Concurrency Control

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Invited Lectures

Extensible Databases - 28/10/2021

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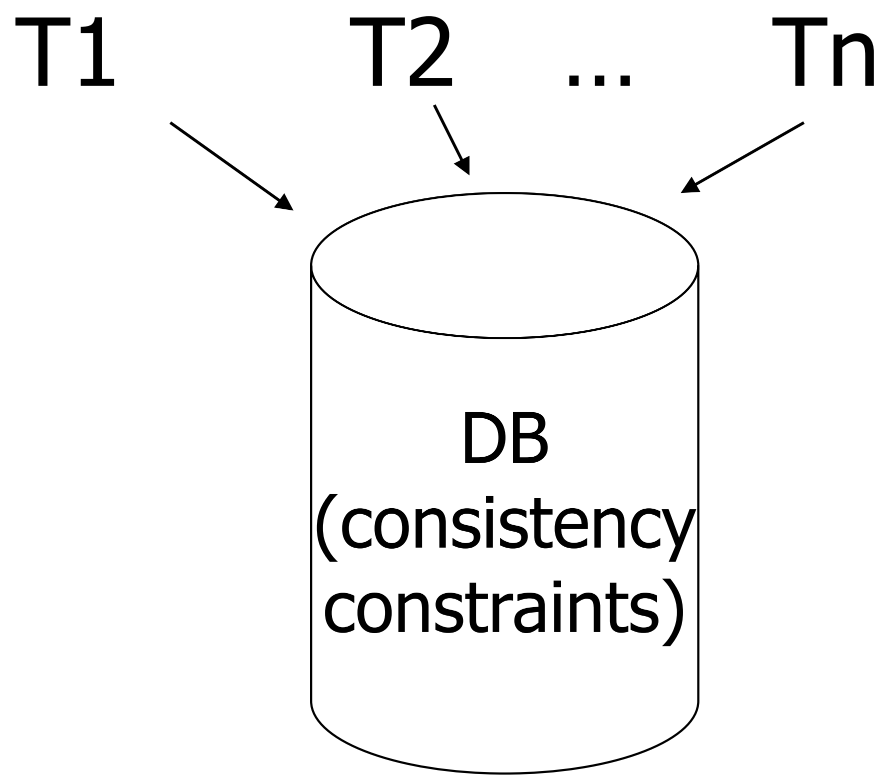
Chapter 18 [18] Concurrency Control



Example:

T1: Read(A)
$A \leftarrow A+100$
Write(A)
Read(B)
$B \leftarrow B+100$
Write(B)

T2: Read(A)
$A \leftarrow A\times 2$
Write(A)
Read(B)
$B \leftarrow B\times 2$
Write(B)

Constraint: $A=B$

Schedule A

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

DB constraints

A = B

Schedule A

T1	T2	A	B
		25	25
Read(A); A $\leftarrow$ A+100			
Write(A);		125	
Read(B); B $\leftarrow$ B+100;			
Write(B);			125
	Read(A);A $\leftarrow$ A$\times$2;		
	Write(A);	250	
	Read(B);B $\leftarrow$ B$\times$2;		
	Write(B);		250
		250	250

Schedule B

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

Schedule B

T1	T2	A	B
		25	25
	Read(A);A $\leftarrow$ A$\times$2;		
	Write(A);	50	
	Read(B);B $\leftarrow$ B$\times$2;		
	Write(B);		50
Read(A); A $\leftarrow$ A+100			
Write(A);		150	
Read(B); B $\leftarrow$ B+100;			
Write(B);			150
		150	150

Schedule C

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

Schedule C

T1	T2	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

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

Schedule D

T1	T2	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

no consistency

Schedule E

Same as Schedule D but with new T2′

T1	T2′
Read(A); A $\leftarrow$ A+100	
Write(A);	
	Read(A);A $\leftarrow$ A$\times$1;
	Write(A);
	Read(B);B $\leftarrow$ B$\times$1;
	Write(B);
Read(B); B $\leftarrow$ B+100;	
Write(B);	

Schedule E

Same as Schedule D but with new T2′

T1	T2′	A	B
		25	25
Read(A); $A \leftarrow A+100$			
Write(A);		125	
	Read(A); $A \leftarrow A \times 1$;		
	Write(A);	125	
	Read(B); $B \leftarrow B \times 1$;		
	Write(B);		25
Read(B); $B \leftarrow B+100$;			
Write(B);			125
		125	125

- Want schedules that are “good”, regardless of
  - initial state and
  - transaction semantics
- Only look at order of read and writes

Example:

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

Example:

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

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

The Transaction Game

A								
B								
T1								
T2								

The Transaction Game

A	**r**	**w**	**r**	**w**				
B					**r**	**w**	**r**	**w**
T1	**r**	**w**			**r**	**w**		
T2			**r**	**w**			**r**	**w**

The Transaction Game

A	r	w	r	w				
B					r	w	r	w
T1	r	w			r	w		
T2			r	w			r	w

until column hits something

can move column

but no collision allowed

⟹ we can't change the order of operations in the same query

A	r	w	r	w				
B					r	w	r	w
T1	r	w			r	w		
T2			r	w			r	w

move

move

A	r	w			r	w		
B			r	w			r	w
T1	r	w	r	w				
T2					r	w	r	w

Full T2

Full T1

$\Longrightarrow$ serializable

Schedule D

A	**r**	**w**	**r**	**w**				
B					**r**	**w**	**r**	**w**
T1	**r**	**w**					**r**	**w**
T2			**r**	**w**	**r**	**w**		

↳ no movement possible

⇒ not serializable

However, for Sd:

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

- as a matter of fact,

  T_2 must precede T_1

  in any equivalent schedule,

  i.e., $T_2 \rightarrow T_1$

- $T_2 \rightarrow T_1$
- Also, $T_1 \rightarrow T_2$

$$\begin{tikzcd} T_1 \arrow[r, bend left] & T_2 \arrow[l, bend left] \end{tikzcd}$$

⇨ Sd cannot be rearranged into a serial schedule

⇨ Sd is not "equivalent" to any serial schedule

⇨ Sd is "bad"

serializable = good
not serializable = bad

Returning to Sc

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

$$T_1 \rightarrow T_2 \qquad\qquad T_1 \rightarrow T_2$$

Returning to Sc

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

$$T_1 \rightarrow T_2 \qquad\qquad T_1 \rightarrow T_2$$

☛ no cycles $\Rightarrow$ Sc is "equivalent" to a serial schedule (in this case T_1,T_2)

Concepts

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

Conflicting actions: $r_1(A)$ / $w_2(A)$ $w_2(A)$ / $r_1(A)$ $w_1(A)$ / $w_2(A)$

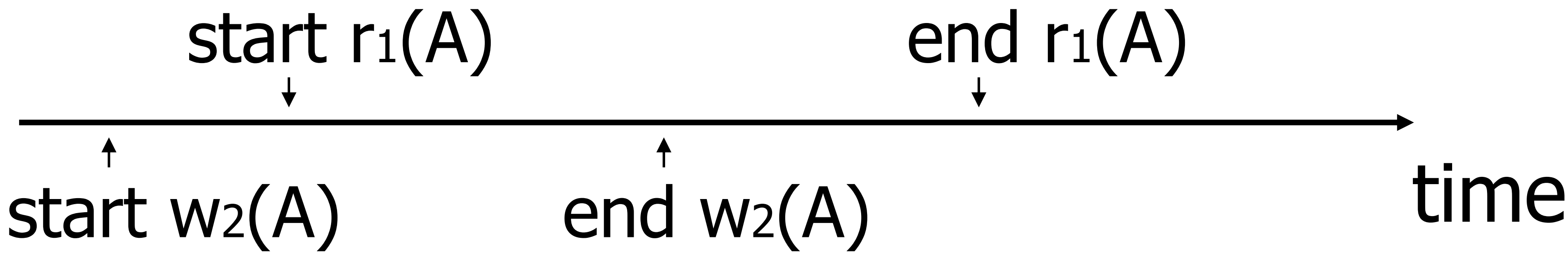
Schedule: represents chronological order in which actions are executed

Serial schedule: no interleaving of actions or transactions

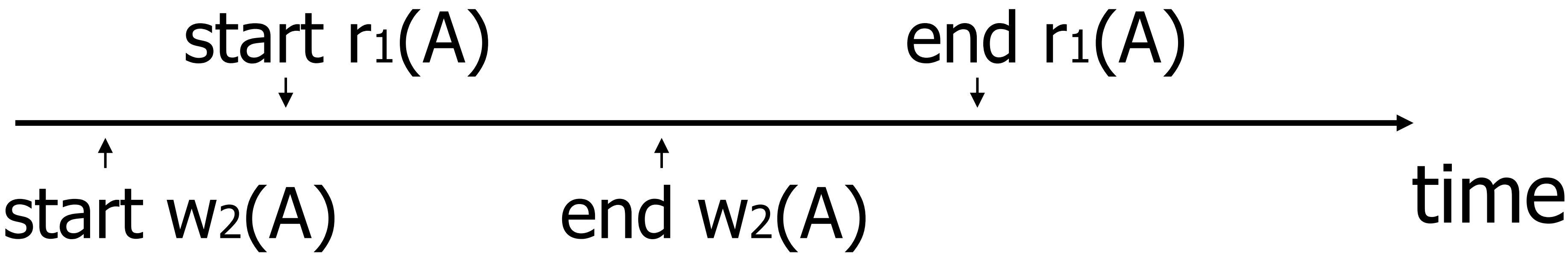
Is it OK to model reads & writes as occurring at a single point in time in a schedule?

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

What about conflicting, concurrent actions on same object?



What about conflicting, concurrent actions on same object?



- Assume equivalent to either $r_1(A)\ w_2(A)$

  or $w_2(A)\ r_1(A)$

- $\Rightarrow$ low level synchronization mechanism
- Assumption called “atomic actions”

Definition

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

Definition

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

Precedence graph P(S) (S is schedule)

Nodes: transactions in S

Arcs: Ti $\rightarrow$ Tj whenever

- $p_i(A)$, $q_j(A)$ are actions in S
- $p_i(A) <_S q_j(A)$
- at least one of p_i, q_j is a write

Exercise:

- What is P(S) for
  $S = w_3(A)\ w_2(C)\ r_1(A)\ w_1(B)\ r_1(C)\ w_2(A)\ r_4(A)\ w_4(D)$

$$\begin{tikzcd}
T_1 \arrow[r] & T_2 \arrow[l, bend right] \arrow[d] \\
T_3 \arrow[u] \arrow[ur] \arrow[r] & T_4
\end{tikzcd}$$

- Is S serializable?

Another Exercise:

- What is P(S) for
  S = $w_1(A)\ r_2(A)\ r_3(A)\ w_4(A)$?

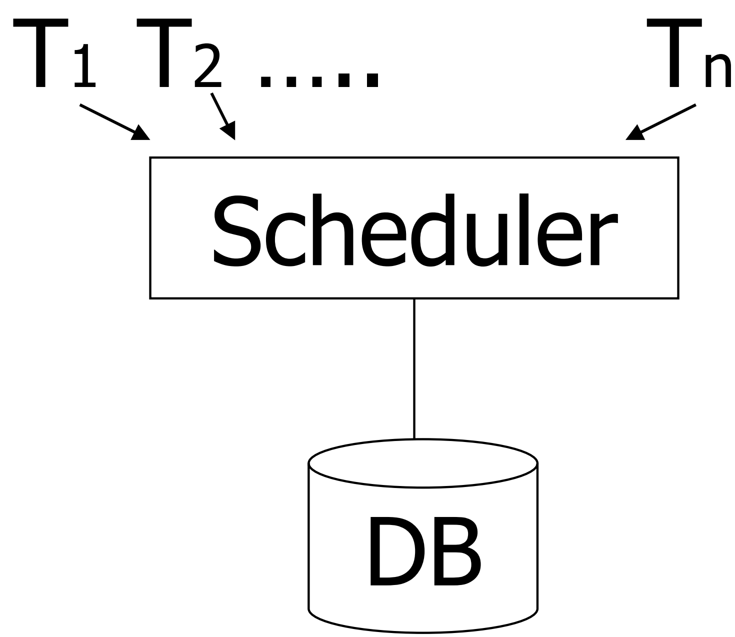
$$\begin{tikzcd} T_1 \arrow[r] \arrow[d] \arrow[dr] & T_2 \arrow[d] \\ T_3 \arrow[r] & T_4 \end{tikzcd}$$

How to enforce serializable schedules?

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

How to enforce serializable schedules?

Option 2: prevent P(S) cycles from occurring

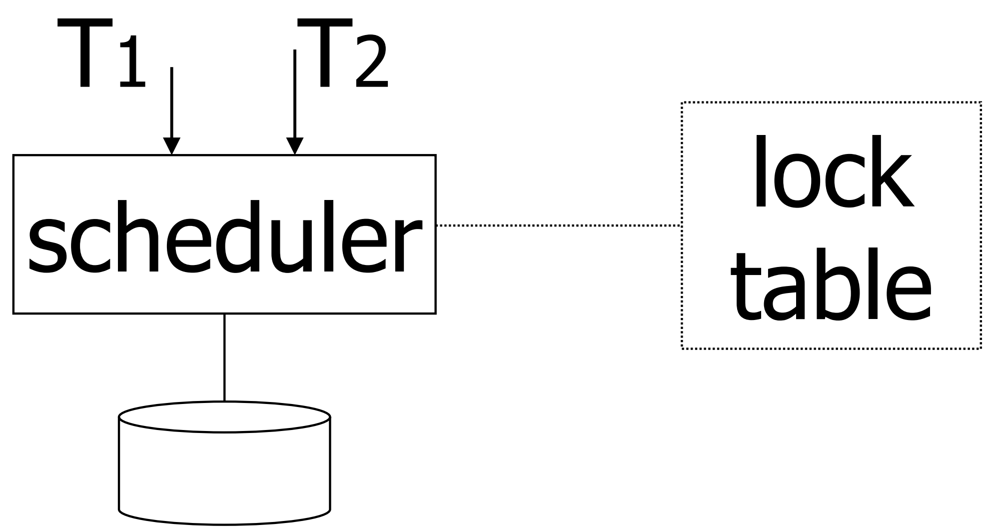


A locking protocol

Two new actions:

lock (exclusive): l_i (A)

unlock: u_i (A)



Rule #1: Well-formed transactions

T_i: … $l_i(A)$ … $p_i(A)$ … $u_i(A)$ ...

Rule #2 Legal scheduler

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

no $l_j(A)$

Exercise:

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

  S1 = $l_1(A)l_1(B)r_1(A)w_1(B)\boxed{l_2(B)}u_1(A)u_1(B)$
  $r_2(B)w_2(B)u_2(B)l_3(B)r_3(B)u_3(B)$

  S2 = $l_1(A)r_1(A)w_1(B)u_1(A)\boxed{u_1(B)}$
  $l_2(B)r_2(B)w_2(B)\boxed{l_3(B)}r_3(B)u_3(B)$ $u_2(B)$?

  S3 = $l_1(A)r_1(A)u_1(A)l_1(B)w_1(B)u_1(B)$
  $l_2(B)r_2(B)w_2(B)u_2(B)l_3(B)r_3(B)u_3(B)$ V

Exercise:

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

  S1 = $l_1(A)l_1(B)r_1(A)w_1(B)l_2(B)u_1(A)u_1(B)$
  $r_2(B)w_2(B)u_2(B)l_3(B)r_3(B)u_3(B)$

  S2 = $l_1(A)r_1(A)w_1(B)u_1(A)u_1(B)$
  $l_2(B)r_2(B)w_2(B)l_3(B)r_3(B)u_3(B)$ $u_2(B)$?

  S3 = $l_1(A)r_1(A)u_1(A)l_1(B)w_1(B)u_1(B)$
  $l_2(B)r_2(B)w_2(B)u_2(B)l_3(B)r_3(B)u_3(B)$

Schedule F

T1	T2
l_1(A);Read(A)	
A $\leftarrow$ A+100;Write(A);u_1(A)	
	l_2(A);Read(A)
	A $\leftarrow$ Ax2;Write(A);u_2(A)
	l_2(B);Read(B)
	B $\leftarrow$ Bx2;Write(B);u_2(B)
l_1(B);Read(B)	
B $\leftarrow$ B+100;Write(B);u_1(B)	

Schedule F

T1	T2	A	B
		25	25
l_1(A);Read(A)			
A←A+100;Write(A);u_1(A)		125	
	l_2(A);Read(A)		
	A←Ax2;Write(A);u_2(A)	250	
	l_2(B);Read(B)		
	B←Bx2;Write(B);u_2(B)		50
l_1(B);Read(B)			
B←B+100;Write(B);u_1(B)			150
		250	150

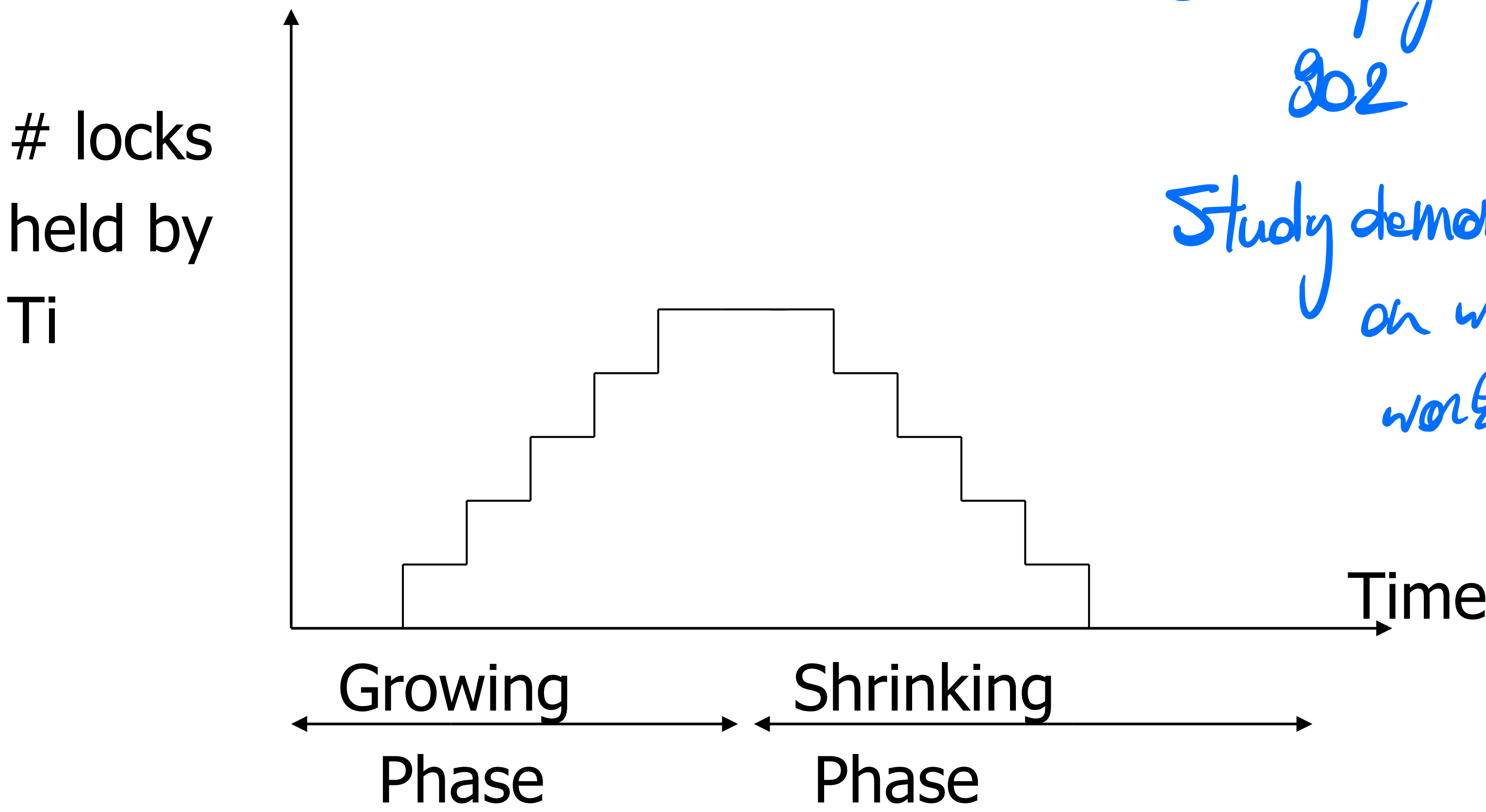
Rule #3 Two phase locking (2PL)

for transactions

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

no unlocks

no locks



Book page:
902

Study demonstration
on why it
works

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)
	$A \leftarrow Ax2$;Write(A);$l_2(B)$

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)
	$A \leftarrow Ax2$;Write(A);$l_2(B)$ delayed
Read(B);$B \leftarrow B+100$	
Write(B); $u_1(B)$	

Schedule G

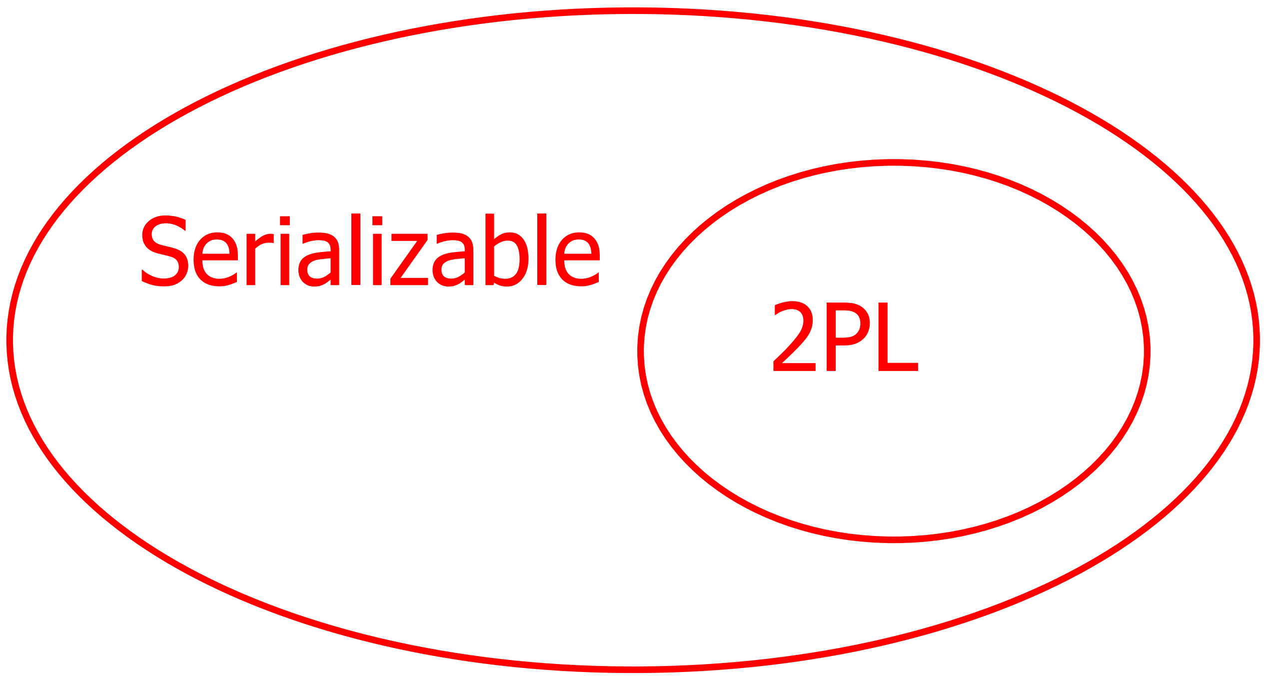
T1	T2
$l_1(A)$;Read(A)	
$A \leftarrow A+100$;Write(A)	
$l_1(B)$; $u_1(A)$	
	delayed
	$l_2(A)$;Read(A)
	$A \leftarrow Ax2$;Write(A);$l_2(B)$
Read(B);$B \leftarrow B+100$	
Write(B); $u_1(B)$	
	$l_2(B)$; $u_2(A)$;Read(B)
	$B \leftarrow Bx2$;Write(B);$u_2(B)$;

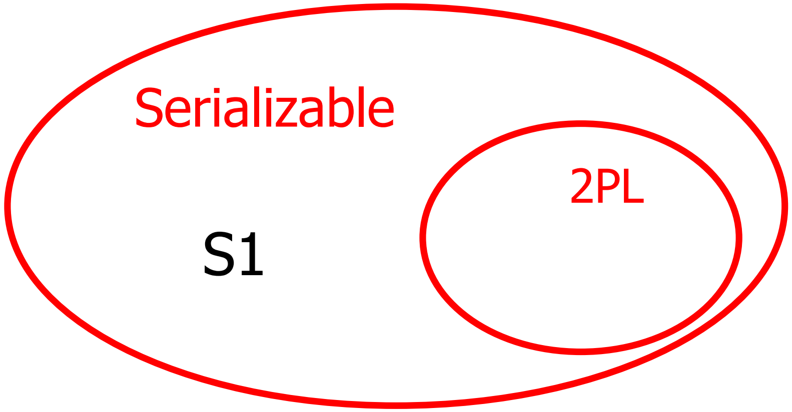
Schedule H (T2 reversed)

T1	T2
l_1(A); Read(A)	l_2(B);Read(B)
A $\leftarrow$ A+100;Write(A)	B $\leftarrow$ Bx2;Write(B)
l_1(B)	l_2(A)
delayed	delayed

2 Phase Locking

2PL subset of Serializable

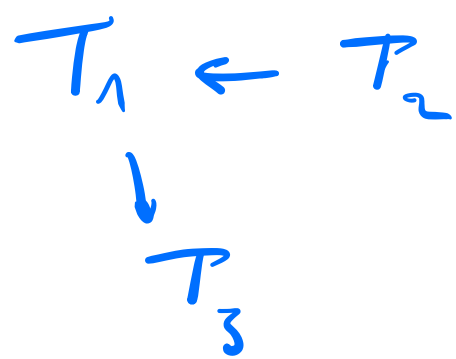




S1: w1(x) w3(x) w2(y) w1(y)

S1: w1(x) w3(x) w2(y) w1(y)

- S1 cannot be achieved via 2PL:
  The lock by T1 for y must occur after w2(y), so the unlock by T1 for x must occur after this point (and before w1(x)). Thus, w3(x) cannot occur under 2PL where shown in S1 because T1 holds the x lock at that point.
- However, S1 is serializable (equivalent to T2, T1, T3).



If you need a bit more practice:

Are our schedules S_C and S_D 2PL schedules?

$l_1 A$ $\quad$ $l_2 A$ X $\quad$ $l_1 B$ $\quad$ $l_2 B$

S_C: w1(A) w2(A) w1(B) w2(B) $\Rightarrow$ not 2PL

require A but it won't be unlocked before

$T_1 \rightarrow T_2$ serializable

$l_1 A$

S_D: w1(A) w2(A) w2(B) w1(B)

$l_2 A$ X

$T_1 \rightleftarrows T_2$ not serializable

$\Rightarrow$ not 2PL

- 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

concurrency control

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:

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

Do not conflict

Instead:

$S = \ldots\ ls_1(A)\ r_1(A)\ ls_2(A)\ r_2(A)\ \ldots.\ us_1(A)\ us_2(A)$

Lock actions (Shared, Exclusive)

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

$u\text{-}t_i(A)$: unlock t mode (t 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) ...

- What about transactions that read and write same object?

<u>Option 1:</u> Request exclusive lock

$T_i = \ldots l\text{-}X_1(A) \ldots r_1(A) \ldots w_1(A) \ldots u(A) \ldots$

- What about transactions that read and write same object?

Option 2: Upgrade

(E.g., need to read, but don't know if will write…)

T_i=… l-S_1(A) … r_1(A) … l-X_1(A) …w_1(A) …u(A)…

Think of
- Get 2nd lock on A, or
- Drop S, get X lock

Rule #2 Legal scheduler

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

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

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

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

A way to summarize Rule #2

Compatibility matrix

Comp

	S	X
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 (shared)
lock (e.g., S $\rightarrow$ X)
- can be allowed in growing phase

Lock types beyond S/X

Examples:

(1) increment lock

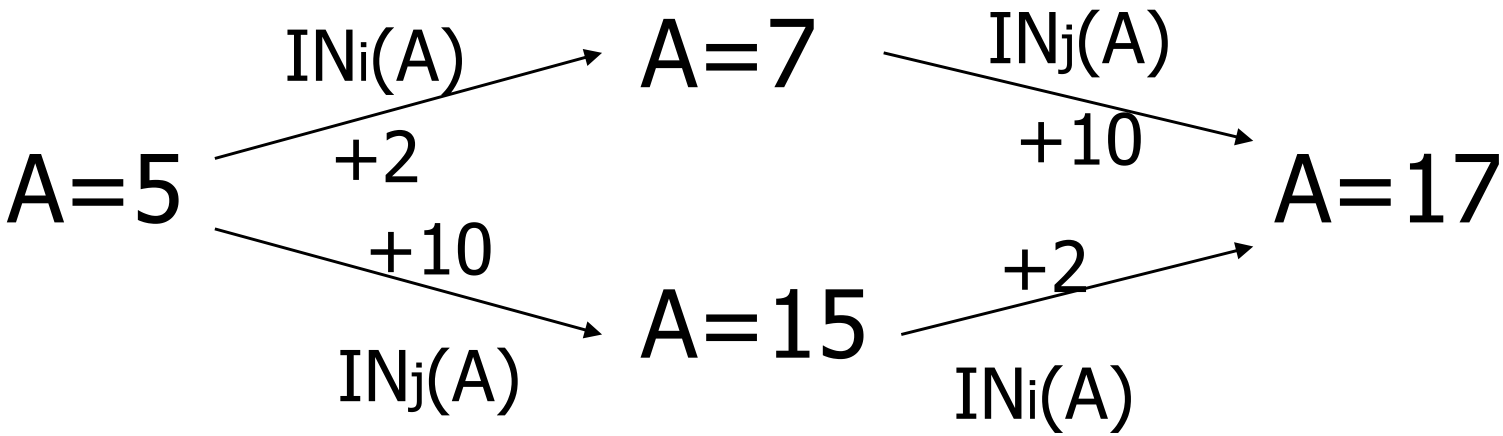
(2) update lock

Example (1): increment lock

- Atomic increment action: $IN_i(A)$

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

- $IN_i(A)$, $IN_j(A)$ do not conflict!



Comp

	S	X	I
S			
X			
I			

Comp

	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 T_i wants to read A and knows it may later want to write A, it requests update lock (not shared) won't even read

Comp

New request

Lock already held in

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

allowed because shared won't write ⇒

could do a read maybe

not allowed because

not allowed because update lock might write in close future

New request

Comp

Lock already held in

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

<u>Note:</u> object A may be locked in different modes at the same time...

we have an update lock on A

$S_1 = \ldots l\text{-}S_1(A) \ldots l\text{-}S_2(A) \ldots l\text{-}U_3(A) \ldots \begin{cases} \cancel{l\text{-}S_4(A)} \ldots ? \\ l\text{-}U_4(A) \ldots ? \end{cases}$

Note: object A may be locked in different modes at the same time...

$$S_1 = \ldots l\text{-}S_1(A) \ldots l\text{-}S_2(A) \ldots l\text{-}U_3(A) \ldots \begin{cases} l\text{-}S_4(A) \ldots ? \\ l\text{-}U_4(A) \ldots ? \end{cases}$$

- To grant a lock in mode t, mode t must be compatible with all currently held locks on object

How does locking work in practice?

- Every system is different

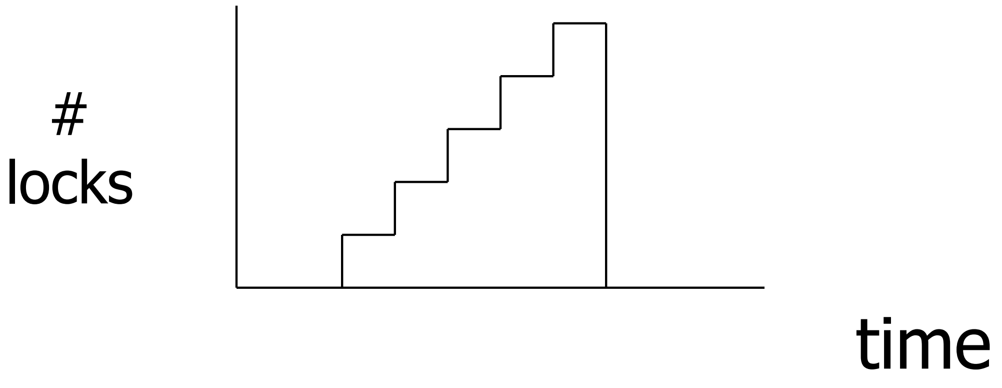
  (E.g., may not even provide
  CONFLICT-SERIALIZABLE schedules)

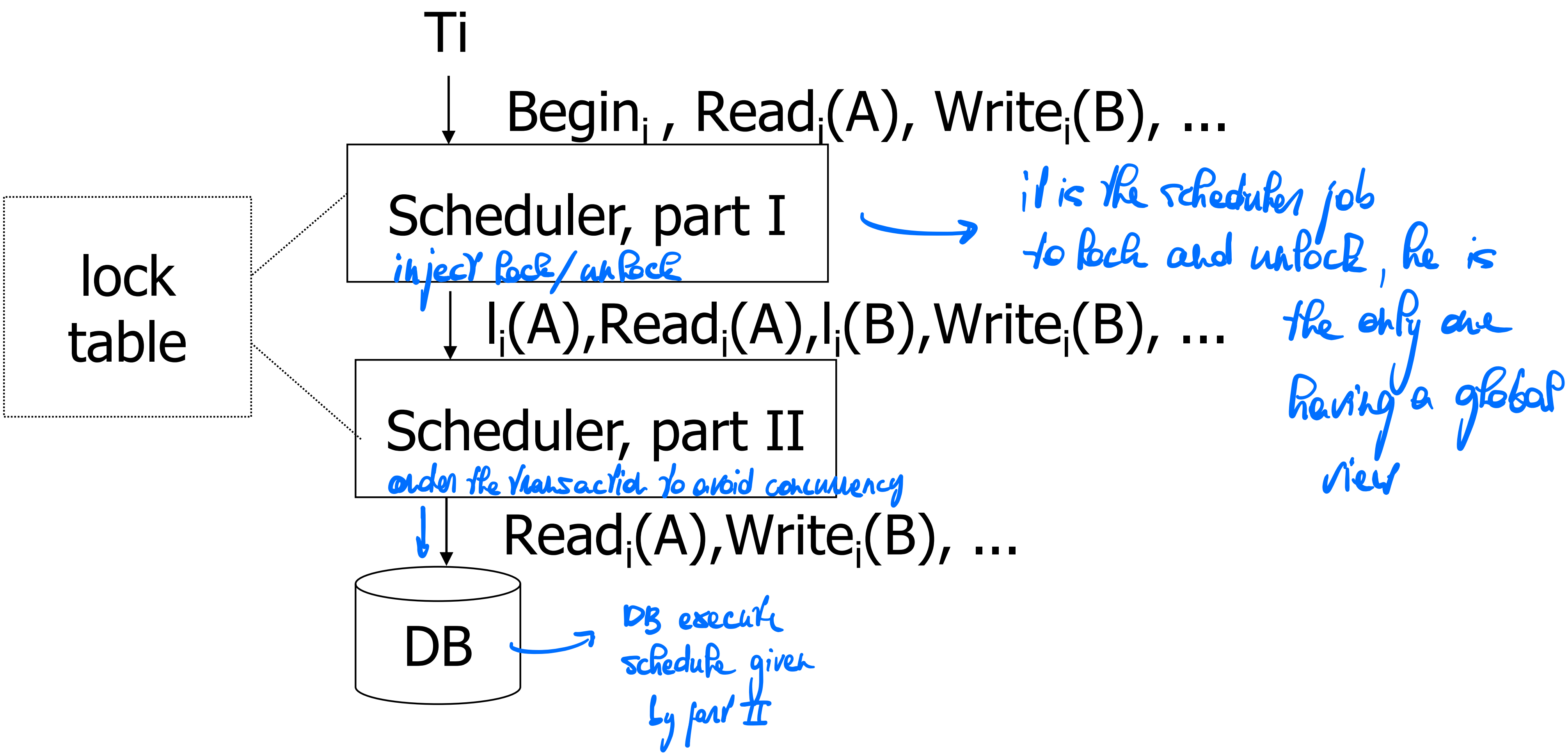
- But here is one (simplified) way ...

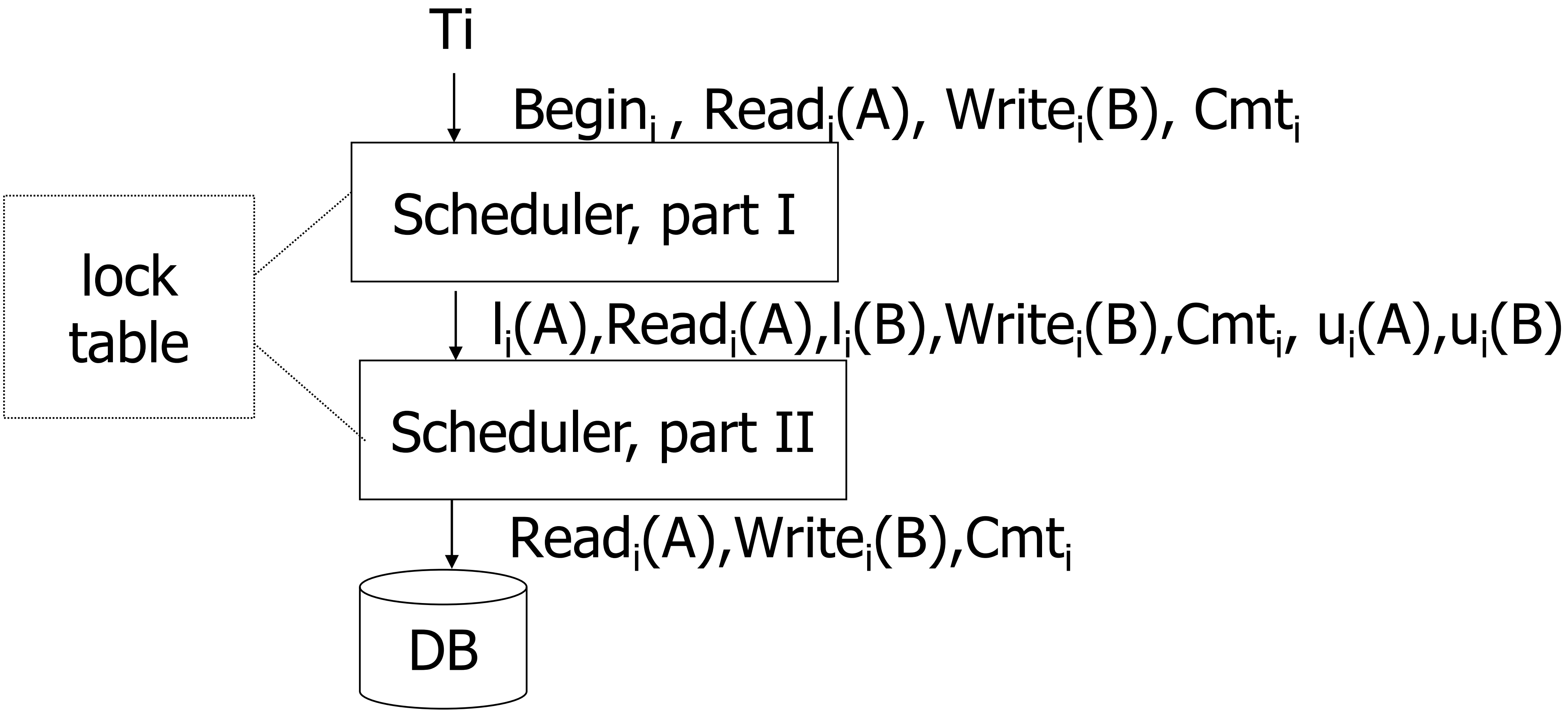
Sample Locking System:

(1) Don't trust transactions to
request/release locks

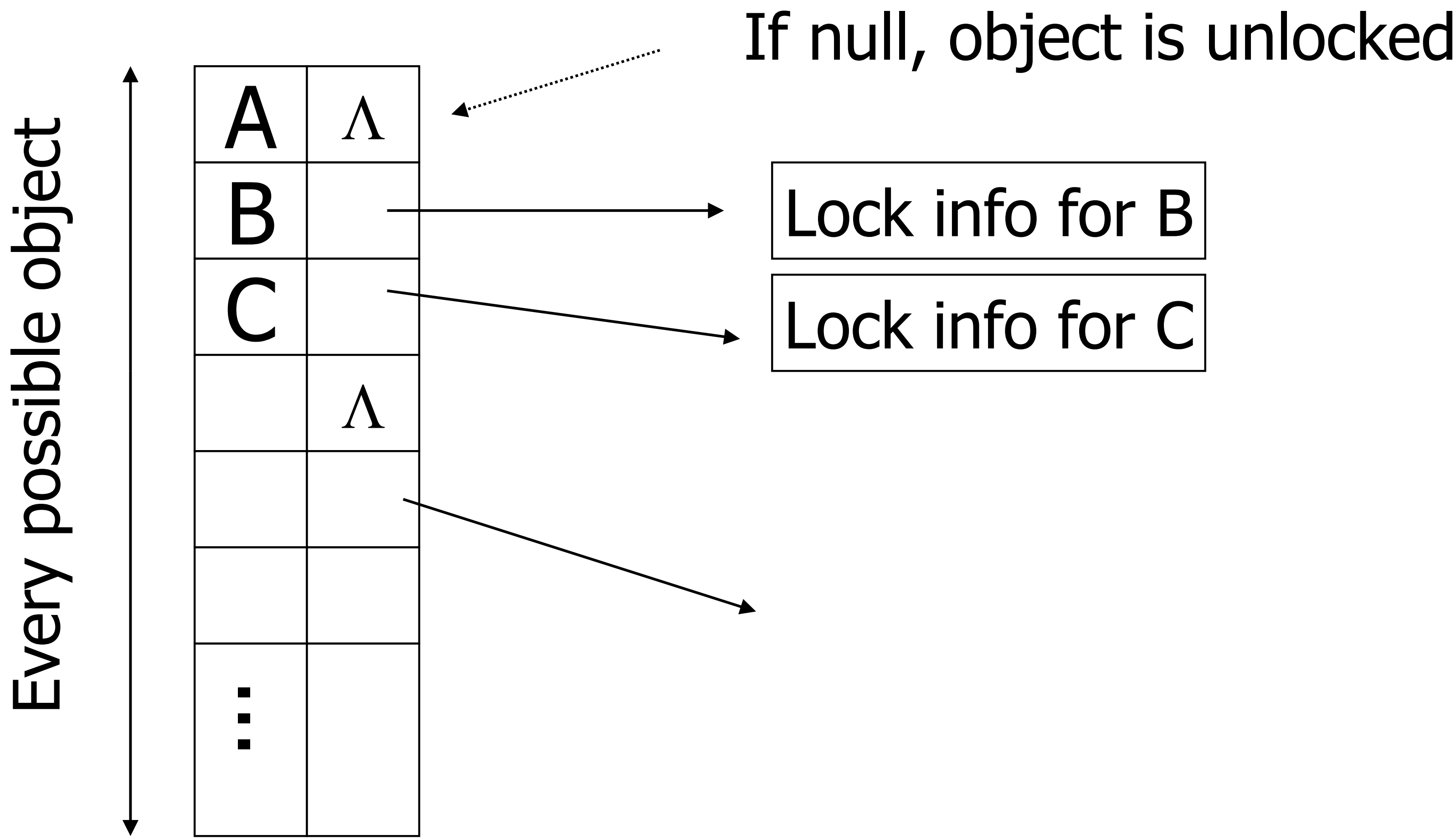
(2) Hold all locks until transaction
commits



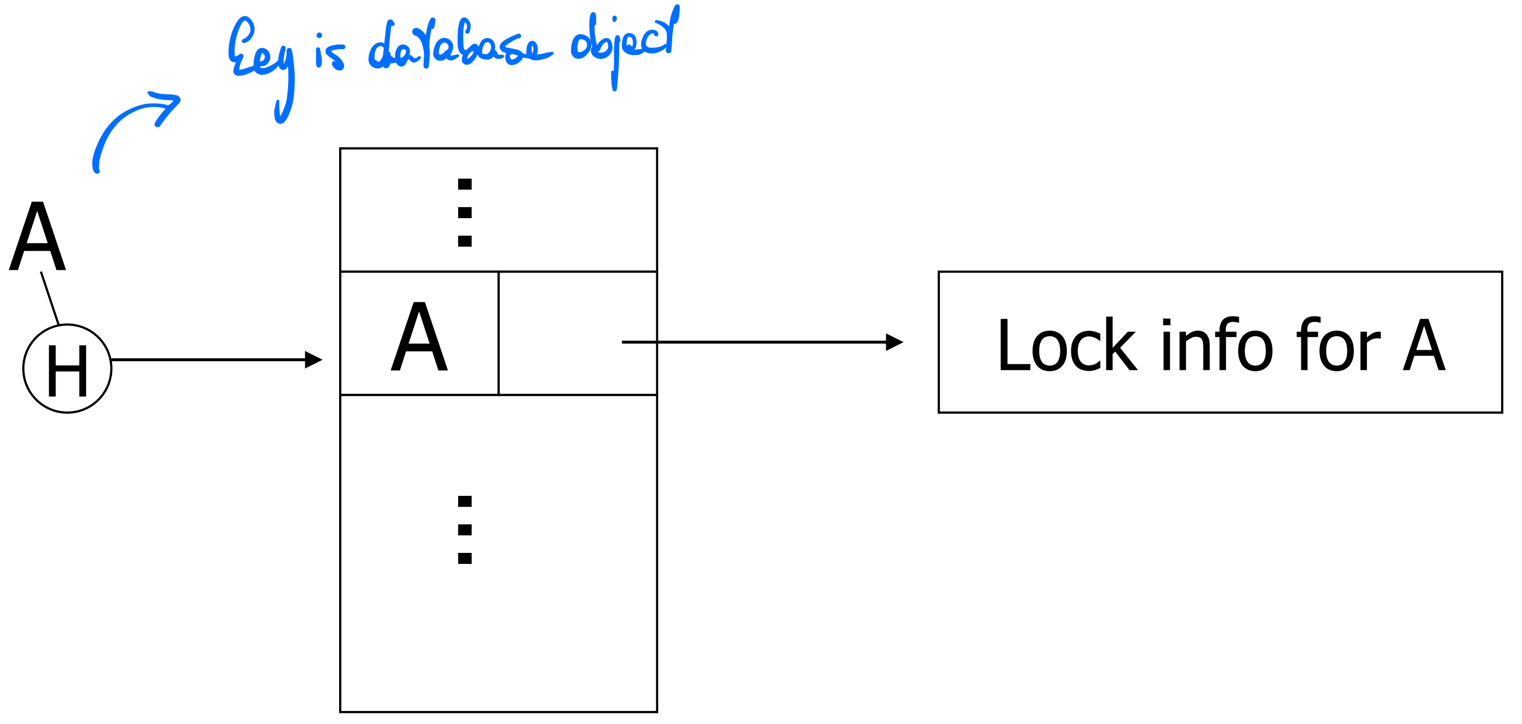

Ti
Begin_i , $\mathrm{Read}_i(A)$, $\mathrm{Write}_i(B)$, ...
Scheduler, part I
inject lock/unlock
it is the scheduler job to lock and unlock, he is the only one having a global view
lock table
$l_i(A)$,$\mathrm{Read}_i(A)$,$l_i(B)$,$\mathrm{Write}_i(B)$, ...
Scheduler, part II
order the transaction to avoid concurrency
$\mathrm{Read}_i(A)$,$\mathrm{Write}_i(B)$, ...
DB
DB execute schedule given by part II


Ti
$Begin_i$, $Read_i(A)$, $Write_i(B)$, Cmt_i
lock table
Scheduler, part I
$l_i(A)$,$Read_i(A)$,$l_i(B)$,$Write_i(B)$,Cmt_i, $u_i(A)$,$u_i(B)$
Scheduler, part II
$Read_i(A)$,$Write_i(B)$,Cmt_i
DB

Lock table Conceptually



But use hash table:



If object not found in hash table, it is unlocked

Lock info for A - example

chain the information about the database object

because might have multiple locks

Object:A
Group mode:U
Waiting:yes
List:

the most strict lock

between those in application

Hash Table

pointing to a linked list

tran	mode	wait?	Nxt	T_link
T1	S	no		
T2	U	no		
T3	X	yes	Λ	

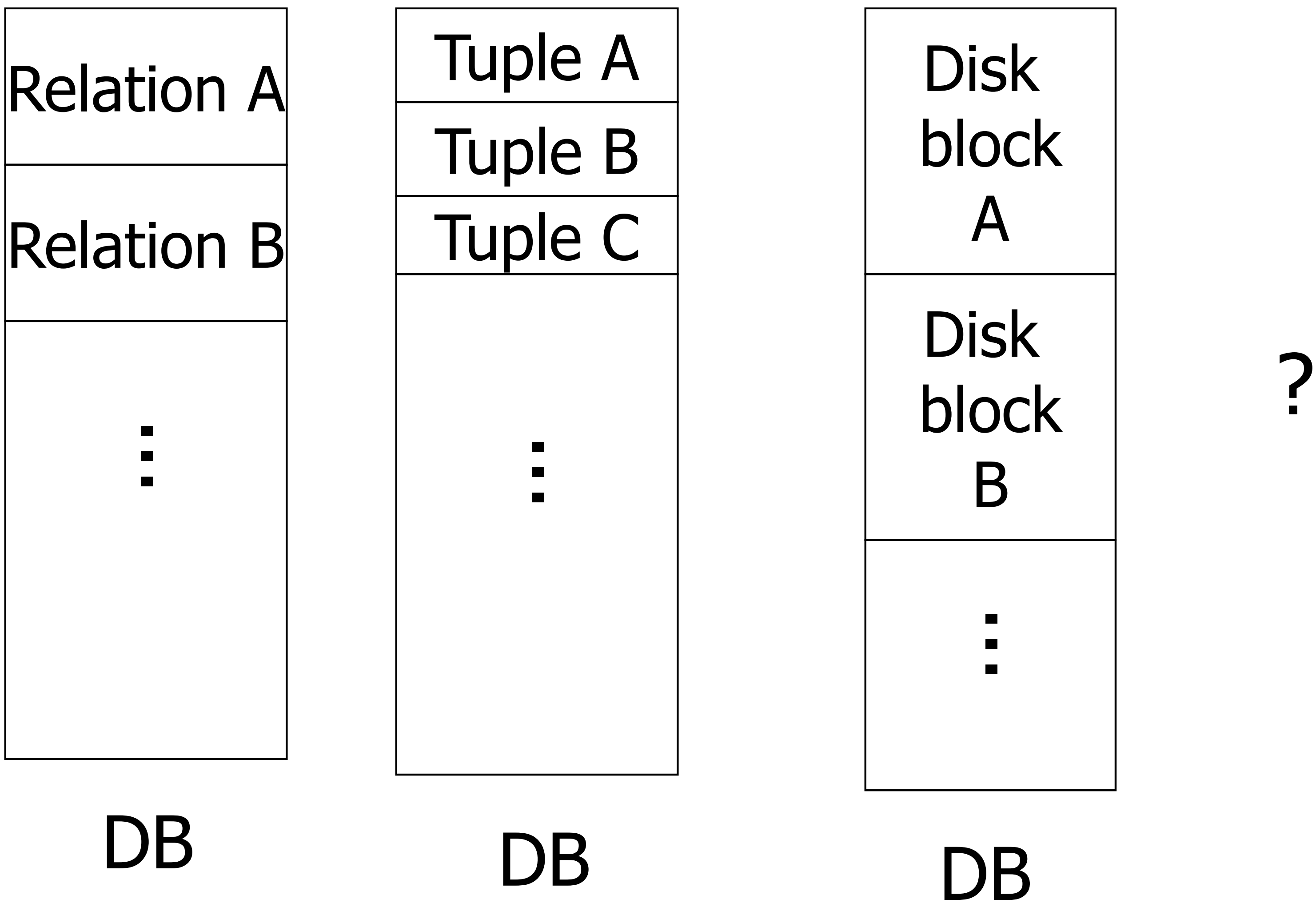
allows to reach all the locks that the transaction uses

must wait because can't X-lock on other lock

To other T3 records

Transaction order is FIFO

What are the objects we lock?

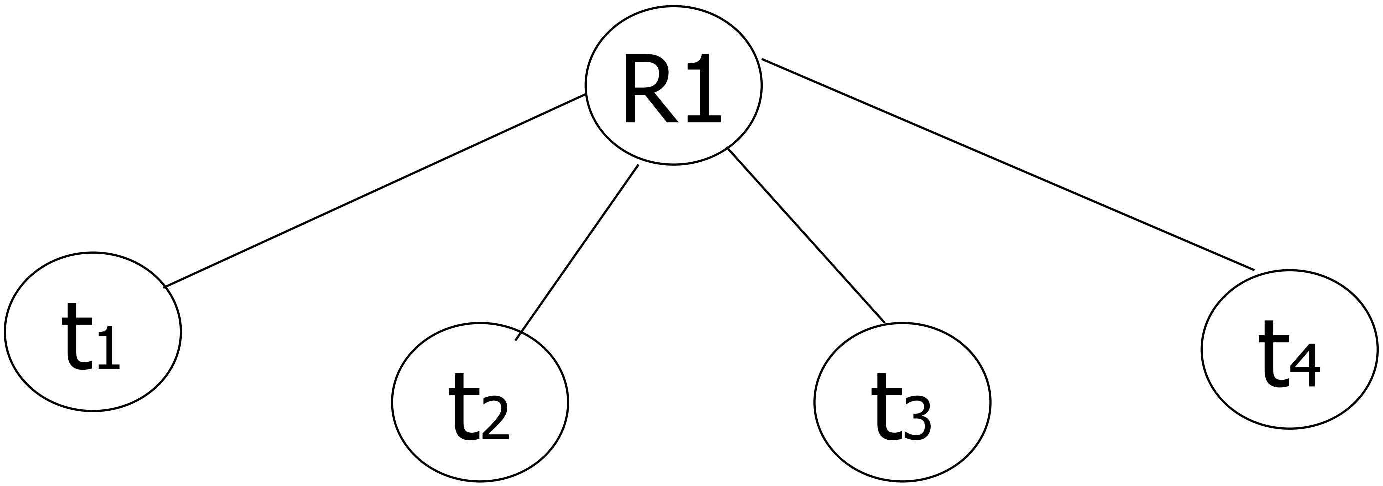


- Locking works in any case, but should we choose small or large objects?

- Locking works in any case, but should we choose <u>small</u> or <u>large objects?</u>

- If we lock <u>large</u> objects (e.g., Relations)
  - Need few locks
  - Low concurrency
- If we lock small objects (e.g., tuples,fields)
  - Need more locks
  - More concurrency

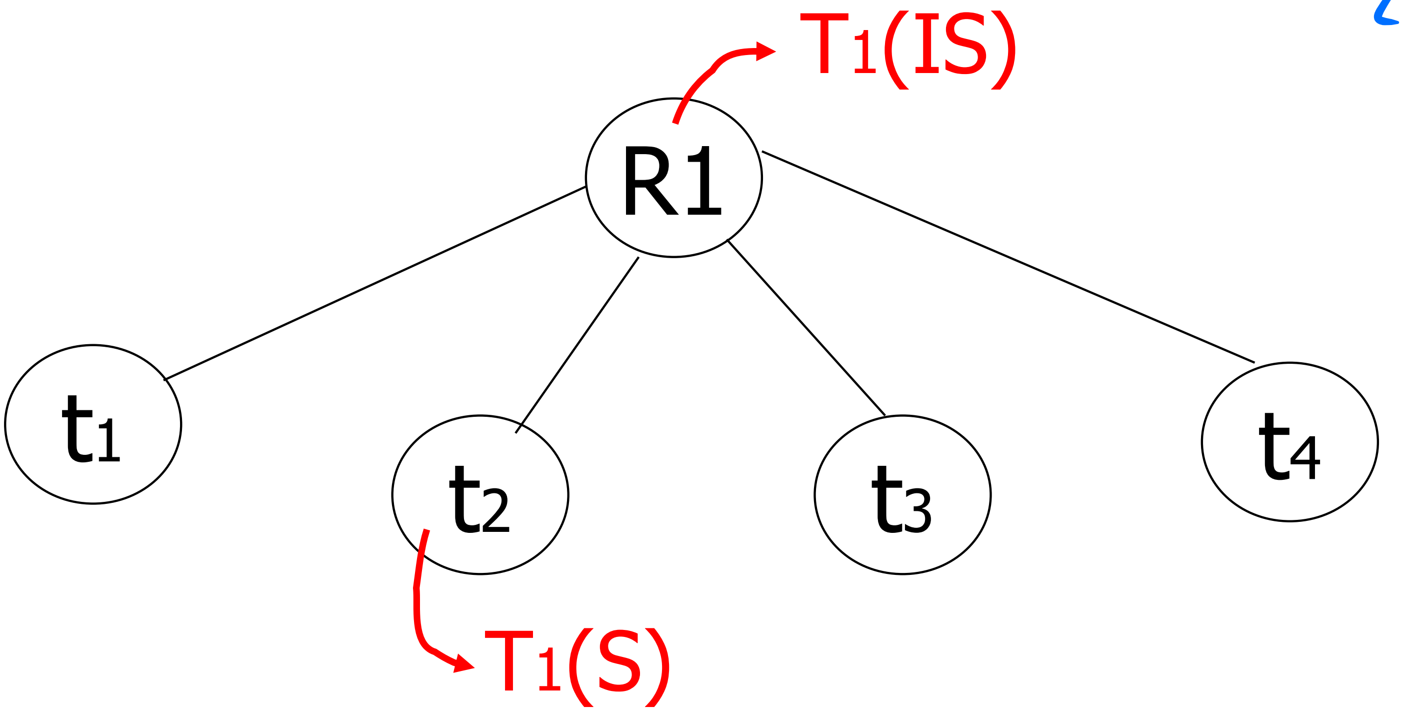
Example



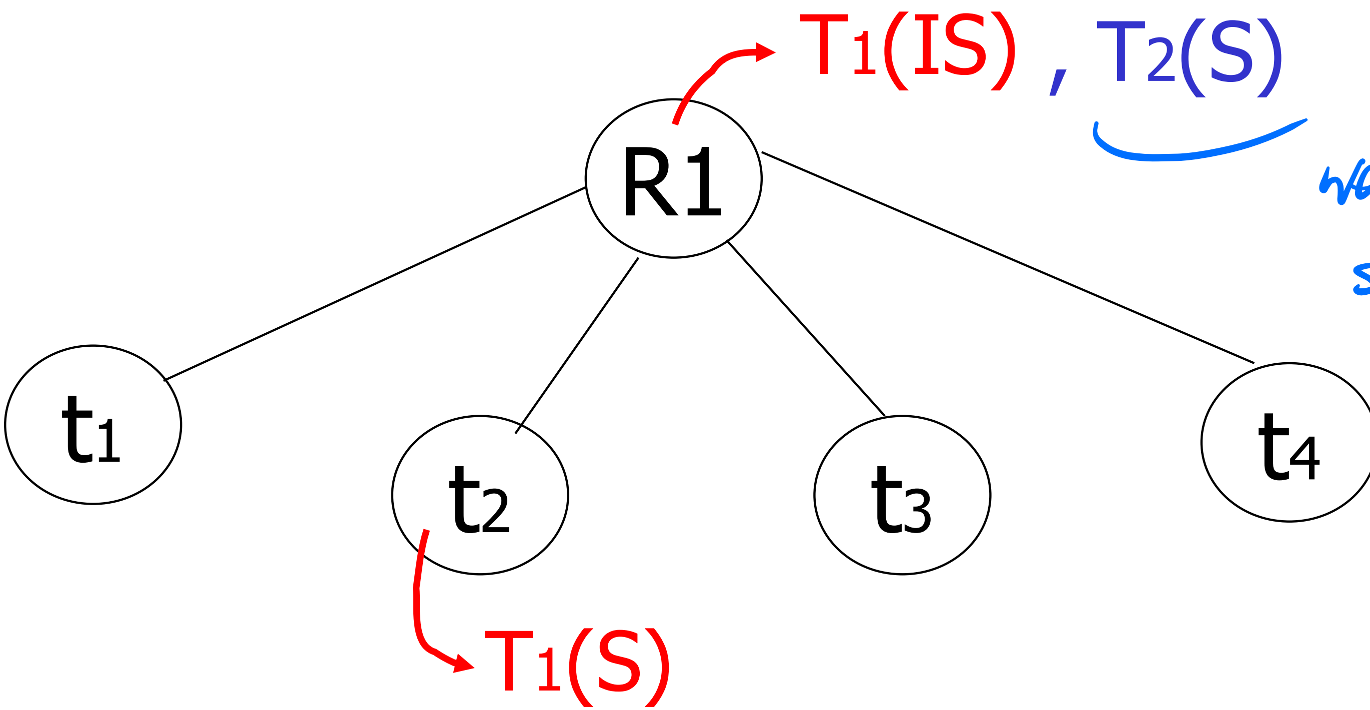
Example

T_1 want to use t_2 $\Rightarrow$ 1. lock at relation level

2. lock the tuple



Example

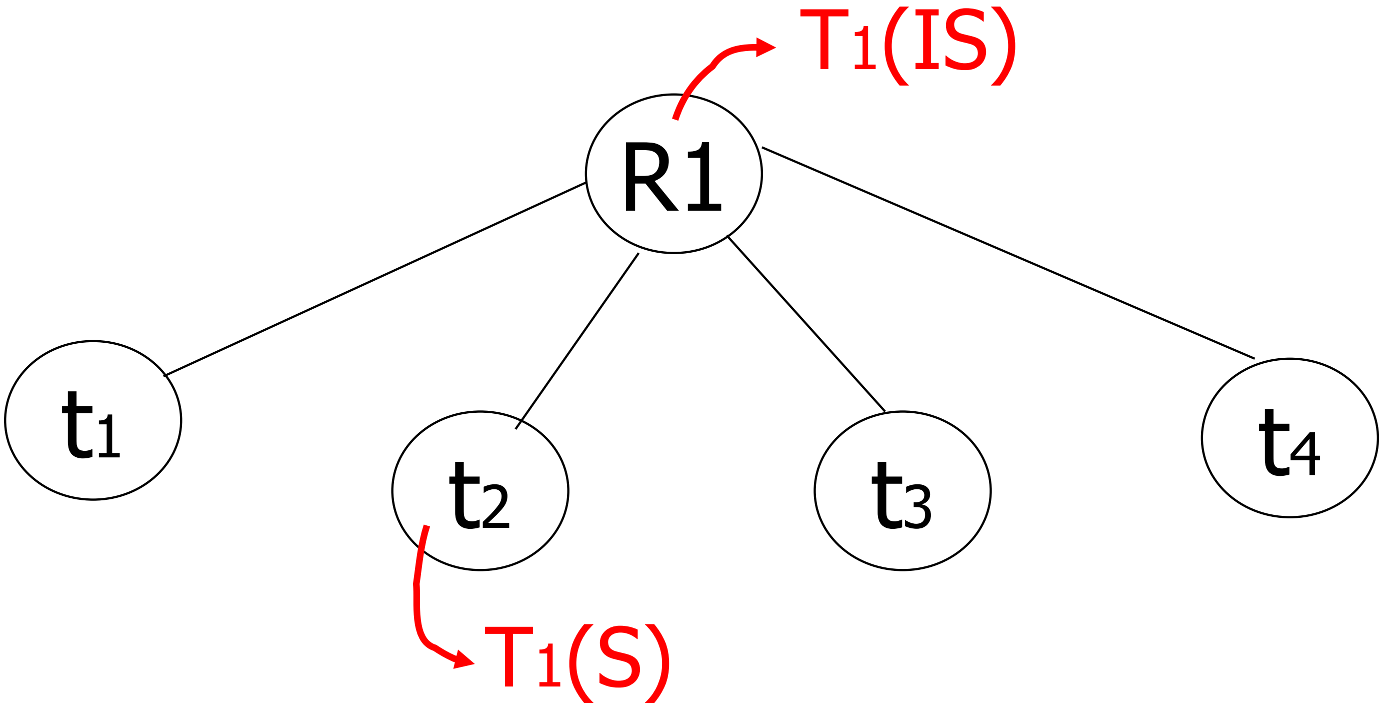


stored at higher granularity

wants to hold a share lock on the whole relation

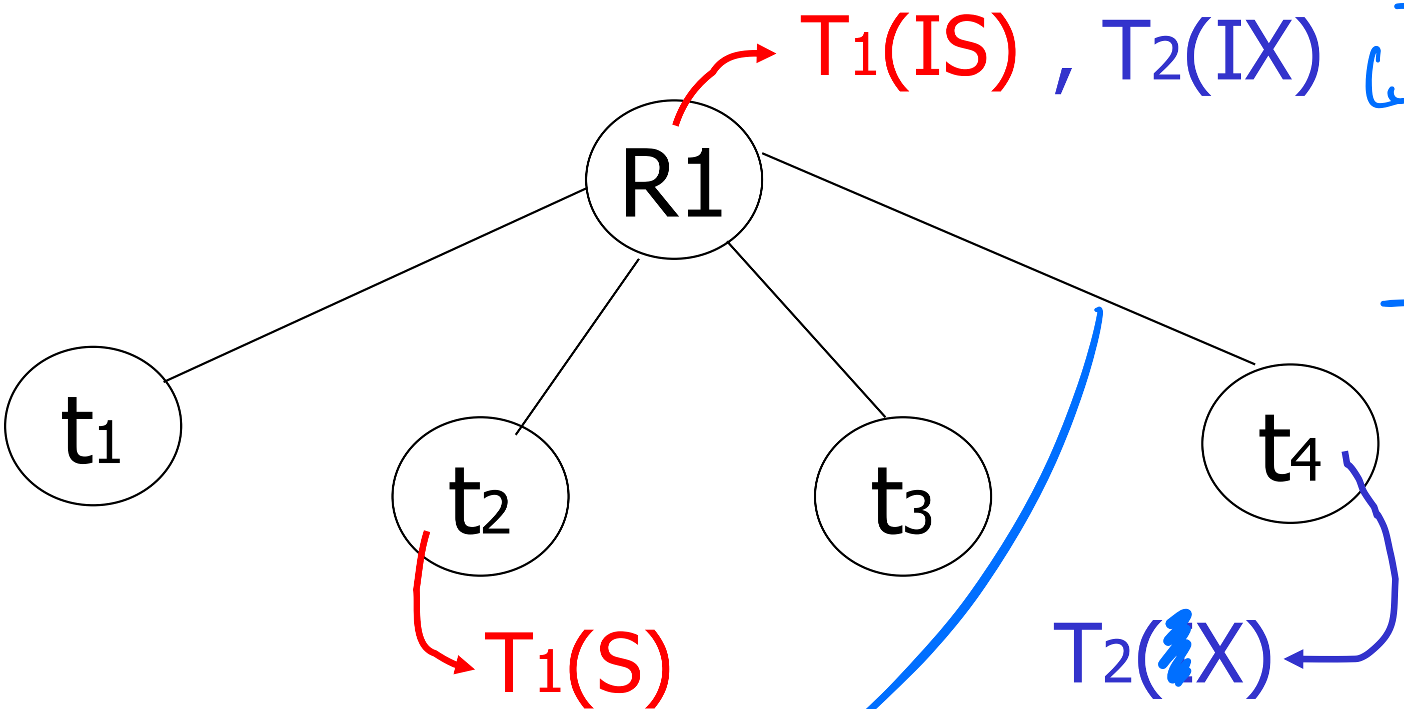
no problem, can be granted since only shared

Example (b)



Example

want to write
on part of R1
↳ conflict?
don't know yet
→ grant
intentional
lock



↳ don't cause
concurrency
⇒ ok

new combination
of locks

⇒ First ask for the lock on the parent, then only we can ask
for a lock on the child → top-down, if relation already

blocked, no need to go deeper, just don't grant yet

Multiple granularity

intentional

Comp Requestor

		IS	IX	S	SIX	X
	IS					
Holder	IX					
	S					
	SIX					
	X					

U I

Multiple granularity

can combine, since we don't know which part yet

Comp Requestor

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

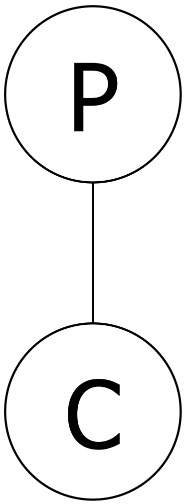
AND

i'm going to change values and nobody can disrupt me while i do so

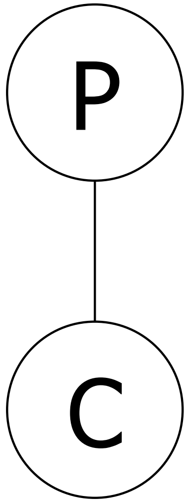
+ can't read values that i'm locking

still full X can't be combined

Parent locked in	Child can be locked in
IS	S, IS, if other children befor
IX	X, IX, S, IX, SIX
S	✓
SIX	X, IX, [SIX]
X	✓



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



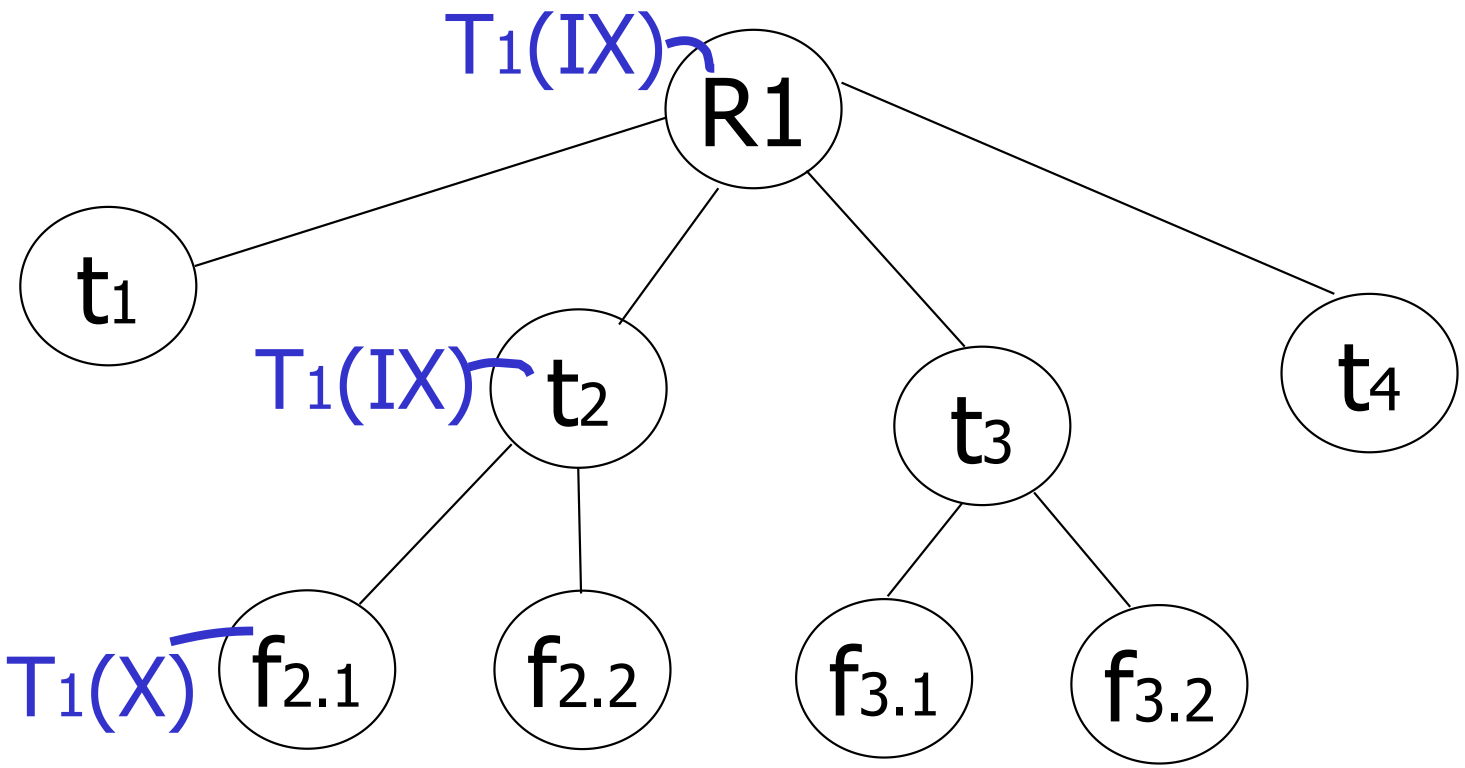
not necessary

Rules

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

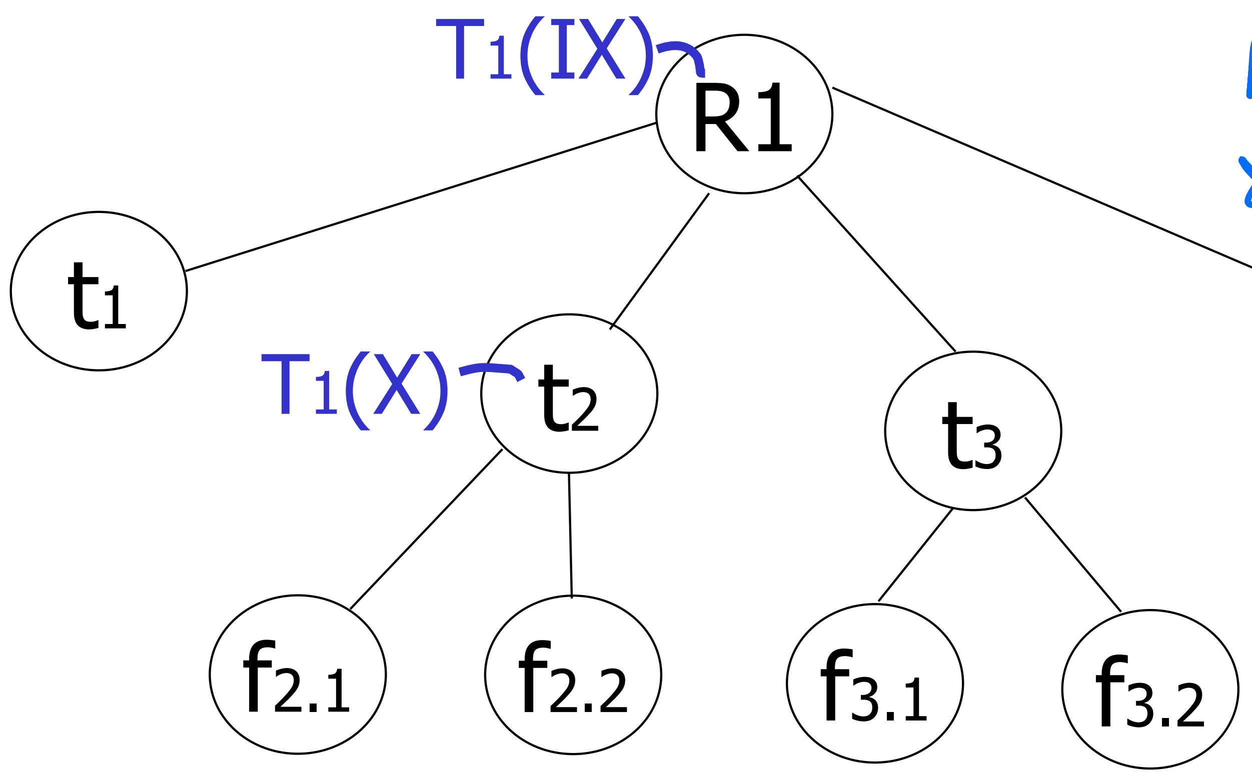
Exercise:

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



Exercise:

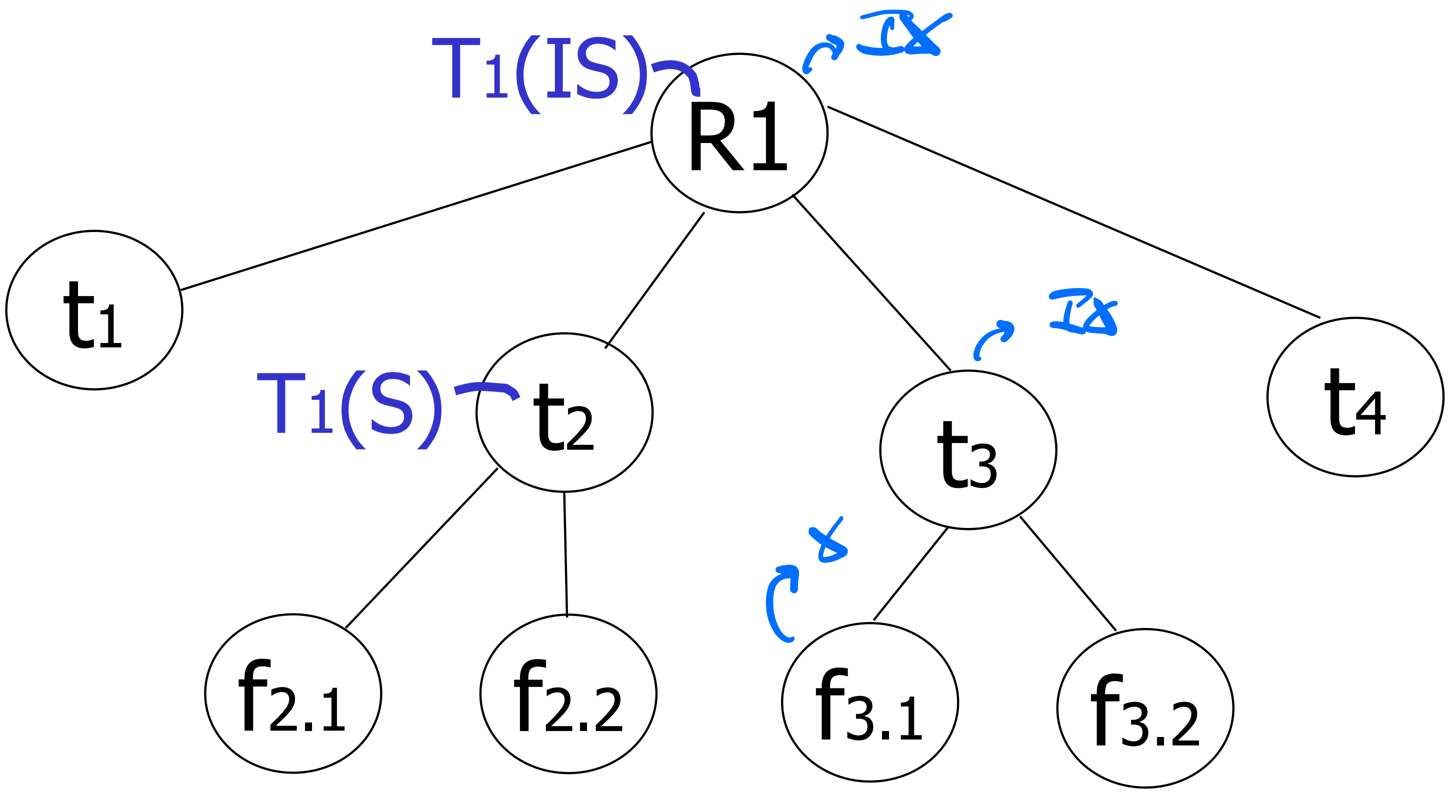
- Can T_2 access object $f_{2.2}$ in X mode? What locks will T_2 get?



No, because X at higher level ⇒ don't grant an other X

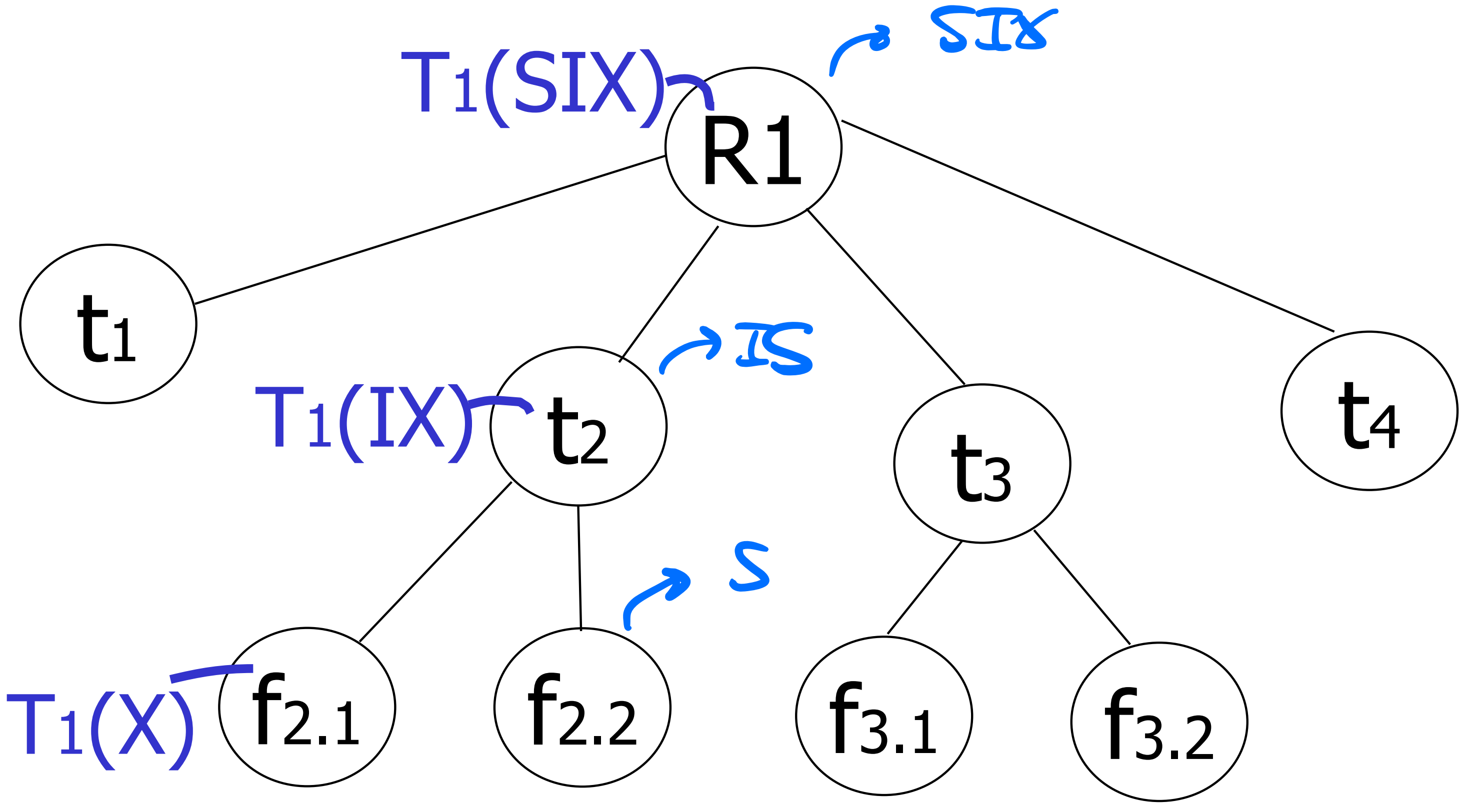
Exercise:

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



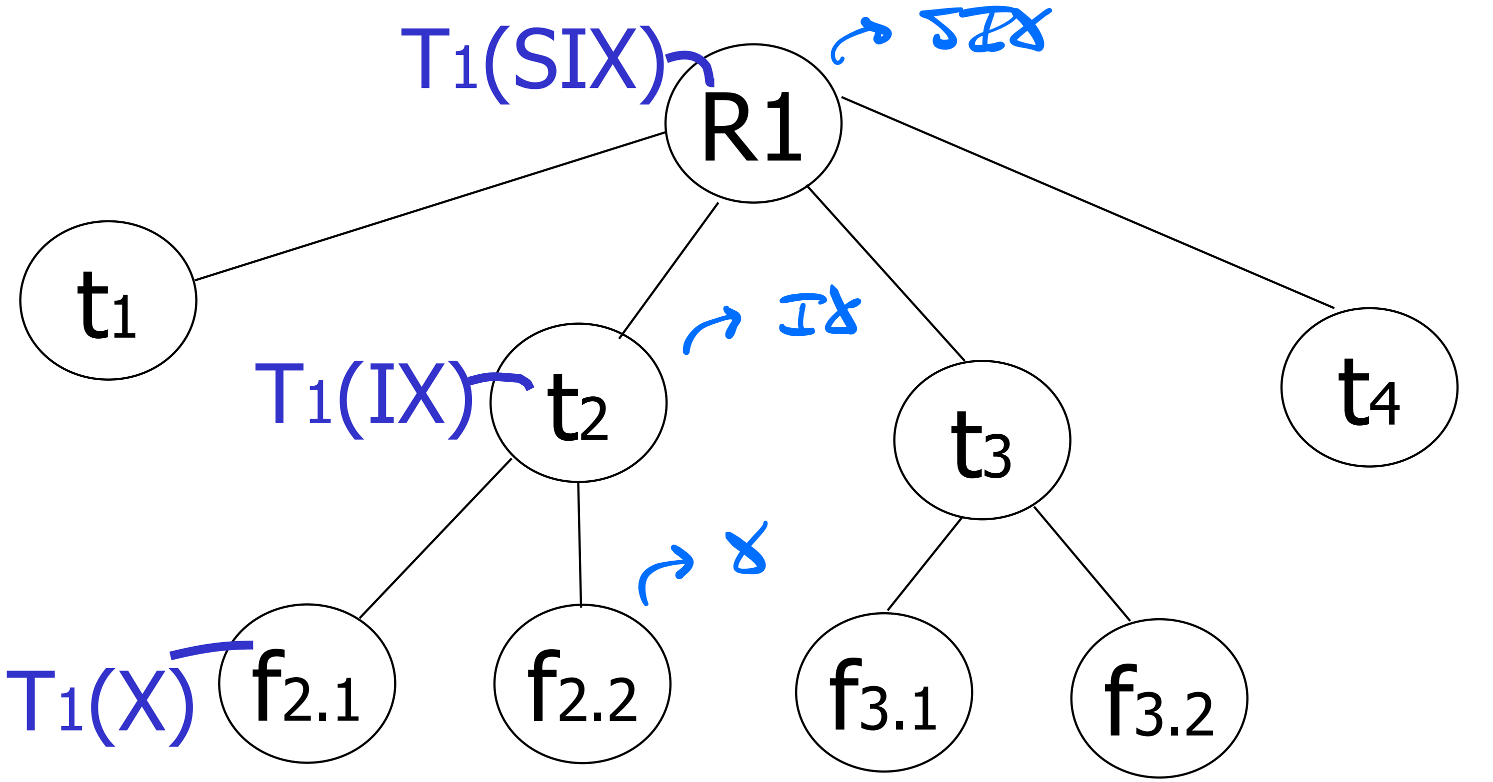
Exercise:

- 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?



Reading

Ch18 Concurrency Control

Héctor García-Molina, Jeffrey Ullman, and Jennifer Widom. Database Systems: The Complete Book.