CSE232: Database System Principles

Concurrency Control

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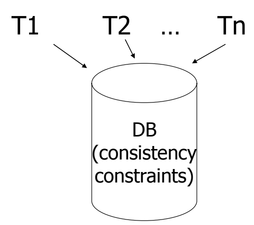
Concurrency Control



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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

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Serial Schedule A ("good" by definition)

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

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Serial Schedule B (equally "good")

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

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Interleaved Schedule C (good because it is equivalent to A)

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

Scoping "equivalence" is tricky; for now think that A and C are equivalent because if they start from same initial values they end up with same results

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Interleaved Schedule D (bad!)

T1	T2	A	B
		25	25
Read(A); A ← A+100			
Write(A);		125	
	Read(A);A ← A×2;		
	Write(A);	250	
	Read(B);B ← B×2;		
	Write(B);		50
Read(B); B ← B+100;			
Write(B);			150
		250	150

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Schedule E (good by "accident")

Same as Schedule D but with new T2′

T1	T2′	A	B
		25	25
Read(A); A ← A+100			
Write(A);		125	
	Read(A);A ← A×1;		
	Write(A);	125	
	Read(B);B ← B×1;		
	Write(B);		25
Read(B); B ← B+100;			
Write(B);			125
		125	125

The accident being the particular semantics of T2′

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- Want schedules that are "good", I.e., equivalent to serial regardless of
  - initial state and
  - transaction semantics
- Only look at order of read and writes

Example:

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

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Example:

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

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

However, for Schedule D:

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., $T_2 \rightarrow T_1$
- And vice versa

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

$T_1 \rightleftarrows T_2$ ⇨ SD cannot be rearranged
into a serial schedule

⇨ SD is not "equivalent" to
any serial schedule

⇨ SD is "bad"

Returning to Sc

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

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

☛ no cycles ⇒ SC is "equivalent" to a serial schedule (in this case T_1,T_2)

Concepts

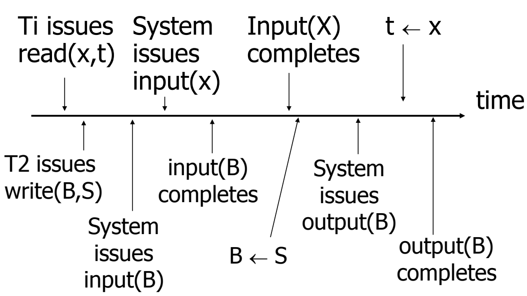
Transaction: sequence of $r_i(x)$, $w_i(x)$ actions

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

Schedule: represents chronological order in which actions are executed

Serial schedule: no interleaving of actions or transactions

What about concurrent actions?



So net effect is either

- $S = \ldots r_1(x) \ldots w_2(B) \ldots$ or
- $S = \ldots w_2(B) \ldots r_1(x) \ldots$

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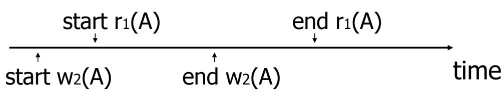
What about conflicting, concurrent actions on same object?



- 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"

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<u>Definition</u>

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

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Definition

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

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Precedence graph P(S) (S is schedule)

Nodes: transactions in S

Arcs: $T_i \rightarrow T_j$ 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

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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?

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Lemma

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

Proof:

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

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

$\Rightarrow S_1 = \ldots p_i(A)\ldots\ q_j(A)\ldots$
$\quad S_2 = \ldots q_j(A)\ldots p_i(A)\ldots$ $\quad \left.\right\}$ p_i, q_j conflict

$\Rightarrow S_1, S_2$ not conflict equivalent

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

Counter example:

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

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

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Theorem

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

($\Leftarrow$) Assume S_1 is conflict serializable

$\Rightarrow \exists\ S_s$: S_s, S_1 conflict equivalent

$\Rightarrow P(S_s) = P(S_1)$

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

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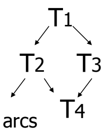
Theorem

$P(S_1)$ 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 incident arcs

(2) Move all T_1 actions to the front

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

(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);
check for P(S) cycles and
declare if execution was good;
or abort transactions as soon
as they generate a cycle

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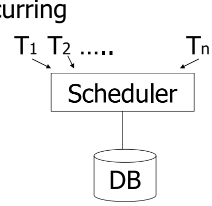
How to enforce serializable schedules?

Option 2: prevent P(S) cycles from
occurring



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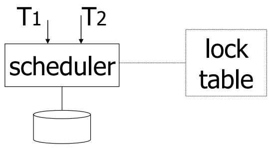
A locking protocol

Two new actions:
lock (exclusive): l_i (A)
unlock: u_i (A)



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Rule #1: Well-formed transactions

T_i: … l_i(A) … p_i(A) … u_i(A) ...

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Rule #2 Legal scheduler

S = …….. l_i(A) ………... u_i(A) ……...

no l_j(A)

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

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

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

  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←A+100;Write(A);$u_1(A)$	
	$l_2(A)$;Read(A)
	A←Ax2;Write(A);$u_2(A)$
	$l_2(B)$;Read(B)
	B←Bx2;Write(B);$u_2(B)$
$l_1(B)$;Read(B)	
B←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

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Rule #3 Two phase locking (2PL)

for transactions

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

no unlocks no locks

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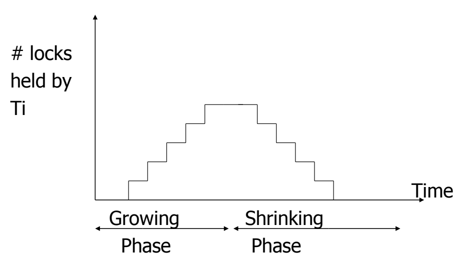

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Schedule G

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

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) delayed
	$A \leftarrow Ax2$;Write(A); $l_2(B)$
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) delayed
	$A \leftarrow Ax2$;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 ← A+100;Write(A)	B ← Bx2;Write(B)
l_1(B)	l_2(A)
delayed	delayed

- Assume deadlocked transactions are rolled back
  - They have no effect
  - They do not appear in schedule

E.g., Schedule H = $\underbrace{\qquad\qquad}_{\text{This space intentionally left blank!}}$

Next step:

Show that rules #1,2,3 ⇒ conflict-serializable schedules

<u>Conflict rules for</u> $l_i(A)$, $u_i(A)$:

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

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

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<u>Theorem</u> Rules #1,2,3 $\Rightarrow$ conflict
(2PL) serializable
schedule

To help in proof:
<u>Definition</u> Shrink(Ti) = SH(Ti) =
first unlock action of Ti

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<u>Lemma</u>
Ti $\rightarrow$ Tj in S $\Rightarrow$ SH(Ti) $<_S$ SH(Tj)

<u>Proof of lemma:</u>
Ti $\rightarrow$ Tj means that
S = … $p_i(A)$ … $q_j(A)$ …; p,q conflict
By rules 1,2:
S = … $p_i(A)$ … $u_i(A)$ … $l_j(A)$ ... $q_j(A)$ …
By rule 3: SH(Ti) SH(Tj)
So, SH(Ti) $<_S$ SH(Tj)

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

Proof:

(1) Assume P(S) has cycle

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

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

(3) Impossible, so P(S) acyclic

(4) $\Rightarrow$ S is conflict serializable

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- 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

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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:

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

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Lock actions

$l\text{-}t_i(A)$: 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

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Rule #1 Well formed transactions

$T_i = \ldots\ l\text{-}S_1(A) \ldots r_1(A) \ldots u_1(A) \ldots$

$T_i = \ldots\ l\text{-}X_1(A) \ldots w_1(A) \ldots u_1(A) \ldots$

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- What about transactions that read and write same object?

Option 1: Request exclusive lock

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

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- 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

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Rule #2 Legal scheduler

S = ...l-S_i(A) … … u_i(A) …

no l-X_j(A)

S = ... l-X_i(A) … … u_i(A) …

no l-X_j(A)
no l-S_j(A)

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A way to summarize Rule #2

Compatibility matrix

Comp

	S	X
S	true	false
X	false	false

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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

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Theorem Rules 1,2,3 $\Rightarrow$ Conf.serializable
for S/X locks schedules

Proof: similar to X locks case

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Lock types beyond S/X

Examples:
(1) increment lock
(2) update lock

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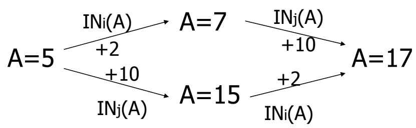
Example (1): increment lock

- Atomic increment action: $IN_i(A)$
  {Read(A); A ← A+k; Write(A)}
- $IN_i(A)$, $IN_j(A)$ do not conflict!



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Comp

	S	X	I
S			
X			
I			

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Comp

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

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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 ---

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Solution

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

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New request

Comp

Lock already held in

	S	X	U
S			
X			
U			

-> symmetric table?

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New request

Comp

Lock already held in

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

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

S_1=...l-S_1(A)...l-S_2(A)...l-U_3(A)... l-S_4(A)...?
l-
U_4(A)...?

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

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How does locking work in practice?

- Every system is different

But here is one (simplified) way ...

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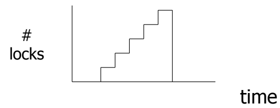
Sample Locking System:

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

(2) Hold all locks until transaction commits



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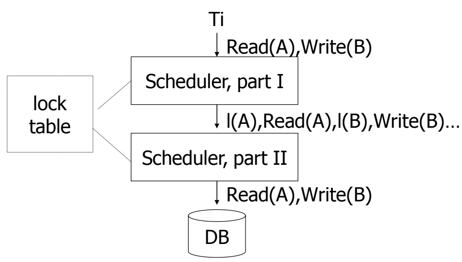

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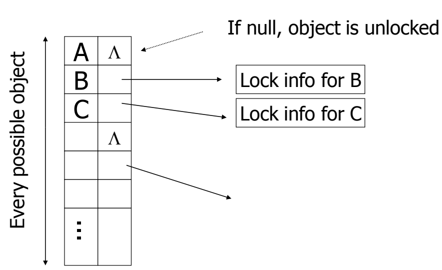
Lock table   Conceptually



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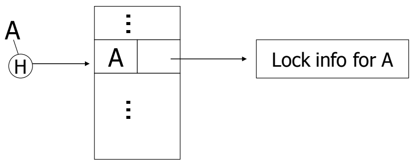
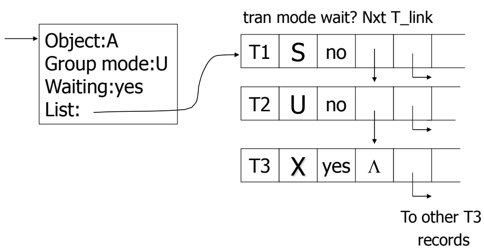
But use hash table:

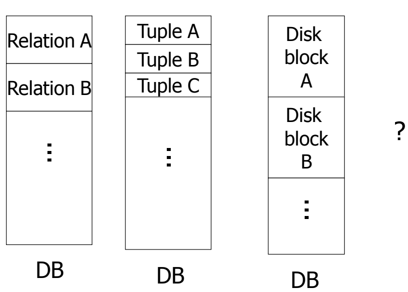


If object not found in hash table, it is unlocked

Lock info for A - example



What are the objects 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

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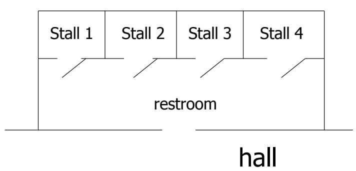
We can have it both ways!!

Ask any janitor to give you the solution...



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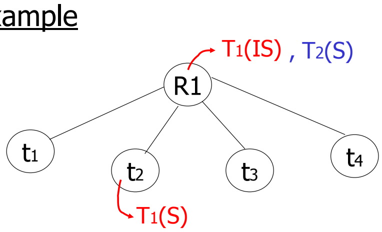
Example



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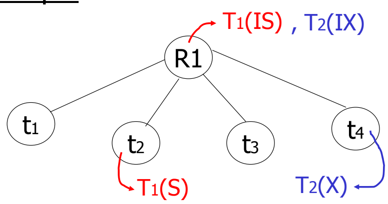
Example



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Multiple granularity

Comp — Requestor

Holder	IS	IX	S	SIX	X
IS					
IX					
S					
SIX					
X					

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Multiple granularity

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

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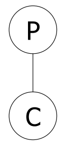
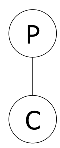
Parent locked in	Child can be locked in
IS	
IX	
S	
SIX	
X	



Parent locked in	Child can be locked in
IS	IS, S
IX	IS, S, IX, X, SIX
S	[S, IS] not necessary
SIX	X, IX, [SIX]
X	none



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

Insert + delete operations

A	
⋮	
Z	
α	← Insert

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Modifications to locking rules:

(1) Get exclusive lock on A before deleting A

(2) At insert A operation by Ti, Ti is given exclusive lock on A

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Still have a problem: **Phantoms**

Example: relation R (E#,name,…)
constraint: E# is key
use tuple locking

R	E#	Name	….
o1	55	Smith	
o2	75	Jones	

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T_1: Insert <99,Gore,…> into R
T_2: Insert <99,Bush,…> into R

T_1	T_2
$S_1(o_1)$	$S_2(o_1)$
$S_1(o_2)$	$S_2(o_2)$
Check Constraint	Check Constraint
⋮	⋮
Insert o_3[99,Gore,..]	
	Insert o_4[99,Bush,..]

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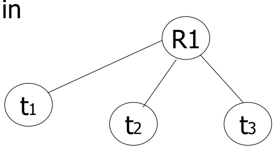
Solution

- Use multiple granularity tree
- Before insert of node Q, lock parent(Q) in X mode



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Back to example

T_1: Insert<99,Gore> T_1	T_2: Insert<99,Bush> T_2
$X_1(R)$	
	$X_2(R)$ *delayed*
Check constraint Insert<99,Gore> U(R)	
	$X_2(R)$ Check constraint Oops! e# = 99 already in R!

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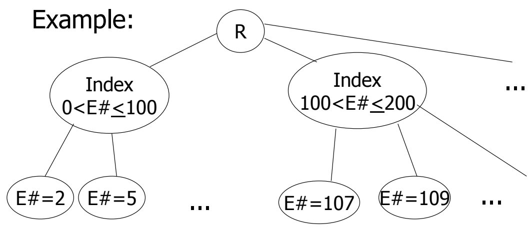
Instead of using R, can use index on R:

Example:



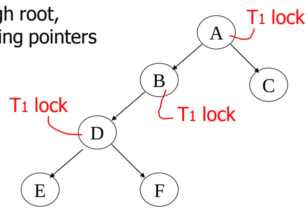
- This approach can be generalized to multiple indexes...

Next:

- Tree-based concurrency control
- Validation concurrency control

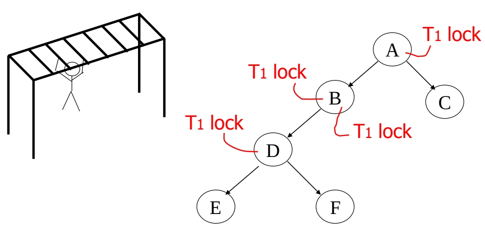
Example

- all objects accessed through root, following pointers



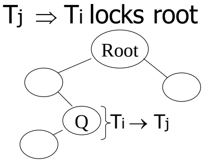
☛ can we release A lock if we no longer need A??

Idea: traverse like "Monkey Bars"



Why does this work?

- Assume all T_i start at root; exclusive lock
- $T_i \rightarrow T_j \Rightarrow T_i$ locks root before T_j



- Actually works if we don't always start at root

Rules: tree protocol (exclusive locks)

(1) First lock by T_i may be on any item

(2) After that, item Q can be locked by T_i only if parent(Q) locked by T_i

(3) Items may be unlocked at any time

(4) After T_i unlocks Q, it cannot relock Q

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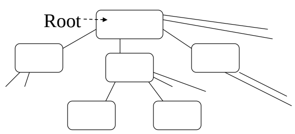
- Tree-like protocols are used typically for B-tree concurrency control



E.g., during insert, do not release parent lock, until you are certain child does not have to split

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Validation-based Concurrency Control

Transactions have 3 phases:

(1) Read
- all DB values read
- writes to temporary storage
- no locking

(2) Validate
- check if schedule so far is serializable

(3) Write
- if validate ok, write to DB

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Key idea

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

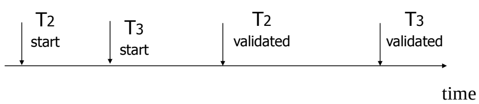
To implement validation, system keeps two sets:

- FIN = transactions that have finished phase 3 (and are all done)
- VAL = transactions that have successfully finished phase 2 (validation)

Example of what validation must prevent:

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

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

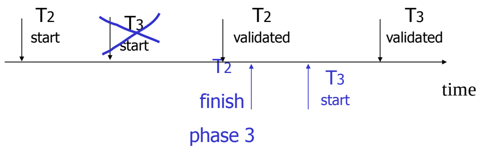


Example of what validation must ~~prevent~~ allow:

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

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

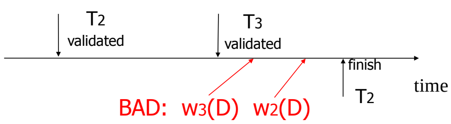
$WS(T_2) \cap RS(T_3) \neq \phi$



Another thing validation must prevent:

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

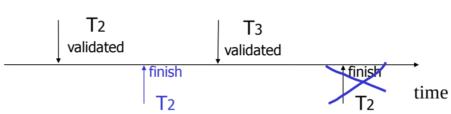
$WS(T_2)=\{D,E\}$ $\quad$ $WS(T_3)=\{C,D\}$



Another thing validation must ~~prevent~~ allow:

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

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



Validation rules for T_j:

(1) When T_j starts phase 1:

ignore(T_j) $\leftarrow$ FIN

(2) at T_j Validation:

if check (T_j) then

[VAL $\leftarrow$ VAL U {T_j};

do write phase;

FIN $\leftarrow$FIN U {T_j}]

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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] THEN RETURN false;

RETURN true;

Is this check too restrictive ?

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Improving Check(T_i)

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;

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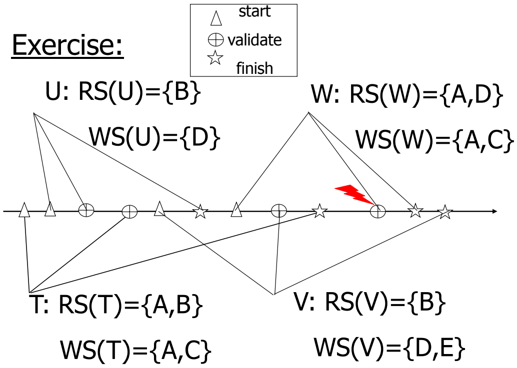
Exercise:



Validation (also called optimistic concurrency control) is useful in some cases:

- Conflicts rare
- System resources plentiful
- Have real time constraints

Summary

Have studied C.C. mechanisms used in practice

- 2 PL
- Multiple granularity
- Tree (index) protocols
- Validation