UMD DATA605 - Big Data Systems

Storage
DB internals

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with thanks to
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Outline

- Storage
  - Physical storage
    - Storage hierarchy
    - Magnetic disks / SSDs
    - RAID
- DB internals

Sources: Silberschatz et al. 2020

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- Storage
  - Physical storage
    - **Storage hierarchy**
    - Magnetic disks / SSDs
    - RAID
- DB internals

Sources: Silberschatz et al. 2020, Chap 12, Physical Storage Systems

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 / 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

The 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

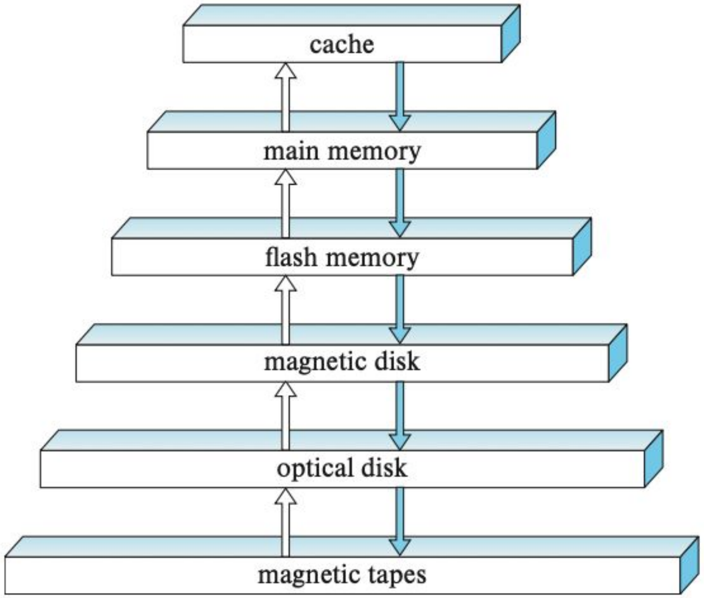
- Long-term on-line storage
- Non-volatile (can survive failures and system crashes)

Optical disk (CD, Blue Ray)

- Mainly read-only

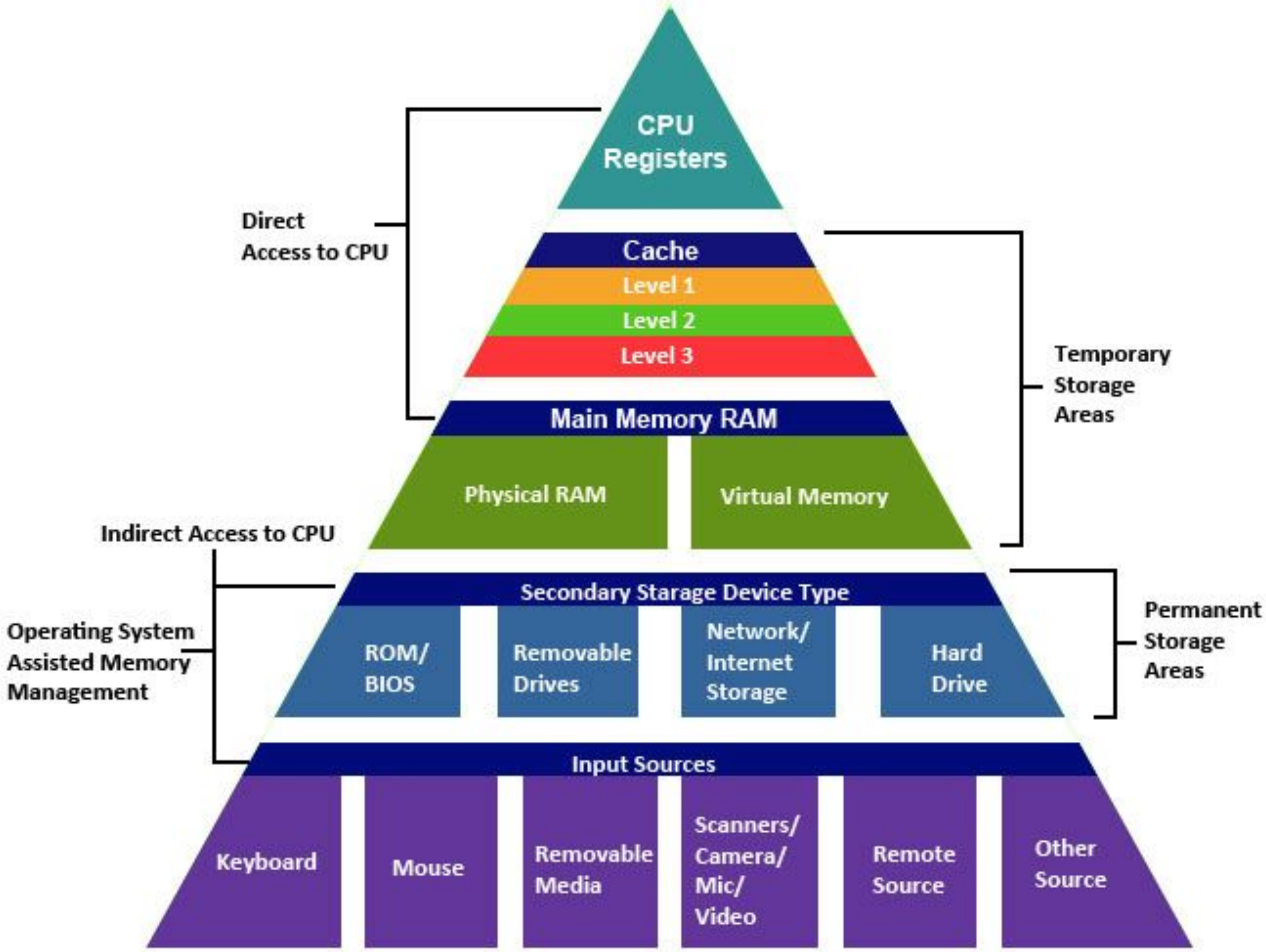
Magnetic tapes

- Backup and archival data
- Stored for long period of time, e.g., for legal reasons
- Sequential-access



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**:
  - Cheaper 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

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    - **Magnetic disks / SSD**
    - RAID
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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

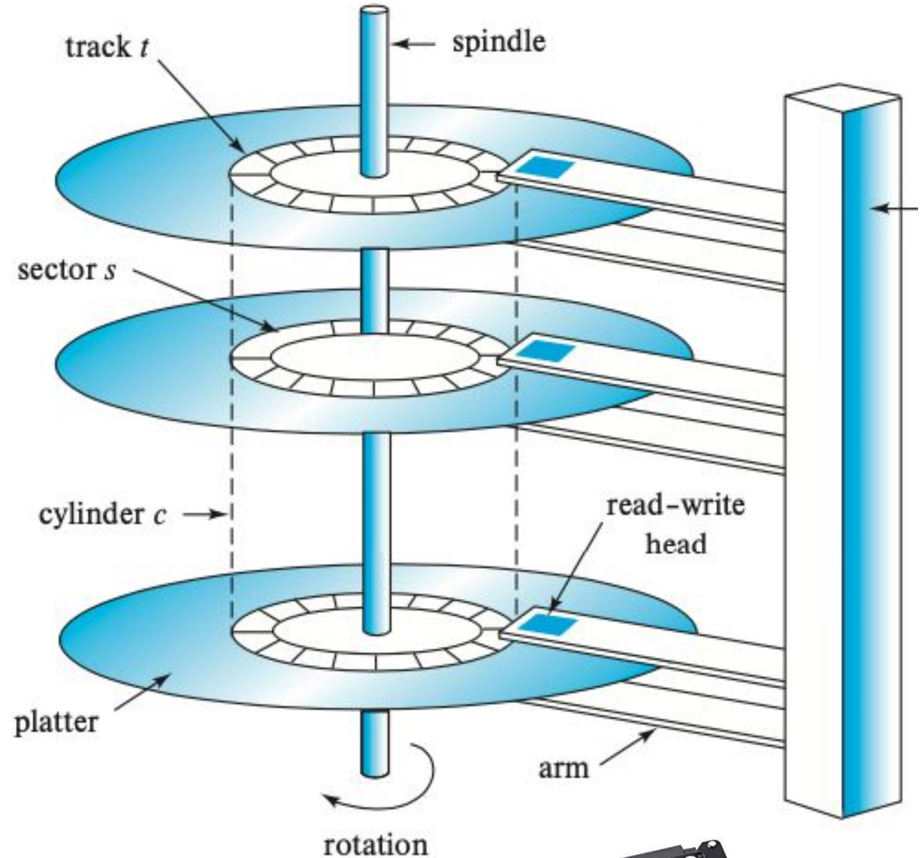
- Store information magnetically on the disk
- Spinning creates a cushion that maintain the heads a few microns from the disk surface
- *Cylinder* is the i-th tracks of all the platters (can be read / written together)

Arm

- Move all the heads along the disks

Disk controller

- Accepts high-level commands to read / write a sector
- Operates arm / heads
- Bad sectors are remapped to a different physical location



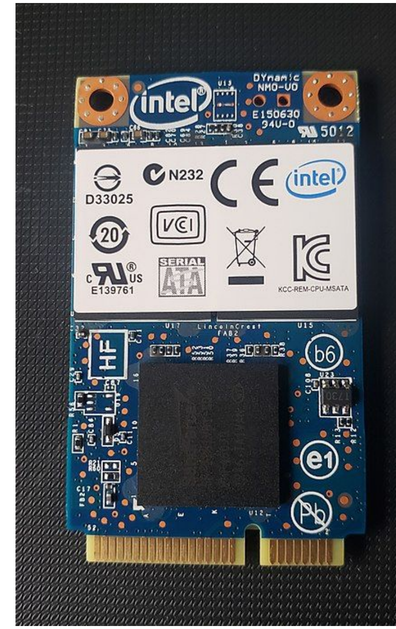
Magnetic Disks: Current Specs

- 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

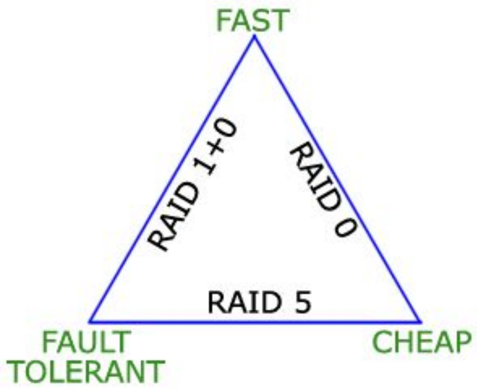
Outline

- Storage
  - Physical storage
    - Storage hierarchy
    - 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 access to multiple disks
  - E.g., mirroring
  - Increase number of read requests, decrease latency
  - Same transfer rate
- Striping data across multiple disks
  - Same number of read requests
  - 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

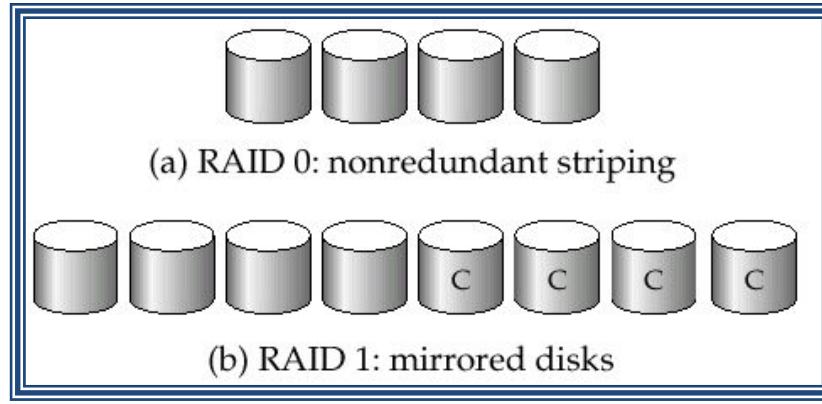
- Use extra bits so we can reconstruct
- Superseded by RAID 5

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)

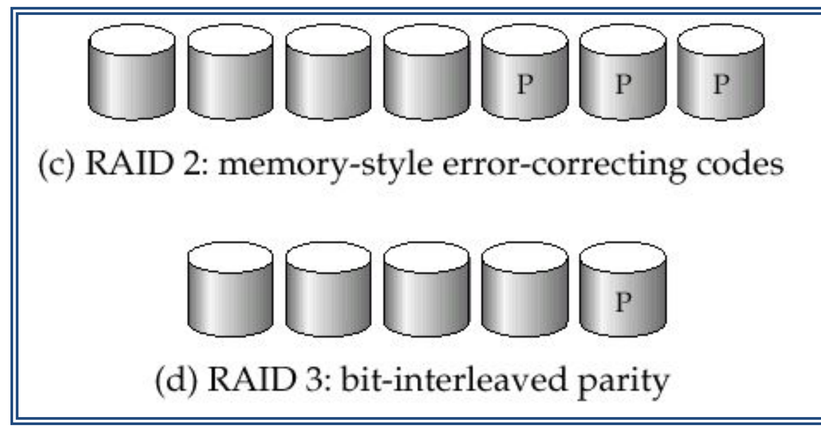
RAID 5: Block-interleaved distributed parity

- Distributed parity “blocks” instead of bits



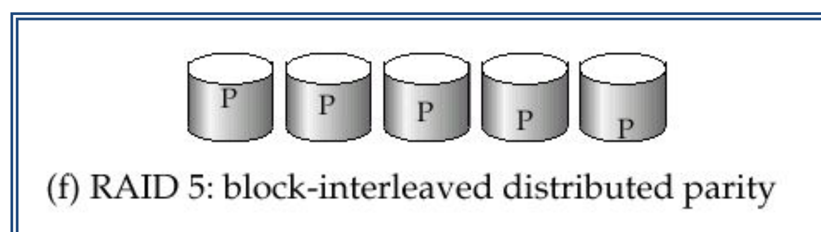
(a) RAID 0: nonredundant striping

(b) RAID 1: mirrored disks



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

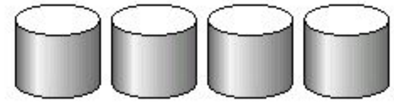
(d) RAID 3: bit-interleaved parity



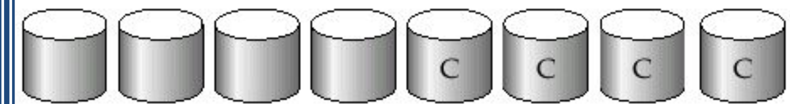
(f) RAID 5: block-interleaved distributed parity

Choosing a RAID Level

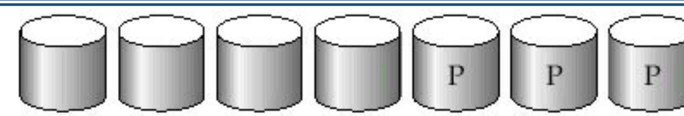
- Main choice between RAID 1 and RAID 5
- **RAID 1 better write performance**
  - E.g., to write a single block
    - RAID 1: only requires 2 block writes
    - RAID 5: 2 block reads and 2 block writes
  - Preferred for applications with *high update rate* and *small data* (e.g., log disks)
- **RAID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



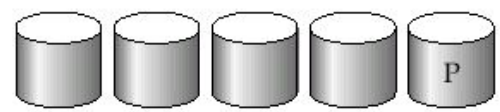
(a) RAID 0: nonredundant striping



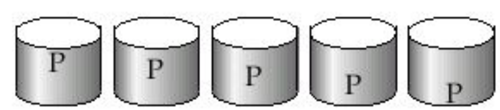
(b) RAID 1: mirrored disks



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



(d) RAID 3: bit-interleaved parity



(f) RAID 5: block-interleaved distributed parity

Outline

- Storage
  - Physical storage
- **DB internals**

Sources:

- Silberschatz et al. 2020, Chap 13: Data Storage Structures

(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

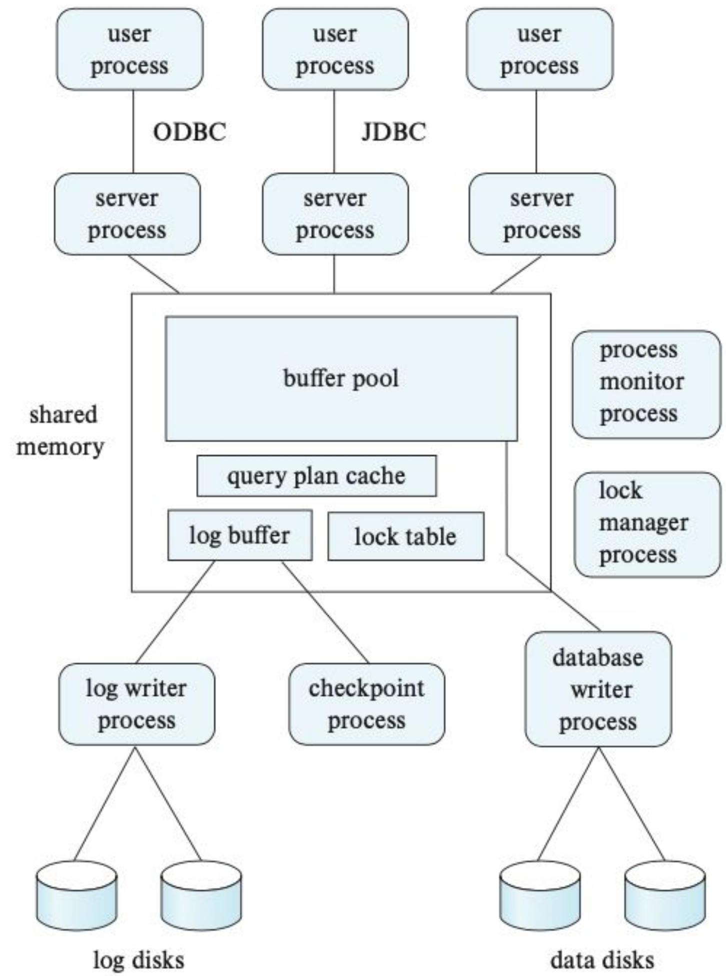
Lock manager process
- Lock grant / release
- Deadlock detection

Database writer process
- Output modified buffer blocks to disk on a continuous basis

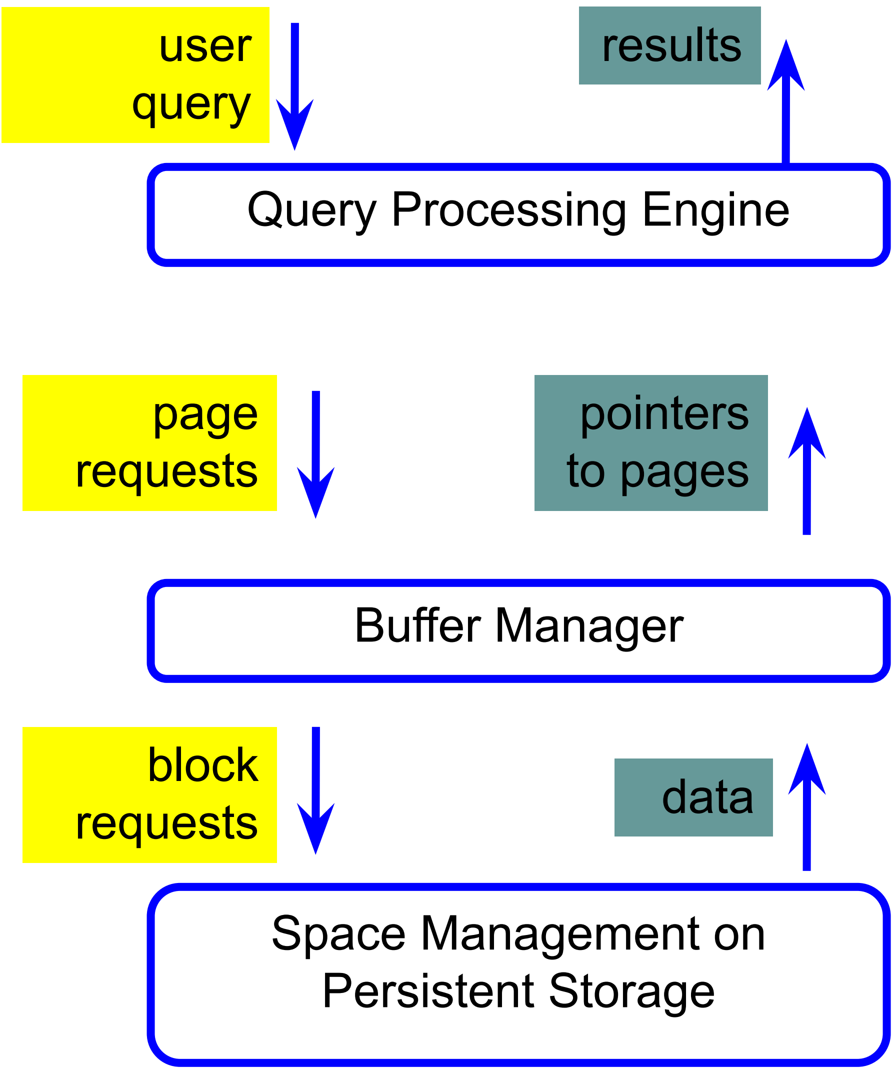
Log writer process
- Output log records to stable storage

Checkpoint process
- Perform periodic checkpoints

Shared memory
- Contain all shared data
  - Buffer pool, Lock table, Log buffer (log records waiting to be saved on stable storage), Caches (e.g., query plans)
- Data needs to be projected by mutual exclusion locks



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?