UNIT V:
TRANSACTION PROCESSING, ERROR RECOVERY, DATA STORAGEAND INDEXES

Transaction processing and Error recovery - concepts of transaction processing, ACID properties, concurrency control, locking based protocols for CC, error recovery and logging, undo, redo, undo-redo logging and recovery methods.

Data Storage and Indexes – file organizations, primary, secondary index structures, various index structures – hash-based, dynamic hashing techniques, multi-level indexes, B+ trees.

Chapter Outline

1 Introduction to Transaction Processing (1)

- **Single-User System**:
  - At most one user at a time can use the system.
- **Multiuser System**:
  - Many users can access the system concurrently.
- **Concurrency**
  - **Interleaved processing**:
    - Concurrent execution of processes is interleaved in a single CPU
  - **Parallel processing**:
    - Processes are concurrently executed in multiple CPUs.

Introduction to Transaction Processing (2)

- A **Transaction**:
  - Logical unit of database processing that includes one or more access operations (read -retrieval, write - insert or update, delete).
- A transaction (set of operations) may be stand-alone specified in a high level language like SQL submitted interactively, or may be embedded within a program.
- **Transaction boundaries**:
  - Begin and End transaction.
- An **application program** may contain several transactions separated by the Begin and End transaction boundaries.

Introduction to Transaction Processing (3)

SIMPLE MODEL OF A DATABASE (for purposes of discussing transactions):

- **A database** is a collection of named data items
- **Granularity** of data - a field, a record , or a whole disk block (Concepts are independent of granularity)
- Basic operations are **read** and **write**
  - **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.

Introduction to Transaction Processing (4)

READ AND WRITE OPERATIONS:

- Basic unit of data transfer from the disk to the computer main memory is one block. In general, a data item (what is read or written) will be the field of some record in the database, although it may be a larger unit such as a record or even a whole block.

- read_item(X) command includes the following steps:
  - Find the address of the disk block that contains item X.
  - Copy that disk block into a buffer in main memory (if that disk block is not already in some main memory buffer).
  - Copy item X from the buffer to the program variable named X.

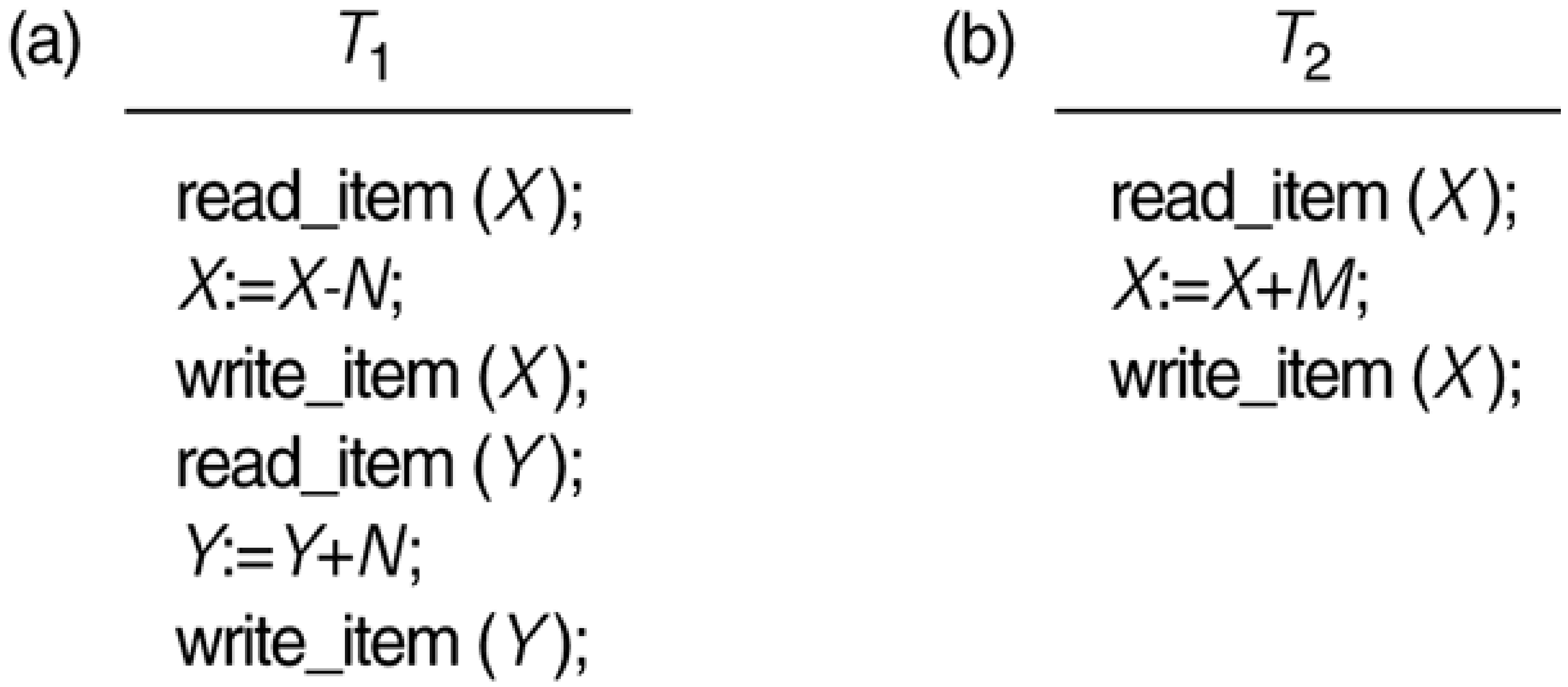
Introduction to Transaction Processing (5)

READ AND WRITE OPERATIONS (contd.):

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

Two sample transactions

- Two sample transactions:



(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);
```

Introduction to Transaction Processing (6)

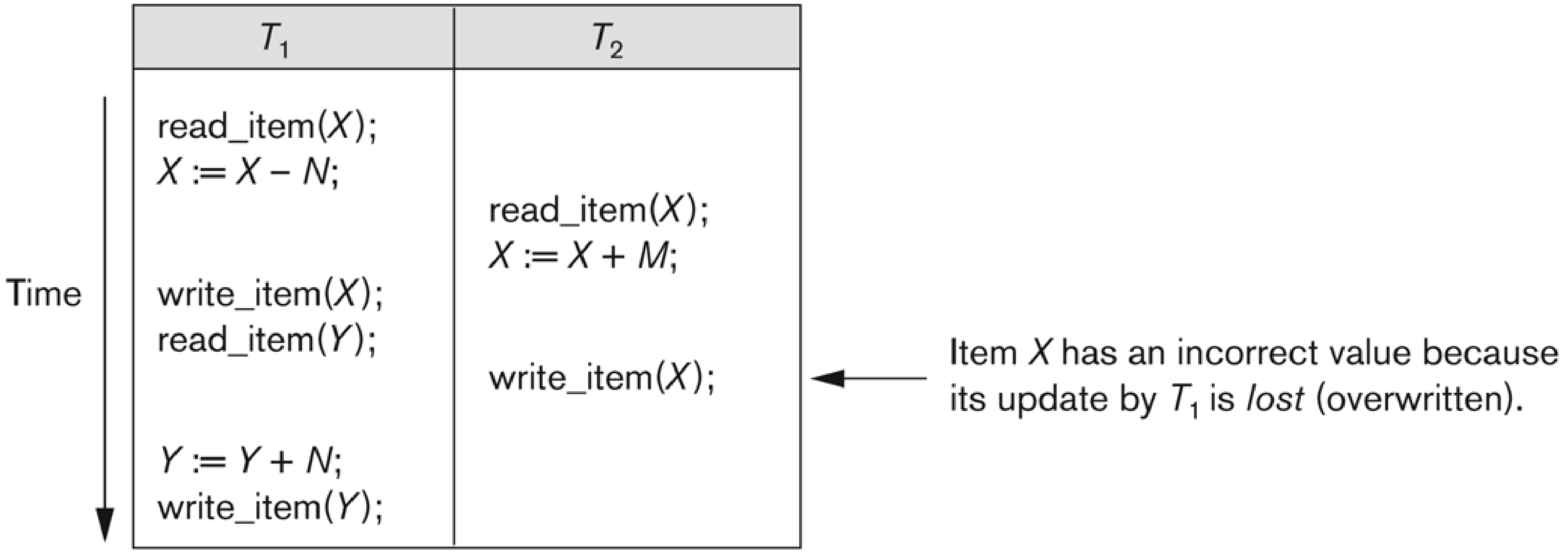
Why Concurrency Control is needed:

- **The Lost Update Problem**
  - This occurs when two transactions that access the same database items have their operations interleaved in a way that makes the value of some database item incorrect.
- **The Temporary Update (or Dirty Read) Problem**
  - This occurs when one transaction updates a database item and then the transaction fails for some reason.
  - The updated item is accessed by another transaction before it is changed back to its original value.
- **The Incorrect Summary Problem**
  - If one transaction is calculating an aggregate summary function on a number of records while other transactions are updating some of these records, the aggregate function may calculate some values before they are updated and others after they are updated.

Concurrent execution is uncontrolled: (a) The lost update problem.

Figure 17.3
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)



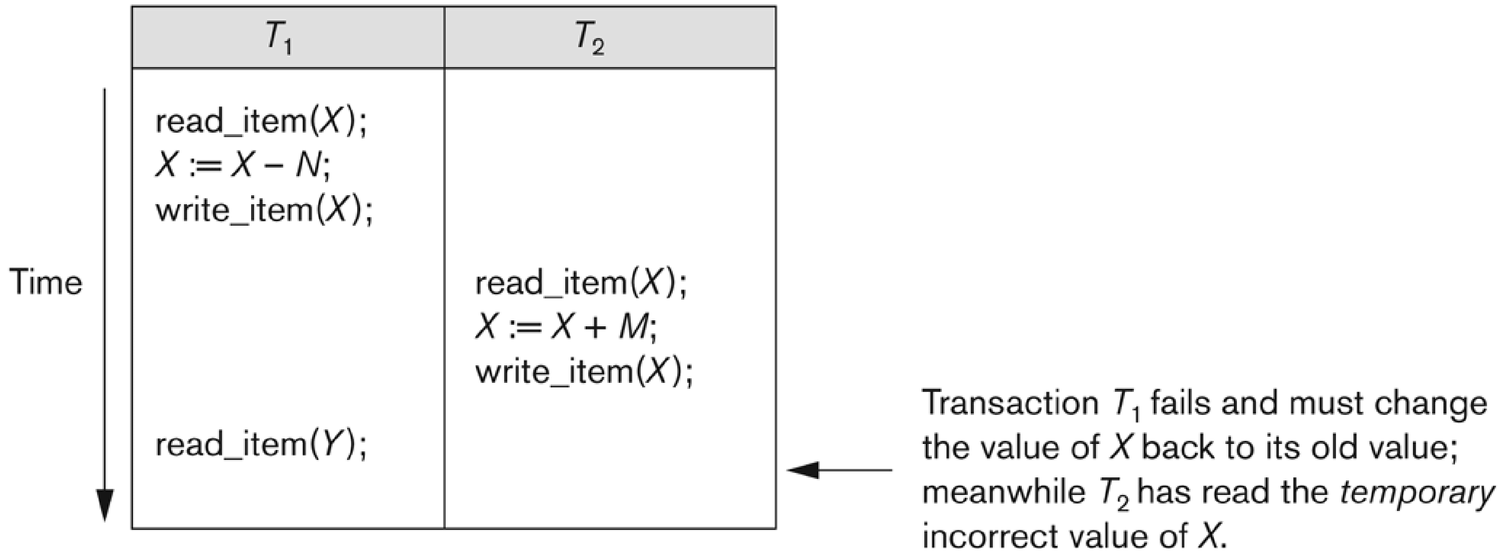
T_1	T_2
read_item(X); $X := X - N$;	
	read_item(X); $X := X + M$;
write_item(X); read_item(Y);	
	write_item(X);
$Y := Y + N$; write_item(Y);	

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

Concurrent execution is uncontrolled: (b) The temporary update problem.

Figure 17.3
Some problems that occur when concurrent execution is uncontrolled. (a) The lost update problem. (b) The temporary update problem. (c) The incorrect summary problem.

(b)



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.

Concurrent execution is uncontrolled: (c) The incorrect summary problem.

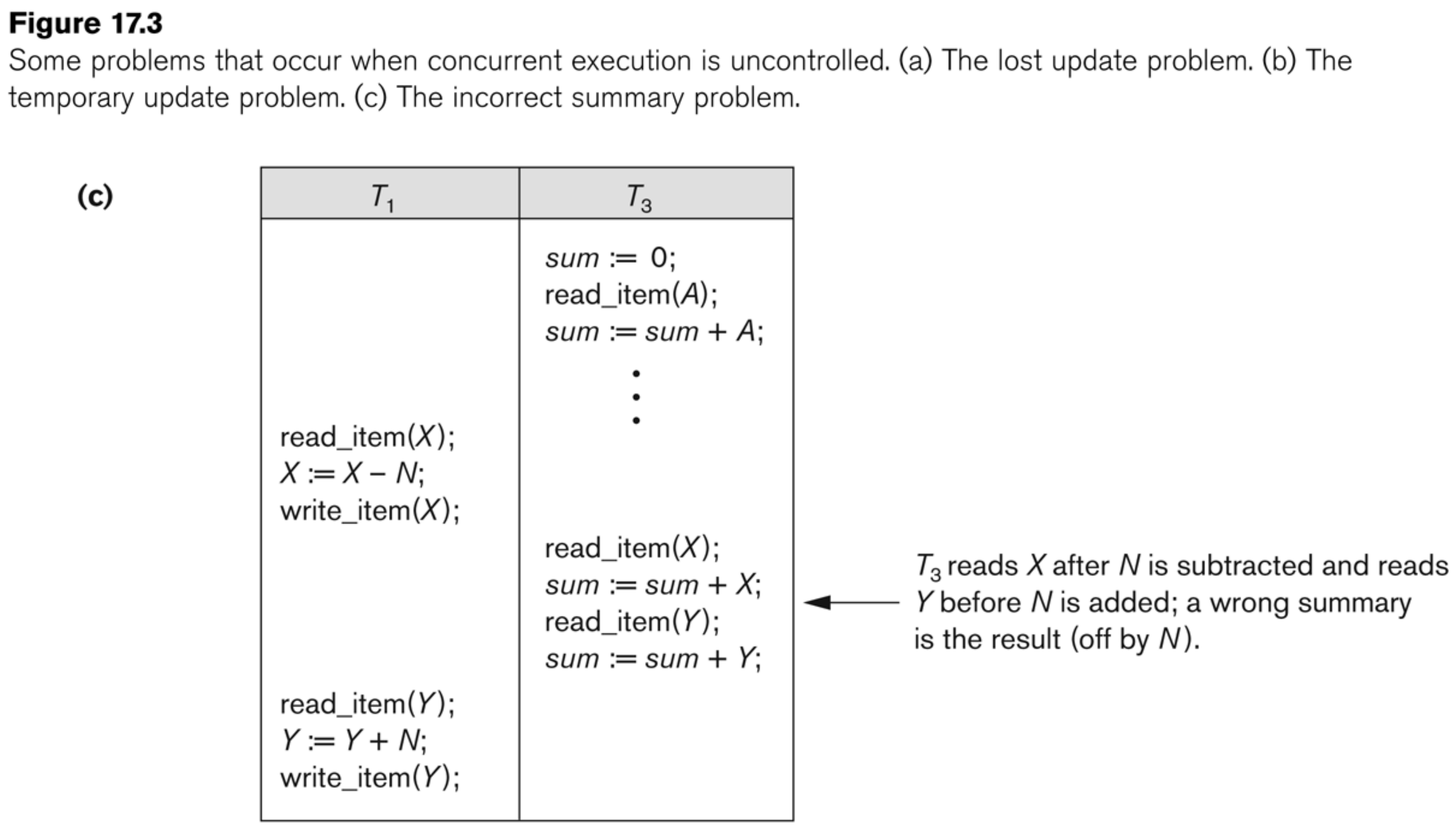


Figure 17.3
Some problems that occur when concurrent execution is uncontrolled. (a) The lost update problem. (b) The temporary update problem. (c) The incorrect summary problem.

(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*).

Introduction to Transaction Processing (12)

Why **recovery** is needed:

(What causes a Transaction to fail)

1. A computer failure (system crash):

   A hardware or software error occurs in the computer system during transaction execution. If the hardware crashes, the contents of the computer's internal memory may be lost.

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. In addition, the user may interrupt the transaction during its execution.

Introduction to Transaction Processing (13)

Why **recovery** is needed (Contd.):

(What causes a Transaction to fail)

3. Local errors or exception conditions detected by the transaction:

   Certain conditions necessitate cancellation of the transaction. For example, data for the transaction may not be found. A condition, such as insufficient account balance in a banking database, may cause a transaction, such as a fund withdrawal from that account, to be canceled.

   A programmed abort in the transaction causes it to fail.

4. Concurrency control enforcement:

   The concurrency control method may decide to abort the transaction, to be restarted later, because it violates serializability or because several transactions are in a state of deadlock (see Chapter 18).

Introduction to Transaction Processing (14)

Why **recovery** is needed (contd.):

(What causes a Transaction to fail)

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.

2 Transaction and System Concepts (1)

- A **transaction** is an atomic unit of work that is either completed in its entirety or not done at all.
  - For recovery purposes, the system needs to keep track of when the transaction starts, terminates, and commits or aborts.
- **Transaction states**:
  - Active state
  - Partially committed state
  - Committed state
  - Failed state
  - Terminated State

Transaction and System Concepts (2)

- Recovery manager keeps 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 limit of transaction execution.
    - At this point it may be necessary to check whether the changes introduced by the transaction can be permanently applied to the database or whether the transaction has to be aborted because it violates concurrency control or for some other reason.

Transaction and System Concepts (3)

- Recovery manager keeps track of the following operations (cont):
  - **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.

Transaction and System Concepts (4)

- Recovery techniques use the following operators:
  - **undo**: Similar to rollback except that it applies to a single operation rather than to a whole transaction.
  - **redo**: This specifies that certain *transaction operations* must be *redone* to ensure that all the operations of a committed transaction have been applied successfully to the database.

State transition diagram illustrating the states for transaction execution

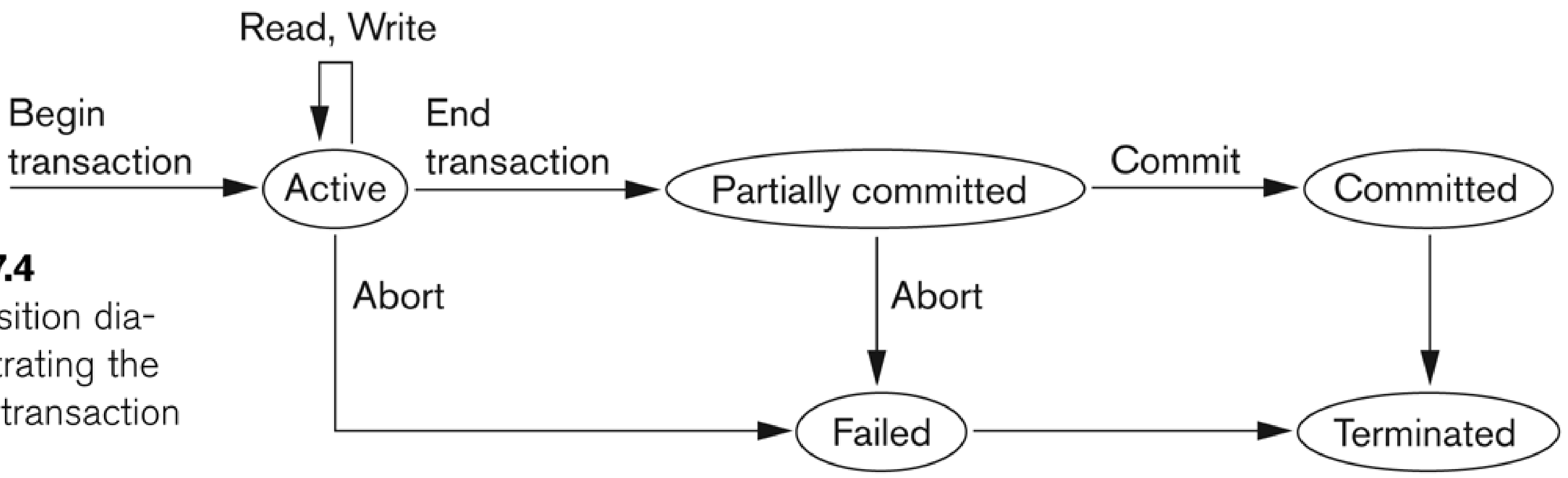


Figure 17.4
State transition diagram illustrating the states for transaction execution.

Transaction and System Concepts (6)

- The System Log
  - **Log** or **Journal**: The log keeps track of all transaction operations that affect the values of database items.
    - This information may be needed to permit recovery from transaction failures.
    - The log is kept on disk, so it is not affected by any type of failure except for disk or catastrophic failure.
    - In addition, the log is periodically backed up to archival storage (tape) to guard against such catastrophic failures.

Transaction and System Concepts (7)

- The System Log (cont):
  - T in the following discussion refers to a unique **transaction-id** that is generated automatically by the system and is used to identify each transaction:
  - Types of log record:
    - [start_transaction,T]: Records that transaction T has started execution.
    - [write_item,T,X,old_value,new_value]: Records that transaction T has changed the value of database item X from old_value to new_value.
    - [read_item,T,X]: Records that transaction T has read the value of database item X.
    - [commit,T]: Records that transaction T has completed successfully, and affirms that its effect can be committed (recorded permanently) to the database.
    - [abort,T]: Records that transaction T has been aborted.

Transaction and System Concepts (8)

- The System Log (cont):
  - Protocols for recovery that *avoid cascading rollbacks do not require that read operations be written to the system log*, whereas other protocols require these entries for recovery.
  - Strict protocols require simpler write entries that do not include new_value (see Section 17.4).

Transaction and System Concepts (9)

Recovery using log records:

- 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 19.
  1. 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.

  1. We can also **redo** the effect of the write operations of a transaction T by tracing forward through the log and setting all items changed by a write operation of T (that did not get done permanently) to their new_values.

Transaction and System Concepts (10)

Commit Point of a Transaction:

- **Definition a Commit Point:**
  - 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 has been recorded in the log.
  - Beyond the commit point, the transaction is said to be committed, and its effect is assumed to be permanently recorded in the database.
  - The transaction then writes an entry [commit,T] into the log.
- **Roll Back of transactions:**
  - Needed for transactions that have a [start_transaction,T] entry into the log but no commit entry [commit,T] into the log.

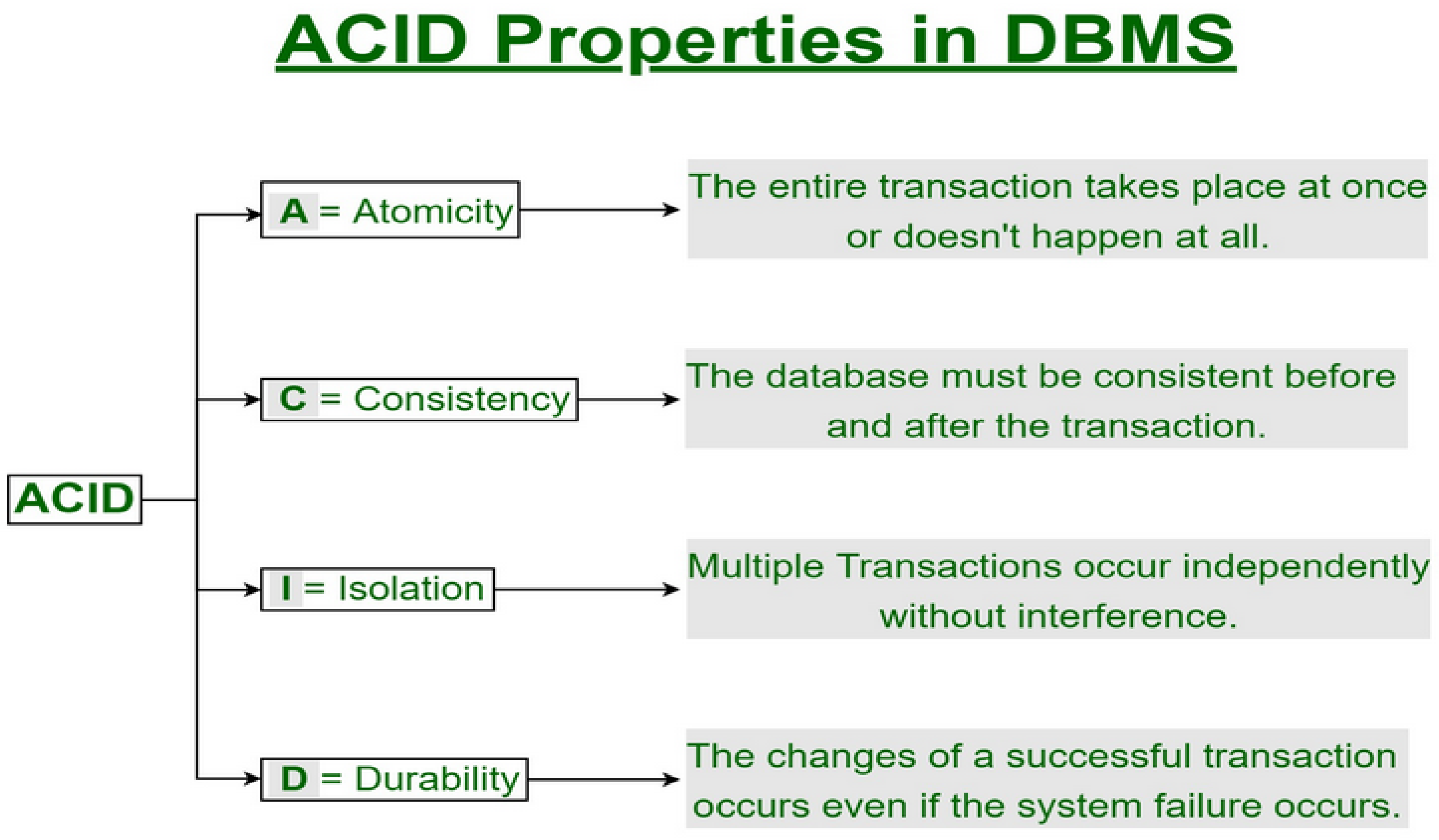
Transaction and System Concepts (11)

Commit Point of a Transaction (cont):

- **Redoing transactions:**
  - Transactions that have written their commit entry in the log must also have recorded all their write operations in the log; otherwise they would not be committed, so their effect on the database can be redone from the log entries. (Notice that the log file must be kept on disk.
  - 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.)
- **Force writing a log:**
  - 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 file before committing a transaction.

3 Desirable Properties of Transactions (1)

The ACID properties, in totality, provide a mechanism to ensure correctness and consistency of a database in a way such that each transaction is a group of operations that acts a single unit, produces consistent results, acts in isolation from other operations and updates that it makes are durably stored.


ACID Properties in DBMS
ACID
A = Atomicity
The entire transaction takes place at once or doesn't happen at all.
C = Consistency
The database must be consistent before and after the transaction.
I = Isolation
Multiple Transactions occur independently without interference.
D = Durability
The changes of a successful transaction occurs even if the system failure occurs.

3 Desirable Properties of Transactions (1)

ACID properties:

- **Atomicity**: A transaction is an atomic unit of processing; it is either performed in its entirety or not performed at all.

There is no midway i.e. transactions do not occur partially. Each transaction is considered as one unit and either runs to completion or is not executed at all.

It involves the following two operations.

—Abort: If a transaction aborts, changes made to database are not visible.

—Commit: If a transaction commits, changes made are visible.

Atomicity is also known as the ‘All or nothing rule’.

3 Desirable Properties of Transactions (1)

ACID properties:

- **Consistency preservation**: A correct execution of the transaction must take the database from one consistent state to another.

- Preservation of consistency is responsibility of the programmers who write the database programs and of the DBMS module that enforces integrity constraints.
- 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.

3 Desirable Properties of Transactions (1)

ACID properties:

- **Isolation**: A transaction should not make its updates visible to other transactions until it is committed; this property, when enforced strictly, solves the temporary update problem and makes cascading rollbacks of transactions unnecessary
- Isolation property is enforced by the concurrency control subsystem of the DBMS.
- Levels of Isolation: A transaction is said to have
  - level 0 (zero) isolation if it does not over-write 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.
  - Level 3 isolation (also called true isolation) has, in addition to level 2 properties, repeatable reads.
  - Another type of isolation is called snapshot isolation, and several practical concurrency control methods are based on this.

3 Desirable Properties of Transactions (1)

ACID properties:

- **Durability or permanency**: Once a transaction changes the database and the changes are committed, these changes must never be lost because of subsequent failure.
- The durability property is the responsibility of the recovery subsystem of the DBMS.
- This property ensures that once the transaction has completed execution, the updates and modifications to the database are stored in and written to disk and they persist even if a system failure occurs.
- These updates now become permanent and are stored in non-volatile memory.
- The effects of the transaction, thus, are never lost.

4 Characterizing Schedules based on Recoverability (1)

- **Transaction schedule or history**:
  - When transactions are executing concurrently in an interleaved fashion, the order of execution of operations from the various transactions forms what is known as a transaction schedule (or history).
- A **schedule** (or **history**) S of n transactions T1, T2, …, Tn:
  - It is an ordering of the operations of the transactions subject to the constraint that, for each transaction Ti that participates in S, the operations of T1 in S must appear in the same order in which they occur in T1.
  - Note, however, that operations from other transactions Tj can be interleaved with the operations of Ti in S.

4 Characterizing Schedules based on Recoverability (1)

- **Transaction schedule or history**:
  - When transactions are executing concurrently in an interleaved fashion, the order of execution of operations from the various transactions forms what is known as a transaction schedule (or history).

Conflicting Operations in a Schedule.

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).

Intuitively, two operations are conflicting if changing their order can result in a different outcome.

4 Characterizing Schedules based on Recoverability (1)

- **Transaction schedule or history**:
  - When transactions are executing concurrently in an interleaved fashion, the order of execution of operations from the various transactions forms what is known as a transaction schedule (or history).

A schedule S of n transactions T1 , T2 , ... , Tn 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.

Characterizing Schedules based on Recoverability (2)

Schedules classified on recoverability:

- **Recoverable schedule**:
  - One where no transaction needs to be rolled back.
  - A schedule S is recoverable if no transaction T in S commits until all transactions T' that have written an item that T reads have committed.
- **Cascadeless schedule**:
  - One where every transaction reads only the items that are written by committed transactions.

Characterizing Schedules based on Recoverability (3)

Schedules classified on recoverability(contd.)

- **Schedules requiring cascaded rollback**:
  - A schedule in which uncommitted transactions that read an item from a failed transaction must be rolled back.
- **Strict Schedules**:
  - A schedule in which a transaction can neither read or write an item X until the last transaction that wrote X has committed.

5 Characterizing Schedules based on Serializability (1)

- Serial schedule:
  - 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 schedule.
- Serializable schedule:
  - A schedule S is serializable if it is equivalent to some serial schedule of the same n transactions.

Characterizing Schedules based on Serializability (2)

- Result equivalent:
  - Two schedules are called result equivalent if they produce the same final state of the database.
- Conflict equivalent:
  - Two schedules are said to be conflict equivalent if the order of any two conflicting operations is the same in both schedules.
- Conflict serializable:
  - A schedule S is said to be conflict serializable if it is conflict equivalent to some serial schedule S’.

Characterizing Schedules based on Serializability (3)

- Being serializable is <u>not</u> the same as being serial
- Being serializable implies that the schedule is a <u>correct</u> schedule.
  - It will leave the database in a consistent state.
  - The interleaving is appropriate and will result in a state as if the transactions were serially executed, yet will achieve efficiency due to concurrent execution.

Characterizing Schedules based on Serializability (4)

- Serializability is hard to check.
  - Interleaving of operations occurs in an operating system through some scheduler
  - Difficult to determine beforehand how the operations in a schedule will be interleaved.

Characterizing Schedules based on Serializability (5)

Practical approach:

- Come up with methods (protocols) to ensure serializability.
- It’s not possible to determine when a schedule begins and when it ends.
  - Hence, we reduce the problem of checking the whole schedule to checking only a **committed project** of the schedule (i.e. operations from only the committed transactions.)
- Current approach used in most DBMSs:
  - Use of locks with two phase locking

Characterizing Schedules based on Serializability (6)

- View equivalence:
  - A less restrictive definition of equivalence of schedules
- View serializability:
  - Definition of serializability based on view equivalence.
  - A schedule is *view serializable* if it is *view equivalent* to a serial schedule.

Characterizing Schedules based on Serializability (7)

- Two schedules 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 Ri(X) of Ti in S, if the value of X read by the operation has been written by an operation Wj(X) of Tj (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 Ri(X) of Ti in S'.
  3. If the operation Wk(Y) of Tk is the last operation to write item Y in S, then Wk(Y) of Tk must also be the last operation to write item Y in S'.

Characterizing Schedules based on Serializability (8)

- The premise behind view equivalence:
  - 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 view**": the read operations are said to see *the same view* in both schedules.

Characterizing Schedules based on Serializability (9)

- **Relationship between view and conflict equivalence**:
  - The two are same under **constrained write assumption** which assumes that if T writes X, it is constrained by the value of X it read; i.e., new X = f(old X)
  - Conflict serializability is **stricter** than view serializability. With unconstrained write (or blind write), a schedule that is view serializable is not necessarily conflict serializable.
  - Any conflict serializable schedule is also view serializable, but not vice versa.

Characterizing Schedules based on Serializability (10)

- Relationship between view and conflict equivalence (cont):
  - Consider the following schedule of three transactions
    - T1: r1(X), w1(X); T2: w2(X); and T3: w3(X):
  - Schedule Sa: r1(X); w2(X); w1(X); w3(X); c1; c2; c3;

- In Sa, the operations w2(X) and w3(X) are blind writes, since T1 and T3 do not read the value of X.
  - Sa is view serializable, since it is view equivalent to the serial schedule T1, T2, T3.
  - However, Sa is not conflict serializable, since it is not conflict equivalent to any serial schedule.

Characterizing Schedules based on Serializability (11)

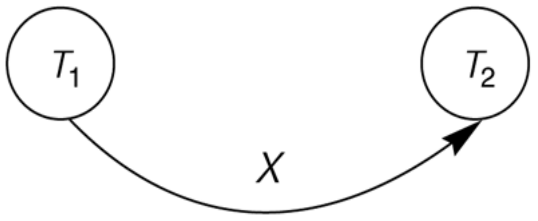
Testing for conflict serializability: Algorithm 17.1:

- Looks at only read_Item (X) and write_Item (X) operations
- Constructs a precedence graph (serialization graph) - a graph with directed edges
- An edge is created from Ti to Tj if one of the operations in Ti appears before a conflicting operation in Tj
- The schedule is serializable if and only if the precedence graph has no cycles.

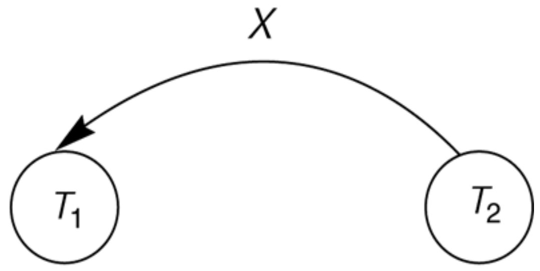
Constructing the Precedence Graphs

- Constructing the precedence graphs for schedules A and D from 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).

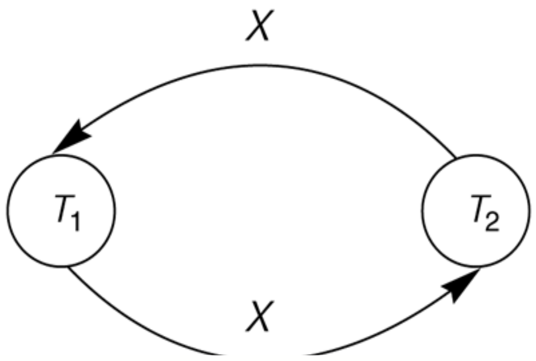
(a)



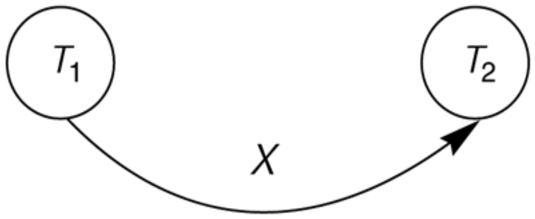
(b)



(c)



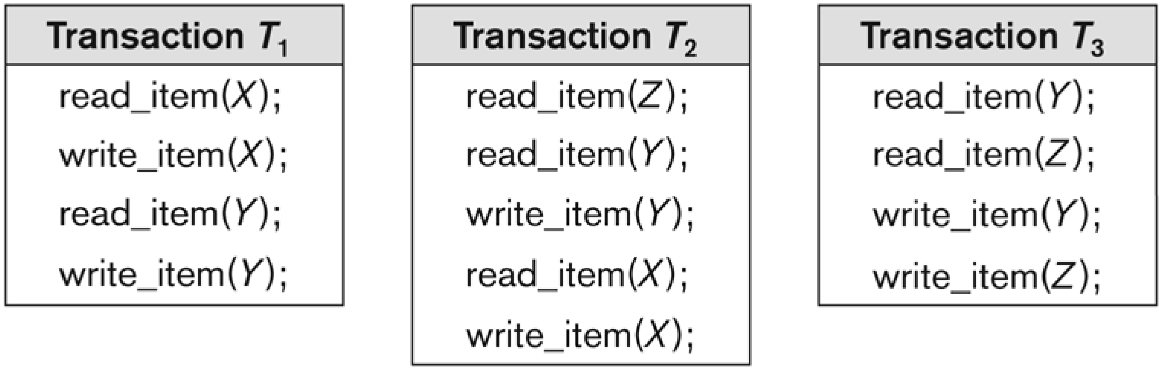
(d)



Another example of serializability Testing

Figure 17.8
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*.

(a)



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

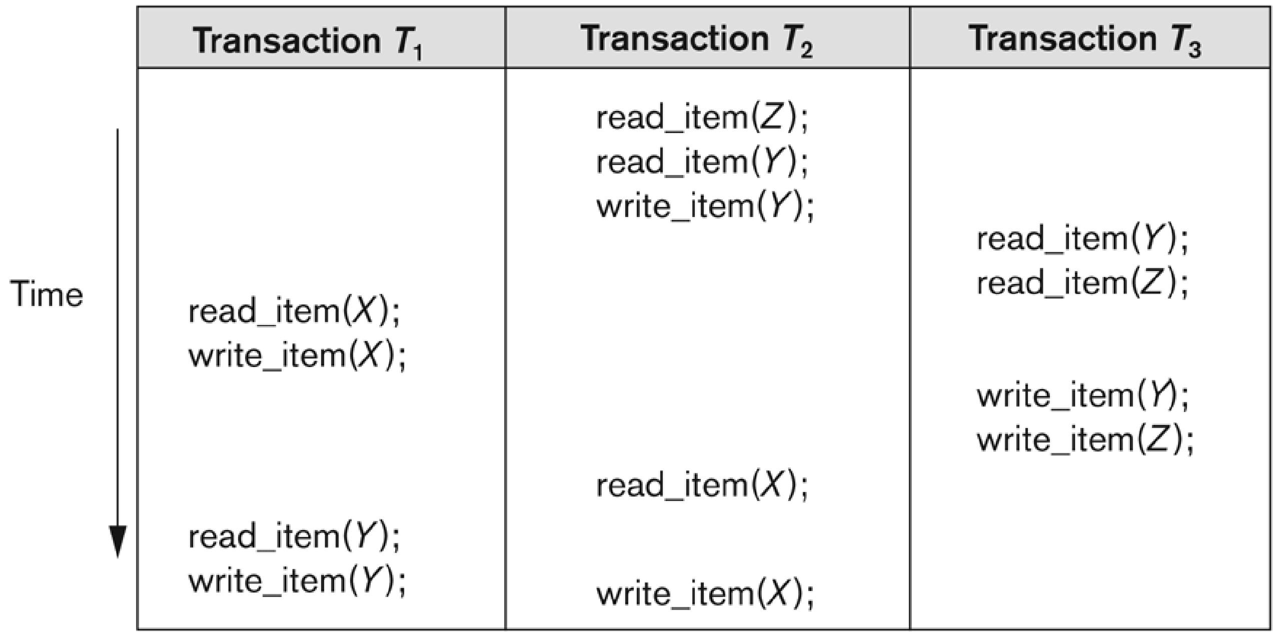
Transaction T_2
read_item(Z);
read_item(Y);
write_item(Y);
read_item(X);
write_item(X);

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

Another Example of Serializability Testing

Figure 17.8
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.

(b)



Time

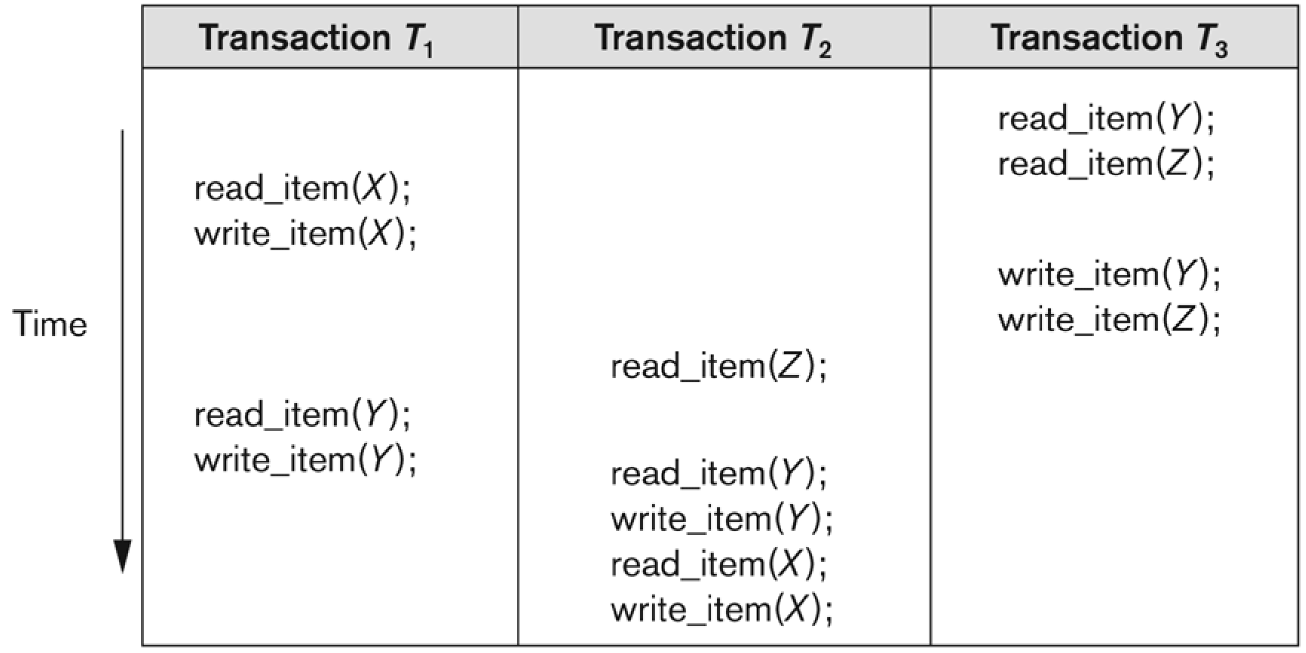
Transaction T_1	Transaction T_2	Transaction T_3
	read_item(Z);	
	read_item(Y);	
	write_item(Y);	
		read_item(Y);
		read_item(Z);
read_item(X);		
write_item(X);		
		write_item(Y);
		write_item(Z);
	read_item(X);	
read_item(Y);		
write_item(Y);		
	write_item(X);	

Schedule E

Another Example of Serializability Testing

Figure 17.8
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*.

(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

Characterizing Schedules based on Serializability (14)

Other Types of Equivalence of Schedules

- Under special **semantic constraints**, schedules that are otherwise not conflict serializable may work correctly.
  - Using commutative operations of addition and subtraction (which can be done in any order) certain non-serializable transactions may work correctly

Characterizing Schedules based on Serializability (15)

Other Types of Equivalence of Schedules (contd.)

- Example: bank credit / debit transactions on a given item are **separable** and **commutative**.
  - Consider the following schedule S for the two transactions:
  - Sh : r1(X); w1(X); r2(Y); w2(Y); r1(Y); w1(Y); r2(X); w2(X);
  - Using conflict serializability, it is **not serializable**.
  - However, if it came from a (read,update, write) sequence as follows:
    - r1(X); X := X – 10; w1(X); r2(Y); Y := Y – 20;r1(Y);
    - Y := Y + 10; w1(Y); r2(X); X := X + 20; (X);
  - Sequence explanation: debit, debit, credit, credit.
  - It is a *correct schedule* <u>*for the given semantics*</u>

Summary

- Transaction and System Concepts
- Desirable Properties of Transactions
- Characterizing Schedules based on Recoverability
- Characterizing Schedules based on Serializability

Concurrency Control Techniques

- Databases Concurrency Control
  1. Purpose of Concurrency Control
  2. Two-Phase locking
  3. Limitations of CCMs
  4. Index Locking
  5. Lock Compatibility Matrix
  6. Lock Granularity

Database Concurrency Control

- 1 Purpose of Concurrency Control
  - To enforce Isolation (through mutual exclusion) among conflicting transactions.
  - To preserve database consistency through consistency preserving execution of transactions.
  - To resolve read-write and write-write conflicts.
- Example:
  - In concurrent execution environment if T1 conflicts with T2 over a data item A, then the existing concurrency control decides if T1 or T2 should get the A and if the other transaction is rolled-back or waits.

Database Concurrency Control

Two-Phase Locking Techniques

- Locking is an operation which secures
  - (a) permission to Read
  - (b) permission to Write a data item for a transaction.
- Example:
  - Lock (X). Data item X is locked in behalf of the requesting transaction.
- Unlocking is an operation which removes these permissions from the data item.
- Example:
  - Unlock (X): Data item X is made available to all other transactions.
- Lock and Unlock are Atomic operations.

Database Concurrency Control

Two-Phase Locking Techniques: Essential components

- Two locks modes:
  - (a) shared (read) (b) exclusive (write).
- Shared mode: shared lock (X)
  - More than one transaction can apply share lock on X for reading its value but no write lock can be applied on X by any other transaction.
- Exclusive mode: Write lock (X)
  - Only one write lock on X can exist at any time and no shared lock can be applied by any other transaction on X.
- Conflict matrix

Read	Write
Y	N
N	N

Database Concurrency Control

Two-Phase Locking Techniques: Essential components

- Lock Manager:
  - Managing locks on data items.
- Lock table:
  - Lock manager uses it to store the identify of transaction locking a data item, the data item, lock mode and pointer to the next data item locked. One simple way to implement a lock table is through linked list.

Transaction ID	Data item id	lock mode	Ptr to next data item
T1	X1	Read	Next

Database Concurrency Control

Two-Phase Locking Techniques: Essential components

- Database requires that all transactions should be well-formed. A transaction is well-formed if:
  - It must lock the data item before it reads or writes to it.
  - It must not lock an already locked data items and it must not try to unlock a free data item.

Database Concurrency Control

Two-Phase Locking Techniques: Essential components

- The following code performs the lock operation:

```
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);
    goto B
    end;
```

Database Concurrency Control

Two-Phase Locking Techniques: Essential components

- The following code performs the unlock operation:

```
LOCK (X) ← 0 (*unlock the item*)
if any transactions are waiting then
  wake up one of the waiting the transactions;
```

Database Concurrency Control

Two-Phase Locking Techniques: Essential components

- The following code performs the read operation:

```
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;
```

Database Concurrency Control

Two-Phase Locking Techniques: Essential components

- The following code performs the write lock operation:

```
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;
```

Database Concurrency Control

Two-Phase Locking Techniques: Essential components

- The following code performs the unlock operation:

```
if LOCK (X) = “write-locked” then
 begin LOCK (X) ← “unlocked”;
      wakes up one of the transactions, if any
 end
 else if 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”;
       wake up one of the transactions, if any
          end
     end;
```

Database Concurrency Control

Two-Phase Locking Techniques: Essential components

- Lock conversion
  - Lock upgrade: existing read lock to write lock

```
if Ti has a read-lock (X) and Tj has no read-lock (X) (i ≠ j) then
     convert read-lock (X) to write-lock (X)
    else
     force Ti to wait until Tj unlocks X
```

  - Lock downgrade: existing write lock to read lock

```
Ti has a write-lock (X)    (*no transaction can have any lock on X*)
convert write-lock (X) to read-lock (X)
```

Database Concurrency Control

Two-Phase Locking Techniques: The algorithm

- Two Phases:
  - (a) Locking (Growing)
  - (b) Unlocking (Shrinking).
- **Locking (Growing) Phase:**
  - A transaction applies locks (read or write) on desired data items one at a time.
- **Unlocking (Shrinking) Phase:**
  - A transaction unlocks its locked data items one at a time.
- **Requirement:**
  - For a transaction these two phases must be mutually exclusively, that is, during locking phase unlocking phase must not start and during unlocking phase locking phase must not begin.

Database Concurrency Control

Two-Phase Locking Techniques: The algorithm

T1	**T2**	**Result**
read_lock (Y);	read_lock (X);	Initial values: X=20; Y=30
read_item (Y);	read_item (X);	Result of serial execution
unlock (Y);	unlock (X);	T1 followed by T2
write_lock (X);	Write_lock (Y);	X=50, Y=80.
read_item (X);	read_item (Y);	Result of serial execution
X:=X+Y;	Y:=X+Y;	T2 followed by T1
write_item (X);	write_item (Y);	X=70, Y=50
unlock (X);	unlock (Y);	

Database Concurrency Control

Two-Phase Locking Techniques: The algorithm

T1	**T2**	**<u>Result</u>**
read_lock (Y);		X=50; Y=50
read_item (Y);		Nonserializable because it.
unlock (Y);		violated two-phase policy.
	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);		

Time $\downarrow$

Database Concurrency Control

Two-Phase Locking Techniques: The algorithm

```
T'1                T'2

read_lock (Y);     read_lock (X);     T1 and T2 follow two-phase
read_item (Y);     read_item (X);     policy but they are subject to
write_lock (X);    Write_lock (Y);    deadlock, which must be
unlock (Y);        unlock (X);        dealt with.
read_item (X);     read_item (Y);
X:=X+Y;            Y:=X+Y;
write_item (X);    write_item (Y);
unlock (X);        unlock (Y);
```

Database Concurrency Control

Two-Phase Locking Techniques: The algorithm

- Two-phase policy generates two locking algorithms
  - (a) **Basic**
  - (b) **Conservative**
- **Conservative**:
  - Prevents deadlock by locking all desired data items before transaction begins execution.
- **Basic**:
  - Transaction locks data items incrementally. This may cause deadlock which is dealt with.
- **Strict**:
  - A more stricter version of Basic algorithm where unlocking is performed after a transaction terminates (commits or aborts and rolled-back). This is the most commonly used two-phase locking algorithm.

Database Concurrency Control

Dealing with Deadlock and Starvation

- **Deadlock**

```
T'1                 T'2

read_lock (Y);                          T1 and T2 did follow two-phase
read_item (Y);                          policy but they are deadlock
              read_lock (X);
              read_item (Y);
write_lock (X);
(waits for X)           write_lock (Y);
              (waits for Y)
```

- Deadlock (T’1 and T’2)

Database Concurrency Control

Dealing with Deadlock and Starvation

- **Deadlock prevention**
  - A transaction locks all data items it refers to before it begins execution.
  - This way of locking prevents deadlock since a transaction never waits for a data item.
  - The conservative two-phase locking uses this approach.

Database Concurrency Control

Dealing with Deadlock and Starvation

- **Deadlock detection and resolution**
  - In this approach, deadlocks are allowed to happen. The scheduler maintains a wait-for-graph for detecting cycle. If a cycle exists, then one transaction involved in the cycle is selected (victim) and rolled-back.
  - A wait-for-graph is created using the lock table. As soon as a transaction is blocked, it is added to the graph. When a chain like: Ti waits for Tj waits for Tk waits for Ti or Tj occurs, then this creates a cycle. One of the transaction o

Database Concurrency Control

Dealing with Deadlock and Starvation

- **Deadlock avoidance**
  - There are many variations of two-phase locking algorithm.
  - Some avoid deadlock by not letting the cycle to complete.
  - That is as soon as the algorithm discovers that blocking a transaction is likely to create a cycle, it rolls back the transaction.
  - Wound-Wait and Wait-Die algorithms use timestamps to avoid deadlocks by rolling-back victim.

Database Concurrency Control

Dealing with Deadlock and Starvation

- **Starvation**
  - Starvation occurs when a particular transaction consistently waits or restarted and never gets a chance to proceed further.
  - In a deadlock resolution it is possible that the same transaction may consistently be selected as victim and rolled-back.
  - This limitation is inherent in all priority based scheduling mechanisms.
  - In Wound-Wait scheme a younger transaction may always be wounded (aborted) by a long running older transaction which may create starvation.

Database Concurrency Control

Timestamp based concurrency control algorithm

- **Timestamp**
  - A monotonically increasing variable (integer) indicating the age of an operation or a transaction. A larger timestamp value indicates a more recent event or operation.
  - Timestamp based algorithm uses timestamp to serialize the execution of concurrent transactions.

Database Concurrency Control

Timestamp based concurrency control algorithm

- **Basic Timestamp Ordering**
  - 1. Transaction T issues a write_item(X) operation:
    - If read_TS(X) > TS(T) or if write_TS(X) > TS(T), then an younger transaction has already read the data item so abort and roll-back T and reject the operation.
    - If the condition in part (a) does not exist, then execute write_item(X) of T and set write_TS(X) to TS(T).
  - 2. Transaction T issues a read_item(X) operation:
    - If write_TS(X) > TS(T), then an younger transaction has already written to the data item so abort and roll-back T and reject the operation.
    - If write_TS(X) $\leq$ TS(T), then execute read_item(X) of T and set read_TS(X) to the larger of TS(T) and the current read_TS(X).

Database Concurrency Control

Timestamp based concurrency control algorithm

- **Strict Timestamp Ordering**
  - 1. Transaction T issues a write_item(X) operation:
    - If TS(T) > read_TS(X), then delay T until the transaction T' that wrote or read X has terminated (committed or aborted).
  - 2. Transaction T issues a read_item(X) operation:
    - If TS(T) > write_TS(X), then delay T until the transaction T' that wrote or read X has terminated (committed or aborted).

Database Concurrency Control

Timestamp based concurrency control algorithm

- **Thomas's Write Rule**
  - If read_TS(X) > TS(T) then abort and roll-back T and reject the operation.
  - If write_TS(X) > TS(T), then just ignore the write operation and continue execution. This is because the most recent writes counts in case of two consecutive writes.
  - If the conditions given in 1 and 2 above do not occur, then execute write_item(X) of T and set write_TS(X) to TS(T).

Database Concurrency Control

Multiversion concurrency control techniques

- This approach maintains a number of versions of a data item and allocates the right version to a read operation of a transaction. Thus unlike other mechanisms a read operation in this mechanism is never rejected.
- Side effect:
  - Significantly more storage (RAM and disk) is required to maintain multiple versions. To check unlimited growth of versions, a garbage collection is run when some criteria is satisfied.

Database Concurrency Control

Multiversion technique based on timestamp ordering

- This approach maintains a number of versions of a data item and allocates the right version to a read operation of a transaction.
  - Thus unlike other mechanisms a read operation in this mechanism is never rejected.
- Side effects: Significantly more storage (RAM and disk) is required to maintain multiple versions. To check unlimited growth of versions, a garbage collection is run when some criteria is satisfied.

Database Concurrency Control

Multiversion technique based on timestamp ordering

- Assume X1, X2, …, Xn are the version of a data item X created by a write operation of transactions. With each Xi a read_TS (read timestamp) and a write_TS (write timestamp) are associated.
- **read_TS(Xi)**: The read timestamp of Xi is the largest of all the timestamps of transactions that have successfully read version Xi.
- **write_TS(Xi)**: The write timestamp of Xi that wrote the value of version Xi.
- A new version of Xi is created only by a write operation.

Database Concurrency Control

Multiversion technique based on timestamp ordering

- To ensure serializability, the following two rules are used.
- If transaction T issues write_item (X) and version i of X has the highest write_TS(Xi) of all versions of X that is also less than or equal to TS(T), and read _TS(Xi) > TS(T), then abort and roll-back T; otherwise create a new version Xi and read_TS(X) = write_TS(Xj) = TS(T).
- If transaction T issues read_item (X), find the version i of X that has the highest write_TS(Xi) of all versions of X that is also less than or equal to TS(T), then return the value of Xi to T, and set the value of read _TS(Xi) to the largest of TS(T) and the current read_TS(Xi).

Database Concurrency Control

Multiversion technique based on timestamp ordering

- To ensure serializability, the following two rules are used.
  - If transaction T issues write_item (X) and version i of X has the highest write_TS(Xi) of all versions of X that is also less than or equal to TS(T), and read _TS(Xi) > TS(T), then abort and roll-back T; otherwise create a new version Xi and read_TS(X) = write_TS(Xj) = TS(T).
  - If transaction T issues read_item (X), find the version i of X that has the highest write_TS(Xi) of all versions of X that is also less than or equal to TS(T), then return the value of Xi to T, and set the value of read _TS(Xi) to the largest of TS(T) and the current read_TS(Xi).
- Rule 2 guarantees that a read will never be rejected.

Database Concurrency Control

Multiversion Two-Phase Locking Using Certify Locks

- Concept
  - Allow a transaction T' to read a data item X while it is write locked by a conflicting transaction T.
  - This is accomplished by maintaining two versions of each data item X where one version must always have been written by some committed transaction. This means a write operation always creates a new version of X.

Database Concurrency Control

Multiversion Two-Phase Locking Using Certify Locks

- Steps
  1. X is the committed version of a data item.
  2. T creates a second version X’ after obtaining a write lock on X.
  3. Other transactions continue to read X.
  4. T is ready to commit so it obtains a certify lock on X’.
  5. The committed version X becomes X’.
  6. T releases its certify lock on X’, which is X now.

Compatibility tables for

	Read	Write
Read	yes	no
Write	no	no

read/write locking scheme

	Read	Write	Certify
Read	yes	no	no
Write	no	no	no
Certify	no	no	no

read/write/certify locking scheme

Database Concurrency Control

Multiversion Two-Phase Locking Using Certify Locks

- Note:
  - In multiversion 2PL read and write operations from conflicting transactions can be processed concurrently.
  - This improves concurrency but it may delay transaction commit because of obtaining certify locks on all its writes. It avoids cascading abort but like strict two phase locking scheme conflicting transactions may get deadlocked.

Database Concurrency Control

Validation (Optimistic) Concurrency Control Schemes

- In this technique only at the time of commit serializability is checked and transactions are aborted in case of non-serializable schedules.
- Three phases:
  1. **Read phase**
  2. **Validation phase**
  3. **Write phase**

1. **Read phase**:

   - A transaction can read values of committed data items. However, updates are applied only to local copies (versions) of the data items (in database cache).

Database Concurrency Control

Validation (Optimistic) Concurrency Control Schemes

2. **Validation phase**: Serializability is checked before transactions write their updates to the database.
   - This phase for Ti checks that, for each transaction Tj that is either committed or is in its validation phase, one of the following conditions holds:
     - Tj completes its write phase before Ti starts its read phase.
     - Ti starts its write phase after Tj completes its write phase, and the read_set of Ti has no items in common with the write_set of Tj
     - Both the read_set and write_set of Ti have no items in common with the write_set of Tj, and Tj completes its read phase.
     - When validating Ti, the first condition is checked first for each transaction Tj, since (1) is the simplest condition to check. If (1) is false then (2) is checked and if (2) is false then (3) is checked. If none of these conditions holds, the validation fails and Ti is aborted.

Database Concurrency Control

Validation (Optimistic) Concurrency Control Schemes

3. **Write phase**: On a successful validation transactions’ updates are applied to the database; otherwise, transactions are restarted.

Database Concurrency Control

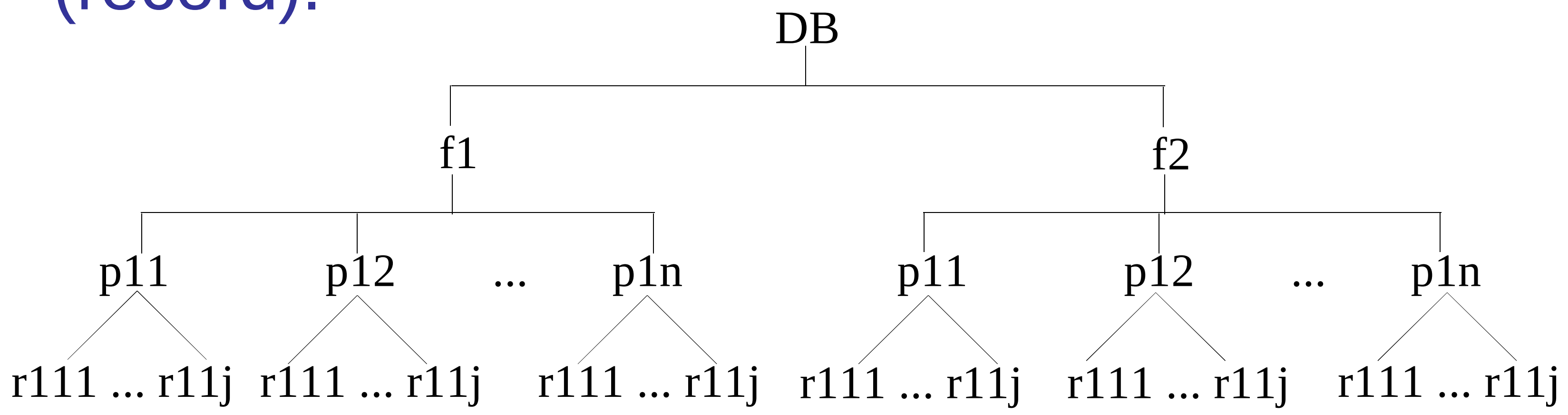
Granularity of data items and Multiple Granularity Locking

- A lockable unit of data defines its granularity. Granularity can be coarse (entire database) or it can be fine (a tuple or an attribute of a relation).
- Data item granularity significantly affects concurrency control performance. Thus, the degree of concurrency is low for coarse granularity and high for fine granularity.
- Example of data item granularity:
  1. A field of a database record (an attribute of a tuple)
  2. A database record (a tuple or a relation)
  3. A disk block
  4. An entire file
  5. The entire database

Database Concurrency Control

Granularity of data items and Multiple Granularity Locking

- The following diagram illustrates a hierarchy of granularity from coarse (database) to fine (record).



Database Concurrency Control

Granularity of data items and Multiple Granularity Locking

- To manage such hierarchy, in addition to read and write, three additional locking modes, called intention lock modes are defined:
  - **Intention-shared (IS)**: indicates that a shared lock(s) will be requested on some descendent nodes(s).
  - **Intention-exclusive (IX)**: indicates that an exclusive lock(s) will be requested on some descendent node(s).
  - **Shared-intention-exclusive (SIX)**: indicates that the current node is locked in shared mode but an exclusive lock(s) will be requested on some descendent nodes(s).

Database Concurrency Control

Granularity of data items and Multiple Granularity Locking

- These locks are applied using the following compatibility matrix:

	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

Intention-shared (IS
Intention-exclusive (IX)
Shared-intention-exclusive (SIX)

Database Concurrency Control

Granularity of data items and Multiple Granularity Locking

- The set of rules which must be followed for producing serializable schedule are
  1. The lock compatibility must 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 IX mode only if the parent node is already locked by T in either IS or IX mode.
  4. A node N can be locked by T in X, IX, or SIX mode only if the parent of N is already locked by T in either IX or SIX mode.
  5. T can lock a node only if it has not unlocked any node (to enforce 2PL policy).
  6. T can unlock a node, N, only if none of the children of N are currently locked by T.

Database Concurrency Control

Granularity of data items and Multiple Granularity Locking: An example of a serializable execution:

T1	T2	T3
IX(db)		
IX(f1)		
	IX(db)	
		IS(db)
		IS(f1)
		IS(p11)
IX(p11)		
X(r111)		
	IX(f1)	
	X(p12)	
		S(r11j)
IX(f2)		
IX(p21)		
IX(r211)		
Unlock (r211)		
Unlock (p21)		
Unlock (f2)		
		S(f2)

Database Concurrency Control

- Granularity of data items and Multiple Granularity Locking: An example of a serializable execution (continued):

T1	T2	T3
	unlock(p12)	
	unlock(f1)	
	unlock(db)	
unlock(r111)		
unlock(p11)		
unlock(f1)		
unlock(db)		
		unlock (r111j)
		unlock (p11)
		unlock (f1)
		unlock(f2)
		unlock(db)

Summary

- Databases Concurrency Control
  1. Purpose of Concurrency Control
  2. Two-Phase locking
  3. Limitations of CCMs
  4. Index Locking
  5. Lock Compatibility Matrix
  6. Lock Granularity

Databases Recovery

Databases Recovery

Databases Recovery

1. Purpose of Database Recovery
2. Types of Failure
3. Transaction Log
4. Data Updates
5. Data Caching
6. Transaction Roll-back (Undo) and Roll-Forward
7. Checkpointing
8. Recovery schemes
9. ARIES Recovery Scheme
10. Recovery in Multidatabase System

Database Recovery

1 Purpose of Database Recovery

To bring the database into the last consistent state, which existed prior to the failure.

To preserve transaction properties (Atomicity, Consistency, Isolation and Durability).

Example:

If the system crashes before a fund transfer transaction completes its execution, then either one or both accounts may have incorrect value. Thus, the database must be restored to the state before the transaction modified any of the accounts.

Database Recovery

2 Types of Failure

The database may become unavailable for use due to

- **Transaction failure**: Transactions may fail because of incorrect input, deadlock, incorrect synchronization.
- **System failure**: System may fail because of addressing error, application error, operating system fault, RAM failure, etc.
- **Media failure**: Disk head crash, power disruption, etc.

Database Recovery

3 Transaction Log

For recovery from any type of failure data values prior to modification (BFIM - BeFore Image) and the new value after modification (AFIM – AFter Image) are required.

These values and other information is stored in a sequential file called Transaction log. A sample log is given below. Back P and Next P point to the previous and next log records of the same transaction.

T ID	Back P	Next P	Operation	Data item	BFIM	AFIM
T1	0	1	Begin			
T1	1	4	Write	X	X = 100	X = 200
T2	0	8	Begin			
T1	2	5	W	Y	Y = 50	Y = 100
T1	4	7	R	M	M = 200	M = 200
T3	0	9	R	N	N = 400	N = 400
T1	5	nil	End			

Database Recovery

4 Data Update

Immediate Update: As soon as a data item is modified in cache, the disk copy is updated.

Deferred Update: All modified data items in the cache is written either after a transaction ends its execution or after a fixed number of transactions have completed their execution.

Shadow update: The modified version of a data item does not overwrite its disk copy but is written at a separate disk location.

In-place update: The disk version of the data item is overwritten by the cache version.

Database Recovery

5 Data Caching

Data items to be modified are first stored into database cache by the Cache Manager (CM) and after modification they are flushed (written) to the disk.

The flushing is controlled by **Modified** and **Pin-Unpin** bits.

- **Pin-Unpin**: Instructs the operating system not to flush the data item.
- **Modified**: Indicates the AFIM of the data item.

Database Recovery

6 Transaction **Roll-back (Undo)** and **Roll-Forward (Redo)**

To maintain atomicity, a transaction’s operations are redone or undone.

- **Undo**: Restore all BFIMs on to disk (Remove all AFIMs).
- **Redo**: Restore all AFIMs on to disk.

Database recovery is achieved either by performing only Undos or only Redos or by a combination of the two. These operations are recorded in the log as they happen.

Database Recovery

(a)

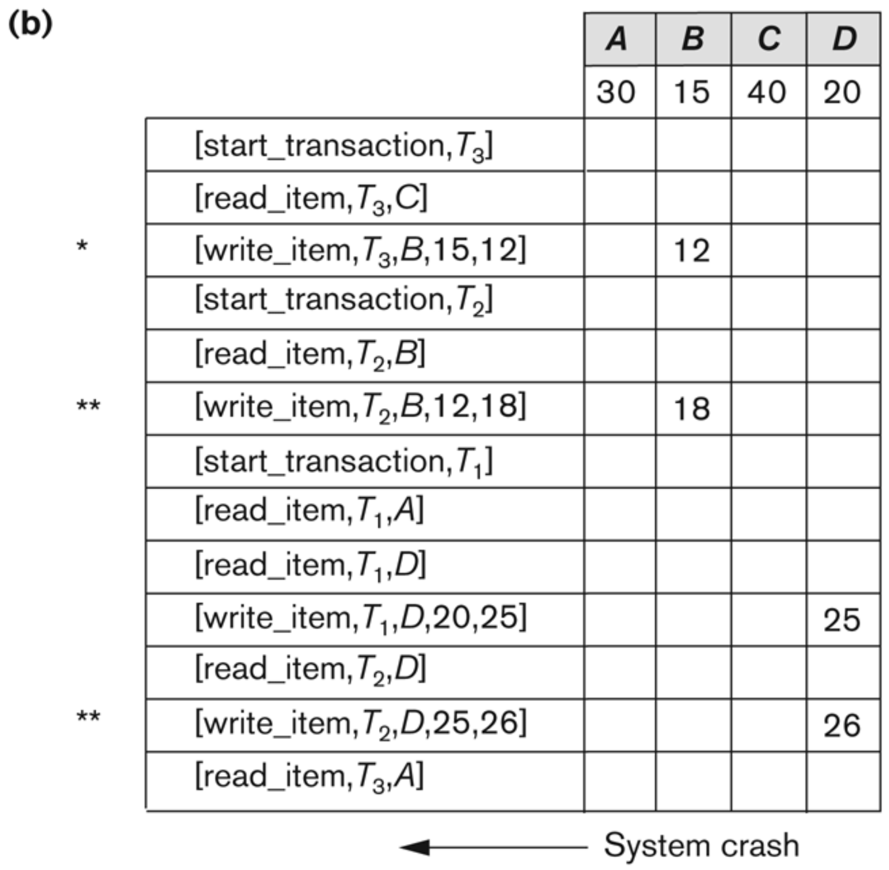
T_1
read_item(A)
read_item(D)
write_item(D)

T_2
read_item(B)
write_item(B)
read_item(D)
write_item(D)

T_3
read_item(C)
write_item(B)
read_item(A)
write_item(A)

Figure 19.1
Illustrating cascading rollback (a process that never occurs in strict or cascadeless schedules). (a) The read and write operations of three transactions. (b) System log at point of crash. (c) Operations before the crash.

Database Recovery



(b)

		A	*B*	*C*	*D*
		30	15	40	20
	[start_transaction,T_3]				
	[read_item,T_3,*C*]				
*	[write_item,T_3,*B*,15,12]		12		
	[start_transaction,T_2]				
	[read_item,T_2,*B*]				
**	[write_item,T_2,*B*,12,18]		18		
	[start_transaction,T_1]				
	[read_item,T_1,*A*]				
	[read_item,T_1,*D*]				
	[write_item,T_1,*D*,20,25]				25
	[read_item,T_2,*D*]				
**	[write_item,T_2,*D*,25,26]				26
	[read_item,T_3,*A*]				

$\longleftarrow$ System crash

Figure 19.1
Illustrating cascading rollback (a process that never occurs in strict or cascadeless schedules). (a) The read and write operations of three transactions. (b) System log at point of crash. (c) Operations before the crash.

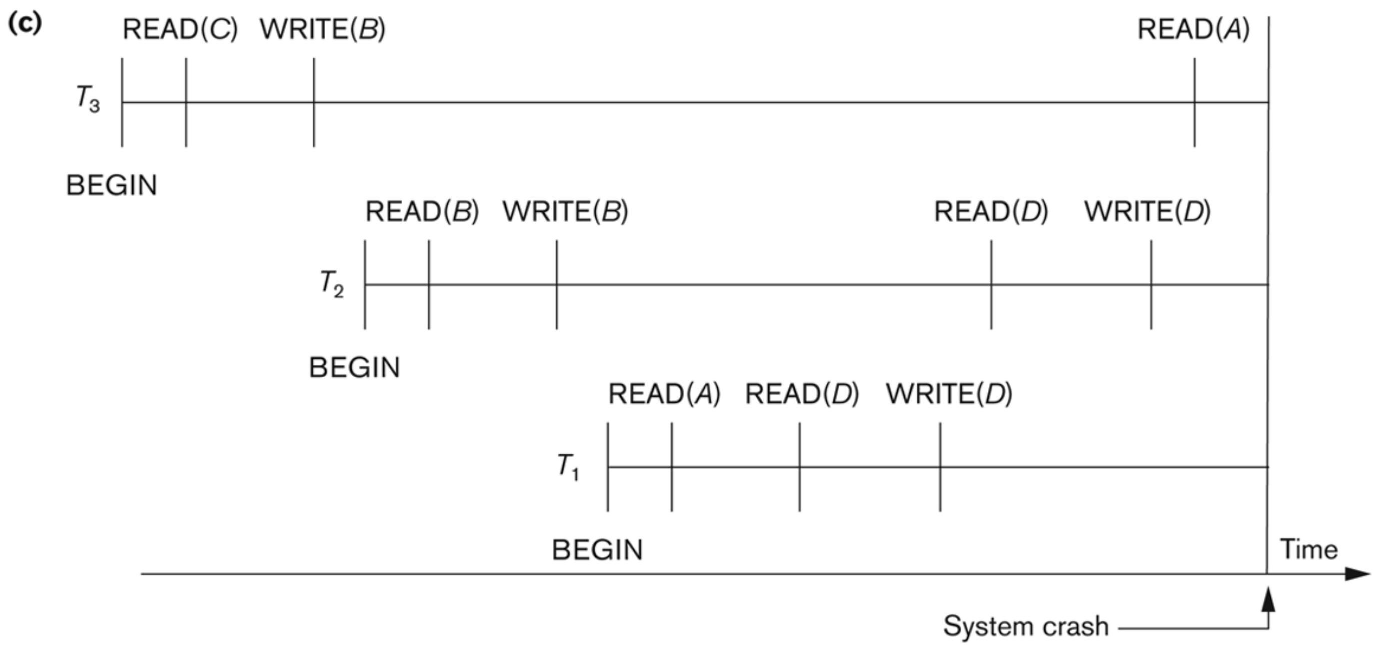
* T_3 is rolled back because it did not reach its commit point.

** T_2 is rolled back because it reads the value of item *B* written by T_3.

Database Recovery

Roll-back: One execution of T1, T2 and T3 as recorded in the log.

Figure 19.1
Illustrating cascading rollback (a process that never occurs in strict or cascadeless schedules).
(a) The read and write operations of three transactions.
(b) System log at point of crash. (c) Operations before the crash.



Database Recovery

Write-Ahead Logging

When **in-place** update (immediate or deferred) is used then log is necessary for recovery and it must be available to recovery manager. This is achieved by **Write-Ahead Logging (WAL)** protocol. WAL states that

For Undo: Before a data item's AFIM is flushed to the database disk (overwriting the BFIM) its BFIM must be written to the log and the log must be saved on a stable store (log disk).

For Redo: Before a transaction executes its commit operation, all its AFIMs must be written to the log and the log must be saved on a stable store.

Database Recovery

7 Checkpointing

- Time to time (randomly or under some criteria) the database flushes its buffer to database disk to minimize the task of recovery. The following steps defines a checkpoint operation:
  1. Suspend execution of transactions temporarily.
  2. Force write modified buffer data to disk.
  3. Write a [checkpoint] record to the log, save the log to disk.
  4. Resume normal transaction execution.
- During recovery redo or undo is required to transactions appearing after [checkpoint] record.

Database Recovery

Steal/No-Steal and Force/No-Force

- Possible ways for flushing database cache to database disk:
  1. Steal: Cache can be flushed before transaction commits.
  2. No-Steal: Cache cannot be flushed before transaction commit.
  3. Force: Cache is immediately flushed (forced) to disk.
  4. No-Force: Cache is deferred until transaction commits
- These give rise to four different ways for handling recovery:
  - Steal/No-Force (Undo/Redo)
  - Steal/Force (Undo/No-redo)
  - No-Steal/No-Force (Redo/No-undo)
  - No-Steal/Force (No-undo/No-redo)

Database Recovery

8 Recovery Scheme

Deferred Update (No Undo/Redo)

The data update goes as follows:

A set of transactions records their updates in the log.

At commit point under WAL scheme these updates are saved on database disk.

After reboot from a failure the log is used to redo all the transactions affected by this failure. No undo is required because no AFIM is flushed to the disk before a transaction commits.

Database Recovery

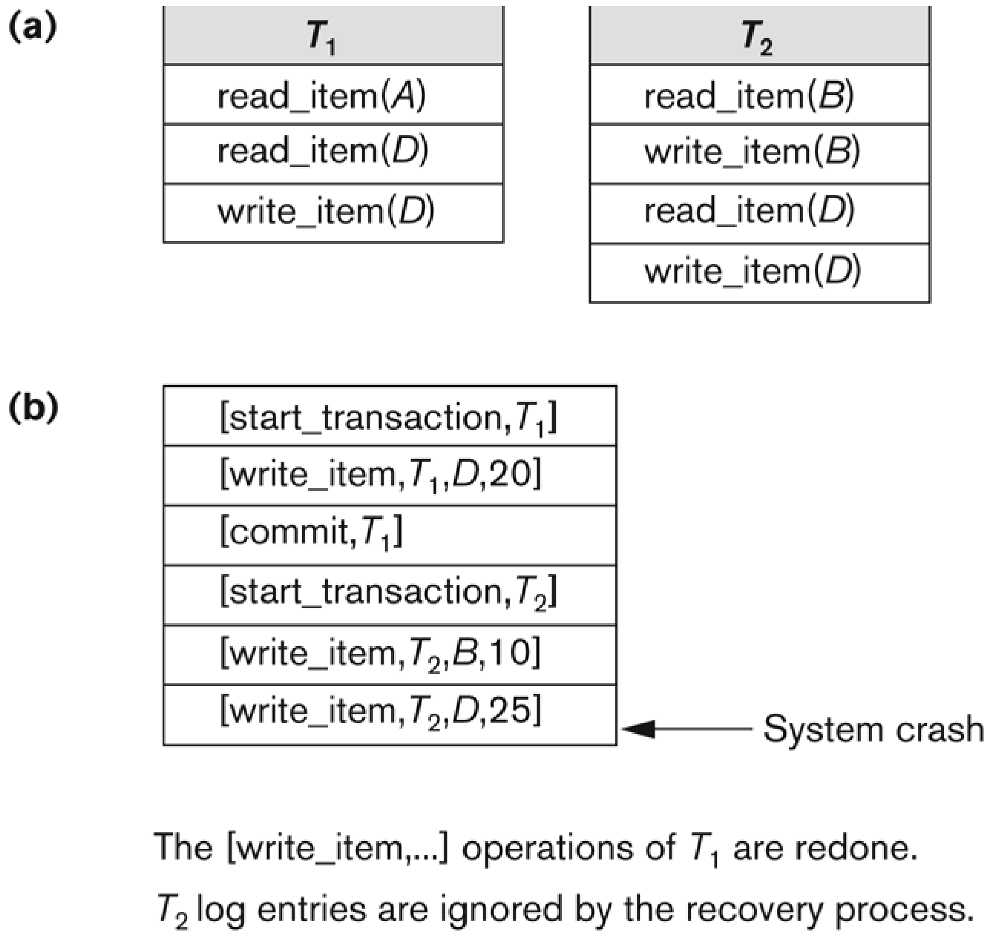
Deferred Update in a single-user system
There is no concurrent data sharing in a single user system.
The data update goes as follows:

A set of transactions records their updates in the log.

At commit point under WAL scheme these updates are saved on database disk.

After reboot from a failure the log is used to redo all the transactions affected by this failure. No undo is required because no AFIM is flushed to the disk before a transaction commits.

Database Recovery



(a)

T_1
read_item(A)
read_item(D)
write_item(D)

T_2
read_item(B)
write_item(B)
read_item(D)
write_item(D)

(b)

[start_transaction,T_1]
[write_item,T_1,D,20]
[commit,T_1]
[start_transaction,T_2]
[write_item,T_2,B,10]
[write_item,T_2,D,25] ← System crash

The [write_item,...] operations of T_1 are redone.

T_2 log entries are ignored by the recovery process.

Figure 19.2
An example of recovery using deferred update in a single-user environment. (a) The READ and WRITE operations of two transactions. (b) The system log at the point of crash.

Database Recovery

Deferred Update with concurrent users

This environment requires some concurrency control mechanism to guarantee **isolation** property of transactions. In a system recovery transactions which were recorded in the log after the last checkpoint were **redone**. The recovery manager may scan some of the transactions recorded before the checkpoint to get the AFIMs.

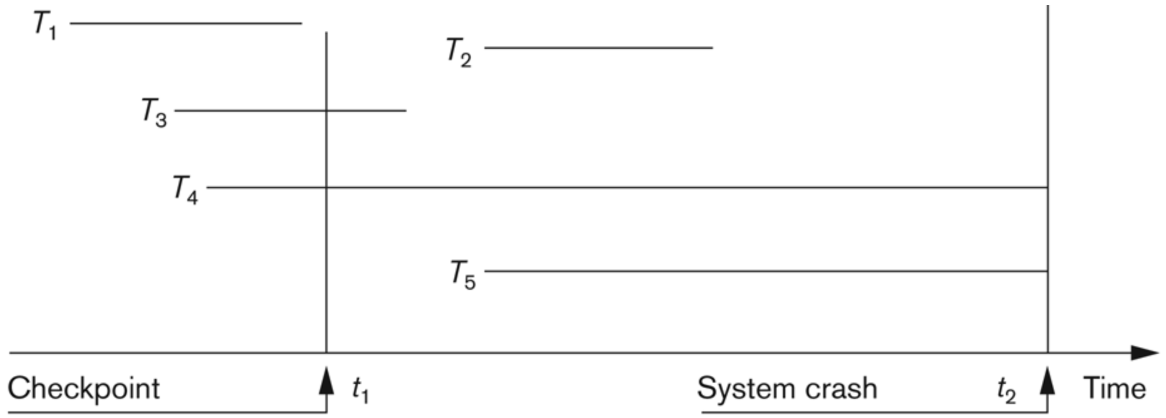
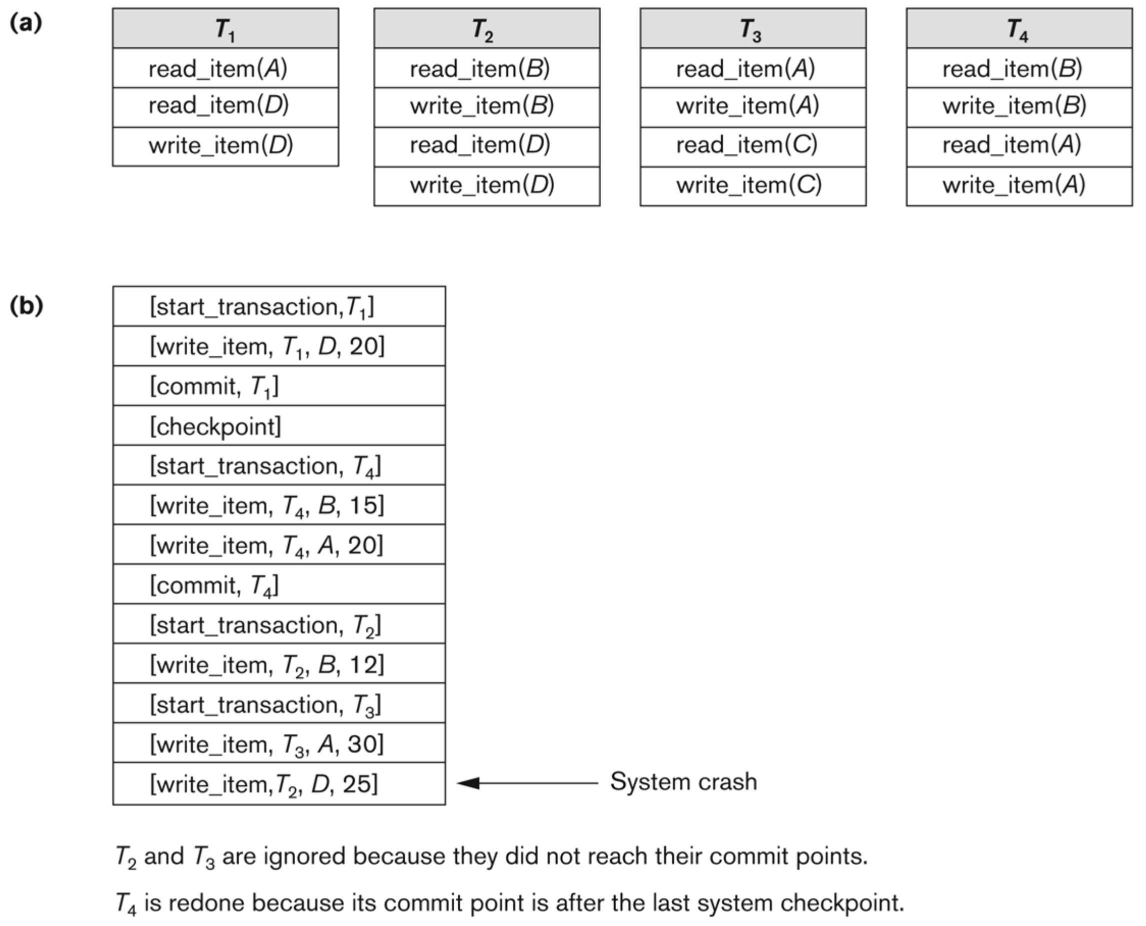


Figure 19.3
An example of recovery in a multi-user environment

Database Recovery



(a)

T_1	T_2	T_3	T_4
read_item(A)	read_item(B)	read_item(A)	read_item(B)
read_item(D)	write_item(B)	write_item(A)	write_item(B)
write_item(D)	read_item(D)	read_item(C)	read_item(A)
	write_item(D)	write_item(C)	write_item(A)

(b)

[start_transaction,T_1]
[write_item, T_1, D, 20]
[commit, T_1]
[checkpoint]
[start_transaction, T_4]
[write_item, T_4, B, 15]
[write_item, T_4, A, 20]
[commit, T_4]
[start_transaction, T_2]
[write_item, T_2, B, 12]
[start_transaction, T_3]
[write_item, T_3, A, 30]
[write_item,T_2, D, 25]

$\longleftarrow$ System crash

T_2 and T_3 are ignored because they did not reach their commit points.

T_4 is redone because its commit point is after the last system checkpoint.

Figure 19.4
An example of recovery using deferred update with concurrent transactions.
(a) The READ and WRITE operations of four transactions. (b) System log at the point of crash.

Database Recovery

Deferred Update with concurrent users

Two tables are required for implementing this protocol:

Active table: All active transactions are entered in this table.

Commit table: Transactions to be committed are entered in this table.

During recovery, all transactions of the **commit** table are redone and all transactions of **active** tables are ignored since none of their AFIMs reached the database. It is possible that a **commit** table transaction may be **redone** twice but this does not create any inconsistency because of a redone is "**idempotent**", that is, one redone for an AFIM is equivalent to multiple redone for the same AFIM.

Database Recovery

Recovery Techniques Based on Immediate Update

Undo/No-redo Algorithm

In this algorithm AFIMs of a transaction are flushed to the database disk under WAL before it commits.

For this reason the recovery manager **undoes** all transactions during recovery.

No transaction is **redone**.

It is possible that a transaction might have completed execution and ready to commit but this transaction is also **undone**.

Database Recovery

Recovery Techniques Based on Immediate Update

Undo/Redo Algorithm (**Single-user** environment)

- Recovery schemes of this category apply **undo** and also **redo** for recovery.
- In a single-user environment no concurrency control is required but a log is maintained under WAL.
- Note that at any time there will be one transaction in the system and it will be either in the commit table or in the active table.
- The recovery manager performs:
  - **Undo** of a transaction if it is in the **active** table.
  - **Redo** of a transaction if it is in the **commit** table.

Database Recovery

Recovery Techniques Based on Immediate Update

Undo/Redo Algorithm (**Concurrent** execution)

Recovery schemes of this category applies **undo** and also **redo** to recover the database from failure.

In concurrent execution environment a concurrency control is required and log is maintained under WAL.

Commit table records transactions to be committed and active table records active transactions. To minimize the work of the recovery manager checkpointing is used.

The recovery performs:

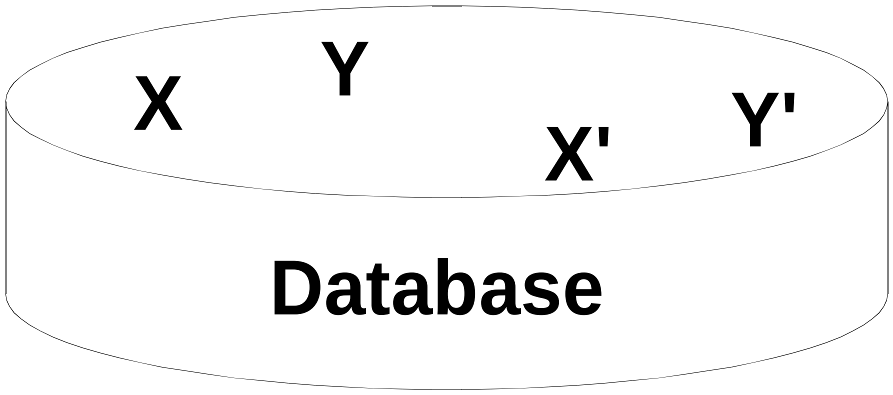
Undo of a transaction if it is in the **active** table.

Redo of a transaction if it is in the **commit** table.

Database Recovery

Shadow Paging

The AFIM does not overwrite its BFIM but recorded at another place on the disk. Thus, at any time a data item has AFIM and BFIM (Shadow copy of the data item) at two different places on the disk.



X and Y: Shadow copies of data items
X' and Y': Current copies of data items

Database Recovery

Shadow Paging

To manage access of data items by concurrent transactions two directories (current and shadow) are used.

The directory arrangement is illustrated below. Here a page is a data item.

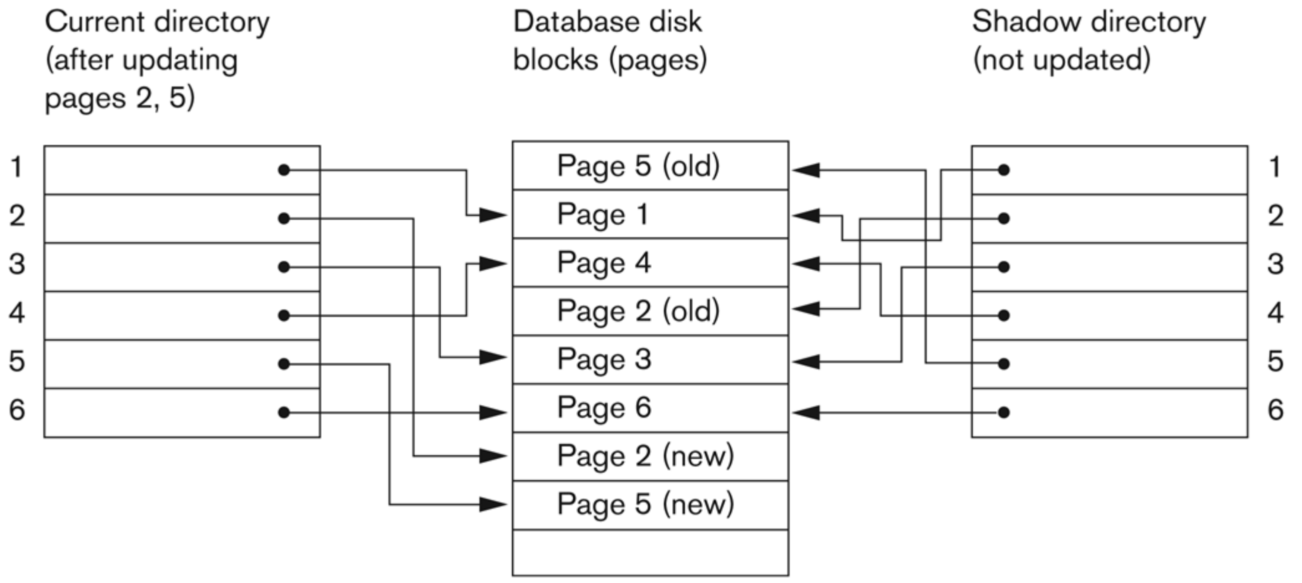

Current directory (after updating pages 2, 5)
Database disk blocks (pages)
Shadow directory (not updated)
1
2
3
4
5
6
Page 5 (old)
Page 1
Page 4
Page 2 (old)
Page 3
Page 6
Page 2 (new)
Page 5 (new)
1
2
3
4
5
6

Figure 19.5
An example of shadow paging.

Database Recovery

The ARIES Recovery Algorithm

The ARIES Recovery Algorithm is based on:

WAL (Write Ahead Logging)

Repeating history during redo:

- ARIES will retrace all actions of the database system prior to the crash to reconstruct the database state when the crash occurred.

Logging changes during undo:

- It will prevent ARIES from repeating the completed undo operations if a failure occurs during recovery, which causes a restart of the recovery process.

Database Recovery

The ARIES Recovery Algorithm (contd.)

- The ARIES recovery algorithm consists of three steps:
  1. **Analysis**: step identifies the dirty (updated) pages in the buffer and the set of transactions active at the time of crash. The appropriate point in the log where redo is to start is also determined.
  2. **Redo**: necessary redo operations are applied.
  3. **Undo**: log is scanned backwards and the operations of transactions active at the time of crash are undone in reverse order.

Database Recovery

The ARIES Recovery Algorithm (contd.)

The Log and Log Sequence Number (LSN)

A log record is written for:

- (a) data update
- (b) transaction commit
- (c) transaction abort
- (d) undo
- (e) transaction end

In the case of undo a compensating log record is written.

Database Recovery

The ARIES Recovery Algorithm (contd.)

The Log and Log Sequence Number (LSN) (contd.)

A unique LSN is associated with every log record.

- LSN increases monotonically and indicates the disk address of the log record it is associated with.
- In addition, each data page stores the LSN of the latest log record corresponding to a change for that page.

A log record stores

- (a) the previous LSN of that transaction
- (b) the transaction ID
- (c) the type of log record.

Database Recovery

The ARIES Recovery Algorithm (contd.)

- **The Log and Log Sequence Number (LSN) (contd.)**
- A log record stores:
  1. Previous LSN of that transaction: It links the log record of each transaction. It is like a back pointer points to the previous record of the same transaction
  2. Transaction ID
  3. Type of log record
- For a write operation the following additional information is logged:
  1. Page ID for the page that includes the item
  2. Length of the updated item
  3. Its offset from the beginning of the page
  4. BFIM of the item
  5. AFIM of the item

Database Recovery

The ARIES Recovery Algorithm (contd.)

The **Transaction table** and the **Dirty Page table**

For efficient recovery following tables are also stored in the log during checkpointing:

- **Transaction table**: Contains an entry for each active transaction, with information such as transaction ID, transaction status and the LSN of the most recent log record for the transaction.
- **Dirty Page table**: Contains an entry for each dirty page in the buffer, which includes the page ID and the LSN corresponding to the earliest update to that page.

Database Recovery

The ARIES Recovery Algorithm (contd.)

Checkpointing

A checkpointing does the following:

- Writes a begin_checkpoint record in the log
- Writes an end_checkpoint record in the log. With this record the contents of transaction table and dirty page table are appended to the end of the log.
- Writes the LSN of the begin_checkpoint record to a special file. This special file is accessed during recovery to locate the last checkpoint information.

To reduce the cost of checkpointing and allow the system to continue to execute transactions, ARIES uses "fuzzy checkpointing".

Database Recovery

The ARIES Recovery Algorithm (contd.)

The following steps are performed for recovery

Analysis phase: Start at the begin_checkpoint record and proceed to the end_checkpoint record. Access transaction table and dirty page table are appended to the end of the log. Note that during this phase some other log records may be written to the log and transaction table may be modified. The analysis phase compiles the set of redo and undo to be performed and ends.

Redo phase: Starts from the point in the log up to where all dirty pages have been flushed, and move forward to the end of the log. Any change that appears in the dirty page table is redone.

Undo phase: Starts from the end of the log and proceeds backward while performing appropriate undo. For each undo it writes a compensating record in the log.

The recovery completes at the end of undo phase.

Database Recovery

(a)

Lsn	Last_lsn	Tran_id	Type	Page_id	Other_information
1	0	T_1	update	*C*	. . .
2	0	T_2	update	*B*	. . .
3	1	T_1	commit		. . .
4	begin checkpoint				
5	end checkpoint				
6	0	T_3	update	*A*	. . .
7	2	T_2	update	*C*	. . .
8	7	T_2	commit		. . .

(b)

TRANSACTION TABLE

Transaction_id	Last_lsn	Status
T_1	3	commit
T_2	2	in progress

DIRTY PAGE TABLE

Page_id	Lsn
C	1
B	2

(c)

TRANSACTION TABLE

Transaction_id	Last_lsn	Status
T_1	3	commit
T_2	8	commit
T_3	6	in progress

DIRTY PAGE TABLE

Page_id	Lsn
C	1
B	2
A	6

Figure 19.6
An example of recovery in ARIES. (a) The log at point of crash.
(b) The Transaction and Dirty Page Tables at time of checkpoint.
(c) The Transaction and Dirty Page Tables after the analysis phase.

Database Recovery

10   Recovery in multidatabase system

A multidatabase system is a special distributed database system where one node may be running relational database system under UNIX, another may be running object-oriented system under Windows and so on.

A transaction may run in a distributed fashion at multiple nodes.

In this execution scenario the transaction commits only when all these multiple nodes agree to commit individually the part of the transaction they were executing.

This commit scheme is referred to as "**two-phase commit**" (**2PC**).

If any one of these nodes fails or cannot commit the part of the transaction, then the transaction is aborted.

Each node recovers the transaction under its own recovery protocol.

Summary

Databases Recovery

Types of Failure

Transaction Log

Data Updates

Data Caching

Transaction Roll-back (Undo) and Roll-Forward

Checkpointing

Recovery schemes

- ARIES Recovery Scheme
- Recovery in Multidatabase System

Disk Storage, Basic File Structures, Hashing, and Modern Storage Architectures

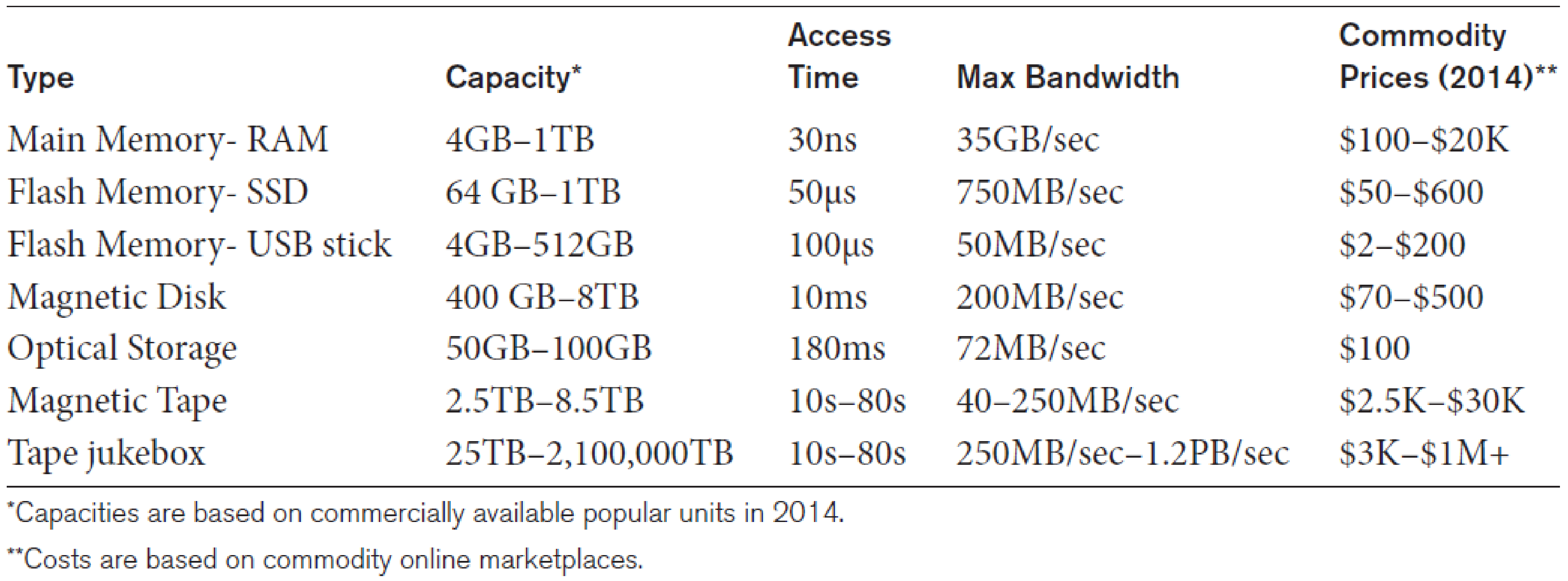
Introduction

- Databases typically stored on magnetic disks
  - Accessed using physical database file structures
- Storage hierarchy
  - Primary storage
    - CPU main memory, cache memory
  - Secondary storage
    - Magnetic disks, flash memory, solid-state drives
  - Tertiary storage
    - Removable media

Memory Hierarchies and Storage Devices

- Cache memory
  - Static RAM
  - DRAM
- Mass storage
  - Magnetic disks
    - CD-ROM, DVD, tape drives
- Flash memory
  - Nonvolatile

Storage Types and Characteristics



Type	Capacity*	Access Time	Max Bandwidth	Commodity Prices (2014)**
Main Memory- RAM	4GB–1TB	30ns	35GB/sec	\$100–\$20K
Flash Memory- SSD	64 GB–1TB	50µs	750MB/sec	\$50–\$600
Flash Memory- USB stick	4GB–512GB	100µs	50MB/sec	\$2–\$200
Magnetic Disk	400 GB–8TB	10ms	200MB/sec	\$70–\$500
Optical Storage	50GB–100GB	180ms	72MB/sec	\$100
Magnetic Tape	2.5TB–8.5TB	10s–80s	40–250MB/sec	\$2.5K–\$30K
Tape jukebox	25TB–2,100,000TB	10s–80s	250MB/sec–1.2PB/sec	\$3K–\$1M+

*Capacities are based on commercially available popular units in 2014.

**Costs are based on commodity online marketplaces.

Table 16.1 Types of Storage with Capacity, Access Time, Max Bandwidth (Transfer Speed), and Commodity Cost

Storage Organization of Databases

- Persistent data
  - Most databases
- Transient data
  - Exists only during program execution
- File organization
  - Determines how records are physically placed on the disk
  - Determines how records are accessed

Secondary Storage Devices

- Hard disk drive
- Bits (ones and zeros)
  - Grouped into bytes or characters
- Disk capacity measures storage size
- Disks may be single or double-sided
- Concentric circles called tracks
  - Tracks divided into blocks or sectors
- Disk packs
  - Cylinder

Single-Sided Disk and Disk Pack

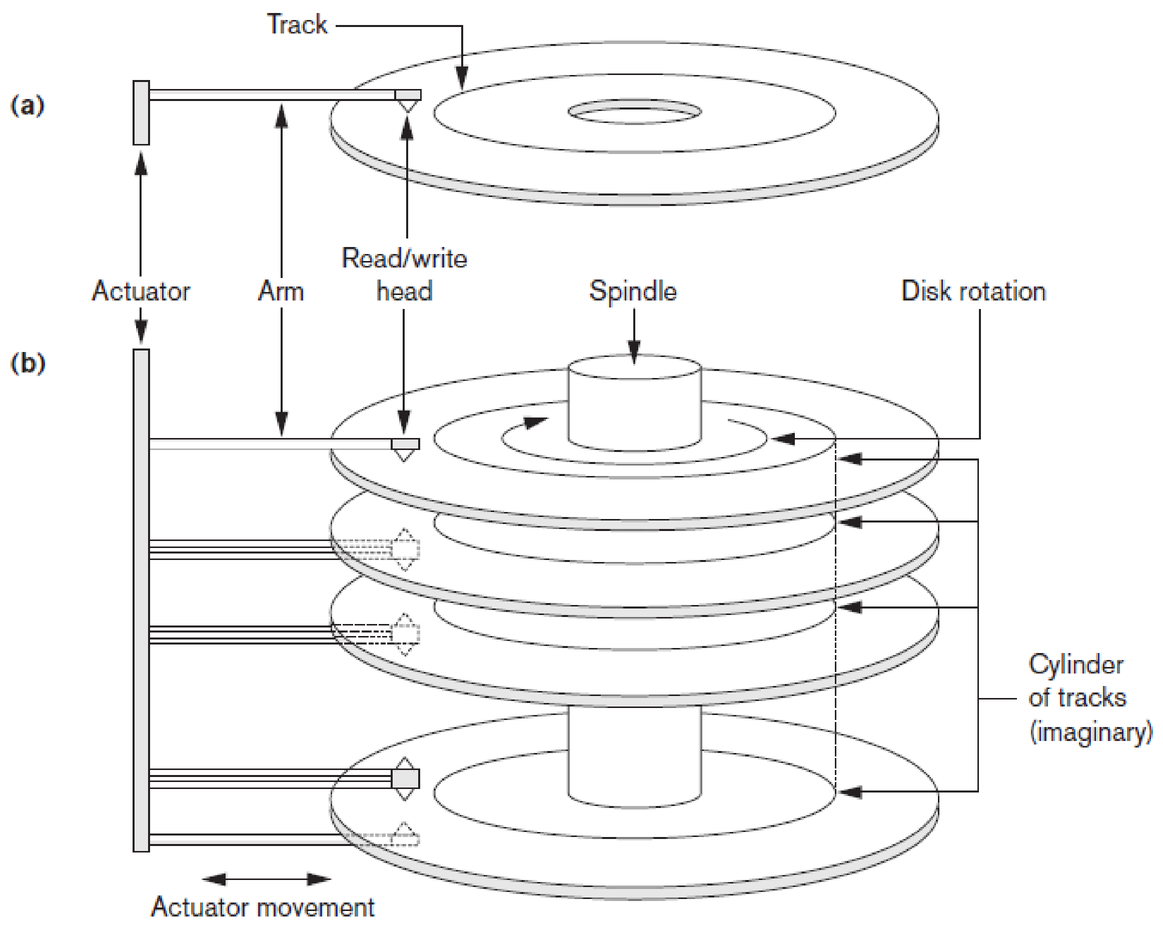


Figure 16.1 (a) A single-sided disk with read/write hardware
(b) A disk pack with read/write hardware

Sectors on a Disk

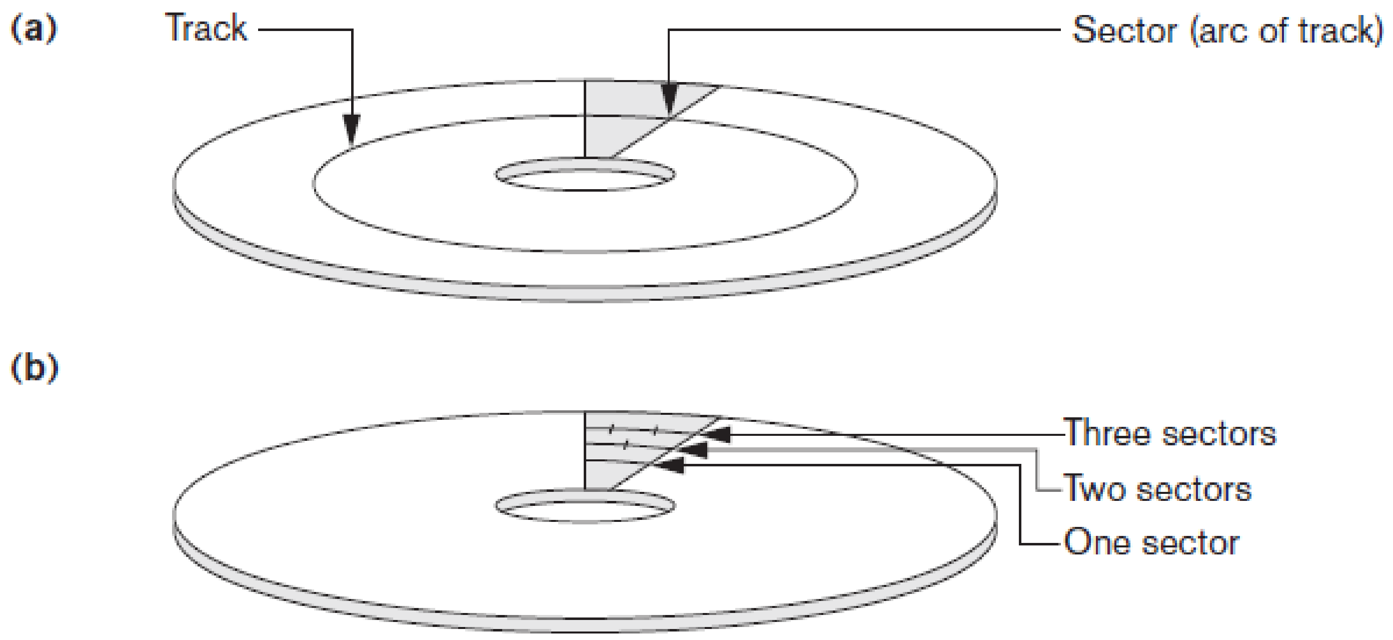


Figure 16.2 Different sector organizations on disk (a) Sectors subtending a fixed angle (b) Sectors maintaining a uniform recording density

Secondary Storage Devices (cont'd.)

- Formatting
  - Divides tracks into equal-sized disk blocks
  - Blocks separated by interblock gaps
- Data transfer in units of disk blocks
  - Hardware address supplied to disk I/O hardware
- Buffer
  - Used in read and write operations
- Read/write head
  - Hardware mechanism for read and write operations

Secondary Storage Devices (cont'd.)

- Disk controller
  - Interfaces disk drive to computer system
  - Standard interfaces
    - SCSI
    - SATA
    - SAS

Secondary Storage Devices (cont'd.)

- Techniques for efficient data access
  - Data buffering
  - Proper organization of data on disk
  - Reading data ahead of request
  - Proper scheduling of I/O requests
  - Use of log disks to temporarily hold writes
  - Use of SSDs or flash memory for recovery purposes

Solid State Device Storage

- Sometimes called flash storage
- Main component: controller
- Set of interconnected flash memory cards
- No moving parts
- Data less likely to be fragmented
- More costly than HDDs
- DRAM-based SSDs available
  - Faster access times compared with flash

Magnetic Tape Storage Devices

- Sequential access
  - Must scan preceding blocks
- Tape is mounted and scanned until required block is under read/write head
- Important functions
  - Backup
  - Archive

Buffering of Blocks

- Buffering most useful when processes can run concurrently in parallel

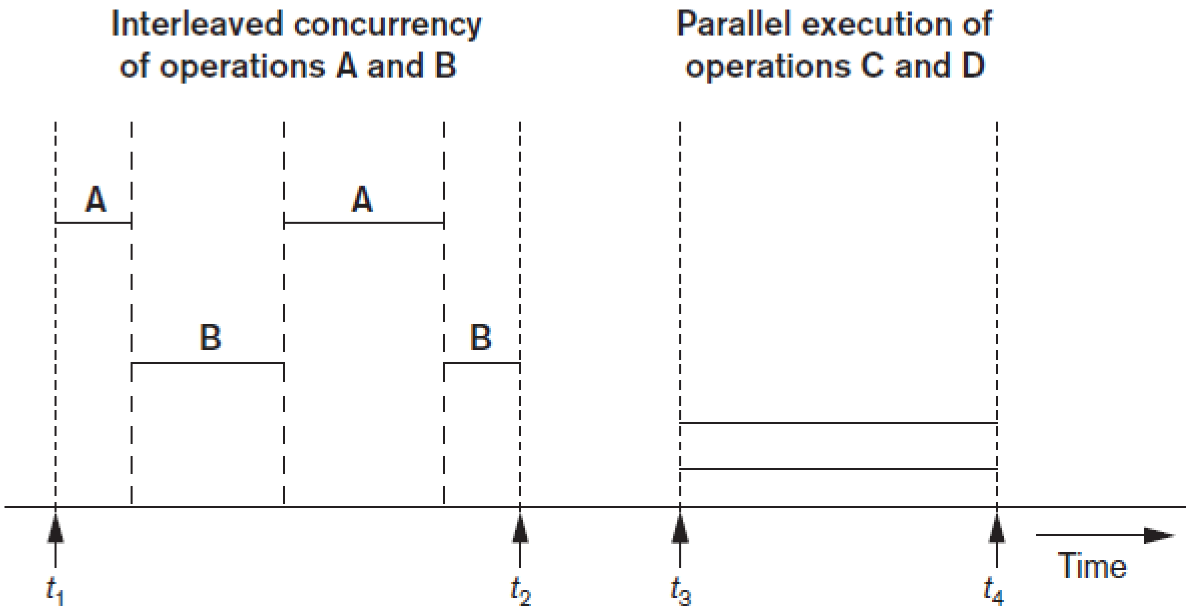

Interleaved concurrency of operations A and B
Parallel execution of operations C and D
A
A
B
B
t_1
t_2
t_3
t_4
Time

Figure 16.3 Interleaved concurrency versus parallel execution

Buffering of Blocks (cont'd.)

- Double buffering can be used to read continuous stream of blocks

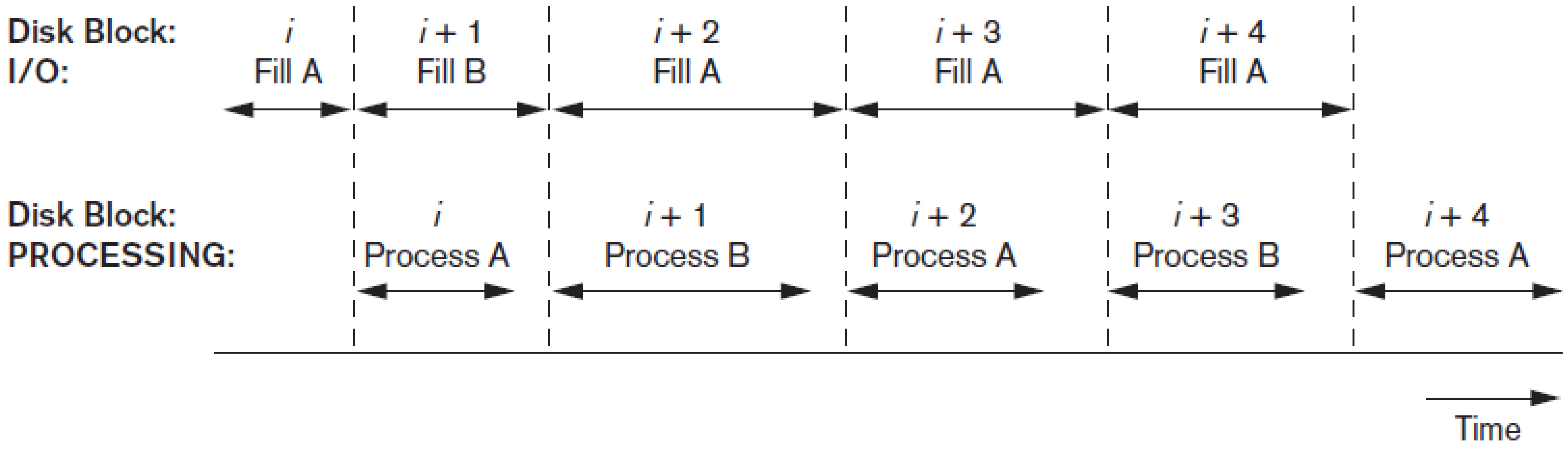


Figure 16.4 Use of two buffers, A and B, for reading from disk

Buffer Management and Replacement Strategies

- Buffer management information
  - Pin count
  - Dirty bit
- Buffer replacement strategies
  - Least recently used (LRU)
  - Clock policy
  - First-in-first-out (FIFO)

Placing File Records on Disk

- Record: collection of related data values or items
  - Values correspond to record field
- Data types
  - Numeric
  - String
  - Boolean
  - Date/time
- Binary large objects (BLOBs)
  - Unstructured objects

Placing File Records on Disk (cont'd.)

- Reasons for variable-length records
  - One or more fields have variable length
  - One or more fields are repeating
  - One or more fields are optional
  - File contains records of different types

Record Blocking and Spanned Versus Unspanned Records

- File records allocated to disk blocks
- Spanned records
  - Larger than a single block
  - Pointer at end of first block points to block containing remainder of record
- Unspanned
  - Records not allowed to cross block boundaries

Record Blocking and Spanned Versus Unspanned Records (cont'd.)

- Blocking factor
  - Average number of records per block for the file

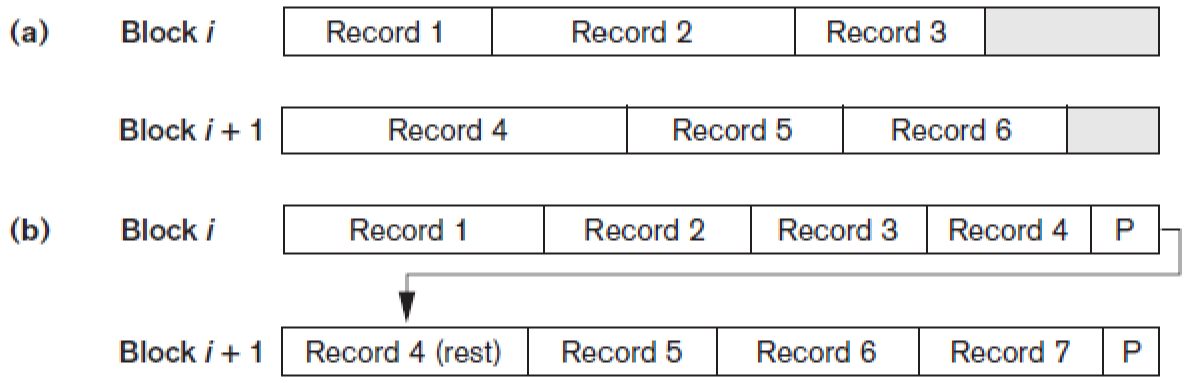


Figure 16.6 Types of record organization (a) Unspanned (b) Spanned

Record Blocking and Spanned Versus Unspanned Records (cont’d.)

- Allocating file blocks on disk
  - Contiguous allocation
  - Linked allocation
  - Indexed allocation
- File header (file descriptor)
  - Contains file information needed by system programs
    - Disk addresses
    - Format descriptions

Operations on Files

- Retrieval operations
  - No change to file data
- Update operations
  - File change by insertion, deletion, or modification
- Records selected based on selection condition

Operations on Files (cont'd.)

- Examples of operations for accessing file records
  - Open
  - Find
  - Read
  - FindNext
  - Delete
  - Insert
  - Close
  - Scan

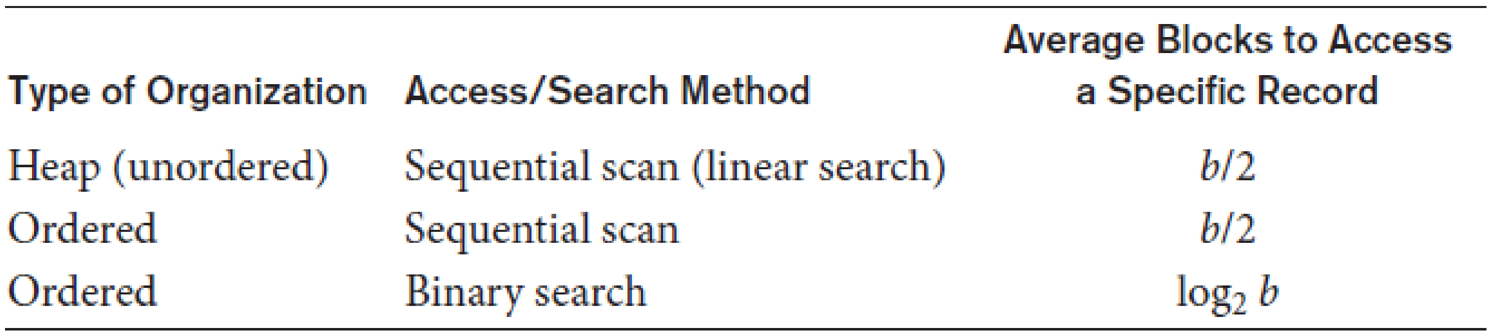
Files of Unordered Records (Heap Files)

- Heap (or pile) file
  - Records placed in file in order of insertion
- Inserting a new record is very efficient
- Searching for a record requires linear search
- Deletion techniques
  - Rewrite the block
  - Use deletion marker

Files of Ordered Records (Sorted Files)

- Ordered (sequential) file
  - Records sorted by ordering field
    - Called ordering key if ordering field is a key field
- Advantages
  - Reading records in order of ordering key value is extremely efficient
  - Finding next record
  - Binary search technique

Access Times for Various File Organizations



Type of Organization	Access/Search Method	Average Blocks to Access a Specific Record
Heap (unordered)	Sequential scan (linear search)	$b/2$
Ordered	Sequential scan	$b/2$
Ordered	Binary search	$\log_2 b$

Table 16.3 Average access times for a file of *b* blocks under basic file organizations

Hashing Techniques

- Hash function (randomizing function)
  - Applied to hash field value of a record
  - Yields address of the disk block of stored record
- Organization called hash file
  - Search condition is equality condition on the hash field
  - Hash field typically key field
- Hashing also internal search structure
  - Used when group of records accessed exclusively by one field value

Hashing Techniques (cont'd.)

- Internal hashing
  - Hash table
- Collision
  - Hash field value for inserted record hashes to address already containing a different record
- Collision resolution
  - Open addressing
  - Chaining
  - Multiple hashing

Hashing Techniques (cont'd.)

- External hashing for disk files
  - Target address space made of buckets
  - Bucket: one disk block or contiguous blocks
- Hashing function maps a key into relative bucket
  - Table in file header converts bucket number to disk block address
- Collision problem less severe with buckets
- Static hashing
  - Fixed number of buckets allocated

Hashing Techniques (cont'd.)

- Hashing techniques that allow dynamic file expansion
  - Extendible hashing
    - File performance does not degrade as file grows
  - Dynamic hashing
    - Maintains tree-structured directory
  - Linear hashing
    - Allows hash file to expand and shrink buckets without needing a directory

Other Primary File Organizations

- Files of mixed records
  - Relationships implemented by logical field references
  - Physical clustering
- B-tree data structure
- Column-based data storage

Parallelizing Disk Access Using RAID Technology

- Redundant arrays of independent disks (RAID)
  - Goal: improve disk speed and access time
- Set of RAID architectures (0 through 6)
- Data striping
  - Bit-level striping
  - Block-level striping
- Improving Performance with RAID
  - Data striping achieves higher transfer rates

Parallelizing Disk Access Using RAID Technology (cont'd.)

- Improving reliability with RAID
  - Redundancy techniques: mirroring and shadowing
- RAID organizations and levels
  - Level 0
    - Data striping, no redundant data
    - Spits data evenly across two or more disks
  - Level 1
    - Uses mirrored disks

Parallelizing Disk Access Using RAID Technology (cont'd.)

- RAID organizations and levels (cont'd.)
  - Level 2
    - Hamming codes for memory-style redundancy
    - Error detection and correction
  - Level 3
    - Single parity disk relying on disk controller
  - Levels 4 and 5
    - Block-level data striping
    - Data distribution across all disks (level 5)

Parallelizing Disk Access Using RAID Technology (cont'd.)

- RAID organizations and levels (cont'd.)
  - Level 6
    - Applies P+Q redundancy scheme
    - Protects against up to two disk failures by using just two redundant disks
- Rebuilding easiest for RAID level 1
  - Other levels require reconstruction by reading multiple disks
- RAID levels 3 and 5 preferred for large volume storage

RAID Levels

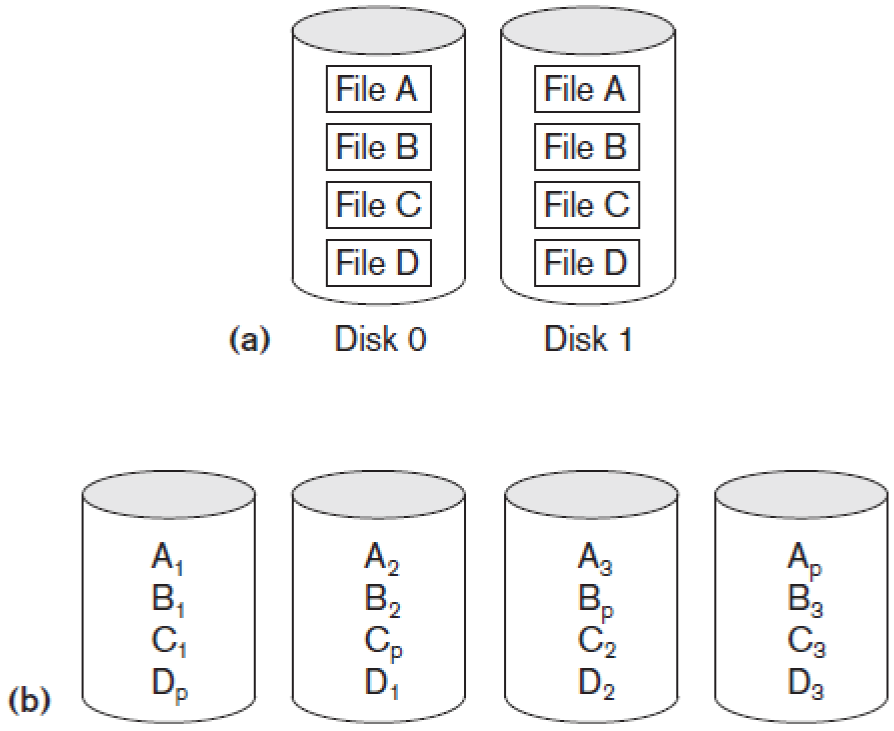


Figure 16.14 Some popular levels of RAID (a) RAID level 1: Mirroring of data on two disks (b) RAID level 5: Striping of data with distributed parity across four disks

Modern Storage Architectures

- Storage area networks
  - Online storage peripherals configured as nodes on high-speed network
- Network-attached storage
  - Servers used for file sharing
  - High degree of scalability, reliability, flexibility, performance
- iSCSI
  - Clients send SCSI commands to SCSI storage devices on remote channels

Modern Storage Architectures (cont'd.)

- Fibre Channel over IP (FCIP)
  - Fibre Channel control codes and data translated into IP packets
  - Transmitted between geographically distant Fibre Channel SANs
- Fibre Channel over Ethernet (FCoE)
  - Similar to iSCSI without the IP

Modern Storage Architectures (cont'd.)

- Automated storage tiering
  - Automatically moves data between different storage types depending on need
    - Frequently-used data moved to solid-state drives
- Object-based storage
  - Data managed in form of objects rather than files made of blocks
  - Objects carry metadata and global identifier
  - Ideally suited for scalable storage of unstructured data

Summary

- Magnetic disks
  - Accessing a disk block is expensive
- Commands for accessing file records
- File organizations: unordered, ordered, hashed
- RAID
- Modern storage trends