Concurrency

In This Lecture

- Concurrency control
- Locks
- 2 Phase Locking protocol (2PL)

Need for concurrency control

- Previous lecture: transactions running concurrently may interfere with each other, causing various problems (lost updates etc.)
- Concurrency control: the process of managing simultaneous operations on the database without having them interfere with each other.

Lost Update

This update
Is lost

T1	T2
Read(X)	
X = X - 5	
	Read(X)
	X = X + 5
Write(X)	
	Write(X)
COMMIT	
	COMMIT

Only this update
succeeds

Uncommitted Update (“dirty read”)

T1	T2
Read(X)	
X = X - 5	
Write(X)	
	Read(X)
	X = X + 5
	Write(X)
ROLLBACK	
	COMMIT

This reads the value of X which it should not have seen

Inconsistent analysis

T1	T2
Read(X)	
X = X - 5	
Write(X)	
	Read(X)
	Read(Y)
	Sum = X+Y
Read(Y)	
Y = Y + 5	
Write(Y)	

Summing up data while it is being updated

Schedules

- A *schedule* is a sequence of the operations by a set of concurrent transactions that preserves the order of operations in each of the individual transactions
- A *serial* schedule is a schedule where operations of each transaction are executed consecutively without any interleaved operations from other transactions (each transaction commits before the next one is allowed to begin)

Serial schedules

- Serial schedules are guaranteed to avoid interference and keep the database consistent
- However databases need concurrent access which means interleaving operations from different transactions

Serialisability

- Two schedules are *equivalent* if they always have the same effect.
- A schedule is *serialisable* if it is equivalent to some serial schedule.
- For example:
  - if two transactions only read some data items, then the order is which they do it is not important
  - If T1 reads and updates X and T2 reads and updates a different data item Y, then again they can be scheduled in any order.

Serial and Serialisable

Interleaved Schedule

T1 Read(X)
T2 Read(X)
T2 Read(Y)
T1 Read(Z)
T1 Read(Y)
T2 Read(Z)

This schedule is serialisable:

Serial Schedule

T2 Read(X)
T2 Read(Y)
T2 Read(Z)

T1 Read(X)
T1 Read(Z)
T1 Read(Y)

Conflict Serialisable Schedule

Interleaved Schedule

T1 Read(X)
T1 Write(X)
T2 Read(X)
T2 Write(X)
T1 Read(Y)
T1 Write(Y)
T2 Read(Y)
T2 Write(Y)

This schedule is serialisable, even though T1 and T2 read and write the same resources X and Y: they have a conflict

Serial Schedule

T1 Read(X)
T1 Write(X)
T1 Read(Y)
T1 Write(Y)

T2 Read(X)
T2 Write(X)
T2 Read(Y)
T2 Write(Y)

Conflict Serialisability

- Two transactions have a conflict:
  - NO If they refer to different resources
  - NO If they are reads
  - YES If at least one is a write and they use the same resource

- A schedule is *conflict serialisable* if transactions in the schedule have a conflict but the schedule is still serialisable

Conflict Serialisability

- Conflict serialisable schedules are the main focus of concurrency control
- They allow for interleaving and at the same time they are guaranteed to behave as a serial schedule

- Important questions: how to determine whether a schedule is conflict serialisable
- How to construct conflict serialisable schedules

Precedence Graphs

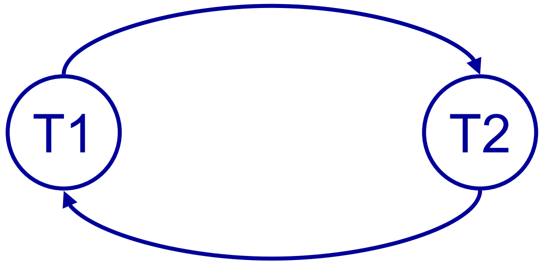
- To determine if a schedule is conflict serialisable we use a precedence graph
  - Transactions are vertices of the graph
  - There is an edge from T1 to T2 if T1 must happen before T2 in any equivalent serial schedule

- Edge T1 → T2 if in the schedule we have:
  - T1 Read(R) followed by T2 Write(R) for the same resource R
  - T1 Write(R) followed by T2 Read(R)
  - T1 Write(R) followed by T2 Write(R)
- The schedule is serialisable if there are no cycles

Precedence Graph Example

- The lost update schedule has the precedence graph:

T1 Write(X) followed by T2 Write(X)



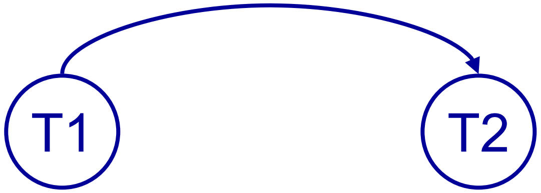
T2 Read(X) followed by T1 Write(X)

T1	T2
Read(X)	
X = X - 5	
	Read(X)
	X = X + 5
Write(X)	
	Write(X)
COMMIT	
	COMMIT

Precedence Graph Example

- No cycles: conflict serialisable schedule

T1 reads X before T2 writes X and
T1 writes X before T2 reads X and
T1 writes X before T2 writes X



T1	T2
`Read(X)`	
`Write(X)`	
	`Read(X)`
	`Write(X)`

Locking

- Locking is a procedure used to control concurrent access to data (to ensure serialisability of concurrent transactions)
- In order to use a ‘resource’ (table, row, etc) a transaction must first acquire a *lock* on that resource
- This may deny access to other transactions to prevent incorrect results

Two types of locks

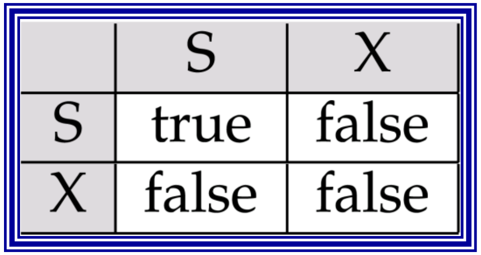
- Two types of lock
  - Shared lock (S-lock or read-lock)
  - Exclusive lock (X-lock or write-lock)
- Read lock allows several transactions simultaneously to read a resource (but no transactions can change it at the same time)
- Write lock allows one transaction exclusive access to write to a resource. No other transaction can read this resource at the same time.
- Lock requests are made to concurrency-control manager. Transaction can proceed only after request is granted.
- The lock manager in the DBMS assigns locks and records them in the data dictionary

Locking

- Before reading from a resource a transaction must acquire a read-lock
- Before writing to a resource a transaction must acquire a write-lock
- Locks are released on commit/rollback
- A transaction may not acquire a lock on any resource that is write-locked by another transaction
- A transaction may not acquire a write-lock on a resource that is locked by another transaction
- If the requested lock is not available, transaction waits

Lock-Based Protocols

- 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 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.)

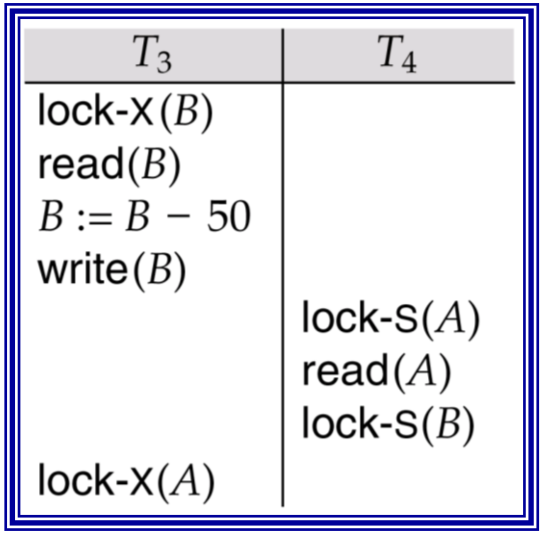
- Example of a transaction performing locking:

```
T2: 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

- The potential for deadlock exists in most locking protocols. Deadlocks are a necessary evil.
- **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.
- Concurrency control manager can be designed to prevent starvation.

Two-Phase Locking

- A transaction follows the *two-phase locking protocol* (2PL) if all locking operations precede the first unlock operation in the transaction

The Two-Phase Locking Protocol

- This is a protocol which ensures conflict-serializable schedules.
- Phase 1: Growing Phase
  - transaction may obtain locks
  - transaction may not release locks
- Phase 2: Shrinking Phase
  - transaction may release locks
  - transaction may not obtain locks
- The protocol assures serializability. It can be proved that 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
- Cascading roll-back is possible under two-phase locking. To avoid this, follow 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. In this protocol transactions can be serialized in the order in which they commit.

The Two-Phase Locking Protocol (Cont.)

- There can be conflict serializable schedules that cannot be obtained if two-phase locking is used.
- However, in the absence of extra information (e.g., ordering of access to data), two-phase locking is needed for conflict serializability in the following sense:

  Given a transaction T_i that does not follow two-phase locking, we can find a transaction T_j that uses two-phase locking, and a schedule for T_i and T_j that is not conflict serializable.

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.

Automatic Acquisition of Locks

- A transaction T_i issues the standard read/write instruction, without explicit locking calls.
- The operation **read**(D) is processed as:

```
if $T_i$ has a lock on $D$
  then
       read($D$)
  else begin
     if necessary wait until no other
       transaction has a lock-X on $D$
          grant $T_i$ a  lock-S on $D$;
          read($D$)
   end
```

Automatic Acquisition of Locks (Cont.)

- **write**(*D*) is processed as:

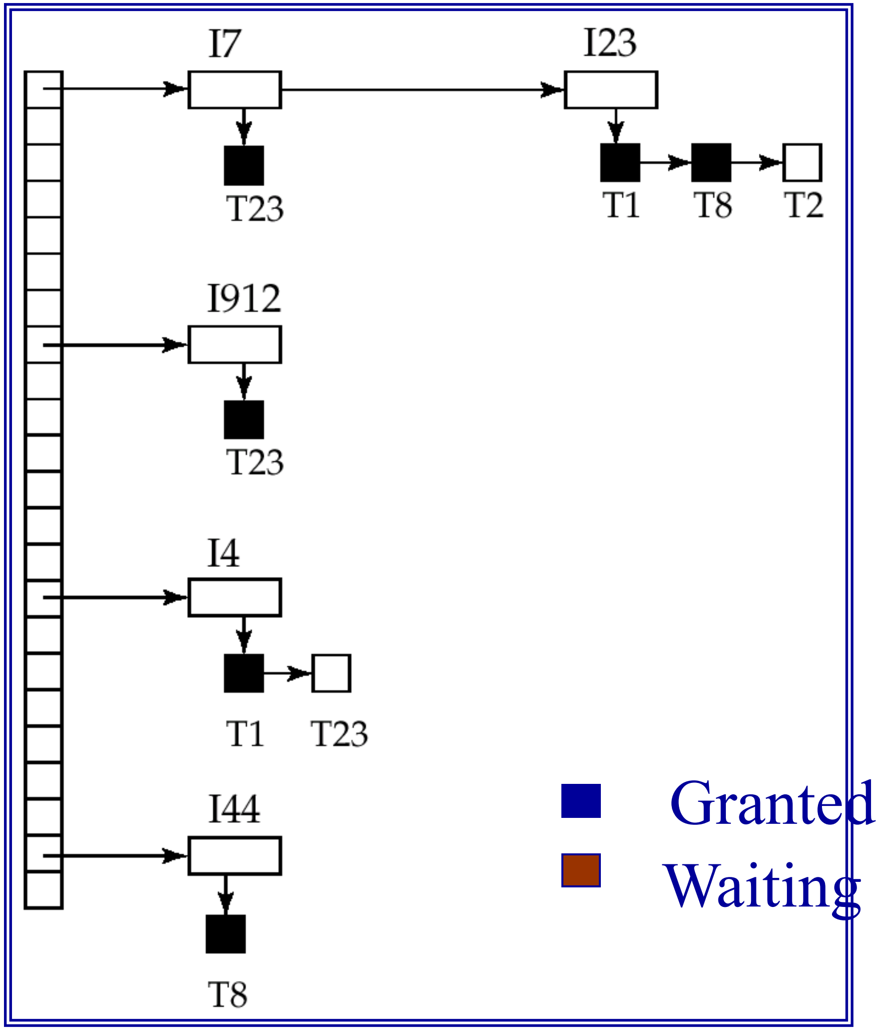
```
if $T_i$ has a lock-X on D
  then
    write(D)
  else begin
      if necessary wait until no other trans. has any lock on D,
      if $T_i$ has a lock-S on D
        then
          upgrade lock on D to lock-X
        else
          grant $T_i$ a lock-X on D
      write(D)
   end;
```

- All locks are released after commit or abort

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

Example

- T1 follows 2PL protocol
  - All of its locks are acquired before it releases any of them
- T2 does not
  - It releases its lock on X and then goes on to later acquire a lock on Y

T1	T2
read-lock(X)	read-lock(X)
Read(X)	Read(X)
write-lock(Y)	unlock(X)
unlock(X)	write-lock(Y)
Read(Y)	Read(Y)
Y = Y + X	Y = Y + X
Write(Y)	Write(Y)
unlock(Y)	unlock(Y)

Serialisability Theorem

Any schedule of two-phased transactions is conflict serialisable

Lost Update can't happen with 2PL

	T1	T2	
read-lock(X)	Read(X)		
	X = X - 5		
		Read(X)	read-lock(X)
		X = X + 5	
cannot acquire write-lock(X): T2 has read-lock(X)	Write(X)		
		Write(X)	cannot acquire write-lock(X): T1 has read-lock(X)
	COMMIT		
		COMMIT	

Uncommitted Update cannot happen with 2PL

	T1	T2	
read-lock(X)	**Read(X)**		
	X = X - 5		
write-lock(X)	**Write(X)**		
		Read(X)	Waits till T1 releases write-lock(X)
		X = X + 5	
		Write(X)	
Locks released	**ROLLBACK**		
		COMMIT	

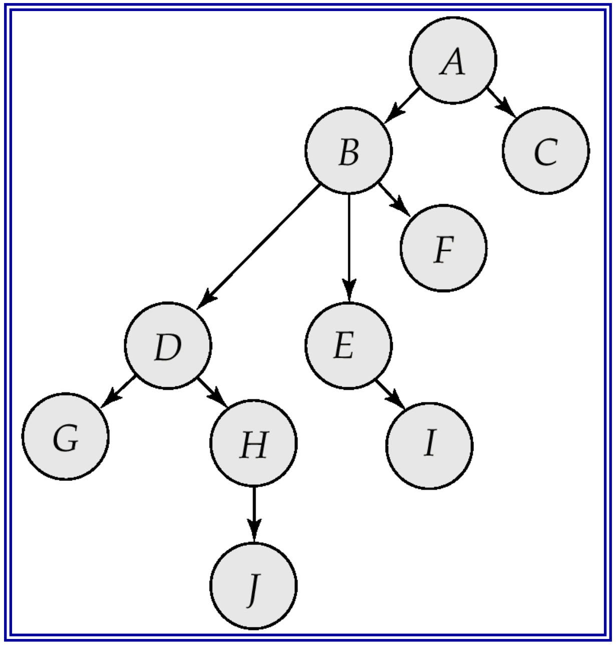
Inconsistent analysis cannot happen with 2PL

	T1	T2	
read-lock(X)	`Read(X)`		
	`X = X - 5`		
write-lock(X)	`Write(X)`		
		`Read(X)`	Waits till T1 releases write-locks on X and Y
		`Read(Y)`	
		`Sum = X+Y`	
read-lock(Y)	`Read(Y)`		
	`Y = Y + 5`		
write-lock(Y)	`Write(Y)`		

Graph-Based Protocols

- Graph-based protocols are an alternative to two-phase locking
- Impose a partial ordering $\rightarrow$ on the set **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

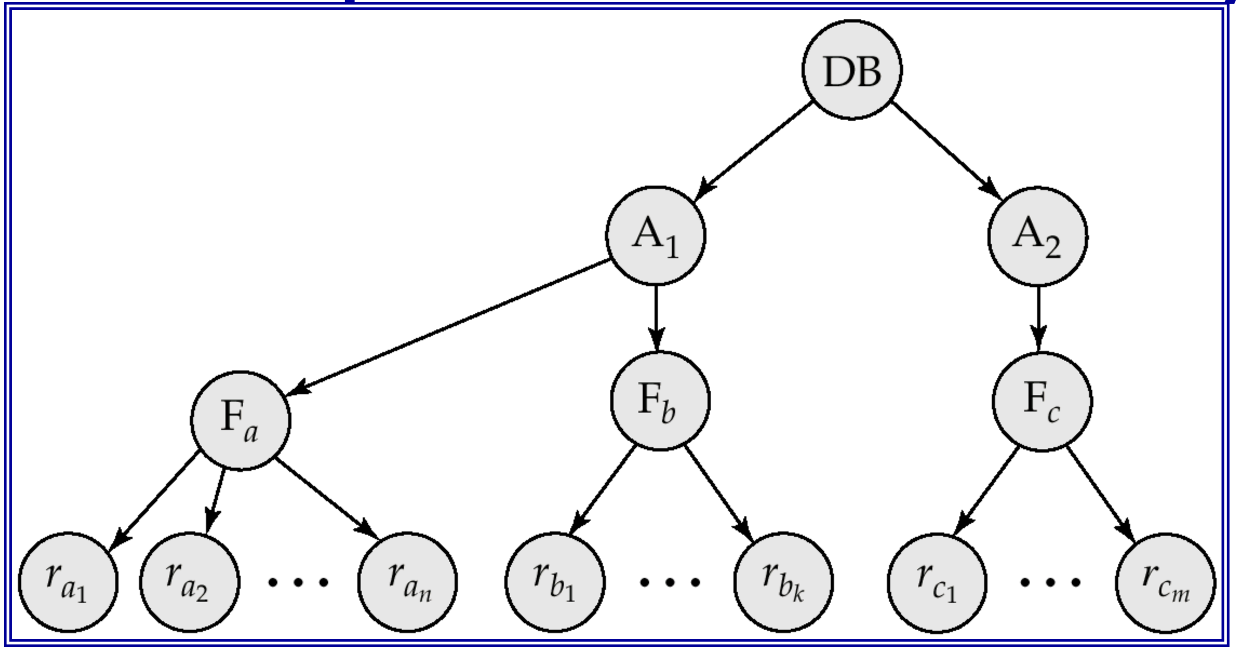
Graph-Based Protocols (Cont.)

- The tree protocol ensures conflict serializability as well as freedom 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
  - protocol is deadlock-free, no rollbacks are required
- Drawbacks
  - 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
- Schedules not possible under two-phase locking are possible under tree protocol, and vice versa.

Multiple Granularity

- Allow data items to be of various sizes and define a hierarchy of data granularities, where the small granularities are nested within larger ones
- Can be represented graphically as a tree (but don't confuse with tree-locking protocol)
- When a transaction locks a node in the tree *explicitly*, it *implicitly* locks all the node's descendents in the same mode.
- Granularity of locking (level in tree where locking is done):
  - **fine granularity** (lower in tree): high concurrency, high locking overhead
  - **coarse granularity** (higher in tree): low locking overhead, low concurrency

Example of Granularity



The levels, starting from the coarsest (top) level are

- *database*
- *area*
- *file*
- *record*

Intention Lock Modes

- In addition to S and X lock modes, there are three additional lock modes with multiple granularity:
    - ***intention-shared*** (IS): indicates explicit locking at a lower level of the tree but only with shared locks.
    - ***intention-exclusive*** (IX): indicates explicit locking at a lower level with exclusive or shared locks
    - ***shared and intention-exclusive*** (SIX): the subtree rooted by that node is locked explicitly in shared mode and explicit locking is being done at a lower level with exclusive-mode locks.
- intention locks allow a higher level node to be locked in S or X mode without having to check all descendent nodes.

Compatibility Matrix with Intention Lock Modes

- The compatibility matrix for all lock modes is:

	IS	IX	S	S IX	X
IS	✓	✓	✓	✓	×
IX	✓	✓	×	×	×
S	✓	×	✓	×	×
S IX	✓	×	×	×	×
X	×	×	×	×	×

Multiple Granularity Locking Scheme

- Transaction T_i can lock a node Q, using the following rules:
  1. The lock compatibility matrix must be observed.
  2. The root of the tree must be locked first, and may be locked in any mode.
  3. A node Q can be locked by T_i in S or IS mode only if the parent of Q is currently locked by T_i in either IX or IS mode.
  4. A node Q can be locked by T_i in X, SIX, or IX mode only if the parent of Q is currently locked by T_i in either IX or SIX mode.
  5. T_i can lock a node only if it has not previously unlocked any node (that is, T_i is two-phase).
  6. T_i can unlock a node Q only if none of the children of Q are currently locked by T_i.
- Observe that locks are acquired in root-to-leaf order, whereas they are released in leaf-to-root order.

More Concurrency

- Deadlock detection
- Deadlock prevention
- Timestamping

Deadlocks

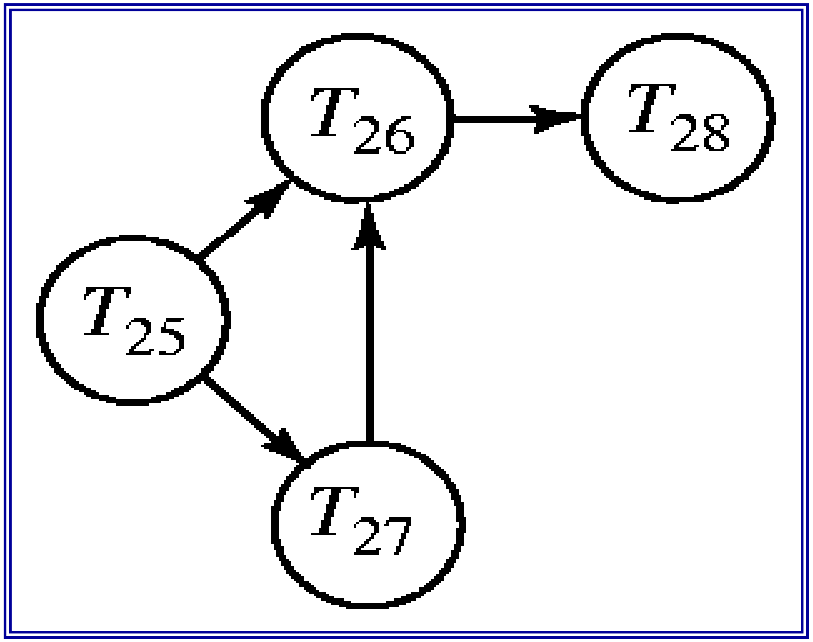
- A deadlock is an impasse that may result when two or more transactions are waiting for locks to be released which are held by each other.
  - For example: T1 has a lock on X and is waiting for a lock on Y, and T2 has a lock on Y and is waiting for a lock on X.

- Given a schedule, we can detect deadlocks which will happen in this schedule using a *wait-for graph* (WFG).

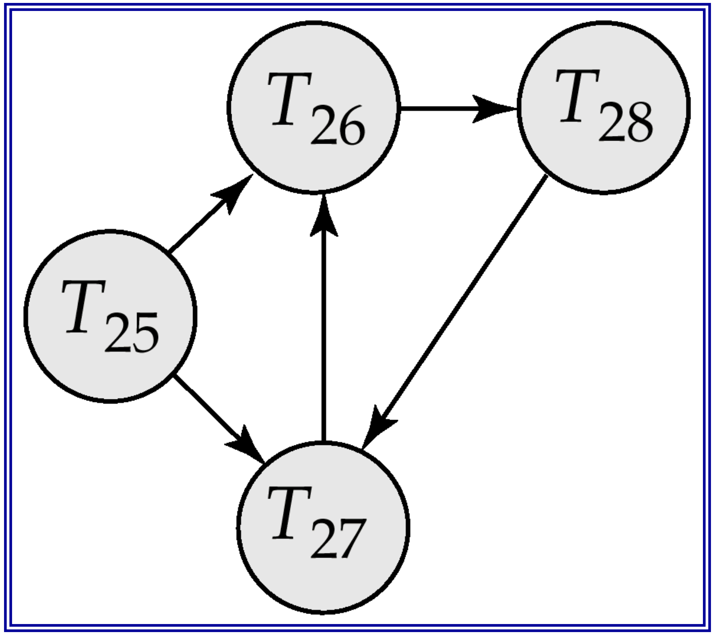
Deadlock Detection

- 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 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

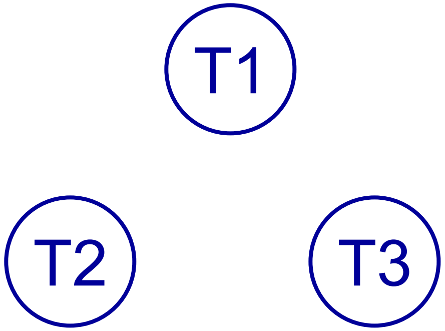
Precedence/Wait-For Graphs

- Precedence graph
  - Each transaction is a vertex
  - Arcs from T1 to T2 if
    - T1 reads X before T2 writes X
    - T1 writes X before T2 reads X
    - T1 writes X before T2 writes X

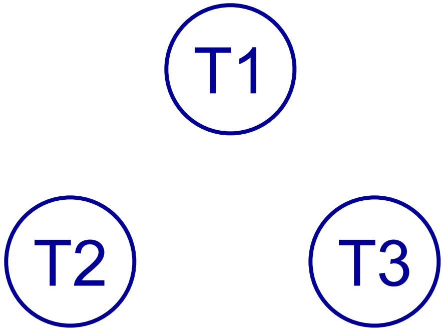
- Wait-for Graph
  - Each transaction is a vertex
  - Arcs from T2 to T1 if
    - T1 read-locks X then T2 tries to write-lock it
    - T1 write-locks X then T2 tries to read-lock it
    - T1 write-locks X then T2 tries to write-lock it

Example

T1 Read(X)
T2 Read(Y)
T1 Write(X)
T2 Read(X)
T3 Read(Z)
T3 Write(Z)
T1 Read(Y)
T3 Read(X)
T1 Write(Y)



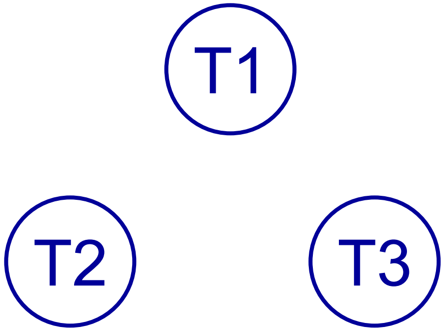
Wait for graph



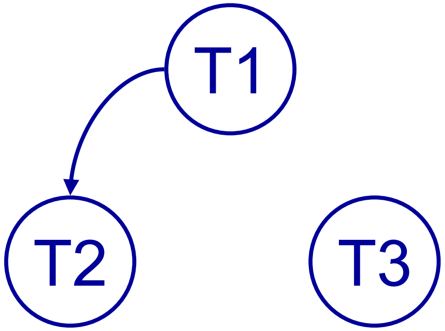
Precedence graph

Example

T1 Read(X)
T2 Read(Y)
T1 Write(X)
T2 Read(X)
T3 Read(Z)
T3 Write(Z)
T1 Read(Y)
T3 Read(X)
T1 Write(Y)



Wait for graph



Precedence graph

Example

T1 Read(X)

T2 Read(Y)

T1 Write(X)

T2 Read(X)

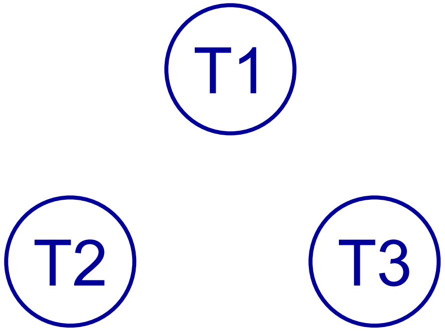
T3 Read(Z)

T3 Write(Z)

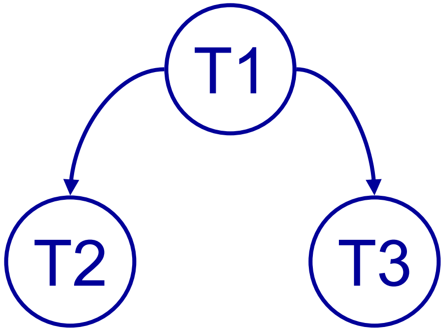
T1 Read(Y)

T3 Read(X)

T1 Write(Y)



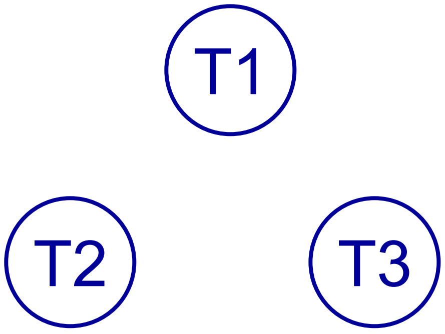
Wait for graph



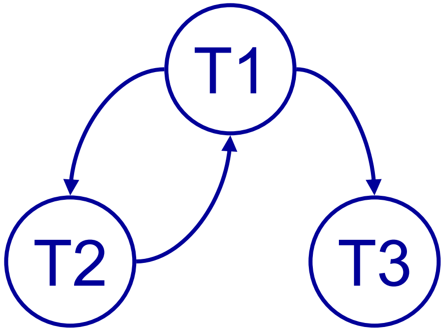
Precedence graph

Example

T1 Read(X)
T2 Read(Y)
T1 Write(X)
T2 Read(X)
T3 Read(Z)
T3 Write(Z)
T1 Read(Y)
T3 Read(X)
T1 Write(Y)



Wait for graph



Precedence graph

Example

T1 Read(X) read-locks(X)

T2 Read(Y) read-locks(Y)

T1 Write(X) **write-lock(X)**

T2 Read(X) **tries read-lock(X)**

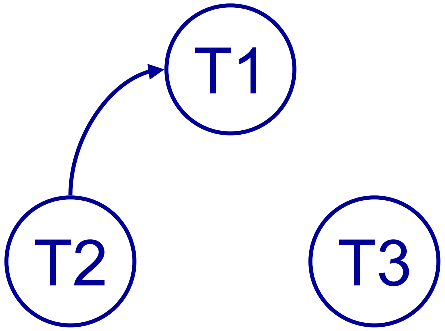
T3 Read(Z)

T3 Write(Z)

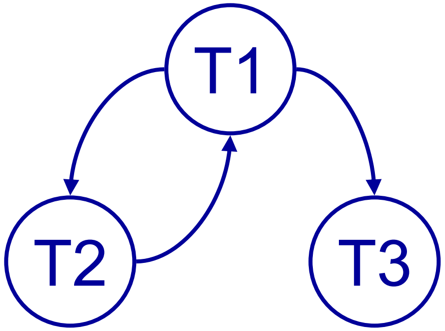
T1 Read(Y)

T3 Read(X)

T1 Write(Y)



Wait for graph



Precedence graph

Example

T1 Read(X) read-locks(X)

T2 Read(Y) read-locks(Y)

T1 Write(X) **write-lock(X)**

T2 Read(X) tries read-lock(X)

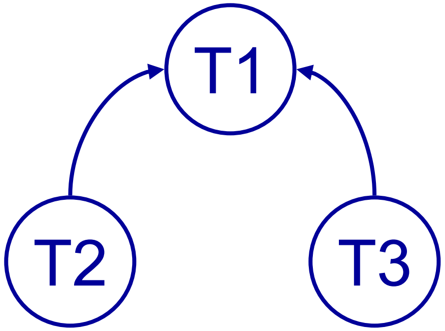
T3 Read(Z) read-lock(Z)

T3 Write(Z) write-lock(Z)

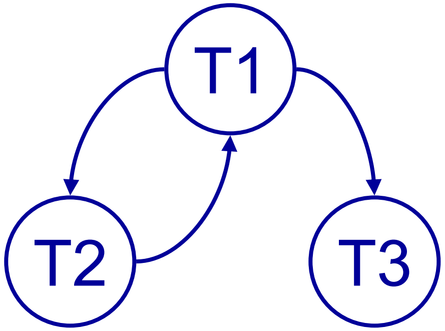
T1 Read(Y) read-lock(Y)

T3 Read(X) **tries read-lock(X)**

T1 Write(Y)



Wait for graph



Precedence graph

Example

T1 Read(X) read-locks(X)

T2 Read(Y) **read-locks(Y)**

T1 Write(X) write-lock(X)

T2 Read(X) tries read-lock(X)

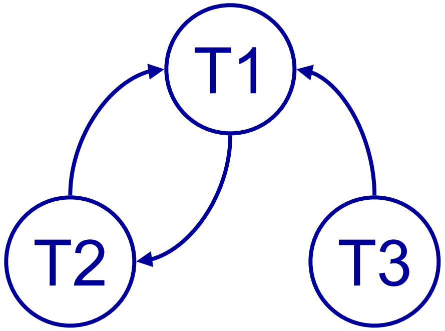
T3 Read(Z) read-lock(Z)

T3 Write(Z) write-lock(Z)

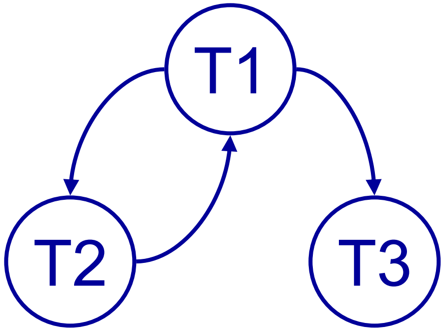
T1 Read(Y) read-lock(Y)

T3 Read(X) tries read-lock(X)

T1 Write(Y) **tries write-lock(Y)**



Wait for graph



Precedence graph

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.
- Deadlocks can arise with 2PL
  - Deadlock is less of a problem than an inconsistent DB
  - We can detect and recover from deadlock
  - It would be nice to avoid it altogether

- Conservative 2PL
  - All locks must be acquired before the transaction starts
  - Hard to predict what locks are needed
  - Low ‘lock utilisation’ - transactions can hold on to locks for a long time, but not use them much

Timestamping

- Transactions can be run concurrently using a variety of techniques
- We looked at using locks to prevent interference

- An alternative is timestamping
  - Requires less overhead in terms of tracking locks or detecting deadlock
  - Determines the order of transactions before they are executed

Timestamping

- Each transaction has a timestamp, TS, and if T1 starts before T2 then TS(T1) < TS(T2)
  - Can use the system clock or an incrementing counter to generate timestamps

- Each resource has two timestamps
  - R(X), the largest timestamp of any transaction that has read X
  - W(X), the largest timestamp of any transaction that has written X

Timestamp Protocol

- If T tries to read X
  - If $TS(T) < W(X)$ T is rolled back and restarted with a later timestamp
  - If $TS(T) \geq W(X)$ then the read succeeds and we set $R(X)$ to be $\max(R(X), TS(T))$

- T tries to write X
  - If $TS(T) < W(X)$ or $TS(T) < R(X)$ then T is rolled back and restarted with a later timestamp
  - Otherwise the write succeeds and we set $W(X)$ to $TS(T)$

Timestamping

- The protocol means that transactions with higher times take precedence
  - Equivalent to running transactions in order of their final time values
  - Transactions don’t wait - no deadlock

- Problems
  - Long transactions might keep getting restarted by new transactions - starvation
  - Rolls back old transactions, which may have done a lot of work

Deadlock Prevention

- ***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).

Deadlock Prevention

- We impose an ordering on the resources
  - Transactions must acquire locks in this order
  - Transactions can be ordered on the last resource they locked

- This prevents deadlock
  - If T1 is waiting for a resource from T2 then that resource must come after all of T1's current locks
  - All the arcs in the wait-for graph point 'forwards' - no cycles

Example of resource ordering

- Suppose resource order is: X < Y
- This means, if you need locks on X and Y, you first acquire a lock on X and only after that a lock on Y
  - (even if you want to write to Y before doing anything to X)

- It is impossible to end up in a situation when T1 is waiting for a lock on X held by T2, and T2 is waiting for a lock on Y held by T1.

Timestamping

- The protocol means that transactions with higher times take precedence
  - Equivalent to running transactions in order of their final time values
  - Transactions don’t wait - no deadlock

- Problems
  - Long transactions might keep getting restarted by new transactions - starvation
  - Rolls back old transactions, which may have done a lot of work

Timestamp-Based Protocols

- Each transaction is issued a timestamp when it enters the system. If an old transaction T_i has time-stamp TS(T_i), a new transaction T_j is assigned time-stamp TS(T_j) such that TS(T_i) <TS(T_j).
- The protocol manages concurrent execution such that the time-stamps determine the serializability order.
- In order to assure such behavior, the protocol maintains for each data Q two timestamp values:
  - **W-timestamp**(Q) is the largest time-stamp of any transaction that executed **write**(Q) successfully.
  - **R-timestamp**(Q) is the largest time-stamp of any transaction that executed **read**(Q) successfully.

Timestamp-Based Protocols (Cont.)

- The timestamp ordering protocol ensures that any conflicting **read** and **write** operations are executed in timestamp order.
- Suppose a transaction T_i issues a **read**(*Q*)

  1. If TS(T_i) ≤ **W**-timestamp(*Q*), then T_i needs to read a value of *Q* that was already overwritten.
     - Hence, the **read** operation is rejected, and T_i is rolled back.
  2. If TS(T_i)≥ **W**-timestamp(*Q*), then the **read** operation is executed, and R-timestamp(*Q*) is set to **max**(R-timestamp(*Q*), TS(T_i)).

Timestamp-Based Protocols (Cont.)

- Suppose that transaction T_i issues **write**(Q).
   1. If TS(T_i) < R-timestamp(Q), then the value of Q that T_i is producing was needed previously, and the system assumed that that value would never be produced.
      - Hence, the **write** operation is rejected, and T_i is rolled back.
   2. If TS(T_i) < W-timestamp(Q), then T_i is attempting to write an obsolete value of Q.
      - Hence, this **write** operation is rejected, and T_i is rolled back.
   3. Otherwise, the **write** operation is executed, and W-timestamp(Q) is set to TS(T_i).

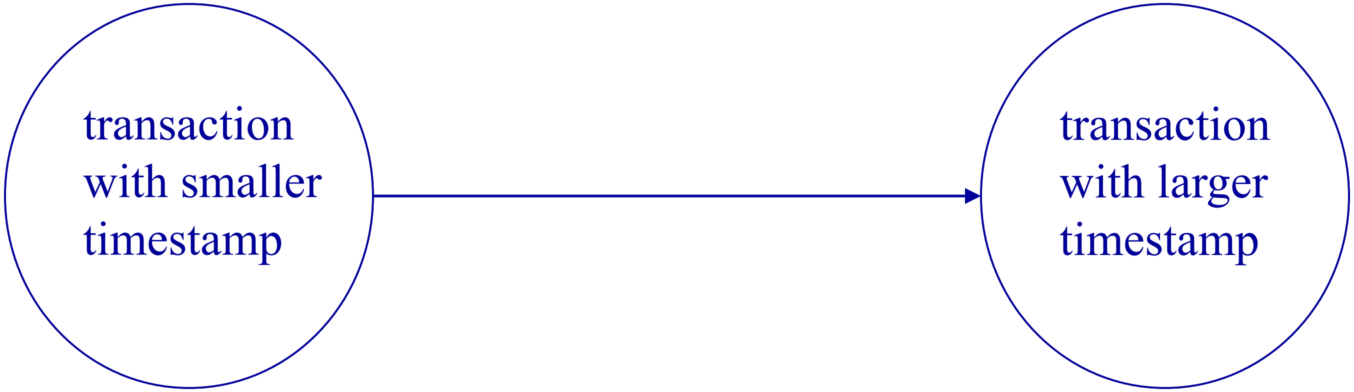
Example Use of the Protocol

A partial schedule for several data items for transactions with timestamps 1, 2, 3, 4, 5

T_1	T_2	T_3	T_4	T_5
				read(X)
	read(Y)			
read(Y)				
		write(Y)		
		write(Z)		
				read(Z)
	read(X)			
	abort			
read(X)				
		write(Z)		
		abort		
				write(Y)
				write(Z)

Correctness of Timestamp-Ordering Protocol

- The timestamp-ordering protocol guarantees serializability since all the arcs in the precedence graph are of the form:


transaction with smaller timestamp
transaction with larger timestamp

Thus, there will be no cycles in the precedence graph

- Timestamp protocol ensures freedom from deadlock as no transaction ever waits.
- But the schedule may not be cascade-free, and may not even be recoverable.

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 transactions 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.

Recoverability and Cascade Freedom

- Problem with timestamp-ordering protocol:
  - Suppose T_i aborts, but T_j has read a data item written by T_i

    Then T_j must abort; if T_j had been allowed to commit earlier, the schedule is not recoverable.
  - Further, any transaction that has read a data item written by T_j must abort

    This can lead to cascading rollback --- that is, a chain of rollbacks
- Solution 1:
  - A transaction is structured such that its writes are all performed at the end of its processing
  - All writes of a transaction form an atomic action; no transaction may execute while a transaction is being written
  - A transaction that aborts is restarted with a new timestamp
- Solution 2: Limited form of locking: wait for data to be committed before reading it
- Solution 3: Use commit dependencies to ensure recoverability

Thomas’ Write Rule

- Modified version of the timestamp-ordering protocol in which obsolete **write** operations may be ignored under certain circumstances.
- When T_i attempts to write data item Q, if TS(T_i) < W-timestamp(Q), then T_i is attempting to write an obsolete value of {Q}.
  - Rather than rolling back T_i as the timestamp ordering protocol would have done, this {**write**} operation can be ignored.
- Otherwise this protocol is the same as the timestamp ordering protocol.
- Thomas' Write Rule allows greater potential concurrency.
  - Allows some view-serializable schedules that are not conflict-serializable.