Concurrency Control

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Outline

What makes a schedule serializable?

Conflict serializability

Precedence graphs

Enforcing serializability via 2-phase locking

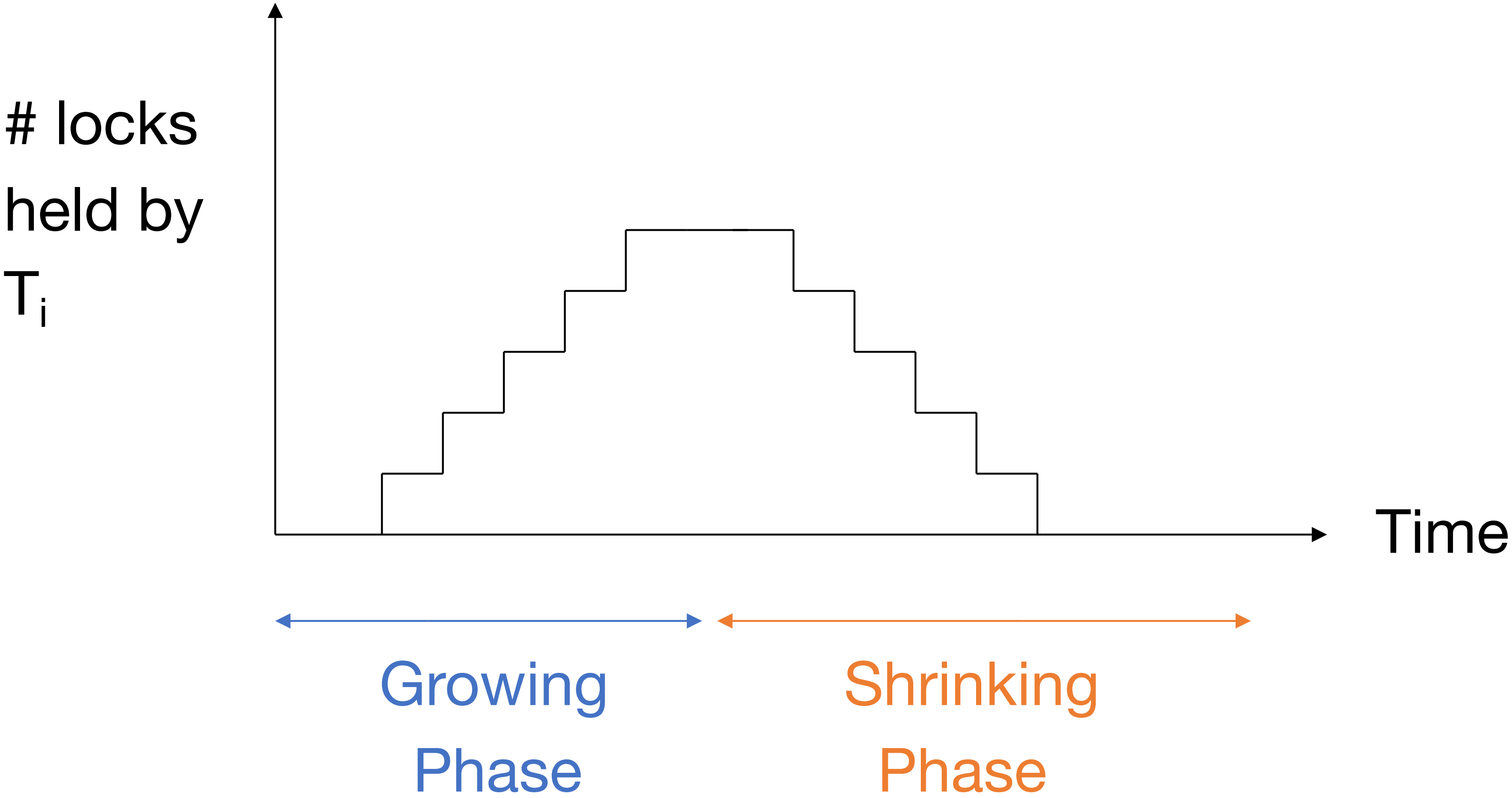
- Shared and exclusive locks
- Lock tables and multi-level locking

Optimistic concurrency with validation

Concurrency control + recovery

Beyond serializability

Recap: 2-Phase Locking (2PL)



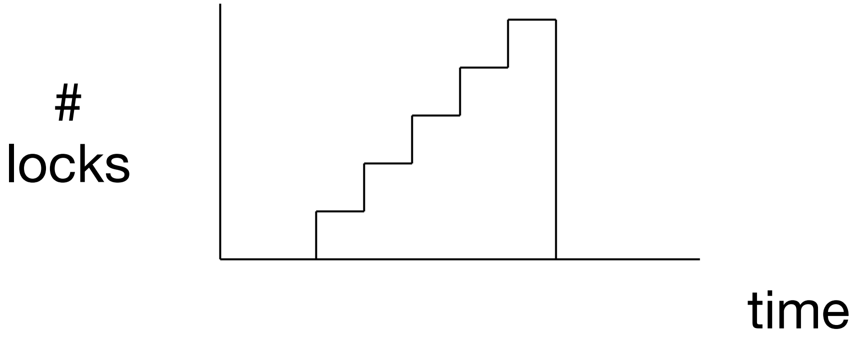
How Is 2PL Implemented In Practice?

Every system is different, but we'll show one simplified way

Sample Locking System

1. Don’t ask transactions to request/release locks: just get a lock for each action they do

2. Hold all locks until a transaction commits



Sample Locking System

Under the hood: lock manager that keeps track of which objects are locked

- » E.g., hash table

Also need ways to block transactions until locks are available, and to find deadlocks

Optimizing Performance

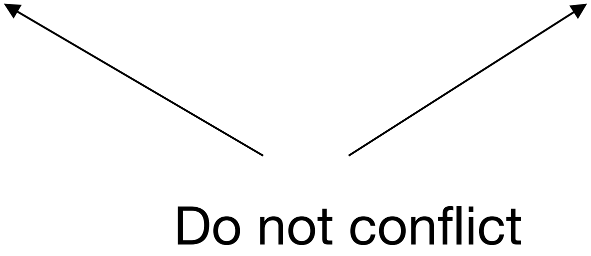
Beyond the base 2PL protocol, many ways to improve performance & concurrency:

- Shared locks
- Multiple granularity
- Inserts, deletes and phantoms
- Other types of C.C. mechanisms

Shared Locks

So far:

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



Do not conflict

Shared Locks

So far:

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

Do not conflict

Instead:

S=... l-$S_1(A)$ $r_1(A)$ l-$S_2(A)$ $r_2(A)$ …. $u_1(A)$ $u_2(A)$

Multiple Lock Modes

Lock actions

l-m_i(A): lock A in mode m (m is S or X)

u-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 replacing S lock with X lock.)

Rule 2: Legal Scheduler

S = ... $l\text{-}S_i(A)$ …   … $u_i(A)$ …

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

S = ... $l\text{-}X_i(A)$ …   … $u_i(A)$ …

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

Lock already held in

	S	X
S	true	false
X	false	false

Rule 3: 2PL Transactions

No change except for upgrades: allow upgrades from S to X only in growing phase

Rules 1,2,3 ⇒ 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

(3) hierarchical locks

Increment Locks

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

Lock already held in

compat	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
I-S_1(A)	
	I-S_2(A)
I-X_1(A)	
	I-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

	S	X	U
S	T	F	
X	F	F	
U			

Lock already held in

Compatibility Matrix

compat

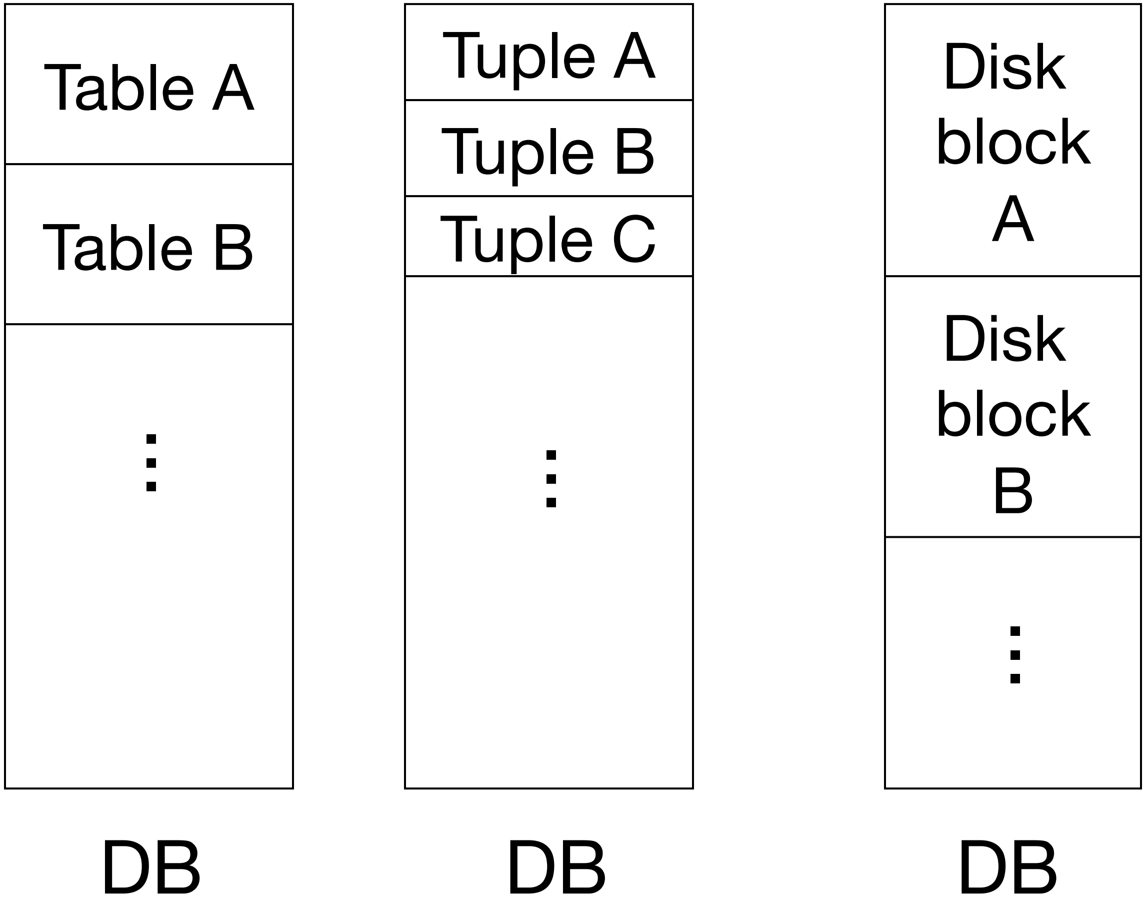
New request

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)

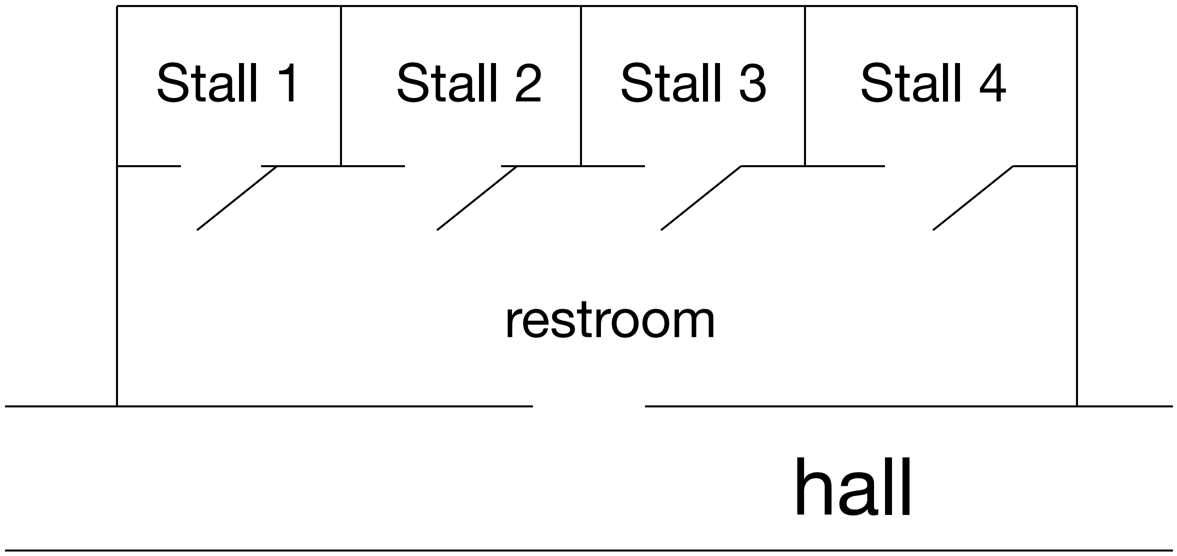
- Need few locks
- Low concurrency

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

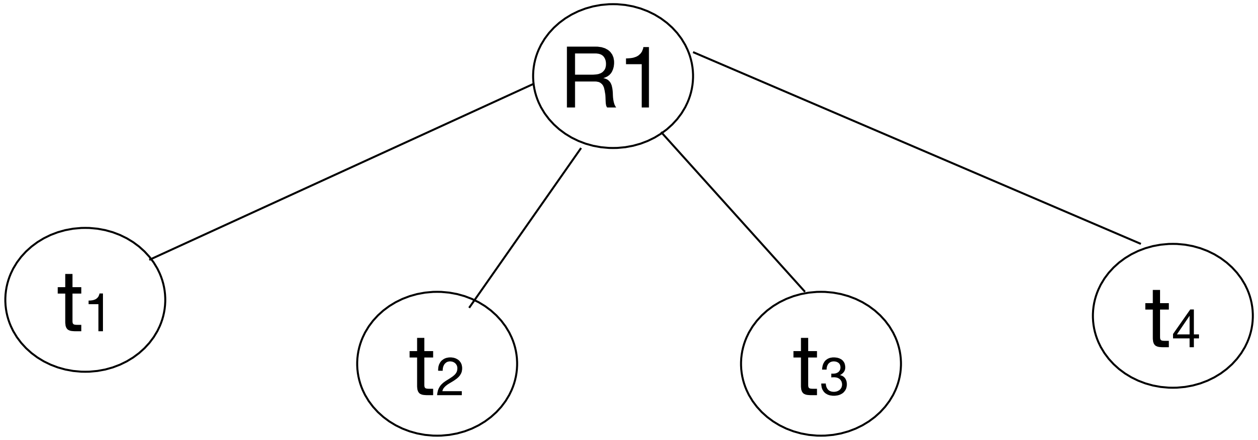
- Need more locks
- More concurrency

We Can Have It Both Ways!

Ask any janitor to give you the solution...



Example



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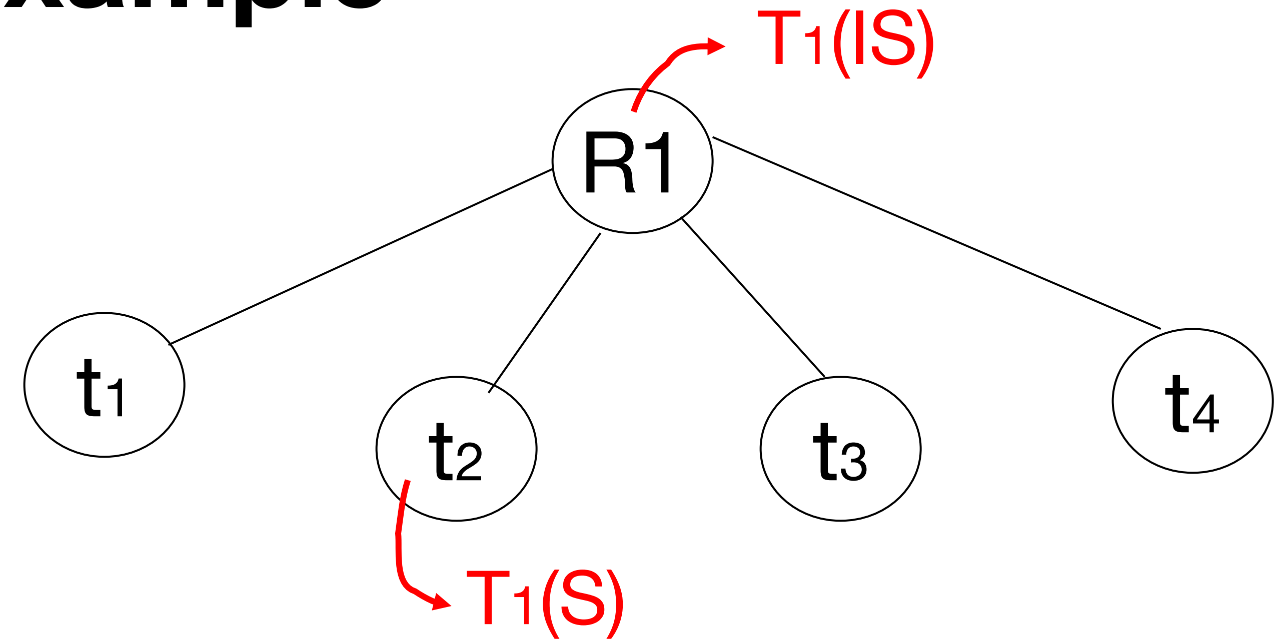
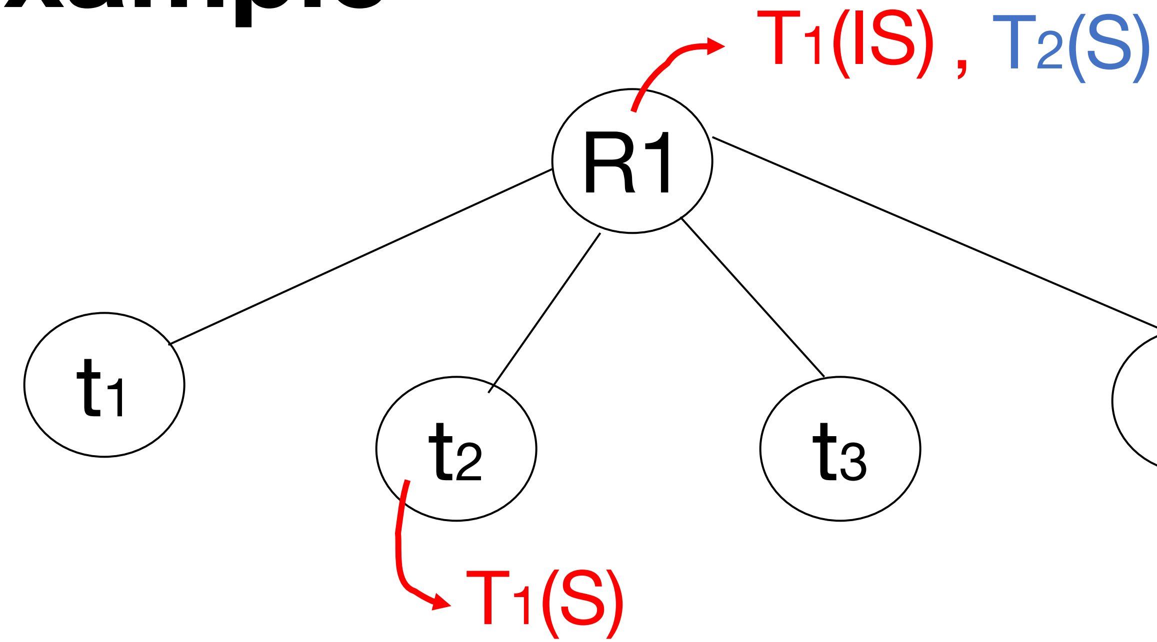
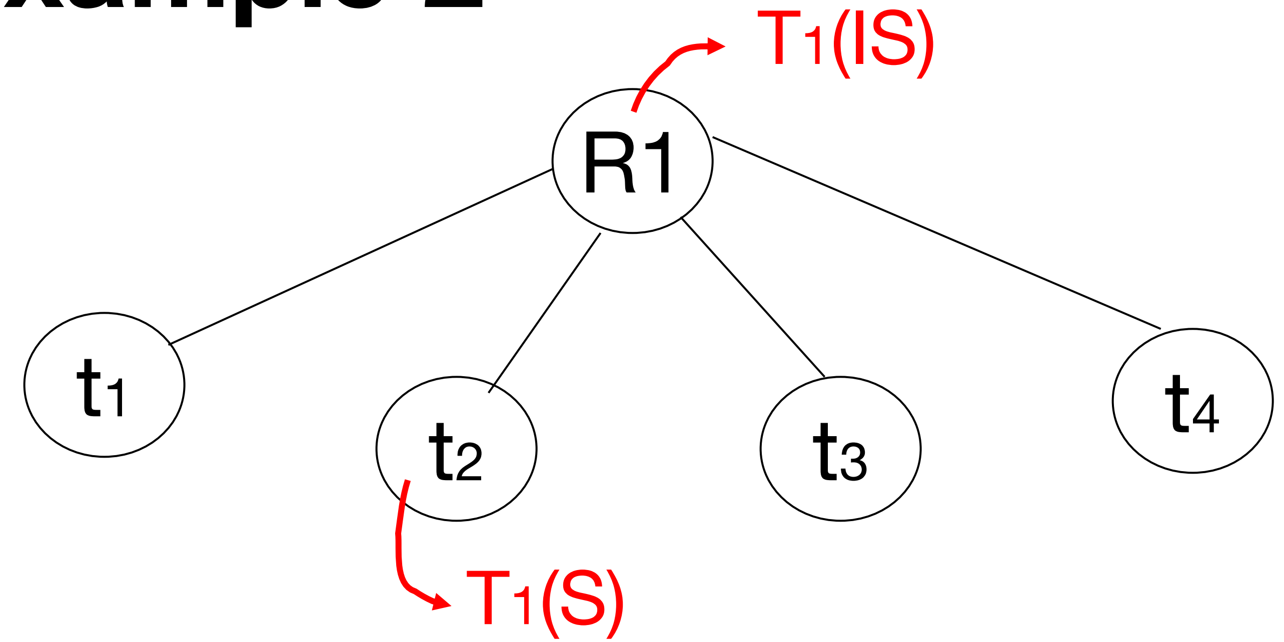


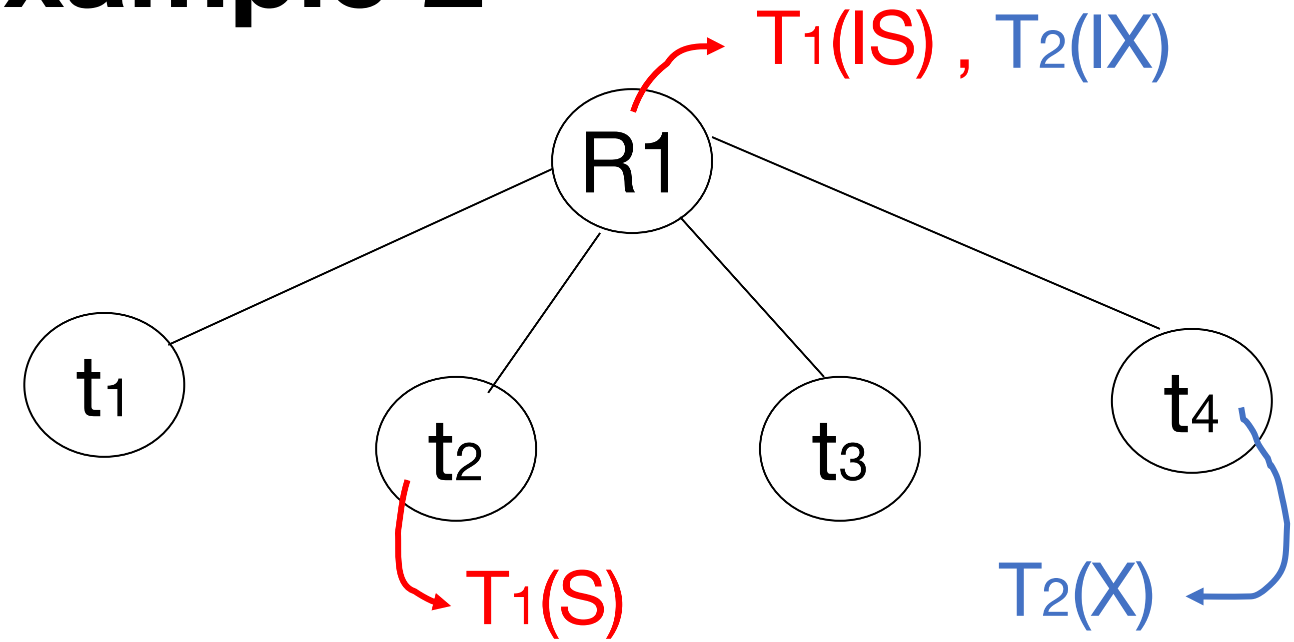
Example



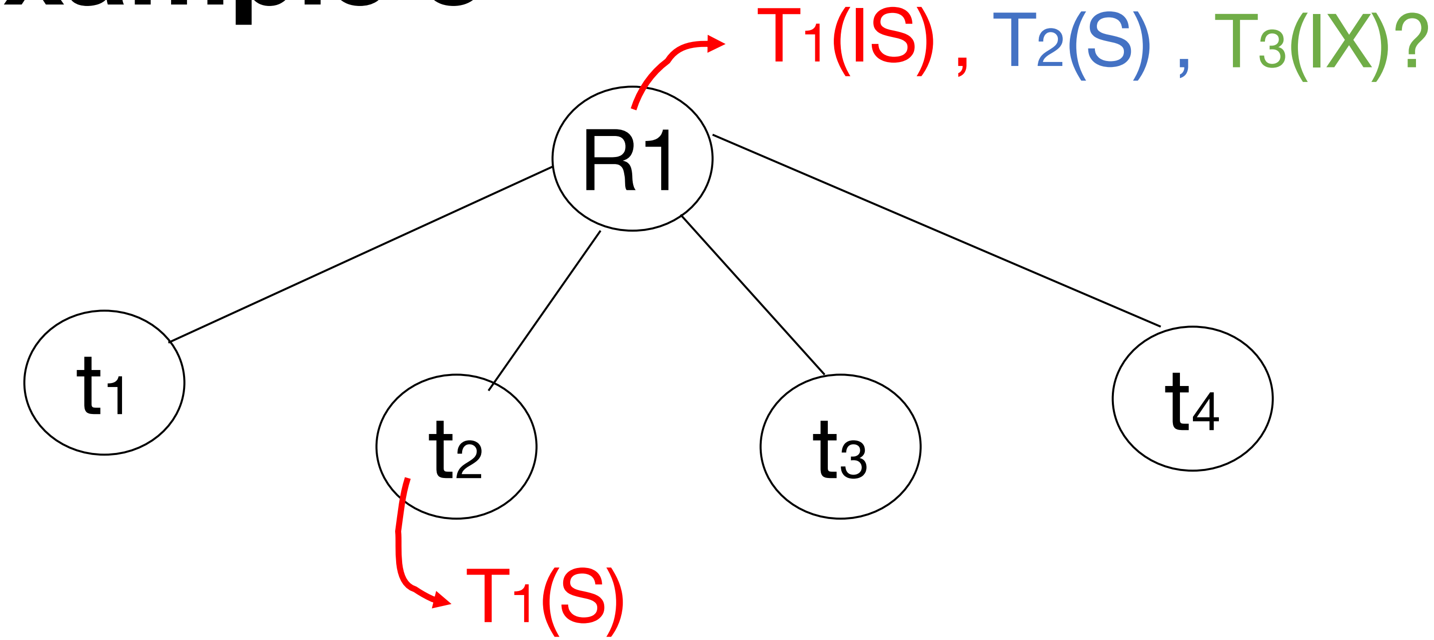
Example 2



Example 2



Example 3

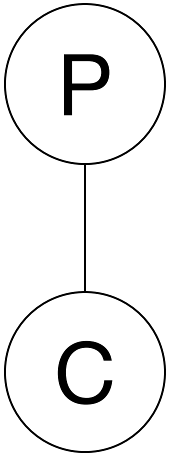


Multiple Granularity Locks

compat		Requester				
		IS	IX	S	SIX	X
Holder	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

Rules Within A Transaction

Parent locked in	Child can be locked by same transaction in
IS	IS, S
IX	IS, S, IX, X, SIX
S	none
SIX	X, IX, SIX
X	none

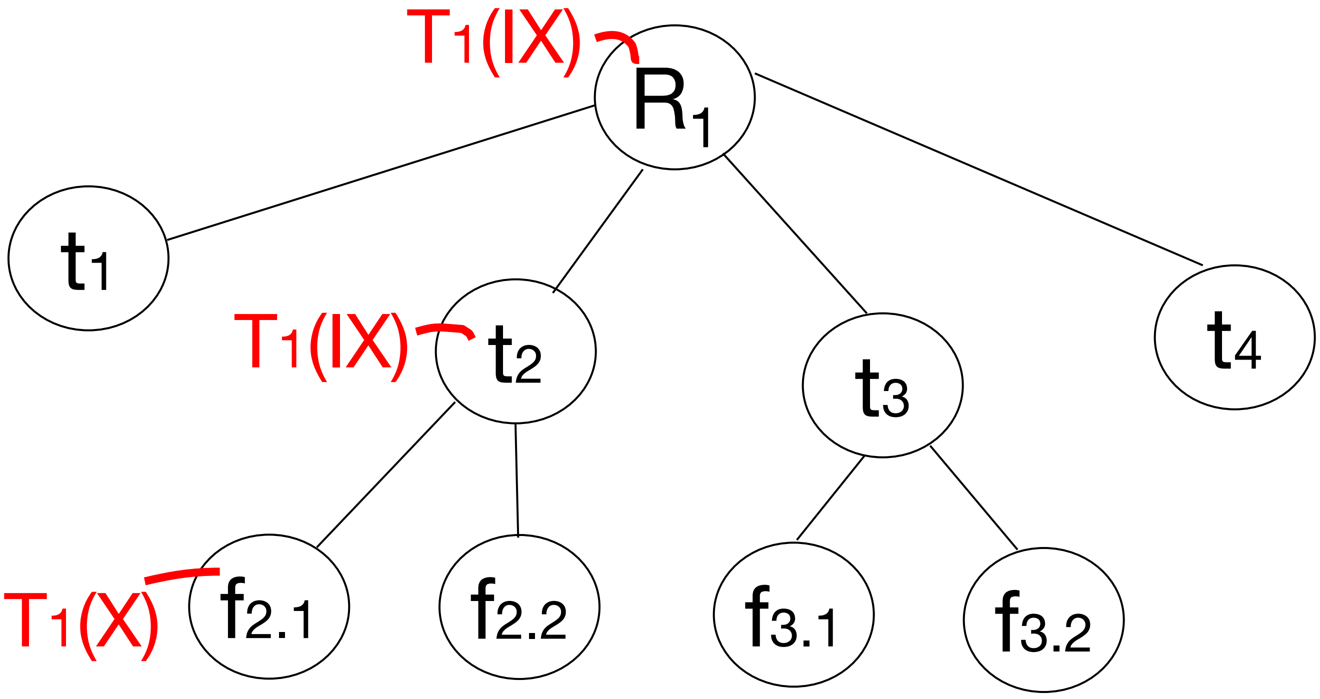


Multi-Granularity 2PL Rules

1. Follow multi-granularity compat function
2. Lock root of tree first, any mode
3. Node Q can be locked by T_i in S or IS only if parent(Q) locked by T_i in IX or IS
4. Node Q can be locked by T_i in X, SIX, IX only if parent(Q) locked by T_i in IX, SIX
5. T_i is two-phase
6. T_i can unlock node Q only if none of Q's children are locked by T_i

Exercise:

Can T_2 access object $f_{2.2}$ in X mode? What locks will T_2 get?



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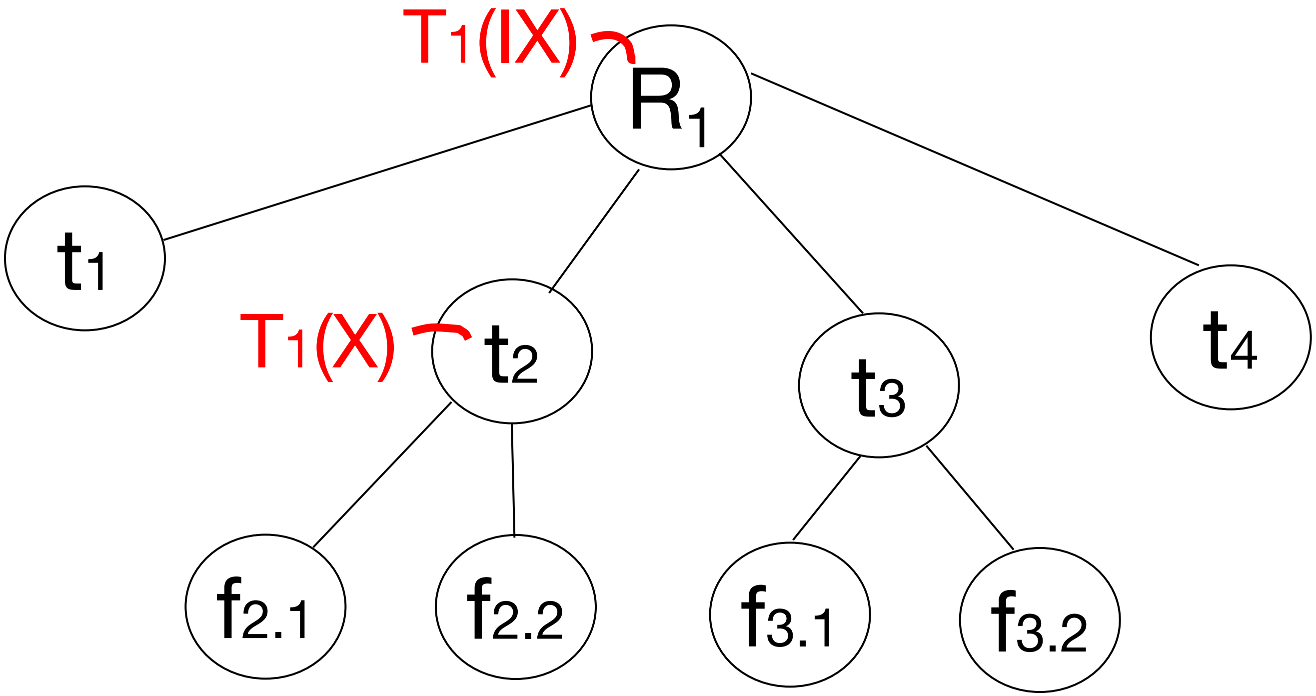
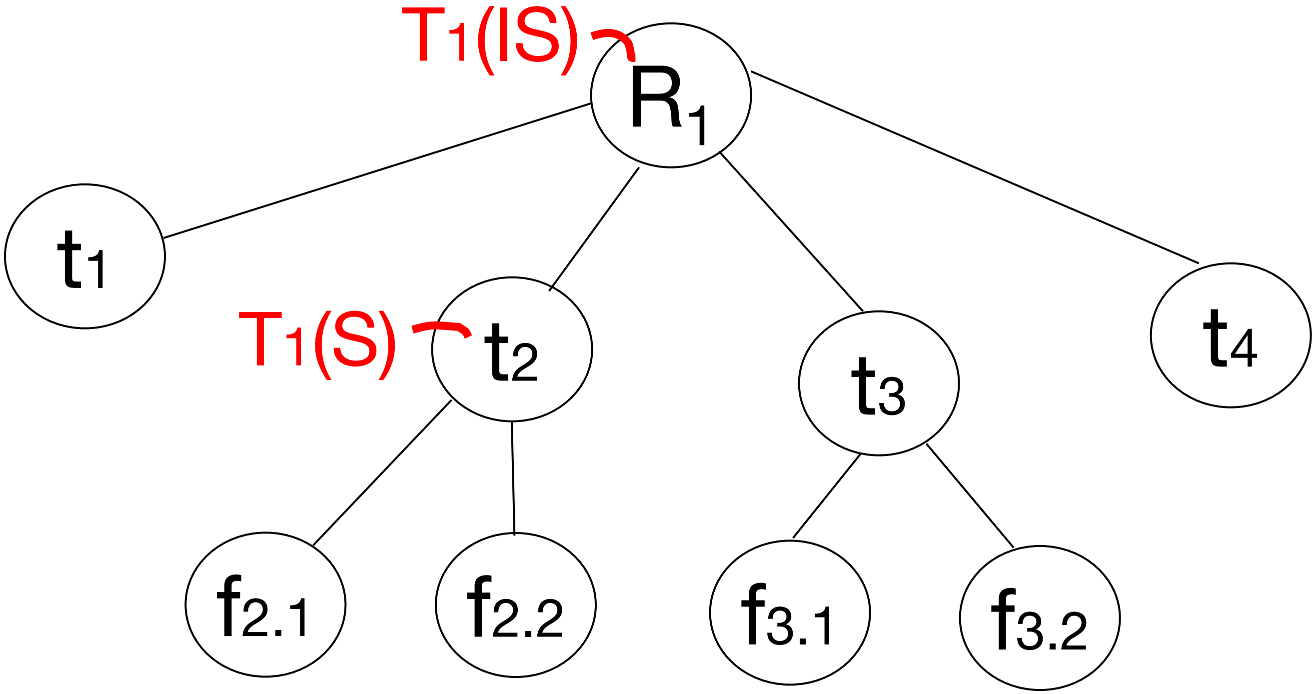
Can T_2 access object $f_{2.2}$ in X mode? What locks will T_2 get?



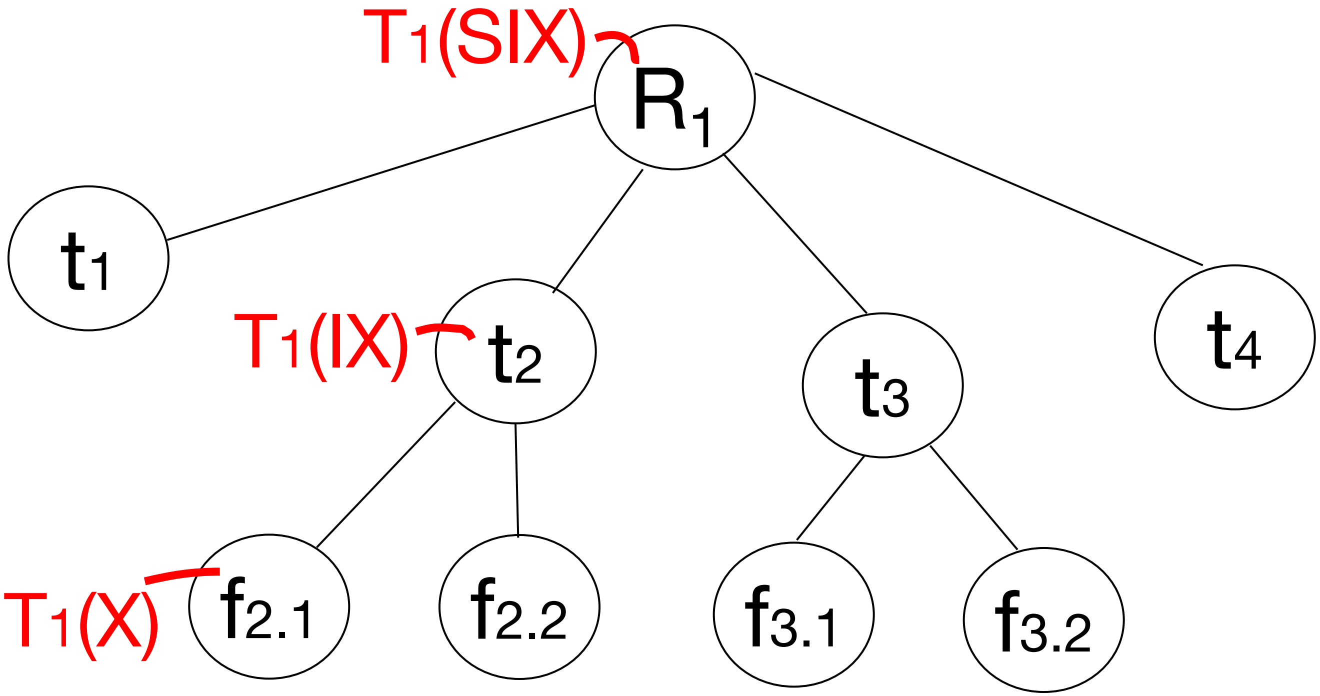
Exercise:

Can T_2 access object $f_{3.1}$ in X mode? What locks will T_2 get?



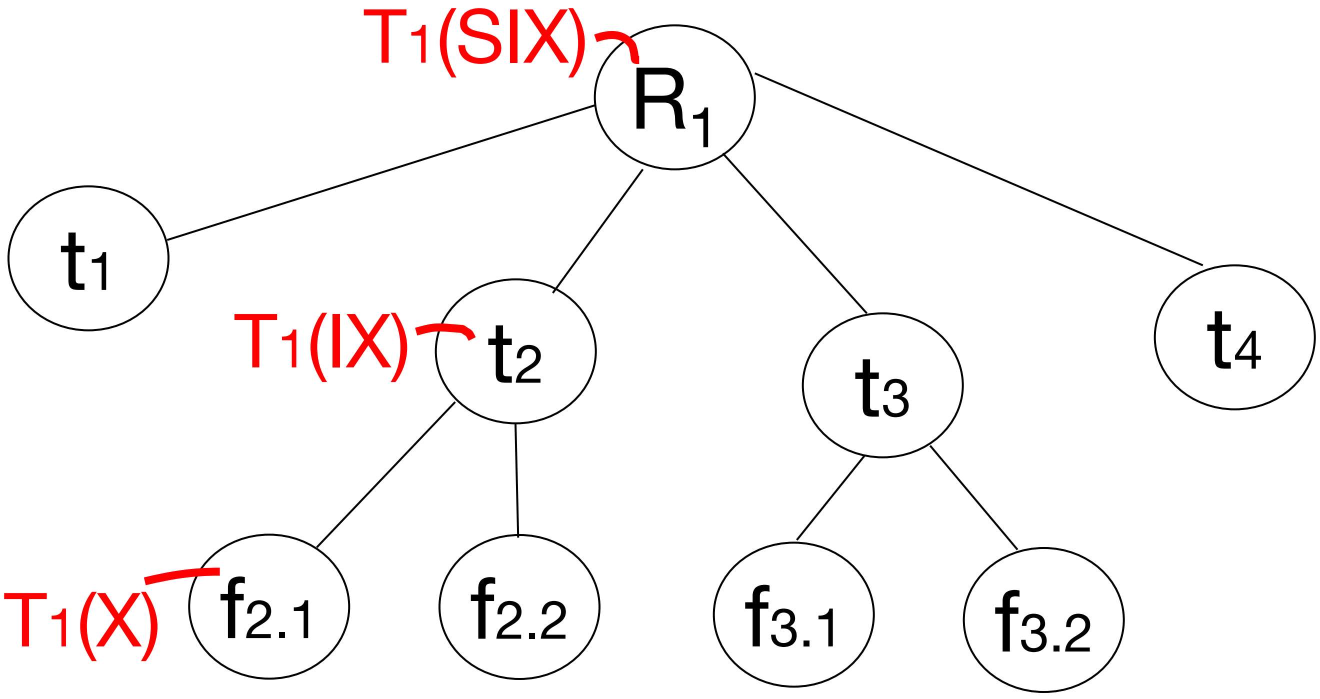
Exercise:

Can T_2 access object $f_{2.2}$ in S mode? What locks will T_2 get?

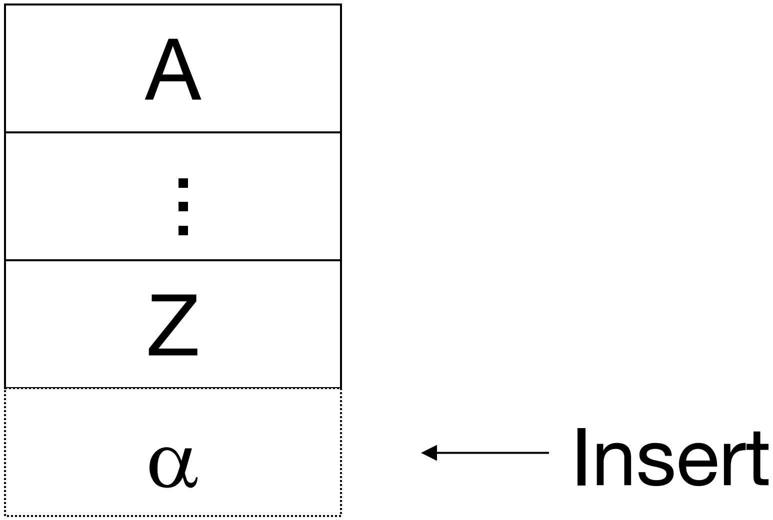


Exercise:

Can T_2 access object $f_{2.2}$ in X mode? What locks will T_2 get?



Insert + Delete Operations



Changes to Locking Rules:

1. Need exclusive lock on A to delete A
2. When T_i inserts an object A, T_i receives an exclusive lock on A

Still Have Problem: Phantoms

Example: relation R (id, name,…)

constraint: id is unique key

use tuple locking

R	id	name	….
o_1	55	Smith	
o_2	75	Jones	

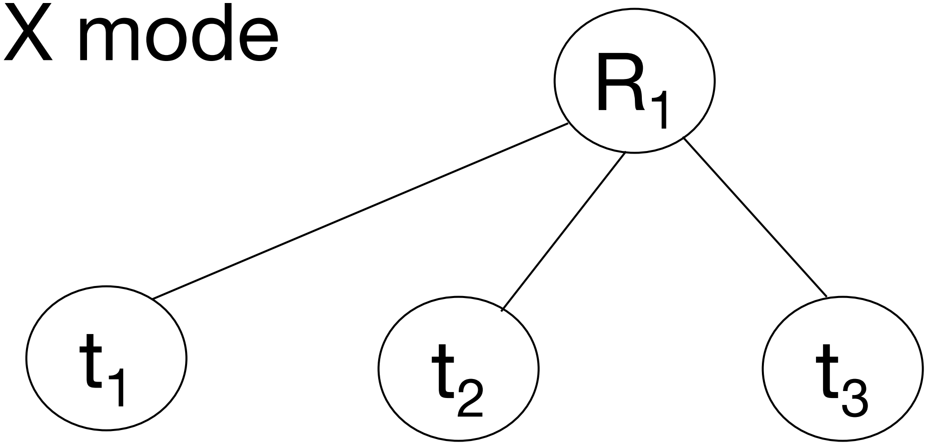
T_1: Insert <12,Mary,…> into R
T_2: Insert <12,Sam,…> into R

T1	T2
I-S_1(o_1)	I-S_2(o_1)
I-S_1(o_2)	I-S_2(o_2)
Check Constraint	Check Constraint
⋮	⋮
Insert o_3[12,Mary,..]	
	Insert o_4[12,Sam,..]

Solution

Use multiple granularity tree

Before insert of node N,
lock parent(N) in X mode



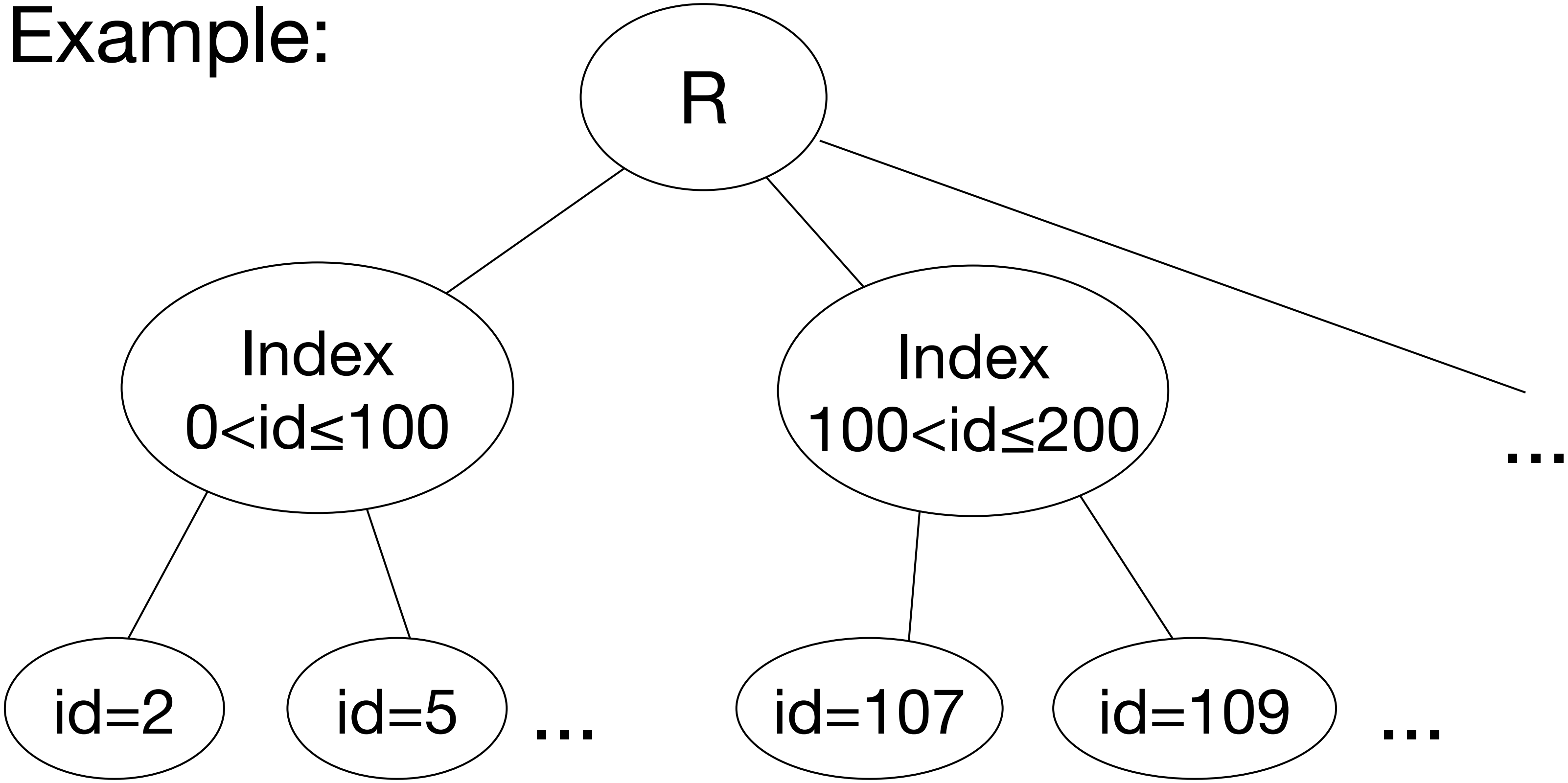
Back to Example

T_1: Insert<12,Mary> | T_2: Insert<12,Sam>

T_1	T_2
$I\text{-}X_1(R)$	
	$I\text{-}X_2(R)$ ← delayed
Check constraint	
Insert<12,Mary>	
$U_1(R)$	
	$I\text{-}X_2(R)$
	Check constraint
	Oops! id=12 already in R!

Instead of Locking All of R, Can Lock Ranges of Keys

Example:



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Optimistic concurrency with validation

Concurrency control + recovery

Beyond serializability

Validation Overview

Transactions have 3 phases:

1. Read
   - » Read all DB values needed
   - » Write to temporary storage
   - » No locking
2. Validate
   - » Check whether schedule so far is serializable
3. Write
   - » If validate OK, write to DB

Key Idea

Make validation atomic

If the validation order is T_1, T_2, T_3, …, then resulting schedule will be conflict equivalent to $S_s = T_1, T_2, T_3, \ldots$

Implementing Validation

System keeps track of two sets:

FIN = transactions that have finished phase 3 (write phase) and are fully done

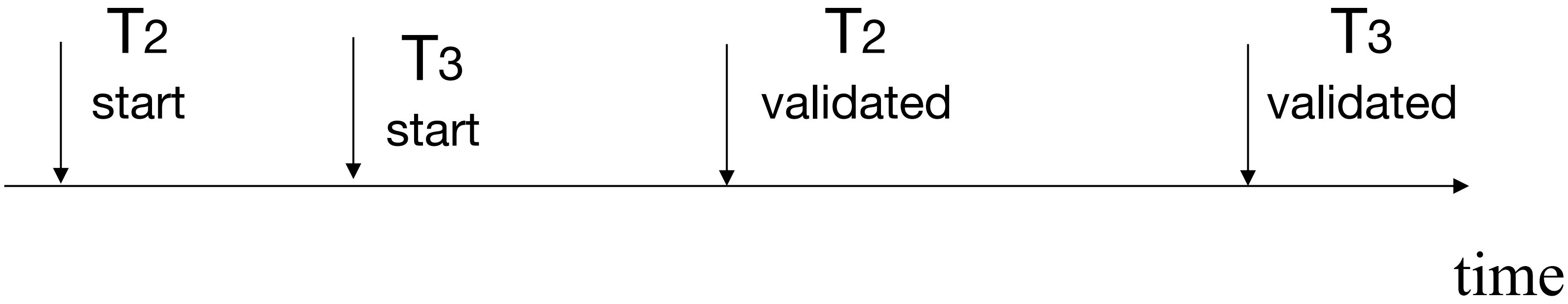
VAL = transactions that have successfully finished phase 2 (validation)

Example That Validation Must Prevent:

$RS(T_2)=\{B\}$ $RS(T_3)=\{A,B\}$ $\neq \emptyset$

$\cap$

$WS(T_2)=\{B,D\}$ $WS(T_3)=\{C\}$



Example That Validation Must Allow:

$RS(T_2)=\{B\}$ $RS(T_3)=\{A,B\}$ $\neq \emptyset$

$\cap$

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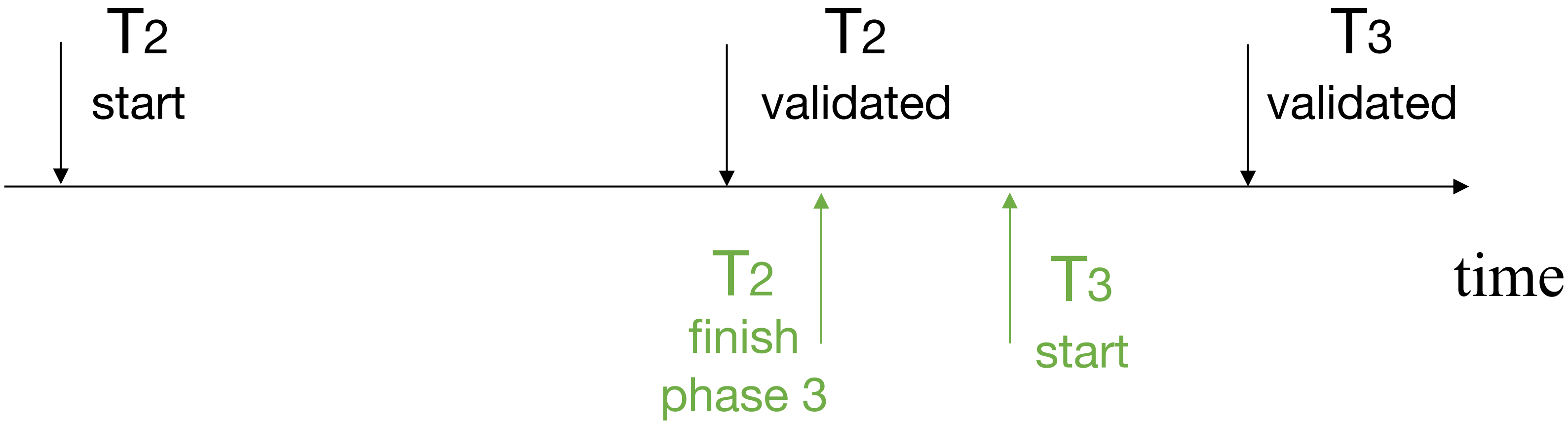
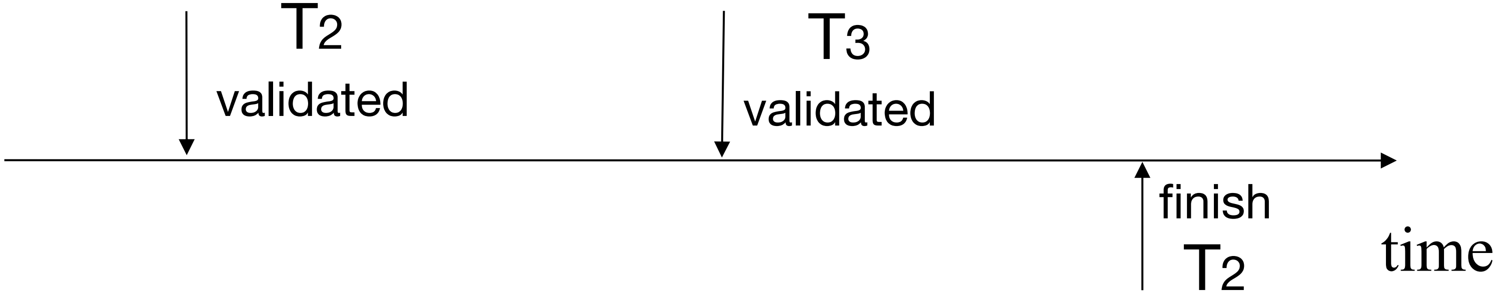


Another Thing Validation Must Prevent:

$RS(T_2)=\{A\}$ $RS(T_3)=\{A,B\}$

$WS(T_2)=\{D,E\}$ $WS(T_3)=\{C,D\}$



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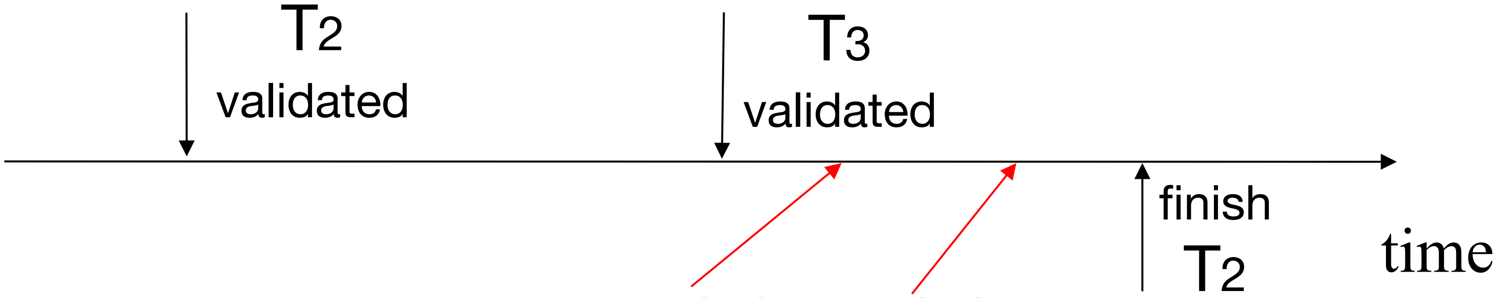
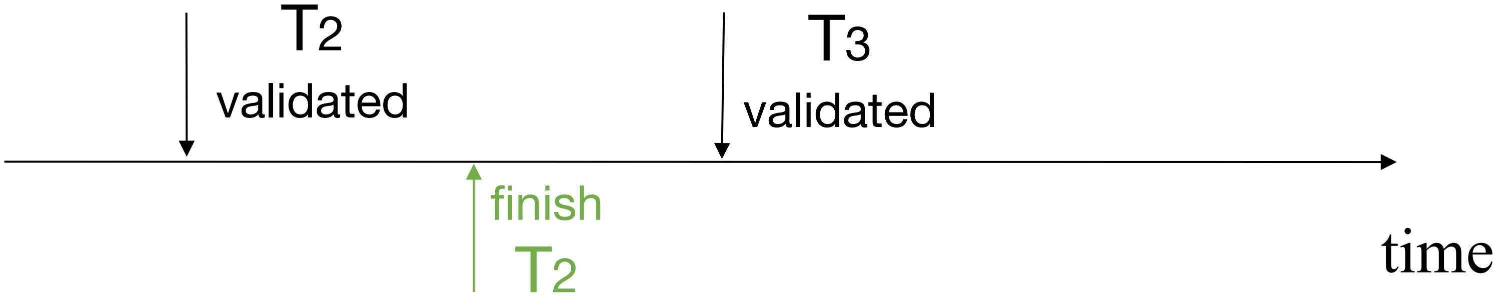


BAD: $w_3(D)$ $w_2(D)$

Another Thing Validation Must Allow:

$RS(T_2)=\{A\}$ $RS(T_3)=\{A,B\}$

$WS(T_2)=\{D,E\}$ $WS(T_3)=\{C,D\}$



Validation Rules for T_j:

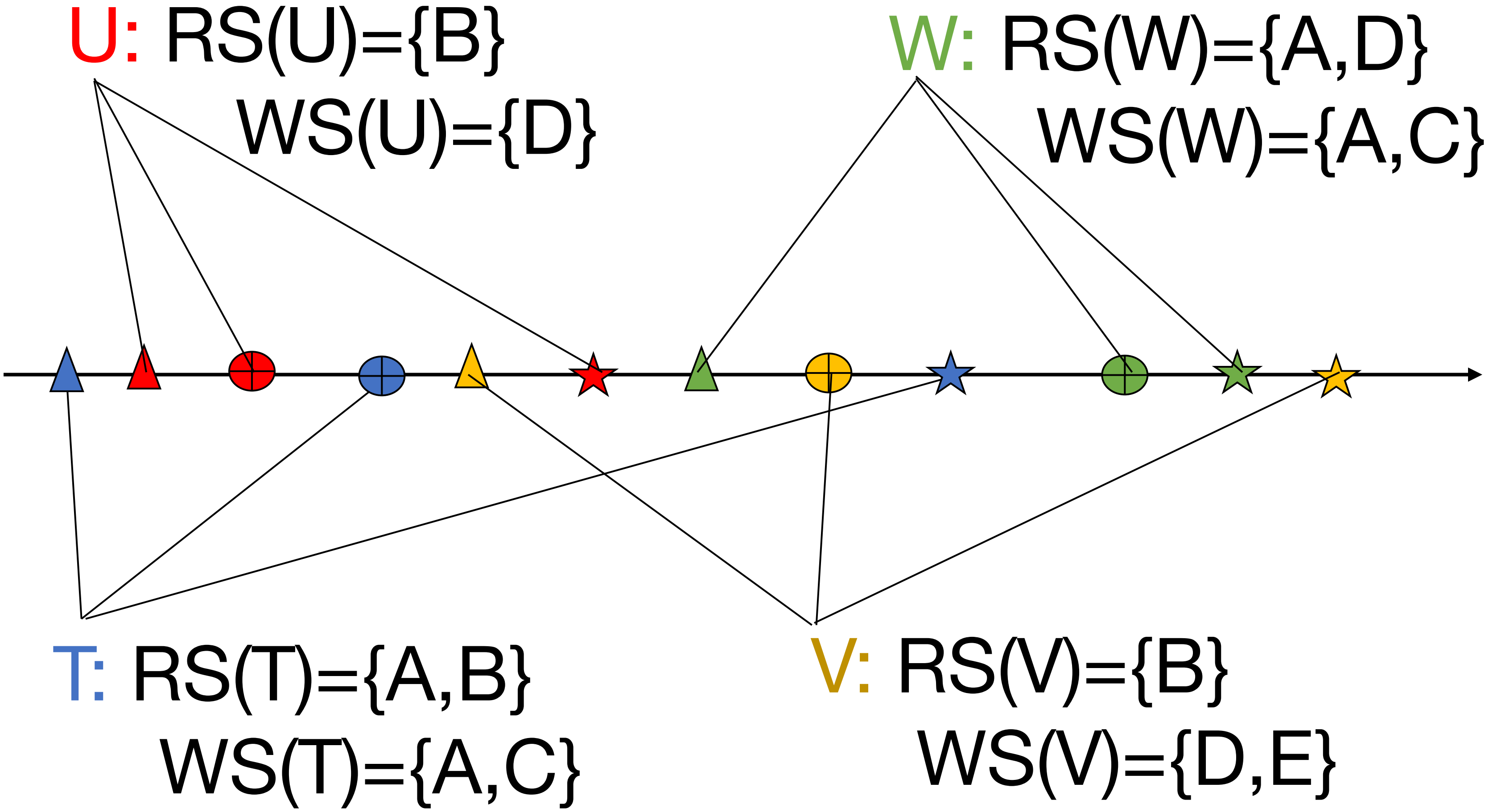
```
when $T_j$ starts phase 1:
    ignore($T_j$) $\leftarrow$ FIN

at $T_j$ Validation:
    if Check($T_j$) then
        VAL $\leftarrow$ VAL $\cup$ {$T_j$}
        do write phase
        FIN $\leftarrow$ FIN $\cup$ {$T_j$}
```

Check(T_j)

```
for $T_i \in VAL - ignore(T_j)$ do
    if ($WS(T_i) \cap RS(T_j) \neq \emptyset$ or
        ($T_i \notin FIN$ and $WS(T_i) \cap WS(T_j) \neq \emptyset$))
            then return false
return true
```

Exercise

△ start
⊕ validate
☆ finish



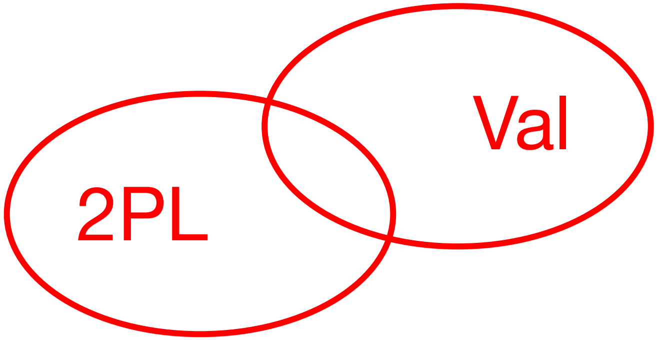
U: RS(U)={B}
WS(U)={D}

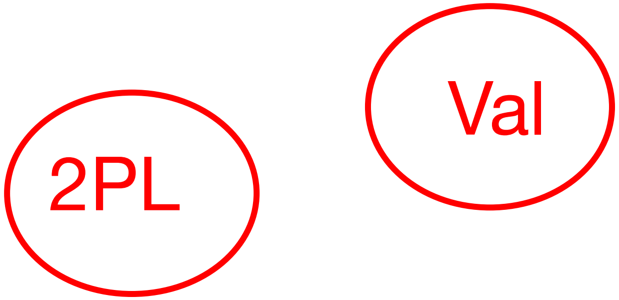
W: RS(W)={A,D}
WS(W)={A,C}

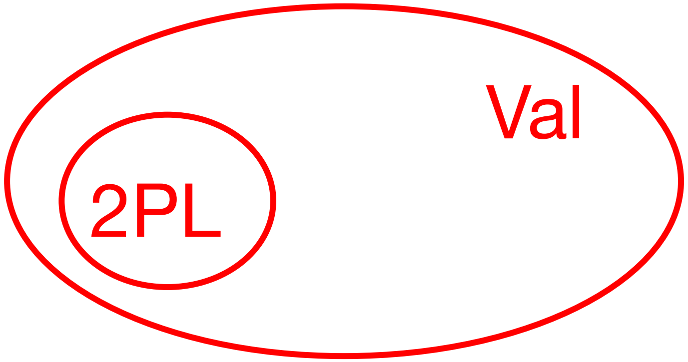
T: RS(T)={A,B}
WS(T)={A,C}

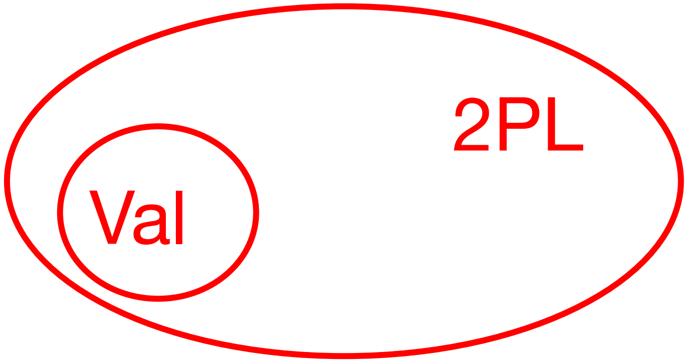
V: RS(V)={B}
WS(V)={D,E}

Is Validation = 2PL?


2PL
Val


2PL
Val


Val
2PL


2PL
Val

S: $w_2(y)$ $w_1(x)$ $w_2(x)$

Achievable with 2PL?

Achievable with validation?

S: $w_2(y)$ $w_1(x)$ $w_2(x)$

S can be achieved with 2PL:
$l_2(y)$ $w_2(y)$ $l_1(x)$ $w_1(x)$ $u_1(x)$ $l_2(x)$ $w_2(x)$ $u_2(x)$ $u_2(y)$

S cannot be achieved by validation:
The validation point of T_2, val_2, must occur before $w_2(y)$ since transactions do not write to the database until after validation. Because of the conflict on x, $val_1 < val_2$, so we must have something like:

S: val_1 val_2 $w_2(y)$ $w_1(x)$ $w_2(x)$

With the validation protocol, the writes of T_2 should not start until T_1 is all done with writes, which is not the case.

Validation Subset of 2PL?

Possible proof (Check!):

- Let S be validation schedule
- For each T in S insert lock/unlocks, get S':
  - At T start: request read locks for all of RS(T)
  - At T validation: request write locks for WS(T); release read locks for read-only objects
  - At T end: release all write locks
- Clearly transactions well-formed and 2PL
- Must show S' is legal (next slide)

Validation Subset of 2PL?

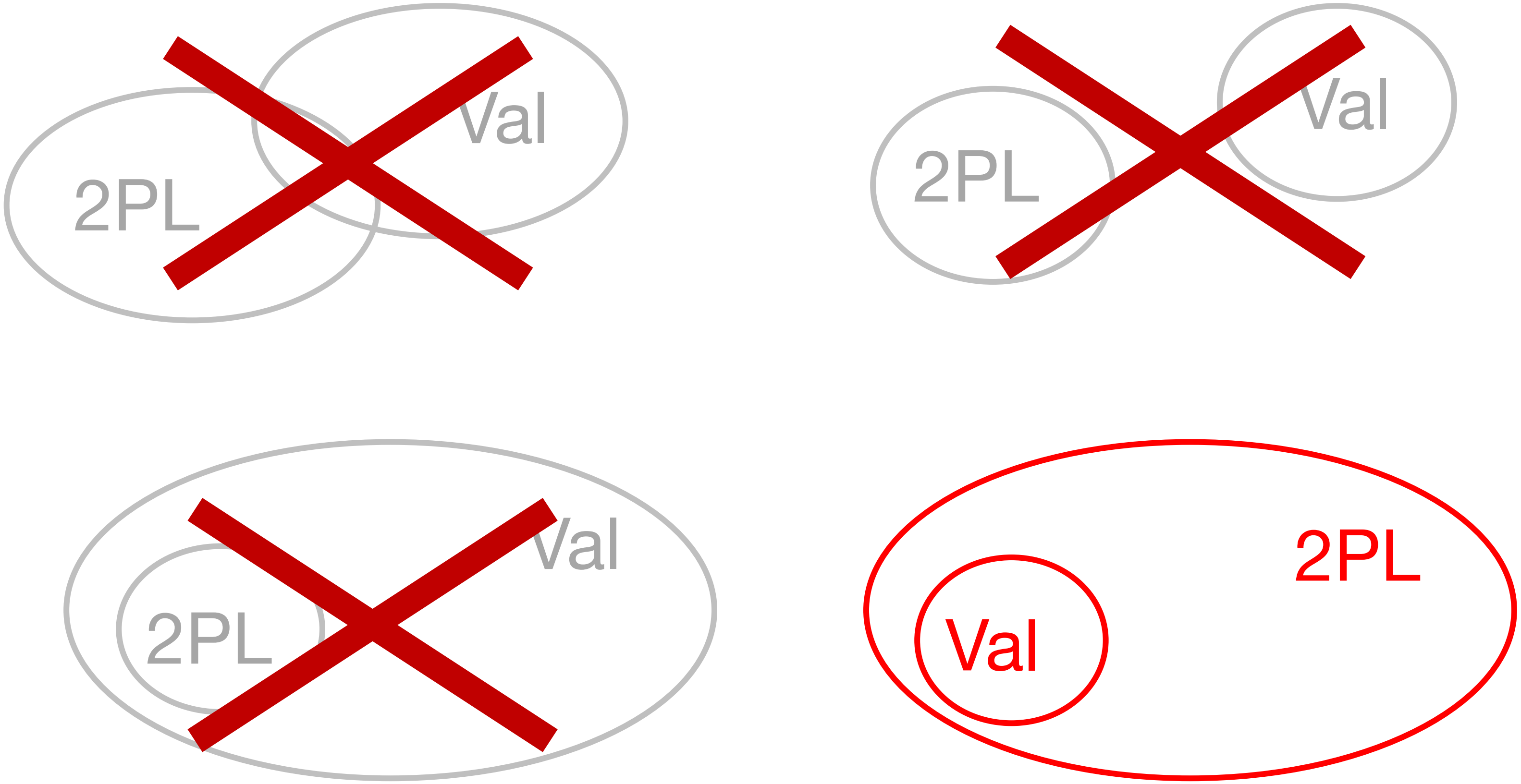
Say S' not legal (due to w-r conflict):
S': ... l1(x)   w2(x) r1(x) val1 u1(x) ...

- At val1: T2 not in Ignore(T1); T2 in VAL
- T1 does not validate: WS(T2) $\cap$ RS(T1) $\neq \emptyset$
- contradiction!

Say S' not legal (due to w-w conflict):
S': ... val1 l1(x)   w2(x) w1(x) u1(x) ...

- Say T2 validates first (proof similar if T1 validates first)
- At val1: T2 not in Ignore(T1); T2 in VAL
- T1 does not validate:
  T2 $\notin$ FIN AND WS(T1) $\cap$ WS(T2) $\neq \emptyset$)
- contradiction!

Is Validation = 2PL?



When to Use Validation?

Validation performs better than locking when:

- Conflicts are rare
- System resources are plentiful
- Have tight latency constraints

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Concurrency control + recovery

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Concurrency Control & Recovery

Example:

T_j	T_i
⋮	⋮
$w_j(A)$	⋮
	$r_i(A)$
⋮	Commit T_i
⋮	⋮
Abort T_j	

Non-persistent commit (bad!)

avoided by recoverable schedules

Concurrency Control & Recovery

Example:

T_j	T_i
⋮	⋮
$w_j(A)$	⋮
⋮	$r_i(A)$
	$w_i(B)$
⋮	⋮
Abort T_j	
	[Commit T_i]

Cascading rollback (bad!)

avoided by avoids-cascading-rollback (ACR) schedules

Core Problem

Schedule is conflict serializable

$T_j \longrightarrow T_i$

But not recoverable

To Resolve This

Need to mark the “final” decision for each transaction in our schedules:

- **Commit decision:** system guarantees transaction will or has completed
- **Abort decision:** system guarantees transaction will or has been rolled back

Model This as 2 New Actions:

c_i = transaction T_i commits

a_i = transaction T_i aborts

Back to Example

T_j	T_i
⋮	⋮
$w_j(A)$	
	$r_i(A)$
⋮	
	⋮
	c_i ← can we commit here?

Definition

T_i **reads from** T_j in S ($T_j \Rightarrow_S T_i$) if:

1. $w_j(A) <_S r_i(A)$

2. $a_j \not<_S r(A)$ ($\not<_S$: does not precede)

3. If $w_j(A) <_S w_k(A) <_S r_i(A)$ then $a_k <_S r_i(A)$

Definition

Schedule S is **recoverable** if

whenever $T_j \Rightarrow_S T_i$ and $j \neq i$ and $c_i \in S$

then $c_j <_S c_i$

Notes

In all transactions, reads and writes must precede commits or aborts

- ⇔ If $c_i \in T_i$, then $r_i(A) < a_i$, $w_i(A) < a_i$
- ⇔ If $a_i \in T_i$, then $r_i(A) < a_i$, $w_i(A) < a_i$

Also, just one of c_i, a_i per transaction

How to Achieve Recoverable Schedules?

With 2PL, Hold Write Locks Until Commit (“Strict 2PL”)

T_j	**T_i**
$W_j(A)$	⋮
⋮	⋮
C_j	⋮
$u_j(A)$	⋮
⋮	$r_i(A)$

With Validation, No Change!

Each transaction’s validation point is its commit point, and only write after

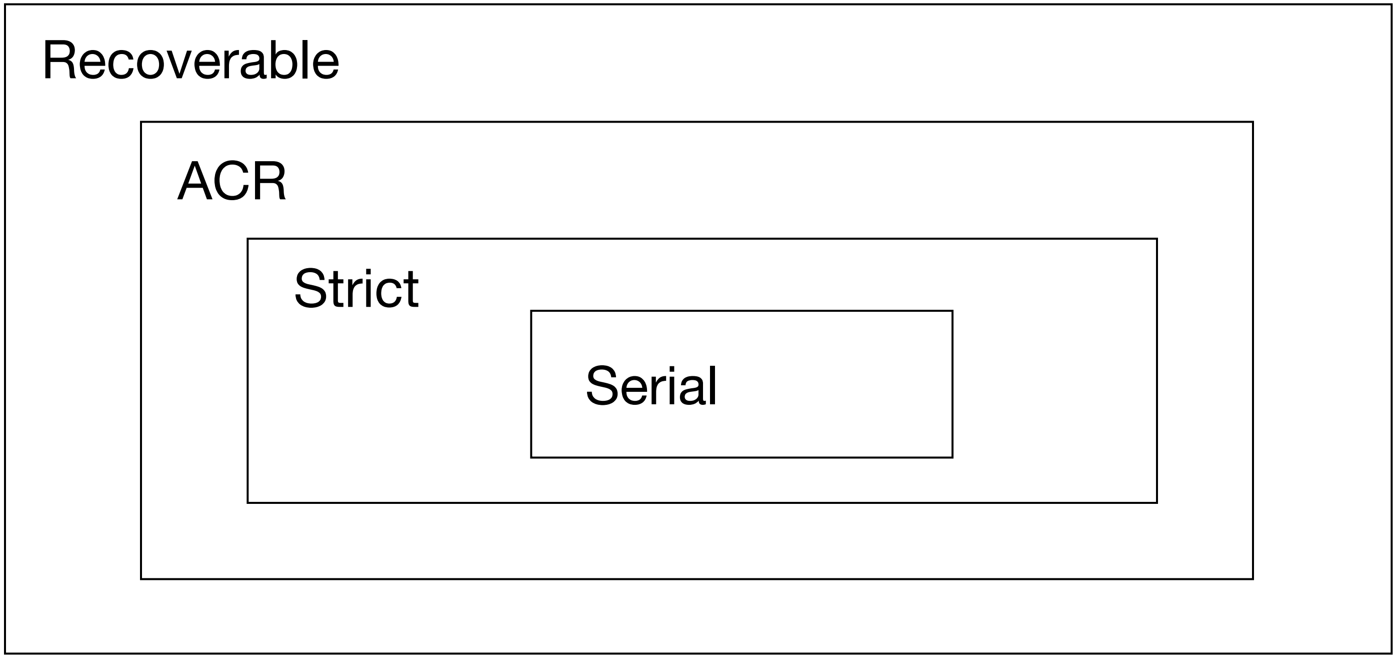
Definitions

S is **recoverable** if each transaction commits only after all transactions from which it read have committed

S **avoids cascading rollback** if each transaction may read only those values written by committed transactions

S is **strict** if each transaction may read and write only items previously written by committed transactions (≡ strict 2PL)

Relationship of Recoverable, ACR & Strict Schedules



Recoverable

ACR

Strict

Serial

Examples

Recoverable:

$w_1(A)\ w_1(B)\ w_2(A)\ r_2(B)\ c_1\ c_2$

Avoids Cascading Rollback:

$w_1(A)\ w_1(B)\ w_2(A)\ c_1\ r_2(B)\ c_2$

Strict:

$w_1(A)\ w_1(B)\ c_1\ w_2(A)\ r_2(B)\ c_2$

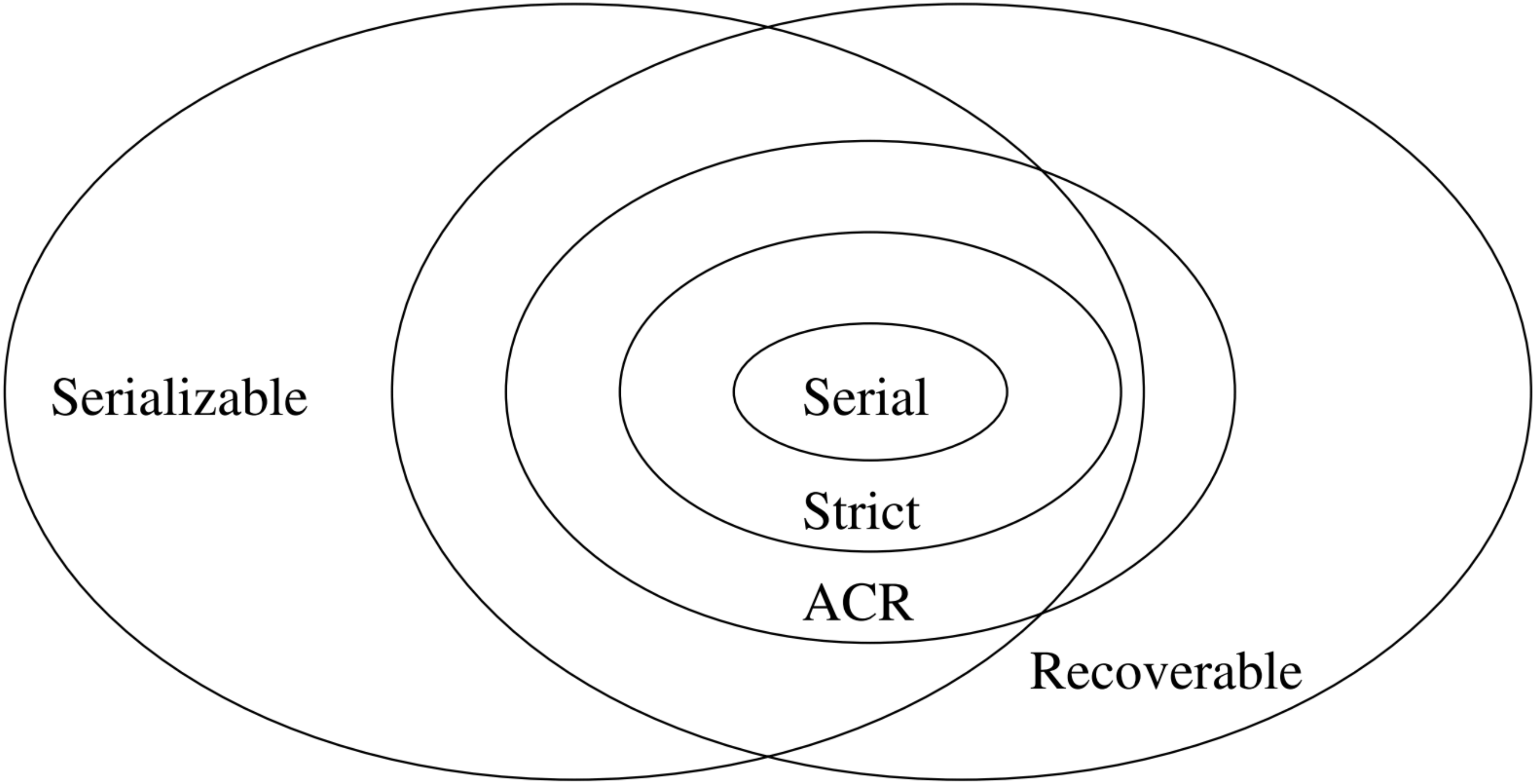
Recoverability & Serializability

Every strict schedule is serializable

Proof: equivalent to serial schedule based on the order of commit points

- » Only read/write from previously committed transactions

Recoverability & Serializability



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

Concurrency control + recovery

Beyond serializability

Weaker Isolation Levels

Dirty reads: Let transactions read values written by other uncommitted transactions

- » Equivalent to having long-duration write locks, but no read locks

Read committed: Can only read values from committed transactions, but they may change

- » Equivalent to having long-duration write locks (X) and short-duration read locks (S)

Weaker Isolation Levels

Repeatable reads: Can only read values from committed transactions, and each value will be the same if read again

- » Equivalent to having long-duration read & write locks (X/S) but not table locks for insert

Remaining problem: phantoms!

Weaker Isolation Levels

Snapshot isolation: Each transaction sees a consistent snapshot of the whole DB (as if we saved all committed values when it began)

- Often implemented with multi-version concurrency control (MVCC)

Still has some anomalies! Example?

Weaker Isolation Levels

Snapshot isolation: Each transaction sees a consistent snapshot of the whole DB (as if we saved all committed values when it began)

» Often implemented with multi-version concurrency control (MVCC)

Write skew anomaly: txns write different values

» Constraint: A+B ≥ 0

» T_1: read A, B; if A+B ≥ 1, subtract 1 from A

» T_2: read A, B; if A+B ≥ 1, subtract 1 from B

» Problem: what if we started with A=1, B=0?

Interesting Fact

Oracle calls their snapshot isolation level “serializable”, and doesn’t implement true serializable

Many other systems provide snapshot isolation as an option

- » MySQL, Postgres, MongoDB, SQL Server