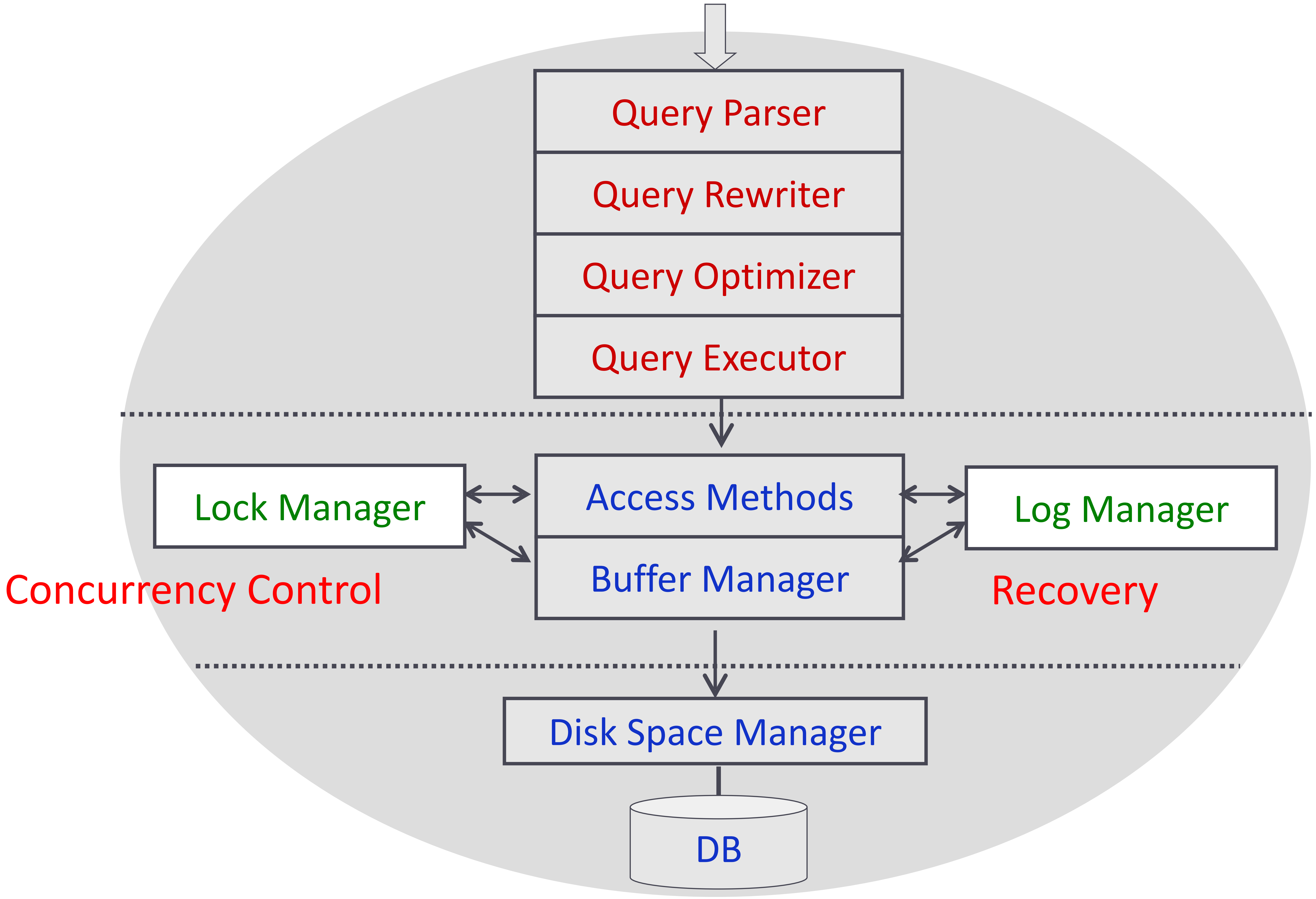
Database Design and Implementation

CS 645

Transactions and Concurrency

DBMS architecture



Who will get the tickets?

Solution?

- Don't allow multiple people / programs access the same data
  - Problem: things can get slow

- Concurrent execution
  - Good performance
  - But, we need to make sure that no "bad" things happen

Topic: How to allow concurrency

How to allow concurrency

1. Which schedules are OK?

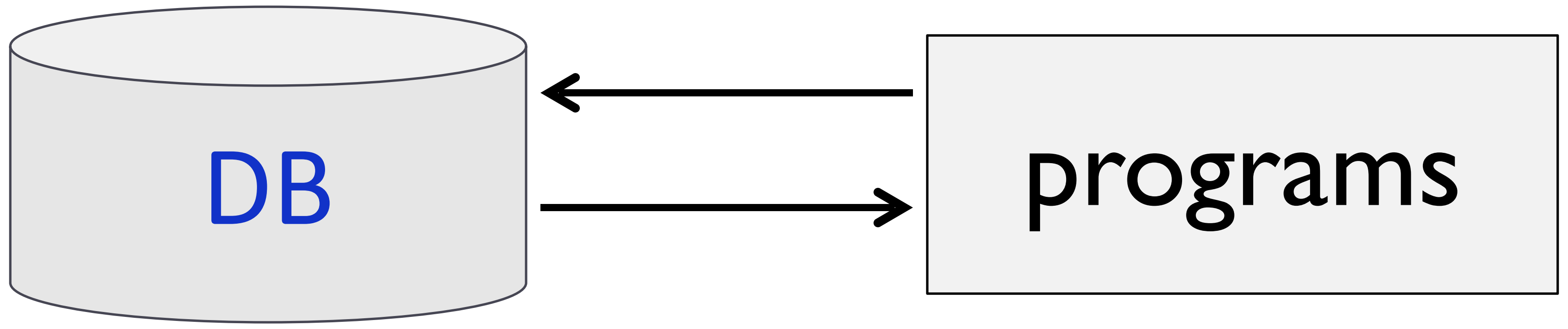
   Serializability
   Conflict-serializability
   View-serializability

2. How do we make sure we get OK schedules?

   Locking
   Optimistic concurrency control

Transactions

- User programs may do many things on the data retrieved.
  - E.g., operations on Bob's bank account.
  - E.g. transfer of money from account A to account B.
  - E.g., search for a ticket, think about it…, and buy it.
- But the DBMS is only concerned about what data is read from/written to the database.
- A *transaction* is DBMS's abstract view of a user program, simply, *a sequence of reads and writes*.



Principles

- Atomicity
  - Either all of the actions of a transaction are performed, or none at all
- Consistency
  - If each transaction leaves the database in a consistent state, concurrent transactions should result in a consistent state
- Isolation
  - A transaction cannot see the effects of other transactions
- Durability
  - If a transaction is successful, its effects persist

The problem

- Multiple transactions are running concurrently
  T1, T2, …
- They read/write some common elements
  A1, A2, …
- How can we prevent unwanted interference ?
- The SCHEDULER is responsible for that

Some famous anomalies

- What could go wrong if we didn't have concurrency control:
  - Dirty reads (including inconsistent reads)
  - Unrepeatable reads
  - Lost updates

Many other things can go wrong too

Dirty reads

Write-Read Conflict

T_1: WRITE(A)

T_1: ABORT

T_2: READ(A)

Inconsistent read

Write-Read Conflict

T_1: A := 20; B := 20;
T_1: WRITE(A)

T_1: WRITE(B)

T_2: READ(A);
T_2: READ(B);

Unrepeatable read

Read-Write Conflict

T_1: WRITE(A)

T_2: READ(A);

T_2: READ(A);

Lost update

Write-Write Conflict

T_1: READ(A)

T_1: A := A+5

T_1: WRITE(A)

T_2: READ(A);

T_2: A := A*1.3

T_2: WRITE(A);

Schedules

- Given multiple transactions
- A schedule is a sequence of interleaved actions from all transactions

Example

T1	T2
READ(A, t)	READ(A,s)
t := t+100	s := s*2
WRITE(A, t)	WRITE(A,s)
READ(B, t)	READ(B,s)
t := t+100	s := s*2
WRITE(B,t)	WRITE(B,s)

a serial schedule

T1	T2	A	B
READ(A, t)		25	25
t := t+100			
WRITE(A, t)		125	
READ(B, t)			
t := t+100			
WRITE(B,t)			125
	READ(A,s)		
	s := s*2		
	WRITE(A,s)	250	
	READ(B,s)		
	s := s*2		
	WRITE(B,s)		250

Serial schedule: (T1,T2)

a serial schedule

Serial schedule: (T2,T1)

T1	T2	A	B
	READ(A,s)	25	25
	s := s*2		
	WRITE(A,s)	50	
	READ(B,s)		
	s := s*2		
	WRITE(B,s)		50
READ(A, t)			
t := t+100			
WRITE(A, t)		150	
READ(B, t)			
t := t+100			
WRITE(B,t)			150

Serializable schedule

- A schedule is serializable if it is equivalent to a serial schedule

A schedule S is serializable, if there is a serial schedule S', such that for every initial database state, the effects of S and S' are the same

a serializable schedule

T1	T2	A	B
READ(A, t)		25	25
t := t+100			
WRITE(A, t)		125	
	READ(A,s)		
	s := s*2		
	WRITE(A,s)	250	
READ(B, t)			
t := t+100			
WRITE(B,t)			125
	READ(B,s)		
	s := s*2		
	WRITE(B,s)		250

Notice:
This is NOT a serial schedule

non-serializable schedule

T1	T2	A	B
READ(A, t)		25	25
t := t+100			
WRITE(A, t)		125	
	READ(A,s)		
	s := s*2		
	WRITE(A,s)	250	
	READ(B,s)		
	s := s*2		
	WRITE(B,s)		50
READ(B, t)			
t := t+100			
WRITE(B,t)			150

transaction semantics

T1	T2	A	B
READ(A, t)		25	25
t := t+100			
WRITE(A, t)		125	
	READ(A,s)		
	s := s+200		
	WRITE(A,s)	325	
	READ(B,s)		
	s := s+200		
	WRITE(B,s)		225
READ(B, t)			
t := t+100			
WRITE(B,t)			325

Is this serializable?

Ignoring details

- Serializability is undecidable!
- Scheduler should not look at transaction details
- Assume worst case updates
  - Only care about reads r(A) and writes w(A)
  - Not the actual values involved

Notation

actions

T_1: $r_1(A)$; $w_1(A)$; $r_1(B)$; $w_1(B)$
T_2: $r_2(A)$; $w_2(A)$; $r_2(B)$; $w_2(B)$

transaction

schedule

$r_1(A)$; $w_1(A)$; $r_2(A)$; $w_2(A)$; $r_1(B)$; $w_1(B)$; $r_2(B)$; $w_2(B)$

Conflict serializability

Conflicts:

Two actions by same transaction T_i: $r_i(X); w_i(Y)$

Two writes by T_i, T_j to same element: $w_i(X); w_j(X)$

Read/write by T_i, T_j to same element: $w_i(X); r_j(X)$

$r_i(X); w_j(X)$

Conflict serializability

- Two schedules are ***conflict equivalent*** if :
  - Involve the same actions of the same transactions.
  - Every pair of ***conflicting actions*** is ordered the same way.
- Schedule S is ***conflict serializable*** if S is conflict equivalent to some serial schedule.
- Given a set of xacts, conflict serializable schedules are a ***subset*** of serializable schedules.
  - There are serializable schedules that can't be detected using conflict serializability.

Conflict serializability

A schedule is conflict serializable if swapping adjacent non-conflicting actions leads to a serial schedule

$r_1(A)$	$w_1(A)$	$r_2(A)$	$w_2(A)$	$r_1(B)$	$w_1(B)$	$r_2(B)$	$w_2(B)$

The precedence graph test

Is a schedule conflict-serializable ?

Simple test:

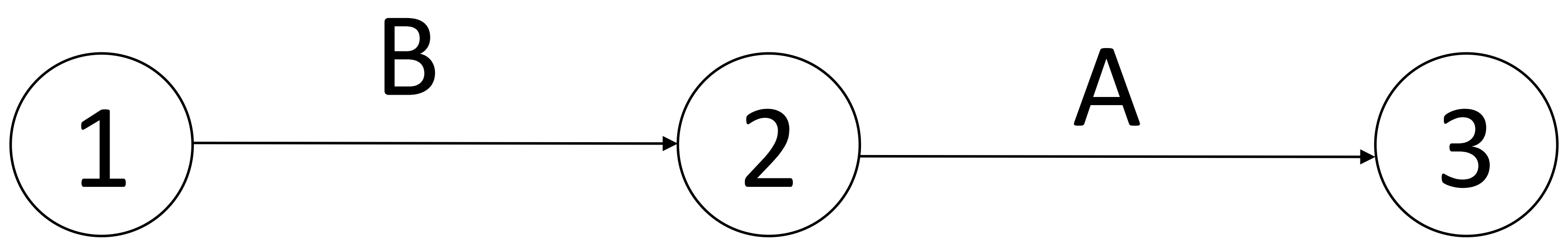
- Build a graph of all transactions T_i

- Edge from T_i to T_j if T_i makes an action that conflicts with one of T_j and comes first

- The test: if the graph has no cycles, then it is conflict serializable !

Example 1

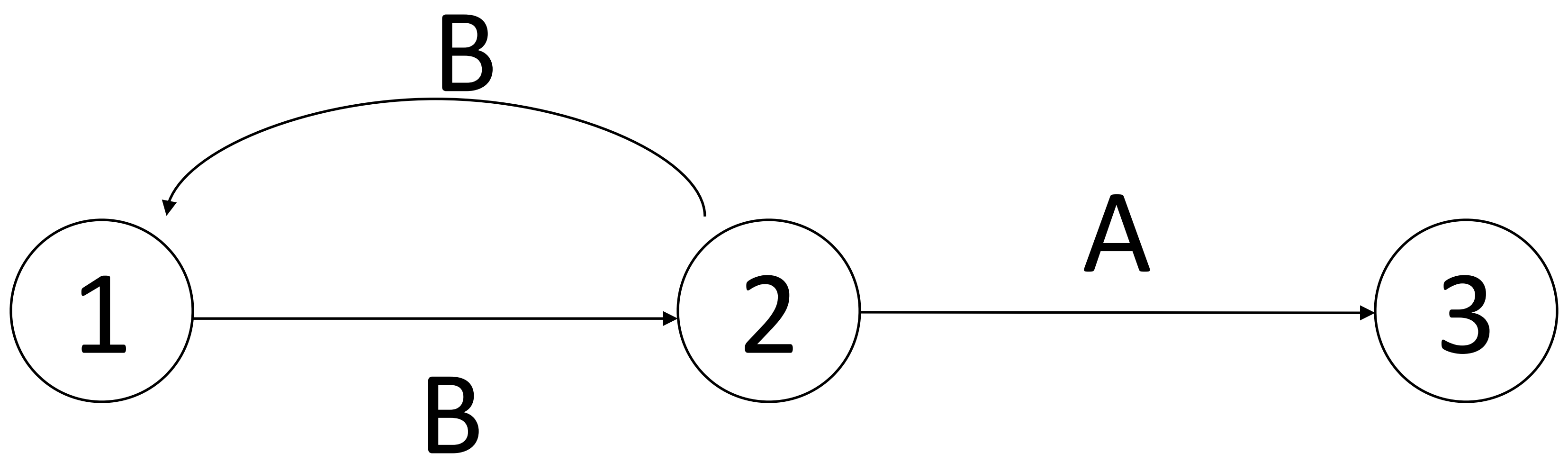
$$r_2(A);\ r_1(B);\ w_2(A);\ r_3(A);\ w_1(B);\ w_3(A);\ r_2(B);\ w_2(B)$$



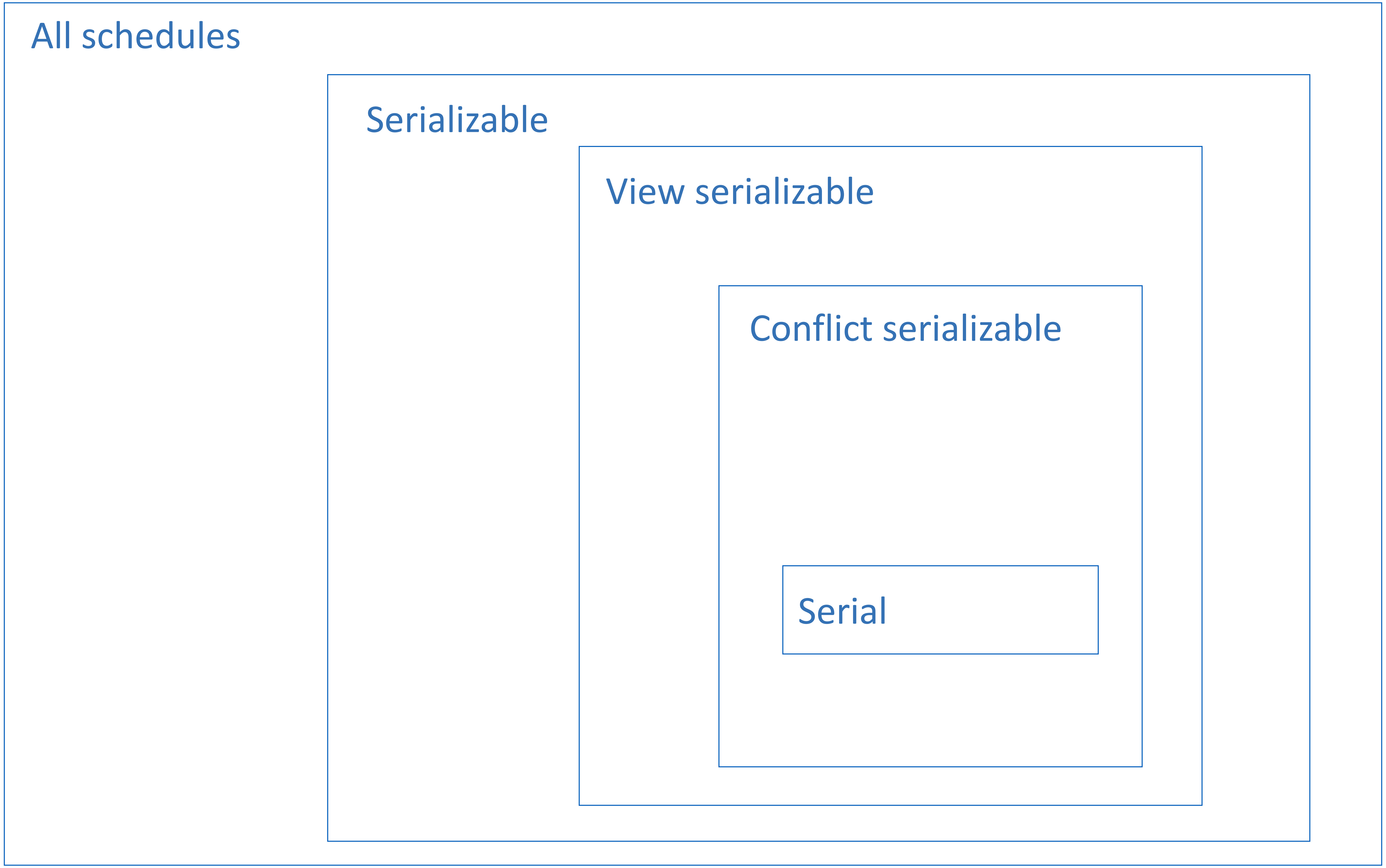
This schedule is conflict-serializable

Example 2

$$r_2(A);\ r_1(B);\ w_2(A);\ r_2(B);\ r_3(A);\ w_1(B);\ w_3(A);\ w_2(B)$$



This schedule is NOT conflict-serializable


All schedules
Serializable
View serializable
Conflict serializable
Serial

View serializability

- Schedules S1 and S2 are view equivalent if:
  - If Ti *reads initial value of A* in S1, then Ti also reads initial value of A in S2
  - If Ti *reads value of A written by* Tj in S1, then Ti also reads value of A written by Tj in S2
  - If Ti *writes final value of A* in S1, then Ti also writes final value of A in S2

```
T1: R(A)          W(A)
T2:       W(A)
T3:                     W(A)
```

```
T1: R(A),W(A)
T2:                 W(A)
T3:                       W(A)
```

View serializability (contd.)

- A schedule is *view serializable* if it is view equivalent to a serial schedule.
- Every conflict serializable schedule is view serializable.
  - The converse is not true.
- Every view serializable schedule that is not conflict serializable contains a *blind write*.

Lost write

$w_1(Y); w_2(Y); w_2(X); w_1(X); w_3(X);$

Equivalent, but can't swap

$w_1(Y); w_1(X); w_2(Y); w_2(X); w_3(X);$

Scheduler

- The scheduler is the module that schedules the transaction's actions, ensuring serializability
- How?
  - Locks
  - Time stamps
  - Validation

Locking scheduler

Simple idea:

- Each element has a unique lock
- Each transaction must first acquire the lock before reading/writing that element
- If the lock is taken by another transaction, then wait
- The transaction must release the lock(s)

Notation

$L_i(A)$ = transaction T_i acquires lock for element A

$U_i(A)$ = transaction T_i releases lock for element A

Example

T1	T2
L_1(A); READ(A, t)	
t := t+100	
WRITE(A, t); U_1(A); L_1(B)	
	L_2(A); READ(A,s)
	s := s*2
	WRITE(A,s); U_2(A);
	L_2(B); **DENIED…**
READ(B, t)	
t := t+100	
WRITE(B,t); U_1(B);	
	…**GRANTED;** READ(B,s)
	s := s*2
	WRITE(B,s); U_2(B);

Scheduler has ensured a conflict-serializable schedule

Example

T1	T2
$L_1(A)$; READ(A, t)	
t := t+100	
WRITE(A, t); $U_1(A)$;	
	$L_2(A)$; READ(A,s)
	s := s*2
	WRITE(A,s); $U_2(A)$;
	$L_2(B)$; READ(B,s)
	s := s*2
	WRITE(B,s); $U_2(B)$;
$L_1(B)$; READ(B, t)	
t := t+100	
WRITE(B,t); $U_1(B)$;	

Locks did not enforce conflict serializability!!

Two Phase Locking (2PL)

The 2PL rule:

- In every transaction, all lock requests must precede all unlock requests

- This ensures conflict serializability! (why?)

Example

T1	T2
$L_1(A)$; $L_1(B)$; READ(A, t)	
t := t+100	
WRITE(A, t); $U_1(A)$;	
	$L_2(A)$; READ(A,s)
	s := s*2
	WRITE(A,s);
	$L_2(B)$; **DENIED…**
READ(B, t)	
t := t+100	
WRITE(B,t); $U_1(B)$;	
	…**GRANTED;** READ(B,s)
	s := s*2
	WRITE(B,s); $U_2(A)$; $U_2(B)$;

Now it is conflict-serializable

Example with abort

T1	T2
$L_1(A)$; $L_1(B)$; READ(A, t)	
t := t+100	
WRITE(A, t); $U_1(A)$;	
	$L_2(A)$; READ(A,s)
	s := s*2
	WRITE(A,s);
	$L_2(B)$; **DENIED…**
READ(B, t)	
t := t+100	
WRITE(B,t); $U_1(B)$;	
	…**GRANTED;** READ(B,s)
	s := s*2
	WRITE(B,s); $U_2(A)$; $U_2(B)$;
ABORT	COMMIT

What about Aborts?

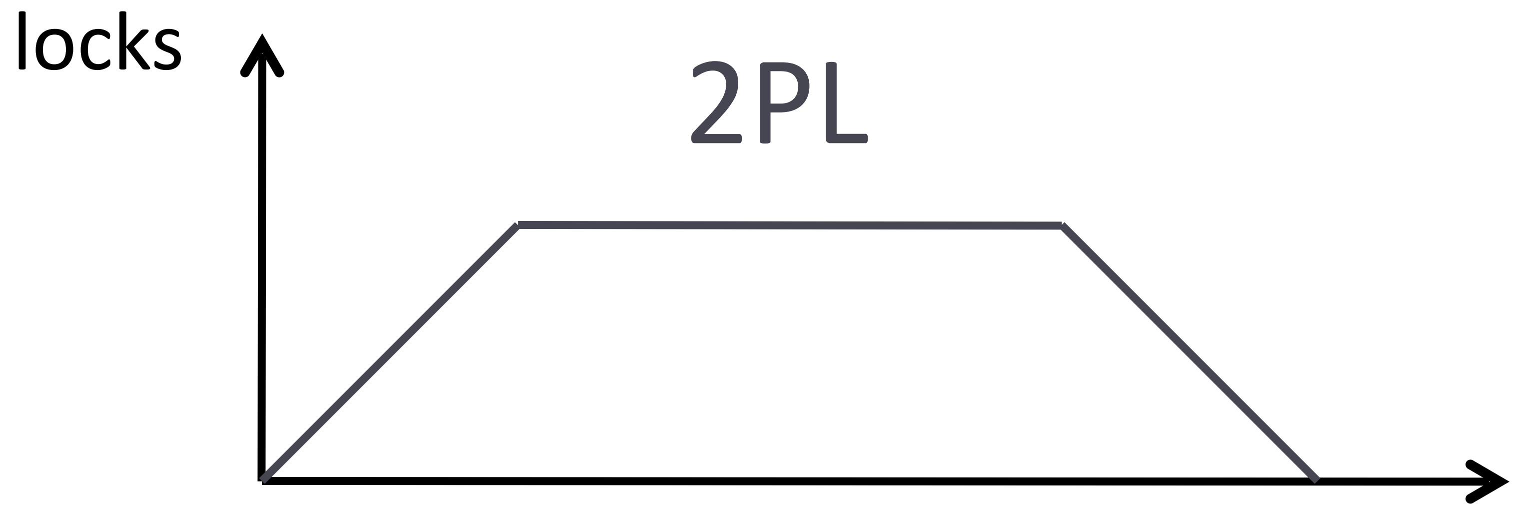
- 2PL enforces conflict-serializable schedules
- But what if a transaction releases its locks and then aborts?

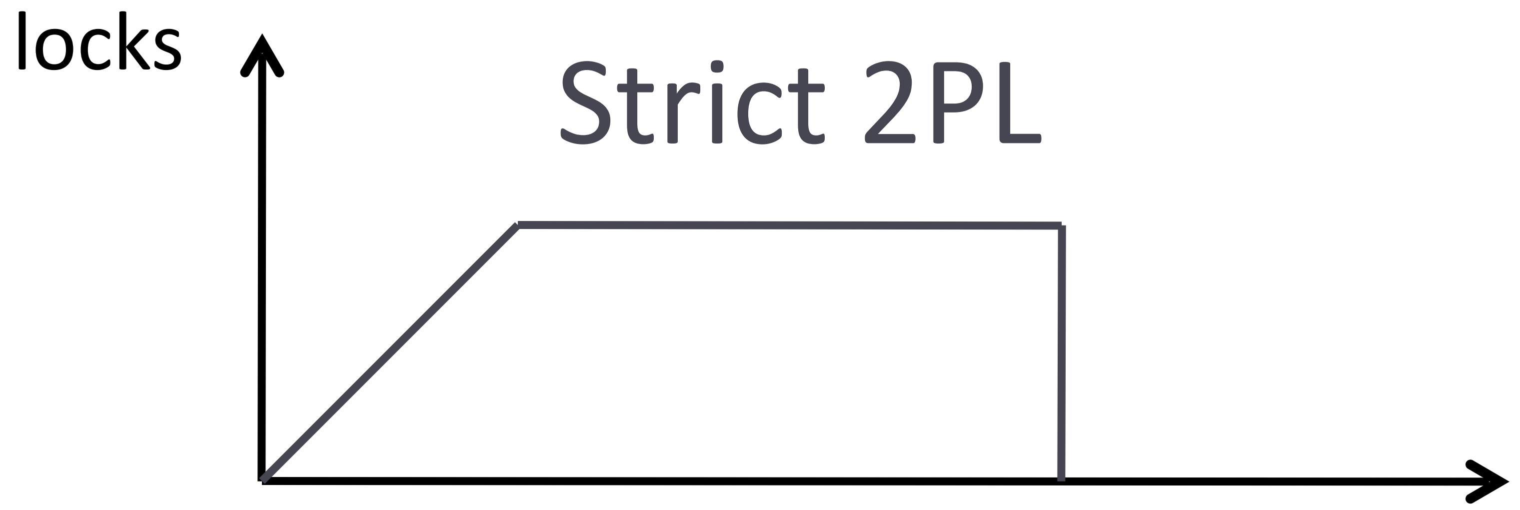
- Serializable schedule definition only considers transactions that commit
  - Relies on assumptions that aborted transactions can be undone completely

Strict 2PL

- Strict 2PL: All locks held by a transaction are released when the transaction is completed

- Ensures that schedules are recoverable
  - Transactions commit only after all transactions whose changes they read also commit
- Avoids cascading rollbacks





The locking scheduler

Task 1:
Add lock/unlock requests to transactions

- Examine all READ(A) or WRITE(A) actions
- Add appropriate lock requests
- Ensure 2PL !

The locking scheduler

Task 2:
Execute the locks accordingly

- Lock table: a big, critical data structure in a DBMS !
- When a lock is requested, check the lock table
  - Grant, or add the transaction to the element's wait list
- When a lock is released, re-activate a transaction from its wait list
- When a transaction aborts, release all its locks
- Check for deadlocks occasionally

Deadlock

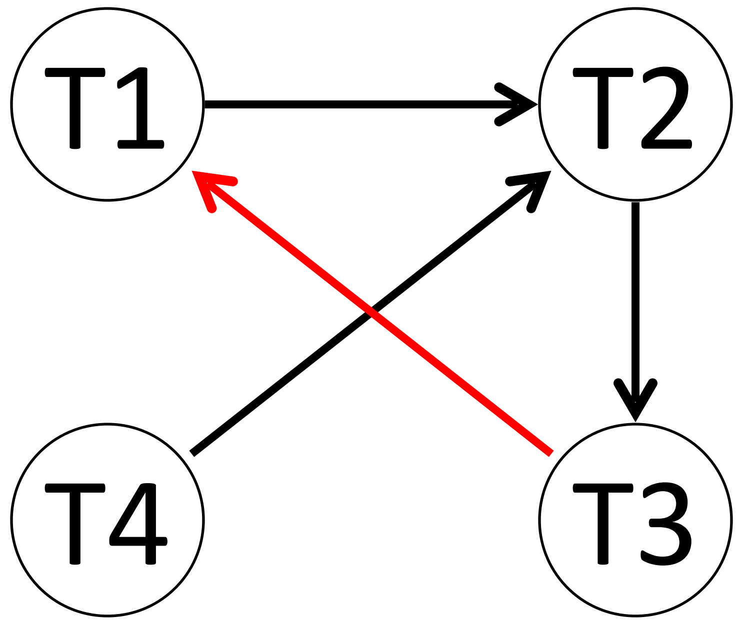
- Transaction T1 waits for a lock held by T2;
- But T2 waits for a lock held by T3;
- While T3 waits for . . . .
- . . .
- . . .and T73 waits for a lock held by T1 !!

- Could be avoided, by ordering all elements, or deadlock detection + rollback

Deadlock: example

T1	T2	T3	T4
L(A)			
R(A)			
	L(B)		
	W(B)		
L(B)			
		L(C)	
		R(C)	
	L(C)		
			L(B)
		L(A)	

Waits-for graph



Deadlock!

Most systems do deadlock detection

Deadlock prevention

T_i requests a lock conflicting with T_j

- Wait-die:
  - If T_i has higher priority, it waits; otherwise it is aborted
- Wound-wait:
  - If T_i has higher priority, abort T_j; otherwise T_i waits

Conservative 2PL

- Acquire all locks at the beginning

Types of locks

- Intuition: it's ok for many Xacts to read the same element.

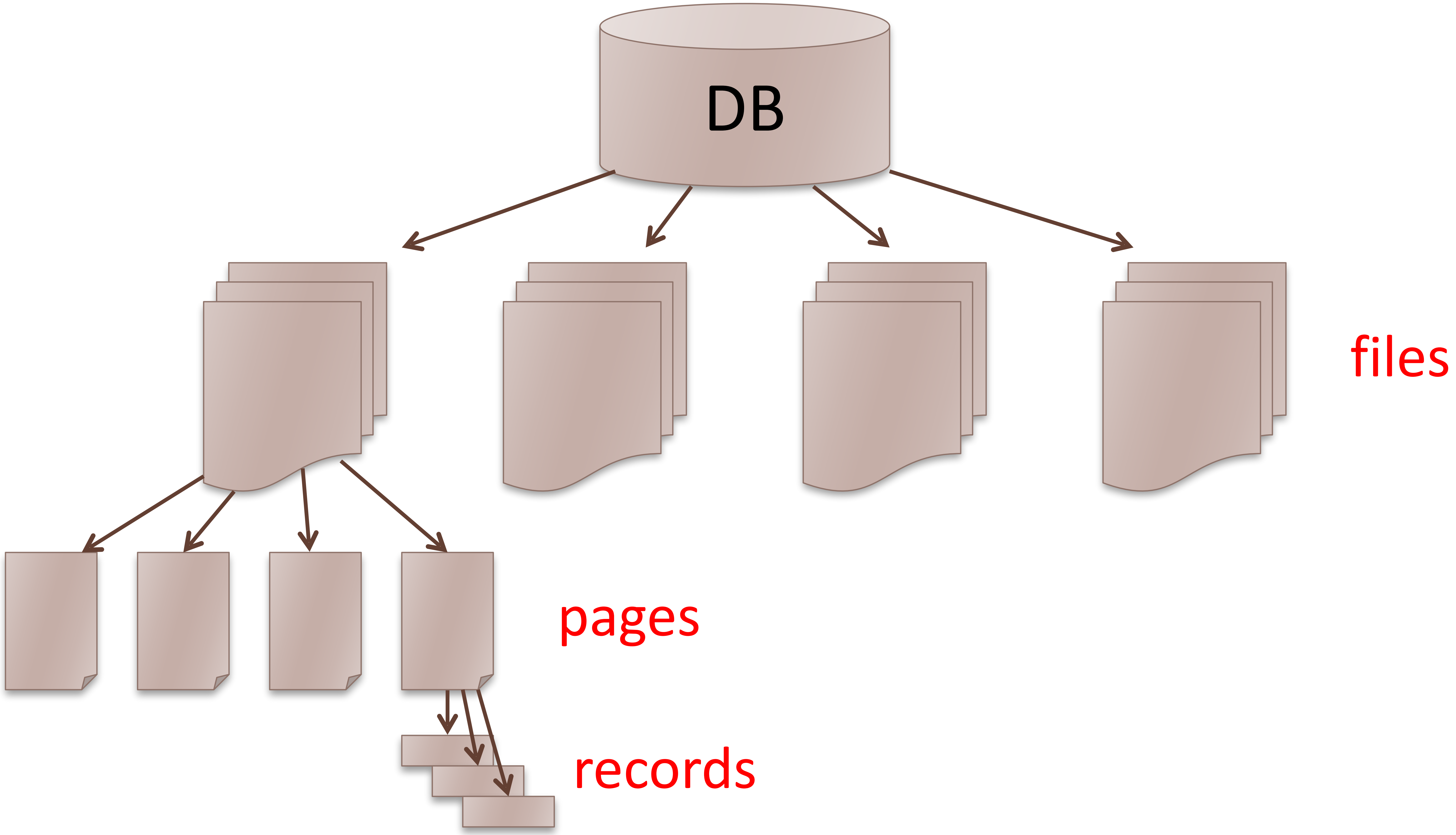
- Shared lock (S) – for reads
- Exclusive lock (X) – for writes

- Update lock (U) – initially S, possibly later upgrade to X

Mode	X	S	U
X	No	No	No
S	No	Yes	Yes
U	No	Yes	No

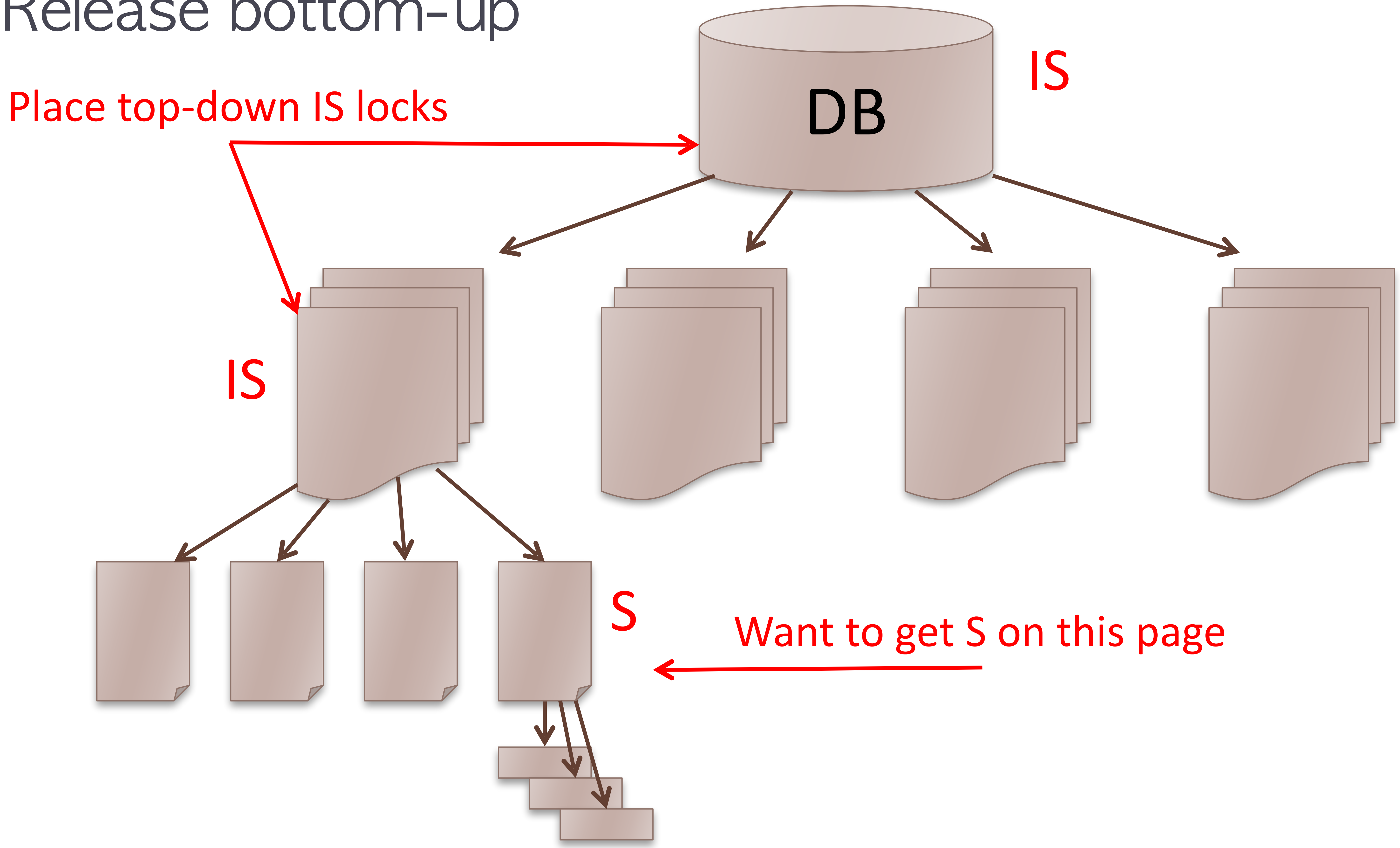
Granularity of locks

- Multiple Granularity Locking
  - Allows locking of different size objects (files, pages, records)



Granularity of locks

- Intention Locks: IS, IX, SIX
  - Lock with appropriate intention locks top down.
  - Release bottom-up



Granularity of locks

Mode	IS	IX	S	SIX	X
IS	Yes	Yes	Yes	Yes	No
IX	Yes	Yes	No	No	No
S	Yes	No	Yes	No	No
SIX	Yes	No	No	No	No
X	No	No	No	No	No

The phantom problem

- We've been looking at updates
  - What about insertions/deletions?

```
T1:
   select count(*) from R where price>20
   . . . .
   . . . .
   . . . .
   . . . .
   select count(*) from R where price>20
```

```
T2:
   . . . .
   . . . .
   insert into R(name,price)
          values('Gizmo', 50)
    . . . .
```

Aha! Phantom tuple!

Solutions:

- Coarse locks (table level)
- Predicate locking (index locking)

Beyond locking

- Optimistic Concurrency Control

- Intuition:
  - There is overhead in locking, so if we don't expect many conflicts, we can sort of "wing it" and hope for the best ☺

Timestamps

- Each transaction receives a unique timestamp TS(T)

- Could be:
  - The system's clock
  - A unique counter, incremented by the scheduler

Timestamps

Main invariant:

The timestamp order defines the serialization order of the transaction

Main idea

- For any two conflicting actions, ensure that their order is the serialized order:
- In each of these cases
  - $W_{T1}(X) \ldots R_{T2}(X)$
  - $R_{T1}(X) \ldots W_{T2}(X)$
  - $W_{T1}(X) \ldots W_{T2}(X)$

Possible conflicts

- Answer: Check that $TS(T1) < TS(T2)$

When T2 wants to read X, $r_{T2}(X)$, how do we know T1, and TS(T1) ?

Timestamps

With each element X, associate:

- RT(X) = the highest timestamp of any transaction that read X
- WT(X) = the highest timestamp of any transaction that wrote X
- C(X) = the commit bit: true when transaction with highest timestamp that wrote X committed

If 1 element = 1 page, these are associated with each page X in the buffer pool

Time-based scheduling

Note: simple version that ignores the commit bit

- Transaction wants to read element X
  - If TS(T) < WT(X) abort
  - Else read and update RT(X) to larger of TS(T) or RT(X)
- Transaction wants to write element X
  - If TS(T) < RT(X) abort
  - Else if TS(T) < WT(X) ignore write & continue (Thomas Write Rule)
  - Otherwise, write X and update WT(X) to TS(T)

Details

Read too late:

- T1 wants to read X, and $TS(T1) < WT(X)$

START(T1) … START(T2) … $W_{T2}(X)$ . . . $R_{T1}(X)$

Need to rollback T1!

Details

Write too late:

- T1 wants to write X, and $TS(T1) < RT(X)$

START(T1) … START(T2) … $R_{T2}(X)$ . . . $W_{T1}(X)$

Need to rollback T1!

Details

Write too late, but we can still handle it:

- T1 wants to write X, and
  $TS(T1) \geq RT(X)$ but $WT(X) > TS(T1)$

START(T1) … START(T2) … $W_{T2}(X)$ . . . $W_{T1}(X)$

Don't write X at all!

More problems

Read dirty data:

- T2 wants to read X, and $WT(X) < TS(T2)$
- Seems OK, but…

START(T1) … START(T2) … $W_{T1}(X)$. . . $R_{T2}(X)$… ABORT(T1)

If C(X)=false, T2 needs to wait for it to become true

More problems

Write dirty data:

- T1 wants to write X, and $WT(X) > TS(T1)$
- Seems OK <u>not</u> to write at all, but …

START(T1) … START(T2) … $W_{T2}(X)$. . . $W_{T1}(X)$… ABORT(T2)

If C(X)=false, T1 needs to wait for it to become true

Timestamp-based scheduling

- When a transaction T requests R(X) or W(X), the scheduler examines RT(X), WT(X), C(X), and decides one of:
  - To grant the request, or
  - To rollback T (and restart) ⟵ With what timestamp?
  - To delay T until C(X) = true

Tradeoffs

- Locks:
  - Great when there are many conflicts
  - Poor when there are few conflicts
- Timestamps
  - Poor when there are many conflicts (rollbacks)
  - Great when there are few conflicts

- Compromise
  - READ ONLY transactions → timestamps
  - READ/WRITE transactions → locks

Concurrency Control by Validation

Kung-Robinson Model

- Each transaction T defines a read set RS(T) and a write set WS(T)
- Each transaction proceeds in three phases:
  - Read all elements in RS(T). Time = START(T)
  - Validate (may need to rollback). Time = VAL(T)
  - Write all elements in WS(T). Time = FIN(T)

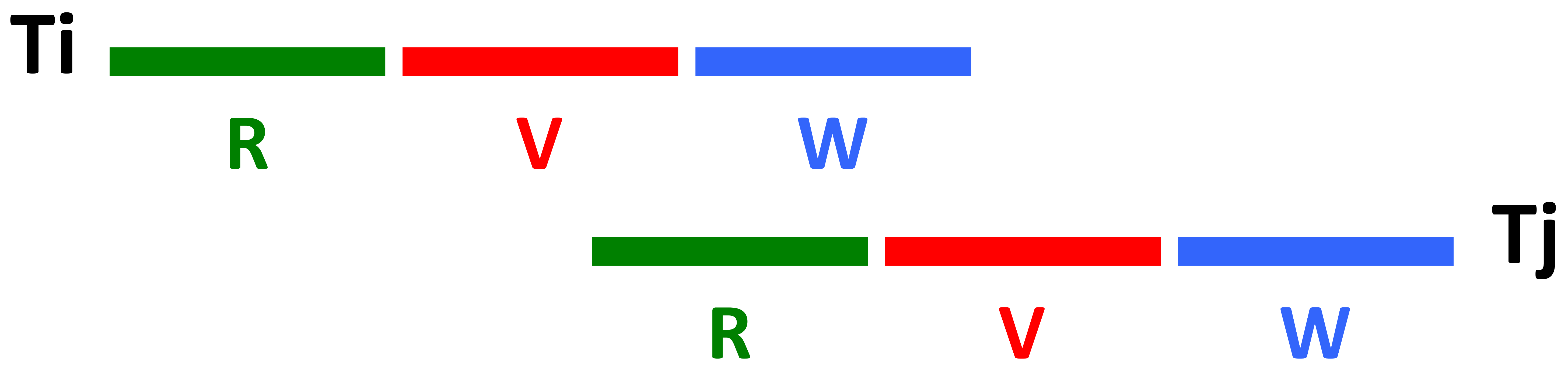
Main invariant: the serialization order is VAL(T)

Test 1

- For all i and j such that Ti < Tj, check that Ti completes before Tj begins.

If Test 1 fails, try Test 2…

- For all i and j such that Ti ＜ Tj, check that:
  - Ti completes before Tj begins its Write phase, and
  - WriteSet(Ti) ∩ ReadSet(Tj) is empty.

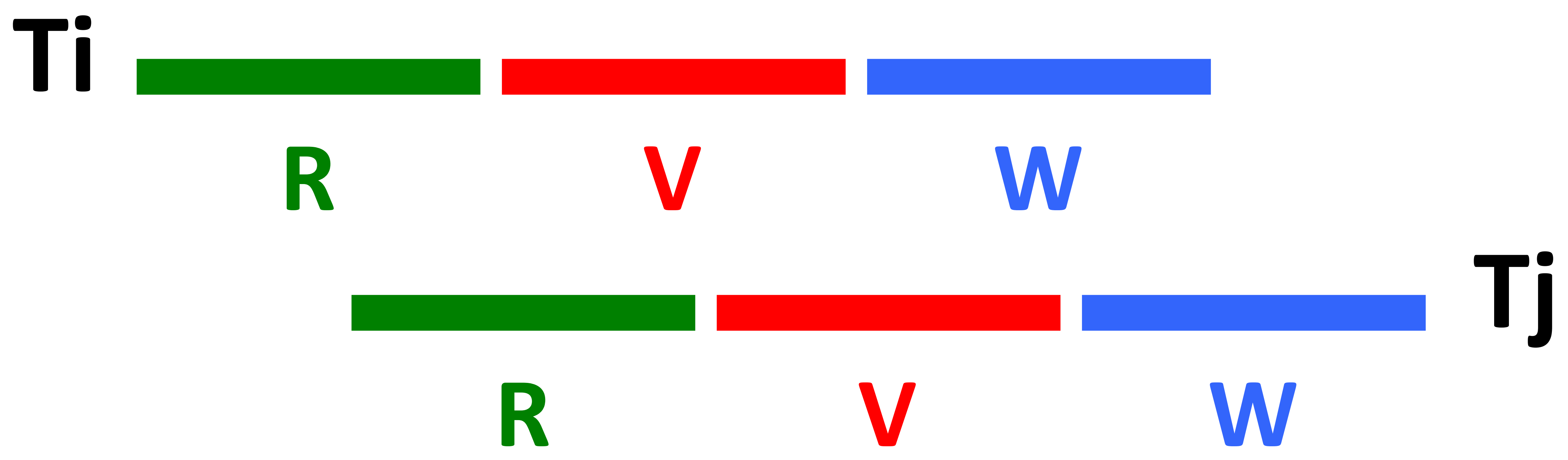


Does Tj read dirty data? Does Tj overwrite Ti's writes?

❖ Check correctness: all three types of conflicts, W-R, R-W, W-W, if present, go one way only.

If Test 2 fails, try Test 3

- For all i and j such that Ti < Tj, check that:
  - Ti completes Read phase before Tj does, and
  - WriteSet(Ti) ∩ ReadSet(Tj) is empty, and
  - WriteSet(Ti) ∩ WriteSet(Tj) is empty.



Does Tj read dirty data? Does Tj overwrite Ti's writes?

- Why is it correct?

Comments on Optimistic CC

- Compared to Locking
  - Optimistic CC: assumes no conflicts first, only fixes problems when conflicts appear, by *restarting* xacts.
  - Locking (pessimistic): conflicts are prevented in advance, by *blocking* from (potentially) nonserializable actions.
- Works well for some workloads:
  - All xacts are readers.
  - Low interference, e.g. large amount of data, each xact accessing a small (likely non-overlapping) amount of data.
- Deadlock free, but may have starvation.
- No phantom problem!

Overheads in Optimistic CC

- Record read/write activity in ReadSet/WriteSet per Xact.
  - Must create and destroy these sets as needed.
- Check for conflicts during validation
  - Code for validation is in a critical section, and critical section can reduce concurrency.
- Make validated writes "global".
  - Scheme for making writes global can reduce clustering of objects. Sequential I/O is unlikely later.
- Restart Xacts that fail validation.
  - Work done so far is wasted; requires clean-up.
  - Starvation may occur.