

Lectures 8 & 9: Transactions

Goals for these lectures

- **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 8: Intro to Transactions & Logging

Today's Lecture

1. Transactions
2. Properties of Transactions: ACID
3. Logging

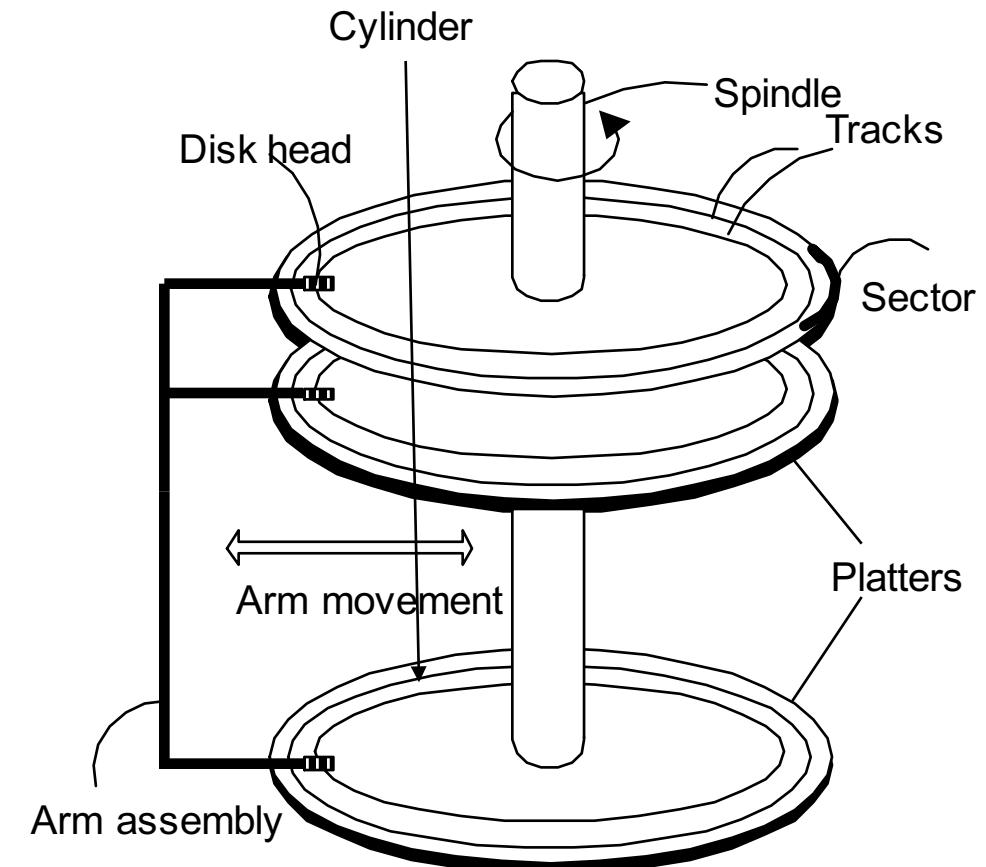
1. Transactions

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*]
5. ACTIVITY: ABORT!!!

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*



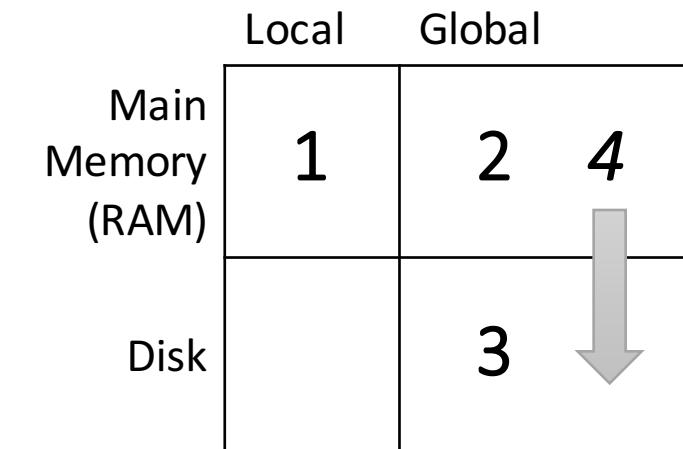
High-level: Disk vs. Main Memory

- Random Access Memory (RAM) or **Main Memory**:
 - *Fast*
 - Random access, byte addressable
 - ~10x faster for sequential access
 - ~100,000x faster for random access!
 - *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

“Flushing 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 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

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

This lecture!

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
```

Crash / abort!

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

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...

Transactions

- **Major** component of database systems
- Critical for many applications (arguably more so than SQL)
- Turing awards to database researchers, all related to TXNs:
 - Charles Bachman 1973
 - Edgar Codd 1981 for inventing relational DBs
 - Jim Gray 1998 for inventing transactions
 - Mike Stonebraker 2015 for postgres

TXNs allow concurrency and **recovery**!

ACTIVITY: Aborts & TXNs in SQLite

\$\$\$

- Instructions: In this activity we'll use SQLite **directly** (rather than via Ipython Notebooks) to demonstrate TXNs
 - 1. Download the file `abort.sql` & take a look- what do you think is *supposed to* happen? What do you think *will* happen?
 - 2. Run it: “`sqlite3 < abort.sql`”
 - 3. View the *accounts* table in sqlite- what happened?
 1. Run “`sqlite3`”
 2. Type “`.open bank.db`”, then “`SELECT * FROM accounts`”
 - 4. Can you use the “`BEGIN TRANSACTION`” and “`END TRANSACTION`” commands to fix this scenario??

Note: on some computers you might need to use a semicolon: “`BEGIN TRANSACTION;`”

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
- 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!)

This 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

TXN 1



No changes persisted

- Durability:

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

TXN 2



All changes persisted

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!

READ ABOUT Bitcoins & TXNs (or lack thereof...):

<http://hackingdistributed.com/2014/04/06/another-one-bites-the-dust-flexcoin/>

and/or time to ask CAs questions!

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

$T: R(A), W(A)$

$A: 0 \rightarrow 1$



A picture of logging

$T: R(A), W(A)$

$A: 0 \rightarrow 1$



Operation recorded in log in main memory!



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

Let's figure out WAL by making a bunch
of mistakes without it!

(What can go wrong...)

Faulty scenario #1:

DBMS Writes A to disk without WAL...

A picture of logging, without WAL...

T: R(A), W(A)

A: 0→1



What happens if we crash or abort now, in the middle of T??



How do we “undo” T?

With WAL!

T: R(A), W(A)

A: 0→1



Now if we crash,
we have the info
to recover A...



However, what is
the correct
value?! Depends
on commit!

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)

A: 0 → 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)

A: 0 → 1



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

OK, Commit!

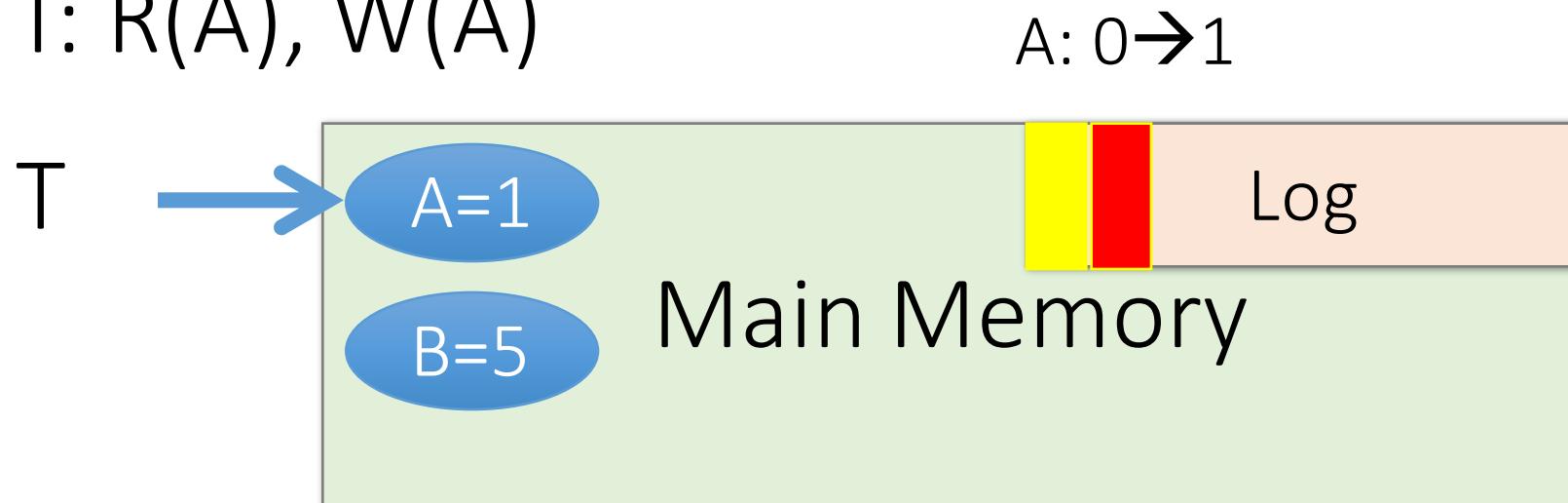
If we crash now, is T
durable? Yes! Except...

**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)



A: 0 → 1



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:
 1. Must *force log record* for an update *before* the corresponding data page goes to storage
 2. Must *write all log records* for a TX *before commit*

Each update is logged! Why not reads?

→ Atomicity

→ 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 9: 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

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

T2: START TRANSACTION

 UPDATE Accounts

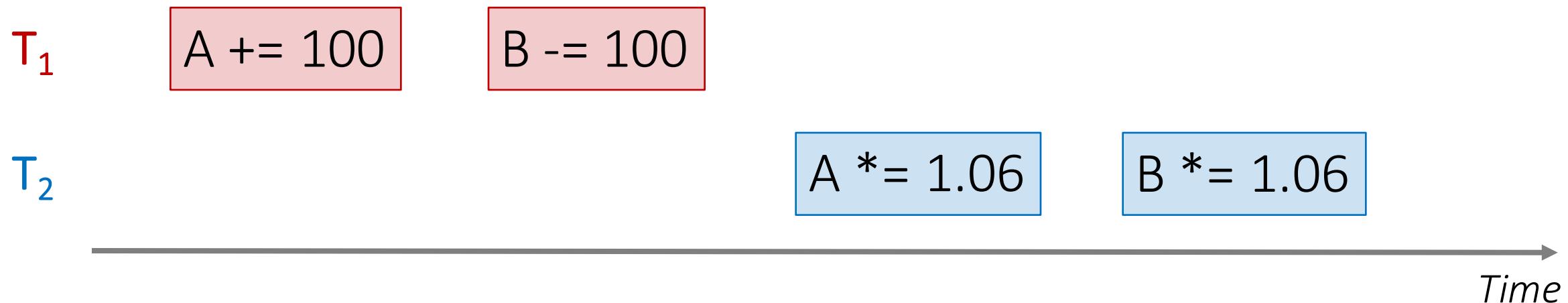
 SET Amt = Amt * 1.06

 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:

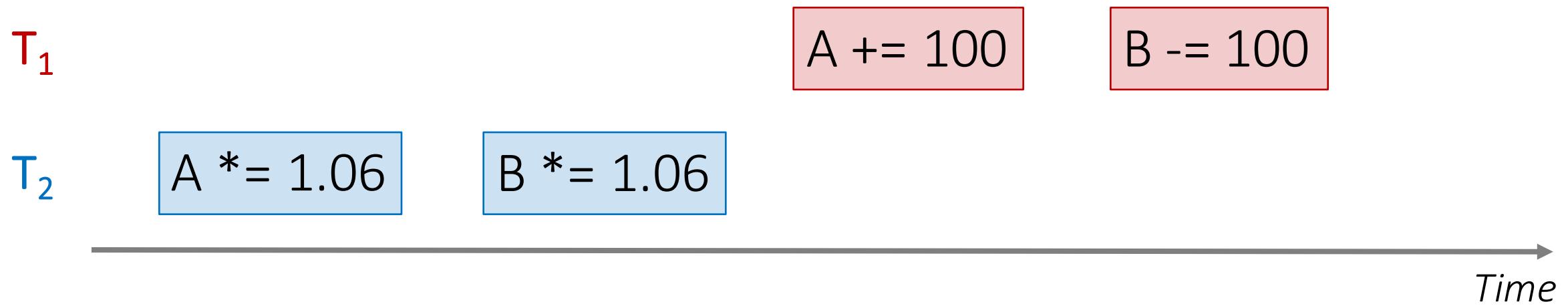


T1 transfers \$100 from B's account
to A's account

T2 credits both accounts with a 6%
interest payment

Example- consider two TXNs:

The TXNs could occur in either order... DBMS allows!

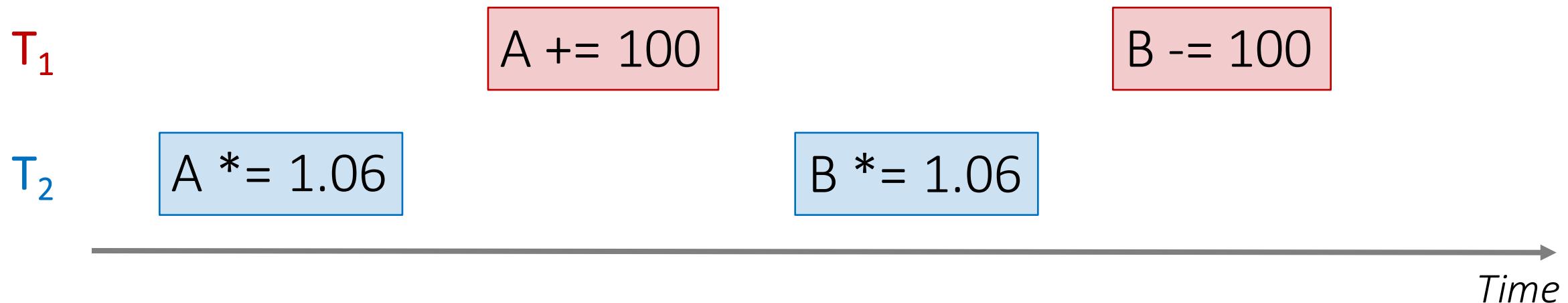


T1 transfers \$100 from B's account
to A's account

T2 credits both accounts with a 6%
interest payment

Example- consider two TXNs:

The DBMS can also **interleave** the TXNs

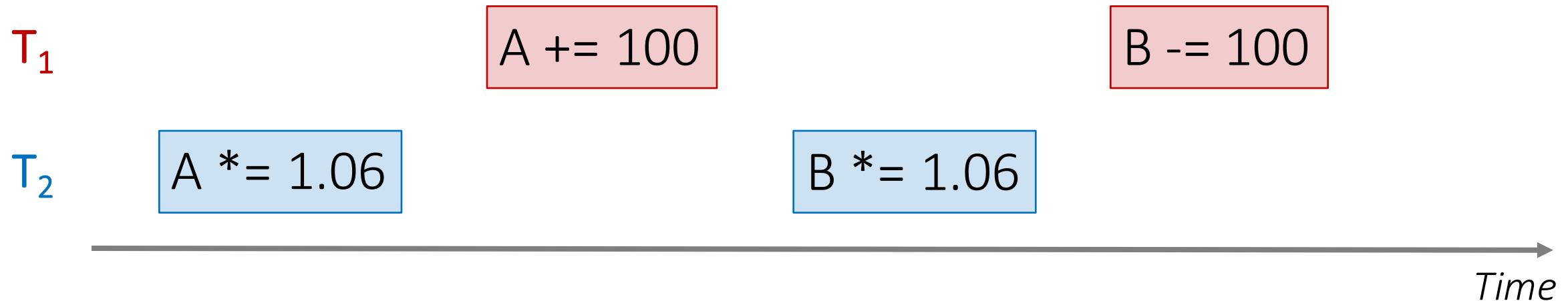


T1 transfers \$100 from B's account
to A's account

T2 credits both accounts with a 6%
interest payment

Example- consider two TXNs:

The DBMS can also **interleave** the TXNs



What goes / could go wrong here??

Recall: Logically Three Types of Regions of Memory

1. **Local / TXN:** In our model each TXN will have its own local memory, where it stores values that only it “sees”
2. **Global / Shared:** Each TXN can read from / write to shared data in main memory
3. **Disk:** Global memory can read from / flush to disk

	Local	Global
Main Memory (RAM)	1	2
Disk		3

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”

ACID

DBMS must pick a schedule which maintains isolation & consistency

Scheduling examples

*Starting
Balance*

A	B
\$50	\$200

Serial schedule:



A	B
\$159	\$106

Interleaved schedule A:



A	B
\$159	\$106

Same result as serial!

Scheduling examples

*Starting
Balance*

A	B
\$50	\$200

Serial schedule:

T₁ A += 100

B -= 100

T₂

A *= 1.06

B *= 1.06

A	B
\$159	\$106

Interleaved schedule B:

T₁ A += 100

B -= 100

T₂

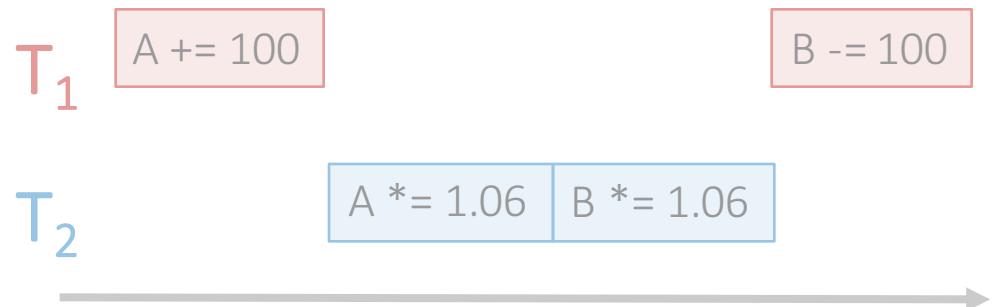
A *= 1.06

B *= 1.06

A	B
\$159	\$112

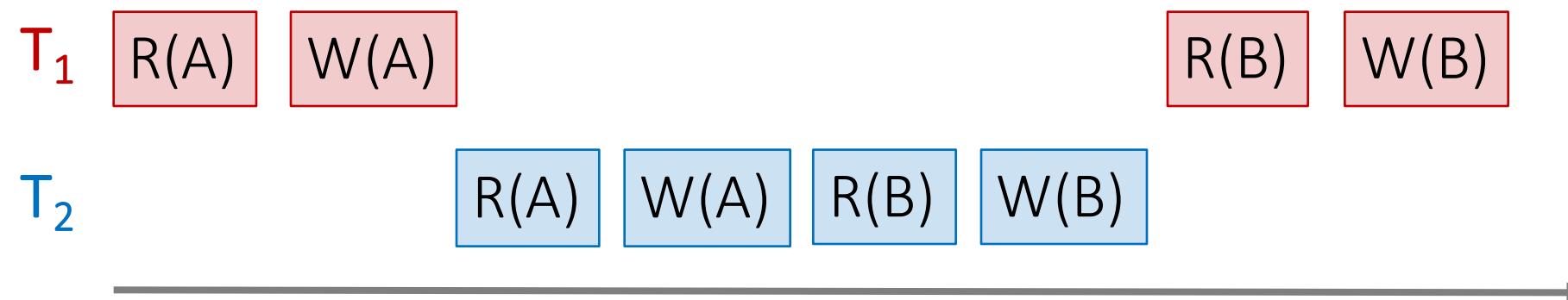
Different
result than
serial!

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!

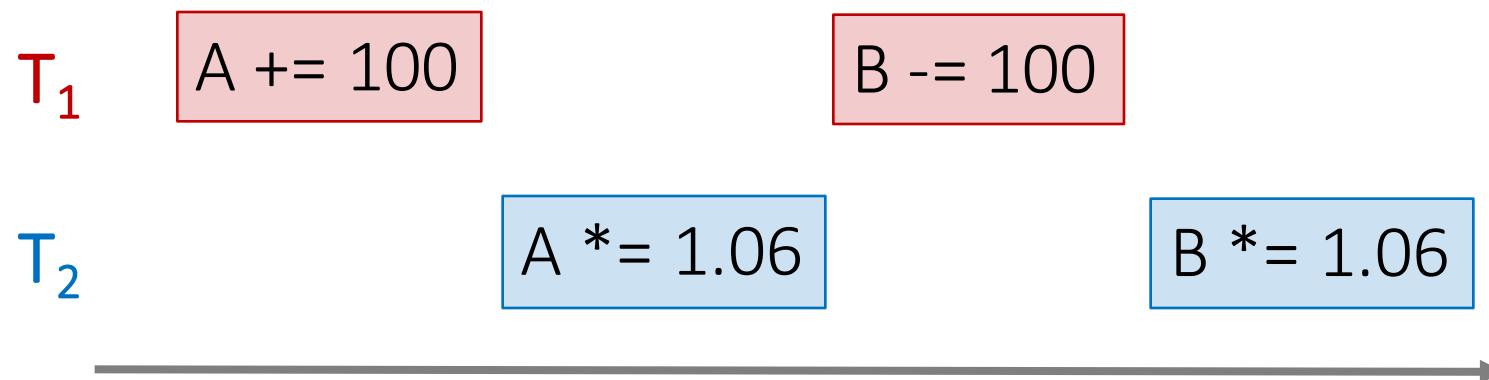


Scheduling Definitions

- 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 def powerful and tricky!

Serializable?



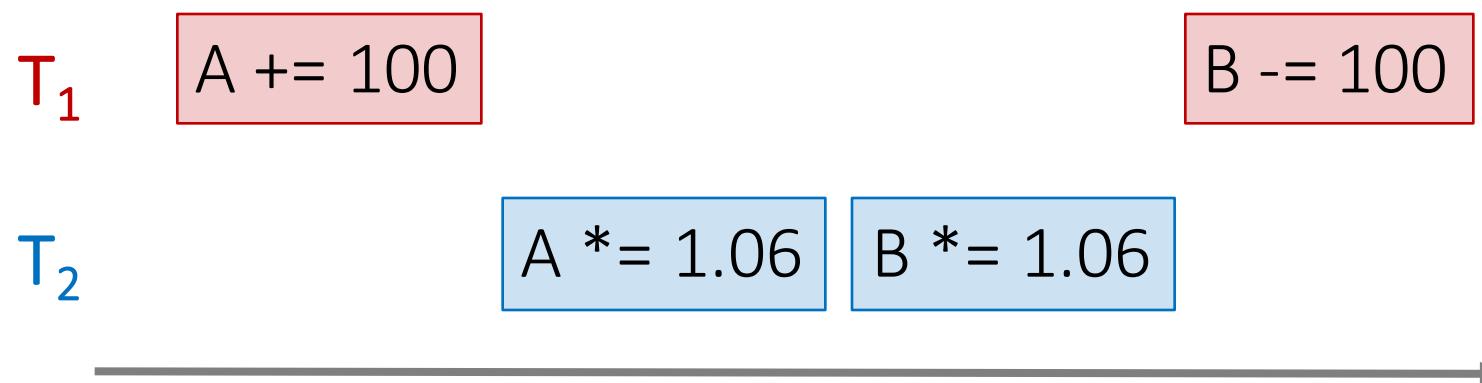
Serial schedules:

	A	B
$T_1 \rightarrow T_2$	$1.06*(A+100)$	$1.06*(B-100)$
$T_2 \rightarrow T_1$	$1.06*A + 100$	$1.06*B - 100$

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

Same as a serial schedule
for all possible values of
 $A, B = \underline{\text{Serializable}}$

Serializable?



Serial schedules:

	A	B
$T_1 \rightarrow T_2$	$1.06*(A+100)$	$1.06*(B-100)$
$T_2 \rightarrow T_1$	$1.06*A + 100$	$1.06*B - 100$

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
 - Fall into broader categories of “conflict types”
 - Often referred to by name...

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)

Note: the ordering (WR vs. RW) refers to ordering in the schedule

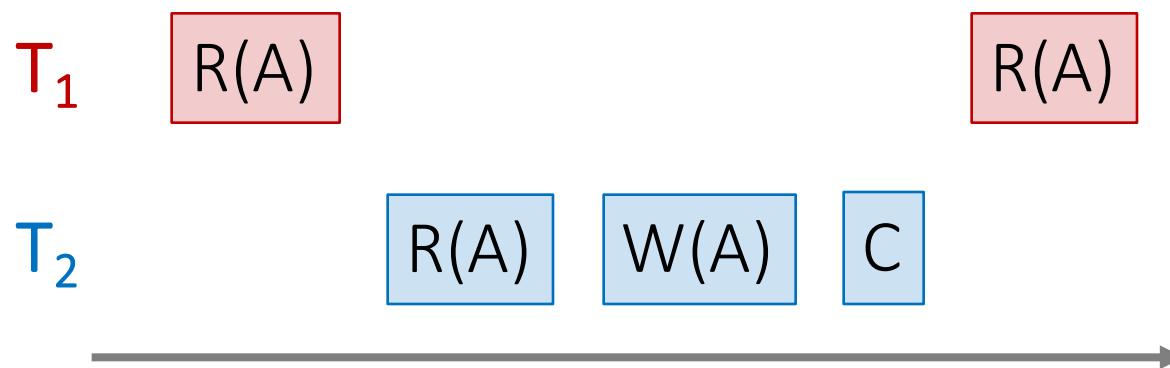
- We will see some example anomalies caused by these types of conflicts next...

Why no “RR Conflict”?

Classic Anomalies with Interleaved Execution

“Unrepeatable read”:

Example:



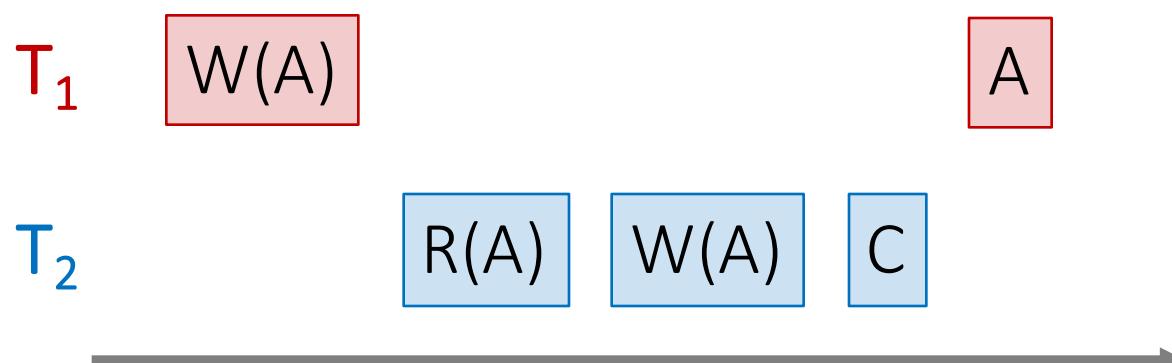
1. T_1 reads some data from A
2. T_2 writes to A
3. Then, T_1 reads from A again
and now gets a different / inconsistent value

This is an example of a *RW conflict*

Classic Anomalies with Interleaved Execution

“Dirty read” / Reading uncommitted data:

Example:



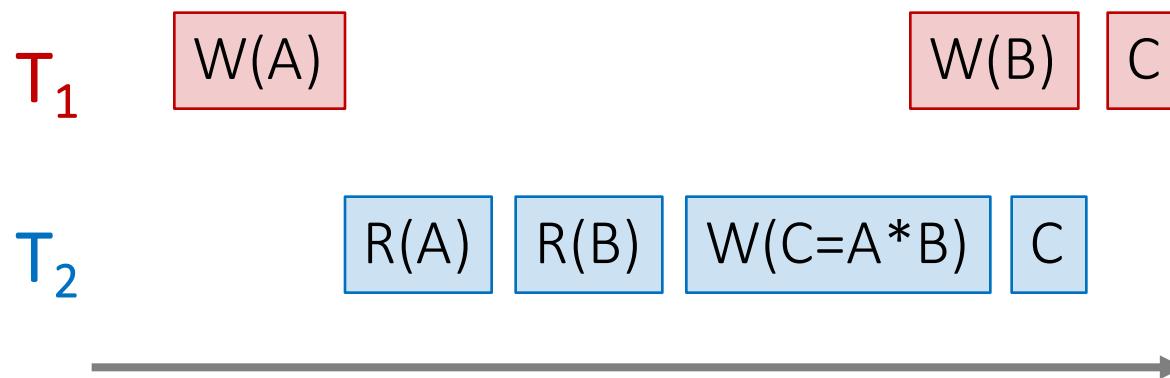
1. T_1 writes some data to A
2. T_2 reads from A, then writes back to A & commits
3. T_1 then aborts- *now T_2 's result is based on an obsolete / inconsistent value*

This is an example of a *WR conflict*

Classic Anomalies with Interleaved Execution

“Inconsistent read” / Reading partial commits:

Example:



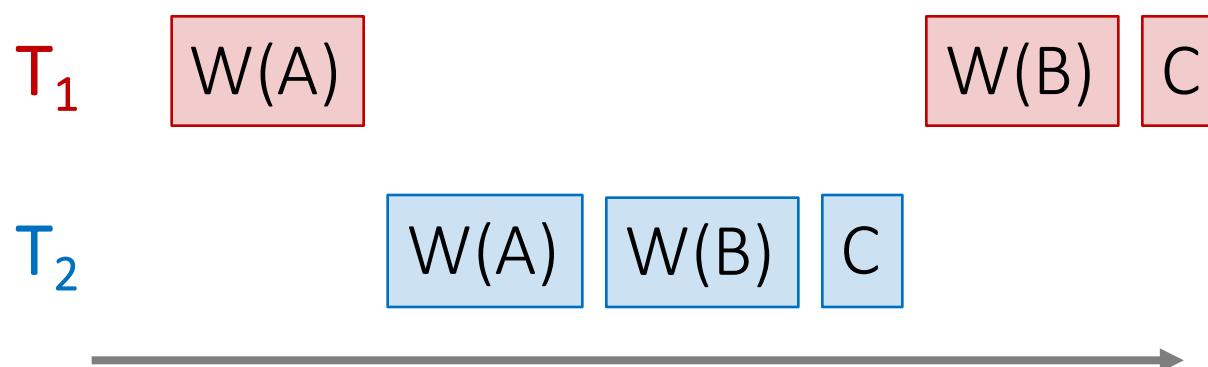
1. T_1 writes some data to A
2. T_2 reads from A and B, and then writes some value which depends on A & B
3. T_2 then writes to B- now T_1 's result is based on an incomplete commit

This is another example of a *WR conflict*

Classic Anomalies with Interleaved Execution

Partially-lost update:

Example:



1. T₁ blind writes some data to A
2. T₂ blind writes to A and B
3. T₁ then blind writes to B; now we have T₂'s value for B and T₁'s value for A- *not equivalent to any serial schedule!*

This is an example of a *WW conflict*

[Activity-9-1.ipynb](#)

2. Locking

What you will learn about in this section

1. Locking: basics & 2PL
2. Conflict serializability
3. Deadlock detection
4. ACTIVITY: TXN viewer

Motivation

- Ensure that TXNs remain **isolated** i.e. that they follow serializable schedules
 - So that we don't encounter any of the types of anomalies just covered!
- One method: **Locking**
 - We will cover a specific locking strategy, *strict two-phase locking (2PL)*

Locking to Avoid Conflicts

- We saw that all data anomalies due to concurrency involve **conflicts**
- We can avoid conflicts by making sure that **two or more TXNs never access the same variable at the same time**, unless they are all **reads**

Recall: Two actions conflict if they are:

- part of different TXNs,
- involve the **same variable**,
- \geq one of them is a **write**

This is what *locking* is!

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

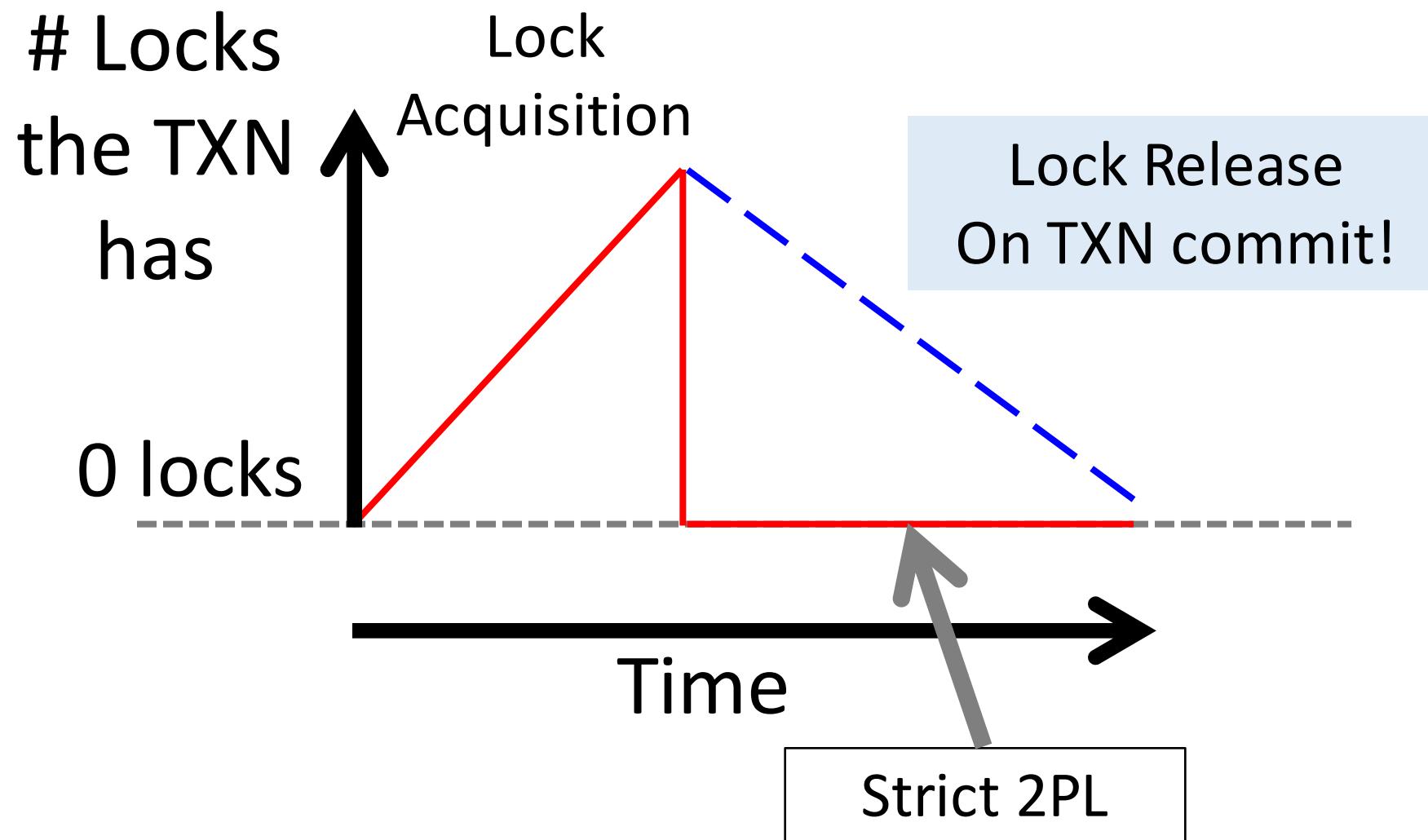
TXNs obtain:

- 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!

These policies ensure that no conflicts (RW/WR/WW) occur!

Picture of 2-Phase Locking (2PL)



Using Strict 2PL Locking & Serializability

Motivation

- You can't understand how your application works without understanding TXNs.
 - Serializability is a slippery notion!
- We'll study lock-based, which is the easiest to understand & essentially what the SQL standard is based on.
 - There are fancier things too (see 245)

Conflict Serializable Schedules

- Two schedules are **conflict equivalent** if:
 - 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

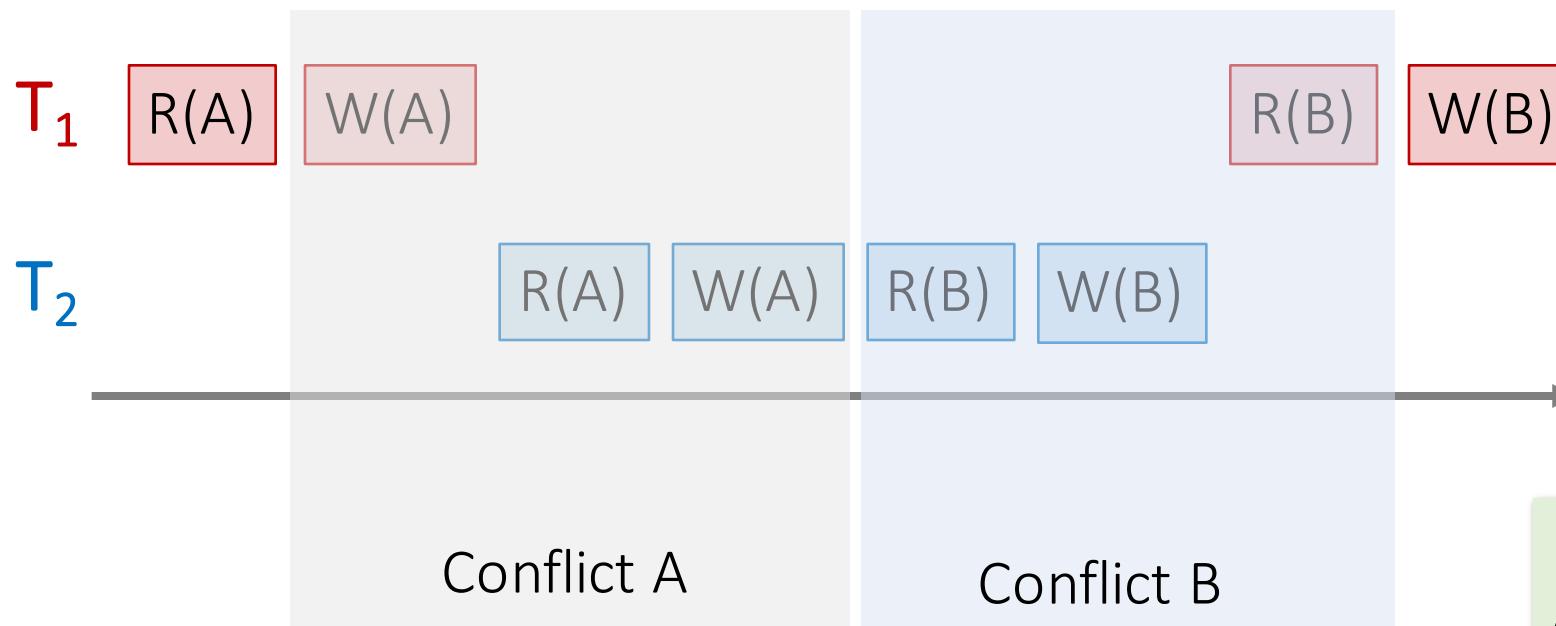
Recall: Two actions conflict if they are:

- part of **different TXNs**,
- involve the **same variable**,
- \geq one of them is a **write**

If a schedule is conflict serializable, then it maintains isolation & consistency- why we care about!

Example

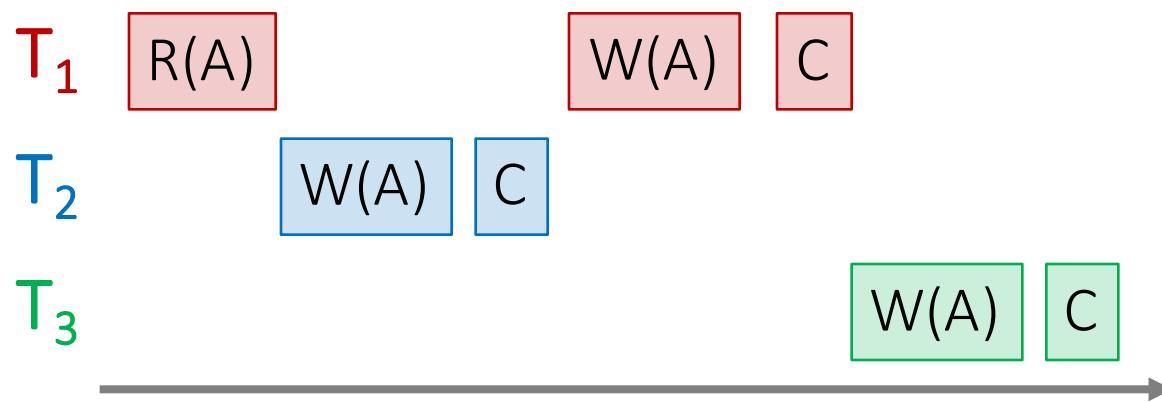
A schedule that is **not** conflict serializable:



No way for the actions of conflicts A & B to *both* happen in this order in a serial schedule!

Serializable vs. Conflict Serializable

Example of serializable but *not* conflict serializable



This is *equivalent* to $T_1 \rightarrow T_2 \rightarrow T_3$, so serializable

But not conflict *equivalent* to $T_1 \rightarrow T_2 \rightarrow T_3$ (or any other serial schedule) so not conflict serializable!

Conflict serializable \Rightarrow serializable, but not the other way around

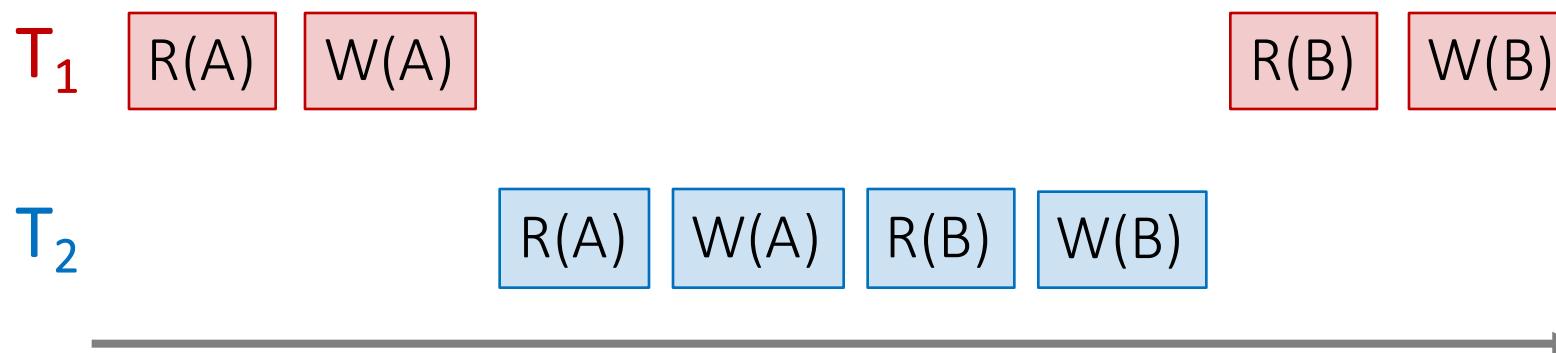
Conflict Dependency Graph

- Node for each committed TXN $T_1 \dots T_N$
- Edge from $T_i \rightarrow T_j$ if an actions in T_i **precedes** and **conflicts** with an action in T_j

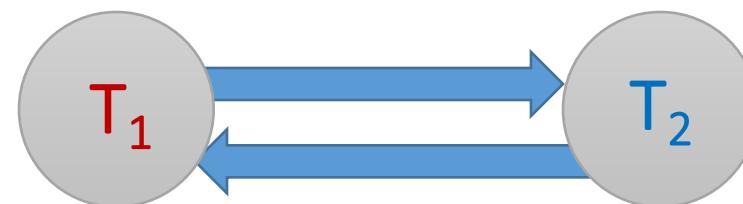
Theorem: Schedule is **conflict serializable** if and only if its dependency graph is acyclic

Conflict Dependency Graph

Example:



Conflict dependency graph:



A non-conflict serializable schedule has a **cyclic** conflict dependency graph!

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 \Rightarrow serializable schedules

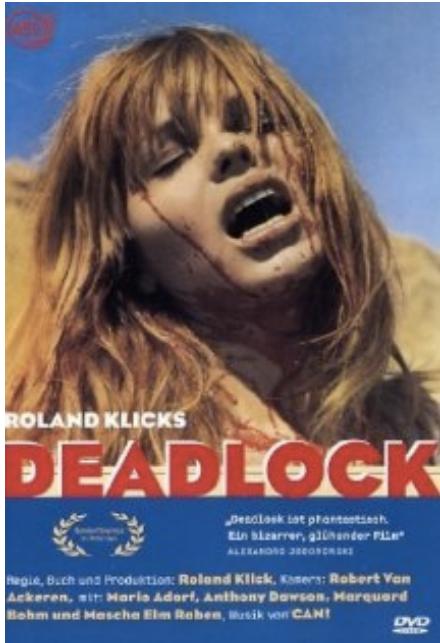
Note however that it does not allow *all* conflict serializable schedules!

Summary So far

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

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 Prevention

- Assign priorities based on timestamps. Assume T_i wants a lock that T_j holds. Two policies are possible:
 - *Wait-Die*: If T_i has higher priority, T_i waits for T_j ; otherwise T_i aborts
 - *Wound-wait*: If T_i has higher priority, T_j aborts; otherwise T_i waits
- Note: If a transaction re-starts, make sure it has its original timestamp

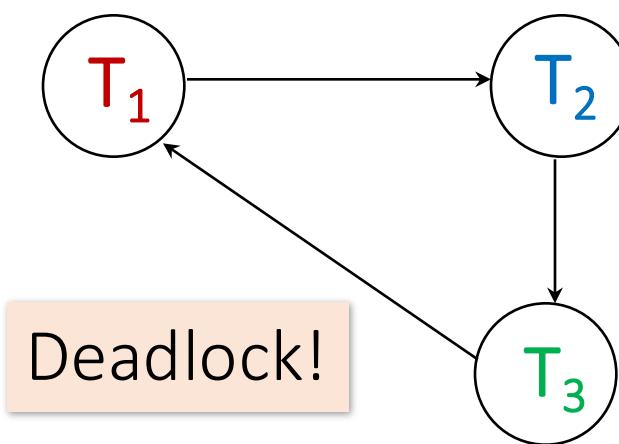
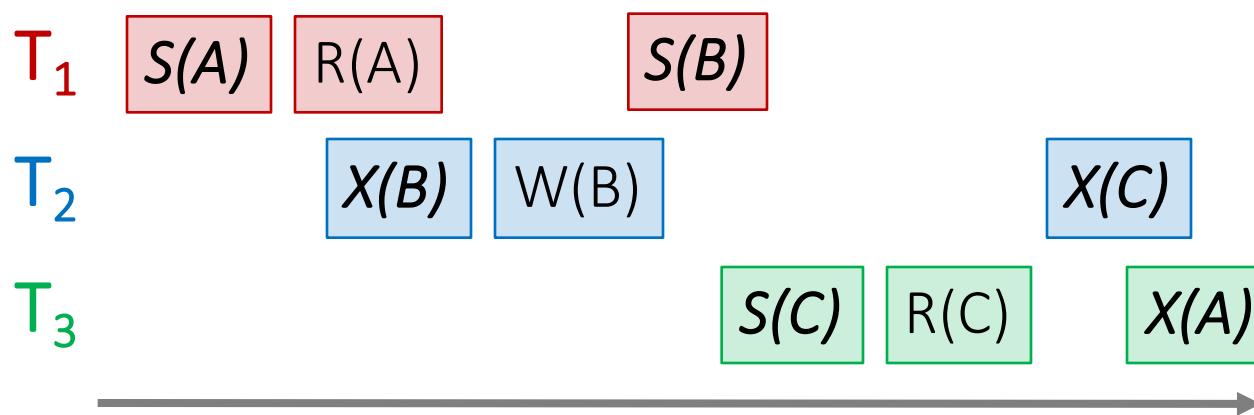
Issue: What if a transaction never makes progress?

Deadlock Detection

- Create a **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

Deadlock Detection

Example:



In general, must search through this big graph. Sounds expensive! Is it?

[Activity-9-2.ipynb](#)

Locking Summary

- Locks must be atomic, primitive operation
- 2PL does not avoid deadlock
- Deadlock detection sounds more expensive than it is....