# File Structures and Indexing

CPS352: Database Systems

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# Agenda

- Check-in
- Database File Structures
- Indexing
- Database Design Tips

# Check-in

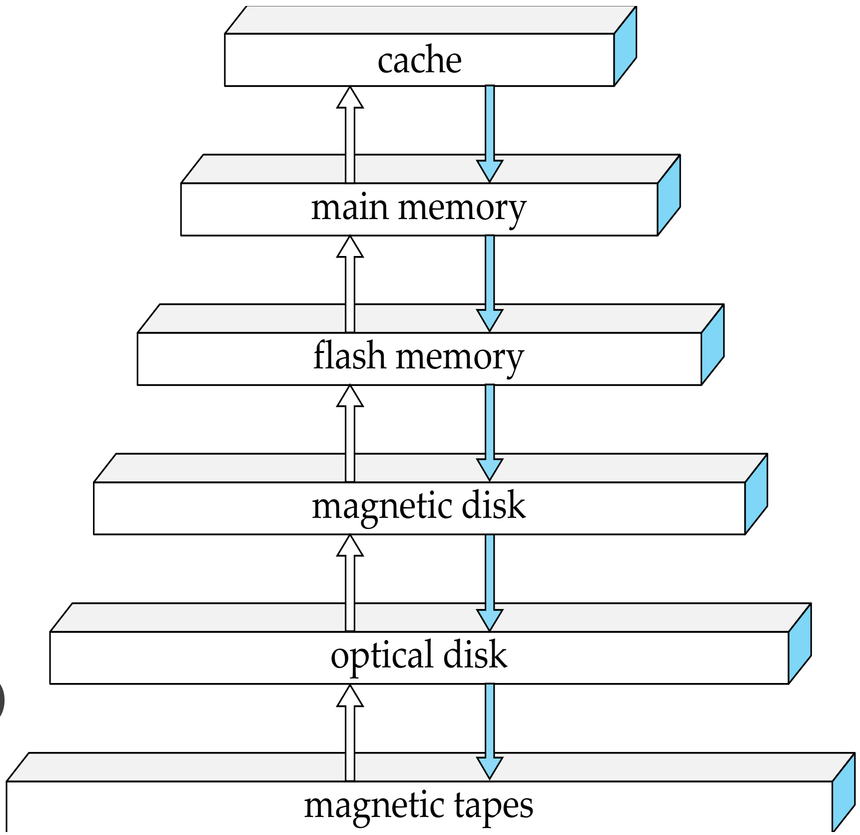
# Database File Structures

# File System Performance

- Often *the* major factor in DBMS performance
  - Response time – time between issuing a command and seeing its results
    - Want to minimize this
  - Throughput – number of operations per unit of time
    - Want to maximize this
    - Especially important for a system with many users (i.e. large scale web site)

# Physical Storage

- Primary storage (memory)
  - Fast
  - Volatile
    - Lost on power or hardware failure
- Secondary storage (disk)
  - Slower (online storage)
    - 100,000 : 1 ratio compared with memory
  - Non-volatile
- Tertiary storage (tape)
  - Not immediately available (offline)
- Capacities of each have increased exponentially
  - Speeds have not - continues to be point of contention



# Disk Access Time

- How long it takes to read or write data to disk
  - Includes
    - Seek time - time needed to to position the disk head to the correct track (4-10 ms)
    - Rotation latency - time needed to rotate the disk so that the desired information starts to pass under the head (4-11 ms for typical disks 5400 – 15000 rpm)
    - Data-transfer rate - time needed to transfer information
      - ~1% of total time
- To optimize this process, data on disk is organized into blocks
  - Chunks of contiguous information
  - System reads or writes entire blocks, not individual bytes

# How a DBMS Minimizes Disk Access

- Keep all data needed for a particular operation in a single block
  - Only one disk access needed
- Keeping copies of recently used information in memory
  - Disk access needed for initial operation, but repeated or similar operations can use in-memory copy
- Parallelism -- spread data across multiple disks
  - Data access happens on several disks at the same time

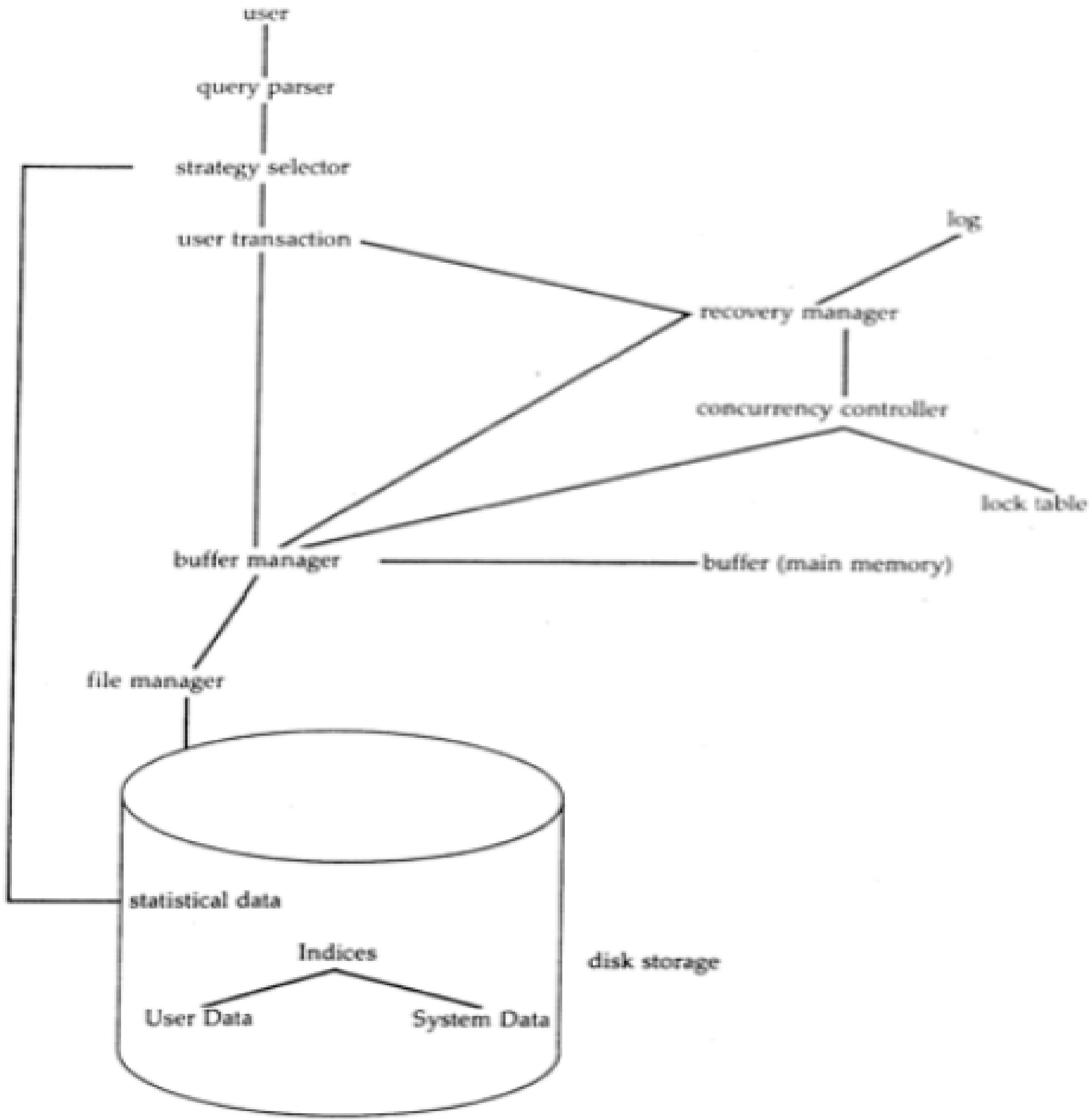
# RAID: Redundant Arrays of Independent Disks

- Disk organization techniques that manage a large numbers of disks, providing a view of a single disk
  - Striping - high capacity and high speed by using multiple disks in parallel (RAID 0)
    - Parallelize large accesses to reduce response time.
  - Mirroring - high reliability by storing data redundantly, so that data can be recovered even if a disk fails (RAID 1)
    - Reads can happen on any disk
      - Load balance multiple small accesses to increase throughput
    - Writes slower because they must be carried out on all disks
- The chance that a single disk will fail in a large system increases as the number of disks goes up
  - e.g., a system with 100 disks, each with MTTF of 100,000 hours (approx. 11 years), will have a system MTTF of 1000 hours (approx. 41 days)

# Common RAID Levels

- RAID 1 + 0 ( RAID 10) –mirroring with striping on top
  - Combines RAID 1 (mirroring) with RAID 0 (striping) – order is important here
  - Adds speed and redundancy at the cost of capacity
    - Good write performance
- RAID 5 – block interleaved distributed parity
  - Stores parity blocks on same disks as data
    - Parity data enables error detection and recovery
    - Allow parallel writes of data and parity if they are on separate disks
  - Adds capacity at the cost of speed
    - Serious performance penalties in degraded state (when disk fails) because of parity data calculations for recovery

# Database System Structure



# Database System Structure: Data Components

- Database itself is stored as one or more files on disk
  - As a collection of files – i.e. one for each table (MySQL)
  - A single large file on the operating system in which the DBMS builds its own file system (DB2)
  - Hybrid of these approaches (Oracle – tablespace files)
- Classifications of data
  - User data
  - Systems data
    - Data dictionary or system catalog
    - User access control data
    - Statistical data about data access
  - Index data
  - Logging data

# Database System Structure: Memory Components

- Main memory buffer pools
  - Stores most recently accessed block from disk for each table (at a minimum)
  - Often, retains data that has been used once and is likely to be used again
  - Logic needed to manage what data is kept in the pool
    - Since memory is usually smaller than the entire database

# Database System Structure: Software Components

- Buffer manager – manages the memory pool
- Query parser -- accepts and translates queries
- Strategy selector – plans the best way to carry out queries
- Crash recovery manager – restores data to a consistent state after an unexpected failure
  - Uses a log of changes made to the database
- Concurrency controller – prevents inconsistencies from simultaneous changes to same data by multiple users

# File Organization Approaches

- Fixed-length records
- Variable-length records

# Fixed-Length Records

- Every record is allocated the same amount of space
  - Records of the same type can reside in a single file (or portion of a file
  - Record offset = ( relative position – 1 ) * record size
- Space from deleted records can be reused
  - Move all records after the deleted one back one slot (expensive)
  - Move the last record into the empty slot (less expensive)
  - Link free slots  together in a *free list*
    - Address of first free (deleted) stored in file header
    - Each deleted record stores the address of the next deleted record

# Variable-Length Records

- Fixed-width records are not always practical
  - Storing arbitrarily long pieces of text (i.e. articles, documents)
  - Storing binary resources (i.e. pictures, videos)
  - Storing multiple record types in a single file
- Approaches
  - Represent variable-length attributes with a fixed size (offset, length), and store their actual values after all other data in the record
  - Store fixed-length record data in one file with pointers to variable-length data in other files
    - Multimedia databases may have pointers to individual files for variable-length values ("clobs" and "blobs")

# Record Organization

- Sequential – sort records in a table by some column value
  - Good choice if most/all queries of the table are done using the sorted criteria
  - Inserts become problematic – need to retain sort order
    - "Buckets" can be used to help address this – all records with same or similar sort key values go into the same bucket
      - Reduces cost of preserving sort order
- Multi-table clustering – sometimes data in multiple tables is related and queried together
  - Store related data from each table on the same (set of) disk block(s)
  - Good for queries involving related data, not so go for queries on individual records
  - Results in variable-length records
  - NoSQL solutions often use this approach

# Buffer Management

- How does the DBMS decide which data is tossed from the buffer when new query results are being loaded?
- Policies
  - Least Recently Used (LRU) – toss the buffer contents which have not been used for the longest period of time
    - Based on the idea that past query patterns are a good predictor of the future
  - Most Recently Used (MRU) – toss the buffer contents which have been used most recently
    - Good when cycling through contents of a table which is too big for memory
  - Based on frequency of block usage
    - Examples: blocks in the data dictionary, root blocks of indexes

# Indexing

# Indexing Overview

- Indexes (indices) used to efficiently search for row(s) in a table that match certain criteria
  - Find the disk block with the desired data with minimal disk accesses
- Index trade-off
  - Improved search efficiency vs.
  - Cost of maintaining the index
    - Disk space required for index
- Search key
  - Attribute(s) used to do lookups on an index
  - Multiple indexes can be created on a table with different search keys

# Index Considerations

- What will the index be used for?
  - Find rows which match exact values
  - Range queries (i.e. values between, greater, or less than some bounds)
  - Sequential access of all rows in the table
- How frequently is the underlying data modified?
  - Lots of inserts, updates, and deletes mean more index maintenance
  - Read-only / read-mostly data can use indexes that facilitate faster data access but are expensive to maintain
- Is the search key a superkey (or the primary key)?
- Can multiple rows share a single key value?

# Ordered vs. Hashed Indexes

- Ordered indexes keep index entries in the order of the search key
  - Facilitates range queries and accessing all rows in search key order
  - Typically structured as B+ trees
- Hashed indexes use a hashing function to evenly distribute index entries among blocks
  - Offers more efficient access and maintenance

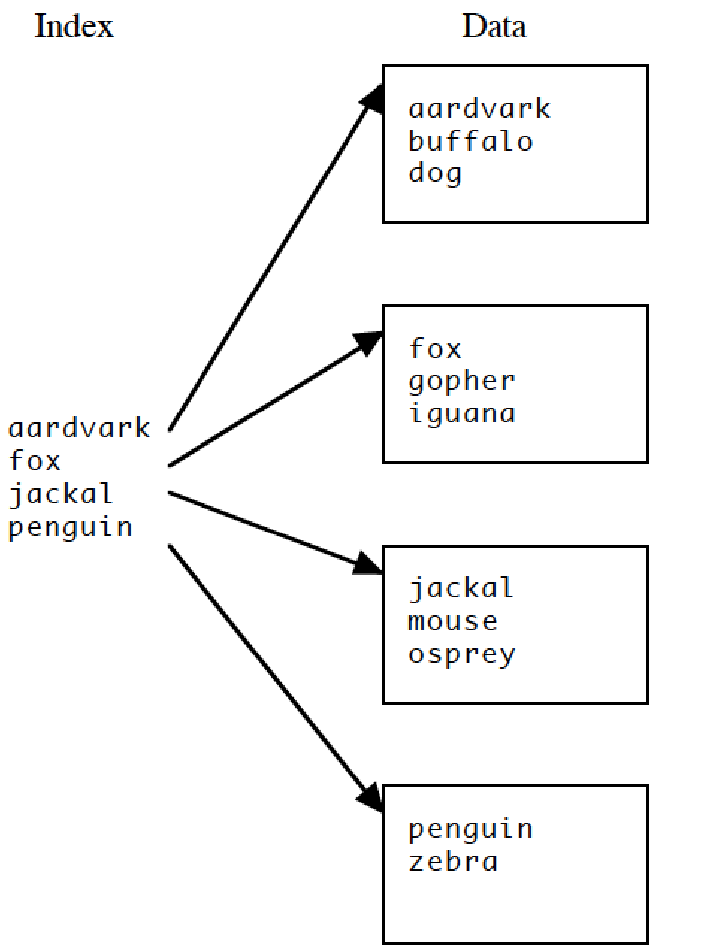
# Clustering Index

- Actual data is stored in the order dictated by the index
  - Only applies to ordered indexes
  - A given file can have at most one clustering index
- Advantages
  - Makes range queries easier – only need to locate first row in the range, and then read subsequent rows
  - Makes accessing rows with the same search key value easier, as they will be adjacent
- Disadvantage
  - Hard to maintain – inserts, updates, and deletes all require moving data
- Sometimes called a primary index (or an index organized table)
  - Other indexes can be referred to as non-clustering or secondary

# Dense vs. Sparse Indexes

- Dense index has one index entry for each distinct search key value
- Sparse index does not
  - Only a clustering index can be sparse – index is used to locate the starting point for a search of the actual data
    - Using the largest entry <= desired value
  - Sparse index typically contains one entry for each data block in the file (the smallest search key value in the block)

# Sparse Index Example



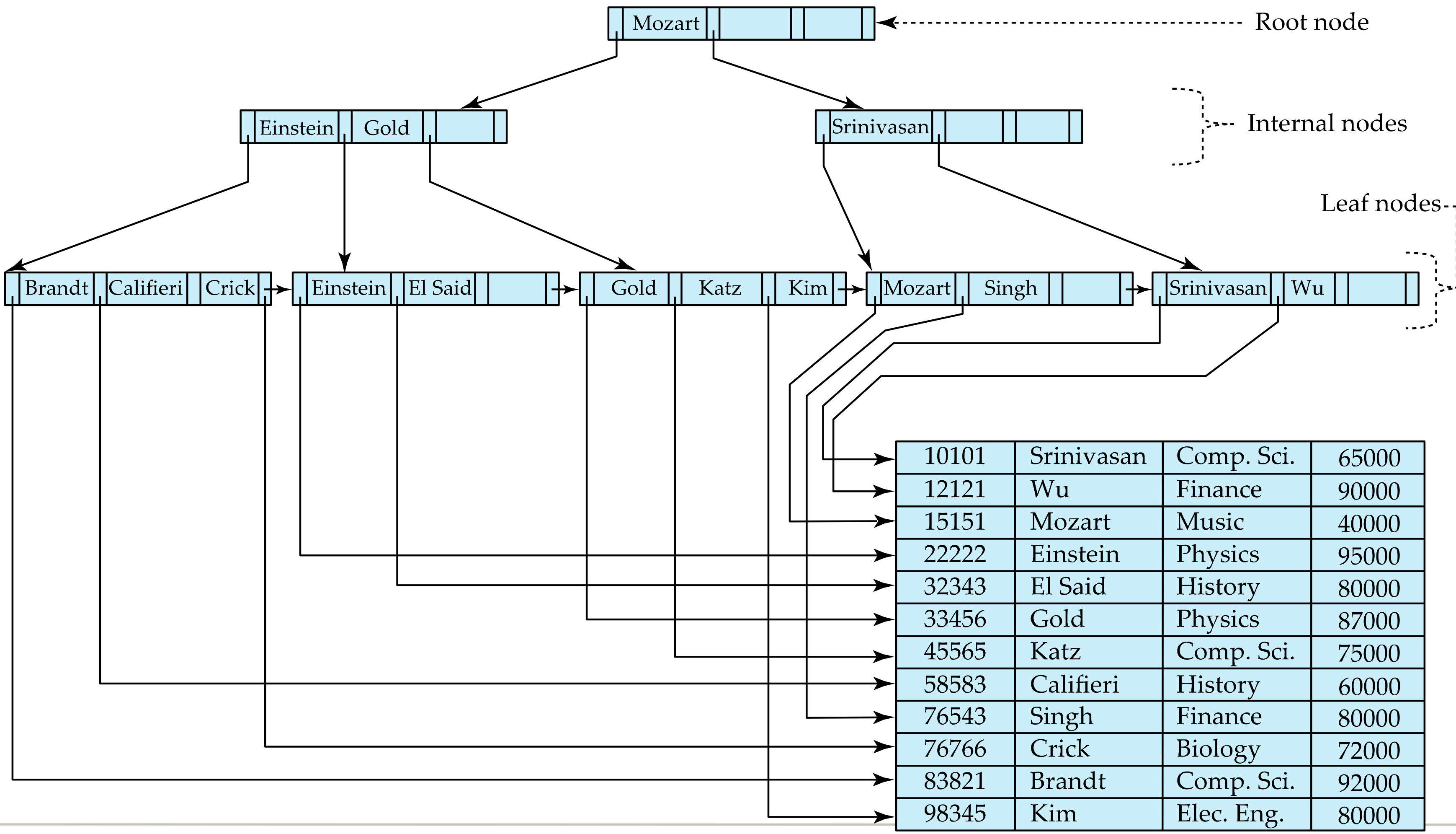
# Multilevel Index

- If primary index does not fit in memory, access becomes expensive.
- Solution: treat primary index kept on disk as a sequential file and construct a sparse index on it.
  - outer index – a sparse index of primary index
  - inner index – the primary index file
- If even outer index is too large to fit in main memory, yet another level of index can be created, and so on.
- Indices at all levels must be updated on insertion or deletion from the file.

# B+ Tree Indexes

- Alternative to clustered indexes
- May be used both primary and secondary indexes
  - As primary index, the tree can contain both index data and the actual records in the table
  - As secondary index, the tree only contains index data
- Advantage of $B^+$-tree index files:
  - Automatically reorganizes itself with small local changes when inserts, updates, and deletes occur
  - Reorganization of entire file is not required to maintain performance

# B+ Tree Example




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

# B+ Tree Structure

- Multi-leveled with all leaf nodes on the same level
- The *order* (n) of a B+ tree is determined by the size of a node and the size of a key-value pair
- Components
  - Root (with at least 2 children)
  - Internal (non-leaf) nodes
  - Leaf nodes

# Internal (Non-leaf) Nodes

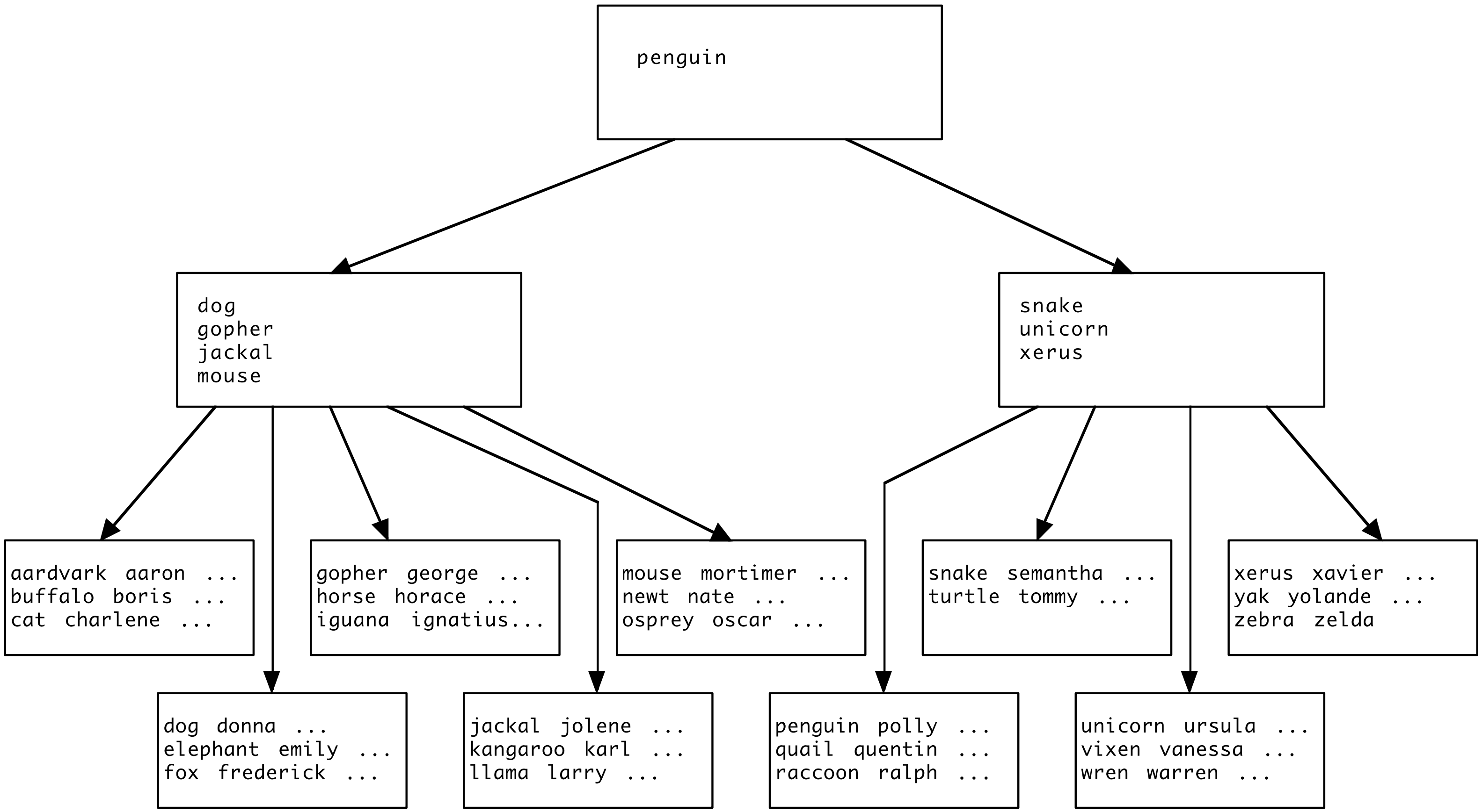
- Contain index data – pairs of search key values and pointers to other nodes on the next level of the tree
  - Form a multi-level sparse index on leaf nodes
- Can hold between □(n-1)/2□ and n-1 keys
- Has between ⌈n/2⌉ and n children
  - A node with k keys has k+1 children
  - Key values separate pointers to nodes or records on next level
- Keys in a node are ordered

| | | | | | | |
|---|---|---|---|---|---|---|
| $P_1$ | $K_1$ | $P_2$ | … | $P_{n-1}$ | $K_{n-1}$ | $P_n$ |

# Leaf Nodes

- Comprised of one of the following
  - Index data -- pairs of search key values with pointers to actual records
    - Contain between $\lceil (n-1)/2 \rceil$ and n-1 search key values
    - Last pointer in an indexing leaf node points to next leaf node (instead of a record)
  - Actual records
    - In primary index
    - Number of records in a leaf depends on the size of each record (separate from order of the B+ tree)
    - May also include pointer to next leaf

# An Order 7 B+ Tree

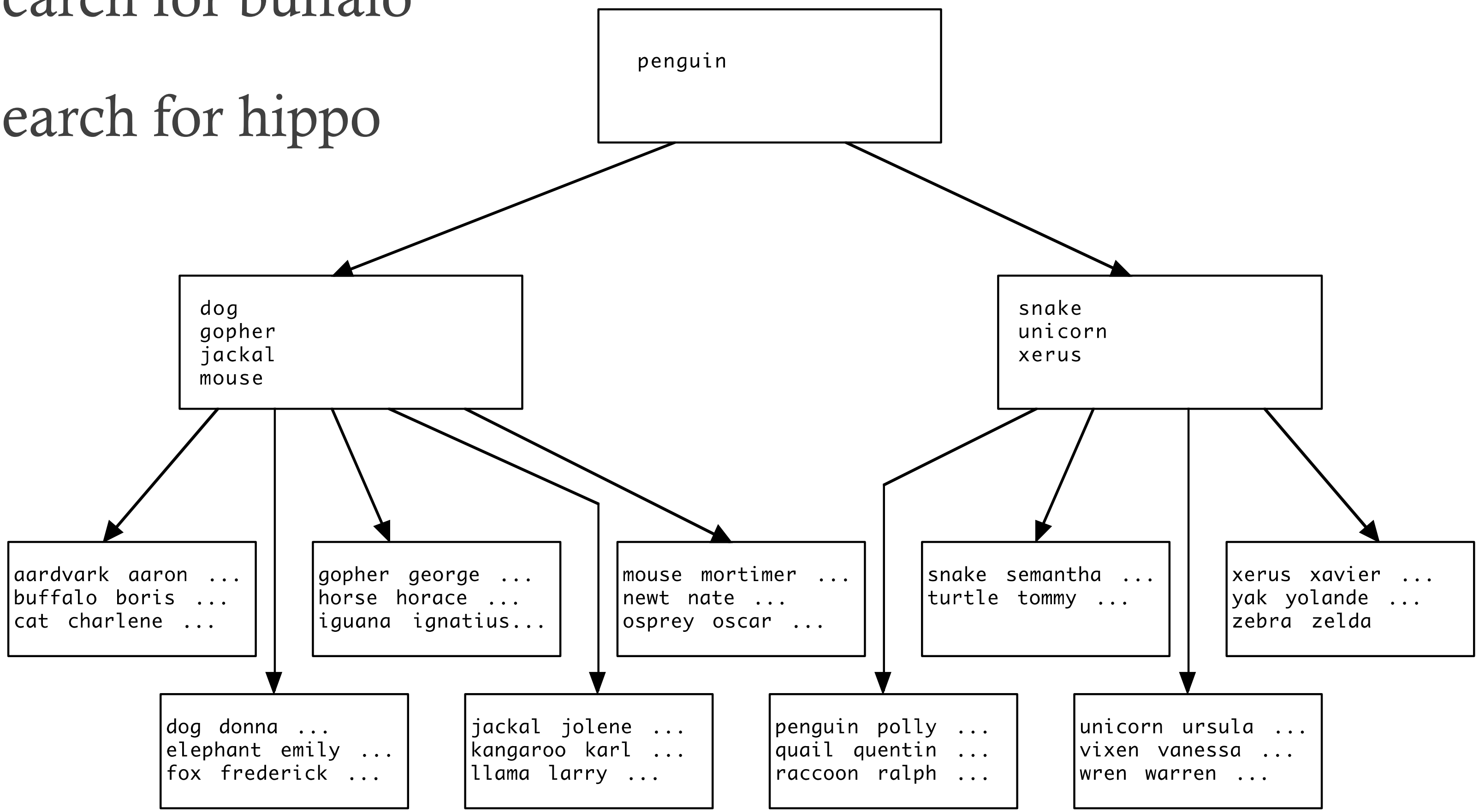


# Searching the B+ Tree

- Algorithm
  - Start at the root
  - while at an internal node:
    - if the value being sought is less than the smallest key stored in the node
      - go to the leftmost child
    - else
      - go to the child corresponding to the largest stored key that is <= the desired value
        - where the second child corresponds to the first key
  - When we reach a leaf node, the desired value will either
    - Be contained in the leaf (found by a sequential search within the node)
    - Not exist in the tree

# B+ Tree Search Examples

- Search for buffalo
- Search for hippo

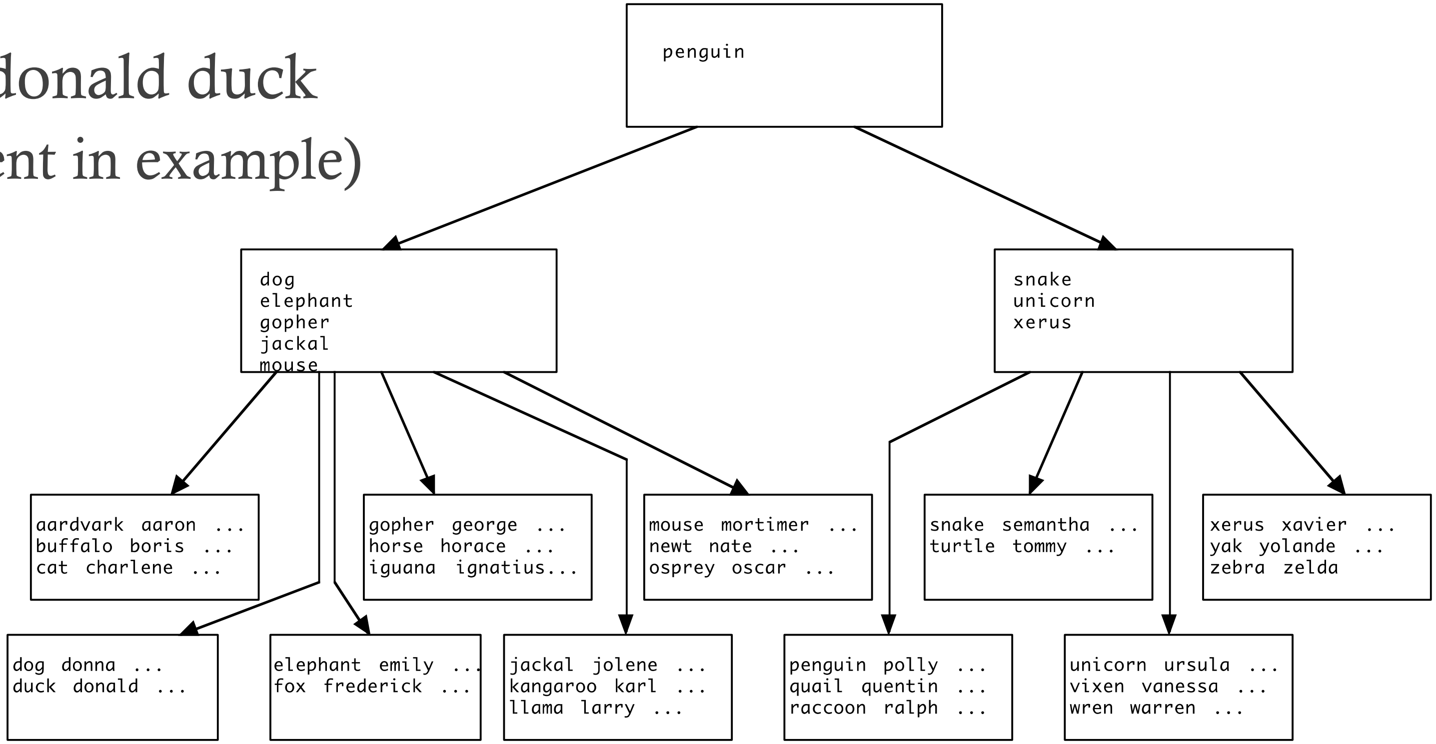


# Inserting into the B+ Tree

- Algorithm
  - Use search procedure to find node where it would be if it was present.
  - if there is room,
    - put it there.
  - else
    - divide the keys in two
    - create a new right block to contain half the keys
    - “promote” the first key in the right block. Insert this key, plus a pointer to the new right block, in the parent
- This may cause the parent to split
  - In this case, create a new internal node and promote the “split key” to the parent
- Root may actually split as well
  - Create new root with halves of original root as its children

# B+ Tree Insert Example

- Insert terrance tortoise
- Insert donald duck
  - (present in example)



# Hashing

- Alternate index structure facilitating fast access
  - Search key hashed to look up records (primary index)
  - Search key hashed to look up record pointers (secondary index)
- Records (or record pointers) reside in one of several buckets
  - A hashing function on the search key determines which bucket a record/pointer goes in

# Hashing Functions

- Worst hash function maps all search-key values to the same bucket; this makes access time proportional to the number of search-key values in the file.
- An ideal hash function is **uniform**, i.e., each bucket is assigned the same number of search-key values from the set of *all* possible values.
- Ideal hash function is **random**, so each bucket will have the same number of records assigned to it irrespective of the *actual distribution* of search-key values in the file.
- Typical hash functions perform computation on the internal binary representation of the search-key.
  - For example, for a string search-key, the binary representations of all the characters in the string could be added and the sum modulo the number of buckets could be returned

# Hashing Example

- Hashing function
  - Sum of ASCII codes in first name
  - modulo 11
  - + 1
- Sequential scan needed of bucket pointed to by the hash function
- Examples
  - Look up tommy
  - Look up terrance

| Bucket | Entries |
| --- | --- |
| 1 | donna dog<br>nate newt<br>yolande yak<br>zelda zebra |
| 2 | aaron aardvark<br>mortimer mouse |
| 3 | quentin quail<br>semantha snake |
| 4 | |
| 5 | boris buffalo<br>larry llama |
| 6 | emily elephant<br>tommy turtle<br>vanessa vixen |
| 7 | george gopher<br>warren wren<br>xavier xerus |
| 8 | ralph raccoon |
| 9 | frederick fox<br>karl kangaroo<br>oscar osprey<br>ursula unicorn |
| 10 | charlene cat |
| 11 | horace horse<br>ignatius iguana<br>jolene jackal<br>polly penguin |

# Hashing Challenges

- What happens when a bucket runs out of room?
  - Because of an insufficient number of buckets
  - Because multiple records have the same search key (and hence, hash value)
  - Because the hashing function is non-uniform
- Possibilities
  - Overflow buckets
  - Reorganize the file with a new hashing function
  - Extendable hashing – dynamically modify the number of buckets

# Comparison of Ordered and Hashed Indexes

- Hashed indexes
  - Allow fast access for exact match queries– usually 1 or 2 disk accesses (for primary and secondary indexes, respectively)
  - Do not support range queries or sequential access of entire table
- Ordered Indexes
  - Slower access – potentially several disk accesses as you work through the B+ tree levels
  - Supports more types of queries

# Creating Indexes

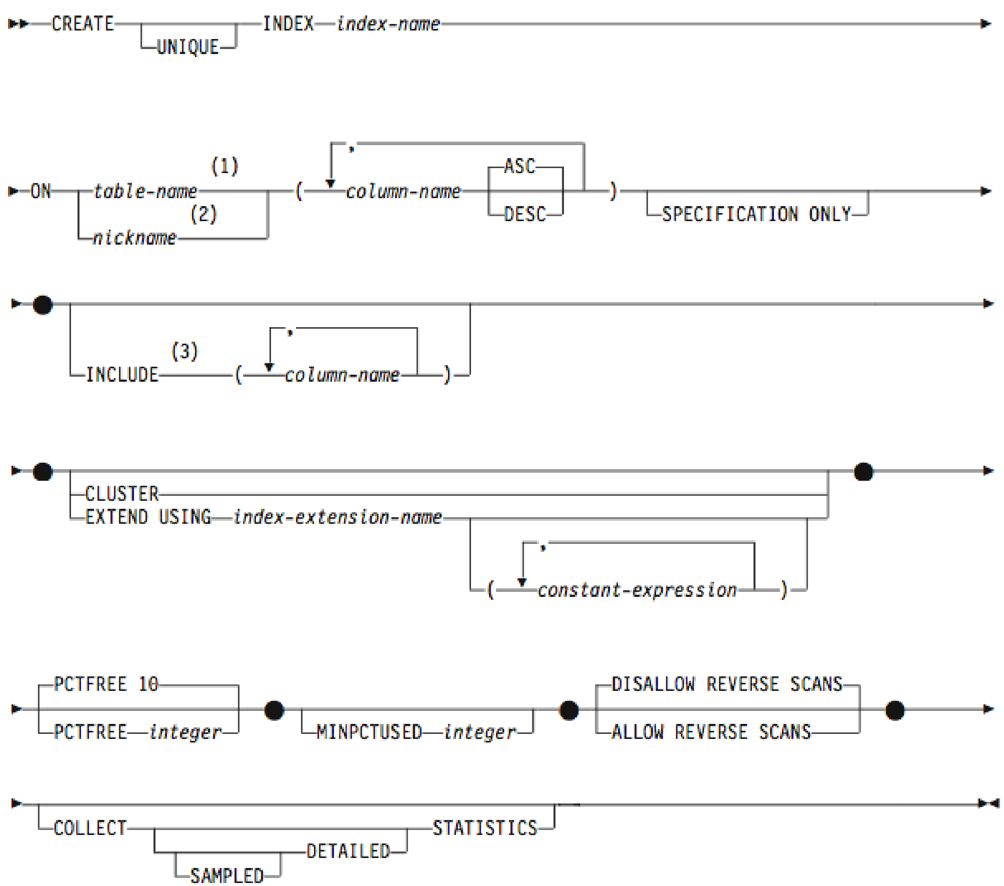
- Database automatically creates indexes for:
  - Primary keys
  - Columns with unique constraints
  - (Sometimes) temporary indexes used for single queries
- Create index SQL statement

mysql

```
CREATE [UNIQUE|FULLTEXT|SPATIAL] INDEX index_name
    [USING index_type]
    ON tbl_name (index_col_name,...)
```

# DB2 Create Index Statement Syntax

db2



# Database Design Tips

# What to Index

- Primary key (automatic)
- Columns with unique constraints (automatic)
- Foreign key columns
- Fixed-width columns – Boolean, numeric, (fixed-width) character, date/time fields
- Any column appearing in a “where” clause
  - Especially a “where” clause in a program (likely to be executed multiple times)
  - Including variable-width character fields
- Efficient function results
  - Indexes are bypassed if a where clause contains null
  - Example:
    - “where export_date is null” – null bypasses index, will scan entire table
    - “where nvl( export_date, to_date( ‘19000101’, ‘yyyymmdd’ ) = ‘19000101’”
      - Create an index on the nvl( … ) function result for a more efficient query

# Don't Index…

- Small tables (< 100 records) that will stay small
  - i.e. list of states and their capitals
- Columns containing binary (blob) or large text (clob) data
- Columns containing data that may be fetched or updated, but will never appear in a "where” clause
  - Long-ish variable width text fields (i.e. product descriptions, review text, comments)

# Index Names

- Explicitly name your indexes
  - Don’t let the database make up names for you
- Index naming conventions
  - Begin with 2-5 letter prefix of table name or abbreviation
  - Column name(s) or abbreviation(s) that comprise the index’s search key
  - End with a date stamp (i.e. 20121011)
    - Gives the index a unique name
    - Helpful when you need to rebuild the index or copy the table
  - Prefix or suffix the following indexes
    - Primary keys – “pk”
    - Foreign keys – “fk”
    - Unique constraints – “uniq

# Datatabases

# ...of the Bible

The Proverbial Database Files and Indexes

Proverbs 1:1-7 (NIV)

# See you in 2 weeks!

Don't forget to finish your design project and prepare your final presentation on it for our next class.