

# Fundamentals of Databases notes

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## Introduction

Databases are core, if largely invisible, components of modern computing architectures in both commercial and scientific contexts. The management of data has evolved from application-specific management of myriad files to organisation-wide approaches that see data as one of the most important assets of modern organisations and, as such, a key factor in their ability to compete and thrive. At this organisation-wide scale, database management systems (DBMSs) are the crucial piece of software infrastructure needed to achieve the desired results with consistent quality and robust efficiency. A modern DBMS is a thing of wonder and embodies in its internal construction and in its wide usability many advances in algorithms and data structures, programming language theory, conceptual modelling, concurrency theory, and distributed computing. This makes the study of databases a data-centric traversal of many of the most exciting topics in modern computing.

## Aims

The aim of this course unit is to introduce the students to the fundamental concepts and techniques that underlie modern database management systems (DBMSs).

The course unit studies the motivation for managing data as an asset and introduces the basic architectural principles underlying modern DBMSs. Different architectures are considered and the application environments they give rise to.

The course unit then devotes time to describing and motivating the relational model of data, the relational database languages, and SQL, including views, triggers, embedded SQL and procedural approaches (e.g., PL/SQL).

The students learn how to derive a conceptual data model (using the Extended Entity Relationship paradigm), how to map such a model to target implementation model (for which the relational model is used), how to assess the quality of the latter using normalisation, and how to write SQL queries against the improved implementation model to validate the resulting design against the data requirements originally posed. For practical work, the Oracle DBMS is used.

The course unit also introduces the fundamentals of transaction management including concurrency (e.g., locking, 2-phase locking, serialisability) and recovery (rollback and commit, 2-phase commit) and of file organisation (e.g., clustering) and the use of indexes for performance.

Finally, the course unit addresses the topic of database security by a study of threats and countermeasures available. In the case of the former, these include potential theft and fraud as well as loss of confidentiality, privacy, integrity and availability. In the case of the latter these primarily include mechanisms for authorization and access control, including the use of views for that purpose. The course unit also addresses the topic of legal frameworks that give rise to obligations on the part of database professionals by introducing exemplars such as the 1995 EU Directive on Data Protection and the 1998 UK Data Protection Act.

## Additional reading

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# 1 These notes

This course is very reading oriented. If I were to write comprehensive notes on the whole course, I'd probably need to take a gap year. Consequently, I've written notes from the content in the lecture slides only. This means that **there is content in the course not covered in these notes**. However, I certainly hope that the stuff in here is enough to get a decent grade.

## 2 An introduction to Database Management Systems

Database Management Systems (DBMS's) are a type of middleware that provide a layer of abstraction for dealing with databases. It is nearly always unnecessary to write software from scratch that interfaces with a database, since a lot of database operations will share a significant amount of logic.

Henceforth, a lot of the functionality required of applications that make use of a database is placed into a DBMS, which application developers can make use and save time. The DBMS acts as a service, that is well implemented and is able to enforce good practices and advanced techniques such as concurrency, sharding, recovery management and transactions.

Some advantages of using a DBMS include:

- It decouples data inside a database from the application using it. Either can be re-written at any time so long as they still provide/use the same interface.
- Since the data is decoupled from the application, using a DBMS (in theory) lowers the development cost of the application.
- Most DBMS are scalable, concurrent, fault tolerant, authorisation control (often role based for organisations).

Even though the DBMS aims to provide a layer of abstraction for a user application, there are several layers of abstraction within the DBMS itself. These are:

<b>Physical</b>	Deals with the file(s) that is written to the storage medium that will hold the database. Needs to know about file formats, indexing, compression, etc.
<b>Logical</b>	Mainly concerned with mapping the raw data into database 'concepts' such as tables, views etc. It is here that the formal specification of the database is defined, commonly used models include <i>relational</i> , <i>XML based</i> and <i>document based</i>
<b>View</b>	Ensures that only authorised people can view the data.

If the database is using a relational format, then it will be defined by a schema. A schema dictates how the database is formatted; what tables there are, and what datatypes their columns take. An instance of a database is the content (data) inside of the database at a particular point in time. There is a certain isomorphism between relational databases and imperative programming languages; a schema would be akin to the declaration of variables (i.e. their names and types), while the instance would be their values at a particular point in the program's execution.

Irrespective of what logical model a database uses, most DBMS use between one and three languages to interface with a user/application. These are:

- Data Definition Language - used for specifying schema.
- Data Manipulation Language - used for mutating the data in the database.
- Data Query Language - used to access data in the database.

Often DBMS languages will be both a DML and a DQL, and sometimes a DDL too! One such example is SQL, does all of the above!

### 3 Relational Algebra and SQL

Relational algebra is designed for modelling data stored in relational databases (i.e. tables) and defining queries on it. It can perform unary operations (such as growing, shrinking and selecting from tables), or binary operations (union, intersection, difference, product, join).

#### 3.1 Selection $\sigma$

The  $\sigma$  operator can select rows that meet a certain criteria from the table.

Alcohol-Selection		
Type	Strength	Colour
Wine	11	Red
Beer	4.2	Yellow
Wine	12.8	White
Port	18	Carmin
Ale	11	Red

If we run  $Fine-Wines := \sigma_{Type=Wine}(Alcohol-Selection)$ , we'll end up with:

Fine-Wines		
Type	Strength	Colour
Wine	11	Red
Wine	12.8	White

#### 3.2 Projection $\pi$

The  $\pi$  operator can select rows instead of columns. If we do  $Anonymous-Drinks := \pi_{Strength,Colour}(Alcohol-Selection)$ :

Anonymous-Drinks	
Strength	Colour
11	Red
4.2	Yellow
12.8	White
18	Carmin

Notice that both the 11% Ale and the 11% Red Wine have the same strength and colour values. Consequently, the projection operator combines those rows into one so the same result isn't displayed twice.

Projection can also be used to do simple arithmetic,  $Test := \pi_{Strength+Strength-DStrength,Colour}(Anonymous-Drinks)$ :

Test	
DStrength	Colour
22	Red
8.4	Yellow
25.6	White
36	Carmin

#### 3.3 Product $\times$

Shops		
Name	Dodginess	Price
Ali's	High	Medium
Tesco	Low	Medium
New Zeland Wines	X.High	Low

We could do a cross product with the Shops and the Alcohol-Selection tables  $Grog-Shops := Shops \times Alcohol-Selection$ :

Grog-Shops					
Name	Dodginess	Price	Type	Strength	Colour
Ali's	High	Medium	Wine	11	Red
Ali's	High	Medium	Beer	4.2	Yellow
Ali's	High	Medium	Wine	12.8	White
Ali's	High	Medium	Port	18	Carmine
Ali's	High	Medium	Ale	11	Red
Tesco	Low	Medium	Wine	11	Red
Tesco	Low	Medium	Beer	4.2	Yellow
Tesco	Low	Medium	Wine	12.8	White
Tesco	Low	Medium	Port	18	Carmine
Tesco	Low	Medium	Ale	11	Red
New Zeland Wines	X.High	Low	Wine	11	Red
New Zeland Wines	X.High	Low	Beer	4.2	Yellow
New Zeland Wines	X.High	Low	Wine	12.8	White
New Zeland Wines	X.High	Low	Port	18	Carmine
New Zeland Wines	X.High	Low	Ale	11	Red

### 3.4 Renaming $\rho$

The notation for renaming columns is pretty simple;  $Drinks := \rho_{Name,Strength,Hue}(Alcohol-Selection)$

Drinks		
Name	Strength	Hue
Wine	11	Red
Beer	4.2	Yellow
Wine	12.8	White
Port	18	Carmine
Ale	11	Red

### 3.5 Join $\bowtie$

If we had:

People	
Name	Drinks
Alice	Wine
Bob	Beer

We could join it with the Grog-Shops table, using  $Fave-Shops := People \bowtie_{People.Drinks=Grog-Shops.Type} (Grog-Shops)$

Fave-Shops						
Person.Name	Grog-Shops.Name	Dodginess	Price	Type	Strength	Colour
Alice	Ali's	High	Medium	Wine	11	Red
Bob	Ali's	High	Medium	Beer	4.2	Yellow
Alice	Ali's	High	Medium	Wine	12.8	White
Alice	Tesco	Low	Medium	Wine	11	Red
Bob	Tesco	Low	Medium	Beer	4.2	Yellow
Alice	Tesco	Low	Medium	Wine	12.8	White
Alice	New Zeland Wines	X.High	Low	Wine	11	Red
Bob	New Zeland Wines	X.High	Low	Beer	4.2	Yellow
Alice	New Zeland Wines	X.High	Low	Wine	12.8	White

If two tables have a column of the same name, then they can be joined naturally without specifying which columns to join explicitly.

### 3.6 Distinct $\delta$

The  $\delta$  operator will ensure that no rows are duplicated.

### 3.7 Chaining operators

Just like in normal algebra, you can chain operators:

$\delta(\pi_{Strength, Colour}(Alcohol-Selection))$

Gives:

Strength	Colour
11	Red
4.2	Yellow
12.8	White
18	Carmin

## 4 SQL Syntax

### 4.1 Selecting rows

The SQL command to select rows from a table is:

```
SELECT <column-name>
FROM <table-name>;
```

If you only want distinct values from a column, use DISTINCT:

```
SELECT DISTINCT <column-name>
FROM <table-name>;
```

If you want all of the columns, use \*:

```
SELECT *
FROM <table-name>;
```

You can also do derivations:

```
SELECT salary/2
FROM <table-name>;
```

In order to specify which rows you want from the table, or you want to join two tables together, use the WHERE clause:

```
SELECT *
WHERE <condition>
FROM <table-name>;
```

```
SELECT *
WHERE table1.columnx = table2.columny
FROM table1, table2;
```

Use AND to chain multiple conditions in a WHERE clause:

```
SELECT *
WHERE x > 100
AND table1.x = table2.y
FROM <table-name>;
```

#### 4.1.1 Where conditions

You can use the standard =, <, > signs for comparisons between columns, but SQL also lets you use LIKE, BETWEEN and IS NULL:

```
SELECT *
FROM <table-name>
WHERE name LIKE ' ';
```

```
SELECT *
FROM <table-name>
WHERE salary BETWEEN 10000 AND 12000;
```

```
SELECT *
FROM <table-name>
WHERE previous-convictions IS NULL;
```

You can also compare tuples:

```
SELECT *
FROM t1, t2
WHERE (t1.parent, t1.age) = ('Janet', t2.age);
```

### 4.2 Set operations

The three main set operations are UNION, EXCEPT and INTERSECT, their meaning is rather self evident given their names. An example usage may be:

```
(SELECT *
FROM <table-name>)
UNION ALL
(SELECT *
FROM <table-name>);
```

## 4.3 Joins

We've already looked at the most common join:

```
SELECT *
WHERE table1.columnx = table2.columny
FROM table1, table2;
```

But you can also do it manually:

```
SELECT *
FROM table1 JOIN table2
USING (<column-name>);
```

Or with a `NATURAL JOIN`, which is automatic, but can only be applied when columns have identical names:

```
SELECT *
FROM table1 NATURAL JOIN table2
```

## 4.4 Renaming tables

You can use the `FROM` clause to rename tables:

```
SELECT *
FROM table1 as a, table2 as b
```

```
where a.col > b.col;
```

## 4.5 Ordering and other operations

`GROUP BY` can be used to sort rows by a column value:

```
SELECT *
FROM <table-name>
GROUP BY height;
```

Other operators such as `AVG` and `COUNT` can also be used:

```
SELECT AVG(salary)
FROM <table-name>;

SELECT COUNT(DISTINCT salary)
FROM <table-name>;
```

```
SELECT COUNT(*)
FROM <table-name>;
```

```
SELECT dept-name, AVG(salary)
FROM staff
GROUP BY dept-name
HAVING AVG(salary) > 30000;
```

# 5 Designing databases

Entity-Relationship (ER) Modelling is a simple, high-level conceptual modelling approach that focuses on data requirements rather than business logic. A conceptual model is what we aim to produce in the design phase of database development. It describes the format of the database, the types of entity that are used, the relationships between entities and constraints on the data.

We can translate a conceptual model into a logical schema, which is often just a language such as SQL. We can use the logical schema directly to create and manipulate our database.

## 5.1 Entity Relationship Modelling

There are three basic constructs in ER modelling; entity types, attribute types and relationship types.

Attribute types consist of the following:

Simple or Composite

A simple type is atomic, whereas a composite type is made of an amalgamation of multiple other types.

Single or Multi valued

Types can either have single values (such as an integer), or they can have a value from discrete set of allowed values (multi-valued).

Stored or Derived

Stored attributes are ones where the value of the attribute is directly stored by the database (e.g. licence start date), while Derived attributes are computed from the values of other attributes (e.g. licence end date = start date + 1 year).

Null valued

Can be null.

Complex-valued

Made of arbitrarily nested composite or multivalued attributes.

Keys are important in ER modelling. Entities with a key are bound by uniqueness constraints; each key must be unique within the entity. There can be more than one key in an entity type, but there can also be no key, and if this is the case, then the entity is said to be **weak**.

**Carnality ratio** constraints specify the ratio of one entity to another in a relationship. It can be  $1 : 1$ ,  $1 : n$ ,  $n : 1$ ,  $n : m$ .

**Participation constraints** specify if an entity depends on another entity. If a participation is **total**, then every entity in the total entity must participate in some relationship, if the participation is **partial**, then some entities may not participate in any relationship. For example, student:program is total:partial.

**Weak entities** can only be properly identified if they are related to some other entity type, an **owner**. An **identifying relationship** is one where a weak entity has a total participation constraint with its owner.

When we're writing a requirements specification, **bold** words are entity types (e.g. **employees**, **departments** and **projects**), *italic* words are attribute types (e.g. *name*, *location*, *phone number*), and underlined words are relationship types (e.g. employees belong to a department).

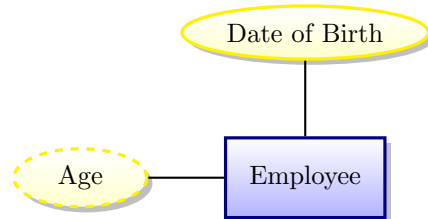
Remember, ER models don't have primary or foreign keys, they only have plain keys. Relationships are modelled explicitly in ER rather than implicitly using keys.

### 5.1.1 ER Notation

Entity type



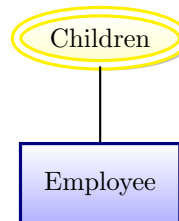
Derived attribute



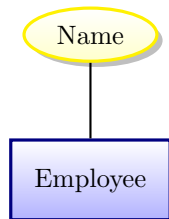
Weak entity type



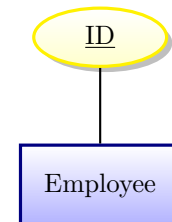
Multivalued



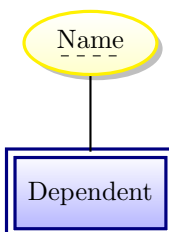
Attribute



Key

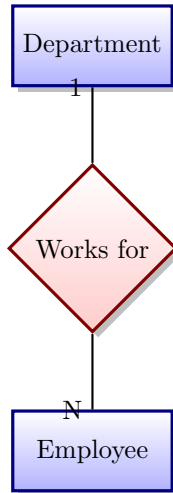


Weak attribute

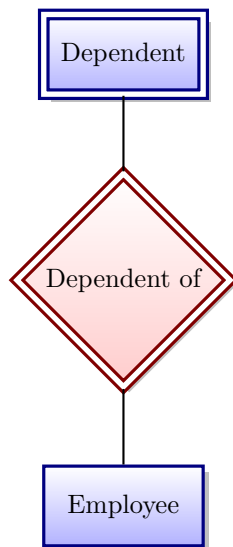


Relationship (plus carnality ratio)

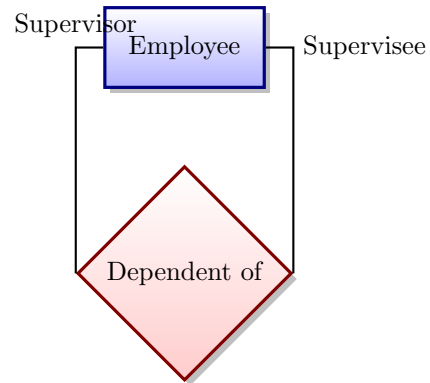




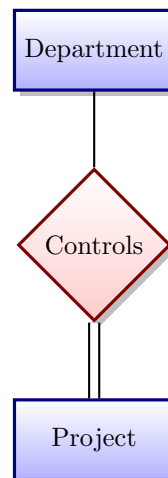
**Identifying relationship**



**Recursive relationship**

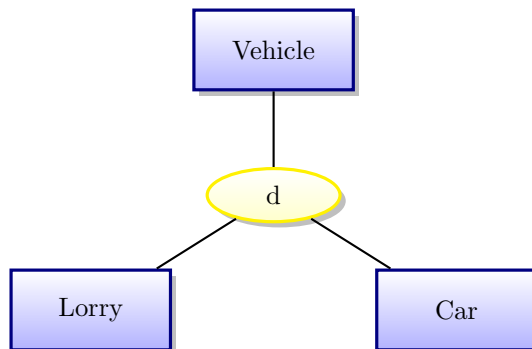


**Participation constraint**



### 5.1.2 Specialising entities

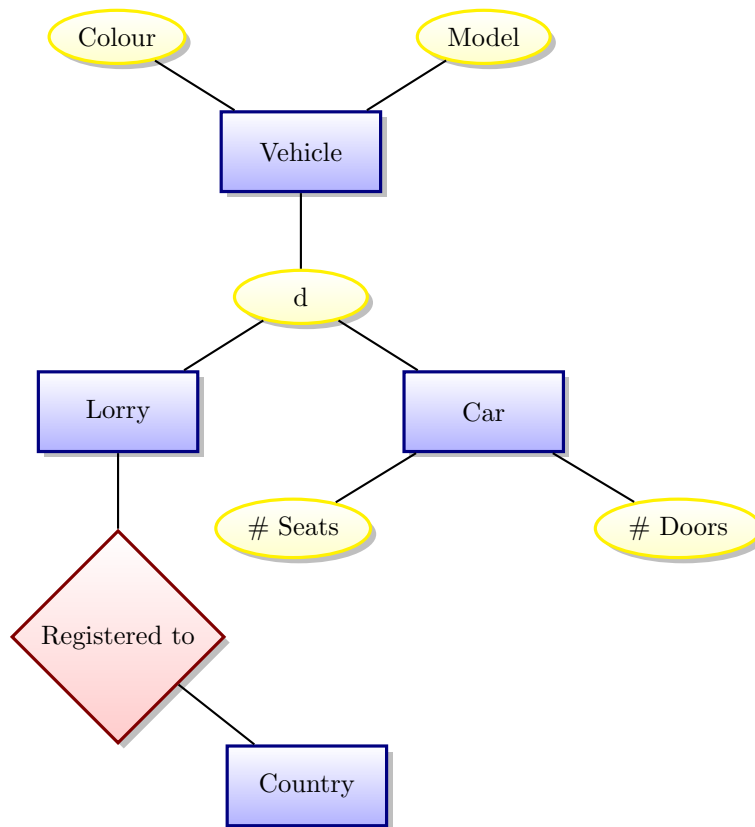
It's often efficient to refine entities into sub-entities if there are fields that are relevant for some members and not others. For example a vehicle entity could have car and lorry sub-entities. One way of doing this is top-down conceptual refinement, which is a fancy way of saying, start with an entity, identify it's subclasses, create sub-entities for them, and then repeat for the newly created sub-entities.



I've not got time to work out how to do  $\cup$  arrowheads now, please draw them on the diagram!

An alternate way to specialise is to do a bottom-up approach. Start with lots of sets, and define a common superset of them. Here, you're generalising rather than specialising.

Each subentity can have it's own attributes and relationships of course:



Entity subtypes can be user, attribute or predicate defined based on whether the user has defined them to be a subtype, their attributes define them to be subtypes or if a predicate has (e.g. if country in EU  $\implies$  EU Member).

In the examples, the attribute 'd' is used to create a subtype. This stands for disjoint, since a car can't also be a lorry. There is also 'o', which is used when an entity could belong to multiple subtypes.

## 6 Converting an ER diagram into a relational language

I refer you to Alvaro's sixth lecture, for this part, since it'd take too long to draw all the diagrams you need. If you're reading this and feeling helpful, you write this section and send me a pull request!

## 7 Normalization

Normalization is the process of decomposing unsatisfactory (i.e. potentially improvable) relations by creating smaller relations from them. The keys and functional dependencies of the relation determine it's normal form.

The normal form indicates a particular quality level of the database schema. 1NF is a relation in its first normal form, where every field contains only atomic values. 2NF, 3NF and BCNF are normal forms that are defined in terms of keys and functional dependencies of a relational schema.

3NF and BCNF (Boyce-Codd Normal Form) are the targets we try and work towards.

The main technique that we use to try and refine schema is **decomposition**. This is the idea of taking a relation ABCD, and decomposing it into two relations; AB and BCD. Decomposition is guided by the functional dependencies that hold over the relation.

An example would be a table of Employees. If there was a column for office id and another for work address, we would have to update all of the employees who worked at a specific office if the office location moved. If there was a separate table of offices, we could simply update the office location in that table, and because of a relation between Employee and Office, we wouldn't have to update Employee at all!

A key is one or more attributes in a relation where each key is unique for that relation. There may be more than one valid key (candidate key) for each entity, if this is the case, then one of them is selected to be the primary key, and the others are said to be secondary keys.

## 7.1 Functional Dependencies

Functional dependencies are a different way of solving the employee-office problem mentioned a few paragraphs ago. A functional dependency is basically a constraint between two attributes in the entity, the notation would be  $\text{Office\_ID} \rightarrow \text{Office\_Location}$ , if we were to create an FD between the office ID and its location.

If an FD is in place, the determinant (the bit before the arrow) determines the bit after the arrow. Determinants of the same value will *always* map onto the same value.

The trouble with functional dependencies is what happens when you want to update the derived value, or insert a new data item that doesn't have a determinant.

## 8 'Advanced SQL'

When it was conceived, SQL was not Turing complete. In order to get encapsulate more logic, programmers would use database API's, or embed SQL commands into another programming language that was Turing complete, where a compiler will resolve them into code in the host language. This was called *Programmatic SQL*, but it was hard to do well, since SQL is a declarative language, and most host languages wouldn't be (they'd be imperative, object oriented or even functional), so the programming styles (and other, more fundamental stuff like type systems) would clash.

Another solution is to extend SQL to make it Turing complete. Oracle did this to create Procedural Language/SQL, which is what we have the privilege of using on the course.

### 8.1 Procedural Language/SQL

#### 8.1.1 Anonymous Block

This is an unnamed block of PL/SQL. This one will print out the number of students in the student table, and log any errors if it can't.

```
DECLARE
    amount NUMBER := 0;
    error_code NUMBER;
    error_message VARCHAR2(255);

BEGIN
    SELECT COUNT(*) INTO amount
    FROM STUDENT;

    DBMS_OUTPUT.PUT_LINE(amount);

EXCEPTION
    error_code := SQLCODE
    error_message = SQLERRM
```

```
INSERT INTO errors VALUES(error_code, error_message);

END;
```

### 8.1.2 Cursors

If we run an SQL command that could return an arbitrary number of rows, we need to use a cursor. This allows us to access one row at a time and iterate over them. It must be declared and opened before use, and closed after it is finished with. Cursors can be used to update content in tables as well as just viewing them.

Anybody familiar with Android development will probably have come across cursors.

```
CURSOR getStudentsDoingCourse(myCourseName Student.courseName%TYPE) IS
  SELECT *
  FROM Students
  WHERE Students.courseName = myCourseName
  ORDER BY Student.id;
```

### 8.1.3 Subprograms; Procedures and Functions

Subprograms are named blocks that can be called with parameters. They aid in abstraction and increase the reusability and maintainability of the code.

Functions always return a single value, whereas procedures don't return any value. In order to return a value, functions use the `RETURN` keyword.

Here is an example procedure:

```
CREATE OR REPLACE PROCEDURE getAverageGrade(sID IN Students.ID%TYPE) AS
  var_name Students.name%TYPE;
  var_grade NUMBER;
  var_count NUMBER;
  var_temp NUMBER;

  CURSOR getStudentGrades(sId StudentGrades.ID%TYPE) IS
    SELECT *
    FROM StudentGrades
    WHERE StudentGrades.ID = sID;

  CURSOR getStudentName(sId Students.ID%TYPE) IS
    SELECT name
    FROM Students
    WHERE Students.ID = sID;

  var_error_code NUMBER;
  var_error_message VARCHAR(255);

BEGIN

  OPEN getStudentGrades(sID);

  LOOP
    FETCH getStudentGrades INTO var_temp;
    EXIT WHEN getStudentGrades%NOTFOUND;

    var_grade := var_grade + var_temp;
    var_count := var_count + 1;
  END LOOP;
```

```

    IF getStudentGrades%ISOPEN
        THEN CLOSE getStudentGrades;
    END IF;

    var_grade := var_grade / var_count;

    OPEN getStudentName(sID);
    FETCH getStudentName INTO var_name;

    DBMS_OUTPUT.PUT_LINE(var_name || ': ' || var_grade || '%');

    IF getStudentName%ISOPEN
        THEN CLOSE getStudentName;
    END IF;

EXCEPTION
    WHEN OTHERS
    THEN
        var_error_code := SQLCODE;
        var_error_message := SUBSTR(SQLERRM, 1, 255);
        DBMS_OUTPUT.PUT_LINE(var_error_code || ': ' || var_error_message);

        IF getStudentName%ISOPEN
            THEN CLOSE getStudentName;
        END IF;

        IF getStudentGrades%ISOPEN
            THEN CLOSE getStudentGrades;
        END IF;
END;

```

To execute a procedure, do `EXECUTE getAverageGrade(8955942)`.

#### 8.1.4 Triggers

Triggers are constructs that react to certain conditions. They obey an **event-condition-action (ECA)** model.

Triggers can be fired by insertions, deletions or updating rows in a table when tables are created, altered or dropped, as well as when error messages are generated. Triggers can fire before, after or instead of the triggering event, and the **action** is a block that is executed if the trigger fires.

Row level triggers execute the action that for each row that has changed in a table, while statement level triggers only execute once per fire event. Triggers can be made to cascade, if the effects of one cause another to fire. It is possible that this could result in non-termination.

```

CREATE TRIGGER name
    (BEFORE | AFTER | INSTEAD OF)
    (INSERT | DELETE | UPDATE [OF columns])
ON tableName
    // (refer to the old/new values of an update)
    [REFERENCING (OLD | NEW) AS (oldName | newName)]
    // Row-level or Statement-level?
    [FOR EACH (ROW | STATEMENT)]
    [WHEN condition]
    triggerAction (e.g. call procedure)
;

```

## 9 Transactions, concurrency and recovery

These are all very important features of a DBMS system, and are some of the greatest advantages of using a DBMS instead of rolling your own system as a programmer.

### 9.1 Transactions

A transaction is a action or series of actions carried out by an application on the database. It can be seen as a logical unit of work on the database, and one level of abstraction sees client applications as just a series of transactions with intervals of non-database work in between.

Each transaction moves the database from one state to another (or possibly the same state). Each state is consistent, however, in between states, the database may be inconsistent (i.e. while processing occurs on the database, constraints may be violated).

Transactions can have two outcomes, success and failure. If the transaction is successful, then it will be committed, and the database will enter a new state. If the transaction fails, then it will be aborted and the database is rolled back to the state it was in before the start of the transaction. Once a transaction is committed, it cannot be aborted, but an aborted transaction can always be restarted later for another attempt.

Transactions have four basic properties, called ACID:

#### **Atomicity**

A transaction is either fully successful, or it's failed; there's no in between. This is sometimes called an 'all or nothing' contract.

#### **Consistency**

The transaction must transform the database from one consistent state to another.

#### **Isolation**

Partial effects of incomplete transactions are not visible to other transactions. All transactions are in effect, sandboxed.

#### **Durability**

The effects of a committed transaction are permanent. If a later transaction fails, then it will not affect previous transactions.

### 9.2 Concurrency

Concurrency control is important since it allows multiple operations on the database to take place simultaneously without interfering with each other.

Without concurrency control, if two transactions were to execute in parallel, they could affect each other and produce incorrect results. Problems can include:

#### **Lost update problem**

If two users update the database at once, the one that finishes first will be overridden by the one that finished second. This is mitigated by stopping concurrent operations from reading objects/tables while another operation is writing to it.

#### **Uncommitted dependency problem**

If one operation reads a piece of data while another operation writes to it, then the first could read data that is in an intermediate state which is inconsistent. To prevent this from occurring, then we must stop reads from occurring on objects that haven't been committed.

#### **Inconsistent analysis problem**

If one transaction reads several values, but they are updated by another transaction part way through the read, then some of them will be inconsistent with the others. To avoid this, again stop one transaction from reading while another is updating and vice versa.

### 9.2.1 Serializability

We want to be able to schedule transactions so that they don't interfere with each other. The easy way of doing this, is to have no concurrency, but this would severely limit performance. Serializability guarantees sequences of execution that will ensure consistency.

Lets define some terminology; a *schedule* is a set of reads and writes to the database by concurrent transactions, a *serial schedule* is when the reads and writes must be executed consecutively with no interleaved operations, and a *non-serial schedule* is one where any operations can be interleaved.

To make the database as efficient as possible, we want to find as many non- serial schedules as we can so that we can get parallel computation. These are called serializable schedules.

The exact order of the reads and writes in the database is important; the transactions need to execute in a serial manner if one transaction is writing while another is reading or writing to the same data item. We can use precedence graphs to test for these conflicts.

In order to create a **precedence graph**, you create a node for each transaction and then create a directed edge from  $T_i$  to  $T_j$  if:

- $T_j$  reads the value of an item written by  $T_i$
- $T_j$  writes a value into an item after it has been read by  $T_i$
- $T_j$  writes a value into an item after it has been written by  $T_i$ .

When you've drawn a precedence graph, you must run a cycle finding algorithm on it (such as Floyd's cycle finding algorithm). If a cycle is present, then the transactions must run in a serial manner.

### 9.2.2 Concurrency control techniques

The two most basic control techniques are locking and timestamping. Both techniques are pessimistic, which means that they delay a transaction in case it conflicts with another transaction.

Locking is when data items are locked to prevent other transactions from viewing or updating them (depending on the type of lock obtained). Transactions must obtain a shared lock on a data item when it wants to read, and an exclusive lock when it wants to write.

In order to ensure that assigning locks doesn't violate isolation and atomicity rules for the database, locks are assigned (usually) using the two-phase-locking (2PL) protocol.

The **Two Phase Locking** protocol, as you might expect, has two phases; the growing phase and the shrinking phase. In the growing phase, the transaction may acquire locks but cannot release them, and in the shrinking phase, it can release locks but cannot acquire them. If all transactions follow 2PL, then the schedule is serializable.

If transactions depend on each other (due to locks being released before a transaction ends), then **cascading rollback** can occur. If T3 depends on T2, which depends on T1 and T1 is rolled back, then both T3 and T2 must also be rolled back. This can be stopped by ensuring that locks are only released at the end of transactions (since they have then been committed), which is called rigorous 2PL.

Deadlock can occur if two transactions are waiting from a lock from each other. If this happens, then one or more of the transactions should be aborted and restarted. Deadlock can be detected using timeouts (only waiting  $n$  seconds to acquire a lock).

### Recovery

You can keep a transaction log of all actions executed on a database. This log is stored in a file on (often) a backup system. If the database becomes corrupted, you can simply replay the

transactions in the log and get the database back to the state it was in.

Shadow paging is another recovery technique, where a copy of the page a transaction is taking place on is created. If the transaction fails, you can simply replace the page with the copy and it will be the same as before.

## 10 File organisation and indexing

Most (certainly the ones in this course) databases store their data on a secondary data store, such as magnetic disk. Data is organised onto files on the disk, and each file is composed of multiple records, each with one or more fields. Typically, a field corresponds to an attribute, a record to an entity, and a file to an entity type.

When data is needed (to be modified or read), the database maps the logical location of the data in the database onto a physical location on the disk.

The physical record is the unit of transfer between main memory (RAM) and the secondary memory. When the DBMS wants to read or modify a part of the stored database, then the necessary page is loaded into primary storage. Each ‘unit’ of physical database is usually referred to as a *page* or, less commonly block.

Files are organised in three different ways:

### Heap files

When the records stored in the file are in no particular order. New records are inserted at the end of the file, which is efficient, but means that finding them again later requires an  $O(n)$  linear search (which is only really kind of efficient if you’re selecting most of the records in the file, such as when doing `SELECT * FROM <tablename>`). Deleting records requires more time than finding them, since the file must be written back to disk. Periodic reorganisation (defragmenting) is required to compact the file and fill in the blank spaces that were left by deletion.

Good for when you’re doing bulk loading of data, a relation requires only a few pages, indexes are used, and every record is almost always accessed.

### Sequential files

When the files are ordered on a given field. This field also serves as a key, called the ordering key. As you might expect, this vastly increases the speed of finding a record, since we can use binary search. However, it also increases the complexity of insertion; because elements must be kept in order, if there’s no free space at a location of the insert we must shift all of the other records over (and potentially cascading this shift to other pages).

One way to minimise the effect of cascading is to have an unordered ‘overflow’ pool at the end of the file. Periodically, the DBMS will merge in this pool with the rest of the file. This reduces the effectiveness of the search, since we’ll need to do a linear search of this section if we don’t find whatever we’re looking for with a binary search of ordered bit.

Q: Where would you insert a record in a page if you wanted to maximise the chance of cascading? A: Near the start.

### Hashed files

A hash function determines at what logical address records reside at in the file.

Each file is organised into  $M$  equal sized buckets (read as partitions). One of the fields in the file is designated as the hash key, and then records are assigned to buckets based on the hash of this key. This means that search is very efficient on this key.

One problem with hashed files is that when a bucket is full, where do we put more records? This is the same problem that datastructures such as HashMaps face, and it is mitigated in similar ways too:



### *Open addressing*

This is when if a bucket is full, a linear search for the next blank space will take place, and it is here that the item will be inserted.

### *Unchained overflow*

Here, a separate area is designated for collision records. This is also organised in terms of buckets.

### *Chained overflow*

If you're a Java whizz, you might have met this before; overflow items are kept in a linked list structure, where each item points to the next. This means searching is a linear operation, but lets you cut down the amount of records you'd need to search otherwise. With this method, every record must have an additional field to hold a pointer to the next record.

### *Multiple hashing*

This is when a second field is used as a secondary hash key if the first produces a collision, aiming to produce a new address for the record. In general, the new hash function is used to place colliding records in the overflow area.

These techniques can be combined in order to provide a comprehensive solution (for example, having multiple hashing, then a chained overflow when the second hash function fails).

When updating a record in a hashed file, you've got to relocate the record if the hash key changes. This can make updating slow.

Using a hash is good when what you're searching for will exactly match the hash key, but not good when you're pattern matching, getting a range of values, updating frequently, or the search parameters aren't exactly on the hash key (i.e. other fields or part of the hash key).

The steps taken by the DBMS to manipulate the pages is called the *access method*.

## **10.1 Indexing**

An index is a datastructure that allows the database to find records more quickly and thus improve query response time. It is similar to the index in a book, and is usually ordered on one key (the search key).

An index can be either dense or sparse; the former has a value for every search key (so every record), while the latter has one for only some keys.

There are three types of index; primary, clustering and secondary. Each file can have one primary or one clustering index, but many secondary indices. The different types of indices are listed here:

### **Single level indices**

#### *Primary indices*

These indices are defined on a single file, that contains records ordered by a key. The primary index is *sparse*, containing an entry for each disk block that can then be searched sequentially.

#### *Clustering indices*

Here, the keys are ordered like in primary indexing, however, the index contains each distinct key value, and points to the start of that key in the list (since they'll probably be lots of repeated keys). This is another *sparse index*.

#### *Secondary indices*

Secondary indices are *dense* because they use keys that the file is not ordered on. This means that they must point to every record individually. They speed up indexing

since they themselves are ordered, so you can do a binary search on them. They are used to complement a primary/clustering index, and there can be more than one of them per file.

### Balanced trees

If a tree has the same depth from root to leaf for all its branches, then it's called a balanced tree. The order (also known as the degree) of the tree is the maximum number of branches per parent node, with larger orders creating shallower trees (as would be expected). The access time is dependent on the breadth of the tree, since it's  $O(n \log_o n)$ , with  $o$  being the order of the tree.

B+-Trees are similar, except their leaves form a linked list. This means they can be traversed in  $O(\log_b n)$  time, where  $b$  is the order of the tree.

B+-Trees are very versatile, since they support pattern matching well, as well as getting a range of or part of a key. Since B+-Trees are dynamic (their structure changes as they are used), their performance is kept optimal, and they also allow for efficient retrieval in the order of the access key.

## 11 DBMS Architectures

What's in a database management system? The following list goes over the main components:

### Storage management

The storage manager is a module in a DBMS that provides the interface between the physical data in the database and the programs and queries that use the system. It's responsible for interacting with the file manager and efficiently storing, retrieving and updating data. It implements a lot of what we covered in the previous section; file organisation, indexing and hashing.

### Transaction management

The transaction manager ensures that the database remains in a consistent (i.e. valid and correct) state despite system failures (unavoidable things like the power failing, the OS crashing etc), and transaction failures.

### Concurrency controller

If multiple users are concurrently updating the same data, then the concurrency controller ensures that the concurrent transactions don't interfere with each other and compromise the consistency of the database.

### Query processor

The query processor evaluates queries (DDL, QL, DML). It has three main phases; parsing and translation, optimisation and evaluation.

There are different ways of evaluating any given query. Many logical expressions are equivalent, and the algorithms used for each different logical operation will have different costs, therefore the cost difference between a good way of evaluating a query and a bad one can be massive. Henceforth, the query optimiser will estimate the cost of operations, and execute the cheapest equivalent one. It does this by analysing statistical information about relations that the database will maintain,

### User roles

Different users of the database will require different permissions. For example administrators will need privileges to monitor users and performance, while more sophisticated users may have access to the command line to implement more detailed logic. Less sophisticated users will probably get a GUI written for them so that they can interact with the database easily.

## 11.1 Types of architectures

How a database system works is greatly influenced by the hardware that is running it. Is all the computation being done on one machine? Is the client on a remote machine? How many parallel threads of computation are there?

### Centralised

Centralised systems run on a single system, and don't need to interact with other systems. These are usually general purpose PC's that have from one to four(ish) CPU's, with access to common memory. Although the computation is only done on one system, multiple other agents can still connect to the database system and use it (it's not air-gapped from everything else).

### Client-server systems

These run on (computationally) large servers that usually have multiple users, aiming to provide capacity for lots of client systems, we assume that the server is many time better resourced than the client is. The functionality can be divided into back end (concurrency, recovery, optimisation, query evaluation etc), and front end (forms, GUI, report construction etc). The interface between the two halves is done using either an API or directly through the SQL engine.

If the front end functionality is migrated to user workstations, then the UI experience often improves (lower latency for the user), there's more functionality for the same cost and it's easier to upgrade and expand systems (just stick a PC wherever and connect it to the server).

There are two types of server in client-server systems:

#### *Transaction servers*

Widely used in relational database systems, these servers take requests from clients, execute the necessary transactions and then send the results back to the client..

Requests are specified using SQL, and communicated using an RPC mechanism. API's for this include the Open Database Connectivity API for C and the JDBC (similar acronym) for Java.

If you did COMP18112, then you'd know that RPC stands for Remote Procedure Call, and is kind of synonymous with an API.

Queries are handled by server processes, and are massively multi-threaded to handle many concurrent requests. Processes run on the server to control access to shared memory, these include the lock manager (controls concurrent access), the database writer (to handle both persistent and volatile storage) and the process monitor (handles commits, aborts, roll-backs etc).

There are trade offs between having these processes to ensure the consistency of the database, since they are also a drain on resources.

As mentioned above, transaction servers implement some form of mutual exclusion in order to stop processes interfering with each other through mediums such as the log buffer, lock table, query plan cache etc.

#### *Data servers*

Data servers are usually made use of when there is a fast connection between the client and the server, and the client has a comparable amount of processing power to the server, or the queries are very computationally intensive.

Instead of the query being executed on the server, the necessary data is sent back the the client where it is processed. This requires a full back end functionality for every client.

More recent developments in databases such as NoSQL rely on lots of equipotent systems (systems of similar processing power) in this manner.

### Parallel systems

These consist of multiple processors with multiple disks that are connected by a fast

network. *Coarse grained* parallel machines have few very powerful processors, while *fine grained* (massively parallel) machines use thousands of smaller processors.

There are two measures of performance; throughput and response. Throughput is the number of tasks that can be completed in a given time interval, while response time is the amount of time it takes to complete a single task. The goal is to improve performance as we increase the amount of parallelism used.

We want a system whose performance will increase in a linear manner as we invest in faster computing resources. A sub-linear speedup means that the full investment on resources is not recouped in time reduction on queries. We can also scale up our architecture by investing in more computing resources, the goal is to keep the latency down as we increase the amount of computing resources.

Factors that make scale and speed up's sublinear include start up costs (it may take a while to make multiple processes synchronise and get into a ready state), interference (multiple processes accessing shared resources can be slowed down by congestion) and skew (more parallel computation means more variance in computation time, and the overall execution time is determined by the slowest tasks).

Parallel systems can share different parts of their architectures:

#### *Shared memory*

Processors and disks can access common memory through a bus or interconnection network. Very efficient communication between processors can be used facilitate accesses to memory without having to use software.

This isn't scalable beyond 32 or 64 (depending on the word size) processors, since the bus becomes a bottleneck. Four or eight processors are more commonly used.

#### *Shared disk*

All the processors can directly access the disks, but their memory is private. This means that the memory bus is not a bottleneck, and the architecture is reasonably fault tolerant (if a processor fails, other ones can take on the work). The main downside is that the disk IO is now the bottleneck (which can be worse). Shared disk systems can scale to much larger numbers of processors than shared memory systems can, but their inter-processor communication is much lower.

#### *Shared nothing*

Here, each computing node has its own processor, memory and disk. Communication is facilitated using a network, and the node serves as the server for the data on it's own disk. The data directly on local disks never leaves the system so resource sharing is minimal (though the data does eventually get out in the form of queries).

This architecture allows you to scale up to thousands of processors without them interfering with each other, but they are hit by a comparatively slow network (sending data requires lots of software interaction at both ends).

#### *Hierarchical*

A hierarchical architecture combines the characteristics of the above three architectures. Here, there's a top level of shared nothing architecture, where each node is made up of shared-disk or shared-memory processors.

The complexity of such a system is reduced by using distributed virtual memory architectures (the memory split over multiple systems, but is addressed using the same address space). It's also called a non-uniform memory architecture.

## **Distributed Systems**

Distributed systems spread data over multiple nodes, connected by a network. Some systems (homogeneous) use the same software or database schema over all the sites, but the data is split among them, while others (heterogeneous) use different systems/software

at different sites with different data too (maybe they're integrating multiple pre-existing systems).

Distributed systems bring the notion of local and global transactions. A local transaction accesses data in the single site where a transaction was initiated, but a global one uses data from a (potentially several) different site(s).

Distributed systems allow data to be shared across sites, each site retains lots of control of the data that is stored locally, and the system as a whole is reliable, since data can be replicated on remote sites so the system can function in the event of one failing.

However, there is an increased development cost and overhead for a multi-site system, coordinating the interactions between the sites is a hard problem. Atomicity is needed across multiple locations for global transactions. This can be achieved using 2PC (two phase commit) protocol. The idea of 2PC is that all the sites execute the transaction until just before the commit, and a coordinator will say whether to commit or not. All the sites must follow the coordinator's decision. 2PC isn't always the answer; other models may be more suited to a specific implementation.

There are two types of network that a distributed system can run on; LAN's and WAN's. Local Area Networks are composed of processors distributed over a small geographical area, such as a building, or street. A Wide Area Network is made of processors that are distributed over a large geographical area, such as the internet. Some applications can work on sites that have a non-continuous connection to a WAN.