Efficiency and Storage

Database Systems

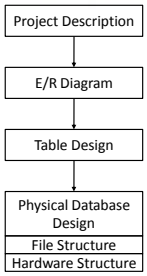
Michael Pound

This Lecture

- Physical Database Design
  - RAID Arrays
  - Parity
- Database File Structures
- Indexes
- Further reading
  - The Manga Guide to Databases, Chapter 5
  - Database Systems, Chapters 7, 18

Physical Design

- Design so far
  - E/R modelling helps find the requirements of a database
  - Normalisation helps to refine a design by removing data redundancy
- Next we need to think about how the files will actually be arranged and stored



Physical Design

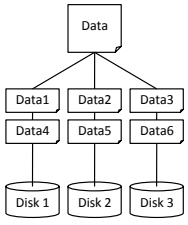
- Hardware
  - Correct storage hardware should be selected to avoid loss of data
  - Speed can also be affected by careful consideration of hardware
  - RAID Arrays
- File Structure
  - Often specifying the structure of files on disks has a huge impact on performance
  - Implementation of these structures is also specific to a DBMS
  - Indexes can be chosen to further improve speed

RAID Arrays

- RAID - redundant array of independent (inexpensive) disks
  - Storing information across more than one physical disk
  - Speed - can access more than one disk
  - Robustness – disk failure doesn't always mean data is lost
- RAID Arrays are controller by software or hardware
  - At the OS level the RAID array will appear to be a single storage device
  - The array may actually contain dozens of disks
- Different levels (RAID 0, RAID 1,…)

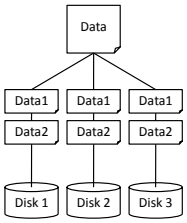
RAID Level 0

- Files are split across several disks (Striping)
  - Each file is split into parts, one part stored on each disk in the same position
  - Sizes of each part is determined by the array controller
  - Vastly improves speed, but no redundancy
  - If any disk fails, all data is unrecoverable



RAID Level 1

- Files are duplicated over all disks (Mirroring)
  - Each file is copied onto every disk
  - Provides improved read performance but no write performance
  - Large amounts of redundancy, if all but a single disk fail the data can still be recovered



Parity Checking

- Above RAID 1 involves calculating parity bits
- Parity reduces the number of disks you need for redundancy
- Parity is often calculated using XOR $\oplus$
- For two bits, A and B, XOR is true if either A is true or B is true, but not both

A	B	$\oplus$
0	0	0
0	1	1
1	0	1
1	1	0

Parity Checking

- The parity of n blocks of data is calculated as $D_1 \oplus D_2 \oplus \ldots \oplus D_n$
- For example:

D_1	00110110
D_2	10110010
D_3	11000000
D_P	01000100

XOR is 0 if there is an even number of '1' bits and 1 if there is an odd number

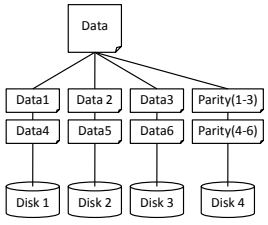
Recovery With Parity

- If any single disk breaks, including the parity disk, XOR can be used to re-calculate that value. For example:

D_1	00110110
D_3	11000000
D_P	01000100
D_2	10110010

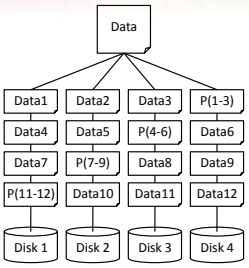
RAID Level 3

- Data is striped over disks, and a parity disk for redundancy
  - Data is split into bytes, bytes are written to separate disks
  - The final disk stores parity information
  - Extremely fast, and will allow for 1 disk failure



RAID Level 5

- Data is striped over disks with a distributed parity
  - Data is split into blocks, parity blocks are distributed throughout all disks
  - Extended version of RAID 3, and will even allow continued use after 1 disk failure



Other RAID Issues

- Other RAID levels consider
  - Allowing more than a single disk failure with the minimum of redundancy
  - Nested RAID levels. For example RAID 10 is a mirrored array of striped arrays
- Considerations with RAID systems
  - Cost of disks
  - Do you need speed or redundancy?
  - How reliable are the individual disks?
  - 'Hot swapping'

File Structure

- The structure of files on a disk is separate to the RAID configuration
- File structure is managed by the DBMS
- Often the designer of a database can have control over aspects of this structure
- In general file structure is concerned with:
  - How files are stored on a disk
  - In what order files are stored
  - The speed at which a file can be retrieved
  - The speed at which files can be inserted or deleted

Pages and Rows

- Row data is generally not written to disk individually. Instead, rows are grouped into pages
- Pages are often used as the atomic unit of I/O, any read or write to the disks will be a page, even if only a single row is affected
- A page will include a header and the row data:

Page Header
Row 1
Row 2
Row 3
Row 4
Row 5

- There are usually many rows in a page, but not always

Pages and Rows

- A table will often span multiple pages
- INSERTs will be added at the last position in the newest page
- Additional pages can be added if the previous one is full
- For a student table:

Page 1

11011465	Jack	...	1
11011658	Robert	...	2
11044348	Sarah	...	3
11051499	Max	...	1

Page 2

11012234	James	...	2
11034868	Mike	...	2
11048345	Anne	...	1

Unordered Files

- Unordered files are often called Heaps
- New records are inserted into the last page of the file
- If the page is full, a new page is added at the end of the file
- This structure makes insertion very efficient
- There is no ordering on values however, so searching must be conducted linearly
- To delete a record, the page is retrieved, a row is marked as deleted, and the page is written back
- This space is difficult to reclaim, so performance will deteriorate over time

Ordered Files

- Data sorted by one or more fields is called a **sequential file**
- Inserting and deleting from an ordered file is difficult
- If there is sufficient space on the correct page, a record can be inserted and that page re-written
- Full pages can propagate along and require many rewrites
- One solution is to temporarily add records to an overflow file, these are merged at a later time
- Overflows improve inserts, but make searches more difficult

Binary Search

- A huge benefit of an ordered data structure is the concept of the binary search
- A binary search is only possible when searching for specific values in a field, where the data is also ordered by that field
- Consider the Student table, ordered by sID:

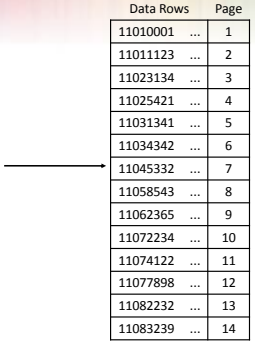
```
SELECT *
 FROM Student
 WHERE sID = 11062365;
```

- A linear search through the database could involve thousands of reads

Binary Search

Searching for: 11062365

- We begin the search by retrieving the page half way through the file
- The ID values in the page are smaller than the one we're looking for so we next look further down the file

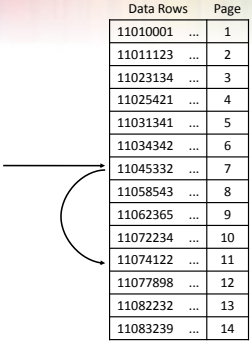


Data Rows	Page
11010001 ...	1
11011123 ...	2
11023134 ...	3
11025421 ...	4
11031341 ...	5
11034342 ...	6
11045332 ...	7
11058543 ...	8
11062365 ...	9
11072234 ...	10
11074122 ...	11
11077898 ...	12
11082232 ...	13
11083239 ...	14

Binary Search

Searching for: 11062365

- We next retrieve the page half way through the remaining half that contains our value
- The values are larger than the ID we are looking for, so we must travel backwards in the file

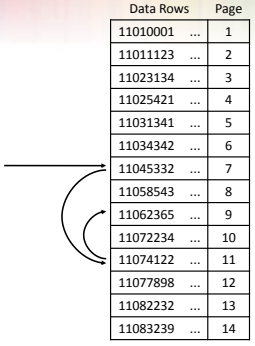


Data Rows	Page
11010001 ...	1
11011123 ...	2
11023134 ...	3
11025421 ...	4
11031341 ...	5
11034342 ...	6
11045332 ...	7
11058543 ...	8
11062365 ...	9
11072234 ...	10
11074122 ...	11
11077898 ...	12
11082232 ...	13
11083239 ...	14

Binary Search

Searching for: 11062365

- We retrieve the page half way between the two previous pages
- The value we are looking for is on this page. We read the remaining row data
- Binary searches complete in $Log_2 n$ time, which is often better than a linear search



Data Rows	Page
11010001 ...	1
11011123 ...	2
11023134 ...	3
11025421 ...	4
11031341 ...	5
11034342 ...	6
11045332 ...	7
11058543 ...	8
11062365 ...	9
11072234 ...	10
11074122 ...	11
11077898 ...	12
11082232 ...	13
11083239 ...	14

Indexes

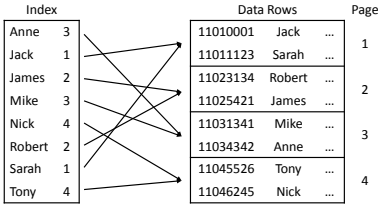
- Strictly speaking, the relational model states that the ordering of tuples does not matter
- In reality this is inefficient, searching and ordering are much easier using sequential files
- We can obtain further improvements with indexes
- An Index is a data structure that resides alongside a table, providing faster access to the rows
- An Index is associated with one of more fields, improving searches involving those fields
- The underlying data may or may not be ordered

Indexes

- Indexes are not unlike those you find in books
  - The aim is to simplify the search for key words or values
  - Often much faster than looking through the book linearly
  - The index will be ordered to improve search efficiency
- There are a number of types indexes
  - **Primary** indexes refer to a sequential file ordered by a key (unique)
  - **Clustered** indexes refer to a sequential file ordered by some fields that may not be unique
  - **Secondary** indexes exists separately to the data ordering

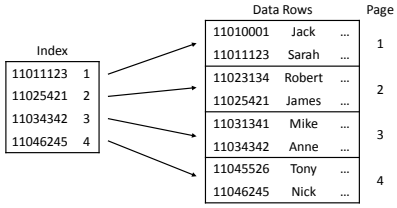
Spares and Dense Indexes

- Indexes can be broadly split into two categories, sparse and dense indexes
  - Dense indexes contain a value matching every row
  - Take up more memory but don't require the data to be sorted



Spares and Dense Indexes

- Indexes can be broadly split into two categories, sparse and dense indexes
  - Sparse indexes only match a subset of the rows
  - Efficient searches using a spare index need to be on a sequential file

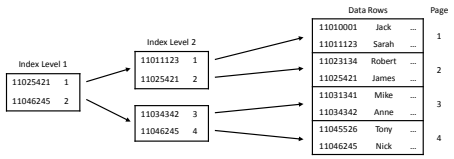


Benefits of Indexing

- Sparse indexes significantly reduce the number of page reads required to retrieve the specific page a search requires
- Indexes are often stored in memory to further improve search speed
- However, every index must be maintained, and this adds complexity to INSERT, UPDATE and DELETE queries

Multi-level Indexes

- It's possible, and often beneficial, to add higher levels of sparse index above existing ones
- Higher levels contain fewer index rows, and point you towards less sparse indexes lower down
- The final level points you towards the table data

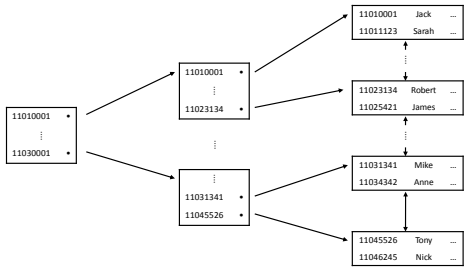


ISAM

- ISAM stands for Indexed Sequential Access Method
  - Essentially a static, sparse, often multi level **primary** index
  - The lowest level index points to anchor rows that represent each page. The index always references pages, rather than specific rows
  - Pages are linked together either by being consecutively stored on disk, or each page holds a pointer to the next one. This means values can be read sequentially extremely fast
  - Because the index is static, it must be reorganised occasionally to prevent a deterioration in speed
  - ISAM is less suitable for databases with very frequent inserts or deletes. Overflow areas are used if necessary

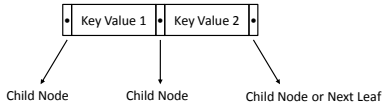
ISAM

- A 2-level ISAM Index for the Student table



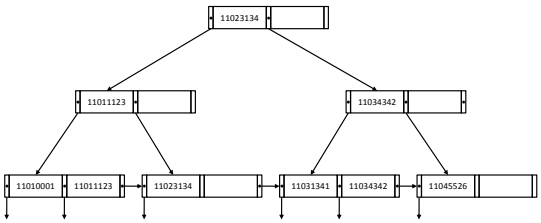
B+-Trees

- B-Trees are balanced tree structures, and are now the most common method for indexing in databases. They are used as a dense index
- A balanced tree is a hierarchy of **nodes** each of which links to child nodes below it, much like ISAM
- The top of the tree is the **root**, nodes with no children are called **leaf** nodes. Leaf nodes are interconnected for sequential access
- An example node would look like this:



Example B+-Tree

- An example B+-Tree Index for the Student table



Benefits of B+-Trees

- B-Trees vastly reduce the number of reads necessary to access a specific database row
  - For example, if the order (the number of allowed children) is 256, then a single row in a database of 16million rows could be accessed with 4 disc reads
  - Inserts and Deletes usually require the tree nodes to be slightly rearranged to balance the tree. This is an efficient procedure, but we will not cover it in this module

Clustered Indexes

- In many modern DBMSs, rather than the leaf nodes of a B+-tree pointing to the locations of the data rows, the leaf nodes themselves are adapted to hold the row data
  - This reduces a read operation where the row has to be looked up
  - This adapted B+-tree is often called a **clustered index** and is the default storage structure in InnoDB and other DBMSs
  - By default, a table in InnoDB will be a clustered index on the primary key

Choosing Indexes

- You can only have one primary or clustered index
  - The most frequently looked-up value is often the best choice
  - Some DBMSs assume the primary key is the primary index, as it is usually used to refer to rowss
- Don't create too many indexes
  - They can speed up queries, but they slow down inserts, updates and deletes
  - Whenever the data is changed, the index may need to change
- Create secondary indexes if another field might often be used for ordering or searching

Creating Indexes

- In SQL we use CREATE INDEX:

```
CREATE INDEX
  <index name>
  ON <table>
  (<columns>)
```

- Example:

```
CREATE INDEX sIndex ON
 Student(sName);

CREATE INDEX smIndex ON
 Student (sName, sMark);
```

Next Lecture

- Database Security
  - Privileges
  - GRANT and REVOKE
- SQL Injection Attacks
  - How to write an injection attack
  - How to secure your system against them
- For more information
  - The Manga Guide to Databases, Chapter 5
  - Database Systems, Chapter 7