

FUNDAMENTALS OF

Database Systems

SEVENTH EDITION

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Databases and Database Users

Databases and database systems are an essential component of life in modern society; most of us encounter several activities every day that involve some interaction with a database. For example, if we go to the bank to deposit or withdraw funds, if we make a hotel or airline reservation, if we access a computerized library catalog to search for a bibliographic item, or if we purchase something online—such as a book, toy, or computer—chances are that our activities will involve someone or some computer program accessing a database. Even purchasing items at a supermarket often automatically updates the database that holds the inventory of grocery items.

These interactions are examples of what we may call **traditional database applications**, in which most of the information that is stored and accessed is either textual or numeric. In the past few years, advances in technology have led to exciting new applications of database systems. The proliferation of social media Web sites, such as Facebook, Twitter, and Flickr, among many others, has required the creation of huge databases that store nontraditional data, such as posts, tweets, images, and video clips. New types of database systems, often referred to as **big data** storage systems, or **NOSQL systems**, have been created to manage data for social media applications. These types of systems are also used by companies such as Google, Amazon, and Yahoo, to manage the data required in their Web search engines, as well as to provide **cloud storage**, whereby users are provided with storage capabilities on the Web for managing all types of data including documents, programs, images, videos and emails. We will give an overview of these new types of database systems in Chapter 24.

We now mention some other applications of databases. The wide availability of photo and video technology on cellphones and other devices has made it possible to

store images, audio clips, and video streams digitally. These types of files are becoming an important component of **multimedia databases**. **Geographic information systems (GISs)** can store and analyze maps, weather data, and satellite images. **Data warehouses** and **online analytical processing (OLAP)** systems are used in many companies to extract and analyze useful business information from very large databases to support decision making. **Real-time** and **active database technology** is used to control industrial and manufacturing processes. And database **search techniques** are being applied to the World Wide Web to improve the search for information that is needed by users browsing the Internet.

To understand the fundamentals of database technology, however, we must start from the basics of traditional database applications. In Section 1.1 we start by defining a database, and then we explain other basic terms. In Section 1.2, we provide a simple UNIVERSITY database example to illustrate our discussion. Section 1.3 describes some of the main characteristics of database systems, and Sections 1.4 and 1.5 categorize the types of personnel whose jobs involve using and interacting with database systems. Sections 1.6, 1.7, and 1.8 offer a more thorough discussion of the various capabilities provided by database systems and discuss some typical database applications. Section 1.9 summarizes the chapter.

The reader who desires a quick introduction to database systems can study Sections 1.1 through 1.5, then skip or browse through Sections 1.6 through 1.8 and go on to Chapter 2.

1.1 Introduction

Databases and database technology have had a major impact on the growing use of computers. It is fair to say that databases play a critical role in almost all areas where computers are used, including business, electronic commerce, social media, engineering, medicine, genetics, law, education, and library science. The word *database* is so commonly used that we must begin by defining what a database is. Our initial definition is quite general.

A **database** is a collection of related data.¹ By **data**, we mean known facts that can be recorded and that have implicit meaning. For example, consider the names, telephone numbers, and addresses of the people you know. Nowadays, this data is typically stored in mobile phones, which have their own simple database software. This data can also be recorded in an indexed address book or stored on a hard drive, using a personal computer and software such as Microsoft Access or Excel. This collection of related data with an implicit meaning is a database.

The preceding definition of database is quite general; for example, we may consider the collection of words that make up this page of text to be related data and hence to

¹We will use the word *data* as both singular and plural, as is common in database literature; the context will determine whether it is singular or plural. In standard English, *data* is used for plural and *datum* for singular.

constitute a database. However, the common use of the term *database* is usually more restricted. A database has the following implicit properties:

- A database represents some aspect of the real world, sometimes called the **miniworld** or the **universe of discourse (UoD)**. Changes to the miniworld are reflected in the database.
- A database is a logically coherent collection of data with some inherent meaning. A random assortment of data cannot correctly be referred to as a database.
- A database is designed, built, and populated with data for a specific purpose. It has an intended group of users and some preconceived applications in which these users are interested.

In other words, a database has some source from which data is derived, some degree of interaction with events in the real world, and an audience that is actively interested in its contents. The end users of a database may perform business transactions (for example, a customer buys a camera) or events may happen (for example, an employee has a baby) that cause the information in the database to change. In order for a database to be accurate and reliable at all times, it must be a true reflection of the miniworld that it represents; therefore, changes must be reflected in the database as soon as possible.

A database can be of any size and complexity. For example, the list of names and addresses referred to earlier may consist of only a few hundred records, each with a simple structure. On the other hand, the computerized catalog of a large library may contain half a million entries organized under different categories—by primary author's last name, by subject, by book title—with each category organized alphabetically. A database of even greater size and complexity would be maintained by a social media company such as Facebook, which has more than a billion users. The database has to maintain information on which users are related to one another as *friends*, the postings of each user, which users are allowed to see each posting, and a vast amount of other types of information needed for the correct operation of their Web site. For such Web sites, a large number of databases are needed to keep track of the constantly changing information required by the social media Web site.

An example of a large commercial database is Amazon.com. It contains data for over 60 million active users, and millions of books, CDs, videos, DVDs, games, electronics, apparel, and other items. The database occupies over 42 terabytes (a terabyte is 10^{12} bytes worth of storage) and is stored on hundreds of computers (called servers). Millions of visitors access Amazon.com each day and use the database to make purchases. The database is continually updated as new books and other items are added to the inventory, and stock quantities are updated as purchases are transacted.

A database may be generated and maintained manually or it may be computerized. For example, a library card catalog is a database that may be created and maintained manually. A computerized database may be created and maintained either by a group of application programs written specifically for that task or by a

database management system. Of course, we are only concerned with computerized databases in this text.

A **database management system (DBMS)** is a computerized system that enables users to create and maintain a database. The DBMS is a *general-purpose software system* that facilitates the processes of *defining, constructing, manipulating, and sharing* databases among various users and applications. **Defining** a database involves specifying the data types, structures, and constraints of the data to be stored in the database. The database definition or descriptive information is also stored by the DBMS in the form of a database catalog or dictionary; it is called **meta-data**. **Constructing** the database is the process of storing the data on some storage medium that is controlled by the DBMS. **Manipulating** a database includes functions such as querying the database to retrieve specific data, updating the database to reflect changes in the miniworld, and generating reports from the data. **Sharing** a database allows multiple users and programs to access the database simultaneously.

An **application program** accesses the database by sending queries or requests for data to the DBMS. A **query**² typically causes some data to be retrieved; a **transaction** may cause some data to be read and some data to be written into the database.

Other important functions provided by the DBMS include *protecting* the database and *maintaining* it over a long period of time. **Protection** includes *system protection* against hardware or software malfunction (or crashes) and *security protection* against unauthorized or malicious access. A typical large database may have a life cycle of many years, so the DBMS must be able to **maintain** the database system by allowing the system to evolve as requirements change over time.

It is not absolutely necessary to use general-purpose DBMS software to implement a computerized database. It is possible to write a customized set of programs to create and maintain the database, in effect creating a *special-purpose* DBMS software for a specific application, such as airlines reservations. In either case—whether we use a general-purpose DBMS or not—a considerable amount of complex software is deployed. In fact, most DBMSs are very complex software systems.

To complete our initial definitions, we will call the database and DBMS software together a **database system**. Figure 1.1 illustrates some of the concepts we have discussed so far.

1.2 An Example

Let us consider a simple example that most readers may be familiar with: a UNIVERSITY database for maintaining information concerning students, courses, and grades in a university environment. Figure 1.2 shows the database structure and a few sample data records. The database is organized as five files, each of which

²The term *query*, originally meaning a question or an inquiry, is sometimes loosely used for all types of interactions with databases, including modifying the data.

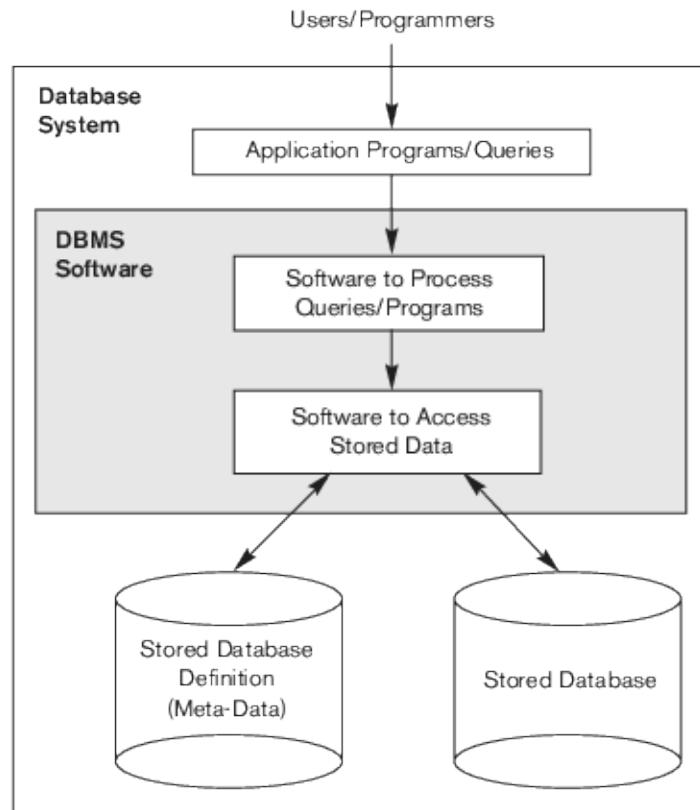


Figure 1.1
A simplified database system environment

stores **data records** of the same type.³ The STUDENT file stores data on each student, the COURSE file stores data on each course, the SECTION file stores data on each section of a course, the GRADE_REPORT file stores the grades that students receive in the various sections they have completed, and the PREREQUISITE file stores the prerequisites of each course.

To *define* this database, we must specify the structure of the records of each file by specifying the different types of **data elements** to be stored in each record. In Figure 1.2, each STUDENT record includes data to represent the student's Name, Student_number, Class (such as freshman or '1', sophomore or '2', and so forth), and Major (such as mathematics or 'MATH' and computer science or 'CS'); each COURSE record includes data to represent the Course_name, Course_number, Credit_hours, and Department (the department that offers the course), and so on. We must also specify a **data type** for each data element within a record. For example, we can specify that Name of STUDENT is a string of alphabetic characters, Student_number of STUDENT is an integer, and Grade of GRADE_REPORT is a

³We use the term *file* informally here. At a conceptual level, a *file* is a collection of records that may or may not be ordered.

STUDENT

Name	Student_number	Class	Major
Smith	17	1	CS
Brown	8	2	CS

COURSE

Course_name	Course_number	Credit_hours	Department
Intro to Computer Science	CS1310	4	CS
Data Structures	CS3320	4	CS
Discrete Mathematics	MATH2410	3	MATH
Database	CS3380	3	CS

SECTION

Section_identifier	Course_number	Semester	Year	Instructor
85	MATH2410	Fall	07	King
92	CS1310	Fall	07	Anderson
102	CS3320	Spring	08	Knuth
112	MATH2410	Fall	08	Chang
119	CS1310	Fall	08	Anderson
135	CS3380	Fall	08	Stone

GRADE_REPORT

Student_number	Section_identifier	Grade
17	112	B
17	119	C
8	85	A
8	92	A
8	102	B
8	135	A

PREREQUISITE

Course_number	Prerequisite_number
CS3380	CS3320
CS3380	MATH2410
CS3320	CS1310

Figure 1.2

A database that stores student and course information.

single character from the set {‘A’, ‘B’, ‘C’, ‘D’, ‘F’, ‘T’}. We may also use a coding scheme to represent the values of a data item. For example, in Figure 1.2 we represent the Class of a STUDENT as 1 for freshman, 2 for sophomore, 3 for junior, 4 for senior, and 5 for graduate student.

To construct the UNIVERSITY database, we store data to represent each student, course, section, grade report, and prerequisite as a record in the appropriate file. Notice that records in the various files may be related. For example, the record for Smith in the STUDENT file is related to two records in the GRADE_REPORT file that specify Smith’s grades in two sections. Similarly, each record in the PREREQUISITE file relates two course records: one representing the course and the other representing the prerequisite. Most medium-size and large databases include many types of records and have *many relationships* among the records.

Database *manipulation* involves querying and updating. Examples of queries are as follows:

- Retrieve the transcript—a list of all courses and grades—of ‘Smith’
- List the names of students who took the section of the ‘Database’ course offered in fall 2008 and their grades in that section
- List the prerequisites of the ‘Database’ course

Examples of updates include the following:

- Change the class of ‘Smith’ to sophomore
- Create a new section for the ‘Database’ course for this semester
- Enter a grade of ‘A’ for ‘Smith’ in the ‘Database’ section of last semester

These informal queries and updates must be specified precisely in the query language of the DBMS before they can be processed.

At this stage, it is useful to describe the database as part of a larger undertaking known as an information system within an organization. The Information Technology (IT) department within an organization designs and maintains an information system consisting of various computers, storage systems, application software, and databases. Design of a new application for an existing database or design of a brand new database starts off with a phase called **requirements specification and analysis**. These requirements are documented in detail and transformed into a **conceptual design** that can be represented and manipulated using some computerized tools so that it can be easily maintained, modified, and transformed into a database implementation. (We will introduce a model called the Entity-Relationship model in Chapter 3 that is used for this purpose.) The design is then translated to a **logical design** that can be expressed in a data model implemented in a commercial DBMS. (Various types of DBMSs are discussed throughout the text, with an emphasis on relational DBMSs in Chapters 5 through 9.)

The final stage is **physical design**, during which further specifications are provided for storing and accessing the database. The database design is implemented, populated with actual data, and continuously maintained to reflect the state of the miniworld.

1.3 Characteristics of the Database Approach

A number of characteristics distinguish the database approach from the much older approach of writing customized programs to access data stored in files. In traditional **file processing**, each user defines and implements the files needed for a specific software application as part of programming the application. For example, one user, the *grade reporting office*, may keep files on students and their grades. Programs to print a student's transcript and to enter new grades are implemented as part of the application. A second user, the *accounting office*, may keep track of students' fees and their payments. Although both users are interested in data about students, each user maintains separate files—and programs to manipulate these files—because each requires some data not available from the other user's files. This redundancy in defining and storing data results in wasted storage space and in redundant efforts to maintain common up-to-date data.

In the database approach, a single repository maintains data that is defined once and then accessed by various users repeatedly through queries, transactions, and application programs. The main characteristics of the database approach versus the file-processing approach are the following:

- Self-describing nature of a database system
- Insulation between programs and data, and data abstraction
- Support of multiple views of the data
- Sharing of data and multiuser transaction processing

We describe each of these characteristics in a separate section. We will discuss additional characteristics of database systems in Sections 1.6 through 1.8.

1.3.1 Self-Describing Nature of a Database System

A fundamental characteristic of the database approach is that the database system contains not only the database itself but also a complete definition or description of the database structure and constraints. This definition is stored in the DBMS catalog, which contains information such as the structure of each file, the type and storage format of each data item, and various constraints on the data. The information stored in the catalog is called **meta-data**, and it describes the structure of the primary database (Figure 1.1). It is important to note that some newer types of database systems, known as NOSQL systems, do not require meta-data. Rather the data is stored as **self-describing data** that includes the data item names and data values together in one structure (see Chapter 24).

The catalog is used by the DBMS software and also by database users who need information about the database structure. A general-purpose DBMS software package is not written for a specific database application. Therefore, it must refer to the catalog to know the structure of the files in a specific database, such as the type and format of data it will access. The DBMS software must work equally well with *any number of database applications*—for example, a university database, a

banking database, or a company database—as long as the database definition is stored in the catalog.

In traditional file processing, data definition is typically part of the application programs themselves. Hence, these programs are constrained to work with only *one specific database*, whose structure is declared in the application programs. For example, an application program written in C++ may have struct or class declarations. Whereas file-processing software can access only specific databases, DBMS software can access diverse databases by extracting the database definitions from the catalog and using these definitions.

For the example shown in Figure 1.2, the DBMS catalog will store the definitions of all the files shown. Figure 1.3 shows some entries in a database catalog. Whenever a request is made to access, say, the Name of a STUDENT record, the DBMS software refers to the catalog to determine the structure of the STUDENT file and the position and size of the Name data item within a STUDENT record. By contrast, in a typical file-processing application, the file structure and, in the extreme case, the exact location of Name within a STUDENT record are already coded within each program that accesses this data item.

RELATIONS

Relation_name	No_of_columns
STUDENT	4
COURSE	4
SECTION	5
GRADE_REPORT	3
PREREQUISITE	2

Figure 1.3

An example of a database catalog for the database in Figure 1.2.

COLUMNS

Column_name	Data_type	Belongs_to_relation
Name	Character (30)	STUDENT
Student_number	Character (4)	STUDENT
Class	Integer (1)	STUDENT
Major	Major_type	STUDENT
Course_name	Character (10)	COURSE
Course_number	XXXXNNNN	COURSE
....
....
....
Prerequisite_number	XXXXNNNN	PREREQUISITE

Note: Major_type is defined as an enumerated type with all known majors.

XXXXNNNN is used to define a type with four alphabetic characters followed by four numeric digits.

1.3.2 Insulation between Programs and Data, and Data Abstraction

In traditional file processing, the structure of data files is embedded in the application programs, so any changes to the structure of a file may require *changing all programs* that access that file. By contrast, DBMS access programs do not require such changes in most cases. The structure of data files is stored in the DBMS catalog separately from the access programs. We call this property **program-data independence**.

For example, a file access program may be written in such a way that it can access only STUDENT records of the structure shown in Figure 1.4. If we want to add another piece of data to each STUDENT record, say the Birth_date, such a program will no longer work and must be changed. By contrast, in a DBMS environment, we only need to change the *description* of STUDENT records in the catalog (Figure 1.3) to reflect the inclusion of the new data item Birth_date; no programs are changed. The next time a DBMS program refers to the catalog, the new structure of STUDENT records will be accessed and used.

In some types of database systems, such as object-oriented and object-relational systems (see Chapter 12), users can define operations on data as part of the database definitions. An **operation** (also called a *function* or *method*) is specified in two parts. The *interface* (or *signature*) of an operation includes the operation name and the data types of its arguments (or parameters). The *implementation* (or *method*) of the operation is specified separately and can be changed without affecting the interface. User application programs can operate on the data by invoking these operations through their names and arguments, regardless of how the operations are implemented. This may be termed **program-operation independence**.

The characteristic that allows program-data independence and program-operation independence is called **data abstraction**. A DBMS provides users with a **conceptual representation** of data that does not include many of the details of how the data is stored or how the operations are implemented. Informally, a **data model** is a type of data abstraction that is used to provide this conceptual representation. The data model uses logical concepts, such as objects, their properties, and their interrelationships, that may be easier for most users to understand than computer storage concepts. Hence, the data model *hides* storage and implementation details that are not of interest to most database users.

Looking at the example in Figures 1.2 and 1.3, the internal implementation of the STUDENT file may be defined by its record length—the number of characters (bytes) in each record—and each data item may be specified by its starting byte within a record and its length in bytes. The STUDENT record would thus be represented as shown in Figure 1.4. But a typical database user is not concerned with the location of each data item within a record or its length; rather, the user is concerned that when a reference is made to Name of STUDENT, the correct value is returned. A conceptual representation of the STUDENT records is shown in Figure 1.2. Many other details of file storage organization—such as the access paths specified on a

Data Item Name	Starting Position in Record	Length in Characters (bytes)
Name	1	30
Student_number	31	4
Class	35	1
Major	36	4

Figure 1.4

Internal storage format for a STUDENT record, based on the database catalog in Figure 1.3.

file—can be hidden from database users by the DBMS; we discuss storage details in Chapters 16 and 17.

In the database approach, the detailed structure and organization of each file are stored in the catalog. Database users and application programs refer to the conceptual representation of the files, and the DBMS extracts the details of file storage from the catalog when these are needed by the DBMS file access modules. Many data models can be used to provide this data abstraction to database users. A major part of this text is devoted to presenting various data models and the concepts they use to abstract the representation of data.

In object-oriented and object-relational databases, the abstraction process includes not only the data structure but also the operations on the data. These operations provide an abstraction of miniworld activities commonly understood by the users. For example, an operation `CALCULATE_GPA` can be applied to a STUDENT object to calculate the grade point average. Such operations can be invoked by the user queries or application programs without having to know the details of how the operations are implemented.

1.3.3 Support of Multiple Views of the Data

A database typically has many types of users, each of whom may require a different perspective or **view** of the database. A view may be a subset of the database or it may contain **virtual data** that is derived from the database files but is not explicitly stored. Some users may not need to be aware of whether the data they refer to is stored or derived. A multiuser DBMS whose users have a variety of distinct applications must provide facilities for defining multiple views. For example, one user of the database of Figure 1.2 may be interested only in accessing and printing the transcript of each student; the view for this user is shown in Figure 1.5(a). A second user, who is interested only in checking that students have taken all the prerequisites of each course for which the student registers, may require the view shown in Figure 1.5(b).

1.3.4 Sharing of Data and Multiuser Transaction Processing

A multiuser DBMS, as its name implies, must allow multiple users to access the database at the same time. This is essential if data for multiple applications is to be integrated and maintained in a single database. The DBMS must include **concurrency control** software to ensure that several users trying to update the same data

TRANSCRIPT

Student_name	Student_transcript				
	Course_number	Grade	Semester	Year	Section_id
Smith	CS1310	C	Fall	08	119
	MATH2410	B	Fall	08	112
Brown	MATH2410	A	Fall	07	85
	CS1310	A	Fall	07	92
	CS3320	B	Spring	08	102
	CS3380	A	Fall	08	135

(a)

COURSE_PREREQUISITES

Course_name	Course_number	Prerequisites
Database	CS3380	CS3320
		MATH2410
Data Structures	CS3320	CS1310

(b)

Figure 1.5

Two views derived from the database in Figure 1.2. (a) The TRANSCRIPT view.

(b) The COURSE_PREREQUISITES view.

do so in a controlled manner so that the result of the updates is correct. For example, when several reservation agents try to assign a seat on an airline flight, the DBMS should ensure that each seat can be accessed by only one agent at a time for assignment to a passenger. These types of applications are generally called **online transaction processing (OLTP)** applications. A fundamental role of multiuser DBMS software is to ensure that concurrent transactions operate correctly and efficiently.

The concept of a **transaction** has become central to many database applications. A transaction is an *executing program or process* that includes one or more database accesses, such as reading or updating of database records. Each transaction is supposed to execute a logically correct database access if executed in its entirety without interference from other transactions. The DBMS must enforce several transaction properties. The **isolation** property ensures that each transaction appears to execute in isolation from other transactions, even though hundreds of transactions may be executing concurrently. The **atomicity** property ensures that either all the database operations in a transaction are executed or none are. We discuss transactions in detail in Part 9.

The preceding characteristics are important in distinguishing a DBMS from traditional file-processing software. In Section 1.6 we discuss additional features that characterize a DBMS. First, however, we categorize the different types of people who work in a database system environment.

1.4 Actors on the Scene

For a small personal database, such as the list of addresses discussed in Section 1.1, one person typically defines, constructs, and manipulates the database, and there is no sharing. However, in large organizations, many people are involved in the design, use, and maintenance of a large database with hundreds or thousands of users. In this section we identify the people whose jobs involve the day-to-day use of a large database; we call them the *actors on the scene*. In Section 1.5 we consider people who may be called *workers behind the scene*—those who work to maintain the database system environment but who are not actively interested in the database contents as part of their daily job.

1.4.1 Database Administrators

In any organization where many people use the same resources, there is a need for a chief administrator to oversee and manage these resources. In a database environment, the primary resource is the database itself, and the secondary resource is the DBMS and related software. Administering these resources is the responsibility of the **database administrator (DBA)**. The DBA is responsible for authorizing access to the database, coordinating and monitoring its use, and acquiring software and hardware resources as needed. The DBA is accountable for problems such as security breaches and poor system response time. In large organizations, the DBA is assisted by a staff that carries out these functions.

1.4.2 Database Designers

Database designers are responsible for identifying the data to be stored in the database and for choosing appropriate structures to represent and store this data. These tasks are mostly undertaken before the database is actually implemented and populated with data. It is the responsibility of database designers to communicate with all prospective database users in order to understand their requirements and to create a design that meets these requirements. In many cases, the designers are on the staff of the DBA and may be assigned other staff responsibilities after the database design is completed. Database designers typically interact with each potential group of users and develop **views** of the database that meet the data and processing requirements of these groups. Each view is then analyzed and *integrated* with the views of other user groups. The final database design must be capable of supporting the requirements of all user groups.

1.4.3 End Users

End users are the people whose jobs require access to the database for querying, updating, and generating reports; the database primarily exists for their use. There are several categories of end users:

- **Casual end users** occasionally access the database, but they may need different information each time. They use a sophisticated database query interface

to specify their requests and are typically middle- or high-level managers or other occasional browsers.

- **Naive or parametric end users** make up a sizable portion of database end users. Their main job function revolves around constantly querying and updating the database, using standard types of queries and updates—called **canned transactions**—that have been carefully programmed and tested. Many of these tasks are now available as **mobile apps** for use with mobile devices. The tasks that such users perform are varied. A few examples are:
 - Bank customers and tellers check account balances and post withdrawals and deposits.
 - Reservation agents or customers for airlines, hotels, and car rental companies check availability for a given request and make reservations.
 - Employees at receiving stations for shipping companies enter package identifications via bar codes and descriptive information through buttons to update a central database of received and in-transit packages.
 - Social media users post and read items on social media Web sites.
- **Sophisticated end users** include engineers, scientists, business analysts, and others who thoroughly familiarize themselves with the facilities of the DBMS in order to implement their own applications to meet their complex requirements.
- **Standalone users** maintain personal databases by using ready-made program packages that provide easy-to-use menu-based or graphics-based interfaces. An example is the user of a financial software package that stores a variety of personal financial data.

A typical DBMS provides multiple facilities to access a database. Naive end users need to learn very little about the facilities provided by the DBMS; they simply have to understand the user interfaces of the mobile apps or standard transactions designed and implemented for their use. Casual users learn only a few facilities that they may use repeatedly. Sophisticated users try to learn most of the DBMS facilities in order to achieve their complex requirements. Standalone users typically become very proficient in using a specific software package.

1.4.4 System Analysts and Application Programmers (Software Engineers)

System analysts determine the requirements of end users, especially naive and parametric end users, and develop specifications for standard canned transactions that meet these requirements. **Application programmers** implement these specifications as programs; then they test, debug, document, and maintain these canned transactions. Such analysts and programmers—commonly referred to as **software developers** or **software engineers**—should be familiar with the full range of capabilities provided by the DBMS to accomplish their tasks.

1.5 Workers behind the Scene

In addition to those who design, use, and administer a database, others are associated with the design, development, and operation of the DBMS *software and system environment*. These persons are typically not interested in the database content itself. We call them the *workers behind the scene*, and they include the following categories:

- **DBMS system designers and implementers** design and implement the DBMS modules and interfaces as a software package. A DBMS is a very complex software system that consists of many components, or **modules**, including modules for implementing the catalog, query language processing, interface processing, accessing and buffering data, controlling concurrency, and handling data recovery and security. The DBMS must interface with other system software, such as the operating system and compilers for various programming languages.
- **Tool developers** design and implement **tools**—the software packages that facilitate database modeling and design, database system design, and improved performance. Tools are optional packages that are often purchased separately. They include packages for database design, performance monitoring, natural language or graphical interfaces, prototyping, simulation, and test data generation. In many cases, independent software vendors develop and market these tools.
- **Operators and maintenance personnel** (system administration personnel) are responsible for the actual running and maintenance of the hardware and software environment for the database system.

Although these categories of workers behind the scene are instrumental in making the database system available to end users, they typically do not use the database contents for their own purposes.

1.6 Advantages of Using the DBMS Approach

In this section we discuss some additional advantages of using a DBMS and the capabilities that a good DBMS should possess. These capabilities are in addition to the four main characteristics discussed in Section 1.3. The DBA must utilize these capabilities to accomplish a variety of objectives related to the design, administration, and use of a large multiuser database.

1.6.1 Controlling Redundancy

In traditional software development utilizing file processing, every user group maintains its own files for handling its data-processing applications. For example, consider the UNIVERSITY database example of Section 1.2; here, two groups of users might be the course registration personnel and the accounting office. In the traditional approach, each group independently keeps files on students. The

accounting office keeps data on registration and related billing information, whereas the registration office keeps track of student courses and grades. Other groups may further duplicate some or all of the same data in their own files.

This **redundancy** in storing the same data multiple times leads to several problems. First, there is the need to perform a single logical update—such as entering data on a new student—multiple times: once for each file where student data is recorded. This leads to *duplication of effort*. Second, *storage space is wasted* when the same data is stored repeatedly, and this problem may be serious for large databases. Third, files that represent the same data may become *inconsistent*. This may happen because an update is applied to some of the files but not to others. Even if an update—such as adding a new student—is applied to all the appropriate files, the data concerning the student may still be *inconsistent* because the updates are applied independently by each user group. For example, one user group may enter a student's birth date erroneously as 'JAN-19-1988', whereas the other user groups may enter the correct value of 'JAN-29-1988'.

In the database approach, the views of different user groups are integrated during database design. Ideally, we should have a database design that stores each logical data item—such as a student's name or birth date—in *only one place* in the database. This is known as **data normalization**, and it ensures consistency and saves storage space (data normalization is described in Part 6 of the text).

However, in practice, it is sometimes necessary to use **controlled redundancy** to improve the performance of queries. For example, we may store `Student_name` and `Course_number` redundantly in a `GRADE_REPORT` file (Figure 1.6(a)) because whenever we retrieve a `GRADE_REPORT` record, we want to retrieve the student name and course number along with the grade, student number, and section identifier. By placing all the data together, we do not have to search multiple files to collect this data. This is known as **denormalization**. In such cases, the DBMS should

Figure 1.6

Redundant storage of `Student_name` and `Course_name` in `GRADE_REPORT`.
 (a) Consistent data.
 (b) Inconsistent record.

GRADE REPORT				
Student_number	Student_name	Section_identifier	Course_number	Grade
17	Smith	112	MATH2410	B
17	Smith	119	CS1310	C
8	Brown	85	MATH2410	A
8	Brown	92	CS1310	A
8	Brown	102	CS3320	B
8	Brown	135	CS3380	A

GRADE REPORT				
Student_number	Student_name	Section_identifier	Course_number	Grade
17	Brown	112	MATH2410	B

have the capability to *control* this redundancy in order to prohibit inconsistencies among the files. This may be done by automatically checking that the Student_name–Student_number values in any GRADE_REPORT record in Figure 1.6(a) match one of the Name–Student_number values of a STUDENT record (Figure 1.2). Similarly, the Section_identifier–Course_number values in GRADE_REPORT can be checked against SECTION records. Such checks can be specified to the DBMS during database design and automatically enforced by the DBMS whenever the GRADE_REPORT file is updated. Figure 1.6(b) shows a GRADE_REPORT record that is inconsistent with the STUDENT file in Figure 1.2; this kind of error may be entered if the redundancy is *not controlled*. Can you tell which part is inconsistent?

1.6.2 Restricting Unauthorized Access

When multiple users share a large database, it is likely that most users will not be authorized to access all information in the database. For example, financial data such as salaries and bonuses is often considered confidential, and only authorized persons are allowed to access such data. In addition, some users may only be permitted to retrieve data, whereas others are allowed to retrieve and update. Hence, the type of access operation—retrieval or update—must also be controlled. Typically, users or user groups are given account numbers protected by passwords, which they can use to gain access to the database. A DBMS should provide a **security and authorization subsystem**, which the DBA uses to create accounts and to specify account restrictions. Then, the DBMS should enforce these restrictions automatically. Notice that we can apply similar controls to the DBMS software. For example, only the DBA’s staff may be allowed to use certain **privileged software**, such as the software for creating new accounts. Similarly, parametric users may be allowed to access the database only through the pre-defined apps or canned transactions developed for their use. We discuss database security and authorization in Chapter 30.

1.6.3 Providing Persistent Storage for Program Objects

Databases can be used to provide **persistent storage** for program objects and data structures. This is one of the main reasons for **object-oriented database systems** (see Chapter 12). Programming languages typically have complex data structures, such as structs or class definitions in C++ or Java. The values of program variables or objects are discarded once a program terminates, unless the programmer explicitly stores them in permanent files, which often involves converting these complex structures into a format suitable for file storage. When the need arises to read this data once more, the programmer must convert from the file format to the program variable or object structure. Object-oriented database systems are compatible with programming languages such as C++ and Java, and the DBMS software automatically performs any necessary conversions. Hence, a complex object in C++ can be stored permanently in an object-oriented DBMS. Such an object is said to be **persistent**, since it survives the termination of program execution and can later be directly retrieved by another program.

The persistent storage of program objects and data structures is an important function of database systems. Traditional database systems often suffered from the so-called **impedance mismatch problem**, since the data structures provided by the DBMS were incompatible with the programming language's data structures. Object-oriented database systems typically offer data structure **compatibility** with one or more object-oriented programming languages.

1.6.4 Providing Storage Structures and Search Techniques for Efficient Query Processing

Database systems must provide capabilities for *efficiently executing queries and updates*. Because the database is typically stored on disk, the DBMS must provide specialized data structures and search techniques to speed up disk search for the desired records. Auxiliary files called **indexes** are often used for this purpose. Indexes are typically based on tree data structures or hash data structures that are suitably modified for disk search. In order to process the database records needed by a particular query, those records must be copied from disk to main memory. Therefore, the DBMS often has a **buffering** or **caching** module that maintains parts of the database in main memory buffers. In general, the operating system is responsible for disk-to-memory buffering. However, because data buffering is crucial to the DBMS performance, most DBMSs do their own data buffering.

The **query processing and optimization** module of the DBMS is responsible for choosing an efficient query execution plan for each query based on the existing storage structures. The choice of which indexes to create and maintain is part of *physical database design and tuning*, which is one of the responsibilities of the DBA staff. We discuss query processing and optimization in Part 8 of the text.

1.6.5 Providing Backup and Recovery

A DBMS must provide facilities for recovering from hardware or software failures. The **backup and recovery subsystem** of the DBMS is responsible for recovery. For example, if the computer system fails in the middle of a complex update transaction, the recovery subsystem is responsible for making sure that the database is restored to the state it was in before the transaction started executing. Disk backup is also necessary in case of a catastrophic disk failure. We discuss recovery and backup in Chapter 22.

1.6.6 Providing Multiple User Interfaces

Because many types of users with varying levels of technical knowledge use a database, a DBMS should provide a variety of user interfaces. These include apps for mobile users, query languages for casual users, programming language interfaces for application programmers, forms and command codes for parametric users, and menu-driven interfaces and natural language interfaces for standalone users. Both forms-style interfaces and menu-driven interfaces are commonly known as

graphical user interfaces (GUIs). Many specialized languages and environments exist for specifying GUIs. Capabilities for providing Web GUI interfaces to a database—or Web-enabling a database—are also quite common.

1.6.7 Representing Complex Relationships among Data

A database may include numerous varieties of data that are interrelated in many ways. Consider the example shown in Figure 1.2. The record for ‘Brown’ in the STUDENT file is related to four records in the GRADE_REPORT file. Similarly, each section record is related to one course record and to a number of GRADE_REPORT records—one for each student who completed that section. A DBMS must have the capability to represent a variety of complex relationships among the data, to define new relationships as they arise, and to retrieve and update related data easily and efficiently.

1.6.8 Enforcing Integrity Constraints

Most database applications have certain **integrity constraints** that must hold for the data. A DBMS should provide capabilities for defining and enforcing these constraints. The simplest type of integrity constraint involves specifying a data type for each data item. For example, in Figure 1.3, we specified that the value of the Class data item within each STUDENT record must be a one-digit integer and that the value of Name must be a string of no more than 30 alphabetic characters. To restrict the value of Class between 1 and 5 would be an additional constraint that is not shown in the current catalog. A more complex type of constraint that frequently occurs involves specifying that a record in one file must be related to records in other files. For example, in Figure 1.2, we can specify that *every section record must be related to a course record*. This is known as a **referential integrity** constraint. Another type of constraint specifies uniqueness on data item values, such as *every course record must have a unique value for Course_number*. This is known as a **key or uniqueness** constraint. These constraints are derived from the meaning or **semantics** of the data and of the miniworld it represents. It is the responsibility of the database designers to identify integrity constraints during database design. Some constraints can be specified to the DBMS and automatically enforced. Other constraints may have to be checked by update programs or at the time of data entry. For typical large applications, it is customary to call such constraints **business rules**.

A data item may be entered erroneously and still satisfy the specified integrity constraints. For example, if a student receives a grade of ‘A’ but a grade of ‘C’ is entered in the database, the DBMS *cannot* discover this error automatically because ‘C’ is a valid value for the Grade data type. Such data entry errors can only be discovered manually (when the student receives the grade and complains) and corrected later by updating the database. However, a grade of ‘Z’ would be rejected automatically by the DBMS because ‘Z’ is not a valid value for the Grade data type. When we discuss each data model in subsequent chapters, we will introduce rules that pertain to

that model implicitly. For example, in the Entity-Relationship model in Chapter 3, a relationship must involve at least two entities. Rules that pertain to a specific data model are called **inherent rules** of the data model.

1.6.9 Permitting Inferencing and Actions Using Rules and Triggers

Some database systems provide capabilities for defining *deduction rules* for *inferencing* new information from the stored database facts. Such systems are called **deductive database systems**. For example, there may be complex rules in the miniworld application for determining when a student is on probation. These can be specified *declaratively* as **rules**, which when compiled and maintained by the DBMS can determine all students on probation. In a traditional DBMS, an explicit *procedural program code* would have to be written to support such applications. But if the miniworld rules change, it is generally more convenient to change the declared deduction rules than to recode procedural programs. In today's relational database systems, it is possible to associate **triggers** with tables. A trigger is a form of a rule activated by updates to the table, which results in performing some additional operations to some other tables, sending messages, and so on. More involved procedures to enforce rules are popularly called **stored procedures**; they become a part of the overall database definition and are invoked appropriately when certain conditions are met. More powerful functionality is provided by **active database systems**, which provide active rules that can automatically initiate actions when certain events and conditions occur (see Chapter 26 for introductions to active databases in Section 26.1 and deductive databases in Section 26.5).

1.6.10 Additional Implications of Using the Database Approach

This section discusses a few additional implications of using the database approach that can benefit most organizations.

Potential for Enforcing Standards. The database approach permits the DBA to define and enforce standards among database users in a large organization. This facilitates communication and cooperation among various departments, projects, and users within the organization. Standards can be defined for names and formats of data elements, display formats, report structures, terminology, and so on. The DBA can enforce standards in a centralized database environment more easily than in an environment where each user group has control of its own data files and software.

Reduced Application Development Time. A prime selling feature of the database approach is that developing a new application—such as the retrieval of certain data from the database for printing a new report—takes very little time. Designing and implementing a large multiuser database from scratch may take more time than writing a single specialized file application. However, once a database is up and running, substantially less time is generally required to create new applications

using DBMS facilities. Development time using a DBMS is estimated to be one-sixth to one-fourth of that for a file system.

Flexibility. It may be necessary to change the structure of a database as requirements change. For example, a new user group may emerge that needs information not currently in the database. In response, it may be necessary to add a file to the database or to extend the data elements in an existing file. Modern DBMSs allow certain types of evolutionary changes to the structure of the database without affecting the stored data and the existing application programs.

Availability of Up-to-Date Information. A DBMS makes the database available to all users. As soon as one user's update is applied to the database, all other users can immediately see this update. This availability of up-to-date information is essential for many transaction-processing applications, such as reservation systems or banking databases, and it is made possible by the concurrency control and recovery subsystems of a DBMS.

Economies of Scale. The DBMS approach permits consolidation of data and applications, thus reducing the amount of wasteful overlap between activities of data-processing personnel in different projects or departments as well as redundancies among applications. This enables the whole organization to invest in more powerful processors, storage devices, or networking gear, rather than having each department purchase its own (lower performance) equipment. This reduces overall costs of operation and management.

1.7 A Brief History of Database Applications

We now give a brief historical overview of the applications that use DBMSs and how these applications provided the impetus for new types of database systems.

1.7.1 Early Database Applications Using Hierarchical and Network Systems

Many early database applications maintained records in large organizations such as corporations, universities, hospitals, and banks. In many of these applications, there were large numbers of records of similar structure. For example, in a university application, similar information would be kept for each student, each course, each grade record, and so on. There were also many types of records and many interrelationships among them.

One of the main problems with early database systems was the intermixing of conceptual relationships with the physical storage and placement of records on disk. Hence, these systems did not provide sufficient *data abstraction* and *program-data independence* capabilities. For example, the grade records of a particular student could be physically stored next to the student record. Although this provided very

efficient access for the original queries and transactions that the database was designed to handle, it did not provide enough flexibility to access records efficiently when new queries and transactions were identified. In particular, new queries that required a different storage organization for efficient processing were quite difficult to implement efficiently. It was also laborious to reorganize the database when changes were made to the application's requirements.

Another shortcoming of early systems was that they provided only programming language interfaces. This made it time-consuming and expensive to implement new queries and transactions, since new programs had to be written, tested, and debugged. Most of these database systems were implemented on large and expensive mainframe computers starting in the mid-1960s and continuing through the 1970s and 1980s. The main types of early systems were based on three main paradigms: hierarchical systems, network model-based systems, and inverted file systems.

1.7.2 Providing Data Abstraction and Application Flexibility with Relational Databases

Relational databases were originally proposed to separate the physical storage of data from its conceptual representation and to provide a mathematical foundation for data representation and querying. The relational data model also introduced high-level query languages that provided an alternative to programming language interfaces, making it much faster to write new queries. Relational representation of data somewhat resembles the example we presented in Figure 1.2. Relational systems were initially targeted to the same applications as earlier systems, and provided flexibility to develop new queries quickly and to reorganize the database as requirements changed. Hence, *data abstraction* and *program-data independence* were much improved when compared to earlier systems.

Early experimental relational systems developed in the late 1970s and the commercial relational database management systems (RDBMS) introduced in the early 1980s were quite slow, since they did not use physical storage pointers or record placement to access related data records. With the development of new storage and indexing techniques and better query processing and optimization, their performance improved. Eventually, relational databases became the dominant type of database system for traditional database applications. Relational databases now exist on almost all types of computers, from small personal computers to large servers.

1.7.3 Object-Oriented Applications and the Need for More Complex Databases

The emergence of object-oriented programming languages in the 1980s and the need to store and share complex, structured objects led to the development of object-oriented databases (OODBs). Initially, OODBs were considered a competitor

to relational databases, since they provided more general data structures. They also incorporated many of the useful object-oriented paradigms, such as abstract data types, encapsulation of operations, inheritance, and object identity. However, the complexity of the model and the lack of an early standard contributed to their limited use. They are now mainly used in specialized applications, such as engineering design, multimedia publishing, and manufacturing systems. Despite expectations that they will make a big impact, their overall penetration into the database products market remains low. In addition, many object-oriented concepts were incorporated into the newer versions of relational DBMSs, leading to object-relational database management systems, known as ORDBMSs.

1.7.4 Interchanging Data on the Web for E-Commerce Using XML

The World Wide Web provides a large network of interconnected computers. Users can create static Web pages using a Web publishing language, such as HyperText Markup Language (HTML), and store these documents on Web servers where other users (clients) can access them and view them through Web browsers. Documents can be linked through **hyperlinks**, which are pointers to other documents. Starting in the 1990s, electronic commerce (e-commerce) emerged as a major application on the Web. Much of the critical information on e-commerce Web pages is dynamically extracted data from DBMSs, such as flight information, product prices, and product availability. A variety of techniques were developed to allow the interchange of dynamically extracted data on the Web for display on Web pages. The eXtended Markup Language (XML) is one standard for interchanging data among various types of databases and Web pages. XML combines concepts from the models used in document systems with database modeling concepts. Chapter 13 is devoted to an overview of XML.

1.7.5 Extending Database Capabilities for New Applications

The success of database systems in traditional applications encouraged developers of other types of applications to attempt to use them. Such applications traditionally used their own specialized software and file and data structures. Database systems now offer extensions to better support the specialized requirements for some of these applications. The following are some examples of these applications:

- **Scientific** applications that store large amounts of data resulting from scientific experiments in areas such as high-energy physics, the mapping of the human genome, and the discovery of protein structures
- Storage and retrieval of **images**, including scanned news or personal photographs, satellite photographic images, and images from medical procedures such as x-rays and MRI (magnetic resonance imaging) tests

- Storage and retrieval of **videos**, such as movies, and **video clips** from news or personal digital cameras
- **Data mining** applications that analyze large amounts of data to search for the occurrences of specific patterns or relationships, and for identifying unusual patterns in areas such as credit card fraud detection
- **Spatial** applications that store and analyze spatial locations of data, such as weather information, maps used in geographical information systems, and automobile navigational systems
- **Time series** applications that store information such as economic data at regular points in time, such as daily sales and monthly gross national product figures

It was quickly apparent that basic relational systems were not very suitable for many of these applications, usually for one or more of the following reasons:

- More complex data structures were needed for modeling the application than the simple relational representation.
- New data types were needed in addition to the basic numeric and character string types.
- New operations and query language constructs were necessary to manipulate the new data types.
- New storage and indexing structures were needed for efficient searching on the new data types.

This led DBMS developers to add functionality to their systems. Some functionality was general purpose, such as incorporating concepts from object-oriented databases into relational systems. Other functionality was special purpose, in the form of optional modules that could be used for specific applications. For example, users could buy a time series module to use with their relational DBMS for their time series application.

1.7.6 Emergence of Big Data Storage Systems and NOSQL Databases

In the first decade of the twenty-first century, the proliferation of applications and platforms such as social media Web sites, large e-commerce companies, Web search indexes, and cloud storage/backup led to a surge in the amount of data stored on large databases and massive servers. New types of database systems were necessary to manage these huge databases—systems that would provide fast search and retrieval as well as reliable and safe storage of nontraditional types of data, such as social media posts and tweets. Some of the requirements of these new systems were not compatible with SQL relational DBMSs (SQL is the standard data model and language for relational databases). The term **NOSQL** is generally interpreted as Not Only SQL, meaning that in systems that manage large amounts of data, some of the data is stored using SQL systems, whereas other data would be stored using NOSQL, depending on the application requirements.

1.8 When Not to Use a DBMS

In spite of the advantages of using a DBMS, there are a few situations in which a DBMS may involve unnecessary overhead costs that would not be incurred in traditional file processing. The overhead costs of using a DBMS are due to the following:

- High initial investment in hardware, software, and training
- The generality that a DBMS provides for defining and processing data
- Overhead for providing security, concurrency control, recovery, and integrity functions

Therefore, it may be more desirable to develop customized database applications under the following circumstances:

- Simple, well-defined database applications that are not expected to change at all
- Stringent, real-time requirements for some application programs that may not be met because of DBMS overhead
- Embedded systems with limited storage capacity, where a general-purpose DBMS would not fit
- No multiple-user access to data

Certain industries and applications have elected not to use general-purpose DBMSs. For example, many computer-aided design (CAD) tools used by mechanical and civil engineers have proprietary file and data management software that is geared for the internal manipulations of drawings and 3D objects. Similarly, communication and switching systems designed by companies like AT&T were early manifestations of database software that was made to run very fast with hierarchically organized data for quick access and routing of calls. GIS implementations often implement their own data organization schemes for efficiently implementing functions related to processing maps, physical contours, lines, polygons, and so on.

1.9 Summary

In this chapter we defined a database as a collection of related data, where *data* means recorded facts. A typical database represents some aspect of the real world and is used for specific purposes by one or more groups of users. A DBMS is a generalized software package for implementing and maintaining a computerized database. The database and software together form a database system. We identified several characteristics that distinguish the database approach from traditional file-processing applications, and we discussed the main categories of database users, or the *actors on the scene*. We noted that in addition to database users, there are several categories of support personnel, or *workers behind the scene*, in a database environment.

We presented a list of capabilities that should be provided by the DBMS software to the DBA, database designers, and end users to help them design, administer, and use a database. Then we gave a brief historical perspective on the evolution of database applications. We pointed out the recent rapid growth of the amounts and types of data that must be stored in databases, and we discussed the emergence of new systems for handling “big data” applications. Finally, we discussed the overhead costs of using a DBMS and discussed some situations in which it may not be advantageous to use one.

Review Questions

- 1.1. Define the following terms: *data*, *database*, *DBMS*, *database system*, *database catalog*, *program-data independence*, *user view*, *DBA*, *end user*, *canned transaction*, *deductive database system*, *persistent object*, *meta-data*, and *transaction-processing application*.
- 1.2. What four main types of actions involve databases? Briefly discuss each.
- 1.3. Discuss the main characteristics of the database approach and how it differs from traditional file systems.
- 1.4. What are the responsibilities of the DBA and the database designers?
- 1.5. What are the different types of database end users? Discuss the main activities of each.
- 1.6. Discuss the capabilities that should be provided by a DBMS.
- 1.7. Discuss the differences between database systems and information retrieval systems.

Exercises

- 1.8. Identify some informal queries and update operations that you would expect to apply to the database shown in Figure 1.2.
- 1.9. What is the difference between controlled and uncontrolled redundancy? Illustrate with examples.
- 1.10. Specify all the relationships among the records of the database shown in Figure 1.2.
- 1.11. Give some additional views that may be needed by other user groups for the database shown in Figure 1.2.
- 1.12. Cite some examples of integrity constraints that you think can apply to the database shown in Figure 1.2.
- 1.13. Give examples of systems in which it may make sense to use traditional file processing instead of a database approach.

1.14. Consider Figure 1.2.

- a. If the name of the ‘CS’ (Computer Science) Department changes to ‘CSSE’ (Computer Science and Software Engineering) Department and the corresponding prefix for the course number also changes, identify the columns in the database that would need to be updated.
- b. Can you restructure the columns in the COURSE, SECTION, and PREREQUISITE tables so that only one column will need to be updated?

Selected Bibliography

The October 1991 issue of *Communications of the ACM* and Kim (1995) include several articles describing next-generation DBMSs; many of the database features discussed in the former are now commercially available. The March 1976 issue of *ACM Computing Surveys* offers an early introduction to database systems and may provide a historical perspective for the interested reader. We will include references to other concepts, systems, and applications introduced in this chapter in the later text chapters that discuss each topic in more detail.

Database System Concepts and Architecture

The architecture of DBMS packages has evolved from the early monolithic systems, where the whole DBMS software package was one tightly integrated system, to the modern DBMS packages that are modular in design, with a client/server system architecture. The recent growth in the amount of data requiring storage has led to database systems with distributed architectures comprised of thousands of computers that manage the data stores. This evolution mirrors the trends in computing, where large centralized mainframe computers are replaced by hundreds of distributed workstations and personal computers connected via communications networks to various types of server machines—Web servers, database servers, file servers, application servers, and so on. The current **cloud computing** environments consist of thousands of large servers managing so-called **big data** for users on the Web.

In a basic client/server DBMS architecture, the system functionality is distributed between two types of modules.¹ A **client module** is typically designed so that it will run on a mobile device, user workstation, or personal computer (PC). Typically, application programs and user interfaces that access the database run in the client module. Hence, the client module handles user interaction and provides the user-friendly interfaces such as apps for mobile devices, or forms- or menu-based GUIs (graphical user interfaces) for PCs. The other kind of module, called a **server module**, typically handles data storage, access, search, and other functions. We discuss client/server architectures in more detail in Section 2.5. First, we must study more basic concepts that will give us a better understanding of modern database architectures.

¹As we shall see in Section 2.5, there are variations on this simple *two-tier* client/server architecture.

In this chapter we present the terminology and basic concepts that will be used throughout the text. Section 2.1 discusses data models and defines the concepts of schemas and instances, which are fundamental to the study of database systems. We discuss the three-schema DBMS architecture and data independence in Section 2.2; this provides a user's perspective on what a DBMS is supposed to do. In Section 2.3 we describe the types of interfaces and languages that are typically provided by a DBMS. Section 2.4 discusses the database system software environment. Section 2.5 gives an overview of various types of client/server architectures. Finally, Section 2.6 presents a classification of the types of DBMS packages. Section 2.7 summarizes the chapter.

The material in Sections 2.4 through 2.6 provides detailed concepts that may be considered as supplementary to the basic introductory material.

2.1 Data Models, Schemas, and Instances

One fundamental characteristic of the database approach is that it provides some level of data abstraction. **Data abstraction** generally refers to the suppression of details of data organization and storage, and the highlighting of the essential features for an improved understanding of data. One of the main characteristics of the database approach is to support data abstraction so that different users can perceive data at their preferred level of detail. A **data model**—a collection of concepts that can be used to describe the structure of a database—provides the necessary means to achieve this abstraction.² By *structure of a database* we mean the data types, relationships, and constraints that apply to the data. Most data models also include a set of **basic operations** for specifying retrievals and updates on the database.

In addition to the basic operations provided by the data model, it is becoming more common to include concepts in the data model to specify the **dynamic aspect** or **behavior** of a database application. This allows the database designer to specify a set of valid user-defined operations that are allowed on the database objects.³ An example of a user-defined operation could be COMPUTE_GPA, which can be applied to a STUDENT object. On the other hand, generic operations to insert, delete, modify, or retrieve any kind of object are often included in the *basic data model operations*. Concepts to specify behavior are fundamental to object-oriented data models (see Chapter 12) but are also being incorporated in more traditional data models. For example, object-relational models (see Chapter 12) extend the basic relational model to include such concepts, among others. In the basic relational data model, there is a provision to attach behavior to the relations in the form of persistent stored modules, popularly known as stored procedures (see Chapter 10).

²Sometimes the word *model* is used to denote a specific database description, or schema—for example, the *marketing data model*. We will not use this interpretation.

³The inclusion of concepts to describe behavior reflects a trend whereby database design and software design activities are increasingly being combined into a single activity. Traditionally, specifying behavior is associated with software design.

2.1.1 Categories of Data Models

Many data models have been proposed, which we can categorize according to the types of concepts they use to describe the database structure. **High-level** or **conceptual data models** provide concepts that are close to the way many users perceive data, whereas **low-level** or **physical data models** provide concepts that describe the details of how data is stored on the computer storage media, typically magnetic disks. Concepts provided by physical data models are generally meant for computer specialists, not for end users. Between these two extremes is a class of **representational** (or **implementation**) **data models**,⁴ which provide concepts that may be easily understood by end users but that are not too far removed from the way data is organized in computer storage. Representational data models hide many details of data storage on disk but can be implemented on a computer system directly.

Conceptual data models use concepts such as entities, attributes, and relationships. An **entity** represents a real-world object or concept, such as an employee or a project from the miniworld that is described in the database. An **attribute** represents some property of interest that further describes an entity, such as the employee's name or salary. A **relationship** among two or more entities represents an association among the entities, for example, a works-on relationship between an employee and a project. Chapter 3 presents the **entity–relationship model**—a popular high-level conceptual data model. Chapter 4 describes additional abstractions used for advanced modeling, such as generalization, specialization, and categories (union types).

Representational or implementation data models are the models used most frequently in traditional commercial DBMSs. These include the widely used **relational data model**, as well as the so-called legacy data models—the **network** and **hierarchical models**—that have been widely used in the past. Part 3 of the text is devoted to the relational data model, and its constraints, operations, and languages.⁵ The SQL standard for relational databases is described in Chapters 6 and 7. Representational data models represent data by using record structures and hence are sometimes called **record-based data models**.

We can regard the **object data model** as an example of a new family of higher-level implementation data models that are closer to conceptual data models. A standard for object databases called the ODMG object model has been proposed by the Object Data Management Group (ODMG). We describe the general characteristics of object databases and the object model proposed standard in Chapter 12. Object data models are also frequently utilized as high-level conceptual models, particularly in the software engineering domain.

Physical data models describe how data is stored as files in the computer by representing information such as record formats, record orderings, and access paths. An

⁴The term *implementation data model* is not a standard term; we have introduced it to refer to the available data models in commercial database systems.

⁵A summary of the hierarchical and network data models is included in Appendices D and E. They are accessible from the book's Web site.

access path is a search structure that makes the search for particular database records efficient, such as indexing or hashing. We discuss physical storage techniques and access structures in Chapters 16 and 17. An **index** is an example of an access path that allows direct access to data using an index term or a keyword. It is similar to the index at the end of this text, except that it may be organized in a linear, hierarchical (tree-structured), or some other fashion.

Another class of data models is known as **self-describing data models**. The data storage in systems based on these models combines the description of the data with the data values themselves. In traditional DBMSs, the description (schema) is separated from the data. These models include **XML** (see Chapter 12) as well as many of the **key-value stores** and **NOSQL systems** (see Chapter 24) that were recently created for managing big data.

2.1.2 Schemas, Instances, and Database State

In a data model, it is important to distinguish between the *description* of the database and the *database itself*. The description of a database is called the **database schema**, which is specified during database design and is not expected to change frequently.⁶ Most data models have certain conventions for displaying schemas as diagrams.⁷ A displayed schema is called a **schema diagram**. Figure 2.1 shows a schema diagram for the database shown in Figure 1.2; the diagram displays the structure of each record type but not the actual instances of records.

Figure 2.1

Schema diagram for the database in Figure 1.2.

STUDENT

Name	Student_number	Class	Major
------	----------------	-------	-------

COURSE

Course_name	Course_number	Credit_hours	Department
-------------	---------------	--------------	------------

PREREQUISITE

Course_number	Prerequisite_number
---------------	---------------------

SECTION

Section_identifier	Course_number	Semester	Year	Instructor
--------------------	---------------	----------	------	------------

GRADE_REPORT

Student_number	Section_identifier	Grade
----------------	--------------------	-------

⁶Schema changes are usually needed as the requirements of the database applications change. Most database systems include operations for allowing schema changes.

⁷It is customary in database parlance to use *schemas* as the plural for *schema*, even though *schemata* is the proper plural form. The word *schema* is also sometimes used to refer to a schema.

We call each object in the schema—such as STUDENT or COURSE—a **schema construct**.

A schema diagram displays only *some aspects* of a schema, such as the names of record types and data items, and some types of constraints. Other aspects are not specified in the schema diagram; for example, Figure 2.1 shows neither the data type of each data item nor the relationships among the various files. Many types of constraints are not represented in schema diagrams. A constraint such as *students majoring in computer science must take CS1310 before the end of their sophomore year* is quite difficult to represent diagrammatically.

The actual data in a database may change quite frequently. For example, the database shown in Figure 1.2 changes every time we add a new student or enter a new grade. The data in the database at a particular moment in time is called a **database state** or **snapshot**. It is also called the *current set of occurrences* or **instances** in the database. In a given database state, each schema construct has its own *current set* of instances; for example, the STUDENT construct will contain the set of individual student entities (records) as its instances. Many database states can be constructed to correspond to a particular database schema. Every time we insert or delete a record or change the value of a data item in a record, we change one state of the database into another state.

The distinction between database schema and database state is very important. When we **define** a new database, we specify its database schema only to the DBMS. At this point, the corresponding database state is the *empty state* with no data. We get the *initial state* of the database when the database is first **populated** or **loaded** with the initial data. From then on, every time an update operation is applied to the database, we get another database state. At any point in time, the database has a *current state*.⁸ The DBMS is partly responsible for ensuring that every state of the database is a **valid state**—that is, a state that satisfies the structure and constraints specified in the schema. Hence, specifying a correct schema to the DBMS is extremely important and the schema must be designed with utmost care. The DBMS stores the descriptions of the schema constructs and constraints—also called the **meta-data**—in the DBMS catalog so that DBMS software can refer to the schema whenever it needs to. The schema is sometimes called the **intension**, and a database state is called an **extension** of the schema.

Although, as mentioned earlier, the schema is not supposed to change frequently, it is not uncommon that changes occasionally need to be applied to the schema as the application requirements change. For example, we may decide that another data item needs to be stored for each record in a file, such as adding the Date_of_birth to the STUDENT schema in Figure 2.1. This is known as **schema evolution**. Most modern DBMSs include some operations for schema evolution that can be applied while the database is operational.

⁸The current state is also called the *current snapshot* of the database. It has also been called a *database instance*, but we prefer to use the term *instance* to refer to individual records.

2.2 Three-Schema Architecture and Data Independence

Three of the four important characteristics of the database approach, listed in Section 1.3, are (1) use of a catalog to store the database description (schema) so as to make it self-describing, (2) insulation of programs and data (program-data and program-operation independence), and (3) support of multiple user views. In this section we specify an architecture for database systems, called the **three-schema architecture**,⁹ that was proposed to help achieve and visualize these characteristics. Then we discuss further the concept of data independence.

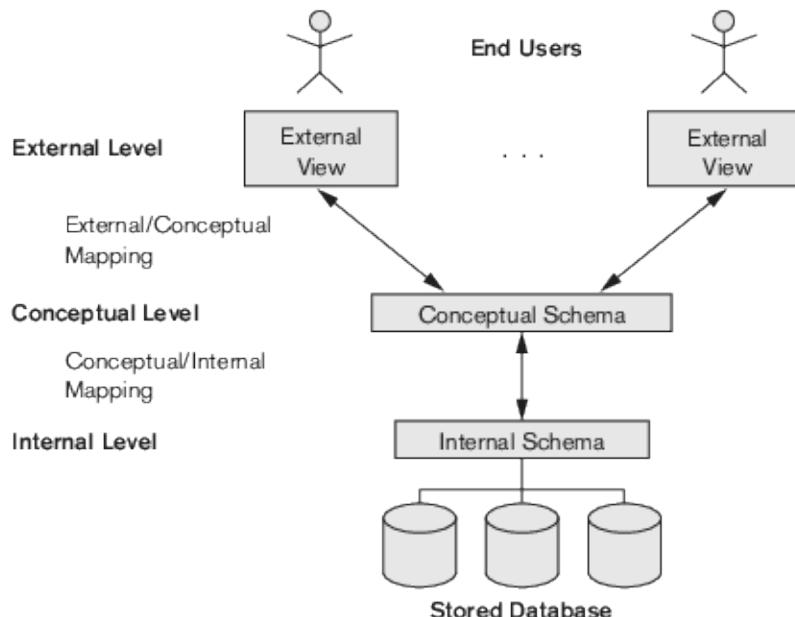
2.2.1 The Three-Schema Architecture

The goal of the three-schema architecture, illustrated in Figure 2.2, is to separate the user applications from the physical database. In this architecture, schemas can be defined at the following three levels:

1. The **internal level** has an **internal schema**, which describes the physical storage structure of the database. The internal schema uses a physical data model and describes the complete details of data storage and access paths for the database.

Figure 2.2

The three-schema architecture.



⁹This is also known as the ANSI/SPARC (American National Standards Institute/ Standards Planning And Requirements Committee) architecture, after the committee that proposed it (Tsichritzis & Klug, 1978).

2. The **conceptual level** has a **conceptual schema**, which describes the structure of the whole database for a community of users. The conceptual schema hides the details of physical storage structures and concentrates on describing entities, data types, relationships, user operations, and constraints. Usually, a representational data model is used to describe the conceptual schema when a database system is implemented. This *implementation conceptual schema* is often based on a *conceptual schema design* in a high-level data model.
3. The **external or view level** includes a number of **external schemas** or **user views**. Each external schema describes the part of the database that a particular user group is interested in and hides the rest of the database from that user group. As in the previous level, each external schema is typically implemented using a representational data model, possibly based on an external schema design in a high-level conceptual data model.

The three-schema architecture is a convenient tool with which the user can visualize the schema levels in a database system. Most DBMSs do not separate the three levels completely and explicitly, but they support the three-schema architecture to some extent. Some older DBMSs may include physical-level details in the conceptual schema. The three-level ANSI architecture has an important place in database technology development because it clearly separates the users' external level, the database's conceptual level, and the internal storage level for designing a database. It is very much applicable in the design of DBMSs, even today. In most DBMSs that support user views, external schemas are specified in the same data model that describes the conceptual-level information (for example, a relational DBMS like Oracle or SQLServer uses SQL for this).

Notice that the three schemas are only *descriptions* of data; the actual data is stored at the physical level only. In the three-schema architecture, each user group refers to its own external schema. Hence, the DBMS must transform a request specified on an external schema into a request against the conceptual schema, and then into a request on the internal schema for processing over the stored database. If the request is a database retrieval, the data extracted from the stored database must be reformatted to match the user's external view. The processes of transforming requests and results between levels are called **mappings**. These mappings may be time-consuming, so some DBMSs—especially those that are meant to support small databases—do not support external views. Even in such systems, however, it is necessary to transform requests between the conceptual and internal levels.

2.2.2 Data Independence

The three-schema architecture can be used to further explain the concept of **data independence**, which can be defined as the capacity to change the schema at one level of a database system without having to change the schema at the next higher level. We can define two types of data independence:

1. **Logical data independence** is the capacity to change the conceptual schema without having to change external schemas or application programs. We

may change the conceptual schema to expand the database (by adding a record type or data item), to change constraints, or to reduce the database (by removing a record type or data item). In the last case, external schemas that refer only to the remaining data should not be affected. For example, the external schema of Figure 1.5(a) should not be affected by changing the GRADE_REPORT file (or record type) shown in Figure 1.2 into the one shown in Figure 1.6(a). Only the view definition and the mappings need to be changed in a DBMS that supports logical data independence. After the conceptual schema undergoes a logical reorganization, application programs that reference the external schema constructs must work as before. Changes to constraints can be applied to the conceptual schema without affecting the external schemas or application programs.

2. **Physical data independence** is the capacity to change the internal schema without having to change the conceptual schema. Hence, the external schemas need not be changed as well. Changes to the internal schema may be needed because some physical files were reorganized—for example, by creating additional access structures—to improve the performance of retrieval or update. If the same data as before remains in the database, we should not have to change the conceptual schema. For example, providing an access path to improve retrieval speed of SECTION records (Figure 1.2) by semester and year should not require a query such as *list all sections offered in fall 2008* to be changed, although the query would be executed more efficiently by the DBMS by utilizing the new access path.

Generally, physical data independence exists in most databases and file environments where physical details, such as the exact location of data on disk, and hardware details of storage encoding, placement, compression, splitting, merging of records, and so on are hidden from the user. Applications remain unaware of these details. On the other hand, logical data independence is harder to achieve because it allows structural and constraint changes without affecting application programs—a much stricter requirement.

Whenever we have a multiple-level DBMS, its catalog must be expanded to include information on how to map requests and data among the various levels. The DBMS uses additional software to accomplish these mappings by referring to the mapping information in the catalog. Data independence occurs because when the schema is changed at some level, the schema at the next higher level remains unchanged; only the *mapping* between the two levels is changed. Hence, application programs referring to the higher-level schema need not be changed.

2.3 Database Languages and Interfaces

In Section 1.4 we discussed the variety of users supported by a DBMS. The DBMS must provide appropriate languages and interfaces for each category of users. In this section we discuss the types of languages and interfaces provided by a DBMS and the user categories targeted by each interface.

2.7 Summary

In this chapter we introduced the main concepts used in database systems. We defined a data model and we distinguished three main categories:

- High-level or conceptual data models (based on entities and relationships)
- Low-level or physical data models
- Representational or implementation data models (record-based, object-oriented)

We distinguished the schema, or description of a database, from the database itself. The schema does not change very often, whereas the database state changes every time data is inserted, deleted, or modified. Then we described the three-schema DBMS architecture, which allows three schema levels:

- An internal schema describes the physical storage structure of the database.
- A conceptual schema is a high-level description of the whole database.
- External schemas describe the views of different user groups.

A DBMS that cleanly separates the three levels must have mappings among the schemas to transform requests and query results from one level to the next. Most DBMSs do not separate the three levels completely. We used the three-schema architecture to define the concepts of logical and physical data independence.

Then we discussed the main types of languages and interfaces that DBMSs support. A data definition language (DDL) is used to define the database conceptual schema. In most DBMSs, the DDL also defines user views and, sometimes, storage structures; in other DBMSs, separate languages or functions exist for specifying storage structures. This distinction is fading away in today's relational implementations, with SQL serving as a catchall language to perform multiple roles, including view definition. The storage definition part (SDL) was included in SQL's early versions, but is now typically implemented as special commands for the DBA in relational DBMSs. The DBMS compiles all schema definitions and stores their descriptions in the DBMS catalog.

A data manipulation language (DML) is used for specifying database retrievals and updates. DMLs can be high level (set-oriented, nonprocedural) or low level (record-oriented, procedural). A high-level DML can be embedded in a host programming language, or it can be used as a standalone language; in the latter case it is often called a query language.

We discussed different types of interfaces provided by DBMSs and the types of DBMS users with which each interface is associated. Then we discussed the database system environment, typical DBMS software modules, and DBMS utilities for helping users and the DBA staff perform their tasks. We continued with an overview of the two-tier and three-tier architectures for database applications.

Finally, we classified DBMSs according to several criteria: data model, number of users, number of sites, types of access paths, and cost. We discussed the availability of DBMSs and additional modules—from no cost in the form of open source software to configurations that annually cost millions to maintain. We also pointed out the variety of licensing arrangements for DBMS and related products. The main classification of DBMSs is based on the data model. We briefly discussed the main data models used in current commercial DBMSs.

Review Questions

- 2.1. Define the following terms: *data model, database schema, database state, internal schema, conceptual schema, external schema, data independence, DDL, DML, SDL, VDL, query language, host language, data sublanguage, database utility, catalog, client/server architecture, three-tier architecture, and n-tier architecture.*
- 2.2. Discuss the main categories of data models. What are the basic differences among the relational model, the object model, and the XML model?
- 2.3. What is the difference between a database schema and a database state?
- 2.4. Describe the three-schema architecture. Why do we need mappings among schema levels? How do different schema definition languages support this architecture?
- 2.5. What is the difference between logical data independence and physical data independence? Which one is harder to achieve? Why?
- 2.6. What is the difference between procedural and nonprocedural DMLs?
- 2.7. Discuss the different types of user-friendly interfaces and the types of users who typically use each.
- 2.8. With what other computer system software does a DBMS interact?
- 2.9. What is the difference between the two-tier and three-tier client/server architectures?
- 2.10. Discuss some types of database utilities and tools and their functions.
- 2.11. What is the additional functionality incorporated in *n*-tier architecture ($n > 3$)?

Exercises

- 2.12. Think of different users for the database shown in Figure 1.2. What types of applications would each user need? To which user category would each belong, and what type of interface would each need?

- 2.13. Choose a database application with which you are familiar. Design a schema and show a sample database for that application, using the notation of Figures 1.2 and 2.1. What types of additional information and constraints would you like to represent in the schema? Think of several users of your database, and design a view for each.
- 2.14. If you were designing a Web-based system to make airline reservations and sell airline tickets, which DBMS architecture would you choose from Section 2.5? Why? Why would the other architectures not be a good choice?
- 2.15. Consider Figure 2.1. In addition to constraints relating the values of columns in one table to columns in another table, there are also constraints that impose restrictions on values in a column or a combination of columns within a table. One such constraint dictates that a column or a group of columns must be unique across all rows in the table. For example, in the STUDENT table, the Student_number column must be unique (to prevent two different students from having the same Student_number). Identify the column or the group of columns in the other tables that must be unique across all rows in the table.

Selected Bibliography

Many database textbooks, including Date (2004), Silberschatz et al. (2011), Ramakrishnan and Gehrke (2003), Garcia-Molina et al. (2002, 2009), and Abiteboul et al. (1995), provide a discussion of the various database concepts presented here. Tsichritzis and Lochoovsky (1982) is an early textbook on data models. Tsichritzis and Klug (1978) and Jardine (1977) present the three-schema architecture, which was first suggested in the DBTG CODASYL report (1971) and later in an American National Standards Institute (ANSI) report (1975). An in-depth analysis of the relational data model and some of its possible extensions is given in Codd (1990). The proposed standard for object-oriented databases is described in Cattell et al. (2000). Many documents describing XML are available on the Web, such as XML (2005).

Examples of database utilities are the ETI Connect, Analyze and Transform tools (<http://www.eti.com>) and the database administration tool, DBArtisan, from Embarcadero Technologies (<http://www.embarcadero.com>).

part **2**

Conceptual Data Modeling and Database Design

Data Modeling Using the Entity–Relationship (ER) Model

Conceptual modeling is a very important phase in designing a successful database application. Generally, the term **database application** refers to a particular database and the associated programs that implement the database queries and updates. For example, a BANK database application that keeps track of customer accounts would include programs that implement database updates corresponding to customer deposits and withdrawals. These programs would provide user-friendly graphical user interfaces (GUIs) utilizing forms and menus for the end users of the application—the bank customers or bank tellers in this example. In addition, it is now common to provide interfaces to these programs to BANK customers via mobile devices using **mobile apps**. Hence, a major part of the database application will require the design, implementation, and testing of these application programs. Traditionally, the design and testing of **application programs** has been considered to be part of *software engineering* rather than *database design*. In many software design tools, the database design methodologies and software engineering methodologies are intertwined since these activities are strongly related.

In this chapter, we follow the traditional approach of concentrating on the database structures and constraints during conceptual database design. The design of application programs is typically covered in software engineering courses. We present the modeling concepts of the **entity–relationship (ER) model**, which is a popular high-level conceptual data model. This model and its variations are frequently used for the conceptual design of database applications, and many database design tools employ its concepts. We describe the basic data-structuring concepts and constraints of the ER model and discuss their use in the design of conceptual schemas for database applications. We also present the diagrammatic notation associated with the ER model, known as **ER diagrams**.

Object modeling methodologies such as the **Unified Modeling Language (UML)** are becoming increasingly popular in both database and software design. These methodologies go beyond database design to specify detailed design of software modules and their interactions using various types of diagrams. An important part of these methodologies—namely, *class diagrams*¹—is similar in many ways to the ER diagrams. In class diagrams, *operations* on objects are specified, in addition to specifying the database schema structure. Operations can be used to specify the *functional requirements* during database design, as we will discuss in Section 3.1. We present some of the UML notation and concepts for class diagrams that are particularly relevant to database design in Section 3.8, and we briefly compare these to ER notation and concepts. Additional UML notation and concepts are presented in Section 4.6.

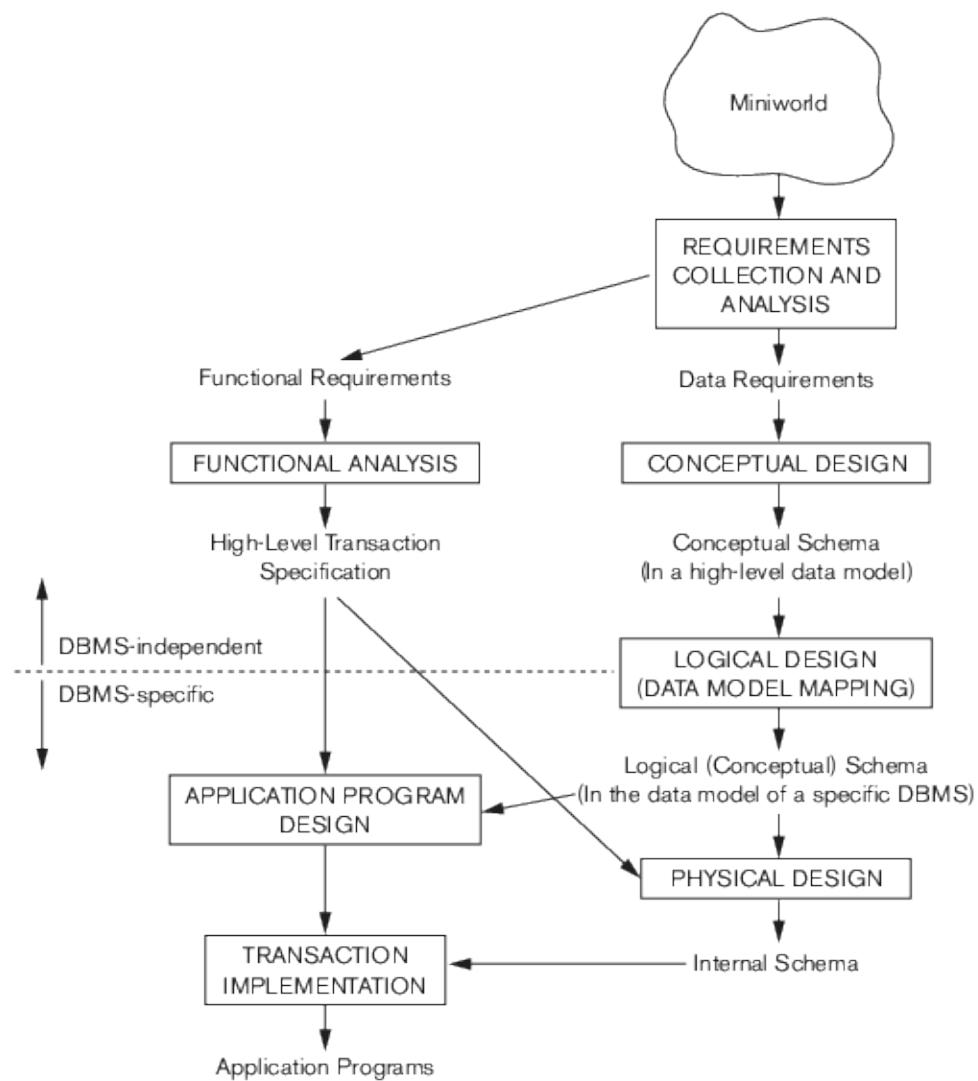
This chapter is organized as follows: Section 3.1 discusses the role of high-level conceptual data models in database design. We introduce the requirements for a sample database application in Section 3.2 to illustrate the use of concepts from the ER model. This sample database is used throughout the text. In Section 3.3 we present the concepts of entities and attributes, and we gradually introduce the diagrammatic technique for displaying an ER schema. In Section 3.4 we introduce the concepts of binary relationships and their roles and structural constraints. Section 3.5 introduces weak entity types. Section 3.6 shows how a schema design is refined to include relationships. Section 3.7 reviews the notation for ER diagrams, summarizes the issues and common pitfalls that occur in schema design, and discusses how to choose the names for database schema constructs such as entity types and relationship types. Section 3.8 introduces some UML class diagram concepts, compares them to ER model concepts, and applies them to the same COMPANY database example. Section 3.9 discusses more complex types of relationships. Section 3.10 summarizes the chapter.

The material in Sections 3.8 and 3.9 may be excluded from an introductory course. If a more thorough coverage of data modeling concepts and conceptual database design is desired, the reader should continue to Chapter 4, where we describe extensions to the ER model that lead to the enhanced-ER (EER) model, which includes concepts such as specialization, generalization, inheritance, and union types (categories).

3.1 Using High-Level Conceptual Data Models for Database Design

Figure 3.1 shows a simplified overview of the database design process. The first step shown is **requirements collection and analysis**. During this step, the database designers interview prospective database users to understand and document their **data requirements**. The result of this step is a concisely written set of users' requirements. These requirements should be specified in as detailed and complete a form as possible. In parallel with specifying the data requirements, it is useful to specify

¹A **class** is similar to an *entity type* in many ways.

**Figure 3.1**

A simplified diagram to illustrate the main phases of database design.

the known **functional requirements** of the application. These consist of the user-defined **operations** (or **transactions**) that will be applied to the database, including both retrievals and updates. In software design, it is common to use *data flow diagrams*, *sequence diagrams*, *scenarios*, and other techniques to specify functional requirements. We will not discuss any of these techniques here; they are usually described in detail in software engineering texts.

Once the requirements have been collected and analyzed, the next step is to create a **conceptual schema** for the database, using a high-level conceptual data model. This

step is called **conceptual design**. The conceptual schema is a concise description of the data requirements of the users and includes detailed descriptions of the entity types, relationships, and constraints; these are expressed using the concepts provided by the high-level data model. Because these concepts do not include implementation details, they are usually easier to understand and can be used to communicate with nontechnical users. The high-level conceptual schema can also be used as a reference to ensure that all users' data requirements are met and that the requirements do not conflict. This approach enables database designers to concentrate on specifying the properties of the data, without being concerned with storage and implementation details, which makes it easier to create a good conceptual database design.

During or after the conceptual schema design, the basic data model operations can be used to specify the high-level user queries and operations identified during functional analysis. This also serves to confirm that the conceptual schema meets all the identified functional requirements. Modifications to the conceptual schema can be introduced if some functional requirements cannot be specified using the initial schema.

The next step in database design is the actual implementation of the database, using a commercial DBMS. Most current commercial DBMSs use an implementation data model—such as the relational (SQL) model—so the conceptual schema is transformed from the high-level data model into the implementation data model. This step is called **logical design** or **data model mapping**; its result is a database schema in the implementation data model of the DBMS. Data model mapping is often automated or semiautomated within the database design tools.

The last step is the **physical design** phase, during which the internal storage structures, file organizations, indexes, access paths, and physical design parameters for the database files are specified. In parallel with these activities, application programs are designed and implemented as database transactions corresponding to the high-level transaction specifications.

We present only the basic ER model concepts for conceptual schema design in this chapter. Additional modeling concepts are discussed in Chapter 4, when we introduce the EER model.

3.2 A Sample Database Application

In this section we describe a sample database application, called **COMPANY**, which serves to illustrate the basic ER model concepts and their use in schema design. We list the data requirements for the database here, and then create its conceptual schema step-by-step as we introduce the modeling concepts of the ER model. The **COMPANY** database keeps track of a company's employees, departments, and projects. Suppose that after the requirements collection and analysis phase, the database designers provide the following description of the *mineworld*—the part of the company that will be represented in the database.

- The company is organized into departments. Each department has a unique name, a unique number, and a particular employee who manages the department. We keep track of the start date when that employee began managing the department. A department may have several locations.
- A department controls a number of projects, each of which has a unique name, a unique number, and a single location.
- The database will store each employee's name, Social Security number,² address, salary, sex (gender), and birth date. An employee is assigned to one department, but may work on several projects, which are not necessarily controlled by the same department. It is required to keep track of the current number of hours per week that an employee works on each project, as well as the direct supervisor of each employee (who is another employee).
- The database will keep track of the dependents of each employee for insurance purposes, including each dependent's first name, sex, birth date, and relationship to the employee.

Figure 3.2 shows how the schema for this database application can be displayed by means of the graphical notation known as **ER diagrams**. This figure will be explained gradually as the ER model concepts are presented. We describe the step-by-step process of deriving this schema from the stated requirements—and explain the ER diagrammatic notation—as we introduce the ER model concepts.

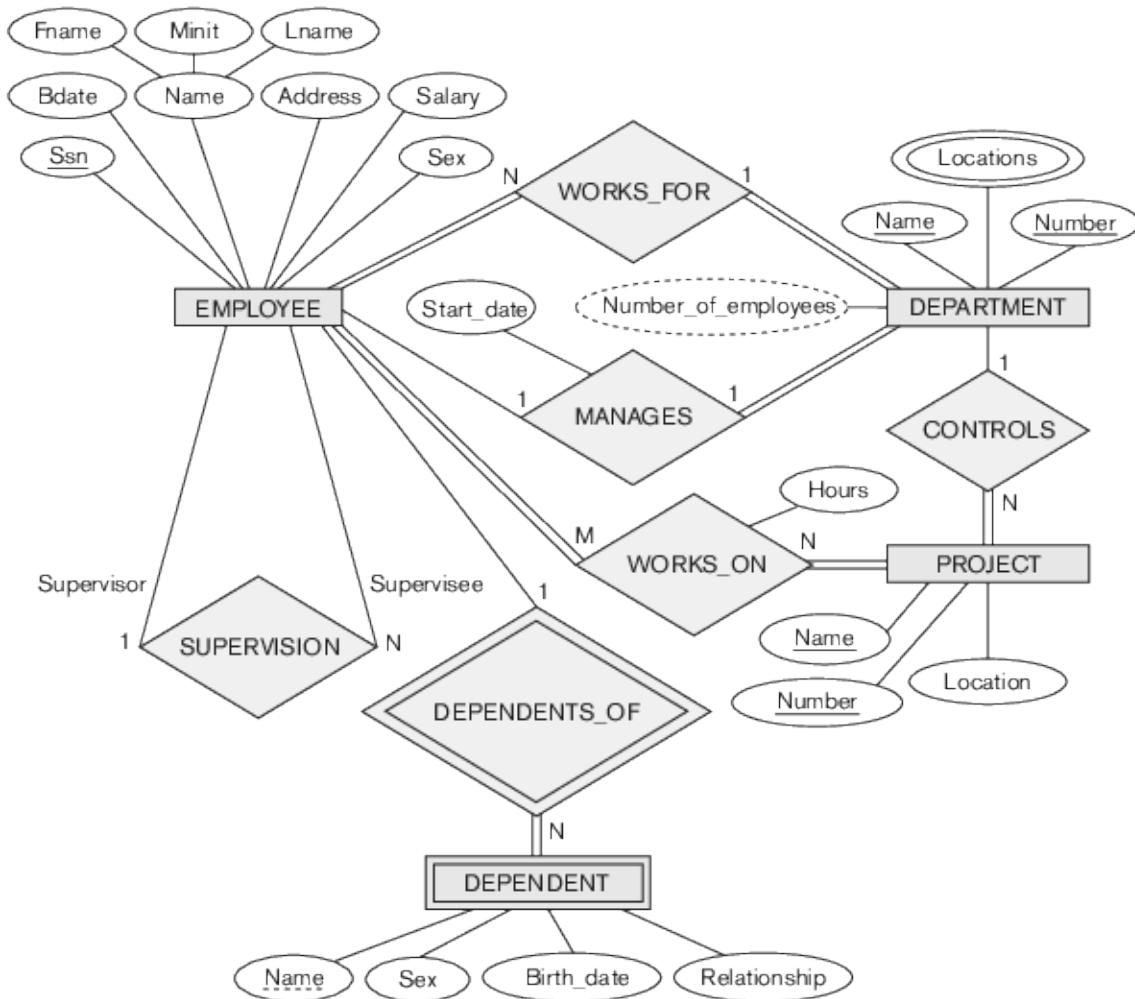
3.3 Entity Types, Entity Sets, Attributes, and Keys

The ER model describes data as *entities*, *relationships*, and *attributes*. In Section 3.3.1 we introduce the concepts of entities and their attributes. We discuss entity types and key attributes in Section 3.3.2. Then, in Section 3.3.3, we specify the initial conceptual design of the entity types for the COMPANY database. We describe relationships in Section 3.4.

3.3.1 Entities and Attributes

Entities and Their Attributes. The basic concept that the ER model represents is an **entity**, which is a *thing* or *object* in the real world with an independent existence. An entity may be an object with a physical existence (for example, a particular person, car, house, or employee) or it may be an object with a conceptual existence (for instance, a company, a job, or a university course). Each entity has **attributes**—the particular properties that describe it. For example, an EMPLOYEE entity may be described by the employee's name, age, address, salary, and job. A particular entity

²The Social Security number, or SSN, is a unique nine-digit identifier assigned to each individual in the United States to keep track of his or her employment, benefits, and taxes. Other countries may have similar identification schemes, such as personal identification card numbers.

**Figure 3.2**

An ER schema diagram for the COMPANY database. The diagrammatic notation is introduced gradually throughout this chapter and is summarized in Figure 3.14.

will have a value for each of its attributes. The attribute values that describe each entity become a major part of the data stored in the database.

Figure 3.3 shows two entities and the values of their attributes. The **EMPLOYEE** entity e_1 has four attributes: Name, Address, Age, and Home_phone; their values are ‘John Smith,’ ‘2311 Kirby, Houston, Texas 77001’, ‘55’, and ‘713-749-2630’, respectively. The **COMPANY** entity c_1 has three attributes: Name, Headquarters, and President; their values are ‘Sunco Oil’, ‘Houston’, and ‘John Smith’, respectively.

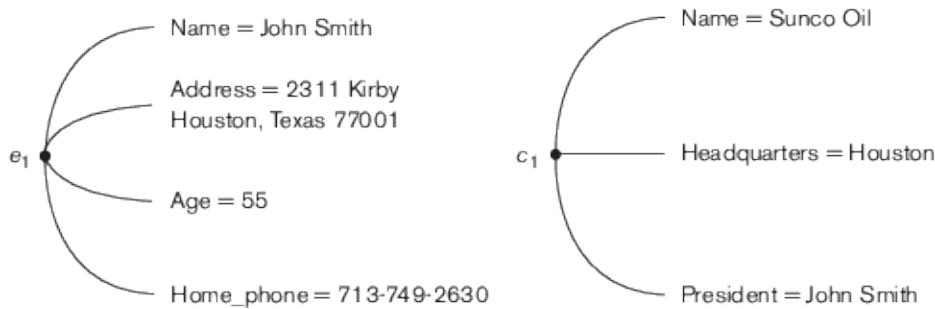


Figure 3.3
Two entities,
EMPLOYEE e_1 , and
COMPANY c_1 , and
their attributes.

Several types of attributes occur in the ER model: *simple* versus *composite*, *single-valued* versus *multivalued*, and *stored* versus *derived*. First we define these attribute types and illustrate their use via examples. Then we discuss the concept of a *NULL value* for an attribute.

Composite versus Simple (Atomic) Attributes. **Composite attributes** can be divided into smaller subparts, which represent more basic attributes with independent meanings. For example, the Address attribute of the EMPLOYEE entity shown in Figure 3.3 can be subdivided into Street_address, City, State, and Zip,³ with the values ‘2311 Kirby’, ‘Houston’, ‘Texas’, and ‘77001’. Attributes that are not divisible are called **simple or atomic attributes**. Composite attributes can form a hierarchy; for example, Street_address can be further subdivided into three simple component attributes: Number, Street, and Apartment_number, as shown in Figure 3.4. The value of a composite attribute is the concatenation of the values of its component simple attributes.

Composite attributes are useful to model situations in which a user sometimes refers to the composite attribute as a unit but at other times refers specifically to its

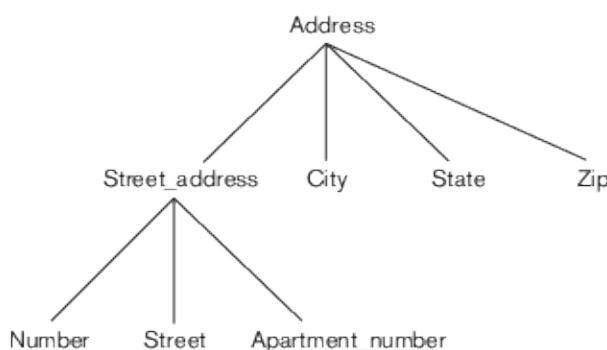


Figure 3.4
A hierarchy of
composite attributes.

³Zip Code is the name used in the United States for a five-digit postal code, such as 76019, which can be extended to nine digits, such as 76019-0015. We use the five-digit Zip in our examples.

components. If the composite attribute is referenced only as a whole, there is no need to subdivide it into component attributes. For example, if there is no need to refer to the individual components of an address (Zip Code, street, and so on), then the whole address can be designated as a simple attribute.

Single-Valued versus Multivalued Attributes. Most attributes have a single value for a particular entity; such attributes are called **single-valued**. For example, Age is a single-valued attribute of a person. In some cases an attribute can have a set of values for the same entity—for instance, a Colors attribute for a car, or a College_degrees attribute for a person. Cars with one color have a single value, whereas two-tone cars have two color values. Similarly, one person may not have any college degrees, another person may have one, and a third person may have two or more degrees; therefore, different people can have different *numbers of values* for the College_degrees attribute. Such attributes are called **multivalued**. A multivalued attribute may have lower and upper bounds to constrain the *number of values* allowed for each individual entity. For example, the Colors attribute of a car may be restricted to have between one and two values, if we assume that a car can have two colors at most.

Stored versus Derived Attributes. In some cases, two (or more) attribute values are related—for example, the Age and Birth_date attributes of a person. For a particular person entity, the value of Age can be determined from the current (today's) date and the value of that person's Birth_date. The Age attribute is hence called a **derived attribute** and is said to be **derivable from** the Birth_date attribute, which is called a **stored attribute**. Some attribute values can be derived from *related entities*; for example, an attribute Number_of_employees of a DEPARTMENT entity can be derived by counting the number of employees related to (working for) that department.

NULL Values. In some cases, a particular entity may not have an applicable value for an attribute. For example, the Apartment_number attribute of an address applies only to addresses that are in apartment buildings and not to other types of residences, such as single-family homes. Similarly, a College_degrees attribute applies only to people with college degrees. For such situations, a special value called **NULL** is created. An address of a single-family home would have NULL for its Apartment_number attribute, and a person with no college degree would have NULL for College_degrees. NULL can also be used if we do not know the value of an attribute for a particular entity—for example, if we do not know the home phone number of 'John Smith' in Figure 3.3. The meaning of the former type of NULL is *not applicable*, whereas the meaning of the latter is *unknown*. The *unknown* category of NULL can be further classified into two cases. The first case arises when it is known that the attribute value exists but is *missing*—for instance, if the Height attribute of a person is listed as NULL. The second case arises when it is *not known* whether the attribute value exists—for example, if the Home_phone attribute of a person is NULL.

Complex Attributes. Notice that, in general, composite and multivalued attributes can be nested arbitrarily. We can represent arbitrary nesting by grouping

```
(Address_phone( {Phone(Area_code,Phone_number)},Address(Street_address
(Number,Street,Apartment_number),City,State,Zip) ))
```

Figure 3.5

A complex attribute:
Address_phone.

components of a composite attribute between parentheses () and separating the components with commas, and by displaying multivalued attributes between braces { }. Such attributes are called **complex attributes**. For example, if a person can have more than one residence and each residence can have a single address and multiple phones, an attribute Address_phone for a person can be specified as shown in Figure 3.5.⁴ Both Phone and Address are themselves composite attributes.

3.3.2 Entity Types, Entity Sets, and Value Sets

Entity Types and Entity Sets. A database usually contains groups of entities that are similar. For example, a company employing hundreds of employees may want to store similar information concerning each of the employees. These employee entities share the same attributes, but each entity has its *own value(s)* for each attribute. An **entity type** defines a *collection* (or *set*) of entities that have the same attributes. Each entity type in the database is described by its name and attributes. Figure 3.6 shows two entity types: EMPLOYEE and COMPANY, and a list of some of the attributes for each. A few individual entities of each type are also illustrated, along with the values of their attributes. The collection of all entities of a particular entity type in the

Entity Type Name:	EMPLOYEE	COMPANY
Entity Set: (Extension)	<p>Name, Age, Salary</p> <div style="border: 1px solid black; padding: 10px;"> $e_1 \bullet$ (John Smith, 55, 80k) $e_2 \bullet$ (Fred Brown, 40, 30K) $e_3 \bullet$ (Judy Clark, 25, 20K) ... </div>	<p>Name, Headquarters, President</p> <div style="border: 1px solid black; padding: 10px;"> $c_1 \bullet$ (Sunco Oil, Houston, John Smith) $c_2 \bullet$ (Fast Computer, Dallas, Bob King) ... </div>

Figure 3.6

Two entity types,
EMPLOYEE and
COMPANY, and some
member entities of
each.

⁴For those familiar with XML, we should note that complex attributes are similar to complex elements in XML (see Chapter 13).

database at any point in time is called an **entity set** or **entity collection**; the entity set is usually referred to using the same name as the entity type, even though they are two separate concepts. For example, EMPLOYEE refers to both a *type of entity* as well as the current collection of *all employee entities* in the database. It is now more common to give separate names to the entity type and entity collection; for example in object and object-relational data models (see Chapter 12).

An entity type is represented in ER diagrams⁵ (see Figure 3.2) as a rectangular box enclosing the entity type name. Attribute names are enclosed in ovals and are attached to their entity type by straight lines. Composite attributes are attached to their component attributes by straight lines. Multivalued attributes are displayed in double ovals. Figure 3.7(a) shows a CAR entity type in this notation.

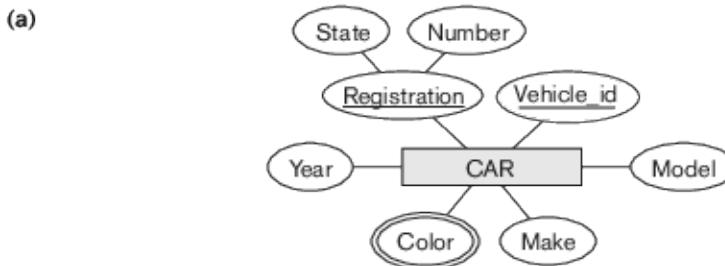
An entity type describes the **schema** or **intension** for a *set of entities* that share the same structure. The collection of entities of a particular entity type is grouped into an entity set, which is also called the **extension** of the entity type.

Key Attributes of an Entity Type. An important constraint on the entities of an entity type is the **key** or **uniqueness constraint** on attributes. An entity type usually has one or more attributes whose values are distinct for each individual entity in the entity set. Such an attribute is called a **key attribute**, and its values can be used to identify each entity uniquely. For example, the Name attribute is a key of the COMPANY entity type in Figure 3.6 because no two companies are allowed to have the same name. For the PERSON entity type, a typical key attribute is Ssn (Social Security number). Sometimes several attributes together form a key, meaning that the *combination* of the attribute values must be distinct for each entity. If a set of attributes possesses this property, the proper way to represent this in the ER model that we describe here is to define a *composite attribute* and designate it as a key attribute of the entity type. Notice that such a composite key must be *minimal*; that is, all component attributes must be included in the composite attribute to have the uniqueness property. Superfluous attributes must not be included in a key. In ER diagrammatic notation, each key attribute has its name **underlined** inside the oval, as illustrated in Figure 3.7(a).

Specifying that an attribute is a key of an entity type means that the preceding uniqueness property must hold for *every entity set* of the entity type. Hence, it is a constraint that prohibits any two entities from having the same value for the key attribute at the same time. It is not the property of a particular entity set; rather, it is a constraint on *any entity set* of the entity type at any point in time. This key constraint (and other constraints we discuss later) is derived from the constraints of the miniworld that the database represents.

Some entity types have *more than one* key attribute. For example, each of the Vehicle_id and Registration attributes of the entity type CAR (Figure 3.7) is a key in

⁵We use a notation for ER diagrams that is close to the original proposed notation (Chen, 1976). Many other notations are in use; we illustrate some of them later in this chapter when we present UML class diagrams, and some additional diagrammatic notations are given in Appendix A.



(b)

CAR
Registration (Number, State), Vehicle_id, Make, Model, Year, {Color}

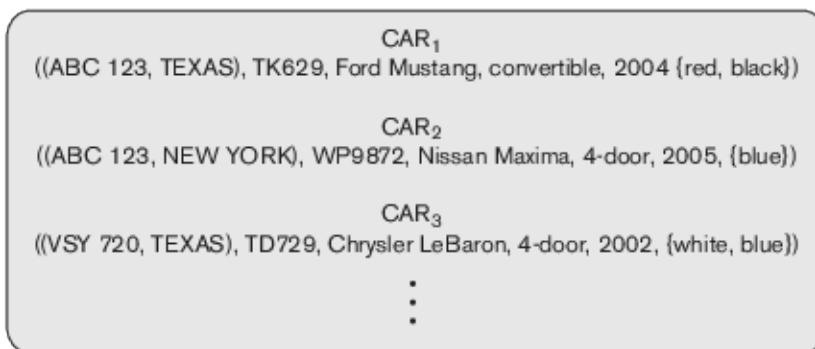


Figure 3.7
The CAR entity type with two key attributes, Registration and Vehicle_id. (a) ER diagram notation. (b) Entity set with three entities.

its own right. The Registration attribute is an example of a composite key formed from two simple component attributes, State and Number, neither of which is a key on its own. An entity type may also have *no key*, in which case it is called a *weak entity type* (see Section 3.5).

In our diagrammatic notation, if two attributes are underlined separately, then *each is a key on its own*. Unlike the relational model (see Section 5.2.2), there is no concept of primary key in the ER model that we present here; the primary key will be chosen during mapping to a relational schema (see Chapter 9).

Value Sets (Domains) of Attributes. Each simple attribute of an entity type is associated with a **value set** (or **domain** of values), which specifies the set of values that may be assigned to that attribute for each individual entity. In Figure 3.6, if the range of ages allowed for employees is between 16 and 70, we can specify the value set of the Age attribute of EMPLOYEE to be the set of integer numbers between 16 and 70. Similarly, we can specify the value set for the Name attribute to be the set of strings of alphabetic characters separated by blank characters, and so on. Value sets are not typically displayed in basic ER diagrams and are similar to the basic **data types** available in most programming languages, such as integer, string, Boolean, float, enumerated type, subrange, and so on. However, data types of attributes can

be specified in UML class diagrams (see Section 3.8) and in other diagrammatic notations used in database design tools. Additional data types to represent common database types, such as date, time, and other concepts, are also employed.

Mathematically, an attribute A of entity set E whose value set is V can be defined as a **function** from E to the power set⁶ $P(V)$ of V :

$$A : E \rightarrow P(V)$$

We refer to the value of attribute A for entity e as $A(e)$. The previous definition covers both single-valued and multivalued attributes, as well as NULLs. A NULL value is represented by the *empty set*. For single-valued attributes, $A(e)$ is restricted to being a *singleton set* for each entity e in E , whereas there is no restriction on multivalued attributes.⁷ For a composite attribute A , the value set V is the power set of the Cartesian product of $P(V_1), P(V_2), \dots, P(V_n)$, where V_1, V_2, \dots, V_n are the value sets of the simple component attributes that form A :

$$V = P(P(V_1) \times P(V_2) \times \cdots \times P(V_n))$$

The value set provides all possible values. Usually only a small number of these values exist in the database at a particular time. Those values represent the data from the current state of the miniworld and correspond to the data as it actually exists in the miniworld.

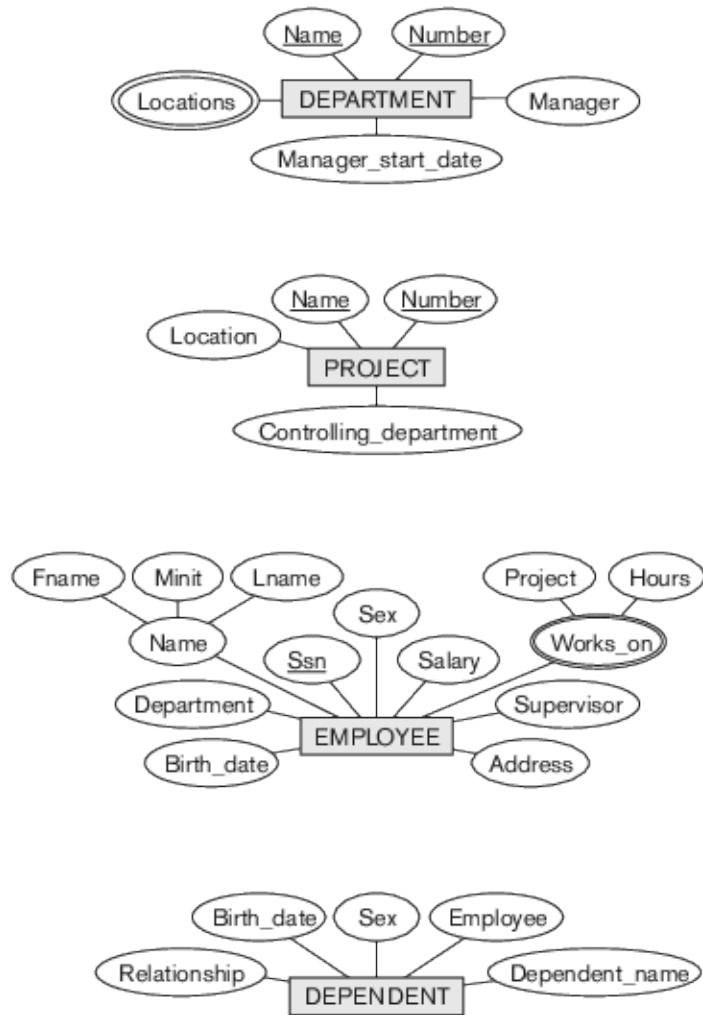
3.3.3 Initial Conceptual Design of the COMPANY Database

We can now define the entity types for the COMPANY database, based on the requirements described in Section 3.2. After defining several entity types and their attributes here, we refine our design in Section 3.4 after we introduce the concept of a relationship. According to the requirements listed in Section 3.2, we can identify four entity types—one corresponding to each of the four items in the specification (see Figure 3.8):

1. An entity type DEPARTMENT with attributes Name, Number, Locations, Manager, and Manager_start_date. Locations is the only multivalued attribute. We can specify that both Name and Number are (separate) key attributes because each was specified to be unique.
2. An entity type PROJECT with attributes Name, Number, Location, and Controlling_department. Both Name and Number are (separate) key attributes.
3. An entity type EMPLOYEE with attributes Name, Ssn, Sex, Address, Salary, Birth_date, Department, and Supervisor. Both Name and Address may be composite attributes; however, this was not specified in the requirements. We must go back to the users to see if any of them will refer to the individual components of Name—First_name, Middle_initial, Last_name—or of Address. In

⁶The **power set** $P(V)$ of a set V is the set of all subsets of V .

⁷A **singleton** set is a set with only one element (value).

**Figure 3.8**

Preliminary design of entity types for the COMPANY database. Some of the shown attributes will be refined into relationships.

our example, Name is modeled as a composite attribute, whereas Address is not, presumably after consultation with the users.

4. An entity type **DEPENDENT** with attributes Employee, Dependent_name, Sex, Birth_date, and Relationship (to the employee).

Another requirement is that an employee can work on several projects, and the database has to store the number of hours per week an employee works on each project. This requirement is listed as part of the third requirement in Section 3.2, and it can be represented by a multivalued composite attribute of **EMPLOYEE** called **Works_on** with the simple components (Project, Hours). Alternatively, it can be represented as a multivalued composite attribute of **PROJECT** called **Workers** with the simple components (Employee, Hours). We choose the first

alternative in Figure 3.8; we shall see in the next section that this will be refined into a many-to-many relationship, once we introduce the concepts of relationships.

3.4 Relationship Types, Relationship Sets, Roles, and Structural Constraints

In Figure 3.8 there are several *implicit relationships* among the various entity types. In fact, whenever an attribute of one entity type refers to another entity type, some relationship exists. For example, the attribute Manager of DEPARTMENT refers to an employee who manages the department; the attribute Controlling_department of PROJECT refers to the department that controls the project; the attribute Supervisor of EMPLOYEE refers to another employee (the one who supervises this employee); the attribute Department of EMPLOYEE refers to the department for which the employee works; and so on. In the ER model, these references should not be represented as attributes but as **relationships**. The initial COMPANY database schema from Figure 3.8 will be refined in Section 3.6 to represent relationships explicitly. In the initial design of entity types, relationships are typically captured in the form of attributes. As the design is refined, these attributes get converted into relationships between entity types.

This section is organized as follows: Section 3.4.1 introduces the concepts of relationship types, relationship sets, and relationship instances. We define the concepts of relationship degree, role names, and recursive relationships in Section 3.4.2, and then we discuss structural constraints on relationships—such as cardinality ratios and existence dependencies—in Section 3.4.3. Section 3.4.4 shows how relationship types can also have attributes.

3.4.1 Relationship Types, Sets, and Instances

A **relationship type** R among n entity types E_1, E_2, \dots, E_n defines a set of associations—or a **relationship set**—among entities from these entity types. Similar to the case of entity types and entity sets, a relationship type and its corresponding relationship set are customarily referred to by the *same name*, R . Mathematically, the relationship set R is a set of **relationship instances** r_i , where each r_i associates n individual entities (e_1, e_2, \dots, e_n) , and each entity e_j in r_i is a member of entity set E_j , $1 \leq j \leq n$. Hence, a relationship set is a mathematical relation on E_1, E_2, \dots, E_n ; alternatively, it can be defined as a subset of the Cartesian product of the entity sets $E_1 \times E_2 \times \dots \times E_n$. Each of the entity types E_1, E_2, \dots, E_n is said to **participate** in the relationship type R ; similarly, each of the individual entities e_1, e_2, \dots, e_n is said to **participate** in the relationship instance $r_i = (e_1, e_2, \dots, e_n)$.

Informally, each relationship instance r_i in R is an association of entities, where the association includes exactly one entity from each participating entity type. Each such relationship instance r_i represents the fact that the entities participating in r_i are related in some way in the corresponding miniworld situation. For example, consider a relationship type WORKS_FOR between the two entity types

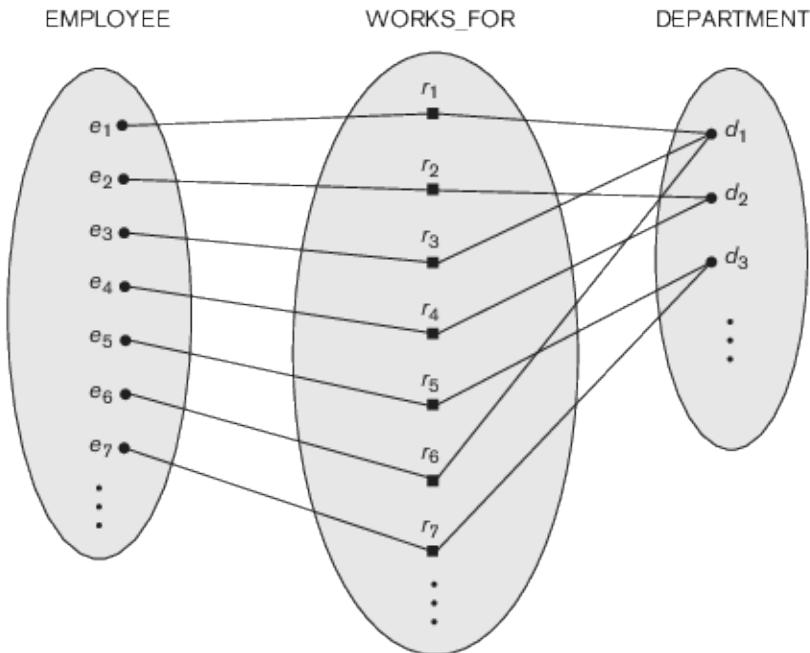


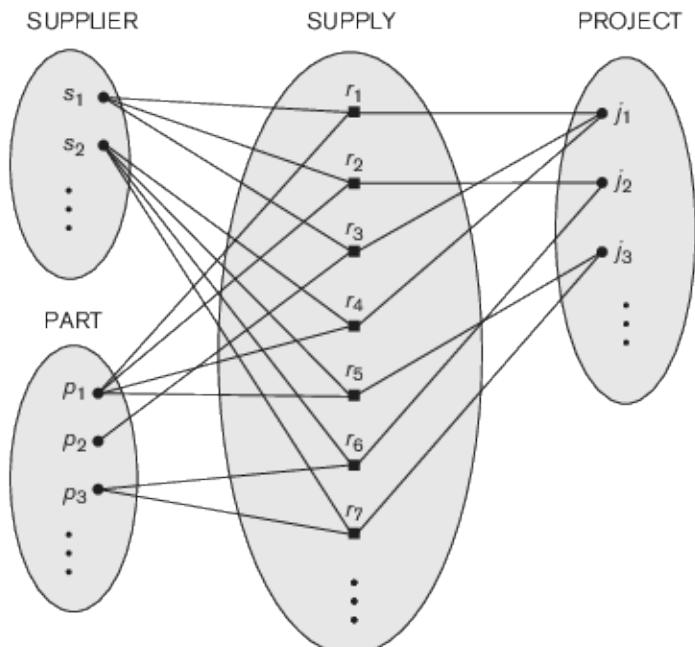
Figure 3.9
Some instances in the WORKS_FOR relationship set, which represents a relationship type WORKS_FOR between EMPLOYEE and DEPARTMENT.

EMPLOYEE and DEPARTMENT, which associates each employee with the department for which the employee works. Each relationship instance in the relationship set WORKS_FOR associates one EMPLOYEE entity and one DEPARTMENT entity. Figure 3.9 illustrates this example, where each relationship instance r_i is shown connected to the EMPLOYEE and DEPARTMENT entities that participate in r_i . In the miniworld represented by Figure 3.9, the employees e_1, e_3 , and e_6 work for department d_1 ; the employees e_2 and e_4 work for department d_2 ; and the employees e_5 and e_7 work for department d_3 .

In ER diagrams, relationship types are displayed as diamond-shaped boxes, which are connected by straight lines to the rectangular boxes representing the participating entity types. The relationship name is displayed in the diamond-shaped box (see Figure 3.2).

3.4.2 Relationship Degree, Role Names, and Recursive Relationships

Degree of a Relationship Type. The **degree** of a relationship type is the number of participating entity types. Hence, the WORKS_FOR relationship is of degree two. A relationship type of degree two is called **binary**, and one of degree three is called **ternary**. An example of a ternary relationship is SUPPLY, shown in Figure 3.10, where each relationship instance r_i associates three entities—a supplier s , a part p , and a project j —whenever s supplies part p to project j . Relationships can

**Figure 3.10**

Some relationship instances in the SUPPLY ternary relationship set.

generally be of any degree, but the ones most common are binary relationships. Higher-degree relationships are generally more complex than binary relationships; we characterize them further in Section 3.9.

Relationships as Attributes. It is sometimes convenient to think of a binary relationship type in terms of attributes, as we discussed in Section 3.3.3. Consider the WORKS_FOR relationship type in Figure 3.9. One can think of an attribute called Department of the EMPLOYEE entity type, where the value of Department for each EMPLOYEE entity is (a reference to) the DEPARTMENT entity for which that employee works. Hence, the value set for this Department attribute is the set of *all* DEPARTMENT entities, which is the DEPARTMENT entity set. This is what we did in Figure 3.8 when we specified the initial design of the entity type EMPLOYEE for the COMPANY database. However, when we think of a binary relationship as an attribute, we always have two options or two points of view. In this example, the alternative point of view is to think of a multivalued attribute Employees of the entity type DEPARTMENT whose value for each DEPARTMENT entity is the set of EMPLOYEE entities who work for that department. The value set of this Employees attribute is the power set of the EMPLOYEE entity set. Either of these two attributes—Department of EMPLOYEE or Employees of DEPARTMENT—can represent the WORKS_FOR relationship type. If both are represented, they are constrained to be inverses of each other.⁸

⁸This concept of representing relationship types as attributes is used in a class of data models called **functional data models**. In object databases (see Chapter 12), relationships can be represented by reference attributes, either in one direction or in both directions as inverses. In relational databases (see Chapter 5), foreign keys are a type of reference attribute used to represent relationships.

Role Names and Recursive Relationships. Each entity type that participates in a relationship type plays a particular role in the relationship. The **role name** signifies the role that a participating entity from the entity type plays in each relationship instance, and it helps to explain what the relationship means. For example, in the WORKS_FOR relationship type, EMPLOYEE plays the role of *employee* or *worker* and DEPARTMENT plays the role of *department* or *employer*.

Role names are not technically necessary in relationship types where all the participating entity types are distinct, since each participating entity type name can be used as the role name. However, in some cases the *same* entity type participates more than once in a relationship type in *different roles*. In such cases the role name becomes essential for distinguishing the meaning of the role that each participating entity plays. Such relationship types are called **recursive relationships** or **self-referencing relationships**. Figure 3.11 shows an example. The SUPERVISION relationship type relates an employee to a supervisor, where both employee and supervisor entities are members of the same EMPLOYEE entity set. Hence, the EMPLOYEE entity type *participates twice* in SUPERVISION: once in the role of *supervisor* (or *boss*), and once in the role of *supervisee* (or *subordinate*). Each relationship instance r_i in SUPERVISION associates two different employee entities e_j and e_k , one of which plays the role of supervisor and the other the role of supervisee. In Figure 3.11, the lines marked '1' represent the supervisor role, and those marked '2' represent the supervisee role; hence, e_1 supervises e_2 and e_3 , e_4 supervises e_6 and e_7 , and e_5 supervises e_1 and e_4 . In this example, each relationship instance must be connected with two lines, one marked with '1' (supervisor) and the other with '2' (supervisee).

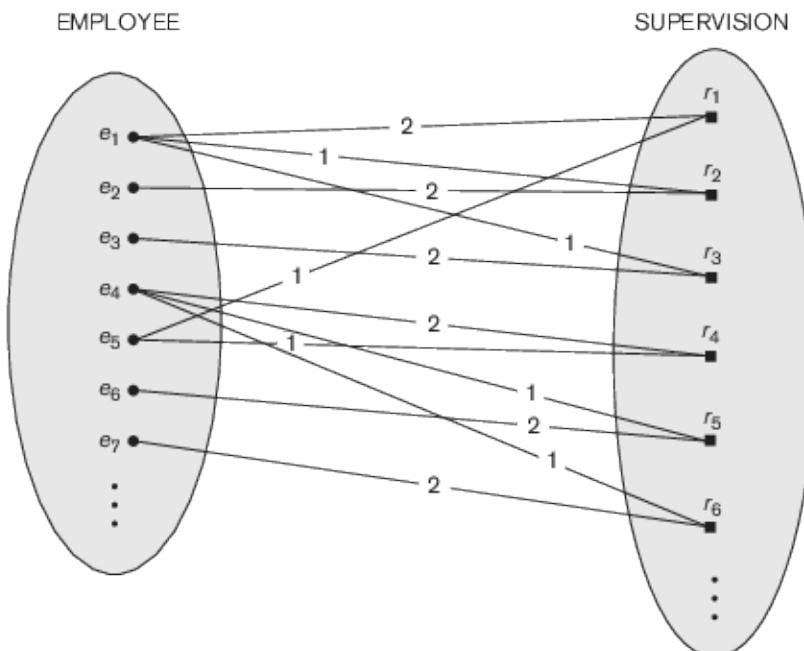


Figure 3.11
A recursive relationship SUPERVISION between EMPLOYEE in the supervisor role (1) and EMPLOYEE in the subordinate role (2).

3.4.3 Constraints on Binary Relationship Types

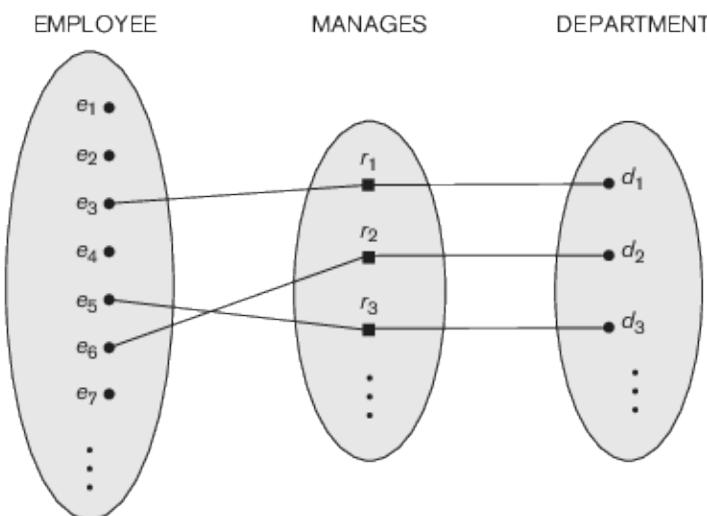
Relationship types usually have certain constraints that limit the possible combinations of entities that may participate in the corresponding relationship set. These constraints are determined from the miniworld situation that the relationships represent. For example, in Figure 3.9, if the company has a rule that each employee must work for exactly one department, then we would like to describe this constraint in the schema. We can distinguish two main types of binary relationship constraints: *cardinality ratio* and *participation*.

Cardinality Ratios for Binary Relationships. The **cardinality ratio** for a binary relationship specifies the *maximum* number of relationship instances that an entity can participate in. For example, in the WORKS_FOR binary relationship type, DEPARTMENT:EMPLOYEE is of cardinality ratio 1:N, meaning that each department can be related to (that is, employs) any number of employees (N),⁹ but an employee can be related to (work for) at most one department (1). This means that for this particular relationship type WORKS_FOR, a particular department entity can be related to any number of employees (N indicates there is no maximum number). On the other hand, an employee can be related to a maximum of one department. The possible cardinality ratios for binary relationship types are 1:1, 1:N, N:1, and M:N.

An example of a 1:1 binary relationship is MANAGES (Figure 3.12), which relates a department entity to the employee who manages that department. This represents the miniworld constraints that—at any point in time—an employee can manage at

Figure 3.12

A 1:1 relationship,
MANAGES.



⁹N stands for any number of related entities (zero or more). In some notations, the asterisk symbol (*) is used instead of N.

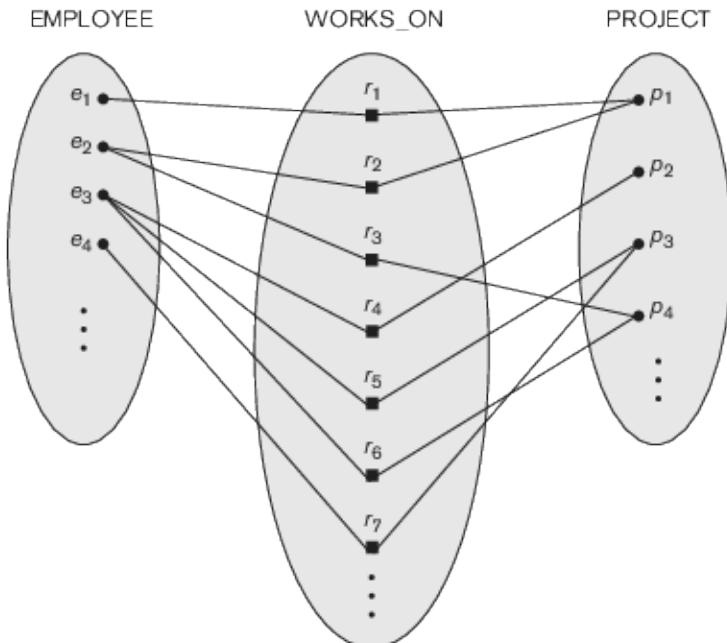


Figure 3.13
An M:N relationship,
WORKS_ON.

most one department and a department can have at most one manager. The relationship type WORKS_ON (Figure 3.13) is of cardinality ratio M:N, because the miniworld rule is that an employee can work on several projects and a project can have several employees.

Cardinality ratios for binary relationships are represented on ER diagrams by displaying 1, M, and N on the diamonds as shown in Figure 3.2. Notice that in this notation, we can either specify no maximum (N) or a maximum of one (1) on participation. An alternative notation (see Section 3.7.4) allows the designer to specify a specific *maximum number* on participation, such as 4 or 5.

Participation Constraints and Existence Dependencies. The **participation constraint** specifies whether the existence of an entity depends on its being related to another entity via the relationship type. This constraint specifies the *minimum* number of relationship instances that each entity can participate in and is sometimes called the **minimum cardinality constraint**. There are two types of participation constraints—total and partial—that we illustrate by example. If a company policy states that *every* employee must work for a department, then an employee entity can exist only if it participates in at least one WORKS_FOR relationship instance (Figure 3.9). Thus, the participation of EMPLOYEE in WORKS_FOR is called **total participation**, meaning that every entity in *the total set* of employee entities must be related to a department entity via WORKS_FOR. Total participation is also called **existence dependency**. In Figure 3.12 we do not expect every employee to manage a department, so the participation of EMPLOYEE in the

MANAGES relationship type is **partial**, meaning that *some or part of the set of employee entities are related to some department entity via MANAGES, but not necessarily all*. We will refer to the cardinality ratio and participation constraints, taken together, as the **structural constraints** of a relationship type.

In ER diagrams, total participation (or existence dependency) is displayed as a *double line* connecting the participating entity type to the relationship, whereas partial participation is represented by a *single line* (see Figure 3.2). Notice that in this notation, we can either specify no minimum (partial participation) or a minimum of one (total participation). An alternative notation (see Section 3.7.4) allows the designer to specify a specific *minimum number* on participation in the relationship, such as 4 or 5.

We will discuss constraints on higher-degree relationships in Section 3.9.

3.4.4 Attributes of Relationship Types

Relationship types can also have attributes, similar to those of entity types. For example, to record the number of hours per week that a particular employee works on a particular project, we can include an attribute Hours for the WORKS_ON relationship type in Figure 3.13. Another example is to include the date on which a manager started managing a department via an attribute Start_date for the MANAGES relationship type in Figure 3.12.

Notice that attributes of 1:1 or 1:N relationship types can be migrated to one of the participating entity types. For example, the Start_date attribute for the MANAGES relationship can be an attribute of either EMPLOYEE (manager) or DEPARTMENT, although conceptually it belongs to MANAGES. This is because MANAGES is a 1:1 relationship, so every department or employee entity participates in *at most one* relationship instance. Hence, the value of the Start_date attribute can be determined separately, either by the participating department entity or by the participating employee (manager) entity.

For a 1:N relationship type, a relationship attribute can be migrated *only* to the entity type on the N-side of the relationship. For example, in Figure 3.9, if the WORKS_FOR relationship also has an attribute Start_date that indicates when an employee started working for a department, this attribute can be included as an attribute of EMPLOYEE. This is because each employee works for at most one department, and hence participates in at most one relationship instance in WORKS_FOR, but a department can have many employees, each with a different start date. In both 1:1 and 1:N relationship types, the decision where to place a relationship attribute—as a relationship type attribute or as an attribute of a participating entity type—is determined subjectively by the schema designer.

For M:N (many-to-many) relationship types, some attributes may be determined by the *combination of participating entities* in a relationship instance, not by any single entity. Such attributes *must be specified as relationship attributes*. An example is the Hours attribute of the M:N relationship WORKS_ON (Figure 3.13); the number of hours per week an employee currently works on a project is determined by an employee-project combination and not separately by either entity.

3.5 Weak Entity Types

Entity types that do not have key attributes of their own are called **weak entity types**. In contrast, **regular entity types** that do have a key attribute—which include all the examples discussed so far—are called **strong entity types**. Entities belonging to a weak entity type are identified by being related to specific entities from another entity type in combination with one of their attribute values. We call this other entity type the **identifying or owner entity type**,¹⁰ and we call the relationship type that relates a weak entity type to its owner the **identifying relationship** of the weak entity type.¹¹ A weak entity type always has a *total participation constraint* (existence dependency) with respect to its identifying relationship because a weak entity cannot be identified without an owner entity. However, not every existence dependency results in a weak entity type. For example, a DRIVER_LICENSE entity cannot exist unless it is related to a PERSON entity, even though it has its own key (*License_number*) and hence is not a weak entity.

Consider the entity type DEPENDENT, related to EMPLOYEE, which is used to keep track of the dependents of each employee via a 1:N relationship (Figure 3.2). In our example, the attributes of DEPENDENT are Name (the first name of the dependent), Birth_date, Sex, and Relationship (to the employee). Two dependents of *two distinct employees* may, by chance, have the same values for Name, Birth_date, Sex, and Relationship, but they are still distinct entities. They are identified as distinct entities only after determining the *particular employee entity* to which each dependent is related. Each employee entity is said to *own* the dependent entities that are related to it.

A weak entity type normally has a **partial key**, which is the attribute that can uniquely identify weak entities that are *related to the same owner entity*.¹² In our example, if we assume that no two dependents of the same employee ever have the same first name, the attribute Name of DEPENDENT is the partial key. In the worst case, a composite attribute of *all the weak entity's attributes* will be the partial key.

In ER diagrams, both a weak entity type and its identifying relationship are distinguished by surrounding their boxes and diamonds with double lines (see Figure 3.2). The partial key attribute is underlined with a dashed or dotted line.

Weak entity types can sometimes be represented as complex (composite, multivalued) attributes. In the preceding example, we could specify a multivalued attribute Dependents for EMPLOYEE, which is a multivalued composite attribute with the component attributes Name, Birth_date, Sex, and Relationship. The choice of which representation to use is made by the database designer. One criterion that may be used is to choose the weak entity type representation if the weak entity type participates independently in relationship types other than its identifying relationship type.

In general, any number of levels of weak entity types can be defined; an owner entity type may itself be a weak entity type. In addition, a weak entity type may have more than one identifying entity type and an identifying relationship type of degree higher than two, as we illustrate in Section 3.9.

¹⁰The identifying entity type is also sometimes called the **parent entity type** or the **dominant entity type**.

¹¹The weak entity type is also sometimes called the **child entity type** or the **subordinate entity type**.

¹²The partial key is sometimes called the **discriminator**.

3.6 Refining the ER Design for the COMPANY Database

We can now refine the database design in Figure 3.8 by changing the attributes that represent relationships into relationship types. The cardinality ratio and participation constraint of each relationship type are determined from the requirements listed in Section 3.2. If some cardinality ratio or dependency cannot be determined from the requirements, the users must be questioned further to determine these structural constraints.

In our example, we specify the following relationship types:

- MANAGES, which is a 1:1(one-to-one) relationship type between EMPLOYEE and DEPARTMENT. EMPLOYEE participation is partial. DEPARTMENT participation is not clear from the requirements. We question the users, who say that a department must have a manager at all times, which implies total participation.¹³ The attribute Start_date is assigned to this relationship type.
- WORKS_FOR, a 1:N (one-to-many) relationship type between DEPARTMENT and EMPLOYEE. Both participations are total.
- CONTROLS, a 1:N relationship type between DEPARTMENT and PROJECT. The participation of PROJECT is total, whereas that of DEPARTMENT is determined to be partial, after consultation with the users indicates that some departments may control no projects.
- SUPERVISION, a 1:N relationship type between EMPLOYEE (in the supervisor role) and EMPLOYEE (in the supervisee role). Both participations are determined to be partial, after the users indicate that not every employee is a supervisor and not every employee has a supervisor.
- WORKS_ON, determined to be an M:N (many-to-many) relationship type with attribute Hours, after the users indicate that a project can have several employees working on it. Both participations are determined to be total.
- DEPENDENTS_OF, a 1:N relationship type between EMPLOYEE and DEPENDENT, which is also the identifying relationship for the weak entity type DEPENDENT. The participation of EMPLOYEE is partial, whereas that of DEPENDENT is total.

After specifying the previous six relationship types, we remove from the entity types in Figure 3.8 all attributes that have been refined into relationships. These include Manager and Manager_start_date from DEPARTMENT; Controlling_department from PROJECT; Department, Supervisor, and Works_on from EMPLOYEE; and Employee from DEPENDENT. It is important to have the least possible redundancy when we design the conceptual schema of a database. If some redundancy is desired at the storage level or at the user view level, it can be introduced later, as discussed in Section 1.6.1.

¹³The rules in the miniworld that determine the constraints are sometimes called the *business rules*, since they are determined by the *business* or organization that will utilize the database.

3.7 ER Diagrams, Naming Conventions, and Design Issues

3.7.1 Summary of Notation for ER Diagrams

Figures 3.9 through 3.13 illustrate examples of the participation of entity types in relationship types by displaying their entity sets and relationship sets (or extensions)—the individual entity instances in an entity set and the individual relationship instances in a relationship set. In ER diagrams the emphasis is on representing the schemas rather than the instances. This is more useful in database design because a database schema changes rarely, whereas the contents of the entity sets may change frequently. In addition, the schema is obviously easier to display, because it is much smaller.

Figure 3.2 displays the COMPANY ER database schema as an ER diagram. We now review the full ER diagram notation. Regular (strong) entity types such as EMPLOYEE, DEPARTMENT, and PROJECT are shown in rectangular boxes. Relationship types such as WORKS_FOR, MANAGES, CONTROLS, and WORKS_ON are shown in diamond-shaped boxes attached to the participating entity types with straight lines. Attributes are shown in ovals, and each attribute is attached by a straight line to its entity type or relationship type. Component attributes of a composite attribute are attached to the oval representing the composite attribute, as illustrated by the Name attribute of EMPLOYEE. Multivalued attributes are shown in double ovals, as illustrated by the Locations attribute of DEPARTMENT. Key attributes have their names underlined. Derived attributes are shown in dotted ovals, as illustrated by the Number_of_employees attribute of DEPARTMENT.

Weak entity types are distinguished by being placed in double rectangles and by having their identifying relationship placed in double diamonds, as illustrated by the DEPENDENT entity type and the DEPENDENTS_OF identifying relationship type. The partial key of the weak entity type is underlined with a dotted line.

In Figure 3.2 the cardinality ratio of each *binary* relationship type is specified by attaching a 1, M, or N on each participating edge. The cardinality ratio of DEPARTMENT:EMPLOYEE in MANAGES is 1:1, whereas it is 1:N for DEPARTMENT: EMPLOYEE in WORKS_FOR, and M:N for WORKS_ON. The participation constraint is specified by a single line for partial participation and by double lines for total participation (existence dependency).

In Figure 3.2 we show the role names for the SUPERVISION relationship type because the same EMPLOYEE entity type plays two distinct roles in that relationship. Notice that the cardinality ratio is 1:N from supervisor to supervisee because each employee in the role of supervisee has at most one direct supervisor, whereas an employee in the role of supervisor can supervise zero or more employees.

Figure 3.14 summarizes the conventions for ER diagrams. It is important to note that there are many other alternative diagrammatic notations (see Section 3.7.4 and Appendix A).

3.7.2 Proper Naming of Schema Constructs

When designing a database schema, the choice of names for entity types, attributes, relationship types, and (particularly) roles is not always straightforward. One should choose names that convey, as much as possible, the meanings attached to the different constructs in the schema. We choose to use *singular names* for entity types, rather than plural ones, because the entity type name applies to each individual entity belonging to that entity type. In our ER diagrams, we will use the convention that entity type and relationship type names are in uppercase letters, attribute names have their initial letter capitalized, and role names are in lowercase letters. We have used this convention in Figure 3.2.

As a general practice, given a narrative description of the database requirements, the *nouns* appearing in the narrative tend to give rise to entity type names, and the *verbs* tend to indicate names of relationship types. Attribute names generally arise from additional nouns that describe the nouns corresponding to entity types.

Another naming consideration involves choosing binary relationship names to make the ER diagram of the schema readable from left to right and from top to bottom. We have generally followed this guideline in Figure 3.2. To explain this naming convention further, we have one exception to the convention in Figure 3.2—the DEPENDENTS_OF relationship type, which reads from bottom to top. When we describe this relationship, we can say that the DEPENDENT entities (bottom entity type) are DEPENDENTS_OF (relationship name) an EMPLOYEE (top entity type). To change this to read from top to bottom, we could rename the relationship type to HAS_DEPENDENTS, which would then read as follows: An EMPLOYEE entity (top entity type) HAS_DEPENDENTS (relationship name) of type DEPENDENT (bottom entity type). Notice that this issue arises because each binary relationship can be described starting from either of the two participating entity types, as discussed in the beginning of Section 3.4.

3.7.3 Design Choices for ER Conceptual Design

It is occasionally difficult to decide whether a particular concept in the miniworld should be modeled as an entity type, an attribute, or a relationship type. In this section, we give some brief guidelines as to which construct should be chosen in particular situations.

In general, the schema design process should be considered an iterative refinement process, where an initial design is created and then iteratively refined until the most suitable design is reached. Some of the refinements that are often used include the following:

- A concept may be first modeled as an attribute and then refined into a relationship because it is determined that the attribute is a reference to another entity type. It is often the case that a pair of such attributes that are inverses of one another are refined into a binary relationship. We discussed this type of refinement in detail in Section 3.6. It is important to note that in our notation,

Symbol	Meaning	Figure 3.14
	Entity	Summary of the notation for ER diagrams.
	Weak Entity	
	Relationship	
	Identifying Relationship	
	Attribute	
	Key Attribute	
	Multivalued Attribute	
	Composite Attribute	
	Derived Attribute	
	Total Participation of E2 in R	
	Cardinality Ratio 1: N for E1 : E2 in R	
	Structural Constraint (min, max) on Participation of E in R	

once an attribute is replaced by a relationship, the attribute itself should be removed from the entity type to avoid duplication and redundancy.

- Similarly, an attribute that exists in several entity types may be elevated or promoted to an independent entity type. For example, suppose that each of several entity types in a UNIVERSITY database, such as STUDENT, INSTRUCTOR, and COURSE, has an attribute Department in the initial design; the designer may then choose to create an entity type DEPARTMENT with a single attribute Dept_name and relate it to the three entity types (STUDENT, INSTRUCTOR, and COURSE) via appropriate relationships. Other attributes/relationships of DEPARTMENT may be discovered later.
- An inverse refinement to the previous case may be applied—for example, if an entity type DEPARTMENT exists in the initial design with a single attribute Dept_name and is related to only one other entity type, STUDENT. In this case, DEPARTMENT may be reduced or demoted to an attribute of STUDENT.
- Section 3.9 discusses choices concerning the degree of a relationship. In Chapter 4, we discuss other refinements concerning specialization/generalization.

3.7.4 Alternative Notations for ER Diagrams

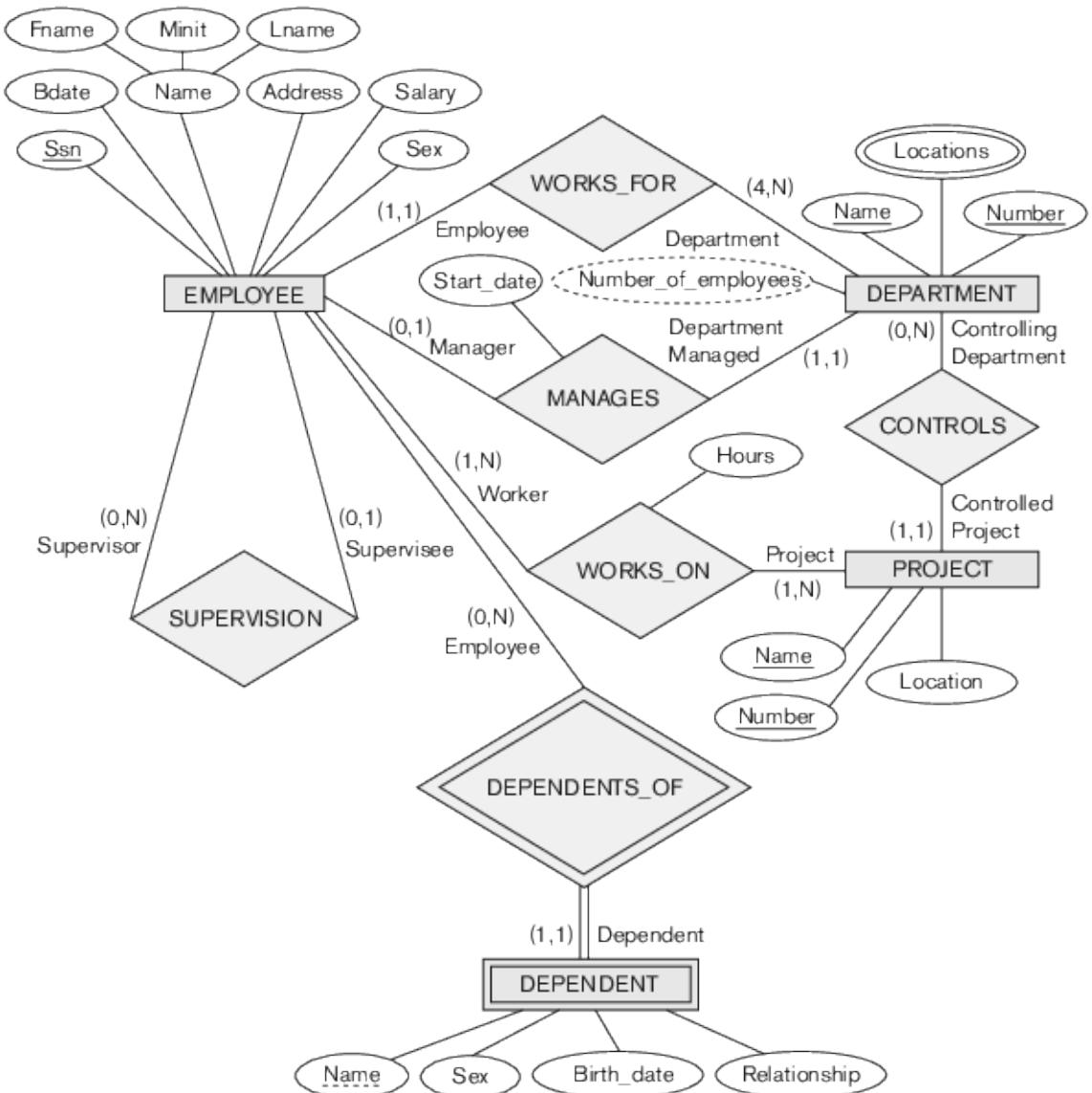
There are many alternative diagrammatic notations for displaying ER diagrams. Appendix A gives some of the more popular notations. In Section 3.8, we introduce the Unified Modeling Language (UML) notation for class diagrams, which has been proposed as a standard for conceptual object modeling.

In this section, we describe one alternative ER notation for specifying structural constraints on relationships, which replaces the cardinality ratio (1:1, 1:N, M:N) and single/double-line notation for participation constraints. This notation involves associating a pair of integer numbers (min, max) with each *participation* of an entity type E in a relationship type R , where $0 \leq \text{min} \leq \text{max}$ and $\text{max} \geq 1$. The numbers mean that for each entity e in E , e must participate in at least min and at most max relationship instances in R *at any point in time*. In this method, $\text{min} = 0$ implies partial participation, whereas $\text{min} > 0$ implies total participation.

Figure 3.15 displays the COMPANY database schema using the (min, max) notation.¹⁴ Usually, one uses either the cardinality ratio/single-line/double-line notation or the (min, max) notation. The (min, max) notation is more precise, and we can use it to specify some structural constraints for relationship types of *higher degree*. However, it is not sufficient for specifying some key constraints on higher-degree relationships, as discussed in Section 3.9.

Figure 3.15 also displays all the role names for the COMPANY database schema.

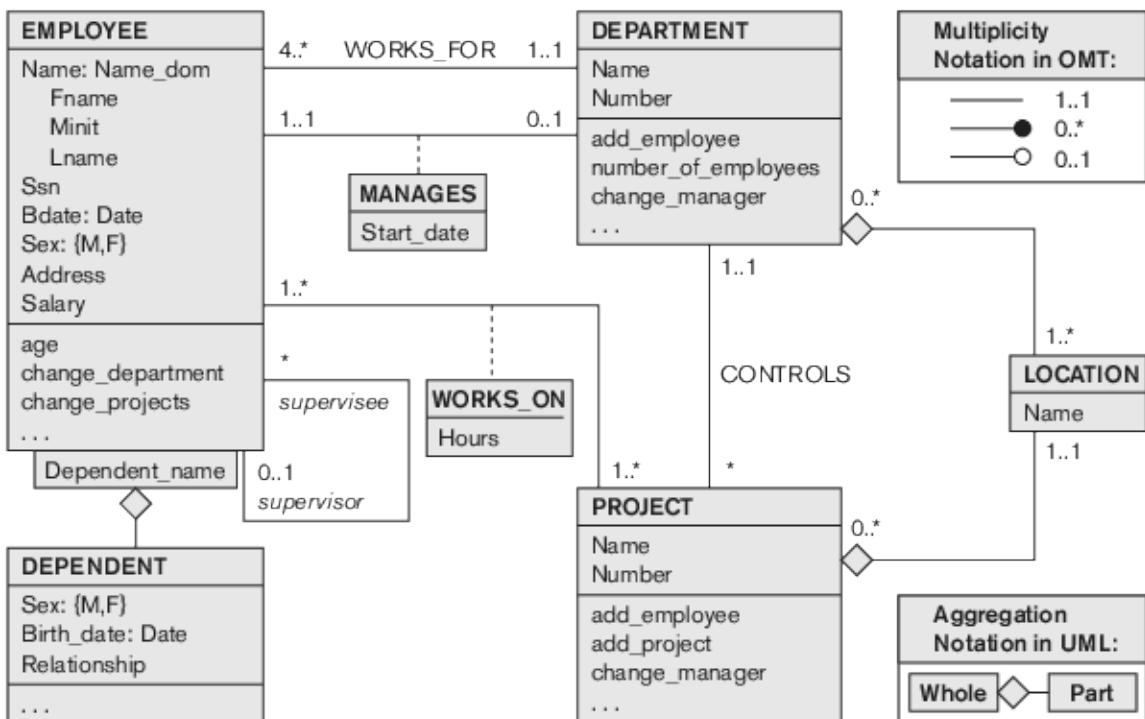
¹⁴In some notations, particularly those used in object modeling methodologies such as UML, the (min, max) is placed on the *opposite sides* to the ones we have shown. For example, for the WORKS_FOR relationship in Figure 3.15, the (1,1) would be on the DEPARTMENT side, and the (4,N) would be on the EMPLOYEE side. Here we used the original notation from Abrial (1974).

**Figure 3.15**

ER diagrams for the company schema, with structural constraints specified using (min, max) notation and role names.

3.8 Example of Other Notation: UML Class Diagrams

The UML methodology is being used extensively in software design and has many types of diagrams for various software design purposes. We only briefly present the basics of **UML class diagrams** here and compare them with ER diagrams. In some

**Figure 3.16**

The COMPANY conceptual schema in UML class diagram notation.

ways, class diagrams can be considered as an alternative notation to ER diagrams. Additional UML notation and concepts are presented in Section 8.6. Figure 3.16 shows how the COMPANY ER database schema in Figure 3.15 can be displayed using UML class diagram notation. The *entity types* in Figure 3.15 are modeled as *classes* in Figure 3.16. An *entity* in ER corresponds to an *object* in UML.

In UML class diagrams, a **class** (similar to an entity type in ER) is displayed as a box (see Figure 3.16) that includes three sections: The top section gives the **class name** (similar to entity type name); the middle section includes the **attributes**; and the last section includes **operations** that can be applied to individual objects (similar to individual entities in an entity set) of the class. Operations are *not* specified in ER diagrams. Consider the EMPLOYEE class in Figure 3.16. Its attributes are Name, Ssn, Bdate, Sex, Address, and Salary. The designer can optionally specify the **domain** (or data type) of an attribute if desired, by placing a colon (:) followed by the domain name or description, as illustrated by the Name, Sex, and Bdate attributes of EMPLOYEE in Figure 3.16. A composite attribute is modeled as a **structured domain**, as illustrated by the Name attribute of EMPLOYEE. A multivalued attribute will generally be modeled as a separate class, as illustrated by the LOCATION class in Figure 3.16.

Relationship types are called **associations** in UML terminology, and relationship instances are called **links**. A **binary association** (binary relationship type) is represented as a line connecting the participating classes (entity types), and may optionally have a name. A relationship attribute, called a **link attribute**, is placed in a box that is connected to the association's line by a dashed line. The (min, max) notation described in Section 3.7.4 is used to specify relationship constraints, which are called **multiplicities** in UML terminology. Multiplicities are specified in the form *min..max*, and an asterisk (*) indicates no maximum limit on participation. However, the multiplicities are placed *on the opposite ends of the relationship* when compared with the (min, max) notation discussed in Section 3.7.4 (compare Figures 3.15 and 3.16). In UML, a single asterisk indicates a multiplicity of $0..*$, and a single 1 indicates a multiplicity of $1..1$. A recursive relationship type (see Section 3.4.2) is called a **reflexive association** in UML, and the role names—like the multiplicities—are placed at the opposite ends of an association when compared with the placing of role names in Figure 3.15.

In UML, there are two types of relationships: association and aggregation. **Aggregation** is meant to represent a relationship between a whole object and its component parts, and it has a distinct diagrammatic notation. In Figure 3.16, we modeled the locations of a department and the single location of a project as aggregations. However, aggregation and association do not have different structural properties, and the choice as to which type of relationship to use—aggregation or association—is somewhat subjective. In the ER model, both are represented as relationships.

UML also distinguishes between **unidirectional** and **bidirectional** associations (or aggregations). In the unidirectional case, the line connecting the classes is displayed with an arrow to indicate that only one direction for accessing related objects is needed. If no arrow is displayed, the bidirectional case is assumed, which is the default. For example, if we always expect to access the manager of a department starting from a DEPARTMENT object, we would draw the association line representing the MANAGES association with an arrow from DEPARTMENT to EMPLOYEE. In addition, relationship instances may be specified to be **ordered**. For example, we could specify that the employee objects related to each department through the WORKS_FOR association (relationship) should be ordered by their Start_date attribute value. Association (relationship) names are *optional* in UML, and relationship attributes are displayed in a box attached with a dashed line to the line representing the association/aggregation (see Start_date and Hours in Figure 3.16).

The operations given in each class are derived from the functional requirements of the application, as we discussed in Section 3.1. It is generally sufficient to specify the operation names initially for the logical operations that are expected to be applied to individual objects of a class, as shown in Figure 3.16. As the design is refined, more details are added, such as the exact argument types (parameters) for each operation, plus a functional description of each operation. UML has *function descriptions* and *sequence diagrams* to specify some of the operation details, but these are beyond the scope of our discussion.

Weak entities can be modeled using the UML construct called **qualified association** (or **qualified aggregation**); this can represent both the identifying relationship and the partial key, which is placed in a box attached to the owner class. This is illustrated by the **DEPENDENT** class and its qualified aggregation to **EMPLOYEE** in Figure 3.16. In UML terminology, the partial key attribute **Dependent_name** is called the **discriminator**, because its value distinguishes the objects associated with (related to) the same **EMPLOYEE** entity. Qualified associations are not restricted to modeling weak entities, and they can be used to model other situations in UML.

This section is not meant to be a complete description of UML class diagrams, but rather to illustrate one popular type of alternative diagrammatic notation that can be used for representing ER modeling concepts.

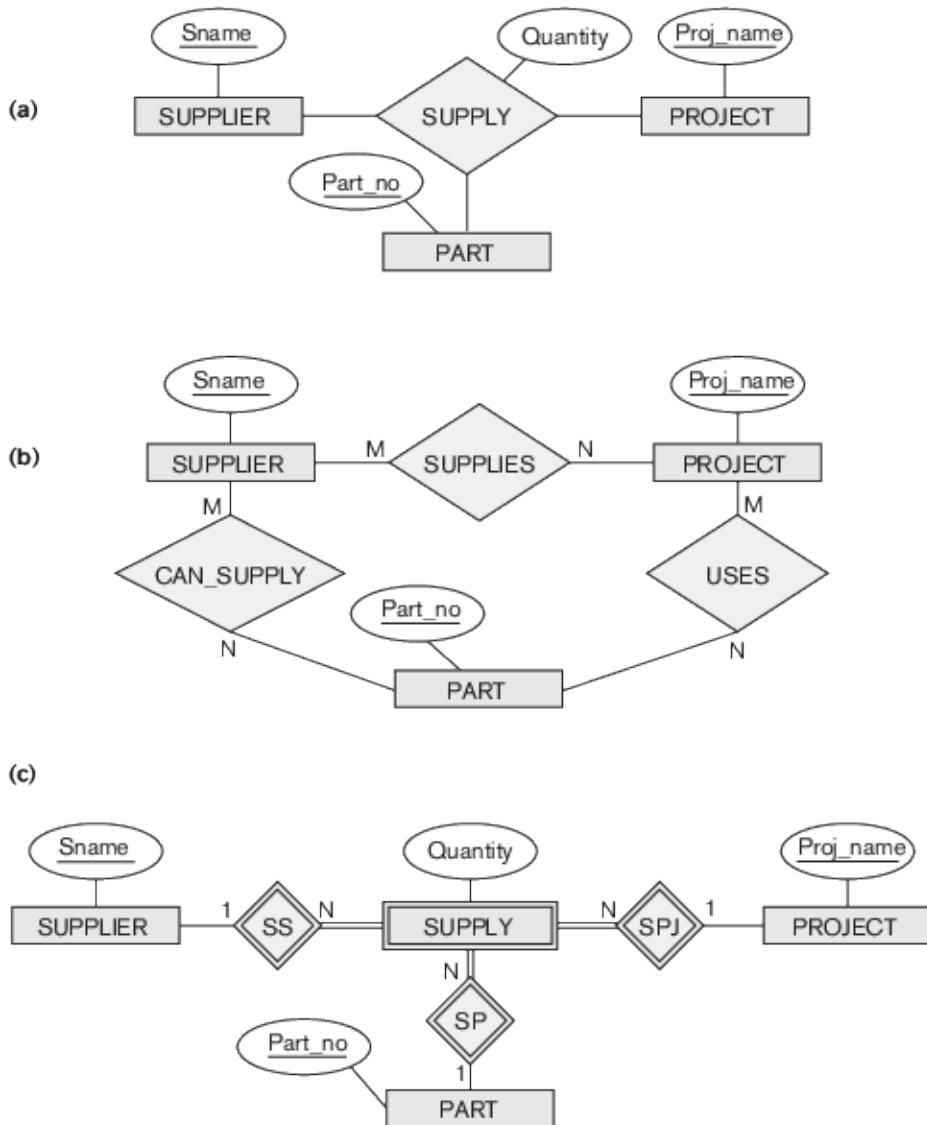
3.9 Relationship Types of Degree Higher than Two

In Section 3.4.2 we defined the **degree** of a relationship type as the number of participating entity types and called a relationship type of degree two *binary* and a relationship type of degree three *ternary*. In this section, we elaborate on the differences between binary and higher-degree relationships, when to choose higher-degree versus binary relationships, and how to specify constraints on higher-degree relationships.

3.9.1 Choosing between Binary and Ternary (or Higher-Degree) Relationships

The ER diagram notation for a ternary relationship type is shown in Figure 3.17(a), which displays the schema for the **SUPPLY** relationship type that was displayed at the instance level in Figure 3.10. Recall that the relationship set of **SUPPLY** is a set of relationship instances (s, j, p) , where the meaning is that s is a **SUPPLIER** who is currently supplying a **PART** p to a **PROJECT** j . In general, a relationship type R of degree n will have n edges in an ER diagram, one connecting R to each participating entity type.

Figure 3.17(b) shows an ER diagram for three binary relationship types **CAN_SUPPLY**, **USES**, and **SUPPLIES**. In general, a ternary relationship type represents different information than do three binary relationship types. Consider the three binary relationship types **CAN_SUPPLY**, **USES**, and **SUPPLIES**. Suppose that **CAN_SUPPLY**, between **SUPPLIER** and **PART**, includes an instance (s, p) whenever supplier s *can supply* part p (to any project); **USES**, between **PROJECT** and **PART**, includes an instance (j, p) whenever project j uses part p ; and **SUPPLIES**, between **SUPPLIER** and **PROJECT**, includes an instance (s, j) whenever supplier s supplies *some part* to project j . The existence of three relationship instances (s, p) , (j, p) , and (s, j) in **CAN_SUPPLY**, **USES**, and **SUPPLIES**, respectively, does not necessarily imply that an instance (s, j, p) exists in the ternary relationship **SUPPLY**, because the *meaning is different*. It is often tricky to decide whether a particular relationship should be represented as a relationship type of degree n or should be

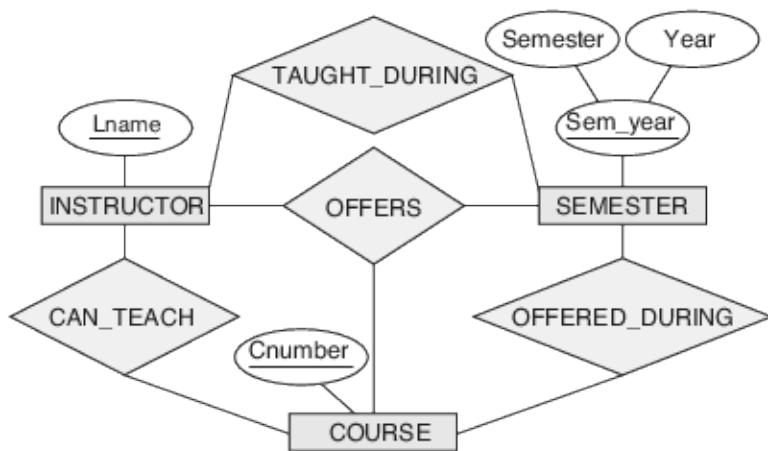
**Figure 3.17**

Ternary relationship types. (a) The SUPPLY relationship. (b) Three binary relationships not equivalent to SUPPLY. (c) SUPPLY represented as a weak entity type.

broken down into several relationship types of smaller degrees. The designer must base this decision on the semantics or meaning of the particular situation being represented. The typical solution is to include the ternary relationship *plus* one or more of the binary relationships, if they represent different meanings and if all are needed by the application.

Figure 3.18

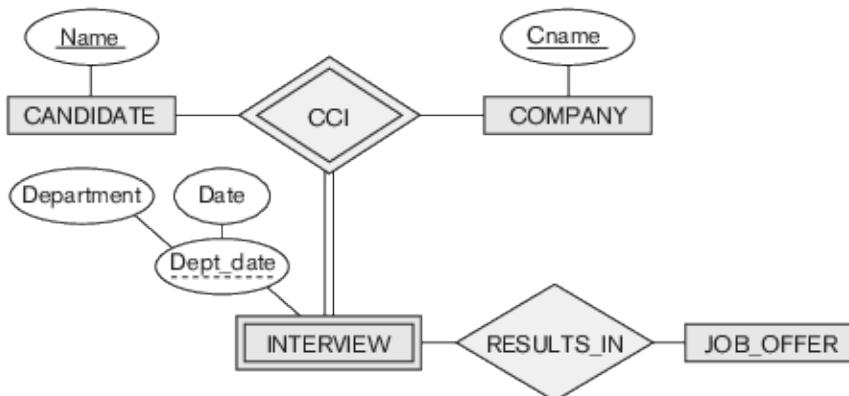
Another example of ternary versus binary relationship types.



Some database design tools are based on variations of the ER model that permit only binary relationships. In this case, a ternary relationship such as SUPPLY must be represented as a weak entity type, with no partial key and with three identifying relationships. The three participating entity types SUPPLIER, PART, and PROJECT are together the owner entity types (see Figure 3.17(c)). Hence, an entity in the weak entity type SUPPLY in Figure 3.17(c) is identified by the combination of its three owner entities from SUPPLIER, PART, and PROJECT.

It is also possible to represent the ternary relationship as a regular entity type by introducing an artificial or surrogate key. In this example, a key attribute Supply_id could be used for the supply entity type, converting it into a regular entity type. Three binary N:1 relationships relate SUPPLY to each of the three participating entity types.

Another example is shown in Figure 3.18. The ternary relationship type OFFERS represents information on instructors offering courses during particular semesters; hence it includes a relationship instance (i, s, c) whenever INSTRUCTOR i offers COURSE c during SEMESTER s . The three binary relationship types shown in Figure 3.18 have the following meanings: CAN_TEACH relates a course to the instructors who *can teach* that course, TAUGHT_DURING relates a semester to the instructors who *taught some course* during that semester, and OFFERED_DURING relates a semester to the courses offered during that semester *by any instructor*. These ternary and binary relationships represent different information, but certain constraints should hold among the relationships. For example, a relationship instance (i, s, c) should not exist in OFFERS unless an instance (i, s) exists in TAUGHT_DURING, an instance (s, c) exists in OFFERED_DURING, and an instance (i, c) exists in CAN_TEACH. However, the reverse is not always true; we may have instances (i, s) , (s, c) , and (i, c) in the three binary relationship types with no corresponding instance (i, s, c) in OFFERS. Note that in this example, based on the meanings of the relationships, we can infer the instances of TAUGHT_DURING and OFFERED_DURING from the instances in OFFERS, but

**Figure 3.19**

A weak entity type INTERVIEW with a ternary identifying relationship type.

we cannot infer the instances of CAN_TEACH; therefore, TAUGHT_DURING and OFFERED_DURING are redundant and can be left out.

Although in general three binary relationships *cannot* replace a ternary relationship, they may do so under certain *additional constraints*. In our example, if the CAN_TEACH relationship is 1:1 (an instructor can teach only one course, and a course can be taught by only one instructor), then the ternary relationship OFFERS can be left out because it can be inferred from the three binary relationships CAN_TEACH, TAUGHT_DURING, and OFFERED_DURING. The schema designer must analyze the meaning of each specific situation to decide which of the binary and ternary relationship types are needed.

Notice that it is possible to have a weak entity type with a ternary (or n -ary) identifying relationship type. In this case, the weak entity type can have *several* owner entity types. An example is shown in Figure 3.19. This example shows part of a database that keeps track of candidates interviewing for jobs at various companies, which may be part of an employment agency database. In the requirements, a candidate can have multiple interviews with the same company (for example, with different company departments or on separate dates), but a job offer is made based on one of the interviews. Here, INTERVIEW is represented as a weak entity with two owners CANDIDATE and COMPANY, and with the partial key Dept_date. An INTERVIEW entity is uniquely identified by a candidate, a company, and the combination of the date and department of the interview.

3.9.2 Constraints on Ternary (or Higher-Degree) Relationships

There are two notations for specifying structural constraints on n -ary relationships, and they specify different constraints. They should thus *both be used* if it is important to fully specify the structural constraints on a ternary or higher-degree relationship. The first notation is based on the cardinality ratio notation of binary relationships displayed in Figure 3.2. Here, a 1, M, or N is specified on each

participation arc (both M and N symbols stand for *many* or *any number*).¹⁵ Let us illustrate this constraint using the SUPPLY relationship in Figure 3.17.

Recall that the relationship set of SUPPLY is a set of relationship instances (s, j, p) , where s is a SUPPLIER, j is a PROJECT, and p is a PART. Suppose that the constraint exists that for a particular project-part combination, only one supplier will be used (only one supplier supplies a particular part to a particular project). In this case, we place 1 on the SUPPLIER participation, and M, N on the PROJECT, PART participations in Figure 3.17. This specifies the constraint that a particular (j, p) combination can appear at most once in the relationship set because each such (PROJECT, PART) combination uniquely determines a single supplier. Hence, any relationship instance (s, j, p) is uniquely identified in the relationship set by its (j, p) combination, which makes (j, p) a key for the relationship set. In this notation, the participations that have a 1 specified on them are not required to be part of the identifying key for the relationship set.¹⁶ If all three cardinalities are M or N, then the key will be the combination of all three participants.

The second notation is based on the (min, max) notation displayed in Figure 3.15 for binary relationships. A (min, max) on a participation here specifies that each entity is related to at least *min* and at most *max* *relationship instances* in the relationship set. These constraints have no bearing on determining the key of an *n*-ary relationship, where $n > 2$,¹⁷ but specify a different type of constraint that places restrictions on how many relationship instances each entity can participate in.

3.10 Another Example: A UNIVERSITY Database

We now present another example, a UNIVERSITY database, to illustrate the ER modeling concepts. Suppose that a database is needed to keep track of student enrollments in classes and students' final grades. After analyzing the miniworld rules and the users' needs, the requirements for this database were determined to be as follows (for brevity, we show the chosen entity type names and attribute names for the conceptual schema in parentheses as we describe the requirements; relationship type names are only shown in the ER schema diagram):

- The university is organized into colleges (COLLEGE), and each college has a unique name (CName), a main office (COffice) and phone (CPhone), and a particular faculty member who is dean of the college. Each college administers a number of academic departments (DEPT). Each department has a unique name (DName), a unique code number (DCode), a main office (DOffice) and phone (DPhone), and a particular faculty member who chairs the department. We keep track of the start date (CStartDate) when that faculty member began chairing the department.

¹⁵This notation allows us to determine the key of the *relationship relation*, as we discuss in Chapter 9.

¹⁶This is also true for cardinality ratios of binary relationships.

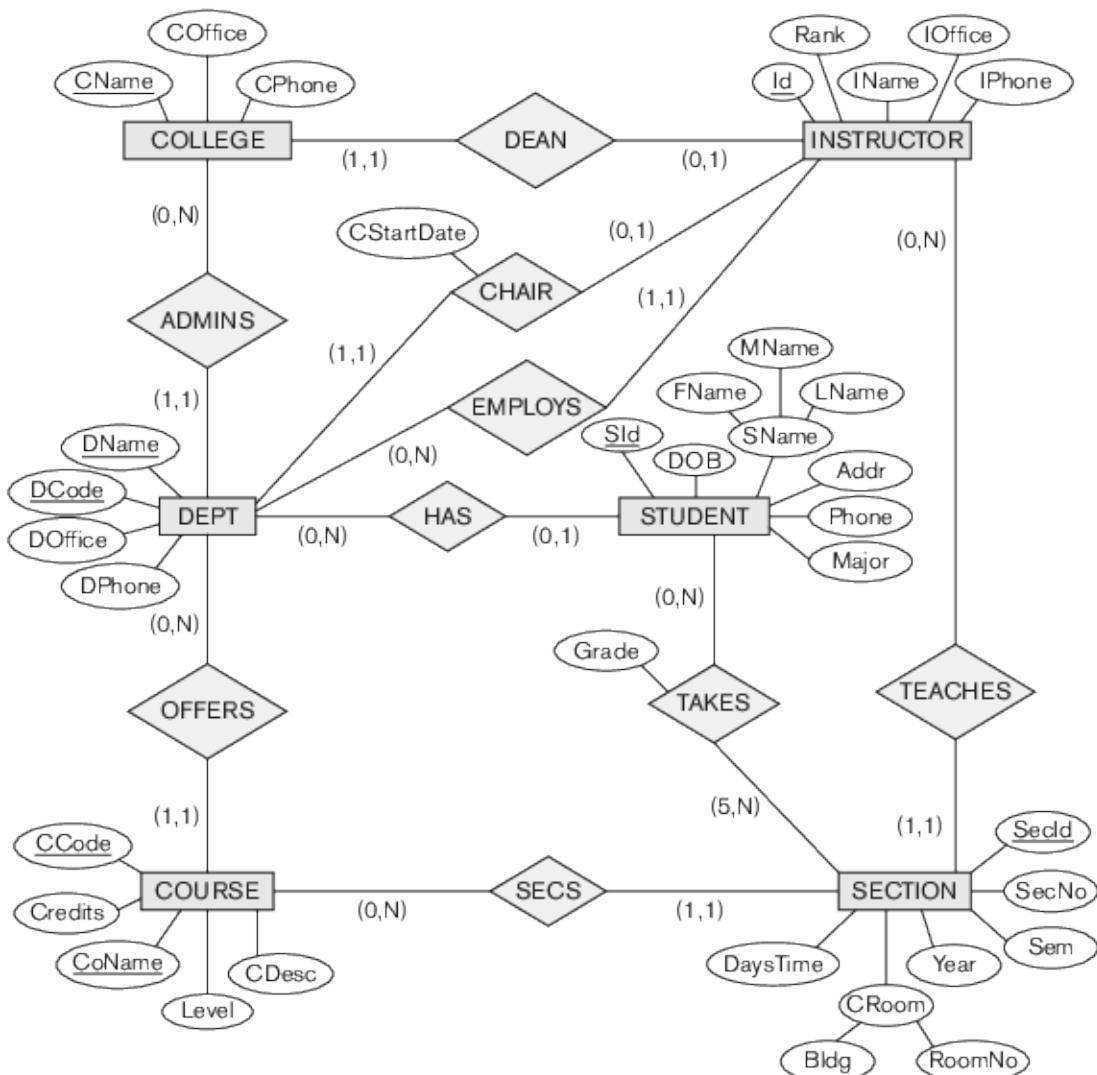
¹⁷The (min, max) constraints can determine the keys for binary relationships.

- A department offers a number of courses (COURSE), each of which has a unique course name (CoName), a unique code number (CCode), a course level (Level: this can be coded as 1 for freshman level, 2 for sophomore, 3 for junior, 4 for senior, 5 for MS level, and 6 for PhD level), a course credit hours (Credits), and a course description (CDesc). The database also keeps track of instructors (INSTRUCTOR); and each instructor has a unique identifier (Id), name (IName), office (IOffice), phone (IPhone), and rank (Rank); in addition, each instructor works for one primary academic department.
- The database will keep student data (STUDENT) and stores each student's name (SName, composed of first name (FName), middle name (MName), last name (LName)), student id (Sid, unique for every student), address (Addr), phone (Phone), major code (Major), and date of birth (DoB). A student is assigned to one primary academic department. It is required to keep track of the student's grades in each section the student has completed.
- Courses are offered as sections (SECTION). Each section is related to a single course and a single instructor and has a unique section identifier (SecId). A section also has a section number (SecNo: this is coded as 1, 2, 3, ... for multiple sections offered during the same semester/year), semester (Sem), year (Year), classroom (CRoom: this is coded as a combination of building code (Bldg) and room number (RoomNo) within the building), and days/times (DaysTime: for example, 'MWF 9am-9.50am' or 'TR 3.30pm-5.20pm'—restricted to only allowed days/time values). (*Note:* The database will keep track of all the sections offered for the past several years, in addition to the current offerings. The SecId is unique for all sections, not just the sections for a particular semester.) The database keeps track of the students in each section, and the grade is recorded when available (this is a many-to-many relationship between students and sections). A section must have at least five students.

The ER diagram for these requirements is shown in Figure 3.20 using the min-max ER diagrammatic notation. Notice that for the SECTION entity type, we only showed SecID as an underlined key, but because of the miniworld constraints, several other combinations of values have to be unique for each section entity. For example, each of the following combinations must be unique based on the typical miniworld constraints:

1. (SecNo, Sem, Year, CCode (of the COURSE related to the SECTION)): This specifies that the section numbers of a particular course must be different during each particular semester and year.
2. (Sem, Year, CRoom, DaysTime): This specifies that in a particular semester and year, a classroom cannot be used by two different sections at the same days/time.
3. (Sem, Year, DaysTime, Id (of the INSTRUCTOR teaching the SECTION)): This specifies that in a particular semester and year, an instructor cannot teach two sections at the same days/time. Note that this rule will not apply if an instructor is allowed to teach two combined sections together in the particular university.

Can you think of any other attribute combinations that have to be unique?

**Figure 3.20**

An ER diagram for a UNIVERSITY database schema.

3.11 Summary

In this chapter we presented the modeling concepts of a high-level conceptual data model, the entity–relationship (ER) model. We started by discussing the role that a high-level data model plays in the database design process, and then we presented a sample set of database requirements for the COMPANY database, which is one of the

examples that is used throughout this text. We defined the basic ER model concepts of entities and their attributes. Then we discussed NULL values and presented the various types of attributes, which can be nested arbitrarily to produce complex attributes:

- Simple or atomic
- Composite
- Multivalued

We also briefly discussed stored versus derived attributes. Then we discussed the ER model concepts at the schema or “intension” level:

- Entity types and their corresponding entity sets
- Key attributes of entity types
- Value sets (domains) of attributes
- Relationship types and their corresponding relationship sets
- Participation roles of entity types in relationship types

We presented two methods for specifying the structural constraints on relationship types. The first method distinguished two types of structural constraints:

- Cardinality ratios (1:1, 1:N, M:N for binary relationships)
- Participation constraints (total, partial)

We noted that, alternatively, another method of specifying structural constraints is to specify minimum and maximum numbers (min, max) on the participation of each entity type in a relationship type. We discussed weak entity types and the related concepts of owner entity types, identifying relationship types and partial key attributes.

Entity–relationship schemas can be represented diagrammatically as ER diagrams. We showed how to design an ER schema for the COMPANY database by first defining the entity types and their attributes and then refining the design to include relationship types. We displayed the ER diagram for the COMPANY database schema. We discussed some of the basic concepts of UML class diagrams and how they relate to ER modeling concepts. We also described ternary and higher-degree relationship types in more detail, and we discussed the circumstances under which they are distinguished from binary relationships. Finally, we presented requirements for a UNIVERSITY database schema as another example, and we showed the ER schema design.

The ER modeling concepts we have presented thus far—entity types, relationship types, attributes, keys, and structural constraints—can model many database applications. However, more complex applications—such as engineering design, medical information systems, and telecommunications—require additional concepts if we want to model them with greater accuracy. We discuss some advanced modeling concepts in Chapter 8 and revisit further advanced data modeling techniques in Chapter 26.

Review Questions

- 3.1. Discuss the role of a high-level data model in the database design process.
- 3.2. List the various cases where use of a NULL value would be appropriate.
- 3.3. Define the following terms: *entity*, *attribute*, *attribute value*, *relationship instance*, *composite attribute*, *multivalued attribute*, *derived attribute*, *complex attribute*, *key attribute*, and *value set (domain)*.
- 3.4. What is an entity type? What is an entity set? Explain the differences among an entity, an entity type, and an entity set.
- 3.5. Explain the difference between an attribute and a value set.
- 3.6. What is a relationship type? Explain the differences among a relationship instance, a relationship type, and a relationship set.
- 3.7. What is a participation role? When is it necessary to use role names in the description of relationship types?
- 3.8. Describe the two alternatives for specifying structural constraints on relationship types. What are the advantages and disadvantages of each?
- 3.9. Under what conditions can an attribute of a binary relationship type be migrated to become an attribute of one of the participating entity types?
- 3.10. When we think of relationships as attributes, what are the value sets of these attributes? What class of data models is based on this concept?
- 3.11. What is meant by a recursive relationship type? Give some examples of recursive relationship types.
- 3.12. When is the concept of a weak entity used in data modeling? Define the terms *owner entity type*, *weak entity type*, *identifying relationship type*, and *partial key*.
- 3.13. Can an identifying relationship of a weak entity type be of a degree greater than two? Give examples to illustrate your answer.
- 3.14. Discuss the conventions for displaying an ER schema as an ER diagram.
- 3.15. Discuss the naming conventions used for ER schema diagrams.

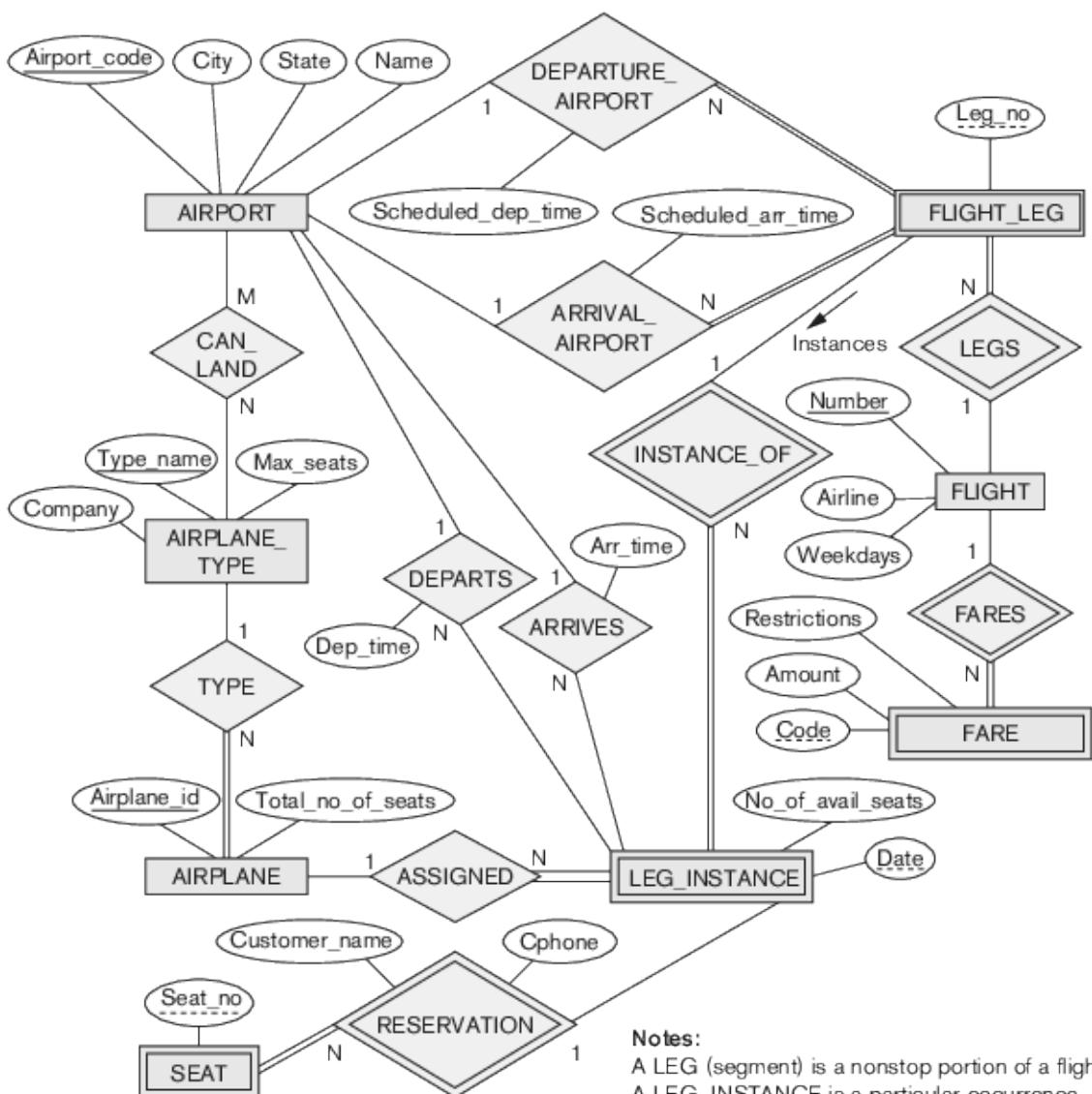
Exercises

- 3.16. Which combinations of attributes have to be unique for each individual SECTION entity in the UNIVERSITY database shown in Figure 3.20 to enforce each of the following miniworld constraints:
 - a. During a particular semester and year, only one section can use a particular classroom at a particular DaysTime value.

- b. During a particular semester and year, an instructor can teach only one section at a particular DaysTime value.
- c. During a particular semester and year, the section numbers for sections offered for the same course must all be different.

Can you think of any other similar constraints?

- 3.17. Composite and multivalued attributes can be nested to any number of levels. Suppose we want to design an attribute for a STUDENT entity type to keep track of previous college education. Such an attribute will have one entry for each college previously attended, and each such entry will be composed of college name, start and end dates, degree entries (degrees awarded at that college, if any), and transcript entries (courses completed at that college, if any). Each degree entry contains the degree name and the month and year the degree was awarded, and each transcript entry contains a course name, semester, year, and grade. Design an attribute to hold this information. Use the conventions in Figure 3.5.
- 3.18. Show an alternative design for the attribute described in Exercise 3.17 that uses only entity types (including weak entity types, if needed) and relationship types.
- 3.19. Consider the ER diagram in Figure 3.21, which shows a simplified schema for an airline reservations system. Extract from the ER diagram the requirements and constraints that produced this schema. Try to be as precise as possible in your requirements and constraints specification.
- 3.20. In Chapters 1 and 2, we discussed the database environment and database users. We can consider many entity types to describe such an environment, such as DBMS, stored database, DBA, and catalog/data dictionary. Try to specify all the entity types that can fully describe a database system and its environment; then specify the relationship types among them, and draw an ER diagram to describe such a general database environment.
- 3.21. Design an ER schema for keeping track of information about votes taken in the U.S. House of Representatives during the current two-year congressional session. The database needs to keep track of each U.S. STATE's Name (e.g., 'Texas', 'New York', 'California') and include the Region of the state (whose domain is {'Northeast', 'Midwest', 'Southeast', 'Southwest', 'West'}). Each CONGRESS_PERSON in the House of Representatives is described by his or her Name, plus the District represented, the Start_date when the congressperson was first elected, and the political Party to which he or she belongs (whose domain is {'Republican', 'Democrat', 'Independent', 'Other'}). The database keeps track of each BILL (i.e., proposed law), including the Bill_name, the Date_of_vote on the bill, whether the bill Passed_or_failed (whose domain is {'Yes', 'No'}), and the Sponsor (the congressperson(s) who sponsored—that is, proposed—the bill). The database also keeps track of how each congressperson voted on each bill (domain

**Figure 3.21**

An ER diagram for an AIRLINE database schema.

of Vote attribute is {‘Yes’, ‘No’, ‘Abstain’, ‘Absent’}). Draw an ER schema diagram for this application. State clearly any assumptions you make.

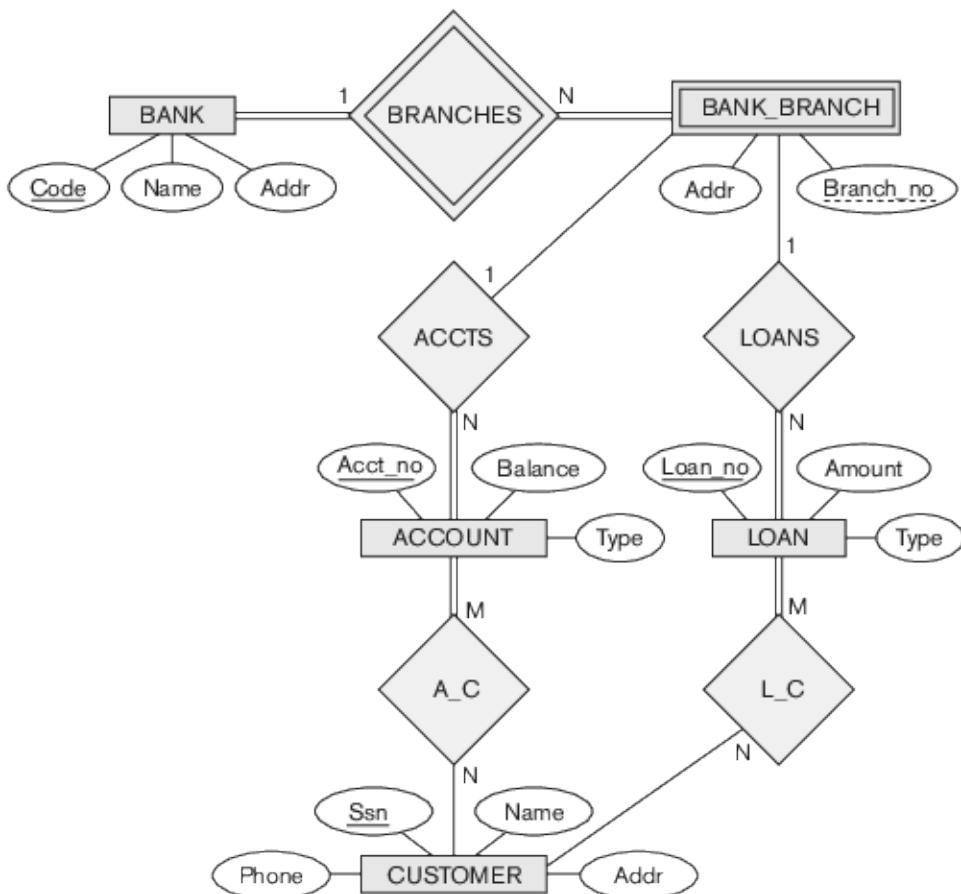
- 3.22. A database is being constructed to keep track of the teams and games of a sports league. A team has a number of players, not all of whom participate in each game. It is desired to keep track of the players participating in each game for each team, the positions they played in that game, and the result of

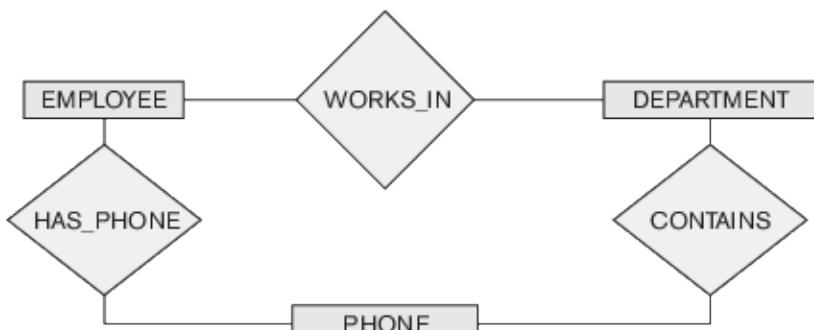
the game. Design an ER schema diagram for this application, stating any assumptions you make. Choose your favorite sport (e.g., soccer, baseball, football).

- 3.23. Consider the ER diagram shown in Figure 3.22 for part of a BANK database. Each bank can have multiple branches, and each branch can have multiple accounts and loans.
- List the strong (nonweak) entity types in the ER diagram.
 - Is there a weak entity type? If so, give its name, partial key, and identifying relationship.
 - What constraints do the partial key and the identifying relationship of the weak entity type specify in this diagram?
 - List the names of all relationship types, and specify the (min, max) constraint on each participation of an entity type in a relationship type. Justify your choices.

Figure 3.22

An ER diagram for a BANK database schema.



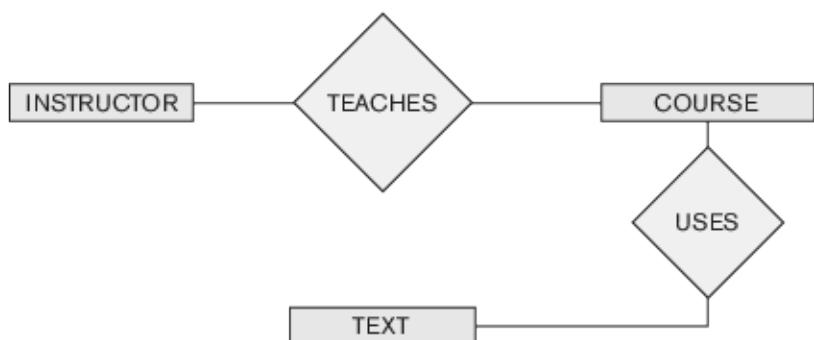
**Figure 3.23**

Part of an ER diagram for a COMPANY database.

- e. List concisely the user requirements that led to this ER schema design.
 - f. Suppose that every customer must have at least one account but is restricted to at most two loans at a time, and that a bank branch cannot have more than 1,000 loans. How does this show up on the (min, max) constraints?
- 3.24. Consider the ER diagram in Figure 3.23. Assume that an employee may work in up to two departments or may not be assigned to any department. Assume that each department must have one and may have up to three phone numbers. Supply (min, max) constraints on this diagram. *State clearly any additional assumptions you make.* Under what conditions would the relationship **HAS_PHONE** be redundant in this example?
- 3.25. Consider the ER diagram in Figure 3.24. Assume that a course may or may not use a textbook, but that a text by definition is a book that is used in some course. A course may not use more than five books. Instructors teach from two to four courses. Supply (min, max) constraints on this diagram. *State clearly any additional assumptions you make.* If we add the relationship **ADOPTS**, to indicate the textbook(s) that an instructor uses for a course, should it be a binary relationship between **INSTRUCTOR** and **TEXT**, or a ternary relationship among all three entity types? What (min, max) constraints would you put on the relationship? Why?

Figure 3.24

Part of an ER diagram for a COURSES database.



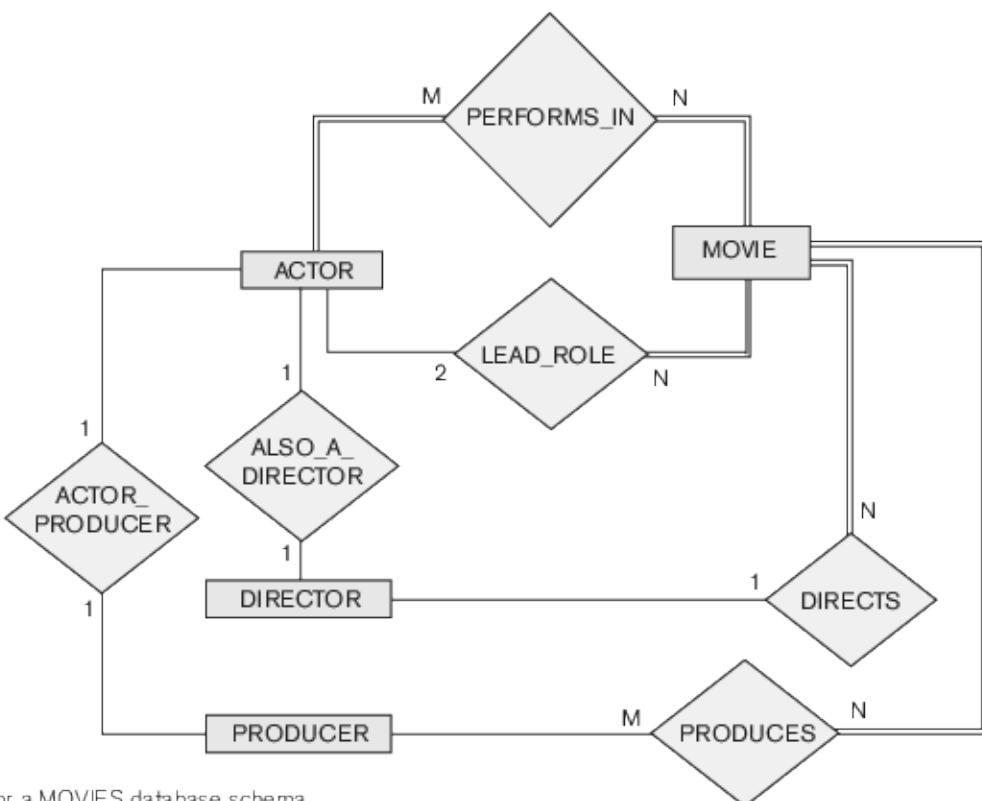
- 3.26. Consider an entity type SECTION in a UNIVERSITY database, which describes the section offerings of courses. The attributes of SECTION are Section_number, Semester, Year, Course_number, Instructor, Room_no (where section is taught), Building (where section is taught), Weekdays (domain is the possible combinations of weekdays in which a section can be offered {'MWF', 'MW', 'TT', and so on}), and Hours (domain is all possible time periods during which sections are offered {'9–9:50 A.M.', '10–10:50 A.M.', . . . , '3:30–4:50 P.M.', '5:30–6:20 P.M.', and so on}). Assume that Section_number is unique for each course within a particular semester/year combination (that is, if a course is offered multiple times during a particular semester, its section offerings are numbered 1, 2, 3, and so on). There are several composite keys for section, and some attributes are components of more than one key. Identify three composite keys, and show how they can be represented in an ER schema diagram.
- 3.27. Cardinality ratios often dictate the detailed design of a database. The cardinality ratio depends on the real-world meaning of the entity types involved and is defined by the specific application. For the following binary relationships, suggest cardinality ratios based on the common-sense meaning of the entity types. Clearly state any assumptions you make.

Entity 1	Cardinality Ratio	Entity 2
1. STUDENT	_____	SOCIAL_SECURITY_CARD
2. STUDENT	_____	TEACHER
3. CLASSROOM	_____	WALL
4. COUNTRY	_____	CURRENT_PRESIDENT
5. COURSE	_____	TEXTBOOK
6. ITEM (that can be found in an order)	_____	ORDER
7. STUDENT	_____	CLASS
8. CLASS	_____	INSTRUCTOR
9. INSTRUCTOR	_____	OFFICE
10. EBAY_AUCTION_ITEM	_____	EBAY_BID

- 3.28. Consider the ER schema for the MOVIES database in Figure 3.25.

Assume that MOVIES is a populated database. ACTOR is used as a generic term and includes actresses. Given the constraints shown in the ER schema, respond to the following statements with *True*, *False*, or *Maybe*. Assign a response of *Maybe* to statements that, although not explicitly shown to be *True*, cannot be proven *False* based on the schema as shown. Justify each answer.

- There are no actors in this database that have been in no movies.
- There are some actors who have acted in more than ten movies.
- Some actors have done a lead role in multiple movies.
- A movie can have only a maximum of two lead actors.

**Figure 3.25**

An ER diagram for a MOVIES database schema.

- e. Every director has been an actor in some movie.
 - f. No producer has ever been an actor.
 - g. A producer cannot be an actor in some other movie.
 - h. There are movies with more than a dozen actors.
 - i. Some producers have been a director as well.
 - j. Most movies have one director and one producer.
 - k. Some movies have one director but several producers.
 - l. There are some actors who have done a lead role, directed a movie, and produced a movie.
 - m. No movie has a director who also acted in that movie.
- 3.29. Given the ER schema for the MOVIES database in Figure 3.25, draw an instance diagram using three movies that have been released recently. Draw instances of each entity type: MOVIES, ACTORS, PRODUCERS, DIRECTORS involved; make up instances of the relationships as they exist in reality for those movies.

- 3.30. Illustrate the UML diagram for Exercise 3.16. Your UML design should observe the following requirements:
- A student should have the ability to compute his/her GPA and add or drop majors and minors.
 - Each department should be able to add or delete courses and hire or terminate faculty.
 - Each instructor should be able to assign or change a student's grade for a course.

Note: Some of these functions may be spread over multiple classes.

Laboratory Exercises

- 3.31. Consider the UNIVERSITY database described in Exercise 3.16. Build the ER schema for this database using a data modeling tool such as ERwin or Rational Rose.
- 3.32. Consider a MAIL_ORDER database in which employees take orders for parts from customers. The data requirements are summarized as follows:
- The mail order company has employees, each identified by a unique employee number, first and last name, and Zip Code.
 - Each customer of the company is identified by a unique customer number, first and last name, and Zip Code.
 - Each part sold by the company is identified by a unique part number, a part name, price, and quantity in stock.
 - Each order placed by a customer is taken by an employee and is given a unique order number. Each order contains specified quantities of one or more parts. Each order has a date of receipt as well as an expected ship date. The actual ship date is also recorded.

Design an entity–relationship diagram for the mail order database and build the design using a data modeling tool such as ERwin or Rational Rose.

- 3.33. Consider a MOVIE database in which data is recorded about the movie industry. The data requirements are summarized as follows:
- Each movie is identified by title and year of release. Each movie has a length in minutes. Each has a production company, and each is classified under one or more genres (such as horror, action, drama, and so forth). Each movie has one or more directors and one or more actors appear in it. Each movie also has a plot outline. Finally, each movie has zero or more quotable quotes, each of which is spoken by a particular actor appearing in the movie.
 - Actors are identified by name and date of birth and appear in one or more movies. Each actor has a role in the movie.

- Directors are also identified by name and date of birth and direct one or more movies. It is possible for a director to act in a movie (including one that he or she may also direct).
- Production companies are identified by name and each has an address. A production company produces one or more movies.

Design an entity–relationship diagram for the movie database and enter the design using a data modeling tool such as ERwin or Rational Rose.

- 3.34. Consider a CONFERENCE REVIEW database in which researchers submit their research papers for consideration. Reviews by reviewers are recorded for use in the paper selection process. The database system caters primarily to reviewers who record answers to evaluation questions for each paper they review and make recommendations regarding whether to accept or reject the paper. The data requirements are summarized as follows:

- Authors of papers are uniquely identified by e-mail id. First and last names are also recorded.
- Each paper is assigned a unique identifier by the system and is described by a title, abstract, and the name of the electronic file containing the paper.
- A paper may have multiple authors, but one of the authors is designated as the contact author.
- Reviewers of papers are uniquely identified by e-mail address. Each reviewer's first name, last name, phone number, affiliation, and topics of interest are also recorded.
- Each paper is assigned between two and four reviewers. A reviewer rates each paper assigned to him or her on a scale of 1 to 10 in four categories: technical merit, readability, originality, and relevance to the conference. Finally, each reviewer provides an overall recommendation regarding each paper.
- Each review contains two types of written comments: one to be seen by the review committee only and the other as feedback to the author(s).

Design an entity–relationship diagram for the CONFERENCE REVIEW database and build the design using a data modeling tool such as ERwin or Rational Rose.

- 3.35. Consider the ER diagram for the AIRLINE database shown in Figure 3.21. Build this design using a data modeling tool such as ERwin or Rational Rose.

Selected Bibliography

The entity–relationship model was introduced by Chen (1976), and related work appears in Schmidt and Swenson (1975), Wiederhold and Elmasri (1979), and Senko (1975). Since then, numerous modifications to the ER model have been suggested. We have incorporated some of these in our presentation. Structural

constraints on relationships are discussed in Abrial (1974), Elmasri and Wiederhold (1980), and Lenzerini and Santucci (1983). Multivalued and composite attributes are incorporated in the ER model in Elmasri et al. (1985). Although we did not discuss languages for the ER model and its extensions, there have been several proposals for such languages. Elmasri and Wiederhold (1981) proposed the GORDAS query language for the ER model. Another ER query language was proposed by Markowitz and Raz (1983). Senko (1980) presented a query language for Senko's DIAM model. A formal set of operations called the ER algebra was presented by Parent and Spaccapietra (1985). Gogolla and Hohenstein (1991) presented another formal language for the ER model. Campbell et al. (1985) presented a set of ER operations and showed that they are relationally complete. A conference for the dissemination of research results related to the ER model has been held regularly since 1979. The conference, now known as the International Conference on Conceptual Modeling, has been held in Los Angeles (ER 1979, ER 1983, ER 1997), Washington, D.C. (ER 1981), Chicago (ER 1985), Dijon, France (ER 1986), New York City (ER 1987), Rome (ER 1988), Toronto (ER 1989), Lausanne, Switzerland (ER 1990), San Mateo, California (ER 1991), Karlsruhe, Germany (ER 1992), Arlington, Texas (ER 1993), Manchester, England (ER 1994), Brisbane, Australia (ER 1995), Cottbus, Germany (ER 1996), Singapore (ER 1998), Paris, France (ER 1999), Salt Lake City, Utah (ER 2000), Yokohama, Japan (ER 2001), Tampere, Finland (ER 2002), Chicago, Illinois (ER 2003), Shanghai, China (ER 2004), Klagenfurt, Austria (ER 2005), Tucson, Arizona (ER 2006), Auckland, New Zealand (ER 2007), Barcelona, Catalonia, Spain (ER 2008), and Gramado, RS, Brazil (ER 2009). The 2010 conference was held in Vancouver, British Columbia, Canada (ER2010), 2011 in Brussels, Belgium (ER2011), 2012 in Florence, Italy (ER2012) , 2013 in Hong Kong, China (ER2013), and the 2014 conference was held in Atlanta, Georgia (ER 2014). The 2015 conference is to be held in Stockholm, Sweden.