CSE 451: Operating Systems
Spring 2009

Module 12
Secondary Storage

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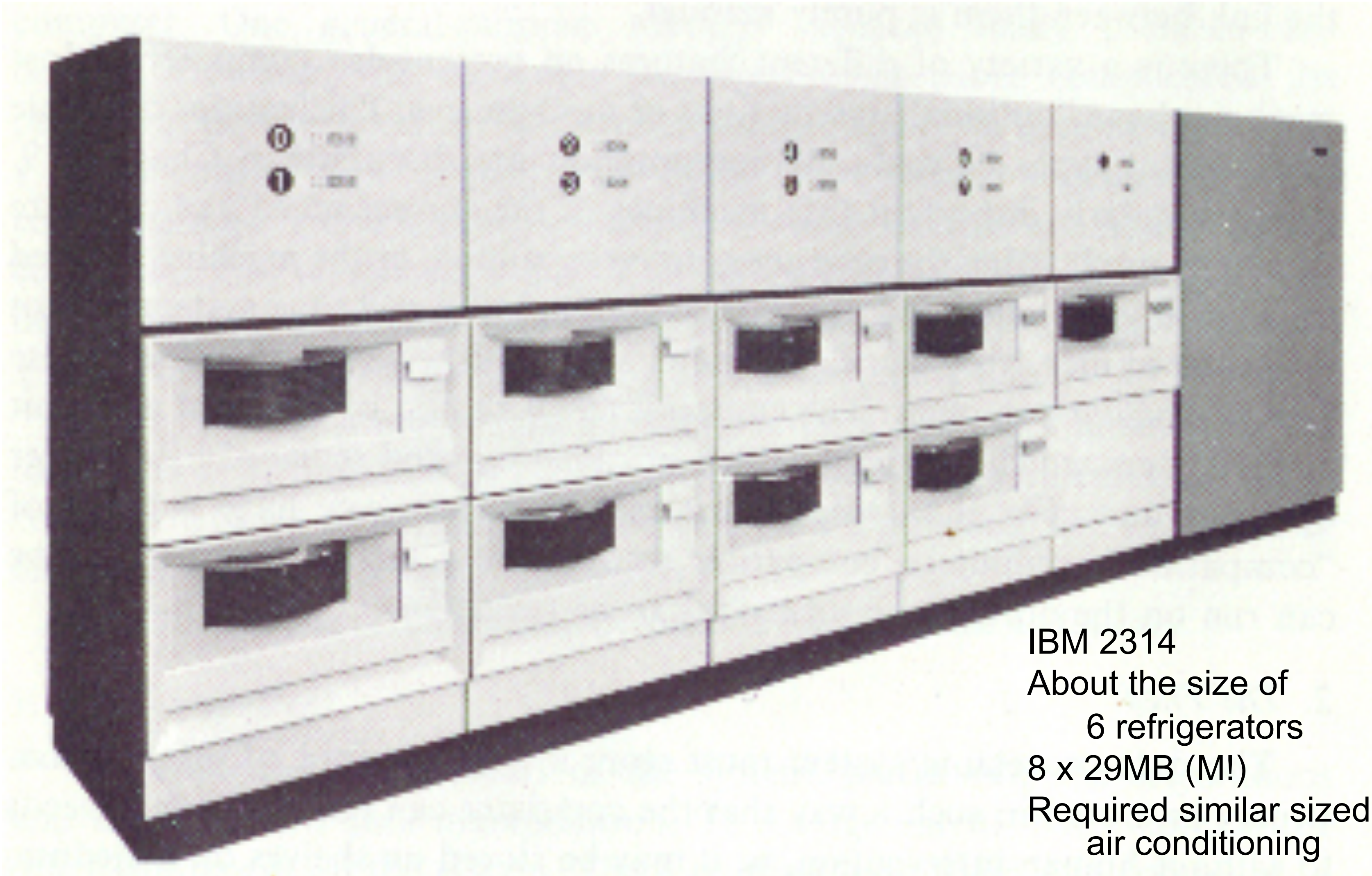
Secondary storage

- Secondary storage typically:
  - is anything that is outside of "primary memory"
  - does not permit direct execution of instructions or data retrieval via machine load/store instructions
- Characteristics:
  - it's large: 50-1000GB (or more!)
  - it's cheap: $0.10/GB for hard drives, $10/GB for SSD
  - it's persistent: data survives power loss
  - it's slow:
    - milliseconds to access for hard drives, microseconds for SSD
    - why is this considered slow?
  - it *does* fail, if rarely
    - Big failures (drive dies)
    - Little failures (read/write errors, one byte in 10^13)

Another trip down memory lane …



IBM 2314
About the size of
6 refrigerators
8 x 29MB (M!)
Required similar sized
air conditioning

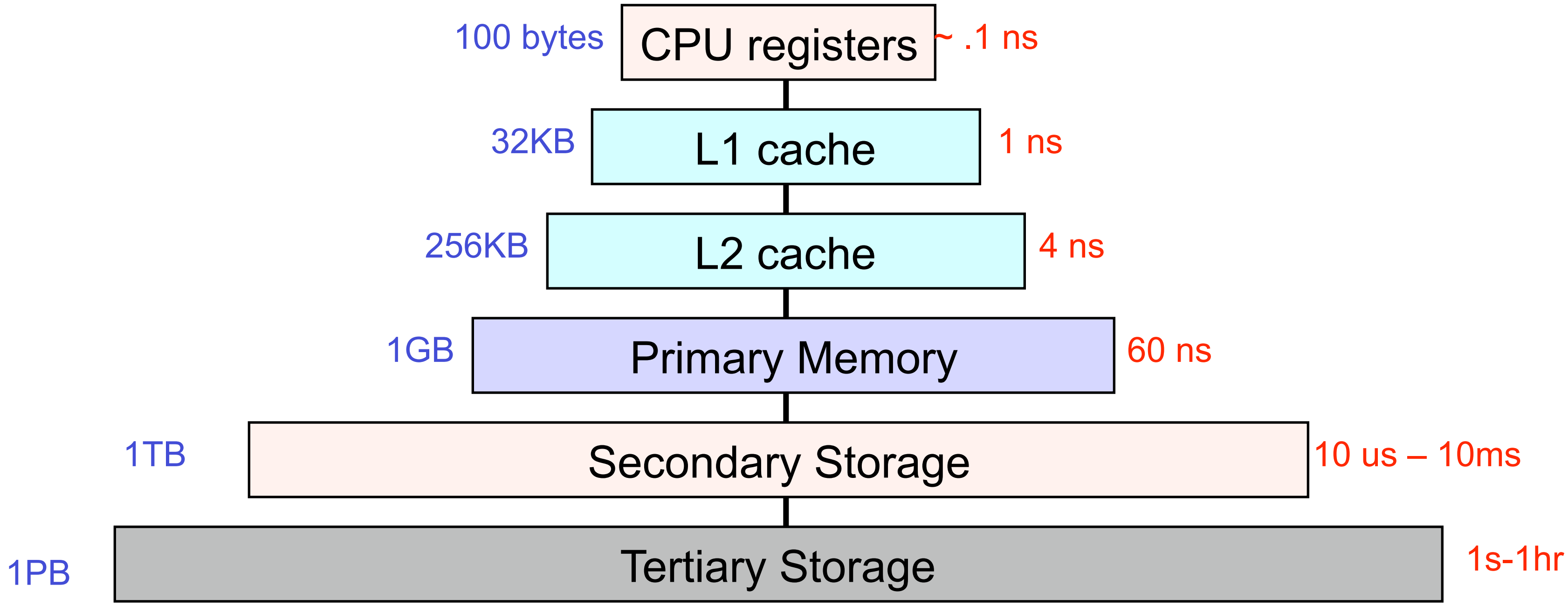
(Hard) Disk trends

- Disk capacity, 1975-1989
  - doubled every 3+ years
  - 25% improvement each year
  - factor of 10 every decade
  - Still exponential, but far less rapid than processor performance
- Disk capacity 1990-2003
  - doubling every 12 months
  - 100% improvement each year
  - factor of 1000 every decade
  - Capacity growth 10x as fast as processor performance!
- Disk capacity 2003-2009
  - Slowed somewhat, doubling every 1.5 years

(Hard) Disk trends

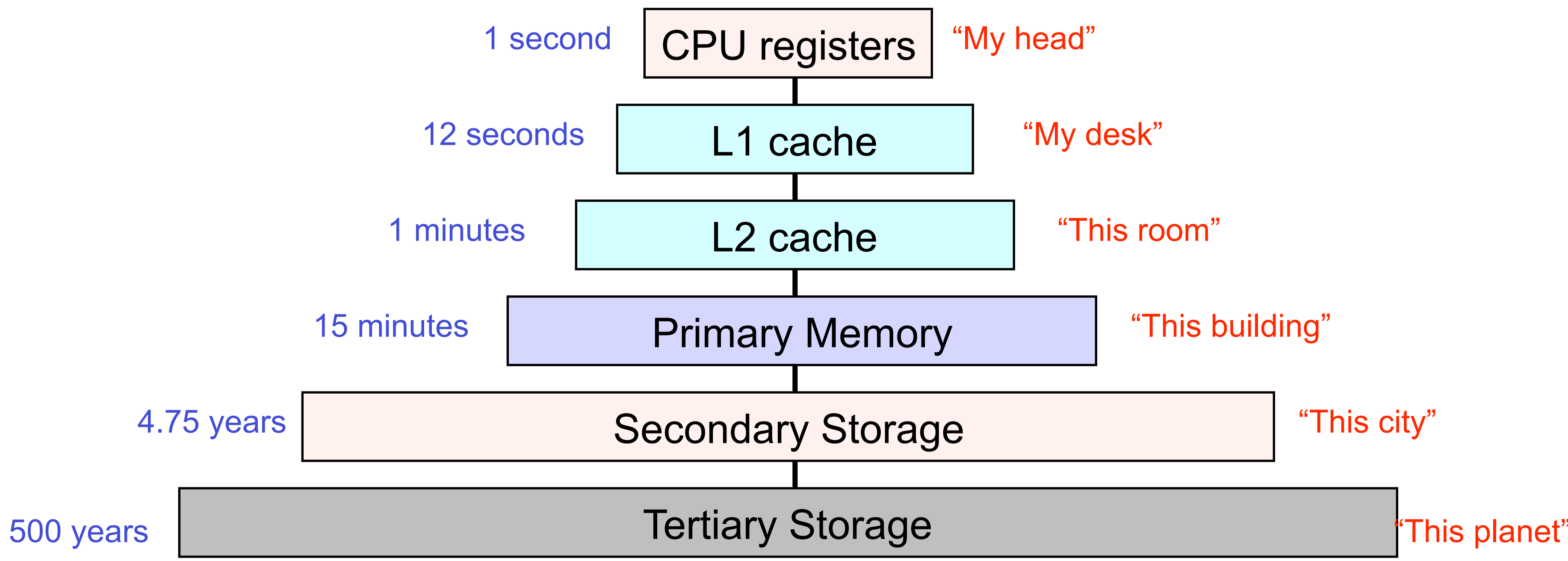
- Only a decade ago, we purchased disks by the megabyte (and it hurt!)
- Today, 1 GB (a billion bytes) costs ~~$1~~ ~~$0.50~~ $0.1- from Dell (except you have to buy in increments of ~~40~~ ~~80~~ ~~250~~ 500 GB or 1TB)
  - => 1 TB costs ~~$1K~~ ~~$500~~ ~~$250~~ $100, 1 PB ~~costs~~ costs ~~$1M~~ ~~$500K~~ ~~$250K~~, $100K
- Technology is amazing
  - Flying 747 six inches above the ground at 600mph
  - Reading/writing a strip of postage stamps
- But…
  - Jet bumps down
  - Bits are so close that cosmic rays/quantum effects change them

Memory hierarchy



- Each level acts as a cache of lower levels

Memory hierarchy: distance analogy



Big Picture

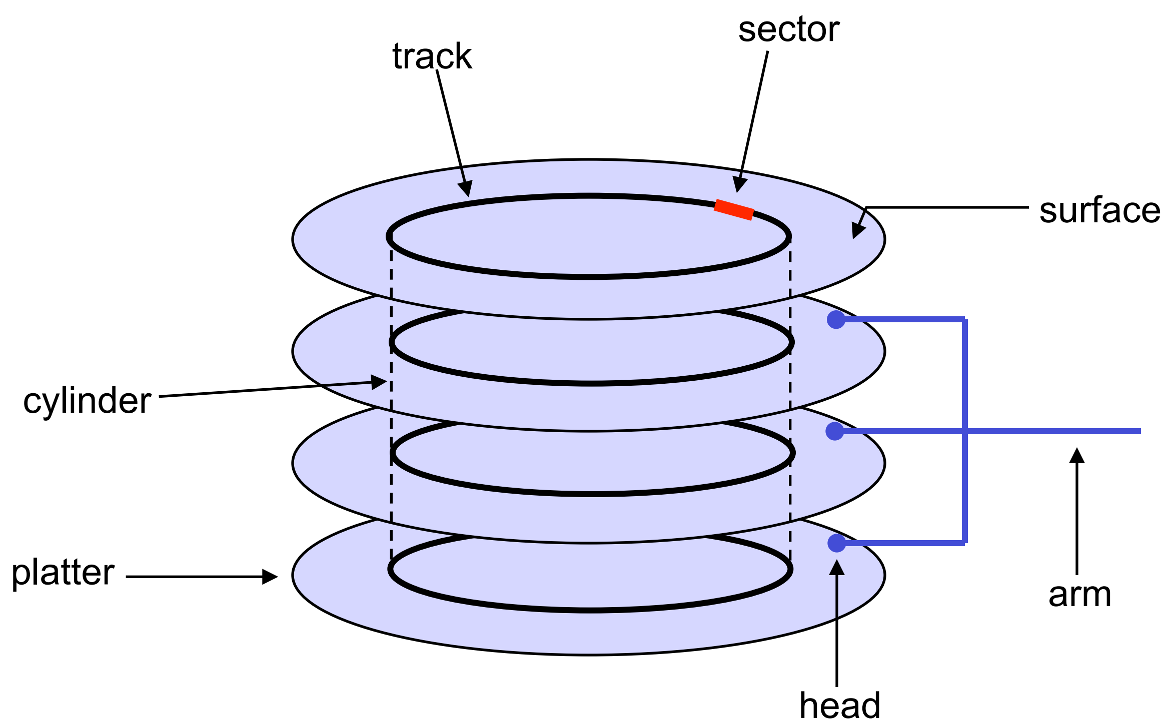
- OS provides abstractions to allow physical HW resources to be shared / protected
  – CPU sharing with threads (virtual CPU)
  – Memory sharing with virtual memory
  – Disk sharing with files

Disks and the OS

- Disks are messy, messy devices
  - errors, bad blocks, etc.
- Job of OS is to hide this mess from higher-level software
  - low-level device drivers (initiate a disk read, etc.)
  - higher-level abstractions (files, databases, etc.)
- OS may provide different levels of disk access to different clients
  - physical disk block (head, cylinder, sector)
  - disk logical block (disk block #)
  - file logical (filename, block or record or byte #)

Physical hard disk structure

- Disk components
  - platters
  - surfaces
  - tracks
  - sectors
  - cylinders
  - arm
  - heads



Disk performance

- Performance depends on a number of steps
  - seek: moving the disk arm to the correct cylinder
    - depends on how fast disk arm can move
      - seek times aren’t diminishing very quickly (why?)
  - rotation (latency): waiting for the sector to rotate under head
    - depends on rotation rate of disk
      - rates are increasing, but slowly (why?)
  - transfer: transferring data from surface into disk controller, and from there sending it back to host
    - depends on density of bytes on disk
      - increasing, relatively quickly
- When the OS uses the disk, it tries to minimize the cost of all of these steps
  - particularly seeks and rotation

Performance via disk layout

- OS may increase file block size in order to reduce seeking
- OS may seek to co-locate “related” items in order to reduce seeking
  - blocks of the same file
  - data and metadata for a file

Performance via caching, pre-fetching

- Keep data or metadata in memory to reduce physical disk access
  - problem?
- If file access is sequential, fetch blocks into memory before requested

Performance via disk scheduling

- Seeks are very expensive, so the OS attempts to schedule disk requests that are queued waiting for the disk
  - FCFS (do nothing)
    - reasonable when load is low
    - long waiting time for long request queues
  - SSTF (shortest seek time first)
    - minimize arm movement (seek time), maximize request rate
    - unfairly favors middle blocks
  - SCAN (elevator algorithm)
    - service requests in one direction until done, then reverse
    - skews wait times non-uniformly (why?)
  - C-SCAN
    - like scan, but only go in one direction (typewriter)
    - uniform wait times

Interacting with disks

- In the old days…
  - OS would have to specify cylinder #, sector #, surface #, transfer size
    - i.e., OS needs to know all of the disk parameters
- Modern disks are even more complicated
  - not all sectors are the same size, sectors are remapped, …
  - disk provides a higher-level interface, e.g., SCSI
    - exports data as a logical array of blocks [0 … N]
    - maps logical blocks to cylinder/surface/sector
    - OS only needs to name logical block #, disk maps this to cylinder/surface/sector
    - on-board cache
    - as a result, physical parameters are hidden from OS
      - both good and bad

Seagate Barracuda 3.5” disk drive

- 1Terabyte of storage (1000 GB)
- $100
- 4 platters, 8 disk heads
- 63 sectors (512 bytes) per track
- 16,383 cylinders (tracks)
- 164 Gbits / inch-squared (!)
- 7200 RPM
- 300 MB/second transfer
- 9 ms avg. seek, 4.5 ms avg. rotational latency
- 1 ms track-to-track seek
- 32 MB cache

Solid state drives: imminent disruption

- Hard drives are based on spinning magnetic platters
  - *mechanics* of drives drive performance characteristics
    - sector addressable, not byte addressable
    - capacity, sequential bandwidth improving exponentially
    - random access latency improving very slowly
  - cost dictated by massive economies of scale, and many decades of commercial development and optimization

- Solid state drives are based on NAND flash memory
  - no moving parts; performance characteristics driven by electronics and physics – more like RAM than spinning disk
  - relative technological newcomer, so costs are still quite high in comparison to hard drives, but dropping fast

SSD performance: reads

- Reads
  - unit of read is a *page*, typically 4KB large
  - today's SSD can typically handle 10,000 – 100,000 reads/s
    - 0.01 – 0.1 ms read latency (50-1000x better than disk seeks)
    - 40-400 MB/s read throughput (1-3x better than disk seq. thpt)

SSD performance: writes

- Writes
  - flash media must be *erased* before it can be written to
  - unit of erase is a block, typically 64-256 pages long
    - usually takes 1-2ms to erase a block
    - blocks can only be erased a certain number of times before they become unusable – typically 100,000 – 1,000,000 times
  - unit of write is a page
    - writing a page can be 2-10x slower than reading a page
- Writing to an SSD is complicated
  - random write to existing block: read block, erase block, write back modified block
    - leads to hard-drive like performance (300 random writes / s)
  - sequential writes to erased blocks: fast!
    - SSD-read like performance (100-200 MB/s)

SSDs: dealing with erases, writes

- Lots of higher-level strategies to hiding the warts of an SSD
  - many of these work by virtualizing pages and blocks on the drive (i.e., exposing logical pages, not physical pages, to the rest of the computer)
  - wear-leveling: when writing, try to spread erases out evenly across physical blocks of of the SSD.
    - Intel promises 100GB/day x 5 years for its SSD drives
  - log-structured filesystems: convert random writes within a filesystem to log appends on the SSD (more later)
  - build drives out of arrays of SSDs, add lots of cache

SSD cost

- Capacity
  - today, flash SSD costs $5-10 / GB
    - 64GB drive costs around $300-600
  - Data on cost trends is a little sketchy and preliminary
  - SSD vendors claim 2x drop in price per year
    - In 2014, $100 buys you a 200GB SSD or a 7TB hard drive
- Energy
  - SSD is typically more energy efficient than a hard drive
    - 1-2 watts to power a SSDs
    - ~10 watts to power a high performance hard drive
      - (can also buy a 1 watt low performance drive)

Intel X-25-E SSD

- 64GB for $800 (~$10/GB)
- Sustained sequential performance
  - Reads: 250 MB/s
  - Writes: 170 MB/s
- Sustained, random 4096byte operations
  - Reads: 35K operations per second
  - Writes: 3.3K operations per second
- Latency
  - Read: 75 microseconds
  - Write: 85 microseconds   (∃ write cache!)
- Lifetime
  - 2 petabytes of random writes