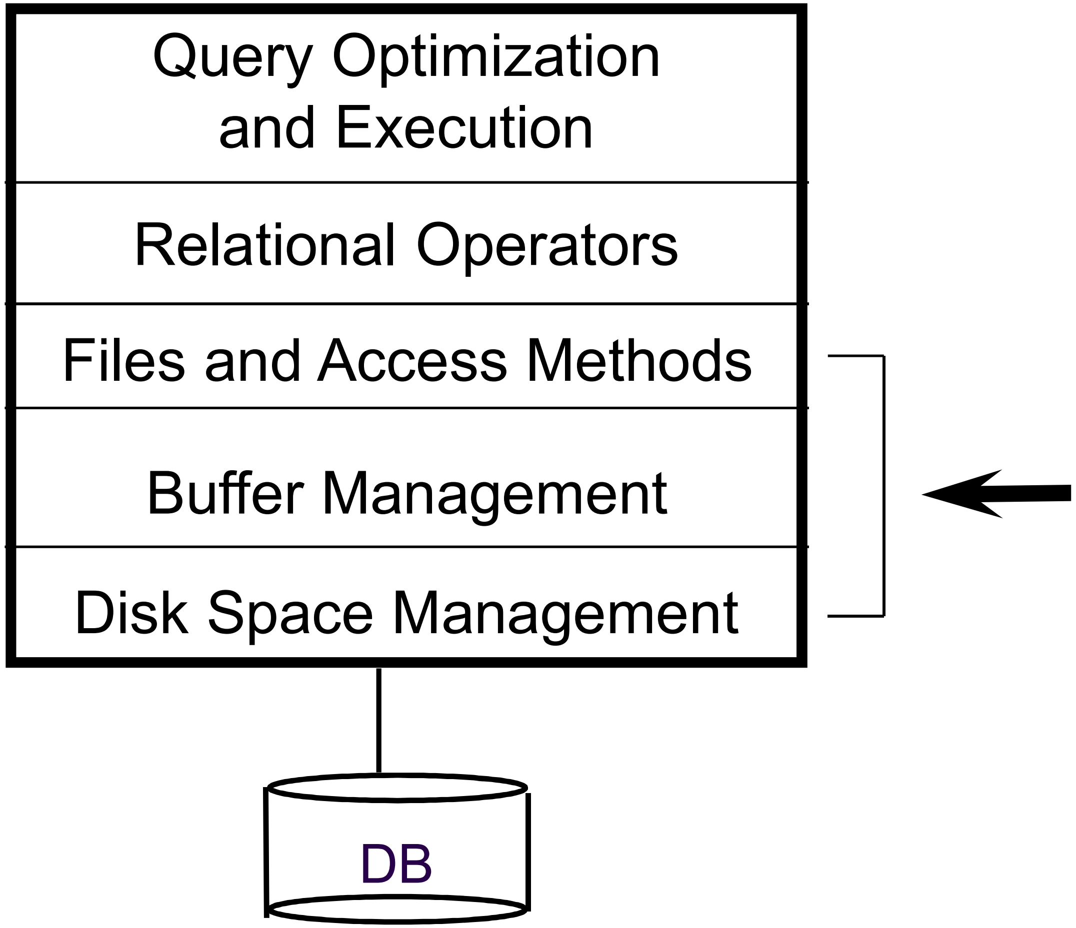
Transaction Management Overview

There are three side effects of acid.
Enhanced long term memory,
decreased short term memory, and
I forget the third.
- Timothy Leary

Structure of a DBMS



These layers must consider concurrency control and recovery (Transaction, Lock, Recovery Managers)

Transactions

- Transaction ("xact")- DBMS's abstract view of a user program (or activity):
  - A sequence of reads and writes of database objects, e.g., a transaction that transfers $100 from account A to account B can be expressed as:
    - Read Account A;
    - Write Updated Account A ($100 less);
    - Read Account B;
    - Write Updated Account B ($100 more);
  - Unit of work that must commit or abort as an atomic unit
- Transaction Manager controls the (correct) execution of Xacts
- User's program logic is invisible to DBMS!
  - Arbitrary computation possible on data fetched from the DB
  - The DBMS only sees data read/written from/to the DB

ACID properties of Transaction Executions

- Atomicity: All actions in the Xact happen, or none happen
- Consistency: If each Xact is consistent, and the DB starts consistent, it ends up consistent
- Isolation: Execution of one Xact is isolated from that of other Xacts
- Durability: If a Xact commits, its effects persist

Atomicity and Durability

A.C.I.D.

- A transaction ends in one of two ways:
  - *commit* after completing all its actions
    - "commit" is a contract with the caller of the DB
  - *abort* (or be aborted by the DBMS) after executing some actions
    - Or *system crash* while the xact is in progress; treat as abort
- Two important properties for a transaction:
  - *Atomicity* : Either execute all its actions, or none of them
  - *Durability* : The effects of a committed xact must survive failures
- DBMS ensures the above by *logging* all actions (Recovery):
  - *Undo* the actions of aborted/failed transactions
  - *Redo* actions of committed transactions not yet propagated to disk when system crashes

Transaction Consistency

A.C.I.D.

- Transactions preserve DB *consistency*
  - Given a consistent DB state, produce another consistent DB state
- DB Consistency expressed as a set of declarative Integrity Constraints
  - CREATE TABLE/ASSERTION statements
    - E.g. Each CS3223 student can only register in one project group. Each group must have 2 students
  - Application-level
    - E.g. Bank account total of each customer must stay the same during a "transfer" from savings to checking account
- Transactions that violate ICs are aborted
  - That's all the DBMS can automatically check!

Isolation (Concurrency)

A.C.I.D.

- DBMS interleaves actions of many xacts concurrently
  - Actions = reads/writes of DB objects
- DBMS ensures xacts do not "step onto" one another
- Each xact executes as if it were running by itself
  - Concurrent accesses have no effect on a transaction's behavior
  - Net effect *must be* identical to executing all transactions for *some* serial order
  - Users & programmers think about transactions in isolation
    - Without considering effects of other concurrent transactions!

Concurrency Control & Recovery

- Concurrency Control
  - Provide correct and highly available data access in the presence of concurrent access by many users
- Recovery
  - Ensures database is fault tolerant, and not corrupted by software, system or media failure
  - 24x7 access to mission critical data
- A boon to application developers!
  - Existence of CC&R allows applications to be written without explicit concern for concurrency and fault tolerance

Transactions

- A transaction (Xact) T_i can be viewed as a sequence of actions:
  - $r_i(O)$ = T_i reads an object O
  - $w_i(O)$ = T_i writes an object O
  - $c_i(O)$ = T_i completes successfully
  - $a_i(O)$ = T_i terminates unsuccessfully
- Each Xact must end with either a commit or an abort
- Example: A Xact T_1 that transfers 100 from A to B can be abstracted as

$$T_1 : r_1(A), r_1(B), w_1(A), w_1(B), c_1$$

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: Serial Schedule

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	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 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);$B \leftarrow B \times 2$;		
	Write(B);		50
Read(B); $B \leftarrow B+100$;			
Write(B);			150
	Constraint not satisfied!! $\longrightarrow$	250	150

Schedule D

Same as Schedule C
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

What are good schedules?

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

Example:

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

Example:

$$Sb = r1(A)w1(A)\underbrace{r2(A)w2(A)}\underbrace{r1(B)w1(B)}r2(B)w2(B)$$

$$T_1 \longrightarrow T_2 \qquad\qquad T_1 \longrightarrow T_2$$

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

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

Example (Cont)

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

The value which it is being read here is
after w2(B), so moving the order will make it different

Example (Cont)

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

Example (Cont)

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

$T_1 \rightarrow T_2$

Also, $T_2 \rightarrow T_1$

T1 T2

Sd cannot be rearranged into a serial schedule

Sd is not "equivalent" to any serial schedule

Sd is "bad"

Concepts

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

Conflicting actions on the same item (A):

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

Schedule: represents *chronological order* in which actions of transactions are executed

Serial schedule: no interleaving of actions from different transactions

Serializable schedule: a schedule whose *effect* on *any consistent database instance* is guaranteed to be *identical* to that of *some* complete *serial schedule*

Anomalies with Interleaved Xact Executions

- Anomalies can arise due to conflicting actions
  - Dirty read problem (due to WR conflicts)
  - Unrepeatable read problem (due to RW conflicts)
  - Lost update problem (due to WW conflicts)

Dirty Read Problem: Example

- Dirty read problem (due to WR conflicts)
  - T_2 reads an object that has been modified by T_1 (which has not yet committed)
  - T_2 could see an inconsistent DB state!

T_1	T_2	**Comments**
		$x = 100$
R(x)		100
$x = x + 20$		
W(x)		$x = 120$
	R(x)	120
	$x = x \times 2$	
	W(x)	$x = 240$

- For every serial schedule, the final value of x is 200

Unrepeatable Read Problem: Example

- Unrepeatable read problem (due to RW conflicts)
  - T_2 updates an object that T_1 has just read while T_1 is still in progress
  - T_1 could get a different value if it reads the object again!

T_1	T_2	**Comments**
		$x = 100$
R(x)		100
	R(x)	100
	$x = x - 20$	
	W(x)	$x = 80$
R(x)		80

- For every serial schedule, both values read by T_1 are the same

Lost Update Problem: Example

- Lost update problem (due to WW conflicts)
  - T_2 overwrites the value of an object that has been modified by T_1 while T_1 is still in progress
  - T_1's update is lost!

T_1	T_2	**Comments**
		$x = 100$
R(x)		100
	R(x)	100
$x = x + 20$		
	$x = x \times 2$	
W(x)		$x = 120$
	W(x)	$x = 200$

- For schedule (T_1, T_2), the final value of x is 240
- For schedule (T_2, T_1), the final value of x is 220

Up to this point …

- We want actions of transactions to interleave (for better throughput)
- Interleaving of actions can mess up the entire database!
- We want the interleaved actions to be serializable

Definition

- S1, S2 are *conflict equivalent* schedules if S1 can be transformed into S2 by a series of swaps on *non-conflicting actions*
  - S1 and S2 order every pair of conflicting actions of two **committed** Xacts in the same way
- A schedule is *conflict serializable* if it is conflict equivalent to some serial schedule

Note: (a) Some serializable schedules are NOT conflict serializable.
A price we pay to achieve efficient enforcement.
(b) There are alternative (weaker) notions of serializability.

Conflict Equivalent: Example

S_1	S_2
$R_1(x)$	$R_2(x)$
$W_1(x)$	$W_2(y)$
$R_1(y)$	$R_1(x)$
$R_2(x)$	$W_1(x)$
$W_2(y)$	$R_1(y)$
$W_1(z)$	$W_1(z)$

Not conflict equivalent

S_1	S_3
$R_1(x)$	$R_1(x)$
$W_1(x)$	$W_1(x)$
$R_1(y)$	$R_1(y)$
$R_2(x)$	$W_1(z)$
$W_2(y)$	$R_2(x)$
$W_1(z)$	$W_2(y)$

Conflict equivalent

Conflict-Serializability is NOT necessary for Serializability

- S1: w1(Y); w1(X); w2(Y); w2(X); w3(X)
    - Serial schedule
- S2: w1(Y); w2(Y); w2(X); w1(X); w3(X)
    - Serializable?
- S1, S2 conflict equivalent?
- What is the problem?
    - In the schedule, what we essentially have are blind writes, i.e., a write on an object O that did not read O prior to the write

Precedence (Conflict Serializability) 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

Nodes are transactions, then edges are the conflicts

Exercise:

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

$$\begin{tikzcd} T3 \arrow[r] & T1 \arrow[r] & T2 \arrow[r] \arrow[l, bend left] & T4 \end{tikzcd}$$

- Is S conflict serializable?

Theorem

$P(S)$ is acyclic $\Leftrightarrow$ S is conflict serializable

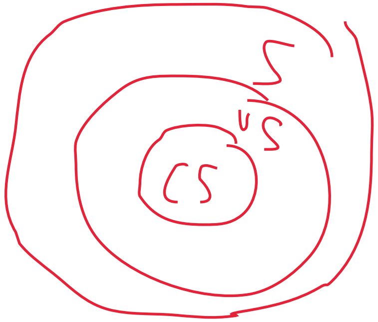
S_1, S_2 conflict equivalent $\Rightarrow$ $P(S_1)=P(S_2)$???

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

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

- $S1 = w_3(A)\ w_2(C)\ r_1(C)\ r_1(A)\ w_2(B)\ w_1(B)\ w_2(A)$
- $S2 = w_3(A)\ r_1(A)\ w_2(B)\ w_1(B)\ r_1(C)\ w_2(C)\ w_2(A)$

$$\begin{tikzcd} T_3 \arrow[r] & T_1 \arrow[r] & T_2 \arrow[l, bend left] \end{tikzcd}$$



View Serializable Schedules

- Two schedules S and S′ are view equivalent if they satisfy all the following conditions:
  - If Ti reads the initial value of A in S, then Ti must also read the initial value of A in S′
  - If Ti reads a value of A written by Tj in S, then Ti must also read the value of A written by Tj in S′
  - For each data object A, the Xact (if any) that performs the final write on A in S must also perform the final write on A in S′
- A schedule S is a view serializable schedule if S is view equivalent to some serial schedule over the same set of Xacts

View Equivalent Schedule: Example

S	S_1
$R_1(x)$	$R_1(x)$
$R_2(y)$	$R_1(y)$
$W_3(x)$	$W_1(z)$
$W_3(z)$	$R_2(y)$
$R_2(x)$	$R_2(x)$
$R_1(y)$	$W_2(z)$
$W_1(z)$	$W_3(x)$
$W_2(z)$	$W_3(z)$

Not view equivalent

S	S_2
$R_1(x)$	$R_1(x)$
$R_2(y)$	$R_1(y)$
$W_3(x)$	$W_1(z)$
$W_3(z)$	$W_3(x)$
$R_2(x)$	$W_3(z)$
$R_1(y)$	$R_2(y)$
$W_1(z)$	$R_2(x)$
$W_2(z)$	$W_2(z)$

View equivalent/serializable

Test for View Serializability

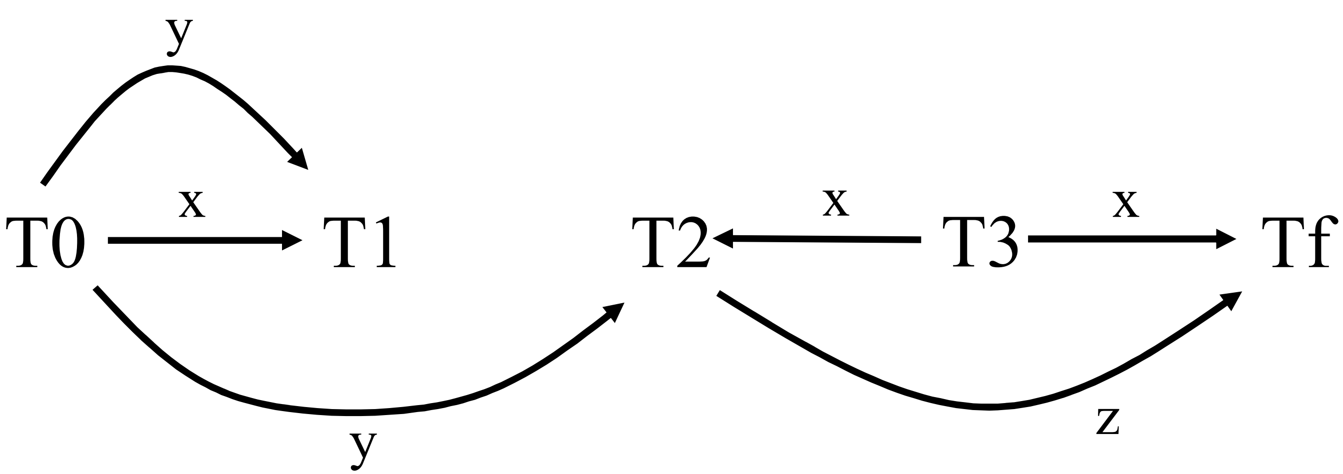
- Polygraphs
  - Generalization of precedence graphs for testing view serializability

- Theorem: Polygraph(S) is acyclic $\Leftrightarrow$ S is view serializable

Polygraph of a schedule S

- 3 rules
  - Nodes
    - A node for each transaction
    - An additional node representing a hypothetical transaction T_0 that wrote initial values for each item read by any transaction in the schedules
    - An additional node representing a hypothetical transaction T_f that reads every item written by one or more transactions after each schedule ends
  - Edges
    - For each action $r_i(X)$ with source T_j, add an arc from T_j to T_i

Polygraph of S: Rules 1 and 2



S
$R_1(x)$
$R_2(y)$
$W_3(x)$
$W_3(z)$
$R_2(x)$
$R_1(y)$
$W_1(z)$
$W_2(z)$

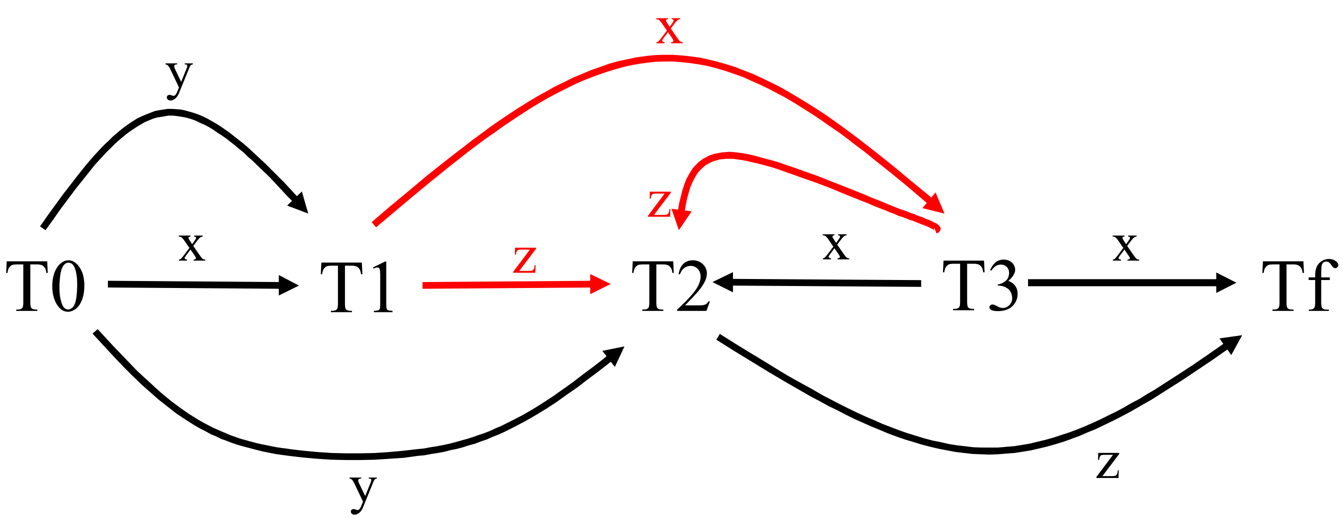
Rule 3

- Let T_j be the source of a read $r_i(X)$, i.e., $T_j \rightarrow T_i$
- Let T_k be another transaction that also writes X
- We cannot allow T_k to intervene between T_j and T_i
- So, T_k must be before T_j or after T_i
- Add edges $T_k \rightarrow T_j$ and $T_i \rightarrow T_k$ to the polygraph
  - Intuitively, only one of these edges is "real"; and we can choose either of them when we try to make the polygraph acyclic at the end of the process
  - Special cases:
    - If T_j is T_0 then it is not possible for T_k to appear before T_j so we need only to add one edge $T_i \rightarrow T_k$
    - If T_i is T_f then it is not possible for T_k to appear after T_i so we need only to add one edge T_k to T_j

Simplifications for rule 3

- When avoiding interference with the edge $T_j \rightarrow T_i$, only need to consider T_k that are
  - Writers of an item that caused the edge $T_j \rightarrow T_i$
- No need to consider T_0 or T_f (since they can never be T_k)
- No need to consider T_i or T_j, which are the ends of the edge itself

Complete Polygraph of S: Rules 1 – 3



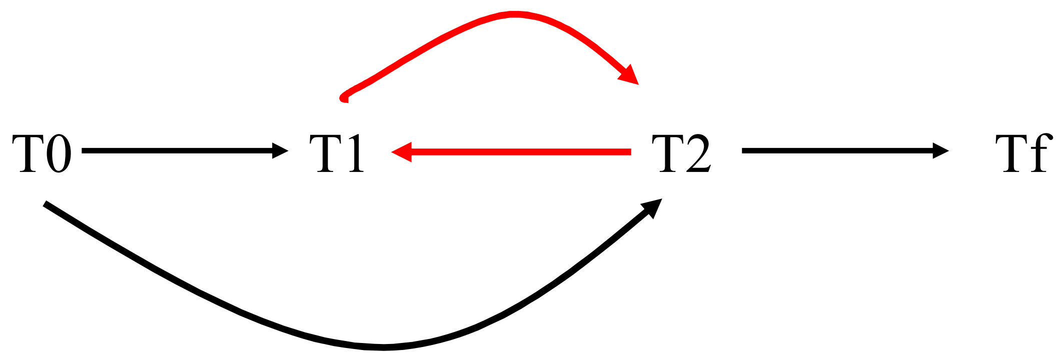
S
$R_1(x)$
$R_2(y)$
$W_3(x)$
$W_3(z)$
$R_2(x)$
$R_1(y)$
$W_1(z)$
$W_2(z)$

The graph is acyclic – with the serial order of T1; T3; T2

It is view serialializable!

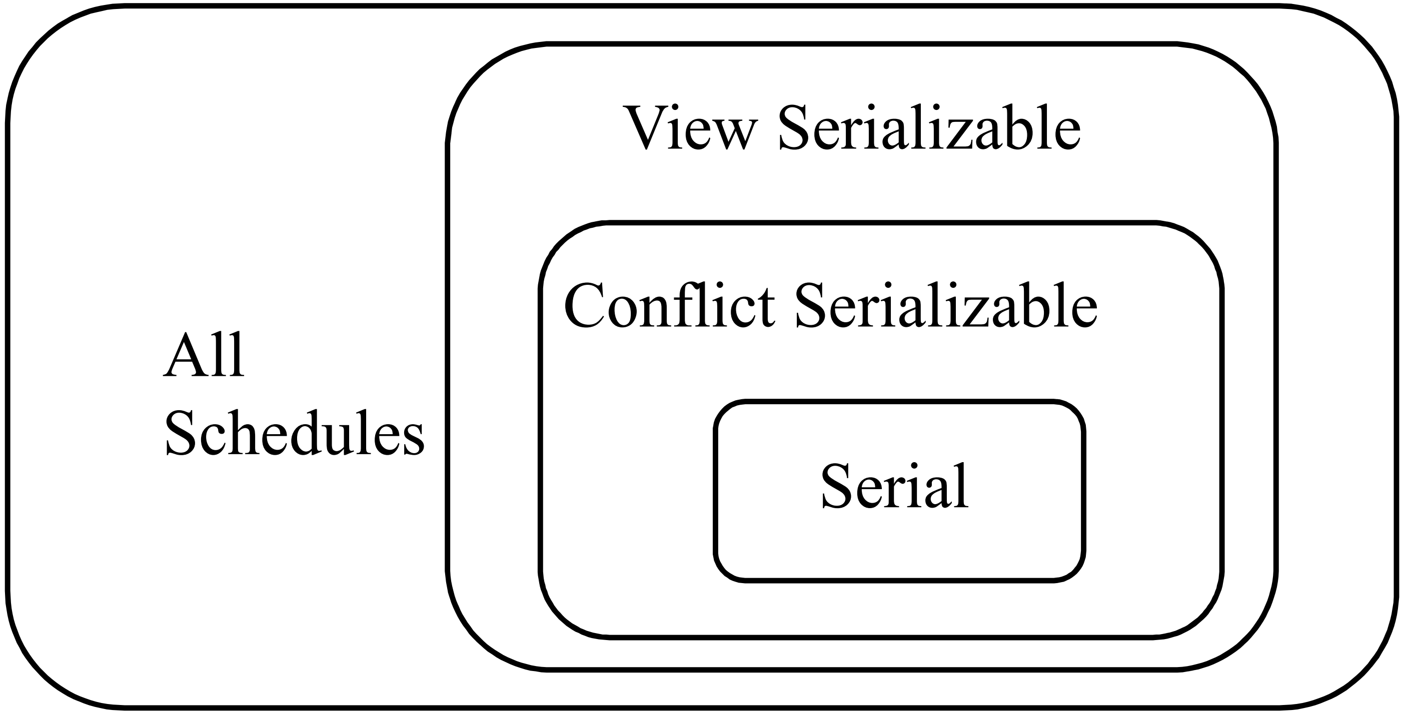
Is the following schedule view serializable?

- R1(X), R2(X), W1(X), W2(X)



Conflict vs View Serializabilility

- Theorem: A schedule that is conflict serializable is also view serializable
- View Serializability: Allows all conflict serializable schedules + blind writes!
- Theorem: If S is view serializable and S has no blind writes, then S is also conflict serializable



Cascading Aborts

- For correctness, if Ti has read from Tj , then Ti must abort if Tj aborts

T_1	T_2	T_3
$W_1(x)$		
	$R_2(x)$	
	$W_2(y)$	
$Abort_1$		$R_3(y)$
	$Abort_2$	$W_3(y)$
		$Abort_3$

- T_1's abort is cascaded to T_2

- Recursive aborting process is known as cascading aborts

Recoverable Schedules

- A schedule S is said to be a recoverable schedule if for every Xact T that commits in S, T must commit after T′ if T reads from T′

T_1	T_2
$W_1(x)$	
	$R_2(x)$
	$W_2(y)$
	$Commit_2$

This is a non-recoverable schedule

Cascadeless (Avoid Cascading Aborts) Schedules

- While recoverable schedules guarantee that committed Xacts will not be aborted, cascading aborts of active Xacts are possible
  - **Example**: if Ti reads from Tj and Tj aborts, Ti must also abort
- Cascading aborts are undesirable because of the cost of bookkeeping to identify them and the performance penalty incurred
- To avoid cascading aborts (or to be cascadeless), DBMS must permit reads only from committed Xacts
- A schedule S is a cascadeless schedule if whenever Ti reads from Tj in S, $Commit_j$ must precede this read action
- **Theorem 4**: A cascadeless schedule is also a recoverable schedule

Strict Schedules

- A schedule S is a strict schedule if for every $W_i(O)$ in S, O is not read or written by another Xact until T_i either aborts or commits
- **Theorem 5**: A strict schedule is also a cascadeless schedule

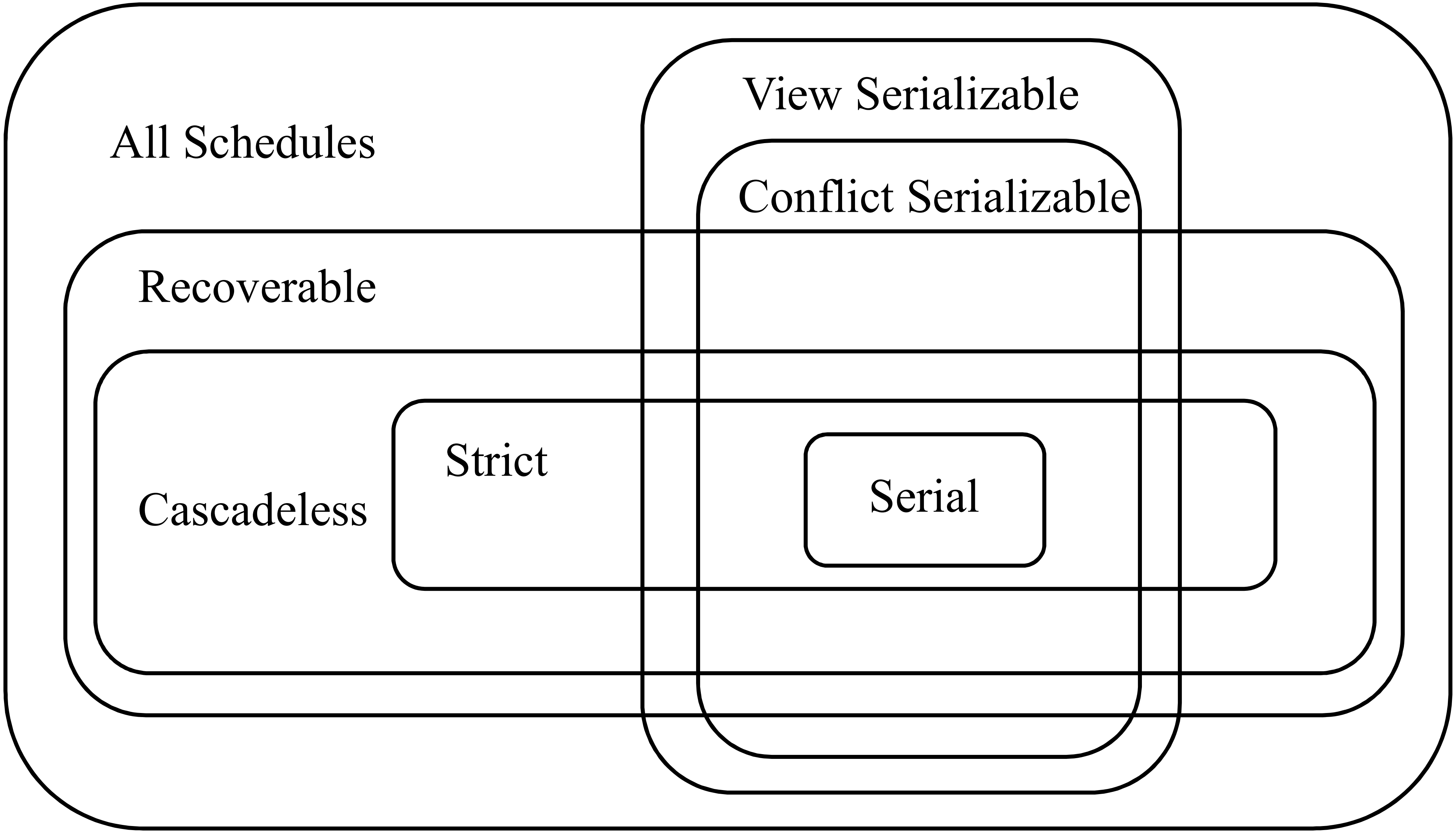
Cascadeless But Not Strict Schedules

T1	T2
	R(A)
R(A)	
W(A)	
	W(A)
Abort	
	~~Commit~~

Then strict

T1	T2
W(A)	
	W(A)
	Commit
R(A)	

Relationships between schedules



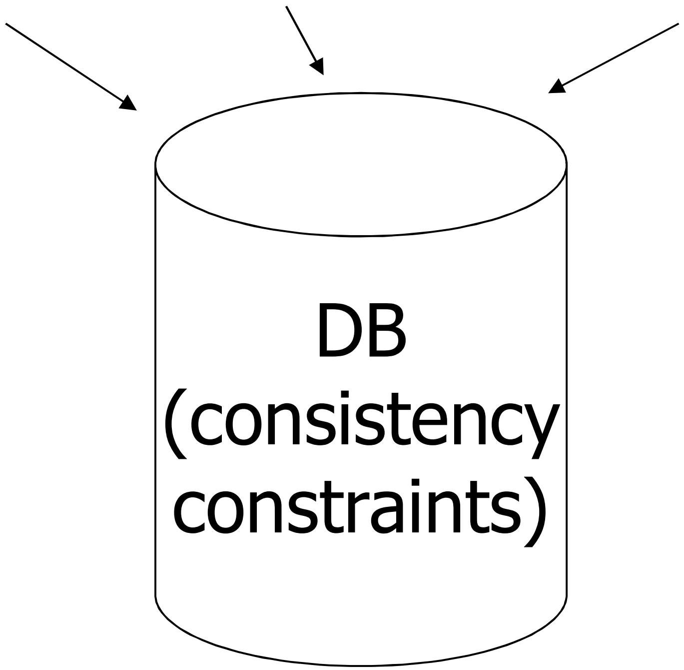
Concurrency Control

Smile, it is the key that fits the lock of everybody's heart.

Anthony J. D'Angelo,
The College Blue Book

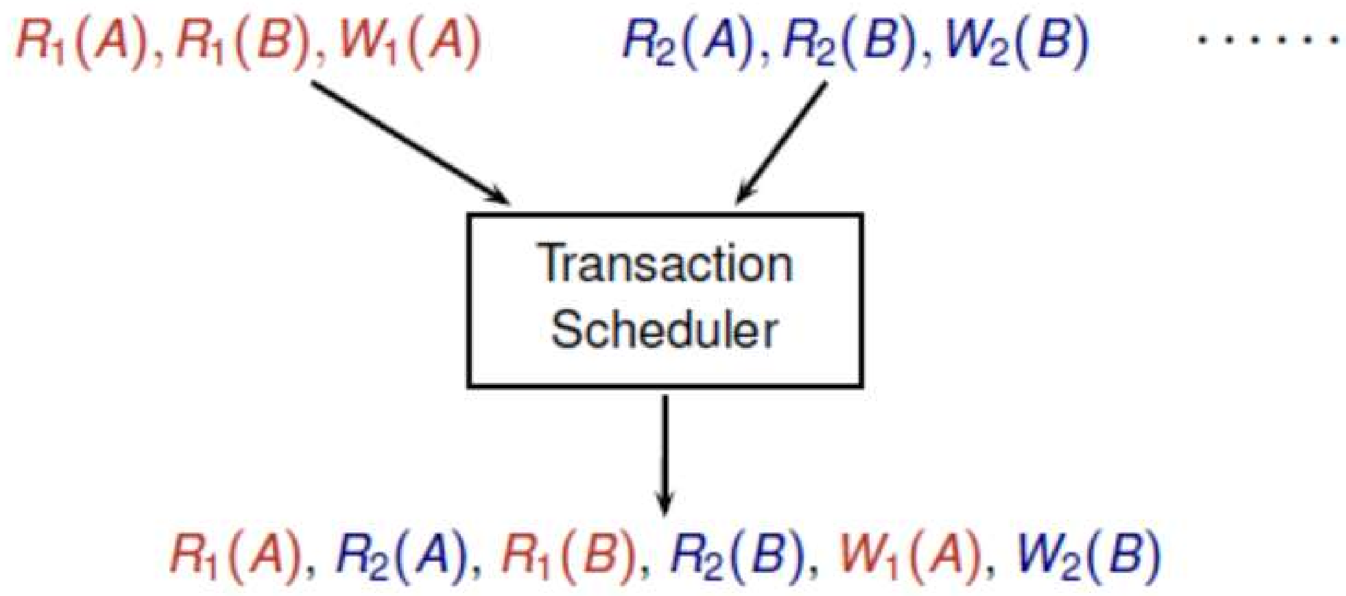
Concurrency Control

T1 T2 … Tn



Improves latency and throughput

How to enforce serializable schedules?



- For each input action (read, write, commit, abort) to the scheduler, the scheduler performs one of the followings:
  - Output the action to the schedule
  - Postpone the action by blocking the transaction, or
  - Reject the action and abort the transaction

Concurrency Control (CC) Algorithms

- Pessimistic CC
  - Lock-based CC
  - Timestamp-based CC
- Multiversion CC
- Optimistic CC

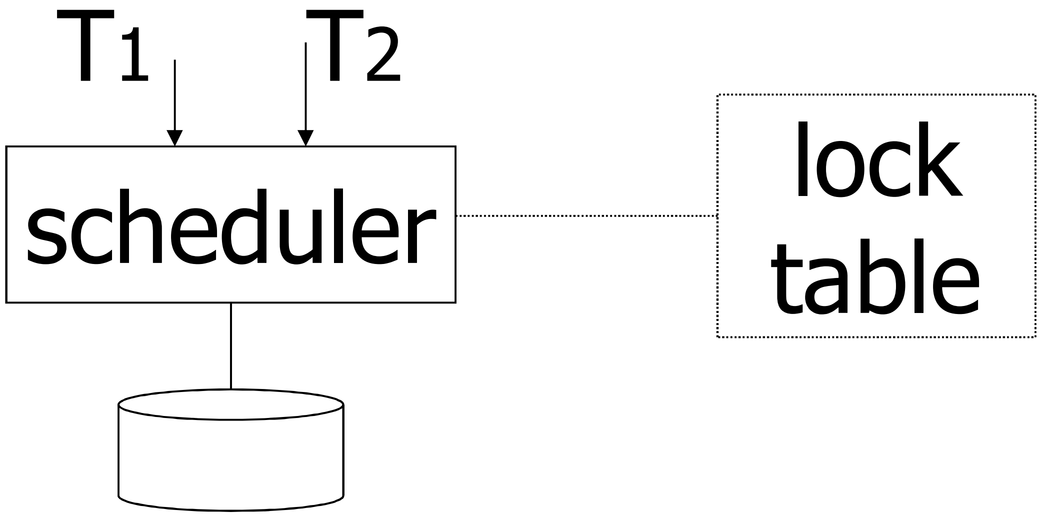
Pessimistic Concurrency Control

A locking protocol

Two new actions:

lock (exclusive): l_i (A)

unlock: u_i (A)



Rules

Rule #1: Well-formed transactions

Ti: … li(A) … pi(A) … ui(A) ...

Transaction i locks A — Transaction i performs action — Transaction i unlocks A

Rule #2: Legal scheduler

S = …….. li(A) ………... ui(A) ……...

no lj(A)

Exercise:

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

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

Not legal

$S2 = l_1(A)r_1(A)w_1(B)u_1(A)u_1(B)$

Not well-formed

$l_2(B)r_2(B)w_2(B)l_3(B)r_3(B)u_3(B)$

Not legal

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

Schedule F (Schedule C with locking)

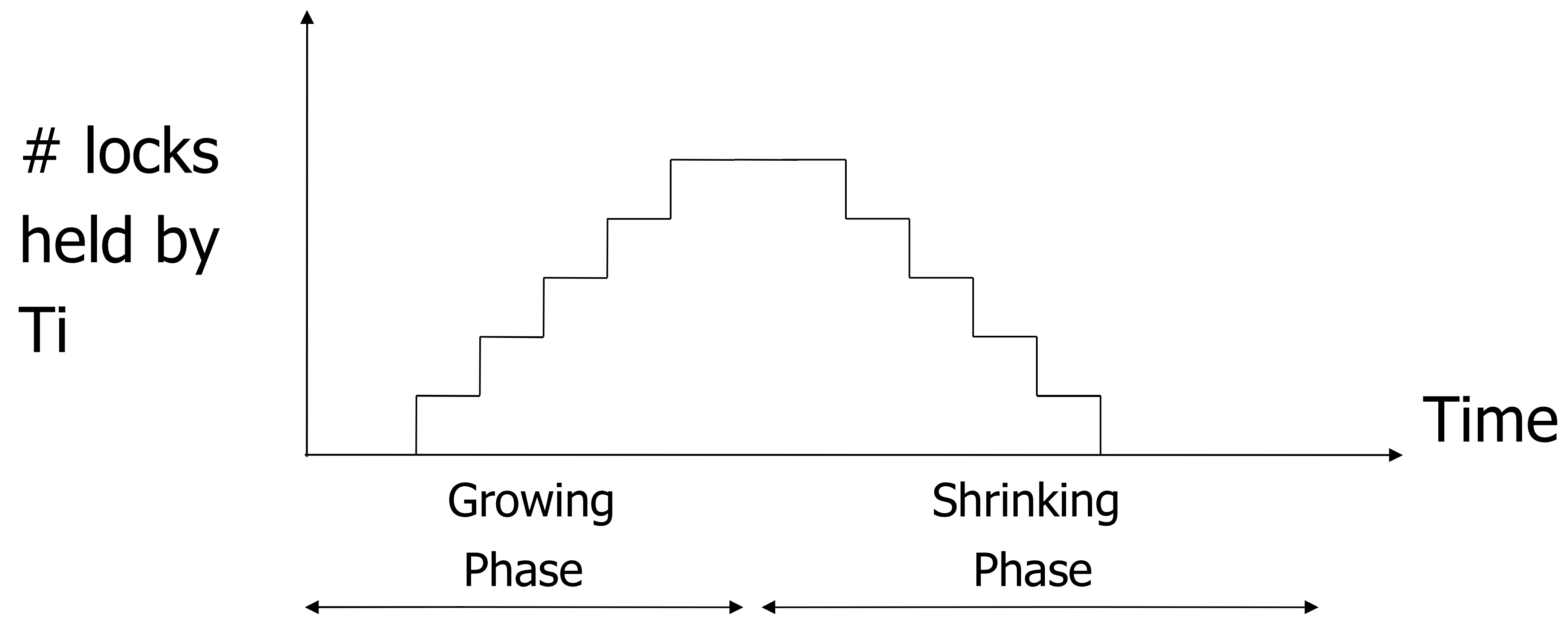
T1	T2	A	B
		25	25
l_1(A);Read(A)			
A←A+100;Write(A);u_1(A)		125	
	l_2(A);Read(A)		
		250	
	l_2(B);Read(B)		
	B ← Bx2;Write(B);u_2(B)		50
l_1(B);Read(B)			
B ← B+100;Write(B);u_1(B)			150
		250	150

Rules 1 & 2 are not enough!

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

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

no unlocks   no locks



Schedule G

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);$u_1(B)$	

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

delayed

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)
delayed	delayed

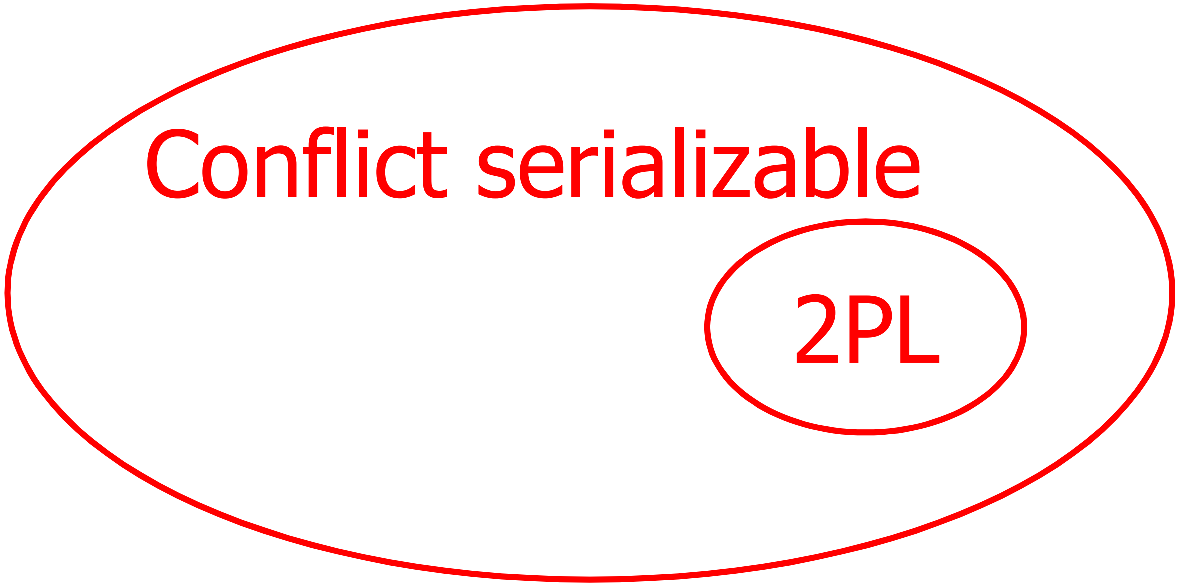
Transactions are *deadlocked*

- Some deadlocked transactions are *aborted* and *rolled back* (and all their actions undone)

Theorem

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

2PL subset of conflict serializable



Are the following schedules conflict serializable and can be produced by 2PL?

$$S_1 : R_1(B)W_3(A)R_2(C)W_2(C)R_3(C)W_1(B)R_3(B)W_3(C)$$

$T_2 \to T_3$

$T_1 \to T_3$

$$S_2 : R_1(A)W_1(A)R_2(B)W_2(C)R_2(A)R_3(C)W_3(B)R_1(B)$$

What else?

- 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 CC mechanisms**

Shared locks

So far (exclusive lock):

S1 = ...l1(A) r1(A) u1(A) … l2(A) r2(A) u2(A) …

Do not conflict (but executed serially!)

<u>Instead:</u>

S2=... ls1(A) r1(A) ls2(A) r2(A) .... us1(A) us2(A)

Interleaved operations

- Both transactions can run concurrently
- Better performance

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 the same object?

Option 1: Request exclusive lock

Ti = ...l-X1(A) … r1(A) ... w1(A) ... u(A) …

Option 2: Upgrade

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

Ti=... l-S1(A) … r1(A) ... l-X1(A) …w1(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

New request

Lock already held in

	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

Theorem

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

Example

T1	T2
l-S_1(A); r_1(A)	
	l-S_2(A); r_2(A)
	l-S_2(B); r_2(B)
l-X_1(B) (Denied)	
	u_2(A); u_2(B)
l-X_1(B); r_1(B); w_1(B)	
u_2(A); u_2(B)	

Strict 2PL Protocol

- Same as 2PL except a Xact must hold on to locks until Xact commits or aborts
- Theorem: Strict 2PL schedules are strict and conflict serializable

How does locking work in practice?

- Every system is different

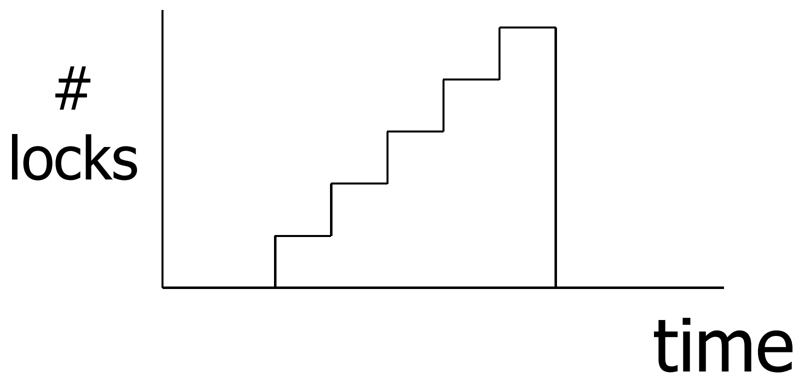
  (E.g., may not even provide
  CONFLICT-SERIALIZABLE schedules)

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

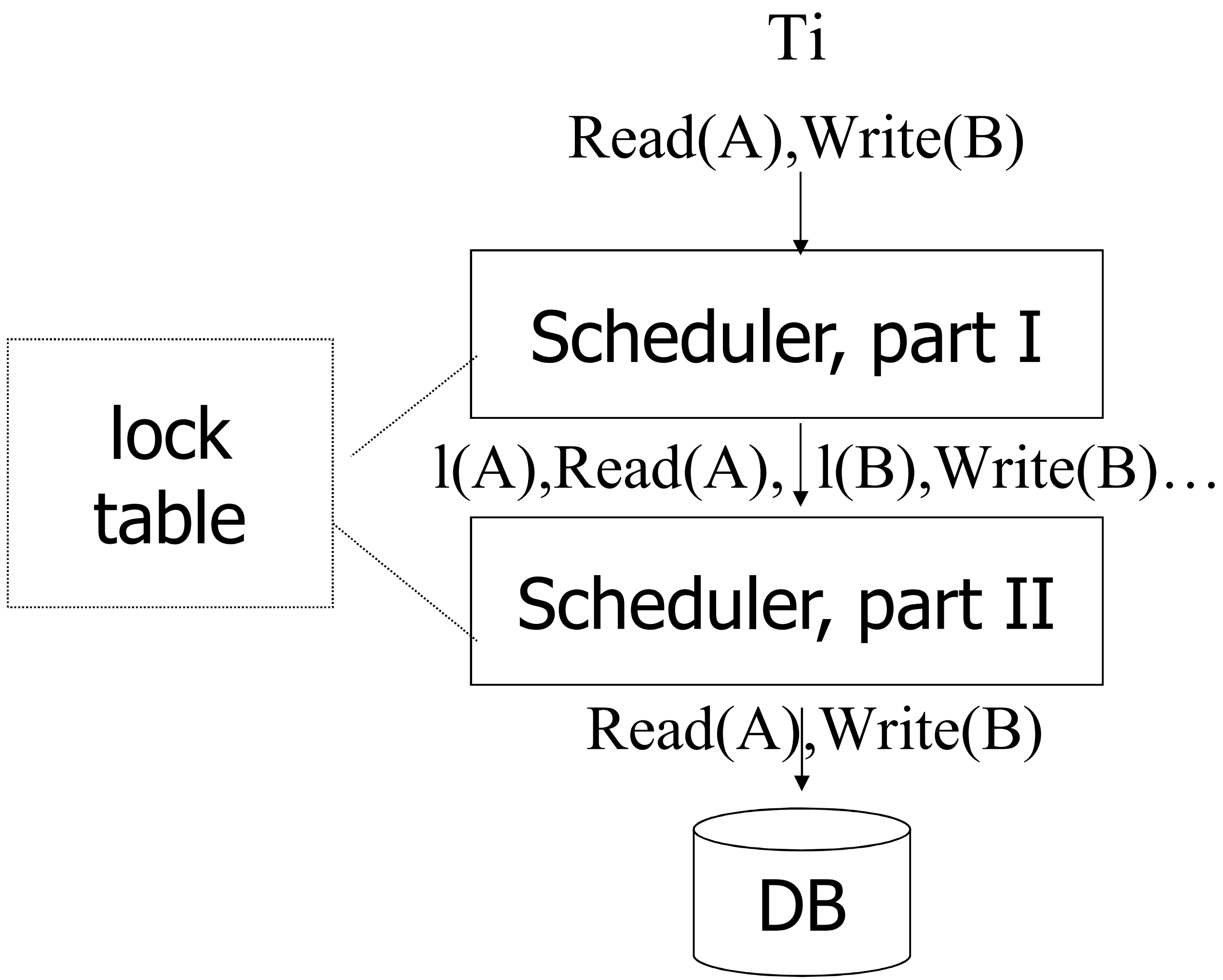
Sample Locking System:

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

(2) Hold all locks until transaction commits

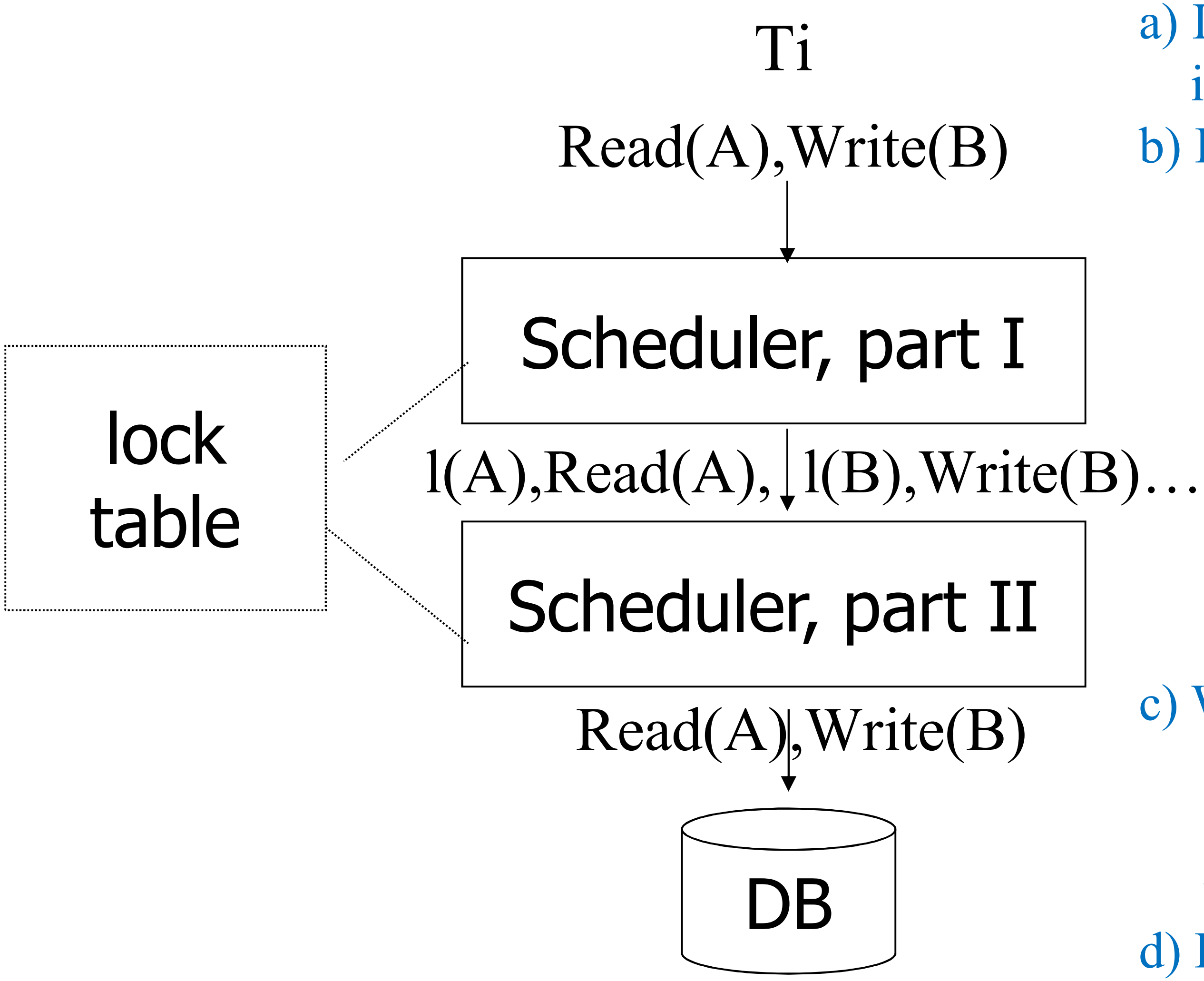


Architecture of a Locking Scheduler



Part I: select appropriate lock mode, and inserts appropriate lock actions ahead of all database operations

Architecture of a Locking Scheduler



Part II:Execute the operations

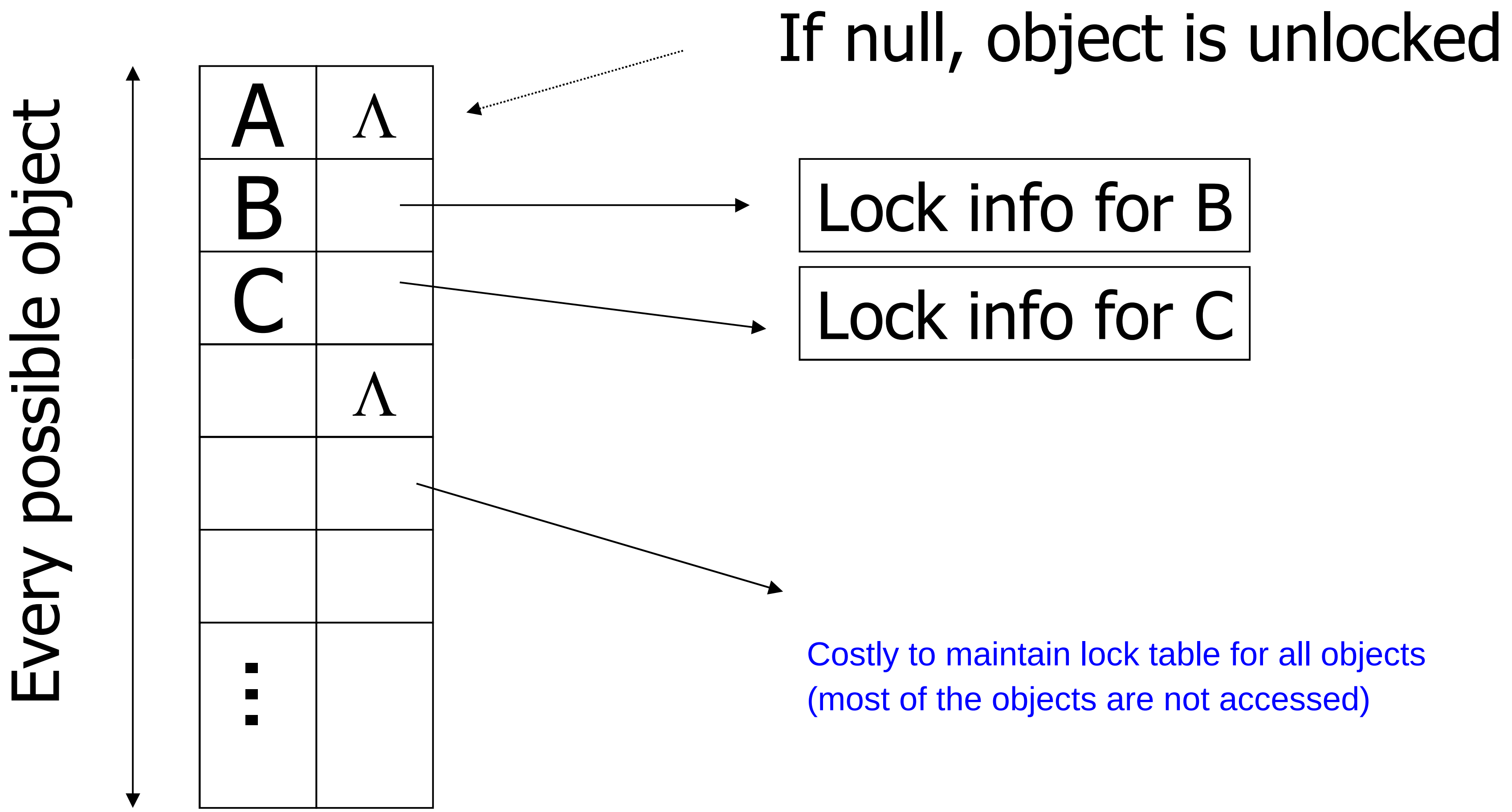
a) It determines if lock should be granted; if not, then transaction is delayed.

b) If transaction is not delayed,
  - If action is a normal opr, then send it to the dbms
  - If action is a lock opr, then check if lock can be granted
    * if so, update lock table
    * if not, delay transaction but update lock table to reflect transaction waiting

c) When a transaction commits/aborts, Part I is notified and releases all locks. Part II will be notified if there are transactions waiting.

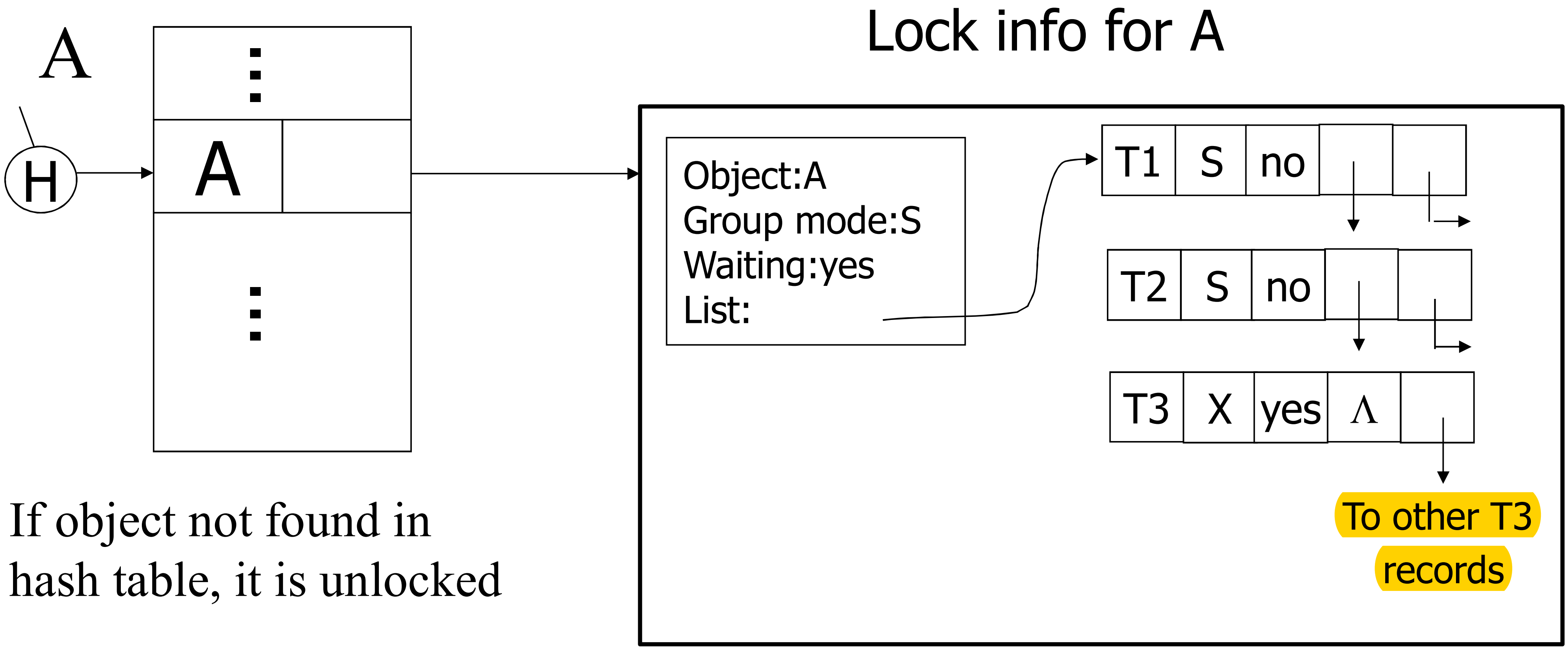
d) Part II determines next transactions to be given the released locks. Those that acquired locks can be processed.

Lock table (Conceptually)



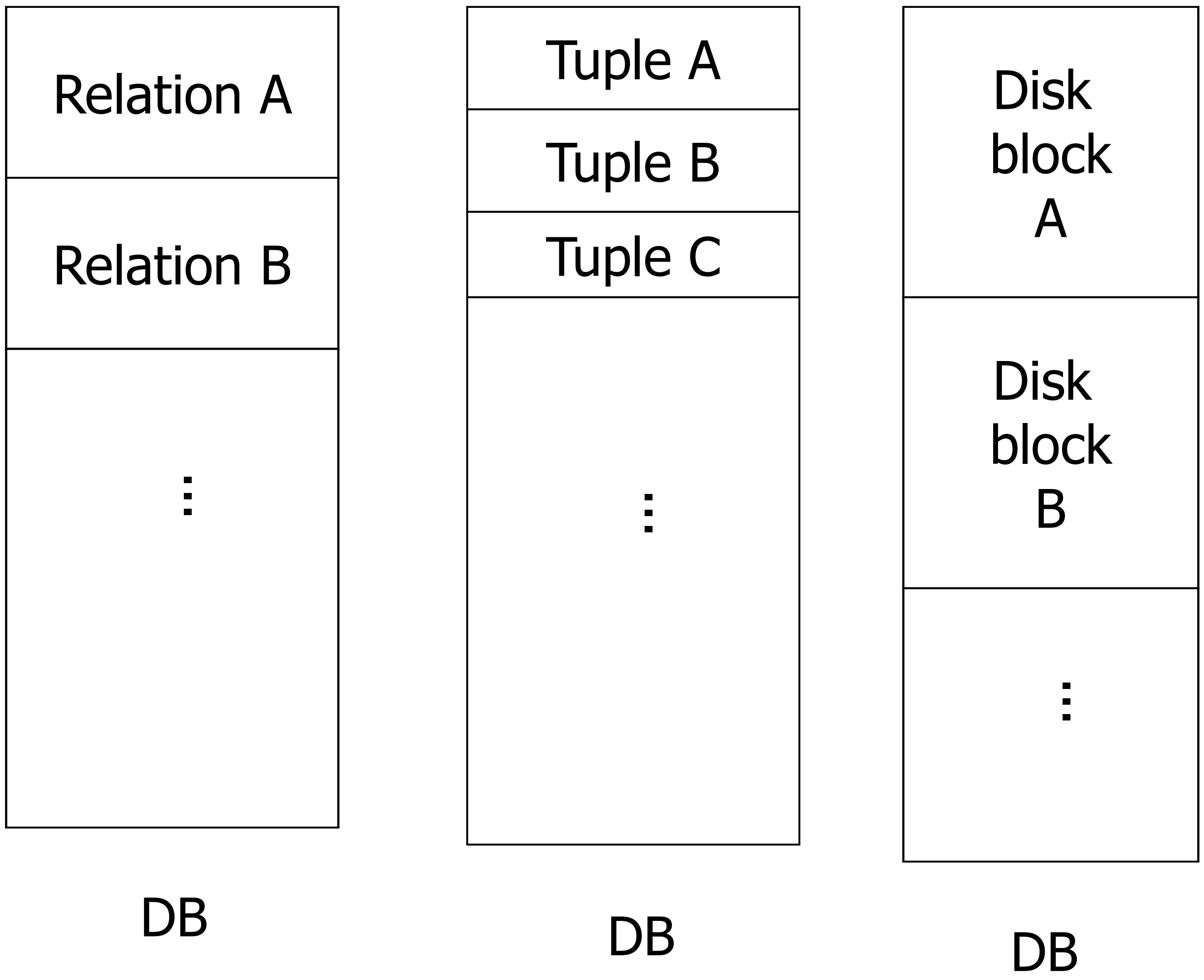
Costly to maintain lock table for all objects
(most of the objects are not accessed)

But use hash table:



If object not found in hash table, it is unlocked

What are the objects we lock?

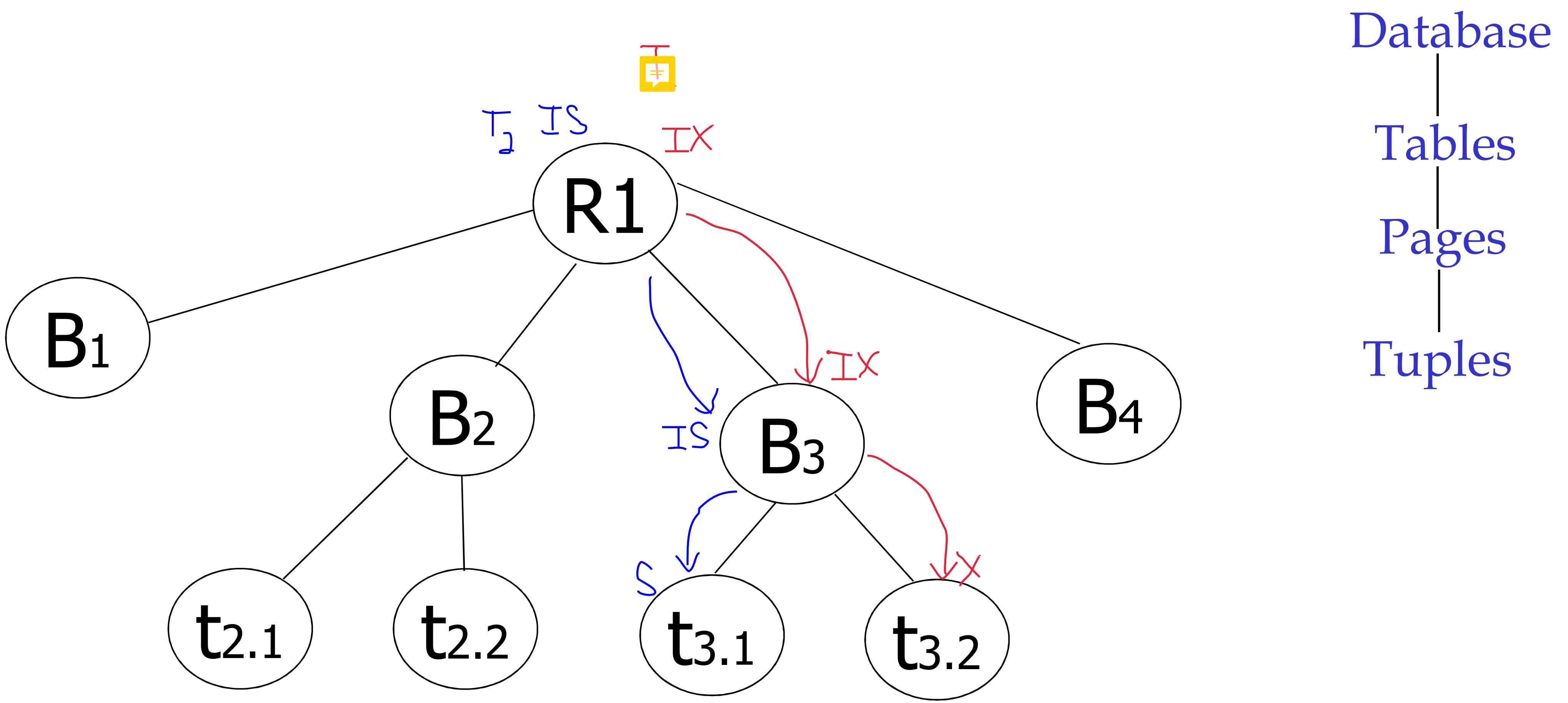


Large objects (e.g., Relations)
- Need few locks
- Low concurrency

Small objects (e.g., tuples,fields)
- Need more locks
- More concurrency

We can have it both ways!!

Managing Hierarchies of Database Elements



resolves any conflicts at the later stage

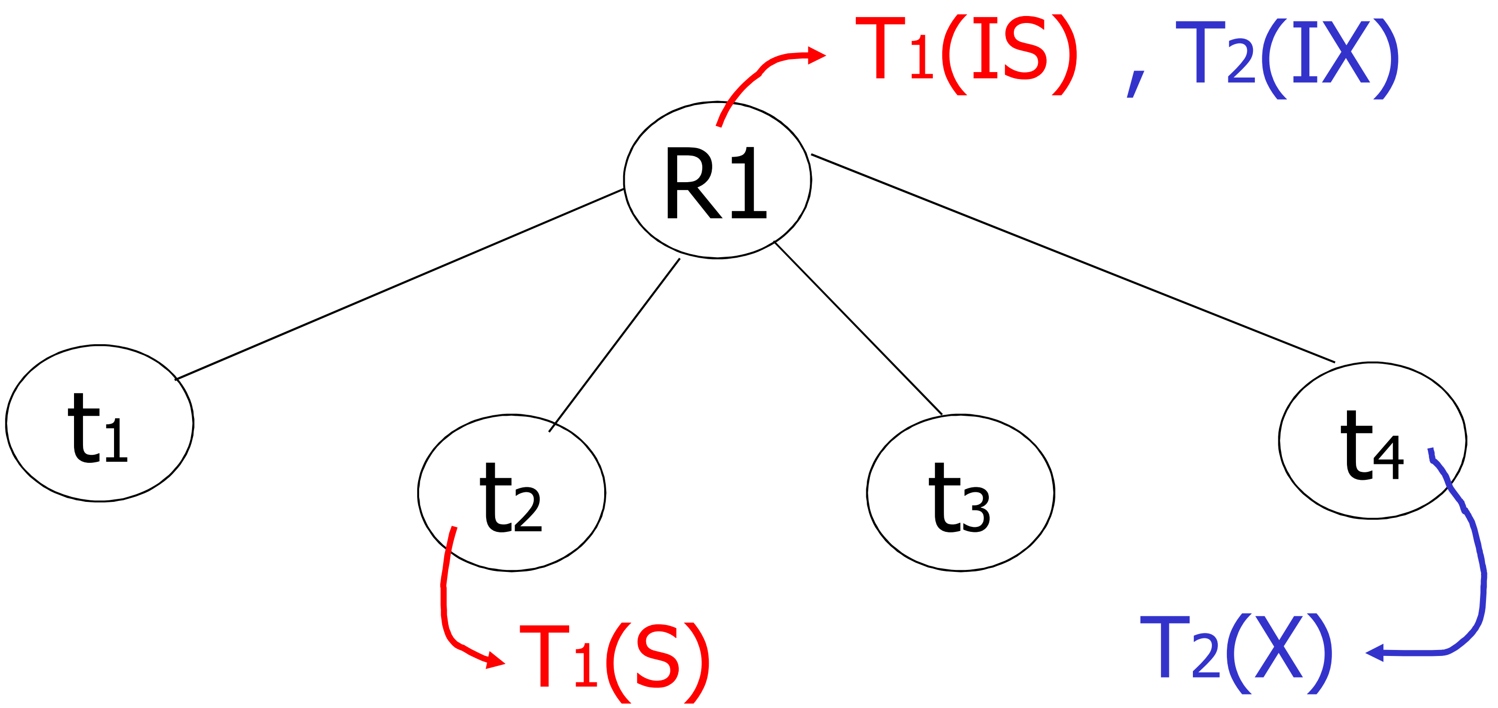
Warning Protocol

Comp | Requestor

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

- IS – Intent to get S lock(s) at *finer granularity*
- IX – Intent to get X lock(s) at *finer granularity*

Multiple Granularity: Warning Protocol



- IS – Intent to get S lock(s) at *finer granularity*
- IX – Intent to get X lock(s) at *finer granularity*

Warning Protocol

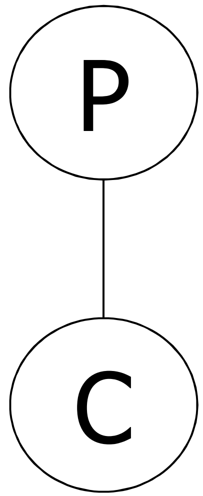
- SIX mode: Like S & IX at the same time

Requestor

Holder		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

Does it make sense to have XIS?

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

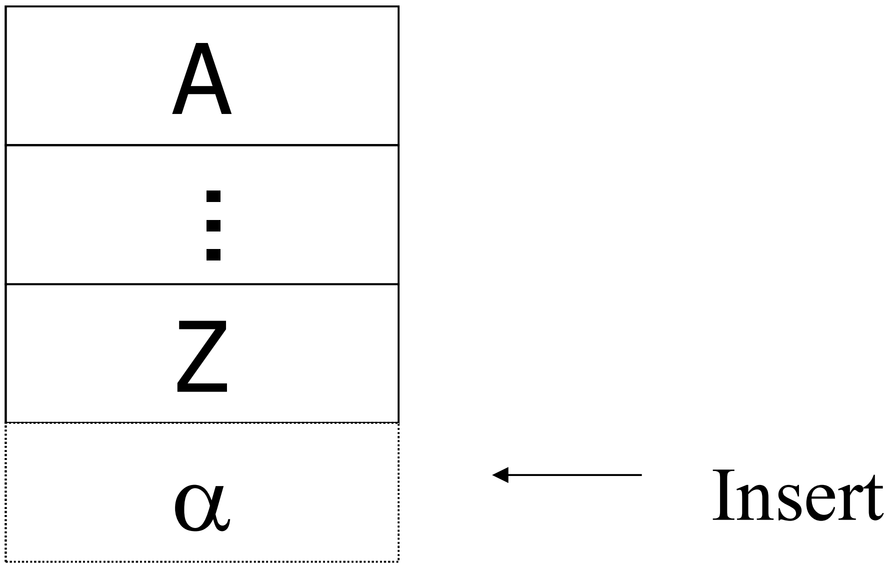
Examples – 2 level hierarchy

Tables
|
Tuples

- T1 scans R, and updates a few tuples:
  - T1 gets an SIX lock on R, then get X lock on tuples that are updated.
- T2 uses an index to read only part of R:
  - T2 gets an IS lock on R, and repeatedly gets an S lock on tuples of R.
- T3 reads all of R:
  - T3 gets an S lock on R.
  - OR, T3 could behave like T2; can use lock escalation to decide which.
  - Lock escalation dynamically asks for coarser-grained locks when too many low level locks acquired

	IS	IX	SIX	S	X
IS	√	√	√	√	
IX	√	√			
SIX	√				
S	√			√	
X					

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

Essentially all insertion and deletion will require exclusive locks too

Concurrency Control Anomalies & Locking

- Dirty read problem: W1(x), R2(x)
- Unrepeatable read problem: R1(x), W2(x), R1(x)
- Lost update problem: R1(x), R2(x), W1(x), W2(x)

- But still has an anomaly: Phantom problem
  - A transaction *re-executes* a query returning a set of rows that satisfy a search condition and finds that the *set of rows* satisfying the condition has changed due to another recently committed transaction

Phantom Read Problem

Accounts

account	name	balance
100	Alice	5000
200	Bob	800
300	Carol	1000

$\rightarrow$

Accounts

account	name	balance
100	Alice	5000
200	Bob	800
300	Carol	1000
400	Dave	3000

```
begin transaction;
select    name
from      Accounts
where     balance > 1000;
                                    begin transaction;
                                    insert into Accounts
                                        values (400,'Dave',3000);
                                    commit;
select    name
from      Accounts
where     balance > 1000;
commit;
```

$R_1(100, Alice, 5000)$
$R_1(200, Bob, 800)$
$R_1(300, Carol, 1000)$
Output: $\{Alice\}$

$W_2(400, Dave, 3000)$
$Commit_2$

$R_1(100, Alice, 5000)$
$R_1(200, Bob, 800)$
$R_1(300, Carol, 1000)$
$R_1(400, Dave, 3000)$
$Commit_1$
Output: $\{Alice, Dave\}$

Phantom Update Problem

Example: relation R (E#,name,…)

constraint: E# is key

use tuple locking

R

	E#	Name	….
o1	55	Smith	
o2	75	Jones	

T1: Insert <99,Gore,...> into R

T2: Insert <99,Bush,...> into R

T1	T2
S1(o1)	S2(o1)
S1(o2)	S2(o2)
Check Constraint	Check Constraint
-- no such key, ok to insert	-- no such key, ok to proceed
⋮	⋮
Insert o3[99,Gore,..]	
	Insert o4[99,Bush,..]

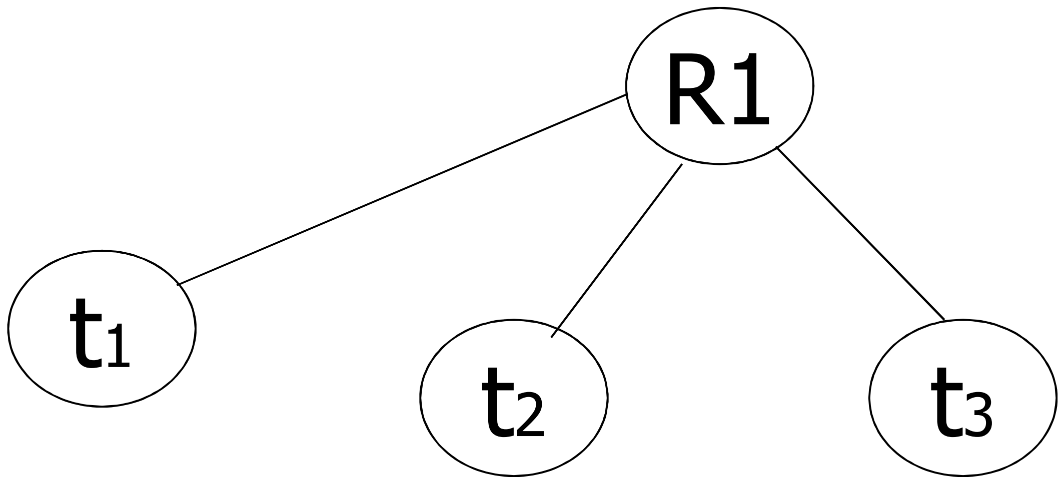
Violation of key constraint!

Solution

- Use multiple granularity tree
- Before insert of node Q,

  lock parent(Q) in

  X mode

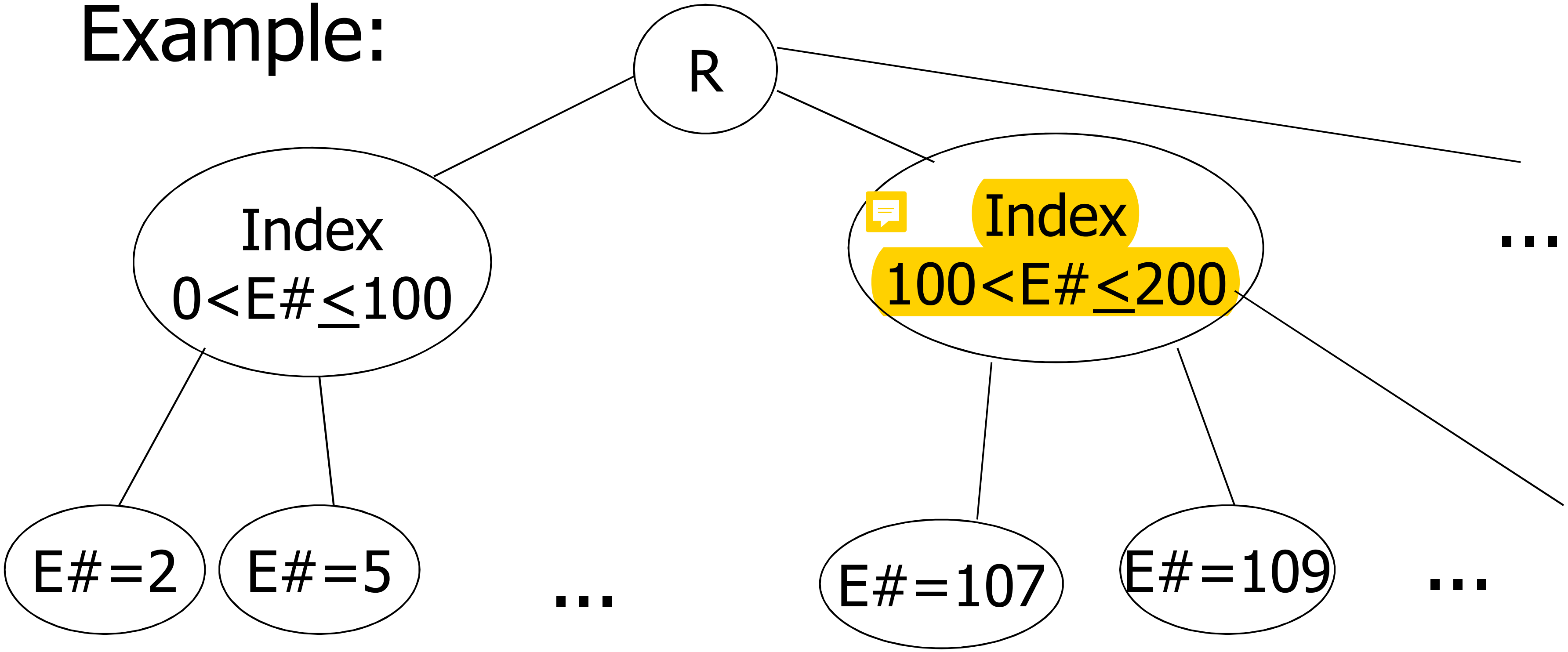


Back to example

T1: Insert<99,Gore>	T2: Insert<99,Bush>
T_1	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!

Instead of using R, can use index on R:

Example:



ANSI SQL Isolation Levels

Isolation Level	Dirty Read	Unrepeatable Read	Phantom Read
READ UNCOMMITTED	possible	possible	possible
READ COMMITTED	not possible	possible	possible
REPEATABLE READ	not possible	not possible	possible
SERIALIZABLE	not possible	not possible	not possible

- SQL's SET TRANSACTION ISOLATION LEVEL command

```
BEGIN TRANSACTION;
SET TRANSACTION ISOLATION LEVEL
            { READ UNCOMMITTED |
              READ COMMITTED |
              REPEATABLE READ |
              SERIALIZABLE };
            ……
COMMIT;
```

- In many DBMSs, the default isolation level is READ COMMITTED
- Isolation level: per transaction and "eye of the beholder"

Welcome to the real world!

Default and maximum isolation levels for ACID and NewSQL databases as of Jan 2013 (provided by Joe Hellerstein)

Database	Default	Maximum
Actian Ingres 10.0/10S	S	S
Aerospike	RC	RC
Akiban Persistit	SI	SI
Clustrix CLX 4100	RR	RR
Greenplum 4.1	RC	S
IBM DB2 10 for z/OS	CS	S
IBM Informix 11.50	Depends	S
MySQL 5.6	RR	S
MemSQL 1b	RC	RC
MS SQL Server 2012	RC	S
NuoDB	CR	CR
Oracle 11g	RC	SI
Oracle Berkeley DB	S	S
Oracle Berkeley DB JE	RR	S
Postgres 9.2.2	RC	S
SAP HANA	RC	SI
ScaleDB 1.02	RC	RC
VoltDB	S	S

RC: read committed, RR: repeatable read, SI: snapshot isolation, S: serializability, CS: cursor stability, CR: consistent read

Deadlocks

Deadlocks

- Deadlocks: cycle of Xacts waiting for locks to be released by each other
- Example:
  T1 requests S-lock on A and is granted
  T2 requests S-lock on B and is granted
  T1 requests X-lock on B and is blocked
  T2 requests X-lock on A and is blocked

T1	T2
l-S1(A)	
	l-S2(B)
l-X1(B) (wait)	
	l-X2(A) (wait)

--- Deadlock ---

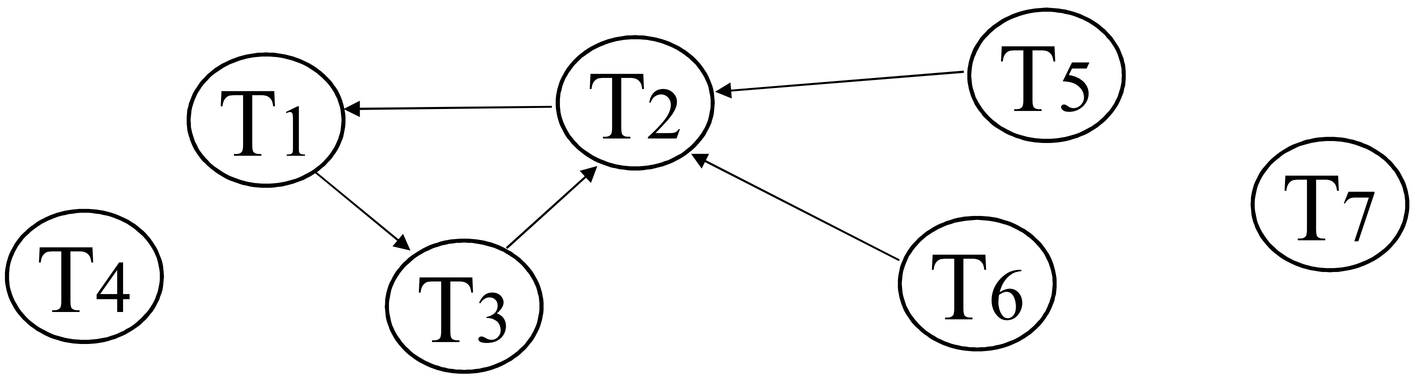
- Solutions:
  - Simple timeout mechanism
  - Detection
    - Wait-for graph
  - Prevention
    - Wait-die
    - Wound-wait

Deadlock Detection

- Build Wait-For graph
  - Nodes represent active Xacts
  - Add an edge Ti → Tj if Ti is waiting for Tj to release lock
- Use lock table structures
- Build incrementally or periodically
  - Adds an edge when it queues a lock request
  - Updates edges when it grants a lock request
- When a *cycle* is found, there is a *deadlock*

Deadlock Detection

- Breaks a deadlock by aborting a Xact in cycle
  - How to determine the victim?
    - Random
    - Most "connected"
    - Workload/time-based
    - …



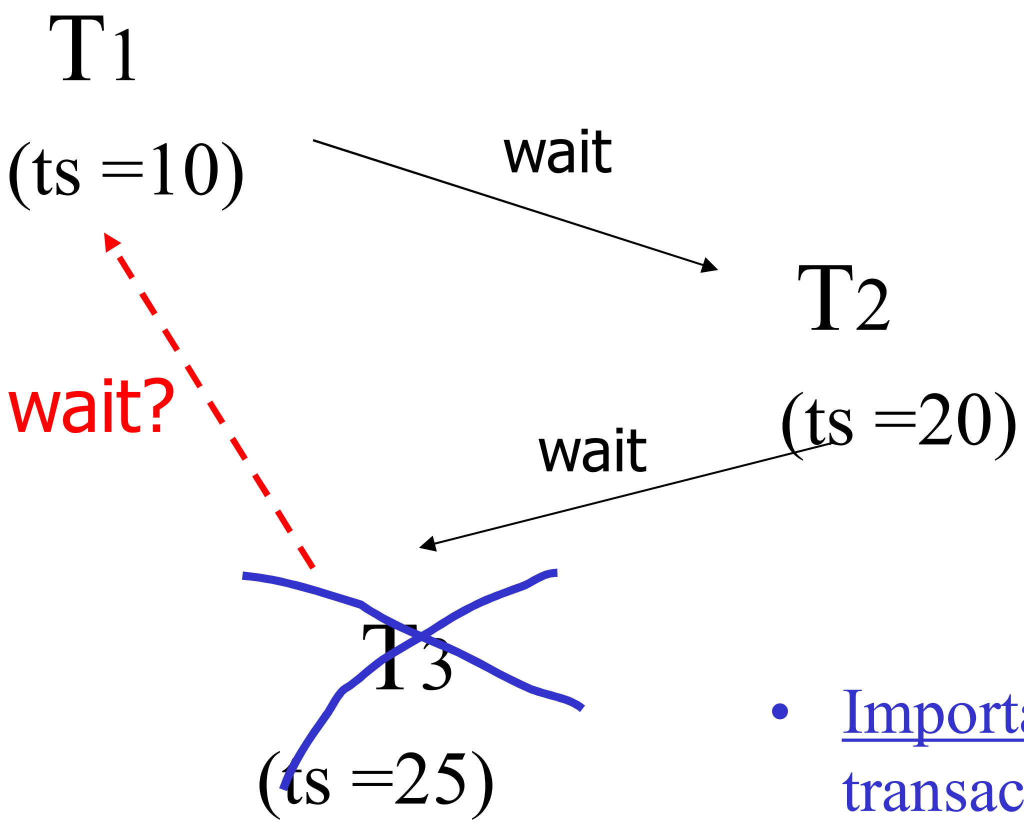
Deadlock Prevention

- Transactions given a timestamp when they arrive …. ts(Ti)
  - An older Xact has a smaller timestamp
- Suppose Ti requests for a lock that conflicts with a lock held by Tj
- Two possible deadlock prevention policies:
  - Wait-die policy: lower-priority Xacts never wait for higher-priority Xacts
  - Wound-wait policy: higher priority Xacts never wait for lower-priority Xacts

Prevention Policy	T_i has higher priority	T_i has lower priority
Wait-die	T_i waits for T_j	T_i aborts
Wound-wait	T_j aborts	T_i waits for T_j

Wait-die Example:

- Ti can only wait for Tj if ts(Ti)< ts(Tj)
  ...else die (i.e., abort)



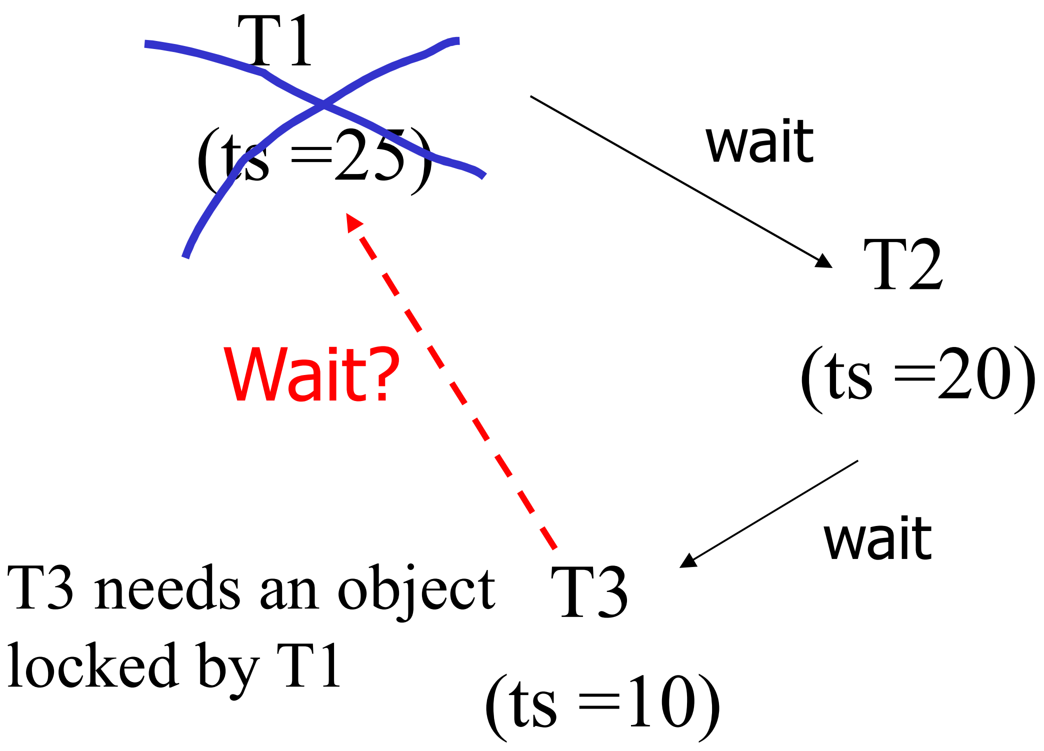
- Important detail: If a transaction re-starts, make sure it gets its original timestamp. Why?

Deadlock Prevention: Wound-wait

- Ti wounds Tj if ts(Ti)< ts(Tj)
  else Ti waits

"Wound": Tj rolls back and gives lock to Ti

Wound-wait Example



Optimistic Concurrency Control

Optimistic & Lock Free Concurrency Control: Validation-based Protocol

Transactions have 3 phases:

(1) Read

- All DB values read/written
  - Make a copy in temporary (local) storage
  - All updates/writes on local storage (no in-place updates/writes)
- No locking
- Maintains *read-set* (RS) and *write-set* (WS)

(2) Validate

- Check if schedule so far is serializable (ensure no conflict between RS/WS sets of transactions)

(3) Write

- If validate ok, write to DB values of WS; if not, “roll-back”

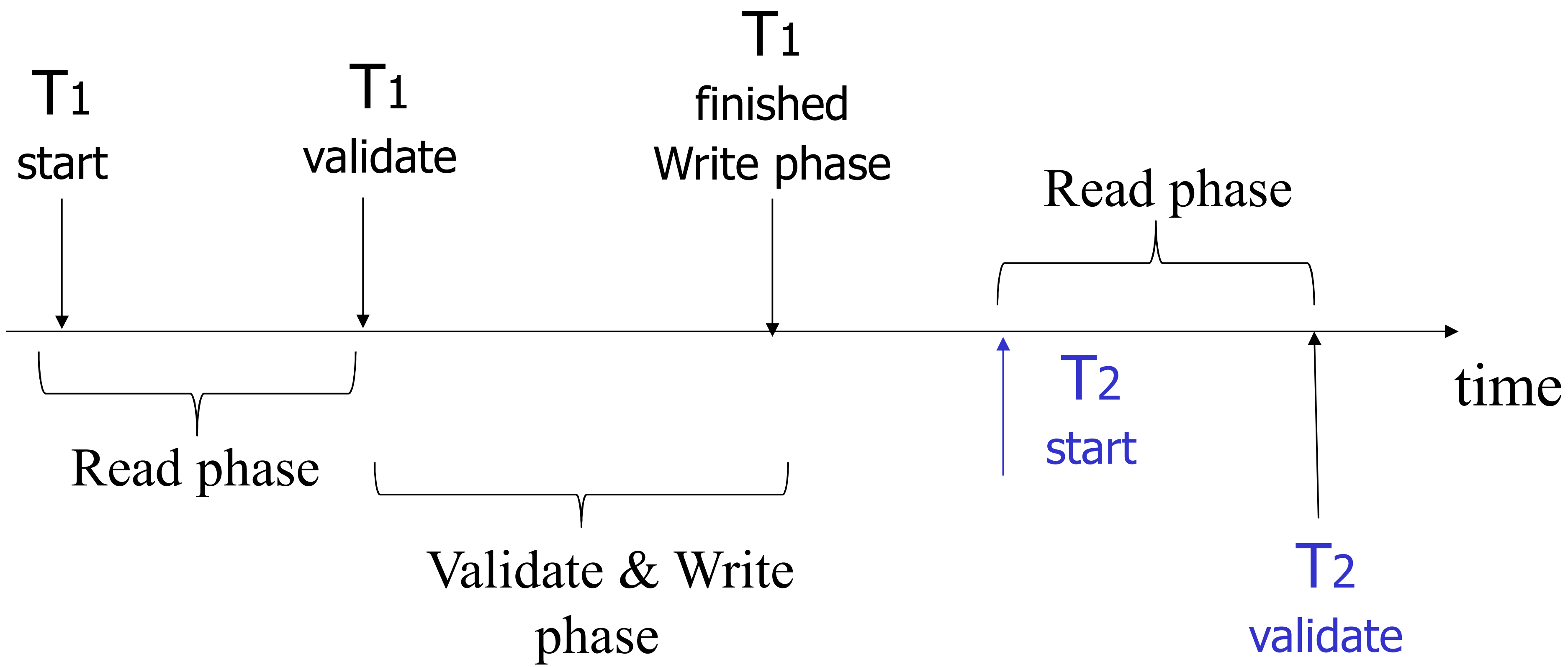
Validation-based Protocol

- Timestamps
  - start(T): start of read phase of T
  - validate(T): start of validate phase of T
  - finish(T): end of write phase
- Timestamp of transaction, ts(T): validate(T)
- Transactions are serialized using ts(T)
  - If ts(T1) < ts(T2) < ts(T3) …, then T1, T2, T3, … is the validation order, i.e., the resulting schedule will be conflict equivalent to serial order T1, T2, T3, ...
- Cascadeless schedule
- No locking! – no deadlocks!
- Starvation (rolled-back transactions restart with a new timestamp!)

Validation tests

- Validating Ti
  - $\forall$ Tj such that ts(Tj) < ts(Ti) // Compare with transactions that have validated
    - Rule 1: Finish(Tj) < start(Ti) **OR**
    - Rule 2: If Start(Ti) < Finish(Tj) < validation(Ti), then read-set(Ti) $\cap$ write-set(Tj) = $\varnothing$ **OR**
    - Rule 3: If Tj finishes after Ti starts and validates, then read-set(Ti) $\cap$ write-set(Tj) = $\varnothing$ **AND** write-set(Ti) $\cap$ write-set(Tj) = $\varnothing$
- Validation passes if the above is true
  - First rule says they are serial
  - Second and third say there are no conflicts

Example of what validation must **allow (Rule 1)**:

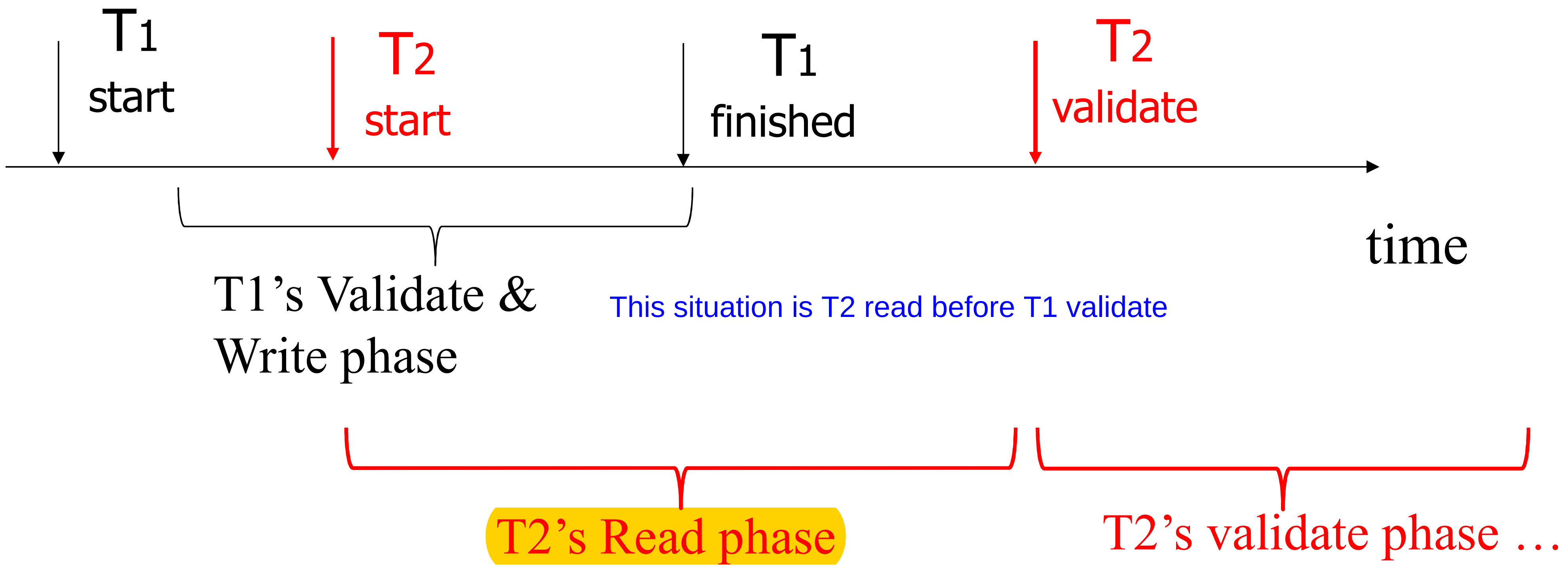


Example of what validation must prevent:

$RS(T_1)=\{B\}$ $\qquad$ $RS(T_2)=\{A,B\}$

$WS(T_1)=\{B,D\}$ $\qquad$ $WS(T_2)=\{C\}$

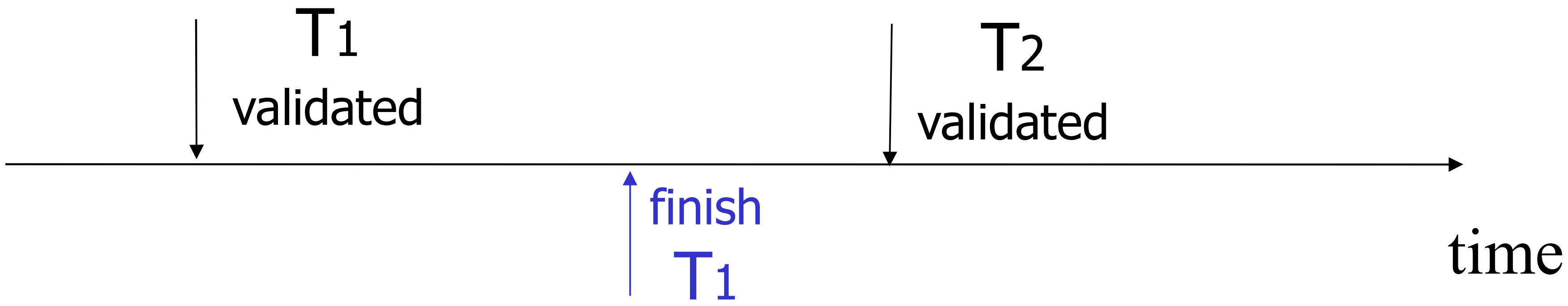
$WS(T_1) \cap RS(T_2) \neq \phi$



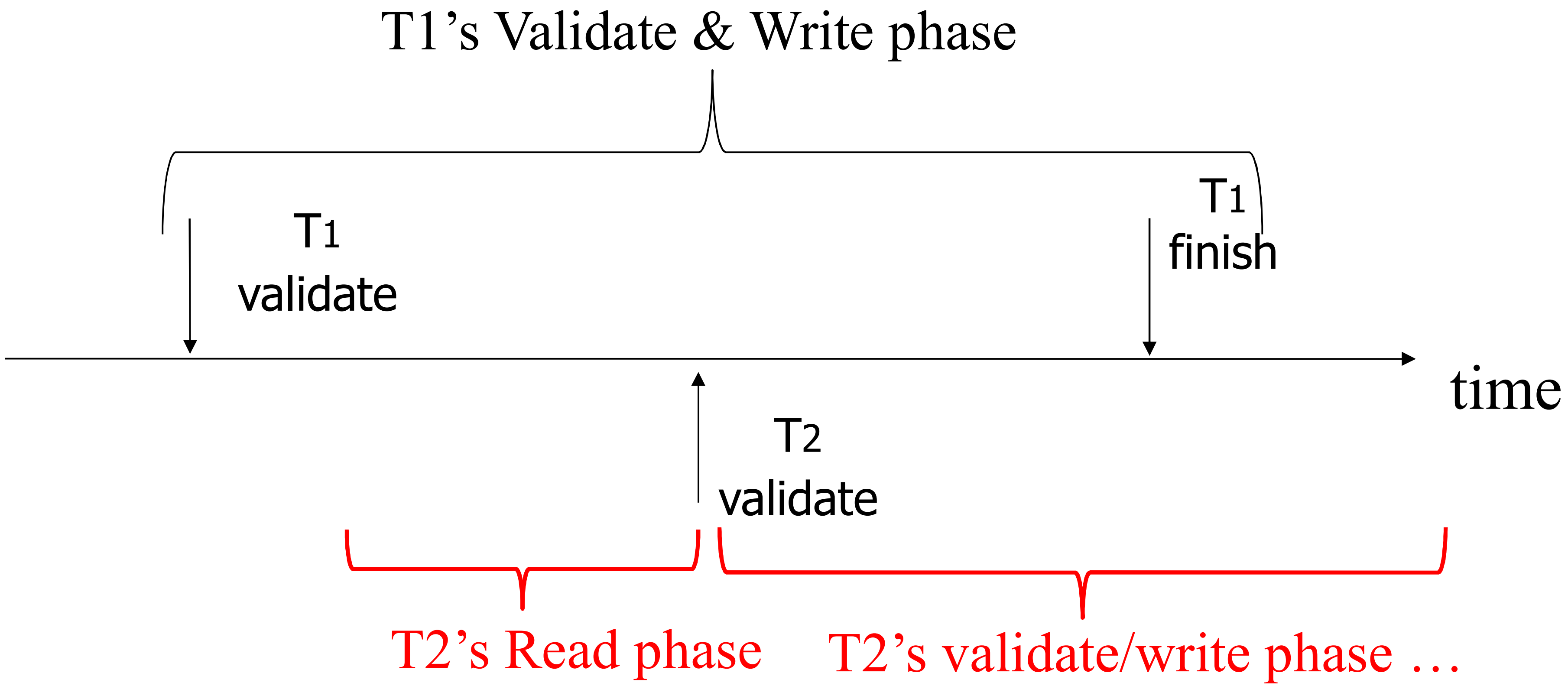
Another thing validation must **allow (Rule 2):**

$RS(T_1)=\{A\}$ $\quad$ $RS(T_2)=\{A,B\}$

$WS(T_1)=\{D,E\}$ $\quad$ $WS(T_2)=\{C,D\}$



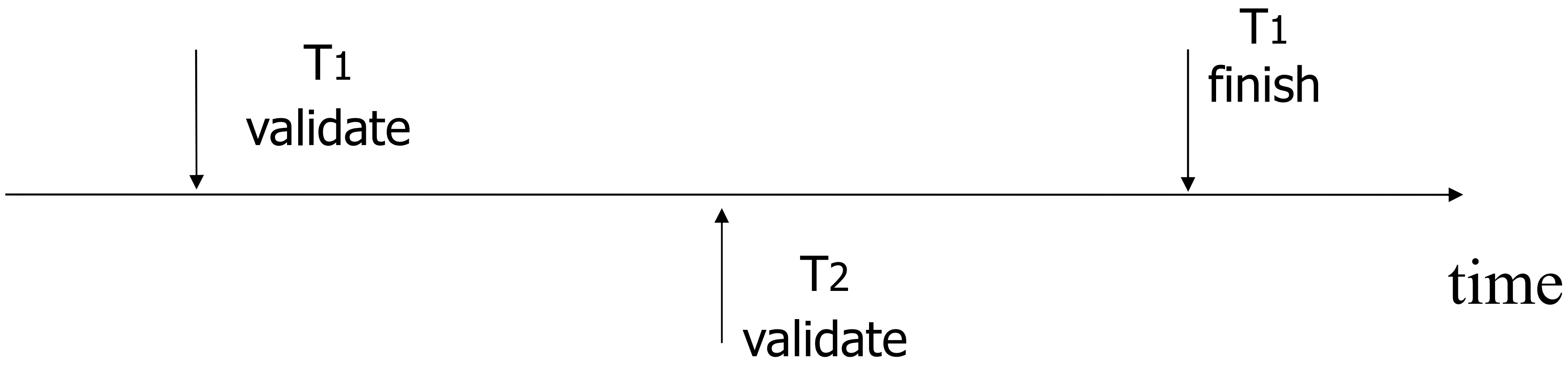
Another thing validation must prevent (?):



Another thing validation must prevent:

$RS(T_1)=\{A\}$ $\qquad$ $RS(T_2)=\{A,B\}$

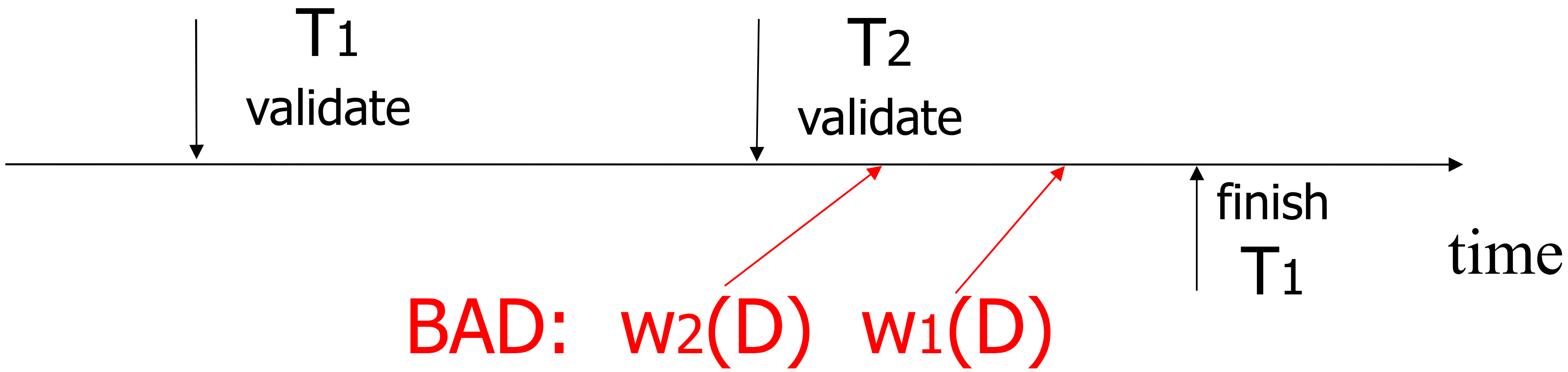
$WS(T_1)=\{D,E\}$ $\qquad$ $WS(T_2)=\{C,D\}$



Another thing validation must prevent:

$RS(T_1)=\{A\}$ $\quad$ $RS(T_2)=\{A,B\}$

$WS(T_1)=\{D,E\}$ $\quad$ $WS(T_2)=\{C,D\}$



T2 validates before T1 finishes

- This would create the situation where T2 writes before T1 writes (losing the update of T2)

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)

Validation rules for T_j:

(1) When T_j starts phase 1:

    ignore(T_j) $\leftarrow$ FIN

(2) At T_j Validation:

    if Valid(T_j) then

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

         do write phase;

         FIN $\leftarrow$ FIN U $\{T_j\}$]

Valid(T_j):

For $T_i \in$ VAL - IGNORE (T_j) DO

IF [$WS(T_i) \cap RS(T_j) \neq \emptyset$ OR “if they wrote and we read”

$(T_i \notin FIN$ AND $WS(T_i) \cap WS(T_j) \neq \emptyset)]$

THEN RETURN false; Ti is not done and we both wrote to the same items”

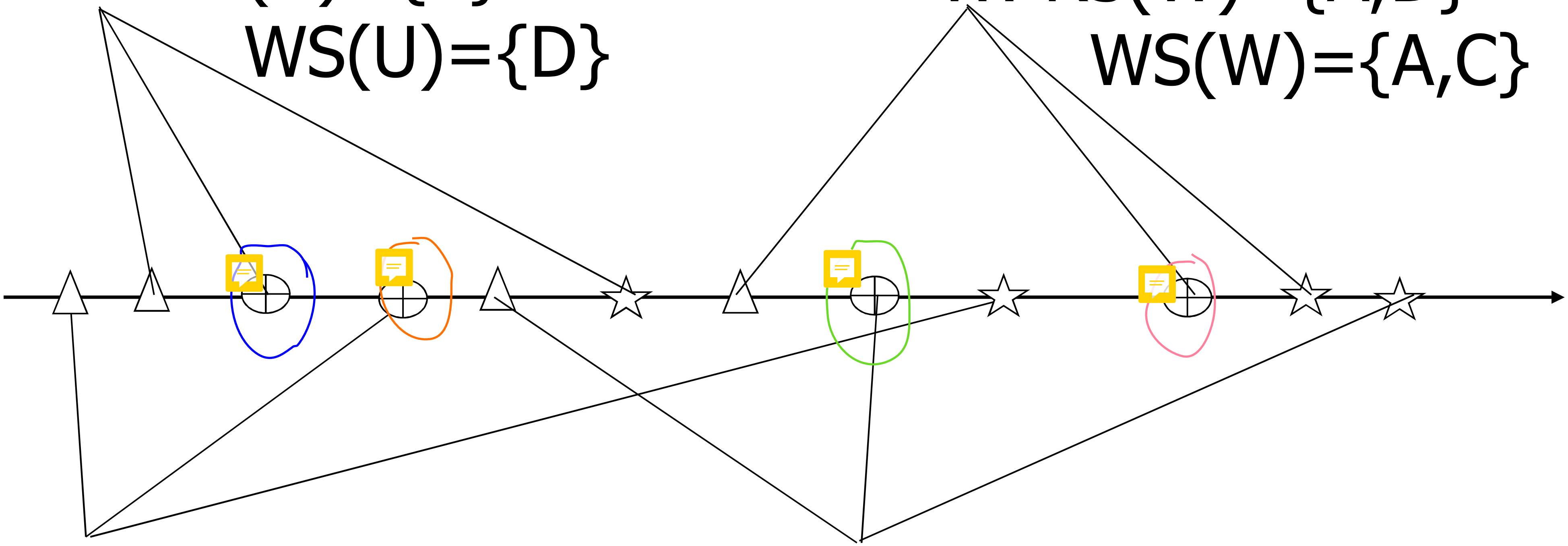
RETURN true;

Exercise:

△ start
⊕ validate — U, T, V, W
☆ 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}

Summary

- Have studied lock-based CC mechanisms
  - 2 PL
  - Multiple granularity
  - Deadlock
  - Validation-based schemes
- There are also non-locking based CC (timestamp) schemes, e.g., Multiversion (Snapshot Isolation)