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
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 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...
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**.

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

In the real world, a TXN either happened completely or not at all.
Transactions: Basic Definition

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

**Examples:**

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

In the real world, a TXN either happened completely or not at all.
Transactions in SQL

• In “ad-hoc” SQL:
  • Default: each statement = one transaction

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

```sql
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 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
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
```

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
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 continues to be a 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!)

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

- **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.
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)

T

A=0

B=5

Main Memory

A=0

Data on Disk

Log

Log on Disk

Lecture 7 > Section 3 > Logging commit protocol
A picture of logging

T: R(A), W(A)

A: 0 → 1

Main Memory
A picture of logging

T: R(A), W(A)

A: 0→1

Main Memory

A=1
B=5

Log

Operation recorded in log in main memory!

T:
R(A), W(A)

A=0→1

Data on Disk

Log on 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

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!

T: R(A), W(A)

A: 0 → 1

Main Memory

A=1

B=5

Log

Data on Disk

A=0

Log on Disk
Incorrect Commit Protocol #2

T: R(A), W(A)

A: 0→1

A=1
B=5

Main Memory

Log

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

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

If we crash now, is T durable?

OK, Commit!
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!

If we crash now, is T durable?

*OK, Commit!*

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*

  → **Atomicity**

  → **Durability**

Each update is logged! Why not reads?
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

2. **Consistency** is maintained: TXNs must leave the DB in a consistent state
   • DBMS handles the details of enforcing integrity constraints
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: A += 100, B -= 100
- T2: A *= 1.06, B *= 1.06

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!

$T_1$ transfers $100 from B's account to A's account

$T_2$ credits both accounts with a 6% interest payment

$T_1$ transfers $100 from B’s account to A’s account
Example- consider two TXNs:

The DBMS can also **interleave** the TXNs

\[ T_1 \]

\[ A += 100 \quad B -= 100 \]

\[ T_2 \]

\[ A *= 1.06 \quad B *= 1.06 \]

**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

$T_1$

$A += 100$

$B -= 100$

$T_2$

$A *= 1.06$

$B *= 1.06$

What goes 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...

<table>
<thead>
<tr>
<th></th>
<th>Local</th>
<th>Global</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Memory</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>(RAM)</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Disk</td>
<td></td>
<td>3</td>
</tr>
</tbody>
</table>

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

“**Flushing** to disk” = writing to disk.
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”
Scheduling examples

Serial schedule $T_1, T_2$:

- $T_1$: $A += 100$  $B -= 100$
- $T_2$: $A *= 1.06$  $B *= 1.06$

Starting Balance:

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$50</td>
<td>$200</td>
</tr>
</tbody>
</table>

$159  $106

Interleaved schedule $A$:

- $T_1$: $A += 100$  $B -= 100$
- $T_2$: $A *= 1.06$  $B *= 1.06$

$159  $106

Same result!
Scheduling examples

Serial schedule $T_1, T_2$:

- $T_1$: $A += 100$  $B -= 100$
- $T_2$: $A *= 1.06$  $B *= 1.06$

Starting Balance:

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$50$</td>
<td>$200$</td>
</tr>
</tbody>
</table>

$A = 159$  $B = 106$

Interleaved schedule $B$:

- $T_1$: $A += 100$
- $T_2$: $A *= 1.06$  $B *= 1.06$

Starting Balance:

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$159$</td>
<td>$112$</td>
</tr>
</tbody>
</table>

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

Serial schedule $T_2, T_1$:

$T_1$

$T_2$

Interleaved schedule $B$:

$T_1$

$T_2$

Starting Balance

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$50$</td>
<td>$200$</td>
<td></td>
</tr>
</tbody>
</table>

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

Interleaved schedule B:

\[ \begin{align*}
  T_1 & : A &+= 100 \\
  T_2 & : A &*= 1.06 \quad B &*= 1.06 \\
  & & B &-= 100
\end{align*} \]

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:

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_1, T_2$</td>
<td>$1.06(A+100)$</td>
<td>$1.06(B-100)$</td>
</tr>
<tr>
<td>$T_2, T_1$</td>
<td>$1.06A + 100$</td>
<td>$1.06B - 100$</td>
</tr>
</tbody>
</table>

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

Serial schedules:

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>T₁, T₂</td>
<td>1.06*(A+100)</td>
<td>1.06*(B-100)</td>
</tr>
<tr>
<td>T₂, T₁</td>
<td>1.06*A + 100</td>
<td>1.06*B - 100</td>
</tr>
</tbody>
</table>

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)

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

Why no “RR Conflict”? See next section for more!
Classic Anomalies with Interleaved Execution

“Unrepeatable read”:

Example:

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

Occurring with / because 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

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 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 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:

\[ T_1 \rightarrow R(A) \rightarrow W(A) \rightarrow R(B) \rightarrow W(B) \]

\[ T_2 \rightarrow R(A) \rightarrow W(A) \rightarrow R(B) \rightarrow W(B) \]

Interleaved Schedule:

\[ T_1 \rightarrow R(A) \rightarrow W(A) \rightarrow R(B) \rightarrow W(B) \]

\[ T_2 \rightarrow R(A) \rightarrow W(A) \rightarrow R(B) \rightarrow W(B) \]

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:**

<table>
<thead>
<tr>
<th>T1</th>
<th>R(A)</th>
<th>W(A)</th>
<th>R(B)</th>
<th>W(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>T1</th>
<th>R(A)</th>
<th>W(A)</th>
<th>R(B)</th>
<th>W(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Interleaved Schedules:**

<table>
<thead>
<tr>
<th>T1</th>
<th>R(A)</th>
<th>W(A)</th>
<th>R(B)</th>
<th>W(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We want to develop ways of discerning “good” vs. “bad” schedules
Ways of Defining “Good” vs. “Bad” Schedules

• Recall from last time: we call a schedule **serializable** if it is equivalent to *some* serial schedule

  • We used this as a notion of a “good” interleaved schedule, since a **serializable schedule will maintain isolation & consistency**

• Now, we’ll define a stricter, but very useful variant:

  • **Conflict serializability**

We’ll need to define *conflicts* first..
Conflicts

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

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

All “conflicts”!
Conflict Serializability

• Two schedules are conflict equivalent if:
  
  • They involve the same actions of the same TXNs
  
  • Every pair of conflicting actions of two TXNs are ordered in the same way

• Schedule S is conflict serializable if S is conflict equivalent to some serial schedule

Conflict serializable $\Rightarrow$ 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 $T_i$ precede and conflict with any actions in $T_j$
What can we say about “good” vs. “bad” conflict graphs?

*Serial Schedule:*

T₁
R(A) → W(A) → R(A) → W(A) → R(B) → W(B) → R(B) → W(B) → T₂

*Interleaved Schedules:*

T₁
R(A) → W(A) → R(B) → W(B) → R(B) → W(B) → R(B) → W(B) → T₂

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

**Serial Schedule:**

- \( T_1 \) → \( T_2 \)

**Interleaved Schedules:**

- \( T_1 \) → \( T_2 \)
- \( T_2 \) → \( T_1 \)

Theorem: Schedule is **conflict serializable** if and only if its conflict graph is **acyclic**
Let’s unpack this notion of acyclic conflict graphs...
DAGs & Topological Orderings

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

• A directed **acyclic** graph (DAG) always has one or more **topological orderings**.
  • (And there exists a topological ordering if and only if there are no directed cycles.)
DAGs & Topological Orderings

- Ex: What is one possible topological ordering here?

Ex: $0, 1, 2, 3$ (or: $0, 1, 3, 2$)
DAGs & Topological Orderings

• Ex: What is one possible topological ordering here?

There is none!
Connection to conflict serializability

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

• Thus an **acyclic** conflict graph $\rightarrow$ 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 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 *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)

# Locks
the TXN has

0 locks

Time

Lock Acquisition

Lock Release
On TXN commit!

Strict 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 $\Rightarrow$ serializable schedules
Strict 2PL

- If a schedule follows strict 2PL and locking, it is conflict serializable...
  - ...and thus serializable
  - ...and thus maintains isolation & consistency!

- Not all serializable schedules are allowed by strict 2PL.

- So let’s use strict 2PL, what could go wrong?
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

T₂ then requests an exclusive lock on A to write to it - now T₂ is waiting on T₁...
Deadlock Detection: Example

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!??!

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!)