UMD DATA605 - Big Data Systems

Storage

~~Query Processing~~

~~Transactions~~

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with thanks to
Prof. Alan Sussman
Prof. Amol Deshpande

Outline

- Storage
  - Physical storage
    - **Storage Hierarchy**
    - Magnetic disks / SSD
    - RAID
  - ~~Logical storage~~
- ~~Query Processing~~
- ~~Transactions~~

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

Storage Characteristics

- Storage media presents a trade-off between:
  - Speed of access (e.g., 200MB / sec)
  - Cost per unit of data (e.g., $50 / GB)
  - 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

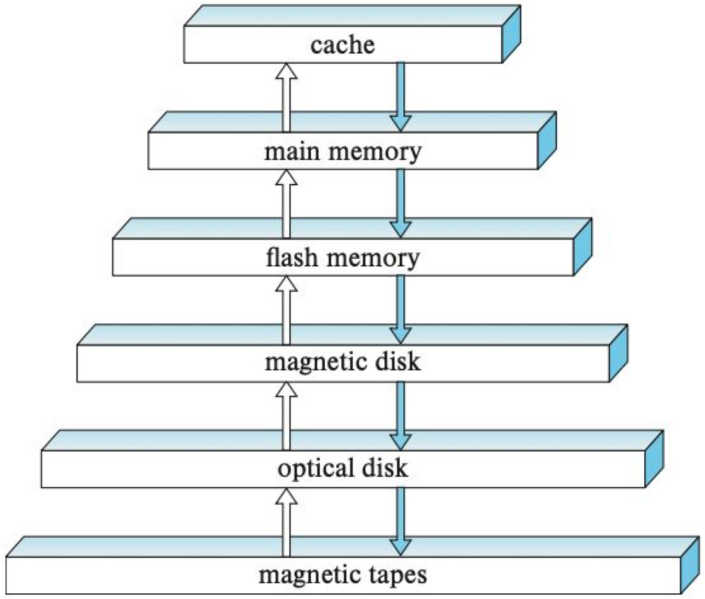
    ```
    SELECT * FROM employee
       WHERE name LIKE ‘Einst*’
    ```

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

Storage Hierarchy

Organize storage in a hierarchy according to speed / cost

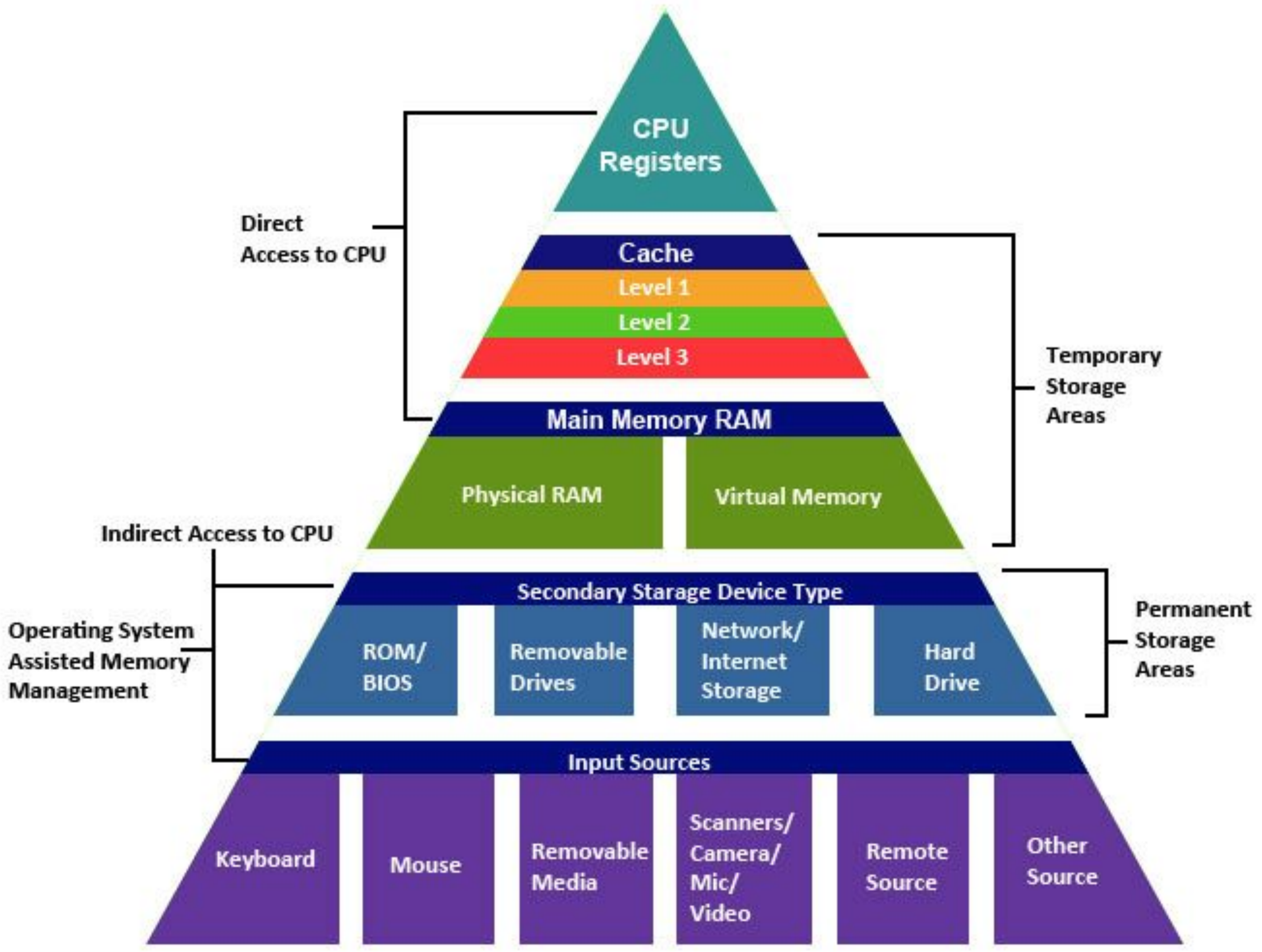
- **Cache memory**
  - Fastest, volatile, and most costly
  - DB developers do pay attention to cache effects
- **Main memory**
  - Up to 100s of GBs
  - Volatile
  - Typically can't store the entire DB in memory
- **Flash memory / SSD**
  - Non-volatile
  - Cost / performance between RAM and magnetic disk
- **Magnetic disk**
  - Long-term on-line storage
  - Non-volatile (can survive failures and system crashes)
- **Optical disk**
  - Mainly read-only
- **Magnetic tapes**
  - Backup and archival data
  - Stored for long period of time, e.g., for legal reasons
  - Sequential-access



Simplified organization

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

Storage Hierarchy



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

How Important is Memory Hierarchy?

- **Trade-offs shifted drastically over last 10-15 years**
  - Several innovations
    - Large memories
    - SSDs
    - Fast network
  - However, the volume of data is growing quite rapidly
- **Observations**
  - Cache is playing more and more important role
  - In-memory DBs
    - Enough memory that data often fits in memory of a cluster of machines
  - It's faster to access another computer's memory through network than accessing your own disk
  - "Disk" considerations less important
    - HDDs vs SSDs
    - Still disks are where most of the data lives today
- **Similar changes for algorithms**
  - Design and pick algorithms based on current trade-offs
  - E.g., many algorithms designed to minimize access time (e.g., elevator algorithms for disk access)

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    - **Magnetic disks / SSD**
    - RAID
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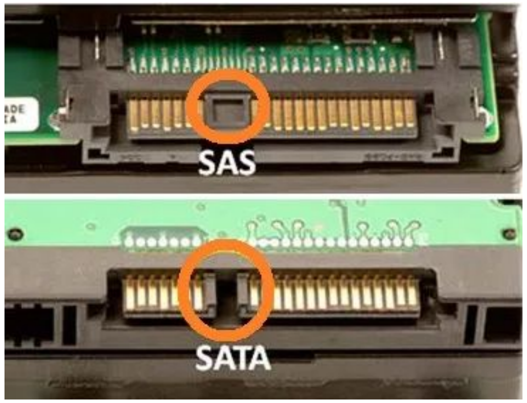
- ~~Query Processing~~
- ~~Transactions~~

Connecting Disks to a Server

- **Disks (magnetic and SSDs) can be connected to computer:**
  - Directly through high-speed interconnection; 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



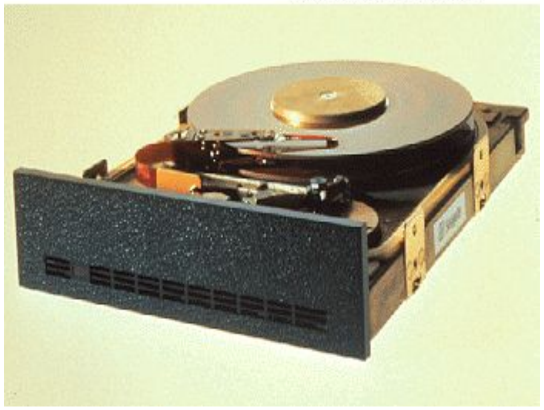
Magnetic Disks

1956

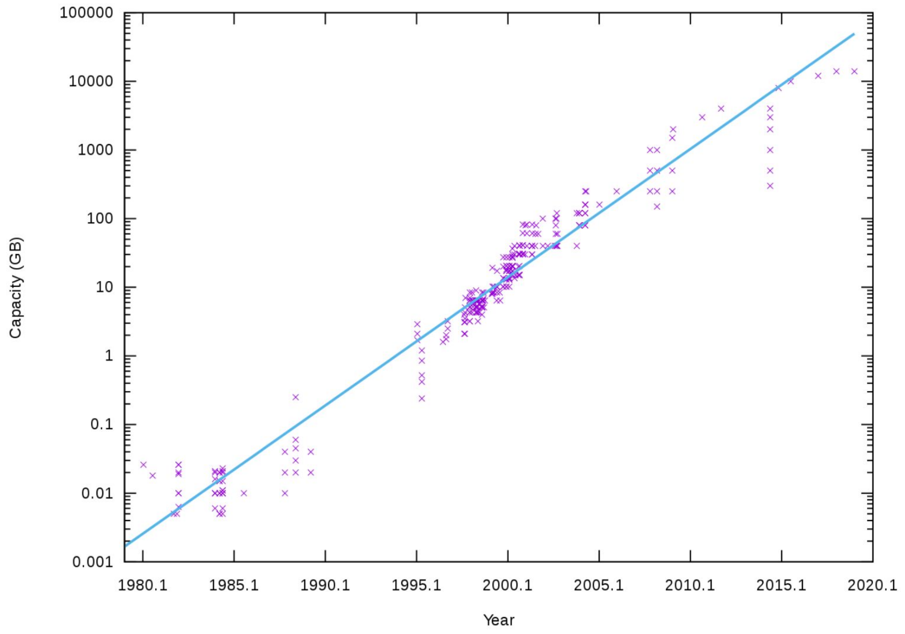
- IBM RAMAC
- 24” platters
- 5 million characters

Magnetic Disks

1979
SEAGATE
5MB



2006
Western Digital
500GB



Exponential increase in capacity over time

Magnetic Disks: Components

Platters

- 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

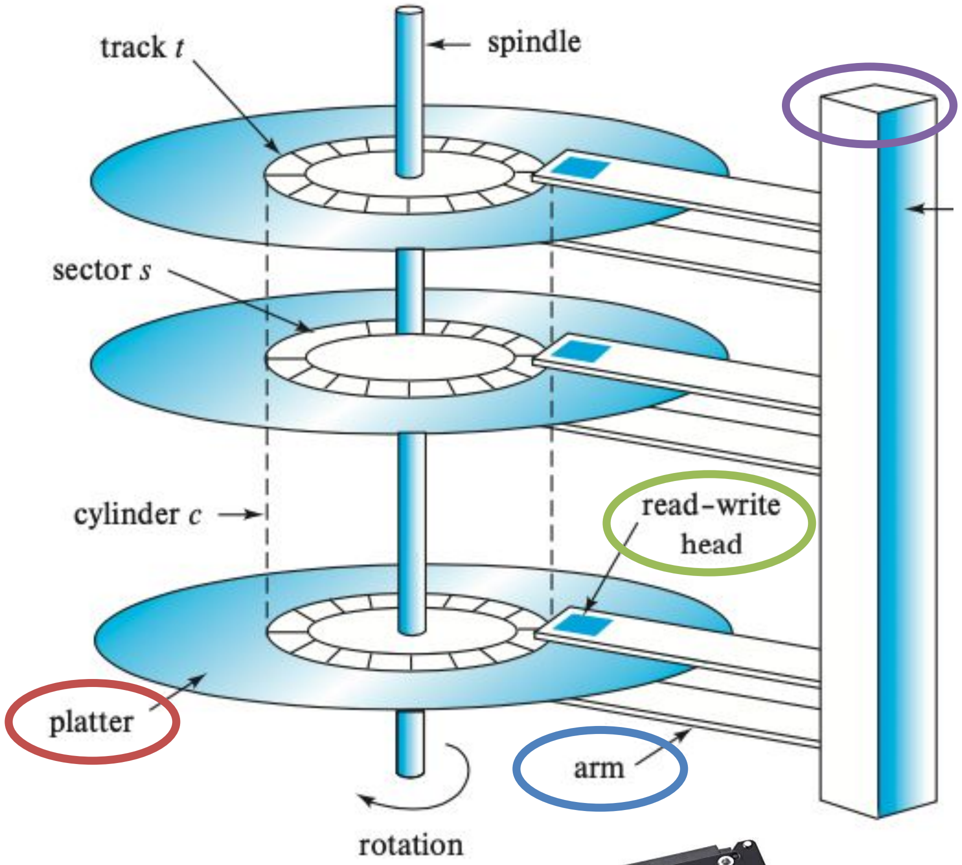
- Store information magnetically on the disk
- Spinning creates a cushion that maintain the heads a few microns from the disk
- ***Cylinder*** is the i-th tracks of all the platters (can be read / written together)

Arm

- Move all the heads along the disks

Disk controller

- Accept commands to read / write data
- Operate arm and heads
- Bad sectors are remapped to a different physical location

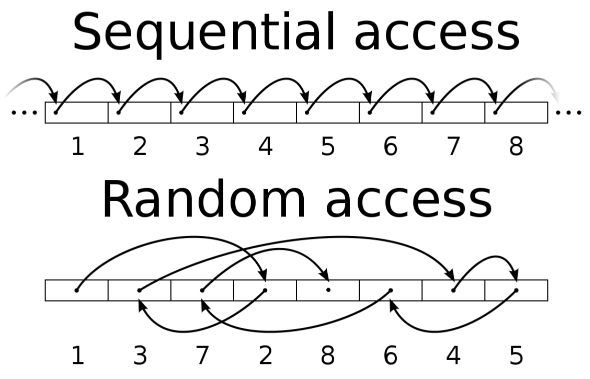


Magnetic Disks: Current Specs

- **Capacity**
  - Terabyte and more
- **Access time**
  - = time to start reading data
  - Seek time to 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 (Input / Output Per Sec) = number of random single block accesses in a second (50-200 IOPS)
- **Reliability**
  - Mean time to failure (MTTF) = the average amount of time that the system runs continuously without a failure
  - Lifespan of an HDD is ~5 years

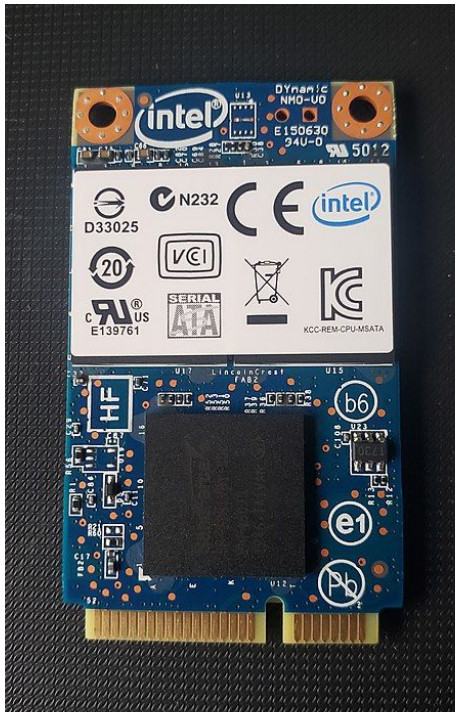
Accessing Data

- **Random data transfer rates**
  - How long it takes to read a random sector
  - Seek time
    - = time to move head to the track
    - Average 2 to 20ms
  - Rotational latency
    - = wait for the sector to get under the head
    - Average 4 to 12ms
  - Transfer time
    - Very low
  - About 10ms per access
    - So if randomly accessed blocks, can only do 100 block transfers
    - 100 / sec x 4 KB per block = 50KB/s
- **Serial data transfer rates**
  - Rate at which data can be transferred (without any seek)
  - 30-50MB/s to up to 200MB/s
- **Reading random data is 1000x slower than reading serial data**
  - Seeks are very 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
    - 500MB/s for SATA
    - 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 page can be erased (~1m times)



Outline

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    - **RAID**
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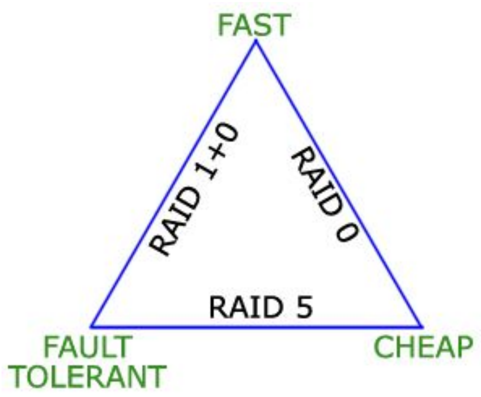
RAID

- RAID = Redundant Array of Independent Disks
- **Problems**
  - Storage capacity has been growing exponentially
  - Data-storage requirement (e.g., web, DBs, multimedia applications) has been growing even faster
  - When you have a lot of disks, the MTTF between failure of any disk gets 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 reliability vs performance (RAID levels)

Improve Reliability / Performance with RAID

Increase reliability

- Use redundancy
  - Store the same data multiple times on multiple disks
  - E.g., mirroring
  - If a disk fails, the data is not lost but it can be reconstructed
  - Increased MTBF
- Assumption is independence of disk failure
  - As disks age, probability of failure increases together
  - Power failures and natural disasters

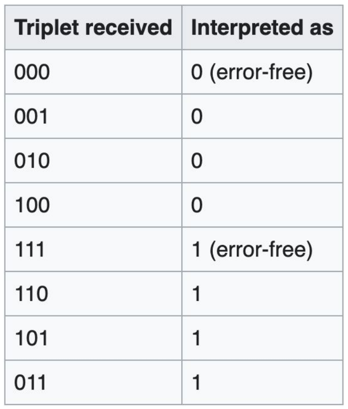


Increase performance

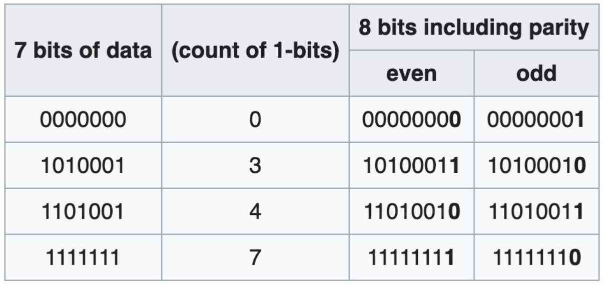
- It depends on how data is replicated
- Striping data across multiple disks (RAID 0)
  - = use multiple disks with no replication
  - Increase number of read requests
  - Same transfer rate
- Mirroring (RAID 1)
  - = data is copied on multiple disks
  - Same number of read requests
  - Increase transfer rate

Error Correction Codes

- = a technique used for controlling errors in data transmission over unreliable communication channels
- **Idea**:
  - the sender encodes the message in a redundant way
  - the receiver can detect errors and correct (a limited number of) errors
- 1940-1960s: Hamming, Reed-Solomon, Shannon, Viterbi
- E.g., triple redundancy
  - Send the same bit 3 times, receiver does majority voting
  - Detect and correct one bit errors
- E.g. parity bit
  - Add an extra bit representing the number of 1s
  - Detect (but not correct) one bit errors



Triplet received	Interpreted as
000	0 (error-free)
001	0
010	0
100	0
111	1 (error-free)
110	1
101	1
011	1



7 bits of data	(count of 1-bits)	8 bits including parity	
		even	odd
0000000	0	0000000**0**	0000000**1**
1010001	3	1010001**1**	1010001**0**
1101001	4	1101001**0**	1101001**1**
1111111	7	1111111**1**	1111111**0**

RAID Levels

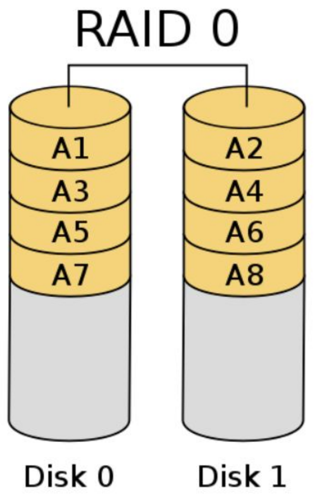
Good article on wikipedia

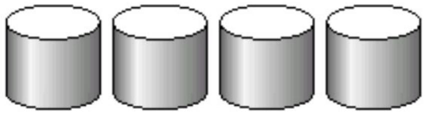
RAID 0: Striping / no redundancy

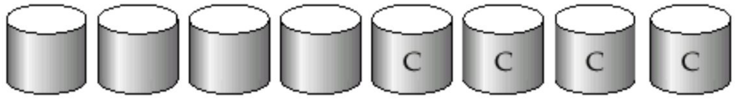
- = array of independent disks
- Same access-time
- Increase transfer rate

RAID 1: Mirroring

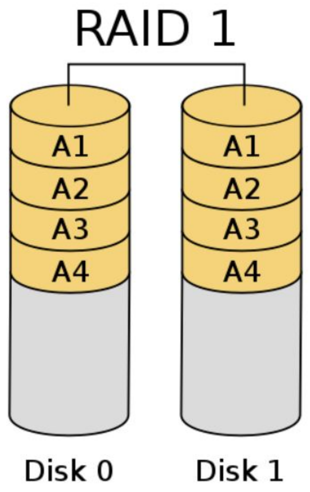
- = make a copy of the disks
- If one disk fails, you have a copy of the data
  - Like double redundancy in ECC
- Also you have parallel access to multiple disks
- Reads
  - Can go to either disk
  - Same access time
  - Increase read latency with same transfer rate
  - Same read latency with increased transfer rate
- Writes
  - Need to write to both disks




(a) RAID 0: nonredundant striping



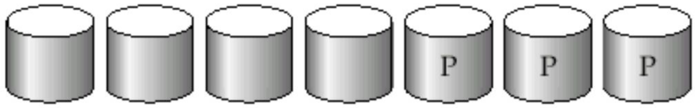
(b) RAID 1: mirrored disks



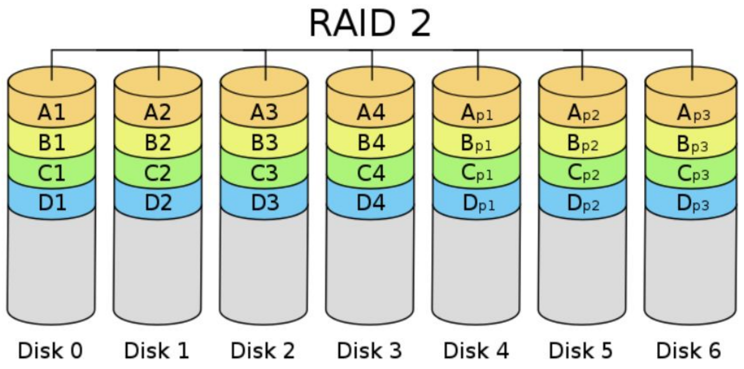
RAID Levels

RAID 2: Memory-style error correction

- = use extra bits so we can reconstruct data (like ECC in RAM)
- Can trade-off different levels of error detection and recovery

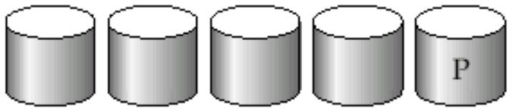


(c) RAID 2: memory-style error-correcting codes



RAID 3: Interleaved parity

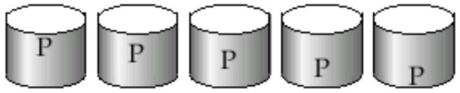
- = one disk contains "parity" for the main data disks
- Can handle a single disk failure
- Little overhead (only 25% in the above case)



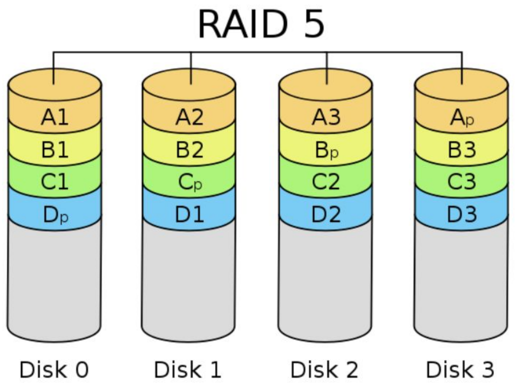
(d) RAID 3: bit-interleaved parity

RAID 5: Block-interleaved distributed parity

- Distributed parity blocks instead of bits

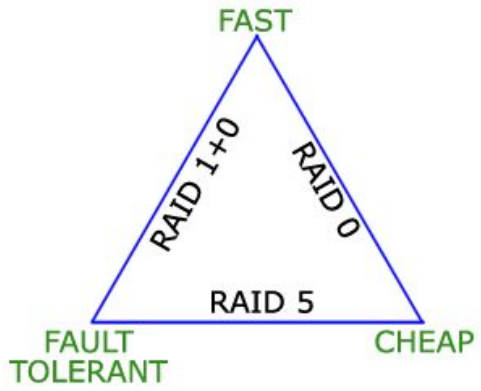


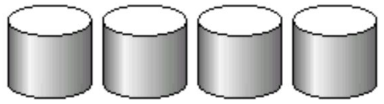
(f) RAID 5: block-interleaved distributed parity

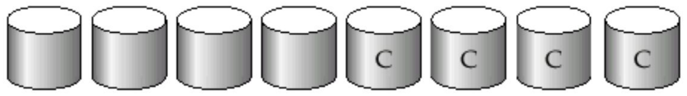


Choosing a RAID Level

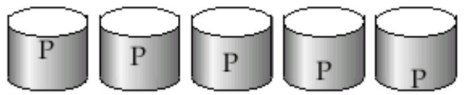
- Main choice between RAID 0, RAID 1, and RAID 5
- RAID 0 (striping(
  - Better performance but no additional reliability
- RAID 1 (mirroring)
  - Better performance and reliability
  - High cost
  - E.g., to write a single block
    - RAID 1: only requires 2 block writes
    - RAID 5: 2 block reads and 2 block writes
  - Preferred for applications with high update rate and small data (e.g., log disks)
- RAID 5 (interleaved parity)
  - Lower storage cost
  - Preferred for applications with low update rate and large amounts of data (e.g., analytics)




(a) RAID 0: nonredundant striping



(b) RAID 1: mirrored disks



(f) RAID 5: block-interleaved distributed parity

BACKUP

Outline

- Storage
  - Physical storage
  - **Logical storage**
    - File Organization
    - Buffer Manager
    - Indexes
- Query Processing
- Transactions

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

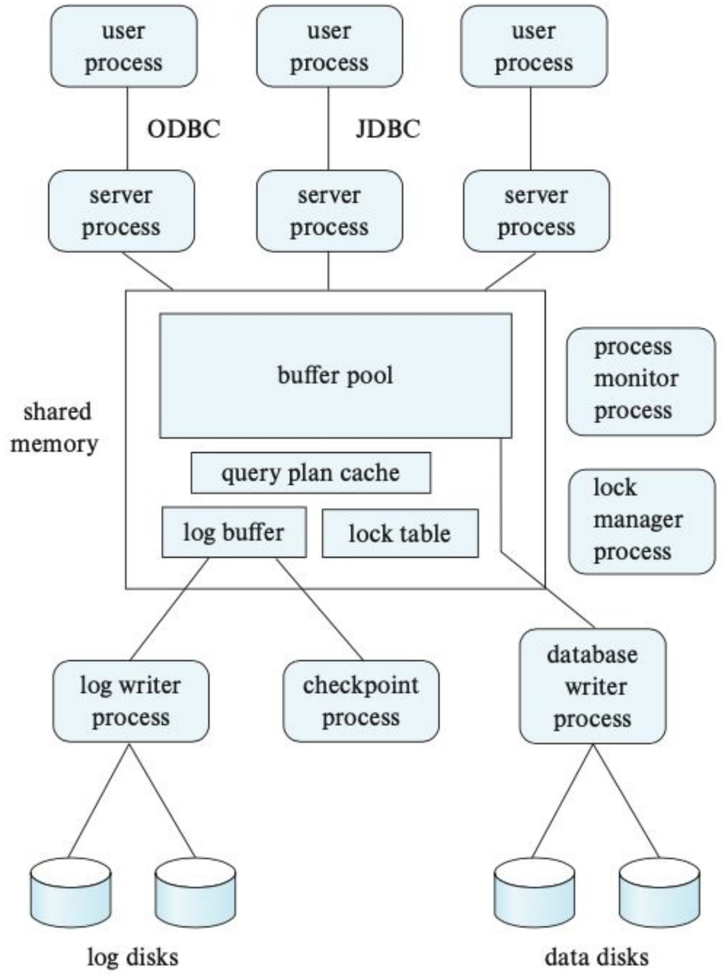
Lock manager process
- Lock grant / release
- Deadlock detection

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

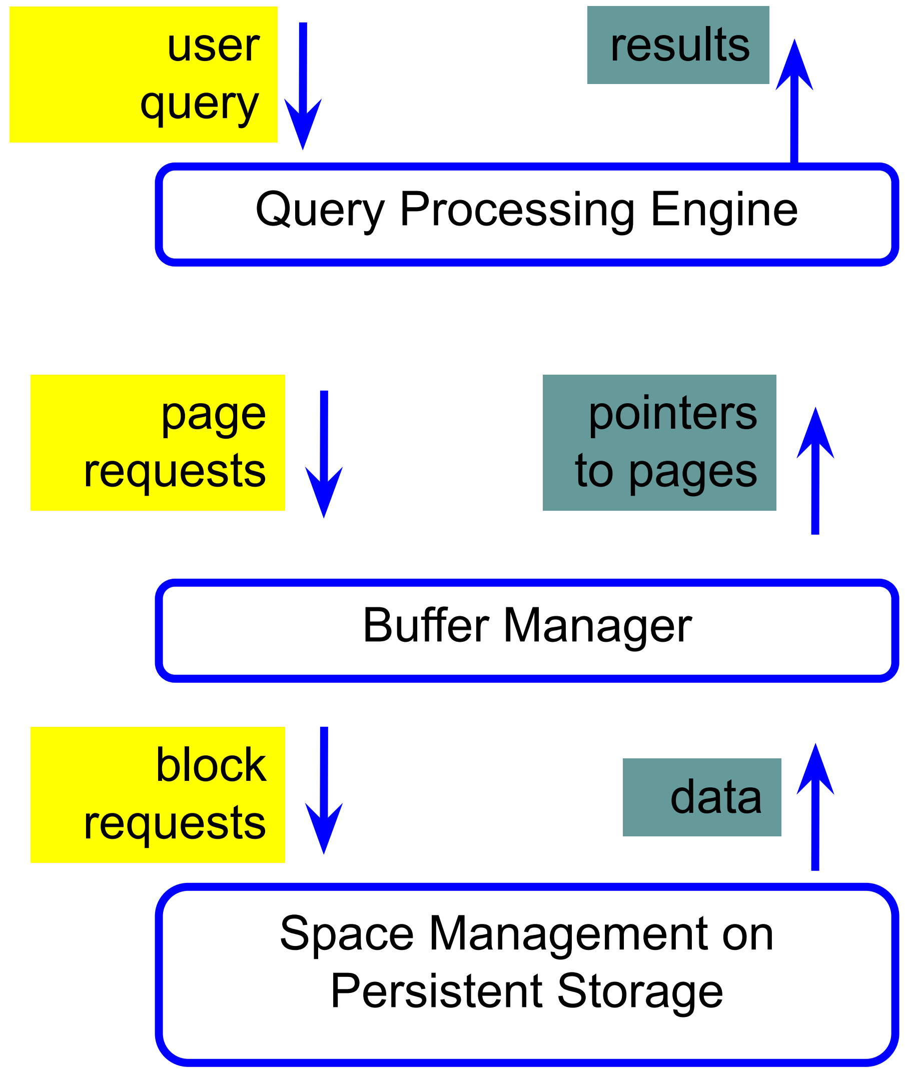
Log writer process
- Output log records to stable storage

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?

BACKUP

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    - Buffer Manager
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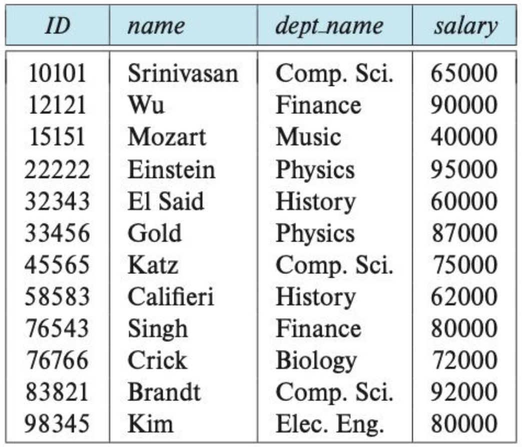
File Organization

- We need to map onto disk files and blocks (aka *pages*):
  - **Tables** (aka *relations*)
  - **Records** (aka *tuples*, *rows*)
  - **Attributes** (aka *fields*, *columns*)

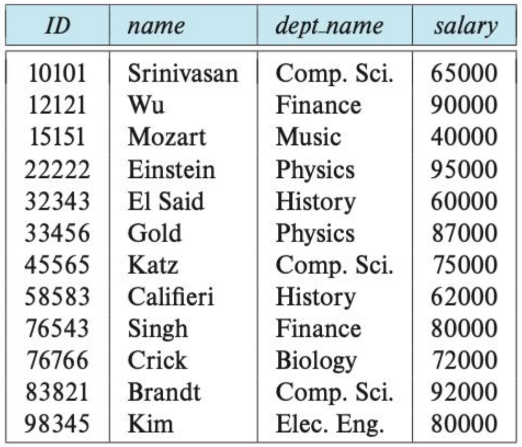
- **How are tables mapped to disk blocks?**
  - File is a collection of blocks (typically 4-16 KBs)
  - Mapping of tables to file
    - One table to one file
    - Advantages in storing multiple tables clustered together (e.g., joins)
  - Use a standard OS file system
  - High-end DB systems have their own OS
    - OS interferes more than helps in many cases
    - Often DB needs to be aware of underlying blocks
    - Read / write directly disk blocks



ID	*name*	*dept_name*	*salary*
10101	Srinivasan	Comp. Sci.	65000
12121	Wu	Finance	90000
15151	Mozart	Music	40000
22222	Einstein	Physics	95000
32343	El Said	History	60000
33456	Gold	Physics	87000
45565	Katz	Comp. Sci.	75000
58583	Califieri	History	62000
76543	Singh	Finance	80000
76766	Crick	Biology	72000
83821	Brandt	Comp. Sci.	92000
98345	Kim	Elec. Eng.	80000

File Organization

- **How are records mapped to disk blocks?**
  - Fetch a particular record, specified by record id
  - Find all records that match a condition (say SSN = 123)
  - Insert / delete of records in the table
- Simplest case
  - Each table is mapped to a file
  - Each record is contained in a single block (i.e., records are not split between blocks)
- **Problem**
  - Attributes are of different sizes
- **Solutions**
  - Fixed-length records
  - Variable-length records



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Records -> Blocks

- **Which block of a file should a record go to?**
  - Heap organization
    - Records are allocated contiguously in no particular order
    - A new record is appended at the end of free space and the header is updated
    - A new record is deleted, the space is freed, the entry is deleted
    - Need to scan the records to find for “SSN = 123”
  - Sorted by key
    - Sequential organization
    - Keeping it sorted is complex
    - Can search with binary search O(log(n))
  - Based on a hash key
    - Hashing organization
    - E.g., Store the record with SSN = x in the block number x%1000

Record Organization

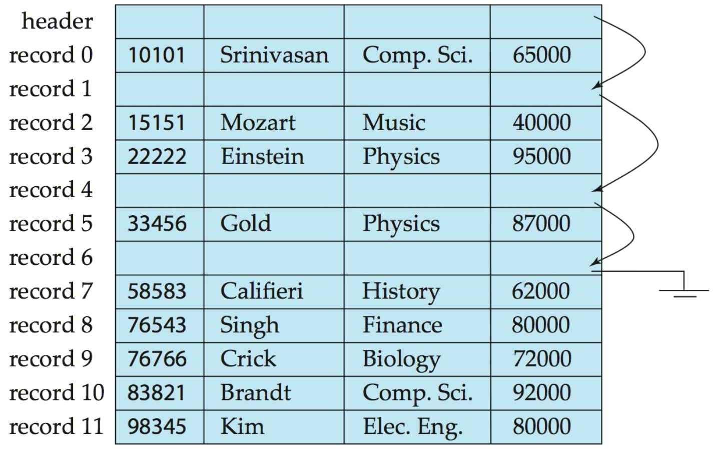
- Heap organization
  - Records are allocated contiguously in no particular order
  - A new record is appended at the end of free space and the header is updated
  - A new record is deleted, the space is freed, the entry is deleted
- Sequential organization
- Keep sorted by some search key
- Insertion
  - Find the block in which the tuple should be
  - If there is free space, insert it
  - Otherwise, must create overflow pages
- Deletions
  - Delete and keep the free space
  - Databases tend to be insert heavy, so free space gets used fast
- Can become *fragmented*
  - Must reorganize once in a while
- What if I want to find a particular record by value ?
  - *Account info for SSN = 123*
- Binary search
  - Takes *log(n)* number of disk accesses
    - Random accesses
  - Too much
    - n = 1,000,000,000 -- log(n) = 30
    - Recall each random access approximately 10 ms
    - 300 ms to find just one account information
    - < 4 requests satisfied per second

Fixed-length Records

- **Physical layout of records on blocks**
  - n = number of bytes per record
  - E.g., a record in *instructor* requires 53 bytes
    - char -> 1 byte
    - numeric(8, 2) -> 8 bytes
    - 5 + 20 + 20 + 8 = 53
- **Fetch i-th record**
  - Store record *i* at position
    - offset = (i – 1) * n
  - The block can contain a non-integer number of records
    - Leave bytes unused
- **Insert a new record**
  - Depends on the policy used for deletion
  - Simply append at the end of the record
- **Delete a record**
  - Deletes are much less frequent than insertions
  - Rearrange (move all the records to reclaim space)
  - Keep a *free list* and use for next insert
    - Like a linked list of free blocks (e.g., after deleting record 1, 4, 6)
  - Conceptually store pointers, in practice file header

```
type instructor = record
                    ID varchar (5);
                    name varchar(20);
                    dept_name varchar (20);
                    salary numeric (8,2);
                  end
```

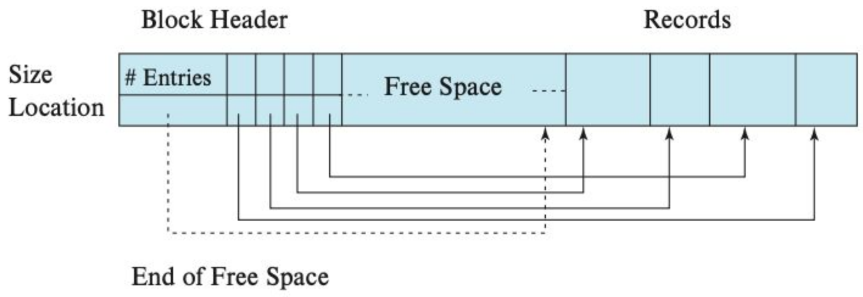
ID	*name*	*dept_name*	*salary*
10101	Srinivasan	Comp. Sci.	65000
12121	Wu	Finance	90000
15151	Mozart	Music	40000
22222	Einstein	Physics	95000
32343	El Said	History	60000
33456	Gold	Physics	87000
45565	Katz	Comp. Sci.	75000
58583	Califieri	History	62000
76543	Singh	Finance	80000
76766	Crick	Biology	72000
83821	Brandt	Comp. Sci.	92000
98345	Kim	Elec. Eng.	80000



header				
record 0	10101	Srinivasan	Comp. Sci.	65000
record 1				
record 2	15151	Mozart	Music	40000
record 3	22222	Einstein	Physics	95000
record 4				
record 5	33456	Gold	Physics	87000
record 6				
record 7	58583	Califieri	History	62000
record 8	76543	Singh	Finance	80000
record 9	76766	Crick	Biology	72000
record 10	83821	Brandt	Comp. Sci.	92000
record 11	98345	Kim	Elec. Eng.	80000

Variable-length Records

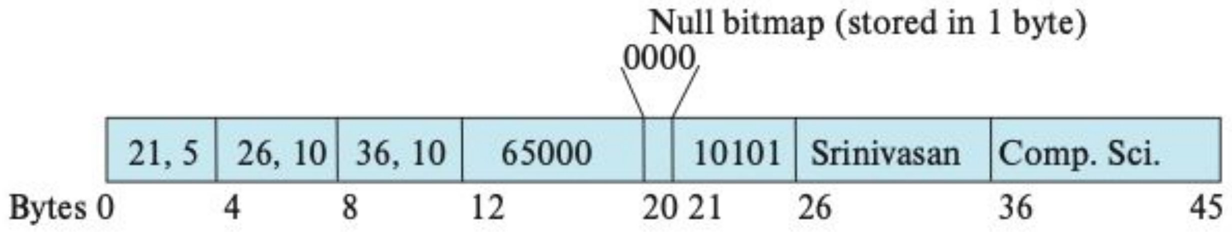
- **Variable-length records occur** due to:
  - The presence of variable-length fields (e.g., strings, arrays, sets)
  - Multiple record types in the same file / blocks
- **How to extract a record of variable-length from a block?**
- Slotted-page structure
  - Number of record entries
  - Array with location and size of each record (indirection)
    - No pointers directly to records
    - Pointers to the entry in the header that contains the location of the record
    - The records may move inside the block, but the outside world is oblivious to it
  - End of free space in the block



Variable-length Attributes

- **How to extract an attribute of variable-length of a record?**
  - The fixed-length attributes are allocated statically at the beginning
  - Variable-length attributes (e.g., `VARCHAR` type) are represented by an offset and length

- How to represent the value `NULL`?
  - Null bitmap
  - Store which attributes of the record have a null value



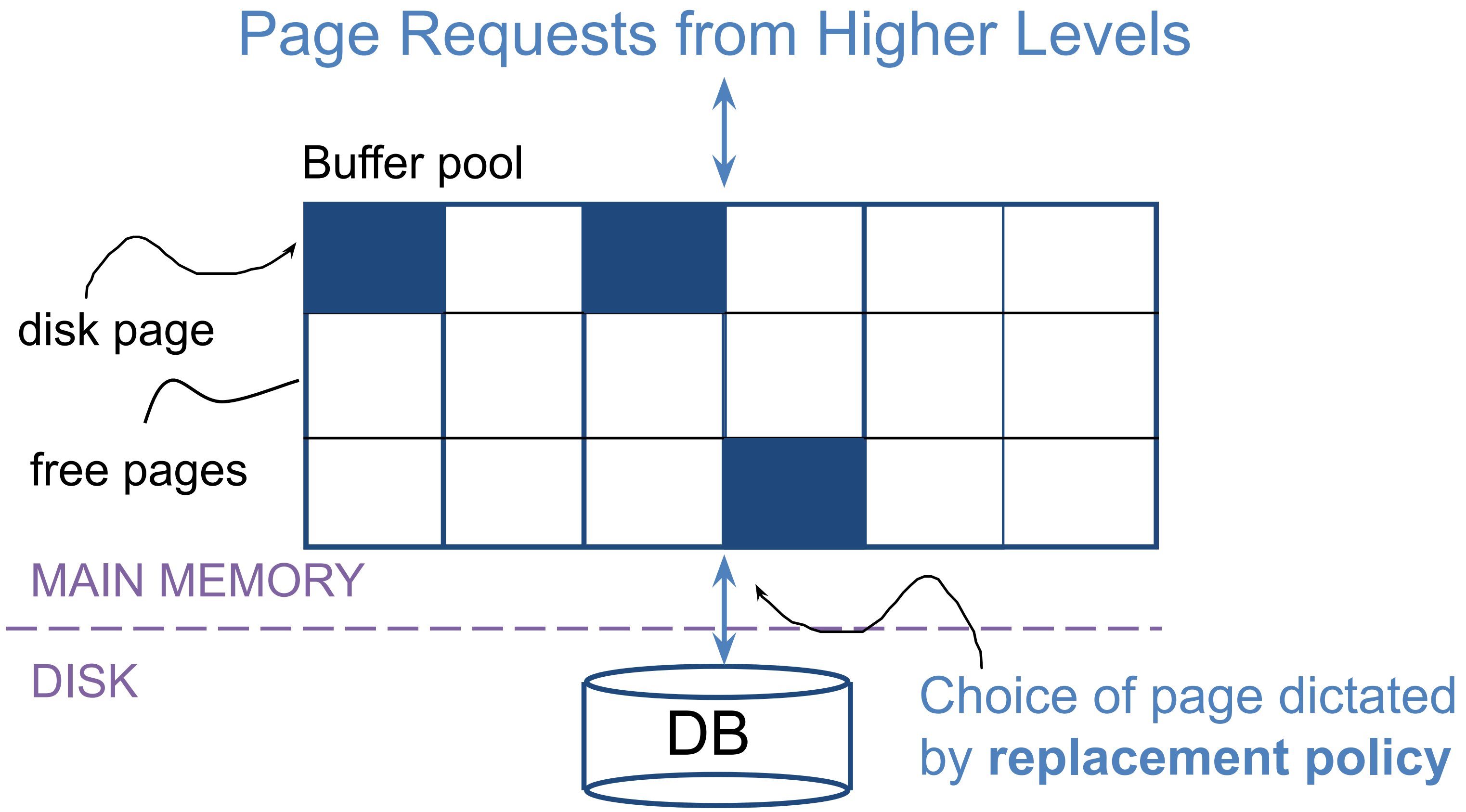
Outline

- Storage
  - Physical storage
  - Logical storage
    - File Organization
    - **Buffer Manager**
    - Indexes
- Query Processing
- Transactions

Buffer Manager

- Many DBs are much larger than available memory on servers
  - 1 PB data can't fit in a 100 GBs memory
  - DB data resides on disk
  - The block must be in memory to operate upon
- When the Query Processor Engine wants a block, it asks the Buffer manager
- **Buffer pool**
  - Similar to OS virtual memory
  - Copy of disk blocks in memory
- **Buffer manager**
  - Similar to OS virtual memory manager
  - If block already in memory, return a pointer to it
  - If not:
    - Allocate space, evicting a current page
      - Either write it back to its original location, or
      - Just throw it away (if it was read from disk, and not modified)
    - Read data
      - Make a request to the storage subsystem to fetch it
    - Pass the address back

Buffer Manager


Page Requests from Higher Levels
Buffer pool
disk page
free pages
MAIN MEMORY
DISK
DB
Choice of page dictated by **replacement policy**

Buffer Manager

- Similar to *virtual memory manager*
- Buffer replacement policies
  - What page to evict?
  - LRU: Least Recently Used
    - Throw out the page that was not used in a long time
  - MRU: Most Recently Used
    - The opposite
    - E.g., during a join there is a nested loop, the block just used won't be used until the next iteration

```
for each tuple i of instructor do
  for each tuple d of department do
    if i[dept_name] = d[dept_name]
    then begin
          let x be a tuple defined as follows:
          x[ID] := i[ID]
          x[dept_name] := i[dept_name]
          x[name] := i[name]
          x[salary] := i[salary]
          x[building] := d[building]
          x[budget] := d[budget]
          include tuple x as part of result of instructor ⋈ department
       end
  end
end
```

Buffer Manager

- **Pinning a block**
  - There can be multiple concurrent processes
  - One block was just read and another query tries to evict it
  - One query pins / unpins the block to lock it while it's being used
- **Writing-ahead a block**
  - The DB can write the update block to disk before it's evicted
  - When the space of that block is needed (eviction), no need to wait the write to go through
- **Forced output of blocks**
  - If there is a crash, the buffer pool and the memory content are lost
  - It is necessary to write a block to disk to make sure the transaction was "committed"

Disk-block Access

- DB systems (i.e., the query processing sub-system) generate requests for disk I/O
  - Data can be stored on OS files
  - Can specify directly logical block
- In case of direct block access techniques to reduce number of random accesses (especially for magnetic disks, less for SSD)
- Buffering
  - Data is read in memory waiting for future requests
- Read-ahead
  - Consecutive blocks are read from the same track to minimize seek time
- Scheduling
  - Read blocks as they pass under the head to minimize disk-arm movement
  - E.g., elevator algorithm
- File organization
  - If data is accessed sequentially keep all data in blocks on adjacent cylinders
- Defragmentation
  - Due to appends to sequential files, the data becomes scattered over the disk
  - Make a copy of the sequential data and delete the old one
- Non-volatile write buffers
  - Save data in non-volatile RAM to speed-up writes and survive system crashes

Outline

- Storage
  - Physical storage
  - Logical storage
    - File Organization
    - Buffer Manager
    - **Indexes**
- Query Processing
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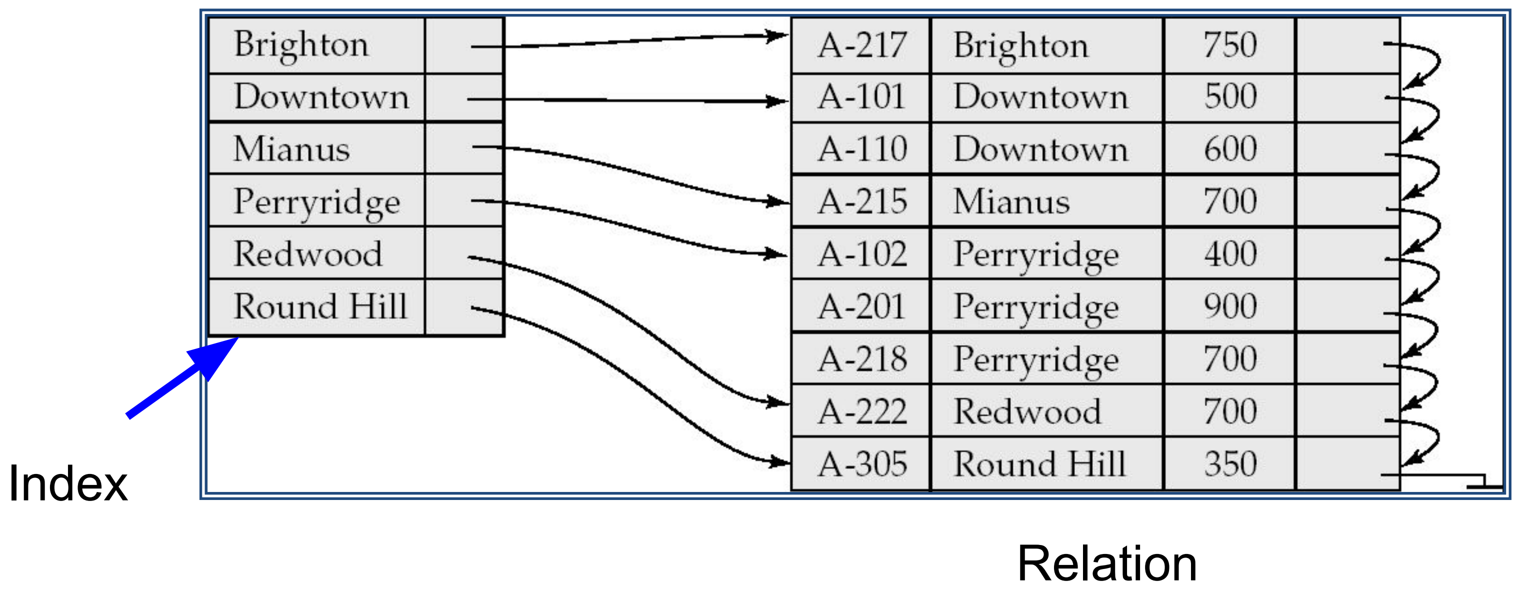
Index

- **Index** = a data structure for efficient search through large databases
- **Search key**
  - Attribute or set of attributes used to look up records
  - E.g. SSN for a *person* table
- Key ideas:
  - Records are mapped to the disk blocks in specific ways
    - Heap, sorted, or hash-based
  - Auxiliary data structures maintained that allow quick search and access
  - Think book index, library catalogue
- **Ordered indexes**
  - Another data structure with search key sorted and pointers to the corresponding records
- **Hash-based indexes**
  - Locate the index
  - Order is not preserved
  - Collisions

Ordered Indexes

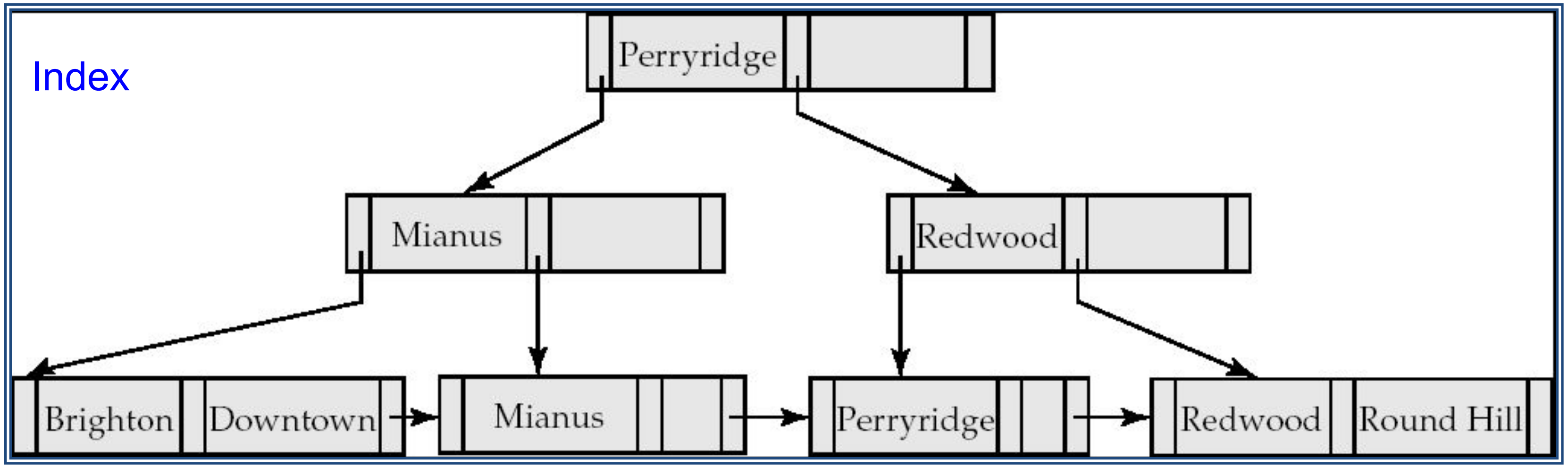
- Map from key to corresponding record / row
- Primary index
  - Key is sorted to allow binary search
  - Can have only one primary index on a relation
- Secondary index
  - Key is not sorted



Brighton	
Downtown	
Mianus	
Perryridge	
Redwood	
Round Hill	

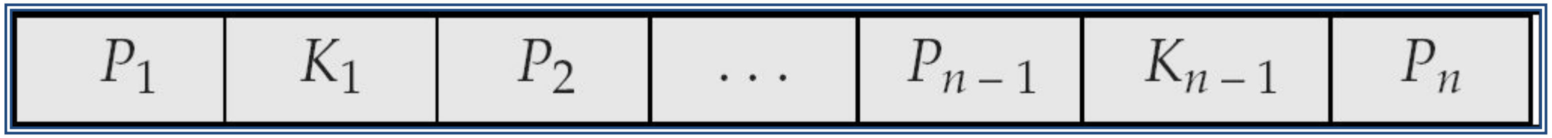
A-217	Brighton	750	
A-101	Downtown	500	
A-110	Downtown	600	
A-215	Mianus	700	
A-102	Perryridge	400	
A-201	Perryridge	900	
A-218	Perryridge	700	
A-222	Redwood	700	
A-305	Round Hill	350	

Example B+-Tree Index



B$^+$-Tree Node Structure

- Typical node

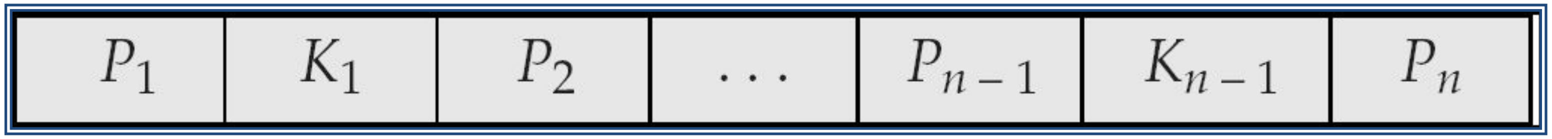


  - K_i are the search-key values
  - P_i are pointers to children (for non-leaf nodes) or pointers to records or buckets of records (for leaf nodes).
- The search-keys in a node are ordered

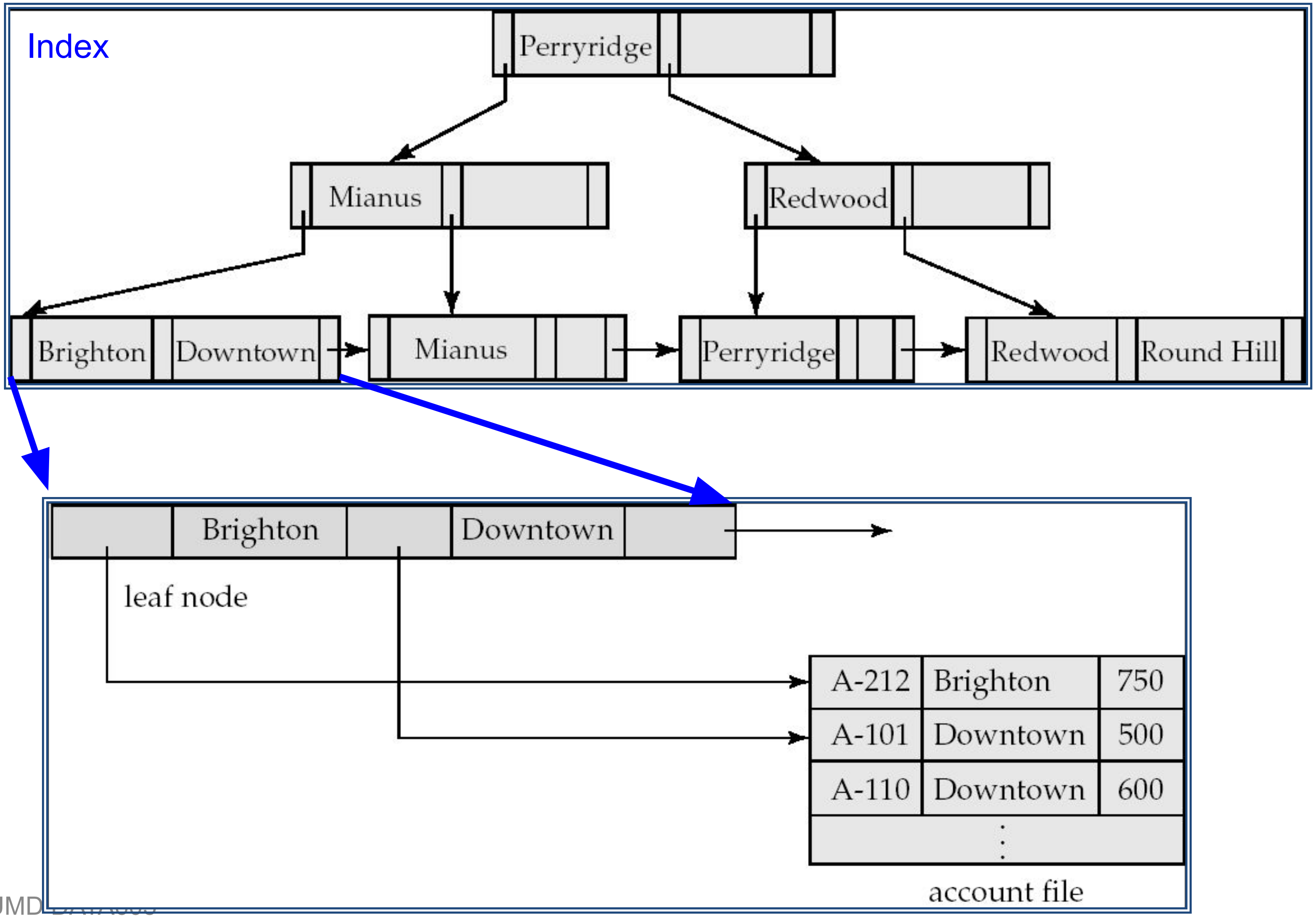
$$K_1 < K_2 < K_3 < \ldots < K_{n-1}$$

Properties of B+-Trees

- It is balanced
  - Every path from the root to a leaf is same length
- Leaf nodes (at the bottom)
  - P_1 contains the pointers to tuple(s) with key K_1
  - …
  - P_n is a pointer to the *next* leaf node
  - Must contain at least n/2 entries



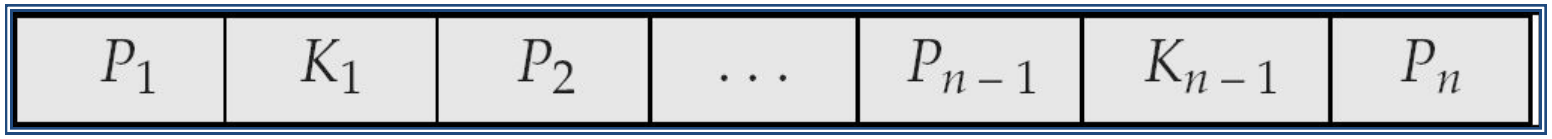
Example B+-Tree Index



A-212	Brighton	750
A-101	Downtown	500
A-110	Downtown	600
⋮		

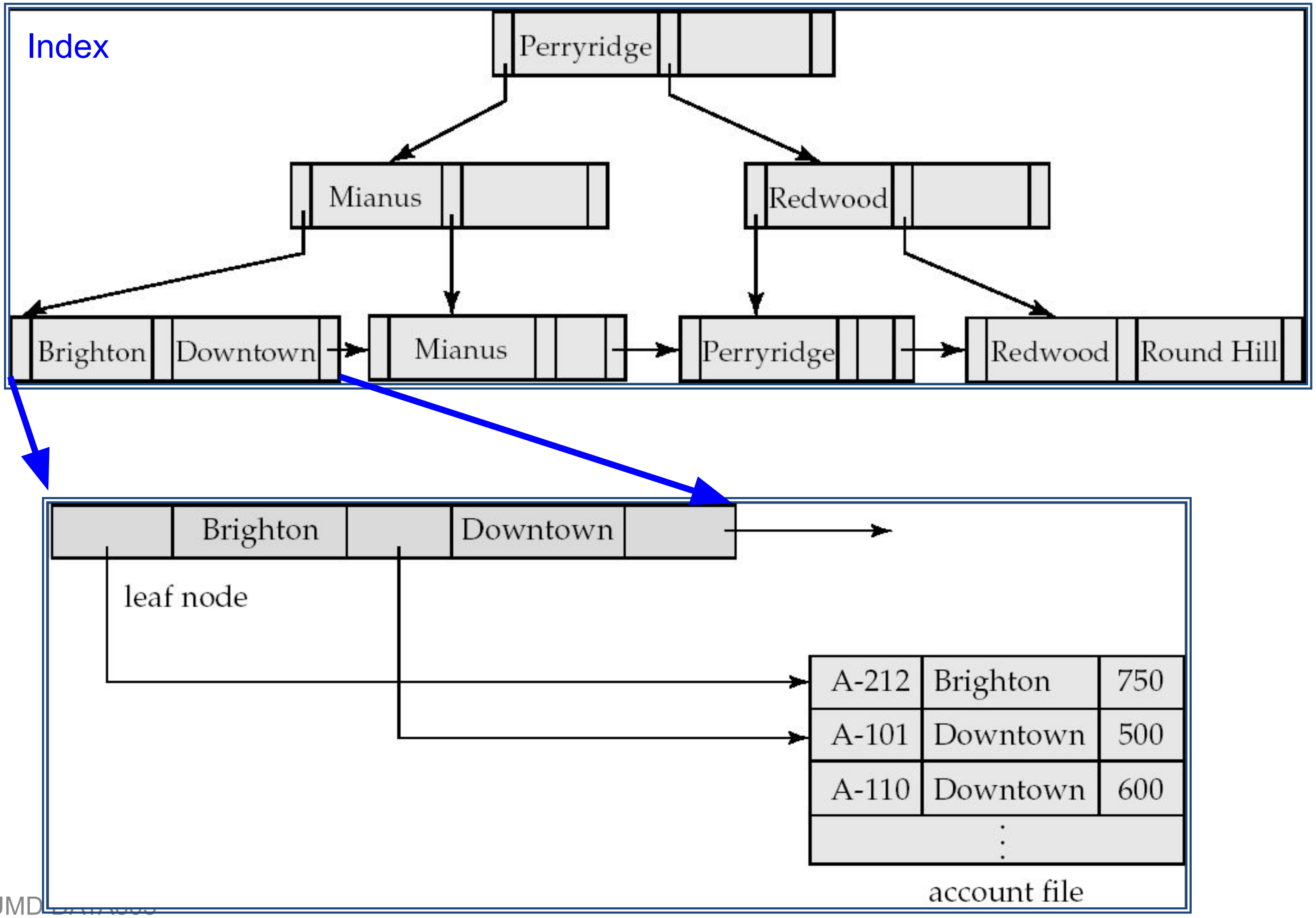
Properties

- Interior nodes



  - All tuples in the subtree pointed to by P_1, have search key $< K_1$
  - To find a tuple with key $K_1' < K_1$, follow P_1
  - …
  - Finally, search keys in the tuples contained in the subtree pointed to by P_n, are all larger than K_{n-1}
  - Must contain at least n/2 entries (unless root)

Example B+-Tree Index

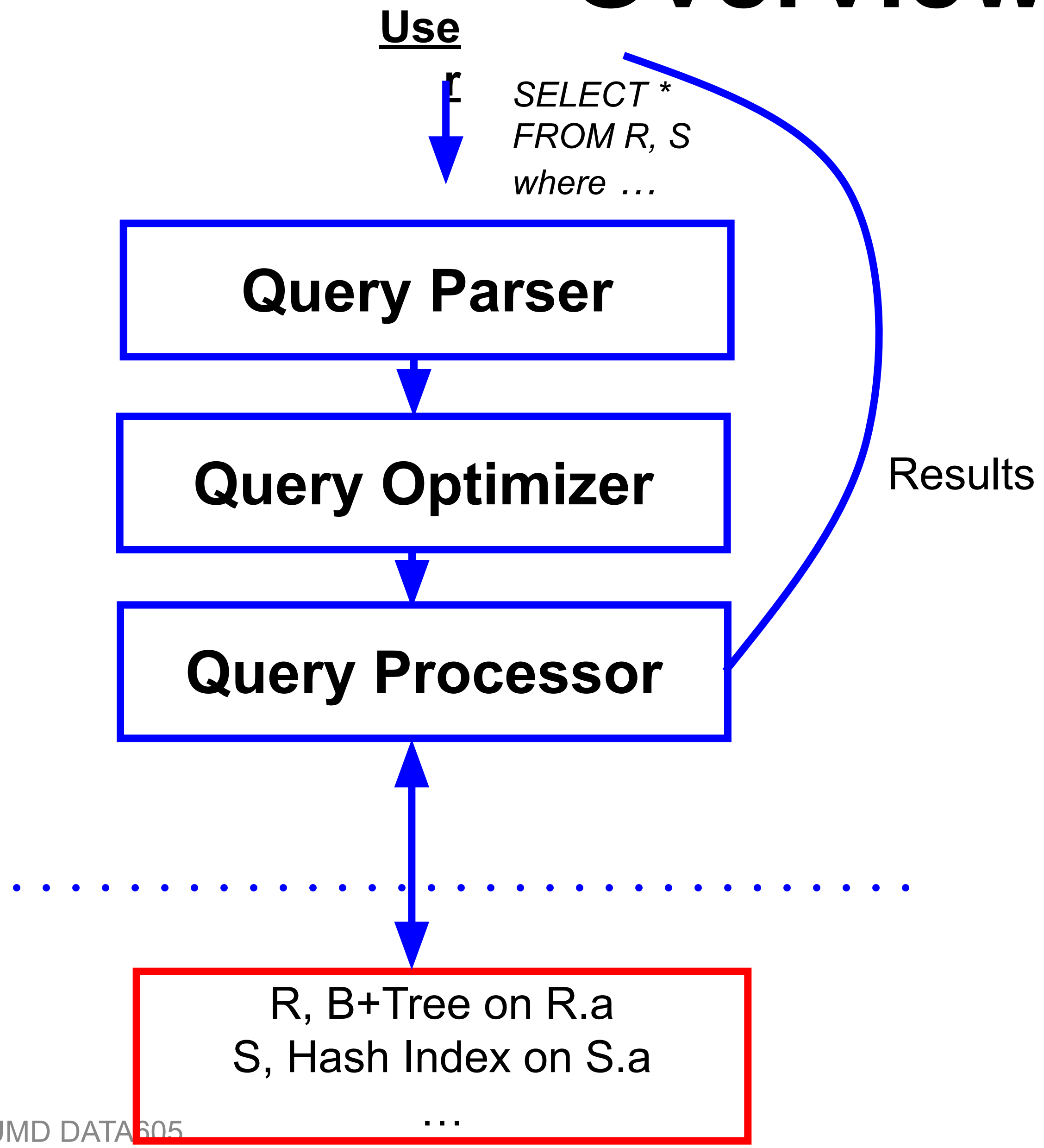


A-212	Brighton	750
A-101	Downtown	500
A-110	Downtown	600
⋮		

Outline

- Storage
- Query Processing
  - Selection operation
  - Join operators
  - Sorting
  - Other operators
  - Putting it all together…
- Transactions

Overview



Resolve the references,
Syntax errors etc.
Converts the query to an internal format
relational algebra like

Find the *best* way to evaluate the query
Which index to use?
What join method to use?
…

Read the data from the files
Do the query processing
joins, selections, aggregates
…

“Cost”

- Complicated to compute
- We will focus on disk:
  - Number of I/Os?
    - Not sufficient
    - Number of seeks matters a lot… why ?
  - t_T – time to transfer one block
  - t_S – time for one seek
  - Cost for *b* block transfers plus *S* seeks

    $$b * t_T + S * t_S$$
  - Measured in *seconds*

Outline

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Selection Operation

```
SELECT * FROM person WHERE SSN = “123”
```

- **Option 1: Sequential Scan**
  - Read the relation start to end and look for “123”
    - Can always be used (not true for the other options)
  - Cost
    - *Let b_r = Number of relation blocks*
    - Then:
      - 1 seek and b_r block transfers
    - So:
      - $t_S + b_r * t_T$ *sec*
    - *Improvements:*
      - *If SSN is a key, then can stop when found*
        - » *So on average, $b_r/2$ blocks accessed*

Selection Operation

```
SELECT * FROM person WHERE SSN = "123"
```

- **Option 2 : Binary Search**
  - Pre-condition:
    - The relation is sorted on SSN
    - Selection condition is an equality
      - E.g. can't apply to "*Name like '%424%'*"
  - Do binary search
    - Cost of finding the *first* tuple that matches
      - $\lceil \log_2(b_r) \rceil * (t_T + t_S)$
      - All I/Os are random, so need a seek for all
        - » The last few are closeby, but we ignore such small effects
  - Not quite: what if 10,000 tuples match the condition?
    - Incurs additional cost

Selection Operation

```
SELECT * FROM person WHERE SSN = “123”
```

- **Option 3 : Use Index**
  - Pre-condition:
    - An appropriate index must exist
  - Use the index
    - Find the first leaf page that contains the search key
    - Retrieve all the tuples that match by following the pointers
      - If primary index, the relation is sorted by the search key
        - » Go to the relation and read blocks sequentially
      - If secondary index, must follow all pointers using the index

Query Processing

- Overview
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Join

- `SELECT * FROM R, S WHERE R.a = S.a`
  - Called an "*equi-join*"
- `SELECT * FROM R, S WHERE |R.a – S.a | < 0.5`
  - *Not an "equi-join"*

- Option 1: Nested-loops

```
for each tuple r in R
    for each tuple s in S
        check if r.a = s.a (or whether |r.a – s.a| < 0.5)
```

- Can be used for any join condition
  - As opposed to some algorithms we will see later
- R called *outer relation*
- S called *inner relation*

Nested-loops Join

- Cost? Depends on the actual values of parameters, especially memory
- b_r, b_s □ *Number of blocks of R and S*
- n_r, n_s □ *Number of tuples of R and S*
- <u>Case 1:</u> Minimum memory required = 3 blocks
  - One to hold the current *R* block, one for current S block, one for the result being produced
  - Blocks transferred:
    - Must scan *R* tuples once: b_r
    - For each *R* tuple, must scan *S:* $n_r * b_s$
  - Seeks?
    - $n_r + b_r$

Nested-loops Join

- <u>Case 1: Minimum memory required = 3 blocks</u>
  - Blocks transferred: $n_r * b_s + b_r$
  - Seeks: $n_r + b_r$
- Example:
  - Number of records -- *R:* $n_r = 10{,}000$*,* *S:* $n_s = 5000$
  - Number of blocks -- *R:* $b_r = 400$ *,* *S:* $b_s = 100$
- Then:
  - blocks transferred: 10000 * 100 + 400 = 1,000,400
  - seeks: 10400
- What if we were to switch R and S ?
  - 2,000,100 block transfers, 5100 seeks
- Matters

Nested-loops Join

- <u>Case 2: *S* fits in memory</u>
  - Blocks transferred: $b_s + b_r$
  - Seeks: *2*
- Example:
  - Number of records -- R: $n_r = 10{,}000$, S: $n_s = 5000$
  - Number of blocks -- R: $b_r = 400$, S: $b_s = 100$
- Then:
  - blocks transferred: 400 + 100 = 500
  - seeks: 2
- This is orders of magnitude difference

Hash Join

- <u>Case 1: Smaller relation *(S)* fits in memory</u>
- Nested-loops join:

```
for each tuple r in R
    for each tuple s in S
        check if r.a = s.a
```

- Cost: $b_r + b_s$ transfers, 2 seeks
- The inner loop is not exactly cheap (high CPU cost)

- Hash join:

```
read S in memory and build a hash index on it
for each tuple r in R
    use the hash index on S to find tuples such that S.a = r.a
```

Hash Join

- Case 1: Smaller relation *(S)* fits in memory
- Hash join:

```
  read S in memory and build a hash index on it
  for each tuple r in R
        use the hash index on S to find tuples such that S.a = r.a
```

- Cost: $b_r + b_s$ transfers, 2 seeks (unchanged)
- Why good ?
  - CPU cost is much better (even though we don't care about it too much)
  - Performs much better than nested-loops join when *S* doesn't fit in memory (next)

Hash Join

- <u>Case 2: Smaller relation *(S)* doesn't fit in memory</u>
- Two "phases"
- Phase 1:
  - Read the relation *R* block by block and partition it using a hash function, *h1(a)*
    - Create one partition for each possible value of *h1(a)*
  - Write the partitions to disk
    - R gets partitioned into R1, R2, …, Rk
  - Similarly, read and partition S, and write partitions S1, S2, …, Sk to disk
  - Only requirement:
    - Each S partition fits in memory

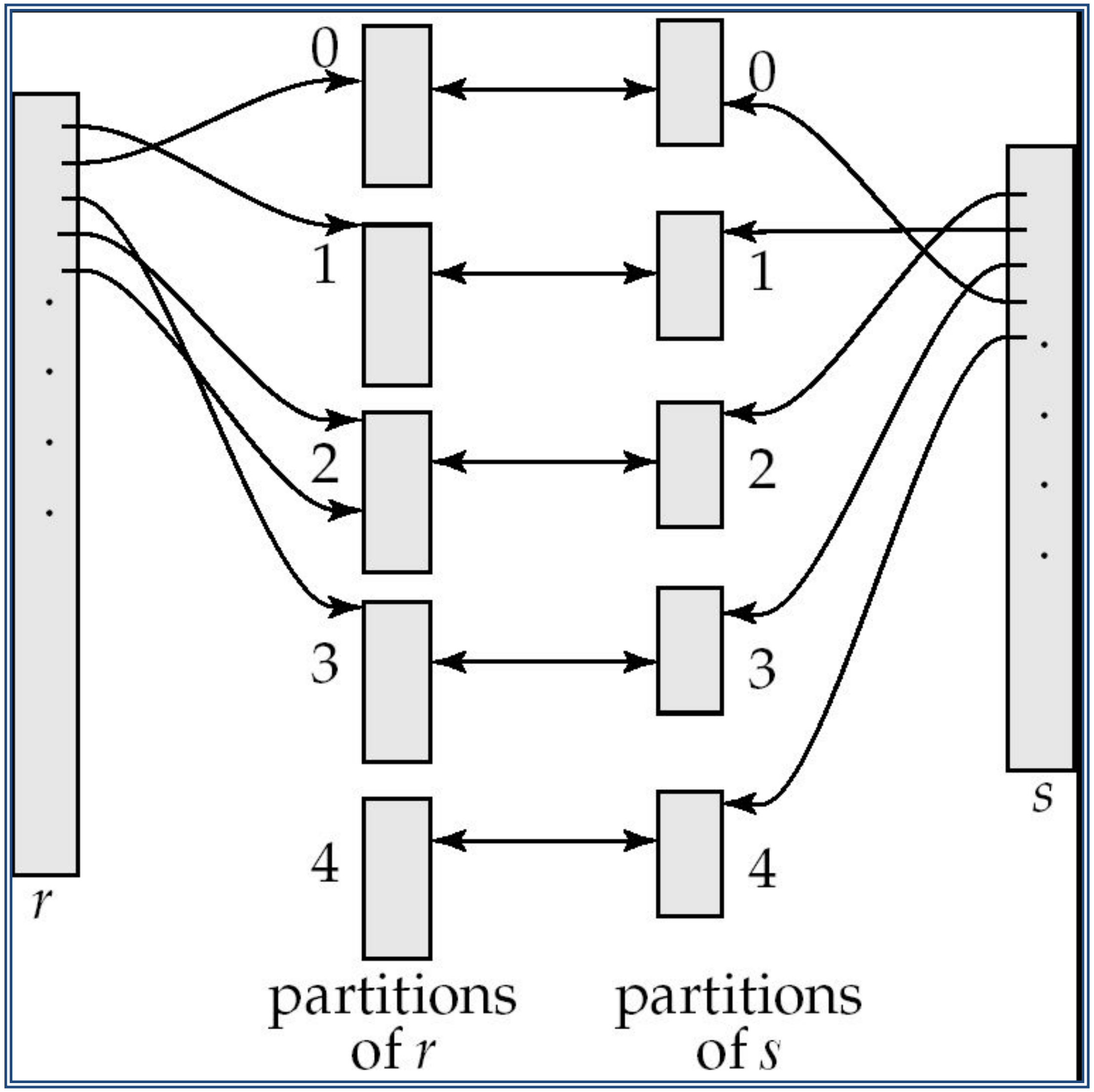
Hash Join

- <u>Case 2: Smaller relation *(S)* doesn't fit in memory</u>
- Two "phases"
- Phase 2:
  - Read S1 into memory, and build a hash index on it (S1 fits in memory)
    - Using a different hash function, $h_2(a)$
  - Read R1 block by block, and use the hash index to find matches.
  - Repeat for S2, R2, and so on.

Hash Join

- <u>Case 2: Smaller relation *(S)* doesn't fit in memory</u>
- Two "phases":
- Phase 1:
  - Partition the relations using one hash function, $h_1(a)$
- Phase 2:
  - Read S_i into memory, and build a hash index on it (S_i fits in memory)
  - Read R_i block by block, and use the hash index to find matches.
- Cost?
  - $3(b_r + b_s) + 4 * n_h$ block transfers + $2(\lceil b_r / b_b \rceil + \lceil b_s / b_b \rceil)$ seeks
    - Where b_b is the size of each output buffer
  - Much better than Nested-loops join under the same conditions

Hash Join



Merge-Join (Sort-merge join)

- Pre-condition:
  - The relations must be sorted by the join attribute
  - If not sorted, can sort first, and then use this algorithms
- Called “sort-merge join” sometimes

```
select *
from r, s
where r.a1 = s.a1
```

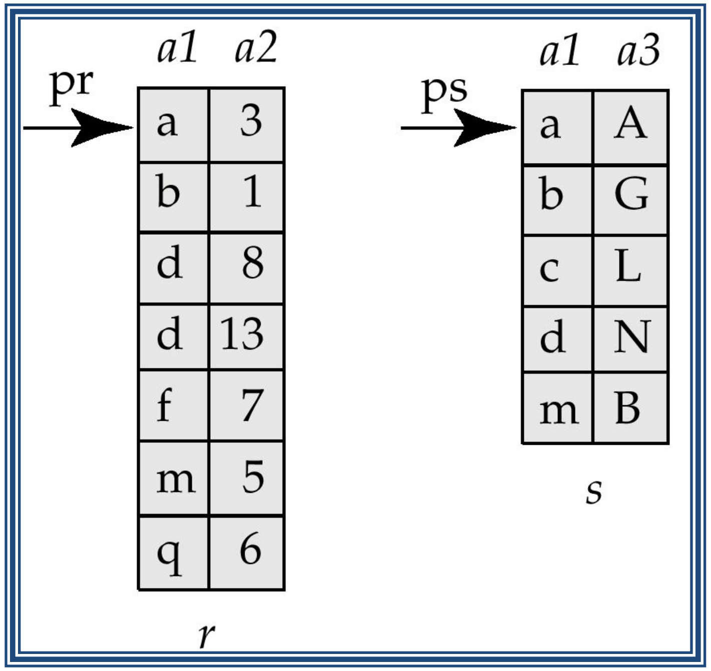
Step:

1. Compare the tuples at pr and ps

2. Move pointers down the list

- Depending on the join condition

3. Repeat



Merge-Join (Sort-merge join)

- Cost:
  - If the relations sorted, then just
    - $b_r + b_s$ block transfers, some seeks depending on memory size
  - What if not sorted?
    - Then sort the relations first
    - In many cases, still very good performance
    - Typically comparable to hash join
- Observation:
  - The final join result will also be sorted on *a1*
  - This might make further operations easier to do
    - E.g., duplicate elimination

Joins: Summary

- Block Nested-loops join
  - Can always be applied irrespective of the join condition
- Index Nested-loops join
  - Only applies if an appropriate index exists
- Hash joins – only for equi-joins
  - Join algorithm of choice when the relations are large
- Hybrid hash join
  - An optimization on hash join that is always implemented
- Sort-merge join
  - Very commonly used – especially since relations are typically sorted
  - Sorted results commonly desired at the output
    - To answer group by queries, for duplicate elimination, because of ASC/DSC

Query Processing

- Overview
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- Other operators
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Sorting

- Commonly required for many operations
  - Duplicate elimination, group by’s, sort-merge join
  - Queries may have ASC or DSC in the query
- One option:
  - Read the lowest level of the index
    - May be enough in many cases
  - But if relation not sorted, this leads to too many random accesses
- If relation small enough…
  - Read in memory, use quick sort (qsort() in C)
- What if relation too large to fit in memory ?
  - External sort-merge

External sort-merge

- Divide and Conquer !!
- Let *M* denote the memory size (in blocks)
- Phase 1:
  - Read first M blocks of relation, sort, and write it to disk
  - Read the next M blocks, sort, and write to disk …
  - Say we have to do this “N” times
  - Result: *N* sorted runs of size *M* blocks each
- Phase 2:
  - Merge the *N* runs (*N-way merge)*
  - Can do it in one shot if *N* < *M*

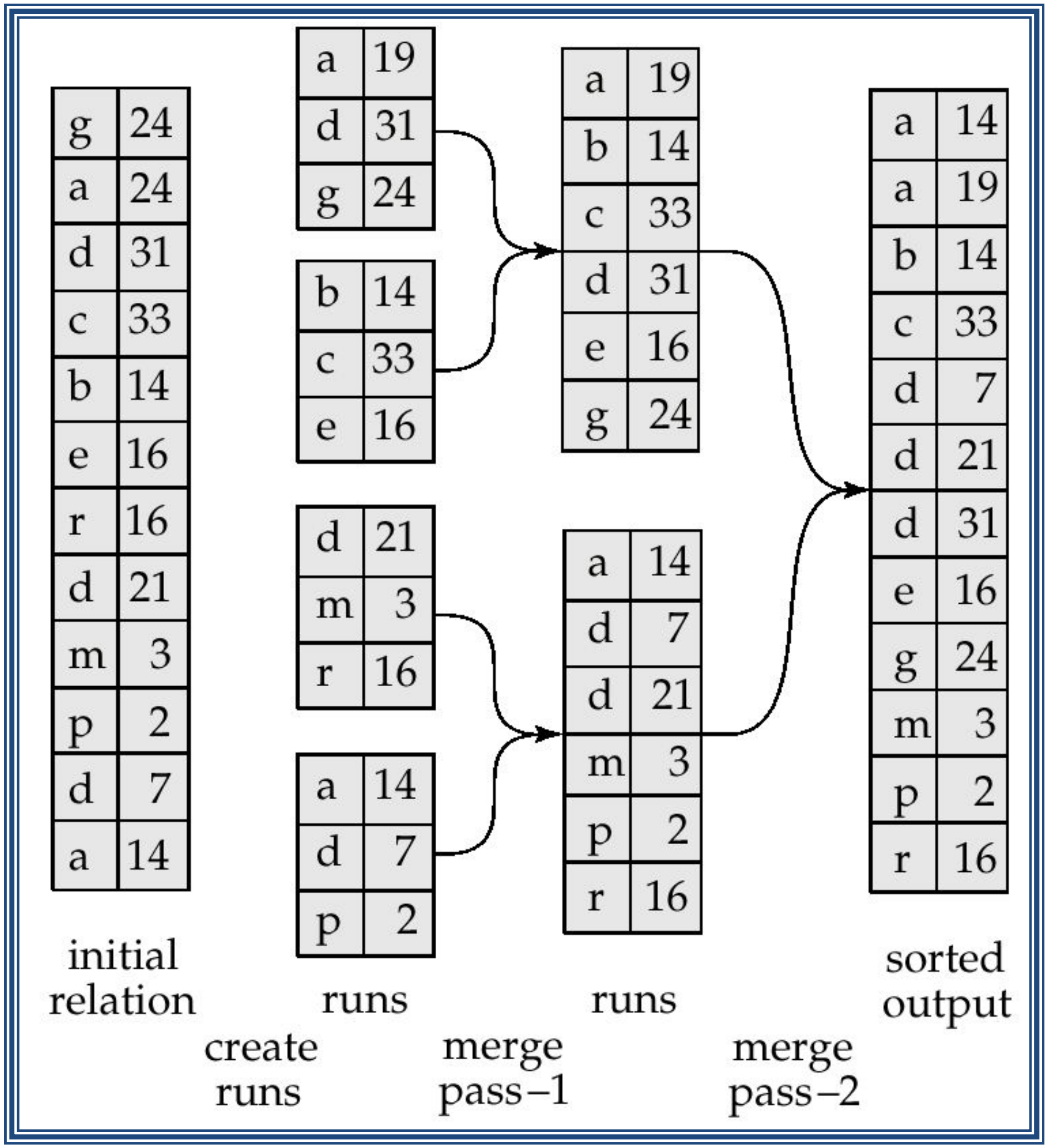
External sort-merge

- Phase 1:
  - Create *sorted runs of size M* each
  - Result: *N* sorted runs of size *M* blocks each

- Phase 2:
  - Merge the *N* runs (*N-way merge)*
  - Can do it in one shot if *N* < *M*

- What if *N* > *M ?*
  - Do it recursively
  - Not expected to happen
  - If *M* = 1000 blocks = 4MB (assuming blocks of 4KB each)
    - Can sort: 4000MB = 4GB of data

Example: External Sorting Using Sort-Merge



External Merge Sort (Cont.)

- Cost analysis:
  - Total number of merge passes required: $\lceil \log_{M-1}(b_r/M) \rceil$.
  - Disk accesses for initial run creation as well as in each pass is $2b_r$
    - for final pass, we don't count write cost
      - we ignore final write cost for all operations since the output of an operation may be sent to the parent operation without being written to disk

Thus total number of disk accesses for external sorting:

$$b_r \left(2 \lceil \log_{M-1}(b_r / M) \rceil + 1 \right)$$

Query Processing

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Group By and Aggregation

select a, count(b)
from R
group by a;

- Hash-based algorithm
- Steps:
  - Create a hash table on *a,* and keep the *count(b) so far*
  - Read *R* tuples one by one
  - For a new *R tuple, “r”*
    - Check if *r.a* exists in the hash table
    - If yes, increment the count
    - If not, insert a new value

Group By and Aggregation

select a, count(b)
from R
group by a;

- Sort-based algorithm
- Steps:
  - Sort *R* on *a*
  - Now all tuples in a single group are contigous
  - Read tuples of *R (sorted)* one by one and compute the aggregates

Group By and Aggregation

select a, AGGR(b) from R group by a;

- sum(), count(), min(), max(): only need to maintain one value per group
  - Called "distributive"
- average() : need to maintain the "sum" and "count" per group
  - Called "algebraic"
- stddev(): algebraic, but need to maintain some more state
- median(): can do efficiently with sort, but need two passes (called "holistic")
  - First to find the number of tuples in each group, and then to find the median tuple in each group
- count(distinct b): must do duplicate elimination before the count

Duplicate Elimination

select distinct a
from R ;

- Best done using sorting – Can also be done using hashing
- Steps:
  - Sort the relation *R*
  - Read tuples of *R* in sorted order
  - prev = null;
  - for each tuple *r* in *R (sorted)*
    - if *r != prev* then
      - Output *r*
      - *prev = r*
    - else
      - Skip *r*

Set operations

*(select * from R) union (select * from S) ;*
*(select * from R) intersect (select * from S) ;*
*(select * from R) union all (select * from S) ;*
*(select * from R) intersect all (select * from S) ;*

- Remember the rules about duplicates
- "union all": just append the tuples of *R and S*
- *"*union": append the tuples of *R and S, and do duplicate elimination*
- *"intersection"*: similar to joins
  - Find tuples of R and S that are identical on all attributes
  - Can use *hash-based or sort-based algorithm*

Query Processing

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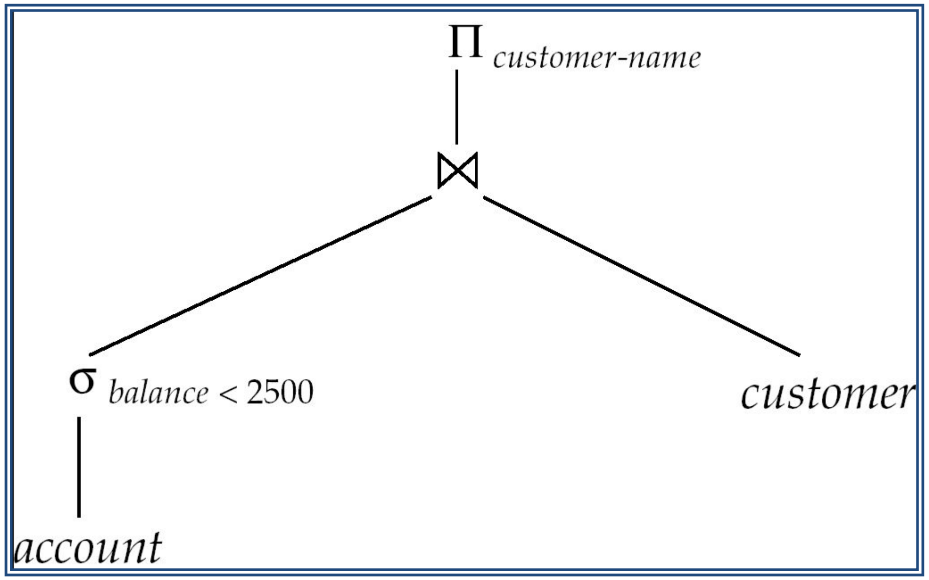
Evaluation of Expressions

```
select customer-name
from account a, customer c
where a.SSN = c.SSN and
        a.balance < 2500
```



- Two options:
  - Materialization
  - Pipelining

Evaluation of Expressions

- Materialization
  - Evaluate each expression separately
    - Store its result on disk in *temporary relations*
    - Read it for next operation

- Pipelining
  - Evaluate multiple operators simultaneously
  - Skip the step of going to disk
  - Usually faster, but requires more memory
  - Also not always possible..
    - E.g., Sort-Merge Join
  - Harder to reason about

Materialization

- Materialized evaluation is always applicable
- Cost of writing results to disk and reading them back can be quite high
  - Our cost formulas for operations ignore cost of writing results to disk, so
    - Overall cost = Sum of costs of individual operations + cost of writing intermediate results to disk
- Double buffering: use two output buffers for each operation, when one is full write it to disk, while the other is getting filled
  - Allows overlap of disk writes with computation and reduces execution time

Pipelining

- Evaluate several operations simultaneously, passing the results of one operation on to the next.
- E.g., in previous expression tree, don't store result of

$$\sigma_{balance < 2500}(account)$$

  - instead, pass tuples directly to the join.. Similarly, don't store result of join, pass tuples directly to projection.
- Much cheaper: no need to store a temporary relation to disk.
- Requires higher amount of memory
  - All operations are executing at the same time (say as processes)
- Somewhat limited applicability
- A "blocking" operation: An operation that has to consume entire input before it starts producing output tuples

Pipelining

- Need operators that generate output tuples while receiving tuples from their inputs
  - Selection: Usually yes.
  - Sort: NO. The sort operation is blocking
  - Sort-merge join: The final (merge) phase can be pipelined
  - Hash join: The partitioning phase is blocking; the second phase can be pipelined
  - Aggregates: Typically no. Need to wait for the entire input before producing output
    - However, there are tricks you can play here
  - Duplicate elimination: Since it requires sort, the final merge phase could be pipelined
  - Set operations: see duplicate elimination

Transactions

- Storage
- Query Processing
- Transactions
  - Overview
  - Concurrency Control
  - Recovery

Overview

- *Transaction*: A sequence of database actions enclosed within special tags
- Properties:
  - ***Atomicity***: Entire transaction or nothing
  - ***Consistency***: Transaction, executed completely, takes database from one consistent state to another
  - ***Isolation***: Concurrent transactions *appear* to run in isolation
  - ***Durability***: Effects of committed transactions are not lost
- Consistency: transaction programmer needs to guarantee that
    - DBMS can do a few things, e.g., enforce constraints on the data
- Rest: DBMS guarantees

Bank application example

- TODO

How does..

- .. this relate to *queries* that we discussed ?
  - Actual queries don't update data, so *durability* and *consistency* not relevant
  - Would want *concurrency*
    - Consider a query computing total balance at the end of the day
  - Would want *isolation*
    - What if somebody makes a *transfer* while we are computing the balance
    - Typically not guaranteed for such long-running queries

Performance benchmark

- Transaction per minute
- TPC-C:
  - OLTP application
  - a wholesale distributor with a small number of warehouses full of inventory servicing a larger number of retail locations
  - Heady on disk I/O
- TPC-E:
  - modern OLTP application
  - a stock brokerage, simulated world driven by fluctuating stock prices and outside world of customers placing market orders, limit orders and stop-limit orders
  - Heavy on RAM
- TPC-H
  - OLAP application
  - Query analytics in a 'data warehouse' context

Assumptions and Goals

- Assumptions:
  - The system can crash at any time
  - Similarly, the power can go out at any point
    - Contents of the main memory won't survive a crash, or power outage
  - BUT… **disks are durable. They might stop, but data is not lost.**
  - Disks only guarantee *atomic* *sector* *writes,* nothing more
  - Transactions are by themselves consistent
- Goals:
  - Guaranteed durability, atomicity
  - As much concurrency as possible, while not compromising isolation and/or consistency
    - Two transactions updating the same account balance… NO
    - Two transactions updating different account balances… YES

Transactions

- Overview
- Concurrency Control
- Recovery

Lock-based Protocols

- A transaction *must* get a *lock* before operating on the data
- Two types of locks:
  - *Shared* (S) locks (also called *read locks)*
    - Obtained if we want to only read an item
  - *Exclusive* (X) locks (also called *write locks)*
    - Obtained for updating a data item

Lock instructions

- New instructions
  - lock-S: shared lock request
  - lock-X: exclusive lock request
  - unlock: release previously held lock

Example schedule:

T1	T2
read(B)	read(A)
B □B-50	read(B)
write(B)	display(A+B)
read(A)	
A □A + 50	
write(A)	

Lock instructions

- New instructions
  - lock-S: shared lock request
  - lock-X: exclusive lock request
  - unlock: release previously held lock

Example schedule:

T1	T2
lock-X(B)	lock-S(A)
read(B)	read(A)
B □B-50	unlock(A)
write(B)	lock-S(B)
unlock(B)	read(B)
lock-X(A)	unlock(B)
read(A)	display(A+B)
A □A + 50	
write(A)	
unlock(A)	

Lock-based Protocols

- Lock requests are made to the *concurrency control manager*
  - It decides whether to *grant* a lock request
- T1 asks for a lock on data item A, and T2 currently has a lock on it?
  - Depends

T2 lock type	**T1 lock type**	**Should allow ?**
Shared	Shared	YES
Shared	Exclusive	NO
Exclusive	-	NO

- If *compatible,* grant the lock, otherwise T1 waits in a *queue.*

Snapshot Isolation

- Very popular scheme, used as the primary scheme by many systems including Oracle, PostgreSQL etc…
  - Several others support this in addition to locking-based protocol

- A type of "optimistic concurrency control"

- Key idea:
  - For each object, maintain past "versions" of the data along with timestamps
    - Every update to an object causes a new version to be generated

Snapshot Isolation

- Read queries:
  - Let “t” be the “time-stamp” of the query, i.e., the time at which it entered the system
  - When the query asks for a data item, provide a version of the data item that was latest as of “t”
    - Even if the data changed in between, provide an old version
  - No locks needed, no waiting for any other transactions or queries
  - The query executes on a consistent snapshot of the database
- Update queries (transactions):
  - Reads processed as above on a snapshot
  - Writes are done in private storage
  - At commit time, for each object that was written, check if some other transaction updated the data item since this transaction started
    - If yes, then abort and restart
    - If no, make all the writes public simultaneously (by making new versions)

Snapshot Isolation

- Advantages:
  - Read query don’t block at all, and run very fast
  - As long as conflicts are rare, update transactions don’t abort either
  - Overall better performance than locking-based protocols

- Major disadvantage:
  - Not serializable
  - Inconsistencies may be introduced
  - See the wikipedia article for more details and an example
    - http://en.wikipedia.org/wiki/Snapshot_isolation

Transactions

- Overview
- Concurrency Control
- Recovery

Context

- ACID properties:
  - We have talked about Isolation and Consistency
  - How do we guarantee Atomicity and Durability?
    - Atomicity: Two problems
      - Part of the transaction is done, but we want to cancel it
        - » ABORT/ROLLBACK
      - System crashes during the transaction. Some changes made it to the disk, some didn't.
    - Durability:
      - Transaction finished. User notified. But changes not sent to disk yet (for performance reasons). System crashed.

- Essentially similar solutions

Reasons for crashes

- Transaction failures
  - **Logical errors**: transaction cannot complete due to some internal error condition
  - **System errors**: the database system must terminate an active transaction due to an error condition (e.g., deadlock)
- System crash
  - Power failures, operating system bugs, etc.
  - **Fail-stop assumption**: non-volatile storage contents are assumed to not be corrupted by system crash
    - Database systems have numerous integrity checks to prevent corruption of disk data
- Disk failure
  - Head crashes; ***we will assume***
    - ***STABLE STORAGE: Data never lost. Can approximate by using RAID and maintaining geographically distant copies of the data***

Log-based Recovery

- Most commonly used recovery method
- Intuitively, a log is a record of everything the database system does
- For every operation done by the database, a *log record* is generated and stored <u>*typically on a different (log) disk*</u>
- *<T1, START>*
- *<T2, COMMIT>*
- *<T2, ABORT>*
- *<T1, A, 100, 200>*
  - T1 modified A; old value = 100, new value = 200