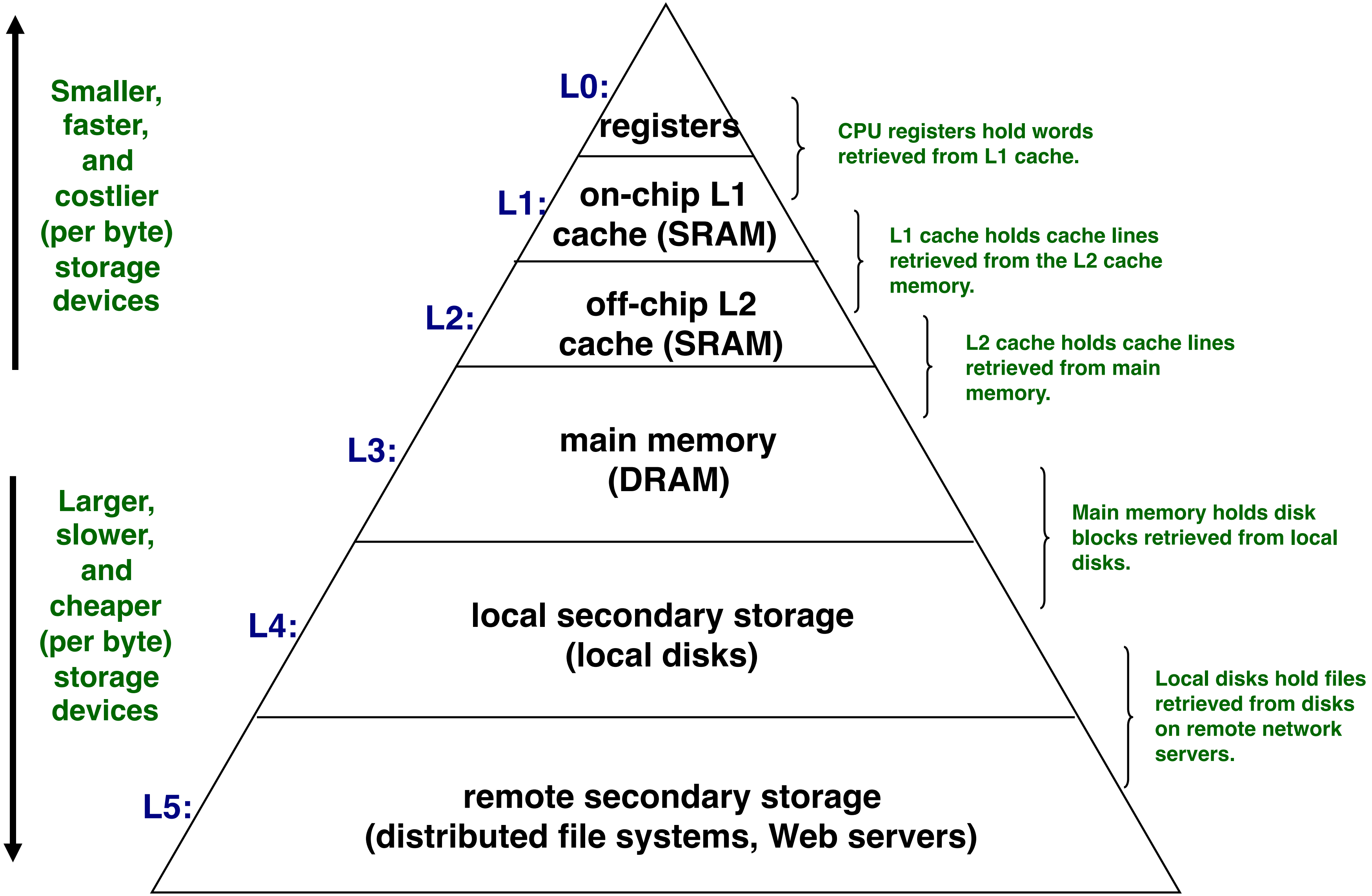
```
int sumarray3d(int a[M][N][N])
{
    int i, j, k, sum = 0;

    for (k = 0; k < N; k++)
        for (i = 0; i < M; i++)
            for (j = 0; j < N; j++)
                sum += a[k][i][j];
    return sum
}
```

Memory hierarchies

- Some fundamental and enduring properties of hardware and software:
  - Fast storage tech cost more per byte and have less capacity.
  - The gap between CPU and main memory speed is widening.
  - Well-written programs tend to exhibit good locality.
- These fundamental properties complement each other beautifully.
- They suggest an approach for organizing memory and storage systems known as a memory hierarchy.

An example memory hierarchy



CPU registers hold words retrieved from L1 cache.

L1 cache holds cache lines retrieved from the L2 cache memory.

L2 cache holds cache lines retrieved from main memory.

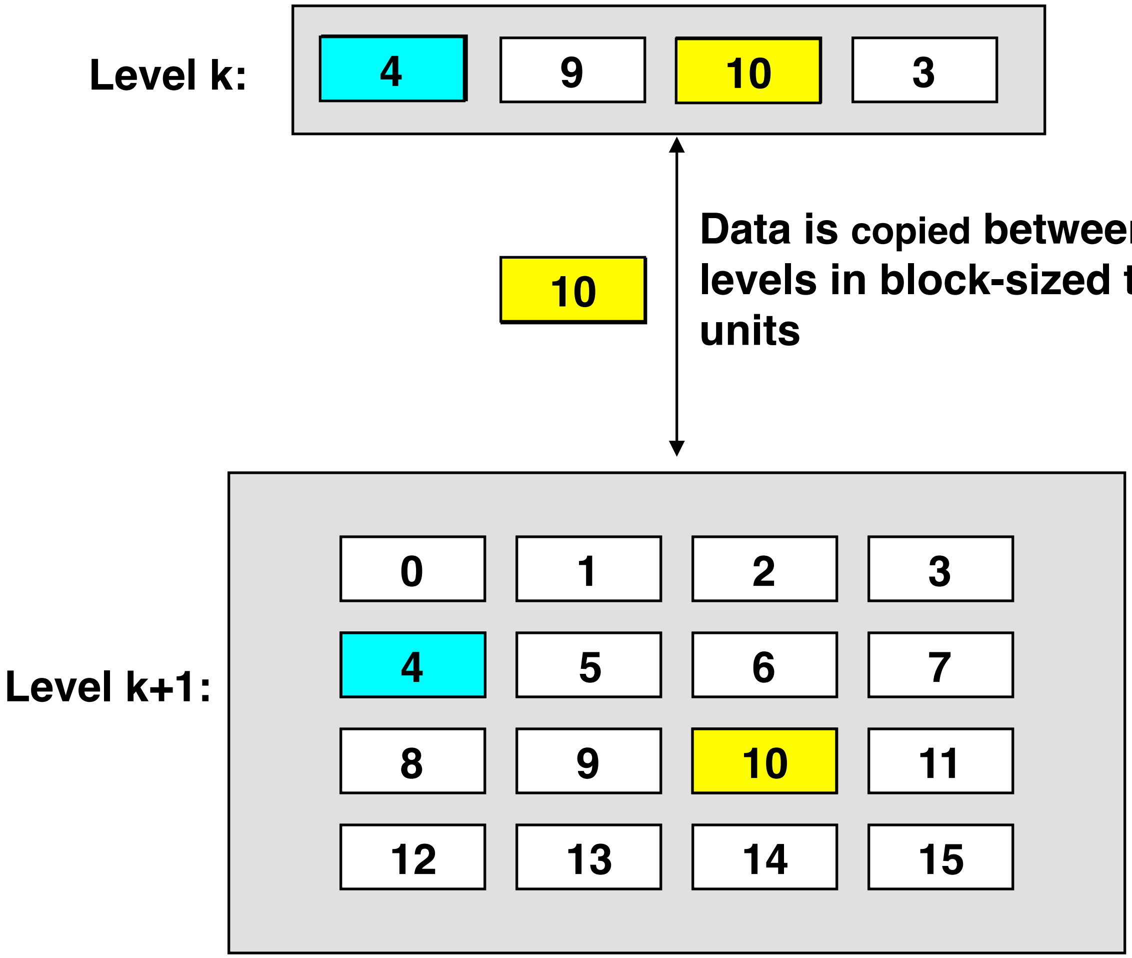
Main memory holds disk blocks retrieved from local disks.

Local disks hold files retrieved from disks on remote network servers.

Caches

- *Cache*: A smaller, faster storage device that acts as a staging area for a subset of the data in a larger, slower device
- Fundamental idea of a memory hierarchy:
  - For each *k*, the faster, smaller device at level *k* serves as a cache for the larger, slower device at level *k+1*
- Why do memory hierarchies work?
  - Programs tend to access the data at level *k* more often than they access the data at level *k+1*
  - Thus, the storage at level *k+1* can be slower, and thus larger and cheaper per bit
  - *Net effect: A **large pool of memory** that **costs as much as the cheap** storage near the bottom, but that serves data to programs at the **rate of the fast** storage near the top*

Caching in a memory hierarchy

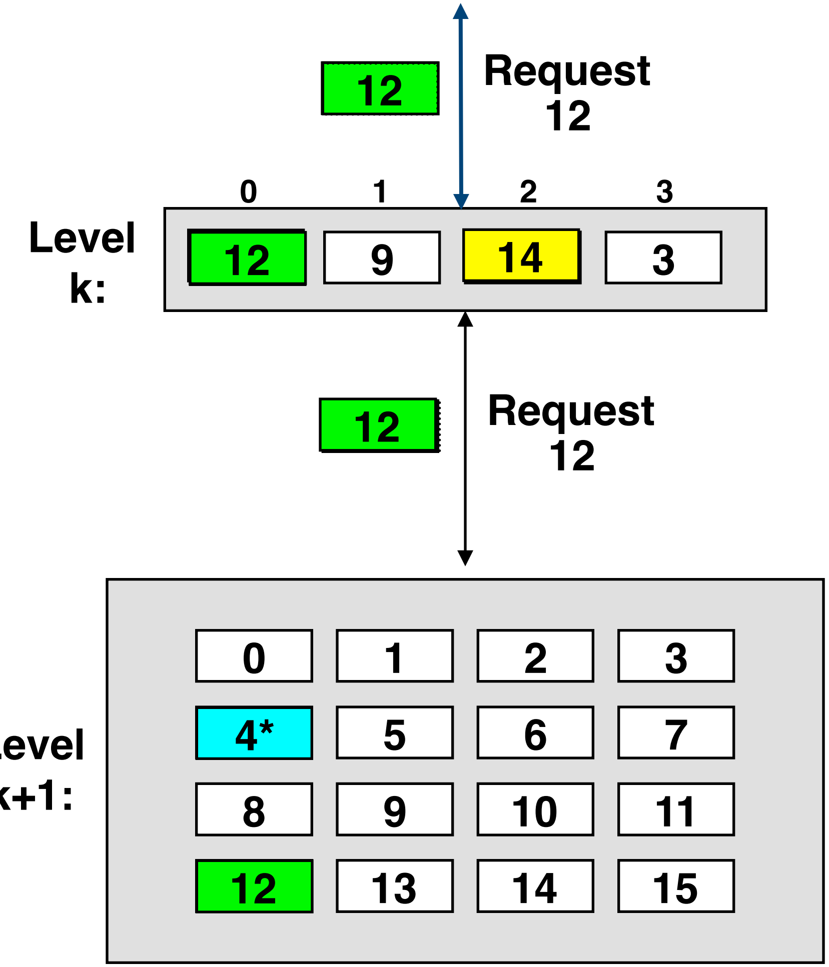


Smaller, faster, more expensive device at level k caches a subset of the blocks from level k+1

Data is copied between levels in block-sized transfer units

Larger, slower, cheaper storage device at level k+1 is partitioned into blocks.

General caching concepts



- Program needs object d, which is stored in some block b
- Cache hit
  - Program finds b in the cache at level k. E.g., block 14
- Cache miss
  - b is not at level k, so level k cache must fetch it from level k+1.   E.g., block 12
  - If level k cache is full, then some current block must be replaced (evicted). Which one is the “victim”?
    - Placement policy: where can the new block go? E.g., b mod 4
    - Replacement policy: which block should be evicted? E.g., LRU

General caching concepts

- Types of cache misses:
  - Cold (compulsary) miss
    - Cold misses occur because the cache is empty
  - Conflict miss
    - Most caches limit blocks at level k+1 to a small subset (sometimes a singleton) of the block positions at level k
    - E.g. Block i at level k+1 must go to block (i mod 4) at level k+1
    - Conflict misses occur when level k cache is large enough, but multiple data objects all map to the same level k block
    - E.g. Referencing blocks 0, 8, 0, 8, 0, 8, ... would miss every time.
  - Capacity miss
    - Occurs when the set of active cache blocks (*working set*) is larger than the cache

Examples of caching in the hierarchy

Cache type	What cached	Where cached	Latency (cycles)	Managed by
Registers	4B word	CPU registers	0	Compiler
TLB	Address translation	On-Chip TLB	0	Hardware
L1 cache	32B block	On-chip L1	1	Hardware
L2 cache	32B block	Off-chip L2	10	Hardware
Virtual memory	4KB page	Main memory	100	Hardware+OS
Buffer cache	Parts of files	Main memory	100	OS
Network buffer cache	Parts of files	Local disks	10,000,000	AFS/NFS client
Browser cache	Web pages	Local disks	10,000,000	Web browser
Web cache	Web pages	Remote server disk	1,000,000,000	Web proxy server

Summary

- Speed gap between CPU, memory and secondary storage keeps growing
- Well written code exhibits locality
- Memory hierarchy based on caching leverages locality to close the gap