Information Management and Data Engineering

CS4D2a – 4CSLL1 – CS3041

Transactions and Concurrency Control

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Introduction

- Airline reservations, Credit Card Processing, Online Shopping etc. are examples of very large real-world database systems
  - can potentially have thousands of users performing operations at the same time
  - operations can be complex, involving a number of separate actions
    - create booking, update remaining seats, charge credit card, issue confirmation….

Introduction

- *Transactions* and *Concurrency Control* are the ways in which a DB manages complex processes and multi-user access
- Transaction
  - a logical unit of DB processing that must be completed in its entirety to ensure correctness
- Concurrency Control
  - used when two operations try to access the same data at the same time

Transactions

- A transaction includes one or more DB access operations
  - Insertion, Deletion, Modification, Retrieval
- Transactions where the DB operations retrieve data, but don’t update any information
  - Read-Only Transactions
- Transactions which update the DB
  - Read-Write Transactions

Transactions

- Transactions take the form:

  BEGIN_TRANSACTION

  READ or WRITE operation 1

  READ or WRITE operation 2

  ….

  READ or WRITE operation n

  END_TRANSACTION

  COMMIT or ROLLBACK

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Transactions

- The end of a transaction is signalled by either
  - commit (successful termination)
  - rollback or abort (unsuccessful termination)
- Commit completes the current transaction, making its changes permanent
- Rollback will undo the operations in the current transaction, cancelling the changes made to the DB

Transaction Failure

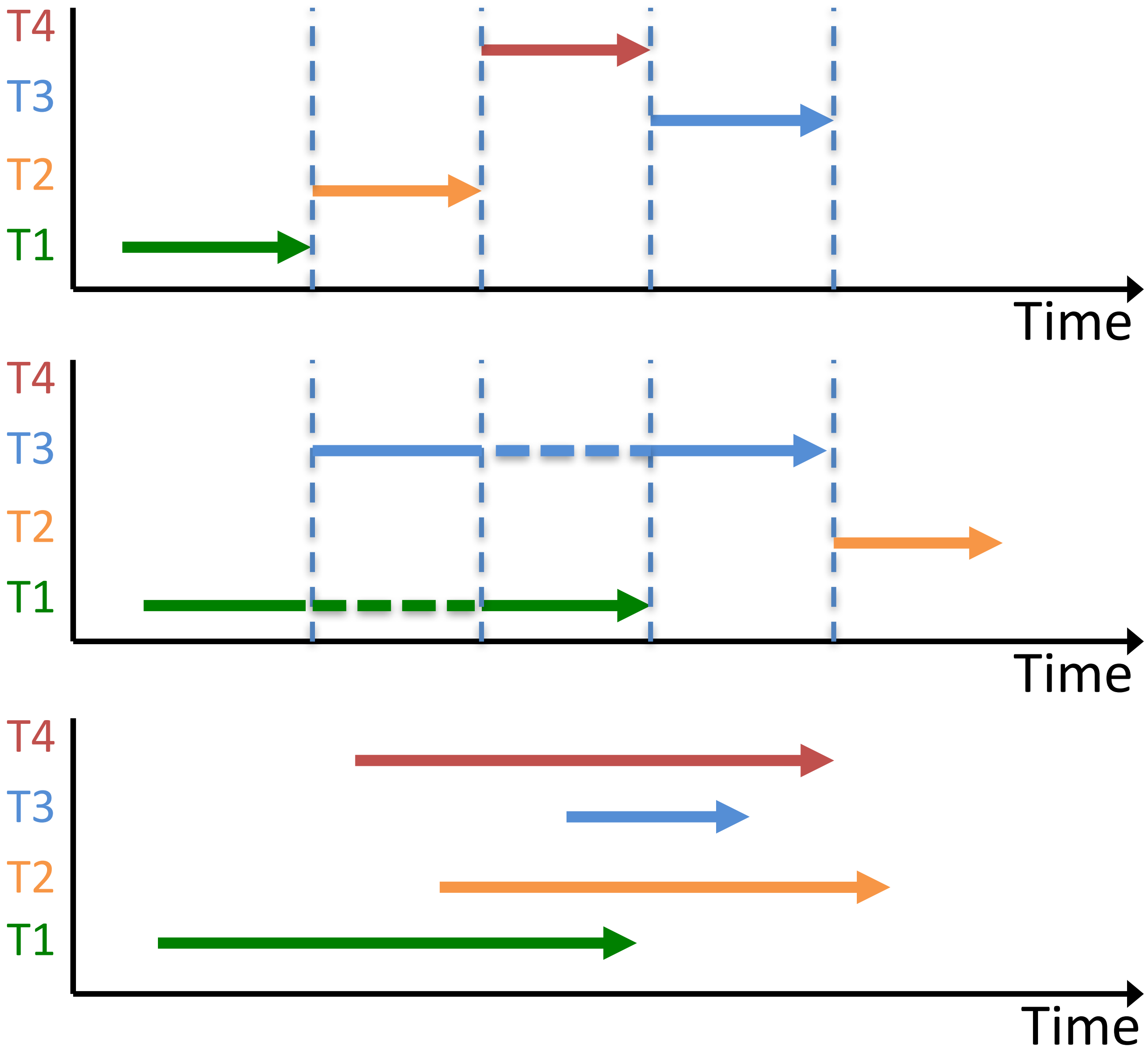
- There are a number of reasons why a transaction might fail
  - System crash
    - Hardware, Software or Network Error
  - Transaction error
    - i.e. divide by zero, incorrect attribute reference, incorrect parameter value
  - Checks can be placed in the transaction
    - i.e. insufficient funds to make a withdrawal

Transaction Properties

- All transactions should posses the ACID properties
  - **A**tomicity
  - **C**onsistency preservation
  - **I**solation
  - **D**urability (or permanency)

Transaction Properties

- **Atomicity**
  - A transaction is an atomic unit of processing
  - It should either be performed in its entirety or not performed at all
- **Consistency preservation**
  - A transaction should preserve the consistency of the DB
  - It should take the database from one consistent state to another
- **Isolation**
  - A transaction should appear as though it is being executed in isolation
  - The execution of a transaction should not be interfered with by any other transactions executing concurrently
- **Durability (or permanency)**
  - The changes applied by a committed transaction must persist in the database.
  - These changes must not be lost because of any failure


T4
T3
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Time

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Concurrency Control

- Consider the following two transactions:

Flight Transfer	Flight Reservation
read(reserved_seats_X) reserved_seats_X = reserved_seats_X – n write(reserved_seats_X) read(reserved_seats_Y) reserved_seats_Y = reserved_seats_Y + n write(reserved_seats_Y)	read(reserved_seats_X) reserved_seats_X = reserved_seats_X + m write(reserved_seats_X)

- A number of problems can occur if these two simple transactions are run concurrently

Lost Update

- This occurs when two or more transactions:
  - access the same data item
  - are executed concurrently
  - are interleaved in such a way that results in an incorrect value being written to the database

Lost Update

Flight Transfer	Flight Reservation
read(reserved_seats_X)	
reserved_seats_X = reserved_seats_X – n	
	read(reserved_seats_X)
	reserved_seats_X = reserved_seats_X + m
write(reserved_seats_X)	
read(reserved_seats_Y)	
	write(reserved_seats_X)
reserved_seats_Y = reserved_seats_Y + n	
write(reserved_seats_Y)	

time

reserved_seats_X has an incorrect value because the update by “Flight Transfer” is lost (overwritten)

Temporary Update

- This occurs when two or more transactions:
  - access the same data item
  - are executed concurrently
  - are interleaved
  - one transaction fails and must Rollback
- This is also known as the “Dirty Read”

Temporary Update

Flight Transfer	Flight Reservation
read(reserved_seats_X) reserved_seats_X = reserved_seats_X – n write(reserved_seats_X)	
	read(reserved_seats_X) reserved_seats_X = reserved_seats_X + m write(reserved_seats_X)
read(reserved_seats_Y) ***transaction fails***	

time

reserved_seats_X has an incorrect value because the update by "Flight Transfer" failed and was rolled back

Incorrect Summary

- This occurs when two or more transactions:
  - access the same data item
  - are executed concurrently
  - are interleaved
  - one transaction is calculating an aggregate summary on attributes while another transaction is updating those attributes

Incorrect Summary

Flight Transfer	Total Reservations
read(reserved_seats_X) reserved_seats_X = reserved_seats_X – n write(reserved_seats_X)	
	read(reserved_seats_X) total_reservations = total_reservations + reserved_seats_X read(reserved_seats_Y) total_reservations = total_reservations + reserved_seats_Y
read(reserved_seats_Y) reserved_seats_Y = reserved_seats_Y + n write(reserved_seats_Y)	

time

reserved_seats_Y has an incorrect value because the update by "Flight Transfer" hasn't happened yet

Schedules

- When transactions are executing concurrently in an interleaved fashion, the order of execution of operations is called the *schedule*
  - Schedule S of n transactions $T_1, T_2, \ldots, T_3$ is the ordering of the operations within those transactions
- Operations from different transactions can be interleaved
  - The operations from each transaction T_i must appear in the same order in S, that they do in T_i

Schedules

- A schedule S is generally written:
  - S_a: $O_i(X)$; $O_i(Y)$; $O_j(X)$; … ; $O_n(Y)$;
  - where $O_i(X)$ indicates either a read or write operation executed by a transaction T_i on a data item X
  - and $O_n(Y)$ indicates either a read or write operation executed by a transaction T_n on a data item Y

Schedules

- A shorthand notation can be used for each operation type
  - b → BEGIN_TRANSACTION
  - r → Read Item
  - w → Write Item
  - e → END_TRANSACTION
  - c → Commit
  - a → Abort (Rollback)

Schedules

time	Flight Transfer (Transaction 1)	Flight Reservation (Transaction 2)
	read(reserved_seats_X) reserved_seats_X = reserved_seats_X – n write(reserved_seats_X)	
		read(reserved_seats_X) reserved_seats_X = reserved_seats_X + m write(reserved_seats_X)
	read(reserved_seats_Y) reserved_seats_Y = reserved_seats_Y + n write(reserved_seats_Y)	

- Is denoted as?

S_1: R_1(reserved_seats_X); W_1(reserved_seats_X); R_2(reserved_seats_X); W_2(reserved_seats_X); R_1(reserved_seats_Y); W_1(reserved_seats_Y);

Schedule Conflicts

- Two operations in a schedule are said to *conflict* if:
  1) they belong to *different transactions*
  2) they access the *same item* X
  3) and *at least one* of the operations is a $\mathrm{write}(\mathrm{X})$
- Intuitively, two operations are conflicting if changing their order can result in a different outcome
  - or cause one of the concurrency issues we have already discussed

Schedule Conflicts

time

Flight Transfer (Transaction 1)	Flight Reservation (Transaction 2)
r_1(reserved_seats_X)	
reserved_seats_X = reserved_seats_X – n	
w_1(reserved_seats_X)	
	r_2(reserved_seats_X)
	reserved_seats_X = reserved_seats_X + m
	w_2(reserved_seats_X)
r_1(reserved_seats_Y)	
reserved_seats_Y = reserved_seats_Y + n	
w_1(reserved_seats_Y)	

S_1: R_1(reserved_seats_X); W_1(reserved_seats_X); R_2(reserved_seats_X); W_2(reserved_seats_X); R_1(reserved_seats_Y); W_1(reserved_seats_Y);

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Serial Schedules

- In a *serial schedule* the operations of each transaction are executed consecutively, without any interleaved operations

Flight Transfer	Flight Reservation
read(reserved_seats_X) reserved_seats_X = reserved_seats_X – n write(reserved_seats_X) read(reserved_seats_Y) reserved_seats_Y = reserved_seats_Y + n write(reserved_seats_Y)	
	read(reserved_seats_X) reserved_seats_X = reserved_seats_X + m write(reserved_seats_X)

time

Serial Schedules

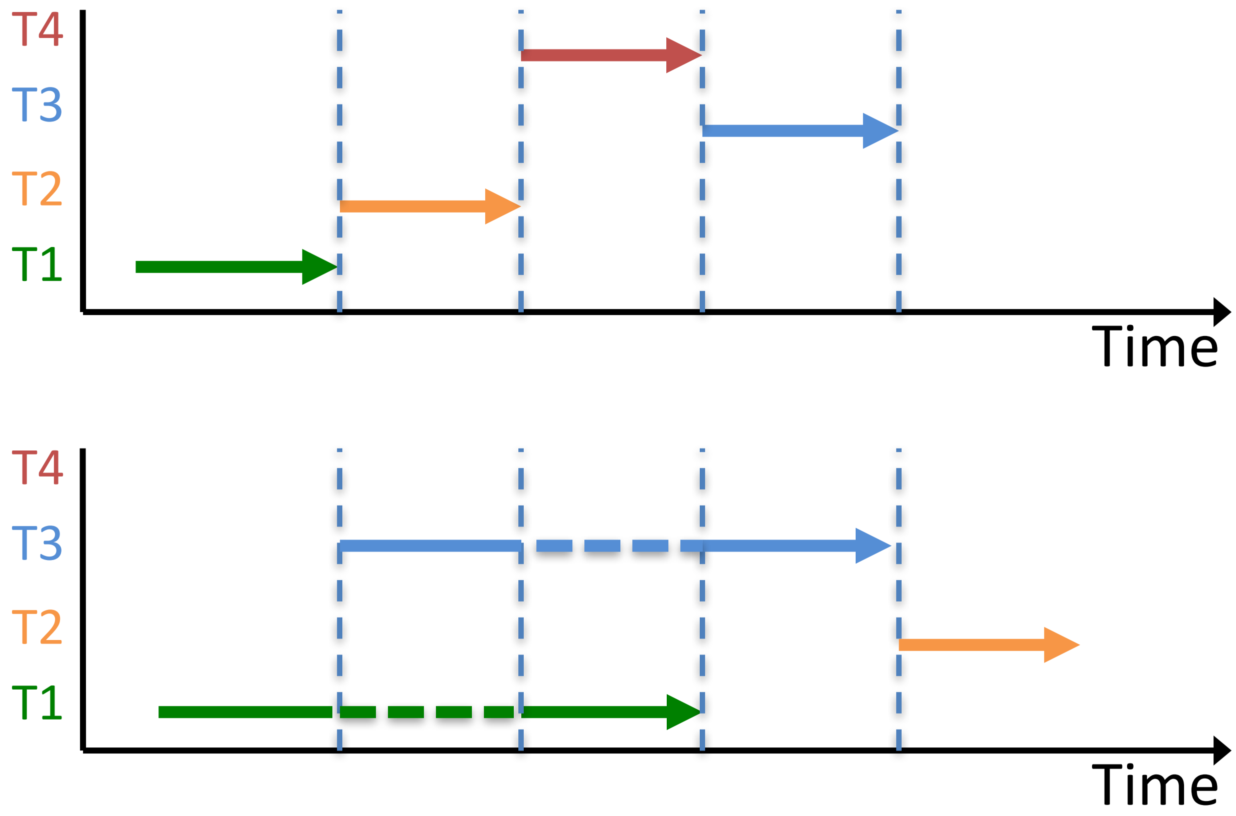
- Formally, a schedule S is *serial* if, for every transaction T participating in the schedule, all operations of T are executed consecutively
  - otherwise the schedule is called *nonserial*
- In a serial schedule, only one transaction is active at a time
  - the commit (or abort) of the active transaction initiates execution of the next transaction

Serial Schedules

- An assumption that can be made is: *every serial schedule is correct*
  - All transactions should be independent (**I**solation)
  - Each transaction is assumed to be correct if executed on its own (**C**onsistency preservation)
  - Hence, the ordering of transactions in a serial schedule does not matter
    - once every transaction is executed from beginning to end

Issues with Serial Schedules

- That is all great….. but:
  - Serial schedules limit concurrency
  - If a transaction is waiting for an operation to complete it is not possible to switch processing to another transaction
  - If a transaction T is very long, all other transactions must wait for T to complete its operations before they can begin
- Hence, serial schedules are considered unacceptable in practice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Time

Serializability

- However, if it can be determined which other schedules are *equivalent* to a serial schedule, those schedules can be allowed to occur
- How is equivalence measured?
  - Result Equivalence
  - Conflict Equivalence
- If a nonserial schedule meets these criteria, it is said to be *serializable*

Result Equivalence

- This is the simplest notion of equivalence
- Two schedules are said to be *result equivalent* if they produce the same final state of the DB
- However two schedules could coincidentally produce the same result:

time ↓

S_1
read(X)
X = X + 10
write(X)

time ↓

S_2
read(X)
X = X * 1.1
write(X)

Conflict Equivalence

- Two schedules are said to be *conflict equivalent* if the order of any two conflicting operations is the same in both schedules
- Reminder: two operations in a schedule are said to *conflict* if:
  1) they belong to *different transactions*
  2) they access the *same item* X
  3) and *at least one* of the operations is a $\mathrm{write}(X)$

Conflict Equivalence

- If two conflicting operations are applied in different orders in two schedules, the effect can be different on the DB
  - hence, the schedules are not conflict equivalent.
- If read and write operations occur in the order
  - $r_1(X)$, $w_2(X)$ in schedule S_1
  - $w_2(X)$, $r_1(X)$ in schedule S_2
  - the value read by $r_1(X)$ may be different in the two schedules as it may have been updated by the write

Conflict Equivalence

- Similarly, if two write operations occur in the order:
  - w1(X), w2(X) in S1
  - w2(X), w1(X) in S2
  - the next r(X) operation in the two schedules will read potentially different values
  - if these are the last two operations in the schedules, the final value of item X in the DB will be different

Example

Schedule A

T_1	T_2
read(X)	
X = X – n	
write(X)	
read(Y)	
Y = Y + n	
write(Y)	
	read(X)
	X = X + m
	write(X)

time

Schedule B

T_1	T_2
read(X)	
X = X – n	
write(X)	
	read(X)
	X = X + m
	write(X)
read(Y)	
Y = Y + n	
write(Y)	

time

Example

Schedule A

T_1	T_2
read(X)	
X = X – n	
write(X)	
read(Y)	
Y = Y + n	
write(Y)	
	read(X)
	X = X + m
	write(X)

time

Schedule C

T_1	T_2
read(X)	
X = X – n	
	read(X)
	X = X + m
write(X)	
read(Y)	
	write(X)
Y = Y + n	
write(Y)	

time

Serializability

- Being able to say that a schedule is serializable, is the same as saying it is correct
  – All serial schedules are correct
  – This is equivalent to a serial schedule
  – Hence, this is also correct
- Serializable schedules give the benefits of concurrent execution without giving up correctness

Serializability

- Most DBMS systems will have a set of protocols which:
  – must be followed by every transaction
  – are enforced by the concurrency control subsystem
  – ensure the serializability of all schedules in which the transactions participate
- Concurrency Control Protocols

Concurrency Control Protocols

- Locking Protocols
  - Data items are locked to prevent multiple transactions from accessing them concurrently
- Timestamps
  - A unique identifier is generated for each transaction based upon transaction start time
- Optimistic Protocols
  - Based upon validation of the transaction after it executes its operations

Locking

- A lock is a variable associated with a data item
  – describes the status of the data item with respect to operations that can be applied to it
  – data items may be at a variety of granularities e.g. DB, table, tuple, attribute etc.
- Locks are used to synchronise access by concurrent transactions
- There are two main types of lock
  – Binary Lock
  – Read/Write Lock

Binary Lock

- A binary lock can have only two states (or values)
  - locked and unlocked
- Two operations are used in binary locking
  - lock_item
  - unlock_item
- Each transaction locks the item before using it, and then unlocks it when finished

Binary Lock

- A transaction which wants to access a data item requests to lock the item
  - If the item is unlocked, the transaction locks it and can use it
  - If the item is already locked, then the transaction must wait until it is unlocked
- Binary locking is rarely used, as it is too restrictive
  - At most, one transaction can access each item at a time
  - Several transactions should be allowed access concurrently if they only need read access

Read/Write Lock

- If multiple transactions want to read an item, then they can access the item concurrently
  - read operations are not conflicting
- However, if a transaction is to write an item, then it must have exclusive access
- The read/write lock implements this form of locking
  - it is called a multiple-mode lock

Read/Write Lock

- There are three locking operations used in read/write locks
  - read_lock
  - write_lock
  - unlock
- A *read-locked* item is also called *share-locked*, as other transactions are allowed to read it
- A *write-locked* item is also called *exclusive-locked* as a single transaction has access to it

Read/Write Lock

- The following rules must be enforced:
  1. A transaction *T* must issue the operation read_lock(X) or write_lock(X) before any read_item(X) operation is performed in *T*
  2. A transaction *T* must issue the operation write_lock(X) before any write_item(X) operation is performed in *T*
  3. A transaction *T* must issue the operation unlock(X) after all read_item(X) and write_item(X) operations are completed in *T*
  4. A transaction *T* will not issue an unlock(X) operation unless it already holds a read (shared) lock or a write (exclusive) lock on item *X*

Lock Conversion

- Some DBMS allow the conversion of a lock from one state to another
- A transaction T can issue a read_lock(X) and then later *upgrade* the lock by issuing a write_lock(X)
  - If T is the only transaction holding a read lock on X at the time it issues the write_lock(X) operation, the lock can be upgraded
  - otherwise, the transaction must wait
- It is also possible for a transaction T to issue a write_lock(X) and then later to *downgrade* the lock by issuing a read_lock(X) operation

Schedule A

T_1	T_2
read_lock(Y);	
read(Y);	
unlock(Y);	
write_lock(X);	
read(X);	
X = X + Y;	
write(X);	
unlock(X);	
	read_lock(X);
	read(X);
	unlock(X);
	write_lock(Y);
	read(Y);
	Y = X + Y;
	write(Y);
	unlock(Y);

time

Schedule B

T_1	T_2
read_lock(Y);	
read(Y);	
unlock(Y);	
	read_lock(X);
	read(X);
	unlock(X);
	write_lock(Y);
	read(Y);
	Y = X + Y;
	write(Y);
	unlock(Y);
write_lock(X);	
read(X);	
X = X + Y;	
write(X);	
unlock(X);	

time

Two-Phase Locking

- Two-Phase Locking is an additional protocol
  - concerns the positioning of locking and unlocking in every transaction
  - used to guarantee serializability
- A transaction is said to follow two-phase locking if all lock operations (read_lock, write_lock) precede the first unlock operation in that transaction

Two-Phase Locking

- Two-Phase Locking transactions are divided into two phases:
  - Expanding phase
    - during which new locks on items can be acquired but none can be released
  - Shrinking phase
    - during which existing locks can be released but no new locks can be acquired.
- If lock conversion is allowed:
  - upgrading of locks (from read-locked to write-locked) must be done during the expanding phase
  - downgrading of locks (from write-locked to read-locked) must be done in the shrinking phase

Two-Phase Locking

- Consider the transactions from our example:

T_1
read_lock(Y);
read(Y);
unlock(Y);
write_lock(X);
read(X);
X = X + Y;
write(X);
unlock(X);

time

T_2
read_lock(X);
read(X);
unlock(X);
write_lock(Y);
read(Y);
Y = X + Y;
write(Y);
unlock(Y);

time

Two-Phase Locking

- Transactions following two-phase locking:

T_1
read_lock(Y);
read(Y);
write_lock(X);
unlock(Y);
read(X);
X = X + Y;
write(X);
unlock(X);

time

T_2
read_lock(X);
read(X);
write_lock(Y);
unlock(X);
read(Y);
Y = X + Y;
write(Y);
unlock(Y);

time

Two-Phase Locking

- It has been proven that:
  - if every transaction in a schedule follows the two-phase locking protocol, the schedule is guaranteed to be *serializable*
- This removes the need to test each schedule produced for serializability
  - However, this comes at a cost

Limitations of Two-Phase Locking

- Can limit the concurrency that can occur in a schedule
- A transaction may not be able to release an item X after it is finished using it, if the transaction must lock an additional item Y at a later point
  - conversely, a transaction may have to lock the additional item Y before it needs it so that it can release X
  - Hence, X must remain locked until all items that the transaction needs to read or write have been locked, only then can X be released
  - Meanwhile, another transaction seeking to access X may be forced to wait

Problems with Locking

- The use of locking in schedules can cause two additional problems:
  - Deadlock
  - Starvation

Deadlock

- Deadlock occurs when:
  - each transaction T_i in a set of two or more transactions is waiting for some item that is locked by some other transaction in the set
  - Hence, each transaction in the set is waiting for one of the other transactions in the set to release the lock on an item
  - But because the other transaction is also waiting, it will never release the lock

Deadlock

Schedule A

T_1	T_2
read_lock(Y);	
read(Y);	
	read_lock(X);
	read(X);
write_lock(X);	
…	write_lock(Y);
…	…
…	…

time

Deadlock Prevention Protocols

- Used to decide what to do with a transaction involved in a possible deadlock situation:
  - Should it be blocked and made to wait?
  - Should it be aborted?
  - Should the transaction preempt another transaction and cause it to abort?
- No Waiting
- Wait-die
- Wound-wait
- Cautious Waiting

Deadlock Prevention Protocols

- Typically use the concept of transaction timestamp
  - unique identifier assigned to each transaction
- Timestamps are based on the order in which transactions are started
  - hence, if transaction T1 starts before transaction T2, then TS(T1) < TS(T2).

No Waiting

- In the *no waiting* approach, if a transaction is unable to obtain a lock, it is immediately aborted
- It is then restarted after a certain time delay without checking whether a deadlock will actually occur or not
- In this case, no transaction ever waits, so no deadlock will occur
  - However, this scheme can cause transactions to abort and restart needlessly

No Waiting

Schedule A

T_1	T_2
read_lock(Y);	
read(Y);	
	read_lock(X);
	read(X);
write_lock(X);	
…	write_lock(Y);
…	…
…	…

time

- Transaction T_1 will abort as it is unable to obtain the lock on X, that way T_2 never encounters a block on locking Y

Wait-die

- Suppose that transaction T_a tries to lock an item X but is not able to because X is locked by some other transaction T_b
- The rules followed by *Wait-die* are:
  - If T_a is older than T_b then T_a is allowed to wait
  - otherwise, if T_a is younger than T_b then abort T_a and restart it later with the same timestamp
  - So T_a either waits or dies

Wait-die

Schedule A

T_1	T_2
read_lock(Y);	
read(Y);	
	read_lock(X);
	read(X);
write_lock(X);	
…	write_lock(Y);
…	…
…	…

time

- Transaction T_1 is older than T_2 and thus is allowed to wait after it is unable to obtain the lock on X
- Transaction T_2 is younger than T_1 and thus is aborted after it is unable to obtain the lock on Y

Wound-wait

- Suppose that transaction T_a tries to lock an item X but is not able to because X is locked by some other transaction T_b
- The rules followed by *Wound-wait* are:
  - If T_a is older than T_b then abort T_b and restart it later with the same timestamp
  - otherwise, if T_a is younger than T_b then T_a is allowed to wait
  - So T_a either wounds T_b or waits

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Wound-wait

Schedule A

time

T_1	T_2
read_lock(Y);	
read(Y);	
	read_lock(X);
	read(X);
write_lock(X);	
…	write_lock(Y);
…	…
…	…

- T_1 is older than T_2 and thus and thus T_2 is aborted after T_1 is unable to obtain the lock on X
  - T_2 is “wounded”

Wait-die and Wound-wait

- Of the two transactions that may be involved in a deadlock, both these approaches abort the transaction that started later
  - assumption is that this will waste less processing
- However, both may cause some transactions to be aborted and restarted needlessly
  - even though those transactions may never actually cause a deadlock.

Cautious Waiting

- Proposed to try to reduce the number of needless aborts
- Suppose that transaction T_a tries to lock an item X but is not able to do so because X is locked by some other transaction T_b
- The cautious waiting rules are:
  - If T_b is not blocked (not waiting for some other locked item), then T_a is blocked and allowed to wait
  - otherwise abort T_a

Cautious Waiting

Schedule A

T_1	T_2
read_lock(Y);	
read(Y);	
	read_lock(X);
	read(X);
write_lock(X);	
…	write_lock(Y);
…	…
…	…

time

- When T_1 is unable to obtain the lock on X, T_2 which holds the lock on X is not blocked, so T_1 can wait
- When T_2 is unable to obtain the lock on Y, T_1 which holds the lock on Y is also blocked, so T_2 is aborted

Deadlock Detection

- Deadlock detection is used to check if a state of deadlock actually exists
  - attractive if there is little interference among transactions i.e. if different transactions rarely access the same items at the same time
  - however, if transactions are long and each transaction uses many items, it may be better to use a deadlock prevention protocol

Deadlock Detection

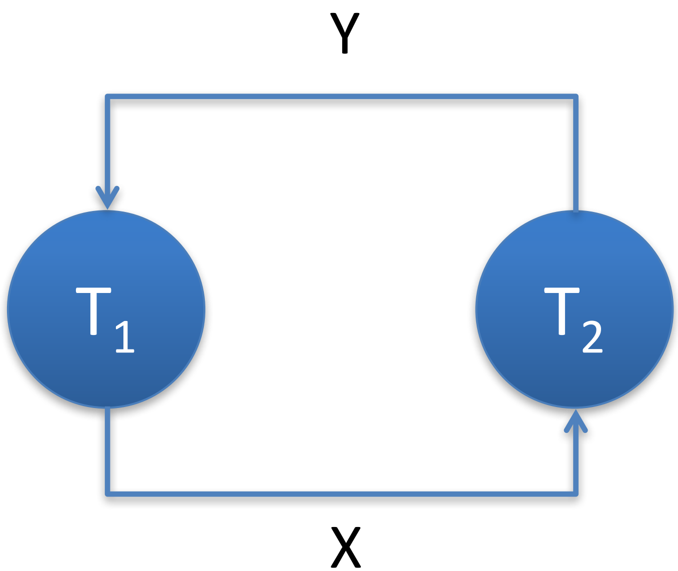
- A simple way to detect deadlock is for the system to construct and maintain a *wait-for graph*
  - One node is created in the wait-for graph for each transaction that is currently executing
  - Whenever a transaction T_a is waiting to lock an item X that is currently locked by a transaction T_b, a directed edge ($T_a \rightarrow T_b$) is created in the wait-for graph
  - When T_b releases the lock(s) on the items that T_a is waiting for, the directed edge is dropped from the wait-for graph.
- There is a state of deadlock if, and only if, the wait-for graph has a loop

Deadlock Detection

Schedule A

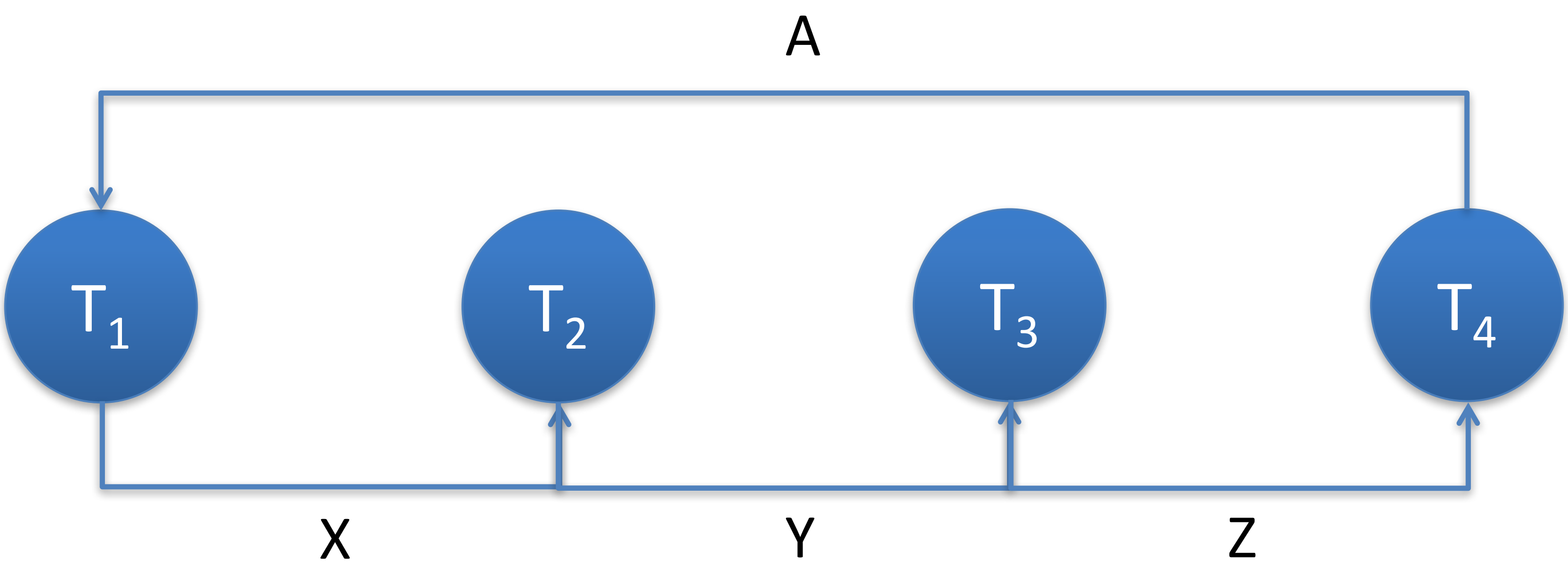
T_1	T_2
read_lock(Y);	
read(Y);	
	read_lock(X);
	read(X);
write_lock(X);	
…	write_lock(Y);
…	…
…	…

time



Deadlock Detection

- Deadlock can occur between two transactions indirectly via a chain of intermediate transactions



Deadlock Detection

- Once detected, deadlock must be resolved by aborting and rolling back one of the transactions
- Choosing which transactions to abort is known as *victim selection*
  – avoid selecting transactions that have run for a long time or have performed many updates
  – instead, select transactions that have not made many changes (younger transactions)

Starvation

- Another problem that may occur when using locking is *starvation*
  - when a transaction cannot proceed for an indefinite period of time while other transactions in the system continue normally
- Can occur if the waiting scheme for locked items gives priority to some transactions over others
- Can also occur because of victim selection
  - if the algorithm repeatedly selects the same victim transaction, causing it to abort and never finish

Starvation Solutions

- first-come-first-served queue
  - transactions are allowed to lock an item in the order in which they originally requested the lock
- waiting list
  - allows some transactions to have priority over others but increases the priority of a transaction the longer it waits, until it eventually gets the highest priority and proceeds
- victim priority
  - assigns higher priorities to transactions that have been aborted multiple times

Timestamp Ordering

- As already discussed, timestamp values are assigned to transactions in the order they are submitted to the system
  - so a timestamp can be thought of as the transaction start time
- There are concurrency control techniques based purely on timestamp ordering which do not use locking
  - hence, deadlocks cannot occur

Timestamp Ordering

- For each data item accessed by conflicting operations in the schedule, the order in which the item is accessed must not violate the timestamp ordering
- This produces serializable schedules which are equivalent to the serial schedule
  - as all conflicting operations are conducted in the same order that they would be in the serial schedule

Timestamp Ordering

- In order to enforce this, the DBMS keeps two timestamp values for each data item:
  - read_TS(X) – This is equal to the timestamp of the most recently started (youngest) transaction that has successfully read item X
  - write_TS(X) – This is equal to the timestamp of the most recently started (youngest) transaction that has successfully written item X

Timestamp Ordering

- Whenever a transaction T issues a write_item(X) operation, the following is checked:
  - If read_TS(X) > TS(T) or if write_TS(X) > TS(T), then abort and rollback T and reject the operation
    - This should be done because some younger transaction with a timestamp greater than TS(T) – and hence after T in the timestamp ordering – has already read or written the value of item X before T had a chance to write X, thus violating the timestamp ordering
  - If read_TS(X) ≤ TS(T) and if write_TS(X) ≤ TS(T), then execute the write_item(X) operation of T and set write_TS(X) to TS(T)

Timestamp Ordering

- Whenever a transaction T issues a read_item(X) operation, the following is checked:
  - If write_TS(X) > TS(T), then abort and rollback T and reject the operation
    - This should be done because some younger transaction with timestamp greater than TS(T) – and hence after T in the timestamp ordering – has already written the value of item X before T had a chance to read X
  - If write_TS(X) ≤ TS(T), then execute the read_item(X) operation of T and set read_TS(X) equal to the larger of TS(T) and the current read_TS(X)