CS162
Operating Systems and Systems Programming
Lecture 19
Transactions, Two Phase Locking (2PL), Two Phase Commit (2PC)

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Goals of Today's Lecture

- Transaction scheduling
- Two phase locking (2PL) and strict 2PL
- Two-phase commit (2PC)

Note: Some slides and/or pictures in the following are adapted from lecture notes by Mike Franklin.

Goals of Transaction Scheduling

- Maximize system utilization, i.e., concurrency
  - Interleave operations from different transactions
- Preserve transaction semantics
  - Semantically equivalent to a serial schedule, i.e., one transaction runs at a time

T1: R, W, R, W **T2:** R, W, R, R, W

Serial schedule (T1, then T2):
R, W, R, W, R, W, R, R, W

Serial schedule (T2, then T1):
R, W, R, R, W, R, W, R, W

Two Key Questions

1) Is a given schedule equivalent to a serial execution of transactions?

Schedule: R, R, W, W, R, R, R, W, W

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Serial schedule (T1, then T2):
R, W, R, W, R, W, R, R, W

Serial schedule (T2, then T1):
R, W, R, R, W, R, W, R, W

2) How do you come up with a schedule equivalent to a serial schedule?

Transaction Scheduling

- **Serial schedule:** A schedule that does not interleave the operations of different transactions
  - Transactions run serially (one at a time)
- **Equivalent schedules:** For any storage/database state, the effect (on storage/database) and output of executing the first schedule is identical to the effect of executing the second schedule
- **Serializable schedule:** A schedule that is equivalent to some serial execution of the transactions
  - Intuitively: with a serializable schedule you only see things that could happen in situations where you were running transactions one-at-a-time

Anomalies with Interleaved Execution

- May violate transaction semantics, e.g., some data read by the transaction changes before committing
- Inconsistent database state, e.g., some updates are lost
- Anomalies always involves a "write"; Why?

Anomalies with Interleaved Execution

- Read-Write conflict (Unrepeatable reads)

```
T1:R(A),           R(A),W(A)
T2:      R(A),W(A)
```

- Violates transaction semantics
- Example: Mary and John want to buy a TV set on Amazon but there is only one left in stock
  - (T1) John logs first, but waits…
  - (T2) Mary logs second and buys the TV set right away
  - (T1) John decides to buy, but it is too late…

Anomalies with Interleaved Execution

- Write-read conflict (reading uncommitted data)

```
T1:R(A),W(A),      W(A)
T2:          R(A),     …
```

- Example:
  - (T1) A user updates value of A in two steps
  - (T2) Another user reads the intermediate value of A, which can be inconsistent
  - Violates transaction semantics since T2 is not supposed to see intermediate state of T1

Anomalies with Interleaved Execution

- Write-write conflict (overwriting uncommitted data)

```
T1:W(A),           W(B)
T2:      W(A),W(B)
```

- Get T1's update of B and T2's update of A
- Violates transaction serializability
- If transactions were serial, you'd get either:
  - T1's updates of A and B
  - T2's updates of A and B

Conflict Serializable Schedules

- Two operations **conflict** if they
  - Belong to different transactions
  - Are on the same data
  - At least one of them is a write
- Two schedules are **conflict equivalent** iff:
  - Involve same operations of same transactions
  - Every pair of **conflicting** operations is ordered the same way
- Schedule S is **conflict serializable** if S is conflict equivalent to some serial schedule

Conflict Equivalence – Intuition

- If you can transform an interleaved schedule by swapping *consecutive non-conflicting* operations of *different transactions* into a serial schedule, then the original schedule is **conflict serializable**
- Example:

```
T1:R(A),W(A),           R(B),W(B)
T2:          R(A),W(A),           R(B),W(B)
```

⇩

```
T1:R(A),W(A),      R(B),      W(B)
T2:          R(A),      W(A),      R(B),W(B)
```

⇩

```
T1:R(A),W(A),R(B),           W(B)
T2:               R(A),W(A),      R(B),W(B)
```


Conflict Equivalence – Intuition (cont'd)

- If you can transform an interleaved schedule by swapping *consecutive non-conflicting* operations of *different transactions* into a serial schedule, then the original schedule is **conflict serializable**
- Example:

```
T1:R(A),W(A),R(B),               W(B)
T2:               R(A),W(A),R(B),W(B)
```

⇩

```
T1:R(A),W(A),R(B),      W(B)
T2:               R(A),      W(A),R(B),W(B)
```

⇩

```
T1:R(A),W(A),R(B),W(B)
T2:                    R(A),W(A),R(B),W(B)
```

Conflict Equivalence – Intuition (cont'd)

- If you can transform an interleaved schedule by swapping *consecutive non-conflicting* operations of *different transactions* into a serial schedule, then the original schedule is **conflict serializable**
- Is this schedule serializable?

```
T1:R(A),          W(A)
T2:      R(A),W(A),
```

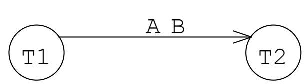

Dependency Graph

- **Dependency graph:**
  - Transactions represented as nodes
  - Edge from Ti to Tj:
    - » an operation of Ti conflicts with an operation of Tj
    - » Ti appears earlier than Tj in the schedule
- **Theorem:** Schedule is conflict serializable if and only if its dependency graph is acyclic

Example

- Conflict serializable schedule:

```
T1:R(A),W(A),              R(B),W(B)
T2:            R(A),W(A),            R(B),W(B)
```



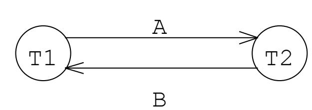
Dependency graph

- No cycle!

Example

- Conflict that is *not* serializable:

```
T1:R(A),W(A),                        R(B),W(B)
T2:            R(A),W(A),R(B),W(B)
```



Dependency graph

- Cycle: The output of T1 depends on T2, and vice-versa

Notes on Conflict Serializability

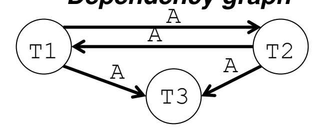
- Conflict Serializability doesn't allow all schedules that you would consider correct
  - This is because it is strictly *syntactic* - it doesn't consider the meanings of the operations or the data
- In practice, Conflict Serializability is what gets used, because it can be done efficiently
  - Note: in order to allow more concurrency, some special cases do get implemented, such as for travel reservations, …
- Two-phase locking (2PL) is how we implement it

Serializability ≠ Conflict Serializability

- Following schedule is **not** conflict serializable

```
T1:R(A),      W(A),
T2:     W(A),
T3:                 WA
```

Dependency graph



- However, the schedule is serializable since its output is equivalent with the following serial schedule

```
T1:R(A),W(A),
T2:          W(A),
T3:               WA
```

- Note: deciding whether a schedule is serializable (not conflict-serializable) is NP-complete

Locks

- "Locks" to control access to data
- Two types of locks:
  - shared (S) lock – multiple concurrent transactions allowed to operate on data
  - exclusive (X) lock – only one transaction can operate on data at a time

Lock Compatibility Matrix

	S	X
S	√	–
X	–	–

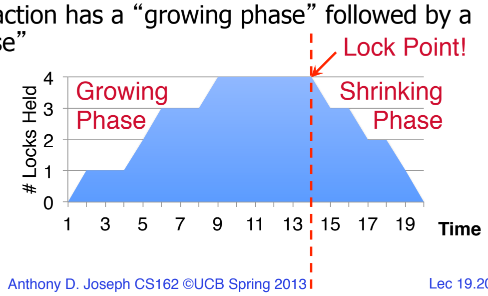
Two-Phase Locking (2PL)

1) Each transaction must obtain:
  - S (*shared*) or X (*exclusive*) lock on data before reading,
  - X (*exclusive*) lock on data before writing

2) A transaction can not request additional locks once it releases any locks

Thus, each transaction has a "growing phase" followed by a "shrinking phase"

Avoid deadlock by acquiring locks in some lexicographic order



Two-Phase Locking (2PL)

- 2PL guarantees conflict serializability
- Doesn't allow dependency cycles. Why?
- Answer: a dependency cycle leads to deadlock
  - Assume there is a cycle between Ti and Tj
  - Edge from Ti to Tj: Ti acquires lock first and Tj needs to wait
  - Edge from Tj to Ti: Tj acquires lock first and Ti needs to wait
  - Thus, both Ti and Tj wait for each other
  - Since with 2PL neither Ti nor Tj release locks before acquiring all locks they need → deadlock
- Schedule of conflicting transactions is conflict equivalent to a serial schedule ordered by "lock point"

Lock Management

- Lock Manager (LM) handles all lock and unlock requests
  - LM contains an entry for each currently held lock
- When lock request arrives see if anyone else holds a conflicting lock
  - If not, create an entry and grant the lock
  - Else, put the requestor on the wait queue
- Locking and unlocking are atomic operations
- Lock upgrade: share lock can be upgraded to exclusive lock

Example

- T1 transfers $50 from account A to account B

```
T1:Read(A),A:=A-50,Write(A),Read(B),B:=B+50,Write(B)
```

- T2 outputs the total of accounts A and B

```
T2:Read(A),Read(B),PRINT(A+B)
```

- Initially, A = $1000 and B = $2000
- What are the possible output values?
  - 3000, 2950, 3050

Is this a 2PL Schedule?

1	**Lock_X(A) <granted>**	
2	**Read(A)**	**Lock_S(A)**
3	**A: = A-50**	
4	**Write(A)**	
5	**Unlock(A)**	**<granted>**
6		**Read(A)**
7		**Unlock(A)**
8		**Lock_S(B) <granted>**
9	**Lock_X(B)**	
10		**Read(B)**
11	**<granted>**	**Unlock(B)**
12		**PRINT(A+B)**
13	**Read(B)**	
14	**B := B +50**	
15	**Write(B)**	
16	**Unlock(B)**	

No, and it is not serializable

Is this a 2PL Schedule?

1	Lock_X(A) <granted>	
2	Read(A)	Lock_S(A)
3	A: = A-50	
4	Write(A)	
5	Lock_X(B) <granted>	
6	Unlock(A)	<granted>
7		Read(A)
8		Lock_S(B)
9	Read(B)	
10	B := B +50	
11	Write(B)	
12	Unlock(B)	<granted>
13		Unlock(A)
14		Read(B)
15		Unlock(B)
16		PRINT(A+B)

Yes, so it is serializable

Cascading Aborts

- Example: T1 aborts
  - Note: this is a 2PL schedule

```
T1:R(A),W(A),           R(B),W(B), Abort
T2:            R(A),W(A)
```

- Rollback of T1 requires rollback of T2, since T2 reads a value written by T1
- Solution: **Strict Two-phase Locking (Strict 2PL)**: same as 2PL except
  - All locks held by a transaction are released only when the transaction completes

Strict 2PL (cont'd)

- All locks held by a transaction are released only when the transaction completes
- In effect, "shrinking phase" is delayed until:

  a) Transaction has committed (commit log record on disk), or

  b) Decision has been made to abort the transaction (then locks can be released after rollback)

Is this a Strict 2PL schedule?

1	Lock_X(A) <granted>	
2	Read(A)	Lock_S(A)
3	A: = A-50	
4	Write(A)	
5	Lock_X(B) <granted>	
6	Unlock(A)	<granted>
7		Read(A)
8		Lock_S(B)
9	Read(B)	
10	B := B +50	
11	Write(B)	
12	Unlock(B)	<granted>
13		Unlock(A)
14		Read(B)
15		Unlock(B)
16		PRINT(A+B)

No: Cascading Abort Possible

Is this a Strict 2PL schedule?

1	Lock_X(A) <granted>	
2	Read(A)	Lock_S(A)
3	A: = A-50	
4	Write(A)	
5	Lock_X(B) <granted>	
6	Read(B)	
7	B := B +50	
8	Write(B)	
9	Unlock(A)	
10	Unlock(B)	<granted>
11		Read(A)
12		Lock_S(B) <granted>
13		Read(B)
14		PRINT(A+B)
15		Unlock(A)
16		Unlock(B)

Quiz 19.1: Transactions

- Q1: True _ False _ It is possible for two read operations to conflict
- Q2: True _ False _ A strict 2PL schedule does not avoid cascading aborts
- Q3: True _ False _ 2PL leads to deadlock if schedule not conflict serializable
- Q4: True _ False _ A conflict serializable schedule is always serializable
- Q5: True _ False _ The following schedule is serializable

```
T1:R(A),W(A),       R(B),      W(B)
T2:            R(A),     W(A),       R(B),W(B)
```


5min Break

bit.ly/hackjam2013

Quiz 19.1: Transactions

- Q1: True _ False X It is possible for two read operations to conflict
- Q2: True _ False X A strict 2PL schedule does not avoid cascading aborts
- Q3: True X False _ 2PL leads to deadlock if schedule not conflict serializable
- Q4: True X False _ A conflict serializable schedule is always serializable
- Q5: True X False _ The following schedule is serializable

```
T1:R(A),W(A),       R(B),      W(B)
T2:            R(A),     W(A),       R(B),W(B)
```

Deadlock

- Recall: if a schedule is not conflict-serializable, 2PL leads to deadlock, i.e.,
  – Cycles of transactions waiting for each other to release locks
- Recall: two ways to deal with deadlocks
  – Deadlock prevention
  – Deadlock detection
- Many systems punt problem by using timeouts instead
  – Associate a timeout with each lock
  – If timeout expires release the lock
  – What is the problem with this solution?

Deadlock Prevention

- Prevent circular waiting
- Assign priorities based on timestamps. Assume Ti wants a lock that Tj holds. Two policies are possible:
  – Wait-Die: If Ti is older, Ti waits for Tj; otherwise Ti aborts
  – Wound-wait: If Ti is older, Tj aborts; otherwise Ti waits
- If a transaction re-starts, make sure it gets its original timestamp
  – Why?

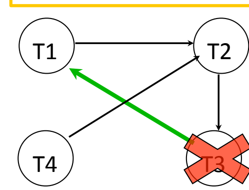
Deadlock Detection

- Allow deadlocks to happen but check for them and fix them if found
- Create a **wait-for graph**:
  – Nodes are transactions
  – There is an edge from Ti to Tj if Ti is waiting for Tj to release a lock
- Periodically check for cycles in the waits-for graph
- If cycle detected – find a transaction whose removal will break the cycle and kill it

Deadlock Detection (Continued)

- Example:

```
• T1: S(A), S(D),           S(B)
• T2:              X(B),                    X(C)
• T3:                        S(D), S(C),         X(A)
• T4:                                                 X(B)
```



Durability and Atomicity

- How do you make sure transaction results persist in the face of failures (e.g., disk failures)?
- Replicate database
  – Commit transaction to each replica
- What happens if you have failures during a transaction commit?
  – Need to ensure atomicity: either transaction is committed on all replicas or none at all

Two Phase (2PC) Commit

- 2PC is a distributed protocol
- High-level problem statement
  – If no node fails and all nodes are ready to commit, then all nodes **COMMIT**
  – Otherwise **ABORT** at all nodes
- Developed by Turing award winner Jim Gray (first Berkeley CS PhD, 1969)

2PC Algorithm

- One coordinator
- N workers (replicas)
- High level algorithm description
  – Coordinator asks all workers if they can commit
  – If all workers reply "VOTE-COMMIT", then coordinator broadcasts "GLOBAL-COMMIT",
    Otherwise coordinator broadcasts "GLOBAL-ABORT"
  – Workers obey the GLOBAL messages

Detailed Algorithm

Coordinator Algorithm

Coordinator sends **VOTE-REQ** to all workers

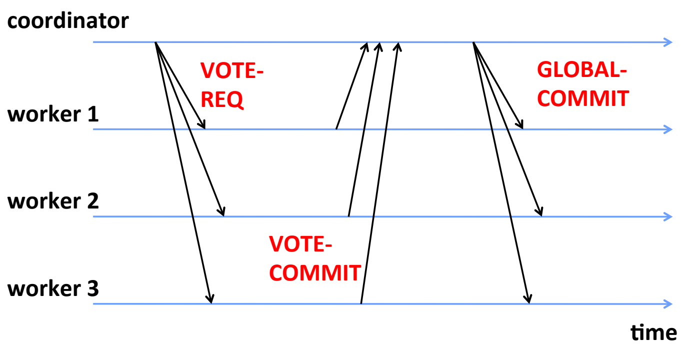
– If receive VOTE-COMMIT from all N workers, send GLOBAL-COMMIT to all workers
– If doesn't receive VOTE-COMMIT from all N workers, send GLOBAL-ABORT to all workers

Worker Algorithm

– Wait for **VOTE-REQ** from coordinator
– If ready, send **VOTE-COMMIT** to coordinator
– If not ready, send **VOTE-ABORT** to coordinator
  – And immediately abort

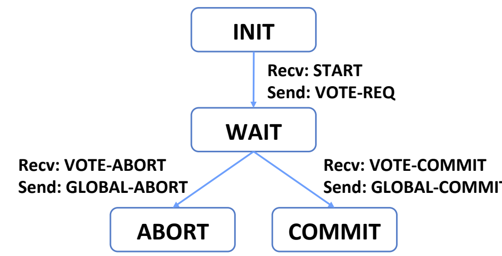
– If receive GLOBAL-COMMIT then commit
– If receive GLOBAL-ABORT then abort

Failure Free Example Execution

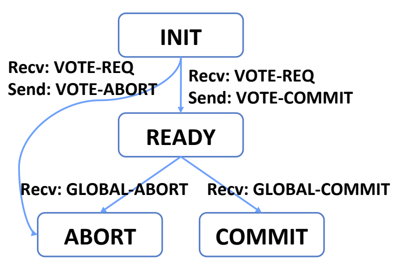


State Machine of Coordinator

- Coordinator implements simple state machine

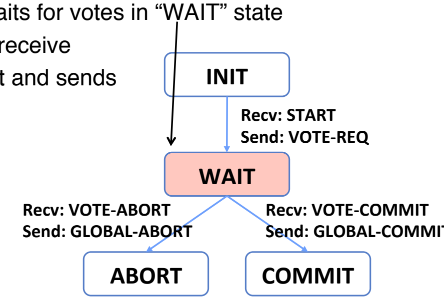


State Machine of Workers

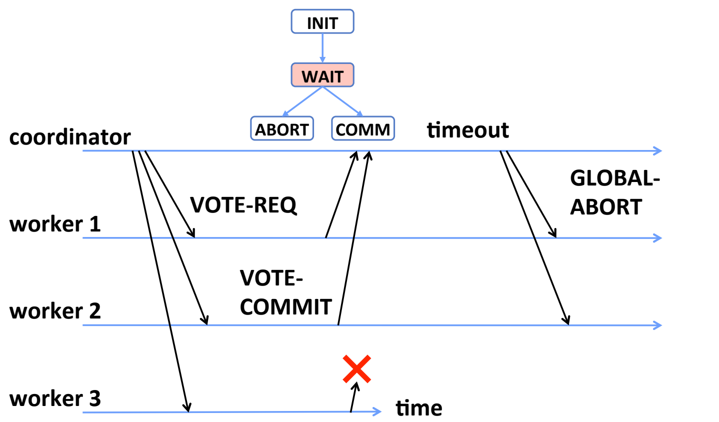


Dealing with Worker Failures

- How to deal with worker failures?
  - Failure only affects states in which the node is waiting for messages
  - Coordinator only waits for votes in "WAIT" state
  - In WAIT, if doesn't receive N votes, it times out and sends GLOBAL-ABORT

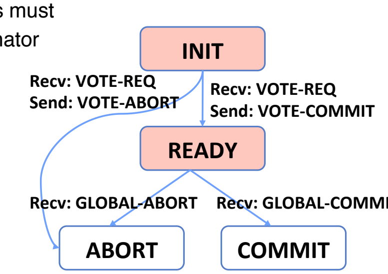


Example of Worker Failure

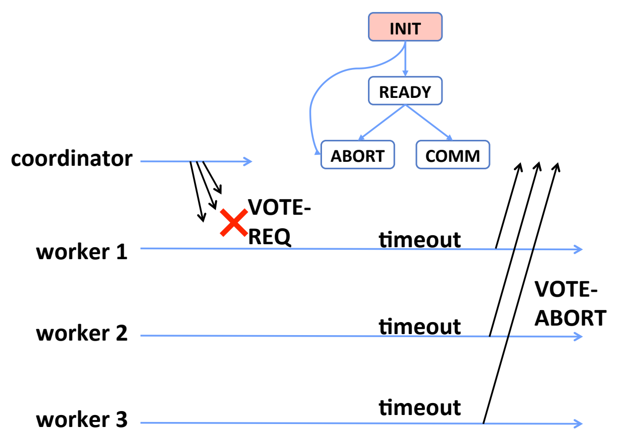


Dealing with Coordinator Failure

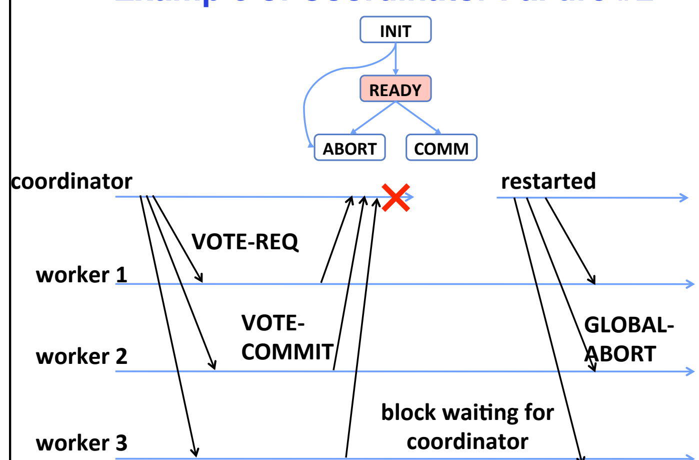
- How to deal with coordinator failures?
  - worker waits for VOTE-REQ in INIT
    - » Worker can time out and abort (coordinator handles it)
  - worker waits for GLOBAL-* message in READY
    - » If coordinator fails, workers must **BLOCK** waiting for coordinator to recover and send GLOBAL_* message



Example of Coordinator Failure #1



Example of Coordinator Failure #2

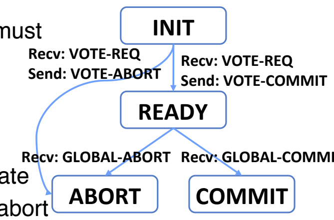


Remembering Where We Were

- All nodes use stable storage to store which state they were in
- Upon recovery, it can restore state and resume:
  - Coordinator aborts in INIT, WAIT, or ABORT
  - Coordinator commits in COMMIT
  - Worker aborts in INIT, READY, ABORT
  - Worker commits in COMMIT
  - Worker asks Coordinator in READY

Blocking for Coordinator to Recover

- A worker waiting for global decision can ask fellow workers about their state
  - If another worker is in ABORT or COMMIT state then coordinator must have sent GLOBAL-*
  - Thus, worker can safely abort or commit, respectively
  - If another worker is still in INIT state then both workers can decide to abort
  - If all workers are in ready, need to **BLOCK** (don't know if coordinator wanted to abort or commit)



Summary

- Correctness criterion for transactions is "Serializability"
  - In practice, we use "Conflict Serializability", which is somewhat more restrictive but easy to enforce
- Two phase locking (2PL) and strict 2PL
  - Ensure conflict-serializability for R/W operations
  - If scheduler not conflict-serializable deadlocks
  - Deadlocks can be either detected or prevented
- Two-phase commit (2PC)
  - Ensure atomicity and durability: a transaction is committed/ aborted either by all replicas or by none of them