Distributed Systems

CS425/ECE428

March 31 2022

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Acknowledgements for the materials: Indy Gupta and Nikita Borisov

Logistics

- HW5 has been released
  - You should be able to solve all questions after today’s class.

Thank you for your feedback

- Some common complaints
  - Time management during OHs.
  - Losing track of materials when I answer questions in class.
  - Pace of lectures.
  - Practice materials and examples.

Lost Update Example with Timestamped Ordering

timestamp 1

timestamp 2

Transaction T1	**Transaction T2**
x = getSeats(ABC123);	
	x = getSeats(ABC123);
if(x > 1)	if(x > 1)
x = x – 1;	
write(x, ABC123); aborted	
	x = x – 1;
	write(x, ABC123);
commit	
	commit

ABC123: state
committed value = 10
committed timestamp = 0
RTS: 1 , 2
TW:

Lost Update Example with Timestamped Ordering

Transaction T1

```
x = getSeats(ABC123);

if(x > 1)
   x = x – 1;
write(x, ABC123);

commit
```

Transaction T2

```
x = getSeats(ABC123);
if(x > 1)

 x = x – 1;

write(x, ABC123);

commit
```

ABC123: state
committed value = 10
committed timestamp = 0
RTS: 1
TW:

Lost Update Example with Timestamped Ordering

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	x = getSeats(ABC123);
if(x > 1)	if(x > 1)
x = x – 1;	
write(x, ABC123);	
	x = x – 1;
	write(x, ABC123);
commit	
	commit

ABC123: state
committed value = 10
committed timestamp = 0
RTS: 1, 2
TW:

Next Example with Timestamped Ordering

Transaction T1

x = getSeats(ABC123); ↙
y = getSeats(ABC789); ↙
write(x-5, ABC123); ·

write(y+5, ABC789); ↙

commit ✓

Transaction T2

wait
x = getSeats(ABC123); ←
y = getSeats(ABC789);

print("Total:" x+y);

commit

ABC123: state
committed value = ~~10~~ 5
committed timestamp = ~~0~~ 1
RTS: 1
TW: ~~(1, 5)~~

ABC789: state
committed value = ~~5~~ 10
committed timestamp = ~~0~~ 1
RTS: 1
TW: ~~(10, 1)~~

Next Example with Timestamped Ordering

Transaction T1

x = getSeats(ABC123);
y = getSeats(ABC789);
write(x-5, ABC123);

write(y+5, ABC789);

commit

Transaction T2

x = getSeats(ABC123);
y = getSeats(ABC789);

print("Total:" x+y);

commit

ABC123: state
committed value = 10
committed timestamp = 0
RTS: 1
TW:

ABC789: state
committed value = 5
committed timestamp = 0
RTS:
TW:

Next Example with Timestamped Ordering

Transaction T1

x = getSeats(ABC123);
y = getSeats(ABC789);
write(x-5, ABC123);

write(y+5, ABC789);

commit

Transaction T2

x = getSeats(ABC123);
y = getSeats(ABC789);

print("Total:" x+y);

commit

ABC123: state
committed value = 10
committed timestamp = 0
RTS: 1
TW:

ABC789: state
committed value = 5
committed timestamp = 0
RTS: 1
TW:

Next Example with Timestamped Ordering

Transaction T1

```
x = getSeats(ABC123);
y = getSeats(ABC789);
write(x-5, ABC123);


write(y+5, ABC789);


commit
```

Transaction T2

```
x = getSeats(ABC123);
y = getSeats(ABC789);


print("Total:" x+y);

commit
```

ABC123: state
committed value = 10
committed timestamp = 0
RTS: 1
TW: (5, 1)

ABC789: state
committed value = 5
committed timestamp = 0
RTS: 1
TW:

Next Example with Timestamped Ordering

Transaction T1	**Transaction T2**
x = getSeats(ABC123);	
y = getSeats(ABC789);	
write(x-5, ABC123);	
	x = getSeats(ABC123); wait
	y = getSeats(ABC789);
write(y+5, ABC789);	
	print("Total:" x+y);
commit	
	commit

ABC123: state
committed value = 10
committed timestamp = 0
RTS: 1
TW: (5, 1)

ABC789: state
committed value = 5
committed timestamp = 0
RTS: 1
TW:

Next Example with Timestamped Ordering

Transaction T1

x = getSeats(ABC123);
y = getSeats(ABC789);
write(x-5, ABC123);

write(y+5, ABC789);

commit

Transaction T2

x = getSeats(ABC123); wait
y = getSeats(ABC789);

print("Total:" x+y);

commit

ABC123: state
committed value = 10
committed timestamp = 0
RTS: 1
TW: (5, 1)

ABC789: state
committed value = 5
committed timestamp = 0
RTS: 1
TW: (10, 1)

Next Example with Timestamped Ordering

Transaction T1	**Transaction T2**
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	x = getSeats(ABC123); wait
	y = getSeats(ABC789);
write(y+5, ABC789);	
	print("Total:" x+y);
commit	
	commit

ABC123: state
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RTS: 1
TW: ~~(5, 1)~~

ABC789: state
committed value = ~~5~~ 10
committed timestamp = ~~0~~ 1
RTS: 1
TW: ~~(10, 1)~~

Next Example with Timestamped Ordering

Transaction T1

x = getSeats(ABC123);
y = getSeats(ABC789);
write(x-5, ABC123);

write(y+5, ABC789);

commit

Transaction T2

x = getSeats(ABC123); wait
y = getSeats(ABC789);

print("Total:" x+y);

commit

T2 then proceeds after T1 commits

ABC123: state
committed value = ~~10~~ 5
committed timestamp = ~~0~~ 1
RTS: 1
TW: ~~(5, 1)~~

ABC789: state
committed value = ~~5~~ 10
committed timestamp = ~~0~~ 1
RTS: 1
TW: ~~(10, 1)~~

Agenda for today

- Distributed Transactions
  - Chapter 17

Transaction Processing

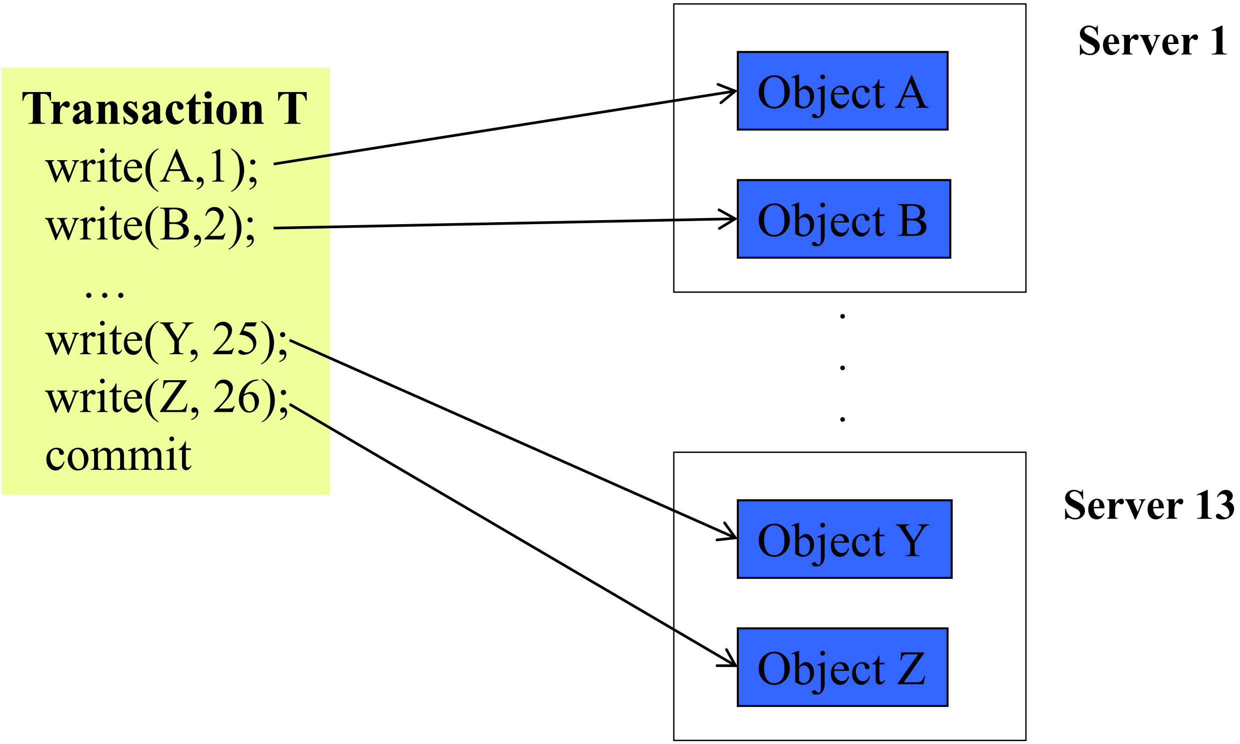
- Required properties: Atomicity, Consistency, Isolation, Durability (ACID).
- *How to prevent transactions from affecting one another?*
- Goal: increase concurrency and transaction throughput while maintaining correctness (ACID).
- Two approaches:
  - Pessimistic concurrency control: locking based.
    - read-write locks with two-phase locking and deadlock detection.
  - Optimistic concurrency control: abort if too late.
    - timestamped ordering.
- Focused on single server and multiple clients.

Distributed Transactions

- Transaction processing can be *distributed* across multiple servers.
  - Different objects can be stored on different servers.
    - Our focus today.
  - An object may be replicated across multiple servers.
    - Next class.

Transactions with Distributed Servers

- Different objects touched by a transaction T may reside on different servers.



Transaction T
write(A,1);
write(B,2);
…
write(Y, 25);
write(Z, 26);
commit

Server 1

Object A

Object B

Server 13

Object Y

Object Z

Distributed Transaction Challenges

- **A**tomic: all-or-nothing
  - *Must ensure atomicity across servers.*
- **C**onsistent: rules maintained
  - *Generally done locally, but may need to check non-local invariants at commit time.*
- **I**solation: multiple transactions do not interfere with each other
  - *Locks at each server. How to detect and handle deadlocks?*
- **D**urability: values preserved even after crashes
  - *Each server keeps local recovery log.*

Distributed Transaction Challenges

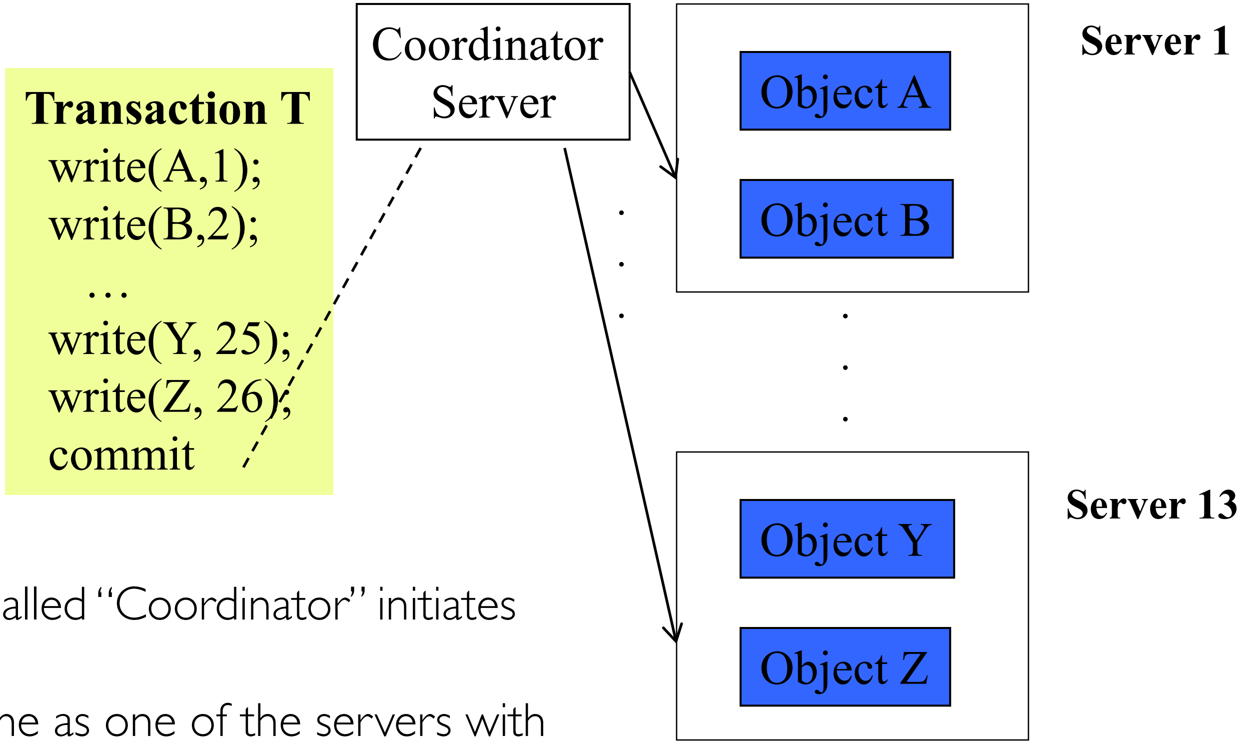
- **Atomic: all-or-nothing**
    - ***Must ensure atomicity across servers.***
- Consistent: rules maintained
    - *Generally done locally, but may need to check non-local invariants at commit time.*
- **Isolation: multiple transactions do not interfere with each other**
    - ***Locks at each server. How to detect and handle deadlocks?***
- Durability: values preserved even after crashes
    - *Each server keeps local recovery log.*

Distributed Transaction Atomicity

- When T tries to commit, need to ensure
  - all these servers commit their updates from T => T will commit
  - Or none of these servers commit => T will abort

- What problem is this?
  - Consensus!
  - (It's also called the "Atomic Commit" problem)

Coordinator Server



Transaction T
write(A,1);
write(B,2);
…
write(Y, 25);
write(Z, 26);
commit

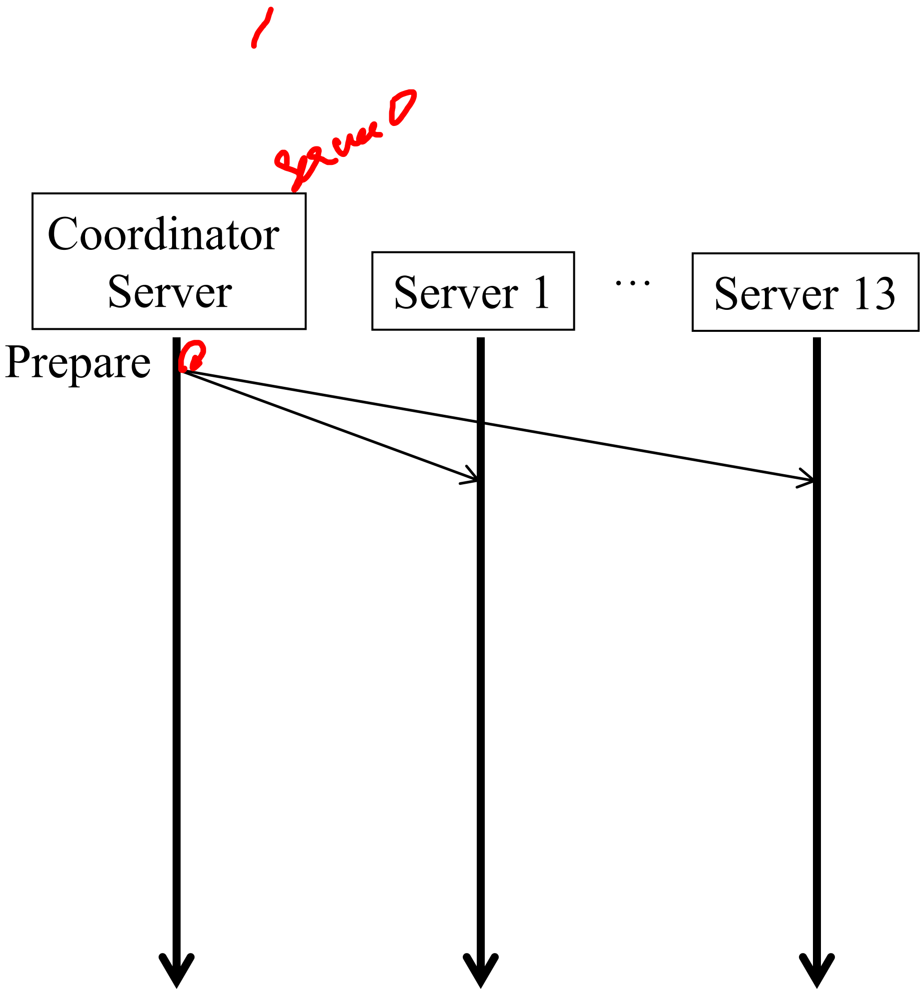
- Special server called "Coordinator" initiates atomic commit.
    - can be same as one of the servers with objects.
- Different transactions may have different coordinators.

One-phase commit

- Client relays the “commit” or “abort” command to the coordinator.
    - Coordinator tells other servers to commit / abort.

- *Issues with this?*
    - Server with object has no say in whether transaction commits or aborts
        - If a local consistency check fails, it just cannot commit (while other servers have committed).
    - A server may crash before receiving commit message, with some updates still in memory.

Two-phase commit



Coordinator Server

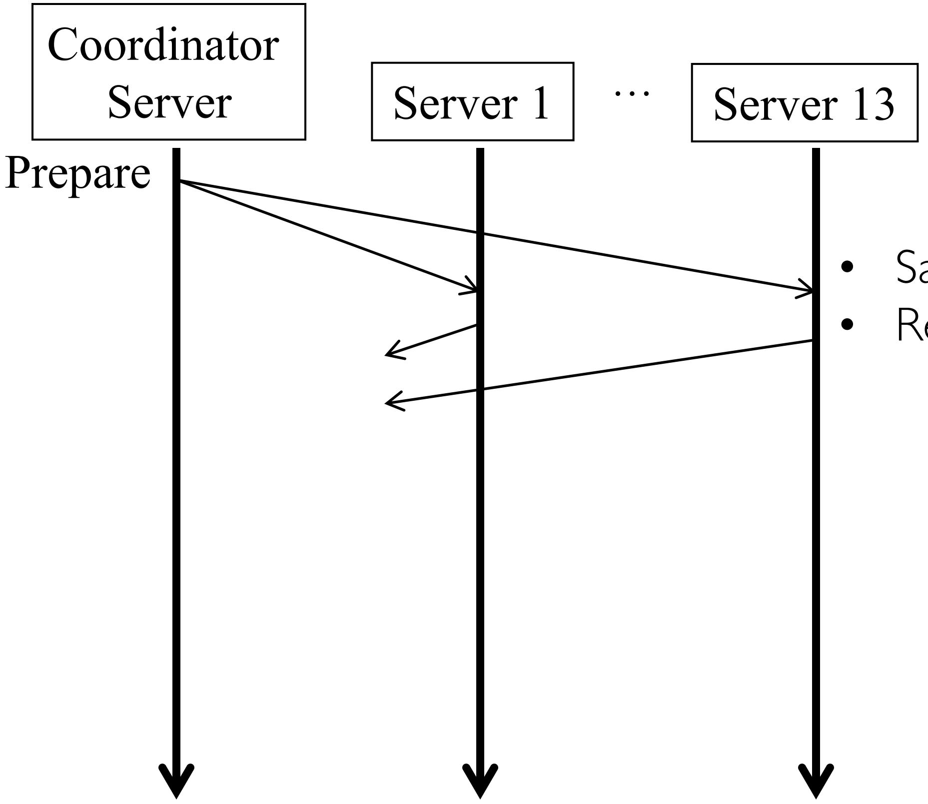
Server 1

…

Server 13

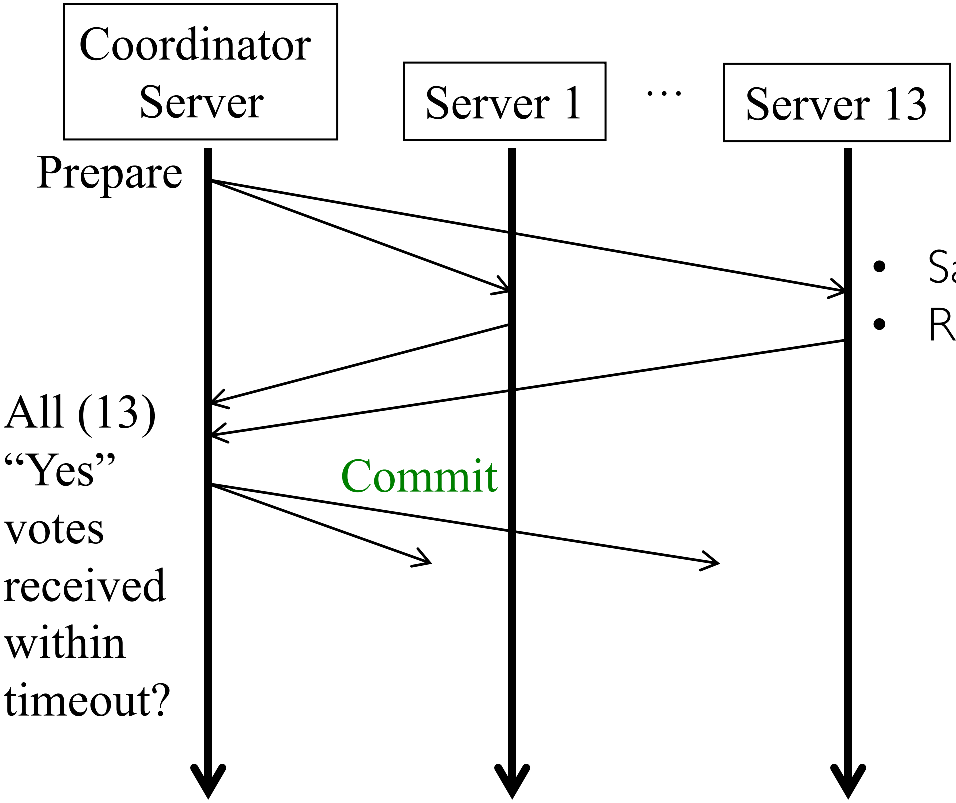
Prepare

Two-phase commit



- Save updates to disk
- Respond with "Yes" or "No"

Two-phase commit



Coordinator Server

Server 1

…

Server 13

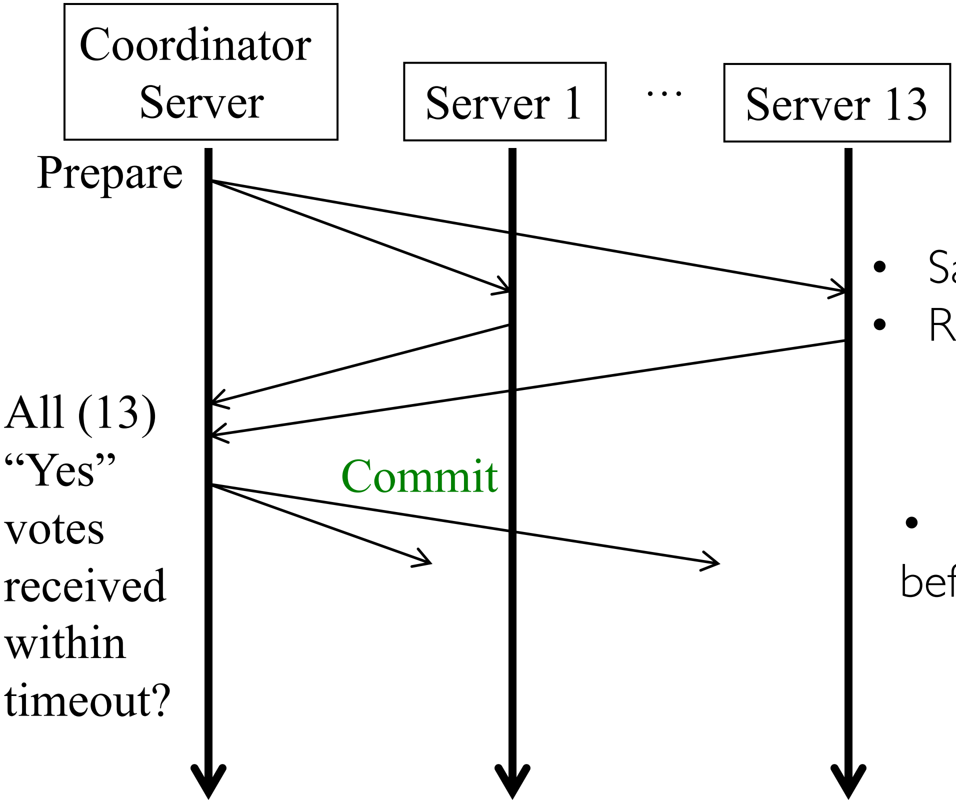
Prepare

- Save updates to disk
- Respond with "Yes" or "No"

All (13) "Yes" votes received within timeout?

Commit

Two-phase commit



Coordinator Server

Server 1

…

Server 13

Prepare

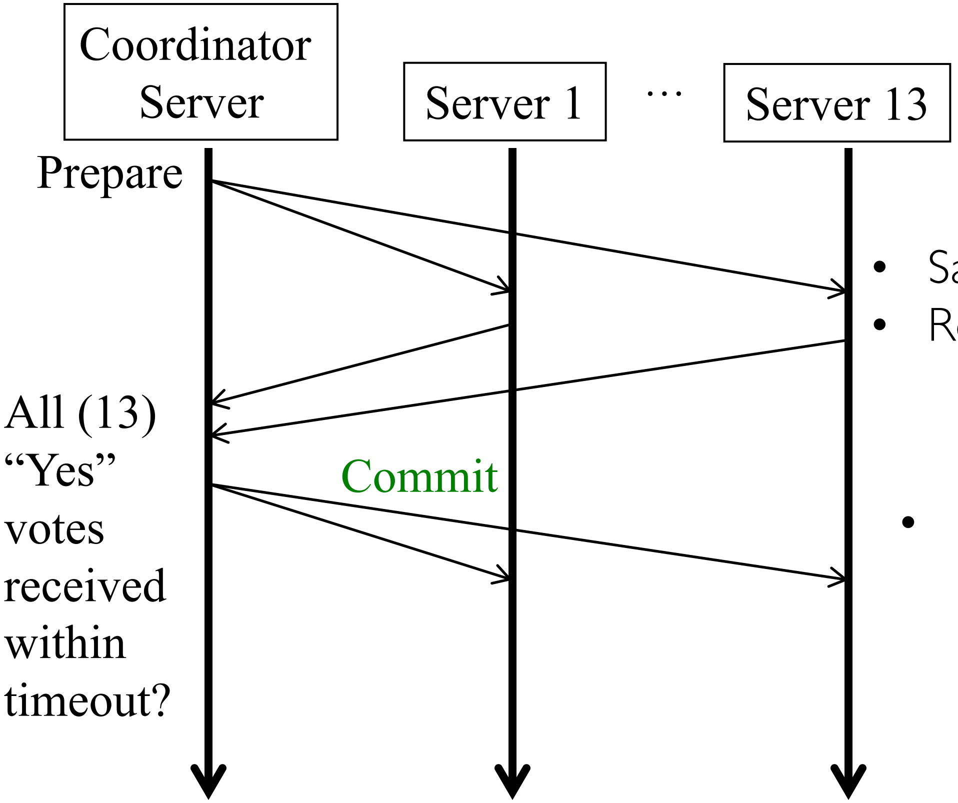
All (13) “Yes” votes received within timeout?

Commit

- Save updates to disk
- Respond with “Yes” or “No”

- Wait! Can’t commit or abort before receiving next message!

Two-phase commit



Coordinator Server

Server 1

…

Server 13

Prepare

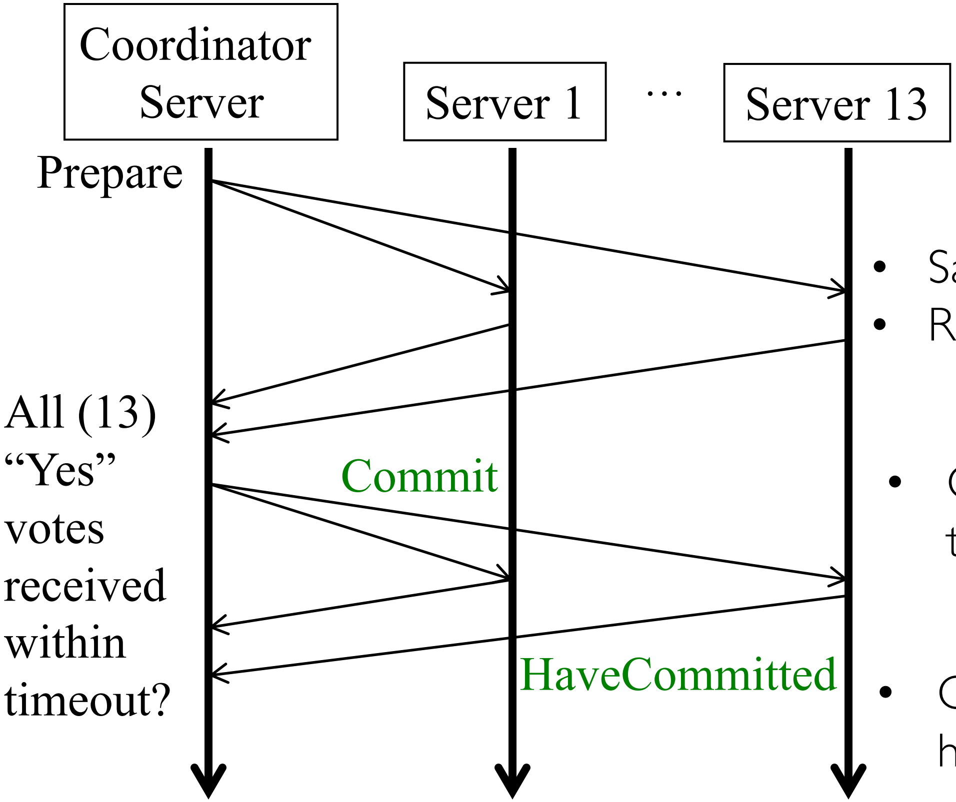
- Save updates to disk
- Respond with “Yes” or “No”

All (13) “Yes” votes received within timeout?

Commit

- Commit updates from disk to store

Two-phase commit



Coordinator Server

Server 1

…

Server 13

Prepare

All (13) "Yes" votes received within timeout?

Commit

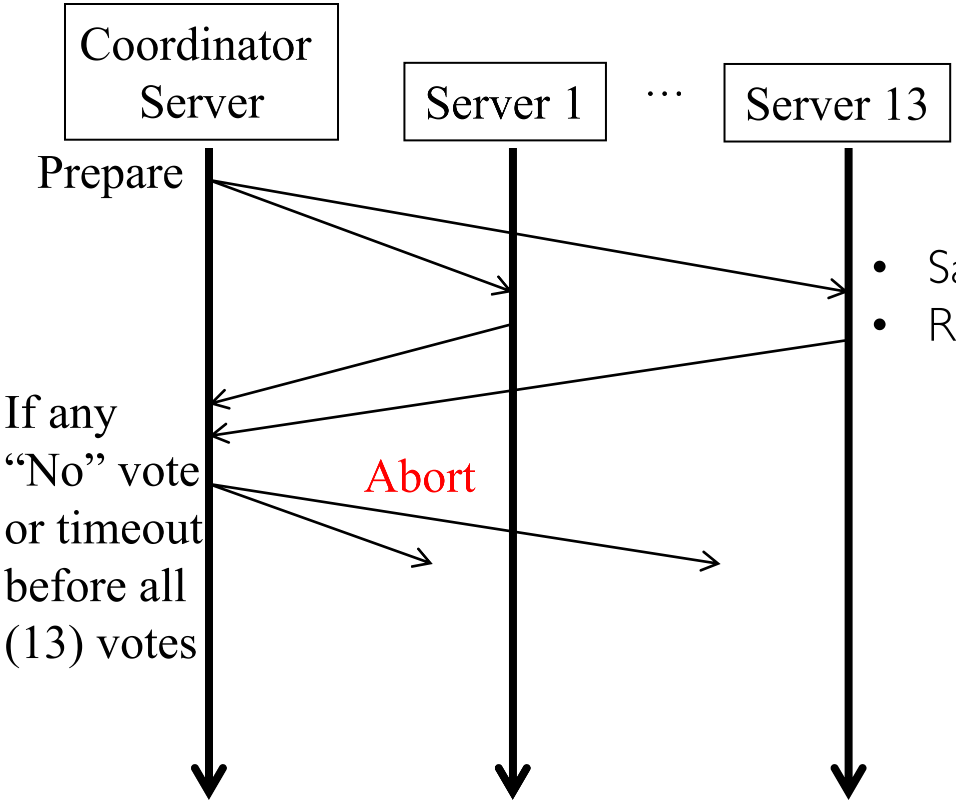
HaveCommitted

- Save updates to disk
- Respond with "Yes" or "No"

- Commit updates from disk to store

- Coordinator now knows that all servers have committed and it can delete the associated transaction information.

Two-phase commit



Coordinator Server

Server 1

…

Server 13

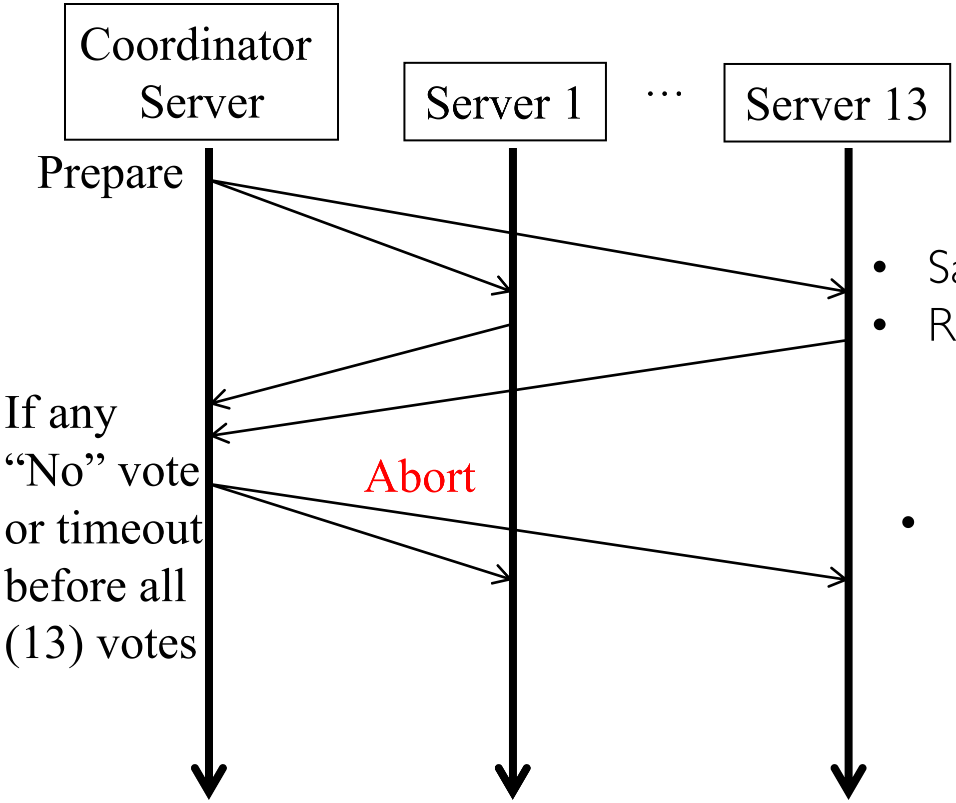
Prepare

- Save updates to disk
- Respond with "Yes" or "No"

If any "No" vote or timeout before all (13) votes

Abort

Two-phase commit



Coordinator Server

Server 1

…

Server 13

Prepare

- Save updates to disk
- Respond with “Yes” or “No”

If any “No” vote or timeout before all (13) votes

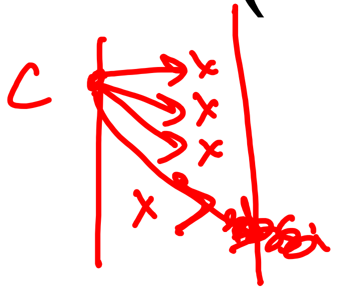
Abort

- Delete tentative updates in disk and abort.

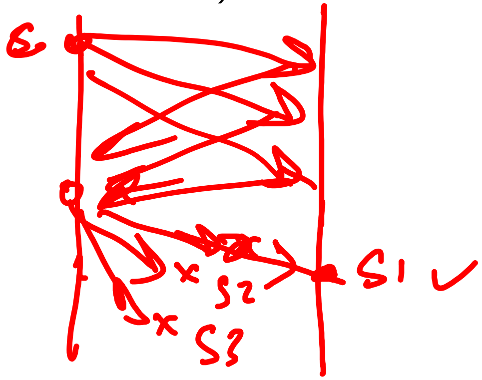
Failures in Two-phase Commit

- If server voted Yes, it cannot commit unilaterally before receiving Commit message.
    - Does not know if other servers voted Yes.
- If server voted No, can abort right away.
    - Knows that the transaction cannot be committed.
- To deal with server crashes
    - Each server saves tentative updates into permanent storage, right before replying Yes/No in first phase. Retrievable after crash recovery.
- To deal with coordinator crashes
    - Coordinator logs all decisions and received/sent messages on disk.
    - After recovery => retrieve the logged state.

Failures in Two-phase Commit (contd)



- To deal with Prepare message loss
  - The server may decide to abort unilaterally after a timeout for first phase (server will vote No, and so coordinator will also eventually abort)
- To deal with Yes/No message loss
  - coordinator aborts the transaction after a timeout (pessimistic!).
  - It must announce Abort message to all.
- To deal with Commit or Abort message loss
  - Server can poll coordinator (repeatedly).



Distributed Transaction Atomicity

- When T tries to commit, need to ensure
  - all these servers commit their updates from T => T will commit
  - Or none of these servers commit => T will abort

- What problem is this?
  - Consensus!
  - (It's also called the "Atomic Commit" problem)

- Consensus is impossible in asynchronous system.
  - What makes two-phase commit work?
  - Crash failures in processes *masked* by replacing the crashed process with a new process whose state is retrieved from permanent storage.
  - *Two-phase commit is blocked until a failed coordinator recovers.*

Distributed Transaction Challenges

- Atomic: all-or-nothing
  - Must ensure atomicity across servers.
- **C**onsistent: rules maintained
  - *Generally done locally, but may need to check non-local invariants at commit time.*
- **Isolation: multiple transactions do not interfere with each other**
  - ***Locks at each server. How to detect and handle deadlocks?***
- **D**urability: values preserved even after crashes
  - *Each server keeps local recovery log.*

Isolation with Distributed Transaction

- Each server is responsible for applying concurrency control to objects it stores.

- Servers are collectively responsible for serial equivalence of operations.

Timestamped Ordering with Distributed Transaction

- Each server is responsible for applying concurrency control to objects it stores.

- Servers are collectively responsible for serial equivalence of operations.

- Timestamped ordering can be applied locally at each server.
    - When a server aborts a transaction, inform the coordinator which will relay the “abort” to other servers.

Locks with Distributed Transaction

- Each server is responsible for applying concurrency control to objects it stores.

- Servers are collectively responsible for serial equivalence of operations.

- Locks are held locally, and cannot be released until all servers involved in a transaction have committed or aborted.

- Locks are retained during 2PC (two-phase commit) protocol.

- How to handle deadlocks?
  - Next class!