chapter 24

Database Security

This chapter discusses techniques for securing databases against a variety of threats. It also presents schemes of providing access privileges to authorized users. Some of the security threats to databases—such as SQL Injection—will be presented. At the end of the chapter we also summarize how a commercial RDBMS—specifically, the Oracle system—provides different types of security. We start in Section 24.1 with an introduction to security issues and the threats to databases, and we give an overview of the control measures that are covered in the rest of this chapter. We also comment on the relationship between data security and privacy as it applies to personal information. Section 24.2 discusses the mechanisms used to grant and revoke privileges in relational database systems and in SQL, mechanisms that are often referred to as **discretionary access control**. In Section 24.3, we present an overview of the mechanisms for enforcing multiple levels of security—a particular concern in database system security that is known as **mandatory access control**. Section 24.3 also introduces the more recently developed strategies of **role-based access control**, and label-based and row-based security. Section 24.3 also provides a brief discussion of XML access control. Section 24.4 discusses a major threat to databases called SQL Injection, and discusses some of the proposed preventive measures against it. Section 24.5 briefly discusses the security problem in statistical databases. Section 24.6 introduces the topic of flow control and mentions problems associated with covert channels. Section 24.7 provides a brief summary of encryption and symmetric key and asymmetric (public) key infrastructure schemes. It also discusses digital certificates. Section 24.8 introduces privacy-preserving techniques, and Section 24.9 presents the current challenges to database security. In Section 24.10, we discuss Oracle label-based security. Finally, Section 24.11 summarizes the chapter. Readers who are interested only in basic database security mechanisms will find it sufficient to cover the material in Sections 24.1 and 24.2.

24.1 Introduction to Database Security Issues[1]

24.1.1 Types of Security

Database security is a broad area that addresses many issues, including the following:

- Various legal and ethical issues regarding the right to access certain information—for example, some information may be deemed to be private and cannot be accessed legally by unauthorized organizations or persons. In the United States, there are numerous laws governing privacy of information.
- Policy issues at the governmental, institutional, or corporate level as to what kinds of information should not be made publicly available—for example, credit ratings and personal medical records.
- System-related issues such as the *system levels* at which various security functions should be enforced—for example, whether a security function should be handled at the physical hardware level, the operating system level, or the DBMS level.
- The need in some organizations to identify multiple *security levels* and to categorize the data and users based on these classifications—for example, top secret, secret, confidential, and unclassified. The security policy of the organization with respect to permitting access to various classifications of data must be enforced.

Threats to Databases. Threats to databases can result in the loss or degradation of some or all of the following commonly accepted security goals: integrity, availability, and confidentiality.

- **Loss of integrity.** Database integrity refers to the requirement that information be protected from improper modification. Modification of data includes creation, insertion, updating, changing the status of data, and deletion. Integrity is lost if unauthorized changes are made to the data by either intentional or accidental acts. If the loss of system or data integrity is not corrected, continued use of the contaminated system or corrupted data could result in inaccuracy, fraud, or erroneous decisions.
- **Loss of availability.** Database availability refers to making objects available to a human user or a program to which they have a legitimate right.
- **Loss of confidentiality.** Database confidentiality refers to the protection of data from unauthorized disclosure. The impact of unauthorized disclosure of confidential information can range from violation of the Data Privacy Act to the jeopardization of national security. Unauthorized, unanticipated, or unintentional disclosure could result in loss of public confidence, embarrassment, or legal action against the organization.

[1]The substantial contribution of Fariborz Farahmand and Bharath Rengarajan to this and subsequent sections in this chapter is much appreciated.

To protect databases against these types of threats, it is common to implement *four kinds of control measures*: access control, inference control, flow control, and encryption. We discuss each of these in this chapter.

In a multiuser database system, the DBMS must provide techniques to enable certain users or user groups to access selected portions of a database without gaining access to the rest of the database. This is particularly important when a large integrated database is to be used by many different users within the same organization. For example, sensitive information such as employee salaries or performance reviews should be kept confidential from most of the database system's users. A DBMS typically includes a **database security and authorization subsystem** that is responsible for ensuring the security of portions of a database against unauthorized access. It is now customary to refer to two types of database security mechanisms:

- **Discretionary security mechanisms.** These are used to grant privileges to users, including the capability to access specific data files, records, or fields in a specified mode (such as read, insert, delete, or update).
- **Mandatory security mechanisms.** These are used to enforce multilevel security by classifying the data and users into various security classes (or levels) and then implementing the appropriate security policy of the organization. For example, a typical security policy is to permit users at a certain classification (or clearance) level to see only the data items classified at the user's own (or lower) classification level. An extension of this is *role-based security*, which enforces policies and privileges based on the concept of organizational roles.

We discuss discretionary security in Section 24.2 and mandatory and role-based security in Section 24.3.

24.1.2 Control Measures

Four main control measures are used to provide security of data in databases:

- Access control
- Inference control
- Flow control
- Data encryption

A security problem common to computer systems is that of preventing unauthorized persons from accessing the system itself, either to obtain information or to make malicious changes in a portion of the database. The security mechanism of a DBMS must include provisions for restricting access to the database system as a whole. This function, called **access control**, is handled by creating user accounts and passwords to control the login process by the DBMS. We discuss access control techniques in Section 24.1.3.

Statistical databases are used to provide statistical information or summaries of values based on various criteria. For example, a database for population statistics may provide statistics based on age groups, income levels, household size, education levels, and other criteria. Statistical database users such as government statisticians or market research firms are allowed to access the database to retrieve statistical information about a population but not to access the detailed confidential information about specific individuals. Security for statistical databases must ensure that information about individuals cannot be accessed. It is sometimes possible to deduce or infer certain facts concerning individuals from queries that involve only summary statistics on groups; consequently, this must not be permitted either. This problem, called **statistical database security**, is discussed briefly in Section 24.4. The corresponding control measures are called **inference control** measures.

Another security issue is that of **flow control**, which prevents information from flowing in such a way that it reaches unauthorized users. It is discussed in Section 24.6. Channels that are pathways for information to flow implicitly in ways that violate the security policy of an organization are called **covert channels**. We briefly discuss some issues related to covert channels in Section 24.6.1.

A final control measure is **data encryption**, which is used to protect sensitive data (such as credit card numbers) that is transmitted via some type of communications network. Encryption can be used to provide additional protection for sensitive portions of a database as well. The data is **encoded** using some coding algorithm. An unauthorized user who accesses encoded data will have difficulty deciphering it, but authorized users are given decoding or decrypting algorithms (or keys) to decipher the data. Encrypting techniques that are very difficult to decode without a key have been developed for military applications. Section 24.7 briefly discusses encryption techniques, including popular techniques such as public key encryption, which is heavily used to support Web-based transactions against databases, and digital signatures, which are used in personal communications.

A comprehensive discussion of security in computer systems and databases is outside the scope of this textbook. We give only a brief overview of database security techniques here. The interested reader can refer to several of the references discussed in the Selected Bibliography at the end of this chapter for a more comprehensive discussion.

24.1.3 Database Security and the DBA

As we discussed in Chapter 1, the database administrator (DBA) is the central authority for managing a database system. The DBA's responsibilities include granting privileges to users who need to use the system and classifying users and data in accordance with the policy of the organization. The DBA has a **DBA account** in the DBMS, sometimes called a **system** or **superuser account**, which provides powerful capabilities that are not made available to regular database accounts and users.[2] DBA-privileged commands include commands for granting and revoking privileges

[2]This account is similar to the *root* or *superuser* accounts that are given to computer system administrators, which allow access to restricted operating system commands.

to individual accounts, users, or user groups and for performing the following types of actions:

1. **Account creation.** This action creates a new account and password for a user or a group of users to enable access to the DBMS.
2. **Privilege granting.** This action permits the DBA to grant certain privileges to certain accounts.
3. **Privilege revocation.** This action permits the DBA to revoke (cancel) certain privileges that were previously given to certain accounts.
4. **Security level assignment.** This action consists of assigning user accounts to the appropriate security clearance level.

The DBA is responsible for the overall security of the database system. Action 1 in the preceding list is used to control access to the DBMS as a whole, whereas actions 2 and 3 are used to control *discretionary* database authorization, and action 4 is used to control *mandatory* authorization.

24.1.4 Access Control, User Accounts, and Database Audits

Whenever a person or a group of persons needs to access a database system, the individual or group must first apply for a user account. The DBA will then create a new **account number** and **password** for the user if there is a legitimate need to access the database. The user must **log in** to the DBMS by entering the account number and password whenever database access is needed. The DBMS checks that the account number and password are valid; if they are, the user is permitted to use the DBMS and to access the database. Application programs can also be considered users and are required to log in to the database (see Chapter 13).

It is straightforward to keep track of database users and their accounts and passwords by creating an encrypted table or file with two fields: AccountNumber and Password. This table can easily be maintained by the DBMS. Whenever a new account is created, a new record is inserted into the table. When an account is canceled, the corresponding record must be deleted from the table.

The database system must also keep track of all operations on the database that are applied by a certain user throughout each **login session**, which consists of the sequence of database interactions that a user performs from the time of logging in to the time of logging off. When a user logs in, the DBMS can record the user's account number and associate it with the computer or device from which the user logged in. All operations applied from that computer or device are attributed to the user's account until the user logs off. It is particularly important to keep track of update operations that are applied to the database so that, if the database is tampered with, the DBA can determine which user did the tampering.

To keep a record of all updates applied to the database and of particular users who applied each update, we can modify the *system log*. Recall from Chapters 21 and 23 that the **system log** includes an entry for each operation applied to the database that may be required for recovery from a transaction failure or system crash. We can expand the log entries so that they also include the account number of the user and the online computer or device ID that applied each operation recorded in the log. If any tampering with the database is suspected, a **database audit** is performed, which consists of reviewing the log to examine all accesses and operations applied to the database during a certain time period. When an illegal or unauthorized operation is found, the DBA can determine the account number used to perform the operation. Database audits are particularly important for sensitive databases that are updated by many transactions and users, such as a banking database that is updated by many bank tellers. A database log that is used mainly for security purposes is sometimes called an **audit trail**.

24.1.5 Sensitive Data and Types of Disclosures

Sensitivity of data is a measure of the importance assigned to the data by its owner, for the purpose of denoting its need for protection. Some databases contain only sensitive data while other databases may contain no sensitive data at all. Handling databases that fall at these two extremes is relatively easy, because these can be covered by access control, which is explained in the next section. The situation becomes tricky when some of the data is sensitive while other data is not.

Several factors can cause data to be classified as sensitive:

1. **Inherently sensitive.** The value of the data itself may be so revealing or confidential that it becomes sensitive—for example, a person's salary or that a patient has HIV/AIDS.
2. **From a sensitive source.** The source of the data may indicate a need for secrecy—for example, an informer whose identity must be kept secret.
3. **Declared sensitive.** The owner of the data may have explicitly declared it as sensitive.
4. **A sensitive attribute or sensitive record.** The particular attribute or record may have been declared sensitive—for example, the salary attribute of an employee or the salary history record in a personnel database.
5. **Sensitive in relation to previously disclosed data.** Some data may not be sensitive by itself but will become sensitive in the presence of some other data—for example, the exact latitude and longitude information for a location where some previously recorded event happened that was later deemed sensitive.

It is the responsibility of the database administrator and security administrator to collectively enforce the security policies of an organization. This dictates whether access should be permitted to a certain database attribute (also known as a *table column* or a *data element*) or not for individual users or for categories of users. Several factors need to be considered before deciding whether it is safe to reveal the data. The three most important factors are data availability, access acceptability, and authenticity assurance.

1. **Data availability.** If a user is updating a field, then this field becomes inaccessible and other users should not be able to view this data. This blocking is

only temporary and only to ensure that no user sees any inaccurate data. This is typically handled by the concurrency control mechanism (see Chapter 22).

2. **Access acceptability.** Data should only be revealed to authorized users. A database administrator may also deny access to a user request even if the request does not directly access a sensitive data item, on the grounds that the requested data may reveal information about the sensitive data that the user is not authorized to have.
3. **Authenticity assurance.** Before granting access, certain external characteristics about the user may also be considered. For example, a user may only be permitted access during working hours. The system may track previous queries to ensure that a combination of queries does not reveal sensitive data. The latter is particularly relevant to statistical database queries (see Section 24.5).

The term *precision*, when used in the security area, refers to allowing as much as possible of the data to be available, subject to protecting exactly the subset of data that is sensitive. The definitions of *security* versus *precision* are as follows:

- **Security:** Means of ensuring that data is kept safe from corruption and that access to it is suitably controlled. To provide security means to disclose only nonsensitive data, and reject any query that references a sensitive field.
- **Precision**: To protect all sensitive data while disclosing as much nonsensitive data as possible.

The ideal combination is to maintain perfect security with maximum precision. If we want to maintain security, some sacrifice has to be made with precision. Hence there is typically a tradeoff between security and precision.

24.1.6 Relationship between Information Security versus Information Privacy

The rapid advancement of the use of information technology (IT) in industry, government, and academia raises challenging questions and problems regarding the protection and use of personal information. Questions of *who* has *what* rights to information about individuals for *which* purposes become more important as we move toward a world in which it is technically possible to know just about anything about anyone.

Deciding how to design privacy considerations in technology for the future includes philosophical, legal, and practical dimensions. There is a considerable overlap between issues related to access to resources (security) and issues related to appropriate use of information (privacy). We now define the difference between *security* versus *privacy*.

Security in information technology refers to many aspects of protecting a system from unauthorized use, including authentication of users, information encryption, access control, firewall policies, and intrusion detection. For our purposes here, we will limit our treatment of security to the concepts associated with how well a system can protect access to information it contains. The concept of **privacy** goes beyond security. Privacy examines how well the use of personal information that the system acquires about a user conforms to the explicit or implicit assumptions regarding that use. From an end user perspective, privacy can be considered from two different perspectives: *preventing storage* of personal information versus *ensuring appropriate use* of personal information.

For the purposes of this chapter, a simple but useful definition of **privacy** is *the ability of individuals to control the terms under which their personal information is acquired and used*. In summary, security involves technology to ensure that information is appropriately protected. Security is a required building block for privacy to exist. Privacy involves mechanisms to support compliance with some basic principles and other explicitly stated policies. One basic principle is that people should be informed about information collection, told in advance what will be done with their information, and given a reasonable opportunity to approve of such use of the information. A related concept**, trust**, relates to both security and privacy, and is seen as increasing when it is perceived that both security and privacy are provided for.

24.2 Discretionary Access Control Based on Granting and Revoking Privileges

The typical method of enforcing **discretionary access control** in a database system is based on the granting and revoking of **privileges**. Let us consider privileges in the context of a relational DBMS. In particular, we will discuss a system of privileges somewhat similar to the one originally developed for the SQL language (see Chapters 4 and 5). Many current relational DBMSs use some variation of this technique. The main idea is to include statements in the query language that allow the DBA and selected users to grant and revoke privileges.

24.2.1 Types of Discretionary Privileges

In SQL2 and later versions,[3] the concept of an **authorization identifier** is used to refer, roughly speaking, to a user account (or group of user accounts). For simplicity, we will use the words *user* or *account* interchangeably in place of *authorization identifier.* The DBMS must provide selective access to each relation in the database based on specific accounts. Operations may also be controlled; thus, having an account does not necessarily entitle the account holder to all the functionality provided by the DBMS. Informally, there are two levels for assigning privileges to use the database system:

- **The account level.** At this level, the DBA specifies the particular privileges that each account holds independently of the relations in the database.
- **The relation (or table) level.** At this level, the DBA can control the privilege to access each individual relation or view in the database.

[3]Discretionary privileges were incorporated into SQL2 and are applicable to later versions of SQL.

The privileges at the **account level** apply to the capabilities provided to the account itself and can include the CREATE SCHEMA or CREATE TABLE privilege, to create a schema or base relation; the CREATE VIEW privilege; the ALTER privilege, to apply schema changes such as adding or removing attributes from relations; the DROP privilege, to delete relations or views; the MODIFY privilege, to insert, delete, or update tuples; and the SELECT privilege, to retrieve information from the database by using a SELECT query. Notice that these account privileges apply to the account in general. If a certain account does not have the CREATE TABLE privilege, no relations can be created from that account. Account-level privileges *are not* defined as part of SQL2; they are left to the DBMS implementers to define. In earlier versions of SQL, a CREATETAB privilege existed to give an account the privilege to create tables (relations).

The second level of privileges applies to the **relation level**, whether they are base relations or virtual (view) relations. These privileges *are* defined for SQL2. In the following discussion, the term *relation* may refer either to a base relation or to a view, unless we explicitly specify one or the other. Privileges at the relation level specify for each user the individual relations on which each type of command can be applied. Some privileges also refer to individual columns (attributes) of relations. SQL2 commands provide privileges at the *relation and attribute level only.* Although this is quite general, it makes it difficult to create accounts with limited privileges. The granting and revoking of privileges generally follow an authorization model for discretionary privileges known as the **access matrix model**, where the rows of a matrix M represent *subjects* (users, accounts, programs) and the columns represent *objects* (relations, records, columns, views, operations). Each position $M(i, j)$ in the matrix represents the types of privileges (read, write, update) that subject i holds on object j.

To control the granting and revoking of relation privileges, each relation R in a database is assigned an **owner account**, which is typically the account that was used when the relation was created in the first place. The owner of a relation is given *all* privileges on that relation. In SQL2, the DBA can assign an owner to a whole schema by creating the schema and associating the appropriate authorization identifier with that schema, using the CREATE SCHEMA command (see Section 4.1.1). The owner account holder can pass privileges on any of the owned relations to other users by **granting** privileges to their accounts. In SQL the following types of privileges can be granted on each individual relation R:

- **SELECT (retrieval or read) privilege on *R*.** Gives the account retrieval privilege. In SQL this gives the account the privilege to use the SELECT statement to retrieve tuples from R.
- **Modification privileges on *R*.** This gives the account the capability to modify the tuples of R. In SQL this includes three privileges: UPDATE, DELETE, and INSERT. These correspond to the three SQL commands (see Section 4.4) for modifying a table R. Additionally, both the INSERT and UPDATE privileges can specify that only certain attributes of R can be modified by the account.

- **References privilege on *R*.** This gives the account the capability to *reference* (or refer to) a relation *R* when specifying integrity constraints. This privilege can also be restricted to specific attributes of *R*.

Notice that to create a view, the account must have the SELECT privilege on *all relations* involved in the view definition in order to specify the query that corresponds to the view.

24.2.2 Specifying Privileges through the Use of Views

The mechanism of **views** is an important *discretionary authorization mechanism* in its own right. For example, if the owner *A* of a relation *R* wants another account *B* to be able to retrieve only some fields of *R*, then *A* can create a view *V* of *R* that includes only those attributes and then grant SELECT on *V* to *B*. The same applies to limiting *B* to retrieving only certain tuples of *R;* a view *V′* can be created by defining the view by means of a query that selects only those tuples from *R* that *A* wants to allow *B* to access. We will illustrate this discussion with the example given in Section 24.2.5.

24.2.3 Revoking of Privileges

In some cases it is desirable to grant a privilege to a user temporarily. For example, the owner of a relation may want to grant the SELECT privilege to a user for a specific task and then revoke that privilege once the task is completed. Hence, a mechanism for **revoking** privileges is needed. In SQL a REVOKE command is included for the purpose of canceling privileges. We will see how the REVOKE command is used in the example in Section 24.2.5.

24.2.4 Propagation of Privileges Using the GRANT OPTION

Whenever the owner *A* of a relation *R* grants a privilege on *R* to another account *B*, the privilege can be given to *B with* or *without* the **GRANT OPTION**. If the GRANT OPTION is given, this means that *B* can also grant that privilege on *R* to other accounts. Suppose that *B* is given the GRANT OPTION by *A* and that *B* then grants the privilege on *R* to a third account *C*, also with the GRANT OPTION. In this way, privileges on *R* can **propagate** to other accounts without the knowledge of the owner of *R*. If the owner account *A* now revokes the privilege granted to *B*, all the privileges that *B* propagated based on that privilege *should automatically be revoked* by the system.

It is possible for a user to receive a certain privilege from two or more sources. For example, A4 may receive a certain UPDATE *R* privilege from *both* A2 and A3. In such a case, if A2 revokes this privilege from A4, A4 will still continue to have the privilege by virtue of having been granted it from A3. If A3 later revokes the privilege from A4, A4 totally loses the privilege. Hence, a DBMS that allows propagation of privileges must keep track of how all the privileges were granted so that revoking of privileges can be done correctly and completely.

24.2.5 An Example to Illustrate Granting and Revoking of Privileges

Suppose that the DBA creates four accounts—A1, A2, A3, and A4—and wants only A1 to be able to create base relations. To do this, the DBA must issue the following GRANT command in SQL:

```
GRANT CREATETAB TO A1;
```

The CREATETAB (create table) privilege gives account A1 the capability to create new database tables (base relations) and is hence an *account privilege.* This privilege was part of earlier versions of SQL but is now left to each individual system implementation to define.

In SQL2 the same effect can be accomplished by having the DBA issue a CREATE SCHEMA command, as follows:

```
CREATE SCHEMA EXAMPLE AUTHORIZATION A1;
```

User account A1 can now create tables under the schema called EXAMPLE. To continue our example, suppose that A1 creates the two base relations EMPLOYEE and DEPARTMENT shown in Figure 24.1; A1 is then the **owner** of these two relations and hence has *all the relation privileges* on each of them.

Next, suppose that account A1 wants to grant to account A2 the privilege to insert and delete tuples in both of these relations. However, A1 does not want A2 to be able to propagate these privileges to additional accounts. A1 can issue the following command:

```
GRANT INSERT, DELETE ON EMPLOYEE, DEPARTMENT TO A2;
```

Notice that the owner account A1 of a relation automatically has the GRANT OPTION, allowing it to grant privileges on the relation to other accounts. However, account A2 cannot grant INSERT and DELETE privileges on the EMPLOYEE and DEPARTMENT tables because A2 was not given the GRANT OPTION in the preceding command.

Next, suppose that A1 wants to allow account A3 to retrieve information from either of the two tables and also to be able to propagate the SELECT privilege to other accounts. A1 can issue the following command:

```
GRANT SELECT ON EMPLOYEE, DEPARTMENT TO A3 WITH GRANT OPTION;
```

EMPLOYEE

Name	Ssn	Bdate	Address	Sex	Salary	Dno

DEPARTMENT

Dnumber	Dname	Mgr_ssn

Figure 24.1
Schemas for the two relations EMPLOYEE and DEPARTMENT.

The clause WITH GRANT OPTION means that A3 can now propagate the privilege to other accounts by using GRANT. For example, A3 can grant the SELECT privilege on the EMPLOYEE relation to A4 by issuing the following command:

```
GRANT SELECT ON EMPLOYEE TO A4;
```

Notice that A4 cannot propagate the SELECT privilege to other accounts because the GRANT OPTION was not given to A4.

Now suppose that A1 decides to revoke the SELECT privilege on the EMPLOYEE relation from A3; A1 then can issue this command:

```
REVOKE SELECT ON EMPLOYEE FROM A3;
```

The DBMS must now revoke the SELECT privilege on EMPLOYEE from A3, and it must also *automatically revoke* the SELECT privilege on EMPLOYEE from A4. This is because A3 granted that privilege to A4, but A3 does not have the privilege any more.

Next, suppose that A1 wants to give back to A3 a limited capability to SELECT from the EMPLOYEE relation and wants to allow A3 to be able to propagate the privilege. The limitation is to retrieve only the Name, Bdate, and Address attributes and only for the tuples with Dno = 5. A1 then can create the following view:

```
CREATE VIEW A3EMPLOYEE AS
SELECT Name, Bdate, Address
FROM EMPLOYEE
WHERE Dno = 5;
```

After the view is created, A1 can grant SELECT on the view A3EMPLOYEE to A3 as follows:

```
GRANT SELECT ON A3EMPLOYEE TO A3 WITH GRANT OPTION;
```

Finally, suppose that A1 wants to allow A4 to update only the Salary attribute of EMPLOYEE; A1 can then issue the following command:

```
GRANT UPDATE ON EMPLOYEE (Salary) TO A4;
```

The UPDATE and INSERT privileges can specify particular attributes that may be updated or inserted in a relation. Other privileges (SELECT, DELETE) are not attribute specific, because this specificity can easily be controlled by creating the appropriate views that include only the desired attributes and granting the corresponding privileges on the views. However, because updating views is not always possible (see Chapter 5), the UPDATE and INSERT privileges are given the option to specify the particular attributes of a base relation that may be updated.

24.2.6 Specifying Limits on Propagation of Privileges

Techniques to limit the propagation of privileges have been developed, although they have not yet been implemented in most DBMSs and *are not a part* of SQL. Limiting **horizontal propagation** to an integer number *i* means that an account *B* given the GRANT OPTION can grant the privilege to at most *i* other accounts.

Vertical propagation is more complicated; it limits the depth of the granting of privileges. Granting a privilege with a vertical propagation of zero is equivalent to granting the privilege with *no* GRANT OPTION. If account *A* grants a privilege to account *B* with the vertical propagation set to an integer number $j > 0$, this means that the account *B* has the GRANT OPTION on that privilege, but *B* can grant the privilege to other accounts only with a vertical propagation *less than j*. In effect, vertical propagation limits the sequence of GRANT OPTIONS that can be given from one account to the next based on a single original grant of the privilege.

We briefly illustrate horizontal and vertical propagation limits—which are *not available* currently in SQL or other relational systems—with an example. Suppose that A1 grants SELECT to A2 on the EMPLOYEE relation with horizontal propagation equal to 1 and vertical propagation equal to 2. A2 can then grant SELECT to at most one account because the horizontal propagation limitation is set to 1. Additionally, A2 cannot grant the privilege to another account except with vertical propagation set to 0 (no GRANT OPTION) or 1; this is because A2 must reduce the vertical propagation by at least 1 when passing the privilege to others. In addition, the horizontal propagation must be less than or equal to the originally granted horizontal propagation. For example, if account *A* grants a privilege to account *B* with the horizontal propagation set to an integer number $j > 0$, this means that *B* can grant the privilege to other accounts only with a horizontal propagation *less than or equal to j*. As this example shows, horizontal and vertical propagation techniques are designed to limit the depth and breadth of propagation of privileges.

24.3 Mandatory Access Control and Role-Based Access Control for Multilevel Security

The discretionary access control technique of granting and revoking privileges on relations has traditionally been the main security mechanism for relational database systems. This is an all-or-nothing method: A user either has or does not have a certain privilege. In many applications, an *additional security policy* is needed that classifies data and users based on security classes. This approach, known as **mandatory access control (MAC)**, would typically be *combined* with the discretionary access control mechanisms described in Section 24.2. It is important to note that most commercial DBMSs currently provide mechanisms only for discretionary access control. However, the need for multilevel security exists in government, military, and intelligence applications, as well as in many industrial and corporate applications. Some DBMS vendors—for example, Oracle—have released special versions of their RDBMSs that incorporate mandatory access control for government use.

Typical **security classes** are top secret (TS), secret (S), confidential (C), and unclassified (U), where TS is the highest level and U the lowest. Other more complex security classification schemes exist, in which the security classes are organized in a lattice. For simplicity, we will use the system with four security classification levels, where $TS \geq S \geq C \geq U$, to illustrate our discussion. The commonly used model for multilevel security, known as the *Bell-LaPadula model*, classifies each **subject** (user, account, program) and **object** (relation, tuple, column, view, operation) into one of the security classifications TS, S, C, or U. We will refer to the **clearance** (classification) of a subject *S* as **class(*S*)** and to the **classification** of an object *O* as **class(*O*)**. Two restrictions are enforced on data access based on the subject/object classifications:

1. A subject *S* is not allowed read access to an object *O* unless class(S) ≥ class(O). This is known as the **simple security property**.
2. A subject *S* is not allowed to write an object *O* unless class(S) ≤ class(O). This is known as the **star property** (or *-property).

The first restriction is intuitive and enforces the obvious rule that no subject can read an object whose security classification is higher than the subject's security clearance. The second restriction is less intuitive. It prohibits a subject from writing an object at a lower security classification than the subject's security clearance. Violation of this rule would allow information to flow from higher to lower classifications, which violates a basic tenet of multilevel security. For example, a user (subject) with TS clearance may make a copy of an object with classification TS and then write it back as a new object with classification U, thus making it visible throughout the system.

To incorporate multilevel security notions into the relational database model, it is common to consider attribute values and tuples as data objects. Hence, each attribute *A* is associated with a **classification attribute** *C* in the schema, and each attribute value in a tuple is associated with a corresponding security classification. In addition, in some models, a **tuple classification** attribute *TC* is added to the relation attributes to provide a classification for each tuple as a whole. The model we describe here is known as the *multilevel model*, because it allows classifications at multiple security levels. A **multilevel relation** schema *R* with *n* attributes would be represented as:

$$R(A_1, C_1, A_2, C_2, ..., A_n, C_n, TC)$$

where each C_i represents the *classification attribute* associated with attribute A_i.

The value of the tuple classification attribute *TC* in each tuple *t*—which is the *highest* of all attribute classification values within *t*—provides a general classification for the tuple itself. Each attribute classification C_i provides a finer security classification for each attribute value within the tuple. The value of *TC* in each tuple *t* is the *highest* of all attribute classification values C_i within *t*.

The **apparent key** of a multilevel relation is the set of attributes that would have formed the primary key in a regular (single-level) relation. A multilevel relation will appear to contain different data to subjects (users) with different clearance levels. In some cases, it is possible to store a single tuple in the relation at a higher classification level and produce the corresponding tuples at a lower-level classification through a process known as **filtering**. In other cases, it is necessary to store two or more tuples at different classification levels with the same value for the *apparent key.*

This leads to the concept of **polyinstantiation**,[4] where several tuples can have the same apparent key value but have different attribute values for users at different clearance levels.

We illustrate these concepts with the simple example of a multilevel relation shown in Figure 24.2(a), where we display the classification attribute values next to each attribute's value. Assume that the Name attribute is the apparent key, and consider the query **SELECT** * **FROM** EMPLOYEE. A user with security clearance *S* would see the same relation shown in Figure 24.2(a), since all tuple classifications are less than or equal to *S*. However, a user with security clearance *C* would not be allowed to see the values for Salary of 'Brown' and Job_performance of 'Smith', since they have higher classification. The tuples would be *filtered* to appear as shown in Figure 24.2(b), with Salary and Job_performance *appearing as null.* For a user with security clearance *U*, the filtering allows only the Name attribute of 'Smith' to appear, with all the other

(a) EMPLOYEE

Name	Salary	JobPerformance	TC
Smith U	40000 C	Fair S	S
Brown C	80000 S	Good C	S

(b) EMPLOYEE

Name	Salary	JobPerformance	TC
Smith U	40000 C	NULL C	C
Brown C	NULL C	Good C	C

(c) EMPLOYEE

Name	Salary	JobPerformance	TC
Smith U	NULL U	NULL U	U

(d) EMPLOYEE

Name	Salary	JobPerformance	TC
Smith U	40000 C	Fair S	S
Smith U	40000 C	Excellent C	C
Brown C	80000 S	Good C	S

Figure 24.2
A multilevel relation to illustrate multilevel security. (a) The original EMPLOYEE tuples. (b) Appearance of EMPLOYEE after filtering for classification C users. (c) Appearance of EMPLOYEE after filtering for classification U users. (d) Polyinstantiation of the Smith tuple.

[4]This is similar to the notion of having multiple versions in the database that represent the same real-world object.

attributes appearing as null (Figure 24.2(c)). Thus, filtering introduces null values for attribute values whose security classification is higher than the user's security clearance.

In general, the **entity integrity** rule for multilevel relations states that all attributes that are members of the apparent key must not be null and must have the *same* security classification within each individual tuple. Additionally, all other attribute values in the tuple must have a security classification greater than or equal to that of the apparent key. This constraint ensures that a user can see the key if the user is permitted to see any part of the tuple. Other integrity rules, called **null integrity** and **interinstance integrity**, informally ensure that if a tuple value at some security level can be filtered (derived) from a higher-classified tuple, then it is sufficient to store the higher-classified tuple in the multilevel relation.

To illustrate polyinstantiation further, suppose that a user with security clearance *C* tries to update the value of Job_performance of 'Smith' in Figure 24.2 to 'Excellent'; this corresponds to the following SQL update being submitted by that user:

```
UPDATE  EMPLOYEE
SET     Job_performance = 'Excellent'
WHERE   Name = 'Smith';
```

Since the view provided to users with security clearance *C* (see Figure 24.2(b)) permits such an update, the system should not reject it; otherwise, the user could *infer* that some nonnull value exists for the Job_performance attribute of 'Smith' rather than the null value that appears. This is an example of inferring information through what is known as a **covert channel**, which should not be permitted in highly secure systems (see Section 24.6.1). However, the user should not be allowed to overwrite the existing value of Job_performance at the higher classification level. The solution is to create a **polyinstantiation** for the 'Smith' tuple at the lower classification level *C*, as shown in Figure 24.2(d). This is necessary since the new tuple cannot be filtered from the existing tuple at classification *S*.

The basic update operations of the relational model (INSERT, DELETE, UPDATE) must be modified to handle this and similar situations, but this aspect of the problem is outside the scope of our presentation. We refer the interested reader to the Selected Bibliography at the end of this chapter for further details.

24.3.1 Comparing Discretionary Access Control and Mandatory Access Control

Discretionary access control (DAC) policies are characterized by a high degree of flexibility, which makes them suitable for a large variety of application domains. The main drawback of DAC models is their vulnerability to malicious attacks, such as Trojan horses embedded in application programs. The reason is that discretionary authorization models do not impose any control on how information is propagated and used once it has been accessed by users authorized to do so. By contrast, mandatory policies ensure a high degree of protection—in a way, they prevent any illegal flow of information. Therefore, they are suitable for military and high security types of applications, which require a higher degree of protection. However, mandatory policies have the drawback of being too rigid in that they require a strict classification of subjects and objects into security levels, and therefore they are applicable to few environments. In many practical situations, discretionary policies are preferred because they offer a better tradeoff between security and applicability.

24.3.2 Role-Based Access Control

Role-based access control (RBAC) emerged rapidly in the 1990s as a proven technology for managing and enforcing security in large-scale enterprise-wide systems. Its basic notion is that privileges and other permissions are associated with organizational **roles**, rather than individual users. Individual users are then assigned to appropriate roles. Roles can be created using the CREATE ROLE and DESTROY ROLE commands. The GRANT and REVOKE commands discussed in Section 24.2 can then be used to assign and revoke privileges from roles, as well as for individual users when needed. For example, a company may have roles such as sales account manager, purchasing agent, mailroom clerk, department manager, and so on. Multiple individuals can be assigned to each role. Security privileges that are common to a role are granted to the role name, and any individual assigned to this role would automatically have those privileges granted.

RBAC can be used with traditional discretionary and mandatory access controls; it ensures that only authorized users in their specified roles are given access to certain data or resources. Users create sessions during which they may activate a subset of roles to which they belong. Each session can be assigned to several roles, but it maps to one user or a single subject only. Many DBMSs have allowed the concept of roles, where privileges can be assigned to roles.

Separation of duties is another important requirement in various commercial DBMSs. It is needed to prevent one user from doing work that requires the involvement of two or more people, thus preventing collusion. One method in which separation of duties can be successfully implemented is with mutual exclusion of roles. Two roles are said to be **mutually exclusive** if both the roles cannot be used simultaneously by the user. **Mutual exclusion of roles** can be categorized into two types, namely *authorization time exclusion (static)* and *runtime exclusion (dynamic)*. In authorization time exclusion, two roles that have been specified as mutually exclusive cannot be part of a user's authorization at the same time. In runtime exclusion, both these roles can be authorized to one user but cannot be activated by the user at the same time. Another variation in mutual exclusion of roles is that of complete and partial exclusion.

The **role hierarchy** in RBAC is a natural way to organize roles to reflect the organization's lines of authority and responsibility. By convention, junior roles at the bottom are connected to progressively senior roles as one moves up the hierarchy. The hierarchic diagrams are partial orders, so they are reflexive, transitive, and antisymmetric. In other words, if a user has one role, the user automatically has roles lower in the hierarchy. Defining a role hierarchy involves choosing the type of hierarchy and the roles, and then implementing the hierarchy by granting roles to other roles. Role hierarchy can be implemented in the following manner:

```
GRANT ROLE full_time TO employee_type1
GRANT ROLE intern TO employee_type2
```

The above are examples of granting the roles *full_time* and *intern* to two types of employees.

Another issue related to security is *identity management*. **Identity** refers to a unique name of an individual person. Since the legal names of persons are not necessarily unique, the identity of a person must include sufficient additional information to make the complete name unique. Authorizing this identity and managing the schema of these identities is called **Identity Management.** Identity Management addresses how organizations can effectively authenticate people and manage their access to confidential information. It has become more visible as a business requirement across all industries affecting organizations of all sizes. Identity Management administrators constantly need to satisfy application owners while keeping expenditures under control and increasing IT efficiency.

Another important consideration in RBAC systems is the possible temporal constraints that may exist on roles, such as the time and duration of role activations, and timed triggering of a role by an activation of another role. Using an RBAC model is a highly desirable goal for addressing the key security requirements of Web-based applications. Roles can be assigned to workflow tasks so that a user with any of the roles related to a task may be authorized to execute it and may play a certain role only for a certain duration.

RBAC models have several desirable features, such as flexibility, policy neutrality, better support for security management and administration, and other aspects that make them attractive candidates for developing secure Web-based applications. These features are lacking in DAC and MAC models. In addition, RBAC models include the capabilities available in traditional DAC and MAC policies. Furthermore, an RBAC model provides mechanisms for addressing the security issues related to the execution of tasks and workflows, and for specifying user-defined and organization-specific policies. Easier deployment over the Internet has been another reason for the success of RBAC models.

24.3.3 Label-Based Security and Row-Level Access Control

Many commercial DBMSs currently use the concept of row-level access control, where sophisticated access control rules can be implemented by considering the data row by row. In row-level access control, each data row is given a label, which is used to store information about data sensitivity. Row-level access control provides finer granularity of data security by allowing the permissions to be set for each row and not just for the table or column. Initially the user is given a default session label by the database administrator. Levels correspond to a hierarchy of data-sensitivity levels to exposure or corruption, with the goal of maintaining privacy or security. Labels are used to prevent unauthorized users from viewing or altering certain data. A user having a low authorization level, usually represented by a low number, is denied access to data having a higher-level number. If no such label is given to a row, a row label is automatically assigned to it depending upon the user's session label.

A policy defined by an administrator is called a **Label Security policy.** Whenever data affected by the policy is accessed or queried through an application, the policy is automatically invoked. When a policy is implemented, a new column is added to each row in the schema. The added column contains the label for each row that reflects the sensitivity of the row as per the policy. Similar to MAC, where each user has a security clearance, each user has an identity in label-based security. This user's identity is compared to the label assigned to each row to determine whether the user has access to view the contents of that row. However, the user can write the label value himself, within certain restrictions and guidelines for that specific row. This label can be set to a value that is between the user's current session label and the user's minimum level. The DBA has the privilege to set an initial default row label.

The Label Security requirements are applied on top of the DAC requirements for each user. Hence, the user must satisfy the DAC requirements and then the label security requirements to access a row. The DAC requirements make sure that the user is legally authorized to carry on that operation on the schema. In most applications, only some of the tables need label-based security. For the majority of the application tables, the protection provided by DAC is sufficient.

Security policies are generally created by managers and human resources personnel. The policies are high-level, technology neutral, and relate to risks. Policies are a result of management instructions to specify organizational procedures, guiding principles, and courses of action that are considered to be expedient, prudent, or advantageous. Policies are typically accompanied by a definition of penalties and countermeasures if the policy is transgressed. These policies are then interpreted and converted to a set of label-oriented policies by the **Label Security administrator**, who defines the security labels for data and authorizations for users; these labels and authorizations govern access to specified protected objects.

Suppose a user has SELECT privileges on a table. When the user executes a SELECT statement on that table, Label Security will automatically evaluate each row returned by the query to determine whether the user has rights to view the data. For example, if the user has a sensitivity of 20, then the user can view all rows having a security level of 20 or lower. The level determines the sensitivity of the information contained in a row; the more sensitive the row, the higher its security label value. Such Label Security can be configured to perform security checks on UPDATE, DELETE, and INSERT statements as well.

24.3.4 XML Access Control

With the worldwide use of XML in commercial and scientific applications, efforts are under way to develop security standards. Among these efforts are digital signatures and encryption standards for XML. The XML Signature Syntax and Processing specification describes an XML syntax for representing the associations between cryptographic signatures and XML documents or other electronic resources. The specification also includes procedures for computing and verifying XML signatures. An XML digital signature differs from other protocols for message signing, such as **PGP** (**Pretty Good Privacy**—a confidentiality and authentication service that can be used for electronic mail and file storage application), in its support for signing only specific portions of the XML tree (see Chapter 12) rather than the complete document. Additionally, the XML signature specification defines mechanisms for countersigning and transformations—so-called *canonicalization* to ensure that two instances of the same text produce the same digest for signing even if their representations differ slightly, for example, in typographic white space.

The XML Encryption Syntax and Processing specification defines XML vocabulary and processing rules for protecting confidentiality of XML documents in whole or in part and of non-XML data as well. The encrypted content and additional processing information for the recipient are represented in well-formed XML so that the result can be further processed using XML tools. In contrast to other commonly used technologies for confidentiality such as SSL (Secure Sockets Layer—a leading Internet security protocol), and virtual private networks, XML encryption also applies to parts of documents and to documents in persistent storage.

24.3.5 Access Control Policies for E-Commerce and the Web

Electronic commerce (**e-commerce**) environments are characterized by any transactions that are done electronically. They require elaborate access control policies that go beyond traditional DBMSs. In conventional database environments, access control is usually performed using a set of authorizations stated by security officers or users according to some security policies. Such a simple paradigm is not well suited for a dynamic environment like e-commerce. Furthermore, in an e-commerce environment the resources to be protected are not only traditional data but also knowledge and experience. Such peculiarities call for more flexibility in specifying access control policies. The access control mechanism must be flexible enough to support a wide spectrum of heterogeneous protection objects.

A second related requirement is the support for content-based access control. **Content-based access control** allows one to express access control policies that take the protection object content into account. In order to support content-based access control, access control policies must allow inclusion of conditions based on the object content.

A third requirement is related to the heterogeneity of subjects, which requires access control policies based on user characteristics and qualifications rather than on specific and individual characteristics (for example, user IDs). A possible solution, to better take into account user profiles in the formulation of access control policies, is to support the notion of credentials. A **credential** is a set of properties concerning a user that are relevant for security purposes (for example, age or position or role within an organization). For instance, by using credentials, one can simply formulate policies such as *Only permanent staff with five or more years of service can access documents related to the internals of the system.*

It is believed that the XML is expected to play a key role in access control for e-commerce applications[5] because XML is becoming the common representation language for document interchange over the Web, and is also becoming the language for e-commerce. Thus, on the one hand there is the need to make XML representations secure, by providing access control mechanisms specifically tailored to the protection of XML documents. On the other hand, access control information (that is, access control policies and user credentials) can be expressed using XML itself. The **Directory Services Markup Language** (DSML) is a representation of directory service information in XML syntax. It provides a foundation for a standard for communicating with the directory services that will be responsible for providing and authenticating user credentials. The uniform presentation of both protection objects and access control policies can be applied to policies and credentials themselves. For instance, some credential properties (such as the user name) may be accessible to everyone, whereas other properties may be visible only to a restricted class of users. Additionally, the use of an XML-based language for specifying credentials and access control policies facilitates secure credential submission and export of access control policies.

24.4 SQL Injection

SQL Injection is one of the most common threats to a database system. We will discuss it in detail later in this section. Some of the other attacks on databases that are quite frequent are:

- **Unauthorized privilege escalation.** This attack is characterized by an individual attempting to elevate his or her privilege by attacking vulnerable points in the database systems.
- **Privilege abuse.** While the previous attack is done by an unauthorized user, this attack is performed by a privileged user. For example, an administrator who is allowed to change student information can use this privilege to update student grades without the instructor's permission.
- **Denial of service.** A **Denial of Service (DOS) attack** is an attempt to make resources unavailable to its intended users. It is a general attack category in which access to network applications or data is denied to intended users by overflowing the buffer or consuming resources.
- **Weak Authentication.** If the user authentication scheme is weak, an attacker can impersonate the identity of a legitimate user by obtaining their login credentials.

[5]See Thuraisingham et al. (2001).

24.4.1 SQL Injection Methods

As we discussed in Chapter 14, Web programs and applications that access a database can send commands and data to the database, as well as display data retrieved from the database through the Web browser. In an **SQL Injection attack**, the attacker injects a string input through the application, which changes or manipulates the SQL statement to the attacker's advantage. An SQL Injection attack can harm the database in various ways, such as unauthorized manipulation of the database, or retrieval of sensitive data. It can also be used to execute system level commands that may cause the system to deny service to the application. This section describes types of injection attacks.

SQL Manipulation. A manipulation attack, which is the most common type of injection attack, changes an SQL command in the application—for example, by adding conditions to the WHERE-clause of a query, or by expanding a query with additional query components using set operations such as UNION, INTERSECT, or MINUS. Other types of manipulation attacks are also possible. A typical manipulation attack occurs during database login. For example, suppose that a simplistic authentication procedure issues the following query and checks to see if any rows were returned:

```
SELECT * FROM users WHERE username = 'jake' and PASSWORD =
    'jakespasswd'.
```

The attacker can try to change (or manipulate) the SQL statement, by changing it as follows:

```
SELECT * FROM users WHERE username = 'jake' and (PASSWORD =
    'jakespasswd' or 'x' = 'x')
```

As a result, the attacker who knows that 'jake' is a valid login of some user is able to log into the database system as 'jake' without knowing his password and is able to do everything that 'jake' may be authorized to do to the database system.

Code Injection. This type of attack attempts to add additional SQL statements or commands to the existing SQL statement by exploiting a computer bug, which is caused by processing invalid data. The attacker can inject or introduce code into a computer program to change the course of execution. Code injection is a popular technique for system hacking or cracking to gain information.

Function Call Injection. In this kind of attack, a database function or operating system function call is inserted into a vulnerable SQL statement to manipulate the data or make a privileged system call. For example, it is possible to exploit a function that performs some aspect related to network communication. In addition, functions that are contained in a customized database package, or any custom database function, can be executed as part of an SQL query. In particular, dynamically created SQL queries (see Chapter 13) can be exploited since they are constructed at run time.

For example, the *dual* table is used in the FROM clause of SQL in Oracle when a user needs to run SQL that does not logically have a table name. To get today's date, we can use:

```
SELECT SYSDATE FROM dual;
```

The following example demonstrates that even the simplest SQL statements can be vulnerable.

```
SELECT TRANSLATE ('user input', 'from_string', 'to_string') FROM dual;
```

Here, TRANSLATE is used to replace a string of characters with another string of characters. The TRANSLATE function above will replace the characters of the 'from_string' with the characters in the 'to_string' one by one. This means that the *f* will be replaced with the *t*, the *r* with the *o*, the *o* with the _, and so on.

This type of SQL statement can be subjected to a function injection attack. Consider the following example:

```
SELECT TRANSLATE (" || UTL_HTTP.REQUEST ('http://129.107.2.1/') || ",
      '98765432', '9876') FROM dual;
```

The user can input the string (" || UTL_HTTP.REQUEST ('http://129.107.2.1/') || "), where || is the concatenate operator, thus requesting a page from a Web server. UTL_HTTP makes Hypertext Transfer Protocol (HTTP) callouts from SQL. The REQUEST object takes a URL ('http://129.107.2.1/' in this example) as a parameter, contacts that site, and returns the data (typically HTML) obtained from that site. The attacker could manipulate the string he inputs, as well as the URL, to include other functions and do other illegal operations. We just used a dummy example to show conversion of '98765432' to '9876', but the user's intent would be to access the URL and get sensitive information. The attacker can then retrieve useful information from the database server—located at the URL that is passed as a parameter—and send it to the Web server (that calls the TRANSLATE function).

24.4.2 Risks Associated with SQL Injection

SQL injection is harmful and the risks associated with it provide motivation for attackers. Some of the risks associated with SQL injection attacks are explained below.

- **Database Fingerprinting.** The attacker can determine the type of database being used in the backend so that he can use database-specific attacks that correspond to weaknesses in a particular DBMS.
- **Denial of Service.** The attacker can flood the server with requests, thus denying service to valid users, or they can delete some data.
- **Bypassing Authentication.** This is one of the most common risks, in which the attacker can gain access to the database as an authorized user and perform all the desired tasks.

- **Identifying Injectable Parameters.** In this type of attack, the attacker gathers important information about the type and structure of the back-end database of a Web application. This attack is made possible by the fact that the default error page returned by application servers is often overly descriptive.
- **Executing Remote Commands.** This provides attackers with a tool to execute arbitrary commands on the database. For example, a remote user can execute stored database procedures and functions from a remote SQL interactive interface.
- **Performing Privilege Escalation.** This type of attack takes advantage of logical flaws within the database to upgrade the access level.

24.4.3 Protection Techniques against SQL Injection

Protection against SQL injection attacks can be achieved by applying certain programming rules to all Web-accessible procedures and functions. This section describes some of these techniques.

Bind Variables (Using Parameterized Statements). The use of bind variables (also known as *parameters*; see Chapter 13) protects against injection attacks and also improves performance.

Consider the following example using Java and JDBC:

```
PreparedStatement stmt = conn.prepareStatement( "SELECT * FROM
    EMPLOYEE WHERE EMPLOYEE_ID=? AND PASSWORD=?");
stmt.setString(1, employee_id);
stmt.setString(2, password);
```

Instead of embedding the user input into the statement, the input should be bound to a parameter. In this example, the input '1' is assigned (bound) to a bind variable 'employee_id' and input '2' to the bind variable 'password' instead of directly passing string parameters.

Filtering Input (Input Validation). This technique can be used to remove escape characters from input strings by using the SQL `Replace` function. For example, the delimiter single quote (') can be replaced by two single quotes (''). Some SQL Manipulation attacks can be prevented by using this technique, since escape characters can be used to inject manipulation attacks. However, because there can be a large number of escape characters, this technique is not reliable.

Function Security. Database functions, both standard and custom, should be restricted, as they can be exploited in the SQL function injection attacks.

24.5 Introduction to Statistical Database Security

Statistical databases are used mainly to produce statistics about various populations. The database may contain confidential data about individuals, which should be protected from user access. However, users are permitted to retrieve statistical information about the populations, such as averages, sums, counts, maximums, minimums, and standard deviations. The techniques that have been developed to protect the privacy of individual information are beyond the scope of this book. We will illustrate the problem with a very simple example, which refers to the relation shown in Figure 24.3. This is a PERSON relation with the attributes Name, Ssn, Income, Address, City, State, Zip, Sex, and Last_degree.

A **population** is a set of tuples of a relation (table) that satisfy some selection condition. Hence, each selection condition on the PERSON relation will specify a particular population of PERSON tuples. For example, the condition Sex = 'M' specifies the male population; the condition ((Sex = 'F') AND (Last_degree = 'M.S.' OR Last_degree = 'Ph.D.')) specifies the female population that has an M.S. or Ph.D. degree as their highest degree; and the condition City = 'Houston' specifies the population that lives in Houston.

Statistical queries involve applying statistical functions to a population of tuples. For example, we may want to retrieve the number of individuals in a population or the average income in the population. However, statistical users are not allowed to retrieve individual data, such as the income of a specific person. **Statistical database security** techniques must prohibit the retrieval of individual data. This can be achieved by prohibiting queries that retrieve attribute values and by allowing only queries that involve statistical aggregate functions such as COUNT, SUM, MIN, MAX, AVERAGE, and STANDARD DEVIATION. Such queries are sometimes called **statistical queries**.

It is the responsibility of a database management system to ensure the confidentiality of information about individuals, while still providing useful statistical summaries of data about those individuals to users. Provision of **privacy protection** of users in a statistical database is paramount; its violation is illustrated in the following example.

In some cases it is possible to **infer** the values of individual tuples from a sequence of statistical queries. This is particularly true when the conditions result in a

PERSON

Name	Ssn	Income	Address	City	State	Zip	Sex	Last_degree

Figure 24.3
The PERSON relation schema for illustrating statistical database security.

population consisting of a small number of tuples. As an illustration, consider the following statistical queries:

```
Q1: SELECT COUNT (*) FROM PERSON
    WHERE <condition>;
Q2: SELECT AVG (Income) FROM PERSON
    WHERE <condition>;
```

Now suppose that we are interested in finding the Salary of Jane Smith, and we know that she has a Ph.D. degree and that she lives in the city of Bellaire, Texas. We issue the statistical query Q1 with the following condition:

(Last_degree='Ph.D.' AND Sex='F' AND City='Bellaire' AND State='Texas')

If we get a result of 1 for this query, we can issue Q2 with the same condition and find the Salary of Jane Smith. Even if the result of Q1 on the preceding condition is not 1 but is a small number—say 2 or 3—we can issue statistical queries using the functions MAX, MIN, and AVERAGE to identify the possible range of values for the Salary of Jane Smith.

The possibility of inferring individual information from statistical queries is reduced if no statistical queries are permitted whenever the number of tuples in the population specified by the selection condition falls below some threshold. Another technique for prohibiting retrieval of individual information is to prohibit sequences of queries that refer repeatedly to the same population of tuples. It is also possible to introduce slight inaccuracies or *noise* into the results of statistical queries deliberately, to make it difficult to deduce individual information from the results. Another technique is partitioning of the database. Partitioning implies that records are stored in groups of some minimum size; queries can refer to any complete group or set of groups, but never to subsets of records within a group. The interested reader is referred to the bibliography at the end of this chapter for a discussion of these techniques.

24.6 Introduction to Flow Control

Flow control regulates the distribution or flow of information among accessible objects. A flow between object *X* and object *Y* occurs when a program reads values from *X* and writes values into *Y*. **Flow controls** check that information contained in some objects does not flow explicitly or implicitly into less protected objects. Thus, a user cannot get indirectly in *Y* what he or she cannot get directly in *X*. Active flow control began in the early 1970s. Most flow controls employ some concept of security class; the transfer of information from a sender to a receiver is allowed only if the receiver's security class is at least as privileged as the sender's. Examples of a flow control include preventing a service program from leaking a customer's confidential data, and blocking the transmission of secret military data to an unknown classified user.

A **flow policy** specifies the channels along which information is allowed to move. The simplest flow policy specifies just two classes of information—confidential (*C*) and nonconfidential (*N*)—and allows all flows except those from class *C* to class *N*. This policy can solve the confinement problem that arises when a service program handles data such as customer information, some of which may be confidential. For example, an income-tax computing service might be allowed to retain a customer's address and the bill for services rendered, but not a customer's income or deductions.

Access control mechanisms are responsible for checking users' authorizations for resource access: Only granted operations are executed. Flow controls can be enforced by an extended access control mechanism, which involves assigning a security class (usually called the *clearance*) to each running program. The program is allowed to read a particular memory segment only if its security class is as high as that of the segment. It is allowed to write in a segment only if its class is as low as that of the segment. This automatically ensures that no information transmitted by the person can move from a higher to a lower class. For example, a military program with a secret clearance can only read from objects that are unclassified and confidential and can only write into objects that are secret or top secret.

Two types of flow can be distinguished: *explicit flows,* occurring as a consequence of assignment instructions, such as $Y := f(X_1, X_n,)$, and *implicit flows* generated by conditional instructions, such as if $f(X_{m+1, \ldots,} X_n)$ then $Y := f(X_1, X_m)$.

Flow control mechanisms must verify that only authorized flows, both explicit and implicit, are executed. A set of rules must be satisfied to ensure secure information flows. Rules can be expressed using flow relations among classes and assigned to information, stating the authorized flows within a system. (An information flow from *A* to *B* occurs when information associated with *A* affects the value of information associated with *B*. The flow results from operations that cause information transfer from one object to another.) These relations can define, for a class, the set of classes where information (classified in that class) can flow, or can state the specific relations to be verified between two classes to allow information to flow from one to the other. In general, flow control mechanisms implement the controls by assigning a label to each object and by specifying the security class of the object. Labels are then used to verify the flow relations defined in the model.

24.6.1 Covert Channels

A covert channel allows a transfer of information that violates the security or the policy. Specifically, a **covert channel** allows information to pass from a higher classification level to a lower classification level through improper means. Covert channels can be classified into two broad categories: timing channels and storage. The distinguishing feature between the two is that in a **timing channel** the information is conveyed by the timing of events or processes, whereas **storage channels** do not require any temporal synchronization, in that information is conveyed by accessing system information or what is otherwise inaccessible to the user.

In a simple example of a covert channel, consider a distributed database system in which two nodes have user security levels of secret (S) and unclassified (U). In order for a transaction to commit, both nodes must agree to commit. They mutually can only do operations that are consistent with the *-property, which states that in any transaction, the *S* site cannot write or pass information to the *U* site. However, if these two sites collude to set up a covert channel between them, a transaction involving secret data may be committed unconditionally by the *U* site, but the *S* site may do so in some predefined agreed-upon way so that certain information may be passed from the *S* site to the *U* site, violating the *-property. This may be achieved where the transaction runs repeatedly, but the actions taken by the *S* site implicitly convey information to the *U* site. Measures such as locking, which we discussed in Chapters 22 and 23, prevent concurrent writing of the information by users with different security levels into the same objects, preventing the storage-type covert channels. Operating systems and distributed databases provide control over the multiprogramming of operations that allows a sharing of resources without the possibility of encroachment of one program or process into another's memory or other resources in the system, thus preventing timing-oriented covert channels. In general, covert channels are not a major problem in well-implemented robust database implementations. However, certain schemes may be contrived by clever users that implicitly transfer information.

Some security experts believe that one way to avoid covert channels is to disallow programmers to actually gain access to sensitive data that a program will process after the program has been put into operation. For example, a programmer for a bank has no need to access the names or balances in depositors' accounts. Programmers for brokerage firms do not need to know what buy and sell orders exist for clients. During program testing, access to a form of real data or some sample test data may be justifiable, but not after the program has been accepted for regular use.

24.7 Encryption and Public Key Infrastructures

The previous methods of access and flow control, despite being strong control measures, may not be able to protect databases from some threats. Suppose we communicate data, but our data falls into the hands of a nonlegitimate user. In this situation, by using encryption we can disguise the message so that even if the transmission is diverted, the message will not be revealed. **Encryption** is the conversion of data into a form, called a **ciphertext**, which cannot be easily understood by unauthorized persons. It enhances security and privacy when access controls are bypassed, because in cases of data loss or theft, encrypted data cannot be easily understood by unauthorized persons.

With this background, we adhere to following standard definitions:[6]

- *Ciphertext*: Encrypted (enciphered) data.

[6]These definitions are from NIST (National Institute of Standards and Technology) from http://csrc.nist.gov/publications/nistpubs/800-67/SP800-67.pdf.

- *Plaintext (or cleartext)*: Intelligible data that has meaning and can be read or acted upon without the application of decryption.
- *Encryption*: The process of transforming plaintext into ciphertext.
- *Decryption*: The process of transforming ciphertext back into plaintext.

Encryption consists of applying an **encryption algorithm** to data using some prespecified **encryption key**. The resulting data has to be **decrypted** using a **decryption key** to recover the original data.

24.7.1 The Data Encryption and Advanced Encryption Standards

The **Data Encryption Standard** (DES) is a system developed by the U.S. government for use by the general public. It has been widely accepted as a cryptographic standard both in the United States and abroad. DES can provide end-to-end encryption on the channel between sender *A* and receiver *B*. The DES algorithm is a careful and complex combination of two of the fundamental building blocks of encryption: substitution and permutation (transposition). The algorithm derives its strength from repeated application of these two techniques for a total of 16 cycles. Plaintext (the original form of the message) is encrypted as blocks of 64 bits. Although the key is 64 bits long, in effect the key can be any 56-bit number. After questioning the adequacy of DES, the NIST introduced the **Advanced Encryption Standard** (AES). This algorithm has a block size of 128 bits, compared with DES's 56-block size, and can use keys of 128, 192, or 256 bits, compared with DES's 56-bit key. AES introduces more possible keys, compared with DES, and thus takes a much longer time to crack.

24.7.2 Symmetric Key Algorithms

A symmetric key is one key that is used for both encryption and decryption. By using a symmetric key, fast encryption and decryption is possible for routine use with sensitive data in the database. A message encrypted with a secret key can be decrypted only with the same secret key. Algorithms used for symmetric key encryption are called **secret-key algorithms**. Since secret-key algorithms are mostly used for encrypting the content of a message, they are also called **content-encryption algorithms**.

The major liability associated with secret-key algorithms is the need for sharing the secret key. A possible method is to derive the secret key from a user-supplied password string by applying the same function to the string at both the sender and receiver; this is known as a *password-based encryption algorithm.* The strength of the symmetric key encryption depends on the size of the key used. For the same algorithm, encrypting using a longer key is tougher to break than the one using a shorter key.

24.7.3 Public (Asymmetric) Key Encryption

In 1976, Diffie and Hellman proposed a new kind of cryptosystem, which they called **public key encryption**. Public key algorithms are based on mathematical functions rather than operations on bit patterns. They address one drawback of symmetric key encryption, namely that both sender and recipient must exchange the common key in a secure manner. In public key systems, two keys are used for encryption/decryption. The *public key* can be transmitted in a non-secure way, whereas the *private key* is not transmitted at all. These algorithms—which use two related keys, a public key and a private key, to perform complementary operations (encryption and decryption)—are known as **asymmetric key encryption algorithms**. The use of two keys can have profound consequences in the areas of confidentiality, key distribution, and authentication. The two keys used for public key encryption are referred to as the **public key** and the **private key**. The private key is kept secret, but it is referred to as a *private key* rather than a *secret key* (the key used in conventional encryption) to avoid confusion with conventional encryption. The two keys are mathematically related, since one of the keys is used to perform encryption and the other to perform decryption. However, it is very difficult to derive the private key from the public key.

A public key encryption scheme, or *infrastructure*, has six ingredients:

1. **Plaintext.** This is the data or readable message that is fed into the algorithm as input.
2. **Encryption algorithm.** This algorithm performs various transformations on the plaintext.
3. and 4. **Public and private keys.** These are a pair of keys that have been selected so that if one is used for encryption, the other is used for decryption. The exact transformations performed by the encryption algorithm depend on the public or private key that is provided as input. For example, if a message is encrypted using the public key, it can only be decrypted using the private key.
5. **Ciphertext.** This is the scrambled message produced as output. It depends on the plaintext and the key. For a given message, two different keys will produce two different ciphertexts.
6. **Decryption algorithm.** This algorithm accepts the ciphertext and the matching key and produces the original plaintext.

As the name suggests, the public key of the pair is made public for others to use, whereas the private key is known only to its owner. A general-purpose public key cryptographic algorithm relies on one key for encryption and a different but related key for decryption. The essential steps are as follows:

1. Each user generates a pair of keys to be used for the encryption and decryption of messages.
2. Each user places one of the two keys in a public register or other accessible file. This is the public key. The companion key is kept private.
3. If a sender wishes to send a private message to a receiver, the sender encrypts the message using the receiver's public key.

4. When the receiver receives the message, he or she decrypts it using the receiver's private key. No other recipient can decrypt the message because only the receiver knows his or her private key.

The RSA Public Key Encryption Algorithm. One of the first public key schemes was introduced in 1978 by Ron Rivest, Adi Shamir, and Len Adleman at MIT and is named after them as the **RSA scheme**. The RSA scheme has since then reigned supreme as the most widely accepted and implemented approach to public key encryption. The RSA encryption algorithm incorporates results from number theory, combined with the difficulty of determining the prime factors of a target. The RSA algorithm also operates with modular arithmetic—mod n.

Two keys, d and e, are used for decryption and encryption. An important property is that they can be interchanged. n is chosen as a large integer that is a product of two large distinct prime numbers, a and b, $n = a \times \mathrm{b}$. The encryption key e is a randomly chosen number between 1 and n that is relatively prime to $(a - 1) \times (b - 1)$. The plaintext block P is encrypted as P^e where $P^e = P \bmod n$. Because the exponentiation is performed mod n, factoring P^e to uncover the encrypted plaintext is difficult. However, the decrypting key d is carefully chosen so that $(P^e)^d \bmod n = P$. The decryption key d can be computed from the condition that $d \times e = 1 \bmod ((a - 1) \times (b - 1))$. Thus, the legitimate receiver who knows d simply computes $(P^e)^d \bmod n = P$ and recovers P without having to factor P^e.

24.7.4 Digital Signatures

A digital signature is an example of using encryption techniques to provide authentication services in electronic commerce applications. Like a handwritten signature, a **digital signature** is a means of associating a mark unique to an individual with a body of text. The mark should be unforgettable, meaning that others should be able to check that the signature comes from the originator.

A digital signature consists of a string of symbols. If a person's digital signature were always the same for each message, then one could easily counterfeit it by simply copying the string of symbols. Thus, signatures must be different for each use. This can be achieved by making each digital signature a function of the message that it is signing, together with a timestamp. To be unique to each signer and counterfeit-proof, each digital signature must also depend on some secret number that is unique to the signer. Thus, in general, a counterfeitproof digital signature must depend on the message and a unique secret number of the signer. The verifier of the signature, however, should not need to know any secret number. Public key techniques are the best means of creating digital signatures with these properties.

24.7.5 Digital Certificates

A digital certificate is used to combine the value of a public key with the identity of the person or service that holds the corresponding private key into a digitally signed statement. Certificates are issued and signed by a certification authority (CA). The entity receiving this certificate from a CA is the subject of that certificate. Instead of requiring each participant in an application to authenticate every user, third-party authentication relies on the use of digital certificates.

The digital certificate itself contains various types of information. For example, both the certification authority and the certificate owner information are included. The following list describes all the information included in the certificate:

1. The certificate owner information, which is represented by a unique identifier known as the distinguished name (DN) of the owner. This includes the owner's name, as well as the owner's organization and other information about the owner.
2. The certificate also includes the public key of the owner.
3. The date of issue of the certificate is also included.
4. The validity period is specified by 'Valid From' and 'Valid To' dates, which are included in each certificate.
5. Issuer identifier information is included in the certificate.
6. Finally, the digital signature of the issuing CA for the certificate is included. All the information listed is encoded through a message-digest function, which creates the digital signature. The digital signature basically certifies that the association between the certificate owner and public key is valid.

24.8 Privacy Issues and Preservation

Preserving data privacy is a growing challenge for database security and privacy experts. In some perspectives, to preserve data privacy we should even limit performing large-scale data mining and analysis. The most commonly used techniques to address this concern are to avoid building mammoth central warehouses as a single repository of vital information. Another possible measure is to intentionally modify or perturb data.

If all data were available at a single warehouse, violating only a single repository's security could expose all data. Avoiding central warehouses and using distributed data mining algorithms minimizes the exchange of data needed to develop globally valid models. By modifying, perturbing, and anonymizing data, we can also mitigate privacy risks associated with data mining. This can be done by removing identity information from the released data and injecting noise into the data. However, by using these techniques, we should pay attention to the quality of the resulting data in the database, which may undergo too many modifications. We must be able to estimate the errors that may be introduced by these modifications.

Privacy is an important area of ongoing research in database management. It is complicated due to its multidisciplinary nature and the issues related to the subjectivity in the interpretation of privacy, trust, and so on. As an example, consider medical and legal records and transactions, which must maintain certain privacy requirements while they are being defined and enforced. Providing access control and privacy for mobile devices is also receiving increased attention. DBMSs need robust techniques for efficient storage of security-relevant information on small devices, as well as trust negotiation techniques. Where to keep information related to user identities, profiles, credentials, and permissions and how to use it for reliable user identification remains an important problem. Because large-sized streams of data are generated in such environments, efficient techniques for access control must be devised and integrated with processing techniques for continuous queries. Finally, the privacy of user location data, acquired from sensors and communication networks, must be ensured.

24.9 Challenges of Database Security

Considering the vast growth in volume and speed of threats to databases and information assets, research efforts need to be devoted to the following issues: data quality, intellectual property rights, and database survivability. These are only some of the main challenges that researchers in database security are trying to address.

24.9.1 Data Quality

The database community needs techniques and organizational solutions to assess and attest the quality of data. These techniques may include simple mechanisms such as quality stamps that are posted on Web sites. We also need techniques that provide more effective integrity semantics verification and tools for the assessment of data quality, based on techniques such as record linkage. Application-level recovery techniques are also needed for automatically repairing incorrect data. The ETL (extract, transform, load) tools widely used to load data in data warehouses (see Section 29.4) are presently grappling with these issues.

24.9.2 Intellectual Property Rights

With the widespread use of the Internet and intranets, legal and informational aspects of data are becoming major concerns of organizations. To address these concerns, watermarking techniques for relational data have been proposed. The main purpose of digital watermarking is to protect content from unauthorized duplication and distribution by enabling provable ownership of the content. It has traditionally relied upon the availability of a large noise domain within which the object can be altered while retaining its essential properties. However, research is needed to assess the robustness of such techniques and to investigate different approaches aimed at preventing intellectual property rights violations.

24.9.3 Database Survivability

Database systems need to operate and continue their functions, even with reduced capabilities, despite disruptive events such as information warfare attacks. A DBMS, in addition to making every effort to prevent an attack and detecting one in the event of occurrence, should be able to do the following:

- **Confinement.** Take immediate action to eliminate the attacker's access to the system and to isolate or contain the problem to prevent further spread.
- **Damage assessment.** Determine the extent of the problem, including failed functions and corrupted data.
- **Reconfiguration.** Reconfigure to allow operation to continue in a degraded mode while recovery proceeds.
- **Repair.** Recover corrupted or lost data and repair or reinstall failed system functions to reestablish a normal level of operation.
- **Fault treatment.** To the extent possible, identify the weaknesses exploited in the attack and take steps to prevent a recurrence.

The goal of the information warfare attacker is to damage the organization's operation and fulfillment of its mission through disruption of its information systems. The specific target of an attack may be the system itself or its data. While attacks that bring the system down outright are severe and dramatic, they must also be well timed to achieve the attacker's goal, since attacks will receive immediate and concentrated attention in order to bring the system back to operational condition, diagnose how the attack took place, and install preventive measures.

To date, issues related to database survivability have not been sufficiently investigated. Much more research needs to be devoted to techniques and methodologies that ensure database system survivability.

24.10 Oracle Label-Based Security

Restricting access to entire tables or isolating sensitive data into separate databases is a costly operation to administer. **Oracle Label Security** overcomes the need for such measures by enabling row-level access control. It is available in Oracle Database 11g Release 1 (11.1) Enterprise Edition at the time of writing. Each database table or view has a security policy associated with it. This policy executes every time the table or view is queried or altered. Developers can readily add label-based access control to their Oracle Database applications. Label-based security provides an adaptable way of controlling access to sensitive data. Both users and data have labels associated with them. Oracle Label Security uses these labels to provide security.

24.10.1 Virtual Private Database (VPD) Technology

Virtual Private Databases (VPDs) is a feature of the Oracle Enterprise Edition that adds predicates to user statements to limit their access in a transparent manner to the user and the application. The VPD concept allows server-enforced, fine-grained access control for a secure application.

VPD provides access control based on policies. These VPD policies enforce object-level access control or row-level security. It provides an application programming interface (API) that allows security policies to be attached to database tables or views. Using PL/SQL, a host programming language used in Oracle applications, developers and security administrators can implement security policies with the help of stored procedures.[7] VPD policies allow developers to remove access security mechanisms from applications and centralize them within the Oracle Database.

VPD is enabled by associating a security "policy" with a table, view, or synonym. An administrator uses the supplied PL/SQL package, DBMS_RLS, to bind a policy function with a database object. When an object having a security policy associated with it is accessed, the function implementing this policy is consulted. The policy function returns a predicate (a WHERE clause) which is then appended to the user's SQL statement, thus *transparently* and *dynamically* modifying the user's data access. Oracle Label Security is a technique of enforcing row-level security in the form of a security policy.

24.10.2 Label Security Architecture

Oracle Label Security is built on the VPD technology delivered in the Oracle Database 11.1 Enterprise Edition. Figure 24.4 illustrates how data is accessed under Oracle Label Security, showing the sequence of DAC and label security checks.

Figure 24.4 shows the sequence of discretionary access control (DAC) and label security checks. The left part of the figure shows an application user in an Oracle Database 11g Release 1 (11.1) session sending out an SQL request. The Oracle DBMS checks the DAC privileges of the user, making sure that he or she has SELECT privileges on the table. Then it checks whether the table has a Virtual Private Database (VPD) policy associated with it to determine if the table is protected using Oracle Label Security. If it is, the VPD SQL modification (WHERE clause) is added to the original SQL statement to find the set of accessible rows for the user to view. Then Oracle Label Security checks the labels on each row, to determine the subset of rows to which the user has access (as explained in the next section). This modified query gets processed, optimized, and executed.

24.10.3 How Data Labels and User Labels Work Together

A user's label indicates the information the user is permitted to access. It also determines the type of access (read or write) that the user has on that information. A row's label shows the sensitivity of the information that the row contains as well as the ownership of the information. When a table in the database has a label-based access associated with it, a row can be accessed only if the user's label meet certain criteria defined in the policy definitions. Access is granted or denied based on the result of comparing the data label and the session label of the user.

Compartments allow a finer classification of sensitivity of the labeled data. All data related to the same project can be labeled with the same compartment. Compartments are optional; a label can contain zero or more compartments.

[7]Stored procedures are discussed in Section 5.2.2.

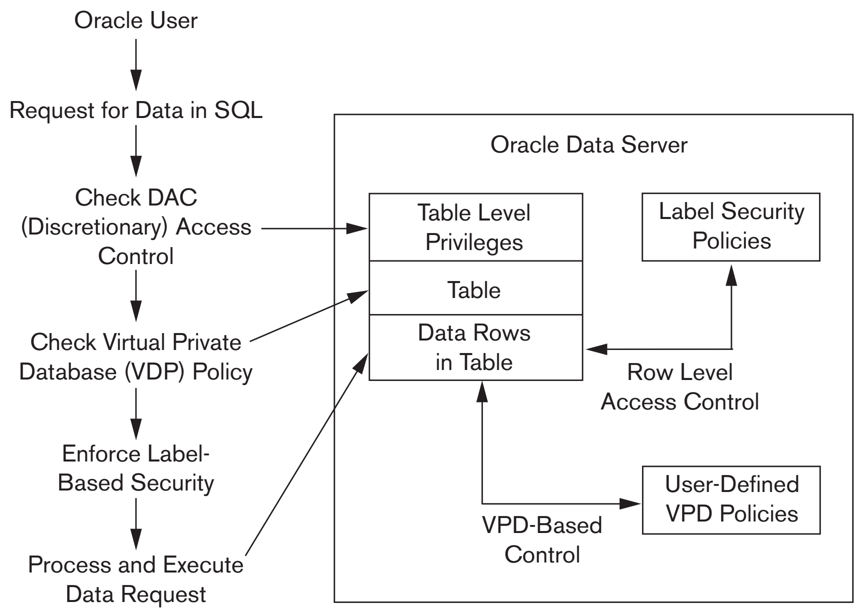
Oracle User
Request for Data in SQL
Check DAC (Discretionary) Access Control
Check Virtual Private Database (VDP) Policy
Enforce Label-Based Security
Process and Execute Data Request
Oracle Data Server
Table Level Privileges
Table
Data Rows in Table
Label Security Policies
Row Level Access Control
User-Defined VPD Policies
VPD-Based Control

Figure 24.4
Oracle Label Security architecture.
Source: Oracle (2007)

Groups are used to identify organizations as owners of the data with corresponding group labels. Groups are hierarchical; for example, a group can be associated with a parent group.

If a user has a maximum level of SENSITIVE, then the user potentially has access to all data having levels SENSITIVE, CONFIDENTIAL, and UNCLASSIFIED. This user has no access to HIGHLY_SENSITIVE data. Figure 24.5 shows how data labels and user labels work together to provide access control in Oracle Label Security.

As shown in Figure 24.5, User 1 can access the rows 2, 3, and 4 because his maximum level is HS (Highly_Sensitive). He has access to the FIN (Finance) compartment, and his access to group WR (Western Region) hierarchically includes group WR_SAL (WR Sales). He cannot access row 1 because he does not have the CHEM (Chemical) compartment. It is important that a user has authorization for all compartments in a row's data label to be able to access that row. Based on this example, user 2 can access both rows 3 and 4, and has a maximum level of S, which is less than the HS in row 2. So, although user 2 has access to the FIN compartment, he can only access the group WR_SAL, and thus cannot acces row 1.

24.11 Summary

In this chapter we discussed several techniques for enforcing database system security. We presented different threats to databases in terms of loss of integrity, availability, and confidentiality. We discussed the types of control measures to deal with these problems: access control, inference control, flow control, and encryption. In

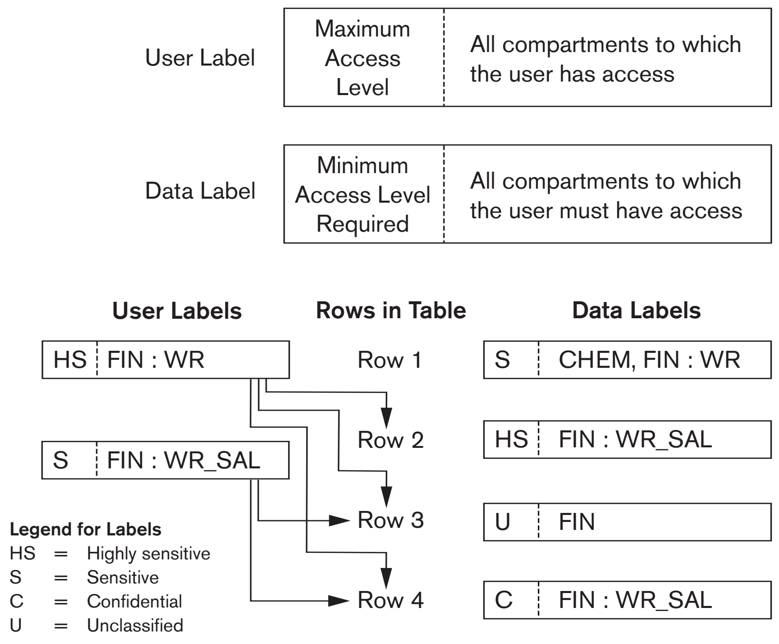

Figure 24.5
Data labels and user labels in Oracle.
Source: Oracle (2007)

the introduction we covered various issues related to security including data sensitivity and type of disclosures, providing security vs. precision in the result when a user requests information, and the relationship between information security and privacy.

Security enforcement deals with controlling access to the database system as a whole and controlling authorization to access specific portions of a database. The former is usually done by assigning accounts with passwords to users. The latter can be accomplished by using a system of granting and revoking privileges to individual accounts for accessing specific parts of the database. This approach is generally referred to as discretionary access control (DAC). We presented some SQL commands for granting and revoking privileges, and we illustrated their use with examples. Then we gave an overview of mandatory access control (MAC) mechanisms that enforce multilevel security. These require the classifications of users and data values into security classes and enforce the rules that prohibit flow of information from higher to lower security levels. Some of the key concepts underlying the multilevel relational model, including filtering and polyinstantiation, were presented. Role-based access control (RBAC) was introduced, which assigns privileges based on roles that users play. We introduced the notion of role hierarchies, mutual exclusion of roles, and row- and label-based security. We briefly discussed the problem of controlling access to statistical databases to protect the privacy of individual information while concurrently providing statistical access to populations of records. We explained the main ideas behind the threat of SQL Injection, the methods in which it can be induced, and the various types of risks associated with it. Then we gave an idea of the various ways SQL injection can be prevented. The issues related to flow control and the problems associated with covert channels were discussed next, as well as encryption and public-private key-based infrastructures. The idea of symmetric key algorithms and the use of the popular asymmetric key-based public key infrastructure (PKI) scheme was explained. We also covered the concepts of digital signatures and digital certificates. We highlighted the importance of privacy issues and hinted at some privacy preservation techniques. We discussed a variety of challenges to security including data quality, intellectual property rights, and data survivability. We ended the chapter by introducing the implementation of security policies by using a combination of label-based security and virtual private databases in Oracle 11g.

Review Questions

24.1. Discuss what is meant by each of the following terms: *database authorization, access control, data encryption, privileged (system) account, database audit, audit trail.*

24.2. Which account is designated as the owner of a relation? What privileges does the owner of a relation have?

24.3. How is the view mechanism used as an authorization mechanism?

24.4. Discuss the types of privileges at the account level and those at the relation level.

24.5. What is meant by granting a privilege? What is meant by revoking a privilege?

24.6. Discuss the system of propagation of privileges and the restraints imposed by horizontal and vertical propagation limits.

24.7. List the types of privileges available in SQL.

24.8. What is the difference between *discretionary* and *mandatory* access control?

24.9. What are the typical security classifications? Discuss the simple security property and the *-property, and explain the justification behind these rules for enforcing multilevel security.

24.10. Describe the multilevel relational data model. Define the following terms: *apparent key, polyinstantiation, filtering.*

24.11. What are the relative merits of using DAC or MAC?

24.12. What is role-based access control? In what ways is it superior to DAC and MAC?

24.13. What are the two types of mutual exclusion in role-based access control?

24.14. What is meant by row-level access control?

24.15. What is label security? How does an administrator enforce it?

24.16. What are the different types of SQL injection attacks?

24.17. What risks are associated with SQL injection attacks?

24.18. What preventive measures are possible against SQL injection attacks?

24.19. What is a statistical database? Discuss the problem of statistical database security.

24.20. How is privacy related to statistical database security? What measures can be taken to ensure some degree of privacy in statistical databases?

24.21. What is flow control as a security measure? What types of flow control exist?

24.22. What are covert channels? Give an example of a covert channel.

24.23. What is the goal of encryption? What process is involved in encrypting data and then recovering it at the other end?

24.24. Give an example of an encryption algorithm and explain how it works.

24.25. Repeat the previous question for the popular RSA algorithm.

24.26. What is a symmetric key algorithm for key-based security?

24.27. What is the public key infrastructure scheme? How does it provide security?

24.28. What are digital signatures? How do they work?

24.29. What type of information does a digital certificate include?

Exercises

24.30. How can privacy of data be preserved in a database?

24.31. What are some of the current outstanding challenges for database security?

24.32. Consider the relational database schema in Figure 3.5. Suppose that all the relations were created by (and hence are owned by) user *X*, who wants to grant the following privileges to user accounts *A*, *B*, *C*, *D*, and *E*:

a. Account *A* can retrieve or modify any relation except DEPENDENT and can grant any of these privileges to other users.

b. Account *B* can retrieve all the attributes of EMPLOYEE and DEPARTMENT except for Salary, Mgr_ssn, and Mgr_start_date.

c. Account *C* can retrieve or modify WORKS_ON but can only retrieve the Fname, Minit, Lname, and Ssn attributes of EMPLOYEE and the Pname and Pnumber attributes of PROJECT.

d. Account *D* can retrieve any attribute of EMPLOYEE or DEPENDENT and can modify DEPENDENT.

e. Account *E* can retrieve any attribute of EMPLOYEE but only for EMPLOYEE tuples that have Dno = 3.

f. Write SQL statements to grant these privileges. Use views where appropriate.

24.33. Suppose that privilege (a) of Exercise 24.32 is to be given with GRANT OPTION but only so that account *A* can grant it to at most five accounts, and each of these accounts can propagate the privilege to other accounts but *without* the GRANT OPTION privilege. What would the horizontal and vertical propagation limits be in this case?

24.34. Consider the relation shown in Figure 24.2(d). How would it appear to a user with classification *U*? Suppose that a classification *U* user tries to update the salary of 'Smith' to $50,000; what would be the result of this action?

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part 9

Transaction Processing, Concurrency Control, and Recovery

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chapter 21

Introduction to Transaction Processing Concepts and Theory

The concept of transaction provides a mechanism for describing logical units of database processing. **Transaction processing systems** are systems with large databases and hundreds of concurrent users executing database transactions. Examples of such systems include airline reservations, banking, credit card processing, online retail purchasing, stock markets, supermarket checkouts, and many other applications. These systems require high availability and fast response time for hundreds of concurrent users. In this chapter we present the concepts that are needed in transaction processing systems. We define the concept of a transaction, which is used to represent a logical unit of database processing that must be completed in its entirety to ensure correctness. A transaction is typically implemented by a computer program, which includes database commands such as retrievals, insertions, deletions, and updates. We introduced some of the basic techniques for database programming in Chapters 13 and 14.

In this chapter, we focus on the basic concepts and theory that are needed to ensure the correct executions of transactions. We discuss the concurrency control problem, which occurs when multiple transactions submitted by various users interfere with one another in a way that produces incorrect results. We also discuss the problems that can occur when transactions fail, and how the database system can recover from various types of failures.

This chapter is organized as follows. Section 21.1 informally discusses why concurrency control and recovery are necessary in a database system. Section 21.2 defines the term *transaction* and discusses additional concepts related to transaction processing in database systems. Section 21.3 presents the important properties of atomicity, consistency preservation, isolation, and durability or permanency—called the

ACID properties—that are considered desirable in transaction processing systems. Section 21.4 introduces the concept of schedules (or histories) of executing transactions and characterizes the *recoverability* of schedules. Section 21.5 discusses the notion of *serializability* of concurrent transaction execution, which can be used to define correct execution sequences (or schedules) of concurrent transactions. In Section 21.6, we present some of the commands that support the transaction concept in SQL. Section 21.7 summarizes the chapter.

The two following chapters continue with more details on the actual methods and techniques used to support transaction processing. Chapter 22 gives an overview of the basic concurrency control protocols and Chapter 23 introduces recovery techniques.

21.1 Introduction to Transaction Processing

In this section we discuss the concepts of concurrent execution of transactions and recovery from transaction failures. Section 21.1.1 compares single-user and multiuser database systems and demonstrates how concurrent execution of transactions can take place in multiuser systems. Section 21.1.2 defines the concept of transaction and presents a simple model of transaction execution based on read and write database operations. This model is used as the basis for defining and formalizing concurrency control and recovery concepts. Section 21.1.3 uses informal examples to show why concurrency control techniques are needed in multiuser systems. Finally, Section 21.1.4 discusses why techniques are needed to handle recovery from system and transaction failures by discussing the different ways in which transactions can fail while executing.

21.1.1 Single-User versus Multiuser Systems

One criterion for classifying a database system is according to the number of users who can use the system **concurrently**. A DBMS is **single-user** if at most one user at a time can use the system, and it is **multiuser** if many users can use the system—and hence access the database—concurrently. Single-user DBMSs are mostly restricted to personal computer systems; most other DBMSs are multiuser. For example, an airline reservations system is used by hundreds of travel agents and reservation clerks concurrently. Database systems used in banks, insurance agencies, stock exchanges, supermarkets, and many other applications are multiuser systems. In these systems, hundreds or thousands of users are typically operating on the database by submitting transactions concurrently to the system.

Multiple users can access databases—and use computer systems—simultaneously because of the concept of **multiprogramming**, which allows the operating system of the computer to execute multiple programs—or **processes**—at the same time. A single central processing unit (CPU) can only execute at most one process at a time. However, **multiprogramming operating systems** execute some commands from one process, then suspend that process and execute some commands from the next

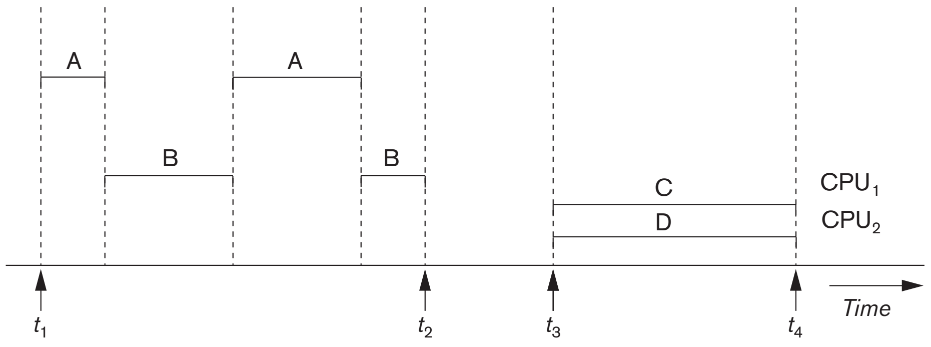


Figure 21.1
Interleaved processing versus parallel processing of concurrent transactions.

process, and so on. A process is resumed at the point where it was suspended whenever it gets its turn to use the CPU again. Hence, concurrent execution of processes is actually **interleaved**, as illustrated in Figure 21.1, which shows two processes, A and B, executing concurrently in an interleaved fashion. Interleaving keeps the CPU busy when a process requires an input or output (I/O) operation, such as reading a block from disk. The CPU is switched to execute another process rather than remaining idle during I/O time. Interleaving also prevents a long process from delaying other processes.

If the computer system has multiple hardware processors (CPUs), **parallel processing** of multiple processes is possible, as illustrated by processes C and D in Figure 21.1. Most of the theory concerning concurrency control in databases is developed in terms of **interleaved concurrency**, so for the remainder of this chapter we assume this model. In a multiuser DBMS, the stored data items are the primary resources that may be accessed concurrently by interactive users or application programs, which are constantly retrieving information from and modifying the database.

21.1.2 Transactions, Database Items, Read and Write Operations, and DBMS Buffers

A **transaction** is an executing program that forms a logical unit of database processing. A transaction includes one or more database access operations—these can include insertion, deletion, modification, or retrieval operations. The database operations that form a transaction can either be embedded within an application program or they can be specified interactively via a high-level query language such as SQL. One way of specifying the transaction boundaries is by specifying explicit **begin transaction** and **end transaction** statements in an application program; in this case, all database access operations between the two are considered as forming one transaction. A single application program may contain more than one transaction if it contains several transaction boundaries. If the database operations in a transaction do not update the database but only retrieve data, the transaction is called a **read-only transaction**; otherwise it is known as a **read-write transaction**.

The *database model* that is used to present transaction processing concepts is quite simple when compared to the data models that we discussed earlier in the book, such as the relational model or the object model. A **database** is basically represented as a collection of *named data items.* The size of a data item is called its **granularity**. A **data item** can be a *database record*, but it can also be a larger unit such as a whole *disk block*, or even a smaller unit such as an individual *field (attribute) value* of some record in the database. The transaction processing concepts we discuss are independent of the data item granularity (size) and apply to data items in general. Each data item has a *unique name*, but this name is not typically used by the programmer; rather, it is just a means to *uniquely identify each data item*. For example, if the data item granularity is one disk block, then the disk block address can be used as the data item name. Using this simplified database model, the basic database access operations that a transaction can include are as follows:

- **read_item(*X*).** Reads a database item named *X* into a program variable. To simplify our notation, we assume that *the program variable is also named X.*
- **write_item(*X*).** Writes the value of program variable *X* into the database item named *X*.

As we discussed in Chapter 17, the basic unit of data transfer from disk to main memory is one block. Executing a read_item(*X*) command includes the following steps:

1. Find the address of the disk block that contains item *X*.
2. Copy that disk block into a buffer in main memory (if that disk block is not already in some main memory buffer).
3. Copy item *X* from the buffer to the program variable named *X*.

Executing a write_item(*X*) command includes the following steps:

1. Find the address of the disk block that contains item *X*.
2. Copy that disk block into a buffer in main memory (if that disk block is not already in some main memory buffer).
3. Copy item *X* from the program variable named *X* into its correct location in the buffer.
4. Store the updated block from the buffer back to disk (either immediately or at some later point in time).

It is step 4 that actually updates the database on disk. In some cases the buffer is not immediately stored to disk, in case additional changes are to be made to the buffer. Usually, the decision about when to store a modified disk block whose contents are in a main memory buffer is handled by the recovery manager of the DBMS in cooperation with the underlying operating system. The DBMS will maintain in the **database cache** a number of **data buffers** in main memory. Each buffer typically holds the contents of one database disk block, which contains some of the database items being processed. When these buffers are all occupied, and additional database disk blocks must be copied into memory, some buffer replacement policy is used to choose which of the current buffers is to be replaced. If the chosen buffer has been modified, it must be written back to disk before it is reused.[1]

A transaction includes read_item and write_item operations to access and update the database. Figure 21.2 shows examples of two very simple transactions. The **read-set** of a transaction is the set of all items that the transaction reads, and the **write-set** is the set of all items that the transaction writes. For example, the read-set of T_1 in Figure 21.2 is $\{X, Y\}$ and its write-set is also $\{X, Y\}$.

Concurrency control and recovery mechanisms are mainly concerned with the database commands in a transaction. Transactions submitted by the various users may execute concurrently and may access and update the same database items. If this concurrent execution is *uncontrolled*, it may lead to problems, such as an inconsistent database. In the next section we informally introduce some of the problems that may occur.

21.1.3 Why Concurrency Control Is Needed

Several problems can occur when concurrent transactions execute in an uncontrolled manner. We illustrate some of these problems by referring to a much simplified airline reservations database in which a record is stored for each airline flight. Each record includes the *number of reserved seats* on that flight as a *named (uniquely identifiable) data item*, among other information. Figure 21.2(a) shows a transaction T_1 that *transfers* N reservations from one flight whose number of reserved seats is stored in the database item named X to another flight whose number of reserved seats is stored in the database item named Y. Figure 21.2(b) shows a simpler transaction T_2 that just *reserves* M seats on the first flight (X) referenced in transaction T_1.[2] To simplify our example, we do not show additional portions of the transactions, such as checking whether a flight has enough seats available before reserving additional seats.

(a)

T_1

read_item(X);
$X := X - N$;
write_item(X);
read_item(Y);
$Y := Y + N$;
write_item(Y);

(b)

T_2

read_item(X);
$X := X + M$;
write_item(X);

Figure 21.2
Two sample transactions. (a) Transaction T_1. (b) Transaction T_2.

[1]We will not discuss buffer replacement policies here because they are typically discussed in operating systems textbooks.

[2]A similar, more commonly used example assumes a bank database, with one transaction doing a transfer of funds from account X to account Y and the other transaction doing a deposit to account X.

When a database access program is written, it has the flight number, flight date, and the number of seats to be booked as parameters; hence, the same program can be used to execute *many different transactions*, each with a different flight number, date, and number of seats to be booked. For concurrency control purposes, a transaction is a *particular execution* of a program on a specific date, flight, and number of seats. In Figure 21.2(a) and (b), the transactions T_1 and T_2 are *specific executions* of the programs that refer to the specific flights whose numbers of seats are stored in data items X and Y in the database. Next we discuss the types of problems we may encounter with these two simple transactions if they run concurrently.

The Lost Update Problem. This problem occurs when two transactions that access the same database items have their operations interleaved in a way that makes the value of some database items incorrect. Suppose that transactions T_1 and T_2 are submitted at approximately the same time, and suppose that their operations are interleaved as shown in Figure 21.3(a); then the final value of item X is incorrect because T_2 reads the value of X *before* T_1 changes it in the database, and hence the updated value resulting from T_1 is lost. For example, if $X = 80$ at the start (originally there were 80 reservations on the flight), $N = 5$ (T_1 transfers 5 seat reservations from the flight corresponding to X to the flight corresponding to Y), and $M = 4$ (T_2 reserves 4 seats on X), the final result should be $X = 79$. However, in the interleaving of operations shown in Figure 21.3(a), it is $X = 84$ because the update in T_1 that removed the five seats from X was *lost*.

The Temporary Update (or Dirty Read) Problem. This problem occurs when one transaction updates a database item and then the transaction fails for some reason (see Section 21.1.4). Meanwhile, the updated item is accessed (read) by another transaction before it is changed back to its original value. Figure 21.3(b) shows an example where T_1 updates item X and then fails before completion, so the system must change X back to its original value. Before it can do so, however, transaction T_2 reads the *temporary* value of X, which will not be recorded permanently in the database because of the failure of T_1. The value of item X that is read by T_2 is called *dirty data* because it has been created by a transaction that has not completed and committed yet; hence, this problem is also known as the *dirty read problem*.

The Incorrect Summary Problem. If one transaction is calculating an aggregate summary function on a number of database items while other transactions are updating some of these items, the aggregate function may calculate some values before they are updated and others after they are updated. For example, suppose that a transaction T_3 is calculating the total number of reservations on all the flights; meanwhile, transaction T_1 is executing. If the interleaving of operations shown in Figure 21.3(c) occurs, the result of T_3 will be off by an amount N because T_3 reads the value of X *after* N seats have been subtracted from it but reads the value of Y *before* those N seats have been added to it.

Figure 21.3
Some problems that occur when concurrent execution is uncontrolled. (a) The lost update problem. (b) The temporary update problem. (c) The incorrect summary problem.

(a)

Time ↓

T_1	T_2
read_item(X); $X := X - N$;	
	read_item(X); $X := X + M$;

write_item(X);
read_item(Y);	

	write_item(X);
$Y := Y + N$; write_item(Y);	

Item X has an incorrect value because its update by T_1 is *lost* (overwritten).

(b)

Time ↓

T_1	T_2

read_item(X);
$X := X - N$;
write_item(X);	

	read_item(X);
	$X := X + M$;
	write_item(X);

read_item(Y);	

Transaction T_1 fails and must change the value of X back to its old value; meanwhile T_2 has read the *temporary* incorrect value of X.

(c)

T_1	T_3

	sum := 0;
	read_item(A);
	sum := *sum* + A;
	•
	•
	•

read_item(X);
$X := X - N$;
write_item(X);	

	read_item(X);
	sum := *sum* + X;
	read_item(Y);
	sum := *sum* + Y;

read_item(Y);
$Y := Y + N$;
write_item(Y);	

T_3 reads X after N is subtracted and reads Y before N is added; a wrong summary is the result (off by N).

The Unrepeatable Read Problem. Another problem that may occur is called *unrepeatable read*, where a transaction T reads the same item twice and the item is changed by another transaction T' between the two reads. Hence, T receives *different values* for its two reads of the same item. This may occur, for example, if during an airline reservation transaction, a customer inquires about seat availability on several flights. When the customer decides on a particular flight, the transaction then reads the number of seats on that flight a second time before completing the reservation, and it may end up reading a different value for the item.

21.1.4 Why Recovery Is Needed

Whenever a transaction is submitted to a DBMS for execution, the system is responsible for making sure that either all the operations in the transaction are completed successfully and their effect is recorded permanently in the database, or that the transaction does not have any effect on the database or any other transactions. In the first case, the transaction is said to be **committed**, whereas in the second case, the transaction is **aborted**. The DBMS must not permit some operations of a transaction T to be applied to the database while other operations of T are not, because *the whole transaction* is a logical unit of database processing. If a transaction **fails** after executing some of its operations but before executing all of them, the operations already executed must be undone and have no lasting effect.

Types of Failures. Failures are generally classified as transaction, system, and media failures. There are several possible reasons for a transaction to fail in the middle of execution:

1. **A computer failure (system crash).** A hardware, software, or network error occurs in the computer system during transaction execution. Hardware crashes are usually media failures—for example, main memory failure.
2. **A transaction or system error.** Some operation in the transaction may cause it to fail, such as integer overflow or division by zero. Transaction failure may also occur because of erroneous parameter values or because of a logical programming error.[3] Additionally, the user may interrupt the transaction during its execution.
3. **Local errors or exception conditions detected by the transaction.** During transaction execution, certain conditions may occur that necessitate cancellation of the transaction. For example, data for the transaction may not be found. An exception condition,[4] such as insufficient account balance in a banking database, may cause a transaction, such as a fund withdrawal, to be canceled. This exception could be programmed in the transaction itself, and in such a case would not be considered as a transaction failure.

[3]In general, a transaction should be thoroughly tested to ensure that it does not have any bugs (logical programming errors).

[4]Exception conditions, if programmed correctly, do not constitute transaction failures.

4. **Concurrency control enforcement.** The concurrency control method (see Chapter 22) may decide to abort a transaction because it violates serializability (see Section 21.5), or it may abort one or more transactions to resolve a state of deadlock among several transactions (see Section 22.1.3). Transactions aborted because of serializability violations or deadlocks are typically restarted automatically at a later time.
5. **Disk failure.** Some disk blocks may lose their data because of a read or write malfunction or because of a disk read/write head crash. This may happen during a read or a write operation of the transaction.
6. **Physical problems and catastrophes.** This refers to an endless list of problems that includes power or air-conditioning failure, fire, theft, sabotage, overwriting disks or tapes by mistake, and mounting of a wrong tape by the operator.

Failures of types 1, 2, 3, and 4 are more common than those of types 5 or 6. Whenever a failure of type 1 through 4 occurs, the system must keep sufficient information to quickly recover from the failure. Disk failure or other catastrophic failures of type 5 or 6 do not happen frequently; if they do occur, recovery is a major task. We discuss recovery from failure in Chapter 23.

The concept of transaction is fundamental to many techniques for concurrency control and recovery from failures.

21.2 Transaction and System Concepts

In this section we discuss additional concepts relevant to transaction processing. Section 21.2.1 describes the various states a transaction can be in, and discusses other operations needed in transaction processing. Section 21.2.2 discusses the system log, which keeps information about transactions and data items that will be needed for recovery. Section 21.2.3 describes the concept of commit points of transactions, and why they are important in transaction processing.

21.2.1 Transaction States and Additional Operations

A transaction is an atomic unit of work that should either be completed in its entirety or not done at all. For recovery purposes, the system needs to keep track of when each transaction starts, terminates, and commits or aborts (see Section 21.2.3). Therefore, the recovery manager of the DBMS needs to keep track of the following operations:

- BEGIN_TRANSACTION. This marks the beginning of transaction execution.
- READ or WRITE. These specify read or write operations on the database items that are executed as part of a transaction.
- END_TRANSACTION. This specifies that READ and WRITE transaction operations have ended and marks the end of transaction execution. However, at this point it may be necessary to check whether the changes introduced by

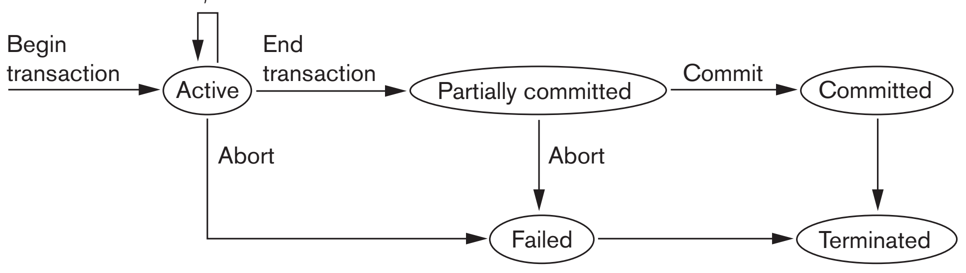
the transaction can be permanently applied to the database (committed) or whether the transaction has to be aborted because it violates serializability (see Section 21.5) or for some other reason.

- COMMIT_TRANSACTION. This signals a *successful end* of the transaction so that any changes (updates) executed by the transaction can be safely **committed** to the database and will not be undone.
- ROLLBACK (or ABORT). This signals that the transaction has *ended unsuccessfully,* so that any changes or effects that the transaction may have applied to the database must be **undone**.

Figure 21.4 shows a state transition diagram that illustrates how a transaction moves through its execution states. A transaction goes into an **active state** immediately after it starts execution, where it can execute its READ and WRITE operations. When the transaction ends, it moves to the **partially committed state**. At this point, some recovery protocols need to ensure that a system failure will not result in an inability to record the changes of the transaction permanently (usually by recording changes in the system log, discussed in the next section).[5] Once this check is successful, the transaction is said to have reached its commit point and enters the **committed state**. Commit points are discussed in more detail in Section 21.2.3. When a transaction is committed, it has concluded its execution successfully and all its changes must be recorded permanently in the database, even if a system failure occurs.

However, a transaction can go to the **failed state** if one of the checks fails or if the transaction is aborted during its active state. The transaction may then have to be rolled back to undo the effect of its WRITE operations on the database. The **terminated state** corresponds to the transaction leaving the system. The transaction information that is maintained in system tables while the transaction has been running is removed when the transaction terminates. Failed or aborted transactions may be *restarted* later—either automatically or after being resubmitted by the user—as brand new transactions.

Figure 21.4
State transition diagram illustrating the states for transaction execution.



[5]Optimistic concurrency control (see Section 22.4) also requires that certain checks are made at this point to ensure that the transaction did not interfere with other executing transactions.

21.2.2 The System Log

To be able to recover from failures that affect transactions, the system maintains a **log**[6] to keep track of all transaction operations that affect the values of database items, as well as other transaction information that may be needed to permit recovery from failures. The log is a sequential, append-only file that is kept on disk, so it is not affected by any type of failure except for disk or catastrophic failure. Typically, one (or more) main memory buffers hold the last part of the log file, so that log entries are first added to the main memory buffer. When the **log buffer** is filled, or when certain other conditions occur, the log buffer is *appended to the end of the log file on disk*. In addition, the log file from disk is periodically backed up to archival storage (tape) to guard against catastrophic failures. The following are the types of entries—called **log records**—that are written to the log file and the corresponding action for each log record. In these entries, *T* refers to a unique **transaction-id** that is generated automatically by the system for each transaction and that is used to identify each transaction:

1. [**start_transaction, *T***]. Indicates that transaction *T* has started execution.
2. [**write_item, *T*, *X*, *old_value*, *new_value***]. Indicates that transaction *T* has changed the value of database item *X* from *old_value* to *new_value.*
3. [**read_item, *T*, *X***]. Indicates that transaction *T* has read the value of database item *X*.
4. [**commit, *T***]. Indicates that transaction *T* has completed successfully, and affirms that its effect can be committed (recorded permanently) to the database.
5. [**abort, *T***]. Indicates that transaction *T* has been aborted.

Protocols for recovery that avoid cascading rollbacks (see Section 21.4.2)—which include nearly all practical protocols—*do not require* that READ operations are written to the system log. However, if the log is also used for other purposes—such as auditing (keeping track of all database operations)—then such entries can be included. Additionally, some recovery protocols require simpler WRITE entries only include one of new_value and old_value instead of including both (see Section 21.4.2).

Notice that we are assuming that all permanent changes to the database occur within transactions, so the notion of recovery from a transaction failure amounts to either undoing or redoing transaction operations individually from the log. If the system crashes, we can recover to a consistent database state by examining the log and using one of the techniques described in Chapter 23. Because the log contains a record of every WRITE operation that changes the value of some database item, it is possible to **undo** the effect of these WRITE operations of a transaction *T* by tracing backward through the log and resetting all items changed by a WRITE operation of *T* to their old_values. **Redo** of an operation may also be necessary if a transaction has its updates recorded in the log but a failure occurs before the system can be sure that

[6]The log has sometimes been called the *DBMS journal*.

all these new_values have been written to the actual database on disk from the main memory buffers.[7]

21.2.3 Commit Point of a Transaction

A transaction *T* reaches its **commit point** when all its operations that access the database have been executed successfully *and* the effect of all the transaction operations on the database have been recorded in the log. Beyond the commit point, the transaction is said to be **committed**, and its effect must be *permanently recorded* in the database. The transaction then writes a commit record [commit, *T*] into the log. If a system failure occurs, we can search back in the log for all transactions *T* that have written a [start_transaction, *T*] record into the log but have not written their [commit, *T*] record yet; these transactions may have to be *rolled back* to *undo their effect* on the database during the recovery process. Transactions that have written their commit record in the log must also have recorded all their WRITE operations in the log, so their effect on the database can be *redone* from the log records.

Notice that the log file must be kept on disk. As discussed in Chapter 17, updating a disk file involves copying the appropriate block of the file from disk to a buffer in main memory, updating the buffer in main memory, and copying the buffer to disk. It is common to keep one or more blocks of the log file in main memory buffers, called the **log buffer**, until they are filled with log entries and then to write them back to disk only once, rather than writing to disk every time a log entry is added. This saves the overhead of multiple disk writes of the same log file buffer. At the time of a system crash, only the log entries that have been *written back to disk* are considered in the recovery process because the contents of main memory may be lost. Hence, *before* a transaction reaches its commit point, any portion of the log that has not been written to the disk yet must now be written to the disk. This process is called **force-writing** the log buffer before committing a transaction.

21.3 Desirable Properties of Transactions

Transactions should possess several properties, often called the **ACID** properties; they should be enforced by the concurrency control and recovery methods of the DBMS. The following are the ACID properties:

- **Atomicity.** A transaction is an atomic unit of processing; it should either be performed in its entirety or not performed at all.
- **Consistency preservation.** A transaction should be consistency preserving, meaning that if it is completely executed from beginning to end without interference from other transactions, it should take the database from one consistent state to another.
- **Isolation.** A transaction should appear as though it is being executed in isolation from other transactions, even though many transactions are executing

[7]Undo and redo are discussed more fully in Chapter 23.

concurrently. That is, the execution of a transaction should not be interfered with by any other transactions executing concurrently.

- **Durability or permanency.** The changes applied to the database by a committed transaction must persist in the database. These changes must not be lost because of any failure.

The *atomicity property* requires that we execute a transaction to completion. It is the responsibility of the *transaction recovery subsystem* of a DBMS to ensure atomicity. If a transaction fails to complete for some reason, such as a system crash in the midst of transaction execution, the recovery technique must undo any effects of the transaction on the database. On the other hand, write operations of a committed transaction must be eventually written to disk.

The preservation of *consistency* is generally considered to be the responsibility of the programmers who write the database programs or of the DBMS module that enforces integrity constraints. Recall that a **database state** is a collection of all the stored data items (values) in the database at a given point in time. A **consistent state** of the database satisfies the constraints specified in the schema as well as any other constraints on the database that should hold. A database program should be written in a way that guarantees that, if the database is in a consistent state before executing the transaction, it will be in a consistent state after the *complete* execution of the transaction, assuming that *no interference with other transactions* occurs.

The *isolation property* is enforced by the *concurrency control subsystem* of the DBMS.[8] If every transaction does not make its updates (write operations) visible to other transactions until it is committed, one form of isolation is enforced that solves the temporary update problem and eliminates cascading rollbacks (see Chapter 23) but does not eliminate all other problems. There have been attempts to define the **level of isolation** of a transaction. A transaction is said to have level 0 (zero) isolation if it does not overwrite the dirty reads of higher-level transactions. Level 1 (one) isolation has no lost updates, and level 2 isolation has no lost updates and no dirty reads. Finally, level 3 isolation (also called *true isolation*) has, in addition to level 2 properties, repeatable reads.[9]

And last, the *durability property* is the responsibility of the *recovery subsystem* of the DBMS. We will introduce how recovery protocols enforce durability and atomicity in the next section and then discuss this in more detail in Chapter 23.

21.4 Characterizing Schedules Based on Recoverability

When transactions are executing concurrently in an interleaved fashion, then the order of execution of operations from all the various transactions is known as a **schedule** (or **history**). In this section, first we define the concept of schedules, and

[8]We will discuss concurrency control protocols in Chapter 22.

[9]The SQL syntax for isolation level discussed later in Section 21.6 is closely related to these levels.

then we characterize the types of schedules that facilitate recovery when failures occur. In Section 21.5, we characterize schedules in terms of the interference of participating transactions, leading to the concepts of serializability and serializable schedules.

21.4.1 Schedules (Histories) of Transactions

A **schedule** (or **history**) S of n transactions $T_1, T_2, \ldots, T_n$ is an ordering of the operations of the transactions. Operations from different transactions can be interleaved in the schedule S. However, for each transaction T_i that participates in the schedule S, the operations of T_i in S must appear in the same order in which they occur in T_i. The order of operations in S is considered to be a *total ordering*, meaning *that for any two operations* in the schedule, one must occur before the other. It is possible theoretically to deal with schedules whose operations form *partial orders* (as we discuss later), but we will assume for now total ordering of the operations in a schedule.

For the purpose of recovery and concurrency control, we are mainly interested in the read_item and write_item operations of the transactions, as well as the commit and abort operations. A shorthand notation for describing a schedule uses the symbols b, r, w, e, c, and a for the operations begin_transaction, read_item, write_item, end_transaction, commit, and abort, respectively, and appends as a *subscript* the transaction id (transaction number) to each operation in the schedule. In this notation, the database item X that is read or written follows the r and w operations in parentheses. In some schedules, we will only show the *read* and *write* operations, whereas in other schedules, we will show all the operations. For example, the schedule in Figure 21.3(a), which we shall call S_a, can be written as follows in this notation:

S_a: $r_1(X)$; $r_2(X)$; $w_1(X)$; $r_1(Y)$; $w_2(X)$; $w_1(Y)$;

Similarly, the schedule for Figure 21.3(b), which we call S_b, can be written as follows, if we assume that transaction T_1 aborted after its read_item(Y) operation:

S_b: $r_1(X)$; $w_1(X)$; $r_2(X)$; $w_2(X)$; $r_1(Y)$; a_1;

Two operations in a schedule are said to **conflict** if they satisfy all three of the following conditions: (1) they belong to *different transactions*; (2) they access the *same item X*; and (3) *at least one* of the operations is a write_item(X). For example, in schedule S_a, the operations $r_1(X)$ and $w_2(X)$ conflict, as do the operations $r_2(X)$ and $w_1(X)$, and the operations $w_1(X)$ and $w_2(X)$. However, the operations $r_1(X)$ and $r_2(X)$ do not conflict, since they are both read operations; the operations $w_2(X)$ and $w_1(Y)$ do not conflict because they operate on distinct data items X and Y; and the operations $r_1(X)$ and $w_1(X)$ do not conflict because they belong to the same transaction.

Intuitively, two operations are conflicting if changing their order can result in a different outcome. For example, if we change the order of the two operations $r_1(X)$; $w_2(X)$ to $w_2(X)$; $r_1(X)$, then the value of X that is read by transaction T_1 changes, because in the second order the value of X is changed by $w_2(X)$ before it is read by

$r_1(X)$, whereas in the first order the value is read before it is changed. This is called a **read-write conflict**. The other type is called a **write-write conflict**, and is illustrated by the case where we change the order of two operations such as $w_1(X)$; $w_2(X)$ to $w_2(X)$; $w_1(X)$. For a write-write conflict, the *last value* of X will differ because in one case it is written by T_2 and in the other case by T_1. Notice that two read operations are not conflicting because changing their order makes no difference in outcome.

The rest of this section covers some theoretical definitions concerning schedules. A schedule S of n transactions T_1, T_2, ..., T_n is said to be a **complete schedule** if the following conditions hold:

1. The operations in S are exactly those operations in T_1, T_2, ..., T_n, including a commit or abort operation as the last operation for each transaction in the schedule.
2. For any pair of operations from the same transaction T_i, their relative order of appearance in S is the same as their order of appearance in T_i.
3. For any two conflicting operations, one of the two must occur before the other in the schedule.[10]

The preceding condition (3) allows for two *nonconflicting operations* to occur in the schedule without defining which occurs first, thus leading to the definition of a schedule as a **partial order** of the operations in the n transactions.[11] However, a total order must be specified in the schedule for any pair of conflicting operations (condition 3) and for any pair of operations from the same transaction (condition 2). Condition 1 simply states that all operations in the transactions must appear in the complete schedule. Since every transaction has either committed or aborted, a complete schedule will *not contain any active transactions* at the end of the schedule.

In general, it is difficult to encounter complete schedules in a transaction processing system because new transactions are continually being submitted to the system. Hence, it is useful to define the concept of the **committed projection** $C(S)$ of a schedule S, which includes only the operations in S that belong to committed transactions—that is, transactions T_i whose commit operation c_i is in S.

21.4.2 Characterizing Schedules Based on Recoverability

For some schedules it is easy to recover from transaction and system failures, whereas for other schedules the recovery process can be quite involved. In some cases, it is even not possible to recover correctly after a failure. Hence, it is important to characterize the types of schedules for which *recovery is possible*, as well as those for which *recovery is relatively simple*. These characterizations do not actually provide the recovery algorithm; they only attempt to theoretically characterize the different types of schedules.

[10]Theoretically, it is not necessary to determine an order between pairs of *nonconflicting* operations.

[11]In practice, most schedules have a total order of operations. If parallel processing is employed, it is theoretically possible to have schedules with partially ordered nonconflicting operations.

First, we would like to ensure that, once a transaction T is committed, it should *never* be necessary to roll back T. This ensures that the durability property of transactions is not violated (see Section 21.3). The schedules that theoretically meet this criterion are called *recoverable schedules;* those that do not are called **nonrecoverable** and hence should not be permitted by the DBMS. The definition of **recoverable schedule** is as follows: A schedule S is recoverable if no transaction T in S commits until all transactions T' that have written some item X that T reads have committed. A transaction T **reads** from transaction T' in a schedule S if some item X is first written by T' and later read by T. In addition, T' should not have been aborted before T reads item X, and there should be no transactions that write X after T' writes it and before T reads it (unless those transactions, if any, have aborted before T reads X).

Some recoverable schedules may require a complex recovery process as we shall see, but if sufficient information is kept (in the log), a recovery algorithm can be devised for any recoverable schedule. The (partial) schedules S_a and S_b from the preceding section are both recoverable, since they satisfy the above definition. Consider the schedule S_a' given below, which is the same as schedule S_a except that two commit operations have been added to S_a:

S_a': $r_1(X); r_2(X); w_1(X); r_1(Y); w_2(X); c_2; w_1(Y); c_1;$

S_a' is recoverable, even though it suffers from the lost update problem; this problem is handled by serializability theory (see Section 21.5). However, consider the two (partial) schedules S_c and S_d that follow:

S_c: $r_1(X); w_1(X); r_2(X); r_1(Y); w_2(X); c_2; a_1;$
S_d: $r_1(X); w_1(X); r_2(X); r_1(Y); w_2(X); w_1(Y); c_1; c_2;$
S_e: $r_1(X); w_1(X); r_2(X); r_1(Y); w_2(X); w_1(Y); a_1; a_2;$

S_c is not recoverable because T_2 reads item X from T_1, but T_2 commits before T_1 commits. The problem occurs if T_1 aborts after the c_2 operation in S_c, then the value of X that T_2 read is no longer valid and T_2 must be aborted *after* it is committed, leading to a schedule that is *not recoverable*. For the schedule to be recoverable, the c_2 operation in S_c must be postponed until after T_1 commits, as shown in S_d. If T_1 aborts instead of committing, then T_2 should also abort as shown in S_e, because the value of X it read is no longer valid. In S_e, aborting T_2 is acceptable since it has not committed yet, which is not the case for the nonrecoverable schedule S_c.

In a recoverable schedule, no committed transaction ever needs to be rolled back, and so the definition of committed transaction as durable is not violated. However, it is possible for a phenomenon known as **cascading rollback** (or **cascading abort**) to occur in some recoverable schedules, where an *uncommitted* transaction has to be rolled back because it read an item from a transaction that failed. This is illustrated in schedule S_e, where transaction T_2 has to be rolled back because it read item X from T_1, and T_1 then aborted.

Because cascading rollback can be quite time-consuming—since numerous transactions can be rolled back (see Chapter 23)—it is important to characterize the schedules where this phenomenon is guaranteed not to occur. A schedule is said to be **cascadeless**, or to **avoid cascading rollback**, if every transaction in the schedule reads only items that were written by committed transactions. In this case, all items read will not be discarded, so no cascading rollback will occur. To satisfy this criterion, the $r_2(X)$ command in schedules S_d and S_e must be postponed until after T_1 has committed (or aborted), thus delaying T_2 but ensuring no cascading rollback if T_1 aborts.

Finally, there is a third, more restrictive type of schedule, called a **strict schedule**, in which transactions can *neither read nor write* an item X until the last transaction that wrote X has committed (or aborted). Strict schedules simplify the recovery process. In a strict schedule, the process of undoing a write_item(X) operation of an aborted transaction is simply to restore the **before image** (old_value or BFIM) of data item X. This simple procedure always works correctly for strict schedules, but it may not work for recoverable or cascadeless schedules. For example, consider schedule S_f:

$S_f : w_1(X, 5); w_2(X, 8); a_1;$

Suppose that the value of X was originally 9, which is the before image stored in the system log along with the $w_1(X, 5)$ operation. If T_1 aborts, as in S_f, the recovery procedure that restores the before image of an aborted write operation will restore the value of X to 9, even though it has already been changed to 8 by transaction T_2, thus leading to potentially incorrect results. Although schedule S_f is cascadeless, it is not a strict schedule, since it permits T_2 to write item X even though the transaction T_1 that last wrote X had not yet committed (or aborted). A strict schedule does not have this problem.

It is important to note that any strict schedule is also cascadeless, and any cascadeless schedule is also recoverable. Suppose we have i transactions $T_1, T_2, \ldots, T_i$, and their number of operations are $n_1, n_2, \ldots, n_i$, respectively. If we make a set of all possible schedules of these transactions, we can divide the schedules into two disjoint subsets: recoverable and nonrecoverable. The cascadeless schedules will be a subset of the recoverable schedules, and the strict schedules will be a subset of the cascadeless schedules. Thus, all strict schedules are cascadeless, and all cascadeless schedules are recoverable.

21.5 Characterizing Schedules Based on Serializability

In the previous section, we characterized schedules based on their recoverability properties. Now we characterize the types of schedules that are always considered to be *correct* when concurrent transactions are executing. Such schedules are known as *serializable schedules*. Suppose that two users—for example, two airline reservations agents—submit to the DBMS transactions T_1 and T_2 in Figure 21.2 at approximately the same time. If no interleaving of operations is permitted, there are only two possible outcomes:

1. Execute all the operations of transaction T_1 (in sequence) followed by all the operations of transaction T_2 (in sequence).

2. Execute all the operations of transaction T_2 (in sequence) followed by all the operations of transaction T_1 (in sequence).

These two schedules—called *serial schedules*—are shown in Figure 21.5(a) and (b), respectively. If interleaving of operations is allowed, there will be many possible orders in which the system can execute the individual operations of the transactions. Two possible schedules are shown in Figure 21.5(c). The concept of **serializability of schedules** is used to identify which schedules are correct when transaction executions have interleaving of their operations in the schedules. This section defines serializability and discusses how it may be used in practice.

Figure 21.5
Examples of serial and nonserial schedules involving transactions T_1 and T_2. (a) Serial schedule A: T_1 followed by T_2. (b) Serial schedule B: T_2 followed by T_1. (c) Two nonserial schedules C and D with interleaving of operations.

(a)

Time ↓

T_1	T_2
read_item(X);	
$X := X - N$;	
write_item(X);	
read_item(Y);	
$Y := Y + N$;	
write_item(Y);	
	read_item(X);
	$X := X + M$;
	write_item(X);

Schedule A

(b)

Time ↓

T_1	T_2
	read_item(X);
	$X := X + M$;
	write_item(X);
read_item(X);	
$X := X - N$;	
write_item(X);	
read_item(Y);	
$Y := Y + N$;	
write_item(Y);	

Schedule B

(c)

Time ↓

T_1	T_2
read_item(X);	
$X := X - N$;	
	read_item(X);
	$X := X + M$;
write_item(X);	
read_item(Y);	
	write_item(X);
$Y := Y + N$;	
write_item(Y);	

Schedule C

Time ↓

T_1	T_2
read_item(X);	
$X := X - N$;	
write_item(X);	
	read_item(X);
	$X := X + M$;
	write_item(X);
read_item(Y);	
$Y := Y + N$;	
write_item(Y);	

Schedule D

21.5.1 Serial, Nonserial, and Conflict-Serializable Schedules

Schedules A and B in Figure 21.5(a) and (b) are called *serial* because the operations of each transaction are executed consecutively, without any interleaved operations from the other transaction. In a serial schedule, entire transactions are performed in serial order: T_1 and then T_2 in Figure 21.5(a), and T_2 and then T_1 in Figure 21.5(b). Schedules C and D in Figure 21.5(c) are called *nonserial* because each sequence interleaves operations from the two transactions.

Formally, a schedule S is **serial** if, for every transaction T participating in the schedule, all the operations of T are executed consecutively in the schedule; otherwise, the schedule is called **nonserial**. Therefore, in a serial schedule, only one transaction at a time is active—the commit (or abort) of the active transaction initiates execution of the next transaction. No interleaving occurs in a serial schedule. One reasonable assumption we can make, if we consider the transactions to be *independent*, is that *every serial schedule is considered correct*. We can assume this because every transaction is assumed to be correct if executed on its own (according to the *consistency preservation* property of Section 21.3). Hence, it does not matter which transaction is executed first. As long as every transaction is executed from beginning to end in isolation from the operations of other transactions, we get a correct end result on the database.

The problem with serial schedules is that they limit concurrency by prohibiting interleaving of operations. In a serial schedule, if a transaction waits for an I/O operation to complete, we cannot switch the CPU processor to another transaction, thus wasting valuable CPU processing time. Additionally, if some transaction T is quite long, the other transactions must wait for T to complete all its operations before starting. Hence, serial schedules are *considered unacceptable* in practice. However, if we can determine which other schedules are *equivalent* to a serial schedule, we can allow these schedules to occur.

To illustrate our discussion, consider the schedules in Figure 21.5, and assume that the initial values of database items are $X = 90$ and $Y = 90$ and that $N = 3$ and $M = 2$. After executing transactions T_1 and T_2, we would expect the database values to be $X = 89$ and $Y = 93$, according to the meaning of the transactions. Sure enough, executing either of the serial schedules A or B gives the correct results. Now consider the nonserial schedules C and D. Schedule C (which is the same as Figure 21.3(a)) gives the results $X = 92$ and $Y = 93$, in which the X value is erroneous, whereas schedule D gives the correct results.

Schedule C gives an erroneous result because of the *lost update problem* discussed in Section 21.1.3; transaction T_2 reads the value of X before it is changed by transaction T_1, so only the effect of T_2 on X is reflected in the database. The effect of T_1 on X is *lost*, overwritten by T_2, leading to the incorrect result for item X. However, some nonserial schedules give the correct expected result, such as schedule D. We would like to determine which of the nonserial schedules *always* give a correct result and which may give erroneous results. The concept used to characterize schedules in this manner is that of serializability of a schedule.

The definition of *serializable schedule* is as follows: A schedule *S* of *n* transactions is **serializable** if it is *equivalent to some serial schedule* of the same *n* transactions. We will define the concept of *equivalence of schedules* shortly. Notice that there are *n*! possible serial schedules of *n* transactions and many more possible nonserial schedules. We can form two disjoint groups of the nonserial schedules—those that are equivalent to one (or more) of the serial schedules and hence are serializable, and those that are not equivalent to *any* serial schedule and hence are not serializable.

Saying that a nonserial schedule *S* is serializable is equivalent to saying that it is correct, because it is equivalent to a serial schedule, which is considered correct. The remaining question is: When are two schedules considered *equivalent*?

There are several ways to define schedule equivalence. The simplest but least satisfactory definition involves comparing the effects of the schedules on the database. Two schedules are called **result equivalent** if they produce the same final state of the database. However, two different schedules may accidentally produce the same final state. For example, in Figure 21.6, schedules S_1 and S_2 will produce the same final database state if they execute on a database with an initial value of $X = 100$; however, for other initial values of *X*, the schedules are *not* result equivalent. Additionally, these schedules execute different transactions, so they definitely should not be considered equivalent. Hence, result equivalence alone cannot be used to define equivalence of schedules. The safest and most general approach to defining schedule equivalence is not to make any assumptions about the types of operations included in the transactions. For two schedules to be equivalent, the operations applied to each data item affected by the schedules should be applied to that item in both schedules *in the same order*. Two definitions of equivalence of schedules are generally used: *conflict equivalence* and *view equivalence*. We discuss conflict equivalence next, which is the more commonly used definition.

The definition of *conflict equivalence* of schedules is as follows: Two schedules are said to be **conflict equivalent** if the order of any two *conflicting operations* is the same in both schedules. Recall from Section 21.4.1 that two operations in a schedule are said to *conflict* if they belong to different transactions, access the same database item, and either both are write_item operations or one is a write_item and the other a read_item. If two conflicting operations are applied in *different orders* in two schedules, the effect can be different on the database or on the transactions in the schedule, and hence the schedules are not conflict equivalent. For example, as we discussed in Section 21.4.1, if a read and write operation occur in the order $r_1(X)$, $w_2(X)$ in schedule S_1, and in the reverse order $w_2(X)$, $r_1(X)$ in schedule S_2, the value read by $r_1(X)$ can be different in the two schedules. Similarly, if two write operations

Figure 21.6
Two schedules that are result equivalent for the initial value of $X = 100$ but are not result equivalent in general.

S_1	S_2

read_item(X);
$X := X + 10$;
write_item(X);
	read_item(X);
	$X := X * 1.1$;
	write_item (X);

occur in the order $w_1(X)$, $w_2(X)$ in S_1, and in the reverse order $w_2(X)$, $w_1(X)$ in S_2, the next $r(X)$ operation in the two schedules will read potentially different values; or if these are the last operations writing item X in the schedules, the final value of item X in the database will be different.

Using the notion of conflict equivalence, we define a schedule S to be **conflict serializable**[12] if it is (conflict) equivalent to some serial schedule S'. In such a case, we can reorder the *nonconflicting* operations in S until we form the equivalent serial schedule S'. According to this definition, schedule D in Figure 21.5(c) is equivalent to the serial schedule A in Figure 21.5(a). In both schedules, the read_item(X) of T_2 reads the value of X written by T_1, while the other read_item operations read the database values from the initial database state. Additionally, T_1 is the last transaction to write Y, and T_2 is the last transaction to write X in both schedules. Because A is a serial schedule and schedule D is equivalent to A, D is a serializable schedule. Notice that the operations $r_1(Y)$ and $w_1(Y)$ of schedule D do not conflict with the operations $r_2(X)$ and $w_2(X)$, since they access different data items. Therefore, we can move $r_1(Y)$, $w_1(Y)$ before $r_2(X)$, $w_2(X)$, leading to the equivalent serial schedule T_1, T_2.

Schedule C in Figure 21.5(c) is not equivalent to either of the two possible serial schedules A and B, and hence is *not serializable*. Trying to reorder the operations of schedule C to find an equivalent serial schedule fails because $r_2(X)$ and $w_1(X)$ conflict, which means that we cannot move $r_2(X)$ down to get the equivalent serial schedule T_1, T_2. Similarly, because $w_1(X)$ and $w_2(X)$ conflict, we cannot move $w_1(X)$ down to get the equivalent serial schedule T_2, T_1.

Another, more complex definition of equivalence—called *view equivalence*, which leads to the concept of view serializability—is discussed in Section 21.5.4.

21.5.2 Testing for Conflict Serializability of a Schedule

There is a simple algorithm for determining whether a particular schedule is conflict serializable or not. Most concurrency control methods do *not* actually test for serializability. Rather protocols, or rules, are developed that guarantee that any schedule that follows these rules will be serializable. We discuss the algorithm for testing conflict serializability of schedules here to gain a better understanding of these concurrency control protocols, which are discussed in Chapter 22.

Algorithm 21.1 can be used to test a schedule for conflict serializability. The algorithm looks at only the read_item and write_item operations in a schedule to construct a **precedence graph** (or **serialization graph**), which is a **directed graph** $G = (N, E)$ that consists of a set of nodes $N = \{T_1, T_2, ..., T_n\}$ and a set of directed edges $E = \{e_1, e_2, ..., e_m\}$. There is one node in the graph for each transaction T_i in the schedule. Each edge e_i in the graph is of the form $(T_j \rightarrow T_k)$, $1 \le j \le n$, $1 \le k \le n$, where T_j is the **starting node** of e_i and T_k is the **ending node** of e_i. Such an edge from node T_j to

[12]We will use *serializable* to mean conflict serializable. Another definition of serializable used in practice (see Section 21.6) is to have repeatable reads, no dirty reads, and no phantom records (see Section 22.7.1 for a discussion on phantoms).

node T_k is created by the algorithm if one of the operations in T_j appears in the schedule before some *conflicting operation* in T_k.

Algorithm 21.1. Testing Conflict Serializability of a Schedule S

1. For each transaction T_i participating in schedule S, create a node labeled T_i in the precedence graph.
2. For each case in S where T_j executes a read_item(X) after T_i executes a write_item(X), create an edge ($T_i \rightarrow T_j$) in the precedence graph.
3. For each case in S where T_j executes a write_item(X) after T_i executes a read_item(X), create an edge ($T_i \rightarrow T_j$) in the precedence graph.
4. For each case in S where T_j executes a write_item(X) after T_i executes a write_item(X), create an edge ($T_i \rightarrow T_j$) in the precedence graph.
5. The schedule S is serializable if and only if the precedence graph has no cycles.

The precedence graph is constructed as described in Algorithm 21.1. If there is a cycle in the precedence graph, schedule S is not (conflict) serializable; if there is no cycle, S is serializable. A **cycle** in a directed graph is a **sequence of edges** $C = ((T_j \rightarrow T_k), (T_k \rightarrow T_p), \ldots, (T_i \rightarrow T_j))$ with the property that the starting node of each edge—except the first edge—is the same as the ending node of the previous edge, and the starting node of the first edge is the same as the ending node of the last edge (the sequence starts and ends at the same node).

In the precedence graph, an edge from T_i to T_j means that transaction T_i must come before transaction T_j in any serial schedule that is equivalent to S, because two conflicting operations appear in the schedule in that order. If there is no cycle in the precedence graph, we can create an **equivalent serial schedule** S' that is equivalent to S, by ordering the transactions that participate in S as follows: Whenever an edge exists in the precedence graph from T_i to T_j, T_i must appear before T_j in the equivalent serial schedule S'.[13] Notice that the edges ($T_i \rightarrow T_j$) in a precedence graph can optionally be labeled by the name(s) of the data item(s) that led to creating the edge. Figure 21.7 shows such labels on the edges.

In general, several serial schedules can be equivalent to S if the precedence graph for S has no cycle. However, if the precedence graph has a cycle, it is easy to show that we cannot create any equivalent serial schedule, so S is not serializable. The precedence graphs created for schedules A to D, respectively, in Figure 21.5 appear in Figure 21.7(a) to (d). The graph for schedule C has a cycle, so it is not serializable. The graph for schedule D has no cycle, so it is serializable, and the equivalent serial schedule is T_1 followed by T_2. The graphs for schedules A and B have no cycles, as expected, because the schedules are serial and hence serializable.

Another example, in which three transactions participate, is shown in Figure 21.8. Figure 21.8(a) shows the read_item and write_item operations in each transaction. Two schedules E and F for these transactions are shown in Figure 21.8(b) and (c),

[13]This process of ordering the nodes of an acrylic graph is known as *topological sorting*.

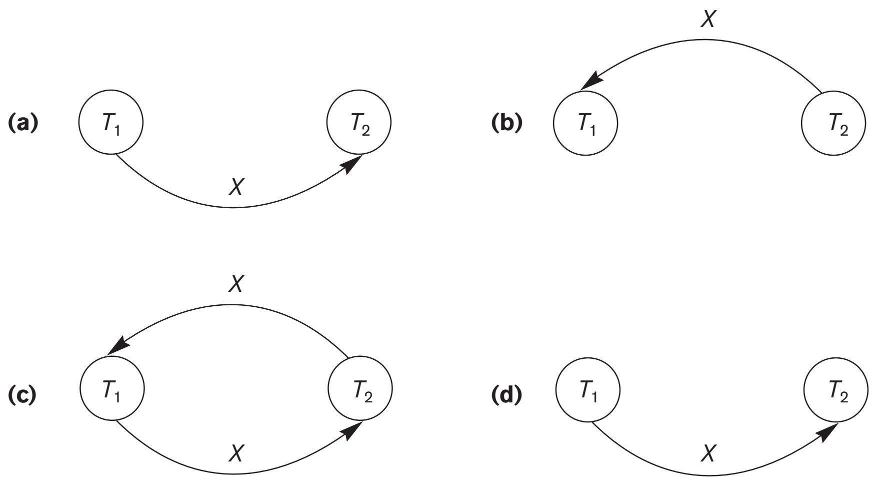


Figure 21.7
Constructing the precedence graphs for schedules A to D from Figure 21.5 to test for conflict serializability. (a) Precedence graph for serial schedule A. (b) Precedence graph for serial schedule B. (c) Precedence graph for schedule C (not serializable). (d) Precedence graph for schedule D (serializable, equivalent to schedule A).

respectively, and the precedence graphs for schedules E and F are shown in parts (d) and (e). Schedule E is not serializable because the corresponding precedence graph has cycles. Schedule F is serializable, and the serial schedule equivalent to *F* is shown in Figure 21.8(e). Although only one equivalent serial schedule exists for *F*, in general there may be more than one equivalent serial schedule for a serializable schedule. Figure 21.8(f) shows a precedence graph representing a schedule that has two equivalent serial schedules. To find an equivalent serial schedule, start with a node that does not have any incoming edges, and then make sure that the node order for every edge is not violated.

21.5.3 How Serializability Is Used for Concurrency Control

As we discussed earlier, saying that a schedule *S* is (conflict) serializable—that is, *S* is (conflict) equivalent to a serial schedule—is tantamount to saying that *S* is correct. Being *serializable* is distinct from being *serial*, however. A serial schedule represents inefficient processing because no interleaving of operations from different transactions is permitted. This can lead to low CPU utilization while a transaction waits for disk I/O, or for another transaction to terminate, thus slowing down processing considerably. A serializable schedule gives the benefits of concurrent execution without giving up any correctness. In practice, it is quite difficult to test for the serializability of a schedule. The interleaving of operations from concurrent transactions—which are usually executed as processes by the operating system—is typically determined by the operating system scheduler, which allocates resources to

(a)

Transaction T_1
read_item(X);
write_item(X);
read_item(Y);
write_item(Y);

Transaction T_2
read_item(Z);
read_item(Y);
write_item(Y);
read_item(X);
write_item(X);

Transaction T_3
read_item(Y);
read_item(Z);
write_item(Y);
write_item(Z);

(b)

Time

Transaction T_1	Transaction T_2	Transaction T_3
	read_item(Z);	
	read_item(Y);	
	write_item(Y);	
		read_item(Y);
		read_item(Z);
read_item(X);		
write_item(X);		
		write_item(Y);
		write_item(Z);
	read_item(X);	
read_item(Y);		
write_item(Y);		
	write_item(X);	

Schedule E

(c)

Time

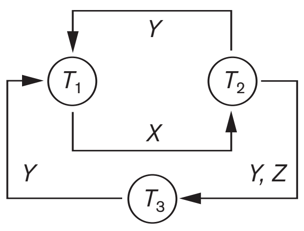
Transaction T_1	Transaction T_2	Transaction T_3
		read_item(Y);
		read_item(Z);
read_item(X);		
write_item(X);		
		write_item(Y);
		write_item(Z);
	read_item(Z);	
read_item(Y);		
write_item(Y);		
	read_item(Y);	
	write_item(Y);	
	read_item(X);	
	write_item(X);	

Schedule F

Figure 21.8
Another example of serializability testing. (a) The read and write operations of three transactions T_1, T_2, and T_3. (b) Schedule E. (c) Schedule F.

all processes. Factors such as system load, time of transaction submission, and priorities of processes contribute to the ordering of operations in a schedule. Hence, it is difficult to determine how the operations of a schedule will be interleaved beforehand to ensure serializability.

(d)



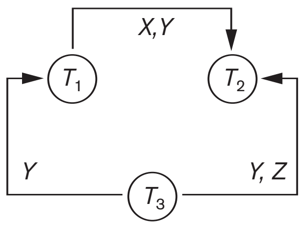
Equivalent serial schedules

None

Reason

Cycle $X(T_1 \rightarrow T_2), Y(T_2 \rightarrow T_1)$
Cycle $X(T_1 \rightarrow T_2), YZ\ (T_2 \rightarrow T_3), Y(T_3 \rightarrow T_1)$

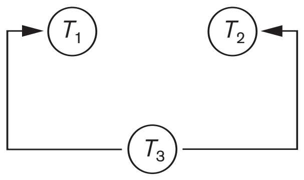
(e)



Equivalent serial schedules

$T_3 \rightarrow T_1 \rightarrow T_2$

(f)



Equivalent serial schedules

$T_3 \rightarrow T_1 \rightarrow T_2$

$T_3 \rightarrow T_2 \rightarrow T_1$

Figure 21.8 (continued)
Another example of serializability testing.
(d) Precedence graph for schedule E.
(e) Precedence graph for schedule F.
(f) Precedence graph with two equivalent serial schedules.

If transactions are executed at will and then the resulting schedule is tested for serializability, we must cancel the effect of the schedule if it turns out not to be serializable. This is a serious problem that makes this approach impractical. Hence, the approach taken in most practical systems is to determine methods or protocols that ensure serializability, without having to test the schedules themselves. The approach taken in most commercial DBMSs is to design **protocols** (sets of rules) that—if followed by *every* individual transaction or if enforced by a DBMS concurrency control subsystem—will ensure serializability of *all schedules in which the transactions participate*.

Another problem appears here: When transactions are submitted continuously to the system, it is difficult to determine when a schedule begins and when it ends. Serializability theory can be adapted to deal with this problem by considering only the committed projection of a schedule *S*. Recall from Section 21.4.1 that the *committed projection* *C*(*S*) of a schedule *S* includes only the operations in *S* that belong to committed transactions. We can theoretically define a schedule *S* to be serializable if its committed projection *C*(*S*) is equivalent to some serial schedule, since only committed transactions are guaranteed by the DBMS.

In Chapter 22, we discuss a number of different concurrency control protocols that guarantee serializability. The most common technique, called *two-phase locking*, is based on locking data items to prevent concurrent transactions from interfering with one another, and enforcing an additional condition that guarantees serializability. This is used in the majority of commercial DBMSs. Other protocols have been proposed;[14] these include *timestamp ordering*, where each transaction is assigned a unique timestamp and the protocol ensures that any conflicting operations are executed in the order of the transaction timestamps; *multiversion protocols*, which are based on maintaining multiple versions of data items; and *optimistic* (also called *certification* or *validation*) *protocols*, which check for possible serializability violations after the transactions terminate but before they are permitted to commit.

21.5.4 View Equivalence and View Serializability

In Section 21.5.1 we defined the concepts of conflict equivalence of schedules and conflict serializability. Another less restrictive definition of equivalence of schedules is called *view equivalence*. This leads to another definition of serializability called *view serializability*. Two schedules S and S' are said to be **view equivalent** if the following three conditions hold:

1. The same set of transactions participates in S and S', and S and S' include the same operations of those transactions.
2. For any operation $r_i(X)$ of T_i in S, if the value of X read by the operation has been written by an operation $w_j(X)$ of T_j (or if it is the original value of X before the schedule started), the same condition must hold for the value of X read by operation $r_i(X)$ of T_i in S'.
3. If the operation $w_k(Y)$ of T_k is the last operation to write item Y in S, then $w_k(Y)$ of T_k must also be the last operation to write item Y in S'.

The idea behind view equivalence is that, as long as each read operation of a transaction reads the result of the same write operation in both schedules, the write operations of each transaction must produce the same results. The read operations are hence said to *see the same view* in both schedules. Condition 3 ensures that the final write operation on each data item is the same in both schedules, so the database state should be the same at the end of both schedules. A schedule S is said to be **view serializable** if it is view equivalent to a serial schedule.

The definitions of conflict serializability and view serializability are similar if a condition known as the **constrained write assumption** (or **no blind writes**) holds on all transactions in the schedule. This condition states that any write operation $w_i(X)$ in T_i is preceded by a $r_i(X)$ in T_i and that the value written by $w_i(X)$ in T_i depends only on the value of X read by $r_i(X)$. This assumes that computation of the new value of X is a function $f(X)$ based on the old value of X read from the database. A **blind write** is a write operation in a transaction T on an item X that is not dependent on the value of X, so it is not preceded by a read of X in the transaction T.

[14]These other protocols have not been incorporated much into commercial systems; most relational DBMSs use some variation of the two-phase locking protocol.

The definition of view serializability is less restrictive than that of conflict serializability under the **unconstrained write assumption**, where the value written by an operation $w_i(X)$ in T_i can be independent of its old value from the database. This is possible when *blind writes* are allowed, and it is illustrated by the following schedule S_g of three transactions T_1: $r_1(X)$; $w_1(X)$; T_2: $w_2(X)$; and T_3: $w_3(X)$:

S_g: $r_1(X)$; $w_2(X)$; $w_1(X)$; $w_3(X)$; c_1; c_2; c_3;

In S_g the operations $w_2(X)$ and $w_3(X)$ are blind writes, since T_2 and T_3 do not read the value of X. The schedule S_g is view serializable, since it is view equivalent to the serial schedule T_1, T_2, T_3. However, S_g is not conflict serializable, since it is not conflict equivalent to any serial schedule. It has been shown that any conflict-serializable schedule is also view serializable but not vice versa, as illustrated by the preceding example. There is an algorithm to test whether a schedule S is view serializable or not. However, the problem of testing for view serializability has been shown to be NP-hard, meaning that finding an efficient polynomial time algorithm for this problem is highly unlikely.

21.5.5 Other Types of Equivalence of Schedules

Serializability of schedules is sometimes considered to be too restrictive as a condition for ensuring the correctness of concurrent executions. Some applications can produce schedules that are correct by satisfying conditions less stringent than either conflict serializability or view serializability. An example is the type of transactions known as **debit-credit transactions**—for example, those that apply deposits and withdrawals to a data item whose value is the current balance of a bank account. The semantics of debit-credit operations is that they update the value of a data item X by either subtracting from or adding to the value of the data item. Because addition and subtraction operations are commutative—that is, they can be applied in any order—it is possible to produce correct schedules that are not serializable. For example, consider the following transactions, each of which may be used to transfer an amount of money between two bank accounts:

T_1: $r_1(X)$; $X := X - 10$; $w_1(X)$; $r_1(Y)$; $Y := Y + 10$; $w_1(Y)$;
T_2: $r_2(Y)$; $Y := Y - 20$; $w_2(Y)$; $r_2(X)$; $X := X + 20$; $w_2(X)$;

Consider the following nonserializable schedule S_h for the two transactions:

S_h: $r_1(X)$; $w_1(X)$; $r_2(Y)$; $w_2(Y)$; $r_1(Y)$; $w_1(Y)$; $r_2(X)$; $w_2(X)$;

With the additional knowledge, or **semantics**, that the operations between each $r_i(I)$ and $w_i(I)$ are commutative, we know that the order of executing the sequences consisting of (read, update, write) is not important as long as each (read, update, write) sequence by a particular transaction T_i on a particular item I is not interrupted by conflicting operations. Hence, the schedule S_h is considered to be correct even though it is not serializable. Researchers have been working on extending concurrency control theory to deal with cases where serializability is considered to be too restrictive as a condition for correctness of schedules. Also, in certain domains of applications such as computer aided design (CAD) of complex systems like aircraft, design transactions last over a long time period. In such applications, more relaxed schemes of concurrency control have been proposed to maintain consistency of the database.

21.6 Transaction Support in SQL

In this section, we give a brief introduction to transaction support in SQL. There are many more details, and the newer standards have more commands for transaction processing. The basic definition of an SQL transaction is similar to our already defined concept of a transaction. That is, it is a logical unit of work and is guaranteed to be atomic. A single SQL statement is always considered to be atomic—either it completes execution without an error or it fails and leaves the database unchanged.

With SQL, there is no explicit Begin_Transaction statement. Transaction initiation is done implicitly when particular SQL statements are encountered. However, every transaction must have an explicit end statement, which is either a COMMIT or a ROLLBACK. Every transaction has certain characteristics attributed to it. These characteristics are specified by a SET TRANSACTION statement in SQL. The characteristics are the *access mode*, the *diagnostic area size*, and the *isolation level*.

The **access mode** can be specified as READ ONLY or READ WRITE. The default is READ WRITE, unless the isolation level of READ UNCOMMITTED is specified (see below), in which case READ ONLY is assumed. A mode of READ WRITE allows select, update, insert, delete, and create commands to be executed. A mode of READ ONLY, as the name implies, is simply for data retrieval.

The **diagnostic area size** option, DIAGNOSTIC SIZE *n*, specifies an integer value *n*, which indicates the number of conditions that can be held simultaneously in the diagnostic area. These conditions supply feedback information (errors or exceptions) to the user or program on the *n* most recently executed SQL statement.

The **isolation level** option is specified using the statement ISOLATION LEVEL <isolation>, where the value for <isolation> can be READ UNCOMMITTED, READ COMMITTED, REPEATABLE READ, or SERIALIZABLE.[15] The default isolation level is SERIALIZABLE, although some systems use READ COMMITTED as their default. The use of the term SERIALIZABLE here is based on not allowing violations that cause dirty read, unrepeatable read, and phantoms,[16] and it is thus not identical to the way serializability was defined earlier in Section 21.5. If a transaction executes at a lower isolation level than SERIALIZABLE, then one or more of the following three violations may occur:

1. **Dirty read.** A transaction T_1 may read the update of a transaction T_2, which has not yet committed. If T_2 fails and is aborted, then T_1 would have read a value that does not exist and is incorrect.

[15]These are similar to the *isolation levels* discussed briefly at the end of Section 21.3.

[16]The dirty read and unrepeatable read problems were discussed in Section 21.1.3. Phantoms are discussed in Section 22.7.1.

2. **Nonrepeatable read.** A transaction T_1 may read a given value from a table. If another transaction T_2 later updates that value and T_1 reads that value again, T_1 will see a different value.
3. **Phantoms.** A transaction T_1 may read a set of rows from a table, perhaps based on some condition specified in the SQL WHERE-clause. Now suppose that a transaction T_2 inserts a new row that also satisfies the WHERE-clause condition used in T_1, into the table used by T_1. If T_1 is repeated, then T_1 will see a phantom, a row that previously did not exist.

Table 21.1 summarizes the possible violations for the different isolation levels. An entry of *Yes* indicates that a violation is possible and an entry of *No* indicates that it is not possible. READ UNCOMMITTED is the most forgiving, and SERIALIZABLE is the most restrictive in that it avoids all three of the problems mentioned above.

A sample SQL transaction might look like the following:

```
EXEC SQL WHENEVER SQLERROR GOTO UNDO;
EXEC SQL SET TRANSACTION
   READ WRITE
   DIAGNOSTIC SIZE 5
   ISOLATION LEVEL SERIALIZABLE;
EXEC SQL INSERT INTO EMPLOYEE (Fname, Lname, Ssn, Dno, Salary)
   VALUES ('Robert', 'Smith', '991004321', 2, 35000);
EXEC SQL UPDATE EMPLOYEE
   SET Salary = Salary * 1.1 WHERE Dno = 2;
EXEC SQL COMMIT;
GOTO THE_END;
UNDO: EXEC SQL ROLLBACK;
THE_END: ... ;
```

The above transaction consists of first inserting a new row in the EMPLOYEE table and then updating the salary of all employees who work in department 2. If an error occurs on any of the SQL statements, the entire transaction is rolled back. This implies that any updated salary (by this transaction) would be restored to its previous value and that the newly inserted row would be removed.

As we have seen, SQL provides a number of transaction-oriented features. The DBA or database programmers can take advantage of these options to try improving

Table 21.1 Possible Violations Based on Isolation Levels as Defined in SQL

	Type of Violation		
Isolation Level	**Dirty Read**	**Nonrepeatable Read**	**Phantom**
READ UNCOMMITTED	Yes	Yes	Yes
READ COMMITTED	No	Yes	Yes
REPEATABLE READ	No	No	Yes
SERIALIZABLE	No	No	No

transaction performance by relaxing serializability if that is acceptable for their applications.

21.7 Summary

In this chapter we discussed DBMS concepts for transaction processing. We introduced the concept of a database transaction and the operations relevant to transaction processing. We compared single-user systems to multiuser systems and then presented examples of how uncontrolled execution of concurrent transactions in a multiuser system can lead to incorrect results and database values. We also discussed the various types of failures that may occur during transaction execution.

Next we introduced the typical states that a transaction passes through during execution, and discussed several concepts that are used in recovery and concurrency control methods. The system log keeps track of database accesses, and the system uses this information to recover from failures. A transaction either succeeds and reaches its commit point or it fails and has to be rolled back. A committed transaction has its changes permanently recorded in the database. We presented an overview of the desirable properties of transactions—atomicity, consistency preservation, isolation, and durability—which are often referred to as the ACID properties.

Then we defined a schedule (or history) as an execution sequence of the operations of several transactions with possible interleaving. We characterized schedules in terms of their recoverability. Recoverable schedules ensure that, once a transaction commits, it never needs to be undone. Cascadeless schedules add an additional condition to ensure that no aborted transaction requires the cascading abort of other transactions. Strict schedules provide an even stronger condition that allows a simple recovery scheme consisting of restoring the old values of items that have been changed by an aborted transaction.

We defined equivalence of schedules and saw that a serializable schedule is equivalent to some serial schedule. We defined the concepts of conflict equivalence and view equivalence, which led to definitions for conflict serializability and view serializability. A serializable schedule is considered correct. We presented an algorithm for testing the (conflict) serializability of a schedule. We discussed why testing for serializability is impractical in a real system, although it can be used to define and verify concurrency control protocols, and we briefly mentioned less restrictive definitions of schedule equivalence. Finally, we gave a brief overview of how transaction concepts are used in practice within SQL.

Review Questions

21.1. What is meant by the concurrent execution of database transactions in a multiuser system? Discuss why concurrency control is needed, and give informal examples.

21.2. Discuss the different types of failures. What is meant by catastrophic failure?

21.3. Discuss the actions taken by the read_item and write_item operations on a database.

21.4. Draw a state diagram and discuss the typical states that a transaction goes through during execution.

21.5. What is the system log used for? What are the typical kinds of records in a system log? What are transaction commit points, and why are they important?

21.6. Discuss the atomicity, durability, isolation, and consistency preservation properties of a database transaction.

21.7. What is a schedule (history)? Define the concepts of recoverable, cascadeless, and strict schedules, and compare them in terms of their recoverability.

21.8. Discuss the different measures of transaction equivalence. What is the difference between conflict equivalence and view equivalence?

21.9. What is a serial schedule? What is a serializable schedule? Why is a serial schedule considered correct? Why is a serializable schedule considered correct?

21.10. What is the difference between the constrained write and the unconstrained write assumptions? Which is more realistic?

21.11. Discuss how serializability is used to enforce concurrency control in a database system. Why is serializability sometimes considered too restrictive as a measure of correctness for schedules?

21.12. Describe the four levels of isolation in SQL.

21.13. Define the violations caused by each of the following: dirty read, nonrepeatable read, and phantoms.

Exercises

21.14. Change transaction T_2 in Figure 21.2(b) to read

```
read_item(X);
X := X + M;
if X > 90 then exit
else write_item(X);
```

Discuss the final result of the different schedules in Figure 21.3(a) and (b), where $M = 2$ and $N = 2$, with respect to the following questions: Does adding the above condition change the final outcome? Does the outcome obey the implied consistency rule (that the capacity of X is 90)?

21.15. Repeat Exercise 21.14, adding a check in T_1 so that Y does not exceed 90.

21.16. Add the operation commit at the end of each of the transactions T_1 and T_2 in Figure 21.2, and then list all possible schedules for the modified transactions. Determine which of the schedules are recoverable, which are cascadeless, and which are strict.

21.17. List all possible schedules for transactions T_1 and T_2 in Figure 21.2, and determine which are conflict serializable (correct) and which are not.

21.18. How many *serial* schedules exist for the three transactions in Figure 21.8(a)? What are they? What is the total number of possible schedules?

21.19. Write a program to create all possible schedules for the three transactions in Figure 21.8(a), and to determine which of those schedules are conflict serializable and which are not. For each conflict-serializable schedule, your program should print the schedule and list all equivalent serial schedules.

21.20. Why is an explicit transaction end statement needed in SQL but not an explicit begin statement?

21.21. Describe situations where each of the different isolation levels would be useful for transaction processing.

21.22. Which of the following schedules is (conflict) serializable? For each serializable schedule, determine the equivalent serial schedules.

a. $r_1(X); r_3(X); w_1(X); r_2(X); w_3(X);$

b. $r_1(X); r_3(X); w_3(X); w_1(X); r_2(X);$

c. $r_3(X); r_2(X); w_3(X); r_1(X); w_1(X);$

d. $r_3(X); r_2(X); r_1(X); w_3(X); w_1(X);$

21.23. Consider the three transactions T_1, T_2, and T_3, and the schedules S_1 and S_2 given below. Draw the serializability (precedence) graphs for S_1 and S_2, and state whether each schedule is serializable or not. If a schedule is serializable, write down the equivalent serial schedule(s).

T_1: $r_1(X); r_1(Z); w_1(X);$
T_2: $r_2(Z); r_2(Y); w_2(Z); w_2(Y);$
T_3: $r_3(X); r_3(Y); w_3(Y);$
S_1: $r_1(X); r_2(Z); r_1(Z); r_3(X); r_3(Y); w_1(X); w_3(Y); r_2(Y); w_2(Z); w_2(Y);$
S_2: $r_1(X); r_2(Z); r_3(X); r_1(Z); r_2(Y); r_3(Y); w_1(X); w_2(Z); w_3(Y); w_2(Y);$

21.24. Consider schedules S_3, S_4, and S_5 below. Determine whether each schedule is strict, cascadeless, recoverable, or nonrecoverable. (Determine the strictest recoverability condition that each schedule satisfies.)

S_3: $r_1(X); r_2(Z); r_1(Z); r_3(X); r_3(Y); w_1(X); c_1; w_3(Y); c_3; r_2(Y); w_2(Z); w_2(Y); c_2;$
S_4: $r_1(X); r_2(Z); r_1(Z); r_3(X); r_3(Y); w_1(X); w_3(Y); r_2(Y); w_2(Z); w_2(Y); c_1; c_2; c_3;$
S_5: $r_1(X); r_2(Z); r_3(X); r_1(Z); r_2(Y); r_3(Y); w_1(X); c_1; w_2(Z); w_3(Y); w_2(Y); c_3; c_2;$

Selected Bibliography

The concept of serializability and related ideas to maintain consistency in a database were introduced in Gray et al. (1975). The concept of the database transaction was first discussed in Gray (1981). Gray won the coveted ACM Turing Award in 1998 for his work on database transactions and implementation of transactions in relational DBMSs. Bernstein, Hadzilacos, and Goodman (1988) focus on concurrency control and recovery techniques in both centralized and distributed database systems; it is an excellent reference. Papadimitriou (1986) offers a more theoretical perspective. A large reference book of more than a thousand pages by Gray and Reuter (1993) offers a more practical perspective of transaction processing concepts and techniques. Elmagarmid (1992) offers collections of research papers on transaction processing for advanced applications. Transaction support in SQL is described in Date and Darwen (1997). View serializability is defined in Yannakakis (1984). Recoverability of schedules and reliability in databases is discussed in Hadzilacos (1983, 1988).

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chapter 22

Concurrency Control Techniques

In this chapter we discuss a number of concurrency control techniques that are used to ensure the noninterference or isolation property of concurrently executing transactions. Most of these techniques ensure serializability of schedules—which we defined in Section 21.5—using **concurrency control protocols** (sets of rules) that guarantee serializability. One important set of protocols—known as *two-phase locking protocols*—employ the technique of **locking** data items to prevent multiple transactions from accessing the items concurrently; a number of locking protocols are described in Sections 22.1 and 22.3.2. Locking protocols are used in most commercial DBMSs. Another set of concurrency control protocols use **timestamps**. A timestamp is a unique identifier for each transaction, generated by the system. Timestamps values are generated in the same order as the transaction start times. Concurrency control protocols that use timestamp ordering to ensure serializability are introduced in Section 22.2. In Section 22.3 we discuss **multiversion** concurrency control protocols that use multiple versions of a data item. One multiversion protocol extends timestamp order to multiversion timestamp ordering (Section 22.3.1), and another extends two-phase locking (Section 22.3.2). In Section 22.4 we present a protocol based on the concept of **validation** or **certification** of a transaction after it executes its operations; these are sometimes called **optimistic protocols**, and also assume that multiple versions of a data item can exist.

Another factor that affects concurrency control is the **granularity** of the data items—that is, what portion of the database a data item represents. An item can be as small as a single attribute (field) value or as large as a disk block, or even a whole file or the entire database. We discuss granularity of items and a multiple granularity concurrency control protocol, which is an extension of two-phase locking, in Section 22.5. In Section 22.6 we describe concurrency control issues that arise when indexes are used to process transactions, and in Section 22.7 we discuss some additional concurrency control concepts. Section 22.8 summarizes the chapter.

It is sufficient to read Sections 22.1, 22.5, 22.6, and 22.7, and possibly 22.3.2, if your main interest is an introduction to the concurrency control techniques that are based on locking, which are used most often in practice. The other techniques are mainly of theoretical interest.

22.1 Two-Phase Locking Techniques for Concurrency Control

Some of the main techniques used to control concurrent execution of transactions are based on the concept of locking data items. A **lock** is a variable associated with a data item that describes the status of the item with respect to possible operations that can be applied to it. Generally, there is one lock for each data item in the database. Locks are used as a means of synchronizing the access by concurrent transactions to the database items. In Section 22.1.1 we discuss the nature and types of locks. Then, in Section 22.1.2 we present protocols that use locking to guarantee serializability of transaction schedules. Finally, in Section 22.1.3 we describe two problems associated with the use of locks—deadlock and starvation—and show how these problems are handled in concurrency control protocols.

22.1.1 Types of Locks and System Lock Tables

Several types of locks are used in concurrency control. To introduce locking concepts gradually, first we discuss binary locks, which are simple, but are also *too restrictive for database concurrency control purposes*, and so are not used in practice. Then we discuss *shared/exclusive* locks—also known as *read/write* locks—which provide more general locking capabilities and are used in practical database locking schemes. In Section 22.3.2 we describe an additional type of lock called a *certify lock*, and show how it can be used to improve performance of locking protocols.

Binary Locks. A **binary lock** can have two **states** or **values:** locked and unlocked (or 1 and 0, for simplicity). A distinct lock is associated with each database item X. If the value of the lock on X is 1, item X *cannot be accessed* by a database operation that requests the item. If the value of the lock on X is 0, the item can be accessed when requested, and the lock value is changed to 1. We refer to the current value (or state) of the lock associated with item X as **lock(*X*)**.

Two operations, lock_item and unlock_item, are used with binary locking. A transaction requests access to an item X by first issuing a **lock_item(*X*)** operation. If LOCK(X) = 1, the transaction is forced to wait. If LOCK(X) = 0, it is set to 1 (the transaction **locks** the item) and the transaction is allowed to access item X. When the transaction is through using the item, it issues an **unlock_item(*X*)** operation, which sets LOCK(X) back to 0 (**unlocks** the item) so that X may be accessed by other transactions. Hence, a binary lock enforces **mutual exclusion** on the data item. A description of the lock_item(X) and unlock_item(X) operations is shown in Figure 22.1.

```
lock_item(X):
B:  if LOCK(X) = 0              (* item is unlocked *)
        then LOCK(X) ←1         (* lock the item *)
    else
        begin
        wait (until LOCK(X) = 0
            and the lock manager wakes up the transaction);
        go to B
        end;
unlock_item(X):
    LOCK(X) ←0;                     (* unlock the item *)
    if any transactions are waiting
        then wakeup one of the waiting transactions;
```

Figure 22.1
Lock and unlock operations for binary locks.

Notice that the lock_item and unlock_item operations must be implemented as indivisible units (known as **critical sections** in operating systems); that is, no interleaving should be allowed once a lock or unlock operation is started until the operation terminates or the transaction waits. In Figure 22.1, the wait command within the lock_item(X) operation is usually implemented by putting the transaction in a waiting queue for item X until X is unlocked and the transaction can be granted access to it. Other transactions that also want to access X are placed in the same queue. Hence, the wait command is considered to be outside the lock_item operation.

It is quite simple to implement a binary lock; all that is needed is a binary-valued variable, LOCK, associated with each data item X in the database. In its simplest form, each lock can be a record with three fields: <Data_item_name, LOCK, Locking_transaction> plus a queue for transactions that are waiting to access the item. The system needs to maintain *only these records for the items that are currently locked* in a **lock table**, which could be organized as a hash file on the item name. Items not in the lock table are considered to be unlocked. The DBMS has a **lock manager subsystem** to keep track of and control access to locks.

If the simple binary locking scheme described here is used, every transaction must obey the following rules:

1. A transaction T must issue the operation lock_item(X) before any read_item(X) or write_item(X) operations are performed in T.
2. A transaction T must issue the operation unlock_item(X) after all read_item(X) and write_item(X) operations are completed in T.
3. A transaction T will not issue a lock_item(X) operation if it already holds the lock on item X.[1]
4. A transaction T will not issue an unlock_item(X) operation unless it already holds the lock on item X.

[1]This rule may be removed if we modify the lock_item (X) operation in Figure 22.1 so that if the item is currently locked *by the requesting transaction*, the lock is granted.

These rules can be enforced by the lock manager module of the DBMS. Between the lock_item(X) and unlock_item(X) operations in transaction T, T is said to **hold the lock** on item X. At most one transaction can hold the lock on a particular item. Thus no two transactions can access the same item concurrently.

Shared/Exclusive (or Read/Write) Locks. The preceding binary locking scheme is too restrictive for database items because at most, one transaction can hold a lock on a given item. We should allow several transactions to access the same item X if they all access X for *reading purposes only*. This is because read operations on the same item by different transactions are not conflicting (see Section 21.4.1). However, if a transaction is to write an item X, it must have exclusive access to X. For this purpose, a different type of lock called a **multiple-mode lock** is used. In this scheme—called **shared/exclusive** or **read/write** locks—there are three locking operations: read_lock(X), write_lock(X), and unlock(X). A lock associated with an item X, LOCK(X), now has three possible states: *read-locked*, *write-locked*, or *unlocked*. A **read-locked item** is also called **share-locked** because other transactions are allowed to read the item, whereas a **write-locked item** is called **exclusive-locked** because a single transaction exclusively holds the lock on the item.

One method for implementing the preceding operations on a read/write lock is to keep track of the number of transactions that hold a shared (read) lock on an item in the lock table. Each record in the lock table will have four fields: <Data_item_name, LOCK, No_of_reads, Locking_transaction(s)>. Again, to save space, the system needs to maintain lock records only for locked items in the lock table. The value (state) of LOCK is either read-locked or write-locked, suitably coded (if we assume no records are kept in the lock table for unlocked items). If LOCK(X)=write-locked, the value of locking_transaction(s) is a single transaction that holds the exclusive (write) lock on X. If LOCK(X)=read-locked, the value of locking transaction(s) is a list of one or more transactions that hold the shared (read) lock on X. The three operations read_lock(X), write_lock(X), and unlock(X) are described in Figure 22.2.[2] As before, each of the three locking operations should be considered indivisible; no interleaving should be allowed once one of the operations is started until either the operation terminates by granting the lock or the transaction is placed in a waiting queue for the item.

When we use the shared/exclusive locking scheme, the system must enforce the following rules:

1. A transaction T must issue the operation read_lock(X) or write_lock(X) before any read_item(X) operation is performed in T.
2. A transaction T must issue the operation write_lock(X) before any write_item(X) operation is performed in T.

[2]These algorithms do not allow *upgrading* or *downgrading* of locks, as described later in this section. The reader can extend the algorithms to allow these additional operations.

```
read_lock(X):
B:  if LOCK(X) = “unlocked”
        then begin LOCK(X) ← “read-locked”;
                no_of_reads(X) ← 1
                end
    else if LOCK(X) = “read-locked”
        then no_of_reads(X) ← no_of_reads(X) + 1
    else begin
            wait (until LOCK(X) = “unlocked”
                and the lock manager wakes up the transaction);
            go to B
            end;
write_lock(X):
B:  if LOCK(X) = “unlocked”
        then LOCK(X) ← “write-locked”
    else begin
            wait (until LOCK(X) = “unlocked”
                and the lock manager wakes up the transaction);
            go to B
            end;
unlock (X):
    if LOCK(X) = “write-locked”
        then begin LOCK(X) ← “unlocked”;
                wakeup one of the waiting transactions, if any
                end
    else it LOCK(X) = “read-locked”
        then begin
                no_of_reads(X) ← no_of_reads(X) −1;
                if no_of_reads(X) = 0
                    then begin LOCK(X) = “unlocked”;
                            wakeup one of the waiting transactions, if any
                            end
                end;
```

Figure 22.2
Locking and unlocking operations for two-mode (read-write or shared-exclusive) locks.

3. A transaction T must issue the operation unlock(X) after all read_item(X) and write_item(X) operations are completed in T.[3]
4. A transaction T will not issue a read_lock(X) operation if it already holds a read (shared) lock or a write (exclusive) lock on item X. This rule may be relaxed, as we discuss shortly.

[3]This rule may be relaxed to allow a transaction to unlock an item, then lock it again later.

5. A transaction T will not issue a write_lock(X) operation if it already holds a read (shared) lock or write (exclusive) lock on item X. This rule may also be relaxed, as we discuss shortly.
6. A transaction T will not issue an unlock(X) operation unless it already holds a read (shared) lock or a write (exclusive) lock on item X.

Conversion of Locks. Sometimes it is desirable to relax conditions 4 and 5 in the preceding list in order to allow **lock conversion**; that is, a transaction that already holds a lock on item X is allowed under certain conditions to **convert** the lock from one locked state to another. For example, it is possible for a transaction T to issue a read_lock(X) and then later to **upgrade** the lock by issuing a write_lock(X) operation. If T is the only transaction holding a read lock on X at the time it issues the write_lock(X) operation, the lock can be upgraded; otherwise, the transaction must wait. It is also possible for a transaction T to issue a write_lock(X) and then later to **downgrade** the lock by issuing a read_lock(X) operation. When upgrading and downgrading of locks is used, the lock table must include transaction identifiers in the record structure for each lock (in the locking_transaction(s) field) to store the information on which transactions hold locks on the item. The descriptions of the read_lock(X) and write_lock(X) operations in Figure 22.2 must be changed appropriately to allow for lock upgrading and downgrading. We leave this as an exercise for the reader.

Using binary locks or read/write locks in transactions, as described earlier, does not guarantee serializability of schedules on its own. Figure 22.3 shows an example where the preceding locking rules are followed but a nonserializable schedule may result. This is because in Figure 22.3(a) the items Y in T_1 and X in T_2 were unlocked too early. This allows a schedule such as the one shown in Figure 22.3(c) to occur, which is not a serializable schedule and hence gives incorrect results. To guarantee serializability, we must follow *an additional protocol* concerning the positioning of locking and unlocking operations in every transaction. The best-known protocol, two-phase locking, is described in the next section.

22.1.2 Guaranteeing Serializability by Two-Phase Locking

A transaction is said to follow the **two-phase locking protocol** if *all* locking operations (read_lock, write_lock) precede the *first* unlock operation in the transaction.[4] Such a transaction can be divided into two phases: an **expanding** or **growing (first) phase**, during which new locks on items can be acquired but none can be released; and a **shrinking (second) phase**, during which existing locks can be released but no new locks can be acquired. If lock conversion is allowed, then upgrading of locks (from read-locked to write-locked) must be done during the expanding phase, and downgrading of locks (from write-locked to read-locked) must be done in the

[4]This is unrelated to the two-phase commit protocol for recovery in distributed databases (see Chapter 25).

(a)

T_1	T_2
read_lock(Y);	read_lock(X);
read_item(Y);	read_item(X);
unlock(Y);	unlock(X);
write_lock(X);	write_lock(Y);
read_item(X);	read_item(Y);
$X := X + Y$;	$Y := X + Y$;
write_item(X);	write_item(Y);
unlock(X);	unlock(Y);

(b) Initial values: X=20, Y=30

Result serial schedule T_1 followed by T_2: X=50, Y=80

Result of serial schedule T_2 followed by T_1: X=70, Y=50

(c)

Time ↓

T_1	T_2
read_lock(Y);	
read_item(Y);	
unlock(Y);	
	read_lock(X);
	read_item(X);
	unlock(X);
	write_lock(Y);
	read_item(Y);
	$Y := X + Y$;
	write_item(Y);
	unlock(Y);
write_lock(X);	
read_item(X);	
$X := X + Y$;	
write_item(X);	
unlock(X);	

Result of schedule S:
X=50, Y=50
(nonserializable)

Figure 22.3
Transactions that do not obey two-phase locking. (a) Two transactions T_1 and T_2. (b) Results of possible serial schedules of T_1 and T_2. (c) A nonserializable schedule S that uses locks.

shrinking phase. Hence, a read_lock(X) operation that downgrades an already held write lock on X can appear only in the shrinking phase.

Transactions T_1 and T_2 in Figure 22.3(a) do not follow the two-phase locking protocol because the write_lock(X) operation follows the unlock(Y) operation in T_1, and similarly the write_lock(Y) operation follows the unlock(X) operation in T_2. If we enforce two-phase locking, the transactions can be rewritten as T_1' and T_2', as shown in Figure 22.4. Now, the schedule shown in Figure 22.3(c) is not permitted for T_1' and T_2' (with their modified order of locking and unlocking operations) under the rules of locking described in Section 22.1.1 because T_1' will issue its write_lock(X) *before* it unlocks item Y; consequently, when T_2' issues its read_lock(X), it is forced to wait until T_1' releases the lock by issuing an unlock (X) in the schedule.

T_1'	T_2'
read_lock(Y);	read_lock(X);
read_item(Y);	read_item(X);
write_lock(X);	write_lock(Y);
unlock(Y)	unlock(X)
read_item(X);	read_item(Y);
$X := X + Y$;	$Y := X + Y$;
write_item(X);	write_item(Y);
unlock(X);	unlock(Y);

Figure 22.4
Transactions T_1' and T_2', which are the same as T_1 and T_2 in Figure 22.3, but follow the two-phase locking protocol. Note that they can produce a deadlock.

It can be proved that, if *every* transaction in a schedule follows the two-phase locking protocol, the schedule is *guaranteed to be serializable*, obviating the need to test for serializability of schedules. The locking protocol, by enforcing two-phase locking rules, also enforces serializability.

Two-phase locking may limit the amount of concurrency that can occur in a schedule because a transaction *T* may not be able to release an item *X* after it is through using it if *T* must lock an additional item *Y* later; or conversely, *T* must lock the additional item *Y* before it needs it so that it can release *X*. Hence, *X* must remain locked by *T* until all items that the transaction needs to read or write have been locked; only then can *X* be released by *T*. Meanwhile, another transaction seeking to access *X* may be forced to wait, even though *T* is done with *X*; conversely, if *Y* is locked earlier than it is needed, another transaction seeking to access *Y* is forced to wait even though *T* is not using *Y* yet. This is the price for guaranteeing serializability of all schedules without having to check the schedules themselves.

Although the two-phase locking protocol guarantees serializability (that is, every schedule that is permitted is serializable), it does not permit *all possible* serializable schedules (that is, some serializable schedules will be prohibited by the protocol).

Basic, Conservative, Strict, and Rigorous Two-Phase Locking. There are a number of variations of two-phase locking (2PL). The technique just described is known as **basic 2PL**. A variation known as **conservative 2PL** (or **static 2PL**) requires a transaction to lock all the items it accesses *before the transaction begins execution*, by **predeclaring** its *read-set* and *write-set*. Recall from Section 21.1.2 that the **read-set** of a transaction is the set of all items that the transaction reads, and the **write-set** is the set of all items that it writes. If any of the predeclared items needed cannot be locked, the transaction does not lock any item; instead, it waits until all the items are available for locking. Conservative 2PL is a deadlock-free protocol, as we will see in Section 22.1.3 when we discuss the deadlock problem. However, it is difficult to use in practice because of the need to predeclare the read-set and write-set, which is not possible in many situations.

In practice, the most popular variation of 2PL is **strict 2PL**, which guarantees strict schedules (see Section 21.4). In this variation, a transaction *T* does not release any of its exclusive (write) locks until *after* it commits or aborts. Hence, no other transaction can read or write an item that is written by *T* unless *T* has committed, leading to a strict schedule for recoverability. Strict 2PL is not deadlock-free. A more restrictive variation of strict 2PL is **rigorous 2PL**, which also guarantees strict schedules. In this variation, a transaction *T* does not release any of its locks (exclusive or shared) until after it commits or aborts, and so it is easier to implement than strict 2PL. Notice the difference between conservative and rigorous 2PL: the former must lock all its items *before it starts*, so once the transaction starts it is in its shrinking phase; the latter does not unlock any of its items until *after it terminates* (by committing or aborting), so the transaction is in its expanding phase until it ends.

In many cases, the **concurrency control subsystem** itself is responsible for generating the read_lock and write_lock requests. For example, suppose the system is to enforce the strict 2PL protocol. Then, whenever transaction *T* issues a read_item(*X*), the system calls the read_lock(*X*) operation on behalf of *T*. If the state of LOCK(*X*) is write_locked by some other transaction *T*′, the system places *T* in the waiting queue for item *X*; otherwise, it grants the read_lock(*X*) request and permits the read_item(*X*) operation of *T* to execute. On the other hand, if transaction *T* issues a write_item(*X*), the system calls the write_lock(*X*) operation on behalf of *T*. If the state of LOCK(*X*) is write_locked or read_locked by some other transaction *T*′, the system places *T* in the waiting queue for item *X*; if the state of LOCK(*X*) is read_locked and *T* itself is the only transaction holding the read lock on *X*, the system upgrades the lock to write_locked and permits the write_item(*X*) operation by *T*. Finally, if the state of LOCK(*X*) is unlocked, the system grants the write_lock(*X*) request and permits the write_item(*X*) operation to execute. After each action, the system must update its lock table appropriately.

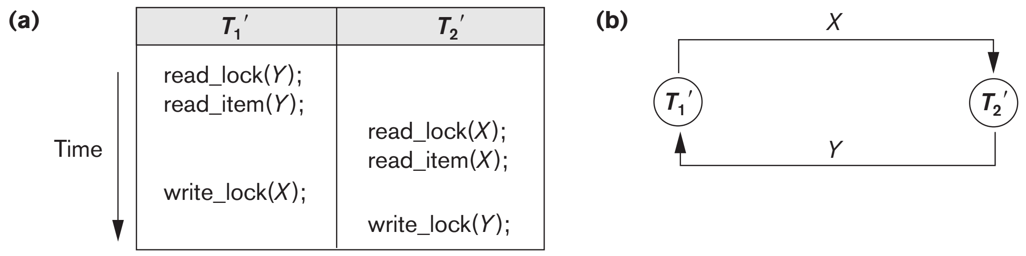
The use of locks can cause two additional problems: deadlock and starvation. We discuss these problems and their solutions in the next section.

22.1.3 Dealing with Deadlock and Starvation

Deadlock occurs when *each* transaction *T* in a set of *two or more transactions* is waiting for some item that is locked by some other transaction *T*′ in the set. Hence, each transaction in the set is in a waiting queue, waiting for one of the other transactions in the set to release the lock on an item. But because the other transaction is also waiting, it will never release the lock. A simple example is shown in Figure 22.5(a), where the two transactions T_1' and T_2' are deadlocked in a partial schedule; T_1' is in the waiting queue for *X*, which is locked by T_2', while T_2' is in the waiting queue for *Y*, which is locked by T_1'. Meanwhile, neither T_1' nor T_2' nor any other transaction can access items *X* and *Y*.

Deadlock Prevention Protocols. One way to prevent deadlock is to use a **deadlock prevention protocol**.[5] One deadlock prevention protocol, which is used

[5]These protocols are not generally used in practice, either because of unrealistic assumptions or because of their possible overhead. Deadlock detection and timeouts (covered in the following sections) are more practical.


(a)

T_1'	T_2'
read_lock(Y);	
read_item(Y);	
	read_lock(X);
	read_item(X);
write_lock(X);	
	write_lock(Y);

Figure 22.5
Illustrating the deadlock problem. (a) A partial schedule of T_1' and T_2' that is in a state of deadlock. (b) A wait-for graph for the partial schedule in (a).

in conservative two-phase locking, requires that every transaction lock *all the items it needs in advance* (which is generally not a practical assumption)—if any of the items cannot be obtained, none of the items are locked. Rather, the transaction waits and then tries again to lock all the items it needs. Obviously this solution further limits concurrency. A second protocol, which also limits concurrency, involves *ordering all the items* in the database and making sure that a transaction that needs several items will lock them according to that order. This requires that the programmer (or the system) is aware of the chosen order of the items, which is also not practical in the database context.

A number of other deadlock prevention schemes have been proposed that make a decision about what to do with a transaction involved in a possible deadlock situation: Should it be blocked and made to wait or should it be aborted, or should the transaction preempt and abort another transaction? Some of these techniques use the concept of **transaction timestamp** TS(T), which is a unique identifier assigned to each transaction. The timestamps are typically based on the order in which transactions are started; hence, if transaction T_1 starts before transaction T_2, then TS(T_1) < TS(T_2). Notice that the *older* transaction (which starts first) has the *smaller* timestamp value. Two schemes that prevent deadlock are called *wait-die* and *wound-wait*. Suppose that transaction T_i tries to lock an item X but is not able to because X is locked by some other transaction T_j with a conflicting lock. The rules followed by these schemes are:

- **Wait-die.** If TS(T_i) < TS(T_j), then (T_i older than T_j) T_i is allowed to wait; otherwise (T_i younger than T_j) abort T_i (T_i *dies*) and restart it later *with the same timestamp.*
- **Wound-wait.** If TS(T_i) < TS(T_j), then (T_i older than T_j) abort T_j (T_i *wounds* T_j) and restart it later *with the same timestamp;* otherwise (T_i younger than T_j) T_i is allowed to wait.

In wait-die, an older transaction is allowed to *wait for a younger transaction*, whereas a younger transaction requesting an item held by an older transaction is aborted and restarted. The wound-wait approach does the opposite: A younger transaction is allowed to *wait for an older one*, whereas an older transaction requesting an item held by a younger transaction *preempts* the younger transaction by aborting it. Both schemes end up aborting the *younger* of the two transactions (the transaction that started later) that *may be involved* in a deadlock, assuming that this will waste less processing. It can be shown that these two techniques are *deadlock-free*, since in wait-die, transactions only wait for younger transactions so no cycle is created. Similarly, in wound-wait, transactions only wait for older transactions so no cycle is created. However, both techniques may cause some transactions to be aborted and restarted needlessly, even though those transactions may *never actually cause a deadlock*.

Another group of protocols that prevent deadlock do not require timestamps. These include the no waiting (NW) and cautious waiting (CW) algorithms. In the **no waiting algorithm**, if a transaction is unable to obtain a lock, it is immediately aborted and then restarted after a certain time delay without checking whether a deadlock will actually occur or not. In this case, no transaction ever waits, so no deadlock will occur. However, this scheme can cause transactions to abort and restart needlessly. The **cautious waiting** algorithm was proposed to try to reduce the number of needless aborts/restarts. Suppose that transaction T_i tries to lock an item X but is not able to do so because X is locked by some other transaction T_j with a conflicting lock. The cautious waiting rules are as follows:

- **Cautious waiting.** If T_j is not blocked (not waiting for some other locked item), then T_i is blocked and allowed to wait; otherwise abort T_i.

It can be shown that cautious waiting is deadlock-free, because no transaction will ever wait for another blocked transaction. By considering the time $b(T)$ at which each blocked transaction T was blocked, if the two transactions T_i and T_j above both become blocked, and T_i is waiting for T_j, then $b(T_i) < b(T_j)$, since T_i can only wait for T_j at a time when T_j is not blocked itself. Hence, the blocking times form a total ordering on all blocked transactions, so no cycle that causes deadlock can occur.

Deadlock Detection. A second, more practical approach to dealing with deadlock is **deadlock detection**, where the system checks if a state of deadlock actually exists. This solution is attractive if we know there will be little interference among the transactions—that is, if different transactions will rarely access the same items at the same time. This can happen if the transactions are short and each transaction locks only a few items, or if the transaction load is light. On the other hand, if transactions are long and each transaction uses many items, or if the transaction load is quite heavy, it may be advantageous to use a deadlock prevention scheme.

A simple way to detect a state of deadlock is for the system to construct and maintain a **wait-for graph**. One node is created in the wait-for graph for each transaction that is currently executing. Whenever a transaction T_i is waiting to lock an item X that is currently locked by a transaction T_j, a directed edge ($T_i \rightarrow T_j$) is created in the wait-for graph. When T_j releases the lock(s) on the items that T_i was waiting for, the directed edge is dropped from the wait-for graph. We have a state of deadlock if and only if the wait-for graph has a cycle. One problem with this approach is the matter of determining *when* the system should check for a deadlock. One possibility is to check for a cycle every time an edge is added to the wait-for graph, but this may cause excessive overhead. Criteria such as the number of currently executing transactions or the period of time several transactions have been waiting to lock items may be used instead to check for a cycle. Figure 22.5(b) shows the wait-for graph for the (partial) schedule shown in Figure 22.5(a).

If the system is in a state of deadlock, some of the transactions causing the deadlock must be aborted. Choosing which transactions to abort is known as **victim selection**. The algorithm for victim selection should generally avoid selecting transactions that have been running for a long time and that have performed many updates, and it should try instead to select transactions that have not made many changes (younger transactions).

Timeouts. Another simple scheme to deal with deadlock is the use of **timeouts**. This method is practical because of its low overhead and simplicity. In this method, if a transaction waits for a period longer than a system-defined timeout period, the system assumes that the transaction may be deadlocked and aborts it—regardless of whether a deadlock actually exists or not.

Starvation. Another problem that may occur when we use locking is **starvation**, which occurs when a transaction cannot proceed for an indefinite period of time while other transactions in the system continue normally. This may occur if the waiting scheme for locked items is unfair, giving priority to some transactions over others. One solution for starvation is to have a fair waiting scheme, such as using a **first-come-first-served** queue; transactions are enabled to lock an item in the order in which they originally requested the lock. Another scheme allows some transactions to have priority over others but increases the priority of a transaction the longer it waits, until it eventually gets the highest priority and proceeds. Starvation can also occur because of victim selection if the algorithm selects the same transaction as victim repeatedly, thus causing it to abort and never finish execution. The algorithm can use higher priorities for transactions that have been aborted multiple times to avoid this problem. The wait-die and wound-wait schemes discussed previously avoid starvation, because they restart a transaction that has been aborted with its same original timestamp, so the possibility that the same transaction is aborted repeatedly is slim.

22.2 Concurrency Control Based on Timestamp Ordering

The use of locks, combined with the 2PL protocol, guarantees serializability of schedules. The serializable schedules produced by 2PL have their equivalent serial schedules based on the order in which executing transactions lock the items they acquire. If a transaction needs an item that is already locked, it may be forced to wait until the item is released. Some transactions may be aborted and restarted because of the deadlock problem. A different approach that guarantees serializability involves using transaction timestamps to order transaction execution for an equivalent serial schedule. In Section 22.2.1 we discuss timestamps, and in Section 22.2.2 we discuss how serializability is enforced by ordering transactions based on their timestamps.

22.2.1 Timestamps

Recall that a **timestamp** is a unique identifier created by the DBMS to identify a transaction. Typically, timestamp values are assigned in the order in which the transactions are submitted to the system, so a timestamp can be thought of as the *transaction start time*. We will refer to the timestamp of transaction T as **TS(*T*)**. Concurrency control techniques based on timestamp ordering do not use locks; hence, *deadlocks cannot occur*.

Timestamps can be generated in several ways. One possibility is to use a counter that is incremented each time its value is assigned to a transaction. The transaction timestamps are numbered 1, 2, 3, ... in this scheme. A computer counter has a finite maximum value, so the system must periodically reset the counter to zero when no transactions are executing for some short period of time. Another way to implement timestamps is to use the current date/time value of the system clock and ensure that no two timestamp values are generated during the same tick of the clock.

22.2.2 The Timestamp Ordering Algorithm

The idea for this scheme is to order the transactions based on their timestamps. A schedule in which the transactions participate is then serializable, and the *only equivalent serial schedule permitted* has the transactions in order of their timestamp values. This is called **timestamp ordering** (**TO**). Notice how this differs from 2PL, where a schedule is serializable by being equivalent to some serial schedule allowed by the locking protocols. In timestamp ordering, however, the schedule is equivalent to the *particular serial order* corresponding to the order of the transaction timestamps. The algorithm must ensure that, for each item accessed by *conflicting operations* in the schedule, the order in which the item is accessed does not violate the timestamp order. To do this, the algorithm associates with each database item X two timestamp (**TS**) values:

1. **read_TS(*X*).** The **read timestamp** of item X is the largest timestamp among all the timestamps of transactions that have successfully read item X—that is, read_TS(X) = TS(T), where T is the *youngest* transaction that has read X successfully.
2. **write_TS(*X*).** The **write timestamp** of item X is the largest of all the timestamps of transactions that have successfully written item X—that is, write_TS(X) = TS(T), where T is the *youngest* transaction that has written X successfully.

Basic Timestamp Ordering (TO). Whenever some transaction T tries to issue a read_item(X) or a write_item(X) operation, the **basic TO** algorithm compares the timestamp of T with read_TS(X) and write_TS(X) to ensure that the timestamp order of transaction execution is not violated. If this order is violated, then transaction T is aborted and resubmitted to the system as a new transaction with a *new timestamp*. If T is aborted and rolled back, any transaction T_1 that may have used a value written by T must also be rolled back. Similarly, any transaction T_2 that may have used a value written by T_1 must also be rolled back, and so on. This effect is known as **cascading rollback** and is one of the problems associated with basic TO, since the schedules produced are not guaranteed to be recoverable. An *additional protocol* must be enforced to ensure that the schedules are recoverable, cascadeless, or strict. We first describe the basic TO algorithm here. The concurrency control algorithm must check whether conflicting operations violate the timestamp ordering in the following two cases:

1. Whenever a transaction T issues a write_item(X) operation, the following is checked:
   a. If read_TS(X) > TS(T) or if write_TS(X) > TS(T), then abort and roll back T and reject the operation. This should be done because some *younger* transaction with a timestamp greater than TS(T)—and hence *after* T in the timestamp ordering—has already read or written the value of item X before T had a chance to write X, thus violating the timestamp ordering.
   b. If the condition in part (a) does not occur, then execute the write_item(X) operation of T and set write_TS(X) to TS(T).
2. Whenever a transaction T issues a read_item(X) operation, the following is checked:
   a. If write_TS(X) > TS(T), then abort and roll back T and reject the operation. This should be done because some younger transaction with timestamp greater than TS(T)—and hence *after* T in the timestamp ordering—has already written the value of item X before T had a chance to read X.
   b. If write_TS(X) ≤ TS(T), then execute the read_item(X) operation of T and set read_TS(X) to the *larger* of TS(T) and the current read_TS(X).

Whenever the basic TO algorithm detects two *conflicting operations* that occur in the incorrect order, it rejects the later of the two operations by aborting the transaction that issued it. The schedules produced by basic TO are hence guaranteed to be *conflict serializable*, like the 2PL protocol. However, some schedules are possible under each protocol that are not allowed under the other. Thus, *neither* protocol allows *all possible* serializable schedules. As mentioned earlier, deadlock does not occur with timestamp ordering. However, cyclic restart (and hence starvation) may occur if a transaction is continually aborted and restarted.

Strict Timestamp Ordering (TO). A variation of basic TO called **strict TO** ensures that the schedules are both **strict** (for easy recoverability) and (conflict) serializable. In this variation, a transaction T that issues a read_item(X) or write_item(X) such that TS(T) > write_TS(X) has its read or write operation *delayed* until the transaction T' that *wrote* the value of X (hence TS(T') = write_TS(X)) has committed or aborted. To implement this algorithm, it is necessary to simulate the locking of an item X that has been written by transaction T' until T' is either committed or aborted. This algorithm *does not cause deadlock*, since T waits for T' only if TS(T) > TS(T').

Thomas's Write Rule. A modification of the basic TO algorithm, known as **Thomas's write rule**, does not enforce conflict serializability, but it rejects fewer write operations by modifying the checks for the write_item(X) operation as follows:

1. If read_TS(X) > TS(T), then abort and roll back T and reject the operation.
2. If write_TS(X) > TS(T), then do not execute the write operation but continue processing. This is because some transaction with timestamp greater than TS(T)—and hence after T in the timestamp ordering—has already written the value of X. Thus, we must ignore the write_item(X) operation of T because it is already outdated and obsolete. Notice that any conflict arising from this situation would be detected by case (1).
3. If neither the condition in part (1) nor the condition in part (2) occurs, then execute the write_item(X) operation of T and set write_TS(X) to TS(T).

22.3 Multiversion Concurrency Control Techniques

Other protocols for concurrency control keep the old values of a data item when the item is updated. These are known as **multiversion concurrency control**, because several versions (values) of an item are maintained. When a transaction requires access to an item, an *appropriate* version is chosen to maintain the serializability of the currently executing schedule, if possible. The idea is that some read operations that would be rejected in other techniques can still be accepted by reading an *older version* of the item to maintain serializability. When a transaction writes an item, it writes a *new version* and the old version(s) of the item are retained. Some multiversion concurrency control algorithms use the concept of view serializability rather than conflict serializability.

An obvious drawback of multiversion techniques is that more storage is needed to maintain multiple versions of the database items. However, older versions may have to be maintained anyway—for example, for recovery purposes. In addition, some database applications require older versions to be kept to maintain a history of the evolution of data item values. The extreme case is a *temporal database* (see Secton 26.2), which keeps track of all changes and the times at which they occurred. In such cases, there is no additional storage penalty for multiversion techniques, since older versions are already maintained.

Several multiversion concurrency control schemes have been proposed. We discuss two schemes here, one based on timestamp ordering and the other based on 2PL. In addition, the validation concurrency control method (see Section 22.4) also maintains multiple versions.

22.3.1 Multiversion Technique Based on Timestamp Ordering

In this method, several versions X_1, X_2, ..., X_k of each data item X are maintained. For *each version*, the value of version X_i and the following two timestamps are kept:

1. **read_TS(X_i).** The **read timestamp** of X_i is the largest of all the timestamps of transactions that have successfully read version X_i.
2. **write_TS(X_i).** The **write timestamp** of X_i is the timestamp of the transaction that wrote the value of version X_i.

Whenever a transaction T is allowed to execute a write_item(X) operation, a new version X_{k+1} of item X is created, with both the write_TS(X_{k+1}) and the read_TS(X_{k+1}) set to TS(T). Correspondingly, when a transaction T is allowed to read the value of version X_i, the value of read_TS(X_i) is set to the larger of the current read_TS(X_i) and TS(T).

To ensure serializability, the following rules are used:

1. If transaction T issues a write_item(X) operation, and version i of X has the highest write_TS(X_i) of all versions of X that is also *less than or equal to* TS(T), and read_TS(X_i) > TS(T), then abort and roll back transaction T; otherwise, create a new version X_j of X with read_TS(X_j) = write_TS(X_j) = TS(T).
2. If transaction T issues a read_item(X) operation, find the version i of X that has the highest write_TS(X_i) of all versions of X that is also *less than or equal to* TS(T); then return the value of X_i to transaction T, and set the value of read_TS(X_i) to the larger of TS(T) and the current read_TS(X_i).

As we can see in case 2, a read_item(X) is always successful, since it finds the appropriate version X_i to read based on the write_TS of the various existing versions of X. In case 1, however, transaction T may be aborted and rolled back. This happens if T attempts to write a version of X that should have been read by another transaction T' whose timestamp is read_TS(X_i); however, T' has already read version X_i, which was written by the transaction with timestamp equal to write_TS(X_i). If this conflict occurs, T is rolled back; otherwise, a new version of X, written by transaction T, is created. Notice that if T is rolled back, cascading rollback may occur. Hence, to ensure recoverability, a transaction T should not be allowed to commit until after all the transactions that have written some version that T has read have committed.

22.3.2 Multiversion Two-Phase Locking Using Certify Locks

In this multiple-mode locking scheme, there are *three locking modes* for an item: read, write, and *certify*, instead of just the two modes (read, write) discussed previously. Hence, the state of LOCK(X) for an item X can be one of read-locked, write-locked, certify-locked, or unlocked. In the standard locking scheme, with only read and write locks (see Section 22.1.1), a write lock is an exclusive lock. We can describe the relationship between read and write locks in the standard scheme by means of the **lock compatibility table** shown in Figure 22.6(a). An entry of *Yes* means that if a transaction T holds the type of lock specified in the column header

(a)

	Read	Write
Read	Yes	No
Write	No	No

(b)

	Read	Write	Certify
Read	Yes	Yes	No
Write	Yes	No	No
Certify	No	No	No

Figure 22.6
Lock compatibility tables.
(a) A compatibility table for read/write locking scheme.
(b) A compatibility table for read/write/certify locking scheme.

on item *X* and if transaction *T′* requests the type of lock specified in the row header on the same item *X*, then *T′ can obtain the lock* because the locking modes are compatible. On the other hand, an entry of *No* in the table indicates that the locks are not compatible, so *T′ must wait* until *T releases* the lock.

In the standard locking scheme, once a transaction obtains a write lock on an item, no other transactions can access that item. The idea behind multiversion 2PL is to allow other transactions *T′* to read an item *X* while a single transaction *T* holds a write lock on *X*. This is accomplished by allowing *two versions* for each item *X*; one version must always have been written by some committed transaction. The second version *X′* is created when a transaction *T* acquires a write lock on the item. Other transactions can continue to read the *committed version* of *X* while *T* holds the write lock. Transaction *T* can write the value of *X′* as needed, without affecting the value of the committed version *X*. However, once *T* is ready to commit, it must obtain a **certify lock** on all items that it currently holds write locks on before it can commit. The certify lock is not compatible with read locks, so the transaction may have to delay its commit until all its write-locked items are released by any reading transactions in order to obtain the certify locks. Once the certify locks—which are exclusive locks—are acquired, the committed version *X* of the data item is set to the value of version *X′*, version *X′* is discarded, and the certify locks are then released. The lock compatibility table for this scheme is shown in Figure 22.6(b).

In this multiversion 2PL scheme, reads can proceed concurrently with a single write operation—an arrangement not permitted under the standard 2PL schemes. The cost is that a transaction may have to delay its commit until it obtains exclusive certify locks on *all the items* it has updated. It can be shown that this scheme avoids cascading aborts, since transactions are only allowed to read the version *X* that was written by a committed transaction. However, deadlocks may occur if upgrading of a read lock to a write lock is allowed, and these must be handled by variations of the techniques discussed in Section 22.1.3.

22.4 Validation (Optimistic) Concurrency Control Techniques

In all the concurrency control techniques we have discussed so far, a certain degree of checking is done *before* a database operation can be executed. For example, in locking, a check is done to determine whether the item being accessed is locked. In timestamp ordering, the transaction timestamp is checked against the read and write timestamps of the item. Such checking represents overhead during transaction execution, with the effect of slowing down the transactions.

In **optimistic concurrency control techniques**, also known as **validation** or **certification techniques**, *no checking* is done while the transaction is executing. Several theoretical concurrency control methods are based on the validation technique. We will describe only one scheme here. In this scheme, updates in the transaction are *not* applied directly to the database items until the transaction reaches its end. During transaction execution, all updates are applied to *local copies* of the data items that are kept for the transaction.[6] At the end of transaction execution, a **validation phase** checks whether any of the transaction's updates violate serializability. Certain information needed by the validation phase must be kept by the system. If serializability is not violated, the transaction is committed and the database is updated from the local copies; otherwise, the transaction is aborted and then restarted later.

There are three phases for this concurrency control protocol:

1. **Read phase.** A transaction can read values of committed data items from the database. However, updates are applied only to local copies (versions) of the data items kept in the transaction workspace.
2. **Validation phase.** Checking is performed to ensure that serializability will not be violated if the transaction updates are applied to the database.
3. **Write phase.** If the validation phase is successful, the transaction updates are applied to the database; otherwise, the updates are discarded and the transaction is restarted.

The idea behind optimistic concurrency control is to do all the checks at once; hence, transaction execution proceeds with a minimum of overhead until the validation phase is reached. If there is little interference among transactions, most will be validated successfully. However, if there is much interference, many transactions that execute to completion will have their results discarded and must be restarted later. Under these circumstances, optimistic techniques do not work well. The techniques are called *optimistic* because they assume that little interference will occur and hence that there is no need to do checking during transaction execution.

The optimistic protocol we describe uses transaction timestamps and also requires that the write_sets and read_sets of the transactions be kept by the system. Additionally, *start* and *end* times for some of the three phases need to be kept for

[6]Note that this can be considered as keeping multiple versions of items!

each transaction. Recall that the write_set of a transaction is the set of items it writes, and the read_set is the set of items it reads. In the validation phase for transaction T_i, the protocol checks that T_i does not interfere with any committed transactions or with any other transactions currently in their validation phase. The validation phase for T_i checks that, for *each* such transaction T_j that is either committed or is in its validation phase, *one* of the following conditions holds:

1. Transaction T_j completes its write phase before T_i starts its read phase.
2. T_i starts its write phase after T_j completes its write phase, and the read_set of T_i has no items in common with the write_set of T_j.
3. Both the read_set and write_set of T_i have no items in common with the write_set of T_j, and T_j completes its read phase before T_i completes its read phase.

When validating transaction T_i, the first condition is checked first for each transaction T_j, since (1) is the simplest condition to check. Only if condition 1 is false is condition 2 checked, and only if (2) is false is condition 3—the most complex to evaluate—checked. If any one of these three conditions holds, there is no interference and T_i is validated successfully. If *none* of these three conditions holds, the validation of transaction T_i fails and it is aborted and restarted later because interference *may* have occurred.

22.5 Granularity of Data Items and Multiple Granularity Locking

All concurrency control techniques assume that the database is formed of a number of named data items. A database item could be chosen to be one of the following:

- A database record
- A field value of a database record
- A disk block
- A whole file
- The whole database

The granularity can affect the performance of concurrency control and recovery. In Section 22.5.1, we discuss some of the tradeoffs with regard to choosing the granularity level used for locking, and in Section 22.5.2 we discuss a multiple granularity locking scheme, where the granularity level (size of the data item) may be changed dynamically.

22.5.1 Granularity Level Considerations for Locking

The size of data items is often called the **data item granularity**. *Fine granularity* refers to small item sizes, whereas *coarse granularity* refers to large item sizes. Several tradeoffs must be considered in choosing the data item size. We will discuss data item size in the context of locking, although similar arguments can be made for other concurrency control techniques.

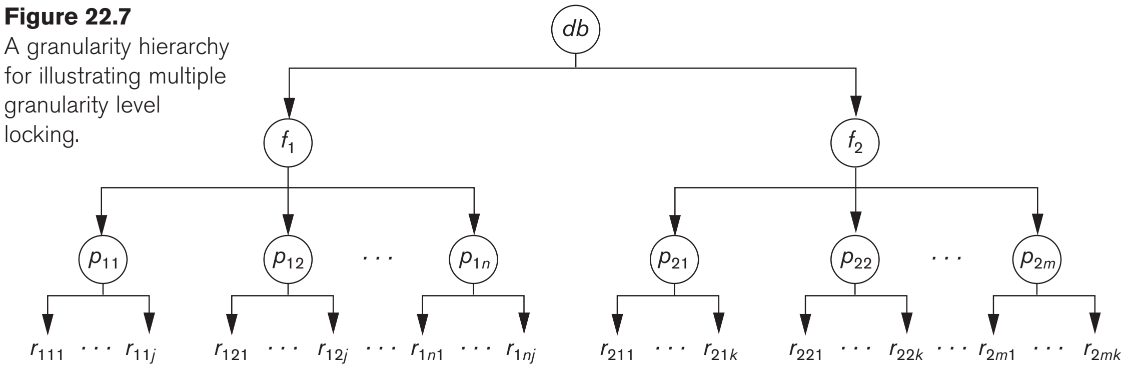
First, notice that the larger the data item size is, the lower the degree of concurrency permitted. For example, if the data item size is a disk block, a transaction *T* that needs to lock a record *B* must lock the whole disk block *X* that contains *B* because a lock is associated with the whole data item (block). Now, if another transaction *S* wants to lock a different record *C* that happens to reside in the same block *X* in a conflicting lock mode, it is forced to wait. If the data item size was a single record, transaction *S* would be able to proceed, because it would be locking a different data item (record).

On the other hand, the smaller the data item size is, the more the number of items in the database. Because every item is associated with a lock, the system will have a larger number of active locks to be handled by the lock manager. More lock and unlock operations will be performed, causing a higher overhead. In addition, more storage space will be required for the lock table. For timestamps, storage is required for the read_TS and write_TS for each data item, and there will be similar overhead for handling a large number of items.

Given the above tradeoffs, an obvious question can be asked: What is the best item size? The answer is that it *depends on the types of transactions involved*. If a typical transaction accesses a small number of records, it is advantageous to have the data item granularity be one record. On the other hand, if a transaction typically accesses many records in the same file, it may be better to have block or file granularity so that the transaction will consider all those records as one (or a few) data items.

22.5.2 Multiple Granularity Level Locking

Since the best granularity size depends on the given transaction, it seems appropriate that a database system should support multiple levels of granularity, where the granularity level can be different for various mixes of transactions. Figure 22.7 shows a simple granularity hierarchy with a database containing two files, each file containing several disk pages, and each page containing several records. This can be used to illustrate a **multiple granularity level** 2PL protocol, where a lock can be requested at any level. However, additional types of locks will be needed to support such a protocol efficiently.



db
f_1
f_2
p_{11}
p_{12}
p_{1n}
p_{21}
p_{22}
p_{2m}
r_{111} . . . r_{11j}
r_{121} . . . r_{12j} . . . r_{1n1} . . . r_{1nj}
r_{211} . . . r_{21k}
r_{221} . . . r_{22k} . . . r_{2m1} . . . r_{2mk}

Figure 22.7
A granularity hierarchy for illustrating multiple granularity level locking.

Consider the following scenario, with only shared and exclusive lock types, that refers to the example in Figure 22.7. Suppose transaction T_1 wants to update *all the records* in file f_1, and T_1 requests and is granted an exclusive lock for f_1. Then all of f_1's pages (p_{11} through p_{1n})—and the records contained on those pages—are locked in exclusive mode. This is beneficial for T_1 because setting a single file-level lock is more efficient than setting n page-level locks or having to lock each individual record. Now suppose another transaction T_2 only wants to read record r_{1nj} from page p_{1n} of file f_1; then T_2 would request a shared record-level lock on r_{1nj}. However, the database system (that is, the transaction manager or more specifically the lock manager) must verify the compatibility of the requested lock with already held locks. One way to verify this is to traverse the tree from the leaf r_{1nj} to p_{1n} to f_1 to *db*. If at any time a conflicting lock is held on any of those items, then the lock request for r_{1nj} is denied and T_2 is blocked and must wait. This traversal would be fairly efficient.

However, what if transaction T_2's request came *before* transaction T_1's request? In this case, the shared record lock is granted to T_2 for r_{1nj}, but when T_1's file-level lock is requested, it is quite difficult for the lock manager to check all nodes (pages and records) that are descendants of node f_1 for a lock conflict. This would be very inefficient and would defeat the purpose of having multiple granularity level locks.

To make multiple granularity level locking practical, additional types of locks, called **intention locks**, are needed. The idea behind intention locks is for a transaction to indicate, along the path from the root to the desired node, what type of lock (shared or exclusive) it will require from one of the node's descendants. There are three types of intention locks:

1. Intention-shared (IS) indicates that one or more shared locks will be requested on some descendant node(s).
2. Intention-exclusive (IX) indicates that one or more exclusive locks will be requested on some descendant node(s).
3. Shared-intention-exclusive (SIX) indicates that the current node is locked in shared mode but that one or more exclusive locks will be requested on some descendant node(s).

The compatibility table of the three intention locks, and the shared and exclusive locks, is shown in Figure 22.8. Besides the introduction of the three types of intention locks, an appropriate locking protocol must be used. The **multiple granularity locking (MGL)** protocol consists of the following rules:

1. The lock compatibility (based on Figure 22.8) must be adhered to.
2. The root of the tree must be locked first, in any mode.
3. A node N can be locked by a transaction T in S or IS mode only if the parent node N is already locked by transaction T in either IS or IX mode.
4. A node N can be locked by a transaction T in X, IX, or SIX mode only if the parent of node N is already locked by transaction T in either IX or SIX mode.
5. A transaction T can lock a node only if it has not unlocked any node (to enforce the 2PL protocol).

	IS	IX	S	SIX	X
IS	Yes	Yes	Yes	Yes	No
IX	Yes	Yes	No	No	No
S	Yes	No	Yes	No	No
SIX	Yes	No	No	No	No
X	No	No	No	No	No

Figure 22.8
Lock compatibility matrix for multiple granularity locking.

6. A transaction *T* can unlock a node, *N*, only if none of the children of node *N* are currently locked by *T*.

Rule 1 simply states that conflicting locks cannot be granted. Rules 2, 3, and 4 state the conditions when a transaction may lock a given node in any of the lock modes. Rules 5 and 6 of the MGL protocol enforce 2PL rules to produce serializable schedules. To illustrate the MGL protocol with the database hierarchy in Figure 22.7, consider the following three transactions:

1. T_1 wants to update record r_{111} and record r_{211}.
2. T_2 wants to update all records on page p_{12}.
3. T_3 wants to read record r_{11j} and the entire f_2 file.

Figure 22.9 shows a possible serializable schedule for these three transactions. Only the lock and unlock operations are shown. The notation <lock_type>(<item>) is used to display the locking operations in the schedule.

The multiple granularity level protocol is especially suited when processing a mix of transactions that include (1) short transactions that access only a few items (records or fields) and (2) long transactions that access entire files. In this environment, less transaction blocking and less locking overhead is incurred by such a protocol when compared to a single level granularity locking approach.

22.6 Using Locks for Concurrency Control in Indexes

Two-phase locking can also be applied to indexes (see Chapter 18), where the nodes of an index correspond to disk pages. However, holding locks on index pages until the shrinking phase of 2PL could cause an undue amount of transaction blocking because searching an index always *starts at the root*. Therefore, if a transaction wants to insert a record (write operation), the root would be locked in exclusive mode, so all other conflicting lock requests for the index must wait until the transaction enters its shrinking phase. This blocks all other transactions from accessing the index, so in practice other approaches to locking an index must be used.

T_1	T_2	T_3
IX(db)		
IX(f_1)		
	IX(db)	
		IS(db)
		IS(f_1)
		IS(p_{11})
IX(p_{11})		
X(r_{111})		
	IX(f_1)	
	X(p_{12})	
		S(r_{11j})
IX(f_2)		
IX(p_{21})		
X(p_{211})		
unlock(r_{211})		
unlock(p_{21})		
unlock(f_2)		
		S(f_2)
	unlock(p_{12})	
	unlock(f_1)	
	unlock(db)	
unlock(r_{111})		
unlock(p_{11})		
unlock(f_1)		
unlock(db)		
		unlock(r_{11j})
		unlock(p_{11})
		unlock(f_1)
		unlock(f_2)
		unlock(db)

Figure 22.9
Lock operations to illustrate a serializable schedule.

The tree structure of the index can be taken advantage of when developing a concurrency control scheme. For example, when an index search (read operation) is being executed, a path in the tree is traversed from the root to a leaf. Once a lower-level node in the path has been accessed, the higher-level nodes in that path will not be used again. So once a read lock on a child node is obtained, the lock on the parent can be released. When an insertion is being applied to a leaf node (that is, when a key and a pointer are inserted), then a specific leaf node must be locked in exclusive mode. However, if that node is not full, the insertion will not cause changes to higher-level index nodes, which implies that they need not be locked exclusively.

A conservative approach for insertions would be to lock the root node in exclusive mode and then to access the appropriate child node of the root. If the child node is not full, then the lock on the root node can be released. This approach can be applied all the way down the tree to the leaf, which is typically three or four levels from the root. Although exclusive locks are held, they are soon released. An alternative, more **optimistic approach** would be to request and hold *shared* locks on the nodes leading to the leaf node, with an *exclusive* lock on the leaf. If the insertion causes the leaf to split, insertion will propagate to one or more higher-level nodes. Then, the locks on the higher-level nodes can be upgraded to exclusive mode.

Another approach to index locking is to use a variant of the B^+-tree, called the **B-link tree**. In a B-link tree, sibling nodes on the same level are linked at every level. This allows shared locks to be used when requesting a page and requires that the lock be released before accessing the child node. For an insert operation, the shared lock on a node would be upgraded to exclusive mode. If a split occurs, the parent node must be relocked in exclusive mode. One complication is for search operations executed concurrently with the update. Suppose that a concurrent update operation follows the same path as the search, and inserts a new entry into the leaf node. Additionally, suppose that the insert causes that leaf node to split. When the insert is done, the search process resumes, following the pointer to the desired leaf, only to find that the key it is looking for is not present because the split has moved that key into a new leaf node, which would be the *right sibling* of the original leaf node. However, the search process can still succeed if it follows the pointer (link) in the original leaf node to its right sibling, where the desired key has been moved.

Handling the deletion case, where two or more nodes from the index tree merge, is also part of the B-link tree concurrency protocol. In this case, locks on the nodes to be merged are held as well as a lock on the parent of the two nodes to be merged.

22.7 Other Concurrency Control Issues

In this section we discuss some other issues relevant to concurrency control. In Section 22.7.1, we discuss problems associated with insertion and deletion of records and the so-called *phantom problem*, which may occur when records are inserted. This problem was described as a potential problem requiring a concurrency control measure in Section 21.6. In Section 22.7.2 we discuss problems that may occur when a transaction outputs some data to a monitor before it commits, and then the transaction is later aborted.

22.7.1 Insertion, Deletion, and Phantom Records

When a new data item is **inserted** in the database, it obviously cannot be accessed until after the item is created and the insert operation is completed. In a locking environment, a lock for the item can be created and set to exclusive (write) mode; the lock can be released at the same time as other write locks would be released, based on the concurrency control protocol being used. For a timestamp-based protocol, the read and write timestamps of the new item are set to the timestamp of the creating transaction.

Next, consider a **deletion operation** that is applied on an existing data item. For locking protocols, again an exclusive (write) lock must be obtained before the transaction can delete the item. For timestamp ordering, the protocol must ensure that no later transaction has read or written the item before allowing the item to be deleted.

A situation known as the **phantom problem** can occur when a new record that is being inserted by some transaction T satisfies a condition that a set of records accessed by another transaction T' must satisfy. For example, suppose that transaction T is inserting a new EMPLOYEE record whose Dno = 5, while transaction T' is accessing all EMPLOYEE records whose Dno = 5 (say, to add up all their Salary values to calculate the personnel budget for department 5). If the equivalent serial order is T followed by T', then T' must read the new EMPLOYEE record and include its Salary in the sum calculation. For the equivalent serial order T' followed by T, the new salary should not be included. Notice that although the transactions logically conflict, in the latter case there is really no record (data item) in common between the two transactions, since T' may have locked all the records with Dno = 5 *before* T inserted the new record. This is because the record that causes the conflict is a **phantom record** that has suddenly appeared in the database on being inserted. If other operations in the two transactions conflict, the conflict due to the phantom record may not be recognized by the concurrency control protocol.

One solution to the phantom record problem is to use **index locking**, as discussed in Section 22.6. Recall from Chapter 18 that an index includes entries that have an attribute value, plus a set of pointers to all records in the file with that value. For example, an index on Dno of EMPLOYEE would include an entry for each distinct Dno value, plus a set of pointers to all EMPLOYEE records with that value. If the index entry is locked before the record itself can be accessed, then the conflict on the phantom record can be detected, because transaction T' would request a read lock on the *index entry* for Dno = 5, and T would request a write lock on the same entry *before* they could place the locks on the actual records. Since the index locks conflict, the phantom conflict would be detected.

A more general technique, called **predicate locking**, would lock access to all records that satisfy an arbitrary *predicate* (condition) in a similar manner; however, predicate locks have proved to be difficult to implement efficiently.

22.7.2 Interactive Transactions

Another problem occurs when interactive transactions read input and write output to an interactive device, such as a monitor screen, before they are committed. The problem is that a user can input a value of a data item to a transaction T that is based on some value written to the screen by transaction T', which may not have committed. This dependency between T and T' cannot be modeled by the system concurrency control method, since it is only based on the user interacting with the two transactions.

An approach to dealing with this problem is to postpone output of transactions to the screen until they have committed.

22.7.3 Latches

Locks held for a short duration are typically called **latches**. Latches do not follow the usual concurrency control protocol such as two-phase locking. For example, a latch can be used to guarantee the physical integrity of a page when that page is being written from the buffer to disk. A latch would be acquired for the page, the page written to disk, and then the latch released.

22.8 Summary

In this chapter we discussed DBMS techniques for concurrency control. We started by discussing lock-based protocols, which are by far the most commonly used in practice. We described the two-phase locking (2PL) protocol and a number of its variations: basic 2PL, strict 2PL, conservative 2PL, and rigorous 2PL. The strict and rigorous variations are more common because of their better recoverability properties. We introduced the concepts of shared (read) and exclusive (write) locks, and showed how locking can guarantee serializability when used in conjunction with the two-phase locking rule. We also presented various techniques for dealing with the deadlock problem, which can occur with locking. In practice, it is common to use timeouts and deadlock detection (wait-for graphs).

We presented other concurrency control protocols that are not used often in practice but are important for the theoretical alternatives they show for solving this problem. These include the timestamp ordering protocol, which ensures serializability based on the order of transaction timestamps. Timestamps are unique, system-generated transaction identifiers. We discussed Thomas's write rule, which improves performance but does not guarantee conflict serializability. The strict timestamp ordering protocol was also presented. We discussed two multiversion protocols, which assume that older versions of data items can be kept in the database. One technique, called multiversion two-phase locking (which has been used in practice), assumes that two versions can exist for an item and attempts to increase concurrency by making write and read locks compatible (at the cost of introducing an additional certify lock mode). We also presented a multiversion protocol based on timestamp ordering, and an example of an optimistic protocol, which is also known as a certification or validation protocol.

Then we turned our attention to the important practical issue of data item granularity. We described a multigranularity locking protocol that allows the change of granularity (item size) based on the current transaction mix, with the goal of improving the performance of concurrency control. An important practical issue was then presented, which is to develop locking protocols for indexes so that indexes do not become a hindrance to concurrent access. Finally, we introduced the phantom problem and problems with interactive transactions, and briefly described the concept of latches and how it differs from locks.

Review Questions

22.1. What is the two-phase locking protocol? How does it guarantee serializability?

22.2. What are some variations of the two-phase locking protocol? Why is strict or rigorous two-phase locking often preferred?

22.3. Discuss the problems of deadlock and starvation, and the different approaches to dealing with these problems.

22.4. Compare binary locks to exclusive/shared locks. Why is the latter type of locks preferable?

22.5. Describe the wait-die and wound-wait protocols for deadlock prevention.

22.6. Describe the cautious waiting, no waiting, and timeout protocols for deadlock prevention.

22.7. What is a timestamp? How does the system generate timestamps?

22.8. Discuss the timestamp ordering protocol for concurrency control. How does strict timestamp ordering differ from basic timestamp ordering?

22.9. Discuss two multiversion techniques for concurrency control.

22.10. What is a certify lock? What are the advantages and disadvantages of using certify locks?

22.11. How do optimistic concurrency control techniques differ from other concurrency control techniques? Why are they also called validation or certification techniques? Discuss the typical phases of an optimistic concurrency control method.

22.12. How does the granularity of data items affect the performance of concurrency control? What factors affect selection of granularity size for data items?

22.13. What type of lock is needed for insert and delete operations?

22.14. What is multiple granularity locking? Under what circumstances is it used?

22.15. What are intention locks?

22.16. When are latches used?

22.17. What is a phantom record? Discuss the problem that a phantom record can cause for concurrency control.

22.18. How does index locking resolve the phantom problem?

22.19. What is a predicate lock?

Exercises

22.20. Prove that the basic two-phase locking protocol guarantees conflict serializability of schedules. (*Hint*: Show that if a serializability graph for a schedule has a cycle, then at least one of the transactions participating in the schedule does not obey the two-phase locking protocol.)

22.21. Modify the data structures for multiple-mode locks and the algorithms for read_lock(X), write_lock(X), and unlock(X) so that upgrading and downgrading of locks are possible. (*Hint*: The lock needs to check the transaction id(s) that hold the lock, if any.)

22.22. Prove that strict two-phase locking guarantees strict schedules.

22.23. Prove that the wait-die and wound-wait protocols avoid deadlock and starvation.

22.24. Prove that cautious waiting avoids deadlock.

22.25. Apply the timestamp ordering algorithm to the schedules in Figure 21.8(b) and (c), and determine whether the algorithm will allow the execution of the schedules.

22.26. Repeat Exercise 22.25, but use the multiversion timestamp ordering method.

22.27. Why is two-phase locking not used as a concurrency control method for indexes such as B$^+$-trees?

22.28. The compatibility matrix in Figure 22.8 shows that IS and IX locks are compatible. Explain why this is valid.

22.29. The MGL protocol states that a transaction T can unlock a node N, only if none of the children of node N are still locked by transaction T. Show that without this condition, the MGL protocol would be incorrect.

Selected Bibliography

The two-phase locking protocol and the concept of predicate locks were first proposed by Eswaran et al. (1976). Bernstein et al. (1987), Gray and Reuter (1993), and Papadimitriou (1986) focus on concurrency control and recovery. Kumar (1996) focuses on performance of concurrency control methods. Locking is discussed in Gray et al. (1975), Lien and Weinberger (1978), Kedem and Silbershatz (1980), and Korth (1983). Deadlocks and wait-for graphs were formalized by Holt (1972), and the wait-wound and wound-die schemes are presented in Rosenkrantz et al. (1978). Cautious waiting is discussed in Hsu and Zhang (1992). Helal et al. (1993) compares various locking approaches. Timestamp-based concurrency control techniques are discussed in Bernstein and Goodman (1980) and Reed (1983). Optimistic concurrency control is discussed in Kung and Robinson (1981) and Bassiouni (1988). Papadimitriou and Kanellakis (1979) and Bernstein and

Goodman (1983) discuss multiversion techniques. Multiversion timestamp ordering was proposed in Reed (1979, 1983), and multiversion two-phase locking is discussed in Lai and Wilkinson (1984). A method for multiple locking granularities was proposed in Gray et al. (1975), and the effects of locking granularities are analyzed in Ries and Stonebraker (1977). Bhargava and Reidl (1988) presents an approach for dynamically choosing among various concurrency control and recovery methods. Concurrency control methods for indexes are presented in Lehman and Yao (1981) and in Shasha and Goodman (1988). A performance study of various B^+-tree concurrency control algorithms is presented in Srinivasan and Carey (1991).

Other work on concurrency control includes semantic-based concurrency control (Badrinath and Ramamritham, 1992), transaction models for long-running activities (Dayal et al., 1991), and multilevel transaction management (Hasse and Weikum, 1991).

CHAPTER

17

Triggers

This chapter describes Triggers under PL/SQL:

Triggers are stored programs, which are automatically executed or fired when some events occur. Triggers are, in fact, written to be executed in response to any of the following events:

- A database manipulation (DML) statement (DELETE, INSERT, or UPDATE).
- A database definition (DDL) statement (CREATE, ALTER, or DROP).
- A database operation (SERVERERROR, LOGON, LOGOFF, STARTUP, or SHUTDOWN).

Triggers could be defined on the table, view, schema, or database with which the event is associated.

Benefits of Triggers

Triggers can be written for the following purposes:

- Generating some derived column values automatically
- Enforcing referential integrity
- Event logging and storing information on table access
- Auditing
- Synchronous replication of tables
- Imposing security authorizations
- Preventing invalid transactions

Creating Triggers

The syntax for creating a trigger is:

```
CREATE [OR REPLACE ] TRIGGER trigger_name
{BEFORE | AFTER | INSTEAD OF }
{INSERT [OR] | UPDATE [OR] | DELETE}
[OF col_name]
ON table_name
[REFERENCING OLD AS o NEW AS n]
[FOR EACH ROW]
WHEN (condition)
DECLARE
   Declaration-statements
BEGIN
   Executable-statements
EXCEPTION
   Exception-handling-statements
END;
```

Where,

- CREATE [OR REPLACE] TRIGGER trigger_name: Creates or replaces an existing trigger with the *trigger_name*.
- {BEFORE | AFTER | INSTEAD OF}: This specifies when the trigger would be executed. The INSTEAD OF clause is used for creating trigger on a view.
- {INSERT [OR] | UPDATE [OR] | DELETE}: This specifies the DML operation.
- [OF col_name]: This specifies the column name that would be updated.
- [ON table_name]: This specifies the name of the table associated with the trigger.
- [REFERENCING OLD AS o NEW AS n]: This allows you to refer new and old values for various DML statements, like INSERT, UPDATE, and DELETE.
- [FOR EACH ROW]: This specifies a row level trigger, i.e., the trigger would be executed for each row being affected. Otherwise the trigger will execute just once when the SQL statement is executed, which is called a table level trigger.
- WHEN (condition): This provides a condition for rows for which the trigger would fire. This clause is valid only for row level triggers.

Example:

To start with, we will be using the CUSTOMERS table we had created and used in the previous chapters:

```
Select * from customers;

+----+----------+-----+-----------+----------+
| ID | NAME     | AGE | ADDRESS   | SALARY   |
+----+----------+-----+-----------+----------+
|  1 | Ramesh   |  32 | Ahmedabad |  2000.00 |
|  2 | Khilan   |  25 | Delhi     |  1500.00 |
|  3 | kaushik  |  23 | Kota      |  2000.00 |
|  4 | Chaitali |  25 | Mumbai    |  6500.00 |
|  5 | Hardik   |  27 | Bhopal    |  8500.00 |
|  6 | Komal    |  22 | MP        |  4500.00 |
+----+----------+-----+-----------+----------+
```

The following program creates a row level trigger for the customers table that would fire for INSERT or UPDATE or DELETE operations performed on the CUSTOMERS table. This trigger will display the salary difference between the old values and new values:

```
CREATE OR REPLACE TRIGGER display_salary_changes
BEFORE DELETE OR INSERT OR UPDATE ON customers
FOR EACH ROW
WHEN (NEW.ID > 0)
DECLARE
   sal_diff number;
BEGIN
   sal_diff := :NEW.salary  - :OLD.salary;
   dbms_output.put_line('Old salary: ' || :OLD.salary);
   dbms_output.put_line('New salary: ' || :NEW.salary);
   dbms_output.put_line('Salary difference: ' || sal_diff);
END;
/
```

When the above code is executed at SQL prompt, it produces the following result:

```
Trigger created.
```

Here following two points are important and should be noted carefully:

- OLD and NEW references are not available for table level triggers, rather you can use them for record level triggers.
- If you want to query the table in the same trigger, then you should use the AFTER keyword, because triggers can query the table or change it again only after the initial changes are applied and the table is back in a consistent state.
- Above trigger has been written in such a way that it will fire before any DELETE or INSERT or UPDATE operation on the table, but you can write your trigger on a single or multiple operations, for example BEFORE DELETE, which will fire whenever a record will be deleted using DELETE operation on the table.

Triggering a Trigger

Let us perform some DML operations on the CUSTOMERS table. Here is one INSERT statement, which will create a new record in the table:

```
INSERT INTO CUSTOMERS (ID,NAME,AGE,ADDRESS,SALARY)
VALUES (7, 'Kriti', 22, 'HP', 7500.00 );
```

When a record is created in CUSTOMERS table, above create trigger display_salary_changes will be fired and it will display the following result:

```
Old salary:
New salary: 7500
```

```
Salary difference:
```

Because this is a new record so old salary is not available and above result is coming as null. Now, let us perform one more DML operation on the CUSTOMERS table. Here is one UPDATE statement, which will update an existing record in the table:

```
UPDATE customers
SET salary = salary + 500
WHERE id = 2;
```

When a record is updated in CUSTOMERS table, above create trigger display_salary_changes will be fired and it will display the following result:

```
Old salary: 1500
New salary: 2000
Salary difference: 500
```

CHAPTER

18

Packages

This chapter describes Packages under PL/SQL:

PL/SQL packages are schema objects that groups logically related PL/SQL types, variables and subprograms.

A package will have two mandatory parts:

- Package specification
- Package body or definition

Package Specification

The specification is the interface to the package. It just DECLARES the types, variables, constants, exceptions, cursors, and subprograms that can be referenced from outside the package. In other words, it contains all information about the content of the package, but excludes the code for the subprograms.

All objects placed in the specification are called public objects. Any subprogram not in the package specification but coded in the package body is called a private object.

The following code snippet shows a package specification having a single procedure. You can have many global variables defined and multiple procedures or functions inside a package.

```
CREATE PACKAGE cust_sal AS
   PROCEDURE find_sal(c_id customers.id%type);
END cust_sal;
/
```

When the above code is executed at SQL prompt, it produces the following result:

```
Package created.
```

Package Body

The package body has the codes for various methods declared in the package specification and other private declarations, which are hidden from code outside the package.

The CREATE PACKAGE BODY Statement is used for creating the package body. The following code snippet shows the package body declaration for the *cust_sal* package created above. I assumed that we already have CUSTOMERS table created in our database as mentioned in PL/SQL - Variableschapter.

```
CREATE OR REPLACE PACKAGE BODY cust_sal AS
   PROCEDURE find_sal(c_id customers.id%TYPE) IS
   c_sal customers.salary%TYPE;
   BEGIN
      SELECT salary INTO c_sal
      FROM customers
      WHERE id = c_id;
      dbms_output.put_line('Salary: '|| c_sal);
   END find_sal;
END cust_sal;
/
```

When the above code is executed at SQL prompt, it produces the following result:

```
Package body created.
```

Using the Package Elements

The package elements (variables, procedures or functions) are accessed with the following syntax:

```
package_name.element_name;
```

Consider, we already have created above package in our database schema, the following program uses the find_sal method of the cust_sal package:

```
DECLARE
   code customers.id%type := &cc_id;
BEGIN
   cust_sal.find_sal(code);
END;
/
```

When the above code is executed at SQL prompt, it prompt to enter customer ID and when you enter an ID, it displays corresponding salary as follows:

```
Enter value for cc_id: 1
Salary: 3000

PL/SQL procedure successfully completed.
```

Example:

The following program provides a more complete package. We will use the CUSTOMERS table stored in our database with the following records:

```
Select * from customers;

+----+----------+-----+-----------+----------+
| ID | NAME     | AGE | ADDRESS   | SALARY   |
+----+----------+-----+-----------+----------+
|  1 | Ramesh   |  32 | Ahmedabad |  3000.00 |
|  2 | Khilan   |  25 | Delhi     |  3000.00 |
|  3 | kaushik  |  23 | Kota      |  3000.00 |
|  4 | Chaitali |  25 | Mumbai    |  7500.00 |
|  5 | Hardik   |  27 | Bhopal    |  9500.00 |
|  6 | Komal    |  22 | MP        |  5500.00 |
+----+----------+-----+-----------+----------+
```

THE PACKAGE SPECIFICATION:

```
CREATE OR REPLACE PACKAGE c_package AS
   -- Adds a customer
   PROCEDURE addCustomer(c_id   customers.id%type,
   c_name  customers.name%type,
   c_age  customers.age%type,
   c_addr customers.address%type,
   c_sal  customers.salary%type);

   -- Removes a customer
   PROCEDURE delCustomer(c_id  customers.id%TYPE);
   --Lists all customers
   PROCEDURE listCustomer;

END c_package;
/
```

When the above code is executed at SQL prompt, it creates the above package and displays the following result:

```
Package created.
```

CREATING THE PACKAGE BODY:

```
CREATE OR REPLACE PACKAGE BODY c_package AS
   PROCEDURE addCustomer(c_id  customers.id%type,
      c_name customers.name%type,
      c_age  customers.age%type,
      c_addr  customers.address%type,
      c_sal   customers.salary%type)
   IS
   BEGIN
      INSERT INTO customers (id,name,age,address,salary)
         VALUES(c_id, c_name, c_age, c_addr, c_sal);
   END addCustomer;

   PROCEDURE delCustomer(c_id   customers.id%type) IS
   BEGIN
       DELETE FROM customers
         WHERE id = c_id;
   END delCustomer;
   PROCEDURE listCustomer IS
   CURSOR c_customers is
      SELECT  name FROM customers;
   TYPE c_list is TABLE OF customers.name%type;
   name_list c_list := c_list();
   counter integer :=0;
   BEGIN
      FOR n IN c_customers LOOP
      counter := counter +1;
      name_list.extend;
      name_list(counter)  := n.name;
      dbms_output.put_line('Customer(' ||counter||
')'||name_list(counter));
      END LOOP;
   END listCustomer;
END c_package;
/
```

Above example makes use of **nested table** which we will discuss in the next chapter. When the above code is executed at SQL prompt, it produces the following result:

```
Package body created.
```

USING THE PACKAGE:

The following program uses the methods declared and defined in the package c_package.

```
DECLARE
   code customers.id%type:= 8;
BEGIN
      c_package.addcustomer(7, 'Rajnish', 25, 'Chennai', 3500);
         c_package.addcustomer(8, 'Subham', 32, 'Delhi', 7500);
         c_package.listcustomer;
      c_package.delcustomer(code);
      c_package.listcustomer;
END;
/
```

When the above code is executed at SQL prompt, it produces the following result:

```
Customer(1): Ramesh
Customer(2): Khilan
Customer(3): kaushik
Customer(4): Chaitali
Customer(5): Hardik
Customer(6): Komal
Customer(7): Rajnish
Customer(8): Subham
Customer(1): Ramesh
Customer(2): Khilan
Customer(3): kaushik
Customer(4): Chaitali
Customer(5): Hardik
Customer(6): Komal
Customer(7): Rajnish

PL/SQL procedure successfully completed
```

CHAPTER

23

Object Oriented

This chapter describes the Object oriented concept:

PL/SQL allows defining an object type, which helps in designing object-oriented database in Oracle. An object type allows you to crate composite types. Using objects allow you implementing real world objects with specific structure of data and methods for operating it. Objects have attributes and methods. Attributes are properties of an object and are used for storing an object's state; and methods are used for modeling its behaviors.

Objects are created using the CREATE [OR REPLACE] TYPE statement. Below is an example to create a simple **address** object consisting of few attributes:

```
CREATE OR REPLACE TYPE address AS OBJECT
(house_no varchar2(10),
 street varchar2(30),
 city varchar2(20),
 state varchar2(10),
 pincode varchar2(10)
);
/
```

When the above code is executed at SQL prompt, it produces the following result:

```
Type created.
```

Let's create one more object **customer** where we will wrap **attributes** and **methods** together to have object oriented feeling:

```
CREATE OR REPLACE TYPE customer AS OBJECT
(code number(5),
 name varchar2(30),
 contact_no varchar2(12),
 addr address,
 member procedure display
);
/
```

When the above code is executed at SQL prompt, it produces the following result:

```
Type created.
```

Instantiating an Object

Defining an object type provides a blueprint for the object. To use this object, you need to create instances of this object. You can access the attributes and methods of the object using the instance name and **the access operator (.)** as follows:

```
DECLARE
   residence address;
BEGIN
   residence := address('103A', 'M.G.Road', 'Jaipur', 
'Rajasthan','201301');
   dbms_output.put_line('House No: '|| residence.house_no);
   dbms_output.put_line('Street: '|| residence.street);
   dbms_output.put_line('City: '|| residence.city);
   dbms_output.put_line('State: '|| residence.state);
   dbms_output.put_line('Pincode: '|| residence.pincode);
END;
/
```

When the above code is executed at SQL prompt, it produces the following result:

```
House No: 103A
Street: M.G.Road
City: Jaipur
State: Rajasthan
Pincode: 201301

PL/SQL procedure successfully completed.
```

Member Methods

Member **methods** are used for manipulating the **attributes** of the object. You provide the declaration of a member method while declaring the object type. The object body defines the code for the member methods. The object body is created using the CREATE TYPE BODY statement.
Constructors are functions that return a new object as its value. Every object has a system defined constructor method. The name of the constructor is same as the object type. For example:

```
residence := address('103A', 'M.G.Road', 'Jaipur', 
'Rajasthan','201301');
```

The **comparison methods** are used for comparing objects. There are two ways to compare objects:

- **Map method**: The **Map method** is a function implemented in such a way that its value depends upon the value of the attributes. For example, for a customer object, if the customer code is same for two customers, both customers could be the same and one. So the relationship between these two objects would depend upon the value of code.
- **Order method**: The **Order methods** implement some internal logic for comparing two objects. For example, for a rectangle object, a rectangle is bigger than another rectangle if both its sides are bigger.

Using Map method

Let us try to understand above concepts using the following rectangle object:

```
CREATE OR REPLACE TYPE rectangle AS OBJECT
(length number,
 width number,
 member function enlarge( inc number) return rectangle,
 member procedure display,
 map member function measure return number
);
/
```

When the above code is executed at SQL prompt, it produces the following result:

```
Type created.
```

Creating the type body:

```
CREATE OR REPLACE TYPE BODY rectangle AS
   MEMBER FUNCTION enlarge(inc number) return rectangle IS
   BEGIN
      return rectangle(self.length + inc, self.width + inc);
   END enlarge;

   MEMBER PROCEDURE display IS
   BEGIN
      dbms_output.put_line('Length: '|| length);
      dbms_output.put_line('Width: '|| width);
   END display;

   MAP MEMBER FUNCTION measure return number IS
   BEGIN
      return (sqrt(length*length + width*width));
   END measure;
END;
/
```

When the above code is executed at SQL prompt, it produces the following result:

```
Type body created.
```

Now using the rectangle object and its member functions:

```
DECLARE
   r1 rectangle;
   r2 rectangle;
   r3 rectangle;
   inc_factor number := 5;
BEGIN
   r1 := rectangle(3, 4);
   r2 := rectangle(5, 7);
   r3 := r1.enlarge(inc_factor);
   r3.display;
   IF (r1 > r2) THEN -- calling measure function
      r1.display;
   ELSE
      r2.display;
   END IF;
END;
/
```

When the above code is executed at SQL prompt, it produces the following result:

```
Length: 8
Width: 9
Length: 5
Width: 7

PL/SQL procedure successfully completed.
```

Using Order method

Now, the **same effect could be achieved using an order method**. Let us recreate the rectangle object using an order method:

```
CREATE OR REPLACE TYPE rectangle AS OBJECT
(length number,
 width number,
 member procedure display,
 order member function measure(r rectangle) return number
);
/
```

When the above code is executed at SQL prompt, it produces the following result:

```
Type created.
```

Creating the type body:

```
CREATE OR REPLACE TYPE BODY rectangle AS
   MEMBER PROCEDURE display IS
   BEGIN
      dbms_output.put_line('Length: '|| length);
      dbms_output.put_line('Width: '|| width);
   END display;

   ORDER MEMBER FUNCTION measure(r rectangle) return number IS
   BEGIN
      IF(sqrt(self.length*self.length + self.width*self.width)>
sqrt(r.length*r.length + r.width*r.width)) then
         return(1);
      ELSE
         return(-1);
      END IF;
   END measure;
END;
/
```

When the above code is executed at SQL prompt, it produces the following result:

```
Type body created.
```

Using the rectangle object and its member functions:

```
DECLARE
   r1 rectangle;
   r2 rectangle;
BEGIN
   r1 := rectangle(23, 44);
   r2 := rectangle(15, 17);
   r1.display;
   r2.display;
   IF (r1 > r2) THEN -- calling measure function
      r1.display;
   ELSE
      r2.display;
   END IF;
END;
/
```

When the above code is executed at SQL prompt, it produces the following result:

```
Length: 23
Width: 44
Length: 15
Width: 17
Length: 23
Width: 44

PL/SQL procedure successfully completed.
```

Inheritance for PL/SQL Objects:

PL/SQL allows creating object from existing base objects. To implement inheritance, the base objects should be declared as NOT FINAL. The default is FINAL.

The following programs illustrate inheritance in PL/SQL Objects. Let us create another object named TableTop, which is inheriting from the Rectangle object. Creating the base *rectangle* object:

```
CREATE OR REPLACE TYPE rectangle AS OBJECT
(length number,
 width number,
 member function enlarge( inc number) return rectangle,
 NOT FINAL member procedure display) NOT FINAL
/
```

When the above code is executed at SQL prompt, it produces the following result:

```
Type created.
```

Creating the base type body:

```
CREATE OR REPLACE TYPE BODY rectangle AS
   MEMBER FUNCTION enlarge(inc number) return rectangle IS
   BEGIN
      return rectangle(self.length + inc, self.width + inc);
   END enlarge;

   MEMBER PROCEDURE display IS
   BEGIN
      dbms_output.put_line('Length: '|| length);
      dbms_output.put_line('Width: '|| width);
   END display;
END;
/
```

When the above code is executed at SQL prompt, it produces the following result:

```
Type body created.
```

Creating the child object *tabletop*:

```
CREATE OR REPLACE TYPE tabletop UNDER rectangle
(
   material varchar2(20);
   OVERRIDING member procedure display
)
/
```

When the above code is executed at SQL prompt, it produces the following result:

```
Type created.
```

Creating the type body for the child object tabletop:

```
CREATE OR REPLACE TYPE BODY tabletop AS
OVERRIDING MEMBER PROCEDURE display IS
BEGIN
   dbms_output.put_line('Length: '|| length);
   dbms_output.put_line('Width: '|| width);
   dbms_output.put_line('Material: '|| material);
END display;
/
```

When the above code is executed at SQL prompt, it produces the following result:

```
Type body created.
```

Using the tabletop object and its member functions:

```
DECLARE
   t1 tabletop;
   t2 tabletop;
BEGIN
   t1:= tabletop(20, 10, 'Wood');
   t2 := tabletop(50, 30, 'Steel');
   t1.display;
   t2.display;
END;
/
```

When the above code is executed at SQL prompt, it produces the following result:

```
Length: 20
Width: 10
Material: Wood
Length: 50
Width: 30
Material: Steel

PL/SQL procedure successfully completed.
```

Abstract Objects in PL/SQL

The NOT INSTANTIABLE clause allows you to declare an abstract object. You cannot use an abstract object as it is; you will have to create a subtype or child type of such objects to use its functionalities.

For example,

```
CREATE OR REPLACE TYPE rectangle AS OBJECT
(length number,
 width number,
 NOT INSTANTIABLE NOT FINAL MEMBER PROCEDURE display)
 NOT INSTANTIABLE NOT FINAL
/
```

When the above code is executed at SQL prompt, it produces the following result:

```
Type created.
```