Transaction Management Part I: Concurrency Control

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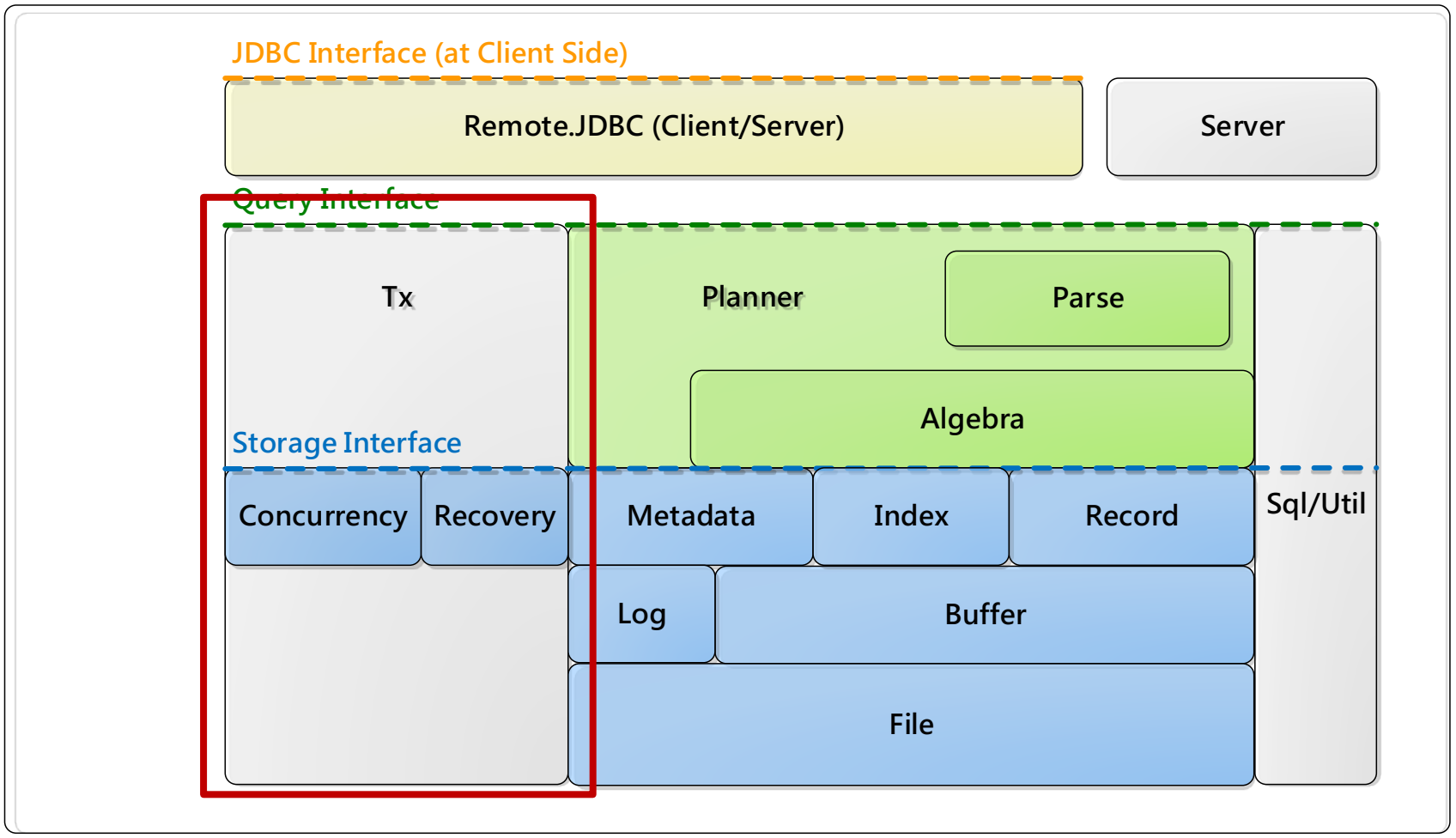
Tx Management

VanillaCore



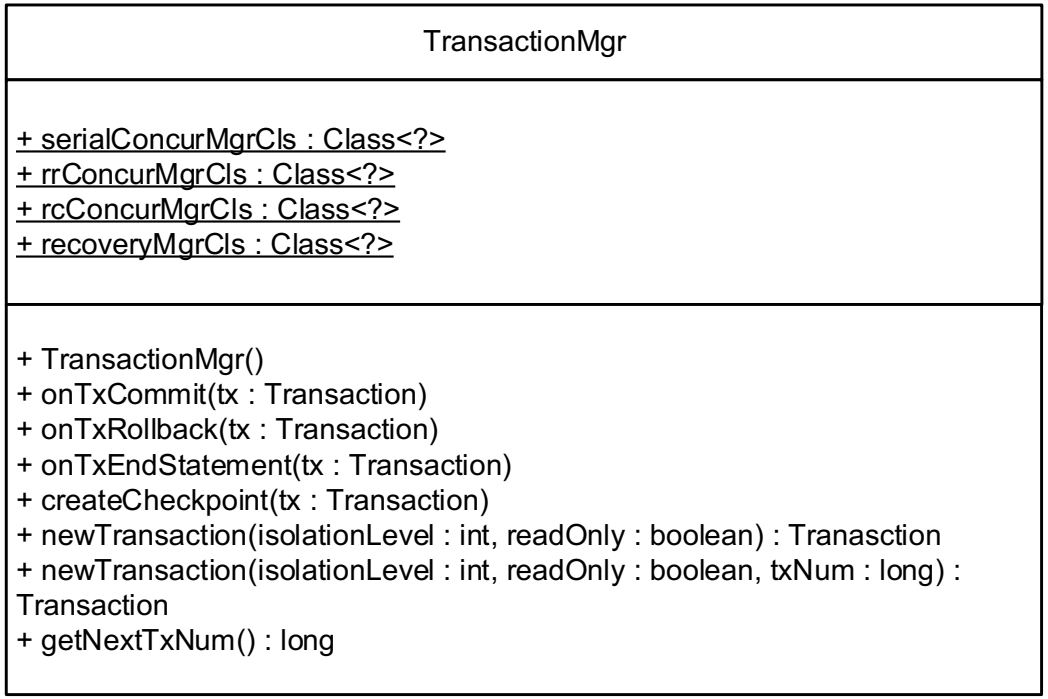
Native API Revisited

```
VanillaDb.init("studentdb");

// Step 1
Transaction tx =
VanillaDb.txMgr().newTransaction(
Connection.TRANSACTION_SERIALIZABLE, true);

// Step 2
Planner planner = VanillaDb.newPlanner();
String query = "SELECT s-name, d-name FROM
departments, "
+ "students WHERE major-id = d-id";
Plan plan = planner.createQueryPlan(query,
tx);
Scan scan = plan.open();

// Step 3
System.out.println("name\tmajor");
System.out.println("-------\t-------");
while (scan.next()) {
String sName = (String) scan.getVal("s-
name").asJavaVal();
String dName = (String) scan.getVal("d-
name").asJavaVal();
System.out.println(sName + "\t" + dName);
}
scan.close();

// Step 4
tx.commit();
```

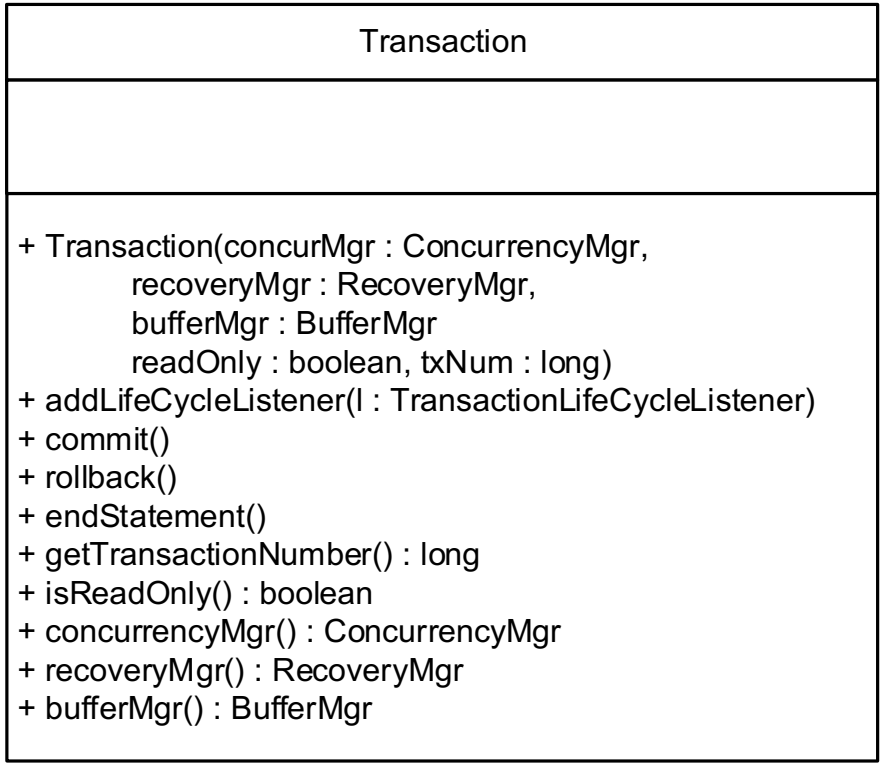
- A tx is created upon accepting an JDBC connection
  - by `VanillaDb.txMgr().newTransaction()`
- Passed as a parameter to Planners/Scanners/RecordFiles

Transaction Manager in VanillaDB

- `VanillaDb.txMgr()` is responsible for creating new transaction and maintaining the active transaction list

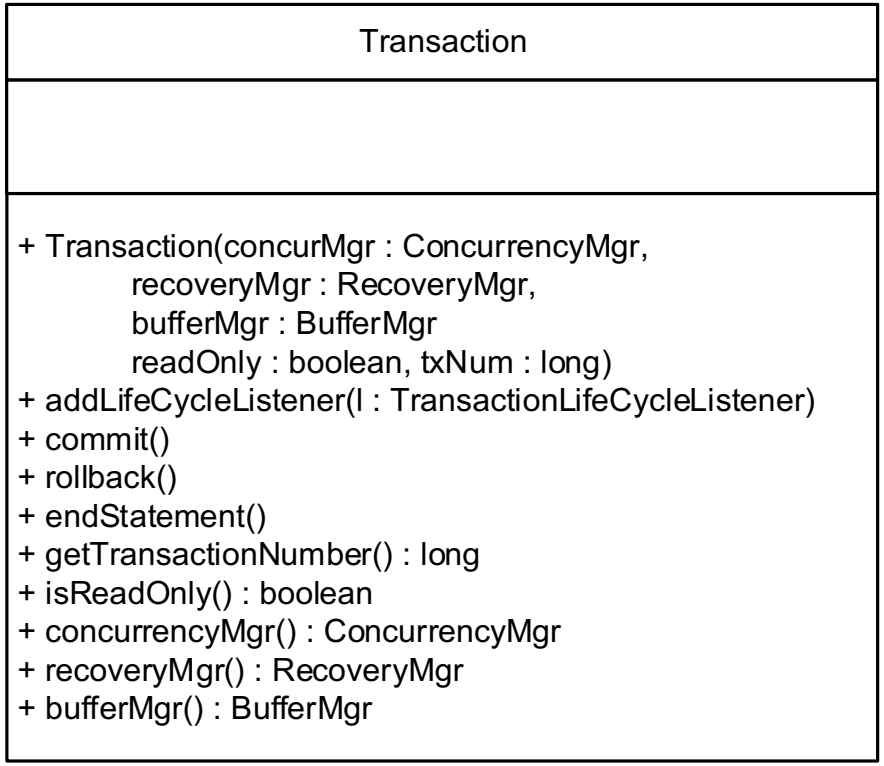


Transactions



- Ensures ACID
- ***Concurrency manager*** for C and I
- ***Recovery manager*** for A and D

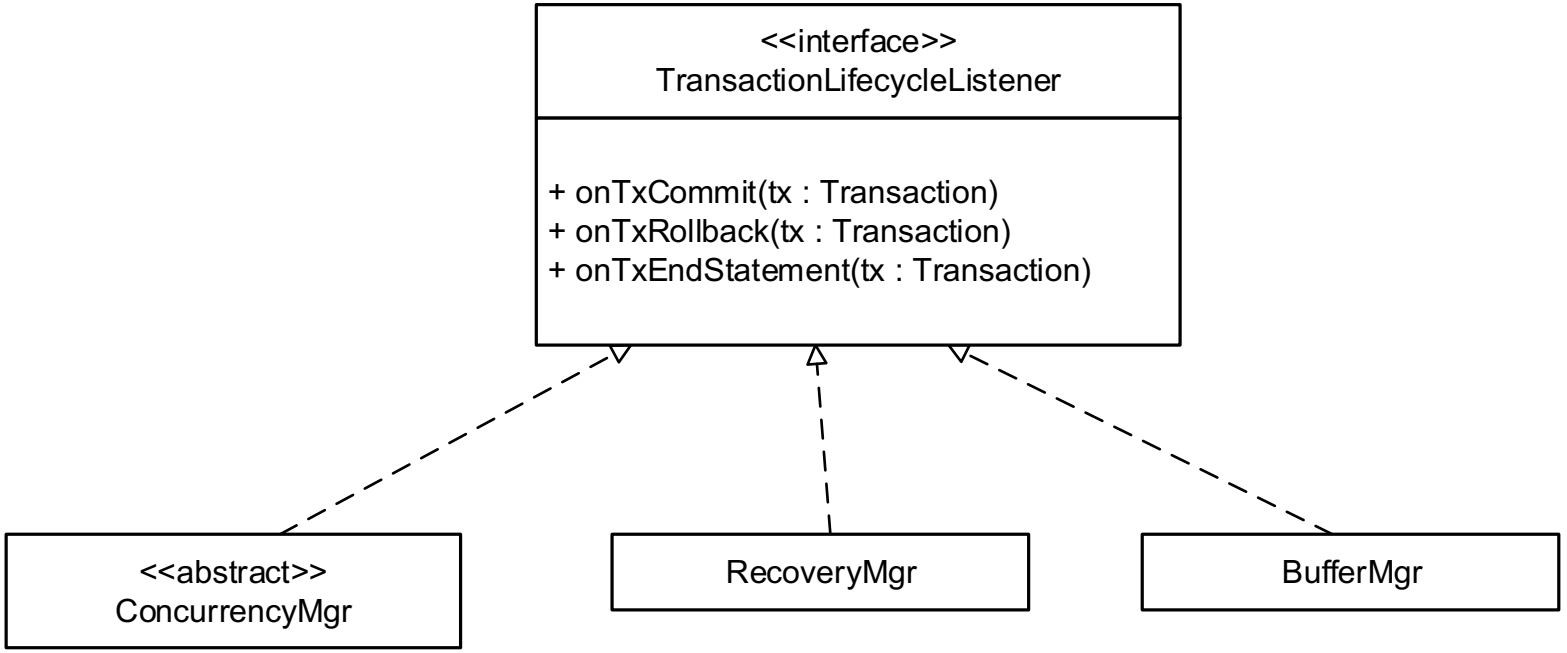
Transaction Lifecycle



1. Begin
2. End statement
   - If spanning across multiple statements
3. Commit or rollback

Lifecycle Listeners

- Tx lifecycle listener
  - Takes actions to tx life cycle events



Lifecycle Listener: Buffer Mgr

- Buffer manager
  - On tx rollback/commit: unpins all pages pinned by the current tx
  - Registered itself as a life cycle listener on start of each tx

```
@Override
public void onTxCommit(Transaction tx) {
      unpinAll(tx);
}

@Override
public void onTxRollback(Transaction tx) {
      unpinAll(tx);
}

@Override
public void onTxEndStatement(Transaction tx) {
      // do nothing
}
```

Lifecycle Listener: Recovery Mgr

- (Naive) Recovery manager
  - Commit: flushes dirty pages and then `commit` log
  - Rollback: undo all modifications by reading log records

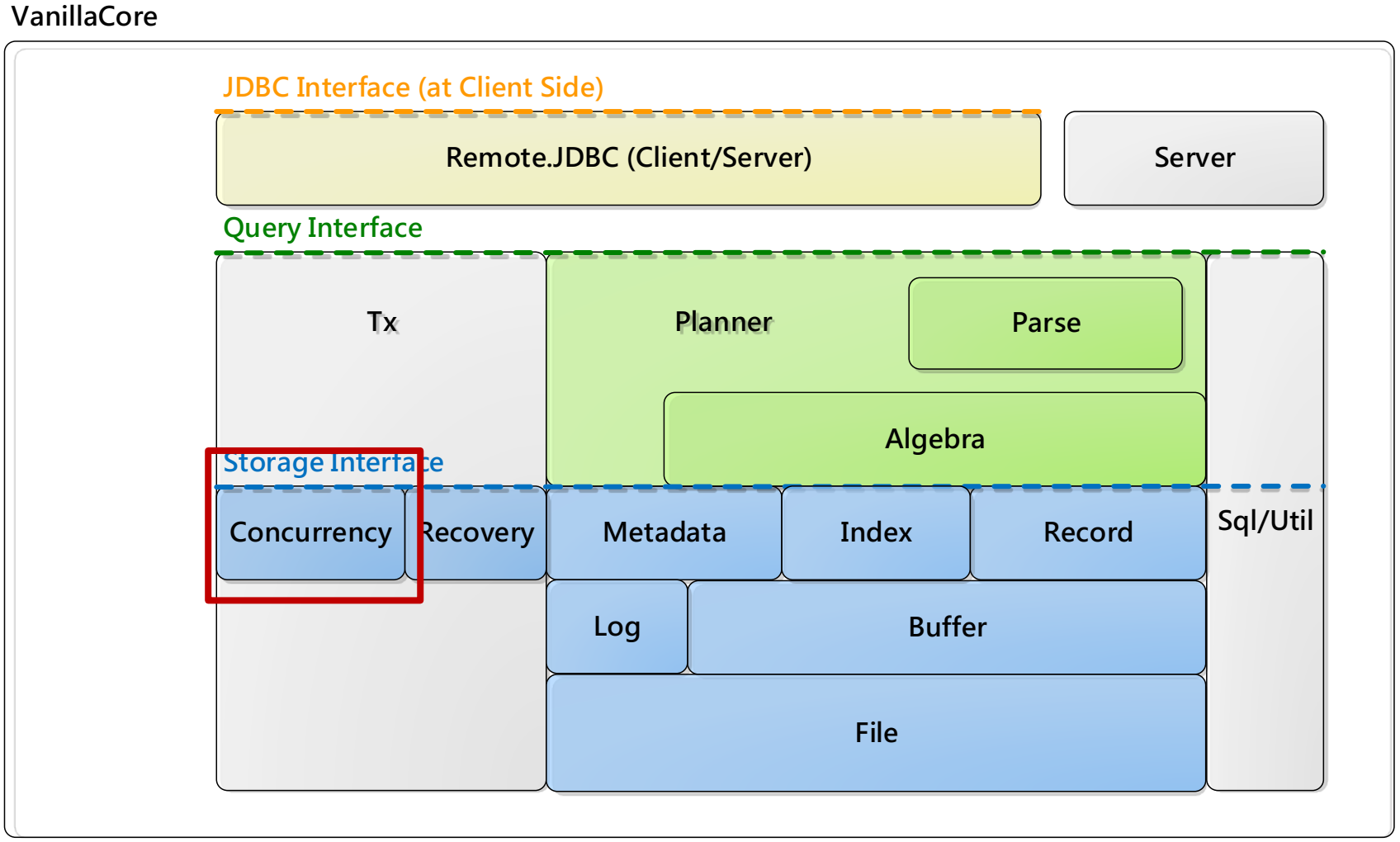
```
@Override
public void onTxCommit(Transaction tx) {
	VanillaDb.bufferMgr().flushAll(txNum);
	long lsn = new CommitRecord(txNum).writeToLog();
	VanillaDb.logMgr().flush(lsn);
}

@Override
public void onTxRollback(Transaction tx) {
	doRollback(tx);
	VanillaDb.bufferMgr().flushAll(txNum);
	long lsn = new RollbackRecord(txNum).writeToLog();
	VanillaDb.logMgr().flush(lsn);
}

@Override
public void onTxEndStatement(Transaction tx) {
	// do nothing
}
```

Lifecycle Listener: Concurrency Mgr

- (Naive) Concurrency manager
  - On tx commit/rollback: releases all locks

```
@Override
public void onTxCommit(Transaction tx) {
     lockTbl.releaseAll(txNum, false);
}

@Override
public void onTxRollback(Transaction tx) {
     lockTbl.releaseAll(txNum, false);
}

@Override
public void onTxEndStatement(Transaction tx) {
     // do nothing
}
```

Today's Focus: Concurrency Mgr



Outline

- Schedules
- Anomalies
- Lock-based concurrency control
  - 2PL and S2PL
  - Deadlock
  - Granularity of locks
- Dynamic databases
  - Phantom
  - Isolation levels
- Meta-structures
- Concurrency manager in VanillaCore

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Concurrency Manager

- Ensures ***consistency*** and ***isolation***

Consistency

- ***Consistency***
  - Txs will leave the database in a consistent state
  - I.e., all integrity constraints (ICs) are meet
    - Primary and foreign key constrains
    - Non-null constrain
    - (Field) type constrain
    - …
  - Users are responsible for issuing “valid” txs

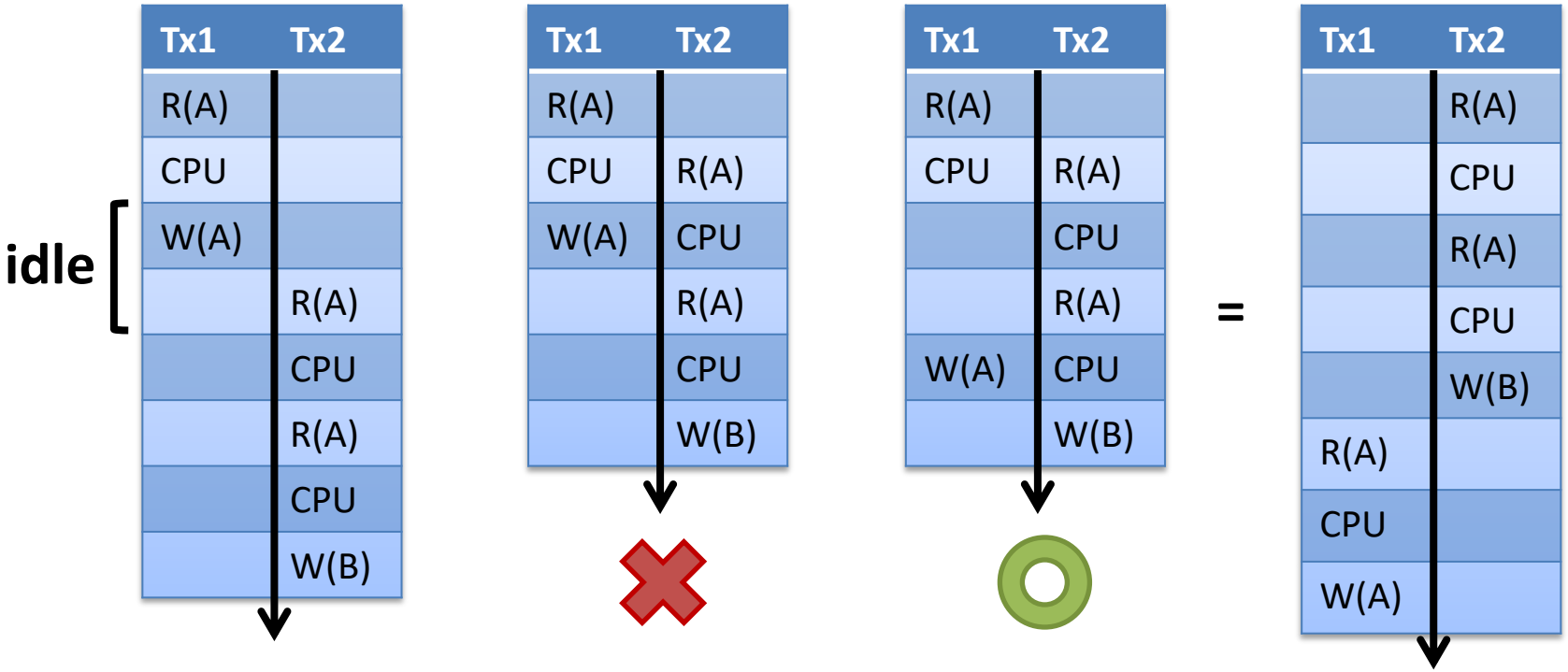
Isolation

- ***Isolation***
  - Interleaved execution of txs should have the net effect identical to executing tx in ***some*** serial order
  - T_1 and T_2 are executed concurrently, isolation gives that the net effect to be equivalent to either
    - T_1 followed by T_2 or
    - T_2 followed by T_1
  - The DBMS does ***not*** guarantee to result in ***which particular*** order

Why do we need to interleave txs?

Concurrent Txs

- Since I/O is slow, it is better to execute Tx1 and Tx2 concurrently to reduce CPU idle time



- The concurrent result should be the same as serial execution in ***some*** order
  - Better concurrency

Concurrent Txs

- Pros:
  - Increases throughput (via CPU and I/O pipelining)
  - Shortens response time for short txs
- But operations must be interleaved correctly

Transactions and Schedules

- Before executing T_1 and T_2:
  - A = 300, B = 400

T1:	BEGIN	A=A+100, B=B-100	END
T2:	BEGIN	A=1.06*A, B=1.06*B	END

- Two possible execution results
  - T_1 followed by T_2
    - A = 400, B = 300 → A = 424, B = 318
  - T_2 followed by T_1
    - A = 318, B = 424 → A = 418, B = 324

Transactions and Schedules

- A ***schedule*** is a list of actions/operations from a set of transaction
- If the actions of different transactions are not interleaved, we call this schedule a ***serial schedule***

T1:	A=A+100, B=B-100	
T2:		A=1.06*A, B=1.06*B

Transactions and Schedules

- Equivalent schedules
  - The effect of executing the first schedule is identical to the effect of executing the second schedule
- ***Serializable schedule***
  - A schedule that is equivalent to some serial execution of the transactions

Transactions and Schedules

- A possible interleaving schedule

T1:	A=A+100,		B=B-100
T2:		A=1.06*A,	B=1.06*B

  - Result: A = 424, B = 318
  - A serializable schedule
    - Equivalent to T_1 followed by T_2

T1:	A=A+100,	B=B-100		
T2:			A=1.06*A,	B=1.06*B

Transactions and Schedules

- How about this schedule?

T1:	A=A+100,	B=B-100
T2:	A=1.06*A, B=1.06*B	

  - Result: ***A = 424***, ***B = 324***
  - A non-serializable schedule
  - Violates the isolation requirement

Goal

- Interleave operations while making sure the schedules are serializable
- How?

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Simplified Notation

T1:	A=A+100,	B=B-100
T2:	A=1.06*A, B=1.06*B	

- Can be simplified to:

T1:	R(A), W(A),	R(B), W(B)
T2:	R(A), W(A), R(B), W(B)	

- Here, we care about operations, not values

Anomalies

- Weird situations that would happen when interleaving operations
  - But not in serial schedules
- Mainly due to the ***conflicting*** operations

Conflict Operations

- Two operations on the same object are ***conflict*** if they are operated by different txs and at least one of these operations is a write

Types

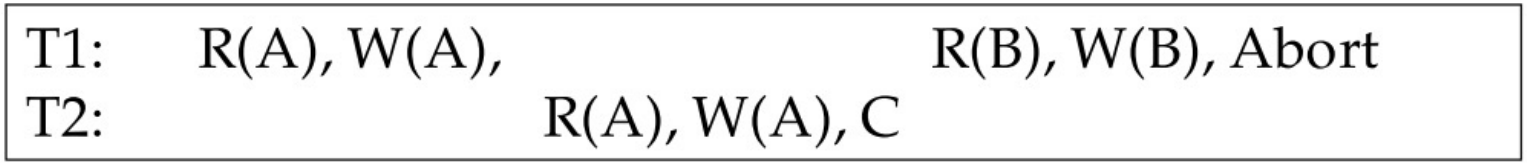
- Write-read conflict
- Read-write conflict
- Write-write conflict

- Read-read conflict?
  - No anomaly

Anomalies due to Write-Read Conflict

- Reading uncommitted data
  - ***Dirty reads***

- A ***unrecoverable schedule***

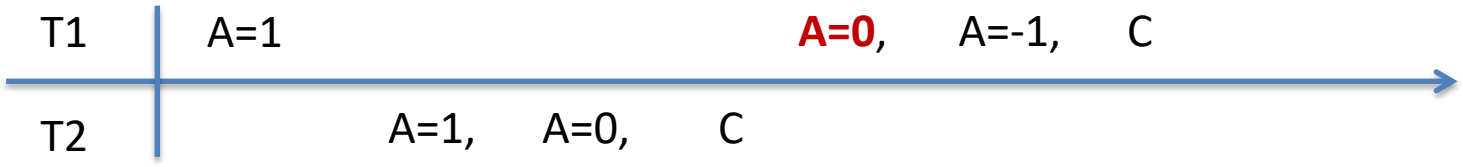


  - T1 cannot abort!
  - ***Cascading aborts*** if T2 completes after T1 aborts

Anomalies due to Read-Write Conflict

- ***Unrepeatable reads***:
  - T_1: $if\ (A > 0)\ A = A - 1;$
  - T_2: $if\ (A > 0)\ A = A - 1;$
  - IC on A: cannot be negative

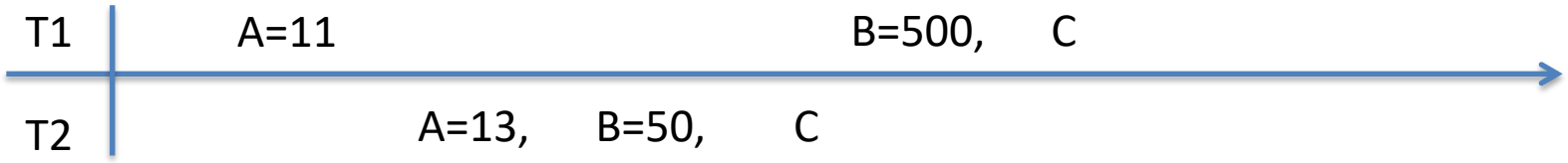
T1:	R(A),		R(A), W(A), C
T2:		R(A), W(A), C	



Anomalies due to Write-Write Conflict

- ***Lost updates***:
  - $T_1: A = A + 1; B = B * 10;$
  - $T_2: A = A + 2; B = B * 5;$
  - Start with A=10, B=10

T1:	W(A),		W(B), C
T2:		W(A), W(B), C	

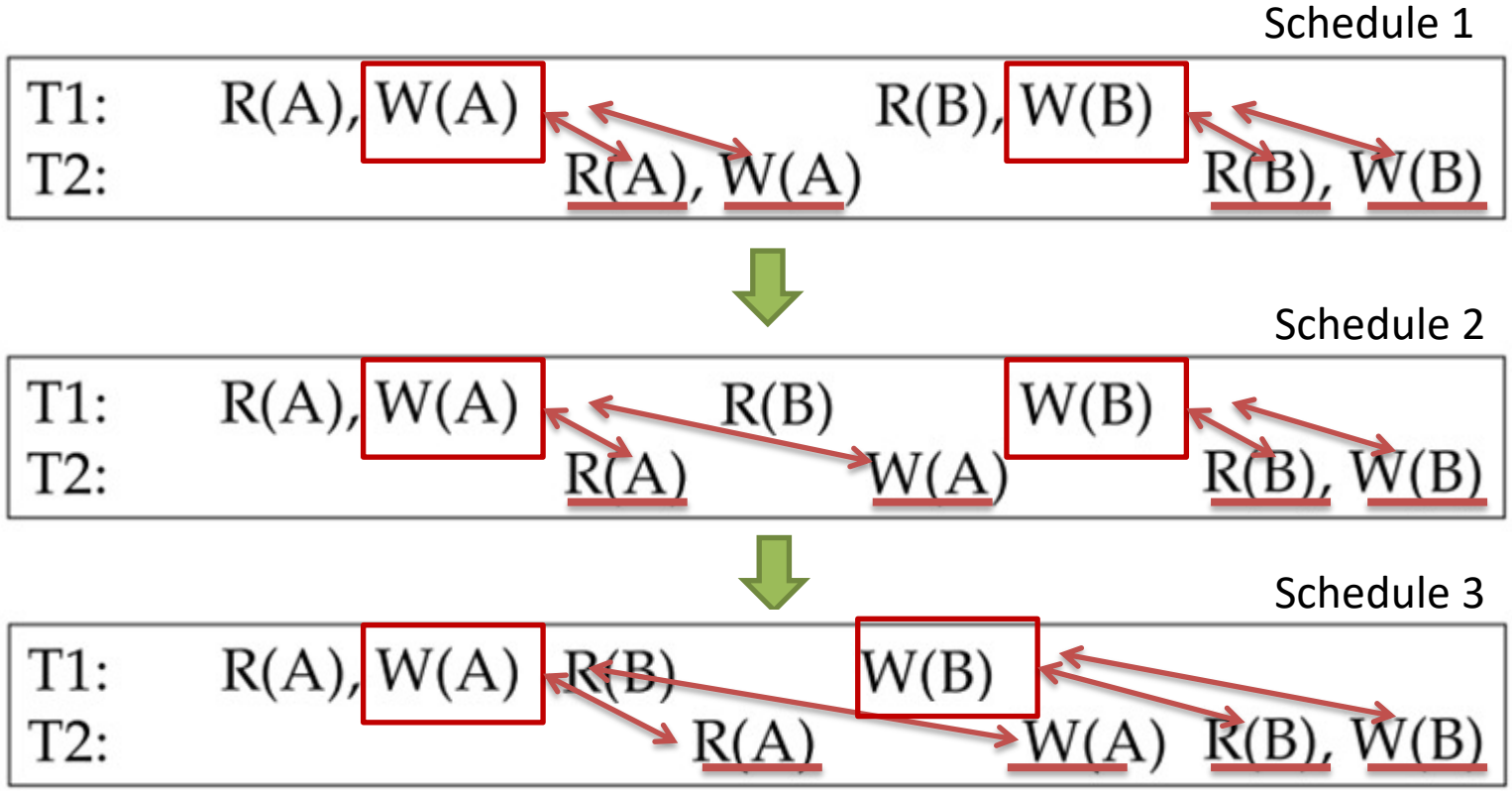


Avoiding Anomalies

- Idea:
- Perform all conflicting actions between T1 and T2 ***in the same order*** (either T1's before T2's or T2's before T1's)
- I.e., to ensure ***conflict serializability***

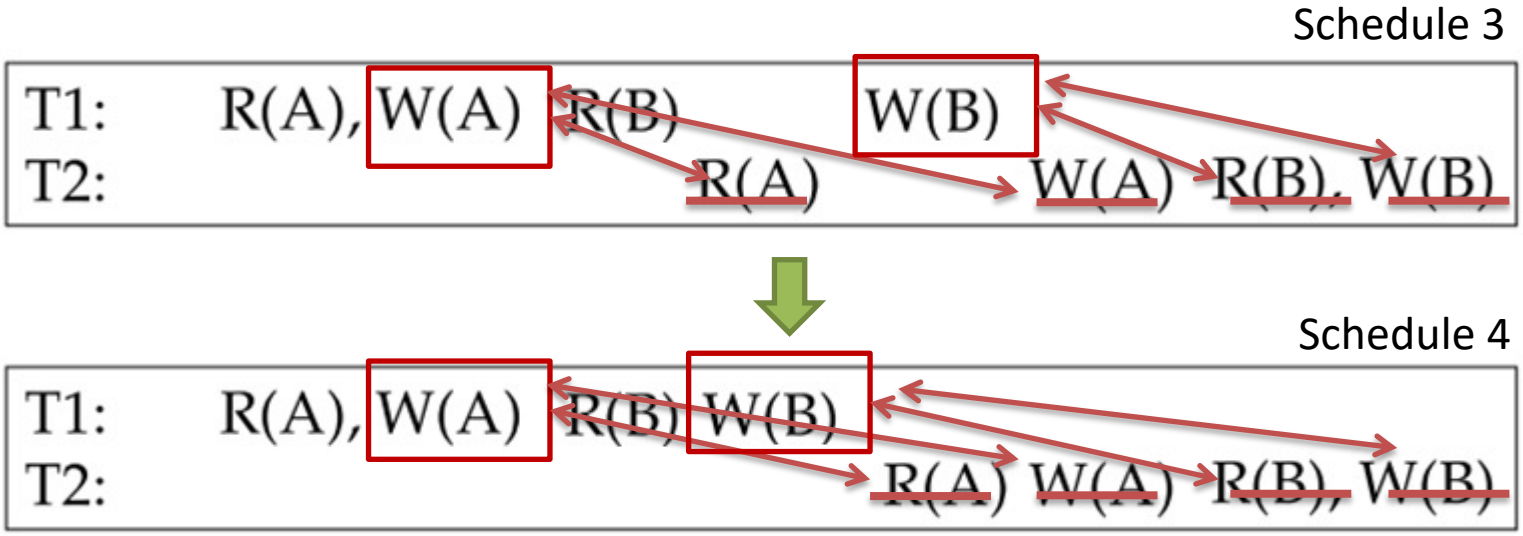
Conflict Equivalent

- If two operations are not conflict, we can ***swap*** them to generate an equivalent schedule
- Schedule 1 is ***conflict equivalent*** to schedule 2 and schedule 3

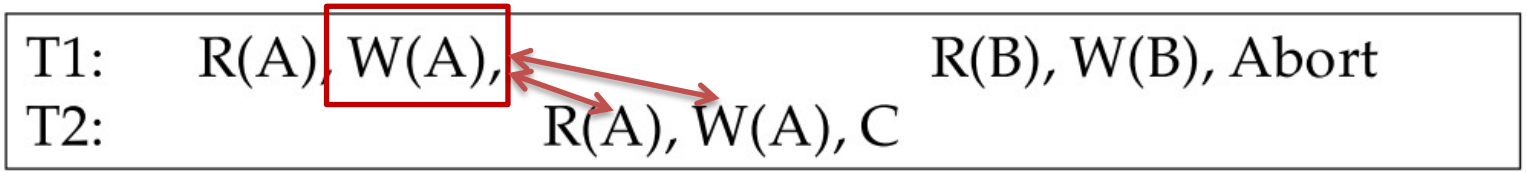


Conflict Serializable

- By swapping non-conflict operations, we can transfer the schedule 1 into a serial schedule 4
- We say that schedule 1 is ***conflict serializable***



Ensuring Conflict Serializability is ***Not Enough***



- Conflict serializable, but ***not*** recoverable

Avoiding Anomalies

- We also need to ensure recoverable schedule
- Definition: A schedule is ***recoverable*** if each tx *T* commits only after all txs whose changes *T* reads, commit
- How?
  - Avoid cascading aborts
  - Disallow a tx from reading uncommitted changes from other txs

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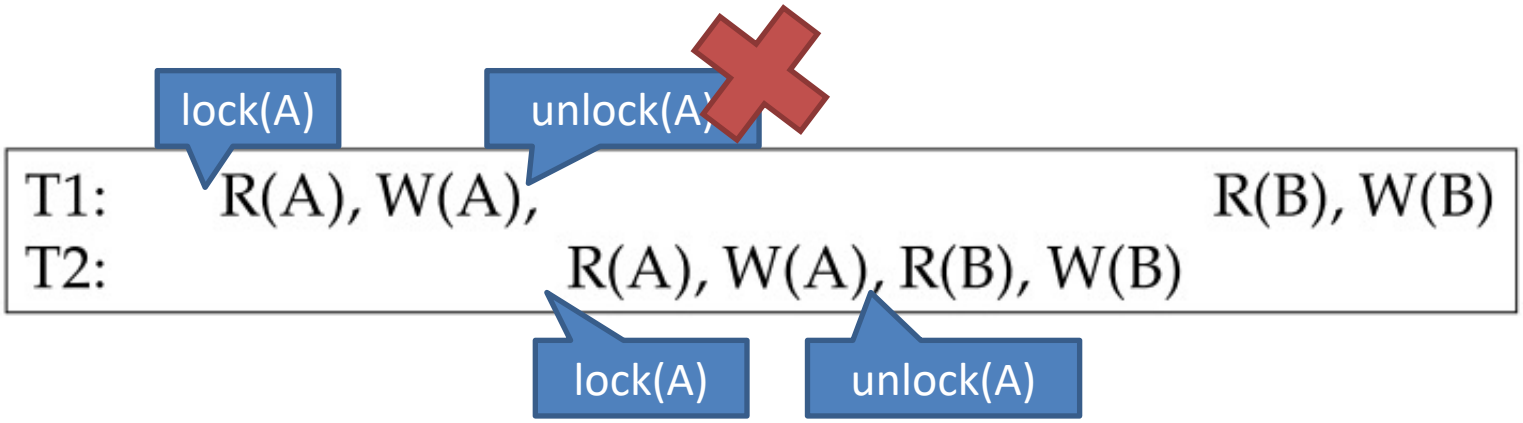
Lock-Based Concurrency Control

- For isolation and consistency, a DBMS should only allow ***serializable***, ***recoverable*** schedules
  - Uncommitted changes cannot be seen (no WR)
  - Ensure repeatable read (no RW)
  - Cannot overwrite uncommitted change (no WW)

- A ***lock*** for each data item seems to be a good solution



Lock $\neq$ latch

- Lock: long-term, tx-level
- Latch: short-term, ds/alg-level

Questions

- What type of lock to get for each operation?
- When should a transaction acquire/release lock?

- We need a ***locking protocol***
  - A set of rules followed by all transactions for requesting and releasing locks

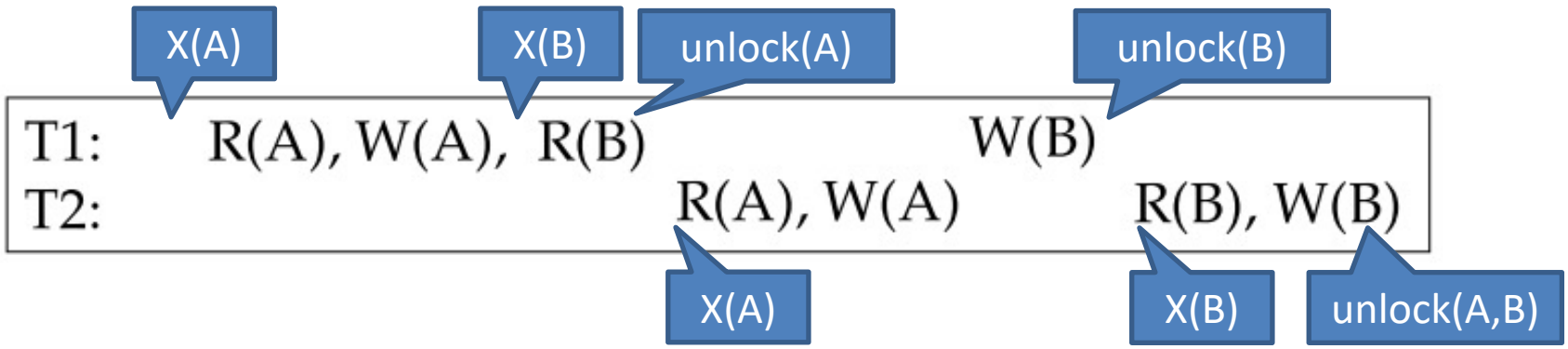
Two-Phase Locking Protocol (2PL)

- Defines two type of locks:
  - ***Shared (S) lock***
  - ***Exclusive (X) lock***

Compatible?	S	X
S	True	False
X	False	False

- Phase 1: Growing Phase
  - Each tx must obtain an S (X) lock on an object before reading (writing) it
- Phase 2: Shrinking Phase
  - A transaction can not request additional locks once it releases any locks
- Ensures conflict serializability

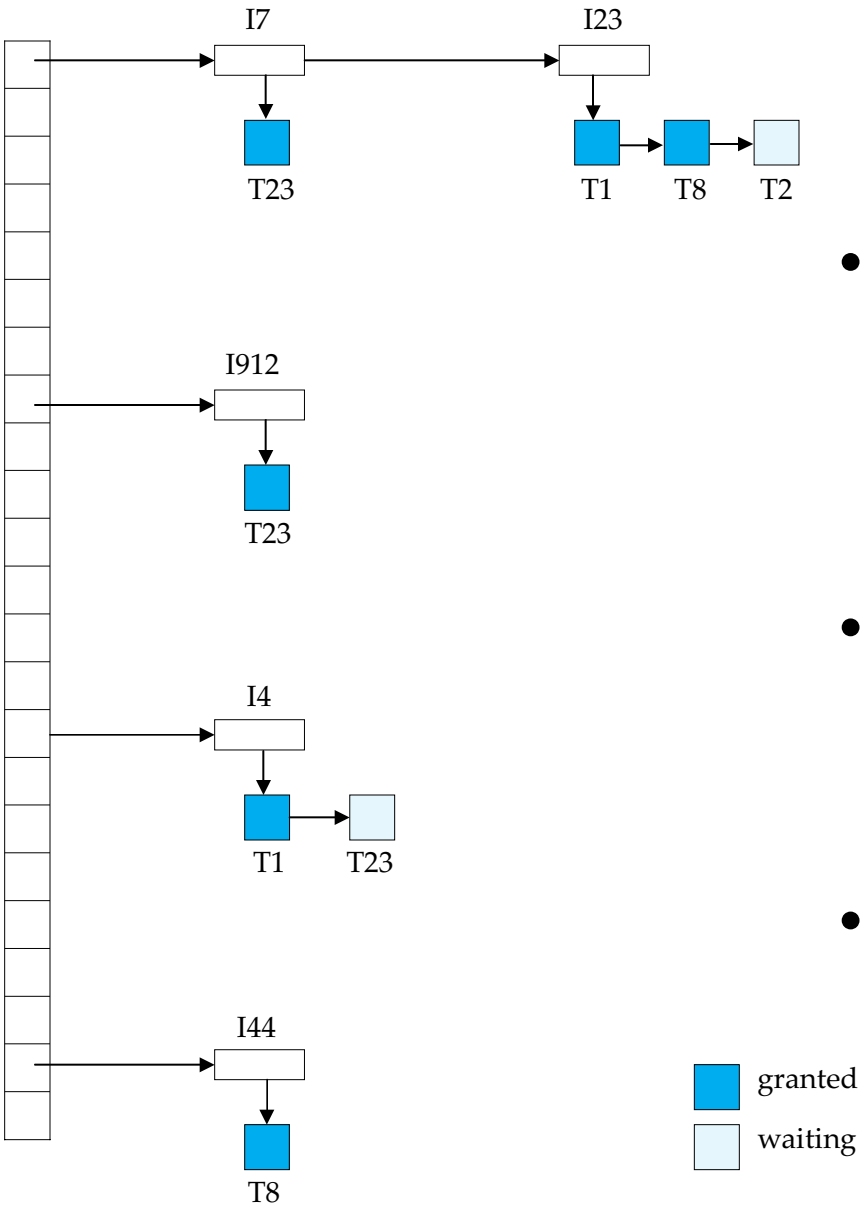
Example



- Ensures conflict serializability

Implementation

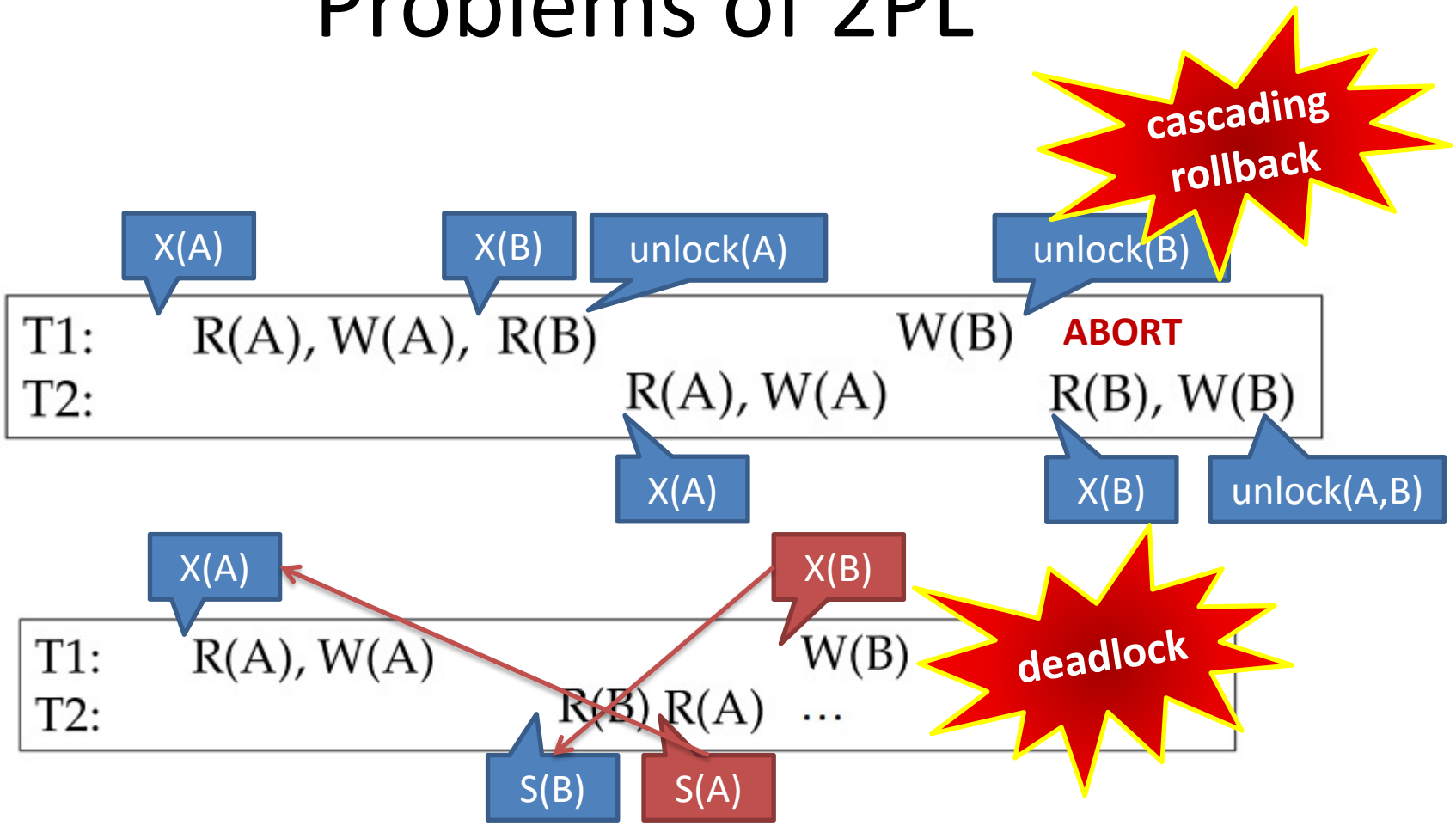
- Lock and unlock requests are handled by the ***lock manager***
  - Shared between concurrency managers
- Lock table entry
  - Number of transactions currently holding a lock
  - Type of lock held
  - Pointer to queue of lock requests
- Locking and unlocking have to be atomic operations



Lock Table

- Implemented as an in-memory hash table indexed on the name of the data item being locked
- New lock request is added to the end of the queue of requests for the data item
- Request is granted if it is compatible with all earlier requests

Problems of 2PL



- ***Starvation*** is also possible if concurrency control manager is badly implemented

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How to improve 2PL to avoid cascading rollback?

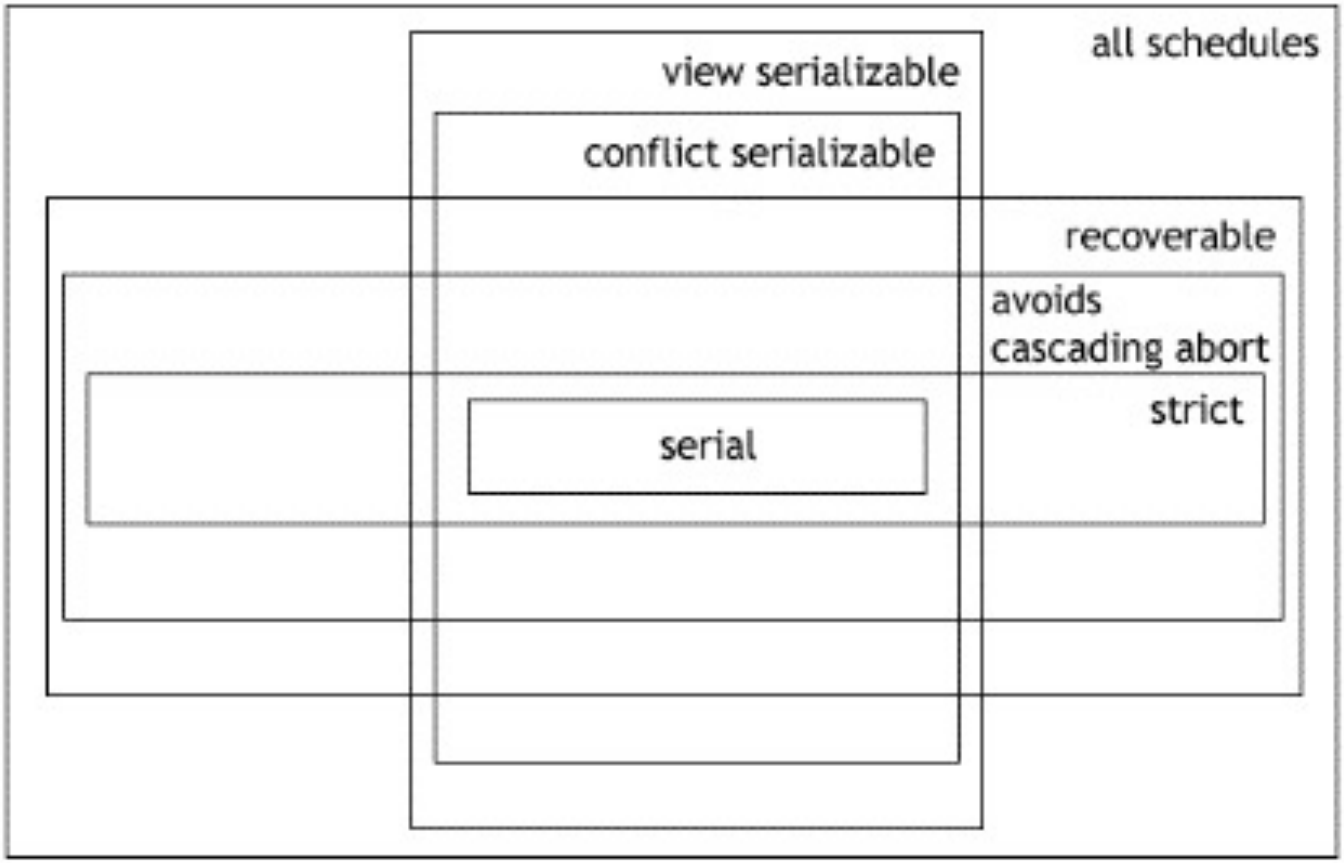
Strict Two-Phase Locking

- S2PL
  1. Each tx obtains locks as in the growing phase in 2PL
  2. But the tx ***holds all locks until it completes***
- Allows only serializable and ***stric*** schedules

Strict Two-Phase Locking

- Definition: A schedule is ***strict*** iff for any two txs T1 and T2, if a write operation of T1 precedes a conflicting operation of T2 (either read or write), then T1 commits before that conflicting operation of T2
  - Strictness → no cascading abort (converse not true)
- Avoids cascading rollback, but still has deadlock

Serializability and Recoverability



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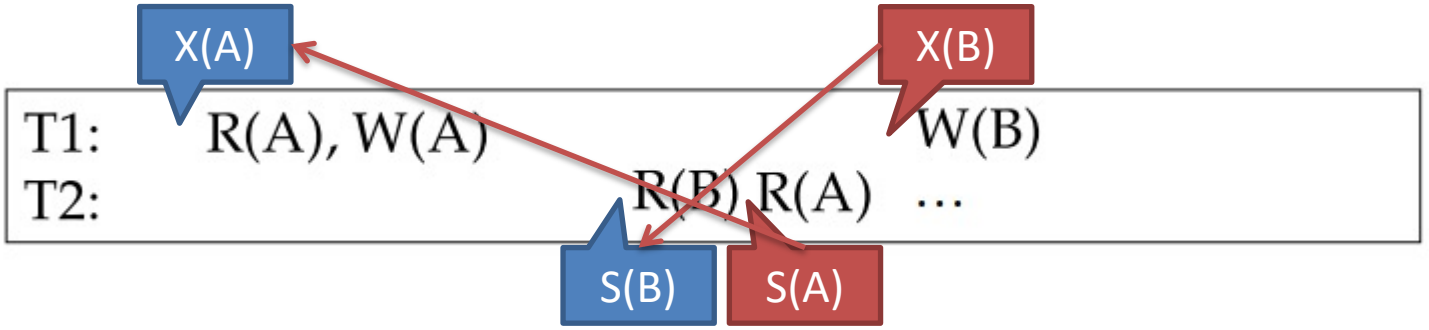
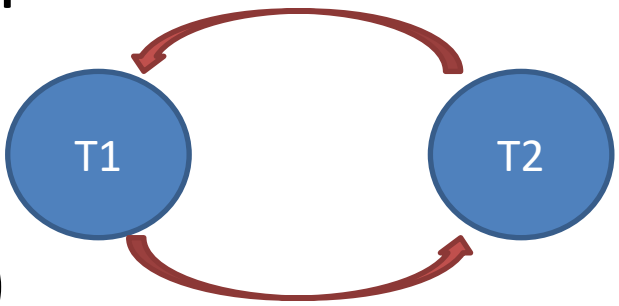
Coping with Deadlocks

- Cycle of transactions waiting for locks to be released by each other



- Detection: ***Waits-for*** graph
  - For detecting cycles
- Checked when acquiring locks (or buffers)



Other Techniques (1)

- ***Timeout & rollack*** (deadlock detection)
  - Assume T_i wants a lock that T_j holds
  1. T_i waits for the lock
  2. If T_i stays on the wait list too long then: T_i is rolled back
- ***Wait-die*** (deadlock prevention)
  - Assume each T_i has a timestamp (e.g., tx number)
  - If T_i wants a lock that T_j holds
  1. If T_i is older than T_i, it waits for T_j;
  2. Otherwise T_i aborts

Other Techniques (2)

- ***Conservative locking*** (deadlock prevention)
  - Every T_i locks ***all objects at once*** (atomically) in the beginning
  - No interleaving for conflicting txs---performs well only if there is no/very few long txs (e.g., in-memory DBMS)
  - How to know which objects to lock before tx execution?
  - Requires the coder of a stored procedure to specify its read- and write-sets explicitly
  - Does not support ad-hoc queries

~~You Have Assignment!~~

Assignment: Conservative Locking

- Implement a ConcurrencyMgr running the conservative locking protocol
  - Modify the stored procedure API to accommodate read-/write-sets

Assignment: Conservative Locking

- Report
  - How you implement the new ConcurrencyMgr
    - API changes and/or new classes
  - Compare the throughputs before and after your modification using the given benchmark & loader
  - Observe and discuss the impact of buffer pool size to your new system

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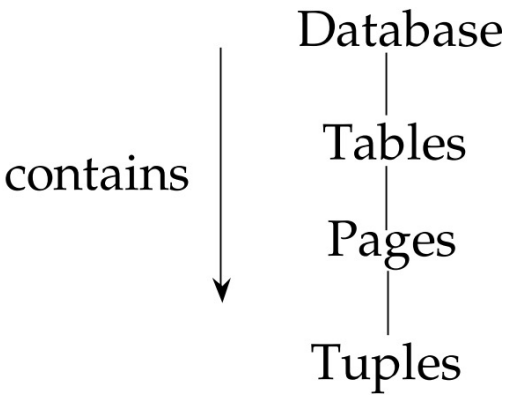
Granularity of Locks

- What “objects” to lock?
  - Records vs. blocks vs. tables/files
- ***Granularity*** of locking objects
  - Fine granularity: high concurrency, high locking overhead
  - Coarse granularity: low locking overhead, low concurrency

Reducing Locking Overhead

- Data “containers” are nested



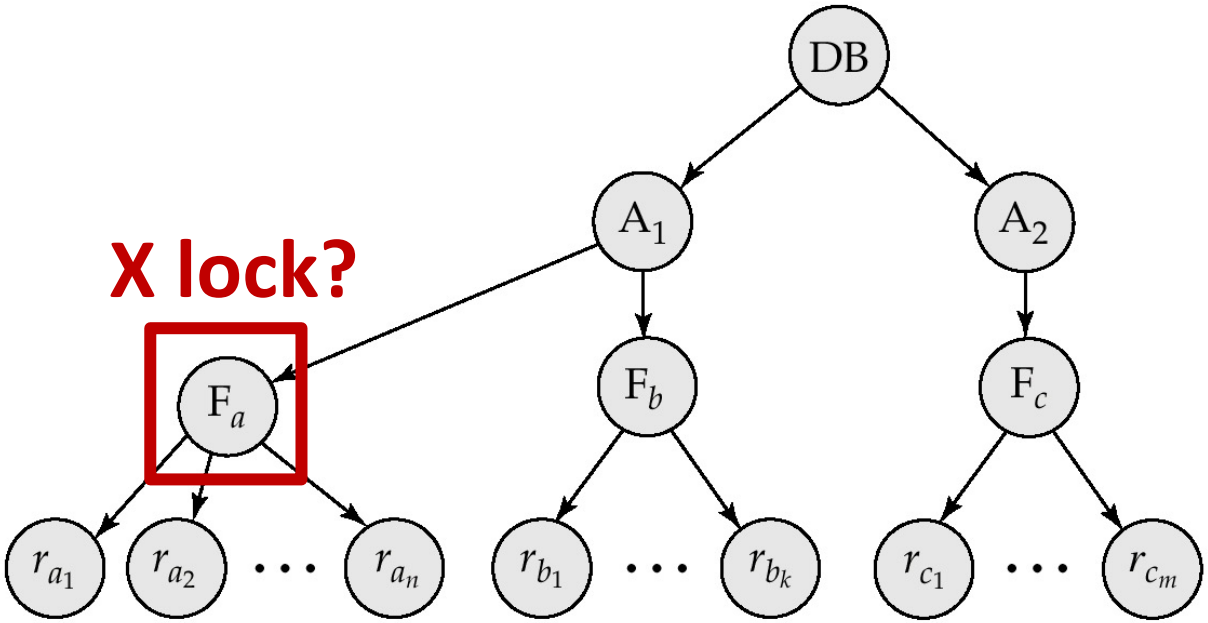
- When scanning, can we lock a file instead of all contained blocks/records to reduce the locking overhead?

Multiple-Granularity Locks

- ***Multiple-granularity locking*** (MGL) allows users to set locks on objects that contain other objects
  - Locking a file implies locking ***all*** contained blocks/records
- How does a lock manager know if a file is lockable?
  - Some other tx may hold a conflicting lock on a block in that file

Checking If An Object Is Locked

- To lock a file, check whether all blocks/records in that file are locked
  - Good strategy?
- Does ***not*** save the locking overhead



Multiple-Granularity Locks

- Allow transactions to lock at each level, but with a special protocol using new "intention" locks:
- ***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

Multiple-Granularity Locks

- The compatibility matrix for all lock modes is:

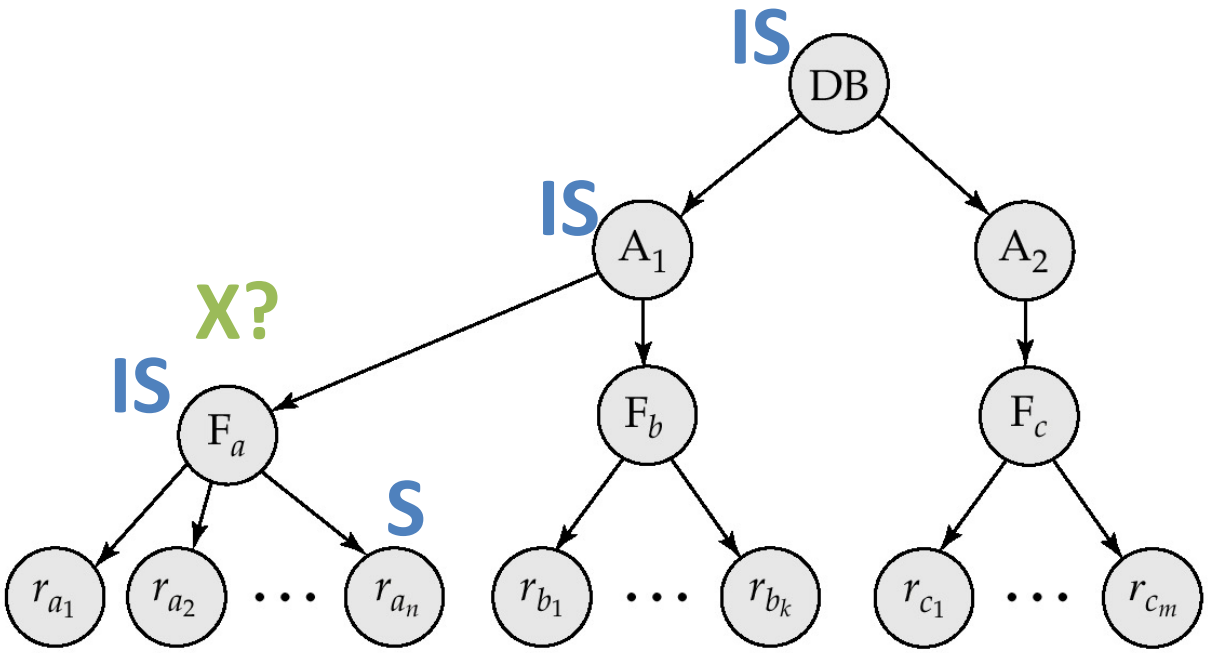
	IS	IX	S	S IX	X
IS	✓	✓	✓	✓	×
IX	✓	✓	×	×	×
S	✓	×	✓	×	×
S IX	✓	×	×	×	×
X	×	×	×	×	×

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

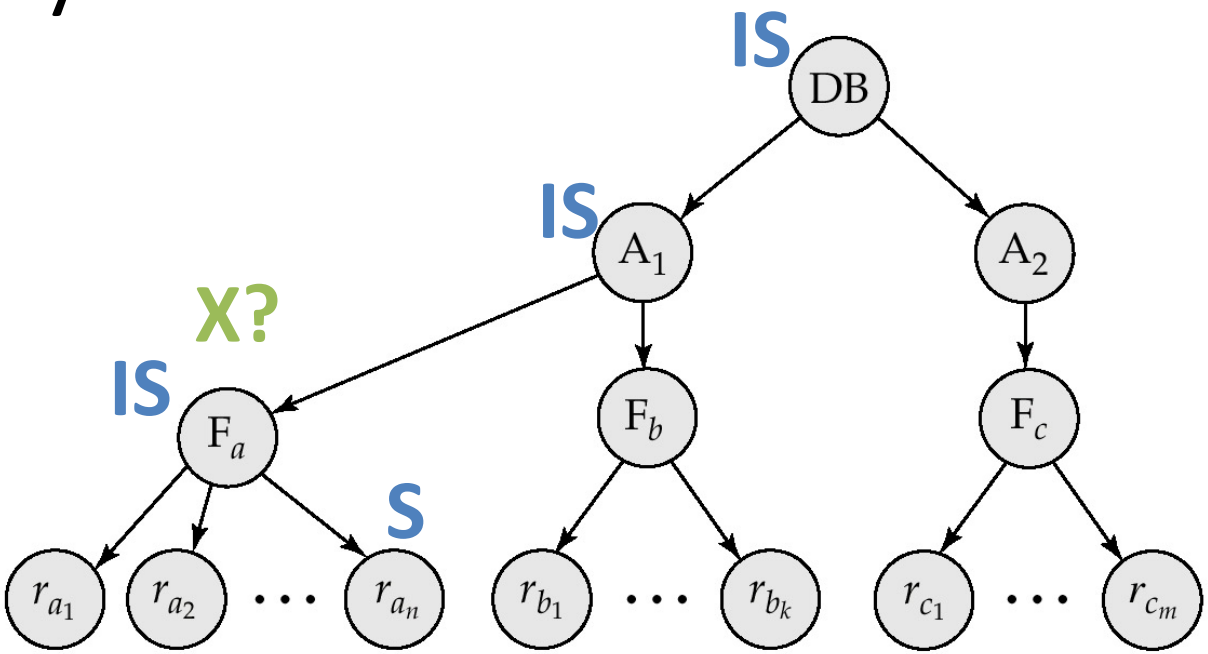
Acquiring Locks in MGL: An Example

- Locks are acquired in ***root-to-leaf*** order
  - Tx1 wants to share-lock a record
  - Tx2 wants to exclusive-lock a file



Releasing Locks in MGL

- Locks need to be released in ***leaf-to-root*** order
- Why?



Usage Examples of MGL

- T_1 scans R, and updates a few tuples:
  - T_1 gets an SIX lock on R, and occasionally get X lock on the tuples under modification
- T_2 uses an index to read only part of R:
  - T_2 gets an IS lock on R, and repeatedly gets an S lock on a tuple of R
- T_3 reads the size of R:
  - T_3 gets an S lock on R

Outline

- Schedules
- Anomalies
- Lock-based concurrency control
  - 2PL and S2PL
  - Deadlock
  - Granularity of locks
- Dynamic databases
  - Phantom
  - Isolation levels
- Meta-structures
- Concurrency manager in VanillaCore

Dynamic Databases

- So far, we have treated a database as a fixed collection of independent data objects
  - Only reads and writes
- However, the database can grow and shrink through the ***insertions*** and ***deletions***
- Any trouble?
- ***Phantoms***

Phantoms Caused by Insertion

- T_1: `SELECT * FROM users WHERE age=10;`
- T_2: `INSERT INTO users`
  `VALUES (3, 'Bob', 10); COMMIT;`
- T_1: `SELECT * FROM users WHERE age=10;`

- A transaction that reads the entire contents of a table multiple times will see different data
  - E.g., in a join query

Phantoms Caused by Update

- T_1: `SELECT * FROM users WHERE age=10;`
- T_2: `UPDATE users SET age=10 WHERE id=7;`
  `COMMIT;`
- T_1: `SELECT * FROM users WHERE age=10;`

- T_1 only share locks the records with the age equals to 10
- The record with id=7 is not in the locking item set of T_1, so T_2 can update this record

How to Prevent Phantoms?

- EOF locks or multi-granularity locks
  - X-lock the containing file when inserting/updating records in a block
  - Hurt performance (no concurrent inserts/updates)
  - Usually used to prevent phantoms by insert
  - But ***not*** phantoms by update
- Index (or predicate) locking
  - Prevent phantoms caused by both insert and update
  - Works only if indices for the inserting/updating fields are created

Phantom and Conservative Locking

- Phantom problem remains

- ***Assignment bonus***: implement MGL to prevent phantom due to inserts

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Transaction Characteristics

- SQL allows users to specify the followings:
- ***Access model***
  - `READ ONLY` or `READ WRITE`
  - By `Connection.setReadOnly()` in JDBC
- ***Isolation level***
  - Trade anomalies for better tx concurrency
  - By `Connection.setTransactionIsolation()`

Isolation Levels

- Defined by the ANSI/ISO SQL standard

Isolation level	Dirty reads	Unrepeatable reads	Phantoms
`Read Uncommitted`	Maybe	Maybe	Maybe
`Read Committed`	No	Maybe	Maybe
`Repeatable Read`	No	No	Maybe
`Serializable`	No	No	No

- How to implement these using a locking protocol?

Isolation Levels

- Defined by the ANSI/ISO SQL standard

Isolation level	Dirty reads	Unrepeatable reads	Phantoms
`Read Uncommitted`	Maybe	Maybe	Maybe
`Read Committed`	No	Maybe	Maybe
`Repeatable Read`	No	No	Maybe
`Serializable`	No	No	No

Isolation level	Shared Lock	Predicate Lock
`Read Uncommitted`	No	No
`Read Committed`	Released early	No
`Repeatable Read`	Held to completion	No
`Serializable`	Held to completion	Held to completion

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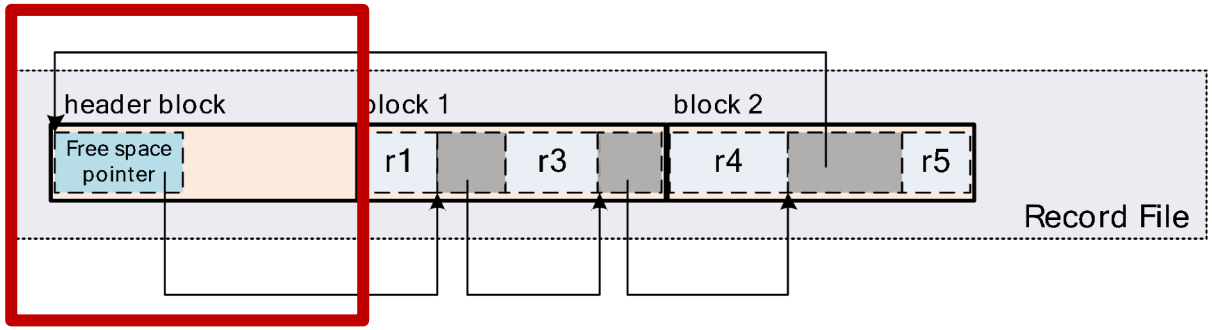
Meta-Structures

- DBMS maintains some ***meta-structures*** in addition to data perceived by users
  - E.g., `FileHeaderPage` in `RecordFile`



Concurrency Control of Access to Meta-Structures

- Access to `FileHeaderPage`?
  - Whenever insertions/deletions of records happen
- How to lock `FileHeaderPage`?
  - S2PL?
- S2PL will serialize all insertions and deletions
  - Hurts performance if we have many inserts/deletes

Early Lock Release

- Actually, lock of `FileHeaderPage` can be ***released early***
  - No "data" revealed; no hurt to I
- Locking steps for a (logical) insertion/deletion:
  - Acquire locks of `FileHeaderPage` and target object (`RecordPage` or a record) in order
  - Perform changes
  - ***Release*** the lock of `FileHeaderPage` (but not the object)
- Better concurrency for I
- No harm to C
- Needs special care to ensure A and D

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Concurrency Manager

- In `storage.tx.concurrency`
- Lock-based protocol
  - MGL granularities: file, block, and record
  - S2PL
  - Deadlock detection: time-limit
- Support txs at different isolation levels ***concurrently***
  - `Serializable`
  - `Repeatable Read`
  - `Read Committed`

Lock Modes in Practice (1/2)

- DBMS needs to support concurrent txs in ***different*** modes

Prevent phantoms due to inserts, but not updates

	Read rec	Modify/delete rec	Insert rec
SERIALIZABLE	IS lock on file and block S lock on record	IX lock on file and block X lock on record	X lock on file and block X lock on record
REPEATABLE READ	IS lock on file and block; release immediately S lock on record	IX lock on file and block X lock on record	X lock on file and block X lock on record

Read committed and avoid cascading abort

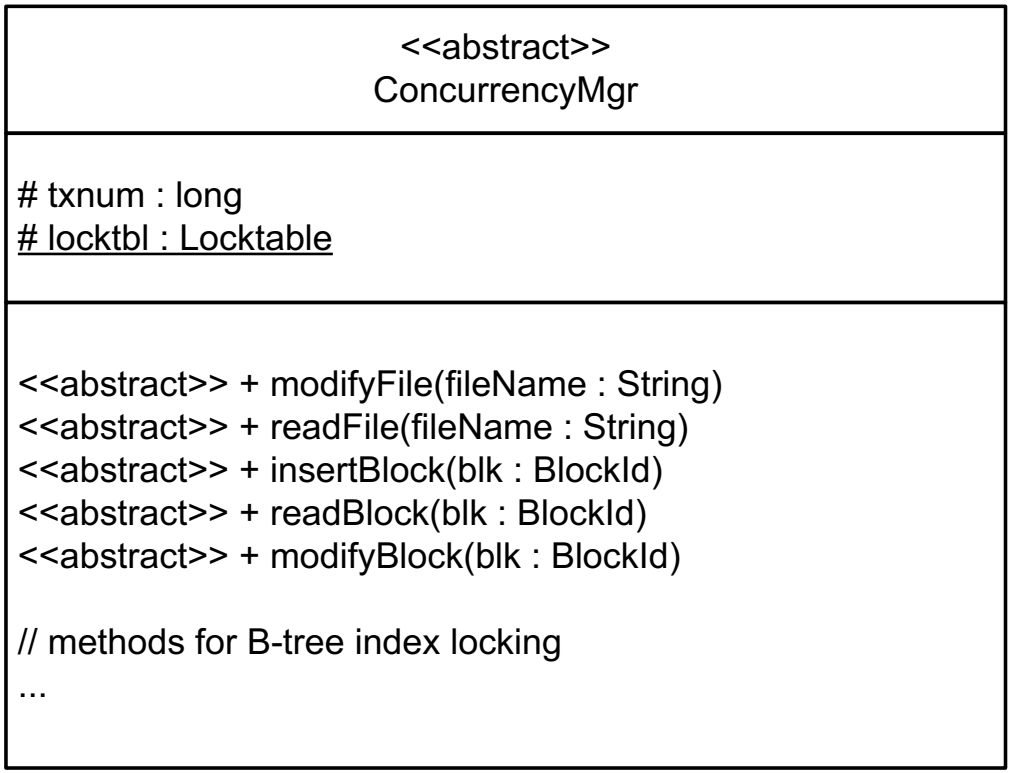
Lock Modes in Practice (1/2)

	Read rec	Modify/delete rec	Insert rec
`READ COMMITTED`	IS lock on file and block; release immediately	IX lock on file and block	X lock on file and block
	S lock on record and release it upon end statement	X lock on record	X lock on record

Allow non-repeatable reads

Concurrency Manager

- Decide what locks to obtain along the access path

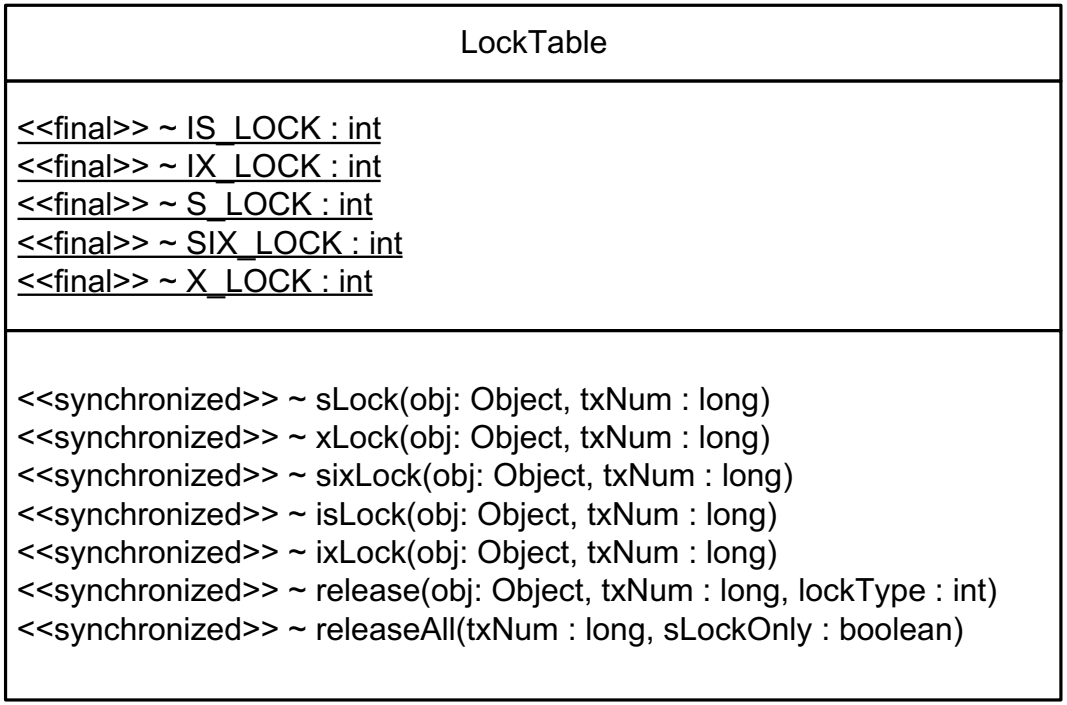


Concurrency Manager

- CCMgr for three isolation levels
  - `SerializableConcurrencyMgr`
  - `RepeatableRead1ConcurrencyMgr`
  - `ReadCommittedConcurrencyMgr`
- Every transaction has its own concurrency managers corresponding to the isolation level

Lock Table

- Implements the compatibility table
- Use time-limit strategy to resolve deadlock



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