CS 245: Database System Principles

**Notes 09: Concurrency Control**

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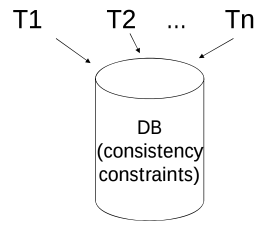
## Chapter 18 [18] Concurrency Control






## Example:

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



## 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 ← A×2; | | |
| | Write(A); | 50 | |
| | Read(B);B ← B×2; | | |
| | Write(B); | | 50 |
| Read(A); A ← A+100 | | | |
| Write(A); | | 150 | |
| Read(B); B ← B+100; | | | |
| Write(B); | | | 150 |
| | | 150 | 150 |



## Schedule C

| T1 | T2 |
|---|---|
| Read(A); A ← A+100 | |
| Write(A); | |
| | Read(A);A ← A×2; |
| | Write(A); |
| Read(B); B ← B+100; | |
| Write(B); | |
| | Read(B);B ← B×2; |
| | Write(B); |



## Schedule C

| 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+100; | | | |
| Write(B); | | | 125 |
| | Read(B);B ← B×2; | | |
| | Write(B); | | 250 |
| | | 250 | 250 |



## Schedule D

| T1 | T2 |
|---|---|
| Read(A); A ← A+100 | |
| Write(A); | |
| | Read(A);A ← A×2; |
| | Write(A); |
| | Read(B);B ← B×2; |
| | Write(B); |
| Read(B); B ← B+100; | |
| Write(B); | |



## Schedule D

| 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 |



## Schedule E

Same as Schedule D but with new T2'

| T1 | T2' |
|---|---|
| Read(A); A ← A+100 | |
| Write(A); | |
| | Read(A);A ← A×1; |
| | Write(A); |
| | Read(B);B ← B×1; |
| | Write(B); |
| Read(B); B ← B+100; | |
| Write(B); | |

## Schedule E

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 |



- 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

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **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 |



## Schedule D

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **A** | r | w | r | w | | | | |
| **B** | | | | | r | w | r | w |
| **T1** | r | w | | | | | r | w |
| **T2** | | | r | w | r | w | | |



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, $T_1 \rightarrow T_2$

$T_1 \rightleftarrows T_2$

⇨ Sd cannot be rearranged into a serial schedule

⇨ Sd is not “equivalent” to any serial schedule

⇨ Sd is “bad”



Returning to Sc

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

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



Returning to Sc

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

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

☛ 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?

start $r_1(A)$ end $r_1(A)$

start $w_2(A)$ end $w_2(A)$ time



What about conflicting, concurrent actions on same object?

start $r_1(A)$ end $r_1(A)$

start $w_2(A)$ end $w_2(A)$ time

- 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: $T_i \rightarrow T_j$ 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



## 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 $S_2$

$$\left.\begin{array}{l} \Rightarrow S_1 = \ldots p_i(A) \ldots q_j(A) \ldots \\ \quad\ S_2 = \ldots q_j(A) \ldots p_i(A) \ldots \end{array}\right\} p_i, q_j \text{ conflict}$$

$\Rightarrow S_1, S_2$ 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

<u>Counter example:</u>

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

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



## <u>Theorem</u>

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



## <u>Theorem</u>

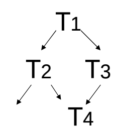
$P(S_1)$ acyclic $\Longleftrightarrow$ $S_1$ conflict serializable

($\Leftarrow$) 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



## <u>Theorem</u>

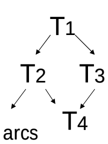
$P(S_1)$ acyclic $\Longleftrightarrow$ $S_1$ conflict serializable






## <u>Theorem</u>

$P(S_1)$ 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

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

(3) we now have $S_1 = <T_1 \text{ actions} ><\ldots \text{ rest } \ldots>$
(4) repeat above steps to serialize rest!

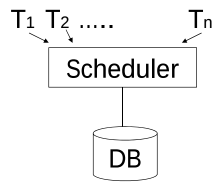


## <u>How to enforce serializable schedules?</u>

*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



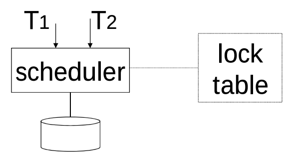



## A locking protocol

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

no $l_j(A)$



## Exercise:

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

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

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

  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) | | | |
| $A \leftarrow A+100$;Write(A);$u_1(A)$ | | 125 | |
| | $l_2(A)$;Read(A) | | |
| | $A \leftarrow Ax2$;Write(A);$u_2(A)$ | 250 | |
| | $l_2(B)$;Read(B) | | |
| | $B \leftarrow Bx2$;Write(B);$u_2(B)$ | | 50 |
| $l_1(B)$;Read(B) | | | |
| $B \leftarrow B+100$;Write(B);$u_1(B)$ | | | 150 |
| | | 250 | 150 |



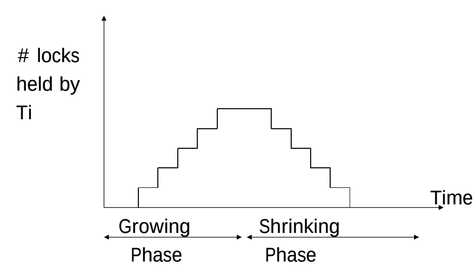
## Rule #3 Two phase locking (2PL)

for transactions

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

no unlocks — no locks








## 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); 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); delayed |
| Read(B);$B \leftarrow B+100$ | |
| Write(B); $u_1(B)$ | |

## Schedule G

| T1 | T2 |
|---|---|
| $l_1(A)$;Read(A) | |
| A←A+100;Write(A) | |
| $l_1(B)$; $u_1(A)$ | |
| | $l_2(A)$;Read(A) |
| | A←Ax2;Write(A); delayed |
| Read(B);B ← B+100 | |
| Write(B); $u_1(B)$ | |
| | $l_2(B)$; $u_2(A)$;Read(B) |
| | B ← 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) |
| delayed | delayed |



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

E.g., Schedule H = $\underbrace{\qquad\qquad\qquad}$

This space intentionally left blank!



## Next step:

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



## Conflict rules for $l_i(A)$, $u_i(A)$:

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

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



**Theorem** Rules #1,2,3 ⇒ conflict serializable schedule
(2PL)

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

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



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



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

Proof of lemma:
Ti $\rightarrow$ Tj means that
S = ... $p_i(A)$ ... $q_j(A)$ ...; p,q conflict
By rules 1,2:
S = ... $p_i(A)$ ... $u_i(A)$ ... $l_j(A)$ ... $q_j(A)$ ...



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

Proof of lemma:
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)

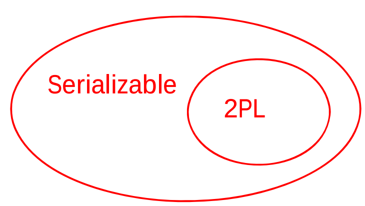


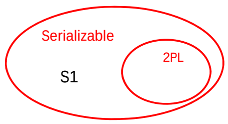
Theorem Rules #1,2,3 $\Rightarrow$ conflict
(2PL) serializable
schedule

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



## 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?

$S_C$: w1(A) w2(A) w1(B) w2(B)

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



- 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) … $l_2$(A) $r_2$(A) $u_2$(A) …

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

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



## Rule #1 Well formed transactions

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

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



- What about transactions that read and write same object?

Option 1: Request exclusive lock

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



- What about transactions that read and write same object?

Option 2: Upgrade

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

$T_i$=... $l\text{-}S_1(A)$ ... $r_1(A)$ ... $l\text{-}X_1(A)$ ...$w_1(A)$ ...u(A)...

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



## Rule #2 Legal scheduler

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

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

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 → {S, X}) then no change!

(II) If upgrade releases read (shared) lock (e.g., S → X)
- can be allowed in growing phase



Theorem  Rules 1,2,3 ⇒ Conf.serializable
for S/X locks   schedules

Proof: similar to X locks case

Detail:

l-$t_i$(A), l-$r_j$(A) do not conflict if comp(t,r)

l-$t_i$(A), u-$r_j$(A) do not conflict if comp(t,r)



## Lock types beyond S/X

Examples:

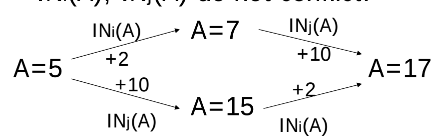
(1) increment lock

(2) update lock



## Example (1): increment lock

- Atomic increment action: $IN_i$(A)
  {Read(A); A ← 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 |
|---|---|
| $l\text{-}S_1(A)$ | |
| | $l\text{-}S_2(A)$ |

--- Deadlock ---



## Solution

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



Comp

New request

| Lock already held in | S | X | U |
|---|---|---|---|
| S | | | |
| X | | | |
| U | | | |



Comp

New request

| Lock already held in | S | X | U |
|---|---|---|---|
| S | T | F | T |
| X | F | F | F |
| U | TorF | F | F |

-> symmetric table?



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

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



<u>Note:</u> 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?

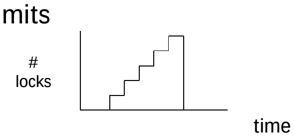
- Every system is different
  (E.g., may not even provide CONFLICT-SERIALIZABLE schedules)
- But here is one (simplified) way ...



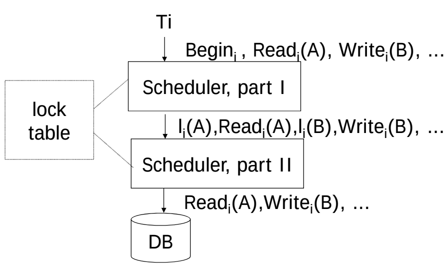
## Sample Locking System:

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

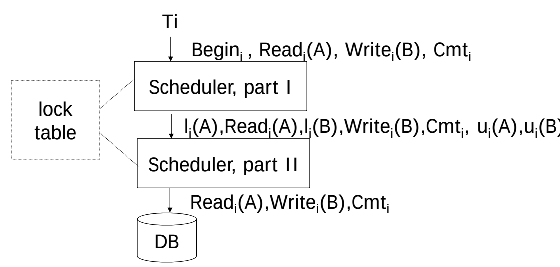
(2) Hold all locks until transaction commits





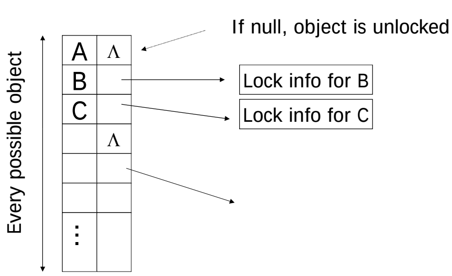





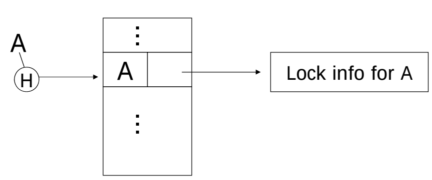



## Lock table    Conceptually



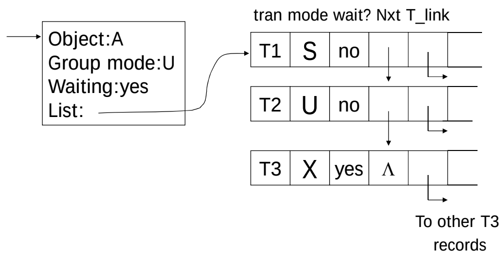



## But use hash table:



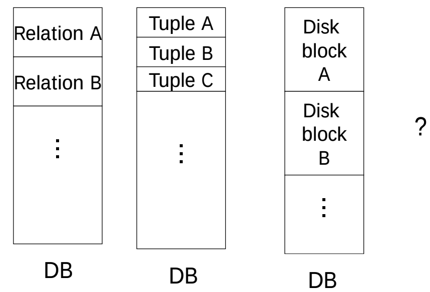

If object not found in hash table, it is unlocked

## Lock info for A - example






## What are the objects we lock?






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



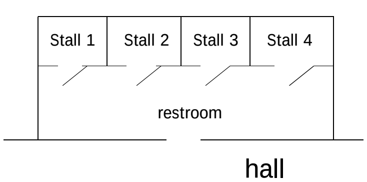
- Locking works in any case, but should we choose small or large objects?

- 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



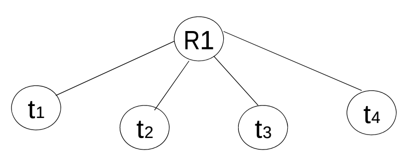
## We can have it both ways!!

Ask any janitor to give you the solution...

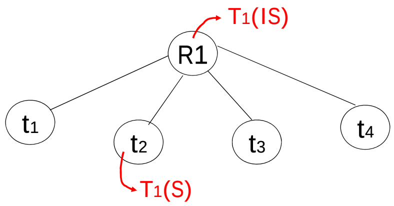





## Example

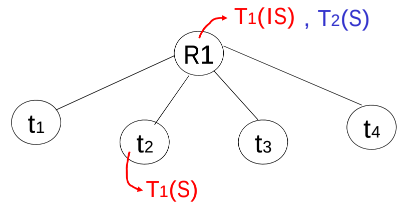


## Example




CS 245 Notes 09 103

## Example

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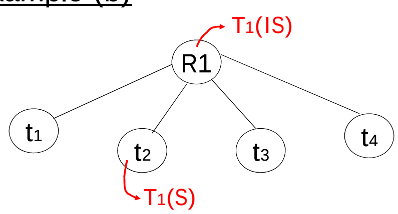
## Example (b)

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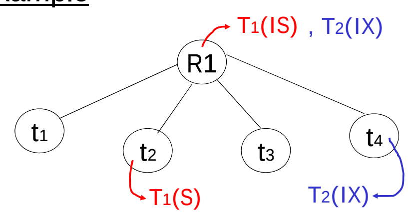
## Example

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## Multiple granularity

Comp — Requestor

| | | IS | IX | S | SIX | X |
|---|---|---|---|---|---|---|
| | IS | | | | | |
| Holder | IX | | | | | |
| | S | | | | | |
| | SIX | | | | | |
| | X | | | | | |

CS 245 Notes 09 107

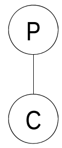
## Multiple granularity

Comp — Requestor

| | | IS | IX | S | SIX | X |
|---|---|---|---|---|---|---|
| | IS | T | T | T | T | F |
| Holder | IX | T | T | F | F | F |
| | S | T | F | T | F | F |
| | SIX | T | F | F | F | F |
| | X | F | F | F | F | F |

CS 245 Notes 09 108

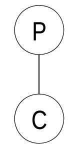
| Parent locked in | Child can be locked in |
|---|---|
| IS | |
| IX | |
| S | |
| SIX | |
| X | |






| 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





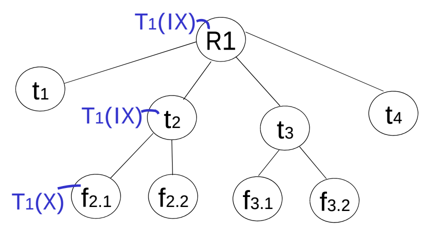

## Rules

(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:

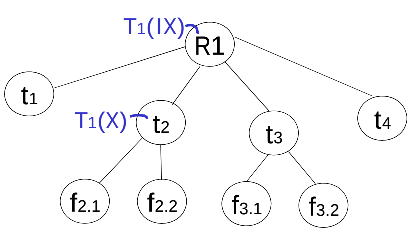
- Can $T_2$ access object $f_{2.2}$ in X mode? What locks will $T_2$ get?






## Exercise:

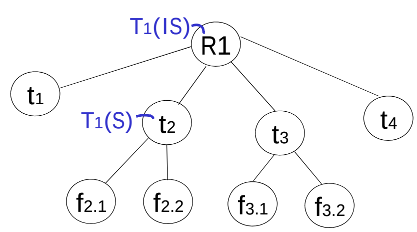
- Can $T_2$ access object $f_{2.2}$ in X mode? What locks will $T_2$ get?





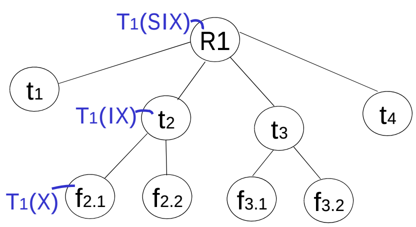

## Exercise:

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



## Exercise:

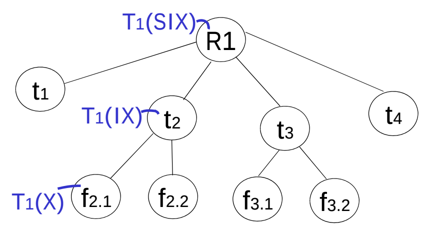
- Can $T_2$ access object $f_{2.2}$ in S mode? What locks will $T_2$ get?





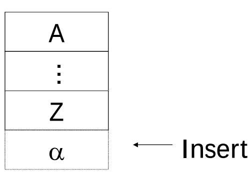

## Exercise:

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






## Insert + delete operations






## 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



## 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 | |

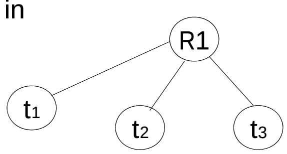


$T_1$: Insert <12,Obama,...> into R
$T_2$: Insert <12,Romney,...> into R

| $T_1$ | $T_2$ |
|---|---|
| $S_1(o_1)$ | $S_2(o_1)$ |
| $S_1(o_2)$ | $S_2(o_2)$ |
| Check Constraint | Check Constraint |
| ⋮ | ⋮ |
| Insert $o_3$[12,Obama,..] | |
| | Insert $o_4$[12,Romney,..] |

## Solution

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






## Back to example

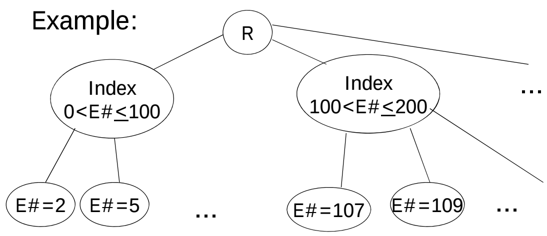
$T_1$: Insert<12,Obama> | $T_2$: Insert<12,Romney>

| $T_1$ | $T_2$ |
|---|---|
| $X_1(R)$ | *delayed* |
| Check constraint<br>Insert<12,Obama><br>$U_1(R)$ | |
| | $X_2(R)$<br>Check constraint<br>Oops! e# = 12 already in R! |



Instead of using R, can use index on R:

Example:






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



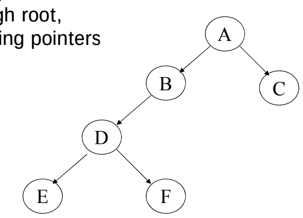
## Next:

- Tree-based concurrency control
- Validation concurrency control



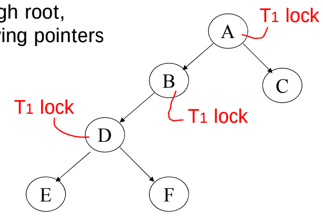
## Example

- all objects accessed through root, following pointers



## Example

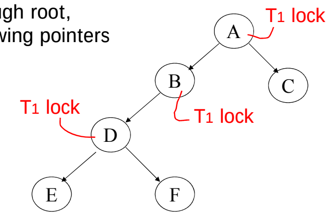
- all objects accessed through root, following pointers






## Example

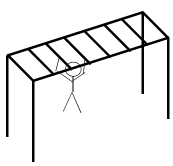
- all objects accessed through root, following pointers

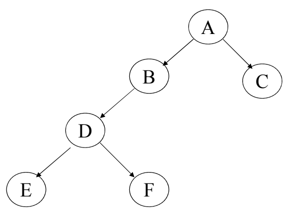



☛ can we release A lock if we no longer need A??



## Idea: traverse like "Monkey Bars"





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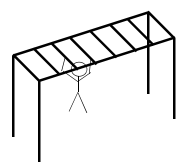

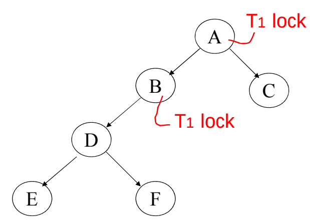




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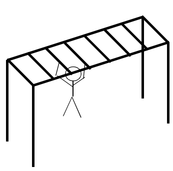
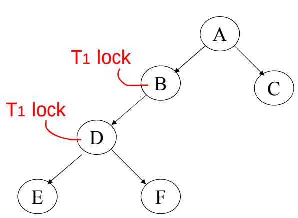
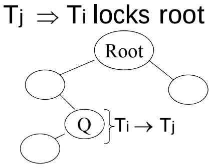







## Why does this work?

- 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

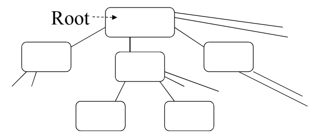
(2) After that, item Q can be locked by $T_i$ only if parent(Q) locked by $T_i$

(3) Items may be unlocked at any time

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



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

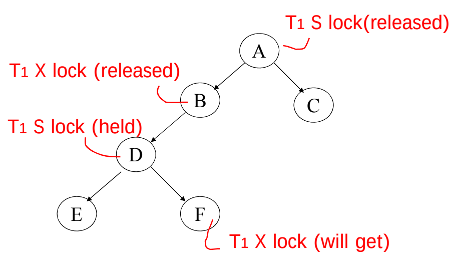



E.g., during insert, do not release parent lock, until you are certain child does not have to split



## Tree Protocol with Shared Locks

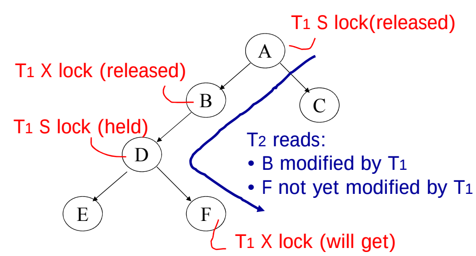
- Rules for shared & exclusive locks?






## Tree Protocol with Shared Locks

- Rules for shared & exclusive locks?






## Tree Protocol with Shared Locks

- Need more restrictive protocol
- Will this work??
  - Once $T_1$ locks one object in X mode, all further locks down the tree must be in X mode



## Validation

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

## 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:

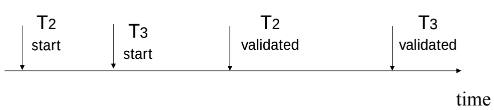
- FIN = transactions that have finished phase 3 (and are all done)
- VAL = transactions that have successfully finished phase 2 (validation)



## Example of what validation must prevent:

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

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

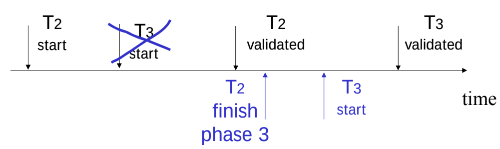





## Example of what validation must ~~prevent~~ allow:

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

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

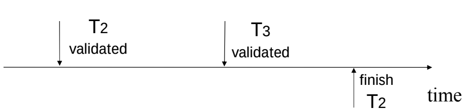





## Another thing validation must prevent:

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

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

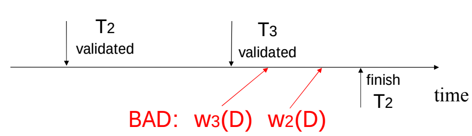





## Another thing validation must prevent:

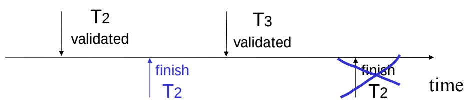
$RS(T_2)=\{A\}$ $\quad\quad$ $RS(T_3)=\{A,B\}$

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



Another thing validation must ~~prevent~~ allow:

RS($T_2$)={A}  RS($T_3$)={A,B}
WS($T_2$)={D,E}  WS($T_3$)={C,D}






Validation rules for $T_j$:

(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 {$T_j$} ]



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;



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 ?

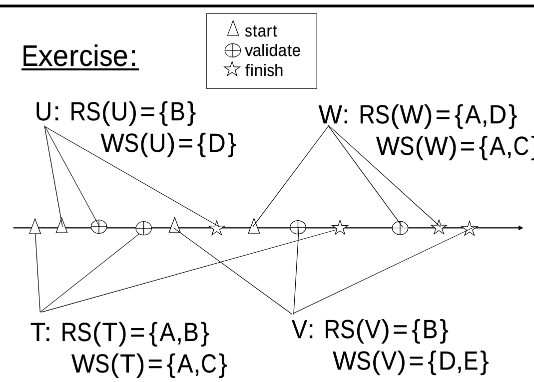


Improving Check($T_j$)

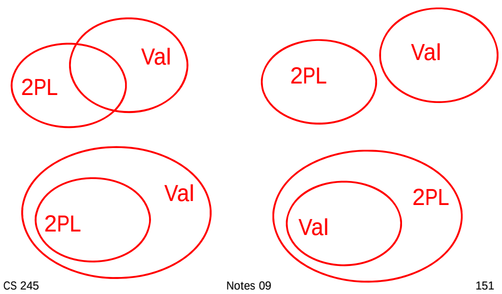
For $T_i \in$ VAL - IGNORE ($T_j$) DO
IF [ WS($T_i$) $\cap$ RS($T_j$) $\neq \emptyset$ OR
($T_i \notin$ FIN AND WS($T_i$) $\cap$ WS($T_j$) $\neq \emptyset$)]
THEN RETURN false;
RETURN true;



Exercise:



## Is Validation = 2PL?






## S2: w2(y) w1(x) w2(x)

- Achievable with 2PL?
- Achievable with validation?



## S2: w2(y) w1(x) w2(x)

- S2 can be achieved with 2PL:
  l2(y) w2(y) l1(x) w1(x) u1(x) l2(x) w2(x) u2(y) u2(x)
- S2 cannot be achieved by validation:
  The validation point of T2, val2 must occur before w2(y) since transactions do not write to the database until after validation. Because of the conflict on x, val1 < val2, so we must have something like
  S2: val1 val2 w2(y) w1(x) w2(x)
  With the validation protocol, the writes of T2 should not start until T1 is all done with its writes, which is not the case.



## Validation subset of 2PL?

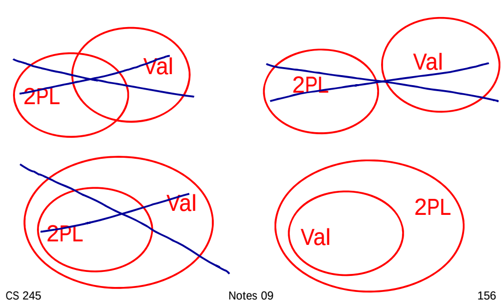
- Possible proof (Check!):
  - Let S be validation schedule
  - For each T in S insert lock/unlocks, get S':
    - At T start: request read locks for all of RS(T)
    - At T validation: request write locks for WS(T); release read locks for read-only objects
    - At T end: release all write locks
  -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



- 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!



## Conclusion:
## Validation subset 2PL



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