Part 1 Background

Chapter 1 Introduction to Databases

Chapter Objectives

In this chapter you will learn:

- Some common uses of database systems.
- The characteristics of file-based systems.
- The problems with the file-based approach.
- The meaning of the term 'database'.
- The meaning of the term 'database management system' (DBMS).
- The typical functions of a DBMS.
- The major components of the DBMS environment.
- The personnel involved in the DBMS environment.
- The history of the development of DBMSs.
- The advantages and disadvantages of DBMSs.

> The history of database system research is one of exceptional productivity and startling economic impact. Barely 20 years old as a basic science research field, database research has fueled an information services industry estimated at $10 billion per year in the U.S. alone. Achievements in database research underpin fundamental advances in communications systems, transportation and logistics, financial management, knowledge-based systems, accessibility to scientific literature, and a host of other civilian and defense applications. They also serve as the foundation for considerable progress in the basic science fields ranging from computing to biology.
>
> (Silberschatz *et al*., 1990, 1996)

This quotation is from a workshop on database systems at the beginning of the 1990s and expanded upon in a subsequent workshop in 1996, and it provides substantial motivation for the study of the subject of this book: the **database system**. Since these workshops, the importance of the database system has, if anything, increased with the significant developments in hardware capability, hardware capacity, and communications, including the

emergence of the Internet, electronic commerce, business intelligence, mobile communications, and grid computing. The database system is arguably the most important development in the field of software engineering, and the database is now the underlying framework of the information system, fundamentally changing the way that many organizations operate. Database technology has been an exciting area to work in and, since its emergence, has been the catalyst for many important developments in software engineering. The workshop emphasized that the developments in database systems were not over, as some people thought. In fact, to paraphrase an old saying, it may be that we are only *at the end of the beginning* of the development. The applications that will have to be handled in the future are so much more complex that we will have to rethink many of the algorithms currently being used, such as the algorithms for file storage and access, and query optimization. The development of these original algorithms has had significant ramifications in software engineering and, without doubt, the development of new algorithms will have similar effects. In this first chapter we introduce the database system.

Structure of this Chapter

In Section 1.1 we examine some uses of database systems that we find in everyday life but are not necessarily aware of. In Sections 1.2 and 1.3 we compare the early file-based approach to computerizing the manual file system with the modern, and more usable, database approach. In Section 1.4 we discuss the four types of role that people perform in the database environment, namely: data and database administrators, database designers, application developers, and the end-users. In Section 1.5 we provide a brief history of database systems, and follow that in Section 1.6 with a discussion of the advantages and disadvantages of database systems.

Throughout this book, we illustrate concepts using a case study based on a fictitious property management company called *DreamHome*. We provide a detailed description of this case study in Section 10.4 and Appendix A. In Appendix B we present further case studies that are intended to provide additional realistic projects for the reader. There will be exercises based on these case studies at the end of many chapters.

1.1 Introduction

The database is now such an integral part of our day-to-day life that often we are not aware we are using one. To start our discussion of databases, in this section we examine some applications of database systems. For the purposes of this discussion, we consider a *database* to be a collection of related data and the *Database Management System* (DBMS) to be the software that manages and controls access to the database. A *database application* is simply a program that interacts with the database at some point in its execution. We also use the more inclusive term *database system* to be a collection of application programs that interact with the database along with the DBMS and database itself. We provide more accurate definitions in Section 1.3.

Purchases from the supermarket

When you purchase goods from your local supermarket, it is likely that a database is accessed. The checkout assistant uses a bar code reader to scan each of your purchases. This is linked to an application program that uses the bar code to find out the price of the item from a product database. The program then reduces the number of such items in stock and displays the price on the cash register. If the reorder level falls below a specified threshold, the database system may automatically place an order to obtain more stocks of that item. If a customer telephones the supermarket, an assistant can check whether an item is in stock by running an application program that determines availability from the database.

Purchases using your credit card

When you purchase goods using your credit card, the assistant normally checks that you have sufficient credit left to make the purchase. This check may be carried out by telephone or it may be carried out automatically by a card reader linked to a computer system. In either case, there is a database somewhere that contains information about the purchases that you have made using your credit card. To check your credit, there is a database application program that uses your credit card number to check that the price of the goods you wish to buy together with the sum of the purchases you have already made this month is within your credit limit. When the purchase is confirmed, the details of the purchase are added to this database. The application program also accesses the database to check that the credit card is not on the list of stolen or lost cards before authorizing the purchase. There are other application programs to send out monthly statements to each cardholder and to credit accounts when payment is received.

Booking a holiday at the travel agents

When you make inquiries about a holiday, the travel agent may access several databases containing holiday and flight details. When you book your holiday, the database system has to make all the necessary booking arrangements. In this case, the system has to ensure that two different agents do not book the same holiday or overbook the seats on the flight. For example, if there is only one seat left on the flight from London to New York and two agents try to reserve the last seat at the same time, the system has to recognize this situation, allow one booking to proceed, and inform the other agent that there are now no seats available. The travel agent may have another, usually separate, database for invoicing.

Using the local library

Your local library probably has a database containing details of the books in the library, details of the readers, reservations, and so on. There will be a computerized index that allows readers to find a book based on its title, or its authors, or its subject area. The database system handles reservations to allow a reader to reserve a book and to be informed by mail when the book is available. The system also sends reminders to borrowers who have failed to return books by the due date. Typically, the system will have a bar code

reader, similar to that used by the supermarket described earlier, which is used to keep track of books coming in and going out of the library.

Taking out insurance

Whenever you wish to take out insurance, for example personal insurance, building, and contents insurance for your house, or car insurance, your broker may access several databases containing figures for various insurance organizations. The personal details that you supply, such as name, address, age, and whether you drink or smoke, are used by the database system to determine the cost of the insurance. The broker can search several databases to find the organization that gives you the best deal.

Renting a video

When you wish to rent a video from a video rental company, you will probably find that the company maintains a database consisting of the video titles that it stocks, details on the copies it has for each title, whether the copy is available for rent or whether it is currently on loan, details of its members (the renters), and which videos they are currently renting and date they are returned. The database may even store more detailed information on each video, such as its director and its actors. The company can use this information to monitor stock usage and predict future buying trends based on historic rental data.

Using the Internet

Many of the sites on the Internet are driven by database applications. For example, you may visit an online bookstore that allows you to browse and buy books, such as Amazon.com. The bookstore allows you to browse books in different categories, such as computing or management, or it may allow you to browse books by author name. In either case, there is a database on the organization's Web server that consists of book details, availability, shipping information, stock levels, and on-order information. Book details include book titles, ISBNs, authors, prices, sales histories, publishers, reviews, and detailed descriptions. The database allows books to be cross-referenced: for example, a book may be listed under several categories, such as computing, programming languages, bestsellers, and recommended titles. The cross-referencing also allows Amazon to give you information on other books that are typically ordered along with the title you are interested in.

As with an earlier example, you can provide your credit card details to purchase one or more books online. Amazon.com personalizes its service for customers who return to its site by keeping a record of all previous transactions, including items purchased, shipping, and credit card details. When you return to the site, you can now be greeted by name and you can be presented with a list of recommended titles based on previous purchases.

Studying at university

If you are at university, there will be a database system containing information about yourself, the course you are enrolled in, details about your grant, the modules you have taken in previous years or are taking this year, and details of all your examination results. There

may also be a database containing details relating to the next year's admissions and a database containing details of the staff who work at the university, giving personal details and salary-related details for the payroll office.

1.2 Traditional File-Based Systems

It is almost a tradition that comprehensive database books introduce the database system with a review of its predecessor, the file-based system. We will not depart from this tradition. Although the file-based approach is largely obsolete, there are good reasons for studying it:

- Understanding the problems inherent in file-based systems may prevent us from repeating these problems in database systems. In other words, we should learn from our earlier mistakes. Actually, using the word 'mistakes' is derogatory and does not give any cognizance to the work that served a useful purpose for many years. However, we have learned from this work that there are better ways to handle data.
- If you wish to convert a file-based system to a database system, understanding how the file system works will be extremely useful, if not essential.

1.2.1 File-Based Approach

File-based system A collection of application programs that perform services for the end-users such as the production of reports. Each program defines and manages its own data.

File-based systems were an early attempt to computerize the manual filing system that we are all familiar with. For example, in an organization a manual file is set up to hold all external and internal correspondence relating to a project, product, task, client, or employee. Typically, there are many such files, and for safety they are labeled and stored in one or more cabinets. For security, the cabinets may have locks or may be located in secure areas of the building. In our own home, we probably have some sort of filing system which contains receipts, guarantees, invoices, bank statements, and such like. When we need to look something up, we go to the filing system and search through the system starting from the first entry until we find what we want. Alternatively, we may have an indexing system that helps locate what we want more quickly. For example, we may have divisions in the filing system or separate folders for different types of item that are in some way *logically related*.

The manual filing system works well while the number of items to be stored is small. It even works quite adequately when there are large numbers of items and we have only to store and retrieve them. However, the manual filing system breaks down when we have to cross-reference or process the information in the files. For example, a typical real estate agent's office might have a separate file for each property for sale or rent, each potential buyer and renter, and each member of staff. Consider the effort that would be required to answer the following questions:

- What three-bedroom properties do you have for sale with a garden and garage?
- What flats do you have for rent within three miles of the city center?
- What is the average rent for a two-bedroom flat?
- What is the total annual salary bill for staff?
- How does last month's turnover compare with the projected figure for this month?
- What is the expected monthly turnover for the next financial year?

Increasingly, nowadays, clients, senior managers, and staff want more and more information. In some areas there is a legal requirement to produce detailed monthly, quarterly, and annual reports. Clearly, the manual system is inadequate for this type of work. The file-based system was developed in response to the needs of industry for more efficient data access. However, rather than establish a centralized store for the organization's operational data, a decentralized approach was taken, where each department, with the assistance of **Data Processing** (DP) staff, stored and controlled its own data. To understand what this means, consider the *DreamHome* example.

The Sales Department is responsible for the selling and renting of properties. For example, whenever a client approaches the Sales Department with a view to marketing his or her property for rent, a form is completed, similar to that shown in Figure 1.1(a). This gives details of the property such as address and number of rooms together with the owner's details. The Sales Department also handles inquiries from clients, and a form similar to the one shown in Figure 1.1(b) is completed for each one. With the assistance of the DP Department, the Sales Department creates an information system to handle the renting of property. The system consists of three files containing property, owner, and client details, as illustrated in Figure 1.2. For simplicity, we omit details relating to members of staff, branch offices, and business owners.

The Contracts Department is responsible for handling the lease agreements associated with properties for rent. Whenever a client agrees to rent a property, a form is filled in by one of the Sales staff giving the client and property details, as shown in Figure 1.3. This form is passed to the Contracts Department which allocates a lease number and completes the payment and rental period details. Again, with the assistance of the DP Department, the Contracts Department creates an information system to handle lease agreements. The system consists of three files storing lease, property, and client details, containing similar data to that held by the Sales Department, as illustrated in Figure 1.4.

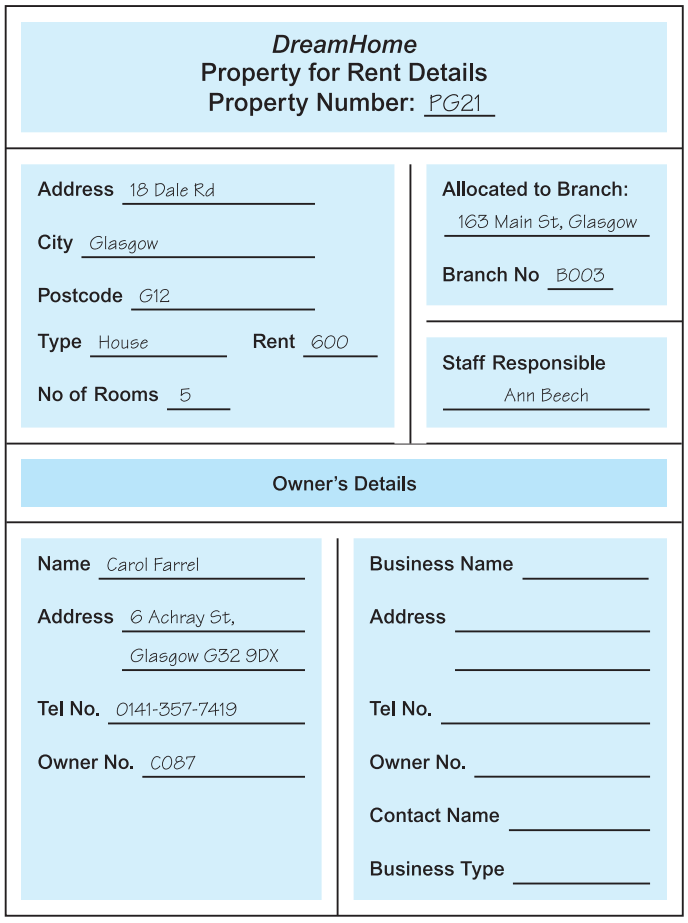
The situation is illustrated in Figure 1.5. It shows each department accessing their own files through application programs written specially for them. Each set of departmental application programs handles data entry, file maintenance, and the generation of a fixed set of specific reports. What is more important, the physical structure and storage of the data files and records are defined in the application code.

We can find similar examples in other departments. For example, the Payroll Department stores details relating to each member of staff's salary, namely:

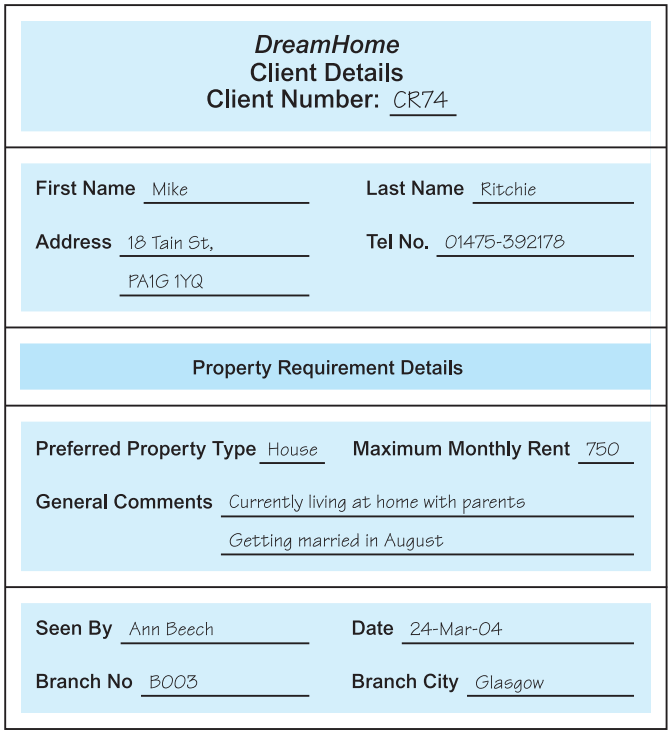
StaffSalary(staffNo, fName, lName, sex, salary, branchNo)

The Personnel Department also stores staff details, namely:

Staff(staffNo, fName, lName, position, sex, dateOfBirth, salary, branchNo)



(a)



(b)

Figure 1.1 Sales Department forms: (a) Property for Rent Details form; (b) Client Details form.

Figure 1.2
The PropertyForRent, PrivateOwner, and Client files used by Sales.

PropertyForRent

propertyNo	street	city	postcode	type	rooms	rent	ownerNo
PA14	16 Holhead	Aberdeen	AB7 5SU	House	6	650	CO46
PL94	6 Argyll St	London	NW2	Flat	4	400	CO87
PG4	6 Lawrence St	Glasgow	G11 9QX	Flat	3	350	CO40
PG36	2 Manor Rd	Glasgow	G32 4QX	Flat	3	375	CO93
PG21	18 Dale Rd	Glasgow	G12	House	5	600	CO87
PG16	5 Novar Dr	Glasgow	G12 9AX	Flat	4	450	CO93

PrivateOwner

ownerNo	fName	lName	address	telNo
CO46	Joe	Keogh	2 Fergus Dr, Aberdeen AB2 7SX	01224-861212
CO87	Carol	Farrel	6 Achray St, Glasgow G32 9DX	0141-357-7419
CO40	Tina	Murphy	63 Well St, Glasgow G42	0141-943-1728
CO93	Tony	Shaw	12 Park Pl, Glasgow G4 0QR	0141-225-7025

Client

clientNo	fName	lName	address	telNo	prefType	maxRent
CR76	John	Kay	56 High St, London SW1 4EH	0207-774-5632	Flat	425
CR56	Aline	Stewart	64 Fern Dr, Glasgow G42 0BL	0141-848-1825	Flat	350
CR74	Mike	Ritchie	18 Tain St, PA1G 1YQ	01475-392178	House	750
CR62	Mary	Tregear	5 Tarbot Rd, Aberdeen AB9 3ST	01224-196720	Flat	600

Figure 1.3
Lease Details form used by Contracts Department.

DreamHome
Lease Details
Lease Number: 10012

Client No. CR74
Full Name Mike Ritchie
Address (previous) 18 Tain St, PA1G 1YQ
Tel No. 01475-392178

Property No. PG21
Address 18 Dale Rd, Glasgow G12

Payment Details

Monthly Rent 600
Payment Method Cheque
Deposit 1200 Paid (Y or N) Y

Rent Start Date 1-Jul-04
Rent Finish Date 30-Jun-05
Duration 1 Year

Lease

leaseNo	propertyNo	clientNo	rent	payment Method	deposit	paid	rentStart	rentFinish	duration
10024	PA14	CR62	650	Visa	1300	Y	1-Jun-05	31-May-05	12
10075	PL94	CR76	400	Cash	800	N	1-Aug-05	31-Jan-05	6
10012	PG21	CR74	600	Cheque	1200	Y	1-Jul-05	30-Jun-05	12

PropertyForRent

propertyNo	street	city	postcode	rent
PA14	16 Holhead	Aberdeen	AB7 5SU	650
PL94	6 Argyll St	London	NW2	400
PG21	18 Dale Rd	Glasgow	G12	600

Client

clientNo	fName	lName	address	telNo
CR76	John	Kay	56 High St, London SW1 4EH	0171-774-5632
CR74	Mike	Ritchie	18 Tain St, PA1G 1YQ	01475-392178
CR62	Mary	Tregear	5 Tarbot Rd, Aberdeen AB9 3ST	01224-196720

Figure 1.4
The Lease, PropertyForRent, and Client files used by Contracts.

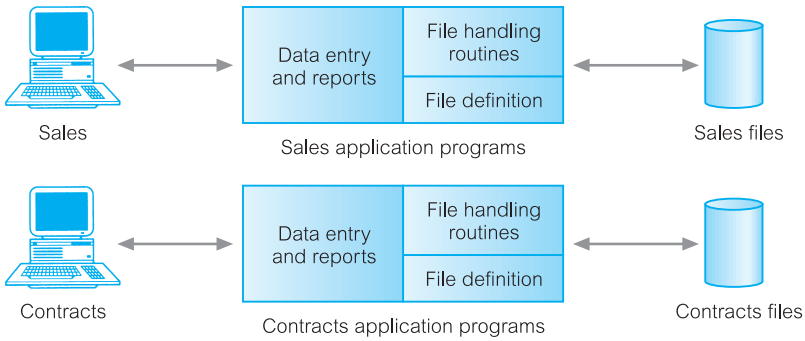


Figure 1.5
File-based processing.

Sales Files

PropertyForRent (propertyNo, street, city, postcode, type, rooms, rent, ownerNo)
PrivateOwner (ownerNo, fName, lName, address, telNo)
Client (clientNo, fName, lName, address, telNo, prefType, maxRent)

Contracts Files

Lease (leaseNo, propertyNo, clientNo, rent, paymentMethod, deposit, paid, rentStart, rentFinish, duration)
PropertyForRent (propertyNo, street, city, postcode, rent)
Client (clientNo, fName, lName, address, telNo)

It can be seen quite clearly that there is a significant amount of duplication of data in these departments, and this is generally true of file-based systems. Before we discuss the limitations of this approach, it may be useful to understand the terminology used in file-based systems. A file is simply a collection of **records**, which contains **logically related**

data. For example, the PropertyForRent file in Figure 1.2 contains six records, one for each property. Each record contains a logically connected set of one or more **fields**, where each field represents some characteristic of the real-world object that is being modeled. In Figure 1.2, the fields of the PropertyForRent file represent characteristics of properties, such as address, property type, and number of rooms.

1.2.2 Limitations of the File-Based Approach

This brief description of traditional file-based systems should be sufficient to discuss the limitations of this approach. We list five problems in Table 1.1.

Separation and isolation of data

When data is isolated in separate files, it is more difficult to access data that should be available. For example, if we want to produce a list of all houses that match the requirements of clients, we first need to create a temporary file of those clients who have 'house' as the preferred type. We then search the PropertyForRent file for those properties where the property type is 'house' and the rent is less than the client's maximum rent. With file systems, such processing is difficult. The application developer must synchronize the processing of two files to ensure the correct data is extracted. This difficulty is compounded if we require data from more than two files.

Duplication of data

Owing to the decentralized approach taken by each department, the file-based approach encouraged, if not necessitated, the uncontrolled duplication of data. For example, in Figure 1.5 we can clearly see that there is duplication of both property and client details in the Sales and Contracts Departments. Uncontrolled duplication of data is undesirable for several reasons, including:

- Duplication is wasteful. It costs time and money to enter the data more than once.
- It takes up additional storage space, again with associated costs. Often, the duplication of data can be avoided by sharing data files.
- Perhaps more importantly, duplication can lead to loss of data integrity; in other words, the data is no longer consistent. For example, consider the duplication of data between

Table 1.1 Limitations of file-based systems.

Separation and isolation of data
Duplication of data
Data dependence
Incompatible file formats
Fixed queries/proliferation of application programs

the Payroll and Personnel Departments described above. If a member of staff moves house and the change of address is communicated only to Personnel and not to Payroll, the person's payslip will be sent to the wrong address. A more serious problem occurs if an employee is promoted with an associated increase in salary. Again, the change is notified to Personnel but the change does not filter through to Payroll. Now, the employee is receiving the wrong salary. When this error is detected, it will take time and effort to resolve. Both these examples illustrate inconsistencies that may result from the duplication of data. As there is no automatic way for Personnel to update the data in the Payroll files, it is not difficult to foresee such inconsistencies arising. Even if Payroll is notified of the changes, it is possible that the data will be entered incorrectly.

Data dependence

As we have already mentioned, the physical structure and storage of the data files and records are defined in the application code. This means that changes to an existing structure are difficult to make. For example, increasing the size of the PropertyForRent address field from 40 to 41 characters sounds like a simple change, but it requires the creation of a one-off program (that is, a program that is run only once and can then be discarded) that converts the PropertyForRent file to the new format. This program has to:

- open the original PropertyForRent file for reading;
- open a temporary file with the new structure;
- read a record from the original file, convert the data to conform to the new structure, and write it to the temporary file. Repeat this step for all records in the original file;
- delete the original PropertyForRent file;
- rename the temporary file as PropertyForRent.

In addition, all programs that access the PropertyForRent file must be modified to conform to the new file structure. There might be many such programs that access the PropertyForRent file. Thus, the programmer needs to identify all the affected programs, modify them, and then retest them. Note that a program does not even have to use the address field to be affected: it has only to use the PropertyForRent file. Clearly, this could be very time-consuming and subject to error. This characteristic of file-based systems is known as **program–data dependence**.

Incompatible file formats

Because the structure of files is embedded in the application programs, the structures are dependent on the application programming language. For example, the structure of a file generated by a COBOL program may be different from the structure of a file generated by a 'C' program. The direct incompatibility of such files makes them difficult to process jointly.

For example, suppose that the Contracts Department wants to find the names and addresses of all owners whose property is currently rented out. Unfortunately, Contracts

does not hold the details of property owners; only the Sales Department holds these. However, Contracts has the property number (propertyNo), which can be used to find the corresponding property number in the Sales Department's PropertyForRent file. This file holds the owner number (ownerNo), which can be used to find the owner details in the PrivateOwner file. The Contracts Department programs in COBOL and the Sales Department programs in 'C'. Therefore, to match propertyNo fields in the two PropertyForRent files requires an application developer to write software to convert the files to some common format to facilitate processing. Again, this can be time-consuming and expensive.

Fixed queries/proliferation of application programs

From the end-user's point of view, file-based systems proved to be a great improvement over manual systems. Consequently, the requirement for new or modified queries grew. However, file-based systems are very dependent upon the application developer, who has to write any queries or reports that are required. As a result, two things happened. In some organizations, the type of query or report that could be produced was fixed. There was no facility for asking unplanned (that is, spur-of-the-moment or *ad hoc*) queries either about the data itself or about which types of data were available.

In other organizations, there was a proliferation of files and application programs. Eventually, this reached a point where the DP Department, with its current resources, could not handle all the work. This put tremendous pressure on the DP staff, resulting in programs that were inadequate or inefficient in meeting the demands of the users, documentation that was limited, and maintenance that was difficult. Often, certain types of functionality were omitted including:

- there was no provision for security or integrity;
- recovery, in the event of a hardware or software failure, was limited or non-existent;
- access to the files was restricted to one user at a time – there was no provision for shared access by staff in the same department.

In either case, the outcome was not acceptable. Another solution was required.

1.3 Database Approach

All the above limitations of the file-based approach can be attributed to two factors:

(1) the definition of the data is embedded in the application programs, rather than being stored separately and independently;

(2) there is no control over the access and manipulation of data beyond that imposed by the application programs.

To become more effective, a new approach was required. What emerged were the **database** and the **Database Management System** (DBMS). In this section, we provide a more formal definition of these terms, and examine the components that we might expect in a DBMS environment.

The Database 1.3.1

Database A shared collection of logically related data, and a description of this data, designed to meet the information needs of an organization.

We now examine the definition of a database to understand the concept fully. The database is a single, possibly large repository of data that can be used simultaneously by many departments and users. Instead of disconnected files with redundant data, all data items are integrated with a minimum amount of duplication. The database is no longer owned by one department but is a shared corporate resource. The database holds not only the organization's operational data but also a description of this data. For this reason, a database is also defined as a *self-describing collection of integrated records*. The description of the data is known as the **system catalog** (or **data dictionary** or **metadata** – the 'data about data'). It is the self-describing nature of a database that provides **program–data independence**.

The approach taken with database systems, where the definition of data is separated from the application programs, is similar to the approach taken in modern software development, where an internal definition of an object and a separate external definition are provided. The users of an object see only the external definition and are unaware of how the object is defined and how it functions. One advantage of this approach, known as **data abstraction**, is that we can change the internal definition of an object without affecting the users of the object, provided the external definition remains the same. In the same way, the database approach separates the structure of the data from the application programs and stores it in the database. If new data structures are added or existing structures are modified then the application programs are unaffected, provided they do not directly depend upon what has been modified. For example, if we add a new field to a record or create a new file, existing applications are unaffected. However, if we remove a field from a file that an application program uses, then that application program is affected by this change and must be modified accordingly.

The final term in the definition of a database that we should explain is 'logically related'. When we analyze the information needs of an organization, we attempt to identify entities, attributes, and relationships. An **entity** is a distinct object (a person, place, thing, concept, or event) in the organization that is to be represented in the database. An **attribute** is a property that describes some aspect of the object that we wish to record, and a **relationship** is an association between entities. For example, Figure 1.6 shows an Entity–Relationship (ER) diagram for part of the *DreamHome* case study. It consists of:

- six entities (the rectangles): Branch, Staff, PropertyForRent, Client, PrivateOwner, and Lease;
- seven relationships (the names adjacent to the lines): *Has*, *Offers*, *Oversees*, *Views*, *Owns*, *LeasedBy*, and *Holds*;
- six attributes, one for each entity: branchNo, staffNo, propertyNo, clientNo, ownerNo, and leaseNo.

The database represents the entities, the attributes, and the logical relationships between the entities. In other words, the database holds data that is logically related. We discuss the Entity–Relationship model in detail in Chapters 11 and 12.

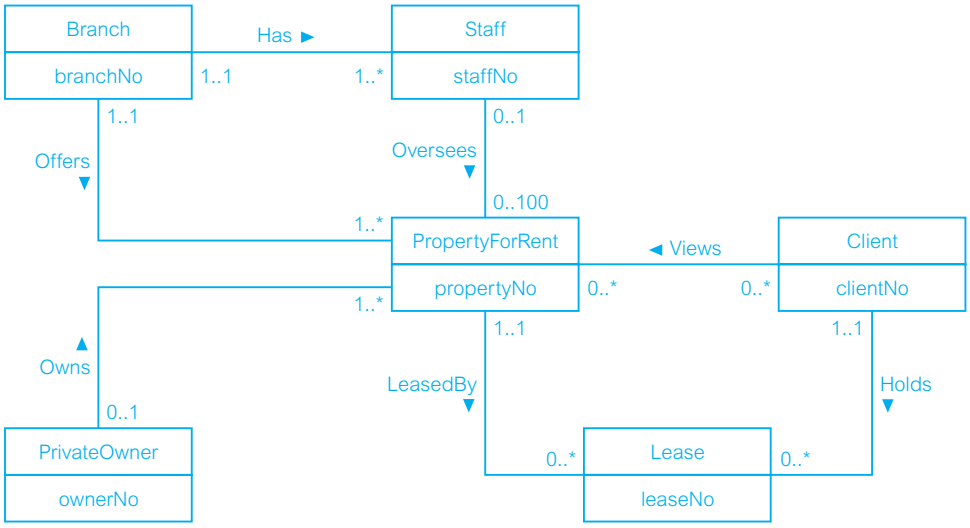


Figure 1.6 Example Entity–Relationship diagram.

1.3.2 The Database Management System (DBMS)

DBMS A software system that enables users to define, create, maintain, and control access to the database.

The DBMS is the software that interacts with the users' application programs and the database. Typically, a DBMS provides the following facilities:

- It allows users to define the database, usually through a **Data Definition Language** (DDL). The DDL allows users to specify the data types and structures and the constraints on the data to be stored in the database.
- It allows users to insert, update, delete, and retrieve data from the database, usually through a **Data Manipulation Language** (DML). Having a central repository for all data and data descriptions allows the DML to provide a general inquiry facility to this data, called a **query language**. The provision of a query language alleviates the problems with file-based systems where the user has to work with a fixed set of queries or there is a proliferation of programs, giving major software management problems. The most common query language is the **Structured Query Language** (SQL, pronounced 'S-Q-L', or sometimes 'See-Quel'), which is now both the formal and *de facto* standard language for relational DBMSs. To emphasize the importance of SQL, we devote Chapters 5 and 6, most of 28, and Appendix E to a comprehensive study of this language.
- It provides controlled access to the database. For example, it may provide:
  - a security system, which prevents unauthorized users accessing the database;
  - an integrity system, which maintains the consistency of stored data;
  - a concurrency control system, which allows shared access of the database;

– a recovery control system, which restores the database to a previous consistent state following a hardware or software failure;
– a user-accessible catalog, which contains descriptions of the data in the database.

(Database) Application Programs 1.3.3

Application program A computer program that interacts with the database by issuing an appropriate request (typically an SQL statement) to the DBMS.

Users interact with the database through a number of **application programs** that are used to create and maintain the database and to generate information. These programs can be conventional batch applications or, more typically nowadays, they will be online applications. The application programs may be written in some programming language or in some higher-level fourth-generation language.

The database approach is illustrated in Figure 1.7, based on the file approach of Figure 1.5. It shows the Sales and Contracts Departments using their application programs to access the database through the DBMS. Each set of departmental application programs handles data entry, data maintenance, and the generation of reports. However, compared with the file-based approach, the physical structure and storage of the data are now managed by the DBMS.

Views

With this functionality, the DBMS is an extremely powerful and useful tool. However, as the end-users are not too interested in how complex or easy a task is for the system, it could be argued that the DBMS has made things more complex because they now see

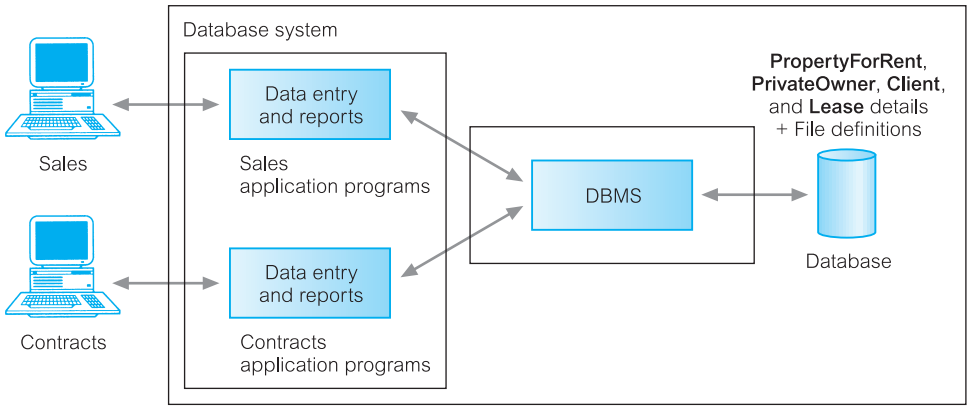


Figure 1.7 Database processing.

PropertyForRent (propertyNo, street, city, postcode, type, rooms, rent, ownerNo)
PrivateOwner (ownerNo, fName, lName, address, telNo)
Client (clientNo, fName, lName, address, telNo, prefType, maxRent)
Lease (leaseNo, propertyNo, clientNo, paymentMethod, deposit, paid, rentStart, rentFinish)

more data than they actually need or want. For example, the details that the Contracts Department wants to see for a rental property, as shown in Figure 1.5, have changed in the database approach, shown in Figure 1.7. Now the database also holds the property type, the number of rooms, and the owner details. In recognition of this problem, a DBMS provides another facility known as a **view mechanism**, which allows each user to have his or her own view of the database (a **view** is in essence some subset of the database). For example, we could set up a view that allows the Contracts Department to see only the data that they want to see for rental properties.

As well as reducing complexity by letting users see the data in the way they want to see it, views have several other benefits:

- *Views provide a level of security*. Views can be set up to exclude data that some users should not see. For example, we could create a view that allows a branch manager and the Payroll Department to see all staff data, including salary details, and we could create a second view that other staff would use that excludes salary details.
- *Views provide a mechanism to customize the appearance of the database*. For example, the Contracts Department may wish to call the monthly rent field (rent) by the more obvious name, Monthly Rent.
- *A view can present a consistent, unchanging picture of the structure of the database*, even if the underlying database is changed (for example, fields added or removed, relationships changed, files split, restructured, or renamed). If fields are added or removed from a file, and these fields are not required by the view, the view is not affected by this change. Thus, a view helps provide the program–data independence we mentioned in the previous section.

The above discussion is general and the actual level of functionality offered by a DBMS differs from product to product. For example, a DBMS for a personal computer may not support concurrent shared access, and it may provide only limited security, integrity, and recovery control. However, modern, large multi-user DBMS products offer all the above functions and much more. Modern systems are extremely complex pieces of software consisting of millions of lines of code, with documentation comprising many volumes. This is a result of having to provide software that handles requirements of a more general nature. Furthermore, the use of DBMSs nowadays requires a system that provides almost total reliability and 24/7 availability (24 hours a day, 7 days a week), even in the presence of hardware or software failure. The DBMS is continually evolving and expanding to cope with new user requirements. For example, some applications now require the storage of graphic images, video, sound, and so on. To reach this market, the DBMS must change. It is likely that new functionality will always be required, so that the functionality of the DBMS will never become static. We discuss the basic functions provided by a DBMS in later chapters.

1.3.4 Components of the DBMS Environment

We can identify five major components in the DBMS environment: hardware, software, data, procedures, and people, as illustrated in Figure 1.8.

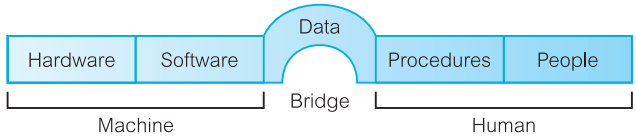


Figure 1.8
DBMS environment.

Hardware

The DBMS and the applications require hardware to run. The hardware can range from a single personal computer, to a single mainframe, to a network of computers. The particular hardware depends on the organization's requirements and the DBMS used. Some DBMSs run only on particular hardware or operating systems, while others run on a wide variety of hardware and operating systems. A DBMS requires a minimum amount of main memory and disk space to run, but this minimum configuration may not necessarily give acceptable performance. A simplified hardware configuration for *DreamHome* is illustrated in Figure 1.9. It consists of a network of minicomputers, with a central computer located in London running the **backend** of the DBMS, that is, the part of the DBMS that manages and controls access to the database. It also shows several computers at various

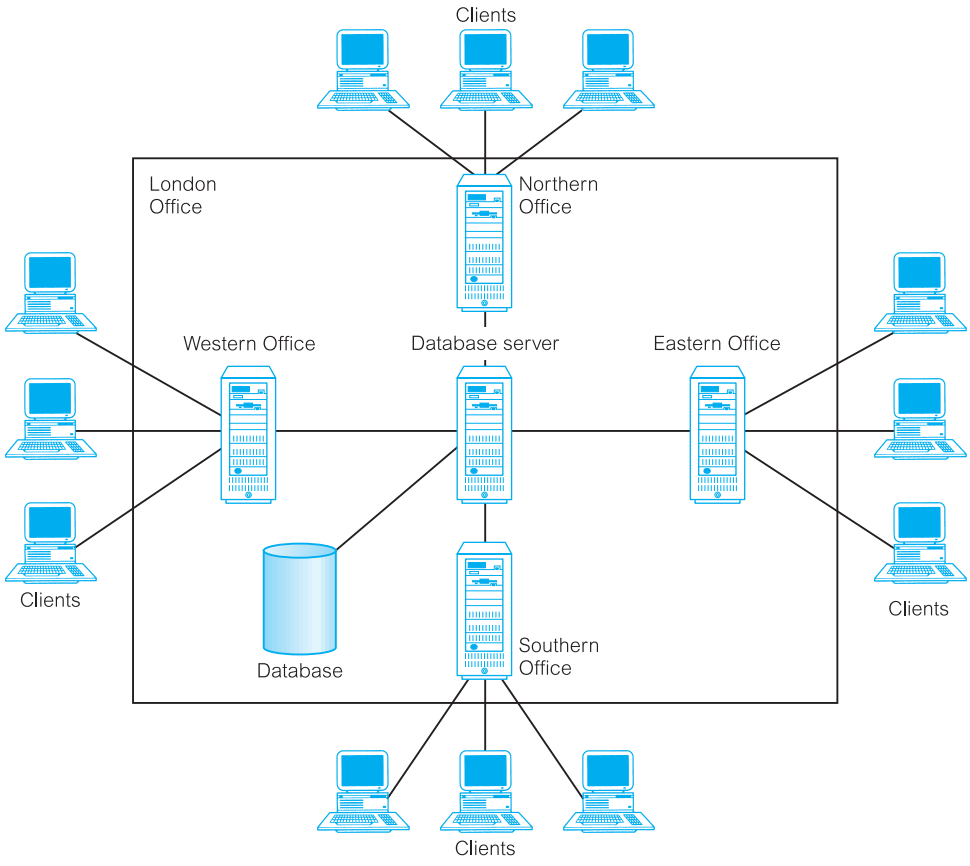


Figure 1.9
DreamHome hardware configuration.

locations running the **frontend** of the DBMS, that is, the part of the DBMS that interfaces with the user. This is called a **client–server** architecture: the backend is the server and the frontends are the clients. We discuss this type of architecture in Section 2.6.

Software

The software component comprises the DBMS software itself and the application programs, together with the operating system, including network software if the DBMS is being used over a network. Typically, application programs are written in a third-generation programming language (3GL), such as 'C', C++, Java, Visual Basic, COBOL, Fortran, Ada, or Pascal, or using a fourth-generation language (4GL), such as SQL, embedded in a third-generation language. The target DBMS may have its own fourth-generation tools that allow rapid development of applications through the provision of non-procedural query languages, reports generators, forms generators, graphics generators, and application generators. The use of fourth-generation tools can improve productivity significantly and produce programs that are easier to maintain. We discuss fourth-generation tools in Section 2.2.3.

Data

Perhaps the most important component of the DBMS environment, certainly from the end-users' point of view, is the data. From Figure 1.8, we observe that the data acts as a bridge between the machine components and the human components. The database contains both the operational data and the metadata, the 'data about data'. The structure of the database is called the **schema**. In Figure 1.7, the schema consists of four files, or **tables**, namely: PropertyForRent, PrivateOwner, Client, and Lease. The PropertyForRent table has eight fields, or **attributes**, namely: propertyNo, street, city, postcode, type (the property type), rooms (the number of rooms), rent (the monthly rent), and ownerNo. The ownerNo attribute models the relationship between PropertyForRent and PrivateOwner: that is, an owner *Owns* a property for rent, as depicted in the Entity–Relationship diagram of Figure 1.6. For example, in Figure 1.2 we observe that owner CO46, Joe Keogh, owns property PA14.

The data also incorporates the system catalog, which we discuss in detail in Section 2.4.

Procedures

Procedures refer to the instructions and rules that govern the design and use of the database. The users of the system and the staff that manage the database require documented procedures on how to use or run the system. These may consist of instructions on how to:

- log on to the DBMS;
- use a particular DBMS facility or application program;
- start and stop the DBMS;
- make backup copies of the database;
- handle hardware or software failures. This may include procedures on how to identify the failed component, how to fix the failed component (for example, telephone the appropriate hardware engineer) and, following the repair of the fault, how to recover the database;

- change the structure of a table, reorganize the database across multiple disks, improve performance, or archive data to secondary storage.

People

The final component is the people involved with the system. We discuss this component in Section 1.4.

Database Design: The Paradigm Shift 1.3.5

Until now, we have taken it for granted that there is a structure to the data in the database. For example, we have identified four tables in Figure 1.7: PropertyForRent, PrivateOwner, Client, and Lease. But how did we get this structure? The answer is quite simple: the structure of the database is determined during **database design**. However, carrying out database design can be extremely complex. To produce a system that will satisfy the organization's information needs requires a different approach from that of file-based systems, where the work was driven by the application needs of individual departments. For the database approach to succeed, the organization now has to think of the data first and the application second. This change in approach is sometimes referred to as a *paradigm shift*. For the system to be acceptable to the end-users, the database design activity is crucial. A poorly designed database will generate errors that may lead to bad decisions being made, which may have serious repercussions for the organization. On the other hand, a well-designed database produces a system that provides the correct information for the decision-making process to succeed in an efficient way.

The objective of this book is to help effect this paradigm shift. We devote several chapters to the presentation of a complete methodology for database design (see Chapters 15–18). It is presented as a series of simple-to-follow steps, with guidelines provided throughout. For example, in the Entity–Relationship diagram of Figure 1.6, we have identified six entities, seven relationships, and six attributes. We provide guidelines to help identify the entities, attributes, and relationships that have to be represented in the database.

Unfortunately, database design methodologies are not very popular. Many organizations and individual designers rely very little on methodologies for conducting the design of databases, and this is commonly considered a major cause of failure in the development of database systems. Owing to the lack of structured approaches to database design, the time or resources required for a database project are typically underestimated, the databases developed are inadequate or inefficient in meeting the demands of applications, documentation is limited, and maintenance is difficult.

Roles in the Database Environment 1.4

In this section, we examine what we listed in the previous section as the fifth component of the DBMS environment: the **people**. We can identify four distinct types of people that participate in the DBMS environment: data and database administrators, database designers, application developers, and the end-users.

1.4.1 Data and Database Administrators

The database and the DBMS are corporate resources that must be managed like any other resource. Data and database administration are the roles generally associated with the management and control of a DBMS and its data. The **Data Administrator** (DA) is responsible for the management of the data resource including database planning, development and maintenance of standards, policies and procedures, and conceptual/logical database design. The DA consults with and advises senior managers, ensuring that the direction of database development will ultimately support corporate objectives.

The **Database Administrator** (DBA) is responsible for the physical realization of the database, including physical database design and implementation, security and integrity control, maintenance of the operational system, and ensuring satisfactory performance of the applications for users. The role of the DBA is more technically oriented than the role of the DA, requiring detailed knowledge of the target DBMS and the system environment. In some organizations there is no distinction between these two roles; in others, the importance of the corporate resources is reflected in the allocation of teams of staff dedicated to each of these roles. We discuss data and database administration in more detail in Section 9.15.

1.4.2 Database Designers

In large database design projects, we can distinguish between two types of designer: logical database designers and physical database designers. The **logical database designer** is concerned with identifying the data (that is, the entities and attributes), the relationships between the data, and the constraints on the data that is to be stored in the database. The logical database designer must have a thorough and complete understanding of the organization's data and any constraints on this data (the constraints are sometimes called **business rules**). These constraints describe the main characteristics of the data as viewed by the organization. Examples of constraints for *DreamHome* are:

- a member of staff cannot manage more than 100 properties for rent or sale at the same time;
- a member of staff cannot handle the sale or rent of his or her own property;
- a solicitor cannot act for both the buyer and seller of a property.

To be effective, the logical database designer must involve all prospective database users in the development of the data model, and this involvement should begin as early in the process as possible. In this book, we split the work of the logical database designer into two stages:

- conceptual database design, which is independent of implementation details such as the target DBMS, application programs, programming languages, or any other physical considerations;
- logical database design, which targets a specific data model, such as relational, network, hierarchical, or object-oriented.

The **physical database designer** decides how the logical database design is to be physically realized. This involves:

- mapping the logical database design into a set of tables and integrity constraints;
- selecting specific storage structures and access methods for the data to achieve good performance;
- designing any security measures required on the data.

Many parts of physical database design are highly dependent on the target DBMS, and there may be more than one way of implementing a mechanism. Consequently, the physical database designer must be fully aware of the functionality of the target DBMS and must understand the advantages and disadvantages of each alternative for a particular implementation. The physical database designer must be capable of selecting a suitable storage strategy that takes account of usage. Whereas conceptual and logical database design are concerned with the *what*, physical database design is concerned with the *how*. It requires different skills, which are often found in different people. We present a methodology for conceptual database design in Chapter 15, for logical database design in Chapter 16, and for physical database design in Chapters 17 and 18.

Application Developers 1.4.3

Once the database has been implemented, the application programs that provide the required functionality for the end-users must be implemented. This is the responsibility of the **application developers**. Typically, the application developers work from a specification produced by systems analysts. Each program contains statements that request the DBMS to perform some operation on the database. This includes retrieving data, inserting, updating, and deleting data. The programs may be written in a third-generation programming language or a fourth-generation language, as discussed in the previous section.

End-Users 1.4.4

The end-users are the 'clients' for the database, which has been designed and implemented, and is being maintained to serve their information needs. End-users can be classified according to the way they use the system:

- **Naïve users** are typically unaware of the DBMS. They access the database through specially written application programs that attempt to make the operations as simple as possible. They invoke database operations by entering simple commands or choosing options from a menu. This means that they do not need to know anything about the database or the DBMS. For example, the checkout assistant at the local supermarket uses a bar code reader to find out the price of the item. However, there is an application program present that reads the bar code, looks up the price of the item in the database, reduces the database field containing the number of such items in stock, and displays the price on the till.

- **Sophisticated users**. At the other end of the spectrum, the sophisticated end-user is familiar with the structure of the database and the facilities offered by the DBMS. Sophisticated end-users may use a high-level query language such as SQL to perform the required operations. Some sophisticated end-users may even write application programs for their own use.

1.5 History of Database Management Systems

We have already seen that the predecessor to the DBMS was the file-based system. However, there was never a time when the database approach began and the file-based system ceased. In fact, the file-based system still exists in specific areas. It has been suggested that the DBMS has its roots in the 1960s Apollo moon-landing project, which was initiated in response to President Kennedy's objective of landing a man on the moon by the end of that decade. At that time there was no system available that would be able to handle and manage the vast amounts of information that the project would generate.

As a result, North American Aviation (NAA, now Rockwell International), the prime contractor for the project, developed software known as **GUAM** (Generalized Update Access Method). GUAM was based on the concept that smaller components come together as parts of larger components, and so on, until the final product is assembled. This structure, which conforms to an upside-down tree, is also known as a **hierarchical structure**. In the mid-1960s, IBM joined NAA to develop GUAM into what is now known as **IMS** (Information Management System). The reason why IBM restricted IMS to the management of hierarchies of records was to allow the use of serial storage devices, most notably magnetic tape, which was a market requirement at that time. This restriction was subsequently dropped. Although one of the earliest commercial DBMSs, IMS is still the main hierarchical DBMS used by most large mainframe installations.

In the mid-1960s, another significant development was the emergence of **IDS** (Integrated Data Store) from General Electric. This work was headed by one of the early pioneers of database systems, Charles Bachmann. This development led to a new type of database system known as the **network** DBMS, which had a profound effect on the information systems of that generation. The network database was developed partly to address the need to represent more complex data relationships than could be modeled with hierarchical structures, and partly to impose a database standard. To help establish such standards, the Conference on Data Systems Languages (**CODASYL**), comprising representatives of the US government and the world of business and commerce, formed a List Processing Task Force in 1965, subsequently renamed the **Data Base Task Group** (DBTG) in 1967. The terms of reference for the DBTG were to define standard specifications for an environment that would allow database creation and data manipulation. A draft report was issued in 1969 and the first definitive report in 1971. The DBTG proposal identified three components:

- the network **schema** – the logical organization of the entire database as seen by the DBA – which includes a definition of the database name, the type of each record, and the components of each record type;
- the **subschema** – the part of the database as seen by the user or application program;
- a data management language to define the data characteristics and the data structure, and to manipulate the data.

For standardization, the DBTG specified three distinct languages:

- a schema **Data Definition Language** (DDL), which enables the DBA to define the schema;
- a subschema **DDL**, which allows the application programs to define the parts of the database they require;
- a **Data Manipulation Language** (DML), to manipulate the data.

Although the report was not formally adopted by the American National Standards Institute (ANSI), a number of systems were subsequently developed following the DBTG proposal. These systems are now known as CODASYL or DBTG systems. The CODASYL and hierarchical approaches represented the **first-generation** of DBMSs. We look more closely at these systems on the Web site for this book (see Preface for the URL). However, these two models have some fundamental disadvantages:

- complex programs have to be written to answer even simple queries based on navigational record-oriented access;
- there is minimal data independence;
- there is no widely accepted theoretical foundation.

In 1970 E. F. Codd of the IBM Research Laboratory produced his highly influential paper on the relational data model. This paper was very timely and addressed the disadvantages of the former approaches. Many experimental relational DBMSs were implemented thereafter, with the first commercial products appearing in the late 1970s and early 1980s. Of particular note is the System R project at IBM's San José Research Laboratory in California, which was developed during the late 1970s (Astrahan *et al.*, 1976). This project was designed to prove the practicality of the relational model by providing an implementation of its data structures and operations, and led to two major developments:

- the development of a structured query language called SQL, which has since become the standard language for relational DBMSs;
- the production of various commercial relational DBMS products during the 1980s, for example DB2 and SQL/DS from IBM and Oracle from Oracle Corporation.

Now there are several hundred relational DBMSs for both mainframe and PC environments, though many are stretching the definition of the relational model. Other examples of multi-user relational DBMSs are Advantage Ingres Enterprise Relational Database from Computer Associates, and Informix from IBM. Examples of PC-based relational DBMSs are Office Access and Visual FoxPro from Microsoft, InterBase and JDataStore from Borland, and R:Base from R:Base Technologies. Relational DBMSs are referred to as **second-generation** DBMSs. We discuss the relational data model in Chapter 3.

The relational model is not without its failings, and in particular its limited modeling capabilities. There has been much research since then attempting to address this problem. In 1976, Chen presented the Entity–Relationship model, which is now a widely accepted technique for database design and the basis for the methodology presented in Chapters 15 and 16 of this book. In 1979, Codd himself attempted to address some of the failings in his original work with an extended version of the relational model called RM/T (1979) and subsequently RM/V2 (1990). The attempts to provide a data model that represents the 'real world' more closely have been loosely classified as **semantic data modeling**.

In response to the increasing complexity of database applications, two 'new' systems have emerged: the **Object-Oriented DBMS** (OODBMS) and the **Object-Relational DBMS** (ORDBMS). However, unlike previous models, the actual composition of these models is not clear. This evolution represents **third-generation** DBMSs, which we discuss in Chapters 25–28.

1.6 Advantages and Disadvantages of DBMSs

The database management system has promising potential advantages. Unfortunately, there are also disadvantages. In this section, we examine these advantages and disadvantages.

Advantages

The advantages of database management systems are listed in Table 1.2.

Control of data redundancy

As we discussed in Section 1.2, traditional file-based systems waste space by storing the same information in more than one file. For example, in Figure 1.5, we stored similar data for properties for rent and clients in both the Sales and Contracts Departments. In contrast, the database approach attempts to eliminate the redundancy by integrating the files so that multiple copies of the same data are not stored. However, the database approach does not eliminate redundancy entirely, but controls the amount of redundancy inherent in the database. Sometimes, it is necessary to duplicate key data items to model relationships. At other times, it is desirable to duplicate some data items to improve performance. The reasons for controlled duplication will become clearer as you read the next few chapters.

Data consistency

By eliminating or controlling redundancy, we reduce the risk of inconsistencies occurring. If a data item is stored only once in the database, any update to its value has to be performed only once and the new value is available immediately to all users. If a data item is stored more than once and the system is aware of this, the system can ensure that all copies

Table 1.2 Advantages of DBMSs.

Control of data redundancy	Economy of scale
Data consistency	Balance of conflicting requirements
More information from the same amount of data	Improved data accessibility and responsiveness
Sharing of data	Increased productivity
Improved data integrity	Improved maintenance through data independence
Improved security	Increased concurrency
Enforcement of standards	Improved backup and recovery services

of the item are kept consistent. Unfortunately, many of today's DBMSs do not automatically ensure this type of consistency.

More information from the same amount of data

With the integration of the operational data, it may be possible for the organization to derive additional information from the same data. For example, in the file-based system illustrated in Figure 1.5, the Contracts Department does not know who owns a leased property. Similarly, the Sales Department has no knowledge of lease details. When we integrate these files, the Contracts Department has access to owner details and the Sales Department has access to lease details. We may now be able to derive more information from the same amount of data.

Sharing of data

Typically, files are owned by the people or departments that use them. On the other hand, the database belongs to the entire organization and can be shared by all authorized users. In this way, more users share more of the data. Furthermore, new applications can build on the existing data in the database and add only data that is not currently stored, rather than having to define all data requirements again. The new applications can also rely on the functions provided by the DBMS, such as data definition and manipulation, and concurrency and recovery control, rather than having to provide these functions themselves.

Improved data integrity

Database integrity refers to the validity and consistency of stored data. Integrity is usually expressed in terms of **constraints**, which are consistency rules that the database is not permitted to violate. Constraints may apply to data items within a single record or they may apply to relationships between records. For example, an integrity constraint could state that a member of staff's salary cannot be greater than £40,000 or that the branch number contained in a staff record, representing the branch where the member of staff works, must correspond to an existing branch office. Again, integration allows the DBA to define, and the DBMS to enforce, integrity constraints.

Improved security

Database security is the protection of the database from unauthorized users. Without suitable security measures, integration makes the data more vulnerable than file-based systems. However, integration allows the DBA to define, and the DBMS to enforce, database security. This may take the form of user names and passwords to identify people authorized to use the database. The access that an authorized user is allowed on the data may be restricted by the operation type (retrieval, insert, update, delete). For example, the DBA has access to all the data in the database; a branch manager may have access to all data that relates to his or her branch office; and a sales assistant may have access to all data relating to properties but no access to sensitive data such as staff salary details.

Enforcement of standards

Again, integration allows the DBA to define and enforce the necessary standards. These may include departmental, organizational, national, or international standards for such

things as data formats to facilitate exchange of data between systems, naming conventions, documentation standards, update procedures, and access rules.

Economy of scale

Combining all the organization's operational data into one database, and creating a set of applications that work on this one source of data, can result in cost savings. In this case, the budget that would normally be allocated to each department for the development and maintenance of its file-based system can be combined, possibly resulting in a lower total cost, leading to an economy of scale. The combined budget can be used to buy a system configuration that is more suited to the organization's needs. This may consist of one large, powerful computer or a network of smaller computers.

Balance of conflicting requirements

Each user or department has needs that may be in conflict with the needs of other users. Since the database is under the control of the DBA, the DBA can make decisions about the design and operational use of the database that provide the best use of resources for the organization as a whole. These decisions will provide optimal performance for important applications, possibly at the expense of less critical ones.

Improved data accessibility and responsiveness

Again, as a result of integration, data that crosses departmental boundaries is directly accessible to the end-users. This provides a system with potentially much more functionality that can, for example, be used to provide better services to the end-user or the organization's clients. Many DBMSs provide query languages or report writers that allow users to ask *ad hoc* questions and to obtain the required information almost immediately at their terminal, without requiring a programmer to write some software to extract this information from the database. For example, a branch manager could list all flats with a monthly rent greater than £400 by entering the following SQL command at a terminal:

```
SELECT*
FROM PropertyForRent
WHERE type = 'Flat' AND rent > 400;
```

Increased productivity

As mentioned previously, the DBMS provides many of the standard functions that the programmer would normally have to write in a file-based application. At a basic level, the DBMS provides all the low-level file-handling routines that are typical in application programs. The provision of these functions allows the programmer to concentrate on the specific functionality required by the users without having to worry about low-level implementation details. Many DBMSs also provide a fourth-generation environment consisting of tools to simplify the development of database applications. This results in increased programmer productivity and reduced development time (with associated cost savings).

Improved maintenance through data independence

In file-based systems, the descriptions of the data and the logic for accessing the data are built into each application program, making the programs dependent on the data. A

change to the structure of the data, for example making an address 41 characters instead of 40 characters, or a change to the way the data is stored on disk, can require substantial alterations to the programs that are affected by the change. In contrast, a DBMS separates the data descriptions from the applications, thereby making applications immune to changes in the data descriptions. This is known as **data independence** and is discussed further in Section 2.1.5. The provision of data independence simplifies database application maintenance.

Increased concurrency

In some file-based systems, if two or more users are allowed to access the same file simultaneously, it is possible that the accesses will interfere with each other, resulting in loss of information or even loss of integrity. Many DBMSs manage concurrent database access and ensure such problems cannot occur. We discuss concurrency control in Chapter 20.

Improved backup and recovery services

Many file-based systems place the responsibility on the user to provide measures to protect the data from failures to the computer system or application program. This may involve taking a nightly backup of the data. In the event of a failure during the next day, the backup is restored and the work that has taken place since this backup is lost and has to be re-entered. In contrast, modern DBMSs provide facilities to minimize the amount of processing that is lost following a failure. We discuss database recovery in Section 20.3.

Disadvantages

The disadvantages of the database approach are summarized in Table 1.3.

Complexity

The provision of the functionality we expect of a good DBMS makes the DBMS an extremely complex piece of software. Database designers and developers, the data and database administrators, and end-users must understand this functionality to take full advantage of it. Failure to understand the system can lead to bad design decisions, which can have serious consequences for an organization.

Table 1.3 Disadvantages of DBMSs.

Complexity
Size
Cost of DBMSs
Additional hardware costs
Cost of conversion
Performance
Higher impact of a failure

Size

The complexity and breadth of functionality makes the DBMS an extremely large piece of software, occupying many megabytes of disk space and requiring substantial amounts of memory to run efficiently.

Cost of DBMSs

The cost of DBMSs varies significantly, depending on the environment and functionality provided. For example, a single-user DBMS for a personal computer may only cost US$100. However, a large mainframe multi-user DBMS servicing hundreds of users can be extremely expensive, perhaps US$100,000 or even US$1,000,000. There is also the recurrent annual maintenance cost, which is typically a percentage of the list price.

Additional hardware costs

The disk storage requirements for the DBMS and the database may necessitate the purchase of additional storage space. Furthermore, to achieve the required performance, it may be necessary to purchase a larger machine, perhaps even a machine dedicated to running the DBMS. The procurement of additional hardware results in further expenditure.

Cost of conversion

In some situations, the cost of the DBMS and extra hardware may be insignificant compared with the cost of converting existing applications to run on the new DBMS and hardware. This cost also includes the cost of training staff to use these new systems, and possibly the employment of specialist staff to help with the conversion and running of the system. This cost is one of the main reasons why some organizations feel tied to their current systems and cannot switch to more modern database technology. The term **legacy system** is sometimes used to refer to an older, and usually inferior, system.

Performance

Typically, a file-based system is written for a specific application, such as invoicing. As a result, performance is generally very good. However, the DBMS is written to be more general, to cater for many applications rather than just one. The effect is that some applications may not run as fast as they used to.

Higher impact of a failure

The centralization of resources increases the vulnerability of the system. Since all users and applications rely on the availability of the DBMS, the failure of certain components can bring operations to a halt.

Chapter Summary

- The **Database Management System** (DBMS) is now the underlying framework of the information system and has fundamentally changed the way that many organizations operate. The database system remains a very active research area and many significant problems have still to be satisfactorily resolved.
- The predecessor to the DBMS was the **file-based system**, which is a collection of application programs that perform services for the end-users, usually the production of reports. Each program defines and manages its own data. Although the file-based system was a great improvement on the manual filing system, it still has significant problems, mainly the amount of data redundancy present and program–data dependence.
- The database approach emerged to resolve the problems with the file-based approach. A **database** is a shared collection of logically related data, and a description of this data, designed to meet the information needs of an organization. A **DBMS** is a software system that enables users to define, create, maintain, and control access to the database. An **application program** is a computer program that interacts with the database by issuing an appropriate request (typically an SQL statement) to the DBMS. The more inclusive term **database system** is used to define a collection of application programs that interact with the database along with the DBMS and database itself.
- All access to the database is through the DBMS. The DBMS provides a **Data Definition Language** (DDL), which allows users to define the database, and a **Data Manipulation Language** (DML), which allows users to insert, update, delete, and retrieve data from the database.
- The DBMS provides controlled access to the database. It provides security, integrity, concurrency and recovery control, and a user-accessible catalog. It also provides a view mechanism to simplify the data that users have to deal with.
- The DBMS environment consists of hardware (the computer), software (the DBMS, operating system, and applications programs), data, procedures, and people. The people include data and database administrators, database designers, application developers, and end-users.
- The roots of the DBMS lie in file-based systems. The hierarchical and CODASYL systems represent the first-generation of DBMSs. The **hierarchical model** is typified by IMS (Information Management System) and the **network** or **CODASYL model** by IDS (Integrated Data Store), both developed in the mid-1960s. The **relational model**, proposed by E. F. Codd in 1970, represents the second-generation of DBMSs. It has had a fundamental effect on the DBMS community and there are now over one hundred relational DBMSs. The third-generation of DBMSs are represented by the **Object-Relational** DBMS and the **Object-Oriented** DBMS.
- Some advantages of the database approach include control of data redundancy, data consistency, sharing of data, and improved security and integrity. Some disadvantages include complexity, cost, reduced performance, and higher impact of a failure.

Review Questions

1.1 List four examples of database systems other than those listed in Section 1.1.

1.2 Discuss each of the following terms:
- (a) data
- (b) database
- (c) database management system
- (d) database application program
- (e) data independence
- (f) security
- (g) integrity
- (h) views.

1.3 Describe the approach taken to the handling of data in the early file-based systems. Discuss the disadvantages of this approach.

1.4 Describe the main characteristics of the database approach and contrast it with the file-based approach.

1.5 Describe the five components of the DBMS environment and discuss how they relate to each other.

1.6 Discuss the roles of the following personnel in the database environment:
- (a) data administrator
- (b) database administrator
- (c) logical database designer
- (d) physical database designer
- (e) application developer
- (f) end-users.

1.7 Discuss the advantages and disadvantages of DBMSs.

Exercises

1.8 Interview some users of database systems. Which DBMS features do they find most useful and why? Which DBMS facilities do they find least useful and why? What do these users perceive to be the advantages and disadvantages of the DBMS?

1.9 Write a small program (using pseudocode if necessary) that allows entry and display of client details including a client number, name, address, telephone number, preferred number of rooms, and maximum rent. The details should be stored in a file. Enter a few records and display the details. Now repeat this process but rather than writing a special program, use any DBMS that you have access to. What can you conclude from these two approaches?

1.10 Study the *DreamHome* case study presented in Section 10.4 and Appendix A. In what ways would a DBMS help this organization? What data can you identify that needs to be represented in the database? What relationships exist between the data items? What queries do you think are required?

1.11 Study the *Wellmeadows Hospital* case study presented in Appendix B.3. In what ways would a DBMS help this organization? What data can you identify that needs to be represented in the database? What relationships exist between the data items?

Chapter 2 Database Environment

Chapter Objectives

In this chapter you will learn:

- The purpose and origin of the three-level database architecture.
- The contents of the external, conceptual, and internal levels.
- The purpose of the external/conceptual and the conceptual/internal mappings.
- The meaning of logical and physical data independence.
- The distinction between a Data Definition Language (DDL) and a Data Manipulation Language (DML).
- A classification of data models.
- The purpose and importance of conceptual modeling.
- The typical functions and services a DBMS should provide.
- The function and importance of the system catalog.
- The software components of a DBMS.
- The meaning of the client–server architecture and the advantages of this type of architecture for a DBMS.
- The function and uses of Transaction Processing (TP) Monitors.

A major aim of a database system is to provide users with an abstract view of data, hiding certain details of how data is stored and manipulated. Therefore, the starting point for the design of a database must be an abstract and general description of the information requirements of the organization that is to be represented in the database. In this chapter, and throughout this book, we use the term 'organization' loosely, to mean the whole organization or part of the organization. For example, in the *DreamHome* case study we may be interested in modeling:

- the 'real world' **entities** Staff, PropertyforRent, PrivateOwner, and Client;
- **attributes** describing properties or qualities of each entity (for example, Staff have a name, position, and salary);
- **relationships** between these entities (for example, Staff *Manages* PropertyForRent).

Furthermore, since a database is a shared resource, each user may require a different view of the data held in the database. To satisfy these needs, the architecture of most commercial DBMSs available today is based to some extent on the so-called ANSI-SPARC architecture. In this chapter, we discuss various architectural and functional characteristics of DBMSs.

Structure of this Chapter

In Section 2.1 we examine the three-level ANSI-SPARC architecture and its associated benefits. In Section 2.2 we consider the types of language that are used by DBMSs, and in Section 2.3 we introduce the concepts of data models and conceptual modeling, which we expand on in later parts of the book. In Section 2.4 we discuss the functions that we would expect a DBMS to provide, and in Sections 2.5 and 2.6 we examine the internal architecture of a typical DBMS. The examples in this chapter are drawn from the *DreamHome* case study, which we discuss more fully in Section 10.4 and Appendix A.

Much of the material in this chapter provides important background information on DBMSs. However, the reader who is new to the area of database systems may find some of the material difficult to appreciate on first reading. Do not be too concerned about this, but be prepared to revisit parts of this chapter at a later date when you have read subsequent chapters of the book.

2.1 The Three-Level ANSI-SPARC Architecture

An early proposal for a standard terminology and general architecture for database systems was produced in 1971 by the DBTG (Data Base Task Group) appointed by the Conference on Data Systems and Languages (CODASYL, 1971). The DBTG recognized the need for a two-level approach with a system view called the **schema** and user views called **subschemas**. The American National Standards Institute (ANSI) Standards Planning and Requirements Committee (SPARC), ANSI/X3/SPARC, produced a similar terminology and architecture in 1975 (ANSI, 1975). ANSI-SPARC recognized the need for a three-level approach with a system catalog. These proposals reflected those published by the IBM user organizations Guide and Share some years previously, and concentrated on the need for an implementation-independent layer to isolate programs from underlying representational issues (Guide/Share, 1970). Although the ANSI-SPARC model did not become a standard, it still provides a basis for understanding some of the functionality of a DBMS.

For our purposes, the fundamental point of these and later reports is the identification of three levels of abstraction, that is, three distinct levels at which data items can be described. The levels form a **three-level architecture** comprising an **external**, a **conceptual**, and an **internal** level, as depicted in Figure 2.1. The way users perceive the data is called the **external level**. The way the DBMS and the operating system perceive the data is the **internal level**, where the data is actually stored using the data structures and file

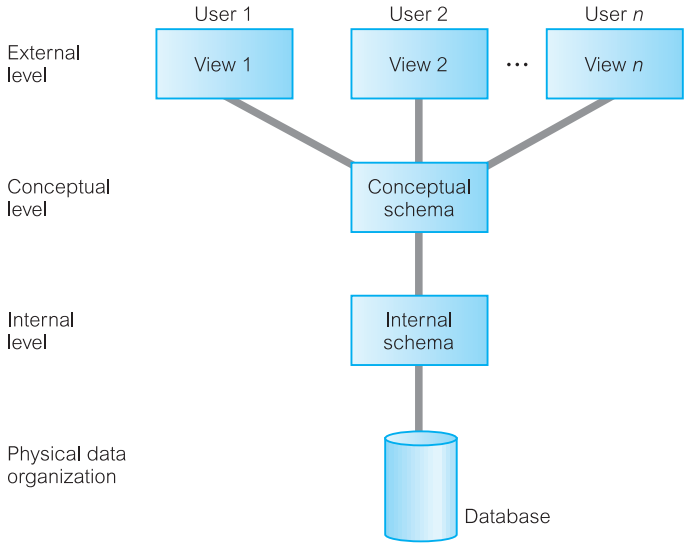


Figure 2.1
The ANSI-SPARC three-level architecture.

organizations described in Appendix C. The **conceptual level** provides both the **mapping** and the desired **independence** between the external and internal levels.

The objective of the three-level architecture is to separate each user's view of the database from the way the database is physically represented. There are several reasons why this separation is desirable:

- Each user should be able to access the same data, but have a different customized view of the data. Each user should be able to change the way he or she views the data, and this change should not affect other users.
- Users should not have to deal directly with physical database storage details, such as indexing or hashing (see Appendix C). In other words, a user's interaction with the database should be independent of storage considerations.
- The Database Administrator (DBA) should be able to change the database storage structures without affecting the users' views.
- The internal structure of the database should be unaffected by changes to the physical aspects of storage, such as the changeover to a new storage device.
- The DBA should be able to change the conceptual structure of the database without affecting all users.

External Level 2.1.1

External level	The users' view of the database. This level describes that part of the database that is relevant to each user.

The external level consists of a number of different external views of the database. Each user has a view of the 'real world' represented in a form that is familiar for that user. The external view includes only those entities, attributes, and relationships in the 'real world' that the user is interested in. Other entities, attributes, or relationships that are not of interest may be represented in the database, but the user will be unaware of them.

In addition, different views may have different representations of the same data. For example, one user may view dates in the form (day, month, year), while another may view dates as (year, month, day). Some views might include derived or calculated data: data not actually stored in the database as such, but created when needed. For example, in the *DreamHome* case study, we may wish to view the age of a member of staff. However, it is unlikely that ages would be stored, as this data would have to be updated daily. Instead, the member of staff's date of birth would be stored and age would be calculated by the DBMS when it is referenced. Views may even include data combined or derived from several entities. We discuss views in more detail in Sections 3.4 and 6.4.

2.1.2 Conceptual Level

Conceptual level	The community view of the database. This level describes *what* data is stored in the database and the relationships among the data.

The middle level in the three-level architecture is the conceptual level. This level contains the logical structure of the entire database as seen by the DBA. It is a complete view of the data requirements of the organization that is independent of any storage considerations. The conceptual level represents:

- all entities, their attributes, and their relationships;
- the constraints on the data;
- semantic information about the data;
- security and integrity information.

The conceptual level supports each external view, in that any data available to a user must be contained in, or derivable from, the conceptual level. However, this level must not contain any storage-dependent details. For instance, the description of an entity should contain only data types of attributes (for example, integer, real, character) and their length (such as the maximum number of digits or characters), but not any storage considerations, such as the number of bytes occupied.

2.1.3 Internal Level

Internal level	The physical representation of the database on the computer. This level describes *how* the data is stored in the database.

The internal level covers the physical implementation of the database to achieve optimal runtime performance and storage space utilization. It covers the data structures and file organizations used to store data on storage devices. It interfaces with the operating system access methods (file management techniques for storing and retrieving data records) to place the data on the storage devices, build the indexes, retrieve the data, and so on. The internal level is concerned with such things as:

- storage space allocation for data and indexes;
- record descriptions for storage (with stored sizes for data items);
- record placement;
- data compression and data encryption techniques.

Below the internal level there is a **physical level** that may be managed by the operating system under the direction of the DBMS. However, the functions of the DBMS and the operating system at the physical level are not clear-cut and vary from system to system. Some DBMSs take advantage of many of the operating system access methods, while others use only the most basic ones and create their own file organizations. The physical level below the DBMS consists of items only the operating system knows, such as exactly how the sequencing is implemented and whether the fields of internal records are stored as contiguous bytes on the disk.

Schemas, Mappings, and Instances 2.1.4

The overall description of the database is called the **database schema**. There are three different types of schema in the database and these are defined according to the levels of abstraction of the three-level architecture illustrated in Figure 2.1. At the highest level, we have multiple **external schemas** (also called **subschemas**) that correspond to different views of the data. At the conceptual level, we have the **conceptual schema**, which describes all the entities, attributes, and relationships together with integrity constraints. At the lowest level of abstraction we have the **internal schema**, which is a complete description of the internal model, containing the definitions of stored records, the methods of representation, the data fields, and the indexes and storage structures used. There is only one conceptual schema and one internal schema per database.

The DBMS is responsible for mapping between these three types of schema. It must also check the schemas for consistency; in other words, the DBMS must check that each external schema is derivable from the conceptual schema, and it must use the information in the conceptual schema to map between each external schema and the internal schema. The conceptual schema is related to the internal schema through a **conceptual/internal mapping**. This enables the DBMS to find the actual record or combination of records in physical storage that constitute a **logical record** in the conceptual schema, together with any constraints to be enforced on the operations for that logical record. It also allows any differences in entity names, attribute names, attribute order, data types, and so on, to be resolved. Finally, each external schema is related to the conceptual schema by the **external/conceptual mapping**. This enables the DBMS to map names in the user's view on to the relevant part of the conceptual schema.

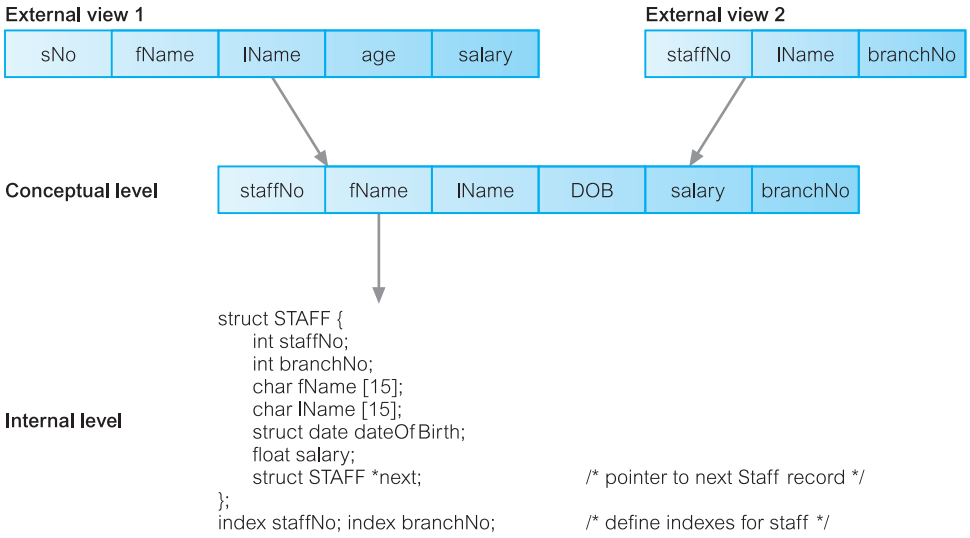


Figure 2.2
Differences between the three levels.

An example of the different levels is shown in Figure 2.2. Two different external views of staff details exist: one consisting of a staff number (sNo), first name (fName), last name (lName), age, and salary; a second consisting of a staff number (staffNo), last name (lName), and the number of the branch the member of staff works at (branchNo). These external views are merged into one conceptual view. In this merging process, the major difference is that the age field has been changed into a date of birth field, DOB. The DBMS maintains the external/conceptual mapping; for example, it maps the sNo field of the first external view to the staffNo field of the conceptual record. The conceptual level is then mapped to the internal level, which contains a physical description of the structure for the conceptual record. At this level, we see a definition of the structure in a high-level language. The structure contains a pointer, next, which allows the list of staff records to be physically linked together to form a chain. Note that the order of fields at the internal level is different from that at the conceptual level. Again, the DBMS maintains the conceptual/internal mapping.

It is important to distinguish between the description of the database and the database itself. The description of the database is the **database schema**. The schema is specified during the database design process and is not expected to change frequently. However, the actual data in the database may change frequently; for example, it changes every time we insert details of a new member of staff or a new property. The data in the database at any particular point in time is called a **database instance**. Therefore, many database instances can correspond to the same database schema. The schema is sometimes called the **intension** of the database, while an instance is called an **extension** (or **state**) of the database.

2.1.5 Data Independence

A major objective for the three-level architecture is to provide **data independence**, which means that upper levels are unaffected by changes to lower levels. There are two kinds of data independence: **logical** and **physical**.

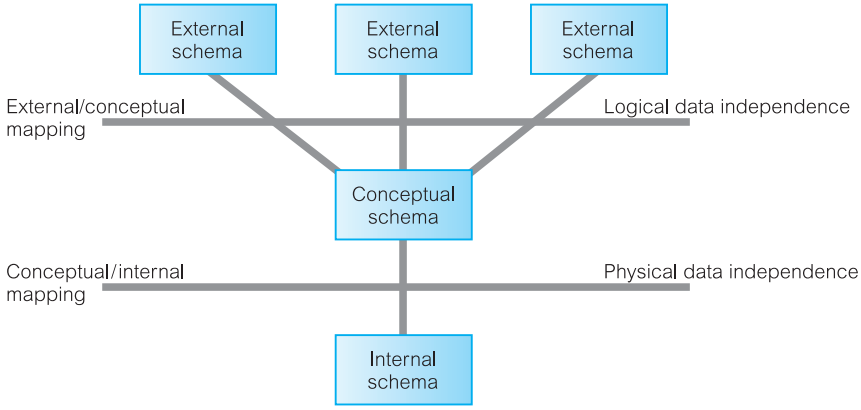


Figure 2.3
Data independence and the ANSI-SPARC three-level architecture.

Logical data independence Logical data independence refers to the immunity of the external schemas to changes in the conceptual schema.

Changes to the conceptual schema, such as the addition or removal of new entities, attributes, or relationships, should be possible without having to change existing external schemas or having to rewrite application programs. Clearly, the users for whom the changes have been made need to be aware of them, but what is important is that other users should not be.

Physical data independence Physical data independence refers to the immunity of the conceptual schema to changes in the internal schema.

Changes to the internal schema, such as using different file organizations or storage structures, using different storage devices, modifying indexes, or hashing algorithms, should be possible without having to change the conceptual or external schemas. From the users' point of view, the only effect that may be noticed is a change in performance. In fact, deterioration in performance is the most common reason for internal schema changes. Figure 2.3 illustrates where each type of data independence occurs in relation to the three-level architecture.

The two-stage mapping in the ANSI-SPARC architecture may be inefficient, but provides greater data independence. However, for more efficient mapping, the ANSI-SPARC model allows the direct mapping of external schemas on to the internal schema, thus bypassing the conceptual schema. This, of course, reduces data independence, so that every time the internal schema changes, the external schema, and any dependent application programs may also have to change.

2.2 Database Languages

A **data sublanguage** consists of two parts: a **Data Definition Language** (DDL) and a **Data Manipulation Language** (DML). The DDL is used to specify the database schema

and the DML is used to both read and update the database. These languages are called *data sublanguages* because they do not include constructs for all computing needs such as conditional or iterative statements, which are provided by the high-level programming languages. Many DBMSs have a facility for *embedding* the sublanguage in a high-level programming language such as COBOL, Fortran, Pascal, Ada, 'C', C++, Java, or Visual Basic. In this case, the high-level language is sometimes referred to as the *host language*. To compile the embedded file, the commands in the data sublanguage are first removed from the host-language program and replaced by function calls. The pre-processed file is then compiled, placed in an object module, linked with a DBMS-specific library containing the replaced functions, and executed when required. Most data sublanguages also provide *non-embedded*, or *interactive*, commands that can be input directly from a terminal.

2.2.1 The Data Definition Language (DDL)

DDL A language that allows the DBA or user to describe and name the entities, attributes, and relationships required for the application, together with any associated integrity and security constraints.

The database schema is specified by a set of definitions expressed by means of a special language called a Data Definition Language. The DDL is used to define a schema or to modify an existing one. It cannot be used to manipulate data.

The result of the compilation of the DDL statements is a set of tables stored in special files collectively called the **system catalog**. The system catalog integrates the **metadata**, that is data that describes objects in the database and makes it easier for those objects to be accessed or manipulated. The metadata contains definitions of records, data items, and other objects that are of interest to users or are required by the DBMS. The DBMS normally consults the system catalog before the actual data is accessed in the database. The terms **data dictionary** and **data directory** are also used to describe the system catalog, although the term 'data dictionary' usually refers to a more general software system than a catalog for a DBMS. We discuss the system catalog further in Section 2.4.

At a theoretical level, we could identify different DDLs for each schema in the three-level architecture, namely a DDL for the external schemas, a DDL for the conceptual schema, and a DDL for the internal schema. However, in practice, there is one comprehensive DDL that allows specification of at least the external and conceptual schemas.

2.2.2 The Data Manipulation Language (DML)

DML A language that provides a set of operations to support the basic data manipulation operations on the data held in the database.

Data manipulation operations usually include the following:

- insertion of new data into the database;
- modification of data stored in the database;
- retrieval of data contained in the database;
- deletion of data from the database.

Therefore, one of the main functions of the DBMS is to support a data manipulation language in which the user can construct statements that will cause such data manipulation to occur. Data manipulation applies to the external, conceptual, and internal levels. However, at the internal level we must define rather complex low-level procedures that allow efficient data access. In contrast, at higher levels, emphasis is placed on ease of use and effort is directed at providing efficient user interaction with the system.

The part of a DML that involves data retrieval is called a **query language**. A query language can be defined as a high-level special-purpose language used to satisfy diverse requests for the retrieval of data held in the database. The term 'query' is therefore reserved to denote a retrieval statement expressed in a query language. The terms 'query language' and 'DML' are commonly used interchangeably, although this is technically incorrect.

DMLs are distinguished by their underlying retrieval constructs. We can distinguish between two types of DML: **procedural** and **non-procedural**. The prime difference between these two data manipulation languages is that procedural languages specify *how* the output of a DML statement is to be obtained, while non-procedural DMLs describe only *what* output is to be obtained. Typically, procedural languages treat records individually, whereas non-procedural languages operate on sets of records.

Procedural DMLs

Procedural DML	A language that allows the user to tell the system what data is needed and exactly *how* to retrieve the data.

With a procedural DML, the user, or more normally the programmer, specifies what data is needed and how to obtain it. This means that the user must express all the data access operations that are to be used by calling appropriate procedures to obtain the information required. Typically, such a procedural DML retrieves a record, processes it and, based on the results obtained by this processing, retrieves another record that would be processed similarly, and so on. This process of retrievals continues until the data requested from the retrieval has been gathered. Typically, procedural DMLs are embedded in a high-level programming language that contains constructs to facilitate iteration and handle navigational logic. Network and hierarchical DMLs are normally procedural (see Section 2.3).

Non-procedural DMLs

Non-procedural DML	A language that allows the user to state *what* data is needed rather than how it is to be retrieved.

Non-procedural DMLs allow the required data to be specified in a single retrieval or update statement. With non-procedural DMLs, the user specifies what data is required without specifying how it is to be obtained. The DBMS translates a DML statement into one or more procedures that manipulate the required sets of records. This frees the user from having to know how data structures are internally implemented and what algorithms are required to retrieve and possibly transform the data, thus providing users with a considerable degree of data independence. Non-procedural languages are also called *declarative languages*. Relational DBMSs usually include some form of non-procedural language for data manipulation, typically SQL (Structured Query Language) or QBE (Query-By-Example). Non-procedural DMLs are normally easier to learn and use than procedural DMLs, as less work is done by the user and more by the DBMS. We examine SQL in detail in Chapters 5, 6, and Appendix E, and QBE in Chapter 7.

2.2.3 Fourth-Generation Languages (4GLs)

There is no consensus about what constitutes a **fourth-generation language**; it is in essence a shorthand programming language. An operation that requires hundreds of lines in a third-generation language (3GL), such as COBOL, generally requires significantly fewer lines in a 4GL.

Compared with a 3GL, which is procedural, a 4GL is non-procedural: the user defines *what* is to be done, not how. A 4GL is expected to rely largely on much higher-level components known as fourth-generation tools. The user does not define the steps that a program needs to perform a task, but instead defines parameters for the tools that use them to generate an application program. It is claimed that 4GLs can improve productivity by a factor of ten, at the cost of limiting the types of problem that can be tackled. Fourth-generation languages encompass:

- presentation languages, such as query languages and report generators;
- speciality languages, such as spreadsheets and database languages;
- application generators that define, insert, update, and retrieve data from the database to build applications;
- very high-level languages that are used to generate application code.

SQL and QBE, mentioned above, are examples of 4GLs. We now briefly discuss some of the other types of 4GL.

Forms generators

A forms generator is an interactive facility for rapidly creating data input and display layouts for screen forms. The forms generator allows the user to define what the screen is to look like, what information is to be displayed, and where on the screen it is to be displayed. It may also allow the definition of colors for screen elements and other characteristics, such as bold, underline, blinking, reverse video, and so on. The better forms generators allow the creation of derived attributes, perhaps using arithmetic operators or aggregates, and the specification of validation checks for data input.

Report generators

A report generator is a facility for creating reports from data stored in the database. It is similar to a query language in that it allows the user to ask questions of the database and retrieve information from it for a report. However, in the case of a report generator, we have much greater control over what the output looks like. We can let the report generator automatically determine how the output should look or we can create our own customized output reports using special report-generator command instructions.

There are two main types of report generator: language-oriented and visually oriented. In the first case, we enter a command in a sublanguage to define what data is to be included in the report and how the report is to be laid out. In the second case, we use a facility similar to a forms generator to define the same information.

Graphics generators

A graphics generator is a facility to retrieve data from the database and display the data as a graph showing trends and relationships in the data. Typically, it allows the user to create bar charts, pie charts, line charts, scatter charts, and so on.

Application generators

An application generator is a facility for producing a program that interfaces with the database. The use of an application generator can reduce the time it takes to design an entire software application. Application generators typically consist of pre-written modules that comprise fundamental functions that most programs use. These modules, usually written in a high-level language, constitute a 'library' of functions to choose from. The user specifies *what* the program is supposed to do; the application generator determines *how* to perform the tasks.

2.3 Data Models and Conceptual Modeling

We mentioned earlier that a schema is written using a data definition language. In fact, it is written in the data definition language of a particular DBMS. Unfortunately, this type of language is too low level to describe the data requirements of an organization in a way that is readily understandable by a variety of users. What we require is a higher-level description of the schema: that is, a **data model**.

Data model An integrated collection of concepts for describing and manipulating data, relationships between data, and constraints on the data in an organization.

A model is a representation of 'real world' objects and events, and their associations. It is an abstraction that concentrates on the essential, inherent aspects of an organization and ignores the accidental properties. A data model represents the organization itself. It should provide the basic concepts and notations that will allow database designers and end-users

unambiguously and accurately to communicate their understanding of the organizational data. A data model can be thought of as comprising three components:

(1) a **structural part**, consisting of a set of rules according to which databases can be constructed;

(2) a **manipulative part**, defining the types of operation that are allowed on the data (this includes the operations that are used for updating or retrieving data from the database and for changing the structure of the database);

(3) possibly a **set of integrity constraints**, which ensures that the data is accurate.

The purpose of a data model is to represent data and to make the data understandable. If it does this, then it can be easily used to design a database. To reflect the ANSI-SPARC architecture introduced in Section 2.1, we can identify three related data models:

(1) an external data model, to represent each user's view of the organization, sometimes called the **Universe of Discourse** (UoD);

(2) a conceptual data model, to represent the logical (or community) view that is DBMS-independent;

(3) an internal data model, to represent the conceptual schema in such a way that it can be understood by the DBMS.

There have been many data models proposed in the literature. They fall into three broad categories: **object-based**, **record-based**, and **physical** data models. The first two are used to describe data at the conceptual and external levels, the latter is used to describe data at the internal level.

2.3.1 Object-Based Data Models

Object-based data models use concepts such as entities, attributes, and relationships. An **entity** is a distinct object (a person, place, thing, concept, event) in the organization that is to be represented in the database. An **attribute** is a property that describes some aspect of the object that we wish to record, and a **relationship** is an association between entities. Some of the more common types of object-based data model are:

- Entity–Relationship
- Semantic
- Functional
- Object-Oriented.

The Entity–Relationship model has emerged as one of the main techniques for database design and forms the basis for the database design methodology used in this book. The object-oriented data model extends the definition of an entity to include not only the attributes that describe the **state** of the object but also the actions that are associated with the object, that is, its **behavior**. The object is said to **encapsulate** both state and behavior. We look at the Entity–Relationship model in depth in Chapters 11 and 12 and

the object-oriented model in Chapters 25–28. We also examine the functional data model in Section 26.1.2.

Record-Based Data Models 2.3.2

In a record-based model, the database consists of a number of fixed-format records possibly of differing types. Each record type defines a fixed number of fields, each typically of a fixed length. There are three principal types of record-based logical data model: the **relational data model**, the **network data model**, and the **hierarchical data model**. The hierarchical and network data models were developed almost a decade before the relational data model, so their links to traditional file processing concepts are more evident.

Relational data model

The relational data model is based on the concept of mathematical relations. In the relational model, data and relationships are represented as tables, each of which has a number of columns with a unique name. Figure 2.4 is a sample instance of a relational schema for part of the *DreamHome* case study, showing branch and staff details. For example, it shows that employee John White is a manager with a salary of £30,000, who works at branch (branchNo) B005, which, from the first table, is at 22 Deer Rd in London. It is important to note that there is a relationship between Staff and Branch: a branch office *has* staff. However, there is no explicit link between these two tables; it is only by knowing that the attribute branchNo in the Staff relation is the same as the branchNo of the Branch relation that we can establish that a relationship exists.

Note that the relational data model requires only that the database be perceived by the user as tables. However, this perception applies only to the logical structure of the

Branch

branchNo	street	city	postCode
B005	22 Deer Rd	London	SW1 4EH
B007	16 Argyll St	Aberdeen	AB2 3SU
B003	163 Main St	Glasgow	G11 9QX
B004	32 Manse Rd	Bristol	BS99 1NZ
B002	56 Clover Dr	London	NW10 6EU

Staff

staffNo	fName	lName	position	sex	DOB	salary	branchNo
SL21	John	White	Manager	M	1-Oct-45	30000	B005
SG37	Ann	Beech	Assistant	F	10-Nov-60	12000	B003
SG14	David	Ford	Supervisor	M	24-Mar-58	18000	B003
SA9	Mary	Howe	Assistant	F	19-Feb-70	9000	B007
SG5	Susan	Brand	Manager	F	3-Jun-40	24000	B003
SL41	Julie	Lee	Assistant	F	13-Jun-65	9000	B005

Figure 2.4
A sample instance of a relational schema.

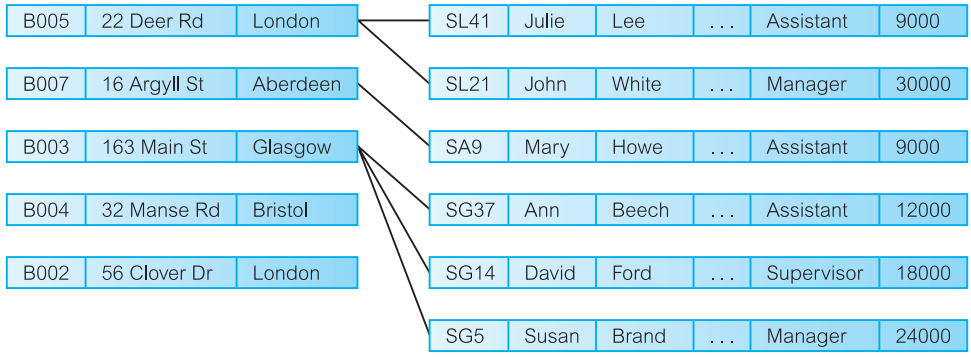


Figure 2.5
A sample instance of a network schema.

database, that is, the external and conceptual levels of the ANSI-SPARC architecture. It does not apply to the physical structure of the database, which can be implemented using a variety of storage structures. We discuss the relational data model in Chapter 3.

Network data model

In the network model, data is represented as collections of **records**, and relationships are represented by **sets**. Compared with the relational model, relationships are explicitly modeled by the sets, which become pointers in the implementation. The records are organized as generalized graph structures with records appearing as **nodes** (also called **segments**) and sets as **edges** in the graph. Figure 2.5 illustrates an instance of a network schema for the same data set presented in Figure 2.4. The most popular network DBMS is Computer Associates' IDMS/R. We discuss the network data model in more detail on the Web site for this book (see Preface for the URL).

Hierarchical data model

The hierarchical model is a restricted type of network model. Again, data is represented as collections of **records** and relationships are represented by **sets**. However, the hierarchical model allows a node to have only one parent. A hierarchical model can be represented as a tree graph, with records appearing as **nodes** (also called **segments**) and sets as **edges**. Figure 2.6 illustrates an instance of a hierarchical schema for the same data set presented in Figure 2.4. The main hierarchical DBMS is IBM's IMS, although IMS also provides non-hierarchical features. We discuss the hierarchical data model in more detail on the Web site for this book (see Preface for the URL).

Record-based (logical) data models are used to specify the overall structure of the database and a higher-level description of the implementation. Their main drawback lies in the fact that they do not provide adequate facilities for explicitly specifying constraints on the data, whereas the object-based data models lack the means of logical structure specification but provide more semantic substance by allowing the user to specify constraints on the data.

The majority of modern commercial systems are based on the relational paradigm, whereas the early database systems were based on either the network or hierarchical data

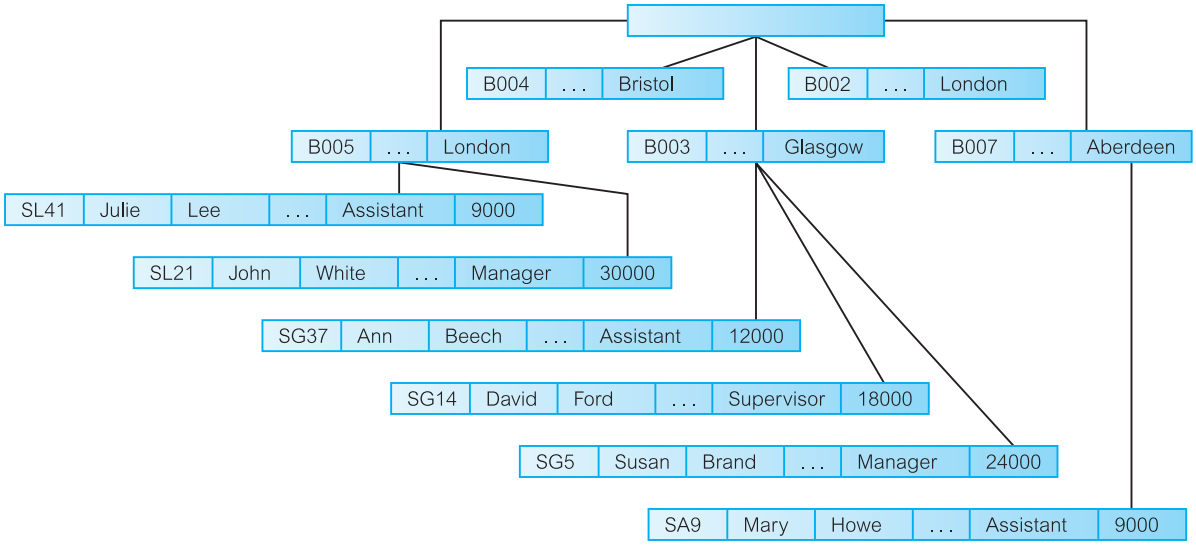


Figure 2.6 A sample instance of a hierarchical schema.

models. The latter two models require the user to have knowledge of the physical database being accessed, whereas the former provides a substantial amount of data independence. Hence, while relational systems adopt a **declarative** approach to database processing (that is, they specify *what* data is to be retrieved), network and hierarchical systems adopt a **navigational** approach (that is, they specify *how* the data is to be retrieved).

Physical Data Models 2.3.3

Physical data models describe how data is stored in the computer, representing information such as record structures, record orderings, and access paths. There are not as many physical data models as logical data models, the most common ones being the *unifying model* and the *frame memory*.

Conceptual Modeling 2.3.4

From an examination of the three-level architecture, we see that the conceptual schema is the 'heart' of the database. It supports all the external views and is, in turn, supported by the internal schema. However, the internal schema is merely the physical implementation of the conceptual schema. The conceptual schema should be a complete and accurate representation of the data requirements of the enterprise.[†] If this is not the case, some information about the enterprise will be missing or incorrectly represented and we will have difficulty fully implementing one or more of the external views.

[†] When we are discussing the organization in the context of database design we normally refer to the business or organization as the *enterprise*.

Conceptual modeling, or **conceptual database design**, is the process of constructing a model of the information use in an enterprise that is independent of implementation details, such as the target DBMS, application programs, programming languages, or any other physical considerations. This model is called a **conceptual data model**. Conceptual models are also referred to as logical models in the literature. However, in this book we make a distinction between conceptual and logical data models. The conceptual model is independent of all implementation details, whereas the logical model assumes knowledge of the underlying data model of the target DBMS. In Chapters 15 and 16 we present a methodology for database design that begins by producing a conceptual data model, which is then refined into a logical model based on the relational data model. We discuss database design in more detail in Section 9.6.

2.4 Functions of a DBMS

In this section we look at the types of function and service we would expect a DBMS to provide. Codd (1982) lists eight services that should be provided by any full-scale DBMS, and we have added two more that might reasonably be expected to be available.

(1) Data storage, retrieval, and update

A DBMS must furnish users with the ability to store, retrieve, and update data in the database.

This is the fundamental function of a DBMS. From the discussion in Section 2.1, clearly in providing this functionality the DBMS should hide the internal physical implementation details (such as file organization and storage structures) from the user.

(2) A user-accessible catalog

A DBMS must furnish a catalog in which descriptions of data items are stored and which is accessible to users.

A key feature of the ANSI-SPARC architecture is the recognition of an integrated **system catalog** to hold data about the schemas, users, applications, and so on. The catalog is expected to be accessible to users as well as to the DBMS. A system catalog, or data dictionary, is a repository of information describing the data in the database: it is, the 'data about the data' or **metadata**. The amount of information and the way the information is used vary with the DBMS. Typically, the system catalog stores:

- names, types, and sizes of data items;
- names of relationships;
- integrity constraints on the data;
- names of authorized users who have access to the data;

- the data items that each user can access and the types of access allowed; for example, insert, update, delete, or read access;
- external, conceptual, and internal schemas and the mappings between the schemas, as described in Section 2.1.4;
- usage statistics, such as the frequencies of transactions and counts on the number of accesses made to objects in the database.

The DBMS system catalog is one of the fundamental components of the system. Many of the software components that we describe in the next section rely on the system catalog for information. Some benefits of a system catalog are:

- Information about data can be collected and stored centrally. This helps to maintain control over the data as a resource.
- The meaning of data can be defined, which will help other users understand the purpose of the data.
- Communication is simplified, since exact meanings are stored. The system catalog may also identify the user or users who own or access the data.
- Redundancy and inconsistencies can be identified more easily since the data is centralized.
- Changes to the database can be recorded.
- The impact of a change can be determined before it is implemented, since the system catalog records each data item, all its relationships, and all its users.
- Security can be enforced.
- Integrity can be ensured.
- Audit information can be provided.

Some authors make a distinction between system catalog and data directory, where a data directory holds information relating to where data is stored and how it is stored. The International Organization for Standardization (ISO) has adopted a standard for data dictionaries called Information Resource Dictionary System (IRDS) (ISO, 1990, 1993). IRDS is a software tool that can be used to control and document an organization's information sources. It provides a definition for the tables that comprise the data dictionary and the operations that can be used to access these tables. We use the term 'system catalog' in this book to refer to all repository information. We discuss other types of statistical information stored in the system catalog to assist with query optimization in Section 21.4.1.

(3) Transaction support

A DBMS must furnish a mechanism which will ensure either that all the updates corresponding to a given transaction are made or that none of them is made.

A transaction is a series of actions, carried out by a single user or application program, which accesses or changes the contents of the database. For example, some simple transactions for the *DreamHome* case study might be to add a new member of staff to the database, to update the salary of a member of staff, or to delete a property from the register.

Figure 2.7
The lost update problem.

Time	T_1	T_2	bal_x
t_1		read(bal_x)	100
t_2	read(bal_x)	$bal_x = bal_x + 100$	100
t_3	$bal_x = bal_x - 10$	write(bal_x)	200
t_4	write(bal_x)		90
t_5			90

A more complicated example might be to delete a member of staff from the database *and* to reassign the properties that he or she managed to another member of staff. In this case, there is more than one change to be made to the database. If the transaction fails during execution, perhaps because of a computer crash, the database will be in an **inconsistent** state: some changes will have been made and others not. Consequently, the changes that have been made will have to be undone to return the database to a consistent state again. We discuss transaction support in Section 20.1.

(4) Concurrency control services

A DBMS must furnish a mechanism to ensure that the database is updated correctly when multiple users are updating the database concurrently.

One major objective in using a DBMS is to enable many users to access shared data concurrently. Concurrent access is relatively easy if all users are only reading data, as there is no way that they can interfere with one another. However, when two or more users are accessing the database simultaneously and at least one of them is updating data, there may be interference that can result in inconsistencies. For example, consider two transactions T_1 and T_2, which are executing concurrently as illustrated in Figure 2.7.

T_1 is withdrawing £10 from an account (with balance bal_x) and T_2 is depositing £100 into the same account. If these transactions were executed **serially**, one after the other with no interleaving of operations, the final balance would be £190 regardless of which was performed first. However, in this example transactions T_1 and T_2 start at nearly the same time and both read the balance as £100. T_2 then increases bal_x by £100 to £200 and stores the update in the database. Meanwhile, transaction T_1 decrements its copy of bal_x by £10 to £90 and stores this value in the database, overwriting the previous update and thereby 'losing' £100.

The DBMS must ensure that, when multiple users are accessing the database, interference cannot occur. We discuss this issue fully in Section 20.2.

(5) Recovery services

A DBMS must furnish a mechanism for recovering the database in the event that the database is damaged in any way.

When discussing transaction support, we mentioned that if the transaction fails then the database has to be returned to a consistent state. This may be a result of a system crash, media failure, a hardware or software error causing the DBMS to stop, or it may be the result of the user detecting an error during the transaction and aborting the transaction before it completes. In all these cases, the DBMS must provide a mechanism to recover the database to a consistent state. We discuss database recovery in Section 20.3.

(6) Authorization services

A DBMS must furnish a mechanism to ensure that only authorized users can access the database.

It is not difficult to envisage instances where we would want to prevent some of the data stored in the database from being seen by all users. For example, we may want only branch managers to see salary-related information for staff and prevent all other users from seeing this data. Additionally, we may want to protect the database from unauthorized access. The term **security** refers to the protection of the database against unauthorized access, either intentional or accidental. We expect the DBMS to provide mechanisms to ensure the data is secure. We discuss security in Chapter 19.

(7) Support for data communication

A DBMS must be capable of integrating with communication software.

Most users access the database from workstations. Sometimes these workstations are connected directly to the computer hosting the DBMS. In other cases, the workstations are at remote locations and communicate with the computer hosting the DBMS over a network. In either case, the DBMS receives requests as **communications messages** and responds in a similar way. All such transmissions are handled by a Data Communication Manager (DCM). Although the DCM is not part of the DBMS, it is necessary for the DBMS to be capable of being integrated with a variety of DCMs if the system is to be commercially viable. Even DBMSs for personal computers should be capable of being run on a local area network so that one centralized database can be established for users to share, rather than having a series of disparate databases, one for each user. This does not imply that the database has to be distributed across the network; rather that users should be able to access a centralized database from remote locations. We refer to this type of topology as *distributed processing* (see Section 22.1.1).

(8) Integrity services

A DBMS must furnish a means to ensure that both the data in the database and changes to the data follow certain rules.

Database integrity refers to the correctness and consistency of stored data: it can be considered as another type of database protection. While integrity is related to security, it has wider implications: integrity is concerned with the quality of data itself. Integrity is usually expressed in terms of *constraints*, which are consistency rules that the database is not permitted to violate. For example, we may want to specify a constraint that no member of staff can manage more than 100 properties at any one time. Here, we would want the DBMS to check when we assign a property to a member of staff that this limit would not be exceeded and to prevent the assignment from occurring if the limit has been reached.

In addition to these eight services, we could also reasonably expect the following two services to be provided by a DBMS.

(9) Services to promote data independence

A DBMS must include facilities to support the independence of programs from the actual structure of the database.

We discussed the concept of data independence in Section 2.1.5. Data independence is normally achieved through a view or subschema mechanism. Physical data independence is easier to achieve: there are usually several types of change that can be made to the physical characteristics of the database without affecting the views. However, complete logical data independence is more difficult to achieve. The addition of a new entity, attribute, or relationship can usually be accommodated, but not their removal. In some systems, any type of change to an existing component in the logical structure is prohibited.

(10) Utility services

A DBMS should provide a set of utility services.

Utility programs help the DBA to administer the database effectively. Some utilities work at the external level, and consequently can be produced by the DBA. Other utilities work at the internal level and can be provided only by the DBMS vendor. Examples of utilities of the latter kind are:

- import facilities, to load the database from flat files, and export facilities, to unload the database to flat files;
- monitoring facilities, to monitor database usage and operation;
- statistical analysis programs, to examine performance or usage statistics;
- index reorganization facilities, to reorganize indexes and their overflows;
- garbage collection and reallocation, to remove deleted records physically from the storage devices, to consolidate the space released, and to reallocate it where it is needed.

2.5 Components of a DBMS

DBMSs are highly complex and sophisticated pieces of software that aim to provide the services discussed in the previous section. It is not possible to generalize the component structure of a DBMS as it varies greatly from system to system. However, it is useful when trying to understand database systems to try to view the components and the relationships between them. In this section, we present a possible architecture for a DBMS. We examine the architecture of the Oracle DBMS in Section 8.2.2.

A DBMS is partitioned into several software components (or *modules*), each of which is assigned a specific operation. As stated previously, some of the functions of the DBMS are supported by the underlying operating system. However, the operating system provides only basic services and the DBMS must be built on top of it. Thus, the design of a DBMS must take into account the interface between the DBMS and the operating system.

The major software components in a DBMS environment are depicted in Figure 2.8. This diagram shows how the DBMS interfaces with other software components, such as user queries and access methods (file management techniques for storing and retrieving data records). We will provide an overview of file organizations and access methods in Appendix C. For a more comprehensive treatment, the interested reader is referred to Teorey and Fry (1982), Weiderhold (1983), Smith and Barnes (1987), and Ullman (1988).

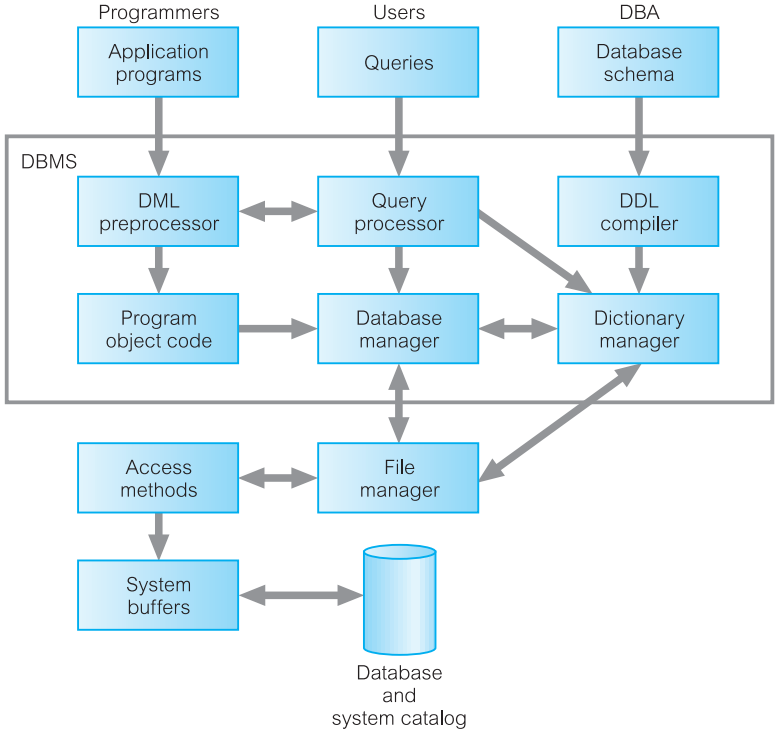


Figure 2.8 Major components of a DBMS.

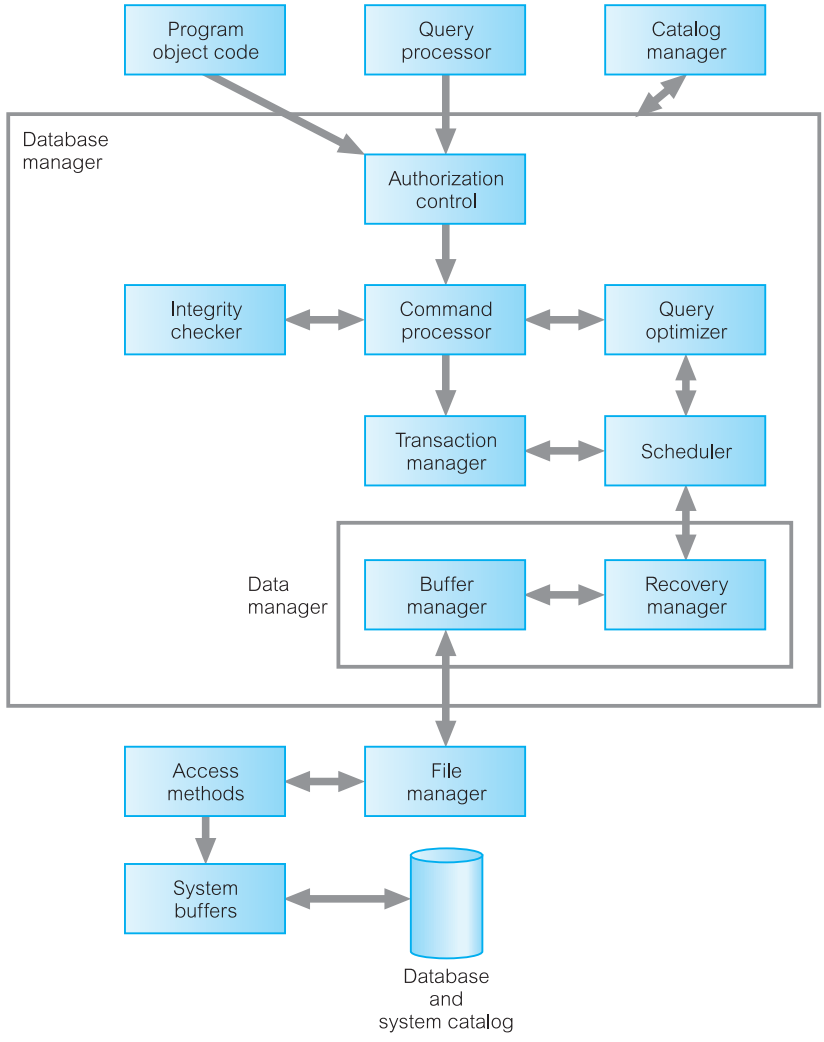


Figure 2.9
Components of a database manager.

Figure 2.8 shows the following components:

- *Query processor* This is a major DBMS component that transforms queries into a series of low-level instructions directed to the database manager. We discuss query processing in Chapter 21.
- *Database manager (DM)* The DM interfaces with user-submitted application programs and queries. The DM accepts queries and examines the external and conceptual schemas to determine what conceptual records are required to satisfy the request. The DM then places a call to the file manager to perform the request. The components of the DM are shown in Figure 2.9.
- *File manager* The file manager manipulates the underlying storage files and manages the allocation of storage space on disk. It establishes and maintains the list of structures

and indexes defined in the internal schema. If hashed files are used it calls on the hashing functions to generate record addresses. However, the file manager does not directly manage the physical input and output of data. Rather it passes the requests on to the appropriate access methods, which either read data from or write data into the system buffer (or *cache*).

- *DML preprocessor* This module converts DML statements embedded in an application program into standard function calls in the host language. The DML preprocessor must interact with the query processor to generate the appropriate code.
- *DDL compiler* The DDL compiler converts DDL statements into a set of tables containing metadata. These tables are then stored in the system catalog while control information is stored in data file headers.
- *Catalog manager* The catalog manager manages access to and maintains the system catalog. The system catalog is accessed by most DBMS components.

The major software components for the *database manager* are as follows:

- *Authorization control* This module checks that the user has the necessary authorization to carry out the required operation.
- *Command processor* Once the system has checked that the user has authority to carry out the operation, control is passed to the command processor.
- *Integrity checker* For an operation that changes the database, the integrity checker checks that the requested operation satisfies all necessary integrity constraints (such as key constraints).
- *Query optimizer* This module determines an optimal strategy for the query execution. We discuss query optimization in Chapter 21.
- *Transaction manager* This module performs the required processing of operations it receives from transactions.
- *Scheduler* This module is responsible for ensuring that concurrent operations on the database proceed without conflicting with one another. It controls the relative order in which transaction operations are executed.
- *Recovery manager* This module ensures that the database remains in a consistent state in the presence of failures. It is responsible for transaction commit and abort.
- *Buffer manager* This module is responsible for the transfer of data between main memory and secondary storage, such as disk and tape. The recovery manager and the buffer manager are sometimes referred to collectively as the *data manager*. The buffer manager is sometimes known as the *cache manager*.

We discuss the last four modules in Chapter 20. In addition to the above modules, several other data structures are required as part of the physical-level implementation. These structures include data and index files, and the system catalog. An attempt has been made to standardize DBMSs, and a reference model was proposed by the Database Architecture Framework Task Group (DAFTG, 1986). The purpose of this reference model was to define a conceptual framework aiming to divide standardization attempts into manageable pieces and to show at a very broad level how these pieces could be interrelated.

2.6 Multi-User DBMS Architectures

In this section we look at the common architectures that are used to implement multi-user database management systems, namely teleprocessing, file-server, and client–server.

2.6.1 Teleprocessing

The traditional architecture for multi-user systems was teleprocessing, where there is one computer with a single central processing unit (CPU) and a number of terminals, as illustrated in Figure 2.10. All processing is performed within the boundaries of the same physical computer. User terminals are typically 'dumb' ones, incapable of functioning on their own. They are cabled to the central computer. The terminals send messages via the communications control subsystem of the operating system to the user's application program, which in turn uses the services of the DBMS. In the same way, messages are routed back to the user's terminal. Unfortunately, this architecture placed a tremendous burden on the central computer, which not only had to run the application programs and the DBMS, but also had to carry out a significant amount of work on behalf of the terminals (such as formatting data for display on the screen).

In recent years, there have been significant advances in the development of high-performance personal computers and networks. There is now an identifiable trend in industry towards **downsizing**, that is, replacing expensive mainframe computers with more cost-effective networks of personal computers that achieve the same, or even better, results. This trend has given rise to the next two architectures: file-server and client–server.

2.6.2 File-Server Architecture

In a file-server environment, the processing is distributed about the network, typically a local area network (LAN). The file-server holds the files required by the applications and the DBMS. However, the applications and the DBMS run on each workstation, requesting

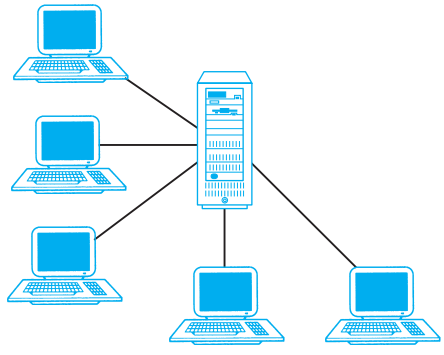


Figure 2.10
Teleprocessing topology.

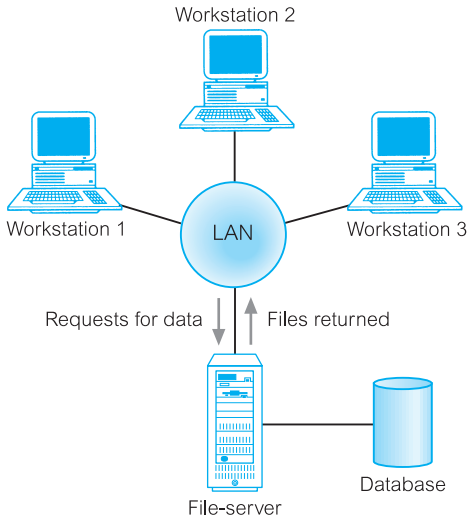


Figure 2.11 File-server architecture.

files from the file-server when necessary, as illustrated in Figure 2.11. In this way, the file-server acts simply as a shared hard disk drive. The DBMS on each workstation sends requests to the file-server for all data that the DBMS requires that is stored on disk. This approach can generate a significant amount of network traffic, which can lead to performance problems. For example, consider a user request that requires the names of staff who work in the branch at 163 Main St. We can express this request in SQL (see Chapter 5) as:

```
SELECT fName, lName
FROM Branch b, Staff s
WHERE b.branchNo = s.branchNo AND b.street = '163 Main St';
```

As the file-server has no knowledge of SQL, the DBMS has to request the files corresponding to the Branch and Staff relations from the file-server, rather than just the staff names that satisfy the query.

The file-server architecture, therefore, has three main disadvantages:

(1) There is a large amount of network traffic.

(2) A full copy of the DBMS is required on each workstation.

(3) Concurrency, recovery, and integrity control are more complex because there can be multiple DBMSs accessing the same files.

Traditional Two-Tier Client–Server Architecture 2.6.3

To overcome the disadvantages of the first two approaches and accommodate an increasingly decentralized business environment, the client–server architecture was developed. Client–server refers to the way in which software components interact to form a system.

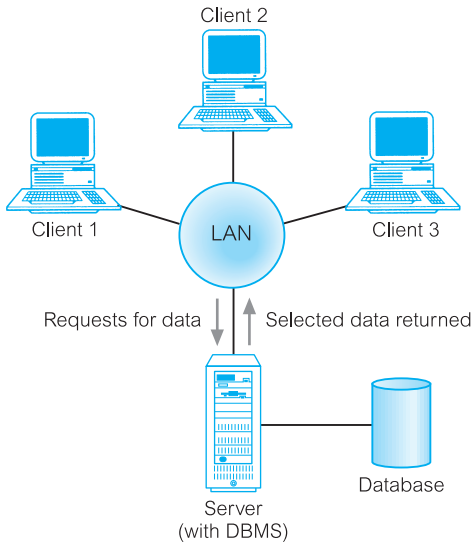


Figure 2.12
Client–server architecture.

As the name suggests, there is a **client** process, which requires some resource, and a **server**, which provides the resource. There is no requirement that the client and server must reside on the same machine. In practice, it is quite common to place a server at one site in a local area network and the clients at the other sites. Figure 2.12 illustrates the client–server architecture and Figure 2.13 shows some possible combinations of the client–server topology.

Data-intensive business applications consist of four major components: the database, the transaction logic, the business and data application logic, and the user interface. The traditional two-tier client–server architecture provides a very basic separation of these components. The client (tier 1) is primarily responsible for the *presentation* of data to the user, and the server (tier 2) is primarily responsible for supplying *data services* to the client, as illustrated in Figure 2.14. Presentation services handle user interface actions and the main business and data application logic. Data services provide limited business application logic, typically validation that the client is unable to carry out due to lack of information, and access to the requested data, independent of its location. The data can come from relational DBMSs, object-relational DBMSs, object-oriented DBMSs, legacy DBMSs, or proprietary data access systems. Typically, the client would run on end-user desktops and interact with a centralized database server over a network.

A typical interaction between client and server is as follows. The client takes the user's request, checks the syntax and generates database requests in SQL or another database language appropriate to the application logic. It then transmits the message to the server, waits for a response, and formats the response for the end-user. The server accepts and processes the database requests, then transmits the results back to the client. The processing involves checking authorization, ensuring integrity, maintaining the system catalog, and performing query and update processing. In addition, it also provides concurrency and recovery control. The operations of client and server are summarized in Table 2.1.

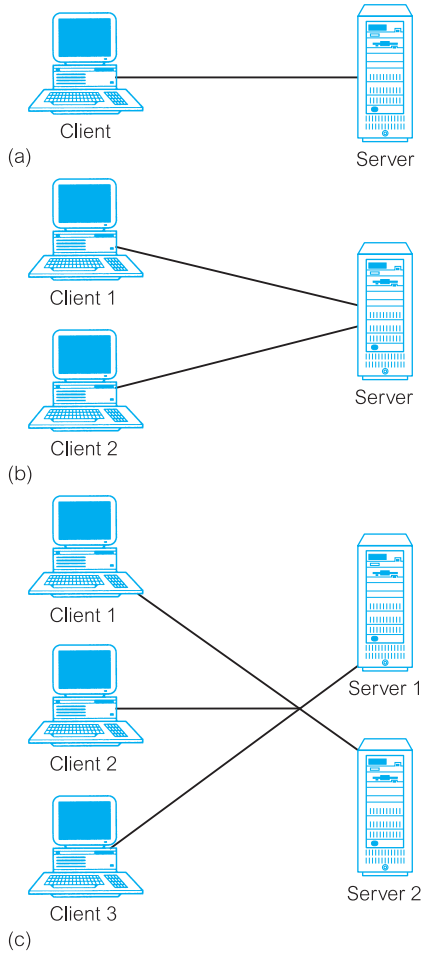


Figure 2.13
Alternative client–server topologies: (a) single client, single server; (b) multiple clients, single server; (c) multiple clients, multiple servers.

There are many advantages to this type of architecture. For example:

- It enables wider access to existing databases.
- Increased performance – if the clients and server reside on different computers then different CPUs can be processing applications in parallel. It should also be easier to tune the server machine if its only task is to perform database processing.
- Hardware costs may be reduced – it is only the server that requires storage and processing power sufficient to store and manage the database.
- Communication costs are reduced – applications carry out part of the operations on the client and send only requests for database access across the network, resulting in less data being sent across the network.

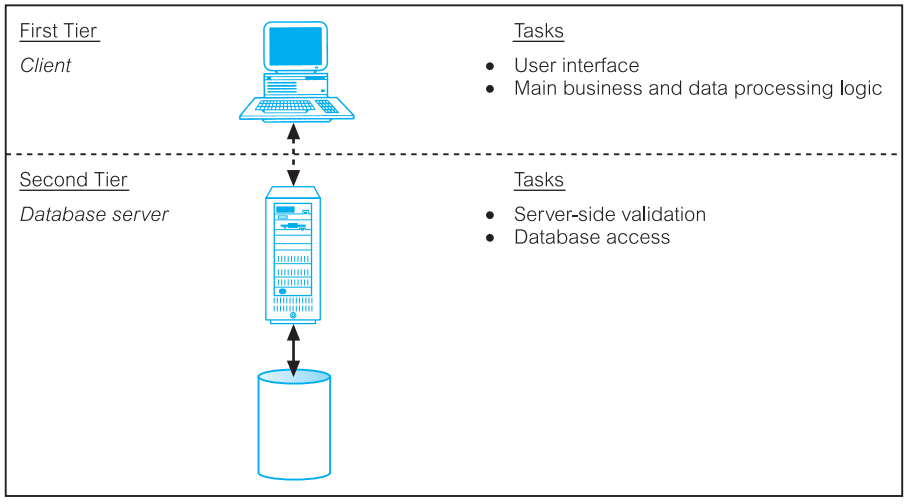


Figure 2.14 The traditional two-tier client–server architecture.

Table 2.1 Summary of client–server functions.

Client	Server
Manages the user interface	Accepts and processes database requests from clients
Accepts and checks syntax of user input	Checks authorization
Processes application logic	Ensures integrity constraints not violated
Generates database requests and transmits to server	Performs query/update processing and transmits response to client
Passes response back to user	Maintains system catalog
	Provides concurrent database access
	Provides recovery control

- Increased consistency – the server can handle integrity checks, so that constraints need be defined and validated only in the one place, rather than having each application program perform its own checking.
- It maps on to open systems architecture quite naturally.

Some database vendors have used this architecture to indicate distributed database capability, that is a collection of multiple, logically interrelated databases distributed over a computer network. However, although the client–server architecture can be used to provide distributed DBMSs, by itself it does not constitute a distributed DBMS. We discuss distributed DBMSs in Chapters 22 and 23.

2.6.4 Three-Tier Client–Server Architecture

The need for enterprise scalability challenged this traditional two-tier client–server model. In the mid-1990s, as applications became more complex and potentially could be deployed

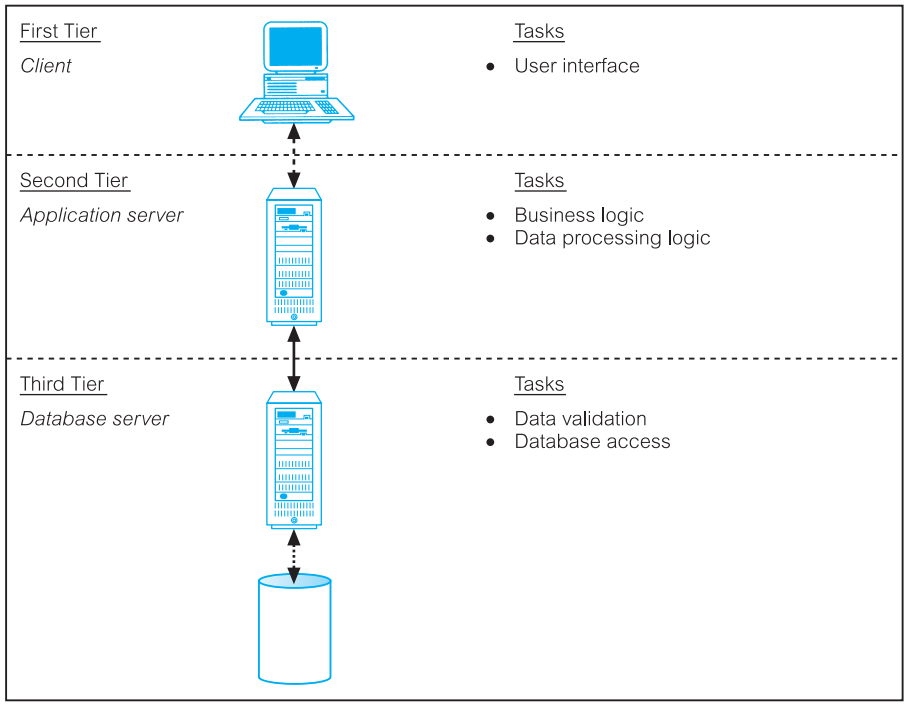


Figure 2.15
The three-tier architecture.

to hundreds or thousands of end-users, the client side presented two problems that prevented true scalability:

- A 'fat' client, requiring considerable resources on the client's computer to run effectively. This includes disk space, RAM, and CPU power.
- A significant client-side administration overhead.

By 1995, a new variation of the traditional two-tier client–server model appeared to solve the problem of enterprise scalability. This new architecture proposed three layers, each potentially running on a different platform:

(1) The user interface layer, which runs on the end-user's computer (the *client*).

(2) The business logic and data processing layer. This middle tier runs on a server and is often called the *application server*.

(3) A DBMS, which stores the data required by the middle tier. This tier may run on a separate server called the *database server*.

As illustrated in Figure 2.15 the client is now responsible only for the application's user interface and perhaps performing some simple logic processing, such as input validation, thereby providing a 'thin' client. The core business logic of the application now resides in its own layer, physically connected to the client and database server over a local area network (LAN) or wide area network (WAN). One application server is designed to serve multiple clients.

The three-tier design has many advantages over traditional two-tier or single-tier designs, which include:

- The need for less expensive hardware because the client is 'thin'.
- Application maintenance is centralized with the transfer of the business logic for many end-users into a single application server. This eliminates the concerns of software distribution that are problematic in the traditional two-tier client–server model.
- The added modularity makes it easier to modify or replace one tier without affecting the other tiers.
- Load balancing is easier with the separation of the core business logic from the database functions.

An additional advantage is that the three-tier architecture maps quite naturally to the Web environment, with a Web browser acting as the 'thin' client, and a Web server acting as the application server. The three-tier architecture can be extended to *n*-tiers, with additional tiers added to provide more flexibility and scalability. For example, the middle tier of the three-tier architecture could be split into two, with one tier for the Web server and another for the application server.

This three-tier architecture has proved more appropriate for some environments, such as the Internet and corporate intranets where a Web browser can be used as a client. It is also an important architecture for **Transaction Processing Monitors**, as we discuss next.

2.6.5 Transaction Processing Monitors

TP Monitor A program that controls data transfer between clients and servers in order to provide a consistent environment, particularly for online transaction processing (OLTP).

Complex applications are often built on top of several **resource managers** (such as DBMSs, operating systems, user interfaces, and messaging software). A Transaction Processing Monitor, or TP Monitor, is a middleware component that provides access to the services of a number of resource managers and provides a uniform interface for programmers who are developing transactional software. A TP Monitor forms the middle tier of a three-tier architecture, as illustrated in Figure 2.16. TP Monitors provide significant advantages, including:

- *Transaction routing* The TP Monitor can increase scalability by directing transactions to specific DBMSs.
- *Managing distributed transactions* The TP Monitor can manage transactions that require access to data held in multiple, possibly heterogeneous, DBMSs. For example, a transaction may require to update data items held in an Oracle DBMS at site 1, an Informix DBMS at site 2, and an IMS DBMS as site 3. TP Monitors normally control transactions using the X/Open Distributed Transaction Processing (DTP) standard. A

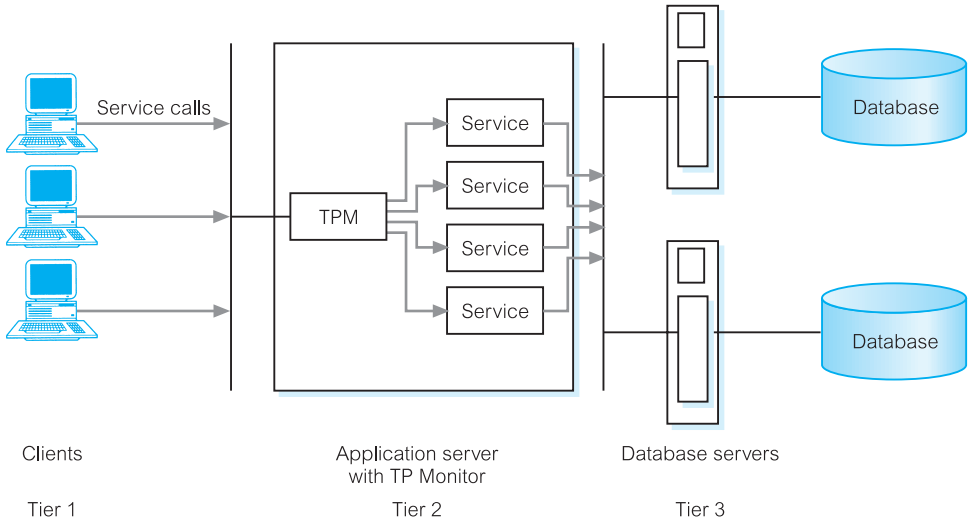


Figure 2.16
Transaction Processing Monitor as the middle tier of a three-tier client–server architecture.

DBMS that supports this standard can function as a resource manager under the control of a TP Monitor acting as a transaction manager. We discuss distributed transactions and the DTP standard in Chapters 22 and 23.

- *Load balancing* The TP Monitor can balance client requests across multiple DBMSs on one or more computers by directing client service calls to the least loaded server. In addition, it can dynamically bring in additional DBMSs as required to provide the necessary performance.
- *Funneling* In environments with a large number of users, it may sometimes be difficult for all users to be logged on simultaneously to the DBMS. In many cases, we would find that users generally do not need continuous access to the DBMS. Instead of each user connecting to the DBMS, the TP Monitor can establish connections with the DBMSs as and when required, and can funnel user requests through these connections. This allows a larger number of users to access the available DBMSs with a potentially much smaller number of connections, which in turn would mean less resource usage.
- *Increased reliability* The TP Monitor acts as a *transaction manager*, performing the necessary actions to maintain the consistency of the database, with the DBMS acting as a *resource manager*. If the DBMS fails, the TP Monitor may be able to resubmit the transaction to another DBMS or can hold the transaction until the DBMS becomes available again.

TP Monitors are typically used in environments with a very high volume of transactions, where the TP Monitor can be used to offload processes from the DBMS server. Prominent examples of TP Monitors include CICS and Encina from IBM (which are primarily used on IBM AIX or Windows NT and bundled now in the IBM TXSeries) and Tuxedo from BEA Systems.

Chapter Summary

- The ANSI-SPARC database architecture uses **three levels** of abstraction: **external**, **conceptual**, and **internal**. The **external level** consists of the users' views of the database. The **conceptual level** is the community view of the database. It specifies the information content of the entire database, independent of storage considerations. The conceptual level represents all entities, their attributes, and their relationships, as well as the constraints on the data, and security and integrity information. The **internal level** is the computer's view of the database. It specifies how data is represented, how records are sequenced, what indexes and pointers exist, and so on.
- The **external/conceptual mapping** transforms requests and results between the external and conceptual levels. The **conceptual/internal mapping** transforms requests and results between the conceptual and internal levels.
- A **database schema** is a description of the database structure. Data independence makes each level immune to changes to lower levels. **Logical data independence** refers to the immunity of the external schemas to changes in the conceptual schema. **Physical data independence** refers to the immunity of the conceptual schema to changes in the internal schema.
- A data sublanguage consists of two parts: a **Data Definition Language (DDL)** and a **Data Manipulation Language (DML)**. The DDL is used to specify the database schema and the DML is used to both read and update the database. The part of a DML that involves data retrieval is called a **query language**.
- A **data model** is a collection of concepts that can be used to describe a set of data, the operations to manipulate the data, and a set of integrity constraints for the data. They fall into three broad categories: **object-based** data models, **record-based** data models, and **physical** data models. The first two are used to describe data at the conceptual and external levels; the latter is used to describe data at the internal level.
- Object-based data models include the Entity–Relationship, semantic, functional, and object-oriented models. Record-based data models include the relational, network, and hierarchical models.
- **Conceptual modeling** is the process of constructing a detailed architecture for a database that is independent of implementation details, such as the target DBMS, application programs, programming languages, or any other physical considerations. The design of the conceptual schema is critical to the overall success of the system. It is worth spending the time and energy necessary to produce the best possible conceptual design.
- **Functions** and **services** of a multi-user DBMS include data storage, retrieval, and update; a user-accessible catalog; transaction support; concurrency control and recovery services; authorization services; support for data communication; integrity services; services to promote data independence; utility services.
- The **system catalog** is one of the fundamental components of a DBMS. It contains 'data about the data', or **metadata**. The catalog should be accessible to users. The Information Resource Dictionary System is an ISO standard that defines a set of access methods for a data dictionary. This allows dictionaries to be shared and transferred from one system to another.
- **Client–server** architecture refers to the way in which software components interact. There is a **client** process that requires some resource, and a **server** that provides the resource. In the two-tier model, the client handles the user interface and business processing logic and the server handles the database functionality. In the Web environment, the traditional two-tier model has been replaced by a three-tier model, consisting of a user interface layer (the **client**), a business logic and data processing layer (the **application server**), and a DBMS (the **database server**), distributed over different machines.
- A **Transaction Processing (TP) Monitor** is a program that controls data transfer between clients and servers in order to provide a consistent environment, particularly for online transaction processing (OLTP). The advantages include transaction routing, distributed transactions, load balancing, funneling, and increased reliability.

Review Questions

2.1 Discuss the concept of data independence and explain its importance in a database environment.

2.2 To address the issue of data independence, the ANSI-SPARC three-level architecture was proposed. Compare and contrast the three levels of this model.

2.3 What is a data model? Discuss the main types of data model.

2.4 Discuss the function and importance of conceptual modeling.

2.5 Describe the types of facility you would expect to be provided in a multi-user DBMS.

2.6 Of the facilities described in your answer to Question 2.5, which ones do you think would *not* be needed in a standalone PC DBMS? Provide justification for your answer.

2.7 Discuss the function and importance of the system catalog.

2.8 Describe the main components in a DBMS and suggest which components are responsible for each facility identified in Question 2.5.

2.9 What is meant by the term 'client–server architecture' and what are the advantages of this approach? Compare the client–server architecture with two other architectures.

2.10 Compare and contrast the two-tier client–server architecture for traditional DBMSs with the three-tier client–server architecture. Why is the latter architecture more appropriate for the Web?

2.11 What is a TP Monitor? What advantages does a TP Monitor bring to an OLTP environment?

Exercises

2.12 Analyze the DBMSs that you are currently using. Determine each system's compliance with the functions that we would expect to be provided by a DBMS. What type of language does each system provide? What type of architecture does each DBMS use? Check the accessibility and extensibility of the system catalog. Is it possible to export the system catalog to another system?

2.13 Write a program that stores names and telephone numbers in a database. Write another program that stores names and addresses in a database. Modify the programs to use external, conceptual, and internal schemas. What are the advantages and disadvantages of this modification?

2.14 Write a program that stores names and dates of birth in a database. Extend the program so that it stores the format of the data in the database: in other words, create a system catalog. Provide an interface that makes this system catalog accessible to external users.

2.15 How would you modify your program in Exercise 2.13 to conform to a client–server architecture? What would be the advantages and disadvantages of this modification?