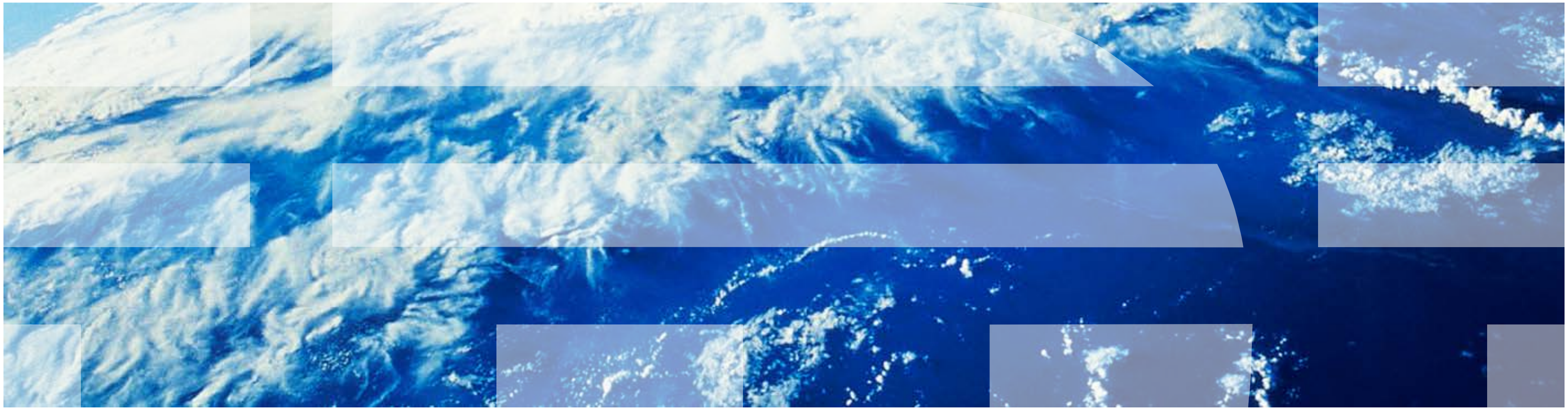
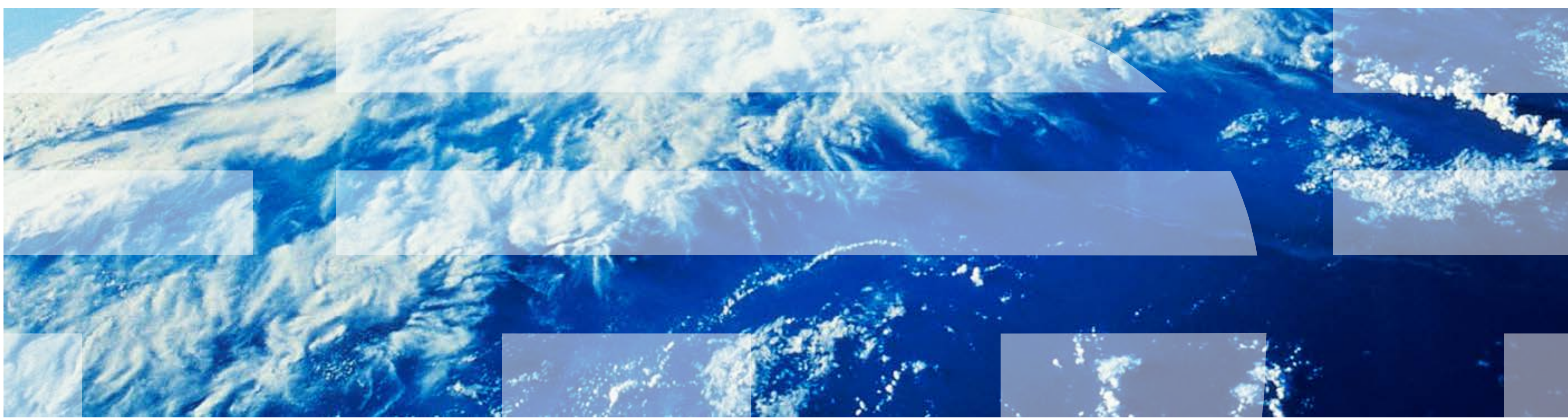
Borrowed from Shiva Shivakumar

Computer Systems for Data Science
Topic 3

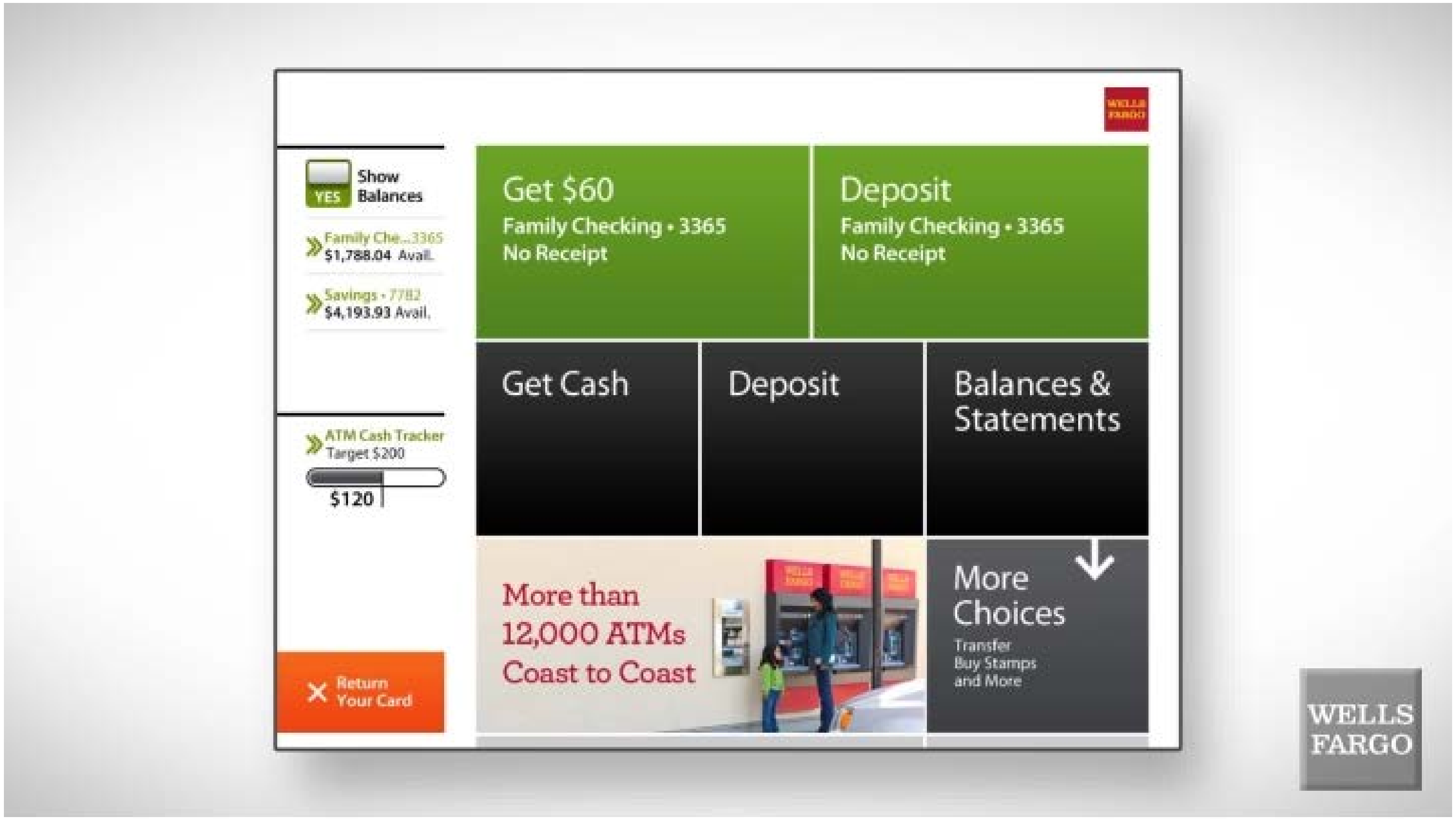
Transactions



Transactions



Motivating example: an ATM



Read Balance		Read Balance
Give money	vs	Update Balance
Update Balance		Give money

It’s not just about having the **correct** balance…

Visa does > 60,000 TXNs/sec with users & merchants

Want your 4$ Starbucks transaction to wait for a 10k$ bet in Las Vegas ?
(Transactions can (1) be quick or take a long time, (2) unrelated to you)

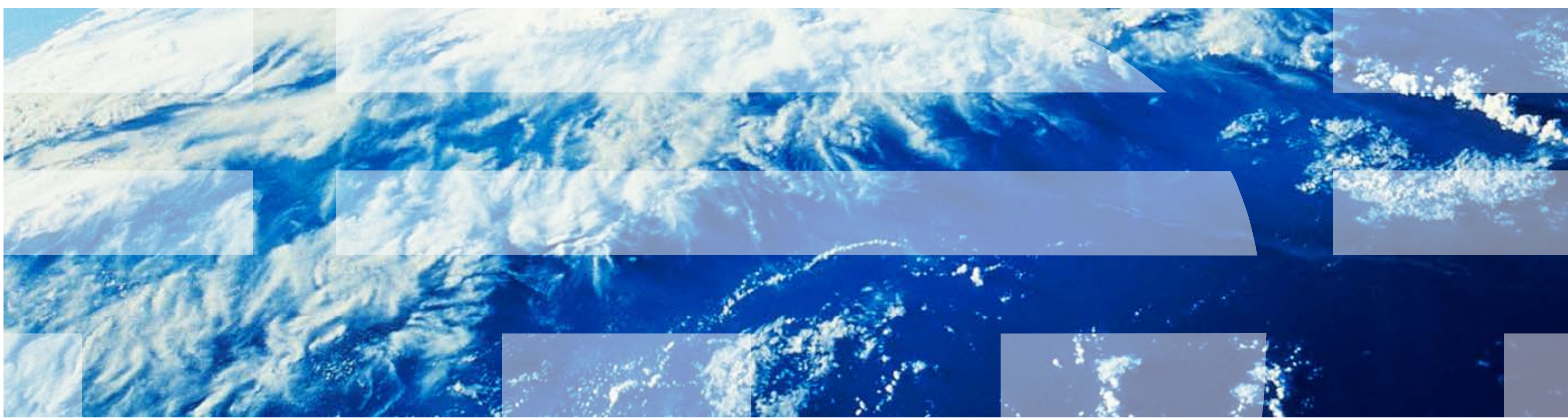
Transactions are not just used for finance

Transactions are at the core of

-- payment, stock market, banks, ticketing

-- Gmail, Google Docs (e.g., multiple people editing)

Transactions



Example: monthly bank interest transaction

Money

Account	....	Balance ($)
3001		500
4001		100
5001		20
6001		60
3002		80
4002		-200
5002		320
...		...
30108		-100
40008		100
50002		20

Money (@4:29 am day+1)

Account	....	Balance ($)
3001		550
4001		110
5001		22
6001		66
3002		88
4002		-220
5002		352
...		
30108		-110
40008		110
50002		22

‘T-Monthly-423’

Monthly Interest 10%

4:28 am Starts run on 10M bank accounts

Takes 24 hours to run

```
UPDATE Money
SET Balance = Balance * 1.1
```

Example: monthly bank interest transaction **with crash**

Money

Account	....	Balance ($)
3001		500
4001		100
5001		20
6001		60
3002		80
4002		-200
5002		320
...		...
30108		-100
40008		100
50002		20

Money (@10:45 am)

Account	....	Balance ($)	
3001		550	??
4001		110	
5001		22	
6001		66	
3002		88	
4002		-200	??
5002		320	??
...			
30108		-110	
40008		110	
50002		22	??

‘T-Monthly-423’

Monthly Interest 10%

4:28 am Starts run on 10M bank accounts

Takes 24 hours to run

Network outage at 10:29 am,

System access at 10:45 am

Transactions: Basic Definition

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

TXN either happened completely or not at all

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

Transactions in SQL

- In "ad-hoc" SQL, 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
```

Motivation for Transactions

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

1. **Recovery and Durability**: Keeping the DB 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 -- Recovery & Durability

1. **Recovery and durability** of user data is essential for reliable database (and other data science systems)

- The database 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 -- Concurrent execution

2. **Concurrent** execution of user programs is essential for good database 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 database handle running several user TXNs concurrently, in order to keep throughput high

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'
```

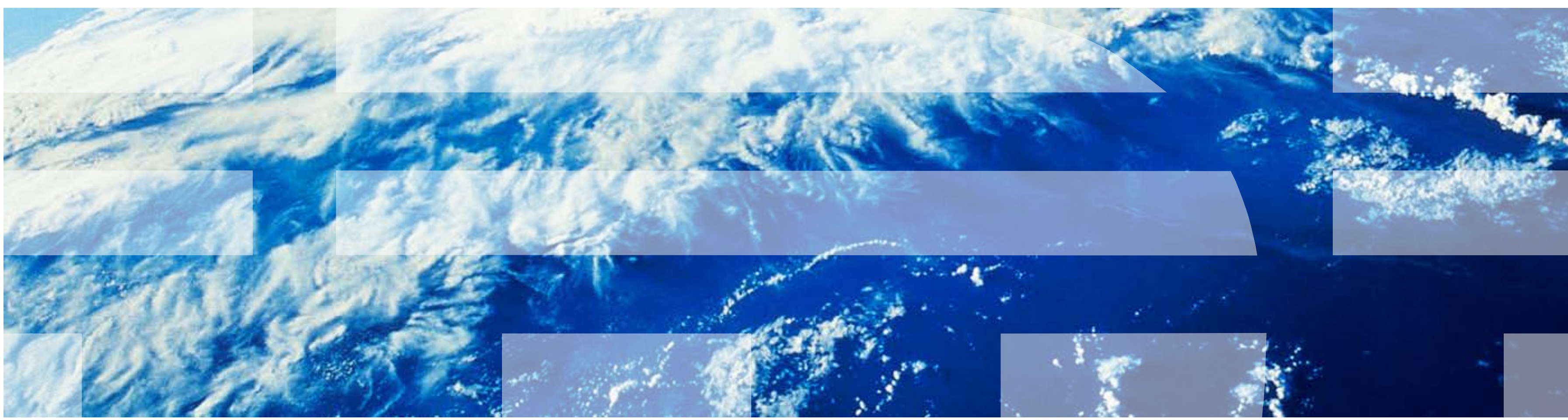
Two managers attempt to discount products *concurrently*-
What could go wrong?

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
```

Lecture 4



Recap of lecture 3

- **SQL (continued)**
  - Foreign keys (adding a constraint on insertions)
  - JOINs
    - Inner
    - Outer
  - Aggregations: SUM/COUNT/MIN/MAX/AVG
  - GROUP BY + aggregates
  - HAVING
  - Nested queries
    - Breaking into steps
    - Including aggregates, GROUP BY
- **Transactions motivation:**
  - Key idea: either entire operations is executed, or it is not
  - Transactions in SQL
  - Two key challenges
    - Durability and recovery (surviving crashes, making sure we can rollback)
    - Concurrent operations (allow transactions to execute in parallel and in isolation)

Today: deep dive on transactions

- ACID
- Atomicity and durability via logging
  - Write ahead log
- Consistency and isolation via locking
  - 2 Phase Locking

- If we have time: conflict serializability

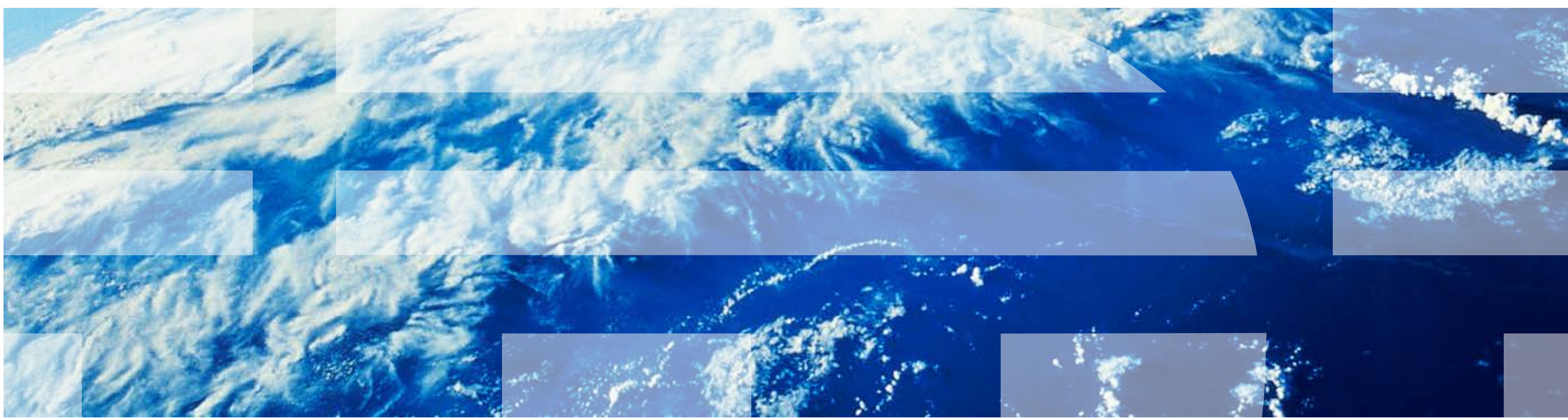
Logistics

- Written homework will be released at the end of this week
  - Meant as preparation for midterm
  - After this class, you will have the material to solve most (but not all) of it

- Reminder: SQL programming homework due next week at **noon on Thursday**
  - We covered all the material to solve it

Borrowed from Shiva Shivakumar

ACID
Atomicity, Consistency, Isolation, 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 writes a TXN to go from one consistent state to a consistent state
  - *System* makes sure that the TXN is atomic
  - → Assuming system maintaining atomicity, this is often the user's responsibily

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

ACI<u>D</u>: <u>D</u>urability

- 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
  - And in data center settings: replicate data, backup, etc.

Challenges for ACID properties

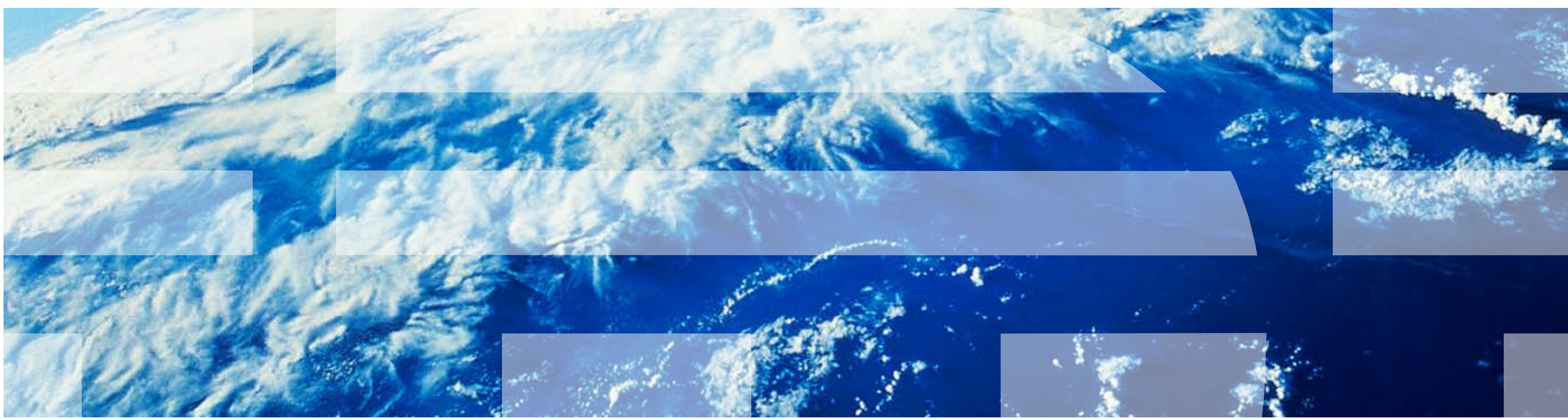
- In spite of power failures (i.e., in spite of loss of memory)
- Users may abort the program: need to “rollback changes”
  - Need to *log* what happened
- Many users executing concurrently

And all this with… Scalability and/or Performance!!

A Note: ACID is contentious!

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

Atomicity and Durability via Logging

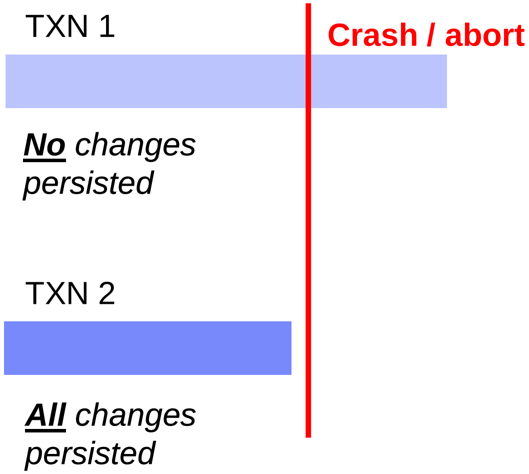


Goal for this lecture: Ensuring Atomicity & Durability

ACI**D**

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

- Durability:
  - If DB 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)

Basic Idea: (Physical) Logging

Idea:

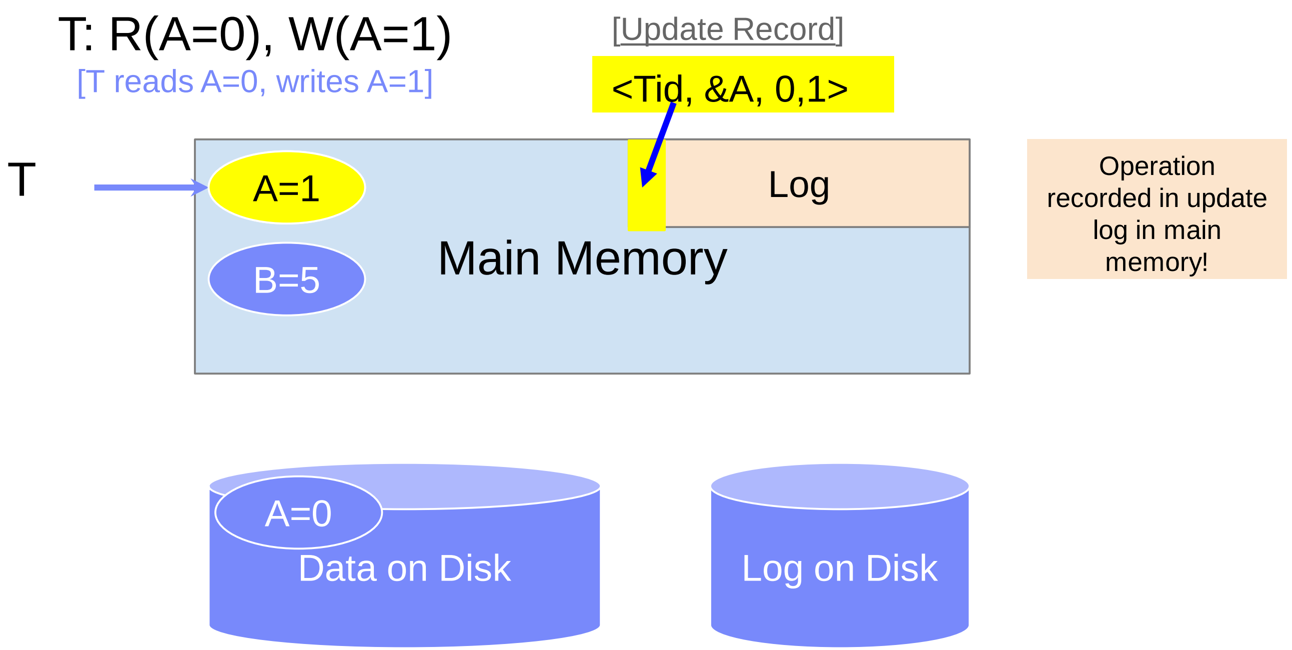
- Log consists of an ordered list of update records
- Log record contains UNDO information for every update!
  <TransactionID, location, old data, new data>

What DB does?

- Owns the log “service” for all applications/transactions.
- Transparent to application or transaction
- Sequential writes to log, can **flush** — force writes to disk

This is sufficient to UNDO any transaction!

A picture of logging



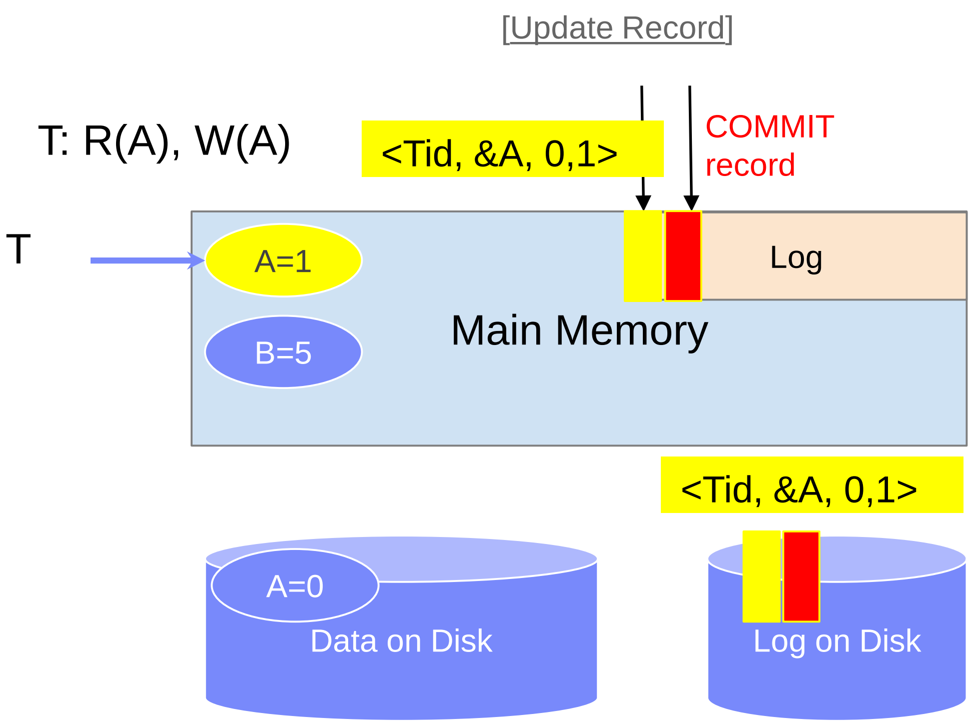
Why do we need logging for atomicity?

- 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!

Write-ahead Logging (WAL) Commit Protocol



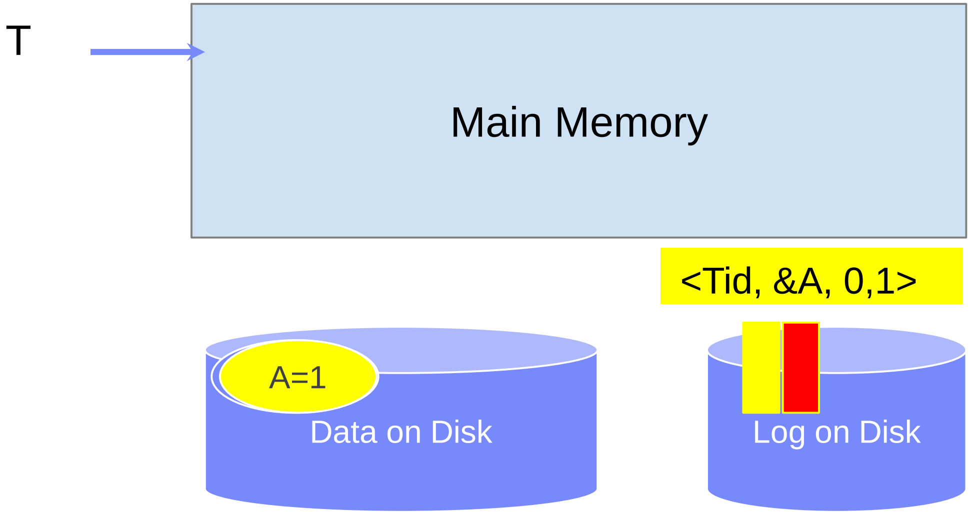
Commit after we’ve written log to disk but before we’ve written data to disk…

OK, Commit!

If we crash now, is T durable?

Write-ahead Logging (WAL) Commit Protocol

T: R(A), W(A)



Commit 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)

Algorithm: WAL

For each record update, write Update Record into LOG

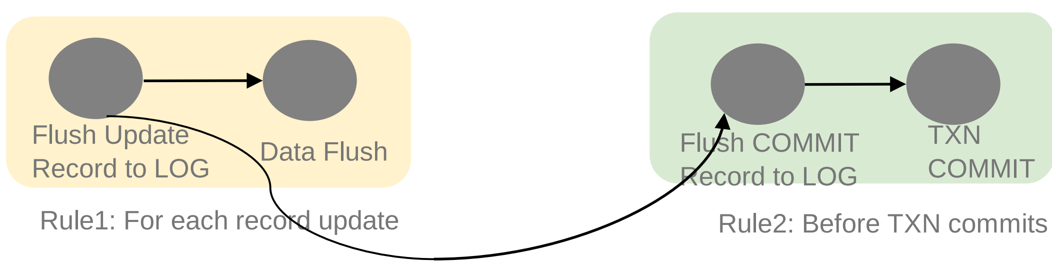
Follow two Flush rules for LOG

- **Rule1**: Flush Update Record *into LOG before* corresponding data page goes to storage
- **Rule2**: Before TXN commits,
  - Flush all Update Records to LOG
  - Flush COMMIT Record to LOG

→ **Durability**

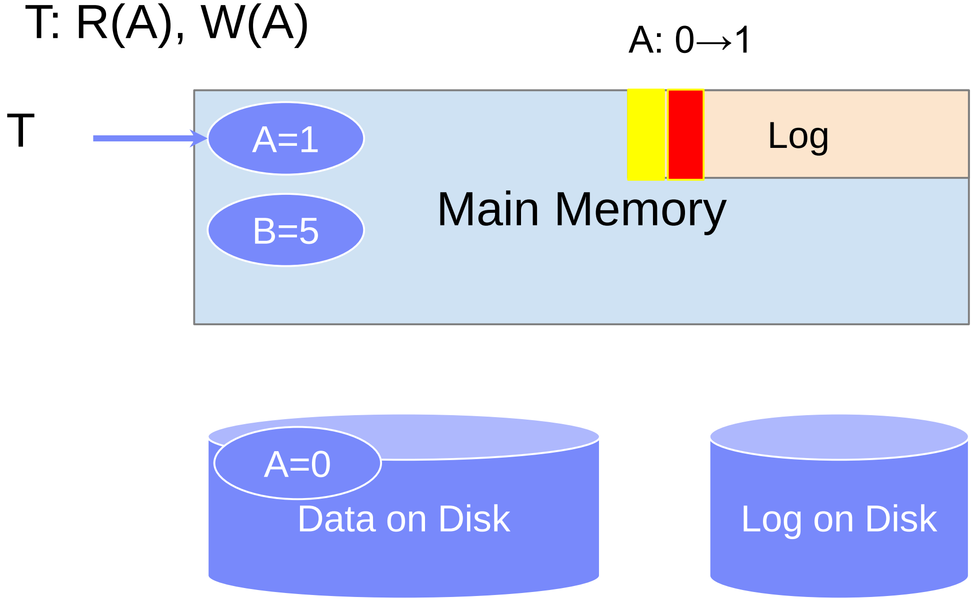
→ **Atomicity**

Transaction is committed *once COMMIT record is on stable storage*



Incorrect Commit Protocol #1

T: R(A), W(A)



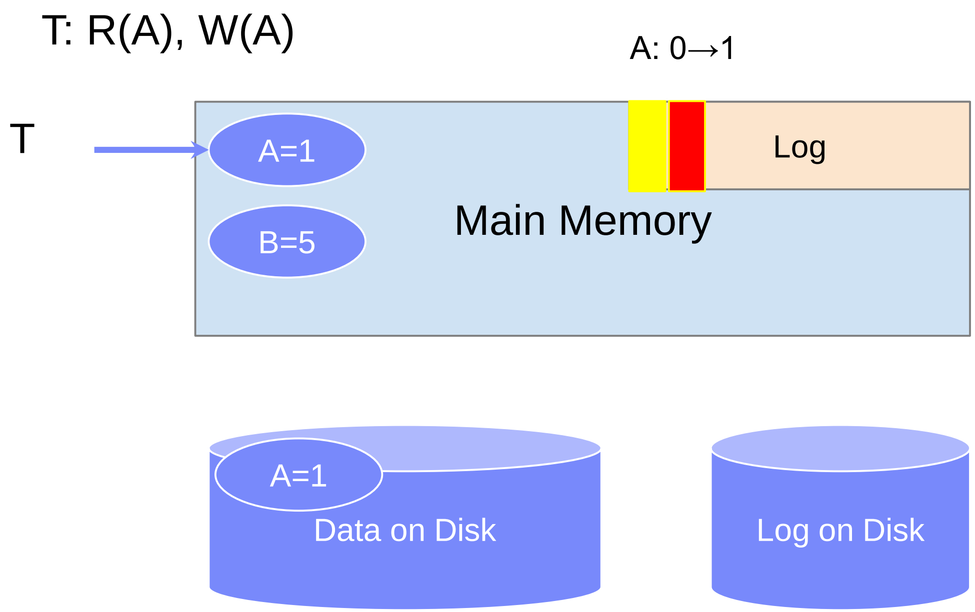
Let's try committing *before* we've written either data or log to disk…

OK, Commit!

If we crash now, is T durable?

Lost T's update!

Incorrect Commit Protocol #2



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??

Bank interest example: full run

Money

Account	....	Balance ($)
3001		500
4001		100
5001		20
6001		60
3002		80
4002		-200
5002		320
...		...
30108		-100
40008		100
50002		20

Money (@4:29 am day+1)

Account	....	Balance ($)
3001		550
4001		110
5001		22
6001		66
3002		88
4002		-220
5002		352
...		
30108		-110
40008		110
50002		22

WAL (@4:29 am day+1)

Update Records

Commit Record

T-Monthly-423	**START TRANSACTION**		
T-Monthly-423	3001	500	550
T-Monthly-423	4001	100	110
T-Monthly-423	5001	20	22
T-Monthly-423	6001	60	66
T-Monthly-423	3002	80	88
T-Monthly-423	4002	-200	-220
T-Monthly-423	5002	320	352
T-Monthly-423	...	...	...
T-Monthly-423	30108	-100	-110
T-Monthly-423	40008	100	110
T-Monthly-423	50002	20	22
T-Monthly-423	**COMMIT**		

‘T-Monthly-423’

Monthly Interest 10%

4:28 am Starts run on 10M bank accounts

Takes 24 hours to run

```
START TRANSACTION
        UPDATE Money
        SET Amt = Amt * 1.10
COMMIT
```

Bank interest example: with crash

Money

Account	....	Balance ($)
3001		500
4001		100
5001		20
6001		60
3002		80
4002		-200
5002		320
...		...
30108		-100
40008		100
50002		20

Money (@10:45 am)

Account	....	Balance ($)	
3001		550	??
4001		110	
5001		22	
6001		66	
3002		88	
4002		-200	??
5002		320	??
...			
30108		-110	
40008		110	
50002		22	??

WAL log (@10:29 am)

T-Monthly-423	**START TRANSACTION**		
T-Monthly-423	3001	500	550
T-Monthly-423	4001	100	110
T-Monthly-423	5001	20	22
T-Monthly-423	6001	60	66
T-Monthly-423	3002	80	88
T-Monthly-423	...	...	...
T-Monthly-423	30108	-100	-110
T-Monthly-423	40008	100	110
T-Monthly-423	50002	20	22
T-Monthly-423	4002	-200	-220
T-Monthly-423	5002	320	352

'T-Monthly-423'

Monthly Interest 10%

4:28 am Starts run on 10M bank accounts

Takes 24 hours to run

Network outage at 10:29 am,

System access at 10:45 am

Did T-Monthly-423 complete?

Which tuples are bad?

Case1: T-Monthly-423 was crashed

Case2: T-Monthly-423 completed. 4002 deposited 20$ at 10:45 am

Bank interest example: with recovery

Money (@10:45 am)

Account	....	Balance ($)
3001		550
4001		110
5001		22
6001		66
3002		88
4002		-200
5002		320
...		
30108		-110
40008		110
50002		22

Money (after recovery)

Account	....	Balance ($)
3001		500
4001		100
5001		20
6001		60
3002		80
4002		-200
5002		320
...		...
30108		-100
40008		100
50002		20

WAL log (@10:29 am)

T-Monthly-423	START TRANSACTION		
T-Monthly-423	3001	500	550
T-Monthly-423	4001	100	110
T-Monthly-423	5001	20	22
T-Monthly-423	6001	60	66
T-Monthly-423	3002	80	88
T-Monthly-423	...	...	...
T-Monthly-423	30108	-100	-110
T-Monthly-423	40008	100	110
T-Monthly-423	50002	20	22

System recovery (after 10:45 am)

1. Rollback uncommitted transactions
   - Restore old values from WALlog (if any)
   - Notify developers about aborted txn
1. Redo Recent transactions (w/ new values)
2. Back in business; Redo (any pending) transactions

A word on performance

- Question: why is a WAL a good idea?
- Answer: updates to WAL are in sequential order!

- Recall: sequential writes are very important both for flash and magnetic disk
  - In a couple of lectures we will understand why

An example of why sequential writes matter

Money

Account	....	Balance ($)
3001		500
4001		100
5001		20
6001		60
3002		80
4002		-200
5002		320
...	...	
30108		-100
40008		100
50002		20

Money (@4:29 am day+1)

Account	....	Balance ($)
3001		550
4001		110
5001		22
6001		66
3002		88
4002		-220
5002		352
...		
30108		-110
40008		110
50002		22

WAL (@4:29 am day+1)

T-Monthly-423	**START TRANSACTION**		
T-Monthly-423	3001	500	550
T-Monthly-423	4001	100	110
T-Monthly-423	5001	20	22
T-Monthly-423	6001	60	66
T-Monthly-423	3002	80	88
T-Monthly-423	4002	-200	-220
T-Monthly-423	5002	320	352
T-Monthly-423	...	...	...
T-Monthly-423	30108	-100	-110
T-Monthly-423	40008	100	110
T-Monthly-423	50002	20	22
T-Monthly-423	**COMMIT**		

Cost to update all data

10M bank accounts → 10M individual random writes? (worst case)

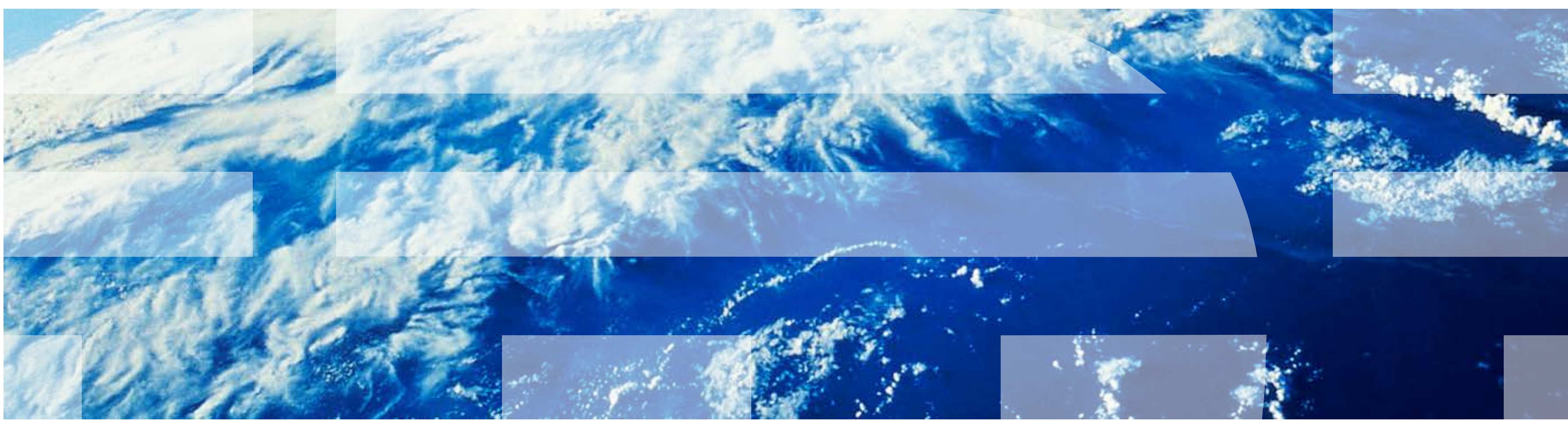
(@10 ms per write for magnetic disk, that's 100,000 secs)

Speedup for commit

100,000 secs vs 1 sec when written sequentially!!!

Borrowed from Shiva Shivakumar

Concurrency and Locking for Transactions



Back to our bank example

Money

Account	....	Balance ($)
3001		500
4001		100
5001		20
6001		60
3002		80
4002		-200
5002		320
...		...
30108		-100
40008		100
50002		20

Money (@4:29 am day+1)

Account	....	Balance ($)
3001		550
4001		110
5001		22
6001		66
3002		88
4002		-220
5002		352
...		
30108		-110
40008		110
50002		22

'T-Monthly-423'

Monthly Interest 10%
4:28 am Starts run on 10M bank accounts
Takes 24 hours to run

```
UPDATE Money
SET Balance = Balance * 1.1
```

Other Transactions

10:02 am Acct 3001: Wants 600$
11:45 am Acct 5002: Wire for 1000$
. . . . .
. . . . .
2:02 pm Acct 3001: Debit card for $12.37

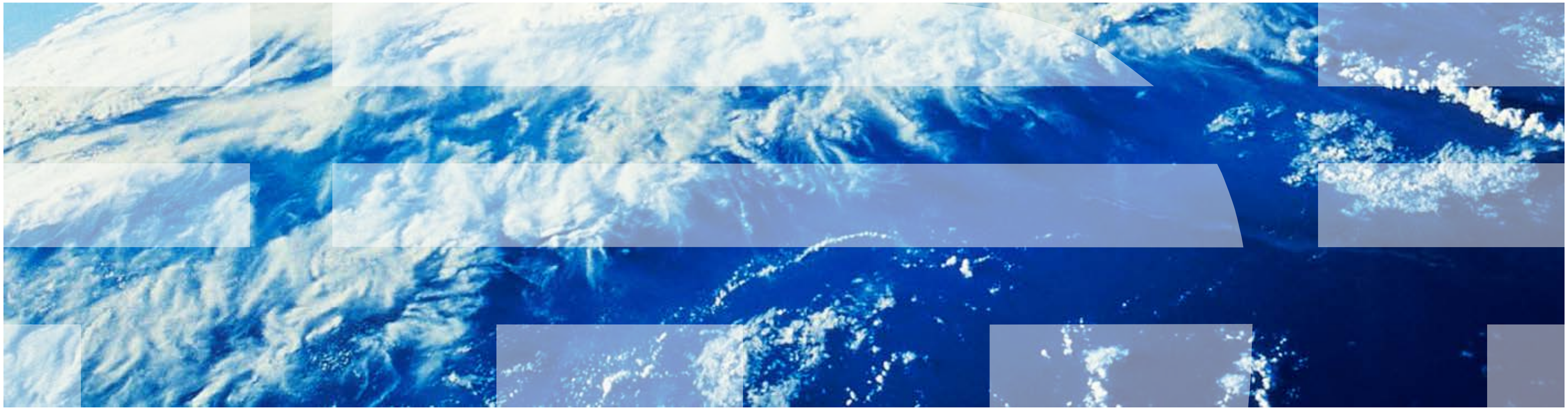
Q: How do I not wait for a day to access my $$$s?

Big idea: locks

- Intuition
  - ”Lock” each record for shortest time possible

- Key questions
  - Which records?
  - For how long?
  - What is the algorithm for holding them?

Concurrency, Scheduling and Anomalies



Concurrency: Isolation & Consistency

- DB is responsible for concurrency so that…

Isolation is maintained: Users must be able to execute each TXN as if they were the only user

AC**I**D

Consistency is maintained: TXNs must leave the DB in consistent state

A**C**ID

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

Note:

1. DB does not care if T1 —> T2 or T2 —> T1 (which TXN executes first)
2. If developer does, what can they do? (Put T1 and T2 inside 1 TXN)

Example

T_1 | A += 100 | B -= 100 | T1 transfers $100 from B's account to A's account

T_2 | A *= 1.06 | B *= 1.06 | T2 credits both accounts with a 6% interest payment

Goal for scheduling transactions:

- Interleave transactions to boost performance
- Data stays in a good state after commits and/or aborts (ACID)

Example- consider two TXNs:

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

T_1 A += 100 B -= 100

T_2 A *= 1.06 B *= 1.06

Time

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… DB allows!

T_1 A += 100 B -= 100

T_2 A *= 1.06 B *= 1.06

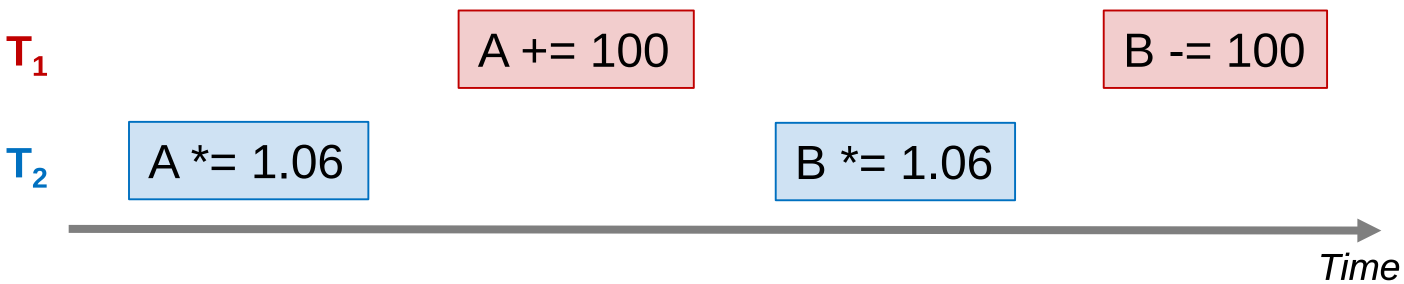
Time

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 DB 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…

Interleaving & Isolation

- The DB 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

DB 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

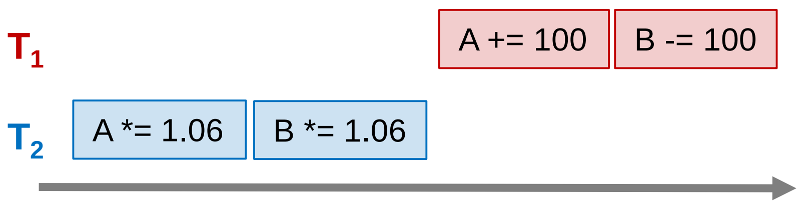
Different result than serial T_1,T_2!

Scheduling examples

Starting Balance

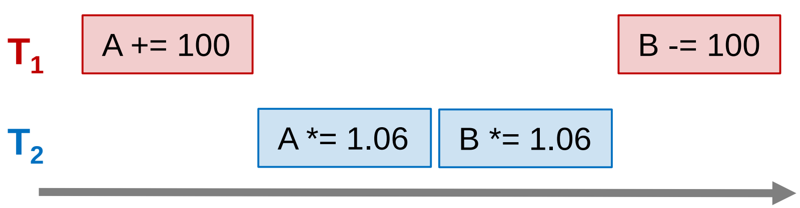
A	B
\$50	\$200

Serial schedule ***T_2,T_1:***



A	B
\$153	\$112

Interleaved schedule B:

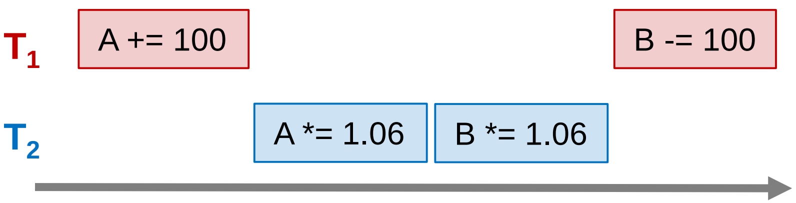


A	B
\$159	\$112

Different result than serial T_2,T_1 ALSO!

Scheduling examples

Interleaved schedule B:



This schedule is different than ***any serial order!*** We say that it is **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!

Serial Schedules

T1		A += 100	B -= 100		
T2				A *= 1.06	B*= 1.06

S1

T1				A += 100	B -= 100
T2		A *= 1.06	B *= 1.06		

S2

Interleaved Schedules

T1		A += 100		B -= 100	
T2			A *= 1.06		B*= 1.06

S3

T1			A += 100		B -= 100
T2		A *= 1.06		B *= 1.06	

S4

T1			A += 100	B -= 100	
T2		A *= 1.06			B*= 1.06

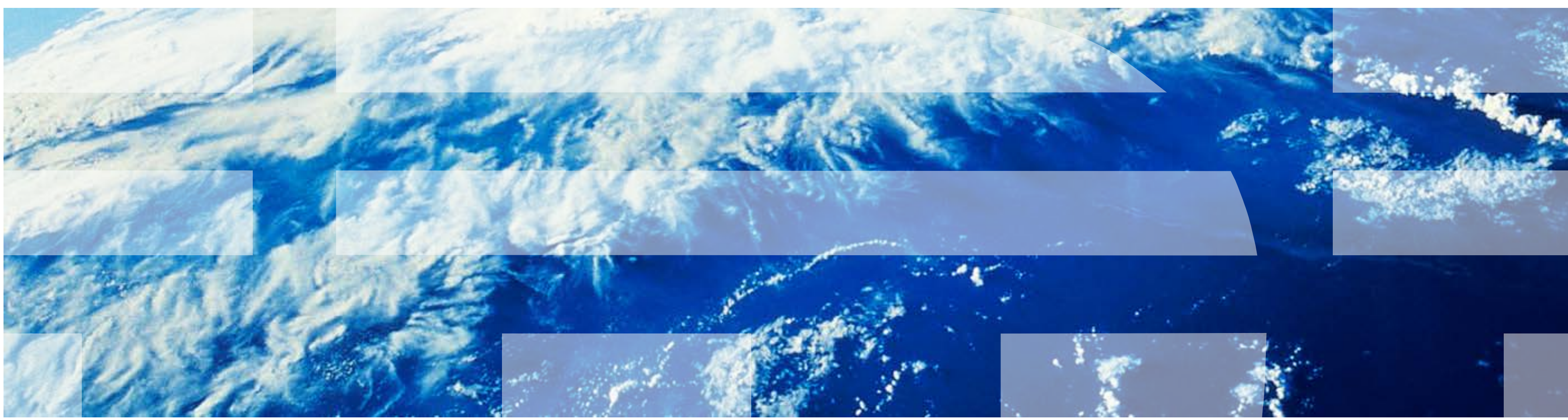
S5

T1		A += 100			B -= 100
T2			A *= 1.06	B *= 1.06	

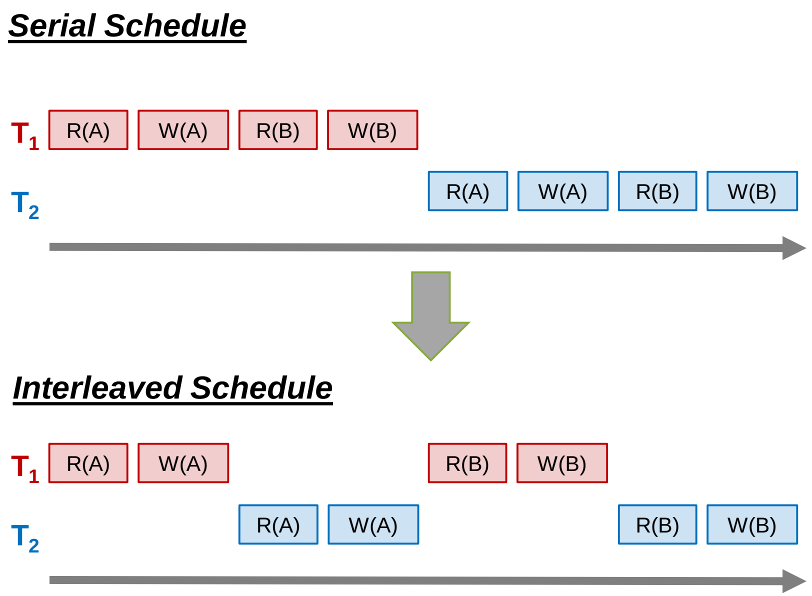
S6

Serial Schedules	S1, S2
Serializable Schedules	S3, S4 (And S1, S2)
Equivalent Schedules	<S1, S3> <S2, S4>
Non-serializable (Bad) Schedules	S5, S6

Conflicts and Anomalies



General DB model:
Concurrency as Interleaving TXNs



Each action in the TXNs *reads a value* and then *writes one back*

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

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

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:

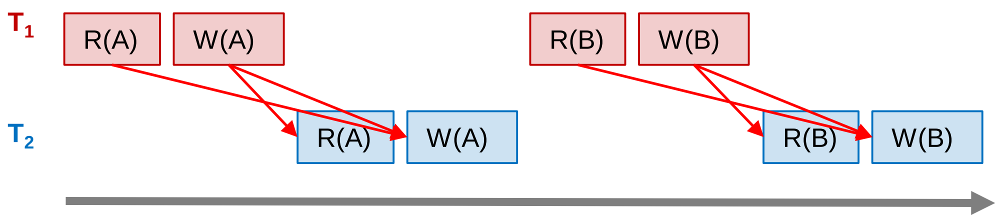
- Read-Write conflicts (RW)
- Write-Read conflicts (WR)
- Write-Write conflicts (WW)

Why no "RR Conflict"?

Note: **<u>conflicts</u>** happen often in many real world transactions. (E.g., two people trying to book an airline ticket)

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”!

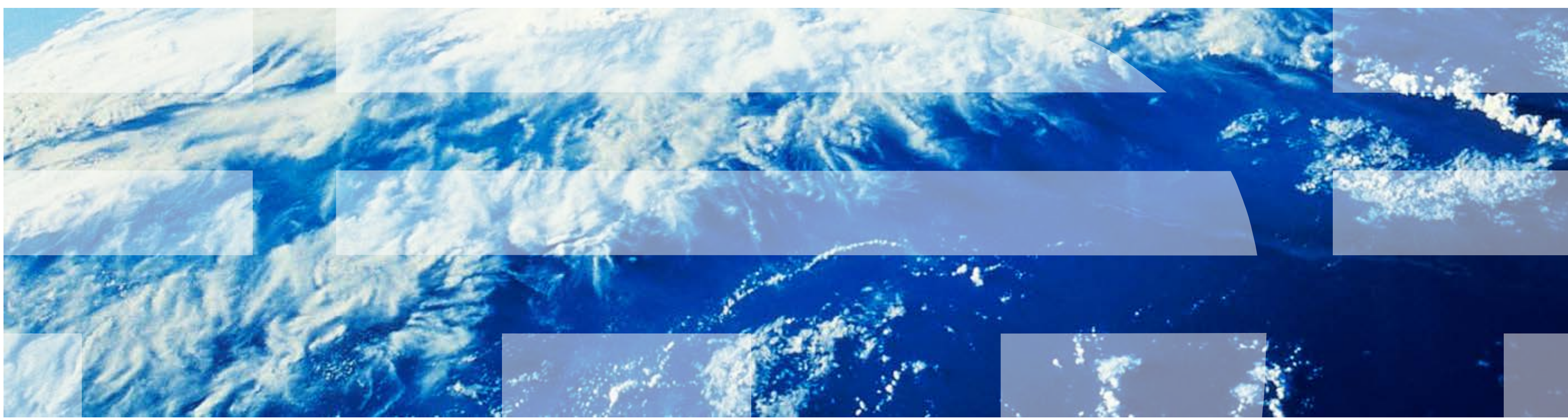
Note: Conflicts vs. Anomalies

Conflicts are in both “good” and “bad” schedules
(they are a property of transactions)

Goal: Avoid Anomalies while interleaving transactions with conflicts!

- Do not create “bad” schedules where isolation and/or consistency is broken (i.e., Anomalies)

Conflict Serializability



Conflict Serializability

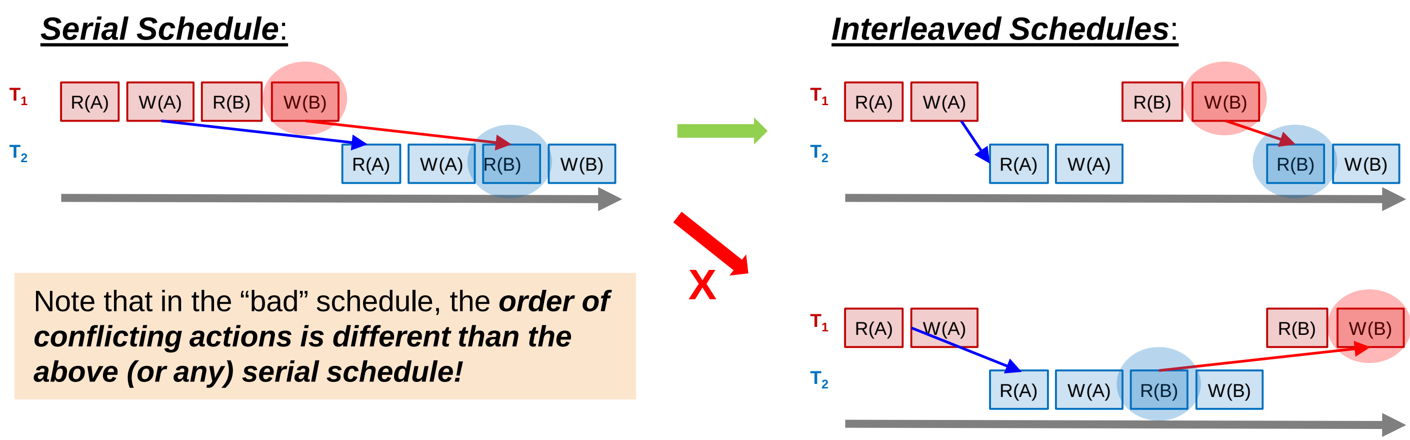
Two schedules are **conflict equivalent** if:

- 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!

Example **"Good" vs. "bad" schedules**

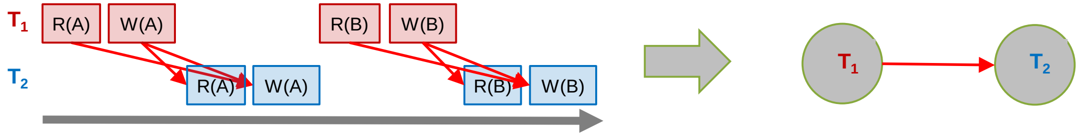


Note that in the "bad" schedule, the ***order of conflicting actions is different than the above (or any) serial schedule!***

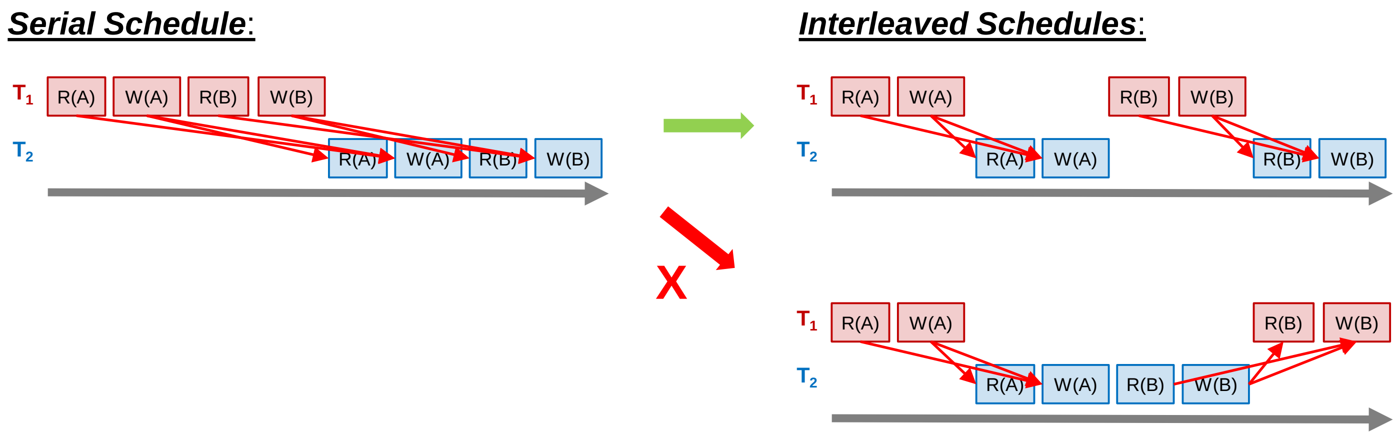
Conflict serializability provides us with an operative notion of "good" vs. "bad" schedules! "Bad" schedules create data <u>Anomalies</u>

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**

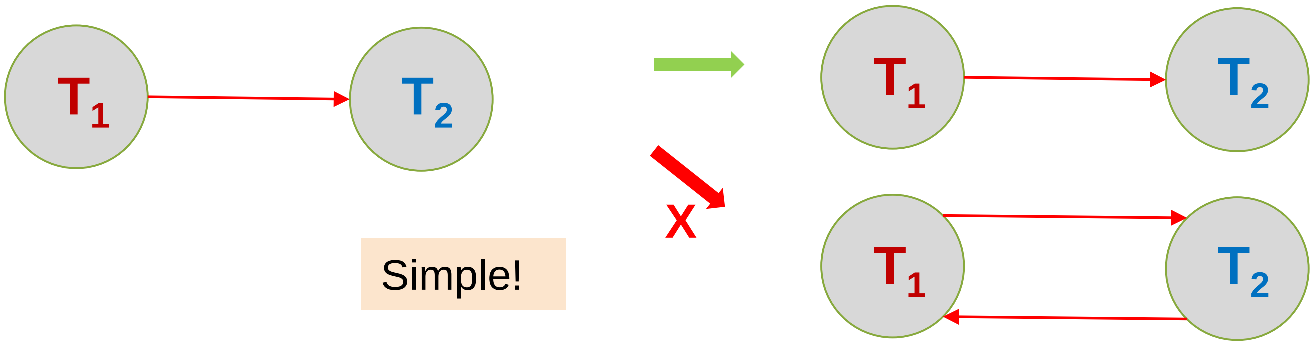


What can we say about "good" vs. "bad" conflict graphs?



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

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

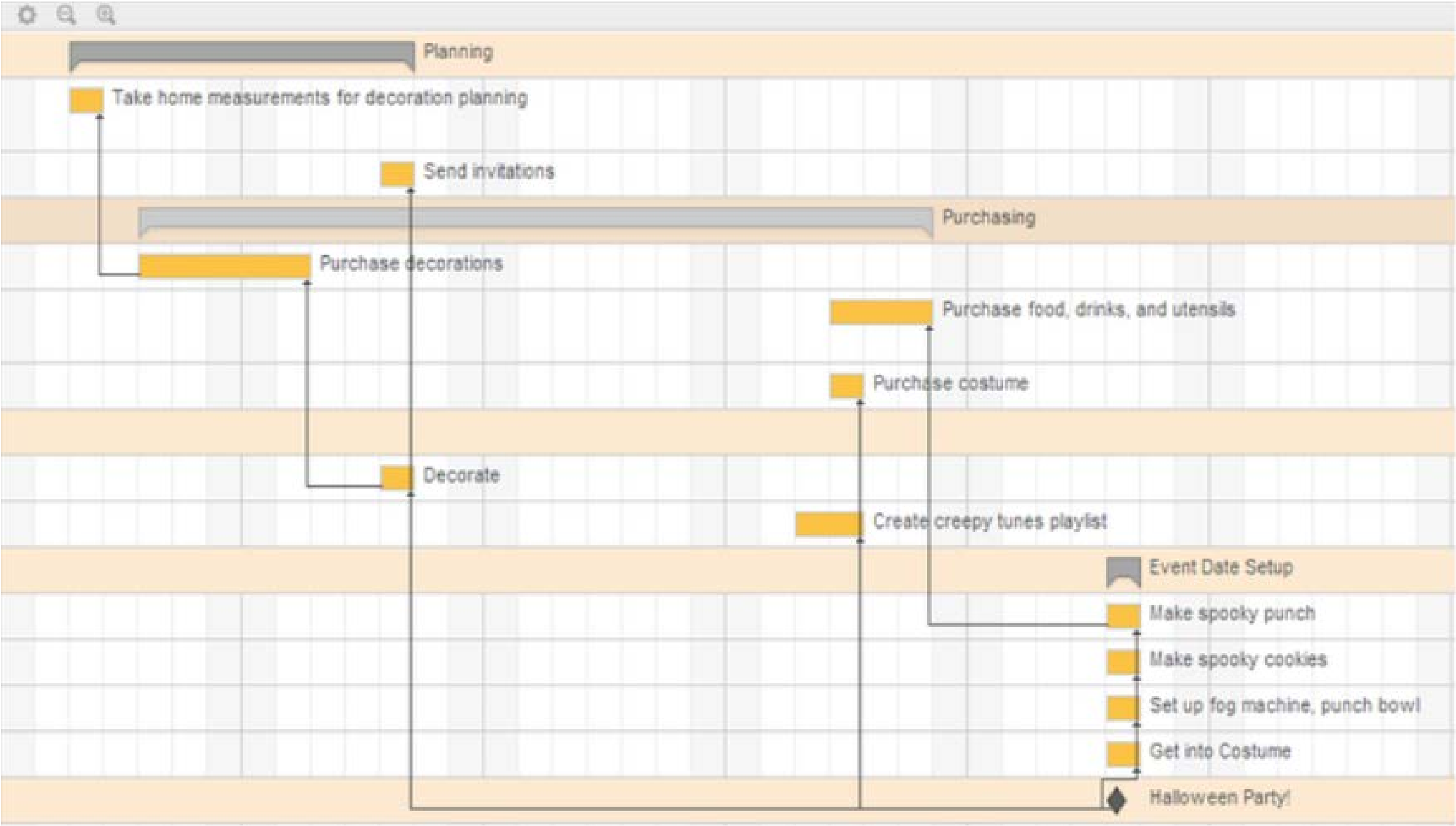


Theorem: Schedule is **conflict serializable** if and only if its conflict graph is **acyclic**

DAGs & Topological Orderings

- A **topological ordering** of a directed graph is a linear ordering of its vertices that respects all the directed edges
- A directed <u>**acyclic**</u> graph (DAG) always has one or more **topological orderings**
  - (And there exists a topological ordering *if and only if* there are no directed cycles)

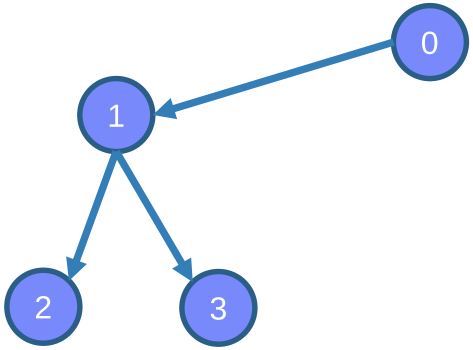
Example: Project dependencies



How would you plan?
What if there are cycles? (dependencies)

DAGs & Topological Orderings

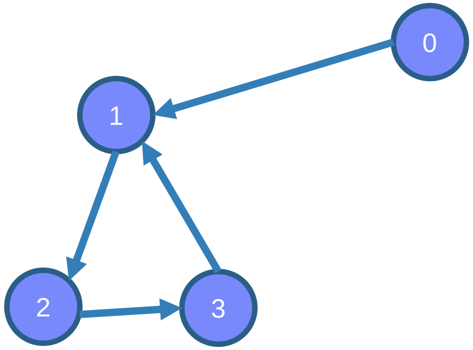
- Ex: What is one possible topological ordering here?



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 **<u>acyclic</u>** conflict graph → conflict serializable!

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

Example with 5 transactions

Schedule S1

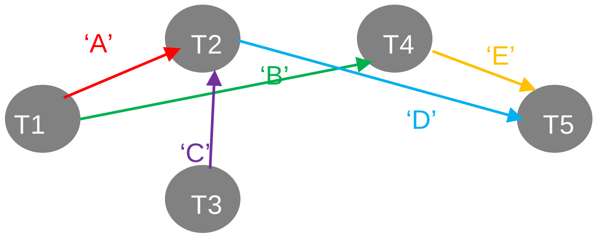
Good or Bad schedule?
Conflict serializable?

w1(A)	r2(A)	w1(B)	w3(C)	r2(C)	r4(B)	w2(D)	w4(E)	r5(D)	w5(E)

<u>Step1</u>
Find conflicts
(RW, WW, WR)

T1	w1(A)		w1(B)							
T2		r2(A)			R2(C)		w2(D)			
T3				w3(C)						
T4						r4(B)		w4(E)		
T5									r5(D)	w5(E)

<u>Step2</u>
Build Conflict graph
Acyclic?



Acyclic
⇒ Conflict serializable!
⇒ Serializable

S2

<u>Step3</u>
Example serial schedule
Conflict Equiv to S1

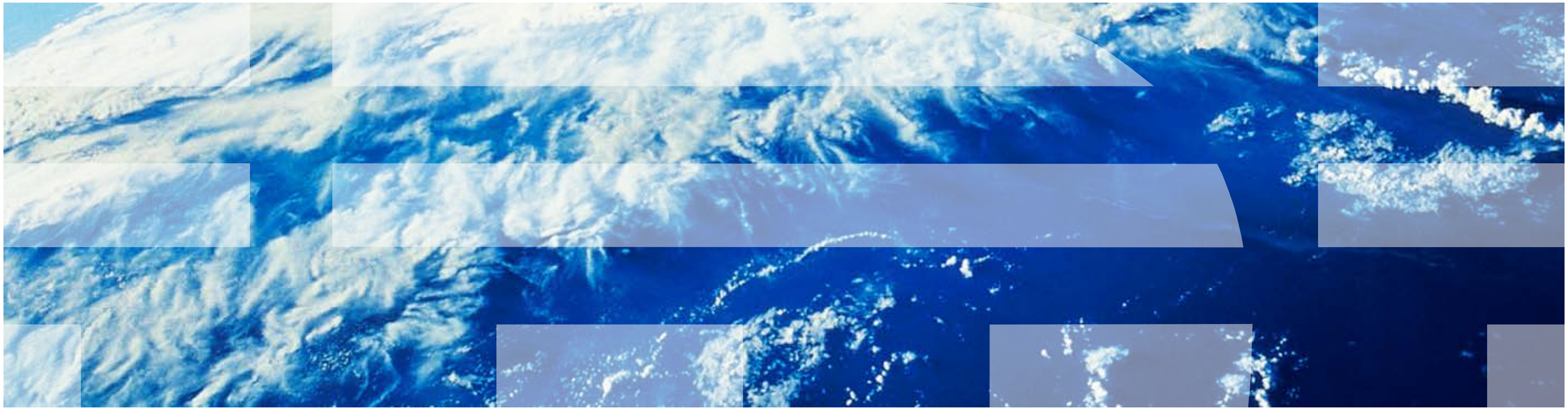
T3	T1	T1	T4	T4	T2	T2	T2	T5	T5
w3(C)	w1(A)	w1(B)	r4(B)	w4(E)	r2(A)	r2(C)	w2(D)	r5(D)	w5(E)

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**

2PL: A Simple Locking Algorithm



Strict Two-Phase Locking (2PL)

- Algorithm: *strict two-phase locking* - as a way to deal with concurrency
    - Guarantees conflict serializability
    - (if it completes- see upcoming…)

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

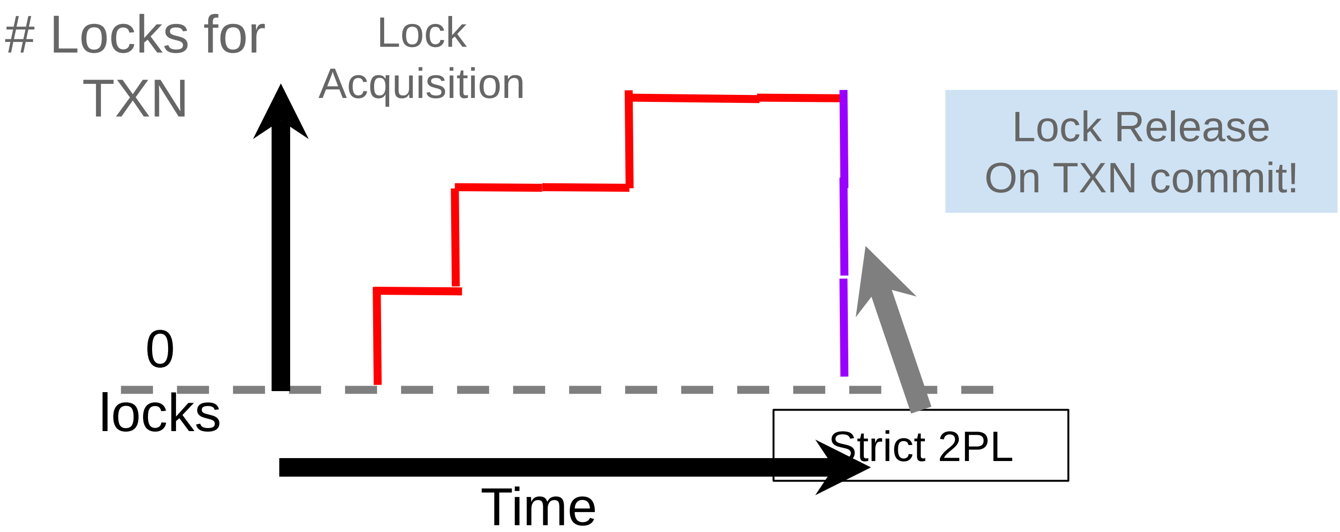
Strict Two-phase Locking (2PL) Protocol

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)



2PL: A transaction can not request additional locks once it releases any locks. Thus, there is a “growing phase” followed by a “shrinking phase”.

Strict 2PL: Release locks only at COMMIT (COMMIT Record flushed) or ABORT

Strict 2PL

If a schedule follows strict 2PL, it is **conflict serializable**…

- …and thus serializable
- …and we get isolation & consistency!

Popular implementation

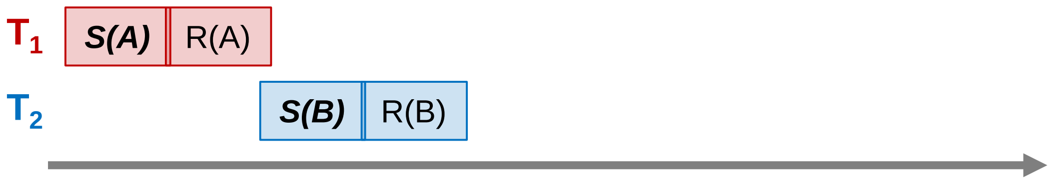
- Simple !
- Produces subset of *all* conflict serializable schedules
- There are MANY more complex LOCKING schemes with better performance. (See CS Database classes)

- One key, subtle problem (next)

Deadlock Detection

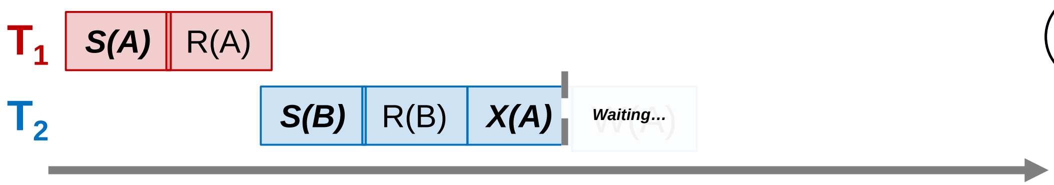
First, T_1 requests a shared lock on A to read from it

Deadlock Detection



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

Deadlock Detection: Example

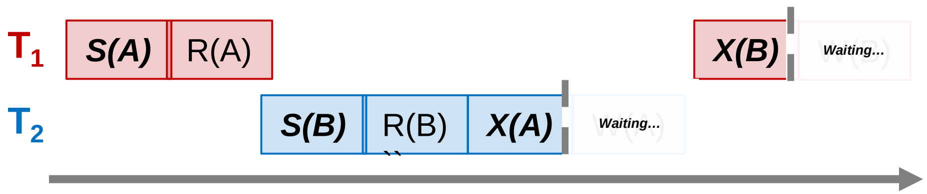


Waits-for graph:

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

Waits-For graph: Track which Transactions are waiting
<u>IMPORTANT</u>: WAITS-FOR graph different than CONFLICT graph we learnt earlier !

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!**

Deadlocks

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

Two ways of dealing with deadlocks:

- Deadlock prevention
- Deadlock detection

Deadlock Prevention

Conservative 2 Phase Locking (C2PL)

- Obtains all locks before the transaction begins
- If cannot obtain ALL locks, release and try again

- Ensures that no deadlocks occurs
- BUT: can degrade performance

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

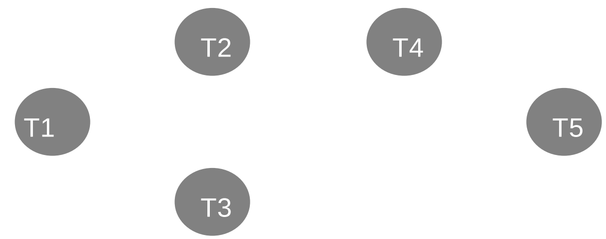
Example with 5 Transactions (2PL)

Schedule S1

w1(A)	r2(A)	w1(B)	w3(C)	r2(C)	r4(B)	w2(D)	w4(E)	r5(D)	w5(E)

Execute with 2PL

T1 **T2** **T3** **T4** **T5**



Waits- For Graph

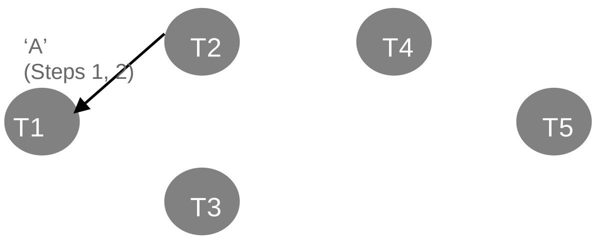
Example with 5 Transactions (2PL)

Schedule S1

w1(A)	r2(A)	w1(B)	w3(C)	r2(C)	r4(B)	w2(D)	w4(E)	r5(D)	w5(E)

Execute with 2PL

	T1	T2	T3	T4	T5
Step 0	X (A) w1(A)				
Step 1		Req S(A)			
Step 2	X (B) w1(B) Unl B, A				
Step 3		Get S(A) r2(A)			
Step 4			X (C) w3(C) Unl C		
Step 5		S(C) r2(C)			
Step 6				S(B) r4(B)	
Step 7		X(D) w2(D) Unl A, C, D			
Step 8				X(E) w4(E) Unl B,E	
Step 9					S(D) r5(D)
Step 10					X (E) w5(E) Unl D, E



Waits- For Graph

Summary

Locking allows only conflict serializable schedules

- If the schedule completes… (it may deadlock!)