UMD DATA605 - Big Data Systems

Relational DB Internals

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- Sources
  - Silberschatz et al. 2020, Chap 12, Physical Storage Systems
  - Silberschatz et al. 2020, Chap 13: Data Storage Structures

- ***Storage***
    - Magnetic disks / SSD
    - RAID
    - DB internals

Storage Characteristics

- Storage media presents a trade-off between:
  - Speed of access (e.g., 500-3,500MB / sec)
  - Cost per unit of data (e.g., 50 USD / TB)
  - Medium reliability
- Volatile vs non-volatile storage
  - **Volatile**: loses contents when power switched off
  - **Non-volatile**: can survive failures and system crashes
- Sequential vs random access
  - **Sequential**: read the data contiguously

```
SELECT * FROM employee
```

- **Random**: read the data from anywhere at any time

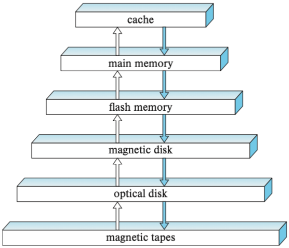
```
SELECT * FROM employee
WHERE name LIKE '\_\_a\_\_b'
```

- Need to know how data is stored in order to optimize access

Storage Hierarchy

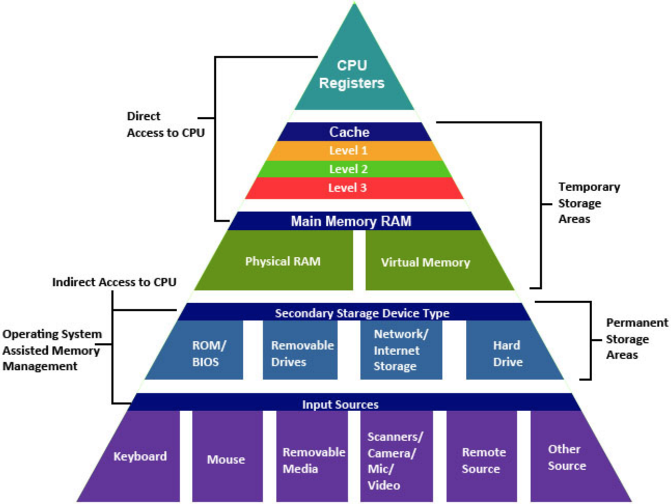
Various storage can be organized in a hierarchy according to (decreasing) speed and cost

- Cache
  - Fastest and most costly
  - ~MBs on chip
  - DB developers do pay attention to cache effects
- Main memory
  - Up to 100s of GBs
  - Typically can't store the entire DB
  - Volatile
- **Flash memory / SSDs**
  - More expensive than RAM but less than magnetic disk
  - Non-volatile, random access
- Magnetic disk
  - Long-term on-line storage
  - Non-volatile (can survive failures and system crashes)
- Optical disk (CD, Blue Ray)
  - Mainly read-only
- Magnetic tapes



- Primary storage: cache, main memory
- Secondary (or online): flash memory, magnetic disk
- **Offline:** optical, magnetic tape

Storage Hierarchy



source: http://cse1.net/recaps/4-memory.html

How Important Is Memory Hierarchy?

- Trade-offs shifted drastically over last 10-15 years
- **Innovations:**
  - Fast network, SSDs, and large memories
  - However, the volume of data is growing rapidly
- **Observations**:
  - Faster to access another computer's memory through network than accessing your own disk
  - Cache is playing more and more important role
  - In-memory DBs
    - Enough memory that data often fits in memory of a cluster of machines
  - Disk considerations less important
    - Still disks are where most of the data lives today
- Similar reasoning for algorithms
  - Best algorithm depends on the technology available

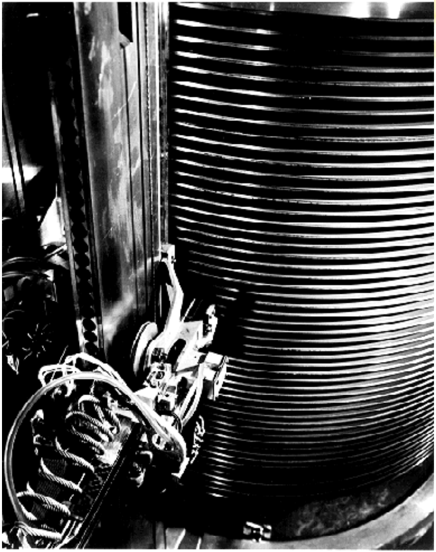
- Storage
  - ***Magnetic disks / SSD***
  - RAID
  - DB internals

Connecting disks to a server

- **Disks** (magnetic and SSDs) can be **connected to computer**:
  - Through high-speed bus interconnections; or
  - Through high-speed network
- **Through a high-speed interconnection**
  - Serial ATA (SATA)
  - Serial Attached SCSI (SAS)
  - NVMe (Non-volatile Memory Express)
- **Through high-speed networks**
  - Storage Area Network (SAN): ISCSI, Fiber Channel, InfiniBand
  - **Network Attached Storage (NAS)**
    - Provides a file-system interface (e.g., NFS)
    - Cloud storage: Data is stored in the cloud and accessed via an API, Object store, High latency

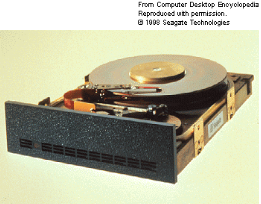
Magnetic Disks

- *1956*
  - IBM RAMAC
  - 24” platters
  - 5 million characters

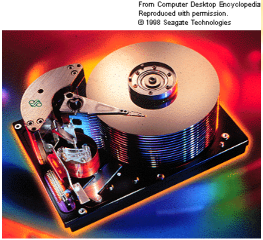


Magnetic Disks

- 1979
- SEAGATE
- 5MB



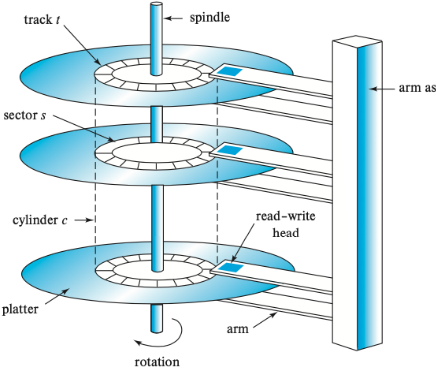
- 1998
- SEAGATE
- 47GB



- 2006
- Western Digital
- 500GB

Magnetic Disks: Components

- **Platters**
  - Made of rigid metal covered with magnetic material on both surfaces
  - It spins at 5400 or 9600 RPM
  - *Tracks* subdivided into *sectors* (smallest unit read or written, with a checksum)
- **Read-write heads**
  - Store information magnetically on the disk
  - Spinning creates a cushion that maintain the heads a few microns from the disk surface
  - *Cylinder* is the i-th tracks of all the platters (can be read / written together)
- **Arm**
  - Move all the heads along the disks
- **Disk controller**
  - Accepts high-level commands to



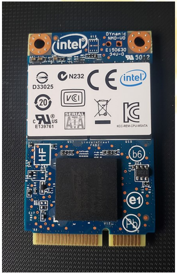
Magnetic Disks: Current Specs

- **Capacity**
  - 10 terabyte and more
- **Access time**
  - = Time to start reading data
  - Seek time
    - = Move the arm across cylinders (2-20ms)
  - Rotational latency time
    - = Wait for sector to be accessed (4-12ms)
- **Data-transfer rate**
  - Once the data is reached the transfer begins
  - Transfer rate = 50-200MB / secs
  - Sector (disk block) = logical unit of storage (4-16KB)
  - Sequential access = when the blocks are on the same or adjacent tracks
  - Random access = each request requires a seek
    - IOPS = number of random single block accesses in a second (50-200 IOPS)
- **Reliability**
  - Mean time to failure (MTTF) = the amount of time that on average the system can run continuously without a failure
  - Lifespan of an HDD is ~5 years

Accessing Data Speed

- Random data transfer rates
  - = how long it takes to read a random sector
  - It has 3 components
    - Seek time: Time to seek to the track (Average 4 to 10ms)
    - Rotational latency: Waiting for the sector to get under the head (Average 4 to 11ms)
    - Transfer time: Time to transfer the data (Very low)
  - About 10ms per access
    - So if randomly accessed blocks, can only do 100 block transfers (100 / sec x 4 KB per block = 50 KB/s)
- Serial data transfer rates
  - = rate at which data can be transferred (without any seek)
  - 30-50MB/s to up to 200MB/s
- Seeks are bad!

Solid State Disk (SSD)



- Mainstream around 2000s
- Like non-volatile RAM (NAND and NOR)
- **Capacity**
  - 250, 500 GBs (vs 1-10 TB for HDD)
- **Access time**
  - Latency for random access is 1,000x smaller than HDD
    - E.g., 20-100 us (vs 10 ms HDDs)
  - Multiple random requests (e.g., 32) in parallel
  - 10,000 IOPS (vs 50/200 for HDDs)
  - Require to read an entire "page" of data (typically 4KB)
    - Equivalent to a block in magnetic disks
- **Data-transfer rate**
  - 1 GB/s (vs 200 MB/s HDD)
  - Typically limited by the interface speed
  - Reads and writes are ~500MB/s for SATA and 2-3 GB/s for NVMe
  - Lower power consumption than HDDs
  - Writing to SSD is slower than reading (~2-3x)
    - It requires erasing all pages in the block
- **Reliability**
  - There is a limit to how many times a flash page can be erased (~1M times)
- Better than an HDD from any point of view, but more expensive per GB

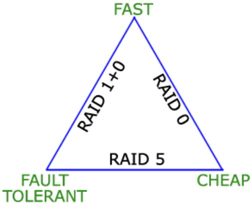
- Storage
    - Magnetic disks / SSD
    - ***RAID***
    - DB internals

RAID

- RAID = Redundant Array of Independent Disks
- **Problem**
  - Storage capacity has been growing exponentially
  - Data-storage requirement (e.g., web, DBs, multimedia applications) has been growing even faster
  - You need a lot of disks
  - MTTF between failure of any disk get smaller (e.g., days)
    - If we store a single copy of the data, the frequency of data loss is unacceptable
- **Observations**
  - Disks are very cheap
  - Failures are very costly
  - Use “extra” disks to ensure reliability
    - Store data redundantly
    - If one disk goes down, the data still survives
  - Bonus: allow faster access to data
- **Goal**
  - Expose a logical view of a single large and reliable disk from many unreliable disks
  - Different RAID “levels” (reliability vs performance)

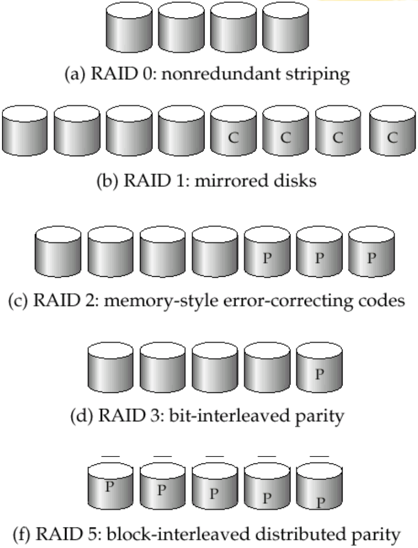
Improve Reliability / Performance with RAID

- **Reliability**
  - Use redundancy
    - Store the same data multiple times: E.g., mirroring (aka shadowing)
    - If a disk fails, the data is not lost but it can be reconstructed
    - Increased MTTF
  - Assumption: independence of disk failure
    - Power failures and natural disasters
    - As disks age, probability of failure increases together
- **Performance**
  - Parallel accessto multiple disks: E.g., mirroring, Increase number of read requests
  - Striping data across multiple disks: Increase transfer rate



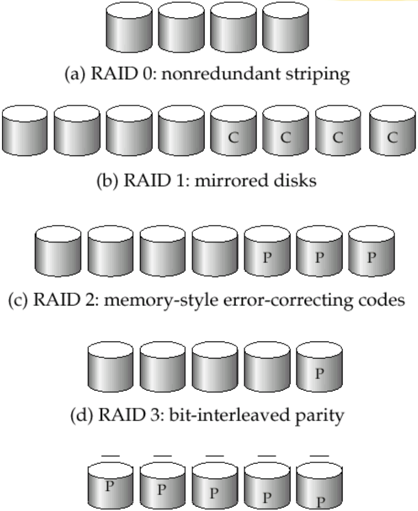
RAID Levels

- **RAID 0: No redundancy**
  - Array of independent disks
  - Same access-time
  - Increased transfer rate
- **RAID 1: Mirroring**
  - Make a copy of the disks
  - If one disk fails, we have a copy
  - Reads: can go to either disk, so higher data rate possible
  - Writes: need to write to both disks
- **RAID 2: Memory-style error correction**
  - Use extra bits so we can reconstruct
  - Superseded by RAID 5
- **RAID 3: Interleaved parity**
  - One disk contains “parity” for the main data disks
  - Can handle a single disk failure
  - Little overhead (only 25% in the above case)



Choosing a RAID Level

- Main choice between RAID 1 and RAID 5
- **RAID 1 better write performance**
  - E.g., to write a single block
    - RAID 1: only requires 2 block writes
    - RAID 5: 2 block reads and 2 block writes
  - Preferred for applications with *high update rate* and *small data* (e.g., log disks)
- **RAID 5 lower storage cost**
  - RAID 1: 2x more disks
  - RAID 5 is preferred for applications with *low update rate* and *large amounts of data*



(a) RAID 0: nonredundant striping

(b) RAID 1: mirrored disks

(c) RAID 2: memory-style error-correcting codes

(d) RAID 3: bit-interleaved parity

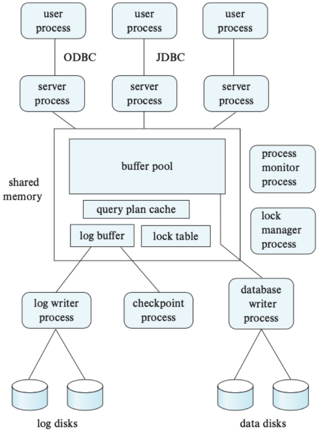
(f) RAID 5: block-interleaved distributed parity

- Storage
  - Magnetic disks / SSD
  - RAID
  - ***DB internals***

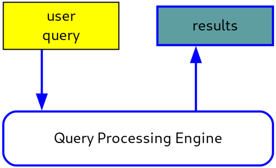
SCIENCE ACADEMY

(Centralized) DB Internals

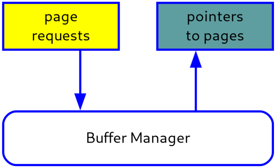
- User processes
  - Issue commands to the DB
- Server processes
  - Receive commands and call into the DB code
- Process monitor process
  - Monitor DB processes
  - Recover processes from failures
- Lock manager process
  - Lock grant / release
  - Deadlock detection
- Database writer process
  - Output modified buffer blocks to disk on a continuous basis
- Log writer process
  - Output log records to stable storage
- Checkpoint process
  - Perform periodic checkpoints
- Shared memory
  - Contain all shared data
  - Buffer pool, Lock table, Log buffer (log records waiting to be saved on



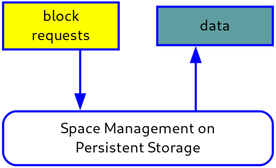
DB Internals



- **Query Processing Engine**
  - Given a user query, decide how to “execute” it
  - Specify sequence of pages to be brought in memory
  - Operate upon the tuples to produce results



- **Buffer Manager**
  - Bring pages from disk to memory
  - Manage the limited memory



- **Storage hierarchy**
  - How are tables mapped to files?
  - How are tuples mapped to disk blocks?