Lectures 7 & 8: Transactions

Goals for this pair of lectures

- **Transactions** are a programming abstraction that enables the DBMS to handle recovery and concurrency for users.

- **Application:** Transactions are critical for users
  - Even casual users of data processing systems!

- **Fundamentals:** The basics of **how** TXNs work
  - Transaction processing is part of the debate around new data processing systems
  - Give you enough information to understand how TXNs work, and the main concerns with using them

If you want to build a TXN engine, CS245 is needed.

Lecture 7: Intro to Transactions & Logging

Today's Lecture

1. Transactions

2. Properties of Transactions: ACID

3. Logging

1. Transactions

What you will learn about in this section

1. Our “model” of the DBMS / computer

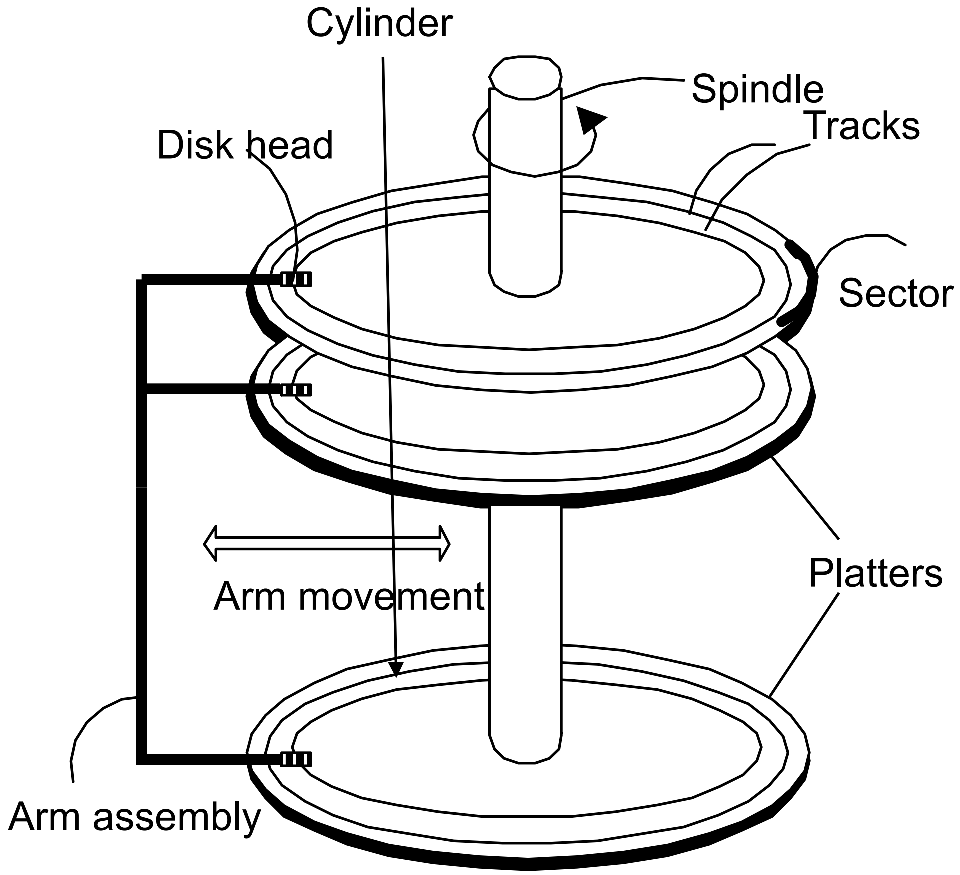
2. Transactions basics

3. Motivation: Recovery & Durability

4. Motivation: Concurrency *[next lecture]*

High-level: Disk vs. Main Memory

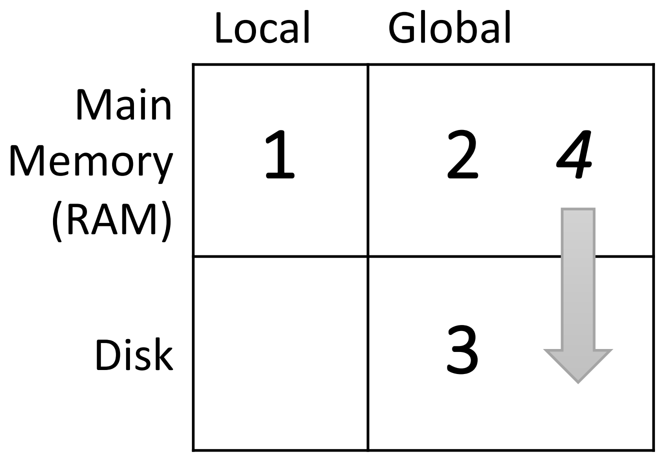
- **Disk**:
  - *Slow*
    - Sequential access
      - (although fast sequential reads)
  - *Durable*
    - We will assume that once on disk, data is safe!
  - Cheap



High-level: Disk vs. Main Memory

- Random Access Memory (RAM) or **Main Memory**:
  - *Fast*
    - Random access, byte addressable
      - ~10x faster for <u>sequential access</u>
      - ~100,000x faster for <u>random access!</u>
  - *Volatile*
    - Data can be lost if e.g. crash occurs, power goes out, etc!
  - Expensive
    - For $100, get 16GB of RAM vs. 2TB of disk!

Our model: 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

"<u>Flushing</u> to disk" = writing to disk + erasing ("evicting") from main memory

High-level: Disk vs. Main Memory

- Keep in mind the tradeoffs here as motivation for the mechanisms we introduce
  - Main memory: fast but limited capacity, volatile
  - Vs. Disk: slow but large capacity, durable

How do we effectively utilize ***both*** ensuring certain critical guarantees?

Transactions

Transactions: Basic Definition

A <u>**transaction ("TXN")**</u> is a sequence of one or more ***operations*** (reads or writes) which reflects ***a single real-world transition***.

In the real world, a TXN either happened completely or not at all

```
START TRANSACTION
      UPDATE Product
      SET Price = Price – 1.99
      WHERE pname = 'Gizmo'
COMMIT
```

Transactions: Basic Definition

A **transaction ("TXN")** is a sequence of one or more ***operations*** (reads or writes) which reflects ***a single real-world transition***.

In the real world, a TXN either happened completely or not at all

Examples:

- Transfer money between accounts
- Purchase a group of products
- Register for a class (either waitlist or allocated)

Transactions in SQL

- In "ad-hoc" SQL:
  - Default: each statement = one transaction

- In a program, multiple statements can be grouped together as a transaction:

```
START TRANSACTION
     UPDATE Bank SET amount = amount – 100
     WHERE name = 'Bob'
     UPDATE Bank SET amount = amount + 100
     WHERE name = 'Joe'
COMMIT
```

Model of Transaction for CS 145

Note: For 145, we assume that the DBMS *only* sees reads and writes to data

- User may do much more
- In real systems, databases do have more info...

Motivation for Transactions

Grouping user actions (reads & writes) into coherent *transactions* helps with two goals:

1. **Recovery & Durability**: Keeping the DBMS data consistent and durable in the face of crashes, aborts, system shutdowns, etc.

This lecture!

2. **Concurrency:** Achieving better performance by parallelizing TXNs *without* creating anomalies

Next lecture

Motivation

1. Recovery & Durability of user data is essential for reliable DBMS usage

- The DBMS may experience crashes (e.g. power outages, etc.)
- Individual TXNs may be aborted (e.g. by the user)

Idea: Make sure that TXNs are either **durably stored in full**, **or not at all**; keep log to be able to “roll-back” TXNs

Protection against crashes / aborts

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

    DELETE Product
        WHERE price <=0.99
```

Crash / abort!

What goes wrong?

Protection against crashes / aborts

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

          DELETE Product
               WHERE price <=0.99
     COMMIT OR ROLLBACK
```

Now we'd be fine! We'll see how / why this lecture

Motivation

2. Concurrent execution of user programs is essential for good DBMS performance.

- Disk accesses may be frequent and **slow**- optimize for throughput (# of TXNs), trade for latency (time for any one TXN)

- Users should still be able to execute TXNs as if in **isolation** and such that **consistency** is maintained

Idea: Have the DBMS handle running several user TXNs concurrently, in order to keep CPUs humming…

Multiple users: single statements

```
Client 1: UPDATE Product
          SET Price = Price – 1.99
          WHERE pname = ‘Gizmo’

Client 2: UPDATE Product
          SET Price = Price*0.5
          WHERE pname=‘Gizmo’
```

Two managers attempt to discount products *concurrently*-
What could go wrong?

Multiple users: single statements

```
Client 1: START TRANSACTION
                  UPDATE Product
                  SET Price = Price – 1.99
                  WHERE pname = ‘Gizmo’
          COMMIT

Client 2: START TRANSACTION
                  UPDATE Product
                  SET Price = Price*0.5
                  WHERE pname=‘Gizmo’
          COMMIT
```

Now works like a charm- we’ll see how / why next lecture…

2. Properties of Transactions

What you will learn about in this section

1. Atomicity
2. Consistency
3. Isolation
4. Durability
5. ACTIVITY?

Transaction Properties: ACID

- Atomic
  - State shows either all the effects of txn, or none of them
- Consistent
  - Txn moves from a state where integrity holds, to another where integrity holds
- Isolated
  - Effect of txns is the same as txns running one after another (ie looks like batch mode)
- Durable
  - Once a txn has committed, its effects remain in the database

ACID is/was source of great debate!

ACID: Atomicity

- TXN's activities are atomic: **all or nothing**
  - Intuitively: in the real world, a transaction is something that would either occur *completely* or *not at all*
- Two possible outcomes for a TXN
  - It *commits*: all the changes are made
  - It *aborts*: no changes are made

ACID: Consistency

- The tables must always satisfy user-specified ***integrity constraints***
  - *Examples:*
    - Account number is unique
    - Stock amount can't be negative
    - Sum of *debits* and of *credits* is 0

- How consistency is achieved:
  - Programmer makes sure a txn takes a consistent state to a consistent state
  - *System* makes sure that the txn is **atomic**

ACID: Isolation

- A transaction executes concurrently with other transactions
- **Isolation**: the effect is as if each transaction executes in *isolation* of the others.
    - E.g. Should not be able to observe changes from other transactions during the run

ACID: Durability

- The effect of a TXN must continue to exist (***"persist"***) after the TXN
  - And after the whole program has terminated
  - And even if there are power failures, crashes, etc.
  - And etc…

- Means: Write data to **disk**

Change on the horizon?
Non-Volatile Ram (NVRam).
Byte addressable.

Challenges for ACID properties

- In spite of failures: Power failures, but not media failures

This lecture

- Users may abort the program: need to “rollback the changes”
  - Need to *log* what happened

- Many users executing concurrently
  - Can be solved via locking (we’ll see this next lecture!)

Next lecture

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…

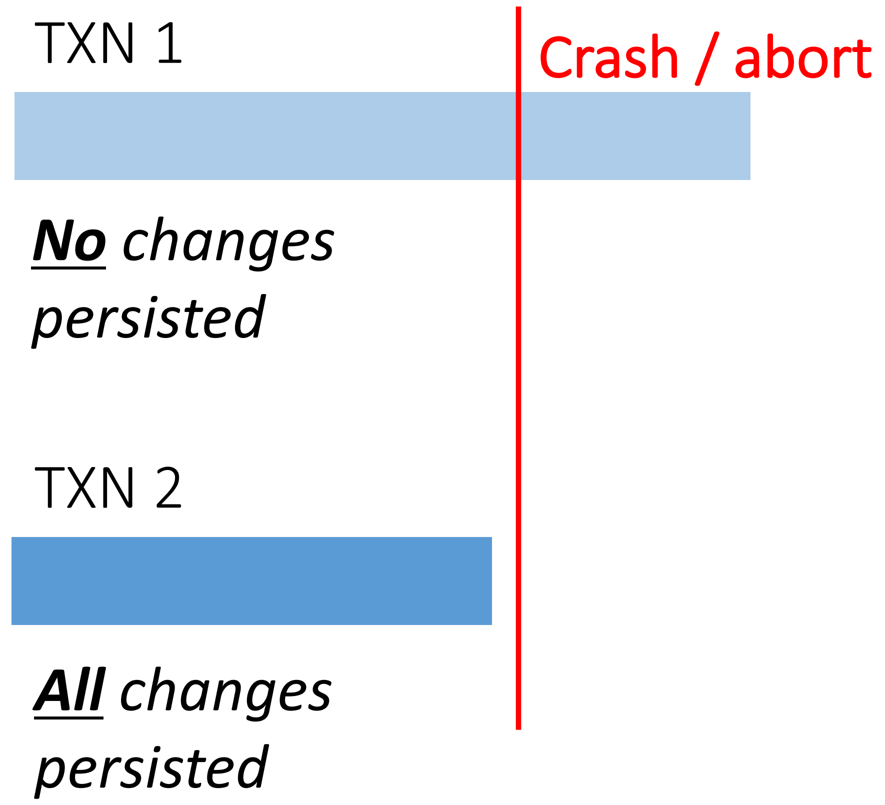
ACID is an extremely important & successful paradigm, but still debated!

Goal for this lecture: 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.
- Can **force write** entries to disk
  - A page goes to disk.
- All log activities ***handled transparently*** the DBMS.

Assume we don’t lose it!

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 ordered list of actions**
  - 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

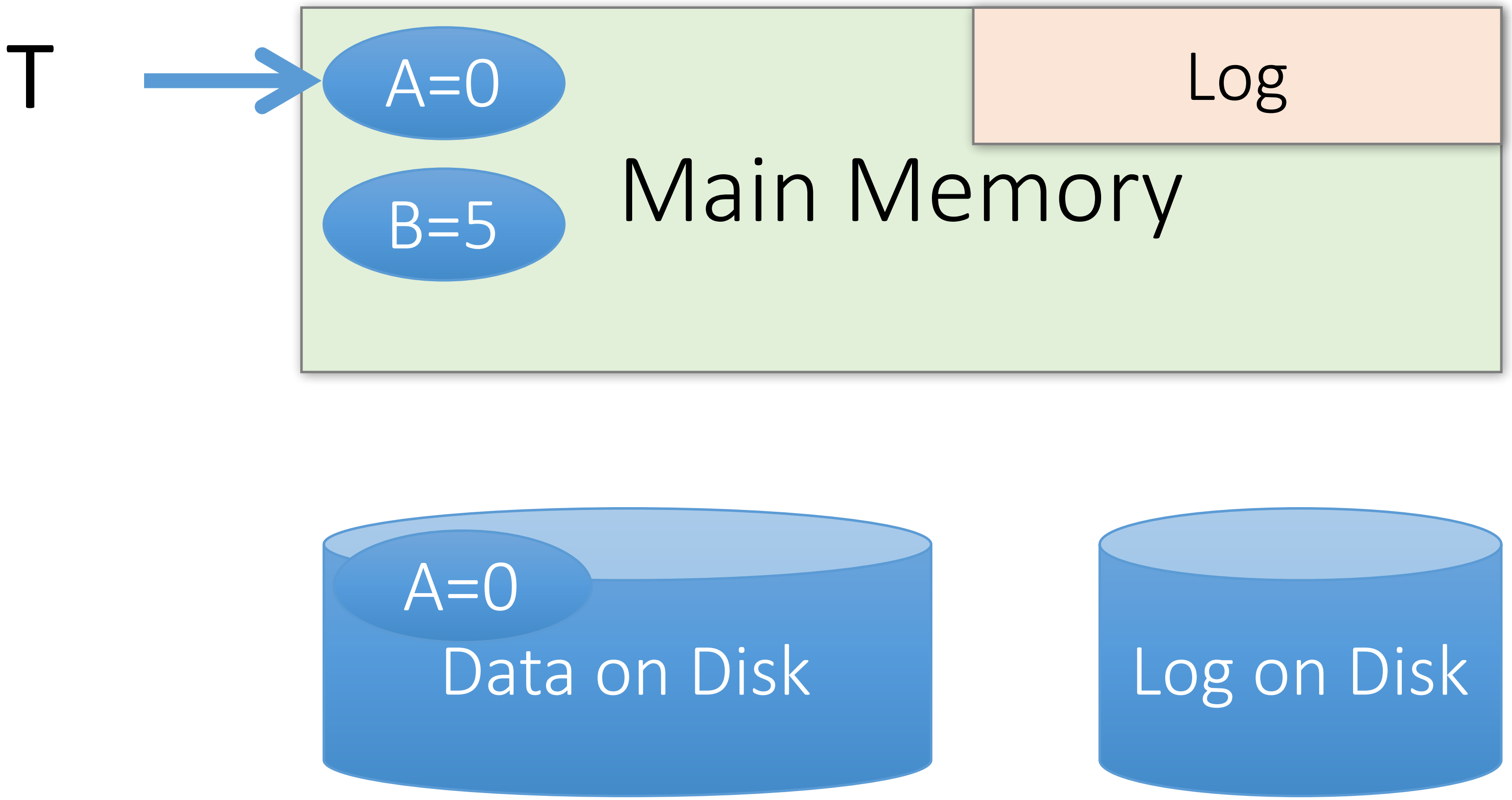
What you will learn about in this section

1. Logging: An animation of commit protocols

A Picture of Logging

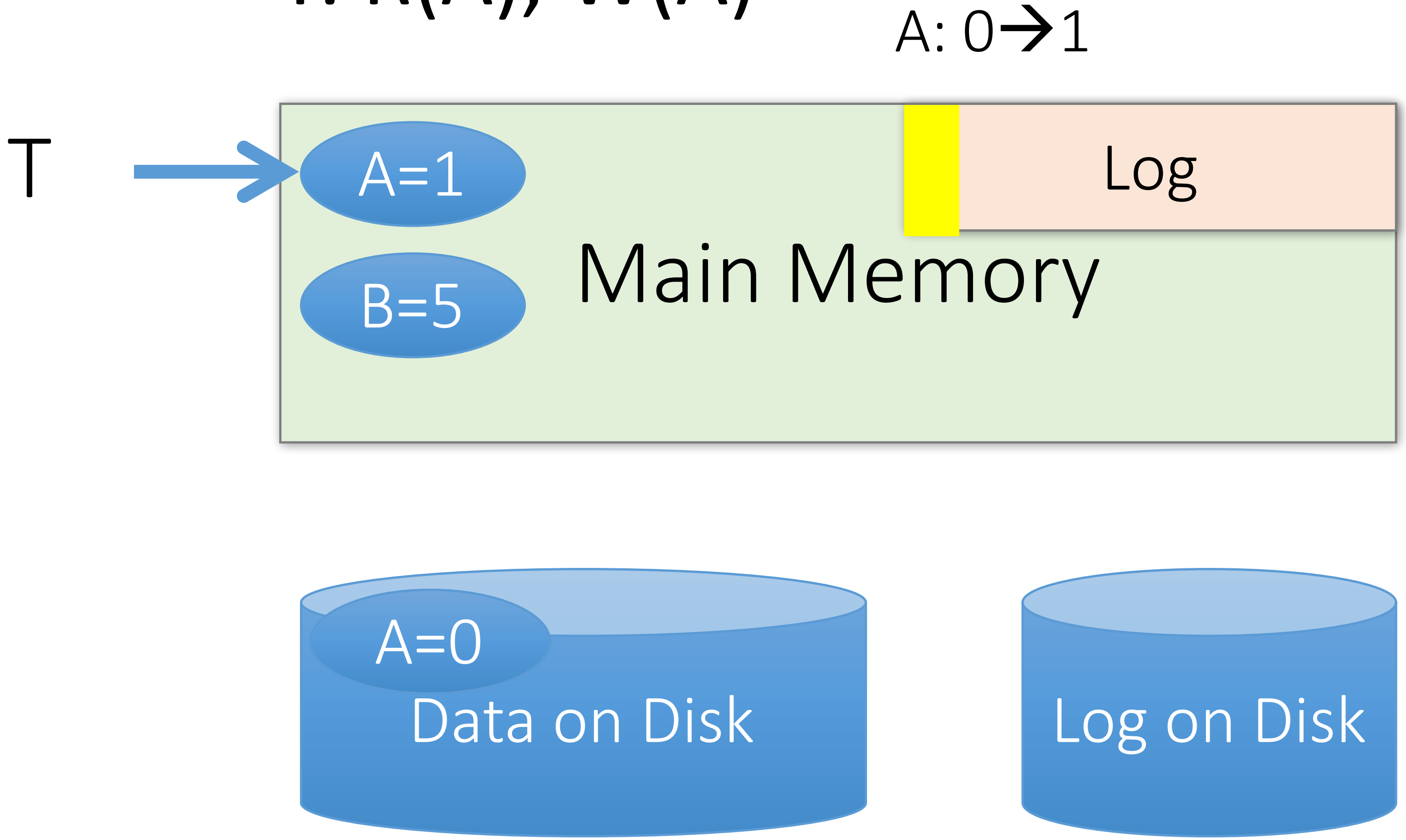
A picture of logging

T: R(A), W(A)



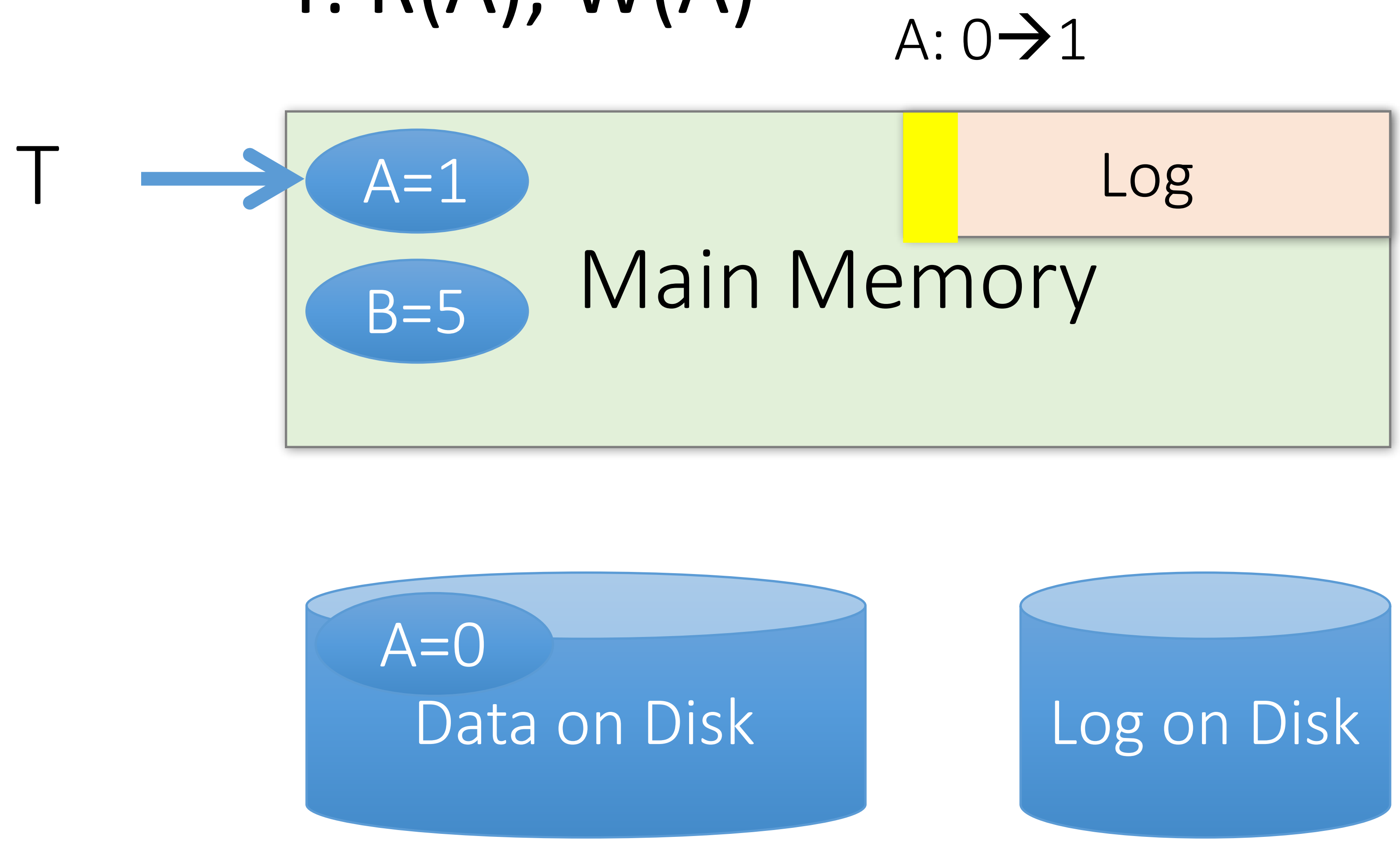
A picture of logging

T: R(A), W(A)



A picture of logging

T: R(A), W(A)



Operation recorded in log in main memory!

NB: Logging can happen after modification, but not before disk!

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

1. FORCE Write **commit** record to log

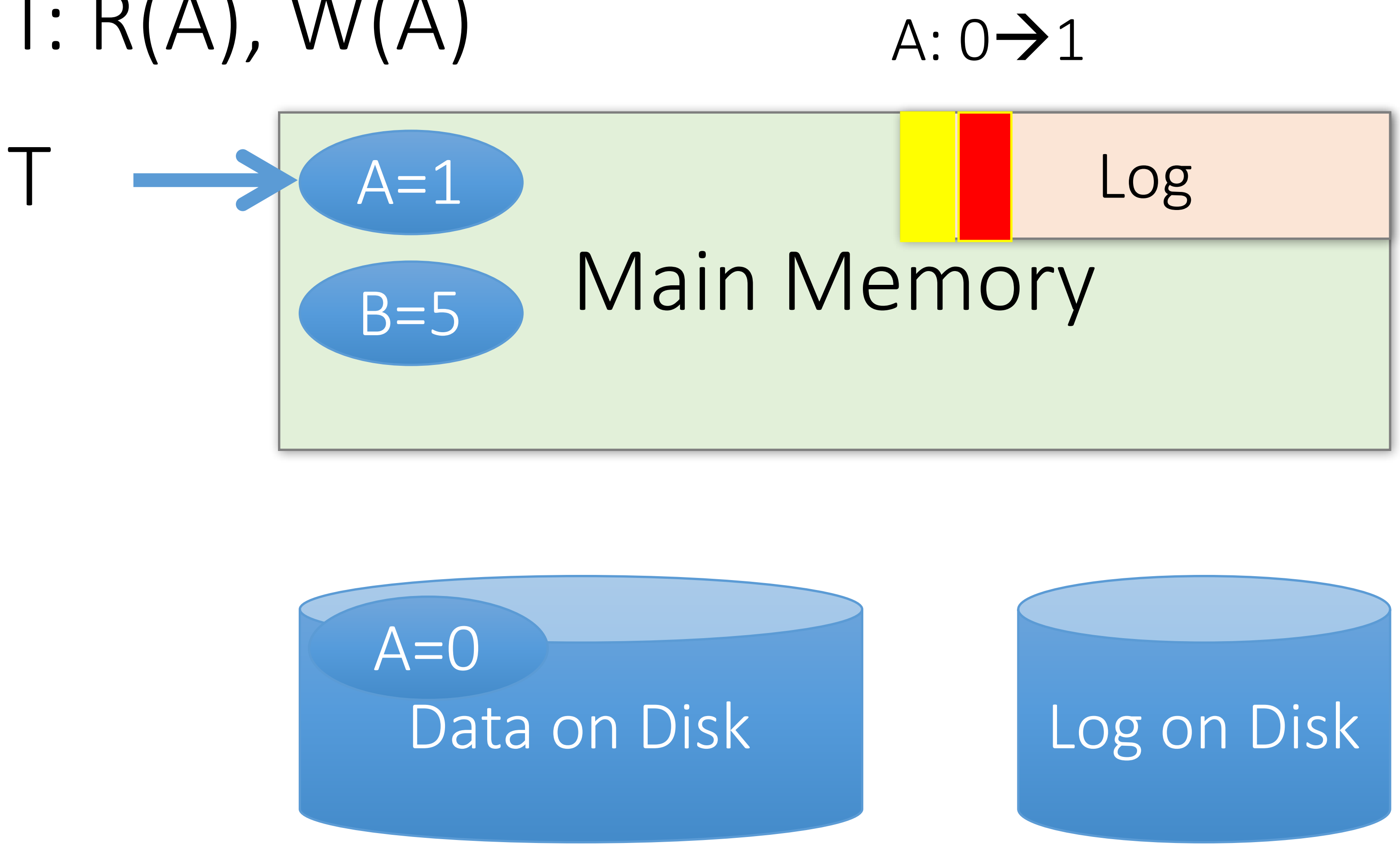
2. All log records up to last update from this TX are FORCED

3. 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!

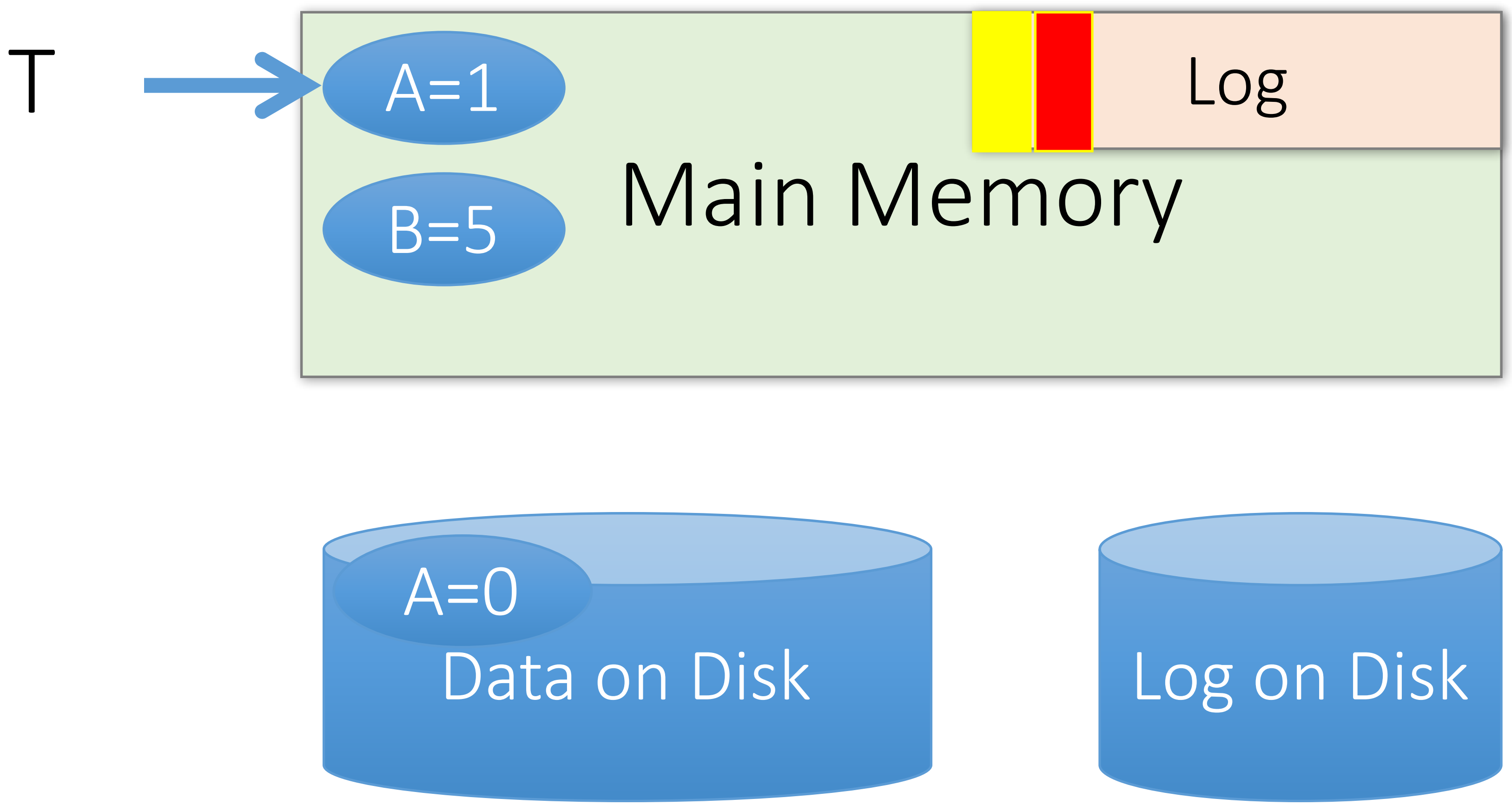
If we crash now, is T durable?

Lost T's update!

Incorrect Commit Protocol #2

T: R(A), W(A)

A: 0→1



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

OK, Commit!

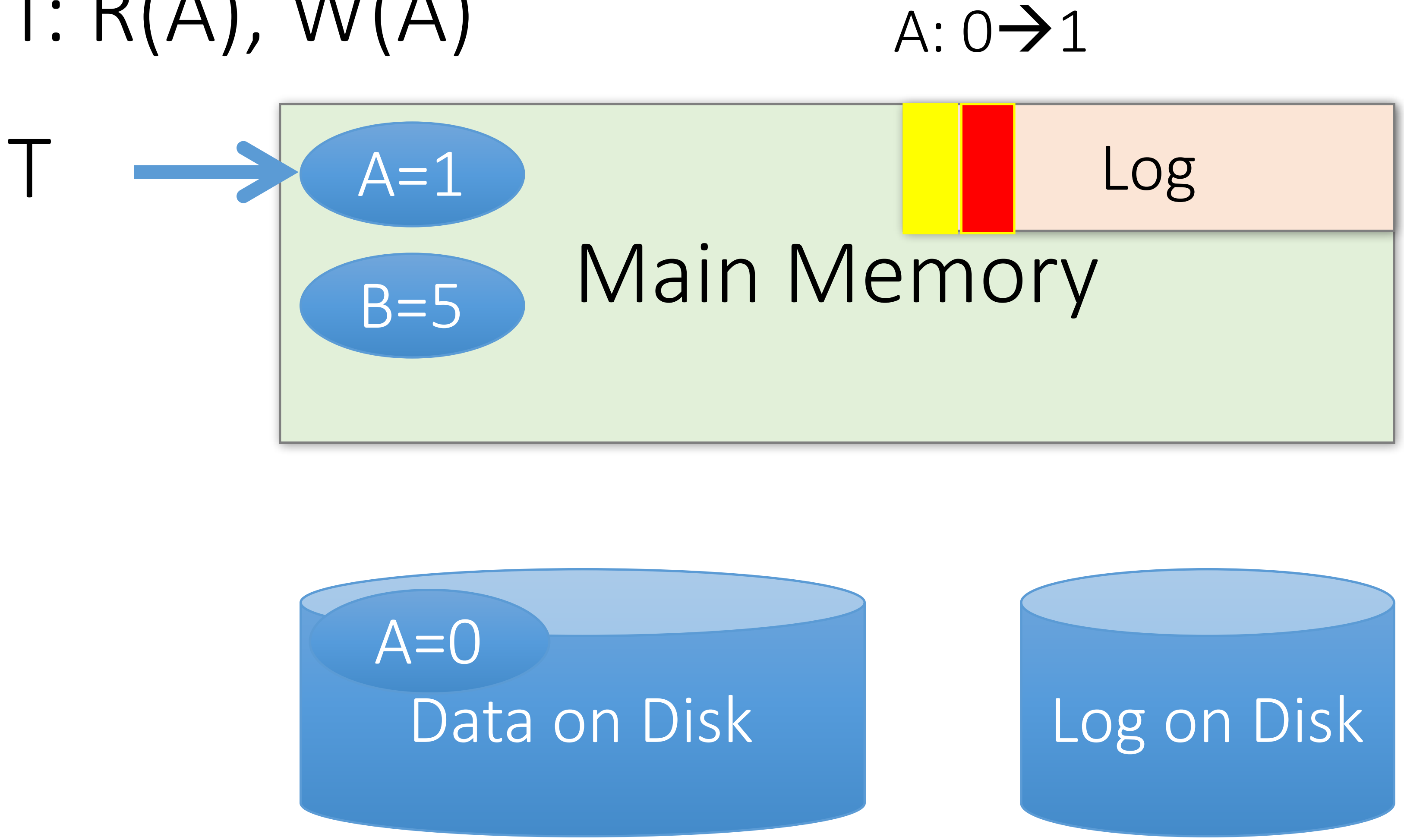
If we crash now, is T durable? Yes! Except…

How do we know whether T was committed??

Improved Commit Protocol (WAL)

Write-ahead Logging (WAL) Commit Protocol

T: R(A), W(A)



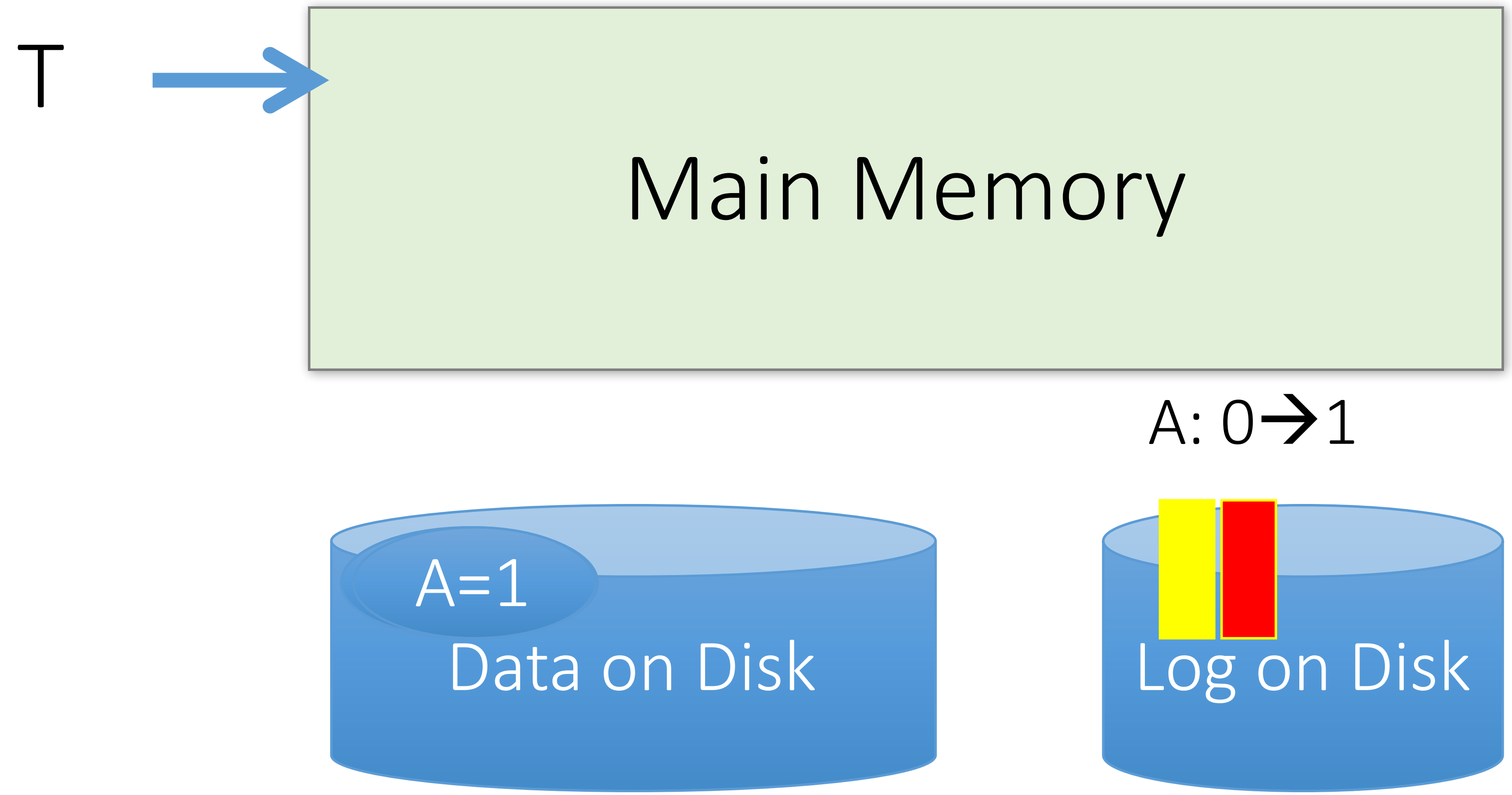
This time, let's try committing ***after* we've written log to disk but** ***before* we've written data to disk**… this is WAL!

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…

Lecture 8: Concurrency & Locking

Today's Lecture

1. Concurrency, scheduling & anomalies

2. Locking: 2PL, conflict serializability, deadlock detection

1. Concurrency, Scheduling & Anomalies

What you will learn about in this section

1. Interleaving & scheduling
2. Conflict & anomaly types
3. ACTIVITY: TXN viewer

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

Note the hard part…

…is the effect of *interleaving* transactions and *crashes*.
See 245 for the gory details!

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
```

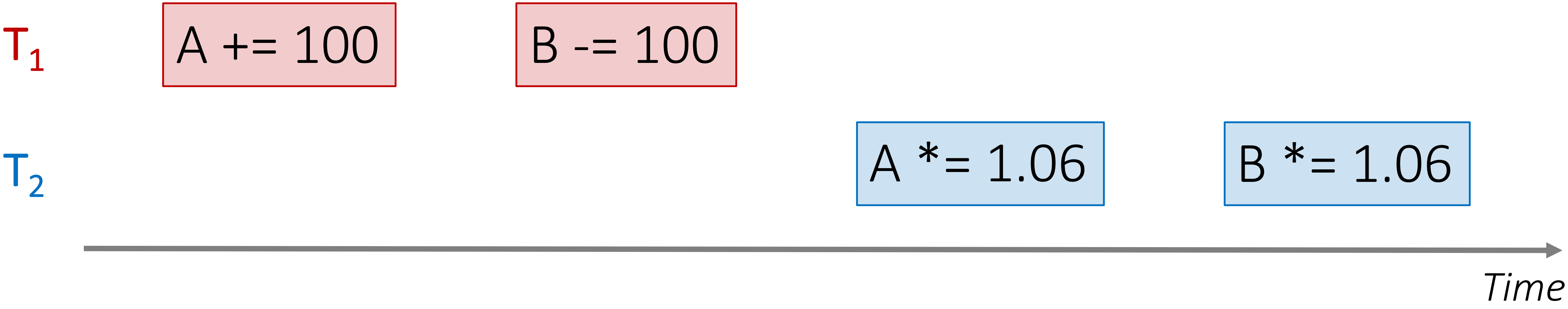
```
T2: START TRANSACTION
     UPDATE Accounts
     SET Amt = Amt * 1.06
COMMIT
```

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

T2 credits both accounts with a 6% interest payment

Example- consider two TXNs:

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

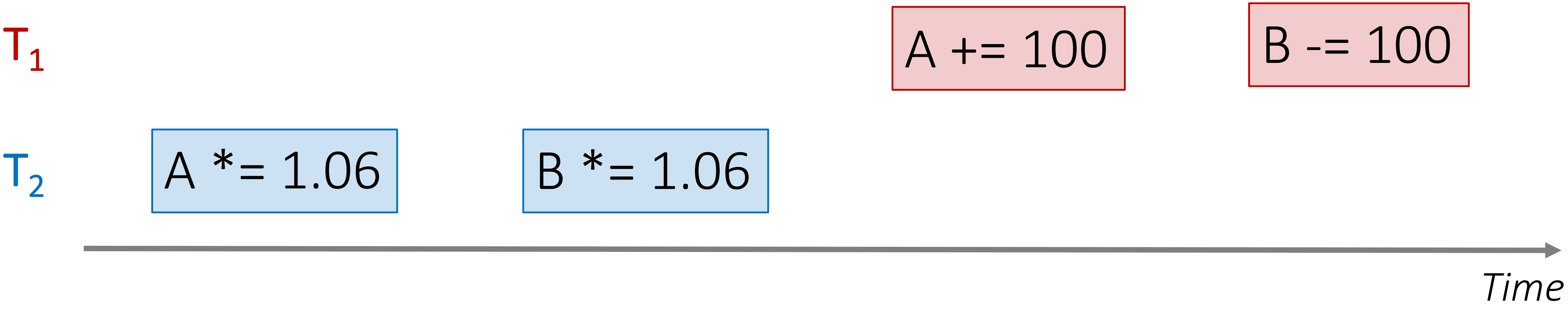


T1 transfers $100 from B's account to A's account

T2 credits both accounts with a 6% interest payment

Example- consider two TXNs:

The TXNs could occur in either order… DBMS allows!

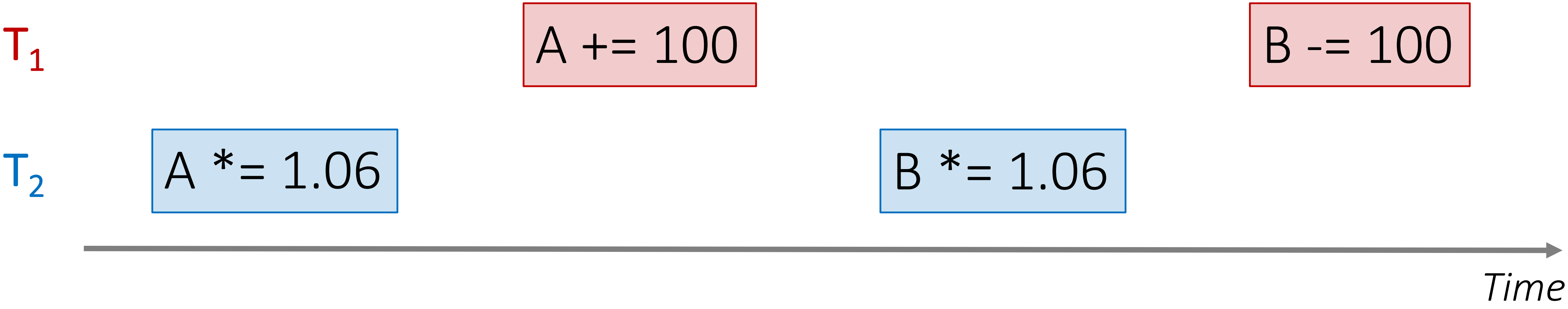


T2 credits both accounts with a 6% interest payment

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

Example- consider two TXNs:

The DBMS can also **interleave** the TXNs

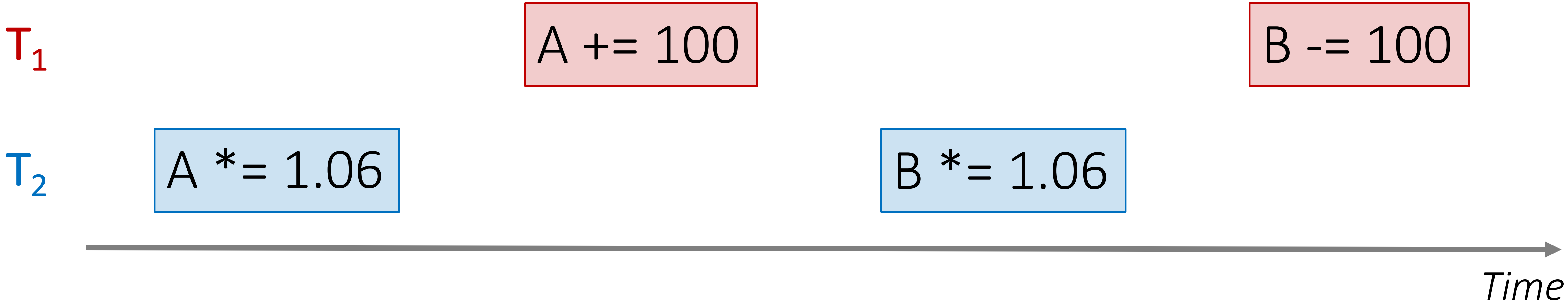


T2 credits A's account with 6% interest payment, then T1 transfers $100 to A's account…

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

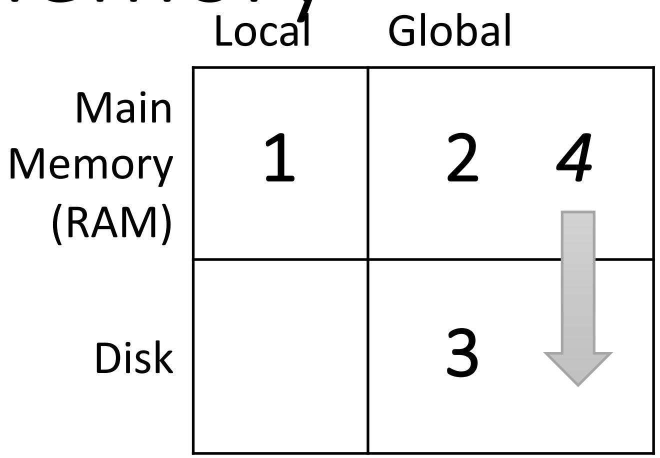
Example- consider two TXNs:

The DBMS can also **interleave** the TXNs



What goes / could go wrong here??

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

"<u>**Flushing**</u> to disk" = writing to disk + erasing ("evicting") 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 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

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 B:

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

Different result than serial T_2, T_1 ALSO!

Interleaved schedule B:

T_1 A += 100 | B -= 100

T_2 A *= 1.06 | B *= 1.06

A	B
$159	$112

Scheduling examples

Interleaved schedule B:

T_1 | A += 100 | B -= 100

T_2 | A *= 1.06 | B *= 1.06

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

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?

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

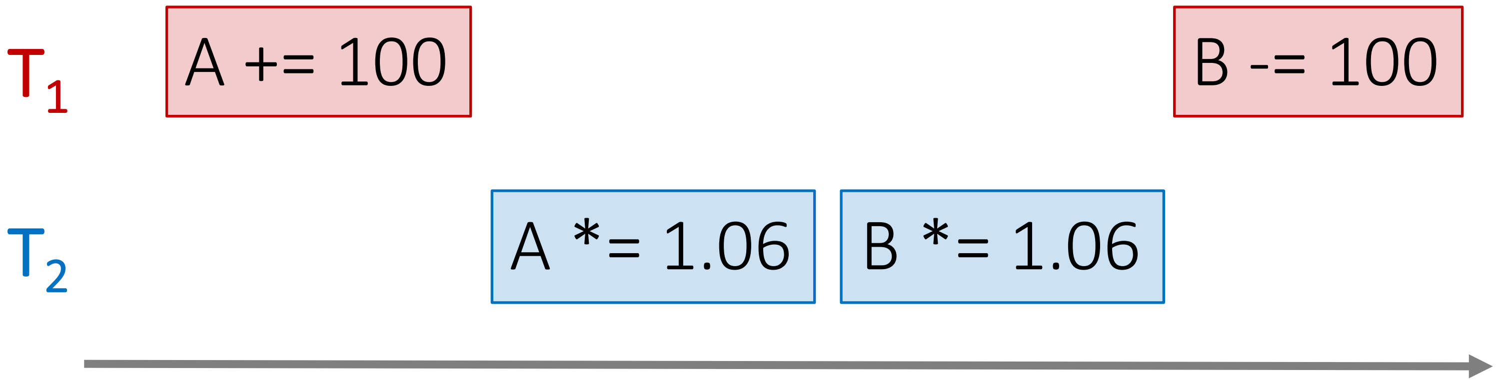
T_1 A += 100 B -= 100

T_2 A *= 1.06 B *= 1.06

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?



<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

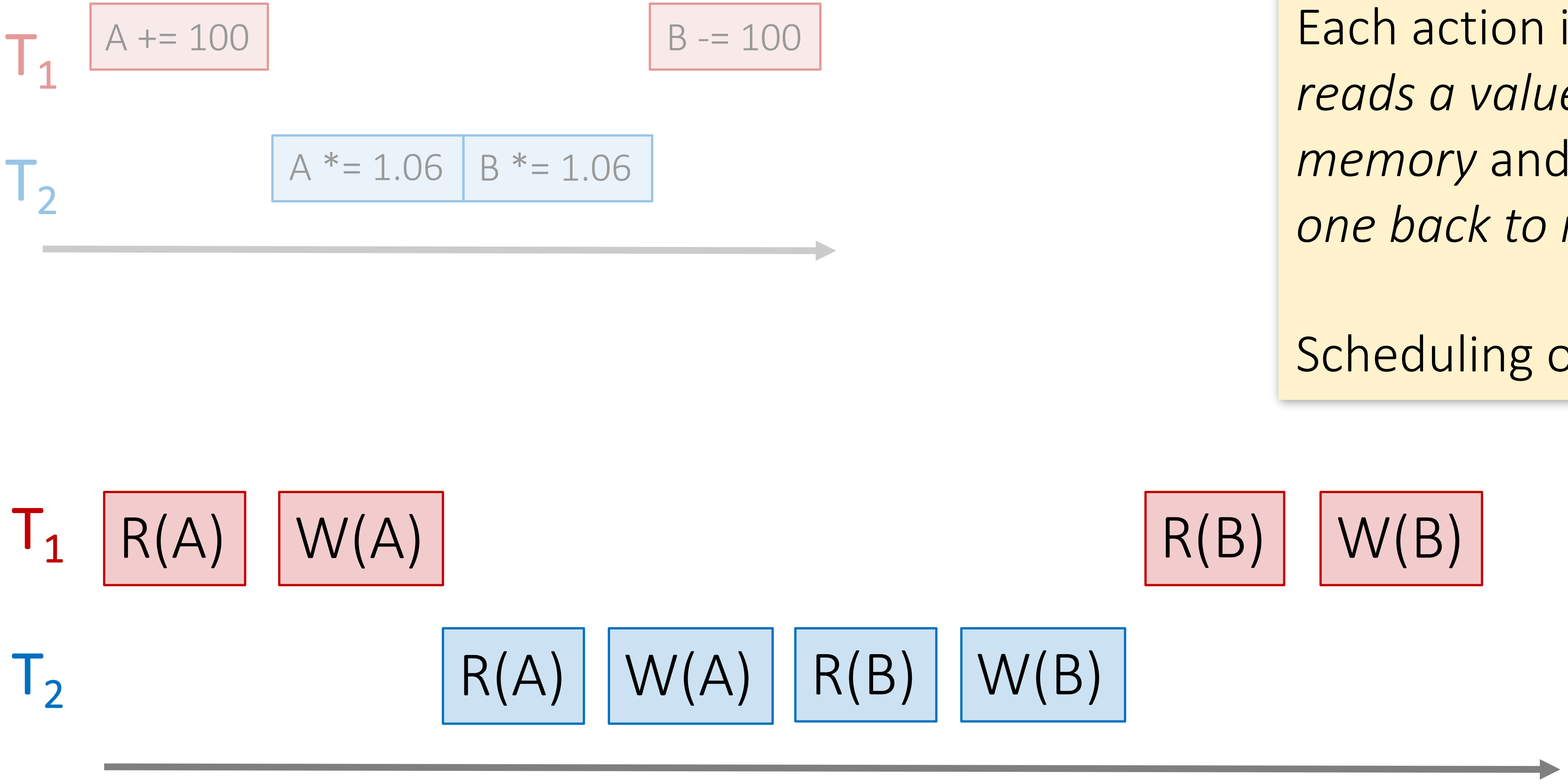
A	B
1.06*(A+100)	1.06*B - 100

Not *equivalent* to any serializable schedule = ***not*** **<u>serializable</u>**

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 <u>**conflict**</u> 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"?

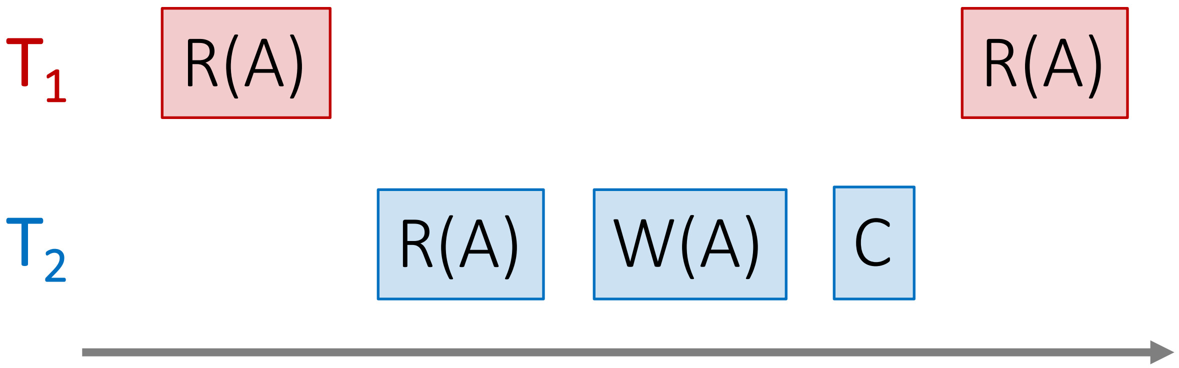
Interleaving anomalies occur with / because of these conflicts between TXNs *(but these conflicts can occur without causing anomalies!)*

See next section for more!

Classic Anomalies with Interleaved Execution

"Unrepeatable read":

Example:



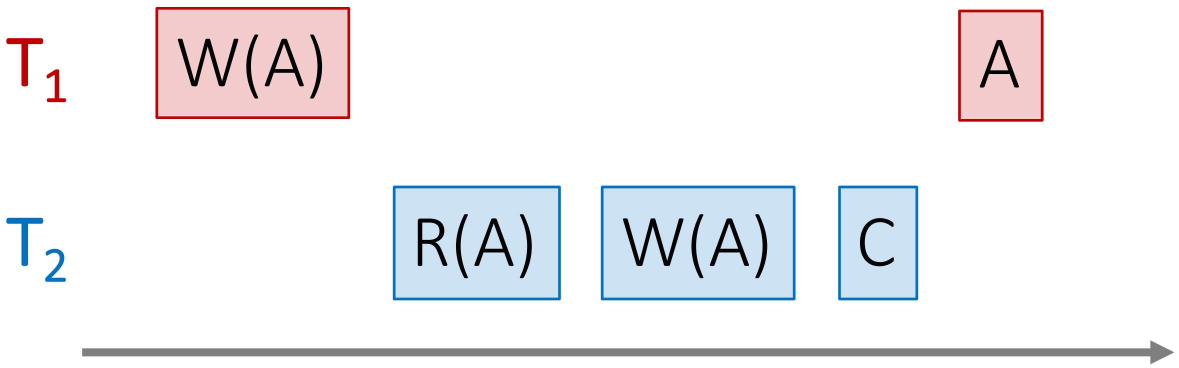
1. T_1 <u>reads</u> some data from A
2. T_2 <u>writes</u> to A
3. Then, T_1 reads from A again *and now gets a different / inconsistent value*

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

Classic Anomalies with Interleaved Execution

"Dirty read" / Reading uncommitted data:

Example:



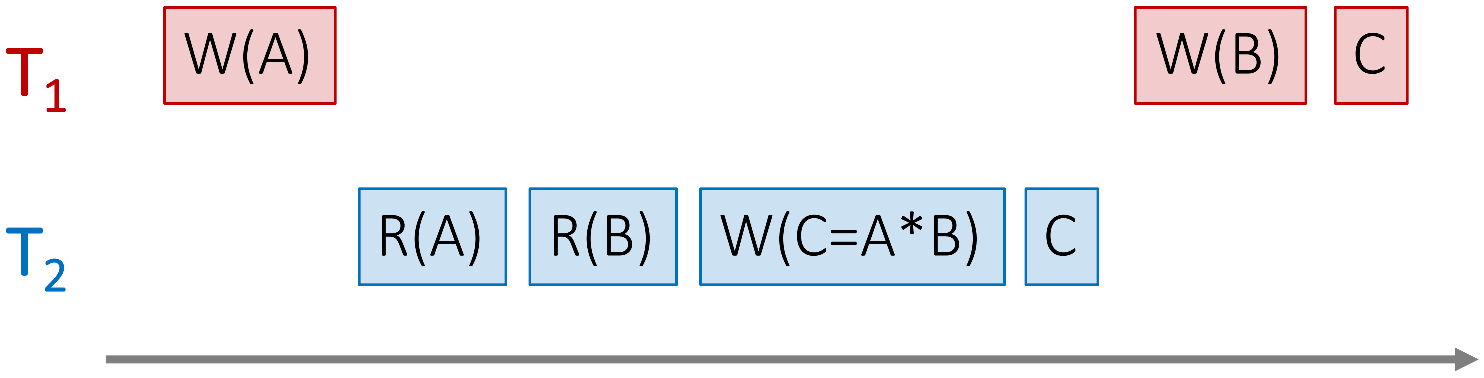
1. T_1 <u>writes</u> some data to A
2. T_2 <u>reads</u> from A, then writes back to A & commits
3. T_1 then aborts- *now T_2's result is based on an obsolete / inconsistent value*

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

Classic Anomalies with Interleaved Execution

"Inconsistent read" / Reading partial commits:

Example:



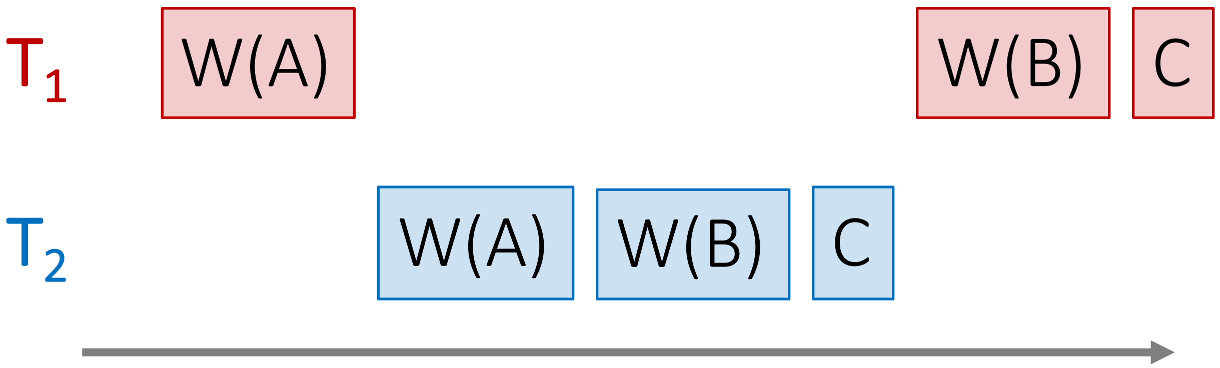
1. T_1 writes some data to A
2. T_2 reads from A *and B*, and then writes some value which depends on A & B
3. T_1 then writes to B- *now T_2's result is based on an incomplete commit*

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

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 with / because of a **WW conflict***

Activity-8-1.ipynb

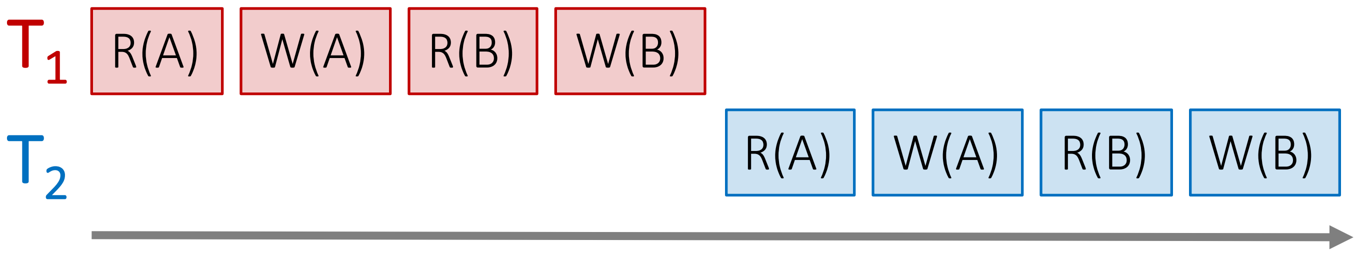
2. Conflict Serializability, Locking & Deadlock

What you will learn about in this section

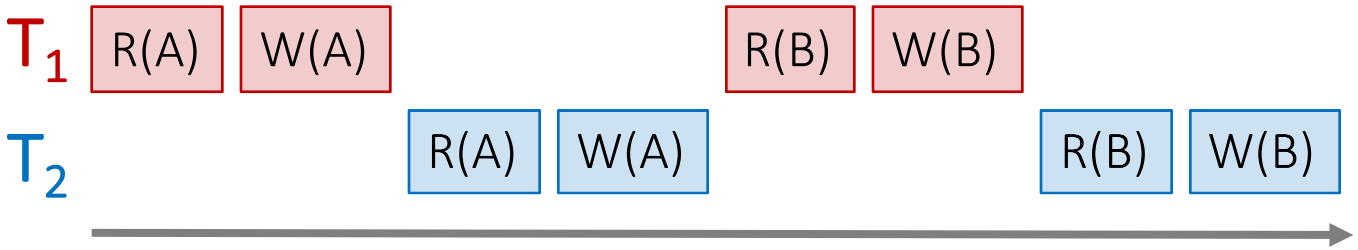
1. RECAP: Concurrency
2. Conflict Serializability
3. DAGs & Topological Orderings
4. Strict 2PL
5. Deadlocks

Recall: Concurrency as Interleaving TXNs

Serial Schedule:



Interleaved Schedule:

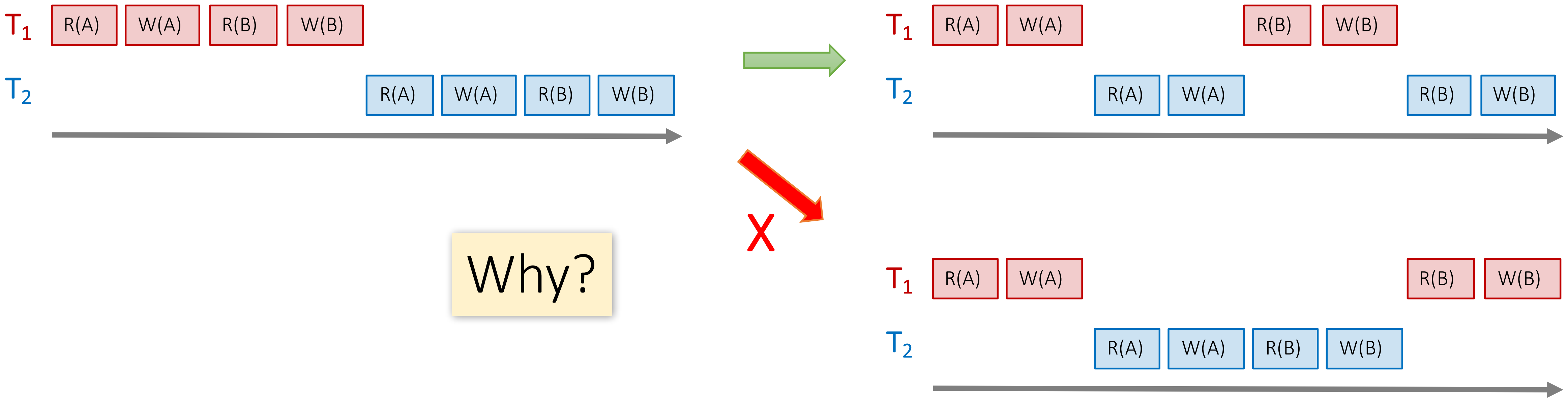


- For our purposes, having TXNs occur concurrently means **interleaving their component actions (R/W)**

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

Recall: “Good” vs. “bad” schedules

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



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

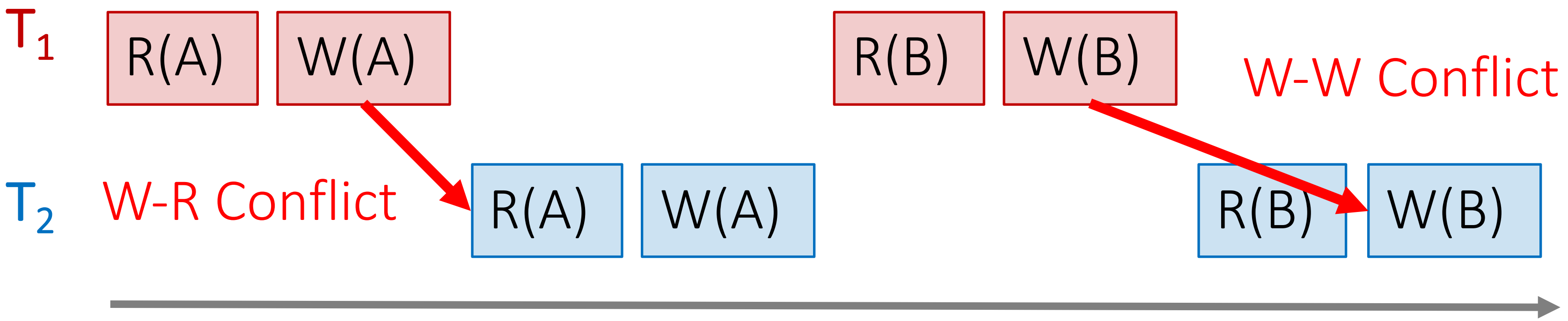
Ways of Defining "Good" vs. "Bad" Schedules

- 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:
    - ***<u>Conflict serializability</u>***

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

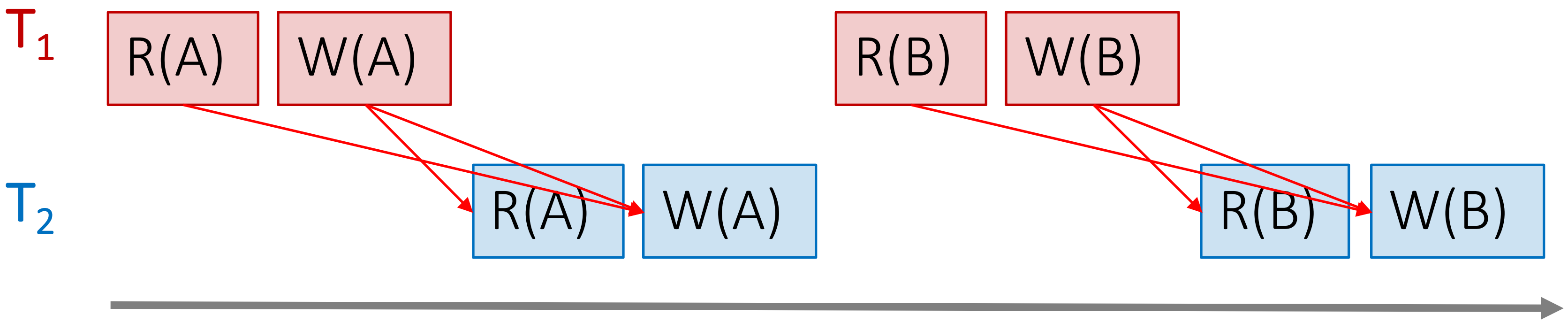
Conflicts

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

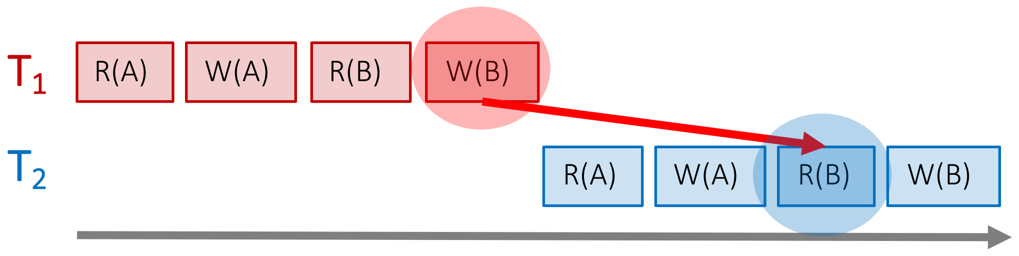
- Two schedules are **conflict equivalent** if:
  - They involve *the same actions of the same TXNs*
  - Every *pair of conflicting actions* of two TXNs are *ordered in the same way*
- Schedule S is **conflict serializable** if S is *conflict equivalent* to some serial schedule

Conflict serializable ⇒ serializable

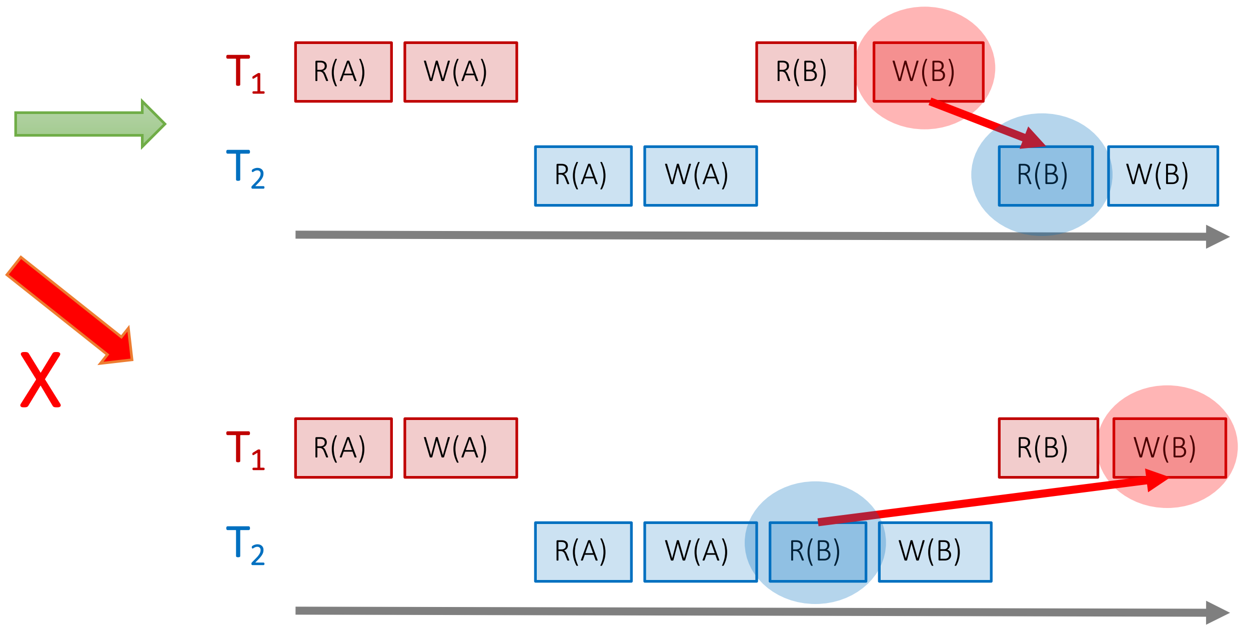
So if we have conflict serializable, we have consistency & isolation!

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

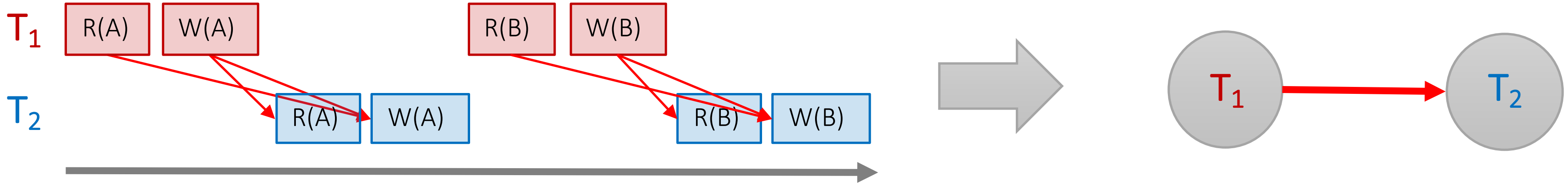
- **Conflicts** are things we talk about to help us characterize different schedules
  - Present in both “good” and “bad” schedules

- **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

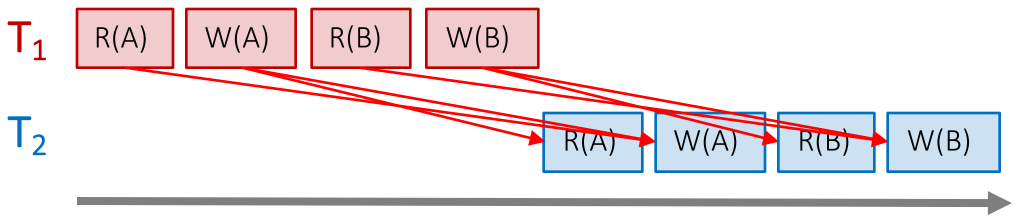
- Let's now consider looking at conflicts **at the TXN level**

- 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**



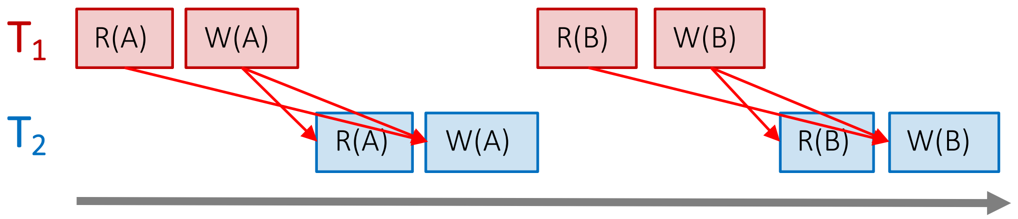
What can we say about “good” vs. “bad” conflict graphs?

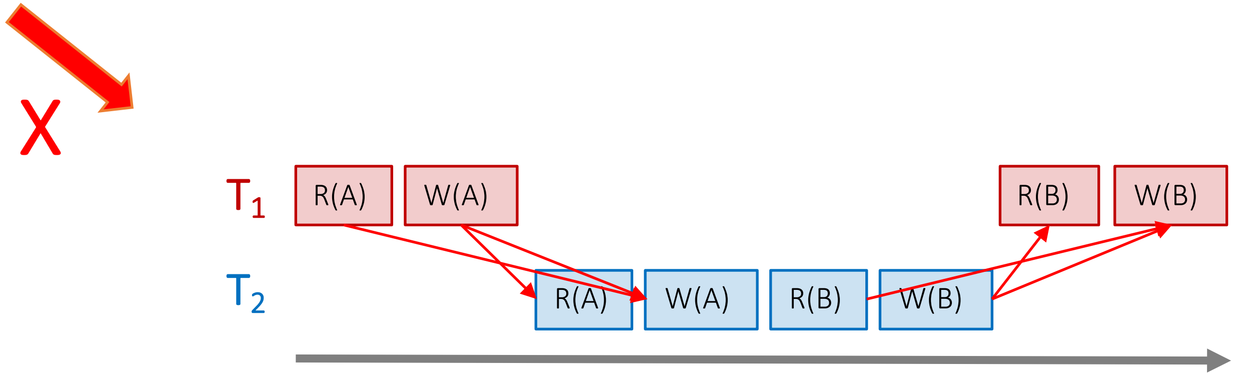
Serial Schedule:



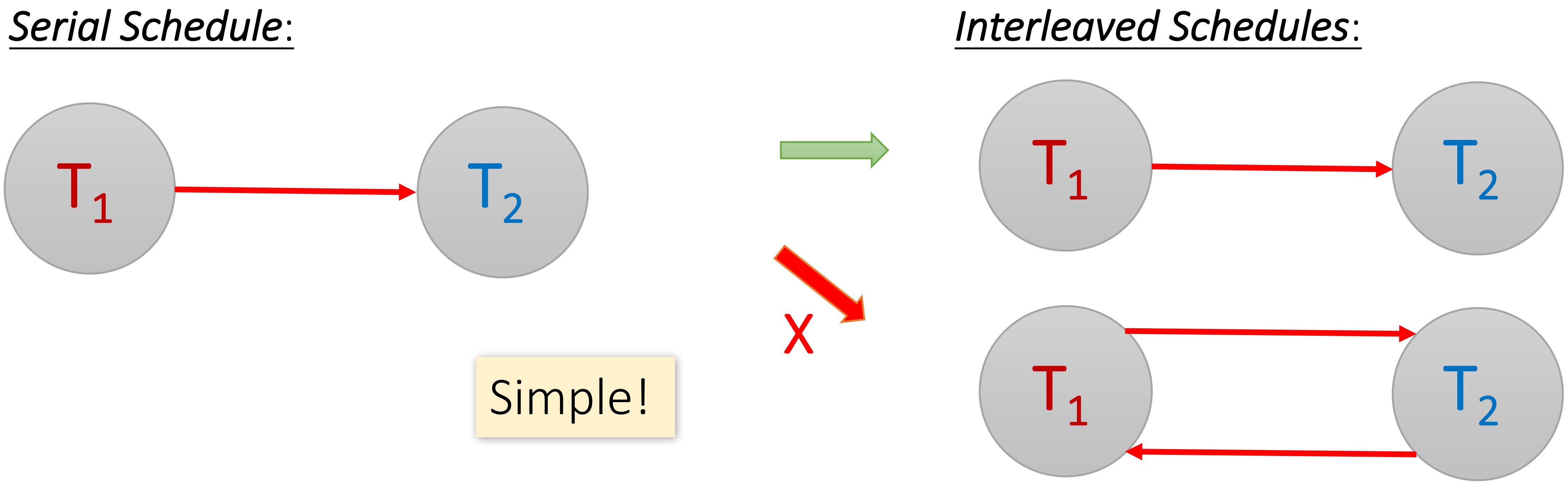
A bit complicated…

Interleaved Schedules:





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



<u>Theorem</u>: Schedule is **conflict serializable** if and only if its conflict graph is **<u>acyclic</u>**

Let’s unpack this notion of acyclic conflict graphs…

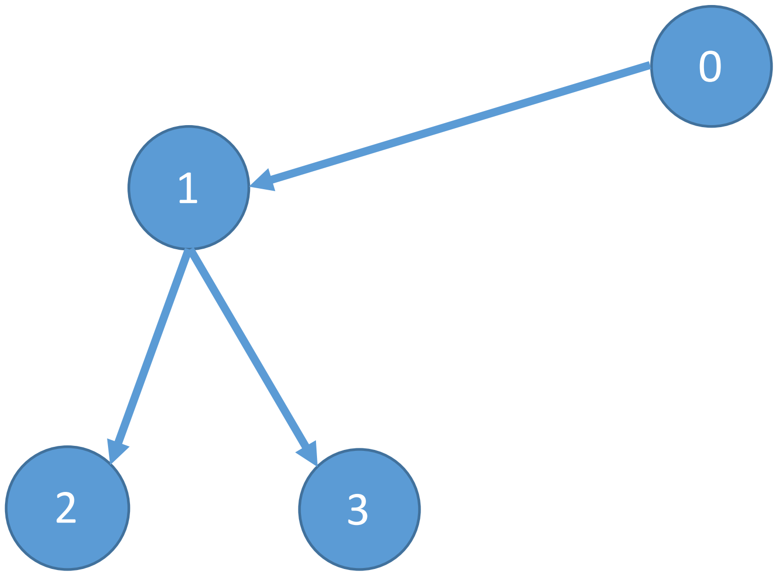
DAGs & Topological Orderings

- 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

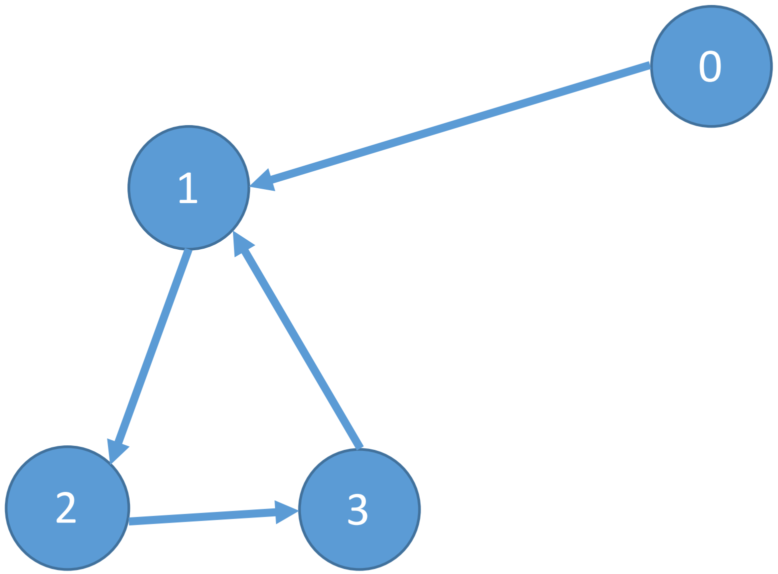
- Ex: What is one possible topological ordering here?



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 $\rightarrow$ 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!

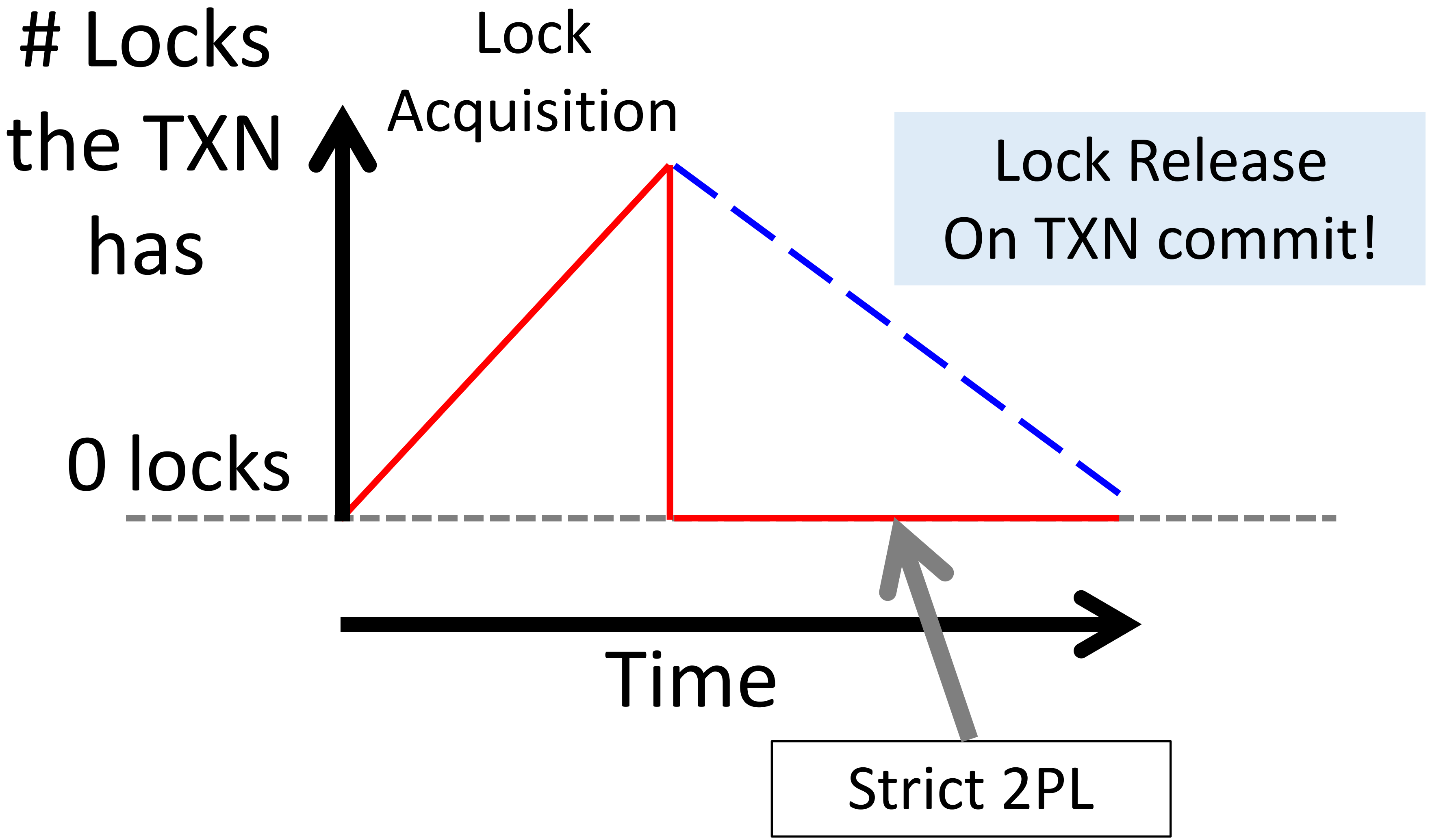
Strict Two-phase Locking (Strict 2PL) Protocol:

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

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:

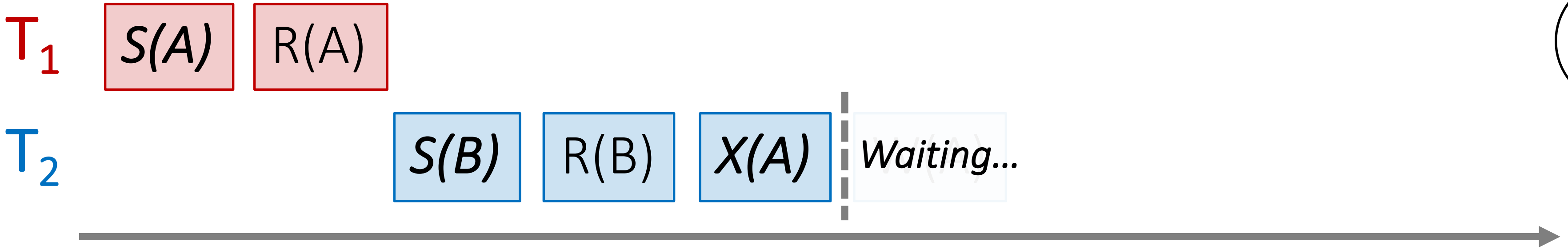
First, T_1 requests a shared lock on A to read from it

Deadlock Detection: Example

Waits-for graph:

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

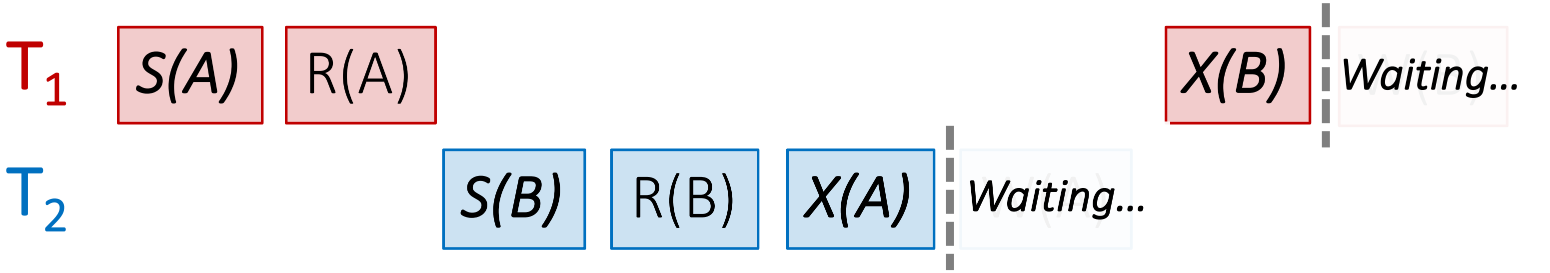
Deadlock Detection: Example



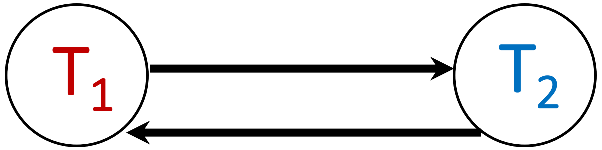
Waits-for graph:

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:

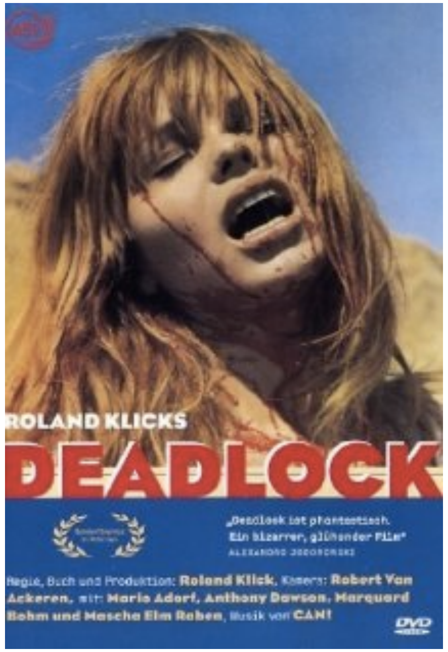


Cycle = DEADLOCK

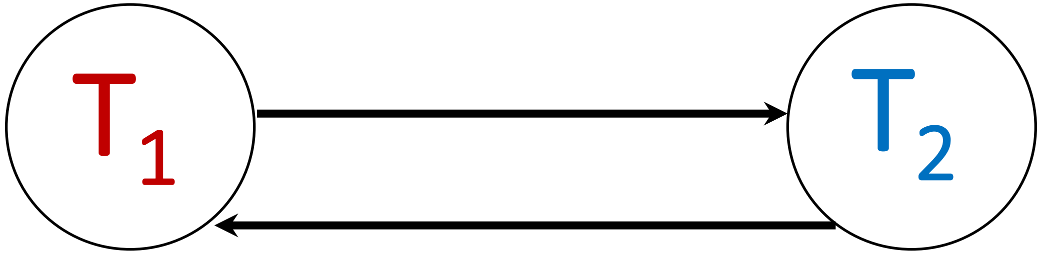
Finally, T_1 requests an exclusive lock on B to write to it- **now T_1 is waiting on T_2… DEADLOCK!**

```
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!)