CS354: DATABASE

Transaction Management, Concurrency Control and Recovery Control

TRANSACTION

- A **transaction** is a *unit* of program execution that accesses and possibly updates various data items.
- E.g. transaction to transfer $50 from account A to account B:
  1. **read**(A)
  2. $A := A - 50$
  3. **write**(A)
  4. **read**(B)
  5. $B := B + 50$
  6. **write**(B)

- Two main issues to deal with:
  - Failures of various kinds, such as hardware failures and system crashes
  - Concurrent execution of multiple transactions

ACID PROPERTIES

- To preserve the integrity of data the database system must ensure:
  - **A**tomicity
  - **C**onsistency
  - **I**solation
  - **D**urability

ATOMICITY

- **Atomicity requirement**
  - Either all operations of the transaction are properly reflected in the database or none are.
  - If the transaction fails after step 3 and before step 6, money will be "lost" leading to an inconsistent database state
    - Failure could be due to software or hardware
  - The system should ensure that updates of a partially executed transaction are not reflected in the database

CONSISTENCY

- Execution of a transaction in isolation preserves the consistency of the database.
- Transaction to transfer \$50 from account A to account B:
  1. **read**(A)
  2. $A := A - 50$
  3. **write**(A)
  4. **read**(B)
  5. $B := B + 50$
  6. **write**(B)
- **Consistency requirement** in above example:
  - the sum of A and B is unchanged by the execution of the transaction

Consistency (contd.)

- In general, consistency requirements include
  - Explicitly specified integrity constraints such as primary keys and foreign keys
  - Implicit integrity constraints
    - e.g. sum of balances of all accounts, minus sum of loan amounts must equal value of cash-in-hand
- A transaction must see a consistent database.
- During transaction execution the database may be temporarily inconsistent.
- When the transaction completes successfully the database must be consistent
  - Erroneous transaction logic can lead to inconsistency

ISOLATION

- Although multiple transactions may execute concurrently, each transaction must be unaware of other concurrently executing transactions.
- Intermediate transaction results must be hidden from other concurrently executed transactions.
  - That is, for every pair of transactions T_i and T_j, it appears to T_i that either T_j, finished execution before T_i started, or T_j started execution after T_i finished.

ISOLATION (CONTD.)

- **Isolation requirement** - if between steps 3 and 6, another transaction T2 is allowed to access the partially updated database, it will see an inconsistent database (the sum $A + B$ will be less than it should be).

T1	T2
1. **read**(A)	
2. $A := A - 50$	
3. **write**(A)	
	read(A), read(B), print(A+B)
4. **read**(B)	
5. $B := B + 50$	
6. **write**(B)	

Isolation (contd.)

- Isolation can be ensured trivially by running transactions **serially**
  - that is, one after the other.
- However, executing multiple transactions concurrently has significant benefits

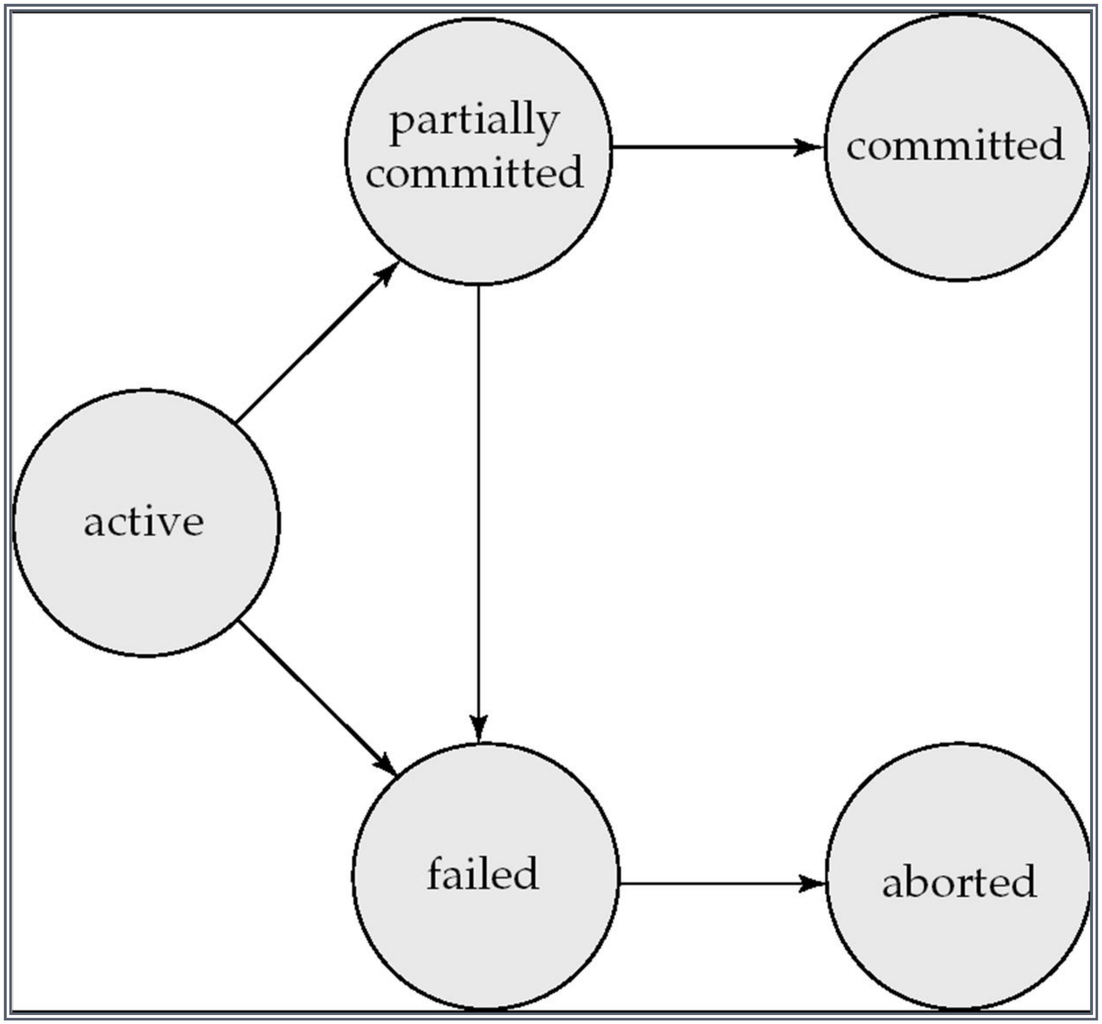
DURABILITY

- **Durability requirement** — once the user has been notified that the transaction has completed (i.e., the transfer of the $50 has taken place), the updates to the database by the transaction must persist even if there are software or hardware failures.

Transaction State

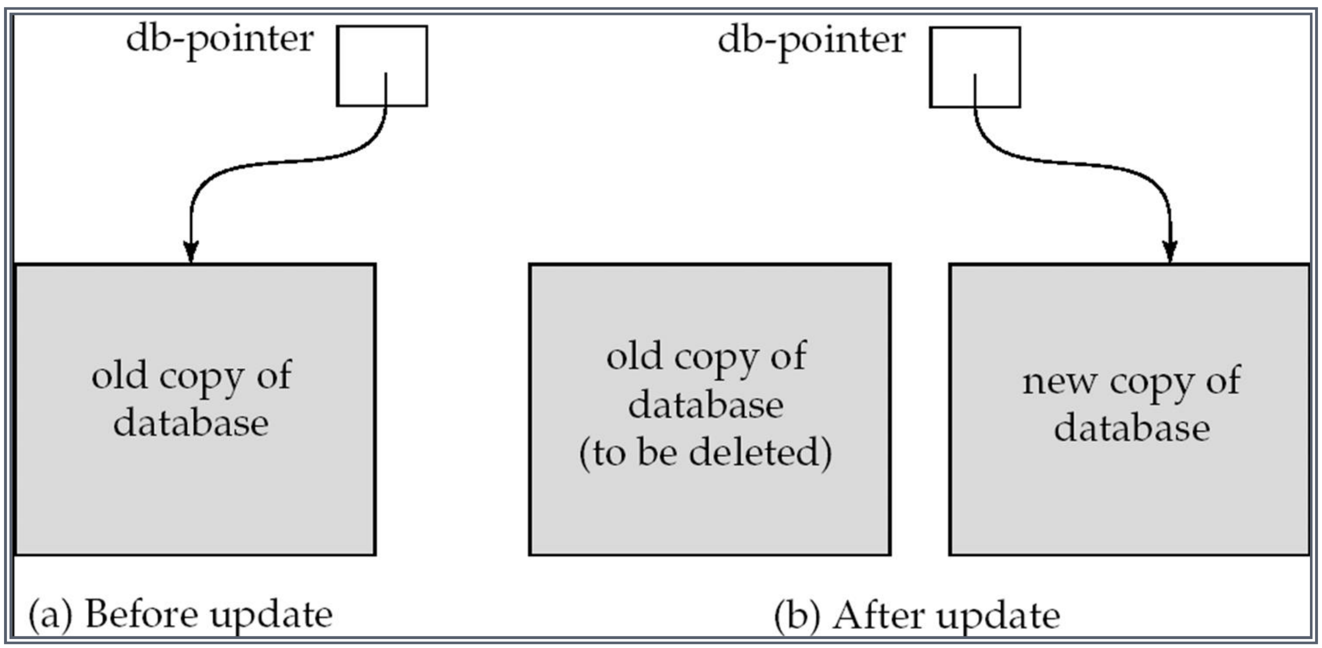
- **Active** – the initial state; the transaction stays in this state while it is executing
- **Partially committed** – after the final statement has been executed.
- **Failed** -- after the discovery that normal execution can no longer proceed.
- **Aborted** – after the transaction has been rolled back and the database restored to its state prior to the start of the transaction. Two options after it has been aborted:
  - Restart the transaction
  - Kill the transaction
- **Committed** – after successful completion.

Transaction state



Implementation of Atomicity and Durability

- The **recovery-management** component of a database system implements the support for atomicity and durability.
- E.g. the ***shadow-database*** scheme:
  - all updates are made on a *shadow copy* of the database
    - **db_pointer** is made to point to the updated shadow copy after
      - the transaction reaches partial commit and
      - all updated pages have been flushed to disk.



Implementation of Atomicity and Durability (Cont.)

- db_pointer always points to the current consistent copy of the database.
  - In case transaction fails, old consistent copy pointed to by **db_pointer** can be used, and the shadow copy can be deleted.
- The shadow-database scheme:
  - Assumes that only one transaction is active at a time.
  - Assumes disks do not fail
  - Useful for text editors, but
    - extremely inefficient for large databases
  - Does not handle concurrent transactions

Concurrent Executions

- Multiple transactions are allowed to run concurrently in the system. Advantages are:
  - **increased processor and disk utilization**, leading to better transaction *throughput*
    - E.g. one transaction can be using the CPU while another is reading from or writing to the disk
  - **reduced average response time** for transactions: short transactions need not wait behind long ones.
- **Concurrency control schemes** – mechanisms to achieve isolation
  - that is, to control the interaction among the concurrent transactions in order to prevent them from destroying the consistency of the database

SCHEDULE

- A sequences of instructions that specify the chronological order in which instructions of concurrent transactions are executed
  - a schedule for a set of transactions must consist of all instructions of those transactions
  - must preserve the order in which the instructions appear in each individual transaction.
- A transaction that successfully completes its execution will have a *commit* instruction as the last statement
  - by default transaction assumed to execute commit instruction as its last step
- A transaction that fails to successfully complete its execution will have an *abort* instruction as the last statement

SCHEDULE 1

- Let T_1 transfers \$50 from A to B, and T_2 transfers 10% of the balance from A to B.
- A *serial* schedule in which T_1 is followed by T_2 :

T_1	T_2
read(A)	
$A := A - 50$	
write (A)	
read(B)	
$B := B + 50$	
write(B)	
	read(A)
	$temp := A * 0.1$
	$A := A - temp$
	write(A)
	read(B)
	$B := B + temp$
	write(B)

SCHEDULE 2

- A serial schedule where T_2 is followed by T_1

T_1	T_2
	read(A)
	$temp := A * 0.1$
	$A := A - temp$
	write(A)
	read(B)
	$B := B + temp$
	write(B)
read(A)	
$A := A - 50$	
write(A)	
read(B)	
$B := B + 50$	
write(B)	

SCHEDULE 3

- Let T_1 and T_2 be the transactions defined previously. The following schedule is not a serial schedule, but it is *equivalent* to Schedule 1.

T_1	T_2
read(A)	
$A := A - 50$	
write(A)	
	read(A)
	$temp := A * 0.1$
	$A := A - temp$
	write(A)
read(B)	
$B := B + 50$	
write(B)	
	read(B)
	$B := B + temp$
	write(B)

In Schedules 1, 2 and 3, the sum A + B is preserved.

SCHEDULE 4

T_1	T_2
read(A)	
$A := A - 50$	
	read(A)
	$temp := A * 0.1$
	$A := A - temp$
	write(A)
	read(B)
write(A)	
read(B)	
$B := B + 50$	
write(B)	
	$B := B + temp$
	write(B)

- The above concurrent schedule does not preserve the value of $(A + B)$.

SERIALIZABILITY

- **Basic Assumption** – Each transaction preserves database consistency.
- Thus serial execution of a set of transactions preserves database consistency.
- A (possibly concurrent) schedule is serializable if it is equivalent to a serial schedule.
- Different forms of schedule equivalence give rise to the notions of:
  1. **conflict serializability**
  2. **view serializability**
- *Simplified view of transactions*
  - We ignore operations other than **read** and **write** instructions
  - We assume that transactions may perform arbitrary computations on data in local buffers in between reads and writes.
  - Our simplified schedules consist of only **read** and **write** instructions.

Conflicting Instructions

- Instructions l_i and l_j of transactions T_i and T_j respectively, **conflict** if and only if there exists some item Q accessed by both l_i and l_j, and at least one of these instructions wrote Q.
  1. l_i = **read**(Q), l_j = **read**(Q). l_i and l_j don't conflict.
  2. l_i = **read**(Q), l_j = **write**(Q). They conflict.
  3. l_i = **write**(Q), l_j = **read**(Q). They conflict
  4. l_i = **write**(Q), l_j = **write**(Q). They conflict
- Intuitively, a conflict between l_i and l_j forces a (logical) temporal order between them.
  - If l_i and l_j are consecutive in a schedule and they do not conflict, their results would remain the same even if they had been interchanged in the schedule.

Conflict Serializability

- If a schedule S can be transformed into a schedule S' by a series of swaps of non-conflicting instructions, we say that S and S' are **conflict equivalent**.
- We say that a schedule S is **conflict serializable** if it is conflict equivalent to a serial schedule

Conflict Serializability (Cont.)

- Schedule 3 can be transformed into Schedule 6, a serial schedule where T_2 follows T_1, by series of swaps of non-conflicting instructions.
  - Therefore Schedule 3 is conflict serializable.

T_1	T_2
read(A)	
write(A)	
	read(A)
	write(A)
read(B)	
write(B)	
	read(B)
	write(B)

Schedule 3

T_1	T_2
read(A)	
write(A)	
read(B)	
write(B)	
	read(A)
	write(A)
	read(B)
	write(B)

Schedule 6

Conflict Serializability (Cont.)

- Example of a schedule that is not conflict serializable:

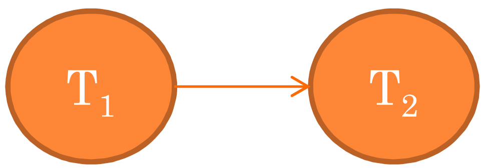
T_3	T_4
read(Q)	
	write(Q)
write(Q)	

- We are unable to swap instructions in the above schedule to obtain either the serial schedule $< T_3, T_4 >$, or the serial schedule $< T_4, T_3 >$.

TESTING FOR SERIALIZABILITY

- Consider some schedule of a set of transactions T_1, T_2, ..., T_n
- **Precedence graph** — a directed graph where the vertices are the transactions participating in the schedule
- We draw an edge from T_i to T_j if the two transaction conflict, i.e.,
  - T_i executes write(Q) before T_j executes read(Q)
  - T_i executes read(Q) before T_j executes write(Q)
  - T_i executes write(Q) before T_j executes write(Q)

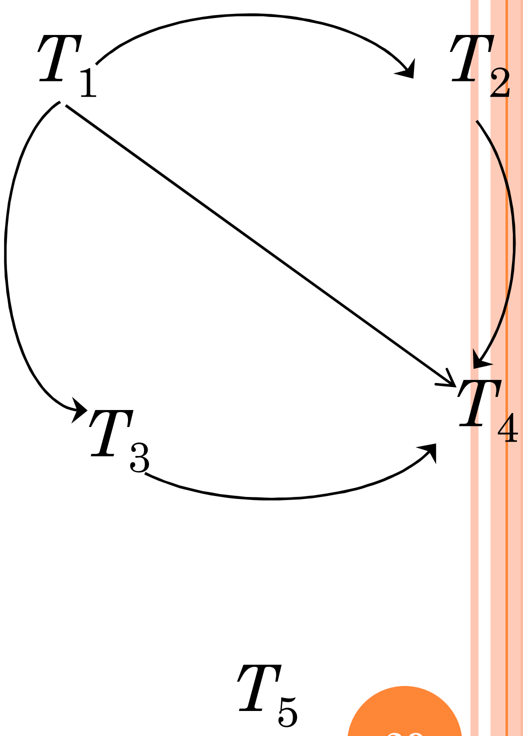
- We may label the arc by the item that was accessed.
- **Example 1**



- Now if an edge $T_1 \rightarrow T_2$ exists in the precedence graph, then, in any serial schedule S′ equivalent to S, T_1 must appear before T_2

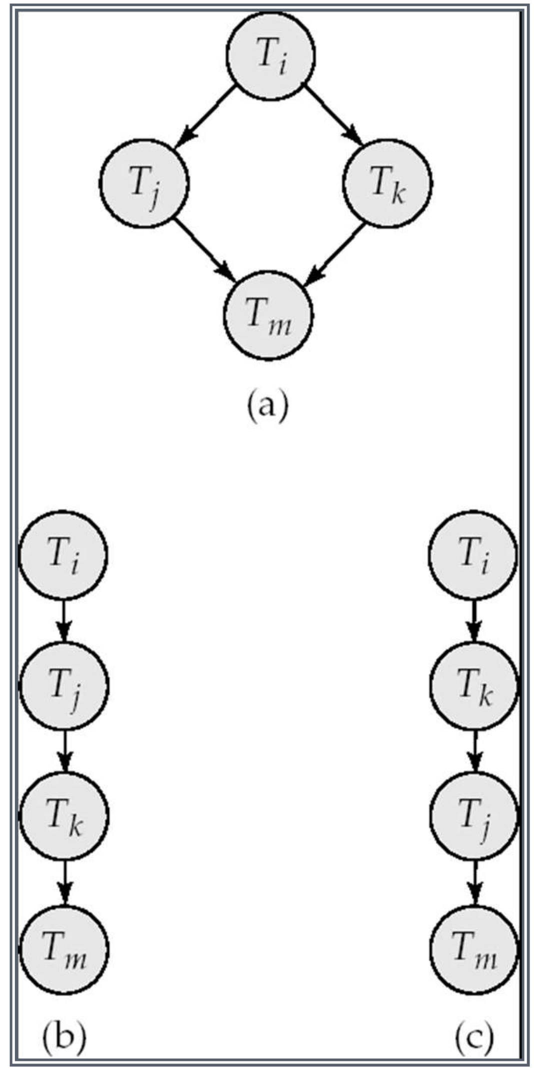
Example Schedule (Schedule A) + Precedence Graph

T_1	T_2	T_3	T_4	T_5
	read(X)			
read(Y)				
read(Z)				
				read(V)
				read(W)
				read(W)
	read(Y)			
	write(Y)			
		write(Z)		
read(U)				
			read(Y)	
			write(Y)	
			read(Z)	
			write(Z)	
read(U)				
write(U)				



Test for Conflict Serializability

- A schedule is conflict serializable if and only if its precedence graph is acyclic.
- Cycle-detection algorithms exist which take order n^2 time, where n is the number of vertices in the graph.
  - (Better algorithms take order $n + e$ where e is the number of edges.)
- If precedence graph is acyclic, the serializability order can be obtained by a *topological sorting* of the graph.
  - This is a linear order consistent with the partial order of the graph.
  - For example, a serializability order for Schedule A would be $T_5 \rightarrow T_1 \rightarrow T_3 \rightarrow T_2 \rightarrow T_4$
    - Are there others?



View Serializability

- Let S and $S´$ be two schedules with the same set of transactions. S and $S´$ are **view equivalent** if the following three conditions are met, for each data item Q,
  1. If in schedule S, transaction T_i **reads** the initial value of Q, then in schedule S' also transaction T_i must **read** the initial value of Q.
  2. If in schedule S transaction T_i executes **read**(Q), and that value was produced by transaction T_j (if any), then in schedule S' also transaction T_i must read the value of Q that was produced by the same **write**(Q) operation of transaction T_j .
  3. The transaction (if any) that performs the final **write**(Q) operation in schedule S must also perform the final **write**(Q) operation in schedule S'.

As can be seen, view equivalence is also based purely on **reads** and **writes** alone.

View Serializability (Cont.)

- A schedule S is **view serializable** if it is view equivalent to a serial schedule.
- Every conflict serializable schedule is also a view serializable but there are view-serializable schedules that are not conflict serializable.

T_3	T_4	T_6
read(Q)		
	write(Q)	
write(Q)		
		write(Q)

- The above schedule is view equivalent to serial schedule <T_3, T_4, T_6>
- Every view serializable schedule that is not conflict serializable has **blind writes**

VIEW SERIALIZABILITY

- View serializability provides weaker conditions then conflict serializability
  - Still this will ensure serializability
- The key difference between view and conflict serializability appears when a transaction writes a value without reading it
- The precedence graph test for conflict serializability cannot be used directly to test for view serializability.
  - Extension to test for view serializability has cost exponential in the size of the precedence graph.

Test for View Serializability

- Imagine that there is a hypothetical transaction T_0
  - *that wrote initial values for each database element read by any transaction in the schedule*
- Another hypothetical transaction T_f
  - *that reads every element written by one or more transaction after each schedule ends*
- T_0 **appears before** all real transactions
- T_f **appears after** all transactions

SCHEDULE S

T1	T2	T3
	Read(B)	
	Write(A)	
Read(A)		
		Read(A)
Write(B)		
	Write(B)	
		Write(B)

Sources and Writers

- Now for Schedule S the **sources of read** instructions are
  - T_0 for read(B) of T_2, T_2 for read(A) of T_1 and read(A) of T_3
  - The source for hypothetical read(A) of T_f is T_2
  - The source for hypothetical read(B) of T_f is T_3
- The **writer** in Schedule S
  - Writer of A: T_0, T_2
  - Writer of B: T_0, T_1, T_2, T_3

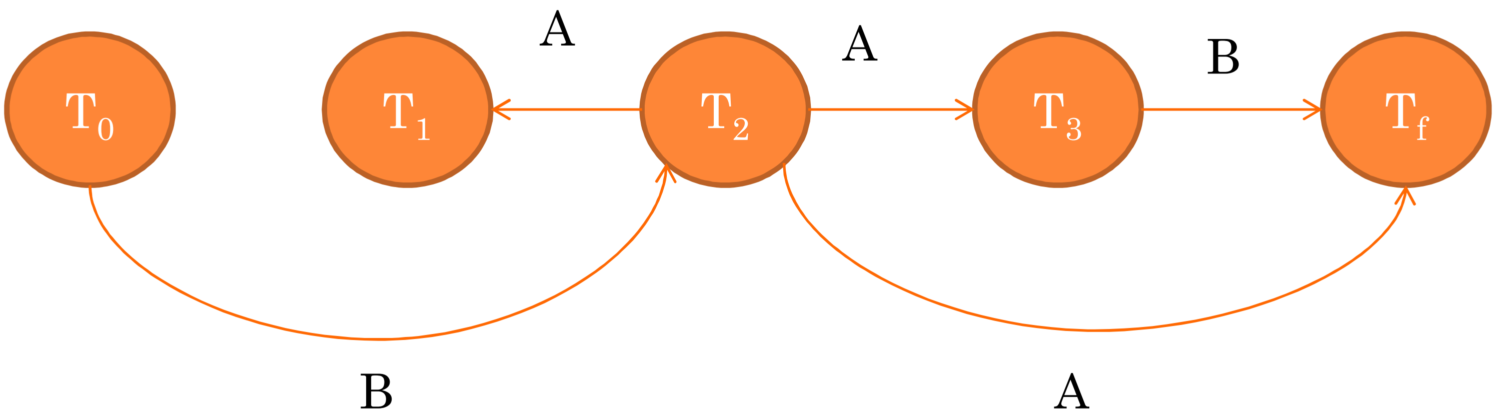
PRECEDENCE GRAPH CONSTRUCTION

- A node for each transaction and additional nodes for the hypothetical transaction T_0 and T_f
- For each action read(x) of Transaction T_i with source T_j, place an arc from T_j to T_i
- Suppose T_j is the source for read(x) of T_i and T_k is another writer of x
  - Then T_k is not allowed to intervene between T_j and T_i so it must appear either before T_j or after T_i
  - This is represented by an dashed arc pair from T_k to T_j and from T_i to T_k
  - One or the other of an arc pair is real
  - Whenever we try to make the graph acyclic, we can pick whichever the pair helps to make it acyclic

PRECEDENCE GRAPH CONSTRUCTION (CONTD.)

- Two special cases when the arc pair becomes a single pair-
  - If T_j is T_0, then it is not possible for T_k to appear before T_j, so we use an arc $T_i \rightarrow T_k$ in place of the arc pair
  - If T_i is T_f, then T_k cannot follow T_i, so we use an arc $T_k \rightarrow T_j$ in place of the arc pair

Initial Precedence graph



The initial precedence graph of Schedule S

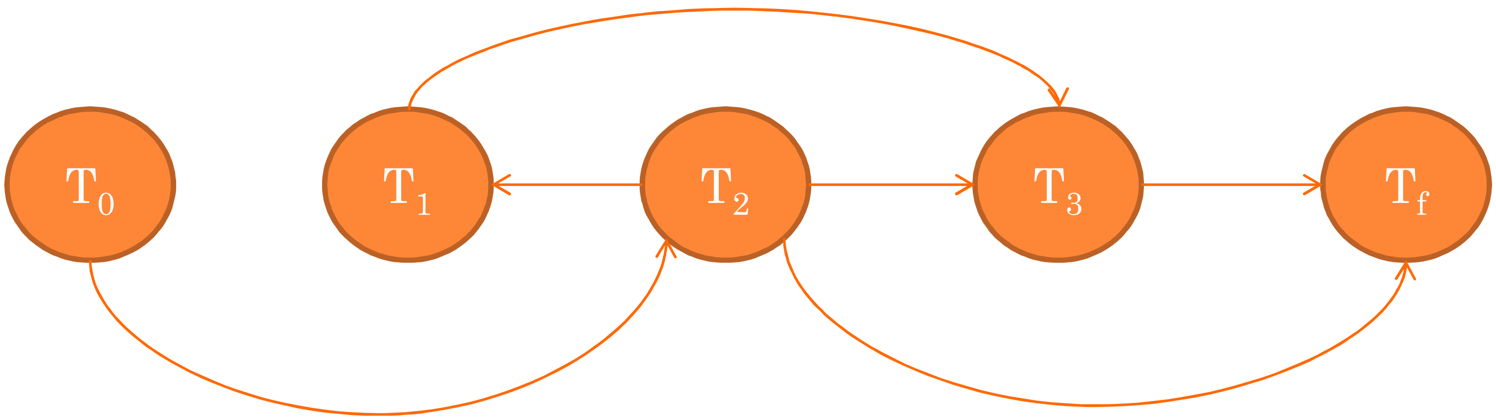
Precedence graph Construction (contd.)

- Now we must consider the transactions that might interfere with each of these five connections by writing the same element between them
- Consider the arc $T_2 \rightarrow T_1$ based on element A
  - The only writers of A are T_0 and T_2
  - Neither of them can interfere
    - Since T_0 cannot move position and T_2 is already at the end of the arc
- Similar arguments hold for arcs $T_2 \rightarrow T_3$ and $T_2 \rightarrow T_f$

Precedence graph Construction (contd.)

- Now considering the arcs based on B
- T_0, T_1, T_2 and T_3 all write B
- Consider the arc $T_0 \rightarrow T_2$ first
  - T_1 and T_3 are other writers of B
  - For T_1, the arc pairs $T_1 \rightarrow T_0$, $T_2 \rightarrow T_1$
  - As nothing can precede T_0, so the option $T_1 \rightarrow T_0$ is not possible
  - So the arc $T_2 \rightarrow T_1$ can only be added but this arc is already present because of A
- Similarly, argument holds for $T_2 \rightarrow T_3$
- For arc $T_3 \rightarrow T_f$, only the arc $T_1 \rightarrow T_3$ can be added

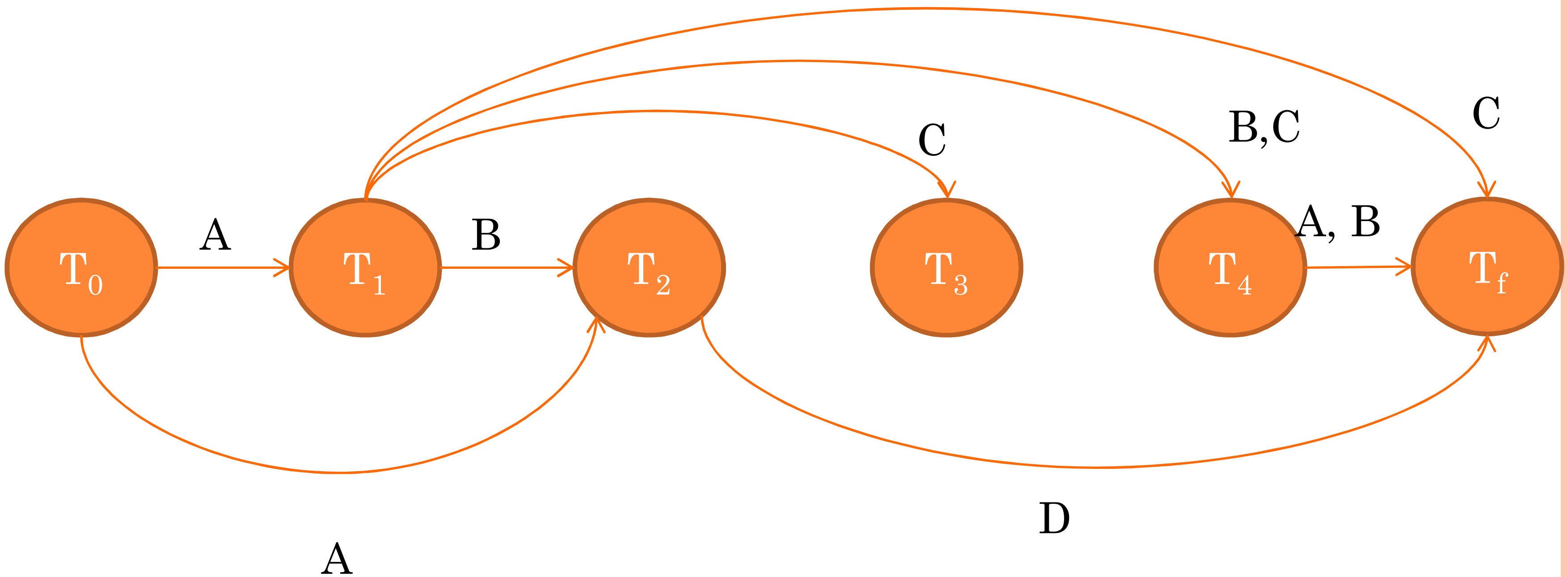
Complete Precedence Graph



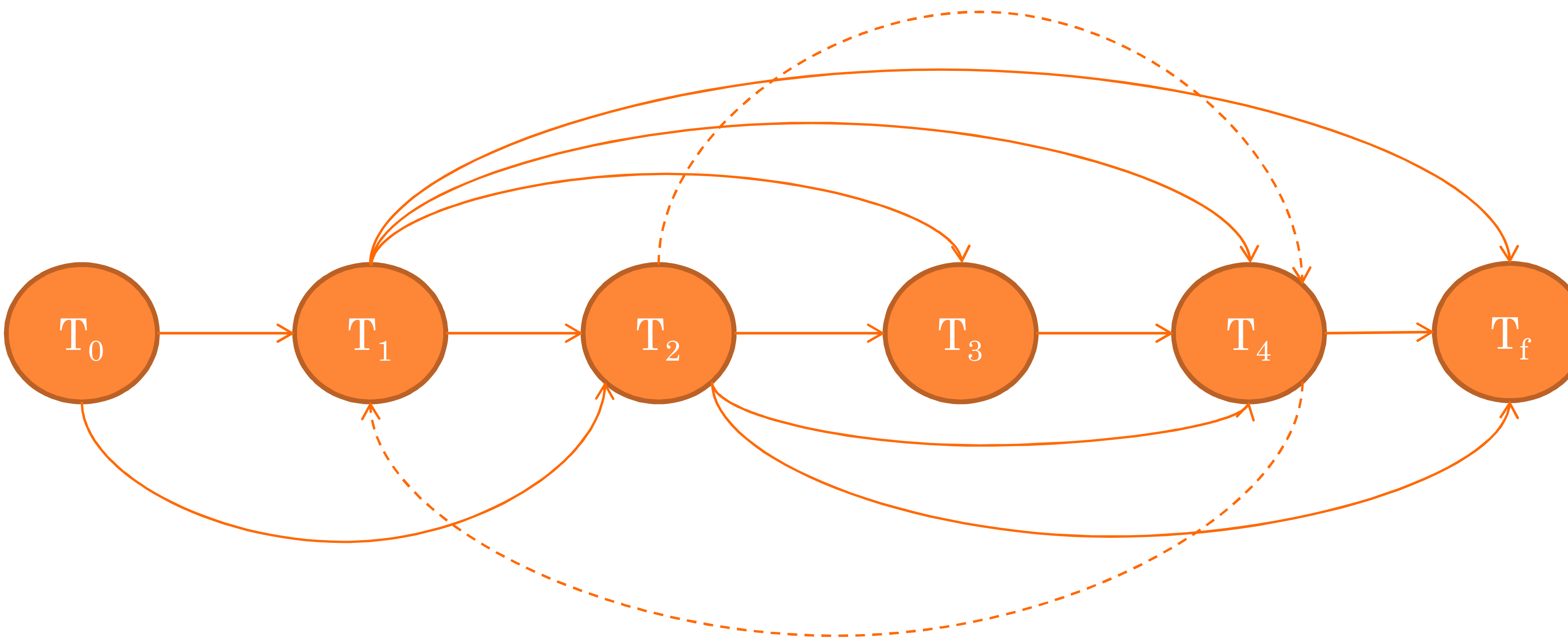
Complete precedence graph for Schedule S

Schedule S1

T1	T2	T3	T4
	Read(A)		
Read(A)			
Write(C)			
		Read(C)	
Write(B)			
			Read(B)
		Write(A)	
			Read(C)
	Write(D)		
	Read(B)		
			Write(A)
			Write(B)



The initial precedence graph of Schedule S1



Complete precedence graph for Schedule S1

- If we select the arc $T_4 \rightarrow T_1$
  - then there will be a cycle in the graph and it cannot be converted to a serial schedule
- But if we select the arc $T_2 \rightarrow T_4$
  - then the resultant graph is acyclic so it can be converted to a serial schedule

Other Notions of Serializability

T_1	T_5
read(A)	
$A := A - 50$	
write(A)	
	read(B)
	$B := B - 10$
	write(B)
read(B)	
$B := B + 50$	
write(B)	
	read(A)
	$A := A + 10$
	write(A)

- The schedule shown produces same outcome as the serial schedule $< T_1, T_5 >$
  - yet is not conflict equivalent or view equivalent to it.

RECOVERABILITY

- So far we have seen whether a schedule is acceptable from the viewpoint of consistency of the database
  - Implicit assumption- no transaction failures
- However if a transaction fails then we need to undo the effect of this transaction to ensure the atomicity property
- If concurrent execution is allowed then a transaction may depend on some other transaction
  - So in the case of a failure, if a transaction is aborted then the dependent transaction may also be aborted

Recoverable Schedules

- Let's consider the following schedule (Schedule 11)

T_8	T_9
read(A)	
write(A)	
	read(A)
read(B)	

- It is not recoverable if T_9 commits immediately after the read
- If T_8 aborts, T_9 would have read (and possibly shown to the user) an inconsistent database state. Hence, database must ensure that schedules are recoverable.
- **Recoverable schedule** — if a transaction T_j reads a data item previously written by a transaction T_i, then the commit operation of T_i appears before the commit operation of T_j.

Cascading Rollbacks

- **Cascading rollback** – a single transaction failure leads to a series of transaction rollbacks.
- Consider the following schedule where none of the transactions have yet committed (so the schedule is recoverable)

T_{10}	T_{11}	T_{12}
read(A)		
read(B)		
write(A)		
	read(A)	
	write(A)	
		read(A)

- If T_{10} fails, T_{11} and T_{12} must also be rolled back.
- Can lead to the undoing of a significant amount of work
- How to avoid cascading rollbacks?

Cascadeless Schedules

- **Cascadeless schedules** — cascading rollbacks cannot occur; for each pair of transactions T_i and T_j such that T_j reads a data item previously written by T_i, the commit operation of T_i appears before the read operation of T_j.
- Every cascadeless schedule is also recoverable
- It is desirable to restrict the schedules to those that are cascadeless

Concurrency Control

- A database must provide a mechanism that will ensure that all possible schedules are
  - *either conflict or view serializable, and*
  - *are recoverable and preferably cascadeless*
- A policy in which only one transaction can execute at a time generates serial schedules, but provides a poor degree of concurrency
- Testing a schedule for serializability *after* it has executed is a little too late!
- **Goal** – to develop concurrency control protocols that will assure serializability.

Lock-Based Protocols

- A lock is a mechanism to control concurrent access to a data item
- Data items can be locked in two modes :

  1. *exclusive (X) mode*. Data item can be both read as well as written. X-lock is requested using **lock-X** instruction.

  2. *shared (S) mode*. Data item can only be read. S-lock is requested using **lock-S** instruction.
- Lock requests are made to concurrency-control manager
- Transaction can proceed only after request is granted.

Lock-Based Protocols (Cont.)

- Lock-compatibility matrix

	S	X
S	true	false
X	false	false

- A transaction may be granted a lock on an item if the requested lock is ***compatible*** with locks already held on the item by other transactions
- Any number of transactions can hold *shared locks* on an item,
  - but if any transaction holds an *exclusive lock* on the item no other transaction may hold any lock on the item.
- If a lock cannot be granted, the requesting transaction is made *to wait till all incompatible locks held by other transactions have been released*
  - the lock is then granted.

Lock-Based Protocols (Cont.)

- Example of a transaction performing locking:

T_1: **lock-X**(*B*);
read (*B*);
B:=B-50;
write (*B*)
unlock(*B*);
lock-X(*A*);
read (*A*);
A:=A+50;
write (*A*);
unlock(*A*);

Lock-Based Protocols (Cont.)

- Example of another transaction performing locking:

  T_2: **lock-S**(A);
  read (A);
  unlock(A);
  lock-S(B);
  read (B);
  unlock(B);
  display$(A+B)$
- Locking as above is not sufficient to guarantee serializability — if A and B get updated in-between the read of A and B, the displayed sum would be wrong.
- A **locking protocol** is a set of rules followed by all transactions while requesting and releasing locks. Locking protocols restrict the set of possible schedules.

Pitfalls of Lock-Based Protocols

- Consider the partial schedule

T_3	T_4
lock-X(B)	
read(B)	
$B := B - 50$	
write(B)	
	lock-S(A)
	read(A)
	lock-S(B)
lock-X(A)	

- Neither T_3 nor T_4 can make progress — executing **lock-S**(*B*) causes T_4 to wait for T_3 to release its lock on B, while executing **lock-X**(*A*) causes T_3 to wait for T_4 to release its lock on A.
- Such a situation is called a **deadlock**.
  - To handle a deadlock one of T_3 or T_4 must be rolled back and its locks released.

Pitfalls of Lock-Based Protocols (Cont.)

- The potential for deadlock exists in most locking protocols.
- Deadlocks are a necessary evil
  - Preferable to inconsistent states

STARVATION

- **Starvation** is also possible if concurrency control manager is badly designed.
- For example:
  - A transaction may be waiting for an X-lock on an item, while a sequence of other transactions request and are granted an S-lock on the same item.
  - The same transaction is repeatedly rolled back due to deadlocks.

Granting of locks

- Concurrency control manager can be designed to prevent *starvation*
- When a transaction T_i requests a lock on data item Q in a particular mode M, the concurrency control manager grants the lock provided that –
  - There is no other transaction holding a lock on Q in a mode that conflicts with M
  - There is no other transaction that is waiting for a lock on Q and that made its lock request before T_i
- Thus a lock request will never get blocked by a lock request that is made later

The Two-Phase Locking Protocol

- This is a protocol which ensures conflict-serializable schedule.
- This protocol issues lock and unlock requests in two phases:
- **Phase 1: Growing Phase**
  - A transaction may obtain locks, but may not release locks
- **Phase 2: Shrinking Phase**
  - A transaction may release locks but may not obtain any new locks
- The transactions can be serialized in the order of their **lock points** (i.e. the point where a transaction acquired its final lock).

The Two-Phase Locking Protocol (Cont.)

- Two-phase locking *does not* ensure freedom from deadlocks

T_3	T_4
lock-X(B)	
read(B)	
$B := B - 50$	
write(B)	
	lock-S(A)
	read(A)
	lock-S(B)
lock-X(A)	

TWO PHASE LOCKING PROTOCOL (CONTD.)

- Cascading roll-back is also possible under two-phase locking.

T5	T6	T7
lock-X(A) read (A) lock-S(B) read (B) write (A) unlock (A)		
	lock-X(A) read (A) write (A) unlock (A)	
		lock-S(A) read (A)

- Cascading rollbacks can be avoided by
  - Following a modified protocol called **strict two-phase locking**. Here a transaction must hold all its *exclusive locks* till it commits/aborts.
  - **Rigorous two-phase locking** is even stricter: here *all* locks are held till commit/abort.

Lock Conversions

- Two-phase locking with lock conversions:
  - First Phase:
    - can acquire a lock-S on item
    - can acquire a lock-X on item
    - can convert a lock-S to a lock-X (upgrade)
  - Second Phase:
    - can release a lock-S
    - can release a lock-X
    - can convert a lock-X to a lock-S (downgrade)
- This protocol assures serializability. But still relies on the programmer to insert the various locking instructions.

- Consider the following two transactions-

T_8	T_9
Read(A_1)	Read(A_1)
Read(A_2)	Read(A_2)
…	display(A_1+ A_2)
Read(A_n)	
Write(A_1)	

If two phase locking protocol is employed, then T_8 must lock A_1 in exclusive mode

However, T_8 needs the exclusive mode lock only at the end

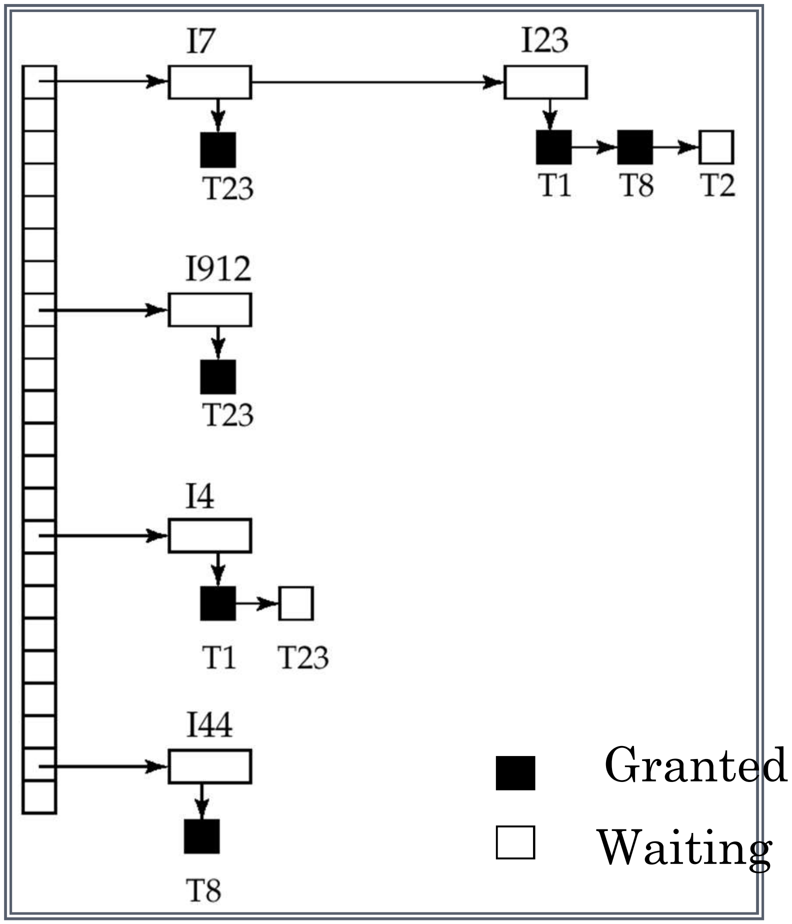
So initially it can lock A_1 in shared mode and later upgrade to exclusive mode

This will allow more concurrency

Implementation of Locking

- A **lock manager** can be implemented as a separate process to which transactions send lock and unlock requests
- The lock manager replies to a lock request by sending a lock grant messages (or a message asking the transaction to roll back, in case of a deadlock)
- The requesting transaction waits until its request is answered
- The lock manager maintains a data-structure called a **lock table** to record granted locks and pending requests
- The lock table is usually implemented as an in-memory hash table indexed on the name of the data item being locked

LOCK TABLE



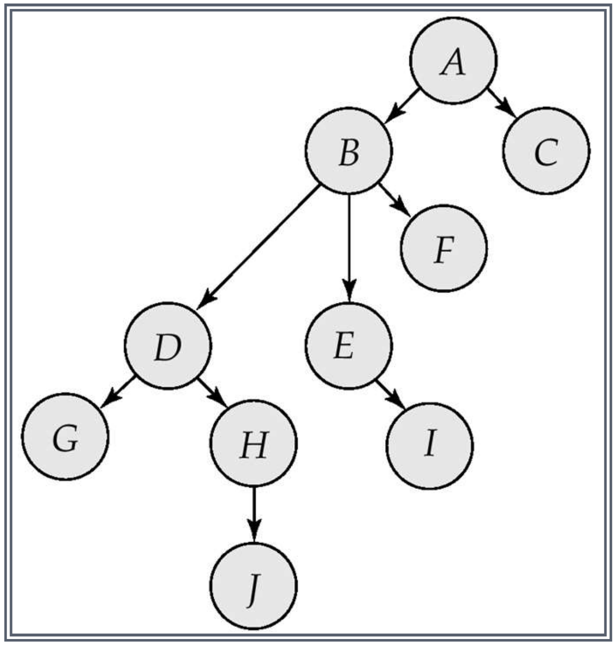
- Black rectangles indicate granted locks, white ones indicate waiting requests
- Lock table also records the type of lock granted or requested
- New request is added to the end of the queue of requests for the data item, and granted if it is compatible with all earlier locks
- Unlock requests result in the request being deleted, and later requests are checked to see if they can now be granted
- If transaction aborts, all waiting or granted requests of the transaction are deleted
  - lock manager may keep a list of locks held by each transaction, to implement this efficiently

Graph-Based Protocols

- Graph-based protocols are an alternative to two-phase locking
- Impose a partial ordering $\rightarrow$ on the set $\mathbf{D} = \{d_1, d_2, \ldots, d_h\}$ of all data items.
  - If $d_i \rightarrow d_j$ then any transaction accessing both d_i and d_j must access d_i before accessing d_j.
  - Implies that the set **D** may now be viewed as a directed acyclic graph, called a *database graph*.
- The *tree-protocol* is a simple kind of graph protocol.

TREE PROTOCOL

1. Only exclusive locks are allowed.
2. The first lock by T_i may be on any data item. Subsequently, a data Q can be locked by T_i only if the parent of Q is currently locked by T_i.
3. Data items may be unlocked at any time.
4. A data item that has been locked and unlocked by T_i cannot subsequently be relocked by T_i



SCHEDULE USING THE TREE PROTOCOL

T_{10}	T_{11}	T_{12}	T_{13}
Lock-X(B)			
	Lock-X(D)		
	Lock-X(H)		
	Unlock (D)		
Lock-X(E)			
Lock-X(D)			
Unlock(B)			
Unlock (E)			
		Lock-X(B)	
		Lock-X(E)	
	Unlock (H)		
Lock-X(G)			
Unlock (D)			
			Lock-X(D)
			Lock-X(H)
			Unlock (D)
			Unlock (H)
		Unlock (E)	
		Unlock (B)	
Unlock (G)			

Graph-Based Protocols (Cont.)

- **Advantages:**
  - The tree protocol ensures conflict serializability
  - No rollback is required as it is free from deadlock
  - Unlocking may occur earlier in the tree-locking protocol than in the two-phase locking protocol.
    - shorter waiting times, and increase in concurrency
- **Disadvantages:**
  - Protocol does not guarantee recoverability or cascade freedom
    - Need to introduce commit dependencies to ensure recoverability
  - Transactions may have to lock data items that they do not access.
    - increased locking overhead, and additional waiting time
    - potential decrease in concurrency

Deadlock Handling

- Consider the following two transactions:

T_1:	write (A)	T_2:	write(B)
	write(B)		write(A)

- Schedule with deadlock

T_1	T_2
lock-X on A	
write (A)	
	lock-X on B
	write (B)
	wait for **lock-X** on A
wait for **lock-X** on B	

Deadlock Handling

- System is deadlocked if there is a set of transactions such that every transaction in the set is waiting for another transaction in the set.
- ***Deadlock prevention*** protocols ensure that the system will *never* enter into a deadlock state.
- Some prevention strategies :
  - Require that each transaction locks all its data items before it begins execution (predeclaration).
  - Impose partial ordering of all data items and require that a transaction can lock data items only in the order specified by the partial order (graph-based protocol).

MORE DEADLOCK PREVENTION STRATEGIES

- Following schemes use transaction timestamps for the sake of deadlock prevention alone.
- **wait-die** scheme — non-preemptive
  - older transaction may wait for younger one to release data item. Younger transactions never wait for older ones; they are rolled back instead.
  - a transaction may die several times before acquiring needed data item
- **wound-wait** scheme — preemptive
  - older transaction *wounds* (forces rollback) of younger transaction instead of waiting for it. Younger transactions may wait for older ones.
  - may be fewer rollbacks than *wait-die* scheme.

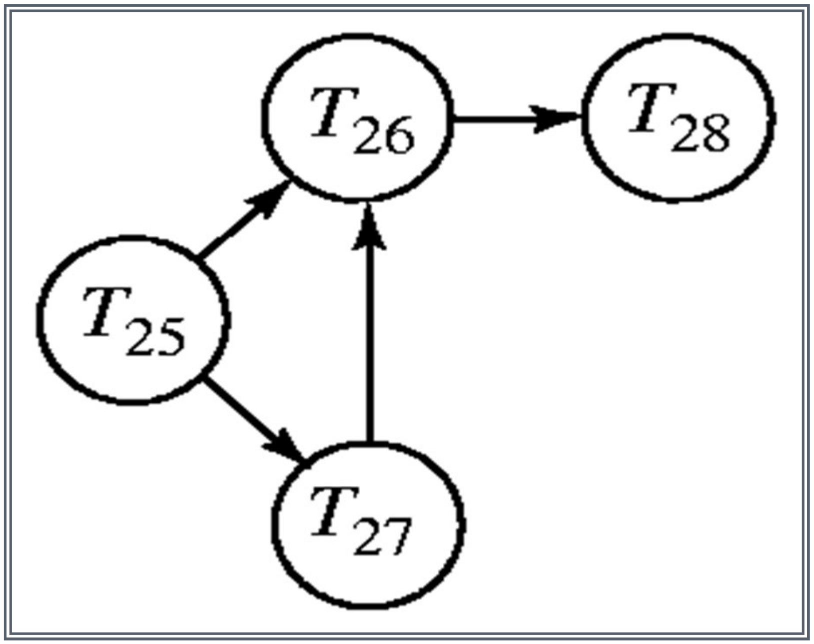
DEADLOCK PREVENTION (CONT.)

- Both in *wait-die* and in *wound-wait* schemes
  - A rolled back transaction is restarted with its original timestamp.
  - Older transactions thus have precedence over newer ones, and starvation is hence avoided.
- Timeout-Based Schemes :
  - A transaction waits for a lock only for a specified amount of time. After that, the wait times out and the transaction is rolled back.
  - Thus deadlocks are not possible
  - Simple to implement; but starvation is possible.
  - Also difficult to determine good value of the timeout interval.

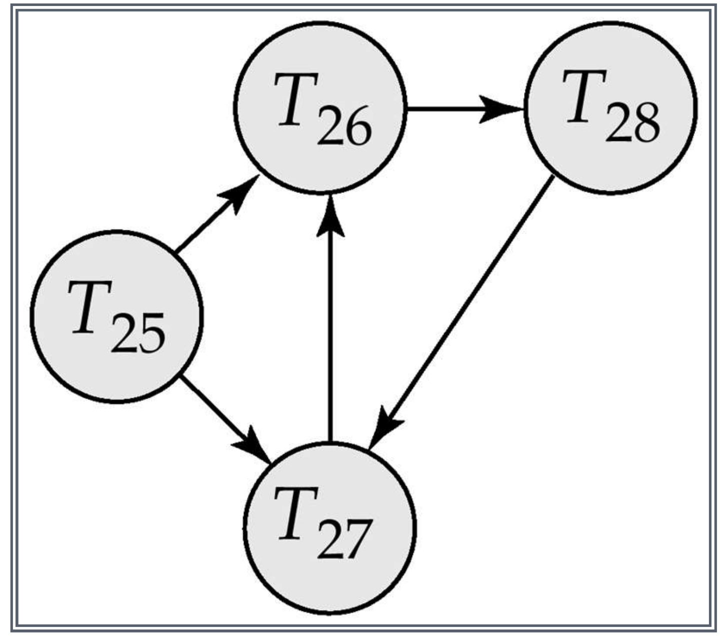
DEADLOCK DETECTION

- Deadlocks can be described as a *wait-for* ***graph***, which consists of a pair $G = (V,E)$,
  - V is a set of vertices (all the transactions in the system)
  - E is a set of edges; each element is an ordered pair $T_i \rightarrow T_j$.
- If $T_i \rightarrow T_j$ is in E, then there is a directed edge from T_i to T_j, implying that T_i is waiting for T_j to release a data item.
- When T_i requests a data item currently being held by T_j, then the edge $T_i \rightarrow T_j$ is inserted in the wait-for graph. This edge is removed only when T_j is no longer holding a data item needed by T_i.
- The system is in a deadlock state if and only if the wait-for graph has a cycle. Must invoke a deadlock-detection algorithm periodically to look for cycles.

Deadlock Detection (Cont.)



Wait-for graph without a cycle



Wait-for graph with a cycle

DEADLOCK RECOVERY

- When deadlock is detected
  - The system must recover from the deadlock state
  - The most common solution is to roll back one or more transactions
- Actions to be taken
  - Selection of a victim
  - Rollback
  - Starvation

Selection of a victim

- Some transactions will have to be rolled back (made a victim) to break deadlock
- Select that transaction as victim that will incur minimum cost while rolling back
- Depends on
  - How long the transaction has computed, and how much longer the transaction will compute before it completes it designated task
  - How many data items the transaction has used
  - How many more data items the transactions needs for it to complete
  - How many transactions will be involved in the rollback

ROLLBACK

- How far a particular transaction should be rolled back
  - Total rollback: abort the transaction and restarts it
  - Partial rollback: rollback the transaction only as far as necessary to break deadlock
    - The system must maintain some additional information – sequence of lock requests/grants, updates performed by the transaction, etc.

STARVATION

- The selection of a victim is based on cost factor
- Starvation happens if same transaction is always chosen as victim
- As a result this transaction never completes its designated task
- A transaction can be picked as a victim only a finite no. of times
- A possible solution:
  - Include the number of rollbacks in the cost factor to avoid starvation

Recovery System

- A computer system is subject to failure from a variety of causes
- In any failure data may be lost
- So a good database system must take actions in advance to ensure that the atomicity and durability properties are preserved
- Recovery system is an integral part of a database system
- The recovery system does the followings-
  - restore the database to a consistent state
  - provide high availability

Failure Classification

- **Transaction failure** :
  - **Logical errors**: transaction cannot complete due to some internal error condition
  - **System errors**: the database system must terminate an active transaction due to an error condition (e.g., deadlock)
- **System crash**: a power failure or other hardware or software failure causes the system to crash.
  - **Fail-stop assumption**: non-volatile storage contents are assumed not to be corrupted by system crash
    - Database systems have numerous integrity checks to prevent corruption of disk data
- **Disk failure**: a head crash or similar disk failure destroys all or part of disk storage
  - Destruction is assumed to be detectable: disk drives use checksums to detect failures

Recovery Algorithms

- Recovery algorithms are techniques to ensure database consistency and transaction atomicity and durability despite failures
- Recovery algorithms have two parts
  1. Actions taken during normal transaction processing
     - to ensure enough information exists to recover from failures
  2. Actions taken after a failure
     - to recover the database contents to a state that ensures atomicity, consistency and durability

Recovery and Atomicity

- To ensure atomicity despite failures
  - we first output information describing the modifications to stable storage without modifying the database itself.
- We study the following approach:
  - **log-based recovery**
- For simplicity, we assume that transactions run serially

Log-Based Recovery

- A **log** is kept on stable storage
  - The log is a sequence of records to keep track of all the update activities in the database
- The fields of a log record
  - Transaction identifier
  - Data item identifier
  - Old value
  - New value

Log-Based Recovery (contd.)

- Update log record:
  - $<T_i, X_j, V_1, V_2>$
    - Transaction T_i has performed a write on data item X_j. X_j had old value V_1 before the write, and will have value V_2 after the write.
- Special log records to record significant events in transaction processing:
  - $<T_i$ **start**$>$
    - Transaction T_i has started
  - $<T_i$ **commit**$>$
    - Transaction T_i has committed
  - $<T_i$ **abort**$>$
    - Transaction T_i has aborted

- We assume for now that log records are written directly to stable storage (that is, they are not buffered)
- Two approaches using logs
  - Deferred database modification
  - Immediate database modification

Deferred Database Modification

- The **deferred database modification** scheme records all modifications to the log, but defers all the **write**s to after partial commit.
- Transaction starts by writing <T_i ***start***> record to log.
- A write(X) operation results in a log record <T_i, X, V> being written, where V is the new value for X
  - Note: old value is not needed for this scheme
  - The write is not performed on X at this time, but is deferred.
- When T_i partially commits, <T_i **commit**> is written to the log
- Finally, the log records are read and used to actually execute the previously deferred writes.

Deferred Database Modification (Cont.)

- During recovery after a crash, a transaction needs to be redone if and only if both <T_i **start**> and<T_i **commit**> are there in the log.
- Redoing a transaction T_i (**redo** T_i) sets the value of all data items updated by the transaction to the new values.
- **redo** operation must be idempotent
  - Executing it several times must be equivalent to executing it once
- Crashes can occur while
  - the transaction is executing the original updates, or
  - while recovery action is being taken

- Example transactions T_0 and T_1 (T_0 executes before T_1):

T_0: **read** (A)

$A := A - 50$

write (A)

read (B)

$B := B + 50$

write (B)

T_1 : **read** (C)

$C := C - 100$

write (C)

Deferred Database Modification (Cont.)

- Below we show the log as it appears at three instances of time.

(a)	(b)	(c)
<T_0 start>	<T_0 start>	<T_0 start>
<T_0, A, 950>	<T_0, A, 950>	<T_0, A, 950>
<T_0, B, 2050>	<T_0, B, 2050>	<T_0, B, 2050>
	<T_0 commit>	<T_0 commit>
	<T_1 start>	<T_1 start>
	<T_1, C, 600>	<T_1, C, 600>
		<T_1 commit>

- If log on stable storage at time of crash is as in case:
  - (a) No redo actions need to be taken
  - (b) redo(T_0) must be performed since <T_0 **commi**t> is present
  - (c) **redo**(T_0) must be performed followed by redo(T_1) since <T_0 **commit**> and <T_1 commit> are present

Immediate Database Modification

- The **immediate database modification** scheme allows database updates of an uncommitted transaction to be made as the writes are issued
  - since undoing may be needed, update logs must have both old value and new value
- Update log record must be written *before* database item is written
  - We assume that the log record is output directly to stable storage
  - Can be extended to postpone log record output, so long as prior to execution of an **output**(B) operation for a data block B, all log records corresponding to items B must be flushed to stable storage
- Output of updated blocks can take place at any time before or after transaction commit
- Order in which blocks are output can be different from the order in which they are written.

Immediate Database Modification Example

Log	Write	Output
<T_0 **start**>		
<T_0, A, 1000, 950>		
<T_o, B, 2000, 2050>		
	$A = 950$	
	$B = 2050$	
<T_0 **commit**>		
<T_1 **start**>		
<T_1, C, 700, 600>		
	$C = 600$	
		B_B, B_C
<T_1 **commit**>		
		B_A

- Note: B_X denotes block containing X.

IMMEDIATE DATABASE MODIFICATION (CONT.)

- Recovery procedure has two operations instead of one:
  - **undo**(T_i) restores the value of all data items updated by T_i to their old values, going backwards from the last log record for T_i
  - **redo**(T_i) sets the value of all data items updated by T_i to the new values, going forward from the first log record for T_i

- Both operations must be **idempotent**
  - That is, even if the operation is executed multiple times the effect is the same as if it is executed once
    - Needed since operations may get re-executed during recovery

Immediate Database Modification (Cont.)

- When recovering after failure:
  - Transaction T_i needs to be undone if the log contains the record <T_i **start**>, but does not contain the record <T_i **commit**>.
  - Transaction T_i needs to be redone if the log contains both the record <T_i **start**> and the record <T_i **commit**>.

IMMEDIATE DB MODIFICATION RECOVERY EXAMPLE

Below we show the log as it appears at three instances of time.

(a)	(b)	(c)
<T_0 start>	<T_0 start>	<T_0 start>
<T_0, A, 1000, 950>	<T_0, A, 1000, 950>	<T_0, A, 1000, 950>
<T_0, B, 2000, 2050>	<T_0, B, 2000, 2050>	<T_0, B, 2000, 2050>
	<T_0 commit>	<T_0 commit>
	<T_1 start>	<T_1 start>
	<T_1, C, 700, 600>	<T_1, C, 700, 600>
		<T_1 commit>

Recovery actions in each case above are:

(a) undo (T_0): B is restored to 2000 and A to 1000.

(b) undo (T_1) and redo (T_0): C is restored to 700, and then A and B are set to 950 and 2050 respectively.

(c) redo (T_0) and redo (T_1): A and B are set to 950 and 2050 respectively. Then C is set to 600

Common Problems in Recovery Procedure

- Searching the entire log is time-consuming
- Unnecessarily redo transactions which have already output their updates to the database

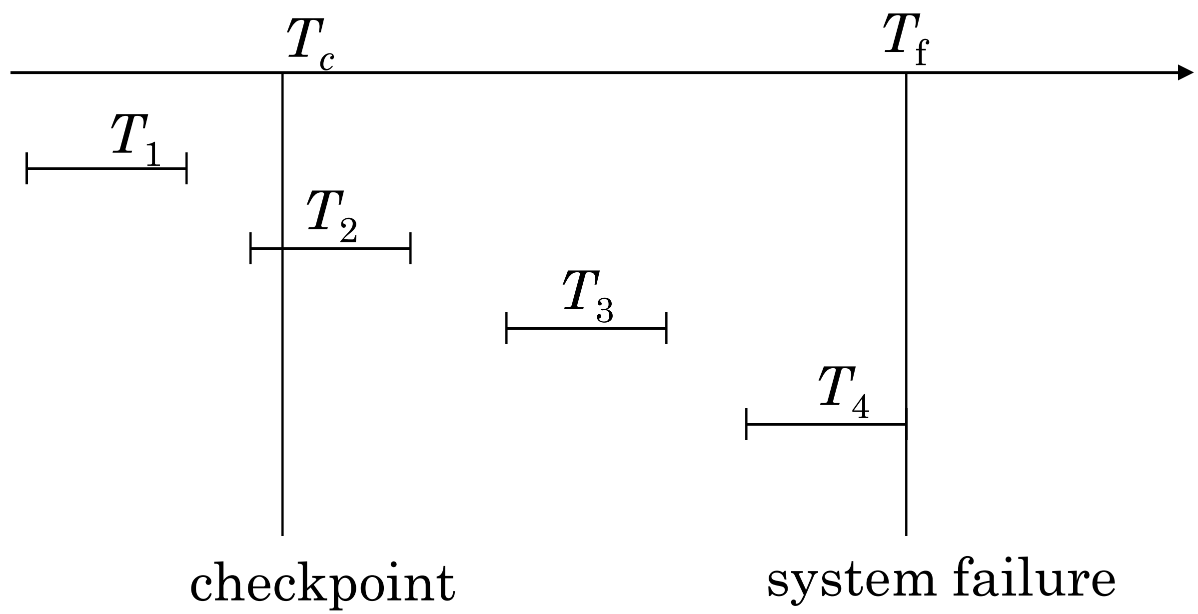
CHECKPOINTING

- Streamline recovery procedure by periodically performing **checkpointing**
- It performs the following sequence of operations-
  1. Output all log records currently residing in main memory onto stable storage.
  2. Output all modified buffer blocks to the disk.
  3. Write a log record < **checkpoint**> onto stable storage
- Transactions are not allowed to perform any update actions such as writing to buffer block or writing a log record, while a checkpoint is in progress

Checkpoints (Cont.)

- During recovery we need to consider only the most recent transaction T_i that started before the checkpoint, and transactions that started after T_i.
  1. Scan backwards from end of log to find the most recent **<checkpoint>** record
  2. Continue scanning backwards till a record <T_i **start**> is found.
  3. Need only to consider the part of log following above **star**t record. Earlier part of log can be ignored during recovery, and can be erased whenever desired.
  4. For all transactions (starting from T_i or later) with no <T_i **commit**>, execute **undo**(T_i). (Done only in case of immediate modification.)
  5. Scanning forward in the log, for all transactions starting from T_i or later with a <T_i **commit**>, execute **redo**(T_i)

EXAMPLE OF CHECKPOINTS



- T_1 can be ignored (updates already output to disk due to checkpoint)
- T_2 and T_3 redone.
- T_4 undone