

# Database System Internals

# Optimistic Concurrency Control

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# About Lab 3

- In lab 3, we implement transactions
- Focus on concurrency control
  - Want to run many transactions at the same time
  - Transactions want to read and write same pages
  - Will use locks to ensure conflict serializable execution
  - Use strict 2PL
- Build your own lock manager
  - Understand how locking works in depth
  - Ensure transactions rather than threads hold locks
    - Many threads can execute different pieces of the same transaction
    - Need to detect deadlocks and resolve them by aborting a transaction
  - But use Java synchronization to protect your data structures

# Recap

- **Several types of schedules:**
  - Serializable, conflict serializable, view serializable
  - Recoverable, without cascading aborts
- **2PL guarantees conflict serializable schedules**
- **Strict 2PL also guarantees no-cascading-aborts**
- **Locking manager: inserts lock/unlock, manages locks**
- **Types of locks: shared, exclusive**

# Isolation Levels in SQL

1. “Dirty reads”

SET TRANSACTION ISOLATION LEVEL READ UNCOMMITTED

2. “Committed reads”

SET TRANSACTION ISOLATION LEVEL READ COMMITTED

3. “Repeatable reads”

SET TRANSACTION ISOLATION LEVEL REPEATABLE READ

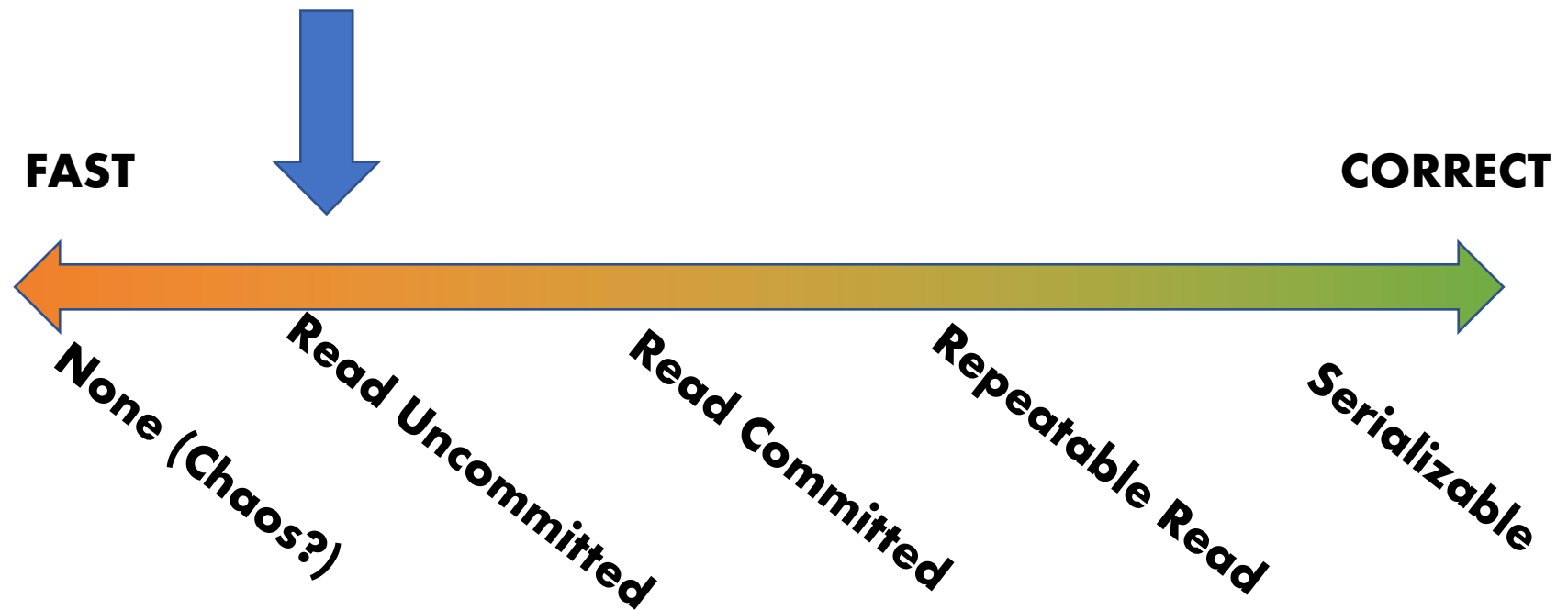
4. Serializable transactions

SET TRANSACTION ISOLATION LEVEL SERIALIZABLE



ACID

# Isolation Level Design Spectrum



# 1. Isolation Level: Dirty Reads

- “Long duration” WRITE locks
  - Strict 2PL
- No READ locks
  - Read-only transactions are never delayed

Possible problems:  
dirty and inconsistent reads

## 2. Isolation Level: Read Committed

- “Long duration” WRITE locks
  - Strict 2PL
- “Short duration” READ locks
  - Only acquire lock while reading (not 2PL)

Unrepeatable reads

When reading same element twice,  
may get two different values

# READ COMMITTED

- Writes → Strict 2PL write locks
- Reads → Short-duration read locks
  - Acquire lock before reading and release lock after (not 2PL)
- **Dirty reads are prevented**

A dirty read could only happen if a read occurs after a write and before a COMMIT/ROLLBACK


T1	T2
X(A) W(A)	
	<del>R(A)</del>
	COMMIT
ABORT U(A)	

# READ COMMITTED

- Writes → Strict 2PL write locks
- Reads → Short-duration read locks
  - Acquire lock before reading and release lock after (not 2PL)
- **Dirty reads are prevented**

A dirty read could only happen if a read occurs after a write and before a COMMIT/ROLLBACK

T1	T2
X(A) W(A)	
	<del>R(A)</del>
	COMMIT
ABORT U(A)	



T1	T2
X(A) W(A)	
	S(A) blocked...
ABORT U(A)	...granted S(A)
	R(A)
	COMMIT U(A)

# READ COMMITTED

- **Unrepeatable reads are possible**

T1	T2
	S(A)
X(A) blocked...	
...	<b>R(A)</b>
...granted X(A)	U(A)
	S(A) blocked...
<b>W(A)</b>	...
COMMIT U(A)	...granted S(A)
	<b>R(A)</b>
	X(A)
	W(A)
	COMMIT U(A)

Common  
UPDATE  
pattern

# READ COMMITTED

- Fast READ since operation happens as soon as write txns are done
- Use cases:
  - Guarantee that read result is valid at some point
  - Often useful for e-commerce situations
    - Guarantee customer has good info to start with but doesn't block other customers from purchasing



## 3. Isolation Level: Repeatable Read

- “Long duration” WRITE locks
  - Strict 2PL
- “Long duration” READ locks
  - Strict 2PL

This is not serializable yet !!!



Why ?

# 4. Isolation Level Serializable

- “Long duration” WRITE locks
  - Strict 2PL
- “Long duration” READ locks
  - Strict 2PL
- Predicate locking
  - To deal with phantoms

# READ-ONLY Transactions

```
Client 1: START TRANSACTION
INSERT INTO SmallProduct(name, price)
SELECT pname, price
FROM Product
WHERE price <= 0.99

DELETE FROM Product
WHERE price <=0.99
COMMIT
```

```
Client 2: SET TRANSACTION READ ONLY
START TRANSACTION
SELECT count(*)
FROM Product

SELECT count(*)
FROM SmallProduct
COMMIT
```



May improve performance

# Commercial Systems

Always check documentation!

- **DB2:** Strict 2PL
- **SQL Server:**
  - Strict 2PL for standard 4 levels of isolation
  - Multiversion concurrency control for snapshot isolation
- **PostgreSQL:** Snapshot isolation; recently: serializable Snapshot isolation (!)
- **Oracle:** Snapshot isolation

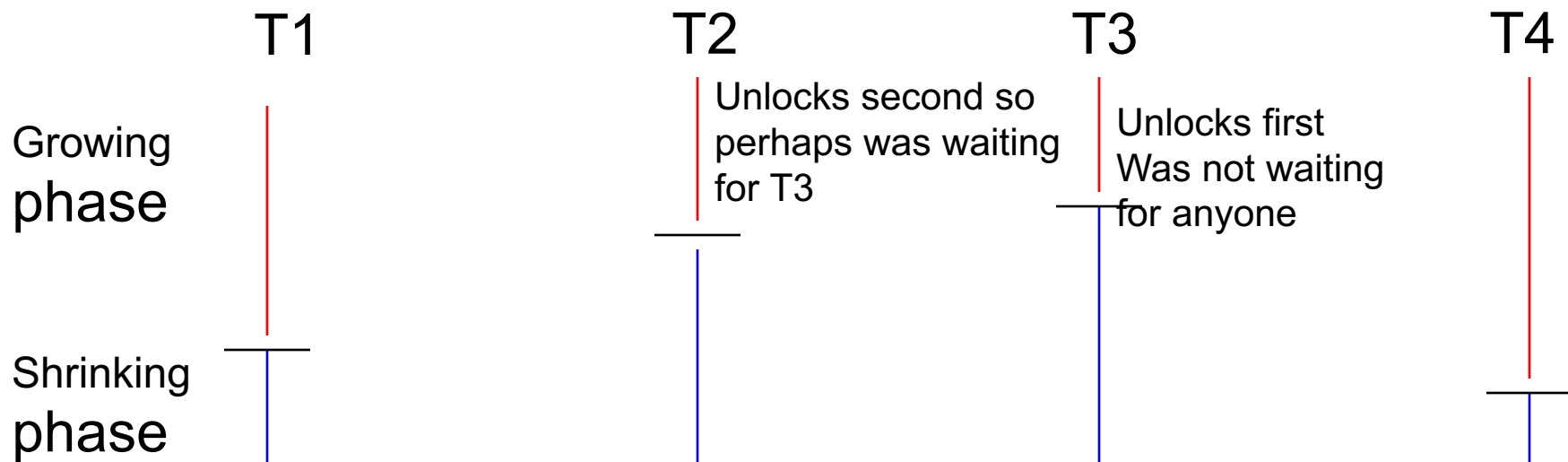
# Pessimistic vs. Optimistic

- **Pessimistic CC (locking)**
  - Prevents unserializable schedules
  - Never abort for serializability (but may abort for deadlocks)
  - Best for workloads with high levels of contention
  
- **Optimistic CC (timestamp, multi-version, validation)**
  - Assume schedule will be serializable
  - Abort when conflicts detected
  - Best for workloads with low levels of contention

# Outline

- **Concurrency control by timestamps (18.8)**
- **Concurrency control by validation (18.9)**
- **Snapshot Isolation**

# Example with Multiple Transactions



Equivalent to each transaction executing entirely the moment it enters shrinking phase

# Timestamps

- Each transaction receives unique timestamp  $TS(T)$

Could be:

- The system's clock
- A unique counter, incremented by the scheduler

# Timestamps

Main invariant:

The timestamp order defines  
the serialization order of the transaction

Will generate a schedule that is view-equivalent  
to a serial schedule, and recoverable

# Main Idea

- Scheduler receives a request,  $r_T(X)$  or  $w_T(X)$
- Should it allow it to proceed? Wait? Abort?
- Consider these cases:

$w_U(X) \dots r_T(X)$   
 $r_U(X) \dots w_T(X)$   
 $w_U(X) \dots w_T(X)$

Should we  
allow the **OP**?

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 $w_U(X) \dots w_T(X)$

Should we  
allow the **OP**?

START(U), ..., START(T), ...,  $w_U(X)$ , ...,  $r_T(X)$

# Main Idea

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Should we  
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OK

START(U), ..., START(T), ...,  $w_U(X)$ , ...,  $r_T(X)$

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 $r_U(X) \dots w_T(X)$   
 $w_U(X) \dots w_T(X)$

Should we allow the **OP**?

OK

START(U), ..., START(T), ...,  $w_U(X)$ , ...,  $r_T(X)$

START(T), ..., START(U), ...,  $w_U(X)$ , ...,  $r_T(X)$

# Main Idea

- Scheduler receives a request,  $r_T(X)$  or  $w_T(X)$
- Should it allow it to proceed? Wait? Abort?
- Consider these cases:

$w_U(X) \dots r_T(X)$   
 $r_U(X) \dots w_T(X)$   
 $w_U(X) \dots w_T(X)$

Should we allow the OP?

OK

START(U), ..., START(T), ...,  $w_U(X)$ , ...,  $r_T(X)$

START(T), ..., START(U), ...,  $w_U(X)$ , ...,  $r_T(X)$

Too late

# Timestamps

With each element  $X$ , associate

- $RT(X)$  = the highest timestamp of any transaction  $U$  that read  $X$
- $WT(X)$  = the highest timestamp of any transaction  $U$  that wrote  $X$
- $C(X)$  = the commit bit: true when transaction with highest timestamp that **wrote**  $X$  committed

# Timestamps

With each element  $X$ , associate

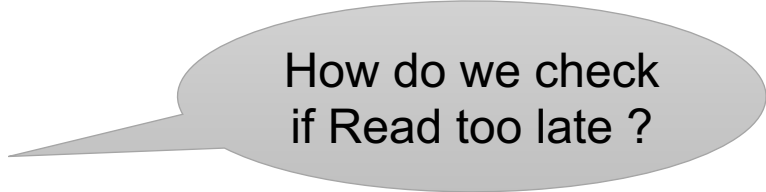
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- $WT(X)$  = the highest timestamp of any transaction  $U$  that wrote  $X$
- $C(X)$  = the commit bit: true when transaction with highest timestamp that **wrote**  $X$  committed

If transactions abort, we must **reset the timestamps**

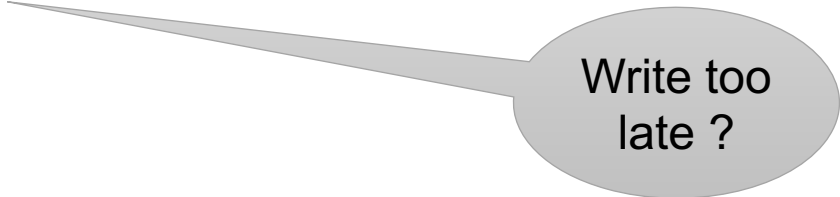
# Main Idea

For any  $r_T(X)$  or  $w_T(X)$  request, check for conflicts:

- $w_U(X) \dots r_T(X)$
- $r_U(X) \dots w_T(X)$
- $w_U(X) \dots w_T(X)$



How do we check  
if Read too late ?

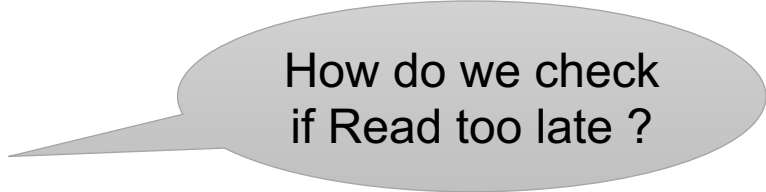


Write too  
late ?

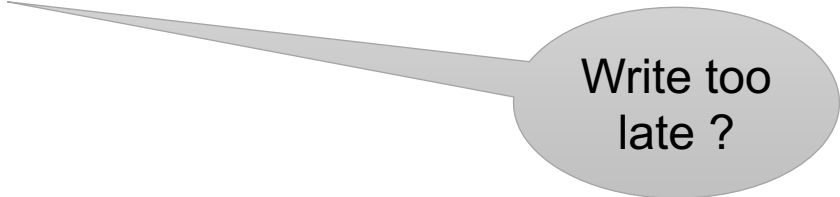
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For any  $r_T(X)$  or  $w_T(X)$  request, check for conflicts:

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- $r_U(X) \dots w_T(X)$
- $w_U(X) \dots w_T(X)$



How do we check  
if Read too late ?

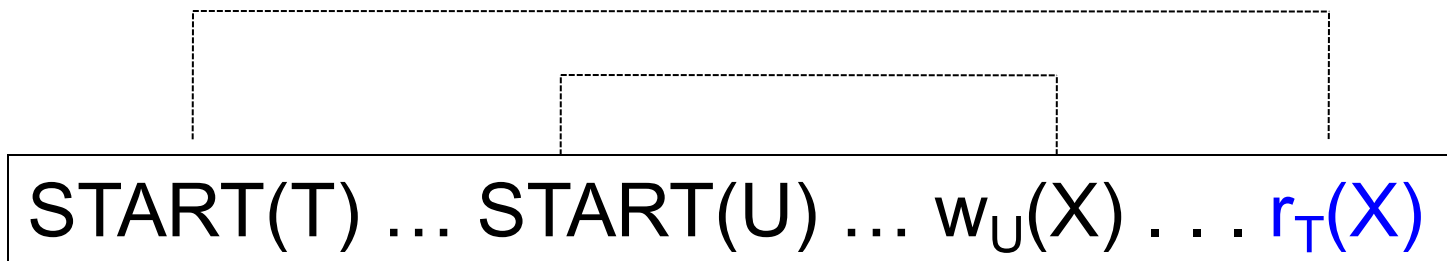


Write too  
late ?

When T requests  $r_T(X)$ , need to check  $TS(U) \leq TS(T)$

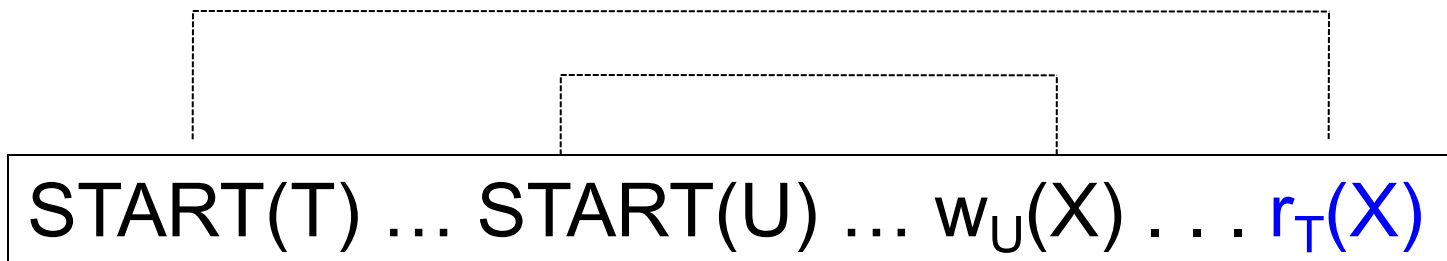
# Read Too Late?

- T wants to read X



# Read Too Late?

- T wants to read X



If  $WT(X) > TS(T)$  then need to rollback T !  
T tried to read **too late**

# Simplified TS-based Schedule (no Aborts)

Request is  $r_T(X)$   
??

# Simplified TS-based Schedule (no Aborts)

Request is  $r_T(X)$

If  $WT(X) > TS(T)$  then ROLLBACK

Else READ and update  $RT(X)$  to larger of  $TS(T)$  or  $RT(X)$

# Write Too Late?

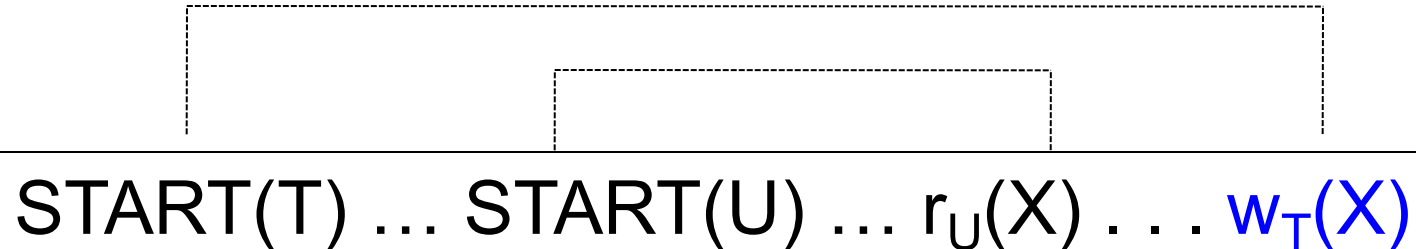
- T wants to write X



START(T) ... START(U) ...  $r_U(X)$  ...  $w_T(X)$

# Write Too Late?

- T wants to write X



START(T) ... START(U) ...  $r_U(X)$  ...  $w_T(X)$

If  $RT(X) > TS(T)$  then need to rollback T !  
T tried to write **too late**

# Simplified TS-based Schedule (no Aborts)

Request is  $r_T(X)$

If  $WT(X) > TS(T)$  then ROLLBACK

Else READ and update  $RT(X)$  to larger of  $TS(T)$  or  $RT(X)$

Request is  $w_T(X)$

???

# Simplified TS-based Schedule (no Aborts)

**Request is  $r_T(X)$**

If  $WT(X) > TS(T)$  then ROLLBACK

Else READ and update  $RT(X)$  to larger of  $TS(T)$  or  $RT(X)$

**Request is  $w_T(X)$**

If  $RT(X) > TS(T)$  then ROLLBACK

what about  $WT(X)$ ?

Otherwise, WRITE and update  $WT(X) = TS(T)$

# Thomas' Rule

But... we can still handle it in one case:

- T wants to write X



START(T) ... START(V) ...  $w_V(X)$  ...  $w_T(X)$

# Thomas' Rule

But we can still handle it:

- T wants to write X

Is this conflict-serializable?

START(T) ... START(V) ...  $w_V(X)$  ...  $w_T(X)$

If  $RT(X) \leq TS(T)$  and  $WT(X) > TS(T)$   
then don't write X at all !

# Thomas' Rule

But we can still handle it:

- T wants to write X

Is this conflict-serializable?

START(T) ... START(V) ...  $w_V(X)$  ...  $w_T(X)$

If  $RT(X) \leq TS(T)$  and  $WT(X) > TS(T)$   
then don't write X at all !

View serializable!

# Simplified TS-based Schedule (no Aborts)

Request is  $r_T(X)$

If  $WT(X) > TS(T)$  then ROLLBACK

Else READ and update  $RT(X)$  to larger of  $TS(T)$  or  $RT(X)$

Request is  $w_T(X)$

If  $RT(X) > TS(T)$  then ROLLBACK

what about  $WT(X)$ ?

Otherwise, WRITE and update  $WT(X) = TS(T)$

# Simplified TS-based Schedule (no Aborts)

Request is  $r_T(X)$

If  $WT(X) > TS(T)$  then ROLLBACK

Else READ and update  $RT(X)$  to larger of  $TS(T)$  or  $RT(X)$

Request is  $w_T(X)$

If  $RT(X) > TS(T)$  then ROLLBACK

Else if  $WT(X) > TS(T)$  ignore write & continue  
(Thomas Write Rule)

Otherwise, WRITE and update  $WT(X) = TS(T)$

View-serializable

# Simplified TS-based Schedule (no Aborts)

- The simplified timestamp-based scheduling with Thomas' rule ensures that the schedule is view-serializable

# Ensuring Recoverable Schedules

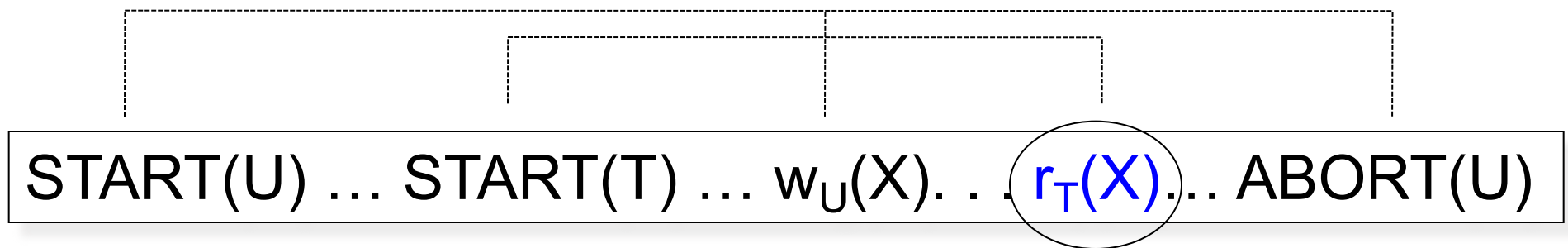
Recall:

- Schedule without cascading aborts:  
when a transaction reads an element, then transaction that wrote it must have **already committed**
- Use the commit bit  **$C(X)$**  to keep track if the transaction that **last wrote**  $X$  has committed  
(just a read will not change the commit bit)

# Ensuring Recoverable Schedules

Read dirty data:

- T wants to read X, and  $WT(X) < TS(T)$
- Seems OK, but...

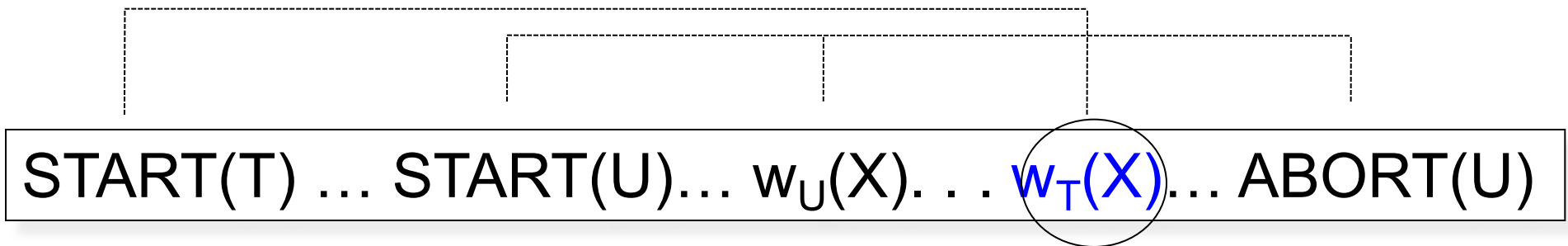


If  $C(X)=\text{false}$ , T needs to wait for it to become true

# Ensuring Recoverable Schedules

Thomas' rule needs to be revised:

- T wants to write X, and  $WT(X) > TS(T)$
- Seems OK not to write at all, but ...



If  $C(X)=\text{false}$ , T needs to wait for it to become true

# Timestamp-based Scheduling

- When a transaction  $T$  requests  $r_T(X)$  or  $w_T(X)$ , the scheduler examines  $RT(X)$ ,  $WT(X)$ ,  $C(X)$ , and decides one of:
  - To grant the request, or
  - To rollback  $T$  (and restart with later timestamp)
  - To delay  $T$  until  $C(X) = \text{true}$

# Timestamp-based Scheduling

**RULES including commit bit**

- There are 4 long rules in Sec. 18.8.4
- You should be able to derive them yourself, based on the previous slides
- Make sure you understand them !

**READING ASSIGNMENT:**  
Garcia-Molina et al. 18.8.4

# Timestamp-based Scheduling (sec. 18.8.4)

Transaction wants to READ element X

If  $WT(X) > TS(T)$  then ROLLBACK

Else If  $C(X) = \text{false}$ , then WAIT

Else READ and update  $RT(X)$  to larger of  $TS(T)$  or  $RT(X)$

Transaction wants to WRITE element X

If  $RT(X) > TS(T)$  then ROLLBACK

Else if  $WT(X) > TS(T)$

Then If  $C(X) = \text{false}$  then WAIT

else IGNORE write (Thomas Write Rule)

Otherwise, WRITE, and update  $WT(X) = TS(T)$ ,  $C(X) = \text{false}$



# Basic Timestamps with Commit Bit

$T_1$	$T_2$	$T_3$	$T_4$	A
1	2	3	4	RT=0 WT=0 C=true
	$W_2(A)$			

Time



# Basic Timestamps with Commit Bit

Time  
↓

$T_1$	$T_2$	$T_3$	$T_4$	A
1	2	3	4	RT=0 WT=0 C=true
	$W_2(A)$			WT=2 C=false RT=0

# Basic Timestamps with Commit Bit

Time  
↓

$T_1$	$T_2$	$T_3$	$T_4$	A
1	2	3	4	RT=0 WT=0 C=true
$R_1(A)$	$W_2(A)$			WT=2 C=false RT=0

# Basic Timestamps with Commit Bit

Time  
↓

$T_1$	$T_2$	$T_3$	$T_4$	A
1	2	3	4	RT=0 WT=0 C=true
$R_1(A)$ <b>Abort</b>	$W_2(A)$			WT=2 C=false RT=0

# Basic Timestamps with Commit Bit

Time  
↓

$T_1$	$T_2$	$T_3$	$T_4$	A
1	2	3	4	RT=0 WT=0 C=true
$R_1(A)$ <b>Abort</b>	$W_2(A)$	$R_3(A)$		WT=2 C=false RT=0

# Basic Timestamps with Commit Bit

Time  
↓

$T_1$	$T_2$	$T_3$	$T_4$	A
1	2	3	4	RT=0 WT=0 C=true
$R_1(A)$ <b>Abort</b>	$W_2(A)$	$R_3(A)$ <b>Delay</b>		WT=2 C=false RT=0

# Basic Timestamps with Commit Bit

Time  
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$T_1$	$T_2$	$T_3$	$T_4$	A
1	2	3	4	RT=0 WT=0 C=true
$R_1(A)$ <b>Abort</b>	$W_2(A)$ C	$R_3(A)$ <b>Delay</b>		WT=2 C=false RT=0

# Basic Timestamps with Commit Bit

Time  
↓

$T_1$	$T_2$	$T_3$	$T_4$	A
1	2	3	4	RT=0 WT=0 C=true
$R_1(A)$ <b>Abort</b>	$W_2(A)$ C	$R_3(A)$ <b>Delay</b>		WT=2 C=false RT=0 C=true

# Basic Timestamps with Commit Bit

Time  
↓

$T_1$	$T_2$	$T_3$	$T_4$	A
1	2	3	4	RT=0 WT=0 C=true
$R_1(A)$ <b>Abort</b>	$W_2(A)$	$R_3(A)$ <b>Delay</b>		WT=2 C=false RT=0
	C	$R_3(A)$		C=true

# Basic Timestamps with Commit Bit

Time  
↓

$T_1$	$T_2$	$T_3$	$T_4$	A
1	2	3	4	RT=0 WT=0 C=true
$R_1(A)$ <b>Abort</b>	$W_2(A)$	$R_3(A)$ <b>Delay</b>		WT=2 C=false RT=0
	C	$R_3(A)$		C=true RT=3

# Basic Timestamps with Commit Bit

Time  
↓

$T_1$	$T_2$	$T_3$	$T_4$	A
1	2	3	4	RT=0 WT=0 C=true
$R_1(A)$ <b>Abort</b>	$W_2(A)$	$R_3(A)$ <b>Delay</b>		WT=2 C=false RT=0
	C	$R_3(A)$	$W_4(A)$	C=true RT=3

# Basic Timestamps with Commit Bit

Time  
↓

$T_1$	$T_2$	$T_3$	$T_4$	A
1	2	3	4	RT=0 WT=0 C=true
$R_1(A)$ <b>Abort</b>	$W_2(A)$	$R_3(A)$ <b>Delay</b>		WT=2 C=false RT=0
	C	$R_3(A)$	$W_4(A)$	C=true RT=3 WT=4 C=false

# Basic Timestamps with Commit Bit

Time  
↓

$T_1$	$T_2$	$T_3$	$T_4$	A
1	2	3	4	RT=0 WT=0 C=true
R <sub>1</sub> (A) <b>Abort</b>	W <sub>2</sub> (A)			WT=2 C=false RT=0
	C	R <sub>3</sub> (A) <b>Delay</b> R <sub>3</sub> (A) W <sub>3</sub> (A)	W <sub>4</sub> (A)	C=true RT=3 WT=4 C=false

# Basic Timestamps with Commit Bit

Time  
↓

$T_1$	$T_2$	$T_3$	$T_4$	A
1	2	3	4	RT=0 WT=0 C=true
R <sub>1</sub> (A) <b>Abort</b>	W <sub>2</sub> (A)			WT=2 C=false RT=0
	C	R <sub>3</sub> (A) <b>Delay</b>		C=true RT=3
		R <sub>3</sub> (A)	W <sub>4</sub> (A)	WT=4 C=false
		W <sub>3</sub> (A) <b>delay</b>		

# Basic Timestamps with Commit Bit

Time  
↓

$T_1$	$T_2$	$T_3$	$T_4$	A
1	2	3	4	RT=0 WT=0 C=true
$R_1(A)$ <b>Abort</b>	$W_2(A)$			WT=2 C=false RT=0
	C	$R_3(A)$ <b>Delay</b>		C=true RT=3
		$R_3(A)$	$W_4(A)$	WT=4 C=false
		$W_3(A)$ <b>delay</b>	<b>abort</b>	

# Basic Timestamps with Commit Bit

Time  
↓

$T_1$	$T_2$	$T_3$	$T_4$	A
1	2	3	4	RT=0 WT=0 C=true
<b>R<sub>1</sub>(A) Abort</b>	$W_2(A)$			WT=2 C=false RT=0
	C	$R_3(A)$ <b>Delay</b>		C=true RT=3
		$R_3(A)$	$W_4(A)$	WT=4 C=false
		$W_3(A)$ <b>delay</b>	<b>abort</b>	WT=2 C=true

# Basic Timestamps with Commit Bit

Time  
↓

$T_1$	$T_2$	$T_3$	$T_4$	A
1	2	3	4	RT=0 WT=0 C=true
<b>R<sub>1</sub>(A) Abort</b>	$W_2(A)$			WT=2 C=false RT=0
	C	$R_3(A)$ <b>Delay</b>		C=true RT=3
		$R_3(A)$	$W_4(A)$	WT=4 C=false
		$W_3(A)$ <b>delay</b>		
			<b>abort</b>	WT=2 C=true
		$W_3(A)$		

# Basic Timestamps with Commit Bit

Time  
↓

$T_1$	$T_2$	$T_3$	$T_4$	A
1	2	3	4	RT=0 WT=0 C=true
<b>R<sub>1</sub>(A) Abort</b>	$W_2(A)$			WT=2 C=false RT=0
	C	$R_3(A)$ <b>Delay</b>		C=true RT=3
		$R_3(A)$	$W_4(A)$	WT=4 C=false
		$W_3(A)$ <b>delay</b>		
			<b>abort</b>	WT=2 C=true
		$W_3(A)$		WT=3 C=false

# Summary of Timestamp-based Scheduling

- View-serializable
- Avoids cascading aborts (hence: recoverable)
- Does NOT handle phantoms
  - These need to be handled separately, e.g. predicate locks

# Multiversion Timestamp

- When transaction  $T$  requests  $r(X)$  but  $WT(X) > TS(T)$ , then  $T$  must rollback

- Idea: keep multiple versions of  $X$ :

$X_t, X_{t-1}, X_{t-2}, \dots$

$$TS(X_t) > TS(X_{t-1}) > TS(X_{t-2}) > \dots$$

# Example (in class)

TS(T)=6

$X_3$

$X_9$

$X_{12}$

$X_{18}$

$R_6(X)$  -- what happens?

$W_{14}(X)$  – what happens?

$R_{15}(X)$  – what happens?

$W_5(X)$  – what happens?

When can we delete  $X_3$ ?

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$W_5(X)$  – what happens? **ABORT**

When can we delete  $X_3$ ?

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When can we delete  $X_3$ ?

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$R_{15}(X)$  – what happens? Return  $X_{14}$

$W_5(X)$  – what happens? ABORT

When can we delete  $X_3$ ? When  $\min TS(T) > 9$   
(i.e. all active transactions are later than time 9)

# Details

- When  $w_T(X)$  occurs,  
if the write is legal then  
create a **new version**, denoted  $X_t$  where  $t = TS(T)$

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find **most recent version**  $X_t$  such that  $t \leq TS(T)$

Notes:

- $WT(X_t) = t$  and it never changes for that version
- $RT(X_t)$  must still be maintained to check legality of writes

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find **most recent version**  $X_t$  such that  $t \leq TS(T)$

Notes:

- $WT(X_t) = t$  and it never changes for that version
- $RT(X_t)$  must still be maintained to check legality of writes  
**keep only the largest value**

- Can delete  $X_t$  if we have a later version  $X_{t_1}$  and all active transactions  $T$  have  $TS(T) > t_1$

# Example w/ Basic Timestamps

	$T_1$	$T_2$	$T_3$	$T_4$	A
Timestamps:	1	2	3	4	RT=0 WT=0
	$R_1(A)$ $W_1(A)$	$R_2(A)$ <b>Abort</b>	$R_3(A)$ $W_3(A)$	$R_4(A)$	RT=1 WT=1 RT=3 WT=3 RT=4

# Example w/ Multiversion

$T_1$	$T_2$	$T_3$	$T_4$	$A_0$
1	2	3	4	
$R_1(A)$				RT=1

# Example w/ Multiversion

$T_1$	$T_2$	$T_3$	$T_4$	$A_0$
1	2	3	4	
$R_1(A)$ $W_1(A)$				RT=1

# Example w/ Multiversion

$T_1$	$T_2$	$T_3$	$T_4$	$A_0$	$A_1$
1	2	3	4		
$R_1(A)$ $W_1(A)$				RT=1	Create

# Example w/ Multiversion

$T_1$	$T_2$	$T_3$	$T_4$	$A_0$	$A_1$
1	2	3	4		
$R_1(A)$ $W_1(A)$		$R_3(A)$		RT=1	Create

# Example w/ Multiversion

$T_1$	$T_2$	$T_3$	$T_4$	$A_0$	$A_1$
1	2	3	4		
$R_1(A)$ $W_1(A)$		$R_3(A)$		$RT=1$	Create $RT=3$

# Example w/ Multiversion

$T_1$	$T_2$	$T_3$	$T_4$	$A_0$	$A_1$
1	2	3	4		
$R_1(A)$ $W_1(A)$		$R_3(A)$ $W_3(A)$		RT=1	Create RT=3

# Example w/ Multiversion

$T_1$	$T_2$	$T_3$	$T_4$	$A_0$	$A_1$	$A_3$
1	2	3	4			
$R_1(A)$ $W_1(A)$		$R_3(A)$ $W_3(A)$		$RT=1$	Create $RT=3$	Create

# Example w/ Multiversion

$T_1$	$T_2$	$T_3$	$T_4$	$A_0$	$A_1$	$A_3$
1	2	3	4			
$R_1(A)$ $W_1(A)$	$R_2(A)$	$R_3(A)$ $W_3(A)$		$RT=1$	Create $RT=3$	Create

# Example w/ Multiversion

$T_1$	$T_2$	$T_3$	$T_4$	$A_0$	$A_1$	$A_3$
1	2	3	4			
$R_1(A)$ $W_1(A)$	$R_2(A)$	$R_3(A)$ $W_3(A)$		$RT=1$	Create $RT=3$	Create
					$RT=2$	

# Example w/ Multiversion

T <sub>1</sub>	T <sub>2</sub>	T <sub>3</sub>	T <sub>4</sub>	A <sub>0</sub>	A <sub>1</sub>	A <sub>3</sub>
1	2	3	4			
R <sub>1</sub> (A) W <sub>1</sub> (A)	R <sub>2</sub> (A)	R <sub>3</sub> (A) W <sub>3</sub> (A)		RT=1	Create RT=3	Create
					<del>RT=2</del>	

Keep only  
max RT

~~RT=2~~

# Example w/ Multiversion

$T_1$	$T_2$	$T_3$	$T_4$	$A_0$	$A_1$	$A_3$
1	2	3	4			
$R_1(A)$ $W_1(A)$	$R_2(A)$ $W_2(A)$	$R_3(A)$ $W_3(A)$		$RT=1$	Create $RT=3$ <del><math>RT=2</math></del>	Create

# Example w/ Multiversion

$T_1$	$T_2$	$T_3$	$T_4$	$A_0$	$A_1$	$A_3$
1	2	3	4			
$R_1(A)$ $W_1(A)$	$R_2(A)$ $W_2(A)$ <b>abort</b>	$R_3(A)$ $W_3(A)$		$RT=1$	<b>Create</b> $RT=3$	<b>Create</b>
					<del><math>RT=2</math></del>	

# Example w/ Multiversion

T <sub>1</sub>	T <sub>2</sub>	T <sub>3</sub>	T <sub>4</sub>	A <sub>0</sub>	A <sub>1</sub>	A <sub>3</sub>
1	2	3	4			
R <sub>1</sub> (A) W <sub>1</sub> (A)	R <sub>2</sub> (A) W <sub>2</sub> (A) <b>abort</b>	R <sub>3</sub> (A) W <sub>3</sub> (A)	R <sub>4</sub> (A)	RT=1	Create RT=3 <del>RT=2</del>	Create

# Example w/ Multiversion

T <sub>1</sub>	T <sub>2</sub>	T <sub>3</sub>	T <sub>4</sub>	A <sub>0</sub>	A <sub>1</sub>	A <sub>3</sub>
1	2	3	4			
R <sub>1</sub> (A) W <sub>1</sub> (A)	R <sub>2</sub> (A) W <sub>2</sub> (A) <b>abort</b>	R <sub>3</sub> (A) W <sub>3</sub> (A)	R <sub>4</sub> (A)	RT=1	Create RT=3 <del>RT=2</del>	Create  RT=4

# Second Example w/ Multiversion

$T_1$	$T_2$	$T_3$	$T_4$	$T_5$	$A_0$	$A_1$	$A_2$	$A_3$	$A_4$	$A_5$
1	2	3	4	5						
			$W_4(A)$							

# Second Example w/ Multiversion

T <sub>1</sub>	T <sub>2</sub>	T <sub>3</sub>	T <sub>4</sub>	T <sub>5</sub>	A <sub>0</sub>	A <sub>1</sub>	A <sub>2</sub>	A <sub>3</sub>	A <sub>4</sub>	A <sub>5</sub>
1	2	3	4	5						
W <sub>1</sub> (A)	R <sub>2</sub> (A)	R <sub>3</sub> (A)	W <sub>4</sub> (A)			Create			Create	
	W <sub>2</sub> (A)					RT=2				
	abort					RT=3				
			R <sub>4</sub> (A)	R <sub>5</sub> (A)					RT=5	
				W <sub>5</sub> (A)					RT=5	Create
R <sub>1</sub> (A)										
C		C			X		RT=3			
						X				

X means that we can delete this version

# Multiversion Concurrency Control

- Does **not** solve cascading aborts and recoverability, need to add Commit bit for those
- Does allow transactions to read in cases when they would have to abort in simple time-stamp based control

# Outline

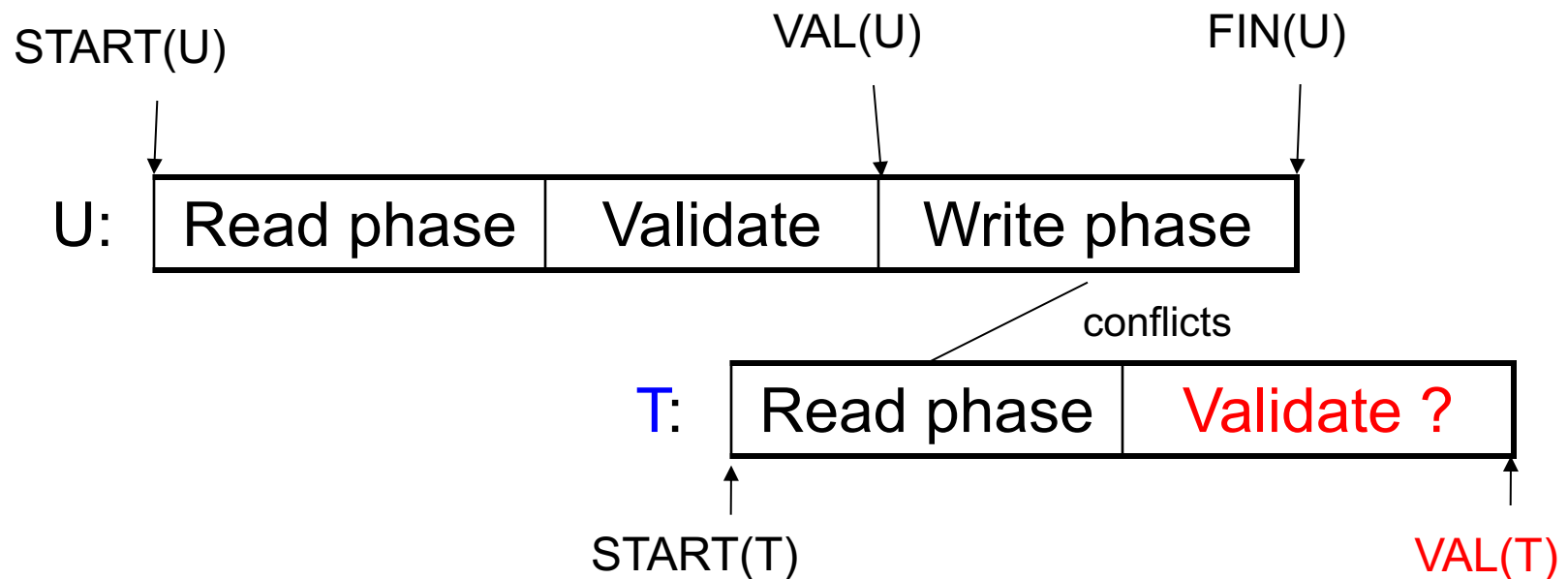
- Concurrency control by timestamps (18.8)
- Concurrency control by validation (18.9)
- Snapshot Isolation

# Concurrency Control by Validation

- Each transaction  $T$  defines:
  - Read set  $RS(T)$  = the elements it reads
  - Write set  $WS(T)$  = the elements it writes
  
- Each transaction  $T$  has three phases:
  - Read phase; time =  $START(T)$
  - Validate phase (may need to rollback); time =  $VAL(T)$
  - Write phase; time =  $FIN(T)$

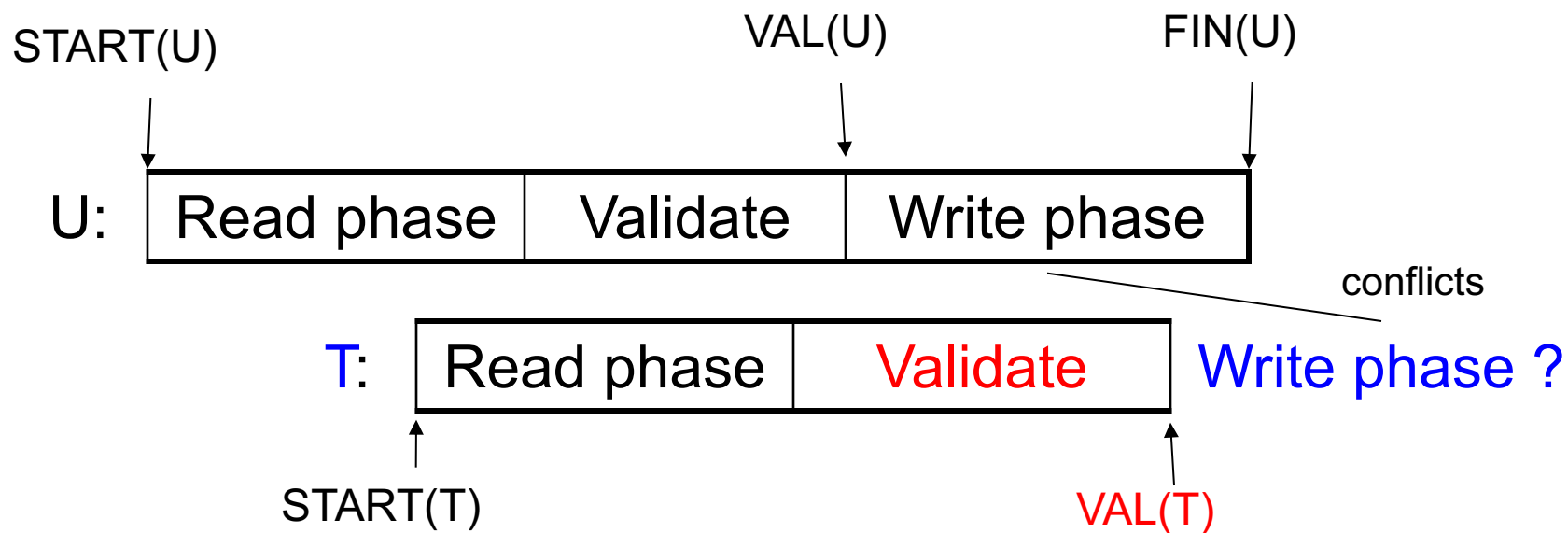
**Main invariant: the serialization order is  $VAL(T)$**

# Avoid $r_T(X) - w_U(X)$ Conflicts



IF  $RS(T) \cap WS(U)$  and  $FIN(U) > START(T)$   
(U has validated and U has not finished before T begun)  
Then **ROLLBACK(T)**

# Avoid $w_T(X) - w_U(X)$ Conflicts



IF  $WS(T) \cap WS(U)$  and  $FIN(U) > VAL(T)$   
(U has validated and U has not finished before T validates)  
Then **ROLLBACK(T)**

# Outline

- Concurrency control by timestamps (18.8)
- Concurrency control by validation (18.9)
- **Snapshot Isolation**
  - Not in the book, but good(?) overview in Wikipedia

# Snapshot Isolation

- A type of multiversion concurrency control algorithm
- Combines techniques we learned:
  - Timestamps
  - Multiversion
  - Validation
- Very popular: Oracle, PostgreSQL, SQL Server 2005
- Prevents many classical anomalies BUT...  
...not serializable (!)
- “Serializable snapshot isolation” now in PostgreSQL

# Snapshot Isolation Overview

- Each transactions receives a timestamp  $TS(T)$
- Transaction  $T$  sees snapshot at time  $TS(T)$  of the database
- $W/W$  conflicts resolved by “**first committer wins**” rule
  - Loser gets aborted
- $R/W$  conflicts are ignored

# Snapshot Isolation Details

- Multiversion concurrency control:
  - Versions of  $X$ :  $X_{t1}, X_{t2}, X_{t3}, \dots$
- When  $T$  reads  $X$ , return  $X_{TS(T)}$ .
- When  $T$  writes  $X$  (to avoid lost update):
  - If latest version of  $X$  is  $TS(T)$  then **proceed**
  - Else if  $C(X) = \text{true}$  then **abort**
  - Else if  $C(X) = \text{false}$  then **wait**
- When  $T$  commits, write its updates to disk

# What Works and What Not

- Reads are ever delayed!
- No dirty reads (Why ?)
  - Start each snapshot with consistent state
- No inconsistent reads (Why ?)
  - Two reads by the same transaction will read same snapshot
- No lost updates (“first committer wins”)
- However: read-write conflicts not caught!
  - A txn can read and commit even though the value had changed in the middle

# Write Skew

```
T1:  
  READ(X);  
  if X >= 50  
    then Y = -50; WRITE(Y)  
  COMMIT
```

```
T2:  
  READ(Y);  
  if Y >= 50  
    then X = -50; WRITE(X)  
  COMMIT
```

In our notation:

```
R1(X), R2(Y), W1(Y), W2(X), C1, C2
```

Starting with X=50, Y=50, we end with X=-50, Y=-50.  
Non-serializable !!!

# Discussion: Tradeoffs

- **Pessimistic CC: Locks**
  - Great when there are many conflicts
  - Poor when there are few conflicts
- **Optimistic CC: Timestamps, Validation, SI**
  - Poor when there are many conflicts (rollbacks)
  - Great when there are few conflicts
- **Compromise**
  - READ ONLY transactions → timestamps
  - READ/WRITE transactions → locks

# Commercial Systems

Always check documentation!

- **DB2**: Strict 2PL
- **SQL Server**:
  - Strict 2PL for standard 4 levels of isolation
  - Multiversion concurrency control for snapshot isolation
- **PostgreSQL**: SI; recently: serializable SI (!)
- **Oracle**: SI