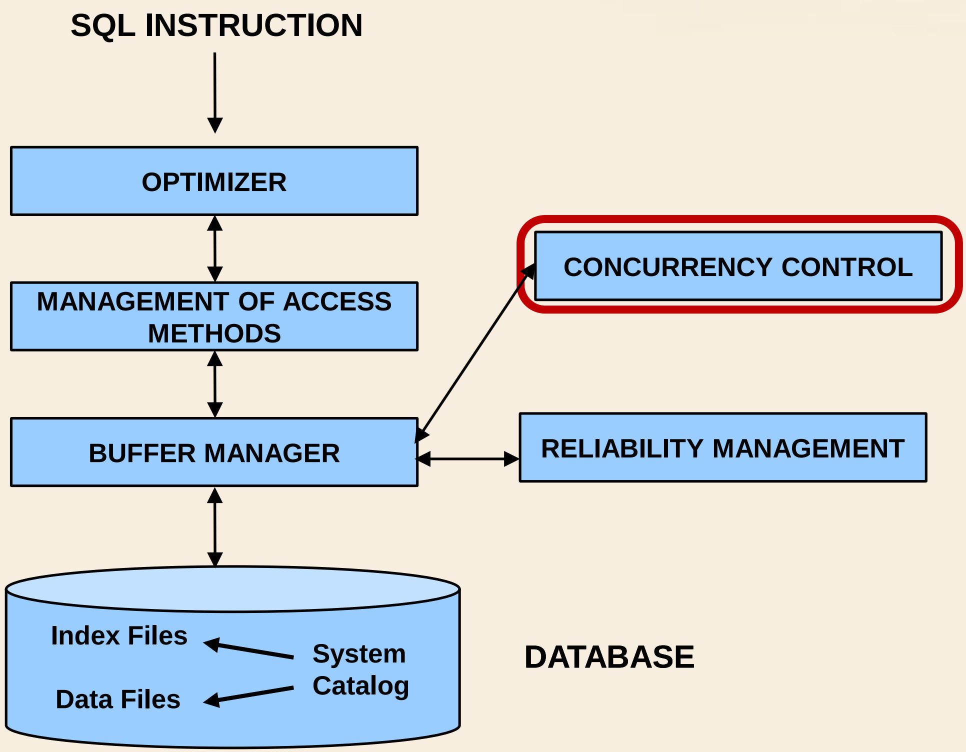
Database Management Systems

Concurrency Control

DBMS Architecture



Concurrency control

- The workload of operational DBMSs is measured in tps, i.e., transactions per second
  - ≈ $10\text{-}10^3$ for banking applications and flight reservations
- Concurrency control provides *concurrent access* to data
  - It increases DBMS efficiency by
    - maximizing the number of transactions per second (throughput)
    - minimizing response time

Elementary I/O operations

- Elementary operations are
  - Read of a single data object x
    - r(x)
  - Write of a single data object x
    - w(x)
- They may require reading from disk or writing to disk an entire page

Scheduler

- The *scheduler*
  - is a block of the concurrency control manager
  - is in charge of deciding if and when read/write requests can be satisfied
- The absence of a scheduler may cause correctness problems
  - also called anomalies

Lost update

	Transaction T_1		Transaction T_2	
	bot			
	$r_1(x)$	$x=2$		
	$x= x+1$	$x=3$		
			bot	
			$r_2(x)$	$x=2$
			$x=x+1$	$x=3$
			$w_2(x)$	$x=3$
			commit	
time	$w_1(x)$	$x=3$		
	commit			

- The *correct* value is $x=4$
- The effect of transaction T_2 is *lost* because both transactions read the same initial value

DBMG

Dirty read

Transaction T_1		Transaction T_2	
bot			
$r_1(x)$	x=2		
x= x+1	x=3		
$w_1(x)$	x=3		
		bot	
		$r_2(x)$	x=3
		x=x+1	x=4
		$w_2(x)$	x=4
		commit	
abort			

time

cascade rollback

- Transaction T_2 reads the value of X in an intermediate state which *never* becomes stable (permanent)

Inconsistent read

Transaction T_1		Transaction T_2	
bot			
$r_1(x)$	$x=2$		
		bot	
		$r_2(x)$	$x=2$
		$x=x+1$	$x=3$
		$w_2(x)$	$x=3$
		commit	
$r_1(x)$	$x=3$		
commit			

time ↓

- Transaction T_1 reads x twice
  - x has a different value each time

Ghost update (a)

Transaction T_1		Transaction T_2	
bot			
$r_1(x)$	x=400		
		bot	
		$r_2(y)$	y=300
$r_1(y)$	y=300		
		y = y -100	y=200
		$r_2(z)$	z=300
		z = z + 100	z=400
		$w_2(y)$	y=200
		$w_2(z)$	z=400
		commit	
$r_1(z)$	z=400		
total = x + y + z	total=1100		
commit			

time

- The *correct* value is total = 400+200+400=1000

Ghost update (a)

- Transaction T_1 only *partially* observes the effect of transaction T_2

Ghost update (b)

time	Transaction T_1	Transaction T_2
	bot read the salary of all employees in department x and compute AVG salary	
		bot insert a new employee in department x commit
	read the salary of all employees in department x and compute AVG salary commit	

Ghost update (b)

- The insert operation is the ghost update
- Problem
  - The data is *not yet* in the database before the insert

Theory of Concurrency Control

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Schedule

- The *transaction* is a sequence of read and write operations characterized by the same TID (Transaction Identifier)

$$r_1(x)\ r_1(y)\ w_1(x)\ w_1(y)$$

- The *schedule* is a sequence of read/write operations presented by concurrent transactions

$$r_1(z)r_2(z)w_1(y)w_2(z)$$

  - Operations in the schedule appear in the arrival order of requests

DBMG

Scheduler

- Concurrency control accepts or rejects schedules to avoid anomalies
- The scheduler has to accept or reject operation execution *without knowing the outcome* of the transactions
  - abort/commit

Commit projection

- Commit projection is a simplifying hypothesis
  - *The schedule only contains transactions performing commit*
- The dirty read anomaly is not addressed
- This hypothesis will be removed later

Serial schedule

- In a *serial schedule*, the actions of each transaction appear in sequence, without interleaved actions belonging to different transactions
- Example

$$\underbrace{r_0(x)\ r_0(y)\ w_0(x)}_{T_0}\ \underbrace{r_2(x)\ r_2(y)\ r_2(z)}_{T_2}\ \underbrace{r_1(y)\ r_1(x)\ w_1(y)}_{T_1}$$

Serializable schedule

- An arbitrary schedule S_i (commit projection) is correct when it yields the same result as an arbitrary serial schedule S_j of the same transactions
- S_i is *serializable*
  - S_i is equivalent to an arbitrary serial schedule of the same transactions

DBMG

Equivalence between schedules

- Different *equivalence classes* between two schedules
  - View equivalence
  - Conflict equivalence
  - 2 phase locking
  - Timestamp equivalence
- Each equivalence class
  - detects a set of acceptable schedules
  - is characterized by a different complexity in detecting equivalence

View equivalence

- Definitions
  - reads-from
    - $r_i(x)$ reads-from $w_j(x)$ when
      - $w_j(x)$ precedes $r_i(x)$ and $i \neq j$
      - there is no other $w_k(x)$ between them
  - final write
    - $w_i(x)$ is a final write if it is the last write of x appearing in the schedule
- Two schedules are *view equivalent* if they have
  - the same reads-from set
  - the same final write set

View serializable schedule

- A schedule is *view serializable* if it is view equivalent to an arbitrary serial schedule of the same transactions
  - VSR: schedules which are view serializable
- Example

$$S_1 = w_0(x)\ r_2(x)\ r_1(x)\ \underline{w_2(x)}\ \underline{w_2(z)}$$

$$S_2 = w_0(x)\ r_1(x)\ r_2(x)\ \underline{w_2(x)}\ \underline{w_2(z)}$$

- S_1 is view serializable because it is view equivalent to S_2

View equivalence

$$S_3 = w_0(x)\ r_2(x)\ \underline{w_2(x)}\ r_1(x)\ \underline{w_2(z)}$$

- S_3 is not view equivalent to S_2
  - the reads-from sets are different

$$S_4 = w_0(x)\ r_2(x)\ \underline{w_2(x)}\ \underline{w_2\ (z)}\ r_1(x)$$

- S_3 is view serializable because it is view equivalent to S_4

DBMG

Lost update anomaly

Transaction T_1	Transaction T_2
bot	
$r_1(x)$	
x= x+1	
	bot
	$r_2(x)$
	x=x+1
	$w_2(x)$
	commit
$w_1(x)$	
commit	

- Corresponding schedule

  $S = r_1(x)\ r_2(x)\ w_2(x)\ w_1(x)$

Lost update anomaly

$$S = r_1(x)\ r_2(x)\ w_2(x)\ \underline{w_1(x)}$$

- Is this schedule serializable?
- Only two possible serial schedules

$$S_1 = r_1(x)\ w_1(x)\ r_2(x)\ \underline{w_2(x)}$$

$$S_2 = r_2(x)\ w_2(x)\ r_1(x)\ \underline{w_1(x)}$$

- S is not view equivalent to any serial schedule
  - not serializable
  - should be rejected

Inconsistent read anomaly

Transaction T_1	Transaction T_2
bot	
$r_1(x)$	
	bot
	$r_2(x)$
	$x=x+1$
	$w_2(x)$
	commit
$r_1(x)$	
commit	

- Corresponding schedule

$$S = r_1(x)\ r_2(x)\ w_2(x)\ r_1(x)$$

Inconsistent read anomaly

$$S = r_1(x)\ r_2(x)\ \underline{w_2(x)}\ r_1(x)$$

- Is this schedule serializable?
- Only two possible serial schedules

$$S_1 = r_1(x)\ r_1(x)\ r_2(x)\ \underline{w_2(x)}$$

$$S_2 = r_2(x)\ \underline{w_2(x)}\ r_1(x)\ r_1(x)$$

- S is not view equivalent to any serial schedule
  - not serializable
  - should be rejected

Ghost Update (a)

Transaction T_1	Transaction T_2
bot	
$r_1(x)$	
	bot
	$r_2(y)$
$r_1(y)$	
	$y = y - 100$
	$r_2(z)$
	$z = z + 100$
	$w_2(y)$
	$w_2(z)$
	commit
$r_1(z)$	
$total = x + y + z$	
commit	

$$S = r_1(x)\ r_2(y)\ r_1(y)\ r_2(z)\ w_2(y)\ w_2(z)\ r_1(z)$$

Ghost Update (a)

$$S = r_1(x)\ r_2(y)\ r_1(y)\ r_2(z)\ \underline{w_2(y)}\ \underline{w_2(z)}\ r_1(z)$$

- Is this schedule serializable?
- Only two possible serial schedules

$$S_1 = r_1(x)\ r_1(y)\ r_1(z)\ r_2(y)\ r_2(z)\ \underline{w_2(y)}\ \underline{w_2(z)}$$

$$S_2 = r_2(y)\ r_2(z)\ \underline{w_2(y)}\ \underline{w_2(z)}\ r_1(x)\ r_1(y)\ r_1(z)$$

- S is not view equivalent to any serial schedule

Checking view serializability

- Detecting view equivalence to a *given* schedule has linear complexity
- Detecting view equivalence to an *arbitrary* serial schedule is NP complete
  - not feasible in real systems
- Less accurate but faster techniques should be considered

Conflict equivalence

- Conflicting actions
  - Action A_i is in conflict with action A_j ($i \neq j$) if both actions operate on the same object and at least one of them is a write
    - Read-Write conflicts (RW or WR)
    - Write-Write conflicts (WW)
- Two schedules are *conflict equivalent* if
  - they have the same conflict set
  - each *conflict pair* is in the same order in both schedules

Conflict serializable schedule

- A schedule is *conflict serializable* if it is equivalent to an arbitrary serial schedule of the same transactions
  - CSR: schedules which are conflict serializable
- Example

$$S = w_0(x)\ r_1(x)\ w_0(z)\ r_1(z)\ r_2(x)\ r_3(z)\ w_3(z)\ w_1(x)$$

$$S_s = w_0(x)\ w_0(z)\ r_2(x)\ r_1(x)\ r_1(z)\ w_1(x)\ r_3(z)\ w_3(z)$$

Conflict serializable schedule

- Example

$$S = w_0(x)\ r_1(x)\ w_0(z)\ r_1(z)\ r_2(x)\ r_3(z)\ w_3(z)\ w_1(x)$$

$$S_s = w_0(x)\ w_0(z)\ r_2(x)\ r_1(x)\ r_1(z)\ w_1(x)\ r_3(z)\ w_3(z)$$

- Schedule S is conflict serializable

Detecting conflict serializability

- To detect conflict serializability it is possible to exploit the *conflict graph*
- Conflict graph
  - a node for each transaction
  - an edge $T_i \rightarrow T_j$ if
    - there exists at least a conflict between an action A_i in T_i and A_j in T_j
    - A_i precedes A_j
- If the conflict graph is acyclic the schedule is CSR
- Checking graph cyclicity is linear in the size of the graph

Example of conflict graph

$$S = w_0(x)\ r_1(x)\ w_0(z)\ r_1(z)\ r_2(x)\ r_3(z)\ w_3(z)\ w_1(x)$$

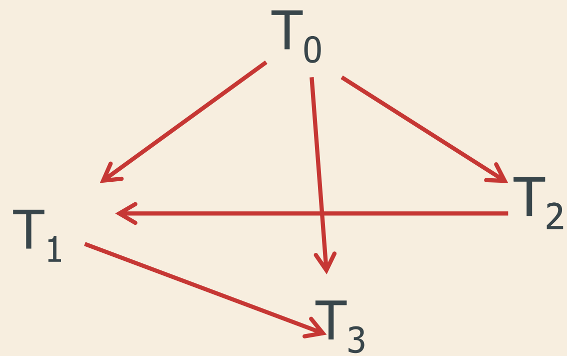
T_0

T_1 T_2

T_3

Example of conflict graph

$$S = w_0(x)\ r_1(x)\ w_0(z)\ r_1(z)\ r_2(x)\ r_3(z)\ w_3(z)\ w_1(x)$$



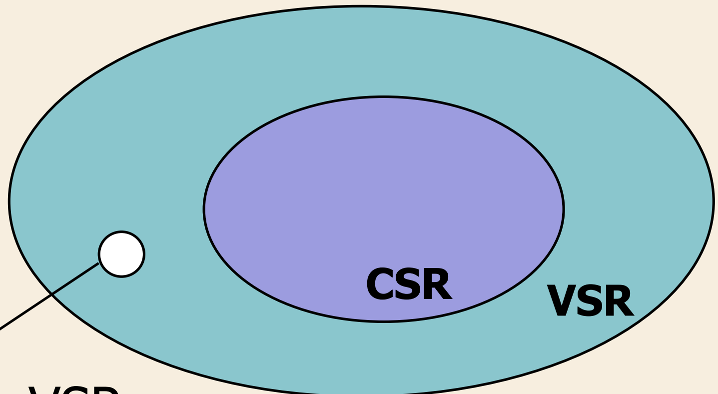
- S is CSR (no cycles)

Detecting conflict serializability

- Real system settings
  - 100 tps (transactions per second)
  - each transaction accesses ≈ 10 pages
  - each transaction lasts ≈ 5s
- The conflict graph is characterized by 500 nodes
  - 100 tps * 5 seconds
- Accesses to be checked for conflicts
  - 500 nodes * 10 page accessed ≈ 5000 accesses
- At each access
  - the graph should be updated
  - cycle absence should be checked

VSR versus CRS

- CSR schedules are a subset of VSR schedules



This schedule is VSR
but not CSR

2 Phase Locking

Locking

- A *lock* is a block on a resource which may prevent access to others
- Lock operation
  - Lock
    - Read lock (R-Lock)
    - Write lock (W-Lock)
  - Unlock
- Each read operation
  - is preceded by a request of R-Lock
  - is followed by a request of unlock
- Similarly for write operation and W-Lock

Locking

- The read lock is *shared* among different transactions
- The write lock is *exclusive*
  - it is not compatible with any other lock (R/W) on the same data
- Lock escalation
  - request of R-Lock followed by W-Lock on the same data

Lock manager

- The scheduler becomes a lock manager
  - It receives transaction requests and grants locks based on locks already granted to other transactions
  - When the lock request is granted
    - The corresponding resource is acquired by the requesting transaction
    - When the transaction performs unlock, the resource becomes again available
  - When the lock is not granted
    - The requesting transaction is put in a waiting state
    - Wait terminates when the resource is unlocked and becomes available

Lock manager

- The lock manager exploits
  - the information in the *lock table* to decide if a given lock can be granted to a transaction
  - the *conflict table* to manage lock conflicts

Conflict table

Request	Resource State		
	Free	R-Locked	W-Locked
R-Lock			
W-Lock			
Unlock			

Conflict table

Request	Resource State		
	Free	**R-Locked**	**W-Locked**
R-Lock	Ok/R-Locked	Ok/R-Locked	No/W-Locked
W-Lock	Ok/W-Locked	No/R-Locked	No/W-Locked
Unlock	Error	Ok/It depends (free if no other R-Locked)	Ok/Free

Read locks

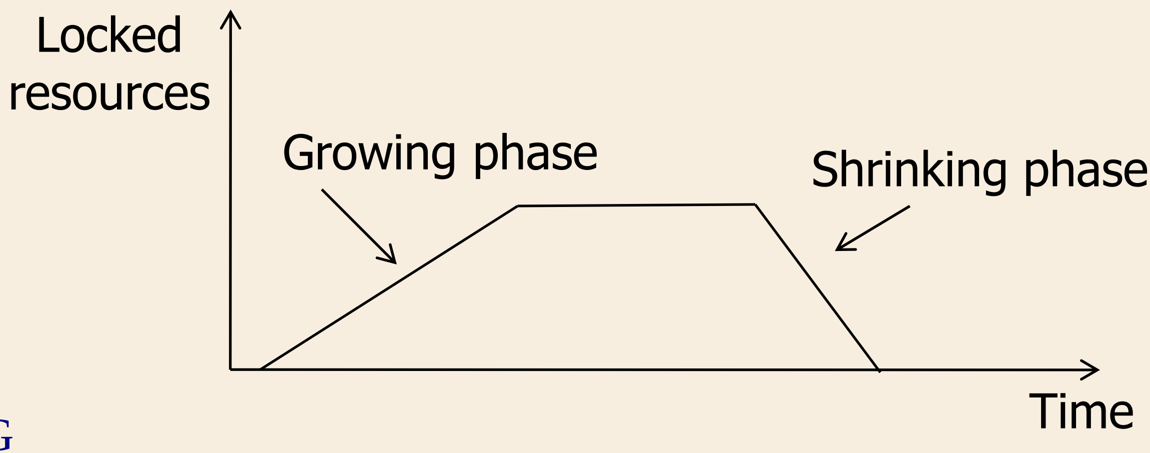
- Read locks are shared
  - Other transactions may lock the same resource
  - A counter is used to count the number of transactions currently holding the R-Lock
    - Free when count = 0

Lock manager

- The lock manager exploits
  - the information in the *lock table* to decide if a given lock can be granted to a transaction
    - stored in main memory
    - for each data object
      - 2 bits to represent the 3 possible object states (free, r_locked, w_locked)
      - a counter to count the number of waiting transactions

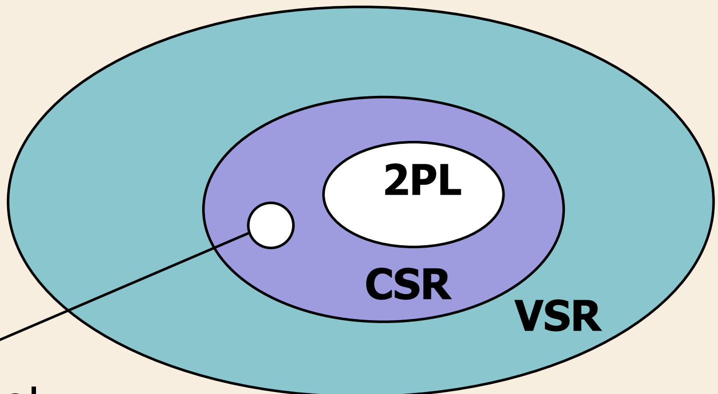
2 Phase Locking

- Exploited by most commercial DBMS
- It is characterized by two phases
  - Growing phase
    - needed locks are acquired
  - Shrinking phase
    - all locks are released



2 Phase Locking

- 2 Phase Locking guarantees serializability
  - *A transaction cannot acquire a new lock after having released any lock*



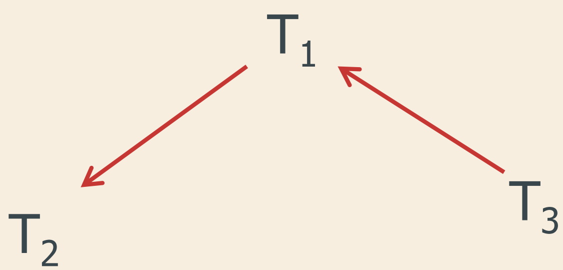
This schedule is not accepted by 2PL but it is serializable

Example

$$S = r_1(x)\ w_1(x)\ r_2(x)\ w_2(x)\ r_3(y)\ w_1(y)$$

T_1 releases the lock on x

T_1 should acquire a new lock on y



- The schedule is CSR but not 2PL

Ghost update (a)

Transactions		Resources		
T_1	T_2	x	y	z
bot		free	free	free
$r\_lock_1(x)$		1: read		
$r_1(x)$				
	bot			
	$r\_lock_2(y)$		2: read	
	$r_2(y)$			
$r\_lock_1(y)$			1,2: read	
$r_1(y)$				
	$r\_lock_2(z)$			2: read
	$r_2(z)$			
	$w\_lock_2(y)$			
$r\_lock_1(z)$				1,2: read
$r_1(z)$				
	wait			

Ghost update (a)

Transactions		Resources		
T_1	T_2	x	y	z
commit	*wait*			
$unlock_1(x)$		free		
$unlock_1(y)$			2: write	
	$w_2(y)$			
	$w\_lock_2(z)$			
	wait			
$unlock_1(z)$				2: write
	$w_2(z)$			
	commit			
	$unlock_2(y)$		free	
	$unlock_2(z)$			free

Strict 2 Phase Locking

- *Strict* 2 Phase Locking allows dropping the commit projection hypothesis
  - A transaction locks may be released only *at the end* of the transaction
    - After COMMIT/ROLLBACK
- After the end of the transaction, data is stable
  - It avoids the dirty read anomaly

Lock Manager service interface

- Primitives
  - R-Lock (T, x, ErrorCode, TimeOut)
  - W-Lock (T, x, ErrorCode, TimeOut)
  - UnLock (T, x)
- Parameters
  - T: Transaction ID of the requesting transaction
  - x: requested resource
  - ErrorCode: return parameter
    - Ok
    - Not Ok (request not satisfied)
  - TimeOut
    - Maximum time for which the transaction is willing to wait

Techniques to manage locking

- A transaction requests a resource x
- If the request *can be satisfied*
  - The lock manager modifies the state of resource x in its internal tables
  - It returns control to the requesting transaction
- The processing delay is very small

Techniques to manage locking

- If the request *cannot be satisfied* immediately
  - The requesting transaction is inserted in a waiting queue and suspended
  - When the resource becomes available
    - the first transaction (process) in the waiting queue is resumed and is granted the lock on the resource
- Probability of a conflict $\approx (K \times M)/N$
  - K is the number of active transactions
  - M is the average number of objects accessed by a transaction
  - N is the number of objects in the database

Techniques to manage locking

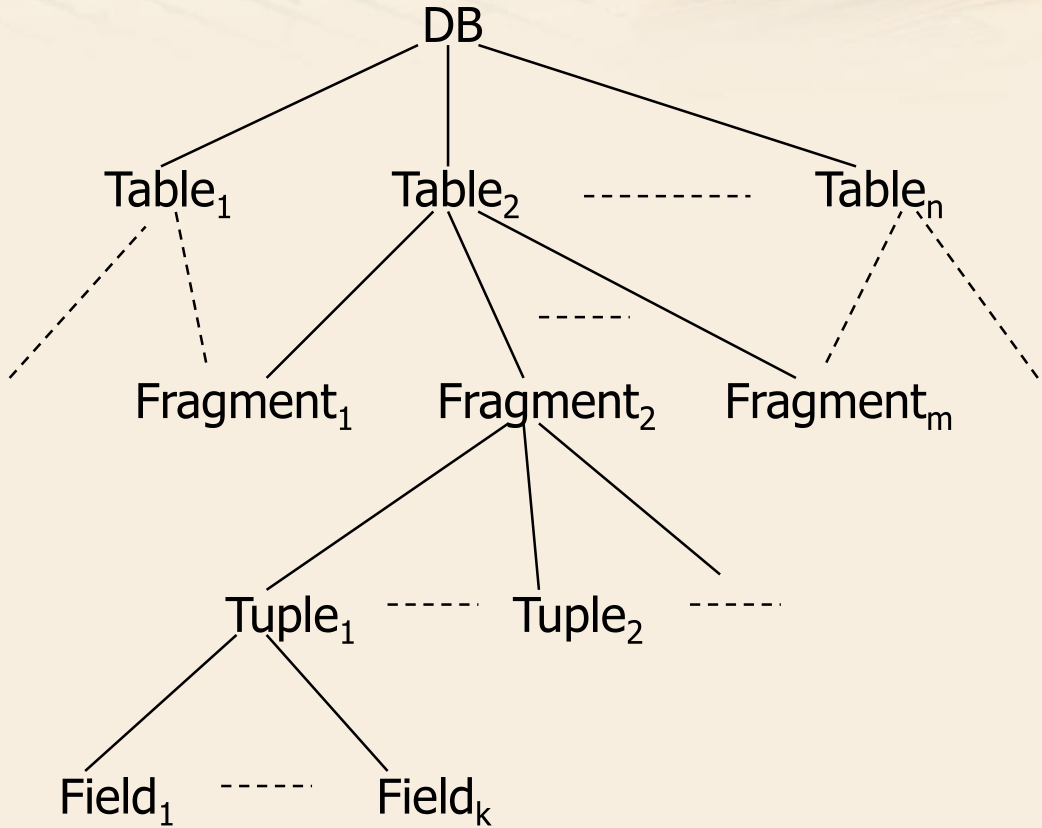
- When a *timeout* expires while a transaction is still waiting, the lock manager
  - extracts the waiting transaction from the queue
  - resumes it
  - returns a not ok error code
- The requesting transaction may
  - perform rollback (and possibly restart)
  - request again the same lock after some time
    - without releasing locks on other acquired resources

Hierarchical Locking

Hierarchical locking

- Table locks can be acquired at different *granularity* levels
  - Table
  - Group of tuples (fragment)
    - Physical partitioning criteria
      - e.g., data page
    - Logical partitioning criteria
      - e.g. tuples satisfying a given property
  - Single tuple
  - Single field in a tuple

Hierarchical locking



Hierarchical locking

- Hierarchical locking is an extension of traditional locking
  - It allows a transaction to request a lock at the appropriate level of the hierarchy
  - It is characterized by a larger set of locking primitives

Locking primitives

- Shared Lock (SL)
- eXclusive Lock (XL)
- Intention of Shared Lock (ISL)
  - It shows the intention of shared locking on an object which is in a lower node in the hierarchy
    - i.e., a descendant of the current node
- Intention of eXclusive Lock (IXL)
  - Analogous to ISL, but for exclusive lock

Locking primitives

- Shared lock and Intention of eXclusive Lock (SIXL)
  - Shared lock of the current object and intention of exclusive lock for one or more objects in a descendant node

Request protocol

1. Locks are always requested starting from the tree root and going down the tree
2. Locks are released starting from the blocked node of smaller granularity and going up the tree
3. To request a SL or an ISL on a given node, a transaction must own an ISL (or IXL) on its parent node in the tree
4. To request an XL, IXL or SIXL on a given node, a transaction must own an IXL or SIXL on its parent node in the tree

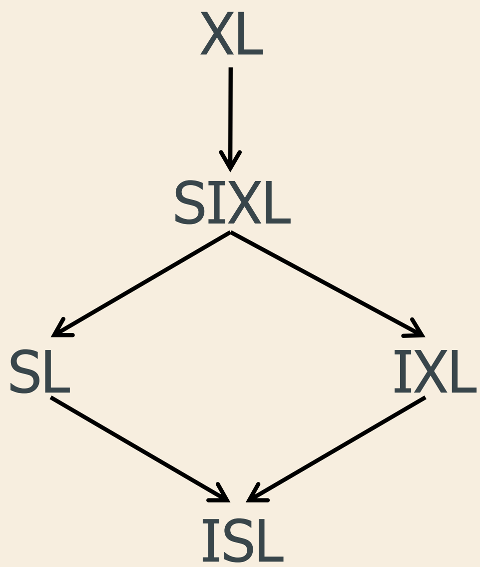
Compatibility matrix

	Resource State				
Request	**ISL**	**IXL**	**SL**	**SIXL**	**XL**
ISL					
IXL					
SL					
SIXL					
XL					

Compatibility matrix

	Resource State				
Request	**ISL**	**IXL**	**SL**	**SIXL**	**XL**
ISL	Ok	Ok	Ok	Ok	No
IXL	Ok	Ok	No	No	No
SL	Ok	No	Ok	No	No
SIXL	Ok	No	No	No	No
XL	No	No	No	No	No

Precedence graph for locks



Selection of lock granularity

- It depends on the application type
  - if it performs *localized* reads or updates of few objects
    - low levels in the hierarchy (detailed granularity)
  - if it performs *massive* reads or updates
    - high levels in the hierarchy (rough granularity)
- Effect of lock granularity
  - if it is too coarse, it reduces concurrency
    - high likeliness of conflicts
  - if it is too fine, it forces a significant overhead on the lock manager

Predicate locking

- It addresses the ghost update of type b (insert) anomaly
  - for 2PL a read operation *is not* in conflict with the insert of a new tuple
    - the new tuple can't be locked in advance
- *Predicate locking* allows locking all data satisfying a given predicate
  - implemented in real systems by locking indices

Locking in SQL2 standard

- Transaction types
  - read-write (default case)
  - read only
    - no data or schema modifications are allowed
    - shared locks are enough
- The *isolation level* of a transaction specifies how it interacts with the other executing transactions
  - it may be set by means of SQL statements

Isolation levels

- SERIALIZABLE
  - the highest isolation level
  - it includes predicate locking
- REPEATABLE READ
  - strict 2PL without predicate locking
  - reads of existing objects can be correctly repeated
  - no protection against ghost update (b) anomaly
    - the computation of aggregate functions cannot be repeated

Isolation levels

- READ COMMITTED
  - not 2PL
  - the read lock is released as soon as the object is read
  - reading intermediate states of a transaction is avoided
    - dirty reads are avoided
- READ UNCOMMITTED
  - not 2PL
  - data is read without acquiring the lock
    - dirty reads are allowed
  - only allowed for read only transactions

Locking in SQL2 standard

- The isolation level of a transaction may be set by means of the statement

  SET TRANSACTION
  [ISOLATION LEVEL <IsolationLevel>]
  [READ ONLY]
  [READ WRITE]

- The isolation level may be reduced only for read operations
- Write operations are always executed under strict 2PL with exclusive lock

Deadlock

Deadlock

Transaction T_1	Transaction T_2
bot	
$r\_lock_1(x)$	
$r_1(x)$	
	bot
	$r\_lock_2(y)$
	$r_2(y)$
$w\_lock_1(y)$	
	$w\_lock_2(x)$
wait	*wait*

time

- Typical situation for concurrent systems managed by means of
  - locking
  - waiting conditions

Solving deadlocks

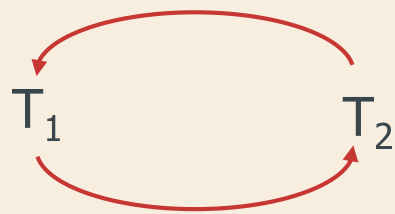
- Timeout
  - the transaction waits for a given time
  - after the expiration of the timeout
    - it receives a negative answer and it performs rollback
- Typically adopted in commercial DBMS
- Length of the timeout interval
  - long
    - long waiting before solving the deadlock
  - short
    - overkill, which overloads the system

Deadlock prevention

- Pessimistic 2PL
  - All needed locks are acquired before the transaction starts
    - not always feasible
- Timestamp
  - only “younger” (or older) transactions are allowed to wait
    - it may cause overkill

Deadlock detection

- Based on the *wait graph*
  - nodes are transactions
  - an edge represents a waiting state between two transactions



- A cycle in the graph represents a deadlock
- Expensive to build and maintain
  - used in distributed DBMS