Transactions: ACID,
Concurrency control (2PL, OCC)
Intro to distributed txns

COS 418: *Advanced Computer Systems*
Lecture 5

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The transaction

- *Definition:* A unit of work:
  - May consist of **multiple** data accesses or updates
  - Must **commit** or **abort** as a **single atomic unit**
- Transactions can either **commit,** or **abort**
  - When **commit,** all updates performed on database are made permanent, visible to other transactions
  - When **abort,** database restored to a state such that the aborting transaction never executed

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Defining properties of transactions

- **Atomicity:** Either **all** constituent operations of the transaction complete successfully, or **none** do
- **Consistency:** Each transaction in isolation preserves a set of **integrity constraints** on the data
- **Isolation:** Transactions' behavior not impacted by presence of **other concurrent transactions**
- **Durability:** The transaction's **effects survive failure** of volatile (memory) or non-volatile (disk) storage

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Goal #1: Handle failures
Atomicity and Durability

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Account transfer transaction

- Transfers $10 from account **A** to account **B**

```
Txn transfer(A, B):
begin_tx
a ← read(A)
if a < 10 then abort_tx
else   write(A, a−10)
       b ← read(B)
       write(B, b+10)
       commit_tx
```


Problem

```
Txn transfer(A, B):
begin_tx
a ← read(A)
if a < 10 then abort_tx
else   write(A, a−10)
       b ← read(B)
       write(B, b+10)
       commit_tx
```

- Suppose $100 in A, $100 in B
- commit_tx starts commit protocol:
  - write(A, $90) to disk
  - write(B, $110) to disk
- What happens if **system crash after first write,** but **before second write?**
  - After recovery: Partial writes, **money is lost**

Lack atomicity in the presence of failures

How to ensure atomicity?

- ***Log:*** A sequential file that stores information about transactions and system state
  - Resides in **separate, non-volatile storage**
- One entry in the log for each update, commit, abort operation: called a ***log record***
- Log record contains:
  - Monotonic-increasing ***log sequence number*** (LSN)
  - **Old value** (***before image***) of the item for **undo**
  - **New value** (***after image***) of the item for **redo**

Write-ahead Logging (WAL)

- Ensures atomicity in the event of system crashes under no-force/steal buffer management

1. **Force all log records** pertaining to an updated page into the (non-volatile) log **before any writes to page itself**
2. A transaction is not considered committed until **all log records** (including commit record) are **forced into log**

WAL example

force_log_entry(A, old=$100, new=$90)
force_log_entry(B, old=$100, new=$110)
write(A, $90)
write(B, $110)
force_log_entry(commit)

Does **not** have to flush to disk

- What if the commit log record size > the page size?
- How to ensure **each log record** is written atomically?
  - **Write a checksum** of entire log entry

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Goal #2: Concurrency control
Transaction **Isolation**

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Two concurrent transactions

transaction **sum(A, B)**:
begin_tx
a ← read(A)
b ← read(B)
print a + b
commit_tx

transaction **transfer(A, B)**:
begin_tx
a ← read(A)
if a < 10 **then** *abort_tx*
else write(A, a−10)
b ← read(B)
write(B, b+10)
commit_tx

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Isolation between transactions

- **Isolation: sum** appears to happen either completely before or completely after **transfer**
- *Schedule* for transactions is an ordering of the operations performed by those transactions

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Problem for concurrent execution: Inconsistent retrieval

- **Serial execution** of transactions—transfer then sum:

transfer: r_A w_A r_B w_B ©

sum: debit credit r_A r_B ©

- Concurrent execution resulting in ***inconsistent retrieval,*** result differing from any serial execution:

transfer: r_A w_A r_B w_B ©

sum: debit r_A r_B © credit

Time →

© = commit

Equivalence of schedules

Two **operations** from **different transactions** are ***conflicting*** if:

1. They **read** and **write** to the **same data item**
2. The **write** and **write** to the **same data item**

Two **schedules** are ***equivalent*** if:

1. They contain the same transactions and operations
2. They **order** all **conflicting** operations of non-aborting transactions in the **same way**

Serializability

- A schedule is ***conflict serializable*** if it is equivalent to some serial schedule
  - *i.e.,* **non-conflicting** operations can be **reordered** to get a **serial** schedule

How to ensure a serializable schedule?

- Locking-based approaches
- **Strawman 1: Big Global Lock**
  - Acquire the lock when transaction starts
  - Release the lock when transaction ends

Results in a ***serial*** transaction schedule at the **cost of performance**

Locking

- Locks maintained by **transaction manager**
  - Transaction requests lock **for a data item**
  - Transaction manager **grants** or **denies** lock
- **Lock types**
  - ***Shared:*** Need to have before read object
  - ***Exclusive:*** Need to have before write object

	Shared (S)	**Exclusive (X)**
Shared (S)	Yes	No
Exclusive (X)	No	No

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How to ensure a serializable schedule?

- **Strawman 2:** Grab locks **independently**, for each data item (*e.g.,* bank accounts A and B

transfer: ◢$_A$ r_A w_A ◣$_A$ ◢$_B$ r_B w_B ◣$_B$ ©

sum: ◿$_A$ r_A ◺$_A$ ◿$_B$ r_B ◺$_B$ ©

Permits this **non-serializable** interleaving

Time →

© = commit

◢ / ◿ = **eXclusive- / Shared-lock**; ◣ / ◺ = **X- / S-unlock**

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Two-phase locking (2PL)

- **2PL rule:** Once a transaction has **released** a lock it is **not allowed to obtain** any other locks
- A **growing phase** when transaction acquires locks
- A **shrinking phase** when transaction releases locks
- In practice:
  - Growing phase is the entire transaction
  - Shrinking phase is during commit

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2PL allows only serializable schedules

- **2PL rule:** Once a transaction has **released** a lock it is **not allowed to obtain** any other locks

transfer: ◢$_A$ r_A w_A ◣$_A$ ◢$_B$ r_B w_B ◣$_B$ ©

sum: ◿$_A$ r_A ◺$_A$ ◿$_B$ r_B ◺$_B$ ©

2PL **precludes** this **non-serializable** interleaving

Time →

© = commit

◢ / ◿ = **X- / S-lock**; ◣ / ◺ = **X- / S-unlock**

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2PL and transaction concurrency

- **2PL rule:** Once a transaction has **released** a lock it is **not allowed to obtain** any other locks

transfer: ⊿$_A$ r_A ◢$_A$ w_A ⊿$_B$ r_B ◢$_B$ w_B ✻©

sum: ⊿$_A$ r_A ⊿$_B$ r_B ✻©

2PL **permits** this **serializable, interleaved** schedule

Time →

© = commit

◢ / ⊿ = **X- / S-lock**; ◣ / ◺ = **X- / S-unlock**

✻ **= release all locks**

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Serializability versus linearizability

- **Linearizability** is a guarantee about **single** operations on **single** objects
  - Once write completes, all later reads (by wall clock) should reflect that write
- **Serializability** is a guarantee about **transactions** over **one or more** objects
  - Doesn't impose real-time constraints

- **Linearizability + serializability =** ***strict serializability***
  - Transaction behavior equivalent to some serial execution
    - **And** that serial execution **agrees with real-time**

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Recall: lock-based concurrency control

- **Big Global Lock:** Results in a **serial** transaction schedule at the cost of performance

- **Two-phase locking with finer-grain locks:**
  - **Growing phase** when txn acquires locks
  - **Shrinking phase** when txn releases locks (typically commit)
  - Allows txn to execute concurrently, improving performance

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Q: What if access patterns rarely, if ever, conflict?

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Be optimistic!

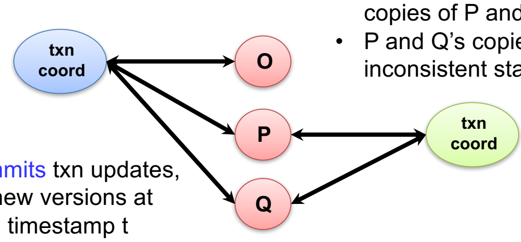
- Goal: Low overhead for non-conflicting txns
- Assume success!
  - Process transaction as if would succeed
  - Check for serializability only at commit time
  - If fails, abort transaction
- **Optimistic Concurrency Control (OCC)**
  - Higher performance when few conflicts vs. locking
  - Lower performance when many conflicts vs. locking

OCC: Three-phase approach

- **Begin:** Record timestamp marking the transaction's beginning
- **Modify** phase:
  - Txn can read values of committed data items
  - Updates only to local copies (versions) of items (in db cache)
- **Validate** phase
- **Commit** phase
  - If validates, transaction's updates applied to DB
  - Otherwise, transaction restarted
  - Care must be taken to avoid "TOCTTOU" issues

OCC: Why validation is necessary

- New txn creates shadow copies of P and Q
- P and Q's copies at inconsistent state



When commits txn updates, create new versions at some timestamp t

OCC: Validate Phase

- Transaction is about to commit.
  System must ensure:
  - Initial consistency: Versions of accessed objects at start consistent
  - No conflicting concurrency: No other txn has committed an operation at object that conflicts with one of this txn's invocations

OCC: Validate Phase

- Validation needed by transaction T to commit:
- For all other txns O either **committed** or **in validation** phase, one of following holds:
  A. O completes commit before T starts modify
  B. T starts commit after O completes commit, and ReadSet T and WriteSet O are disjoint
  C. Both ReadSet T and WriteSet T are disjoint from WriteSet O, and O completes modify phase.
- When validating T, first check (A), then (B), then (C). If all fail, validation fails and T aborted

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2PL & OCC = strict serialization

- Provides semantics as if only one transaction was running on DB at time, in serial order
  + Real-time guarantees
- 2PL: Pessimistically get all the locks first
- OCC: Optimistically create copies, but then recheck all read + written items before commit

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Distributed Transactions

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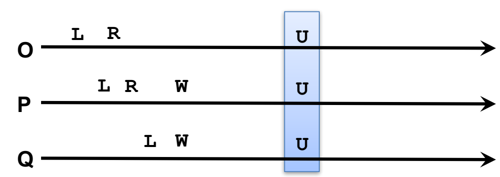
Consider partitioned data over servers



- Why not just use 2PL?
  - Grab locks over entire read and write set
  - Perform writes
  - Release locks (at commit time)

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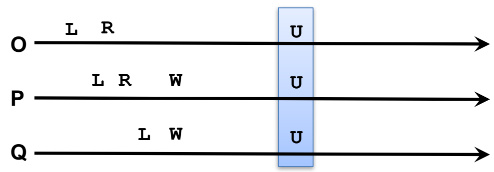
Consider partitioned data over servers



- How do you get serializability?
  - On single machine, single COMMIT op in the WAL
  - In distributed setting, assign global timestamp to txn (at sometime after lock acquisition and before commit)
    - Centralized txn manager
    - Distributed consensus on timestamp (not all ops)

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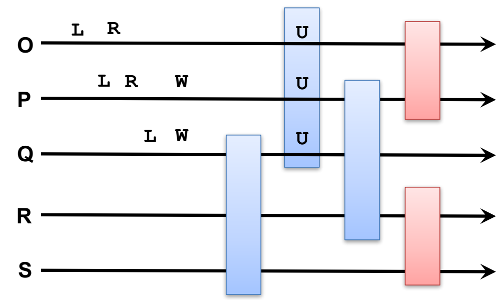
Strawman: Consensus per txn group?



- Single Lamport clock, consensus per group?
  - Linearizability composes!
  - But doesn't solve concurrent, non-overlapping txn problem

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Wednesday

Google Spanner

Distributed Transactions: Calvin, Rococo

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