# Lecture 8--Continued: Concurrency & Locking

# Announcements

- Scores were quite good overall for homework! We're excited!
  - Destroy the midterm!

- Midterm is with CAs.
  - We will post on the page how to divide into overflow rooms
  - Please start posting questions (some very good ones already!)
  - I promise to be there for final CA

- Trolling: no SQL and bitcoin (OPTIONAL!) bitcoin exchange brought down by lack of consistency?

- Today, we end early for small group feedback… we read every element, and we take it seriously!

# Concurrency: Isolation & Consistency

- The DBMS must handle concurrency such that…

1. **Isolation** is maintained: Users must be able to execute each TXN **as if they were the only user**
   - DBMS handles the details of *interleaving* various TXNs

ACID

2. **Consistency** is maintained: TXNs must leave the DB in a **consistent state**
   - DBMS handles the details of enforcing integrity constraints

ACID

# Example- consider two TXNs:

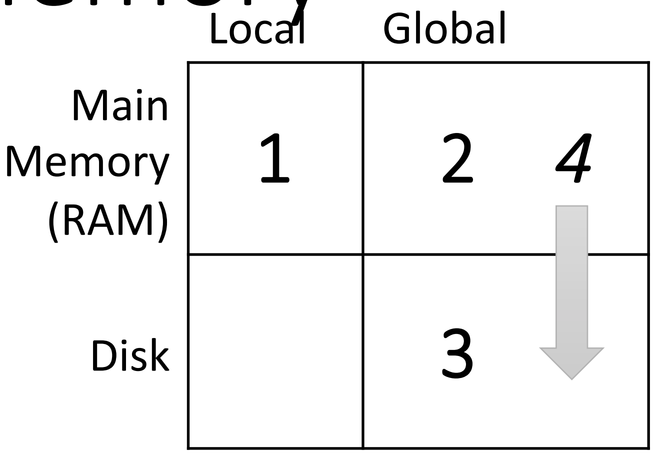
```
T1: START TRANSACTION
      UPDATE Accounts
      SET Amt = Amt + 100
      WHERE Name = ‘A’

      UPDATE Accounts
      SET Amt = Amt - 100
      WHERE Name = ‘B’
COMMIT
```

```
T2: START TRANSACTION
      UPDATE Accounts
      SET Amt = Amt * 1.06
COMMIT
```

T1 transfers $100 from B’s account to A’s account

T2 credits both accounts with a 6% interest payment

# Recall: Three Types of Regions of Memory




1. **Local:** In our model each process in a DBMS has its own local memory, where it stores values that only it "sees"

2. **Global:** Each process can read from / write to shared data in main memory

3. **Disk:** Global memory can read from / flush to disk

4. ***Log:*** *Assume on stable disk storage- spans both main memory and disk…*

Log is a *sequence* from main memory -> disk

"Flushing to disk" = writing to disk.

# Scheduling examples

*Starting Balance*

| A | B |
|---|---|
| $50 | $200 |

Serial schedule $T_1$,$T_2$:

$T_1$ A += 100 B -= 100

$T_2$ A *= 1.06 B *= 1.06

| A | B |
|---|---|
| $159 | $106 |

*Interleaved* schedule A:

$T_1$ A += 100 B -= 100

$T_2$ A *= 1.06 B *= 1.06

| A | B |
|---|---|
| $159 | $106 |

Same result!

# Scheduling examples

*Starting Balance*

| A | B |
|---|---|
| \$50 | \$200 |

<u>Serial schedule $T_1$,$T_2$:</u>

$T_1$ A += 100 B -= 100

$T_2$ A *= 1.06 B *= 1.06

| A | B |
|---|---|
| \$159 | \$106 |

<u>*Interleaved* schedule B:</u>

$T_1$ A += 100 B -= 100

$T_2$ A *= 1.06 B *= 1.06

| A | B |
|---|---|
| \$159 | \$112 |

Different result than serial $T_1$,$T_2$!

# Scheduling examples

*Starting Balance*

| A | B |
|---|---|
| \$50 | \$200 |

Serial schedule $T_2$,$T_1$:

$T_1$: A += 100 | B -= 100

$T_2$: A *= 1.06 | B *= 1.06

| A | B |
|---|---|
| \$153 | \$112 |

*Interleaved* schedule B:

$T_1$: A += 100 | B -= 100

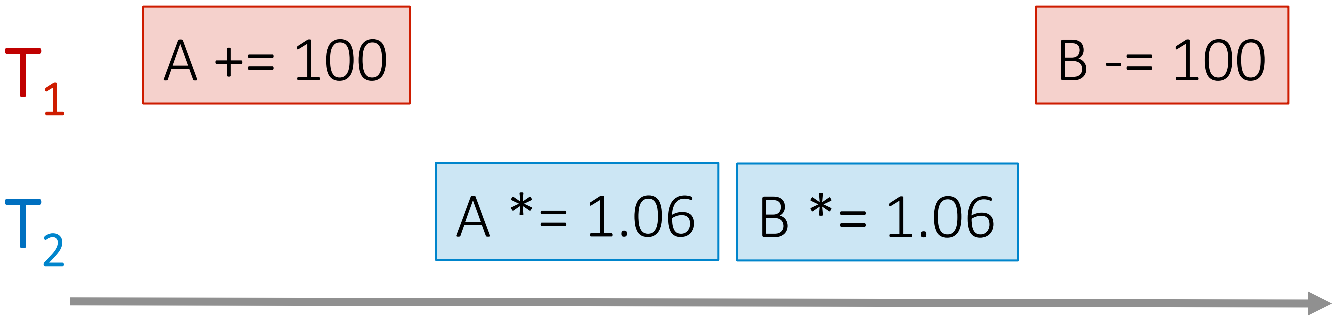
$T_2$: A *= 1.06 | B *= 1.06

| A | B |
|---|---|
| **\$159** | \$112 |

Different result than serial $T_2$,$T_1$ ALSO!

# Scheduling examples

*Interleaved* schedule B:




This schedule is different than *any serial order!* We say that it is <u>not serializable</u>

# Scheduling Definitions

- A **serial schedule** is one that does not interleave the actions of different transactions

- A and B are **equivalent schedules** if, ***for any database state***, the effect on DB of executing A **is identical to** the effect of executing B

- *A* **serializable schedule** is a schedule that is equivalent to ***some*** serial execution of the transactions.

The word "**some**" makes this definition powerful & tricky!

# Serializable?

$T_1$: A += 100 | B -= 100

$T_2$: A *= 1.06 | B *= 1.06

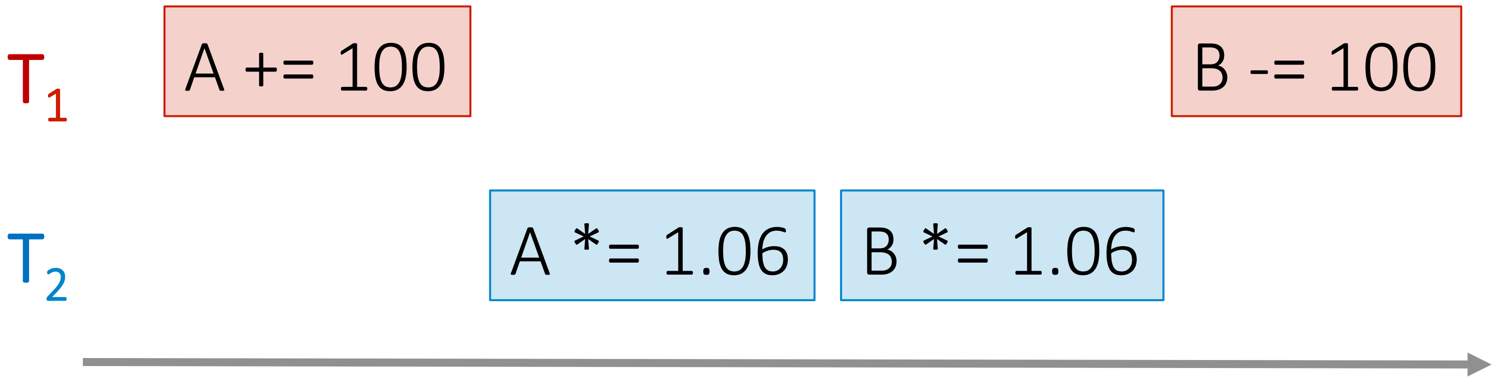
<u>Serial schedules:</u>

| | A | B |
|---|---|---|
| $T_1$,$T_2$ | 1.06*(A+100) | 1.06*(B-100) |
| $T_2$,$T_1$ | 1.06*A + 100 | 1.06*B - 100 |

| A | B |
|---|---|
| 1.06*(A+100) | 1.06*(B-100) |

Same as a serial schedule *for all possible values of A, B* = <u>serializable</u>

# Serializable?




Serial schedules:

| | A | B |
|---|---|---|
| $T_1$,$T_2$ | 1.06*(A+100) | 1.06*(B-100) |
| $T_2$,$T_1$ | 1.06*A + 100 | 1.06*B - 100 |

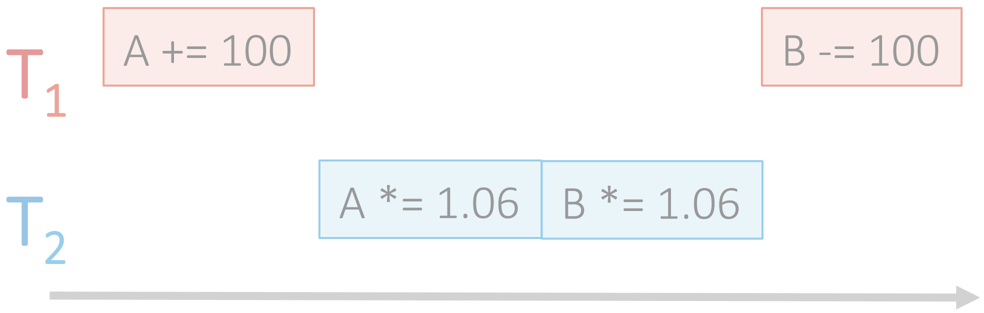
| A | B |
|---|---|
| 1.06*(A+100) | 1.06*B - 100 |

Not *equivalent* to any serializable schedule = *not* serializable

# What else can go wrong with interleaving?

- Various anomalies which break isolation / serializability
  - Often referred to by name…
- Occur because **conflicts** between interleaved TXNs

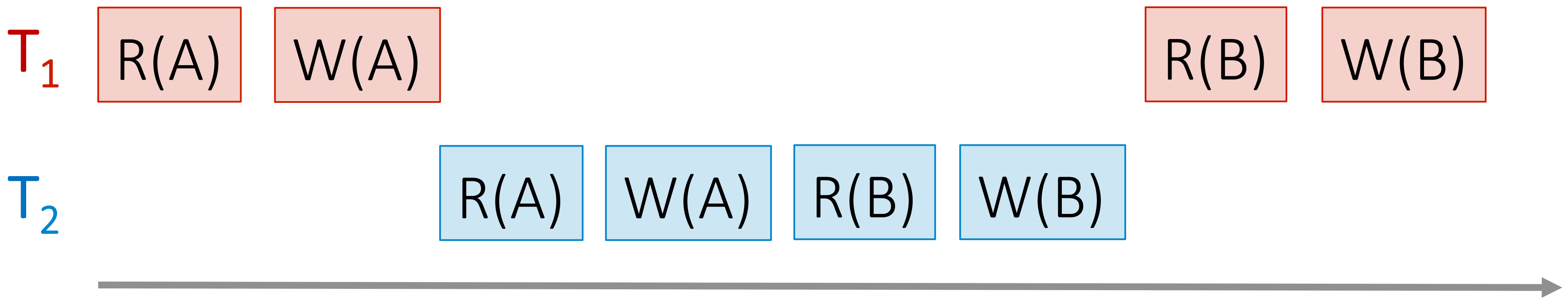
# The DBMS's view of the schedule




An action in the TXNs may

- Reads a value from **global memory** to **local memory**
- Write a value from **local memory** to **global memory**
- Arbitrary computation on local memory...

Scheduling order matters!



# Conflict Types

Two actions **conflict** if they are part of *different* TXNs, involve the same object, and at least one of them is a write

- Thus, there are three types of conflicts:
  - Read-Write conflicts (RW)
  - Write-Read conflicts (WR)
  - Write-Write conflicts (WW)

*Why no "RR Conflict"?*

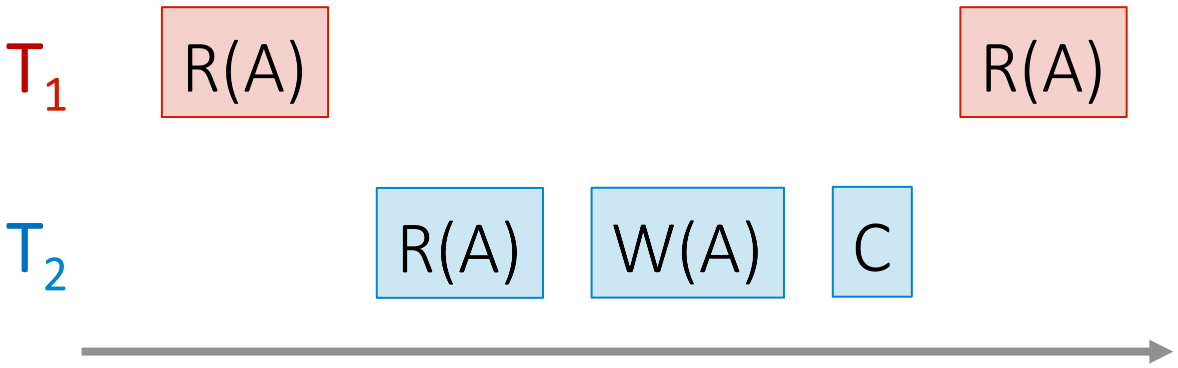
Interleaving anomalies occur with / because of these conflicts between TXNs *(but these conflicts can occur without causing anomalies!)*

*See next section for more!*

# Classic Anomalies with Interleaved Execution

## "Unrepeatable read":

Example:



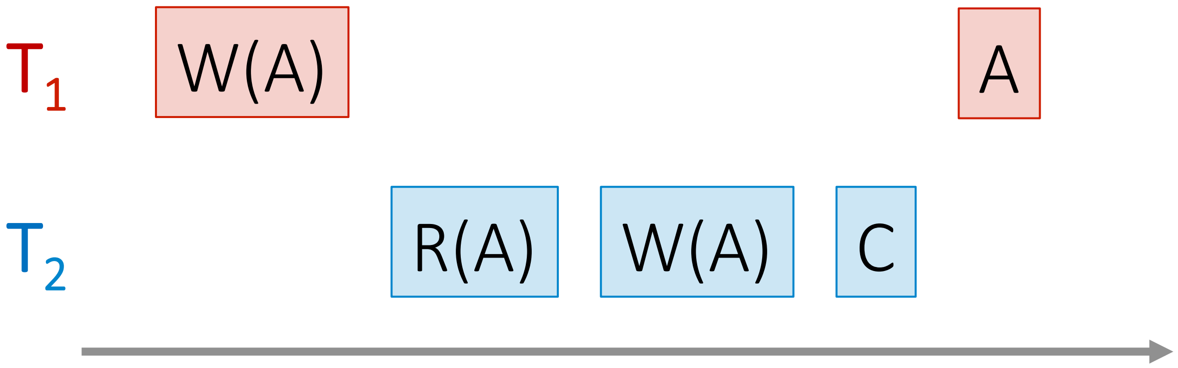

1. $T_1$ reads some data from A
2. $T_2$ writes to A
3. Then, $T_1$ reads from A again *and now gets a different / inconsistent value from its own local memory!*

*Occurring because of a **RW conflict. Which pairs?***

# Classic Anomalies with Interleaved Execution

## "Dirty read" / Reading uncommitted data:

Example:



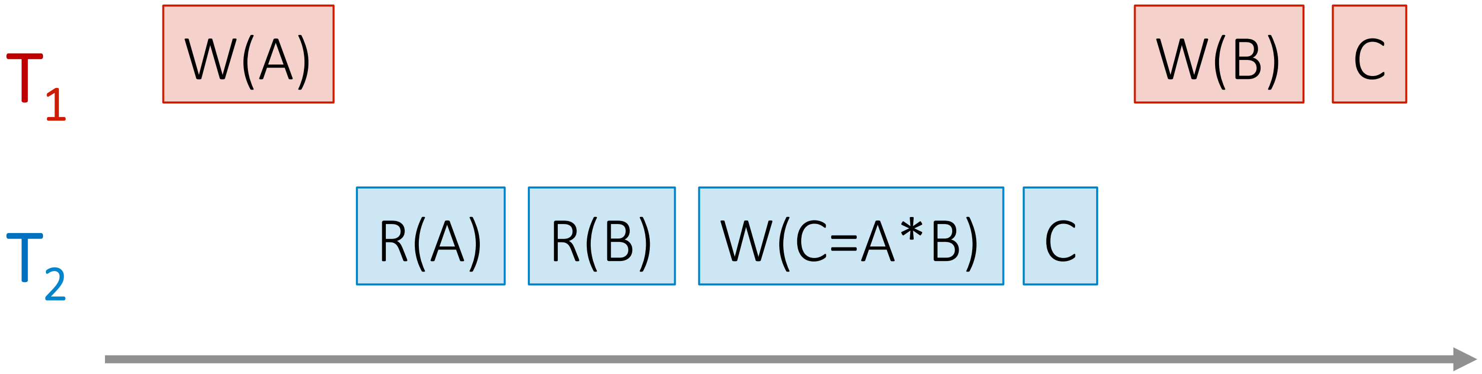

1. $T_1$ writes some data to A
2. $T_2$ reads from A, then writes back to A & commits
3. $T_1$ then aborts- *now $T_2$'s result is based on an obsolete / inconsistent value*

*Occurring because of a* ***WR conflict. Which pairs?***

# Classic Anomalies with Interleaved Execution

## "Inconsistent read" / Reading partial commits:

Example:



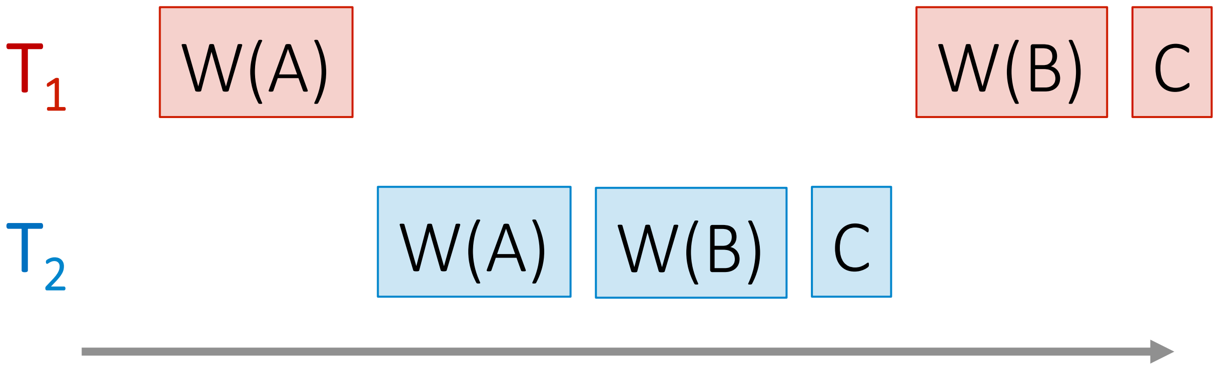

1. $T_1$ <u>writes</u> some data to A
2. $T_2$ <u>reads</u> from A *and B*, and then writes some value which depends on A & B
3. $T_1$ then writes to B- *now $T_2$'s result is based on an incomplete commit*

*Again, occurring because of a* ***WR conflict. Which pairs?***

# Classic Anomalies with Interleaved Execution

## Partially-lost update:

Example:




1. $T_1$ *blind* writes some data to A
2. $T_2$ *blind* writes to A *and B*
3. $T_1$ then *blind* writes to B; now we have $T_2$'s value for B and $T_1$'s value for A- ***not equivalent to any serial schedule!***

*Occurring because of a **WW conflict. Which pairs?***

# Activity-8-1.ipynb

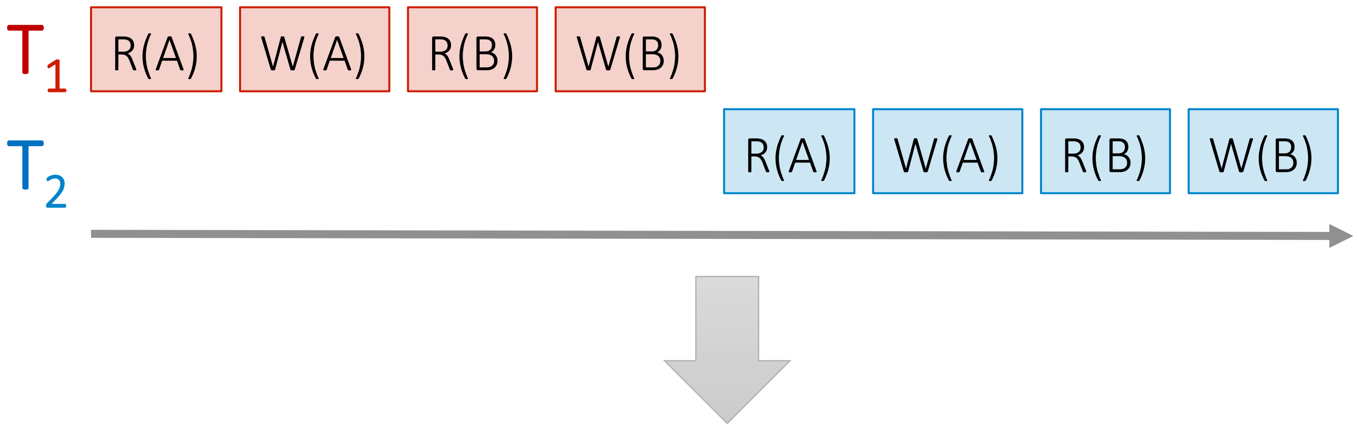
# 2. Conflict Serializability, Locking & Deadlock

# What you will learn about in this section

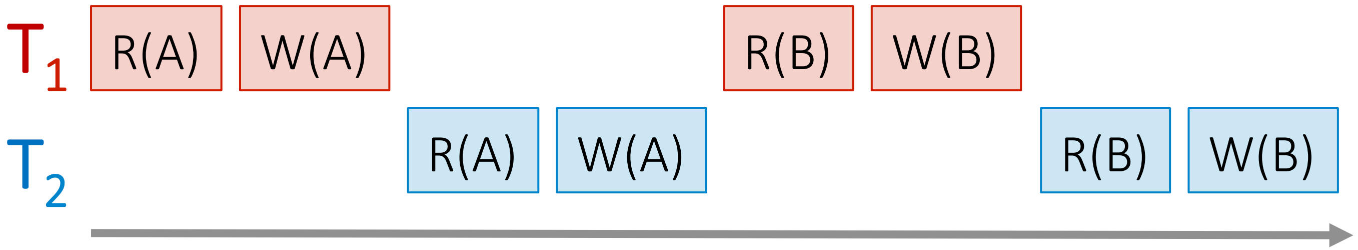
1. RECAP: Concurrency
2. Conflict Serializability
3. DAGs & Topological Orderings
4. Strict 2PL
5. Deadlocks

# Recall: Concurrency as Interleaving TXNs

***Serial Schedule*:**



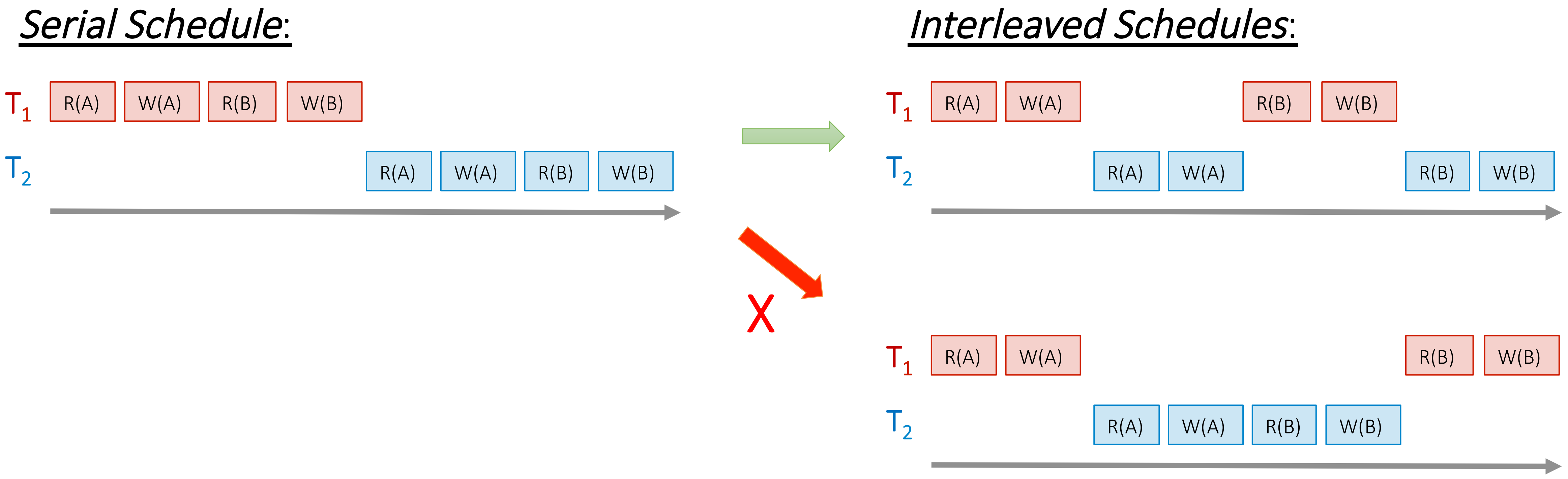

***Interleaved Schedule*:**




- For our purposes, having TXNs occur concurrently means **interleaving their component actions (R/W)**

We call the particular order of interleaving a <u>schedule</u>

# Recall: “Good” vs. “bad” schedules




We want to develop ways of discerning “good” vs. “bad” schedules

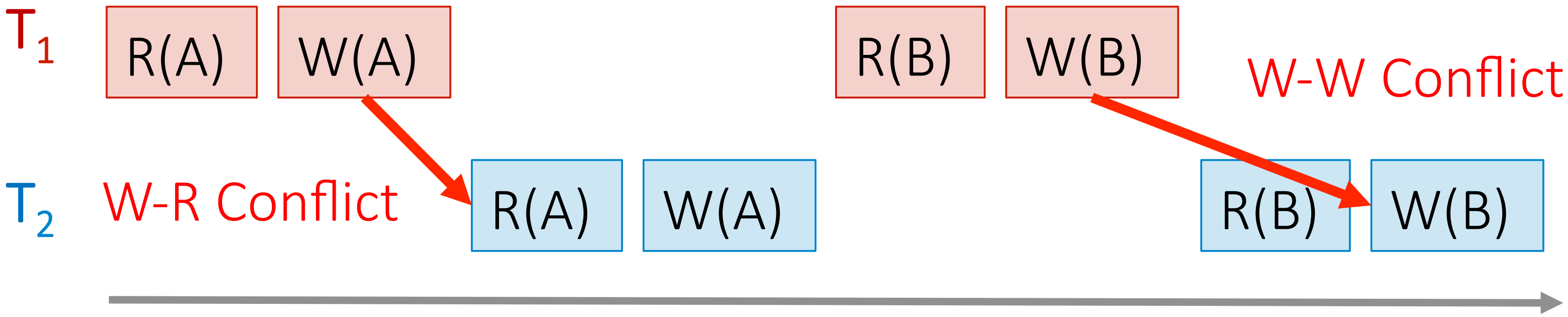
# Ways of Defining "Good" vs. "Bad" Schedules

- Recall from last time: we call a schedule ***serializable*** if it is equivalent to *some* serial schedule
    - We used this as a notion of a "good" interleaved schedule, since **a serializable schedule will maintain isolation & consistency**
- Now, we'll define a stricter, but very useful variant:
    - ***Conflict serializability***

We'll need to define *conflicts* first..

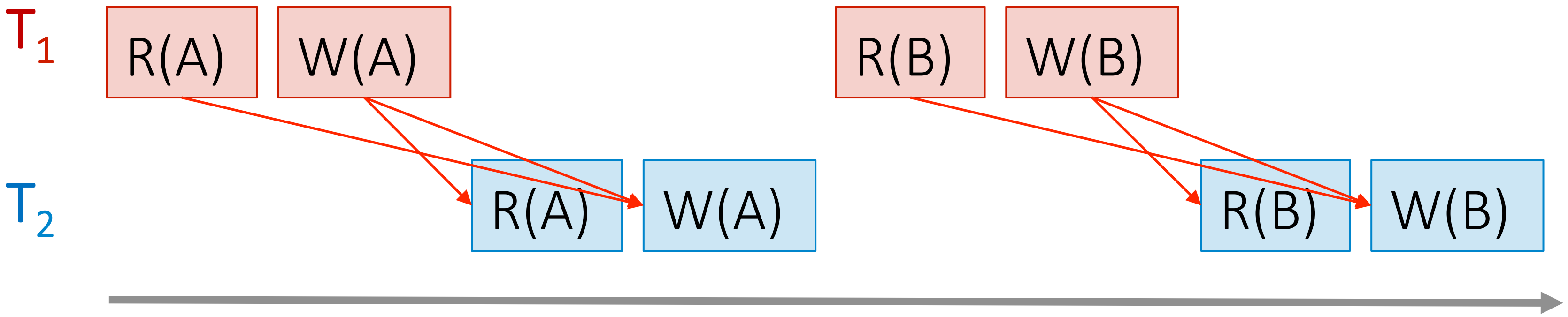
# Conflicts

Two actions **conflict** if they are part of different TXNs, involve the same variable, and at least one of them is a write



# Conflicts

Two actions **conflict** if they are part of different TXNs, involve the same variable, and at least one of them is a write




All "conflicts"!

# Conflict Serializability

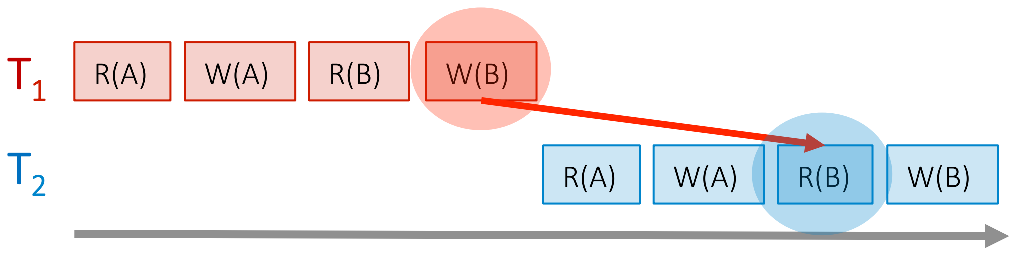
- Two schedules are **conflict equivalent** if:
  - They involve *the same actions of the same TXNs*
  - Every *pair of conflicting actions* of two TXNs are *ordered in the same way*
- Schedule S is **conflict serializable** if S is *conflict equivalent* to some serial schedule

Conflict serializable ⇒ serializable

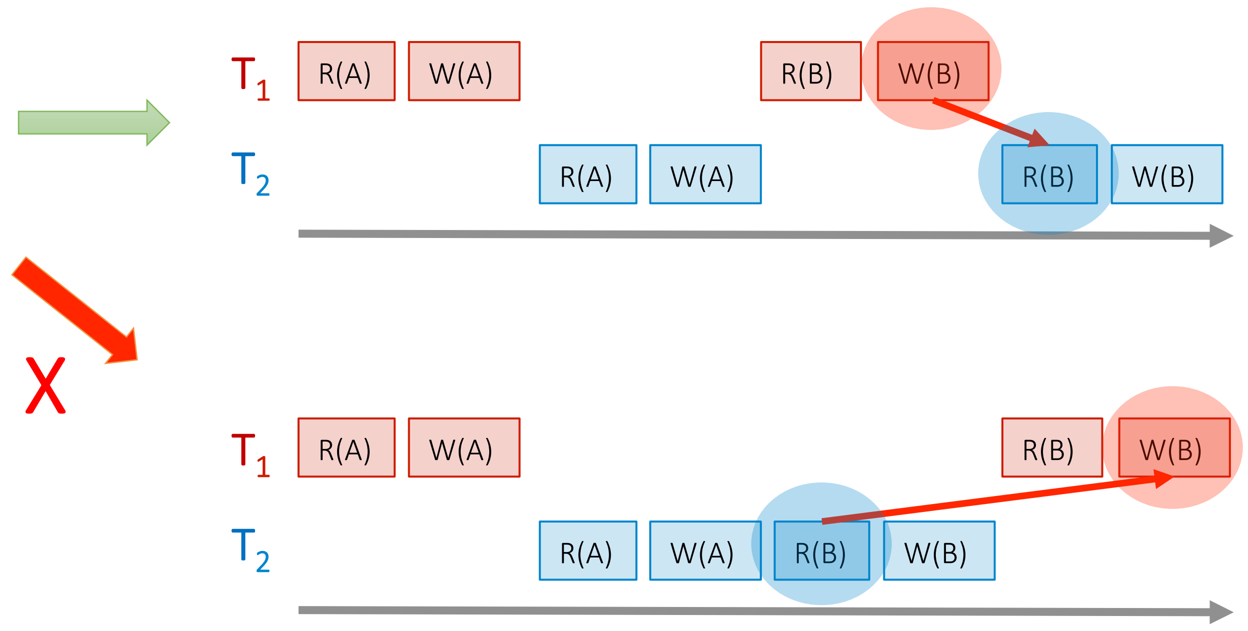
So if we have conflict serializable, we have consistency & isolation!

# Recall: “Good” vs. “bad” schedules

***Serial Schedule:***




***Interleaved Schedules:***




Note that in the “bad” schedule, the *order of conflicting actions is different than the above (or any) serial schedule!*

Conflict serializability also provides us with an operative notion of “good” vs. “bad” schedules!

# Note: Conflicts vs. Anomalies

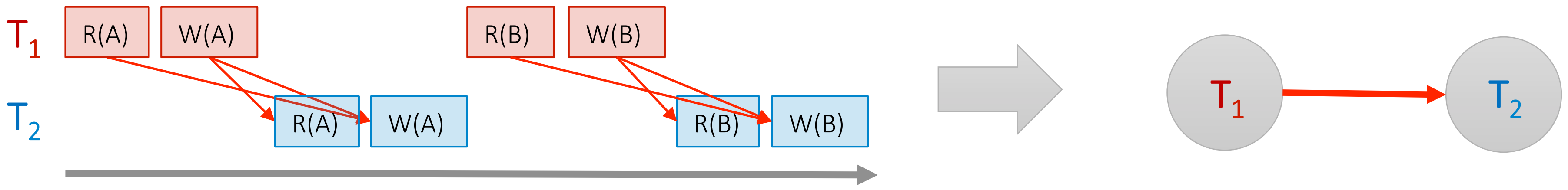
- **Conflicts** are things we talk about to help us characterize different schedules
  - Present in both “good” and “bad” schedules

- **Anomalies** are instances where isolation and/or consistency is broken because of a “bad” schedule
  - We often characterize different anomaly types by what types of conflicts predicated them

# The Conflict Graph

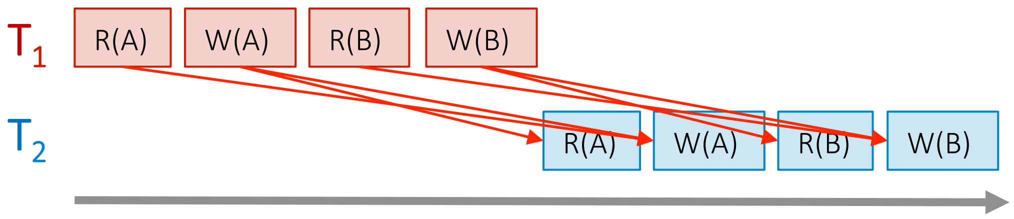
- Let's now consider looking at conflicts **at the TXN level**

- Consider a graph where the **nodes are TXNs**, and there is an edge from $T_i \rightarrow T_j$ **if any actions in $T_i$ <u>precede and conflict with</u> any actions in $T_j$**



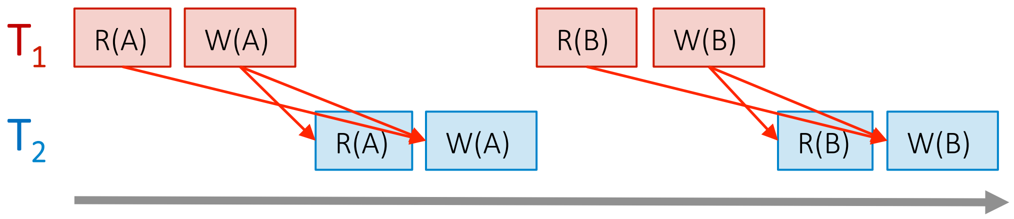
# What can we say about “good” vs. “bad” conflict graphs?

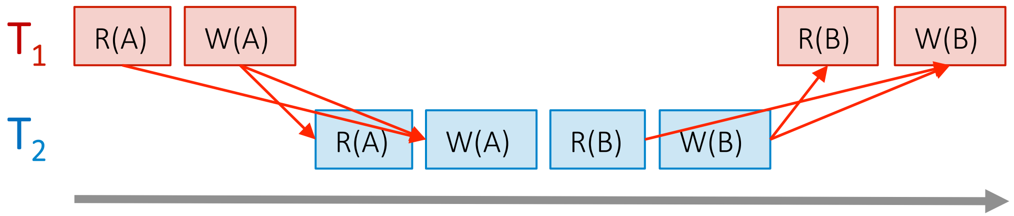
***Serial Schedule:***





***Interleaved Schedules:***

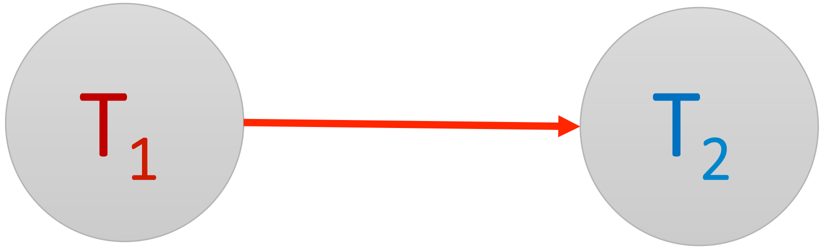



A bit complicated…

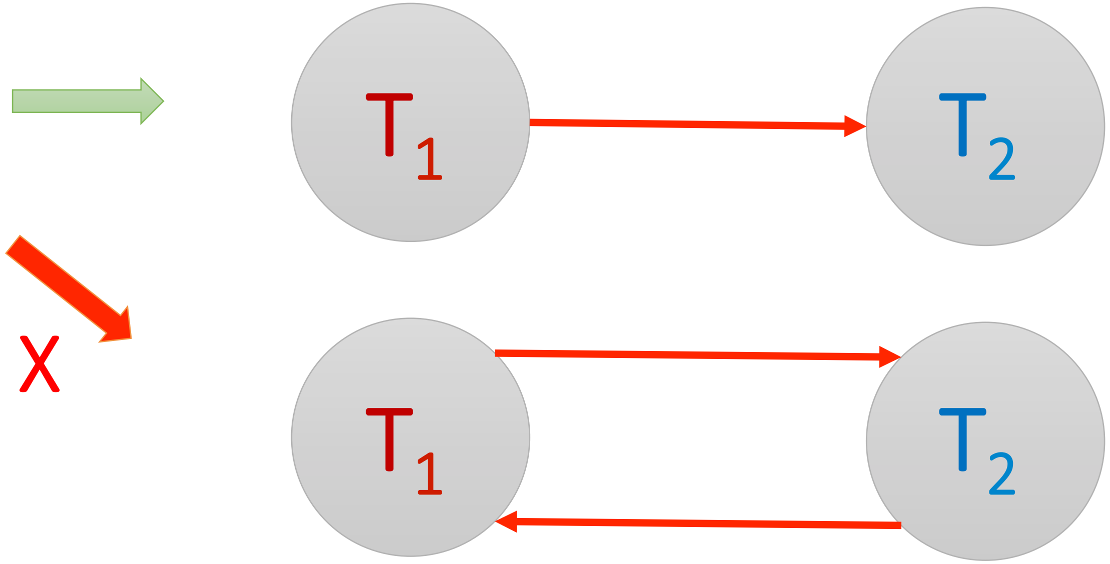
# What can we say about "good" vs. "bad" conflict graphs?

*Serial Schedule*:




Simple!

*Interleaved Schedules*:




Theorem: Schedule is **conflict serializable** if and only if its conflict graph is acyclic

# Let’s unpack this notion of acyclic conflict graphs…

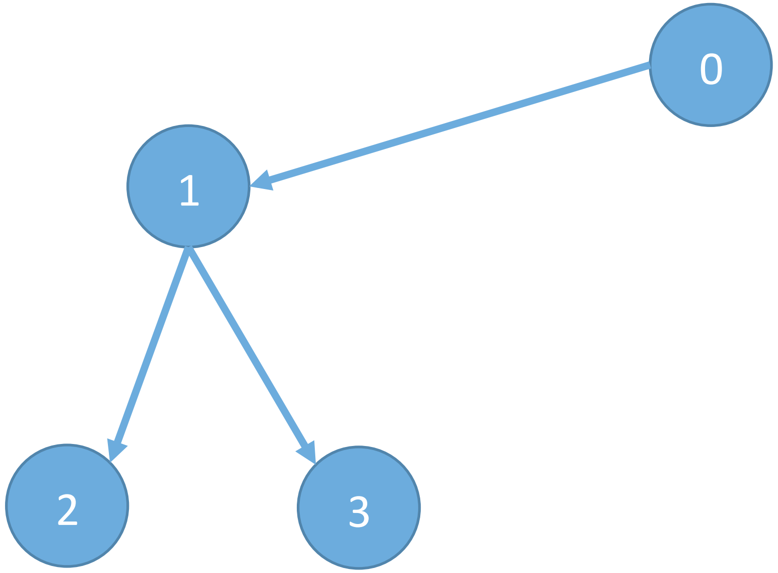
# DAGs & Topological Orderings

- A **topological ordering** of a directed graph is a linear ordering of its vertices that respects all the directed edges

- A directed **acyclic** graph (DAG) always has one or more **topological orderings**
  - (And there exists a topological ordering *if and only if* there are no directed cycles)

# DAGs & Topological Orderings

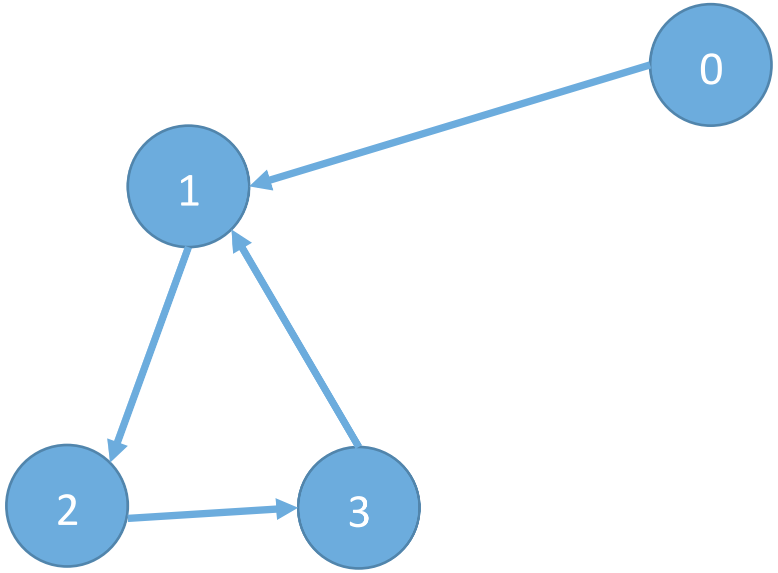
- Ex: What is one possible topological ordering here?




Ex: 0, 1, 2, 3 (or: 0, 1, 3, 2)

# DAGs & Topological Orderings

- Ex: What is one possible topological ordering here?




There is none!

# Connection to conflict serializability

- In the conflict graph, a topological ordering of nodes corresponds to **a serial ordering of TXNs**

- Thus an **acyclic** conflict graph → conflict serializable!

Theorem: Schedule is **conflict serializable** if and only if its conflict graph is acyclic

# Strict Two-Phase Locking

- We consider **locking**- specifically, *strict two-phase locking*- as a way to deal with concurrency, because is **guarantees conflict serializability (if it completes- see upcoming…)**

- Also (*conceptually*) straightforward to implement, and transparent to the user!

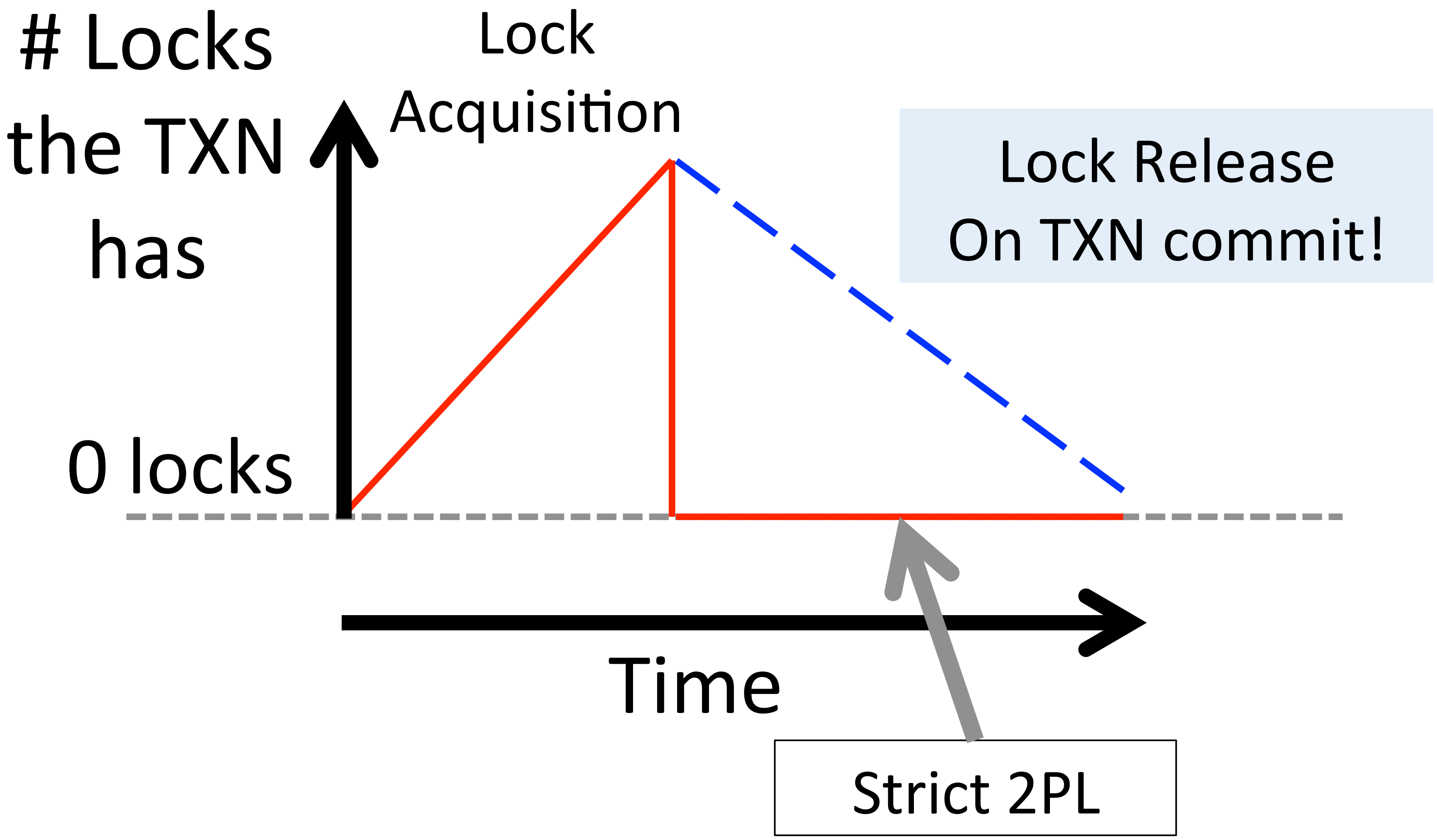
# Strict Two-phase Locking (Strict 2PL) Protocol:

## TXNs obtain:

- An **X (*exclusive*) lock** on object before **writing**.
  - If a TXN holds, no other TXN can get a lock (S or X) on that object.
- An **S (*shared*) lock** on object before **reading**
  - If a TXN holds, no other TXN can get *an X lock* on that object
- All locks held by a TXN are released when TXN completes.

Note: Terminology here- “exclusive”, “shared”- meant to be intuitive- no tricks!

# Picture of 2-Phase Locking (2PL)



# Strict 2PL

<u>Theorem:</u> Strict 2PL allows only schedules whose dependency graph is acyclic

*Proof Intuition:* In strict 2PL, if there is an edge $T_i \rightarrow T_j$ (i.e. $T_i$ and $T_j$ conflict) then $T_j$ needs to wait until $T_i$ is finished – so *cannot* have an edge $T_j \rightarrow T_i$

Therefore, Strict 2PL only allows conflict serializable $\Rightarrow$ serializable schedules

# Strict 2PL

- If a schedule follows strict 2PL and locking, it is conflict serializable…
    - …and thus serializable
    - …and thus maintains isolation & consistency!
- Not all serializable schedules are allowed by strict 2PL.
- So let's use strict 2PL, what could go wrong?

# Deadlock Detection: Example

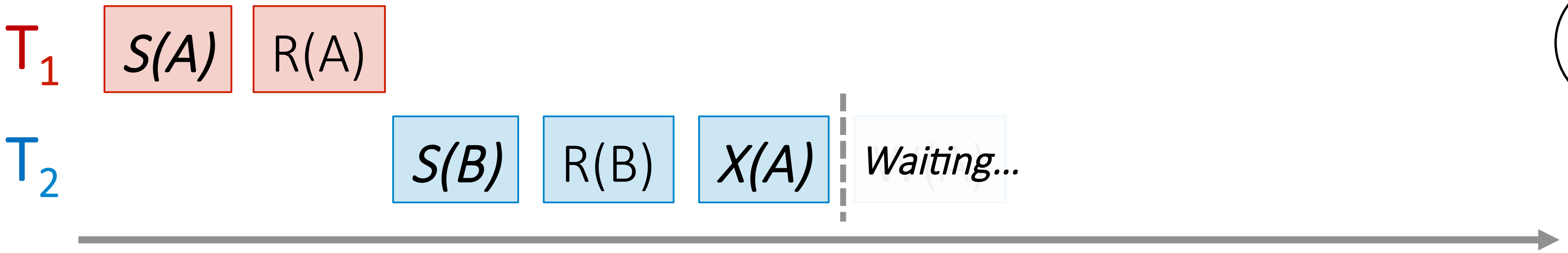

Waits-for graph:


First, $T_1$ requests a shared lock on A to read from it

# Deadlock Detection: Example


Next, $T_2$ requests a shared lock on B to read from it

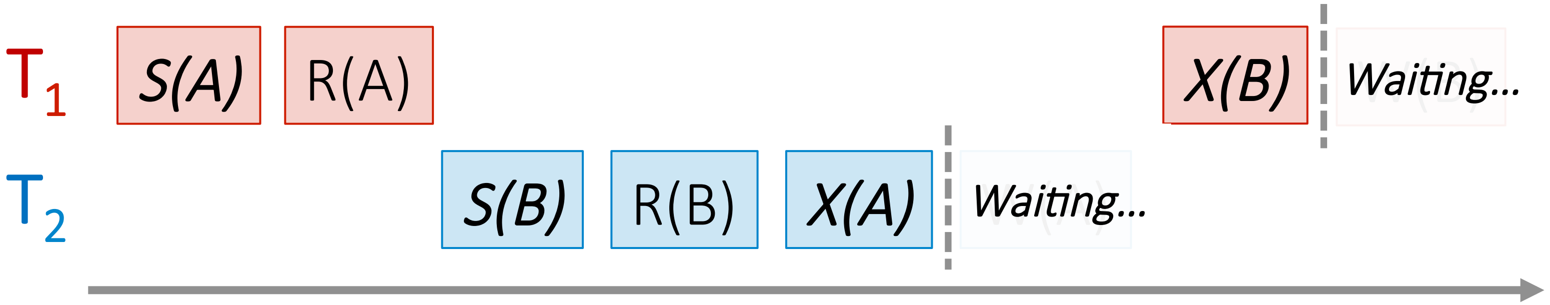
# Deadlock Detection: Example



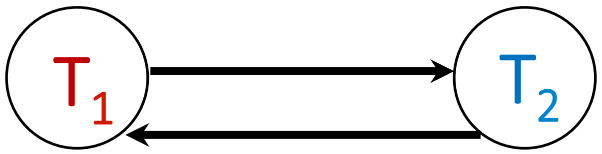

Waits-for graph:


$T_2$ then requests an exclusive lock on A to write to it- **now $T_2$ is waiting on $T_1$…**

# Deadlock Detection: Example




Waits-for graph:

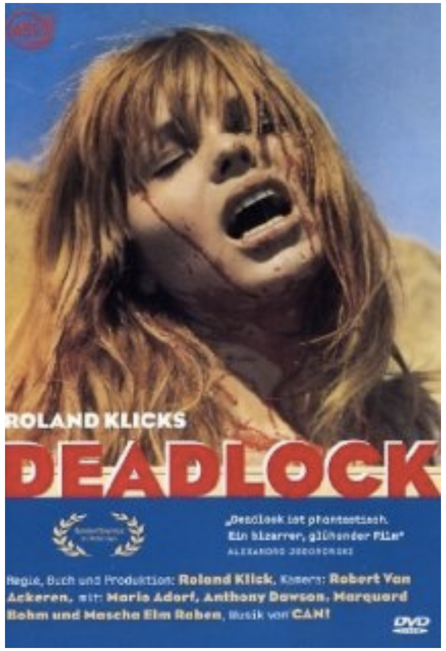



Cycle = DEADLOCK

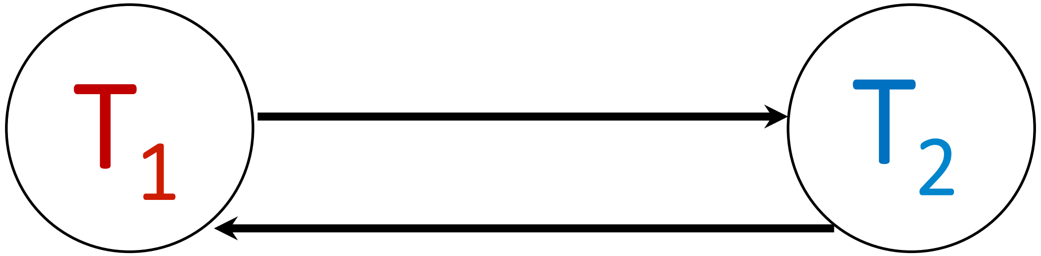
Finally, $T_1$ requests an exclusive lock on B to write to it- **now $T_1$ is waiting on $T_2$… DEADLOCK!**

```
sqlite3.OperationalError: database is locked
```

```
ERROR:  deadlock detected
DETAIL:  Process 321 waits for ExclusiveLock on tuple of
relation 20 of database 12002; blocked by process 4924.
Process 404 waits for ShareLock on transaction 689; blocked
by process 552.
HINT:  See server log for query details.
```




The problem?
Deadlock!??!




NB: Also movie called wedlock (deadlock) set in a futuristic prison…
I haven't seen either of them…

# Deadlocks

- **Deadlock**: Cycle of transactions waiting for locks to be released by each other.

- Two ways of dealing with deadlocks:

  1. Deadlock prevention

  2. Deadlock detection

# Deadlock Detection

- Create the **waits-for graph**:
  - Nodes are transactions
  - There is an edge from $T_i \rightarrow T_j$ if $T_i$ is *waiting for $T_j$ to release a lock*
- Periodically check for (***and break***) cycles in the waits-for graph

# Summary

- Concurrency achieved by **interleaving TXNs** such that **isolation** & **consistency** are maintained
  - We formalized a notion of **serializability** that captured such a "good" interleaving schedule

- We defined **conflict serializability**, which implies serializability

- **Locking** allows only conflict serializable schedules
  - If the schedule completes… (it may deadlock!)