Transactions - ACID

CS 317/387

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Transactions

- Many enterprises use databases to store information about their state
  - *e.g.*, Balances of all depositors at a bank
- When an event occurs in the real world that changes the state of the enterprise, a program is executed to change the database state in a corresponding way
  - *e.g.*, Bank balance must be updated when deposit is made
- Such a program is called a **transaction**

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What does a Transaction do?

- ***Update the database*** to reflect the occurrence of a real world event
  - Deposit transaction: Update customer's balance in database
- ***Cause the occurrence of a real world event***
  - Withdraw transaction: Dispense cash (and update customer's balance in database)
- ***Return information from the database***
  - RequestBalance transaction: Outputs customer's balance

A Sample Transaction

```
Begin_Transaction
get (K1, K2, CHF) from terminal
Select BALANCE Into S1 From ACCOUNT Where ACCOUNTNR = K1;
S1 := S1 - CHF;
Update ACCOUNT Set BALANCE = S1 Where ACCOUNTNR = K1;
Select BALANCE Into S2 From ACCOUNT Where ACCOUNTNR = K2;
S2 := S2 + CHF;
Update ACCOUNT Set BALANCE = S2 Where ACCOUNTNR = K2;
Insert Into BOOKING(ACCOUNTNR,DATE,AMOUNT,TEXT)
    Values (K1, today, -CHF, 'Transfer');
Insert Into BOOKING(ACCOUNTNR,DATE,AMOUNT,TEXT)
    Values (K2, today, CHF, 'Transfer');
If S1<0 Then Abort_Transaction
End_Transaction
```

Transaction = Program that takes database from one consistent state to another consistent state

So what is the issue?

- System crashes during transaction
  - database remains in inconsistent (intermediate) state
  - solution: **recovery**

- Multiple transactions executed at same time
  - other applications have access to inconsistent (intermediate) state
  - solution: **concurrency control**

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DBMS View

- From the viewpoint of a DBMS, a transaction is a sequence of reads and writes that are supposed to make consistent transformations of system states while preserving system consistency

- Transaction is a "*unit of work*", i.e. it must do all the work necessary to update the database and maintain integrity constraints.

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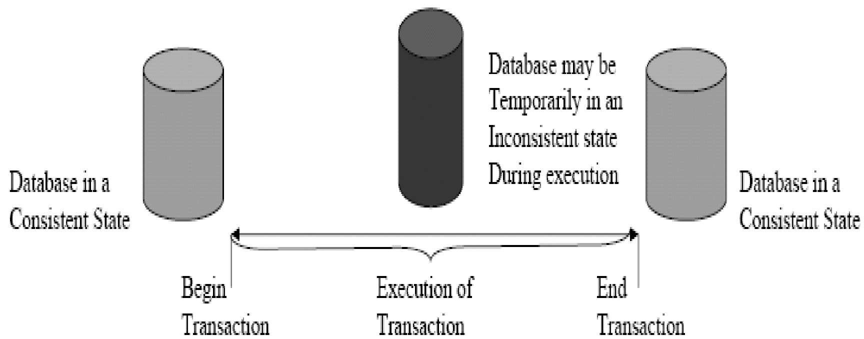

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Model for Transactions

- Assumption: the database is composed of ***elements***
  - Usually 1 element = 1 block
  - Can be smaller (=1 record) or larger (=1 relation)
- Assumption: each transaction reads/writes some elements

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Transaction operations

- A user's program may carry out many operations on the data retrieved from DB but DBMS is only concerned about Read/Write.
- A database transaction is the execution of a program that include database access operations:
  - Begin-transaction
  - Read
  - Write
  - End-transaction
  - Commit-transaction
  - Abort-transaction
  - Undo
  - Redo
- Concurrent execution of user programs is essential for good DBMS performance.

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State of a transaction

- ***Active***: the transaction is executing.
- ***Partially Committed***: the transaction ends after execution of final statement ("commit requested").
- ***Committed***: after successful completion checks.
- ***Failed***: when normal execution can no longer proceed.
- ***Aborted***: after the transaction has been rolled back.

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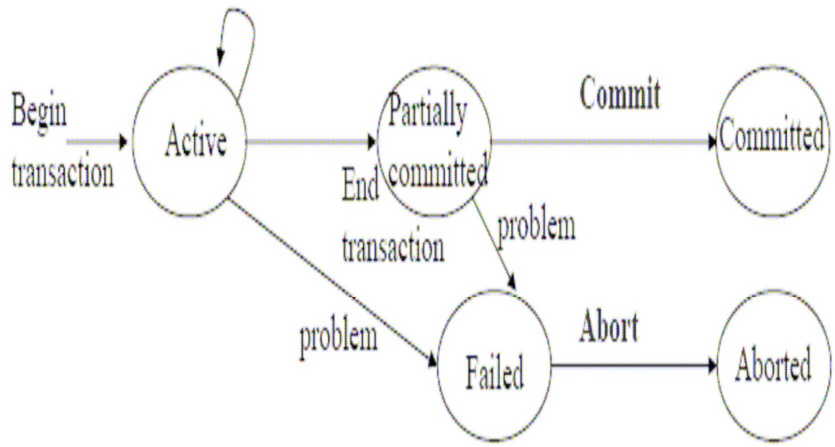

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Properties of a xAction

- The execution of each transaction must maintain the relationship between the database state and the enterprise state (at “all”times)
- Therefore additional requirements are placed on the execution of transactions beyond those placed on ordinary programs:

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ACID Properties

- **A**tomicity
- **C**onsistency
- **I**solation
- **D**urability

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ACID Properties

- **A**tomicity (all or nothing)
  - A transaction is *atomic*: the effect of a transaction on the database should be either the effect of executing *all* its actions, or not executing any actions at all.
- **C**onsistency (no violation of integrity constraints)
  - A transaction must preserve the consistency of a database after execution. (responsibility of the user)
- **I**solation (concurrent changes invisible -> serializable)
  - Transaction is protected from the effects of concurrently executing other transactions.
- **D**urability (committed updates persist)
  - The effect of a committed transaction should persist even in the event of system failures such as a crash.

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Consistency

- **Enterprise (Business) Rules** limit the occurrence of certain real-world events
  - Student cannot register for a course if the current number of registrants equals the maximum allowed
- Correspondingly, allowable database states are restricted, e.g., by
  - *Current_reg* <= *max_reg*
- These limitations are called (static) **integrity constraints***:* assertions that must be satisfied by the database state

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More on consistency

- Other static consistency requirements are related to the fact that the database might store the same information in different ways
  - *cur_reg*= |*list_of_registered_students*|
  - Such limitations are also expressed as integrity constraints
- **Database is consistent** if all static integrity constraints are satisfied

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More on Consistency

- A consistent database state does not necessarily model the actual state of the enterprise
  - A deposit transaction that increments the balance by the wrong amount maintains the integrity constraint *balance* ≥ 0, but does not maintain the relation between the enterprise and database states
- A consistent transaction maintains database consistency ***and*** the correspondence between the database state and the enterprise state (***implements its specification***)
  - Specification of deposit transaction includes
    - *Balance = balance' + amt_deposit*
    - (where b*alance'*is the initial value of *balance*)

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Dynamic Integrity Constraints

- Some constraints restrict allowable state transitions
  - A transaction might transform the database from one consistent state to another, but the transition might not be permissible
  - **Example**: A letter grade in a course (A, B, C, D, F) cannot be changed to an incomplete (I)
- Dynamic constraints cannot be checked by examining the database state

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Transaction Consistency

- A **transaction is consistent** if, assuming the database is in a consistent state initially, when the transaction completes:

1. All static integrity constraints are satisfied (constraints might have been violated in intermediate states)
   - Can be checked by examining a snapshot of the database
2. The new state satisfies the specification of the transaction
   - Cannot be checked from a database snapshot
3. No dynamic constraints have been violated
   - Cannot be checked from a database snapshot

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Checking Constraints

- **Automatic**: Embed constraint in schema.
  - CHECK, ASSERTION for static constraints
  - TRIGGER for dynamic constraints
  - Increases confidence in correctness and decreases maintenance costs
  - Not always desirable since unnecessary checking (overhead) might result in performance degradation
    - Deposit transaction modifies *balance* but cannot violate constraint *balance* ≥ 0
- **Manual**: Perform check in application code.
  - Only necessary checks are performed
  - Scatters references to constraint throughout application
  - Difficult to maintain as transactions are modified/added

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Atomicity

- A real-world event either happens or does not happen
  - Student either registers or does not register
- Similarly, the system must ensure that either the corresponding transaction runs to completion or, if not, it has no effect at all
- Not true of ordinary programs. A crash could leave files partially updated on recovery

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Commit and Abort

- If the transaction successfully completes it is said to **commit**
  - The system is responsible for preserving the transaction's results in spite of possible subsequent failures
- If the transaction does not successfully complete, it is said to **abort**
  - The system is responsible for undoing, or **rolling back,** any changes the transaction has made till the point of abort

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Reasons for Aborting

- System crash
- Transaction aborted by system
  - Execution cannot be made atomic (e.g., if a site is down in a distributed transaction)
  - Execution did not maintain database consistency (integrity constraint is violated)
  - Execution was not isolated
  - Resources not available (deadlock)
- Transaction requests to roll back

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API for Transactions

- DBMS and TP monitor provide commands for setting transaction boundaries. For example:
  - begin transaction
  - commit
  - rollback
- The **commit** command is a request
  - The system might commit the transaction, or it might abort it for one of the reasons on the previous slide
- The **rollback** command will always be executed

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Durability

- The system must ensure that once a transaction commits, its effect on the database state is not lost in spite of subsequent failures
- Not true of ordinary programs. A media failure after a program successfully terminates could cause the file system to be restored to a state that preceded the program's execution

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More on Durability

- Database stored redundantly on mass storage devices
- Architecture of mass storage devices affects type of media failures that can be tolerated
  - **Availability**: extent to which a (possibly distributed) system can provide service despite failures
- Non-stop DBMS (mirrored disks)
- Recovery based DBMS (log)

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Isolation

- **Serial Execution**: Transactions execute one after the other
  - Each one starts after the previous one completes.
  - The execution of each transaction is **isolated** from all others.
  - If the initial database state and all transactions are consistent, all consistency constraints are satisfied and the final database state will accurately reflect the real-world state, *but*

- Serial execution is inadequate from a performance perspective

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Schedules

- **Schedule** = an interleaving of actions (read/write) from a set of transactions, where the actions of any single transaction are in the original order

- **Complete Schedule** = add commit or abort at end

Initial State of DB + Schedule → Final State of DB

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Serial Schedule

- One transaction at a time, no interleaving

```
T1:                   T2:
                      read(acc1)
                      acc1 := acc1 + 20
                      write(acc1)
                      commit

read(acc1)
read(acc1)
sum := sum + acc1
write(sum)
commit
```

- Final state consistent (if transactions are)
- Different serial schedules give different final states

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Isolation (2)

- **Concurrent execution** offers performance benefits:
  - A computer system has multiple resources capable of executing independently (*e.g.*,cpu's, I/O devices), *but*
  - A transaction typically uses only one resource at a time
  - Concurrently executing transactions can make effective use of the system
- Concurrency is achieved by the DBMS by *interleaving* actions (reads/writes of DB objects) of various transactions.

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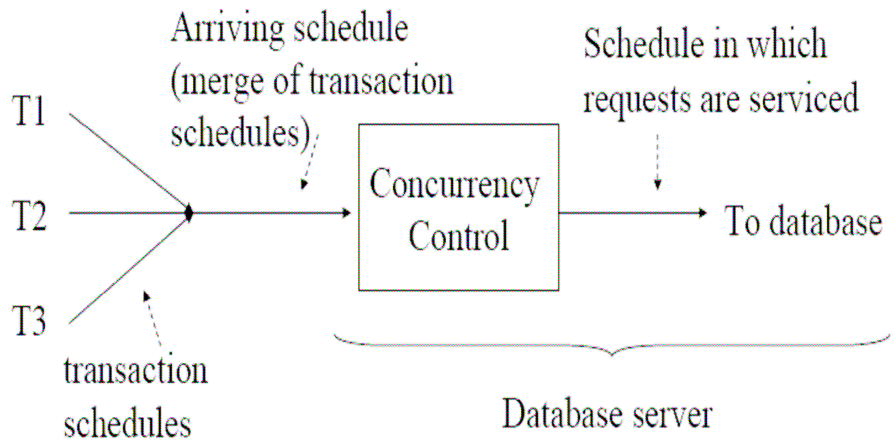
Scheduling + CC



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Issues with Concurrent Scheduling

- Concurrent (interleaved) execution of a set of consistent transactions offers performance benefits, *but* might not be correct
- **Example**: course registration; *cur_reg* is number of current registrants;
- operations: ***r****ead(Attribute: Value),* ***w****rite(Attribute: Value)*

T1: r(cur_reg: 29)		***w(cur_reg: 30)***
T2:	**r(cur_reg:29) w(cur_reg:30)**	

- Result: Violation of static Integrity constraint of current_reg

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Example

- Consider the following bank transactions:
  T1: Begin A=A+100, B=B-100 END
  T2: Begin A=1.06*A, B=1.06*B END

- Intuitively, the first transaction is transferring $100 from B's account to A's account. The second is crediting both accounts with a 6% interest payment.

- There is no guarantee that T1 will execute before T2 or vice-versa, if both are submitted together.

- However: **The net effect should be equivalent *to* running *these two transactions* serially in some order.**

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Interleaving 1

T1	T2
Read(A)	
A=A+100	
Write(A)	
	Read(A)
	A=A*1.06
	Write(A)
Read(B)	
B=B-100	
Write(B)	
	Read(B)
	B=B*1.06
	Write(B)

EFFECT: T1, T2

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Interleaving 2

T1	T2
	Read(A)
	A=A*1.06
	Write(A)
Read(A)	
A=A+100	
Write(A)	
	Read(B)
	B=B*1.06
	Write(B)
Read(B)	
B=B-100	
Write(B)	

EFFECT: T2, T1

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Interleaving 3

T1	T2
Read(A)	
A=A+100	
Write(A)	
	Read(A)
	A=A*1.06
	Write(A)
	Read(B)
	B=B*1.06
	Write(B)
Read(B)	
B=B-100	
Write(B)	

PROBLEM!

Interest for the same
Rs 100 twice!

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Interleaving 4

T1	T2
	Read(A)
	A=A*1.06
	Write(A)
Read(A)	
A=A+100	
Write(A)	
Read(B)	
B=B-100	
Write(B)	
	Read(B)
	B=B*1.06
	Write(B)

PROBLEM!

Missing Interest!

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T1, T2

T1	T2
Read(A)	
A=A+100	
Write(A)	
	Read(A)
	A=A*1.06
	Write(A)
Read(B)	
B=B-100	
Write(B)	
	Read(B)
	B=B*1.06
	Write(B)

T2, T1

T1	T2
	Read(A)
	A=A*1.06
	Write(A)
Read(A)	
A=A+100	
Write(A)	
	Read(B)
	B=B*1.06
	Write(B)
Read(B)	
B=B-100	
Write(B)	

Interest for the same $100 twice

Problem

T1	T2
Read(A)	
A=A+100	
Write(A)	
	Read(A)
	A=A*1.06
	Write(A)
	Read(B)
	B=B*1.06
	Write(B)
Read(B)	
B=B-100	
Write(B)	

Missing interest

Problem

T1	T2
	Read(A)
	A=A*1.06
	Write(A)
Read(A)	
A=A+100	
Write(A)	
Read(B)	
B=B-100	
Write(B)	
	Read(B)
	B=B*1.06
	Write(B)

Atomicity and Isolation

- Let

```
T1: r(bal:10) w(bal, 1010)                              abort
T2:                        r(bal, 1010) w(ok) commit
```

- *T1* deposits 1000
- *T2* grants credit and commits before *T1* completes
- *T1* aborts and rolls balance back to $10
- *T1* has had an effect even though it aborted!

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Concurrency Control

- Transforms arriving schedule into a correct interleaved schedule to be submitted to the DBMS
  - Delays servicing a request (reordering) -causes a transaction to wait
  - Refuses to service a request -causes transaction to abort
- Actions taken by concurrency control have performance costs
  - Goal is to avoid delaying servicing a request

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Equivalence

- For interleaved schedules to be correct, they should be *equivalent* to serial schedules in their effect on the database for *all* applications.
- A strong notion of *Equivalence* (also called *Conflict Equivalence*) is based on the ***commutativity*** of operations
- **Definition:**Database operations *p1*and *p2* ***commute*** if, for all initial database states, they return the same results and leave the database in the same final state when executed in either order.

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Commutativity

- Read
  - *r(x, X)*-copy the value of database variable *x* to local variable *X*
- Write
  - *w(x, X)*-copy the value of local variable *X*to database variable *x*
- We use $r_1(x)$and $w_1(x)$to mean a read or write of *x* by transaction T1

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Commutativity

- *P1* commutes with *p2* if
  - They operate on different data items
    - *w1(x)* commutes with *w2(y)* and *r2(y)*
  - Both are reads
    - *r1(x)*commutes with *r2(x)*
- Operations that do not commute ***conflict***
  - *w1(x)* conflicts with *w2(x)*
  - *w1(x)* conflicts with *r2(x)*

conflicts

		T1	
		Read(x)	Write(x)
T2	Read(x)	No	Yes
	Write(x)	Yes	Yes

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Schedule Equivalence

- An interchange of adjacent operations of different transactions in a schedule creates an ***equivalent schedule*** if the operations commute
  - S1: T_{11}, p_{ij}, p_{kl}, T_{12}
  - S2: T_{11}, p_{kl}, p_{ij}, T_{12} such that $i \neq k$
- Equivalence is *transitive*: If S1is equivalent to S2 (by a series of such interchanges), and S2is equivalent to S3,then S1 is equivalent to S3

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Schedule Equivalence

conflict

S_1: $r_1(x)$ $r_2(x)$ $w_2(x)$ $r_1(y)$ $w_1(y)$

S_2: $r_1(x)$ $r_2(x)$ $r_1(y)$ $w_2(x)$ $w_1(y)$

S_3: $r_1(x)$ $r_1(y)$ $r_2(x)$ $w_2(x)$ $w_1(y)$

S_4: $r_1(x)$ $r_1(y)$ $r_2(x)$ $w_1(y)$ $w_2(x)$

S_5: $r_1(x)$ $r_1(y)$ $w_1(y)$ $r_2(x)$ $w_2(x)$

- S1 and S5 are equivalent
- S5 is the serial schedule T1, T2
- S1 is NOT equivalent to the serial schedule T2, T1

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Schedule Equivalence

- **Theorem**-Schedule S1 can be derived from S2 by a sequence of commutative interchanges if and only if conflicting operations in S1 and S2 are ordered in the same way
  - *Only if:* Commutative interchanges do not reorder conflicting operations
  - *If :* A sequence of commutative interchanges can be determined that takes S1to S2since conflicting operations do not have to be reordered

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Conflict Equivalence

- **Definition**-Two schedules, S1and S2, of the same set of operations are ***conflict equivalent*** if conflicting operations are ordered in the same way in both

- Or (using theorem) if one can be obtained from the other by a series of commutative interchanges

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Conflict Serializable

- **Definition:**A schedule is *conflict serializable iff* it is conflict equivalent to a serial schedule

$$r_1(x)\ w_2(x)\ w_1(y)\ r_2(y) \rightarrow r_1(x)\ w_1(y)\ w_2(x)\ r_2(y)$$

conflict *conflict*

If in S transactions T1and T2 have several pairs of conflicting operations ($p_{1,1}$ conflicts with $p_{2,1}$ and $p_{1,2}$ conflicts with $p_{2,2}$) then $p_{1,1}$ must precede $p_{2,1}$ and $p_{1,2}$ must precede $p_{2,2}$ (or vice versa) in order for S to be serializable.

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Serializable Schedules

- By default, "serializable"means "conflict serializable"
- Transactions are totally isolated in a serializable schedule
- A schedule is correct for *any* application if it is a serializable schedule of consistent transactions
- The schedule :$r_1(x)\ r_2(y)\ w_2(x)\ w_1(y)$ is ***not*** serializable
  - Why?

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Intuition on Serializability

- Because T1 read *x* before T2 wrote it, T1 must precede T2 in any ordering, and because T1 wrote *y* after T2 read it, T1 must follow T2 in any ordering ---c learly an impossibility

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Isolation

- An interleaved schedule of transactions is **isolated** if its effect is the same as if the transactions had executed serially in some order (**serializable**)
- Serializable schedules are always correct (if the single transactions are correct)
- Serializable is better than serial from a performance point of view

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Serializability Graph

- Node for each transaction T_i
- Edge from T_i to T_j if there is an action of T_i that precedes and "conflicts" with an action of T_j
- **Theorem**: ***A schedule is conflict serializable iff its Serializability Graph is acyclic.***

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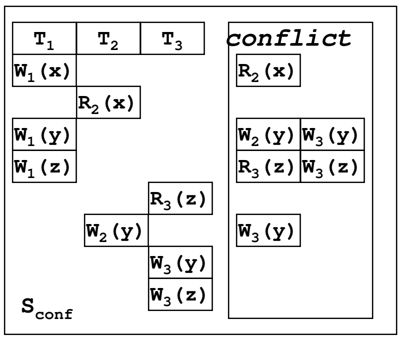
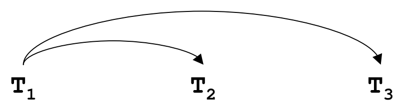
Example





serializability graph

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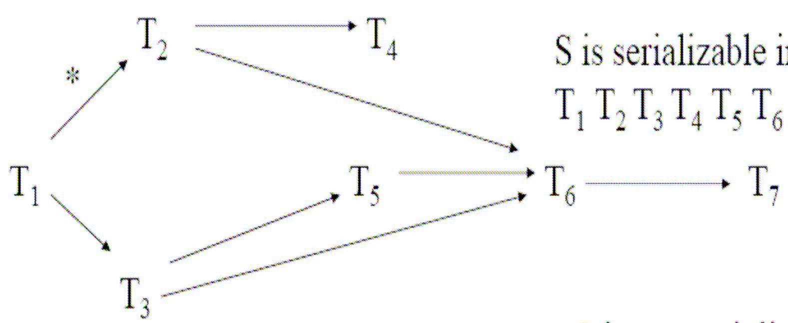
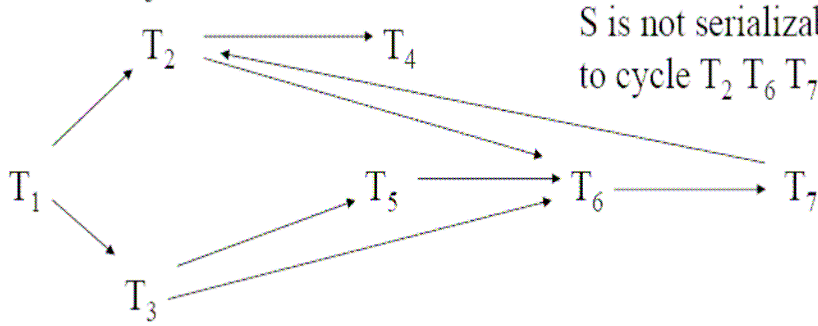


S is serializable in order $T_1\ T_2\ T_3\ T_4\ T_5\ T_6\ T_7$



S is not serializable due to cycle $T_2\ T_6\ T_7\ T_2$

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Recoverability: Schedules with Aborted Transactions

T_1 :		*r (x)*	*w(y)*	*commit*	
T_2:	*w(x)*				*abort*

- T_2 has aborted but has had an indirect effect on the database – schedule is *un*recoverable
- **Problem**: T_1 reads uncommitted data -*dirty read*
- **Solution:**A concurrency control is *recoverable* if it does not allow T_1 to commit until all other transactions that wrote values T_1 read have committed.

T_1 :		*r (x)*	*w(y)*	*req_commit*		*abort*
T_2:	*w(x)*				*abort*	

Cascaded Abort

Recoverable schedules solve abort problem but allow *cascaded abort*: abort of one transaction forces abort of another

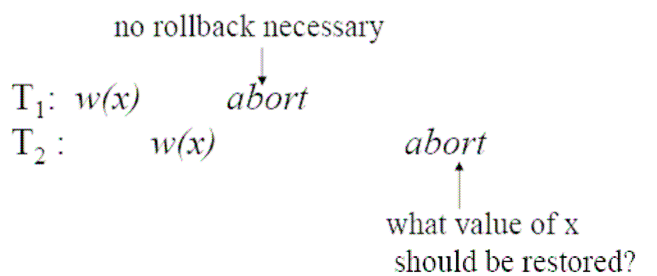
T_1:				*r (y)*	*w(z)*			*abort*
T_2:		*r (x)*	*w(y)*				*abort*	
T_3:	*w(x)*					*abort*		

Better solution: prohibit dirty reads

Dirty Writes

Dirty write: A transaction writes a data item written by an active transaction

Dirty write complicates rollback:



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Strict Schedules

- *Strict schedule*: Dirty writes and dirty reads are prohibited
  - Strict and serializable are two different properties
- Strict, non-serializable schedule
  - *r1(x) w2(x) r2(y) w1(y) c1c2*
- Serializable, non-strict schedule
  - *w2(x) r1(x) w2(y) r1(y) c1c2*

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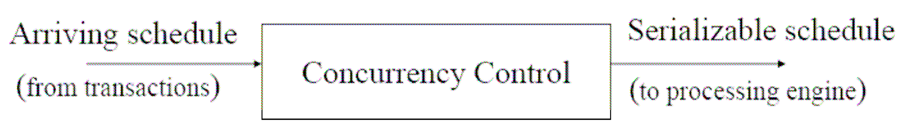
Concurrency Control

- Concurrency control cannot see entire schedule:
  - It sees one request at a time and must decide whether to allow it to be serviced
- Strategy: Do not service a request if:
  - It violates strictness or serializability, or
  - There is a possibility that a subsequent arrival might cause a violation of serializability



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Models of Concurrency Control

- **Immediate Update**
  - A write updates a database item
  - A read copies value from a database item
  - Commit makes updates durable
  - Abort undoes updates
- **Deferred Update**–***(we will likely not discuss this)***
  - A write stores new value in the transaction's intentions list (does not update database)
  - A read copies value from database or transaction's intentions list
  - Commit uses intentions list to durably update database
  - Abort discards intentions list

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Models of Concurrency Control

- **Pessimistic**
  - A transaction requests permission for each database (read/write) operation
  - Concurrency control can:
    - *Grant* the operation (submit it for execution)
    - *Delay* it until a subsequent event occurs (commit or abort of another transaction), or
    - *Abort* the transaction
- Decisions are made *conservatively* so that a commit request can *always* be granted
  - Takes precautions even if conflicts do not occur

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Models of Concurrency Control

- **Optimistic**
  - Request for database operations (read/write) are *always* granted
  - Request to commit *might be denied*
- Transaction is aborted if it performed a non serializable operation
- Assumes that conflicts are not likely
  - The earlier it can aborted the better

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Locking Implementation of an Immediate-Update Pessimistic Control

- A transaction can read a database item if it holds a read (shared) lock on the item
- It can read *or* update the item if it holds a write (exclusive) lock
- If the transaction does not already hold the required lock, a lock request is automatically made as part of the access

Locking

- Request for read lock granted if no transaction currently holds write lock on item
  - Cannot read an item written by an active transaction
- Request for write lock granted if no transaction holds any lock on item
  - Cannot write an item read/written by an active transaction

Requested mode	Granted mode *read*	Granted mode *write*
read	yes	no
write	no	no

Compatibility of locks

All locks held by a transaction are released when the transaction completes (commits or aborts)

Locking

- **Result**: A lock is not granted if the requested access conflicts with a prior access of an active transaction; instead the transaction waits. This enforces the rule:
  - Do not grant a request that imposes an ordering among active transactions (delay the requesting transaction)
- Resulting schedules are serializable and strict

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Deadlocks

- **Problem**: Controls that cause transactions to wait can cause deadlocks
  - *w1(x) w2(y) request_r1(y) request_r2(x)*
- **Solution**: Abort a transaction in the cycle
  - ***Prevent Deadlock -***based on timestamps priorities
  - ***Detect Deadlock -***by detecting a cycle in the wait-for graph when a request is delayed
  - ***Time-Out -***Assume a deadlock when a transaction waits longer than some time-out period

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Deadlock Prevention based on Timestamp Priorities

- Assign priorities based on timestamps (i.e., the older a transaction, the higher its priority).

- Assume Ti wants a lock that conflicts with a lock that Tj holds. Two policies are possible:
  - ***Wait-Die***: If Ti has higher priority, Ti allowed to wait for Tj; otherwise (i.e., Ti younger): Ti aborts
  - ***Wound-wait***: If Ti has higher priority, Tj aborts; otherwise (i.e., Ti younger): Ti waits

- If a transaction re-starts, make sure it has its original timestamp

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Deadlock prevention based on timeouts

- A simple approach to deadlock resolution (pseudo prevention/detection) is based on lock request timeouts

- After requesting a lock on a locked data object, a transaction waits, but if the lock is not granted within a certain period, a deadlock is assumed and the waiting transaction is aborted and re-started.

- Very simple practical solution adopted by many DBMSs.

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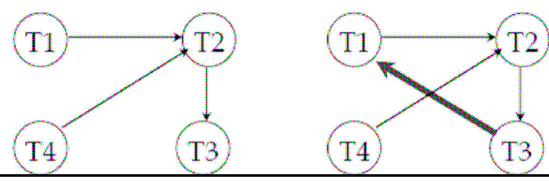
Wait-for Graphs – Deadlock Detection

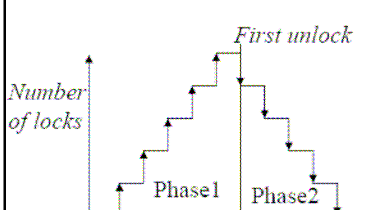
- Create a waits-for graph:
  - Nodes are transactions
  - There is an edge from Ti to Tj if Ti is waiting for Tj to release a lock.
- Deadlock exists if there is a cycle in the graph.
- Periodically check for cycles in the waits-for graph.

T1:	S(A), R(A),		S(B)				
T2:		X(B),W(B)			X(C)		
T3:				S(C), R(C)			X(A)
T4:						X(B)	

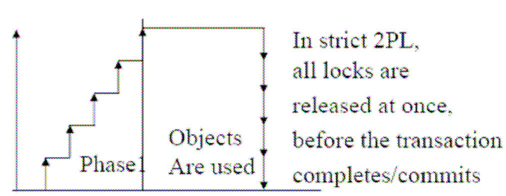


Two Phase Locking

- Transaction does not release a lock until it has all the locks it will ever require.
- Transaction, T, has a locking phase followed by an unlocking phase



Two-phase locking (2PL)



Strict two-phase locking (strict 2PL)

Two Phase Locking

- A schedule produced by a two-phase locking control is:
  - Equivalent to a serial schedule in which transactions are ordered by the time of their first unlock operation
  - Not necessarily recoverable (dirty reads and writes are possible)

lock → $l(x)$ *unlock* → $u(y)$

T1: *l(x) r(x) l(y) w(y) u(y)*   *abort*
T2:   *l(y) r(y) l(z) w(z) u(z) u(y) commit*

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Lock Granularity

- Data item: variable, record, row, table, file
- When an item is accessed, the DBMS locks an entity that contains the item. The size of that entity determines the *granularity* of the lock

1. **Coarse granularity** (large entities locked)
   - **Advantage**: If transactions tend to access multiple items in the same entity, fewer lock requests need to be processed and less lock storage space required
   - **Disadvantage:**Concurrency is reduced since some items are unnecessarily locked
2. **Fine granularity** (small entities locked)
   - Advantages and disadvantages are reversed

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Granularity

- Table locking (*coarse*)
  - Lock entire table when a row is accessed.
- Row (tuple) locking (*fine*)
  - Lock only the row that is accessed.
- Page locking (compromise)
  - When a row is accessed, lock the containing page

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Optimistic Concurrency Control

- No locking (and hence no waiting) means deadlocks are not possible
- Rollback is a problem if optimistic assumption is not valid: work of entire transaction is lost
  - With two-phase locking, rollback occurs only with deadlock
  - With optimistic concurrency control, rollback is only detected before transaction completes

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Locking in RDBMS

- In the simple databases we have been studying, accesses are made to a named item, *x*, (for example *r*(*x*)),which can be locked.
- In relational databases, accesses are made to items that satisfy a predicate (for example, the set of rows returned by a SELECT statement)
  - What should we lock?
  - What is a conflict?

Locking in RDBMS

Audit:

```
SELECT SUM (balance)
FROM Accounts
WHERE name = 'Mary';

SELECT totbal
FROM Depositors
WHERE name = 'Mary'
```

NewAccount:

```
INSERT INTO Accounts
VALUES ('123','Mary',100);

UPDATE Depositors
SET totbal = totbal + 100
WHERE name = 'Mary'
```

- Operations on Accounts and Depositors conflict
- Interleaved execution is not serializable

What do we lock?

- Lock tables:
  - Execution is serializable but ...
  - Performance suffers because lock granularity is coarse
- Lock rows:
  - Performance improves because lock granularity is fine but ...
  - Execution is not serializable

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Problems with Row locking

- Audit

  (1) Locks and reads Mary's rows in Accounts
- NewAccount

  (2) Inserts and locks new row,*t*, in Accounts
  (3) Locks and updates Mary's row in Depositors
  (4) Commits and releases all locks
- Audit

  (5) Locks and reads Mary's row in Depositors

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- Two SELECTs executed by Audit see inconsistent data
  - The second sees effect of NewAccount; the first does not

- **Problem**: Audit's SELECT and NewAccount's INSERT on Accounts do not commute, but the row locks held by Audit did not prevent NewAccount from INSERTing *t*, (which satisfies the WHERE condition).
  - *t* is referred to as a *phantom*

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Phantoms

•Phantoms occur when row locking is used and

•T1 SELECTs, UPDATEs, or DELETEs using a predicate, *P*

•T2 creates a row (using INSERT or UPDATE) satisfying *P*

T_1: UPDATE Table
SET Attr = ….
WHERE *P*

T_2: INSERT INTO Table
VALUES (… satisfies *P*…)

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Preventing Phantoms

- Table locking does it; row locking does not
- ***Predicate locking*** does it
  - A predicate describes a set of rows, some are in a table and some are not; e.g. *name = 'Mary'*
  - Every SQL statement has an associated predicate
  - When executing a statement, acquire a (read or write) lock on the associated predicate
  - Two predicate locks conflict if one is a write and there might be a row (not necessarily in the table) that is contained in both sets of tuples described by the predicates

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Preventing Phantoms

Audit:
```
SELECT SUM (balance)
FROM Accounts
WHERE name = 'Mary'
```

NewAccount:
```
INSERT INTO Accounts
VALUES ('123','Mary',100)
```

• Audit gets read lock on predicate *name='Mary'*.

• NewAccount requests a write lock on predicate ($acctnum='123' \wedge name='Mary' \wedge bal=100$)

• Request denied since predicates overlap

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Preventing Conflicts with Predicate Locks

SELECT SUM (balance) FROM Accounts WHERE name = 'Mary'	DELETE FROM Accounts WHERE bal < 1

•Statements conflict since predicates overlap

•There might be an account with bal < 1 and name = 'Mary'

•Locking is conservative: there might be no rows in Accounts satisfying both predicates SELECT

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Another Example

SELECT SUM (balance) FROM Accounts WHERE name = 'Mary'	DELETE FROM Accounts WHERE name = 'John'

• Statements commute since predicates are disjoint.

• There can be no rows (in or not in Accounts) that satisfy both predicates

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Serializability in Relational DBs

- Predicate locking prevents phantoms and produces serializable schedules, but is very complex
- Table locking prevents phantoms and produces serializable schedules, but seriously affects performance
- Row locking does not prevent phantoms and can produce non-serializable schedules
- SQL defines several ***Isolation Levels*** weaker than SERIALIZABLE that allow non-serializable schedules and hence allow more concurrency

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Weakening Serializability

- Weaker isolation levels:

1. REPEATABLE READ,
2. READ COMMITTED,
3. READ UNCOMMITTED

- Increase performance by eliminating overhead and allowing higher degrees of concurrency
- Trade-off: sometimes you get the .wrong. answer

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Example

CREATE TABLE Account
(accno INTEGER NOT NULL PRIMARY KEY,
name CHAR(30) NOT NULL,
balance FLOAT NOT NULL CHECK(balance >= 0));

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Read Uncommitted

- Can read ***dirty*** data
- A data item is ***dirty*** if it is written by an uncommitted transaction
- Problem: What if the transaction that wrote the dirty data eventually aborts?
- Example: wrong average

```
-- T1:                      -- T2:
UPDATE Account
SET balance = balance - 200
WHERE accno = 142857;       SELECT AVG(balance)
                            FROM Account;
ROLLBACK;
                            COMMIT;
```

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READ Committed

- No dirty reads, but non-repeatable reads possible
- Reading the same data item twice can produce different results
- Example: different averages

-- T1: -- T2:

SELECT AVG(balance) FROM Account;

UPDATE Account

SET balance = balance . 200

WHERE accno = 142857;

COMMIT;

SELECT AVG(balance) FROM Account;

COMMIT;

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Repeatable Read

- Reads are repeatable, but may see ***phantoms***
- Example: different average (still!)

T1: T2:

SELECT AVG(balance) FROM Account;

INSERT INTO Account

VALUES(428571, 1000);

COMMIT;

SELECT AVG(balance) FROM Account;

COMMIT

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Isolation levels compared

Isolation level/anomaly	Dirty reads	Non-repeatable reads	Phantoms
READ UNCOMMITTED	Possible	Possible	Possible
READ COMMITTED	Impossible	Possible	Possible
REPEATABLE READ	Impossible	Impossible	Possible
SERIALIZABLE	Impossible	Impossible	Impossible

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Summary

- Application programmer is responsible for creating consistent transactions
- DBMS and TP monitor are responsible for creating the abstractions of atomicity, durability, and isolation
- This greatly simplifies programmer's task since he or she does not have to be concerned with failures or concurrency

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