L16: Transactions & Concurrency Control
Part 1: Transactions & Logging
Part 2: Concurrency Control

CS3200 Database design (sp18 s2)

https://course.ccs.neu.edu/cs3200sp18s2/

3/15/2018

Announcements!

- Exam2 next week: content is everything seen until today: setup like for Exam1: laptop SQL + paper database design + paper transactions
- Posted: ER examples, HW4 example solutions and FMs, Q8 for next week
- Outline today
  - Transactions
  - Concurrency control

Challenges for ACID properties

- In spite of failures: Power failures, but not media failures
- Users may abort the program: need to "rollback the changes"
  - Need to log what happened
- Many users executing concurrently
  - Can be solved via locking

And all this with… Performance!!

A Note: ACID is contentious!

- Many debates over ACID, both historically and currently
- Many newer “NoSQL” DBMSs relax ACID
- In turn, now “NewSQL” reintroduces ACID compliance to NoSQL-style DBMSs…

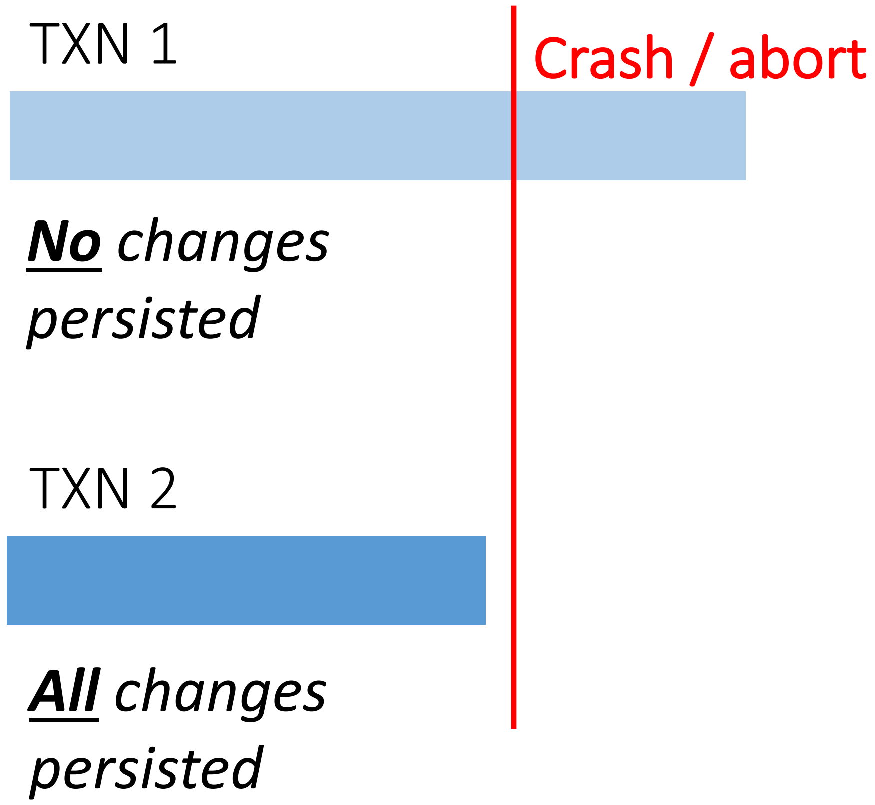
ACID is an extremely important & successful paradigm, but still debated!

Our first Goal: Ensuring Atomicity & Durability

ACID

- Atomicity:
  - TXNs should either happen completely or not at all
  - If abort / crash during TXN, no effects should be seen

- Durability:
  - If DBMS stops running, changes due to completed TXNs should all persist
  - Just store on stable disk



We'll focus on how to accomplish atomicity (via logging)

The Log

- Is a list of modifications

- Log is duplexed and archived on stable storage.

Assume we don't lose it!

- Can force write entries to disk
  - A page goes to disk.

- All log activities handled transparently by the DBMS.

Basic Idea: (Physical) Logging

- Record UNDO information for every update!
  - Sequential writes to log
  - Minimal info (diff) written to log

- The log consists of an <u>ordered list of actions</u>
  - Log record contains:
    - <XID, location, old data, new data>

This is sufficient to UNDO any transaction!

Why do we need logging for atomicity?

- Couldn't we just write TXN to disk only once whole TXN complete?
  - Then, if abort / crash and TXN not complete, it has no effect- atomicity!
  - With unlimited memory and time, this could work…

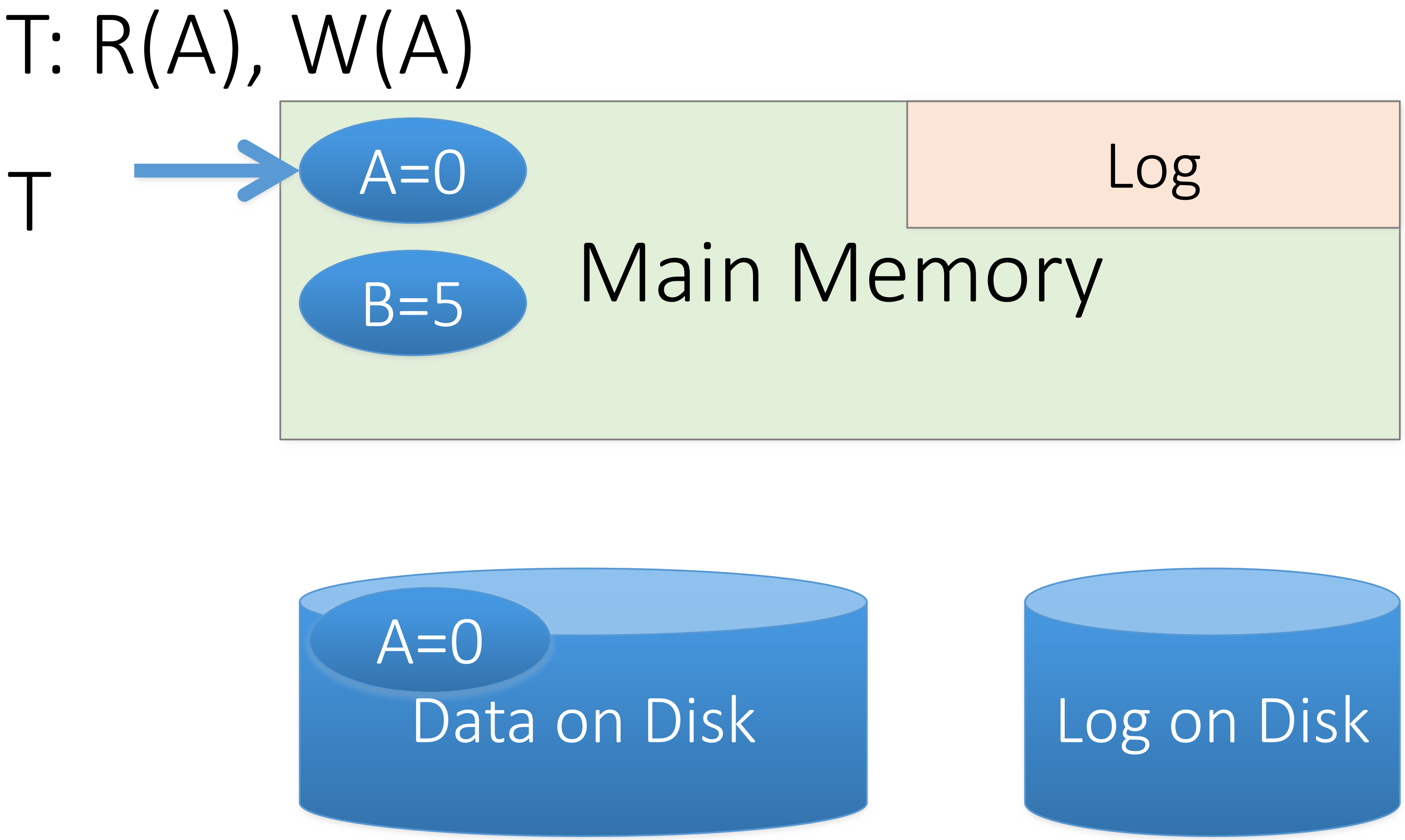
- However, we need to log partial results of TXNs because of:
  - Memory constraints (enough space for full TXN??)
  - Time constraints (what if one TXN takes very long?)

We need to write partial results to disk!
…And so we need a **log** to be able to *undo* these partial results!

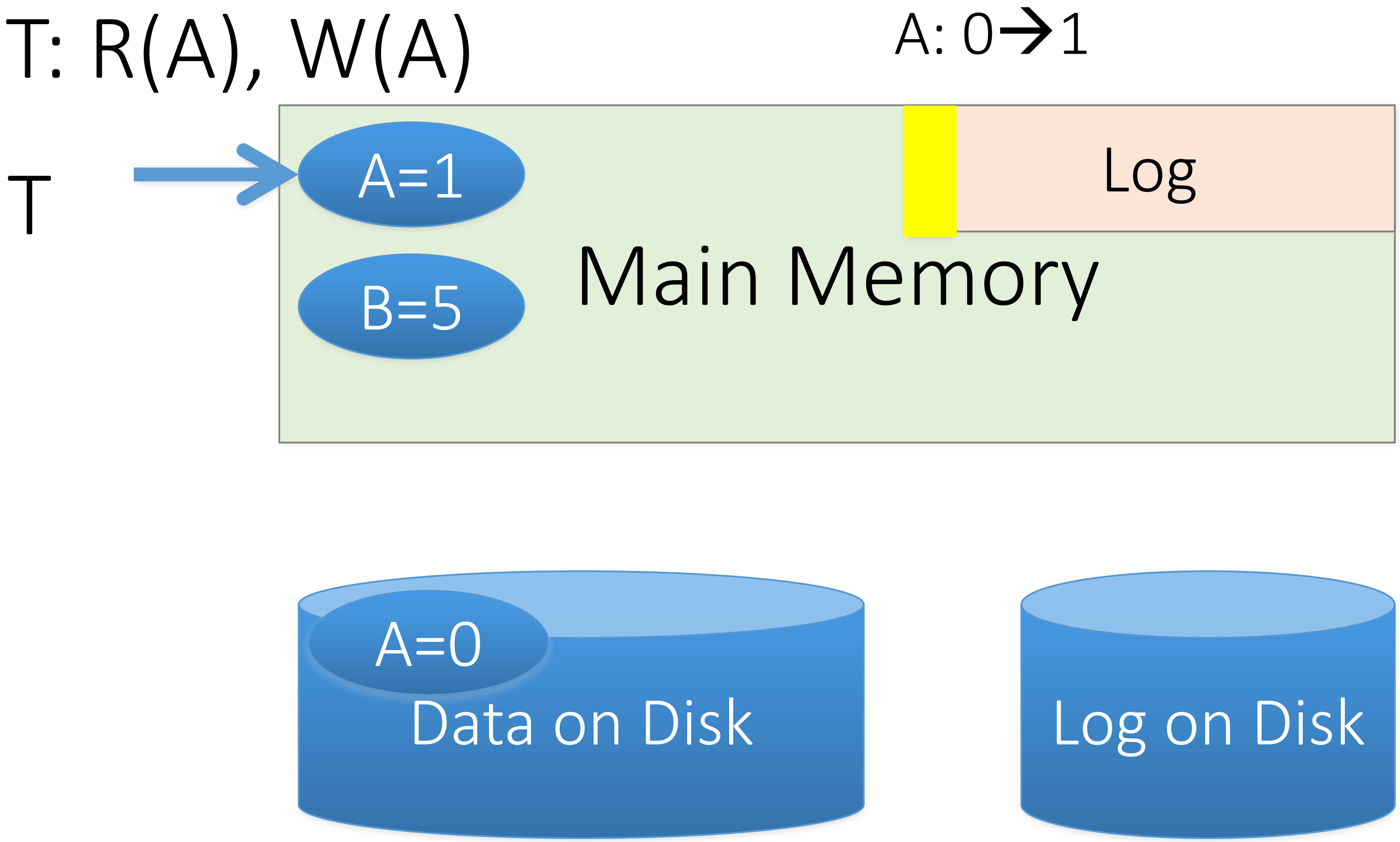
3. Atomicity & Durability via Logging

An animation of commit protocols

A picture of logging



A picture of logging



Operation recorded in log in main memory!

What is the correct way to write this all to disk?

- We'll look at the Write-Ahead Logging (WAL) protocol

- We'll see why it works by looking at other protocols which are incorrect!

Remember: Key idea is to ensure durability *while* maintaining our ability to "undo"!

Write-Ahead Logging (WAL)
TXN Commit Protocol

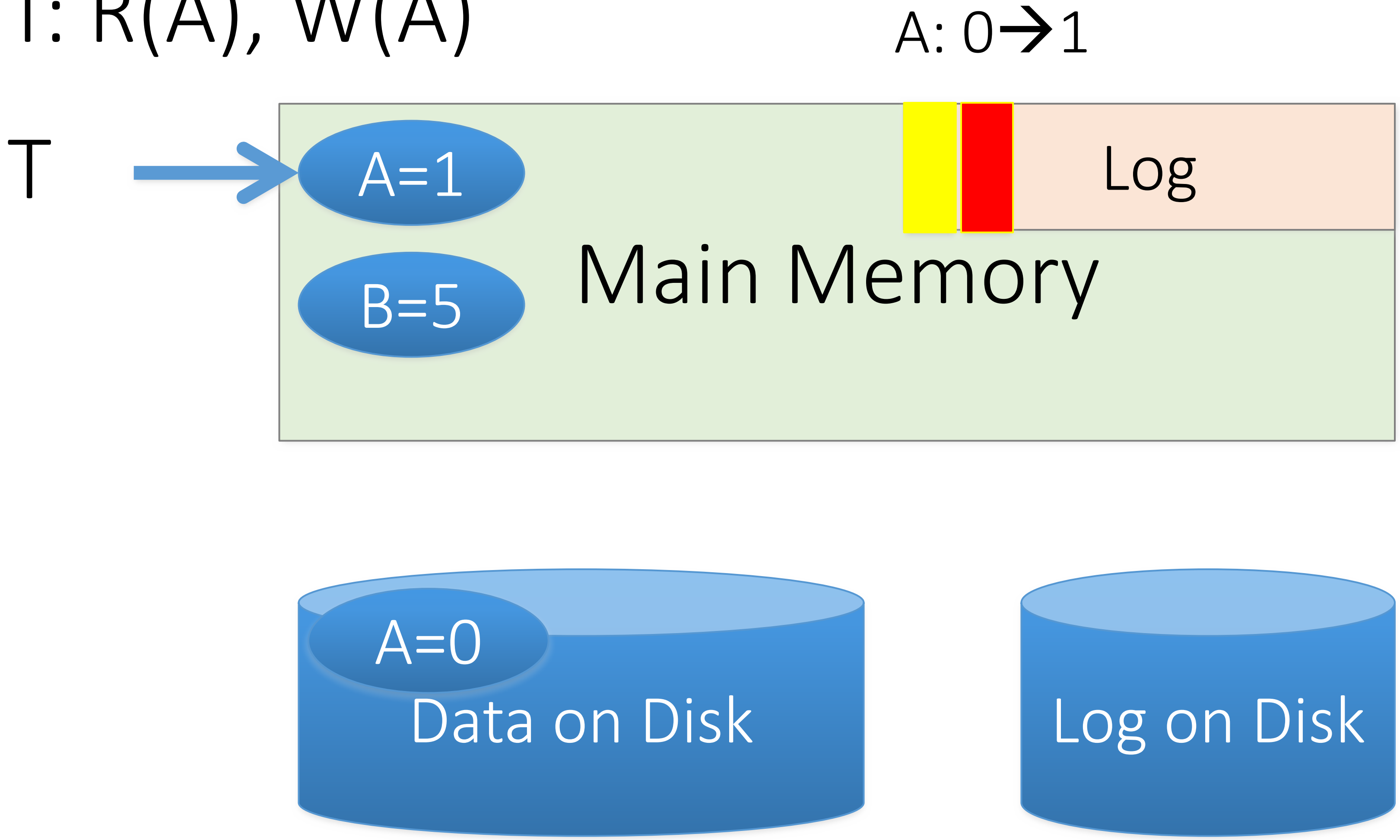
Transaction Commit Process

- FORCE Write commit record to log
- All log records up to last update from this TX are FORCED
- Commit() returns

Transaction is committed *once commit log record is on stable storage*

Incorrect Commit Protocol #1

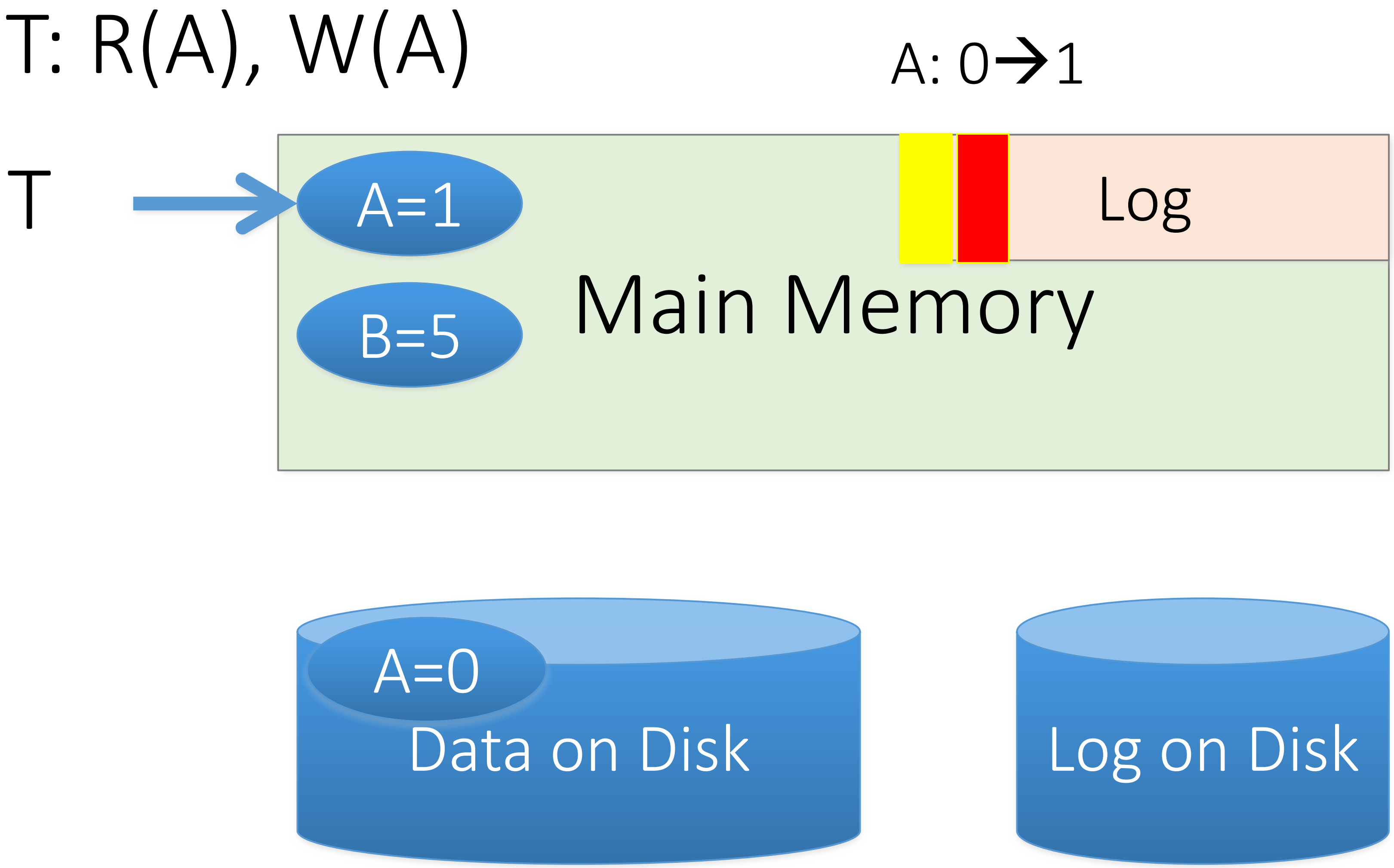
T: R(A), W(A)



Let's try committing *before* we've written either data or log to disk…

OK, Commit!

Incorrect Commit Protocol #1



Let's try committing *before* we've written either data or log to disk…

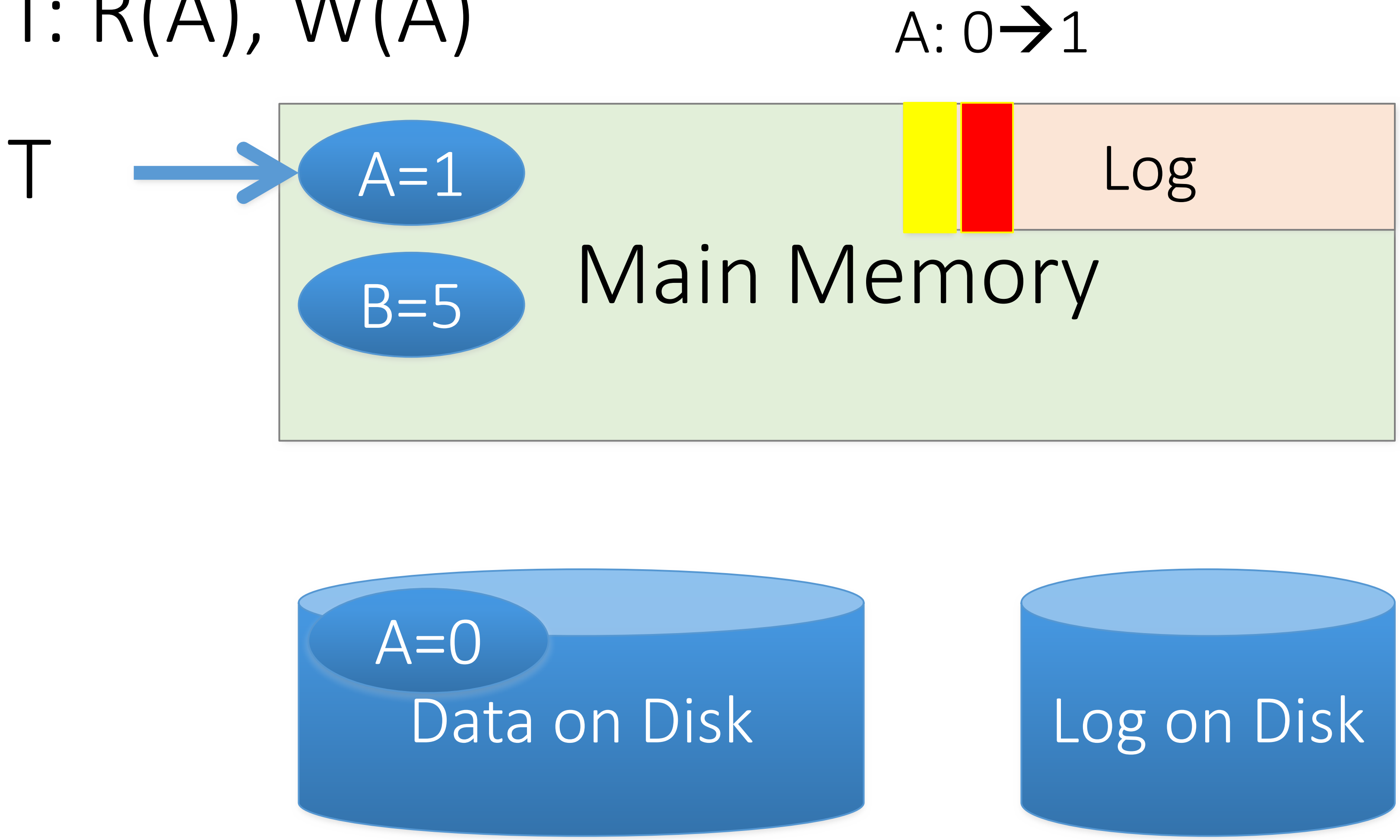
OK, Commit!

If we crash now, is T durable?

Lost T's update!

Incorrect Commit Protocol #2

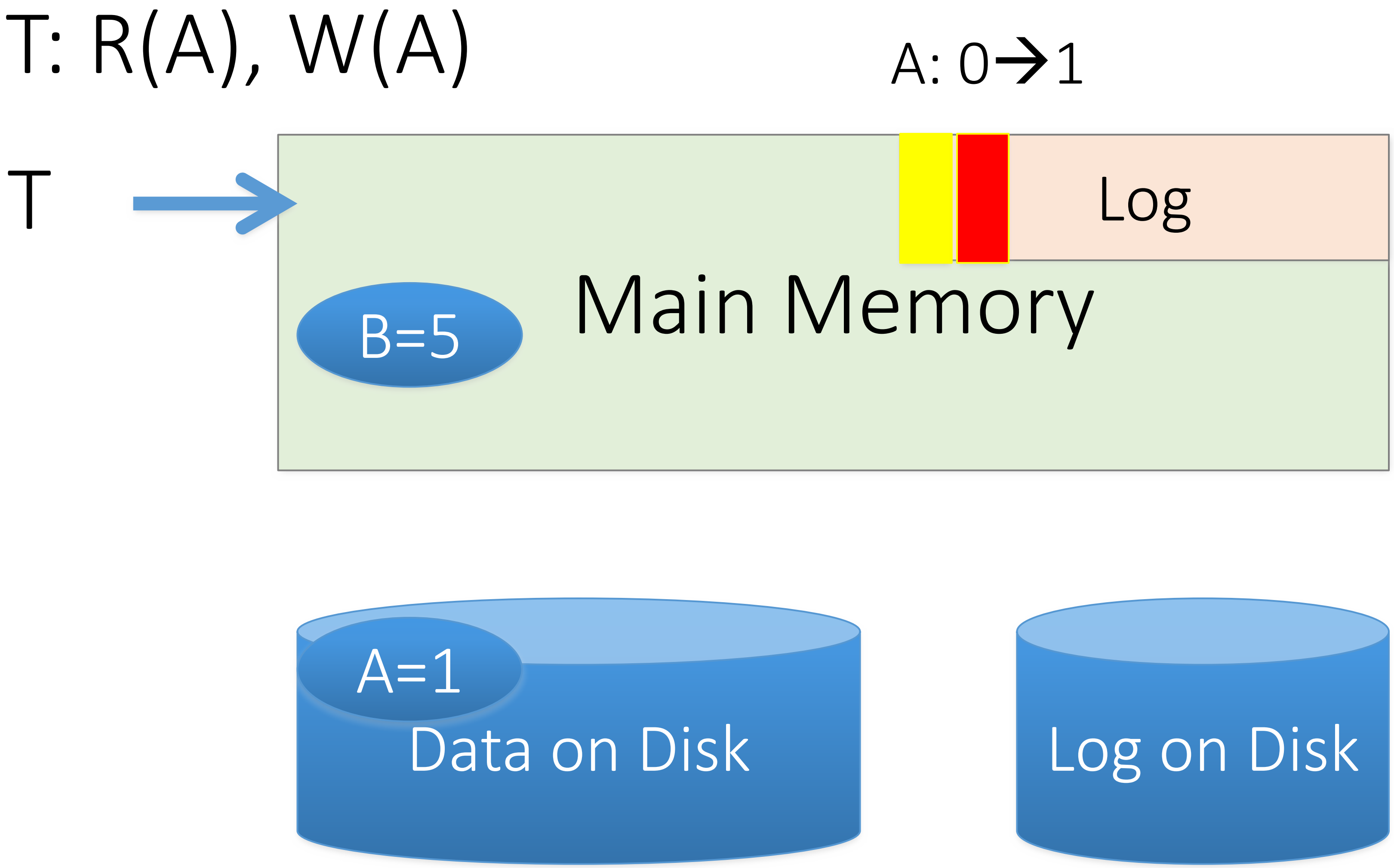
T: R(A), W(A)



Let's try committing *after* we've written data but *before* we've written log to disk…

OK, Commit!

Incorrect Commit Protocol #2



Let's try committing *after* we've written data but *before* we've written log to disk…

OK, Commit!

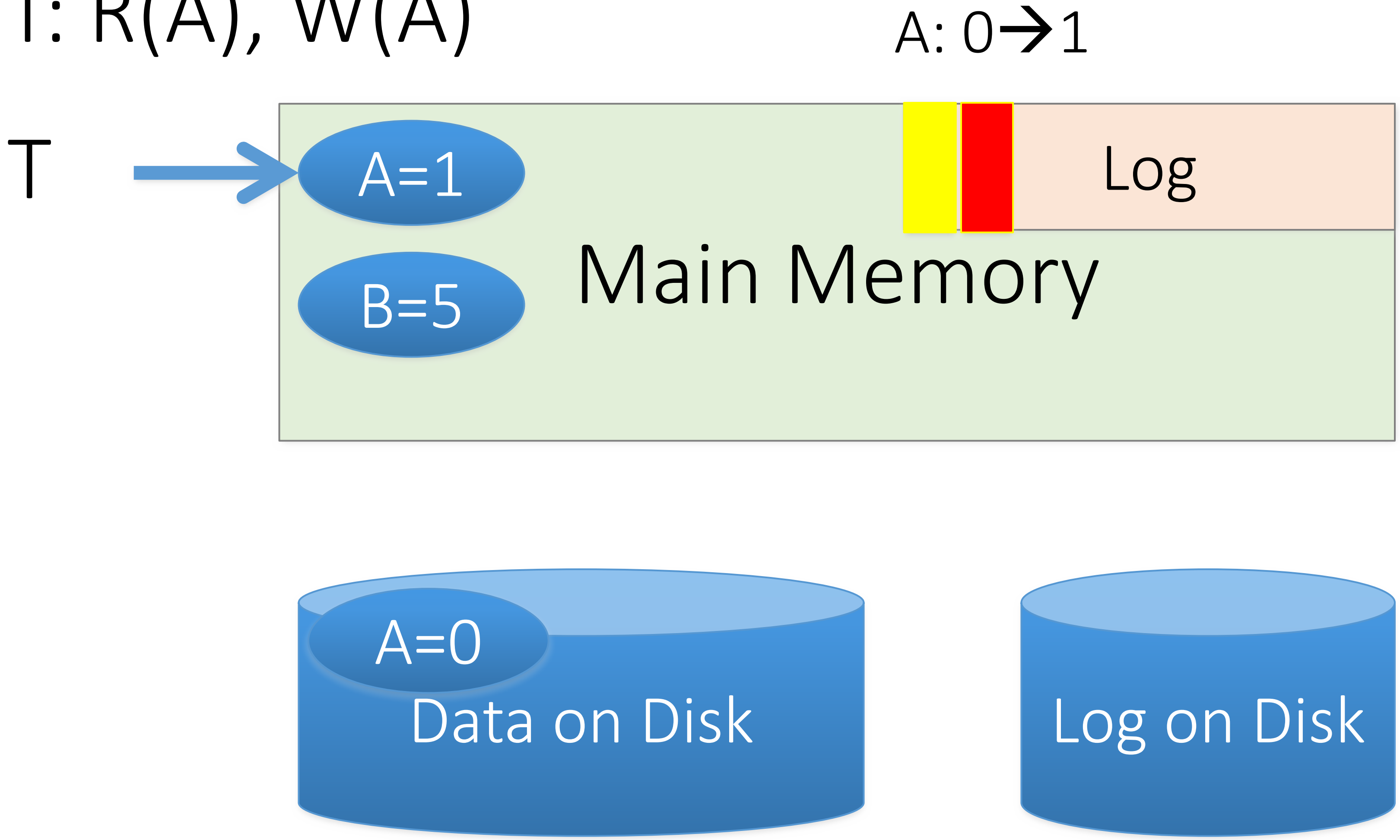
If we crash now, is T durable? Yes! Except…

How do we know whether T was committed??

Improved Commit Protocol (WAL)

Write-ahead Logging (WAL) Commit Protocol

T: R(A), W(A)



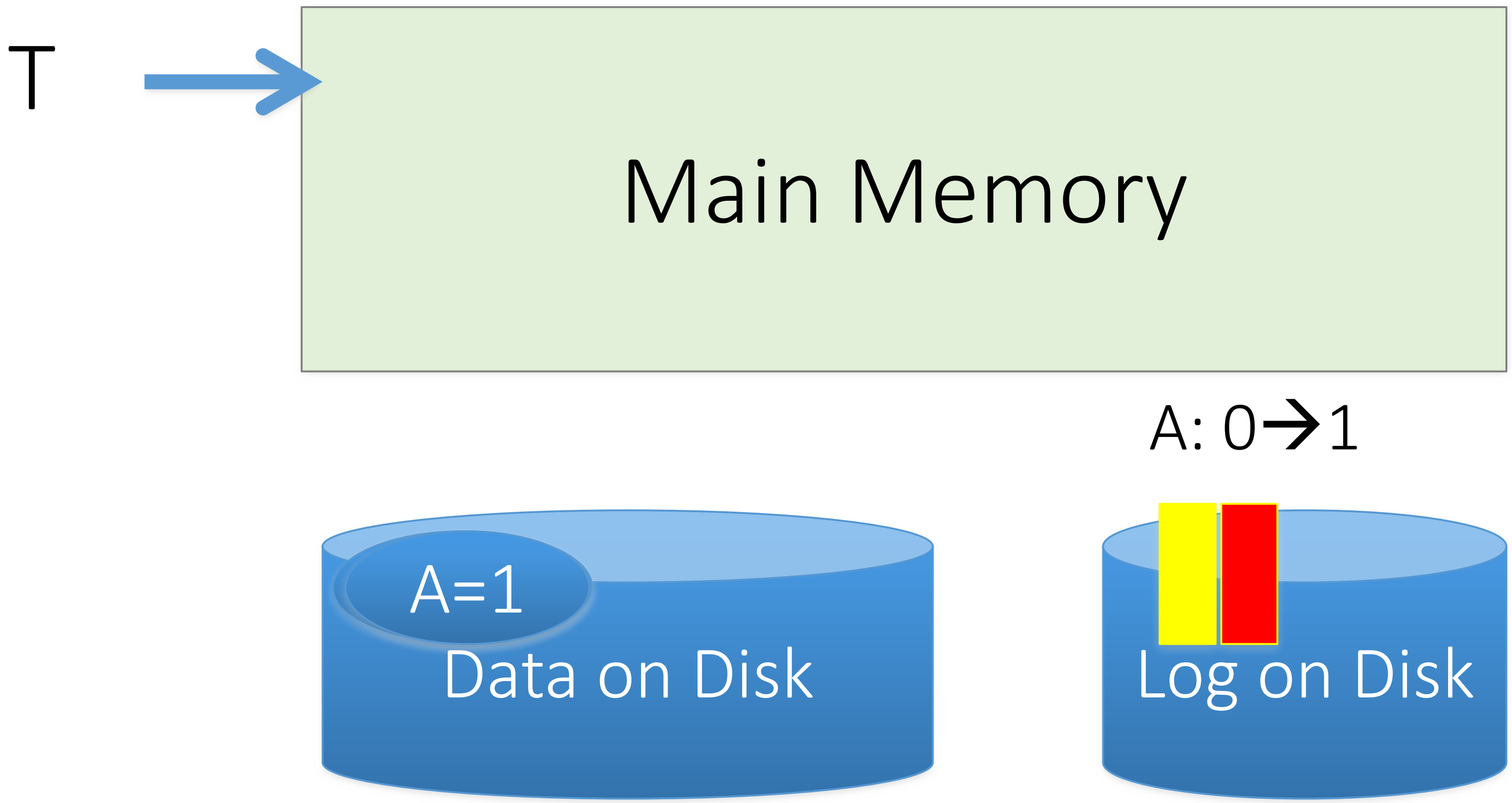
This time, let's try committing ***after* we've written log to disk but *before* we've written data to disk**... this is WAL!

OK, Commit!

If we crash now, is T durable?

Write-ahead Logging (WAL) Commit Protocol

T: R(A), W(A)



This time, let's try committing ***after* we've written log to disk but *before* we've written data to disk**… this is WAL!

OK, Commit!

If we crash now, is T durable?

USE THE LOG!

Write-Ahead Logging (WAL)

- DB uses **Write-Ahead Logging (WAL)** Protocol:

Each update is logged! Why not reads?

1. Must force log record for an update before the corresponding data page goes to storage

→ Atomicity

2. Must write all log records for a TX before commit

→ Durability

Logging Summary

- If DB says TX commits, TX effect remains after database crash
- DB can undo actions and help us with atomicity
- This is only half the story…

Concurrency & Locking

1) Concurrency, scheduling & anomalies
2) Locking: 2PL, conflict serializability, deadlock detection

1. Concurrency, Scheduling & Anomalies

What we will learn next

- Interleaving & scheduling
- Conflict & anomaly types
- ACTIVITY: TXN viewer

Concurrency: Isolation & Consistency

- The DBMS must handle concurrency s.t. …
  - **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
  - **Consistency** is maintained: TXNs must leave the DB in a consistent state
    - DBMS handles the details of enforcing integrity constraints

ACID

ACID

The hard part is the effect of *interleaving* transactions and *crashes*.

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
```

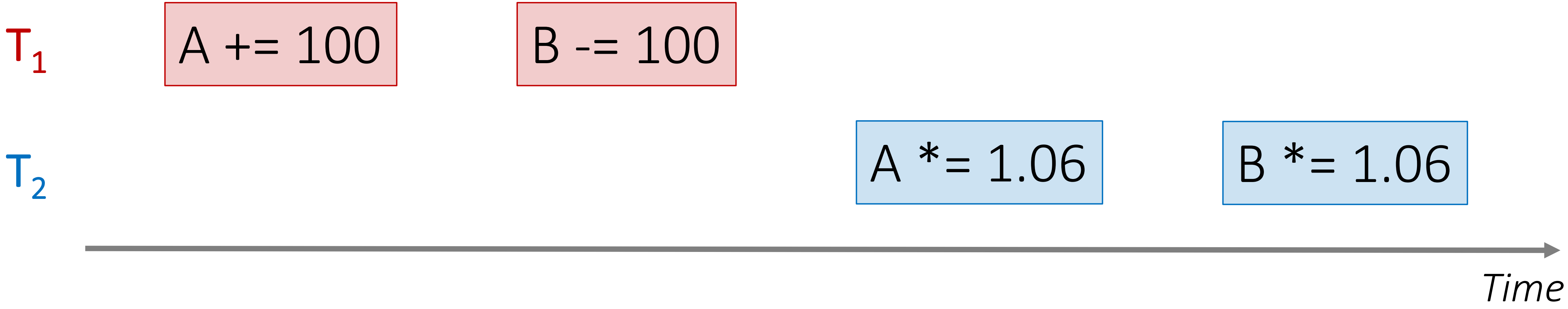
T1 transfers $100 from B’s account to A’s account

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

T2 credits both accounts with a 6% interest payment

Example- consider two TXNs:

We can look at the TXNs in a timeline view- serial execution:

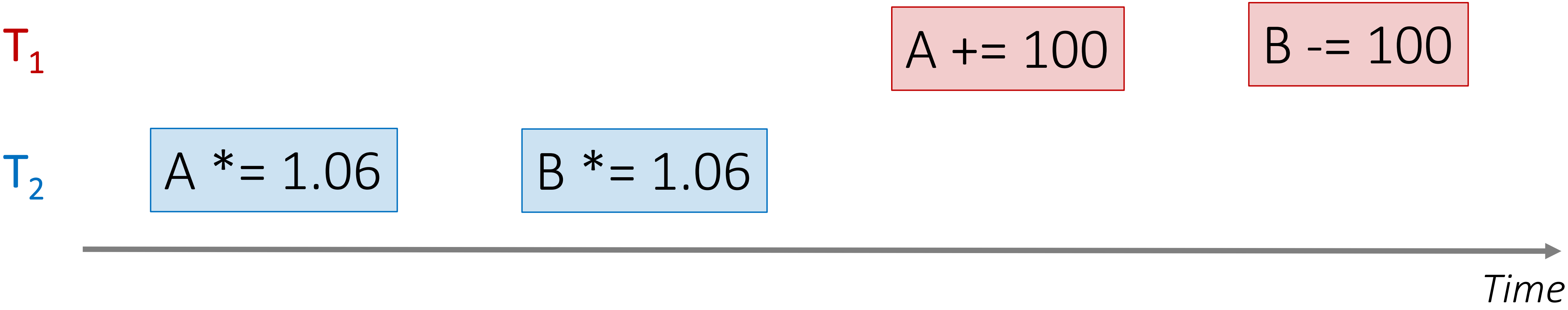


T1 transfers $100 from B's account to A's account

T2 credits both accounts with a 6% interest payment

Example- consider two TXNs:

The TXNs could occur in either order… DBMS allows!

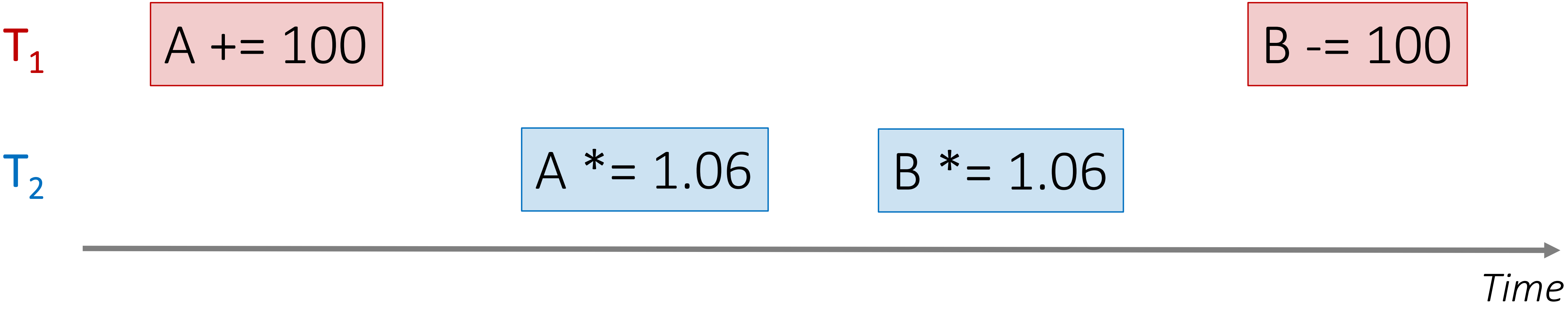


T2 credits both accounts with a 6% interest payment

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

Example- consider two TXNs:

The DBMS can also **interleave** the TXNs

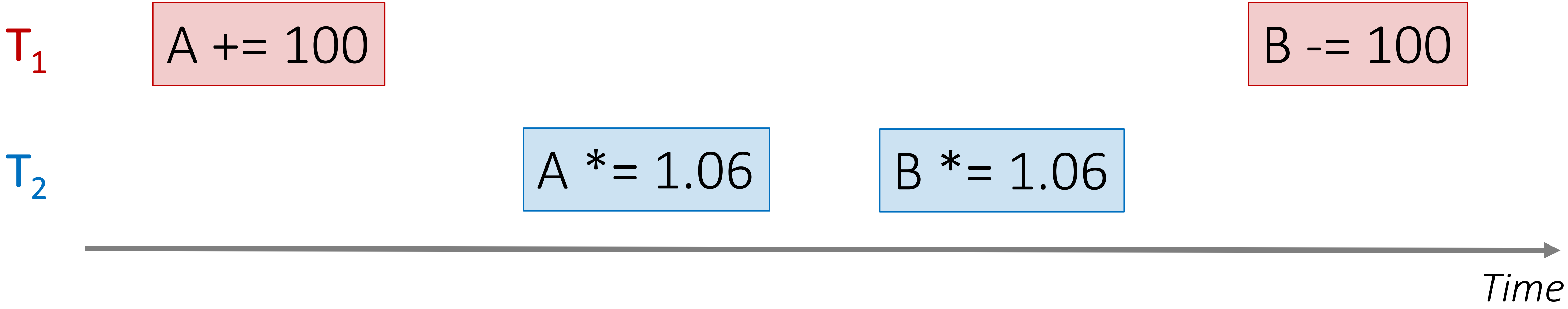


T1 transfers $100 to A's accout, then T2 credits A's account with 6% interest payment

T2 credits B's account with a 6% interest payment, then T1 transfers $100 from B's account…

Example- consider two TXNs:

The DBMS can also **interleave** the TXNs



What goes wrong here??

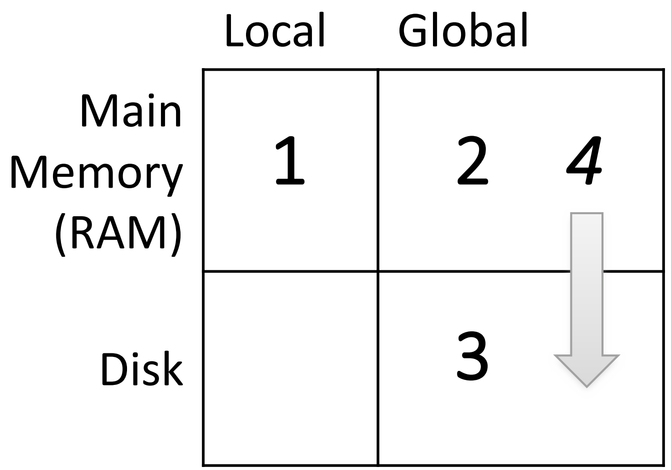
Recall: Three Types of Regions of Memory

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

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

3. <u>Disk</u>: Global memory can read from / flush to disk

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



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

"<u>**Flushing**</u> to disk" = writing to disk from main memory

Why Interleave TXNs?

- Interleaving TXNs might lead to anomalous outcomes… why do it?

- Several important reasons:
  - Individual TXNs might be slow- don't want to block other users during!

  - Disk access may be slow- let some TXNs use CPUs while others accessing disk!

All concern large differences in ***performance***

Interleaving & Isolation

- The DBMS has freedom to interleave TXNs

- However, it must pick an interleaving or schedule such that isolation and consistency are maintained

  – Must be as if the TXNs had executed serially!

"With great power comes great responsibility"

A<u>CI</u>D

DBMS must pick a schedule which maintains isolation & consistency

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 1:

T_1: A += 100 | B -= 100

T_2: A *= 1.06 | B *= 1.06

A	B
$159	$106

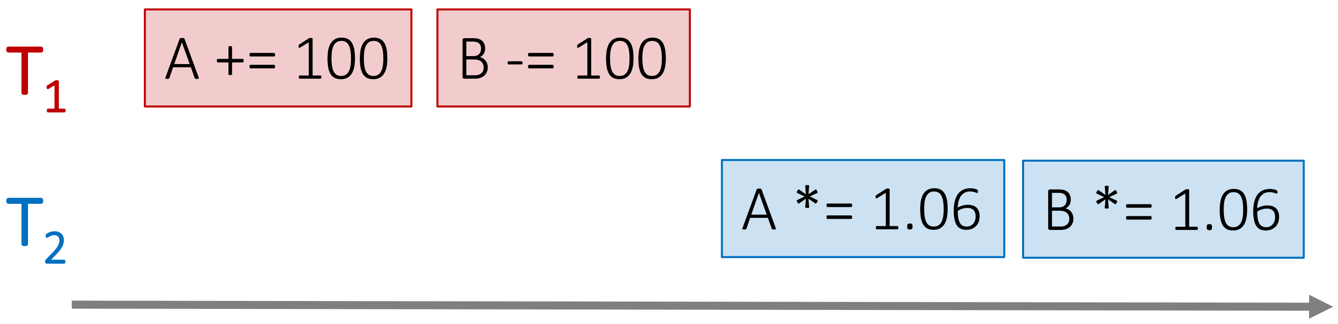
Same result!

Scheduling examples

Starting Balance

A	B
\$50	\$200

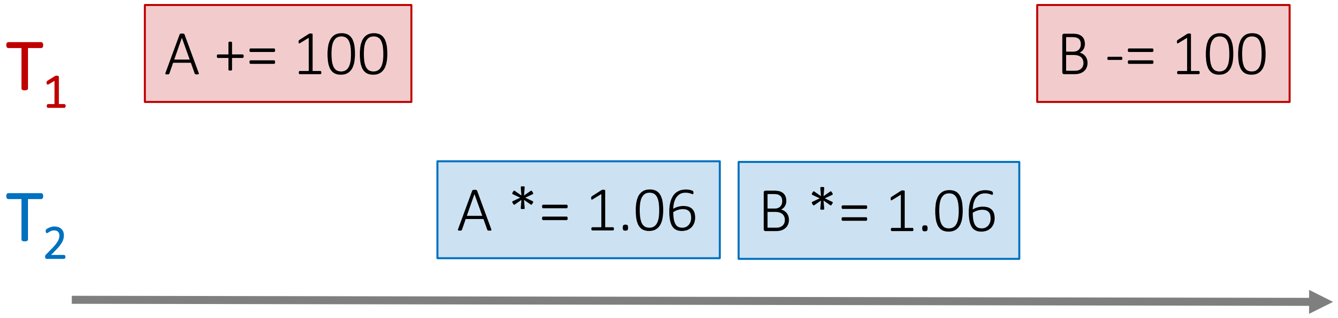
<u>Serial schedule T_1,T_2:</u>



A	B
\$159	\$106

Different result than serial T_1,T_2

<u>*Interleaved* schedule 2:</u>



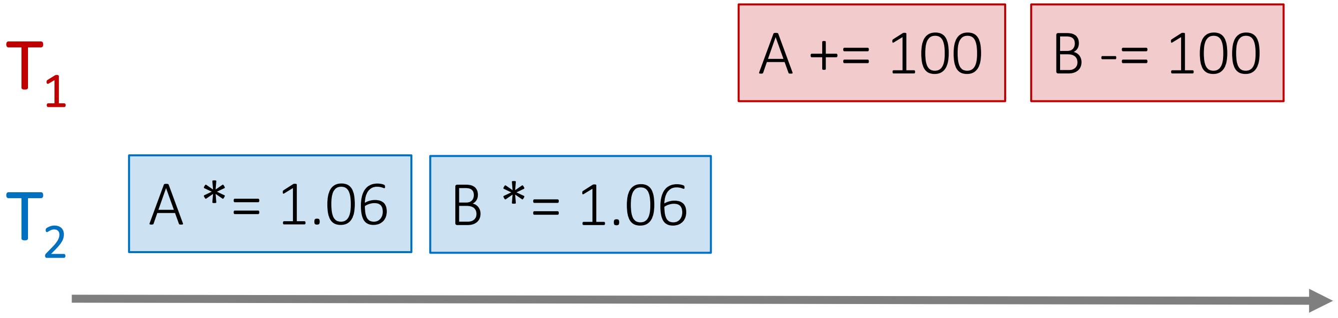
A	B
\$159	**\$112**

Scheduling examples

Starting Balance

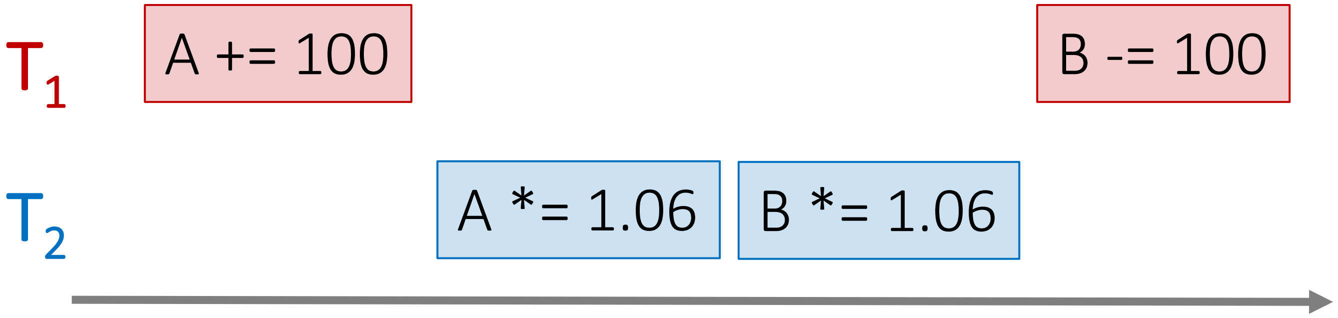
A	B
$50	$200

Serial schedule *T_2,T_1:*



A	B
$153	$112

Interleaved schedule 2:



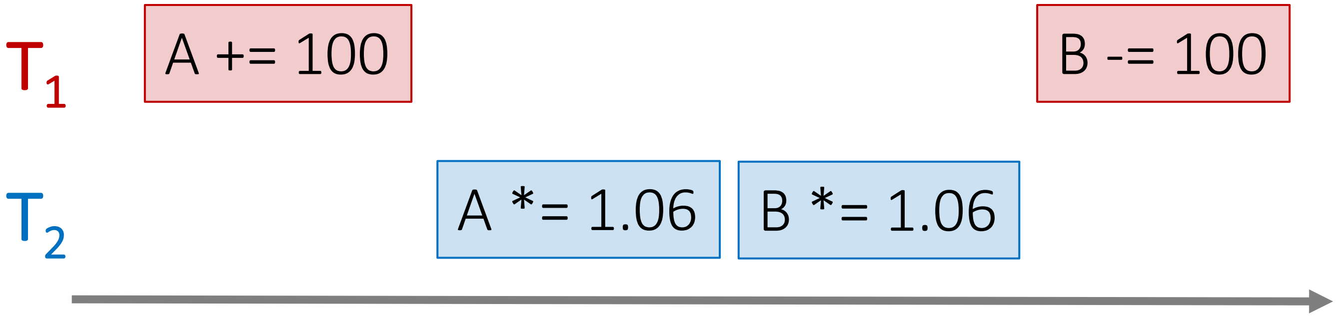
A	B
$159	$112

Different result than serial T_2,T_1 as well!

Scheduling examples

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

<u>*Interleaved* schedule 2:</u>



Scheduling Definitions

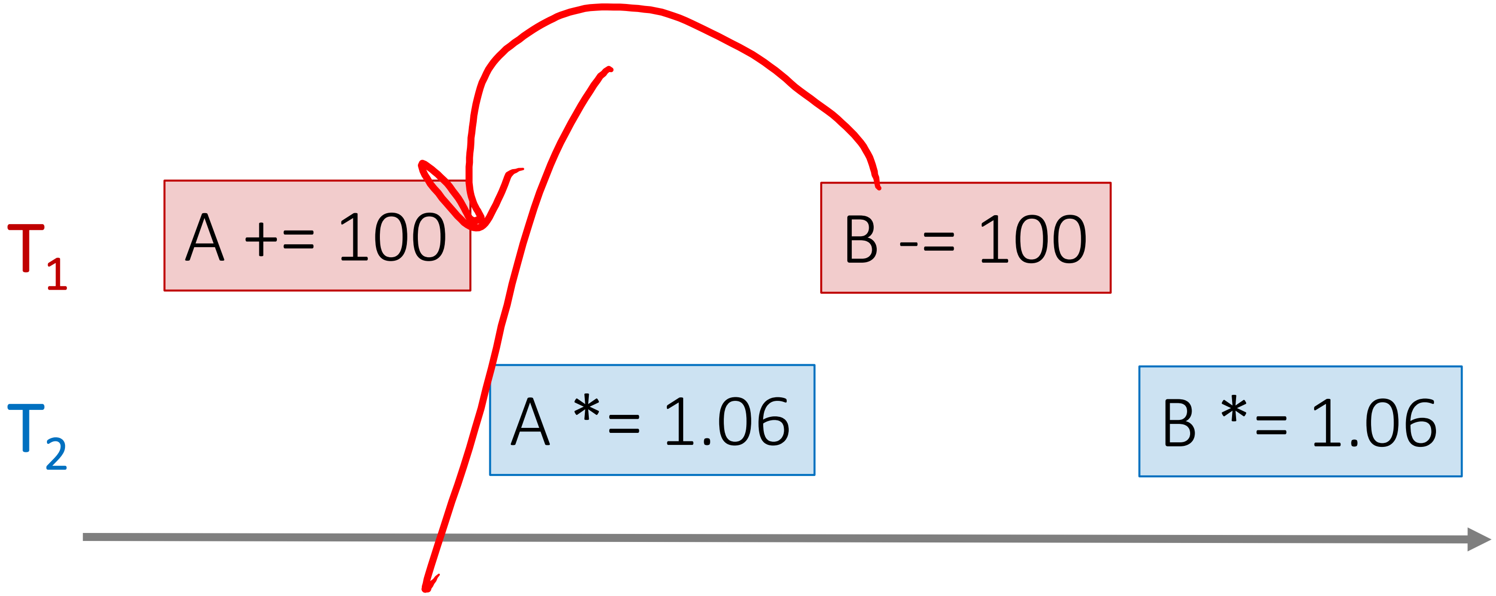
- A **serial schedule** is one that does not interleave the actions of different transactions

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

- 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?



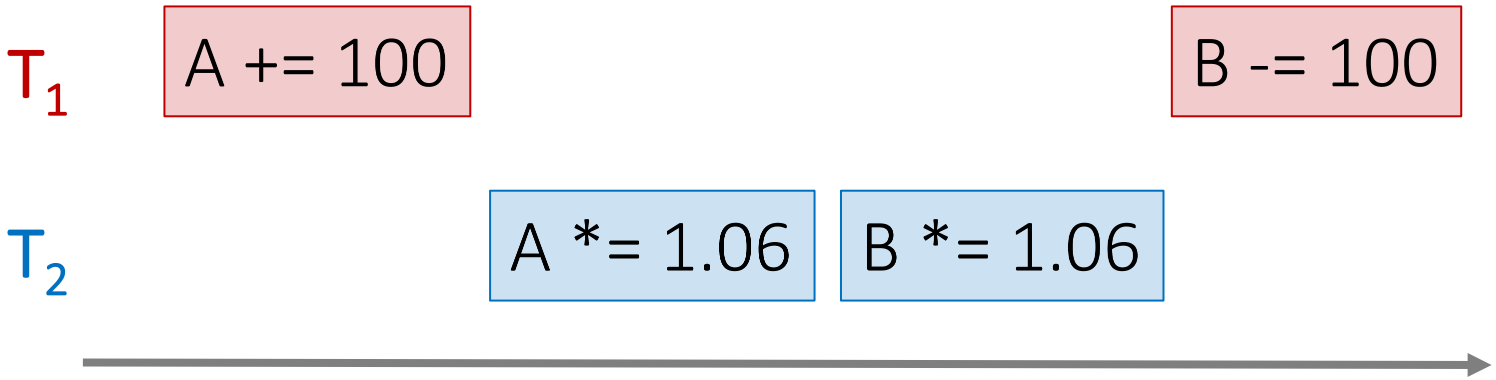
Serial schedules:

	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)

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

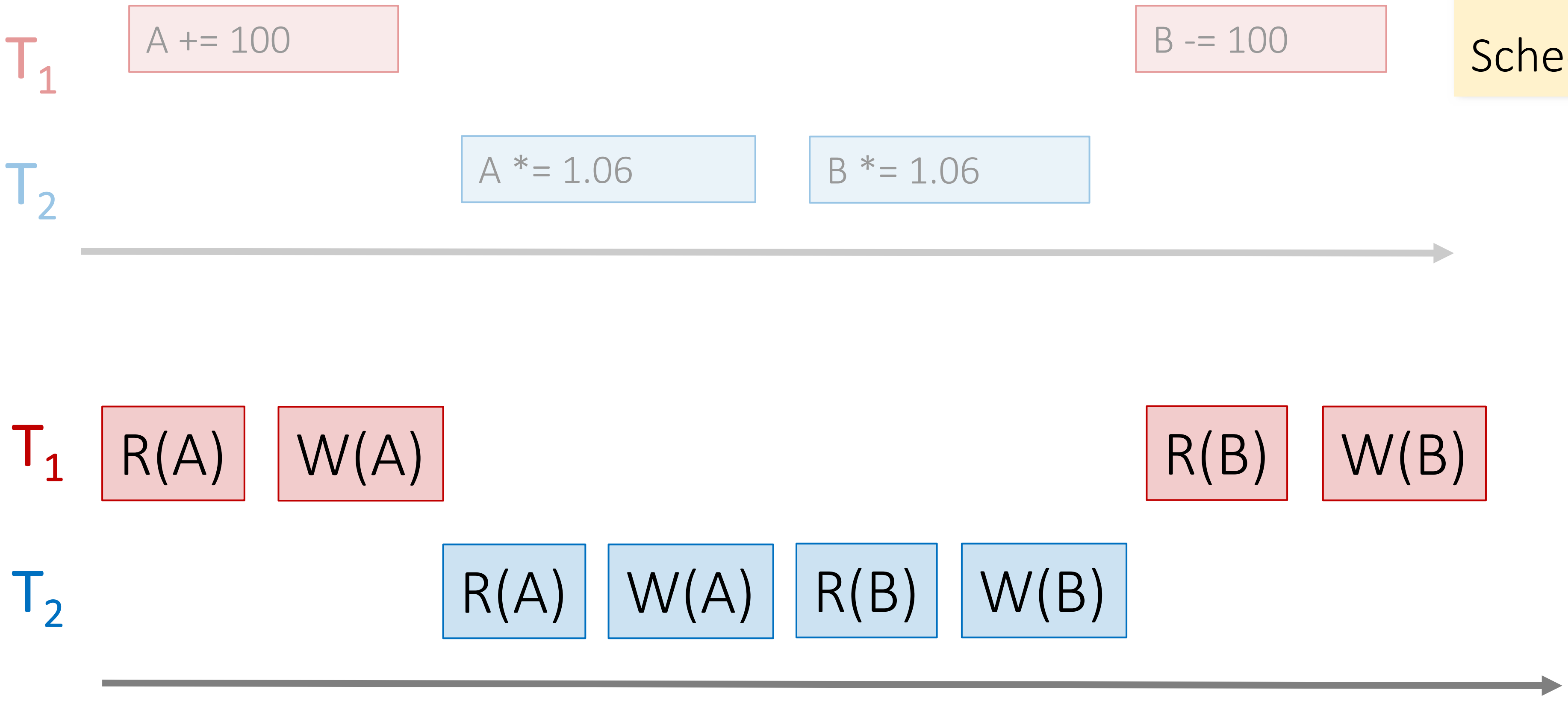
A	B
1.06*(A+100)	1.06*B - 100

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 of / with certain “conflicts” between interleaved TXNs

The DBMS's view of the schedule



Each action in the TXNs *reads a value from global memory* and then *writes one back to it*

Scheduling order matters!

Conflict Types

Two actions **conflict** if they are part of different TXNs, involve the same variable, 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)

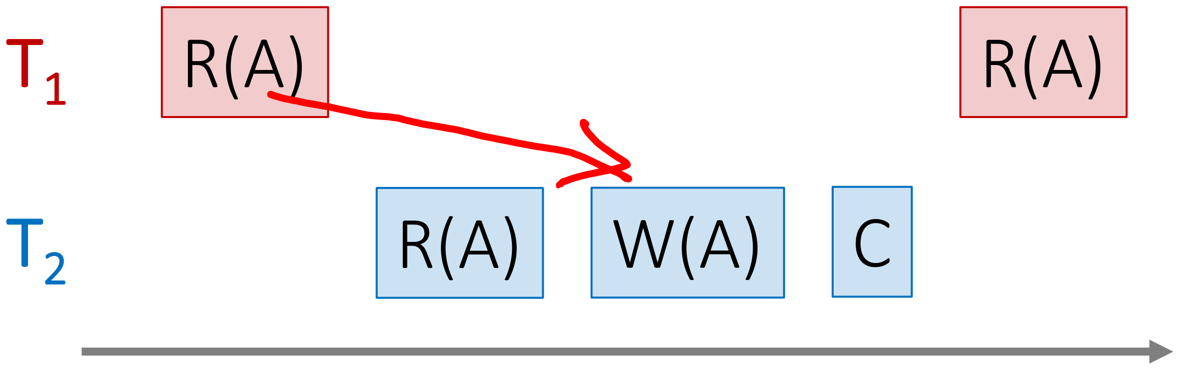
Why no "RR Conflict"?

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

Classic Anomalies with Interleaved Execution

“Unrepeatable read”

Example:

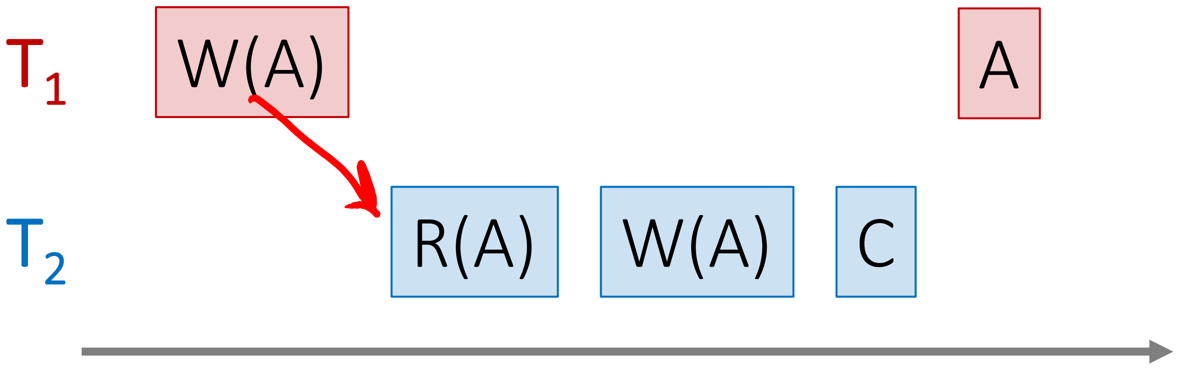


1. T_1 reads some data from A
2. T_2 writes to A
3. Then, T_1 reads from A again *and now gets a different / inconsistent value*

Occurring with / because of a ***RW conflict***

“Dirty read” (Reading uncommitted data)

Example:

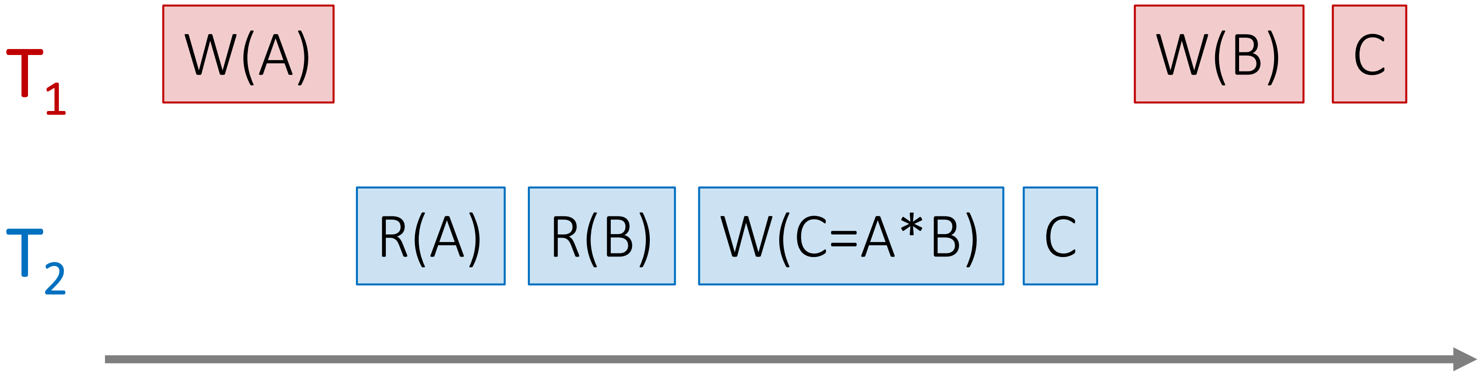


1. T_1 writes some data to A
2. T_2 reads from A, then writes back to A & commits
3. T_1 then aborts- *now T_2’s result is based on an obsolete / inconsistent value*

Occurring with / because of a ***WR conflict***

“Inconsistent read” (Reading partial commits)

Example:

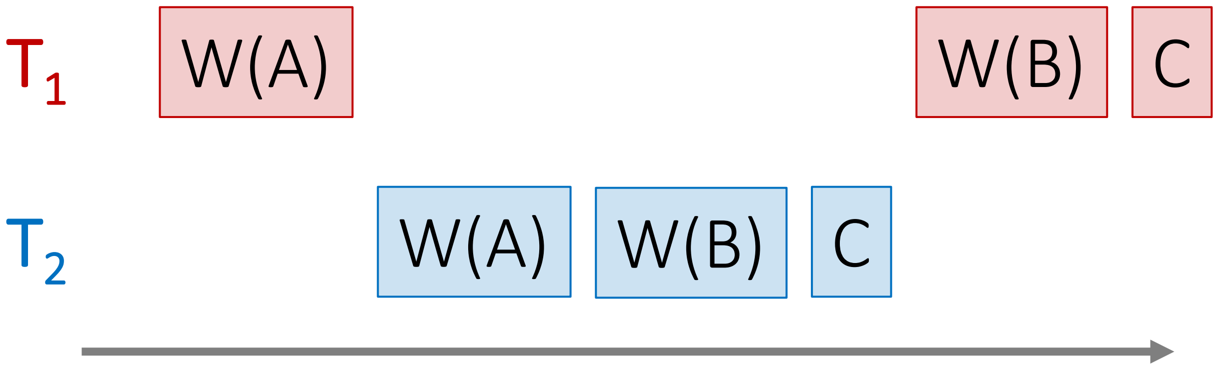


1. T_1 writes some data to A
2. T_2 reads from A *and B*, and then writes some value which depends on A & B
3. T_1 then writes to B- *now T_2’s result is based on an incomplete commit*

Again, occurring because of a ***WR conflict***

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***

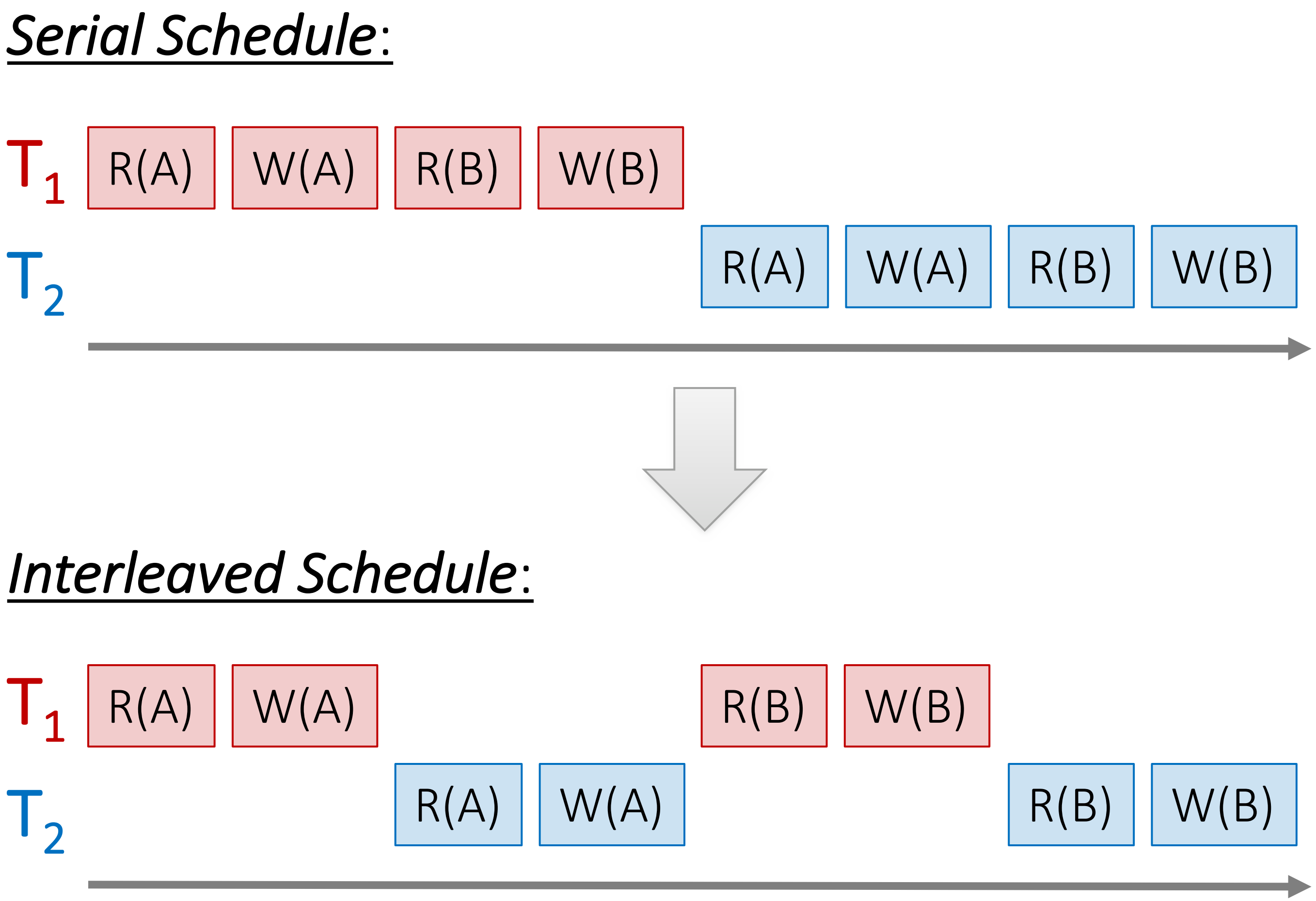
Activity-31.ipynb

2. Conflict Serializability, Locking & Deadlock

What we will learn next

- RECAP: Concurrency
- Conflict Serializability
- DAGs & Topological Orderings
- Strict 2PL
- Deadlocks

Recall: Concurrency as Interleaving TXNs

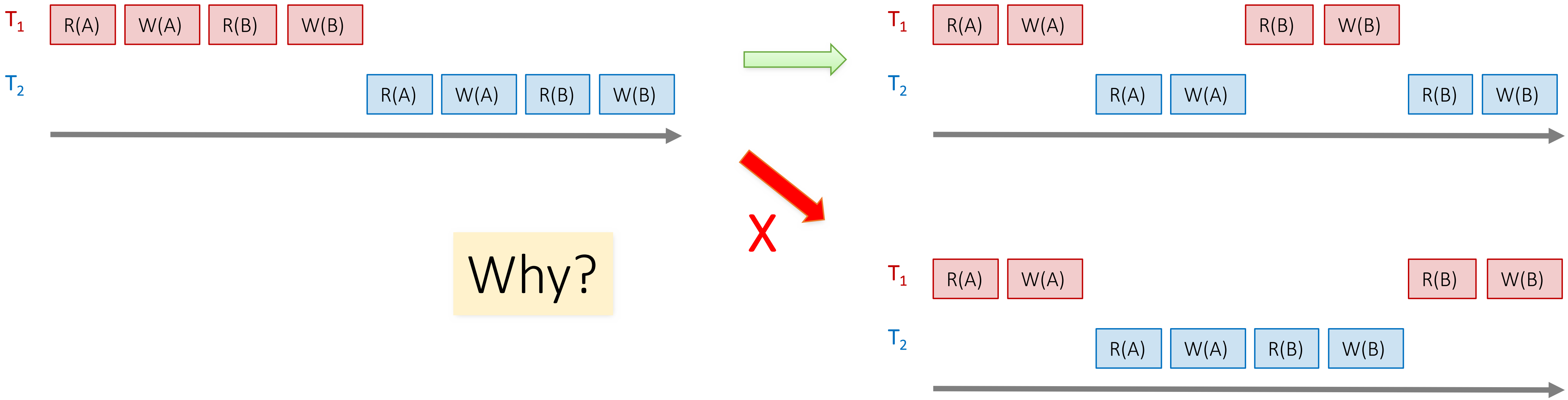


- For our purposes, having TXNs occur concurrently means interleaving their component actions (R/W)

We call the particular order of interleaving a **schedule**

Recall: “Good” vs. “bad” schedules

Serial Schedule: ***Interleaved Schedules***:



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

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

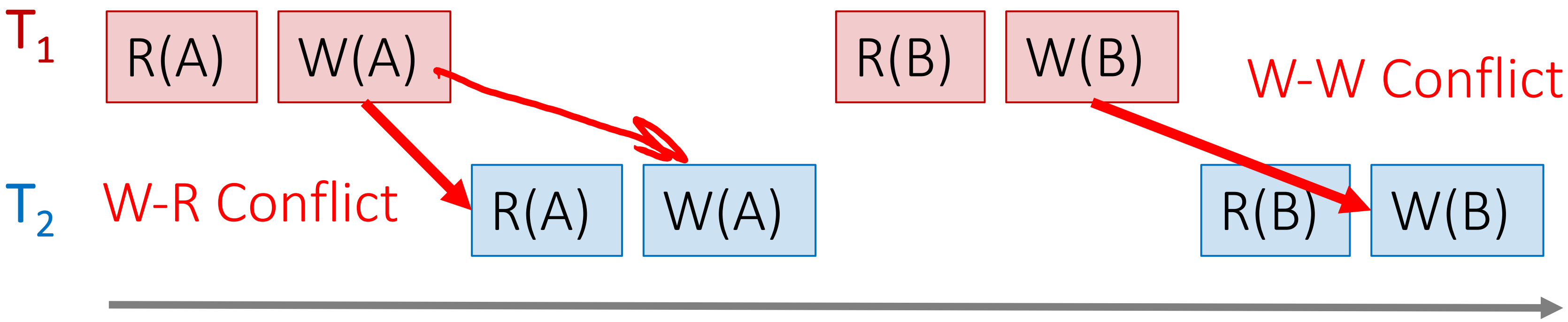
- Recall: we call a schedule serializable if it is equivalent to some serial schedule
  - We used this as a notion of a "good" interleaved schedule, since a serializable schedule will maintain isolation & consistency

- 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

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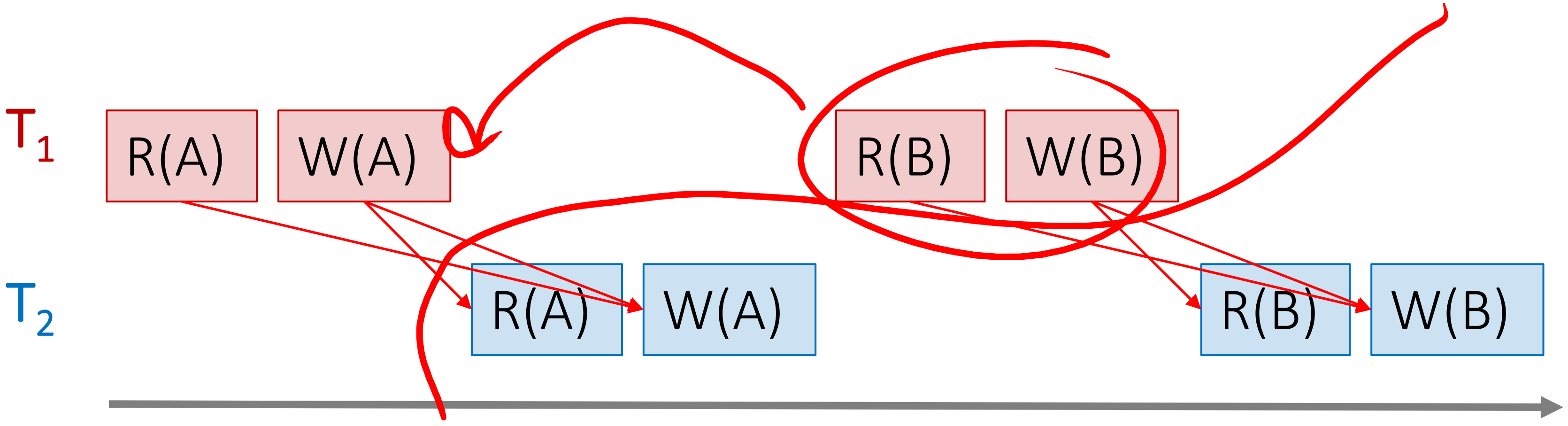


All “conflicts”!

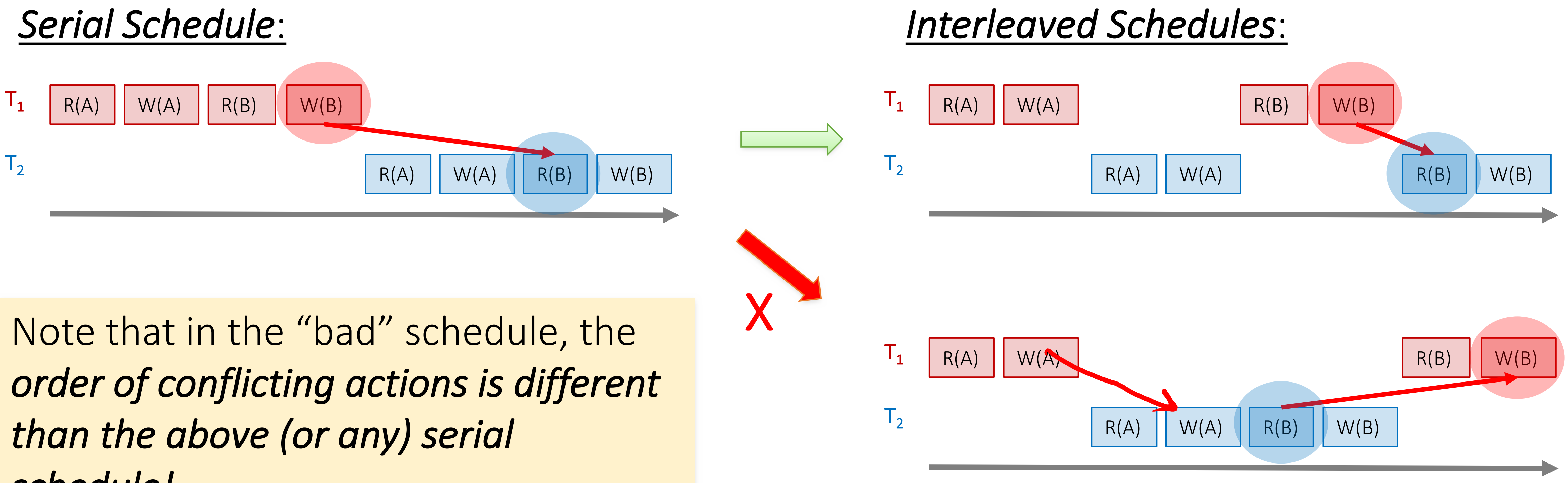
Conflict Serializability

- 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



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

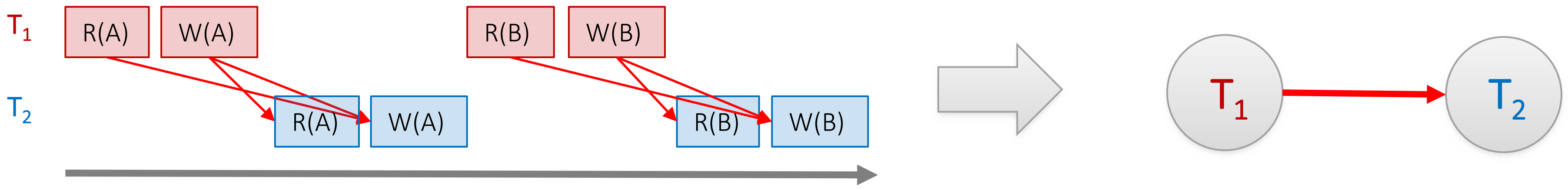
- Conflicts are things we talk about to help us characterize different schedules
  - Present in both “good” and “bad” schedules

- 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

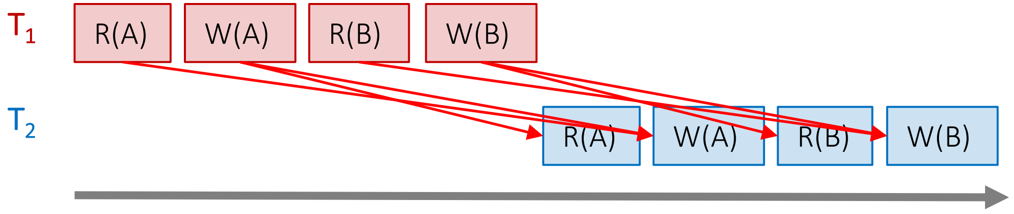
- Let's now consider looking at conflicts at the TXN level

- 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 precede and conflict with any actions in T_j

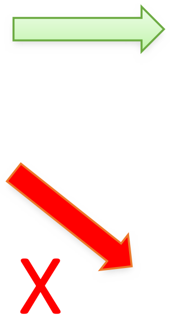


What can we say about “good” vs. “bad” conflict graphs?

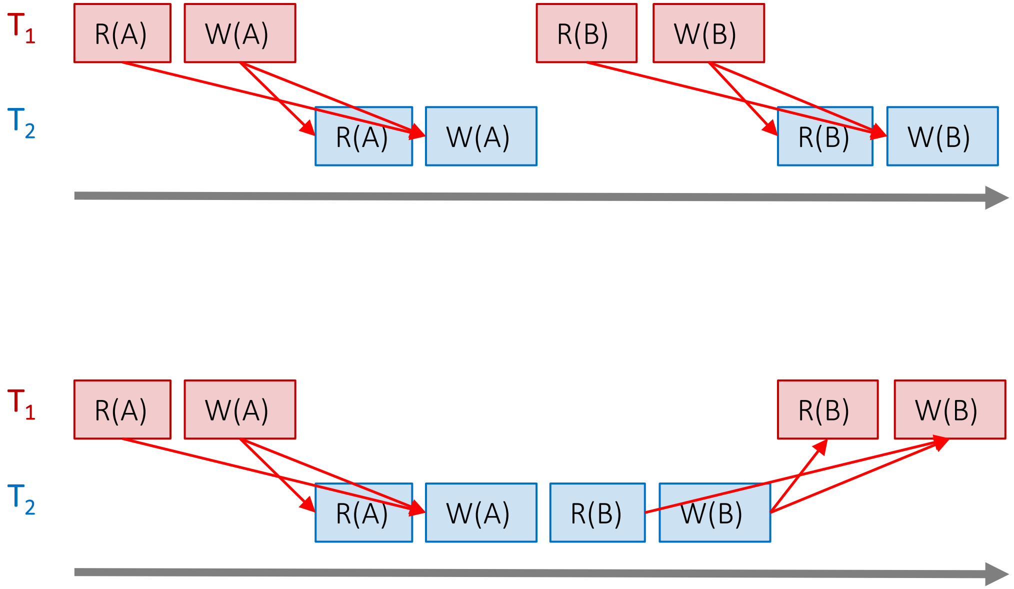
Serial Schedule:



A bit complicated…



Interleaved Schedules:



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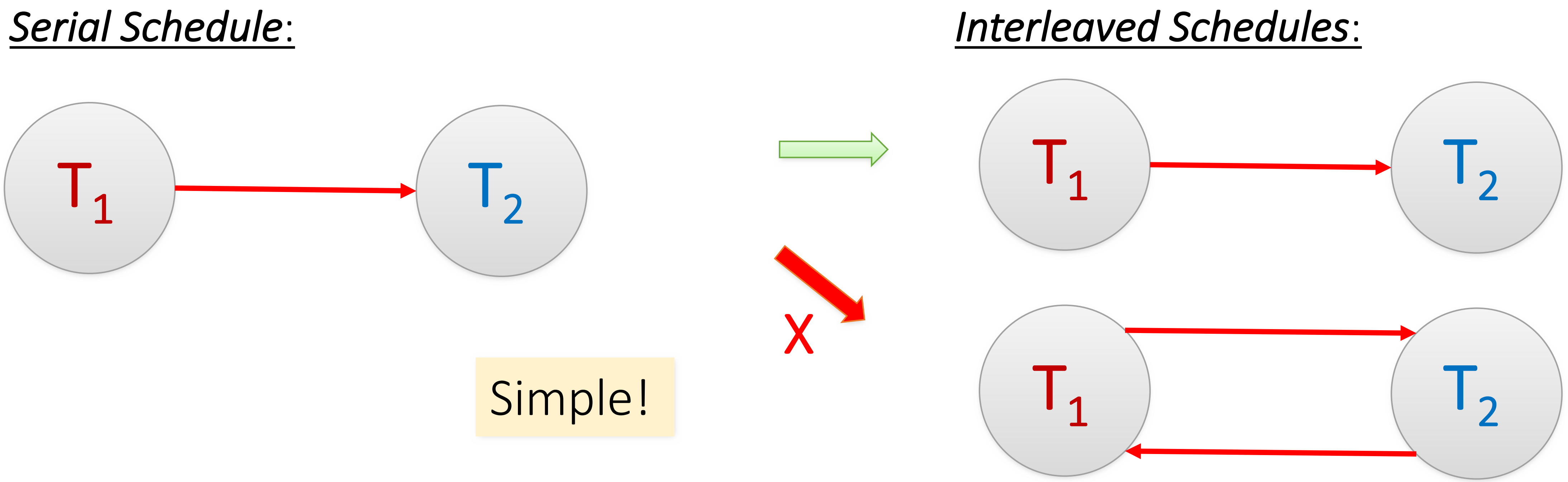


Theorem: Schedule is **conflict serializable** if and only if its conflict graph is **acyclic**

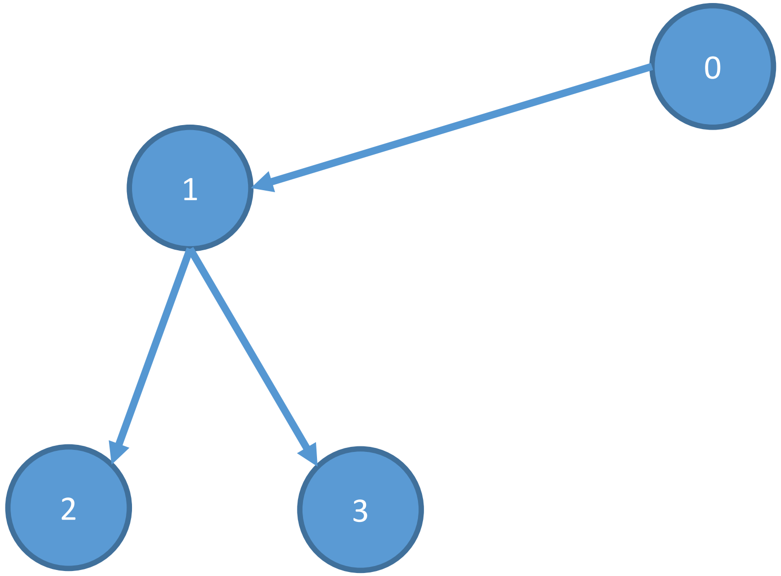
DAGs & Topological Orderings

- 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?



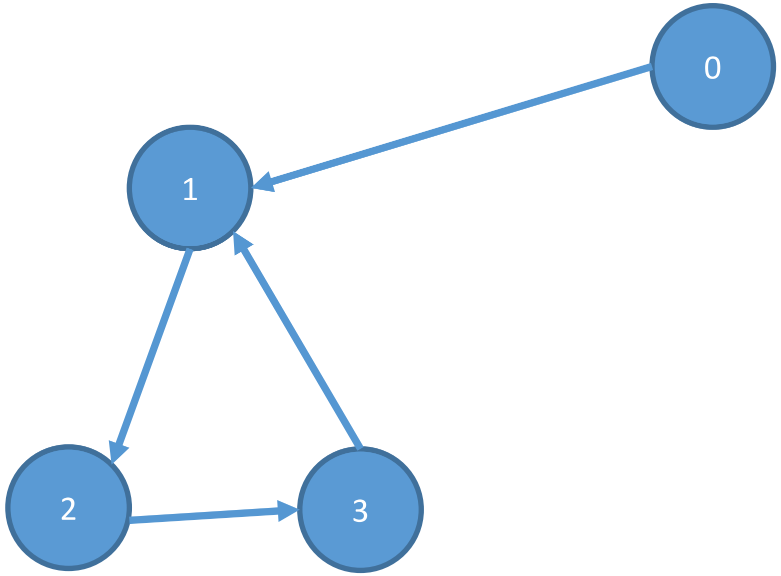
Ex: 0, 1, 2, 3 (or: 0, 1, 3, 2)

0, 1, 2, 3

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 it guarantees conflict serializability (if it completes- see upcoming…)

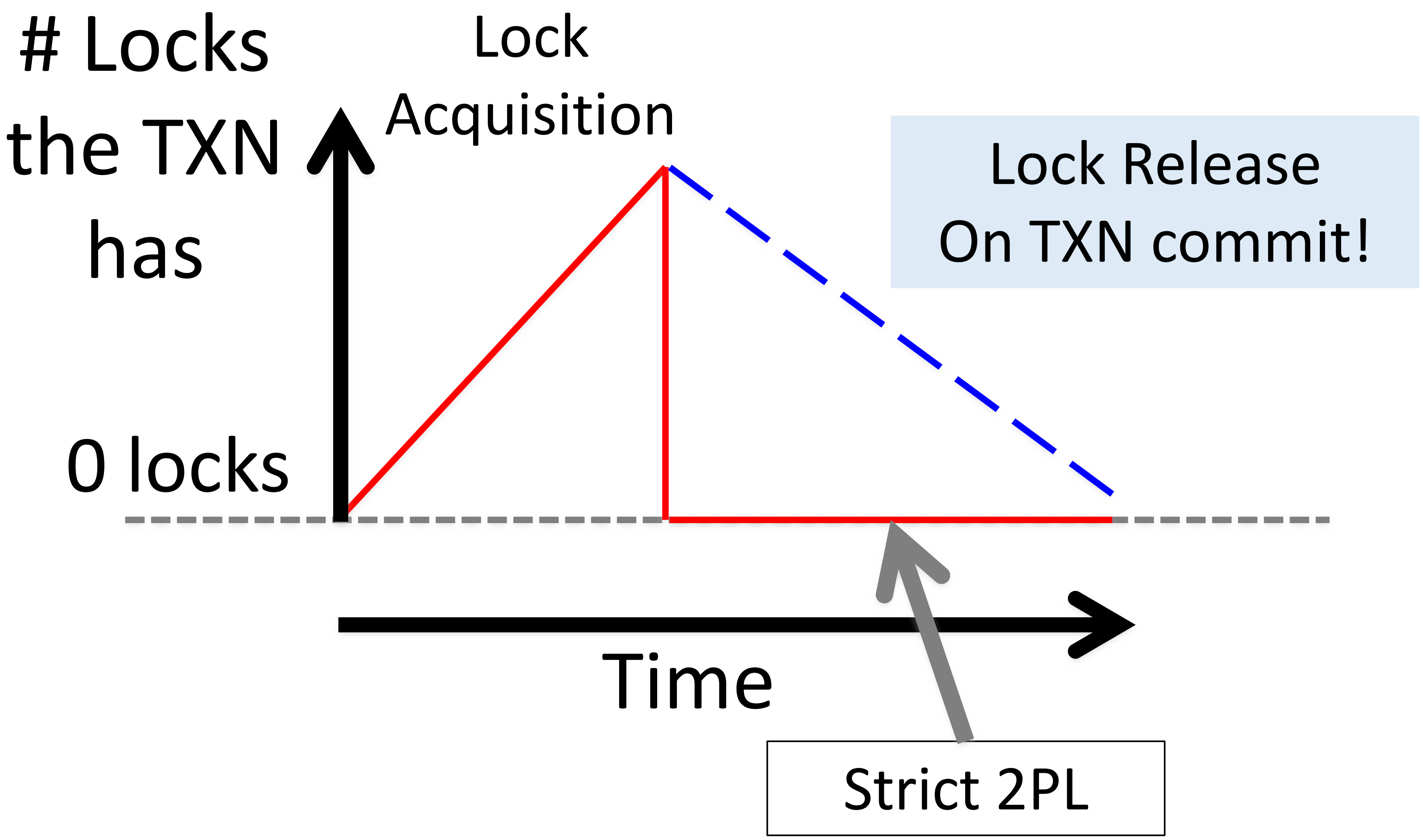
- Also (conceptually) straightforward to implement, and transparent to the user!

Strict Two-Phase Locking (Strict 2PL) Protocol:

- TXNs obtain:
- An <u>X (exclusive) lock</u> on object before <u>writing</u>
  - If a TXN holds, no other TXN can get a lock (S or X) on that object.
- An <u>S (shared) lock</u> on object before <u>reading</u>
  - 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

Theorem: 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 ⇒ 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

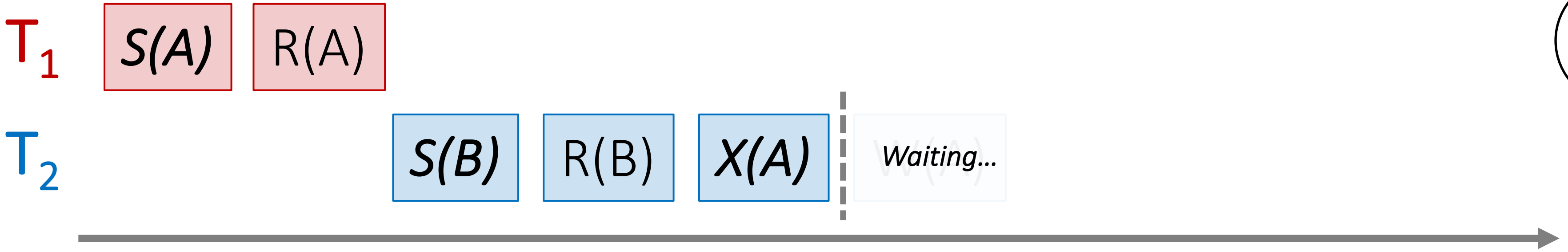
Waits-for graph:

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

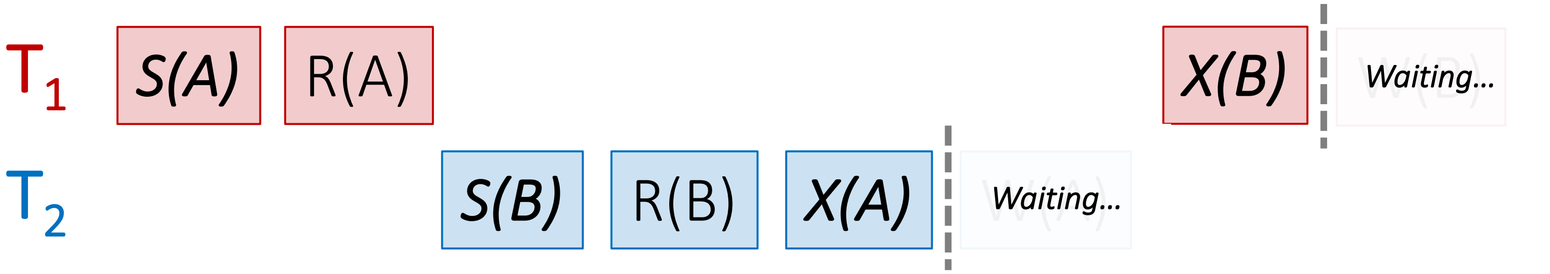
Deadlock Detection: Example



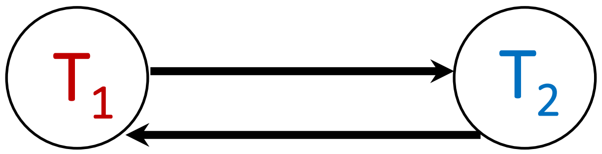
Waits-for graph:

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:



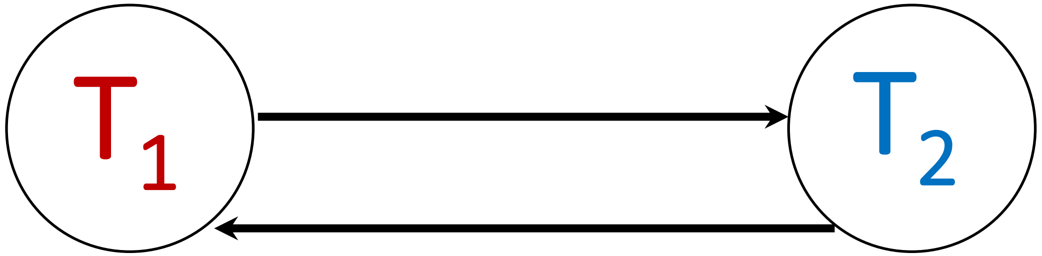
Cycle =
DEADLOCK

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

The problem? 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.
```



Deadlocks

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

- Two ways of dealing with deadlocks:
  - Deadlock prevention
  - 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 <u>interleaving TXNs</u> such that <u>isolation & consistency</u> are maintained
  - We formalized a notion of <u>serializability</u> that captured such a "good" interleaving schedule

- We defined <u>conflict serializability</u>, which implies serializability

- <u>Locking</u> allows only conflict serializable schedules
  - If the schedule completes… (it may deadlock!)