Concurrency Control

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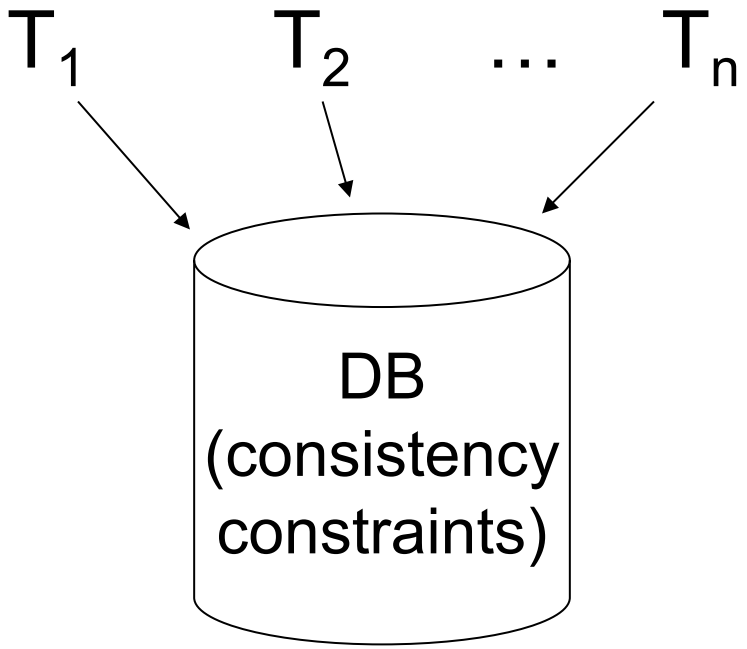
The Problem



Different transactions may need to access data items at the same time, violating constraints

The Problem

Even if each transaction maintains constraints by itself, interleaving their actions does not

Could try to run just one transaction at a time (**serial schedule**), but this has problems

- » **Too slow!** Especially with external clients & IO

High-Level Approach

Define **isolation levels**: sets of guarantees about what transactions may experience

Strongest level: **serializability** (result is same as some serial schedule)

Many others possible: **snapshot isolation**, **read committed**, **read uncommitted**, …

Outline

What makes a schedule serializable?

Conflict serializability

Precedence graphs

Enforcing serializability via 2-phase locking
- » Shared and exclusive locks
- » Lock tables and multi-level locking

Optimistic concurrency with validation

Example

T_1: Read(A)
$A \leftarrow A+100$
Write(A)
Read(B)
$B \leftarrow B+100$
Write(B)

T_2: Read(A)
$A \leftarrow A\times 2$
Write(A)
Read(B)
$B \leftarrow B\times 2$
Write(B)

Constraint: $A=B$

Schedule C

T_1	T_2	A	B
		25	25
Read(A); $A \leftarrow A+100$			
Write(A);		125	
	Read(A); $A \leftarrow A \times 2$;		
	Write(A);	250	
Read(B); $B \leftarrow B+100$;			
Write(B);			125
	Read(B); $B \leftarrow B \times 2$;		
	Write(B);		250
		250	250

Schedule D

T_1	T_2	A	B
		25	25
Read(A); A $\leftarrow$ A+100			
Write(A);		125	
	Read(A); A $\leftarrow$ A$\times$2;		
	Write(A);	250	
	Read(B); B $\leftarrow$ B$\times$2;		
	Write(B);		50
Read(B); B $\leftarrow$ B+100;			
Write(B);			150
		250	150

Our Goal

Want schedules that are “good”, regardless of

» initial state and

» transaction semantics

We don’t know the logic in external client apps!

Only look at **order of read & write operations**

Example:

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

Example:

$$S_C = r_1(A)w_1(A)\underbrace{r_2(A)w_2(A)}\underbrace{r_1(B)w_1(B)}r_2(B)w_2(B)$$

$$S_C' = \underbrace{r_1(A)w_1(A)r_1(B)w_1(B)}_{T_1}\underbrace{r_2(A)w_2(A)r_2(B)w_2(B)}_{T_2}$$

However, for S_D:

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

Another way to view this:

» $r_1(B)$ after $w_2(B)$ means T_1 should be after T_2 in an equivalent serial schedule ($T_2 \rightarrow T_1$)

» $r_2(A)$ after $w_1(A)$ means T_2 should be after T_1 in an equivalent serial schedule ($T_1 \rightarrow T_2$)

» Can't have both of these!

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Concepts

Transaction: sequence of $r_i(x)$, $w_i(x)$ actions

Schedule: a chronological order in which all the transactions' actions are executed

Conflicting actions:

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

pairs of actions that would change the result of a read or write if swapped

Question

Is it OK to model reads & writes as occurring at a single point in time in a schedule?

$S = \ldots\ r_1(x)\ \ldots\ w_2(b)\ \ldots$

Question

What about conflicting, concurrent actions on same object?

Assume “atomic actions” that only occur at one point in time (e.g. implement using locking)

Definition

Schedules S_1, S_2 are **conflict equivalent** if S_1 can be transformed into S_2 by a series of **swaps** of non-conflicting actions

(i.e., can reorder non-conflicting operations in S_1 to obtain S_2)

Definition

A schedule is **conflict serializable** if it is conflict equivalent to some serial schedule

Key idea:

» Conflicts "change" result of reads and writes

» Conflict serializable implies that there exists at least one equivalent serial execution with the same effects

How can we compute whether a schedule is conflict serializable?

Outline

What makes a schedule serializable?

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Precedence Graph P(S)

Nodes: transactions in a schedule S

Edges: $T_i \rightarrow T_j$ whenever

» $p_i(A)$, $q_j(A)$ are actions in S

» $p_i(A) <_S q_j(A)$ (occurs earlier in schedule)

» at least one of p_i, q_j is a write (i.e. $p_i(A)$ and $q_j(A)$ are conflicting actions)

Exercise

What is P(S) for

$S = w_3(A)\ w_2(C)\ r_1(A)\ w_1(B)\ r_1(C)\ w_2(A)\ r_4(A)\ w_4(D)$

Is S serializable?

Another Exercise

What is P(S) for

$S = w_1(A)\ r_2(A)\ r_3(A)\ w_4(A)$

Lemma

S_1, S_2 conflict equivalent $\Rightarrow P(S_1) = P(S_2)$

Lemma

S_1, S_2 conflict equivalent $\Rightarrow P(S_1) = P(S_2)$

Proof:

Assume $P(S_1) \neq P(S_2)$

$\Rightarrow \exists\ T_i$: $T_i \rightarrow T_j$ in S_1 and not in S_2

$\Rightarrow S_1 = \ldots p_i(A) \ldots\ q_j(A) \ldots$

$\quad S_2 = \ldots q_j(A) \ldots\ p_i(A) \ldots$

$\Big\}$ p_i, q_j conflict

$\Rightarrow S_1$, S_2 not conflict equivalent

Note: $P(S_1) = P(S_2) \not\Rightarrow S_1, S_2$ conflict equivalent

Note: $P(S_1) = P(S_2) \not\Rightarrow S_1, S_2$ conflict equivalent

Counter example:

$S_1 = w_1(A)\ r_2(A)\ w_2(B)\ r_1(B)$

$S_2 = r_2(A)\ w_1(A)\ r_1(B)\ w_2(B)$

Theorem

$P(S_1)$ acyclic $\Longleftrightarrow$ S_1 conflict serializable

($\Leftarrow$) Assume S_1 is conflict serializable

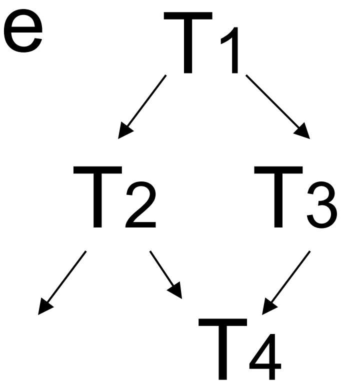
$\Rightarrow$ $\exists$ S_s (serial): S_s, S_1 conflict equivalent

$\Rightarrow$ $P(S_s) = P(S_1)$ (by previous lemma)

$\Rightarrow$ $P(S_1)$ acyclic since $P(S_s)$ is acyclic

Theorem

$P(S_1)$ acyclic $\Longleftrightarrow$ S_1 conflict serializable



($\Rightarrow$) Assume $P(S_1)$ is acyclic

Transform S_1 as follows:

(1) Take T_1 to be transaction with no inbound edges

(2) Move all T_1 actions to the front

$$S_1 = \ldots\ldots\ q_j(A) \ldots\ldots p_1(A) \ldots..$$

(3) we now have S_1 = <T_1 actions><... rest ...>

(4) repeat above steps to serialize rest!

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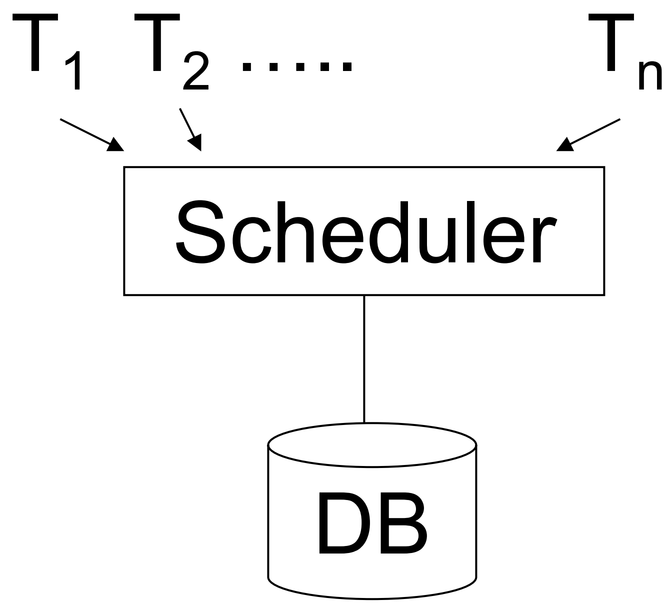
How to Enforce Serializable Schedules?

Option 1: run system, recording P(S); at end of day, check for cycles in P(S) and declare whether execution was good

How to Enforce Serializable Schedules?

Option 2: prevent P(S) cycles from occurring

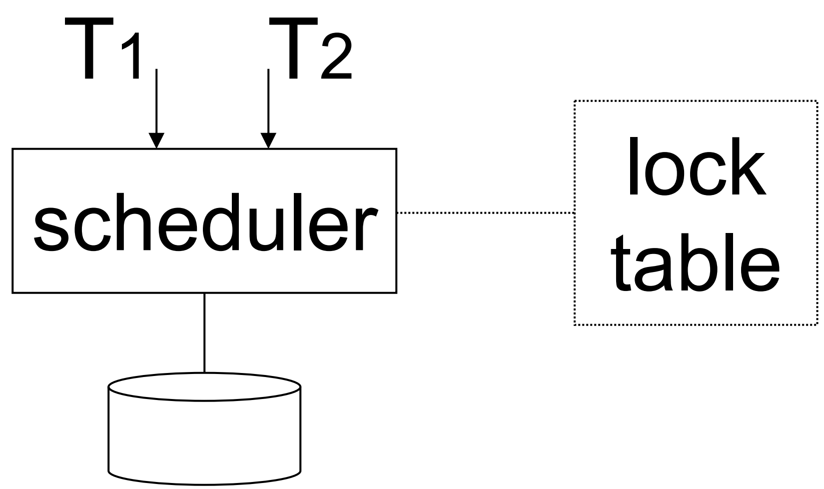


A Locking Protocol

Two new actions:

lock: $l_i(A)$ ← Transaction i locks object A

unlock: $u_i(A)$



Rule #1: Well-Formed Transactions

Ti: … $l_i(A)$ … $r_i(A)$ … $u_i(A)$ ...

Transactions can only operate on locked items

Rule #2: Legal Scheduler

$S = \ldots\ldots\ldots\ l_i(A)\ \ldots\ldots\ldots\ldots\ u_i(A)\ \ldots\ldots\ldots$

$\longleftrightarrow$

no $l_j(A)$

Only one transaction can lock item at a time

Exercise

Which transactions are well-formed?
Which schedules are legal?

$S_1 = l_1(A)\ l_1(B)\ r_1(A)\ w_1(B)\ l_2(B)\ u_1(A)\ u_1(B)$
$r_2(B)\ w_2(B)\ u_2(B)\ l_3(B)\ r_3(B)\ u_3(B)$

$S_2 = l_1(A)\ r_1(A)\ w_1(B)\ u_1(A)\ u_1(B)\ l_2(B)\ r_2(B)$
$w_2(B)\ l_3(B)\ r_3(B)\ u_3(B)$

$S_3 = l_1(A)\ r_1(A)\ u_1(A)\ l_1(B)\ w_1(B)\ u_1(B)\ l_2(B)$
$r_2(B)\ w_2(B)\ u_2(B)\ l_3(B)\ r_3(B)\ u_3(B)$

Exercise

Which transactions are well-formed?
Which schedules are legal?

$S_1 = l_1(A)\ l_1(B)\ r_1(A)\ w_1(B)\ l_2(B)\ u_1(A)\ u_1(B)$
$r_2(B)\ w_2(B)\ u_2(B)\ l_3(B)\ r_3(B)\ u_3(B)$

$S_2 = l_1(A)\ r_1(A)\ w_1(B)\ u_1(A)\ u_1(B)\ l_2(B)\ r_2(B)$
$w_2(B)\ l_3(B)\ r_3(B)\ u_3(B)$ $u_2(B)$ missing

$S_3 = l_1(A)\ r_1(A)\ u_1(A)\ l_1(B)\ w_1(B)\ u_1(B)$
$l_2(B)\ r_2(B)\ w_2(B)\ u_2(B)\ l_3(B)\ r_3(B)\ u_3(B)$

Schedule F

T1	T2	A	B
		25	25
$l_1(A)$;Read(A)			
$A \leftarrow A+100$;Write(A);$u_1(A)$		125	
	$l_2(A)$;Read(A)		
	$A \leftarrow A \times 2$;Write(A);$u_2(A)$	250	
	$l_2(B)$;Read(B)		
	$B \leftarrow B \times 2$;Write(B);$u_2(B)$		50
$l_1(B)$;Read(B)			
$B \leftarrow B+100$;Write(B);$u_1(B)$			150
		250	150

Rule #3: 2-Phase Locking (2PL)

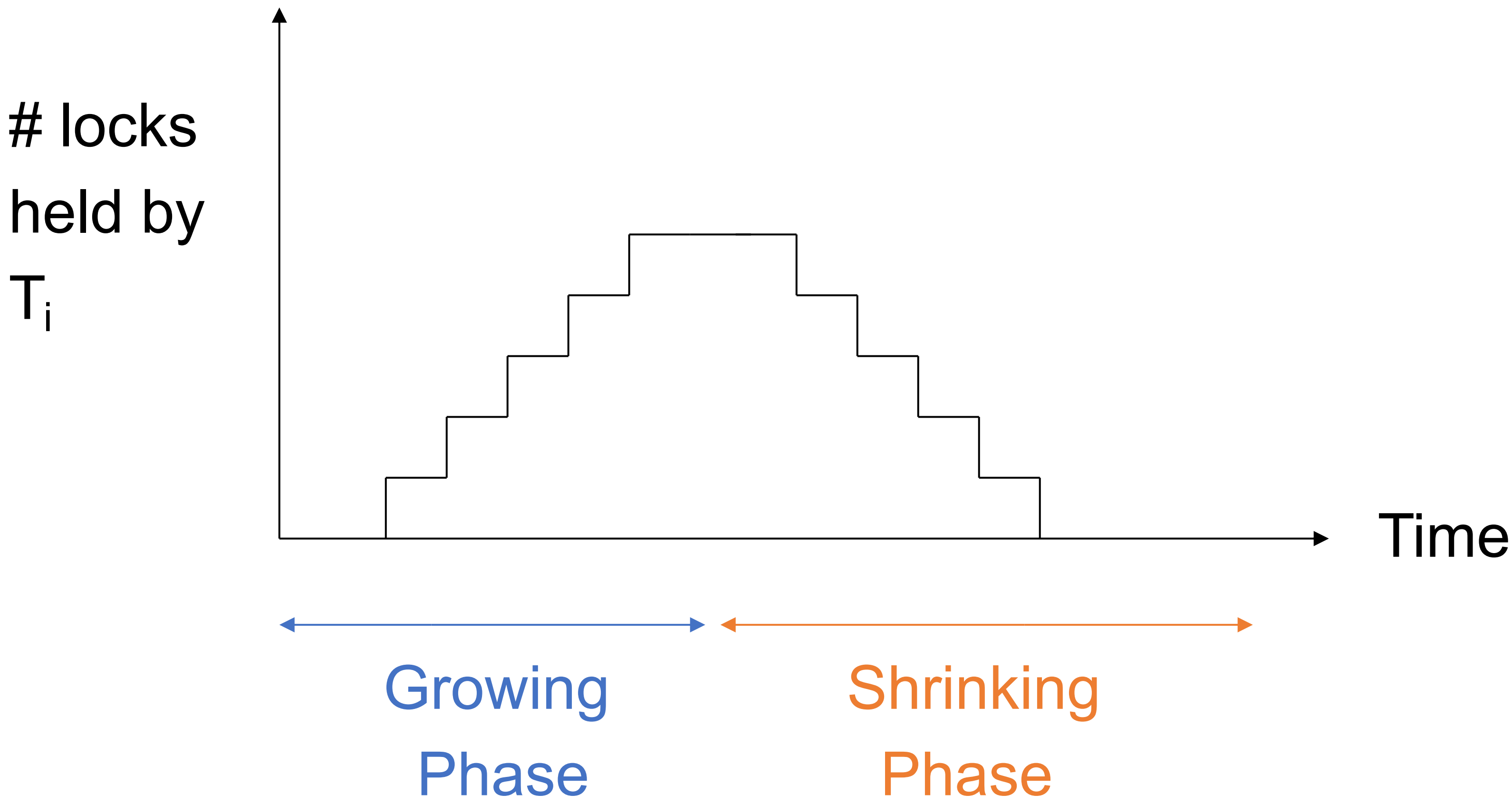
T_i = ……. $l_i(A)$ ………….. $u_i(A)$ ………

no unlocks

no locks

Transactions must first lock all items they need, then unlock them

2-Phase Locking (2PL)



Schedule G

T1	T2
$l_1(A)$;Read(A)	
$A \leftarrow A+100$;Write(A)	
$l_1(B);u_1(A)$	

Schedule G

T1	T2
$l_1(A)$;Read(A)	
$A \leftarrow A+100$;Write(A)	
$l_1(B)$;$u_1(A)$	
	$l_2(A)$;Read(A)
	$A \leftarrow A \times 2$;Write(A)
	$l_2(B)$ $\longleftarrow$ delayed

Schedule G

T1	T2
$l_1(A)$;Read(A)	
$A \leftarrow A+100$;Write(A)	
$l_1(B)$;$u_1(A)$	
	$l_2(A)$;Read(A)
	$A \leftarrow A \times 2$;Write(A)
	$l_2(B)$ $\leftarrow$ delayed
Read(B);$B \leftarrow B+100$	
Write(B);$u_1(B)$	

Schedule G

T1	T2
$l_1(A)$;Read(A)	
$A \leftarrow A+100$;Write(A)	
$l_1(B)$;$u_1(A)$	
	$l_2(A)$;Read(A)
	$A \leftarrow A \times 2$;Write(A)
	$l_2(B)$ ← delayed
Read(B);$B \leftarrow B+100$	
Write(B);$u_1(B)$	
	$l_2(B)$;$u_2(A)$;Read(B)
	$B \leftarrow B \times 2$;Write(B);$u_2(B)$

Schedule H (T2 Ops Reversed)

T1	T2
$l_1(A)$; Read(A)	$l_2(B)$; Read(B)
$A \leftarrow A+100$; Write(A)	$B \leftarrow B \times 2$; Write(B)
$l_1(B)$ ← delayed (T2 holds B)	$l_2(A)$ ← delayed (T1 holds A)

Problem: Deadlock between the transactions

Dealing with Deadlock

Option 1: Detect deadlocks and roll back one of the deadlocked transactions

- » The rolled back transaction no longer appears in our schedule

Option 2: Agree on an order to lock items in that prevents deadlocks

- » E.g. transactions acquire locks in key order
- » Must know which items T_i will need up front!

Is 2PL Correct?

Yes! We can prove that following rules #1,2,3 gives conflict-serializable schedules

Conflict Rules for Lock Ops

$l_i(A)$, $l_j(A)$ conflict

$l_i(A)$, $u_j(A)$ conflict

Note: no conflict $<u_i(A), u_j(A)>$, $<l_i(A), r_j(A)>$,...

Theorem

Rules #1,2,3 $\Rightarrow$ conflict-serializable schedule
(2PL)

To help in proof:

Definition: Shrink(T_i) = SH(T_i) =
first unlock action of T_i

Lemma

$T_i \rightarrow T_j$ in $S \Rightarrow SH(T_i) <_S SH(T_j)$

Proof:

$T_i \rightarrow T_j$ means that

$S = \ldots\ p_i(A)\ \ldots\ \ q_j(A)\ \ldots;$ $\quad$ p, q conflict

By rules 1, 2:

$S = \ldots\ p_i(A)\ \ldots\ u_i(A)\ \ldots\ l_j(A)\ \ldots\ q_j(A)\ \ldots$

By rule 3: $\quad SH(T_i) \qquad SH(T_j)$

So, $SH(T_i) <_S SH(T_j)$

Theorem: Rules #1,2,3 $\Rightarrow$ Conflict Serializable Schedule

Proof:

(1) Assume P(S) has cycle

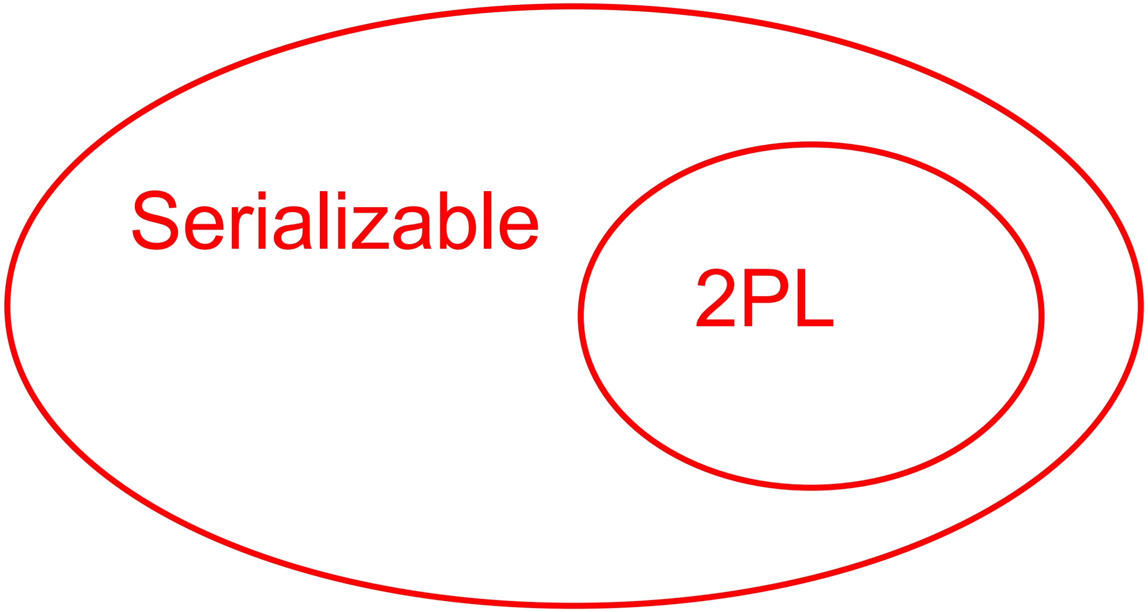
$$T_1 \rightarrow T_2 \rightarrow \ldots. T_n \rightarrow T_1$$

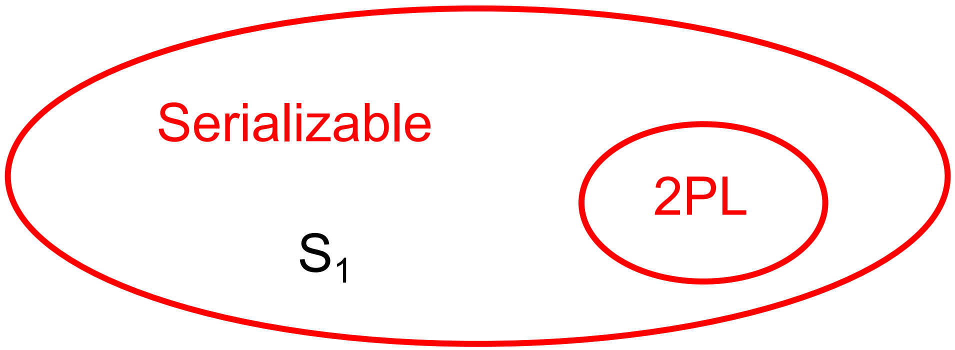
(2) By lemma: $SH(T_1) < SH(T_2) < ... < SH(T_1)$

(3) Impossible, so P(S) acyclic

(4) $\Rightarrow$ S is conflict serializable

2PL is a Subset of Serializable





S_1: $w_1(X)$ $w_3(X)$ $w_2(Y)$ $w_1(Y)$

S_1 cannot be achieved via 2PL:
The lock by T_1 for Y must occur after $w_2(Y)$, so the unlock by T_1 for X must occur after this point (and before $w_1(X)$). Thus, $w_3(X)$ cannot occur under 2PL where shown in S_1.

But S1 is serializable: equivalent to T_2, T_1, T_3.

If You Need More Practice

Are our schedules S_C and S_D 2PL schedules?

S_C: $w_1(A)\ w_2(A)\ w_1(B)\ w_2(B)$

S_D: $w_1(A)\ w_2(A)\ w_2(B)\ w_1(B)$

Optimizing Performance

Beyond this simple 2PL protocol, it is all a matter of improving performance and allowing more concurrency….

» Shared locks

» Multiple granularity

» Inserts, deletes and phantoms

» Other types of C.C. mechanisms

Shared Locks

So far:

$S = ...l_1(A)\ r_1(A)\ u_1(A)\ \ldots\ l_2(A)\ r_2(A)\ u_2(A)\ \ldots$

Do not conflict

Shared Locks

So far:

$S = ...l_1(A)\ r_1(A)\ u_1(A)\ \ldots\ l_2(A)\ r_2(A)\ u_2(A)\ \ldots$

Do not conflict

Instead:

$S= \ldots\ l\text{-}S_1(A)\ r_1(A)\ l\text{-}S_2(A)\ r_2(A)\ \ldots.\ u_1(A)\ u_2(A)$

Multiple Lock Modes

Lock actions

$l\text{-}m_i(A)$: lock A in mode m (m is S or X)

$u\text{-}m_i(A)$: unlock mode m (m is S or X)

Shorthand:

$u_i(A)$: unlock whatever modes T_i has locked A

Rule 1: Well-Formed Transactions

T_i =... l-S_1(A) … r_1(A) … u_1(A) …

T_i =... l-X_1(A) … w_1(A) … u_1(A) …

Transactions must acquire the right lock type for their actions (S for read only, X for r/w).

Rule 1: Well-Formed Transactions

What about transactions that read and write same object?

Option 1: Request exclusive lock

T_1 = ...l-X_1(A) … r_1(A) ... w_1(A) ... u(A) …

Rule 1: Well-Formed Transactions

What about transactions that read and write same object?

Option 2: Upgrade lock to X on write

T_1 = ...l-S_1(A)…r_1(A)...l-X_1(A)…w_1(A)...u_1(A)…

(Think of this as getting a 2nd lock, or dropping S to get X.)

Rule 2: Legal Scheduler

$S = \ldots\ l\text{-}S_i(A) \ldots \quad \ldots\ u_i(A) \ldots$

$\longleftrightarrow$

no $l\text{-}X_j(A)$

$S = \ldots\ l\text{-}X_i(A) \ldots \quad \ldots\ u_i(A) \ldots$

$\longleftrightarrow$

no $l\text{-}X_j(A)$
no $l\text{-}S_j(A)$

A Way to Summarize Rule #2

Lock mode compatibility matrix

compat =

		New request	
		S	X
Lock already held in	S	true	false
	X	false	false

Rule 3: 2PL Transactions

No change except for upgrades:

(I) If upgrade gets more locks

(e.g., S $\rightarrow$ {S, X}) then no change!

(II) If upgrade releases read lock (e.g., S$\rightarrow$X)

can be allowed in growing phase

Rules 1,2,3 $\Rightarrow$ Conf. Serializable Schedules for S/X Locks

Proof: similar to X locks case

Detail:

l-m_i(A), l-n_j(A) do not conflict if compat(m,n)

l-m_i(A), u-n_j(A) do not conflict if compat(m,n)

Lock Modes Beyond S/X

Examples:

(1) increment lock

(2) update lock

Example 1: Increment Lock

Atomic addition action: $IN_i(A)$

$\{Read(A);\ A \leftarrow A+k;\ Write(A)\}$

$IN_i(A)$, $IN_j(A)$ do not conflict, because addition is commutative!

Compatibility Matrix

New request

compat

Lock already held in

	S	X	I
S	T	F	F
X	F	F	F
I	F	F	T

Update Locks

A common deadlock problem with upgrades:

T1	T2
$l\text{-}S_1(A)$	
	$l\text{-}S_2(A)$
$l\text{-}X_1(A)$	
	$l\text{-}X_2(A)$

--- Deadlock ---

Solution

If Ti wants to read A and knows it may later want to write A, it requests an **update lock** (not shared lock)

Compatibility Matrix

New request

compat

Lock already held in

	S	X	U
S	T	F	
X	F	F	
U			

Compatibility Matrix

New request

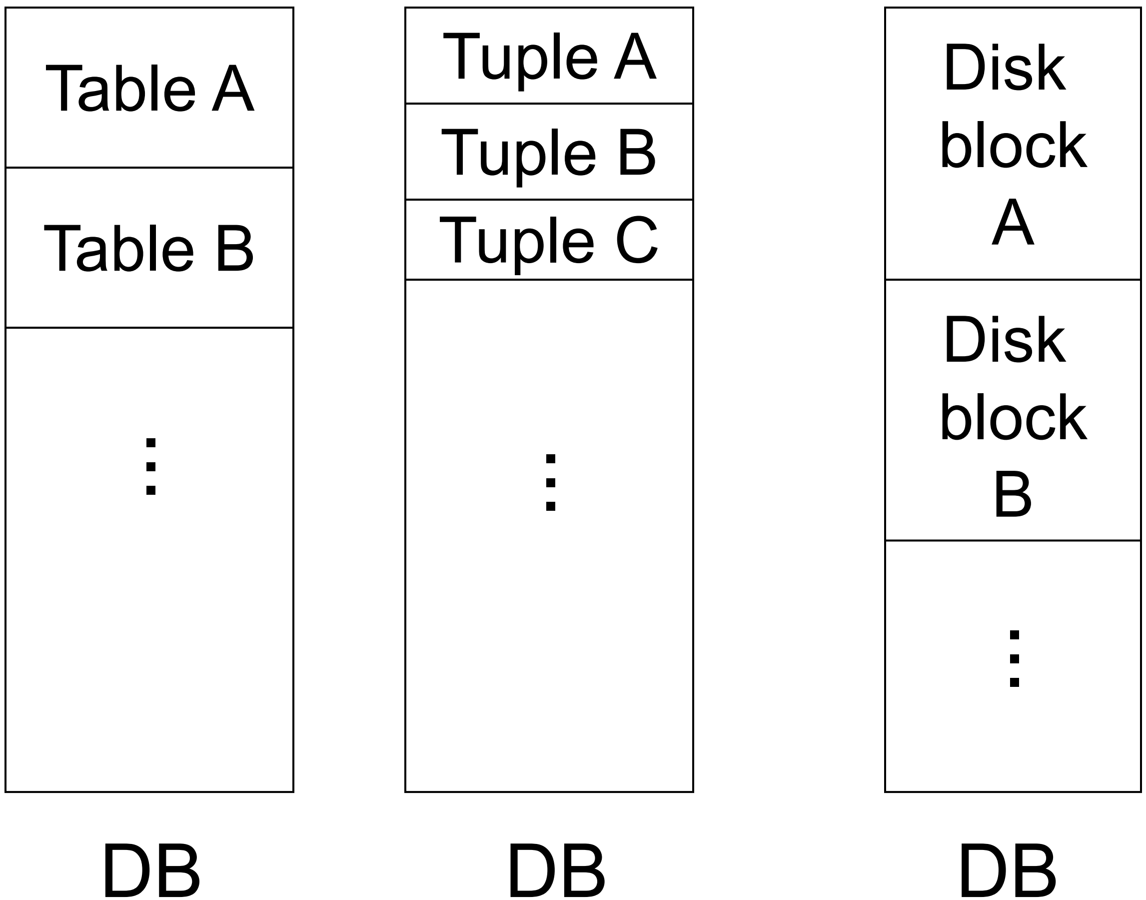
compat

Lock already held in

	S	X	U
S	T	F	T
X	F	F	F
U	F	F	F

Note: asymmetric table!

Which Objects Do We Lock?



Which Objects Do We Lock?

Locking works in any case, but should we choose **small** or **large** objects?

Which Objects Do We Lock?

Locking works in any case, but should we choose **small** or **large** objects?

If we lock **large** objects (e.g., relations)

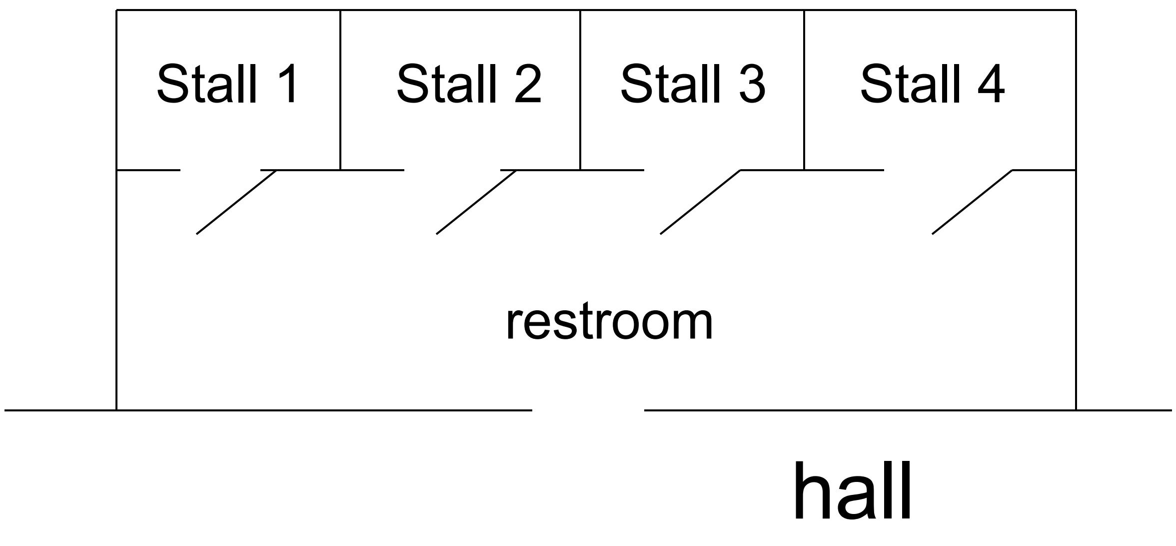
- Need few locks
- Low concurrency

If we lock **small** objects (e.g., tuples, fields)

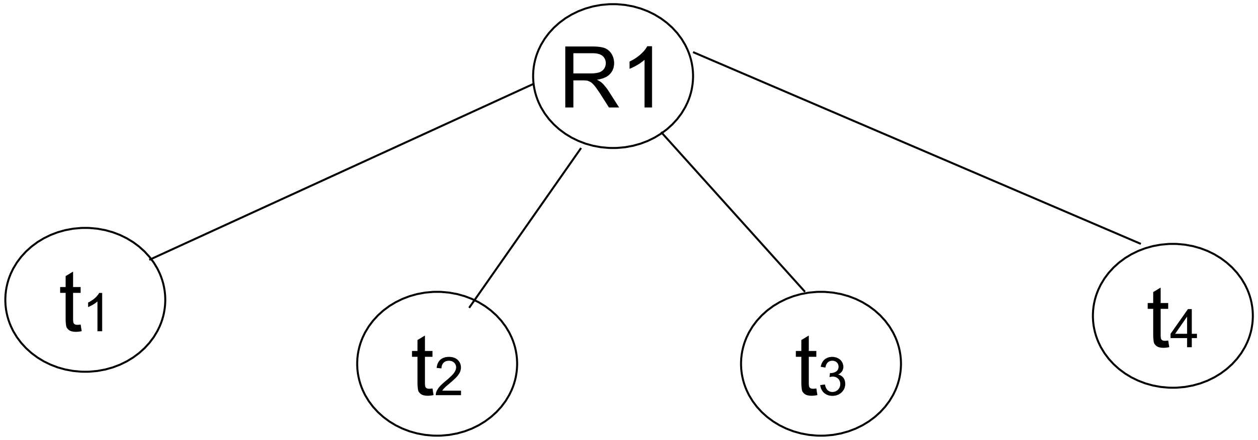
- Need more locks
- More concurrency

We Can Have It Both Ways!

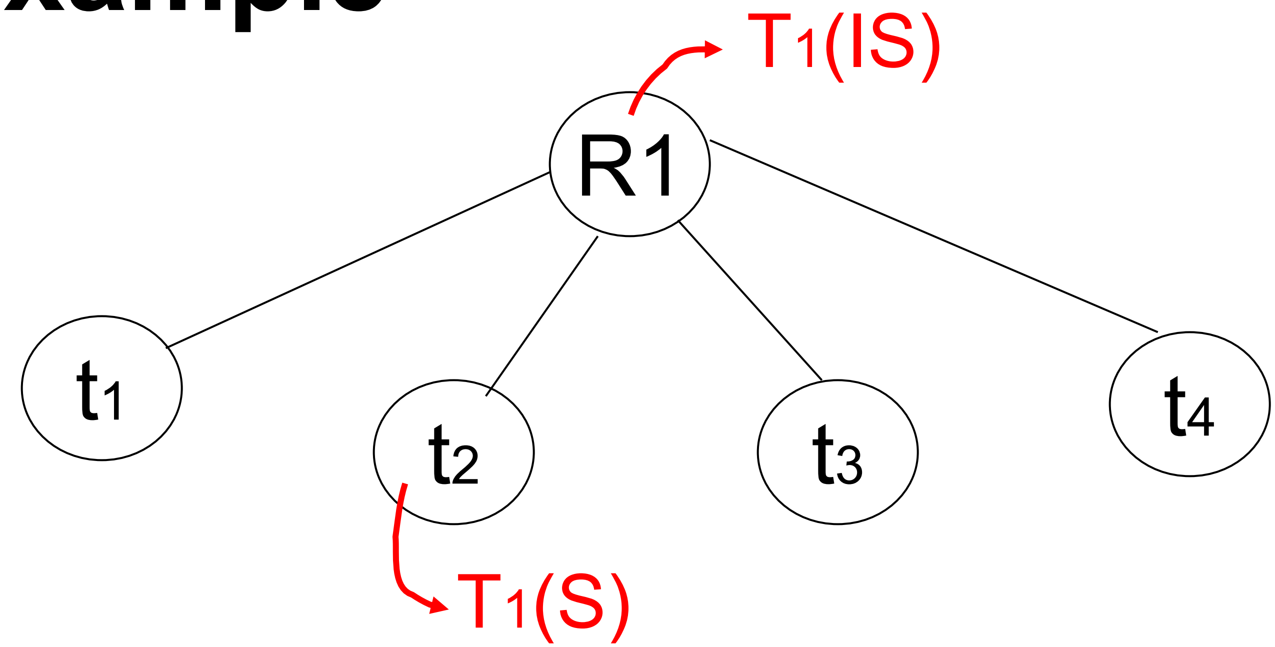
Ask any janitor to give you the solution...



Example



Example



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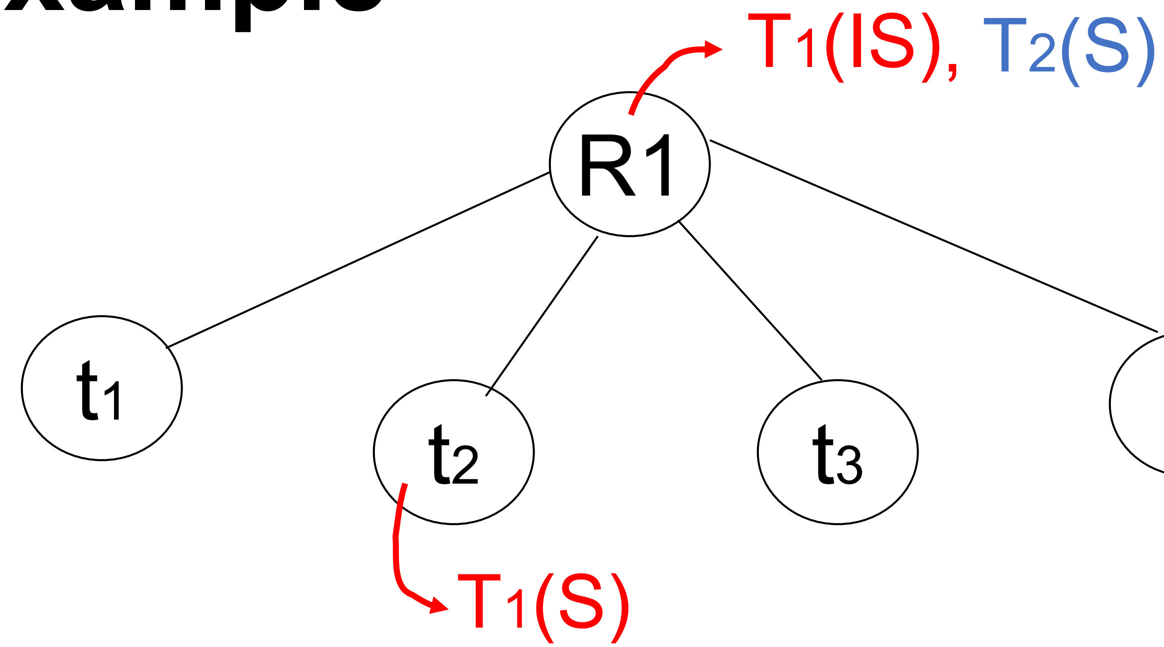
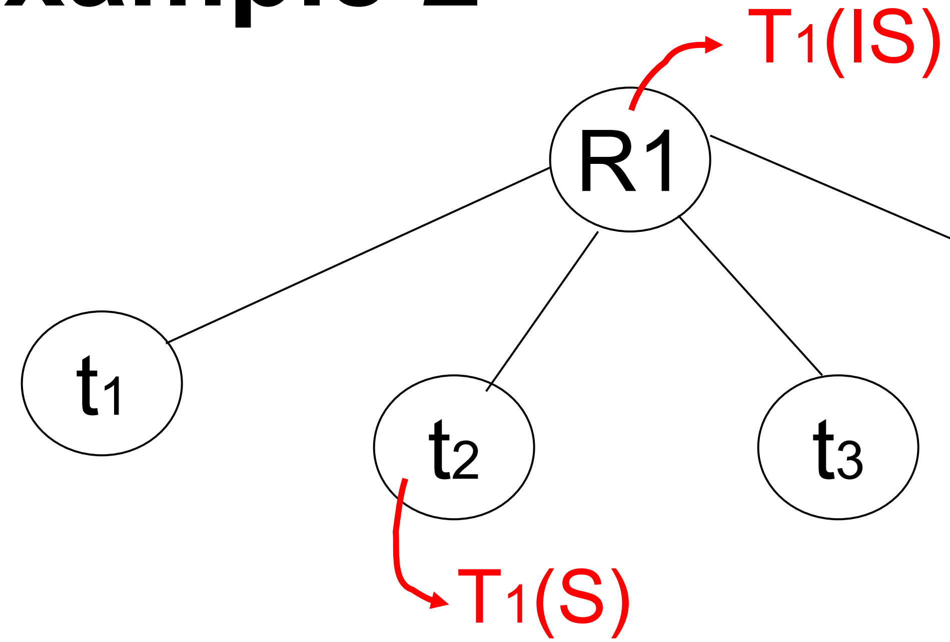


Example 2



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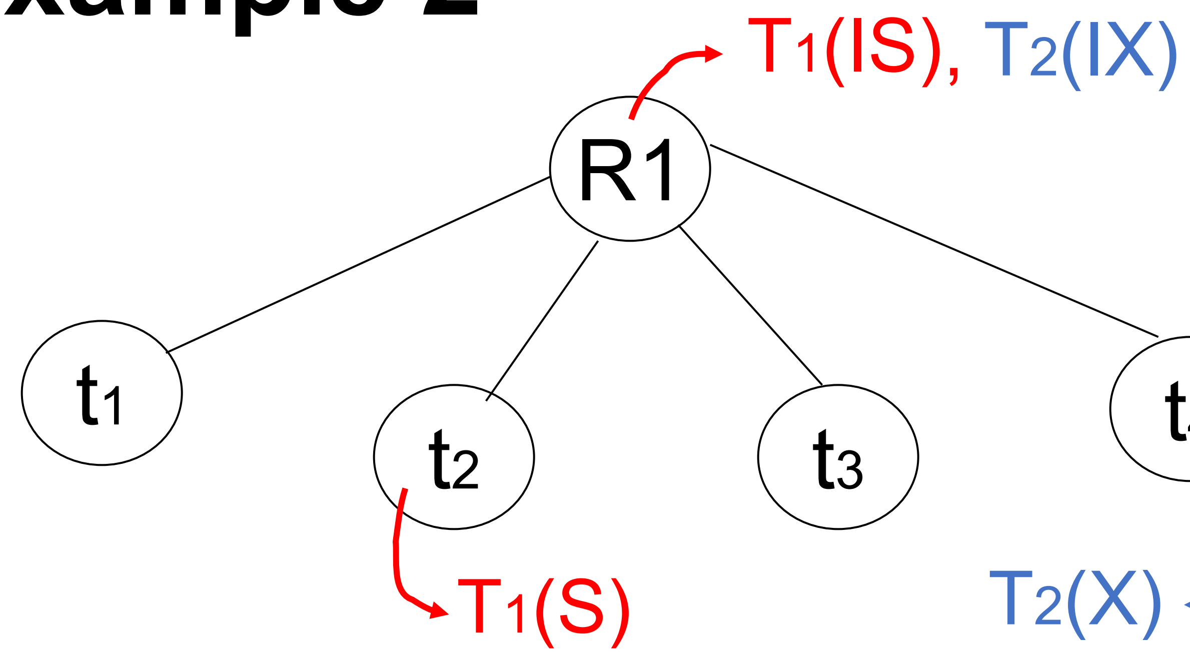
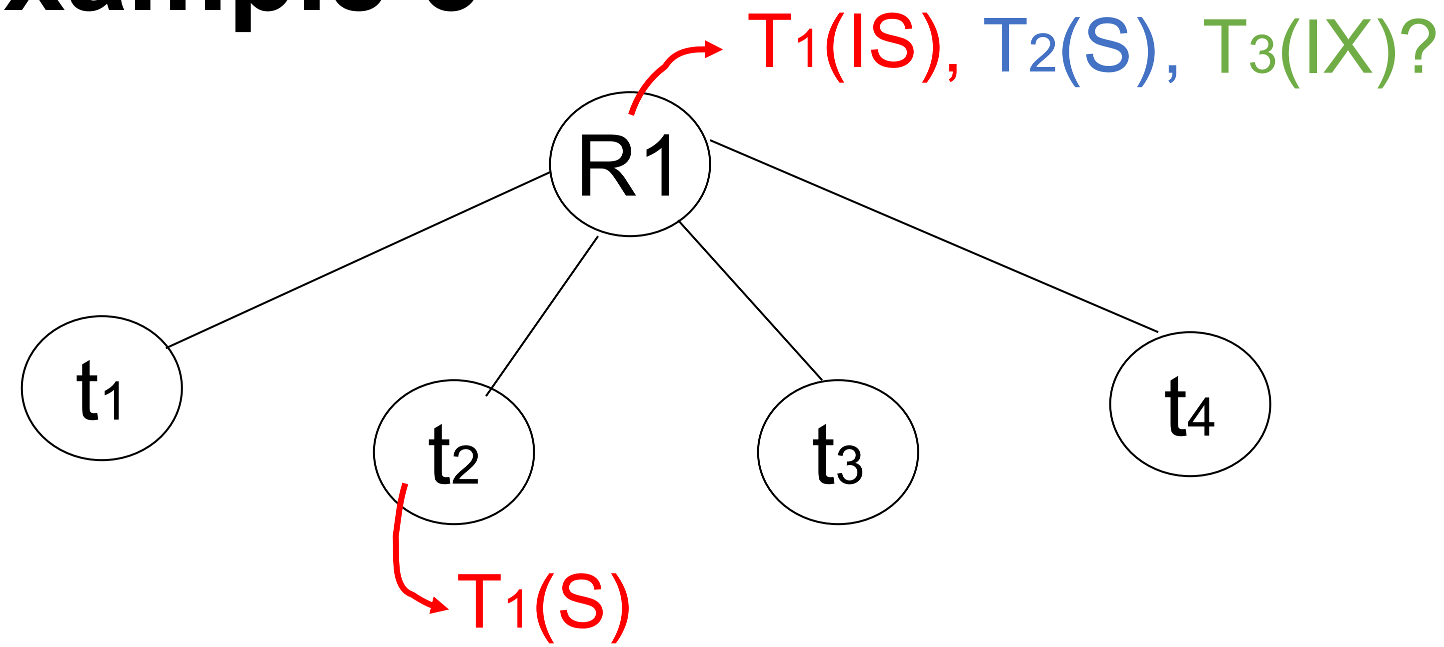


Example 3



Multiple Granularity Locks

compat

		Requester				
		IS	IX	S	SIX	X
Holder	IS					
	IX					
	S					
	SIX					
	X					

Multiple Granularity Locks

compat Requester

Holder

	IS	IX	S	SIX	X
IS	T	T	T	T	F
IX	T	T	F	F	F
S	T	F	T	F	F
SIX	T	F	F	F	F
X	F	F	F	F	F