Distributed Transactions with Two-Phase Commit

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Reading: R&G Chapter 22

Distributed vs. Parallel?

- Earlier we discussed Parallel DBMSs
  - Shared-memory
  - Shared-disk
  - Shared-nothing

- Distributed is basically shared-nothing parallel
  - With machines geographically distributed over network

What's Special About Distributed Computing?

- Inherited from shared-nothing parallel computation
  - Parallel computation
  - No shared memory/disk
- Unreliable Networks
  - Delay, reordering, loss of packets
- Unsynchronized clocks
  - Impossible to have perfect synchrony
- Partial failure: can't know what's up, what's down

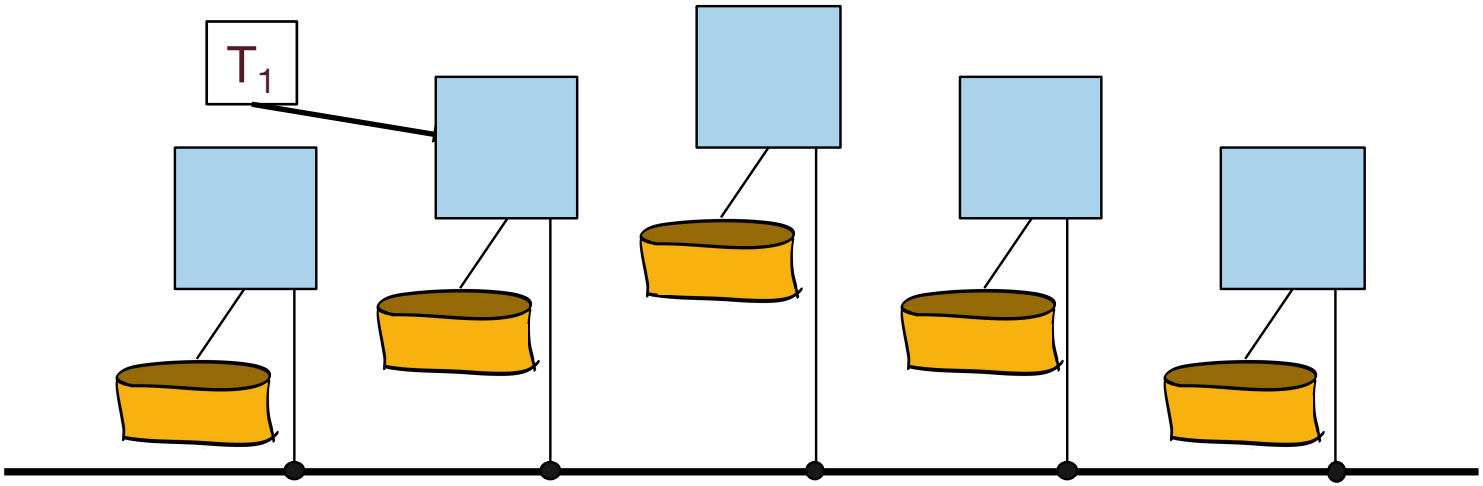
Distributed Database Systems

- DBMS is an influential special case of distributed computing
  - The trickiest part of distributed computing is state, i.e., Data
  - Transactions provide an influential model for concurrency/parallelism
  - DBMSs worried about fault handling early on
- But also a special-case as not all distributed programs are written transactionally
  - And if not, database techniques may not apply
- Many of today's most complex distributed systems are databases
  - Cloud SQL databases like Google BigQuery, AWS Aurora, Azure SQL
  - NoSQL databases like DynamoDB, Cassandra, MongoDB, Couchbase…
- We'll focus on transactional concurrency control and recovery
  - You already know many lessons of distributed query processing

Distributed Locking

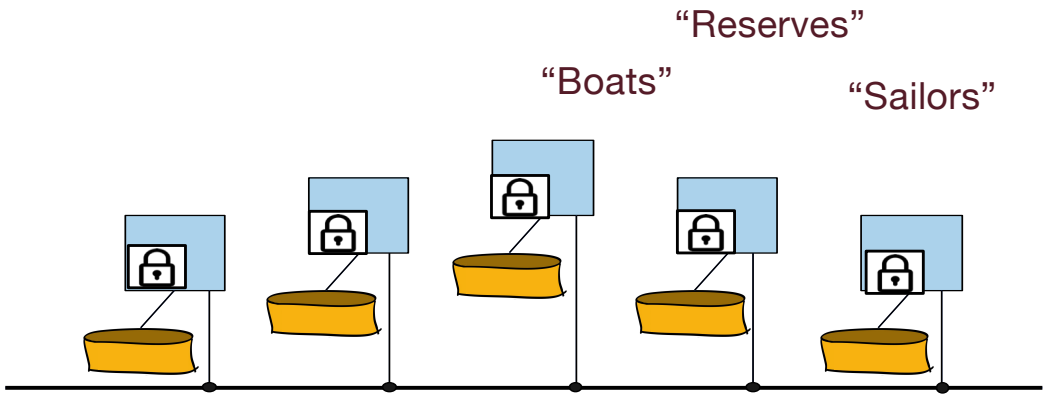
Distributed Concurrency Control

- Consider a shared-nothing distributed DBMS
- For today, assume partitioning but no replication of data
- Each transaction arrives at some node: some machine's memory
  - The "coordinator" for the transaction
    - Can be designated or assigned on the fly



Where is the Lock Table

- Typical design: Locks partitioned with the data
  - Independent: each node manages its own lock table
  - Works for objects that fit on one node (pages, tuples)
- For coarser-grained locks, assign a “home” node
  - Object being locked (table, DB) exists across nodes



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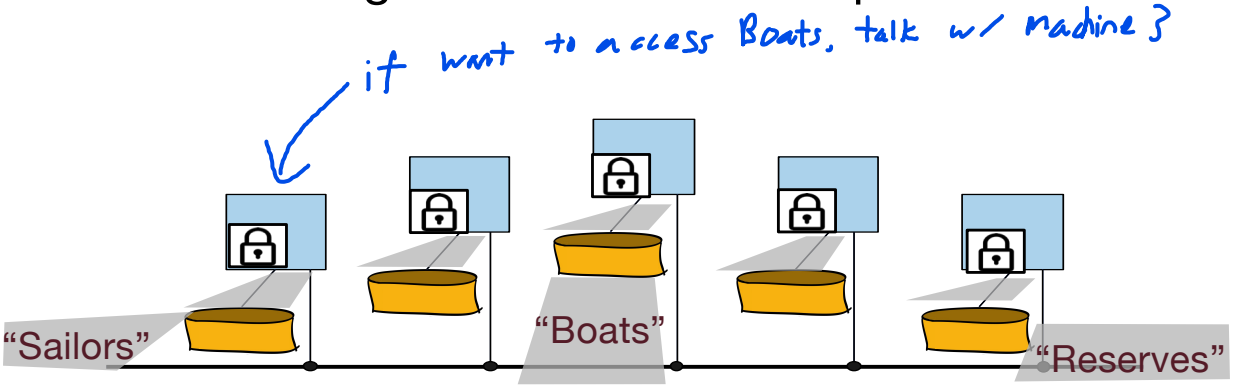
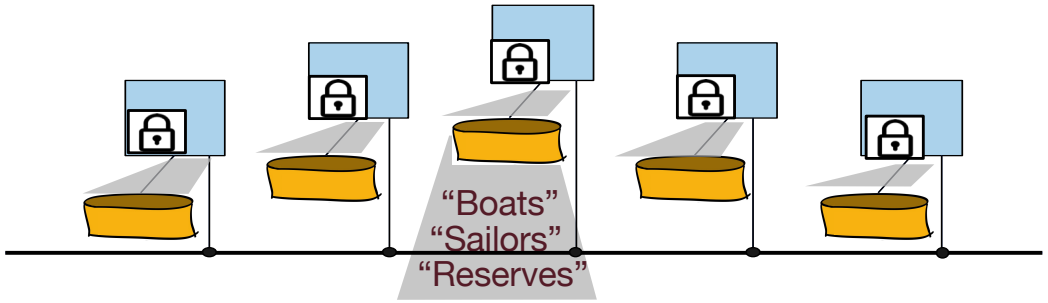


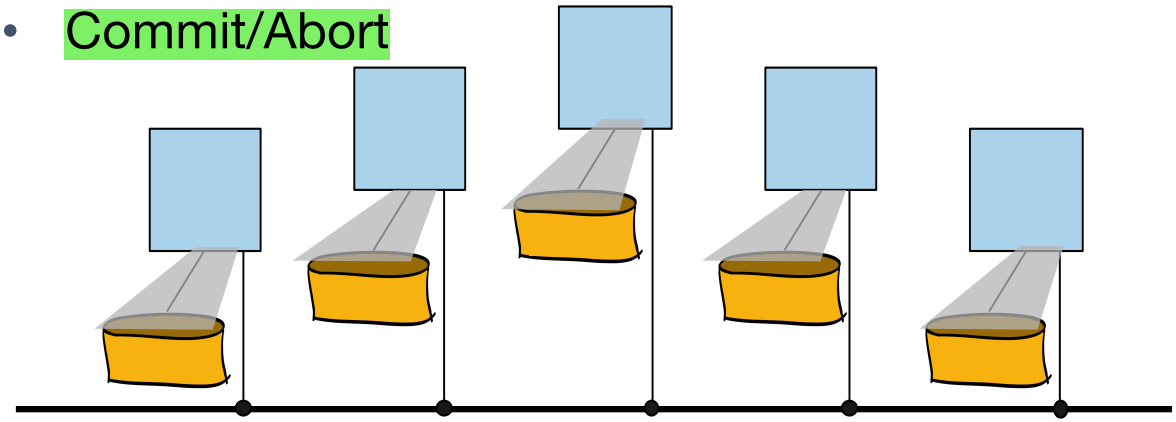
Where is the Lock Table, Pt 3

- Typical design: Locks partitioned with the data
  - Independent: each node manages its own lock table
  - Works for objects that fit on one node (pages, tuples)
- For coarser-grained locks, assign a “home” node
  - Object being locked (table, DB) exists across nodes
  - These coarse-grained locks can be partitioned across nodes
  - Or centralized at a master node



Ignore global coarse-grained locks for a moment…

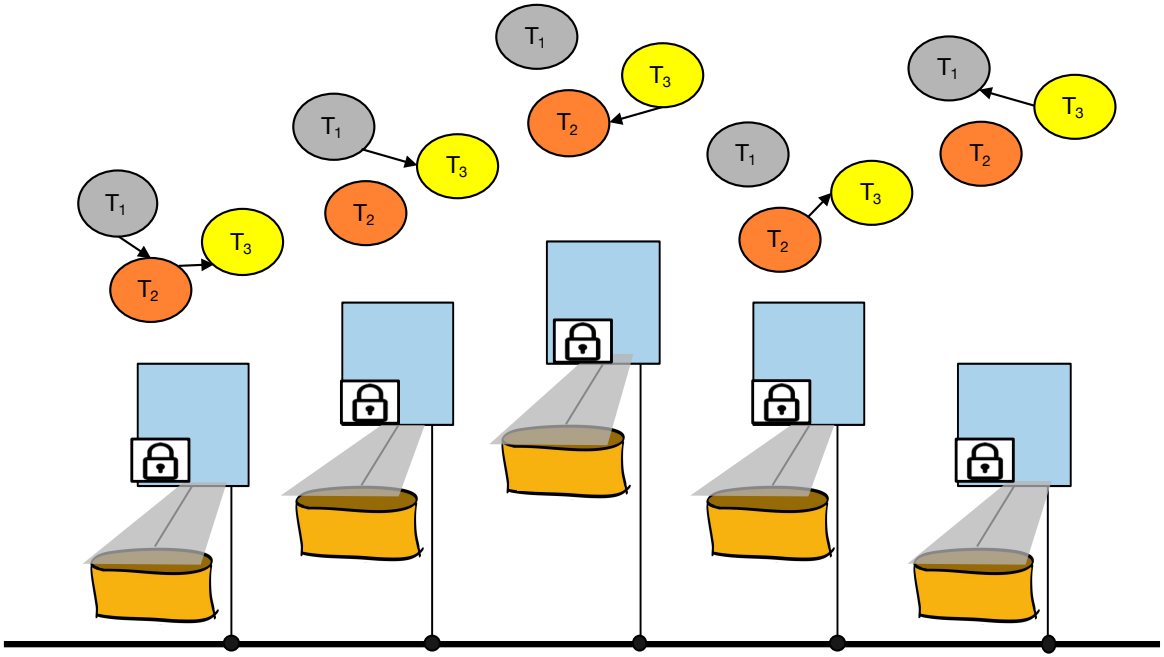
- Every node does its own locking
  - Clean and efficient
  - Nicely generalizes the single-node setting
- "Global" issues remain:
  - Deadlock
  - Commit/Abort



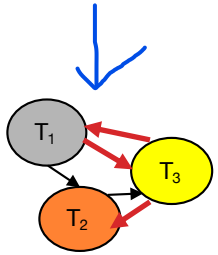
Distributed Deadlock Detection

What Could Go Wrong? #1

- Deadlock detection via waits-for graphs

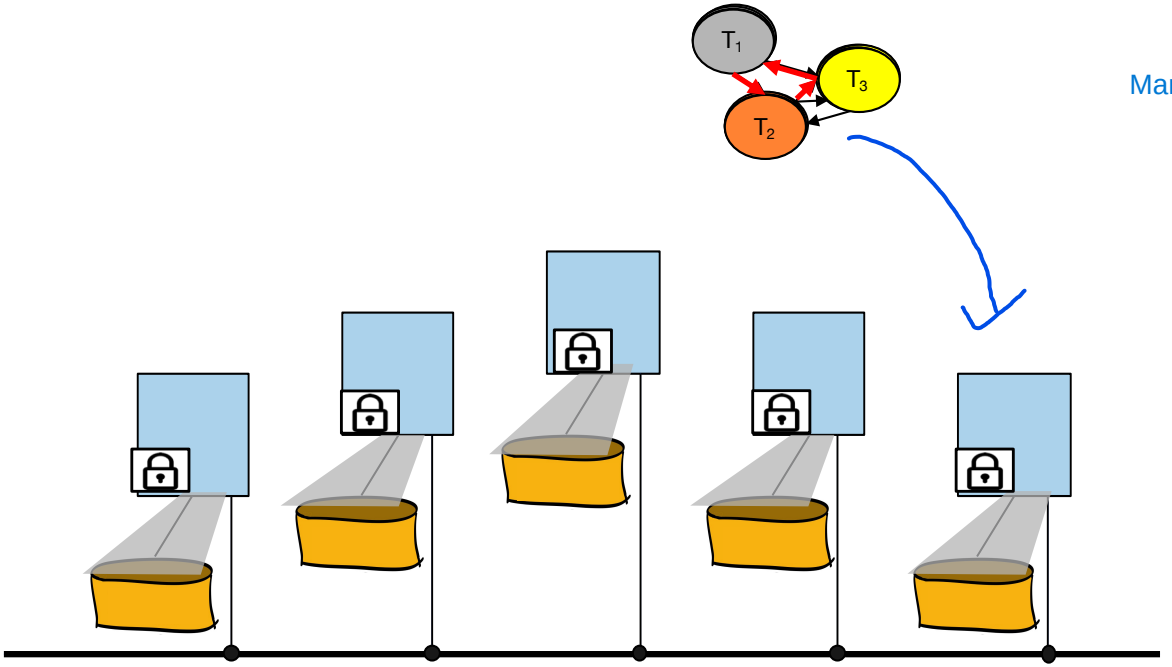


Each machine doesn't have a cycle, but there is a global cycle



What Could Go Wrong? #1 Part 2

- Deadlock detection via waits-for graphs
  - Easy fix: periodically union at designated coordinator



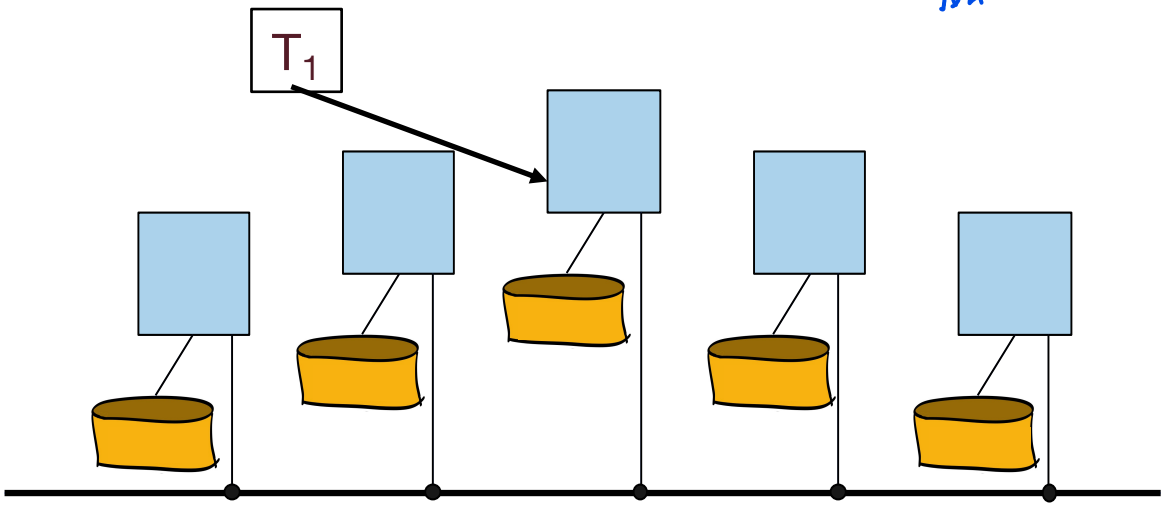
Manage the global waits-for graph on some machine

Distributed Commit: 2PC

Strawman: Coordinator makes Decision

- Recall that every txn has a coordinator node
- Coordinator decides if the txn is going to commit or abort.
- Lets all the other nodes know.
- Q: Why is this scheme problematic?

So all machines will rollback the txn

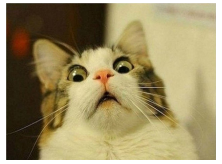


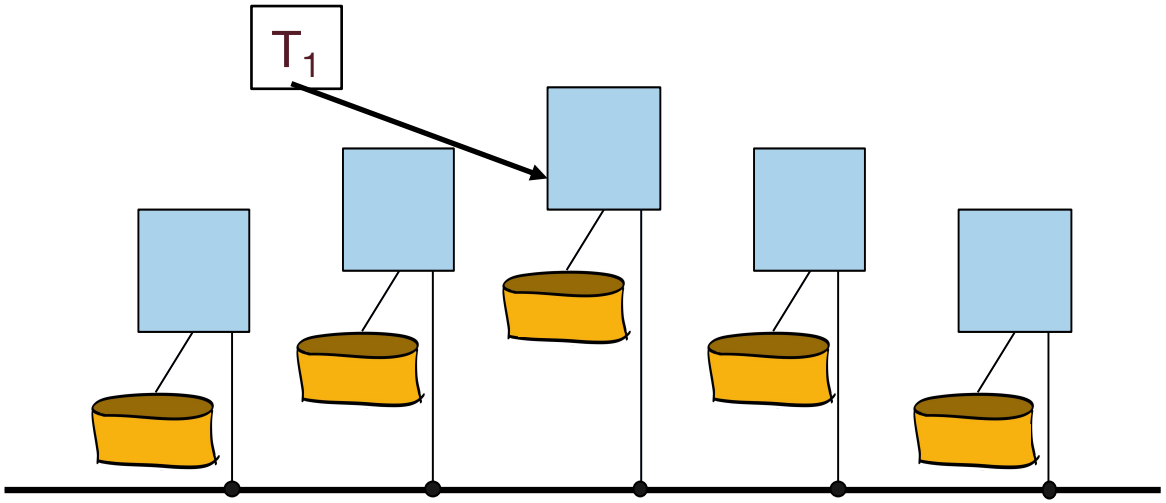
Strawman: Coordinator makes Decision

- Recall that every txn has a coordinator node
- Coordinator decides if the txn is going to commit or abort.
- Lets all the other nodes know.
- Q: Why is this scheme problematic?

So do we commit or abort?

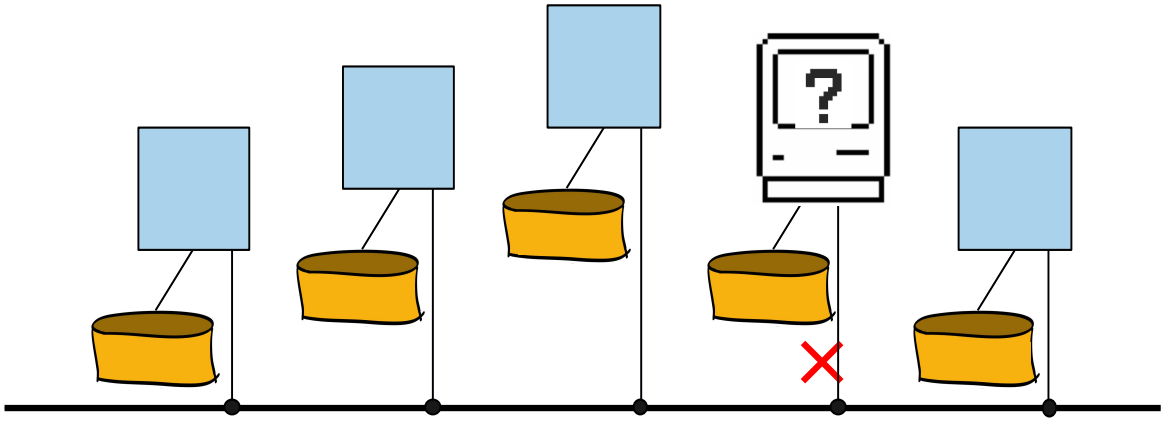
  - Among other things, one of the nodes may want to abort, even if the coordinator wants to commit
  - Some nodes may actually be down (so any txn touching their data shouldn't proceed)





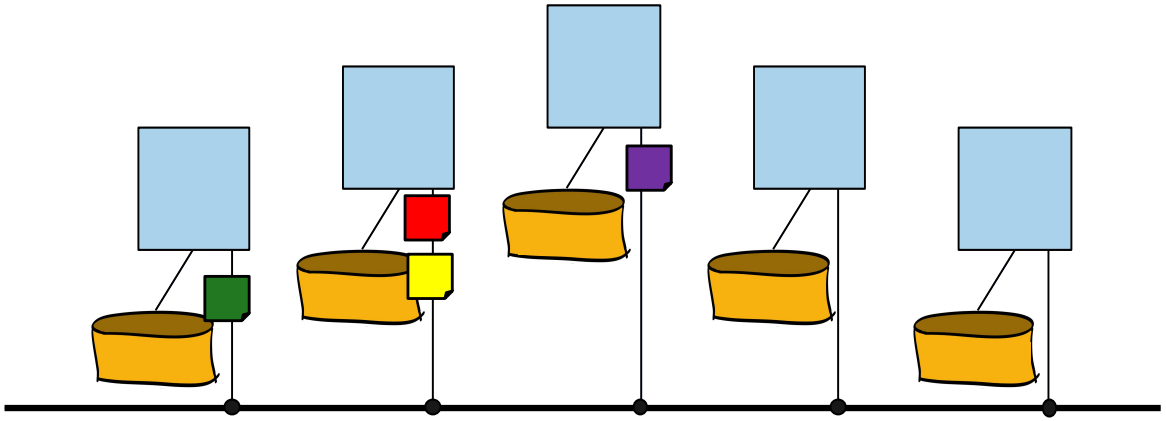
In General, What Could Go Wrong? #2

- Failures/Delays: Nodes
  - Commit? Abort?
    - If we haven't heard from a node, we don't know if is alive or dead.
    - The decision may hinge on this node (imagine a FK violation at that node)
  - When the node comes back, how does it recover in a world that moved forward?



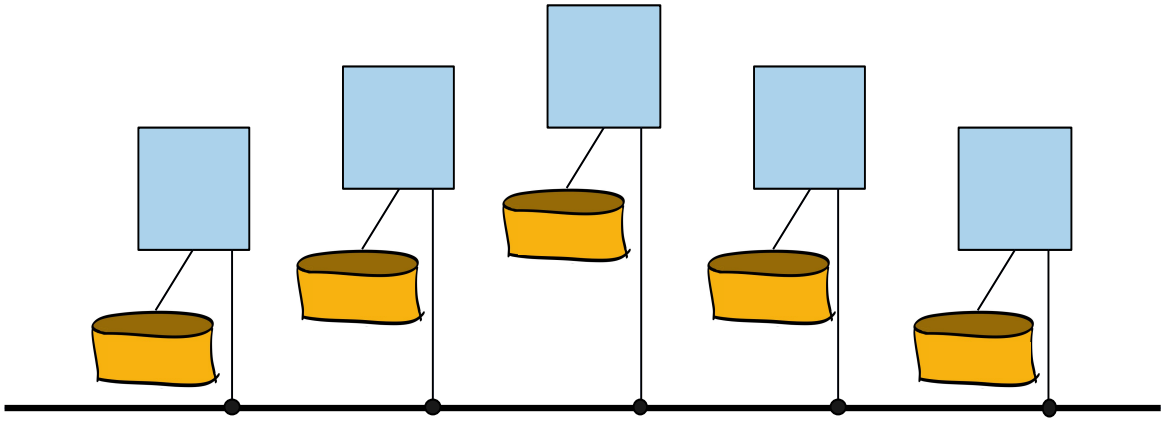
What Could Go Wrong? #2, Part 2

- Failures/Delays: Nodes
- Failures/Delays: Messages
  - Non-deterministic reordering per channel, interleaving across channels
  - “Lost” (very delayed) messages
    - How long should we wait for this?



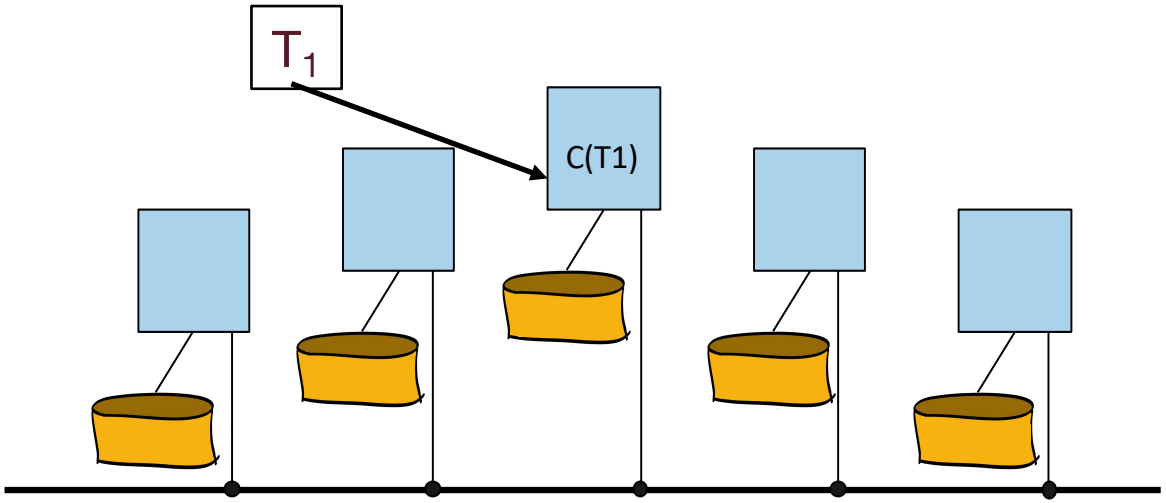
What Could Go Wrong? #2, Part 3

- Failures/Delays: Nodes
- Failures/Delays: Messages
  - Non-deterministic reordering per channel, interleaving across channels
  - “Lost” (very delayed) messages
- Given this, how do all nodes agree on Commit vs. Abort?



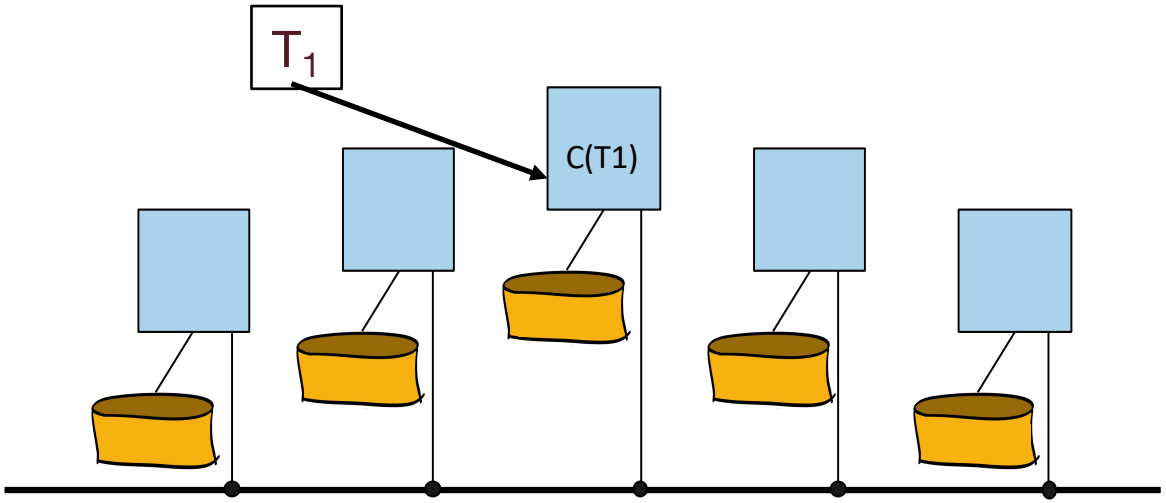
Basic Idea: Distributed Voting

- Vote for Commitment
  - How many votes does a commit need to win?
  - Any single node could observe a problem (e.g., deadlock, constraint violation)
  - Hence must be unanimous. in order to win commit



Distributed voting? How?

- How do we implement distributed voting?!
  - In the face of message/node failure/delay?



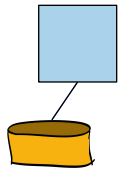
2-Phase Commit

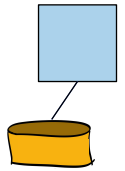
- A.k.a. 2PC. (Not to be confused with 2PL!)
- Like a wedding ceremony!
- **Phase 1: "do you take this person..."**
  - Coordinator tells participants to "prepare"
  - Participants respond with yes/no votes
    - Unanimity required for yes!
- **Phase 2: "I now pronounce you..."**
  - Coordinator disseminates result of the vote
- Need to do some logging for failure handling....

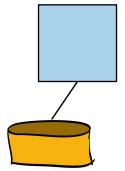
2-Phase Commit, Part 1

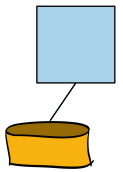
- **Phase 1:**
  - **Coordinator tells participants to "prepare"**
  - Participants respond with yes/no votes
    - Unanimity required for commit!
- Phase 2:
  - Coordinator disseminates result of the vote
  - Participants respond with Ack

make sure all writes prepared aka all operations done

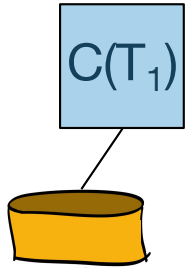








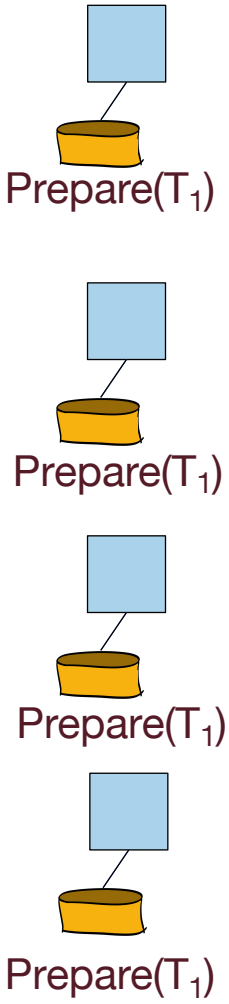
Coord

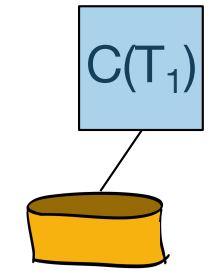


Prepare(T_1)

2-Phase Commit, Part 2

- **Phase 1:**
  - **Coordinator tells participants to "prepare"**
  - Participants respond with yes/no votes
    - Unanimity required for commit!
- Phase 2:
  - Coordinator disseminates result of the vote
  - Participants respond with Ack





2-Phase Commit, Part 3

- **Phase 1:**
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- Phase 2:
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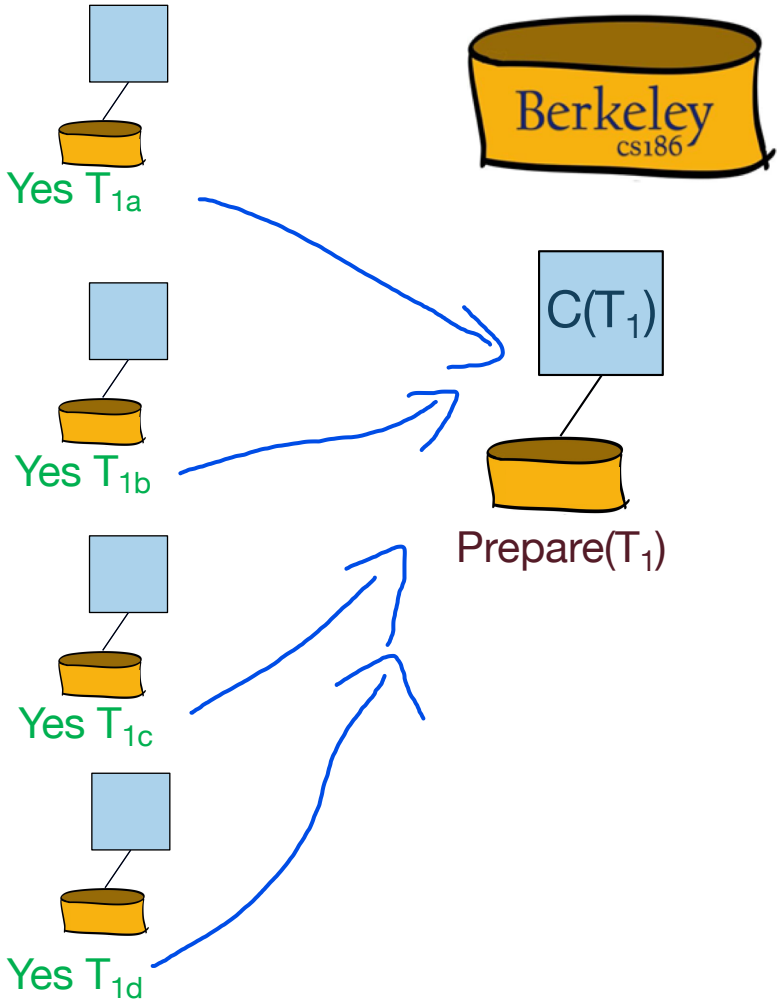

2-Phase Commit, Part 4

- **Phase 1:**
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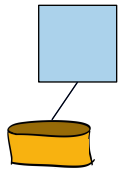
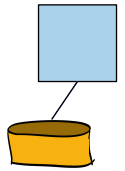
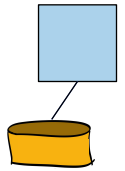
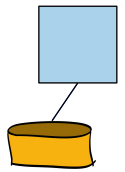
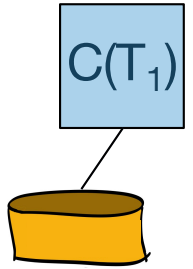
  - Participants respond with Ack





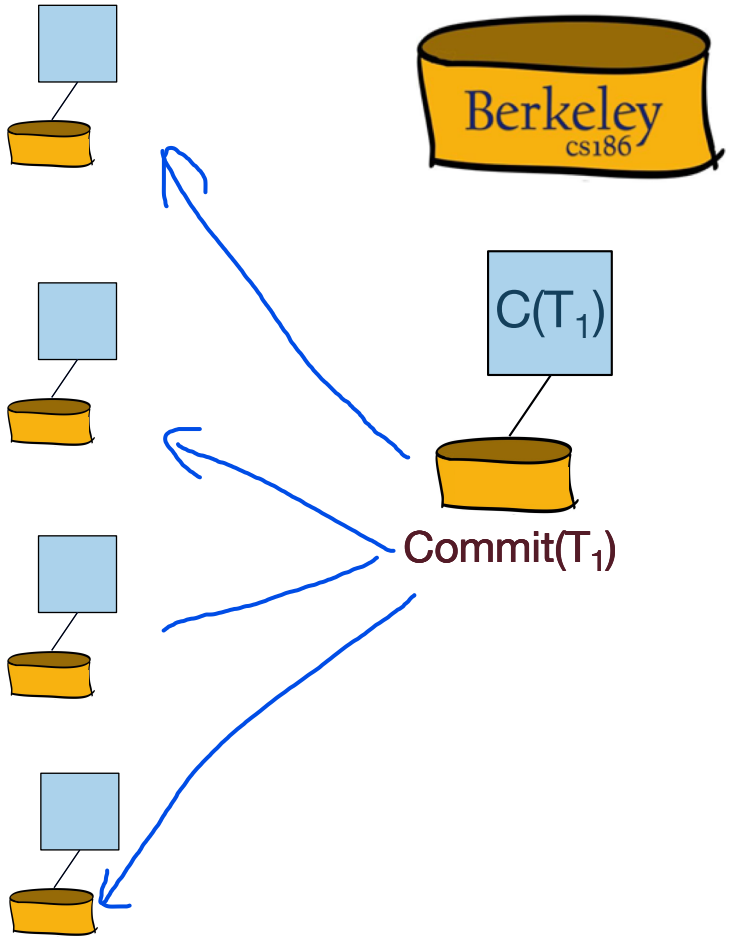






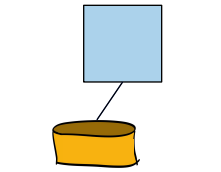
2-Phase Commit, Part 5

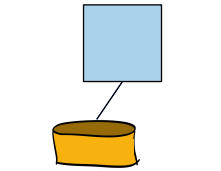
- Phase 1:
  - Coordinator tells participants to “prepare”
  - Participants respond with yes/no votes
    - Unanimity required for commit!
- **Phase 2:**
  - **Coordinator disseminates result of the vote**
  - Participants respond with Ack

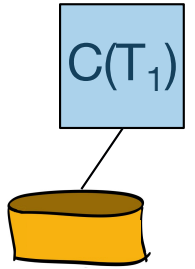


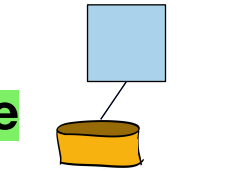
2-Phase Commit, Part 6

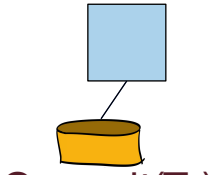
- Phase 1:
  - Coordinator tells participants to “prepare”
  - Participants respond with yes/no votes
    - Unanimity required for commit!
- **Phase 2:**
  - **Coordinator disseminates result of the vote**
  - Participants respond with Ack





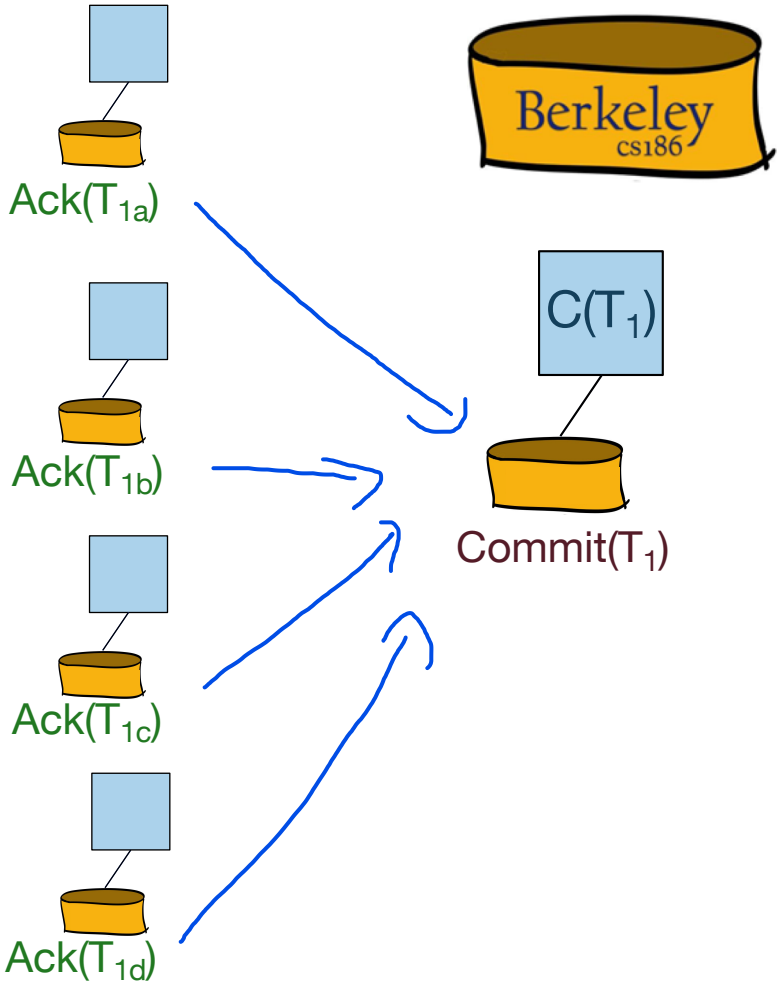






2-Phase Commit, Part 7

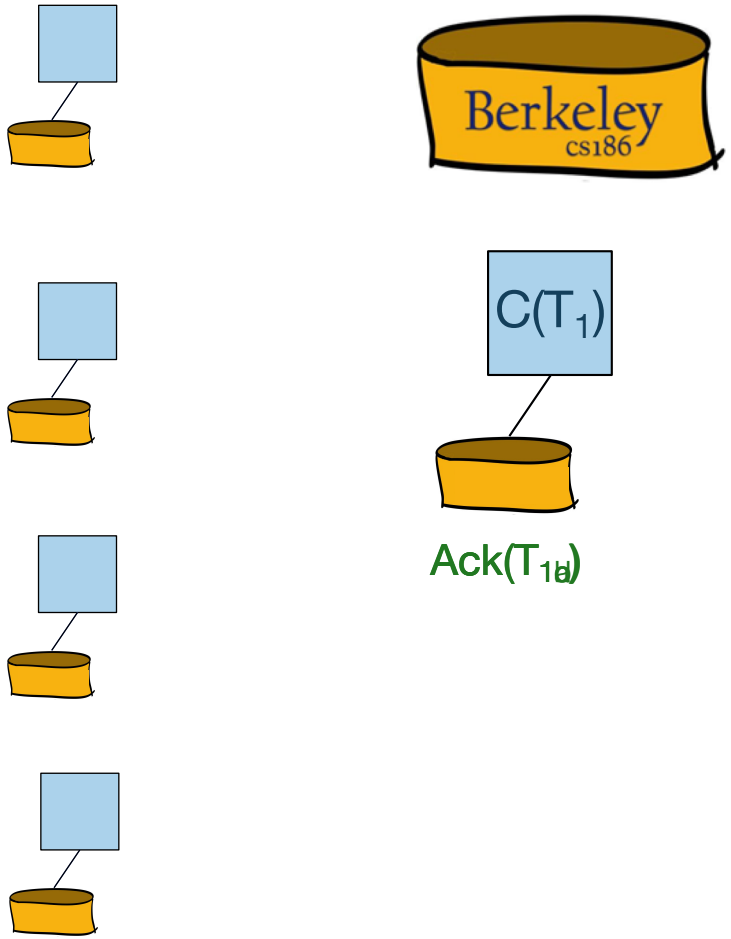
- Phase 1:
  - Coordinator tells participants to “prepare”
  - Participants respond with yes/no votes
    - Unanimity required for commit!
- **Phase 2:**
  - Coordinator disseminates result of the vote
  - **Participants respond with Ack**



2-Phase Commit, Part 8

- Phase 1:
  - Coordinator tells participants to “prepare”
  - Participants respond with yes/no votes
    - Unanimity required for commit!
- **Phase 2:**
  - Coordinator disseminates result of the vote
  - **Participants respond with Ack**

When the coordinator receives messages from all participants, txn is complete

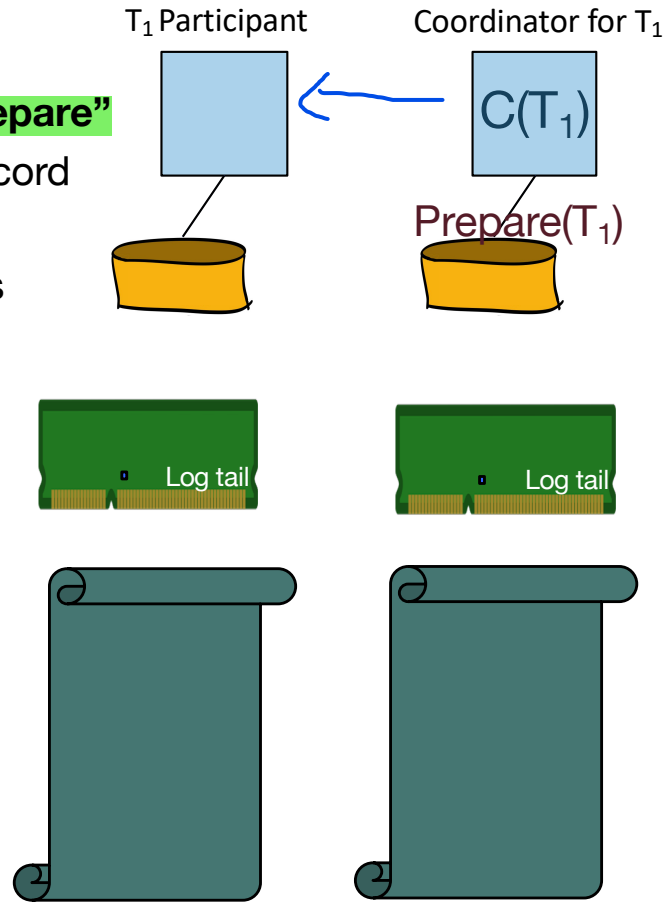


Recovery and Locking

Phase 1

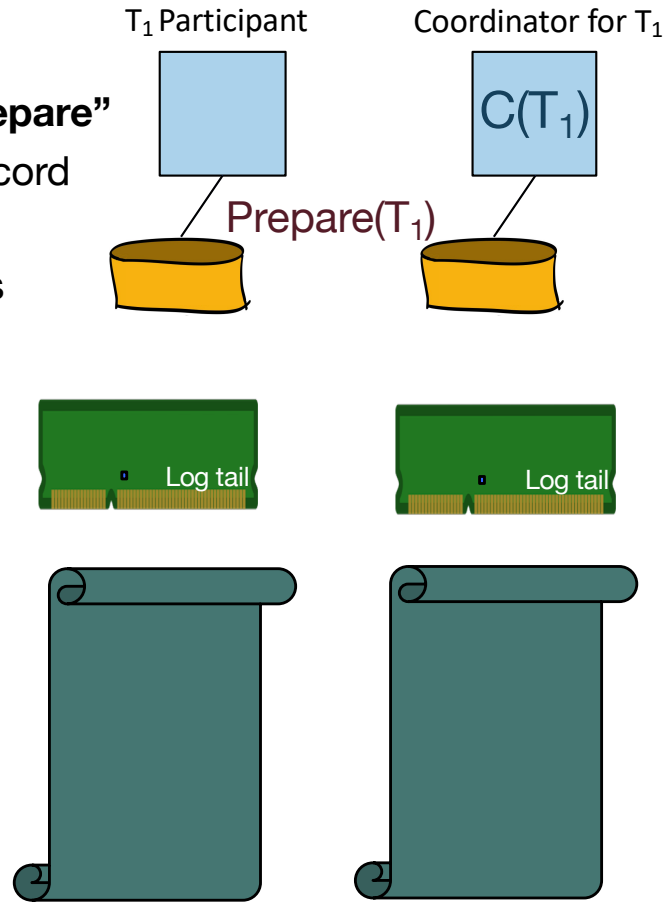
One More Time, With Logging

- **Phase 1**
- **Coordinator tells participants to "prepare"**
- Participants generate prepare/abort record
- Participants flush prepare/abort record
- Participants respond with yes/no votes
- Coordinator generates commit record
- Coordinator flushes commit record



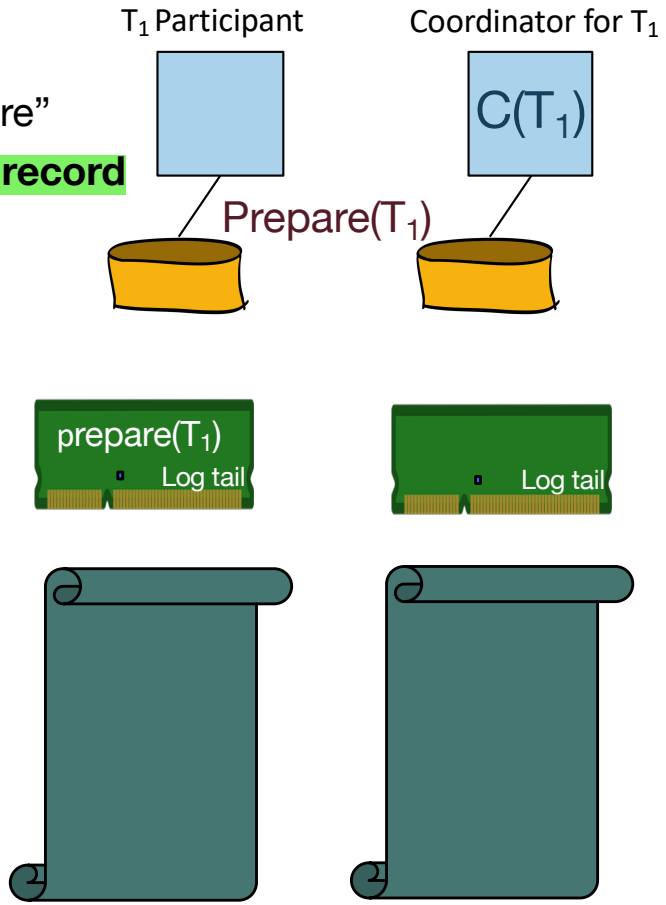
One More Time, With Logging, Part 2

- **Phase 1**
- **Coordinator tells participants to "prepare"**
- Participants generate prepare/abort record
- Participants flush prepare/abort record
- Participants respond with yes/no votes
- Coordinator generates commit record
- Coordinator flushes commit record



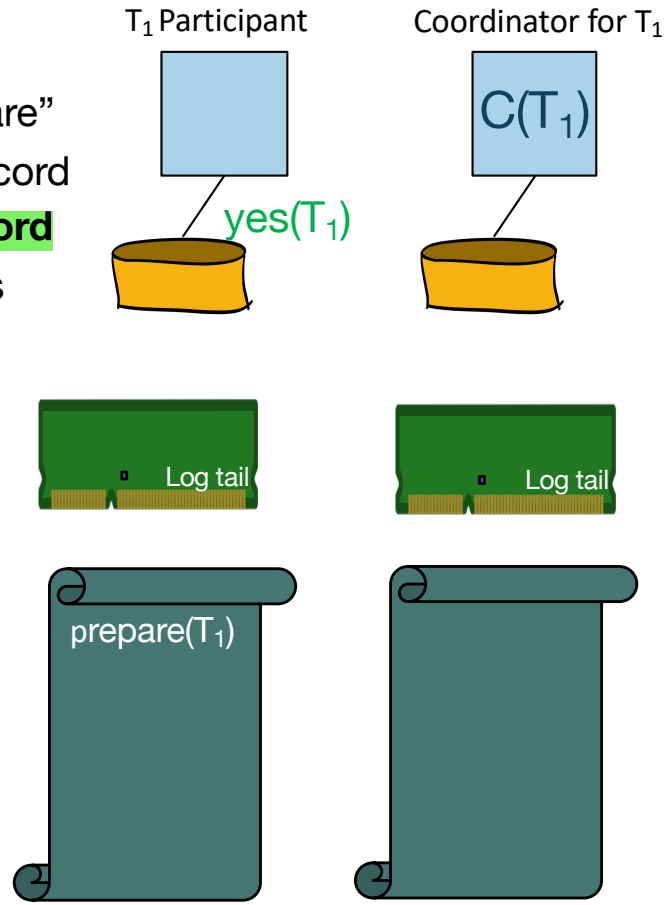
One More Time, With Logging, Part 3

- **Phase 1**
- Coordinator tells participants to “prepare”
- **Participants generate prepare/abort record**
- Participants flush prepare/abort record
- Participants respond with yes/no votes
- Coordinator generates commit record
- Coordinator flushes commit record



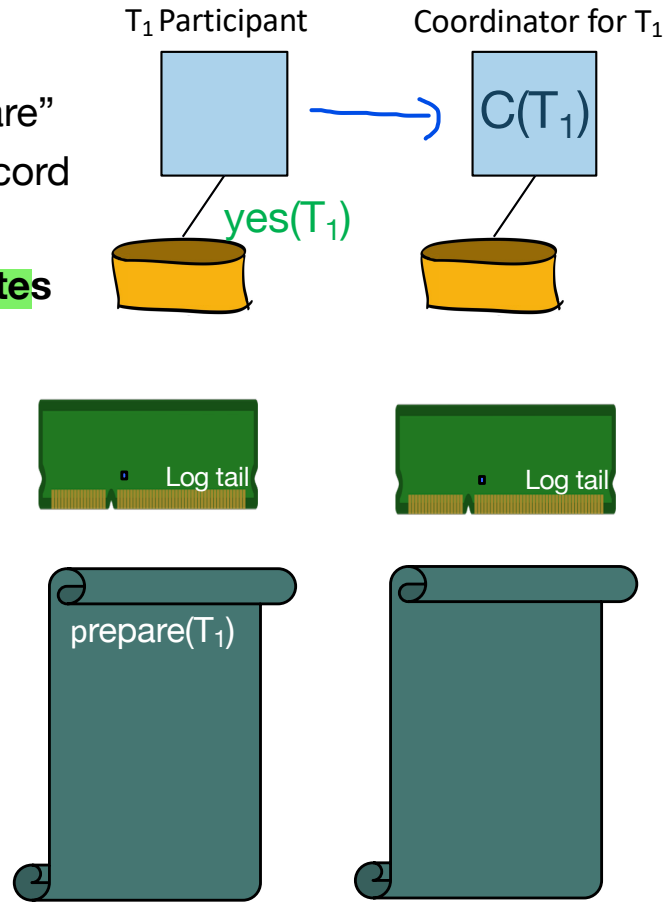
One More Time, With Logging, Part 4

- **Phase 1**
- Coordinator tells participants to “prepare”
- Participants generate prepare/abort record
- **Participants flush prepare/abort record**
- Participants respond with yes/no votes
- Coordinator generates commit record
- Coordinator flushes commit record



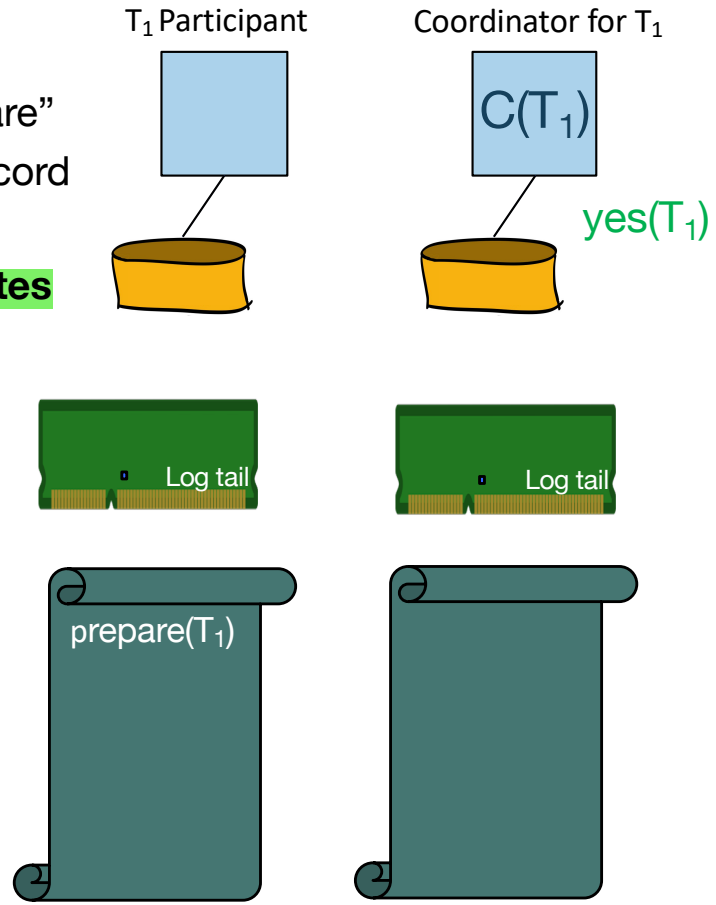
One More Time, With Logging, Part 5

- **Phase 1**
- Coordinator tells participants to “prepare”
- Participants generate prepare/abort record
- Participants flush prepare/abort record
- **Participants respond with yes/no votes**
- Coordinator generates commit record
- Coordinator flushes commit record



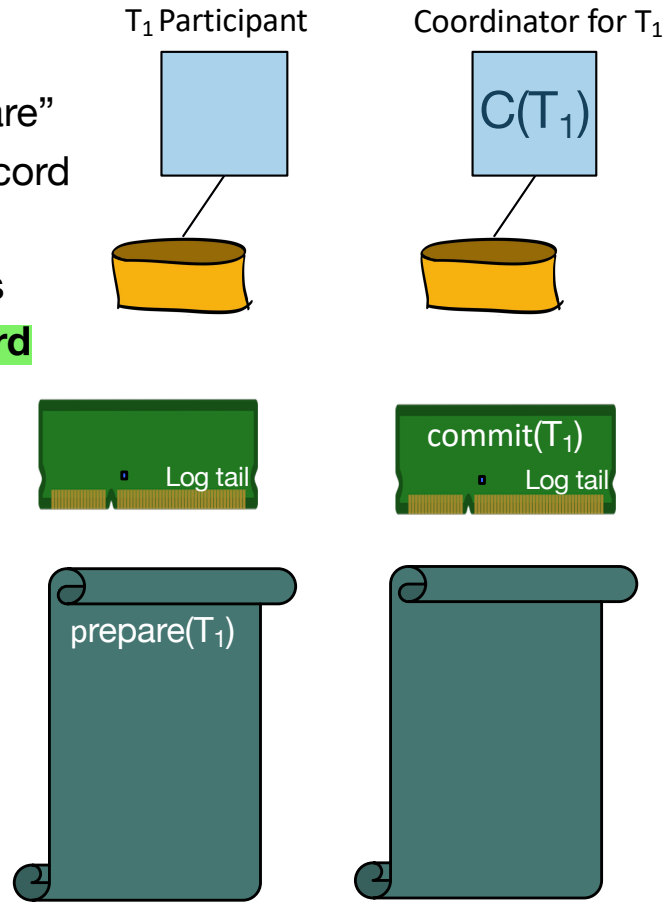
One More Time, With Logging, Part 6

- **Phase 1**
- Coordinator tells participants to “prepare”
- Participants generate prepare/abort record
- Participants flush prepare/abort record
- **Participants respond with yes/no votes**
- Coordinator generates commit record
- Coordinator flushes commit record



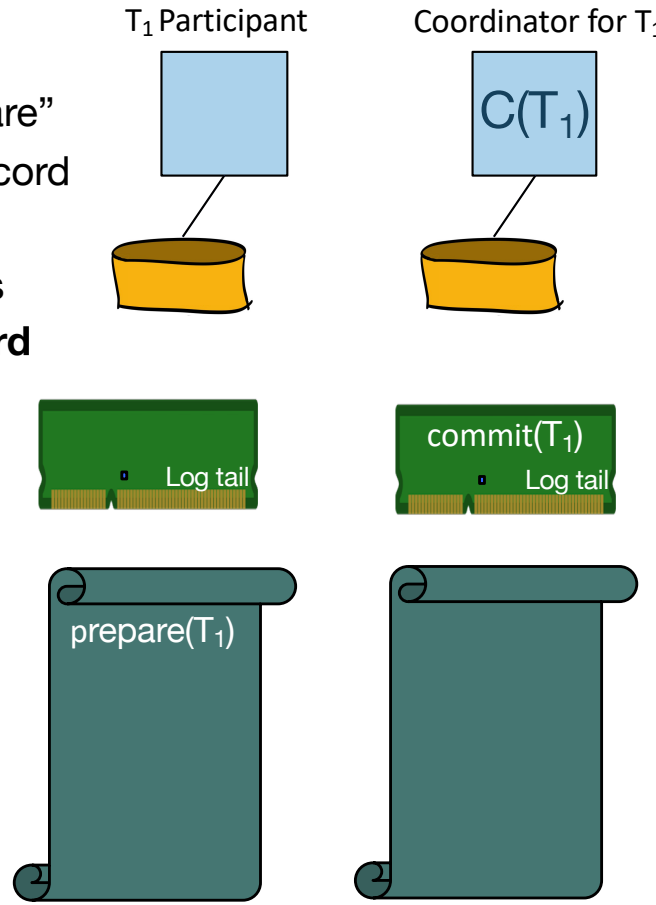
One More Time, With Logging, Part 7

- **Phase 1**
- Coordinator tells participants to “prepare”
- Participants generate prepare/abort record
- Participants flush prepare/abort record
- Participants respond with yes/no votes
- **Coordinator generates commit record**
- Coordinator flushes commit record



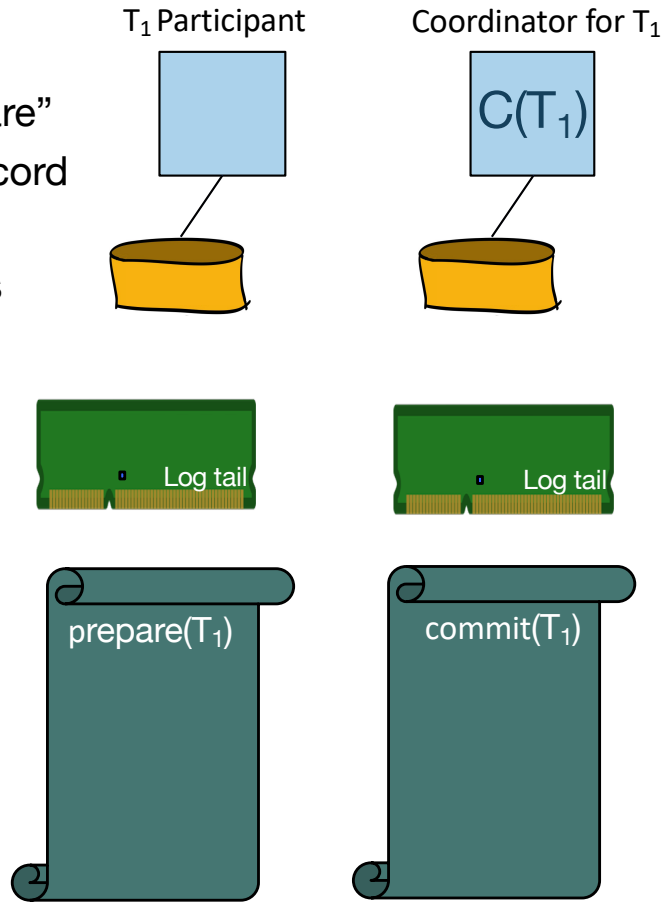
One More Time, With Logging, Part 8

- **Phase 1**
- Coordinator tells participants to “prepare”
- Participants generate prepare/abort record
- Participants flush prepare/abort record
- Participants respond with yes/no votes
- **Coordinator generates commit record**
- Coordinator flushes commit record



One More Time, With Logging, Part 9

- **Phase 1**
- Coordinator tells participants to “prepare”
- Participants generate prepare/abort record
- Participants flush prepare/abort record
- Participants respond with yes/no votes
- Coordinator generates commit record
- **Coordinator flushes commit record**

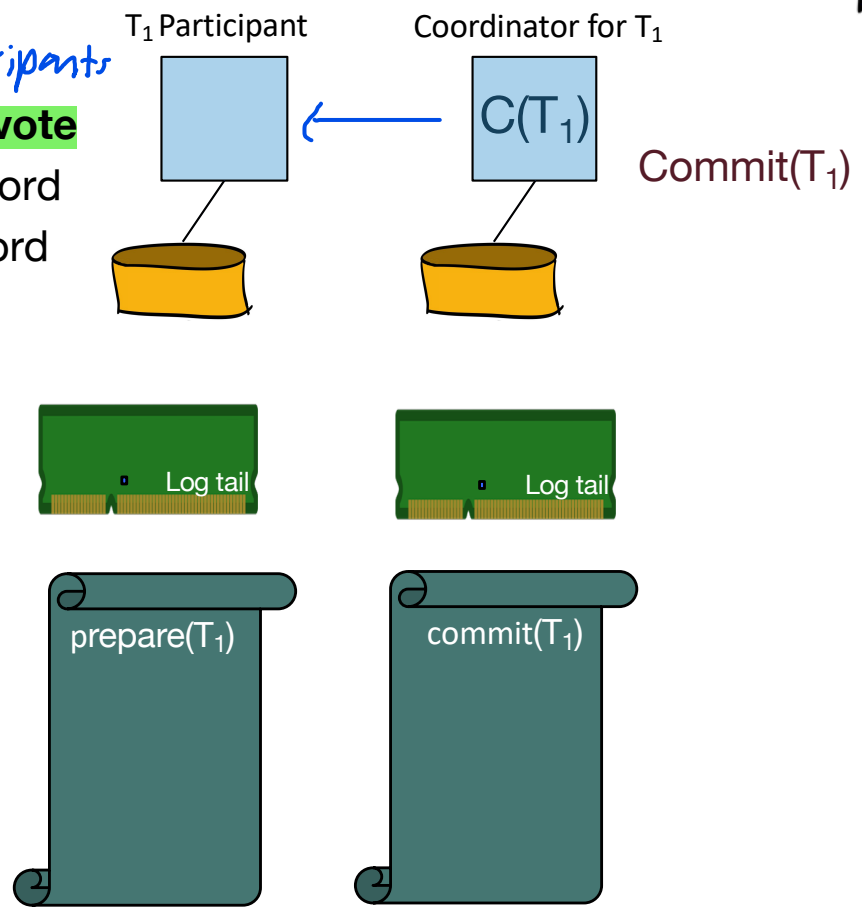


Phase 2

One More Time, With Logging, Part 10

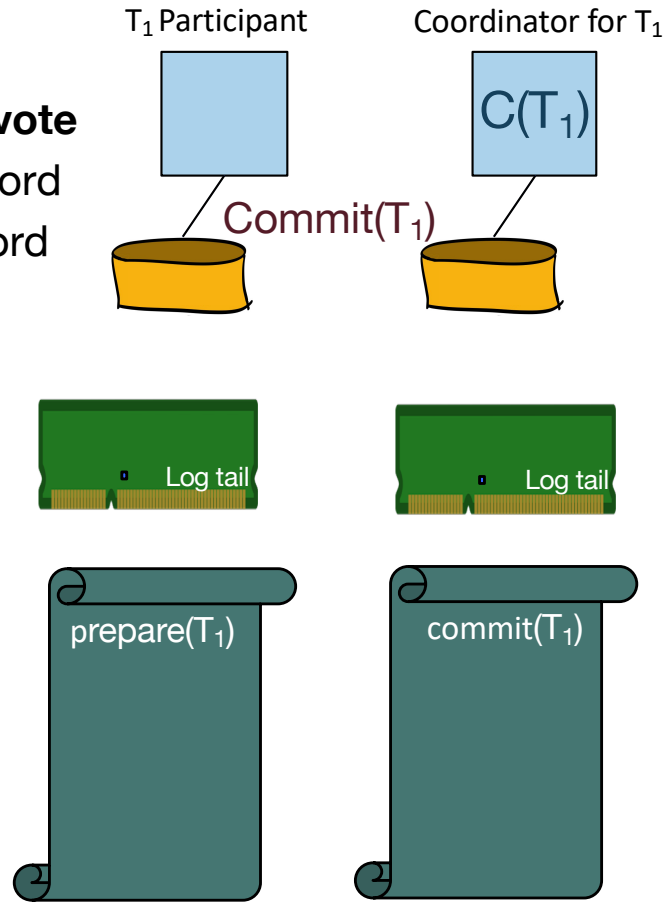
- **Phase 2:**
- **Coordinator broadcasts result of vote**
- Participants make commit/abort record
- Participants flush commit/abort record
- Participants respond with Ack
- Coordinator generates end record
- Coordinator flushes end record

to participants



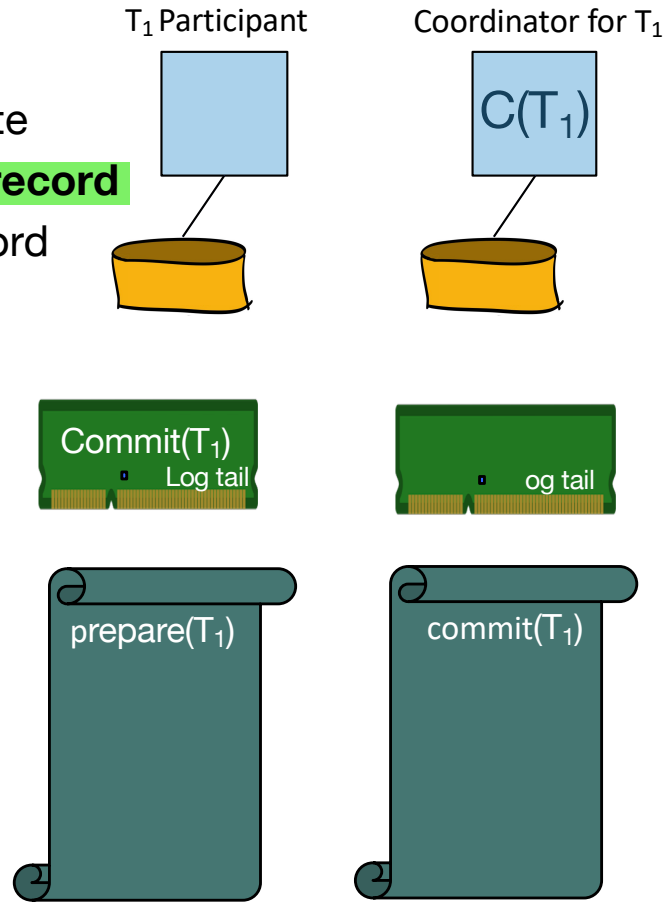
One More Time, With Logging, Part 11

- **Phase 2:**
- **Coordinator broadcasts result of vote**
- Participants make commit/abort record
- Participants flush commit/abort record
- Participants respond with Ack
- Coordinator generates end record
- Coordinator flushes end record



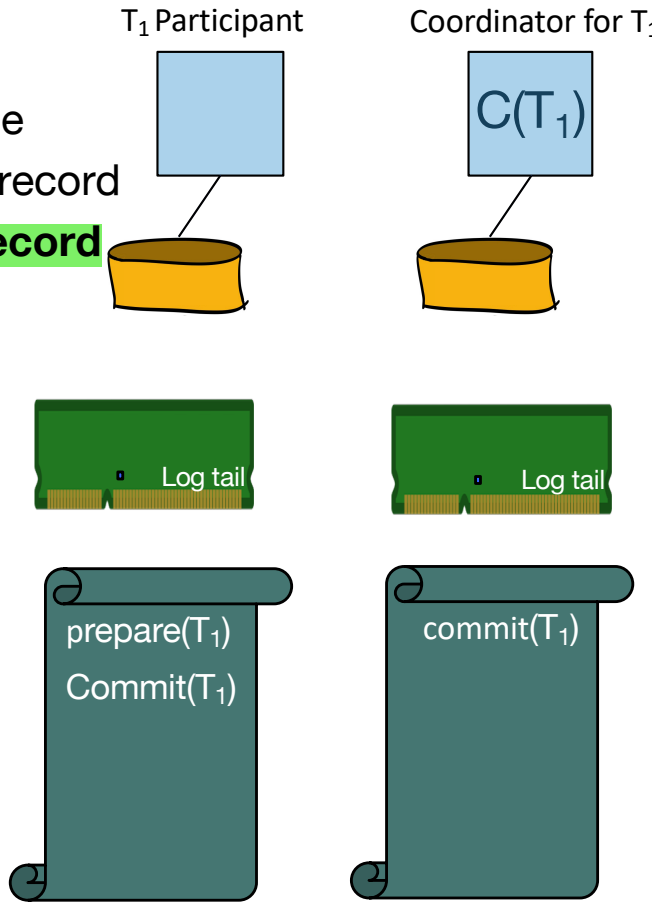
One More Time, With Logging, Part 12

- **Phase 2:**
- Coordinator broadcasts result of vote
- **Participants make commit/abort record**
- Participants flush commit/abort record
- Participants respond with Ack
- Coordinator generates end record
- Coordinator flushes end record



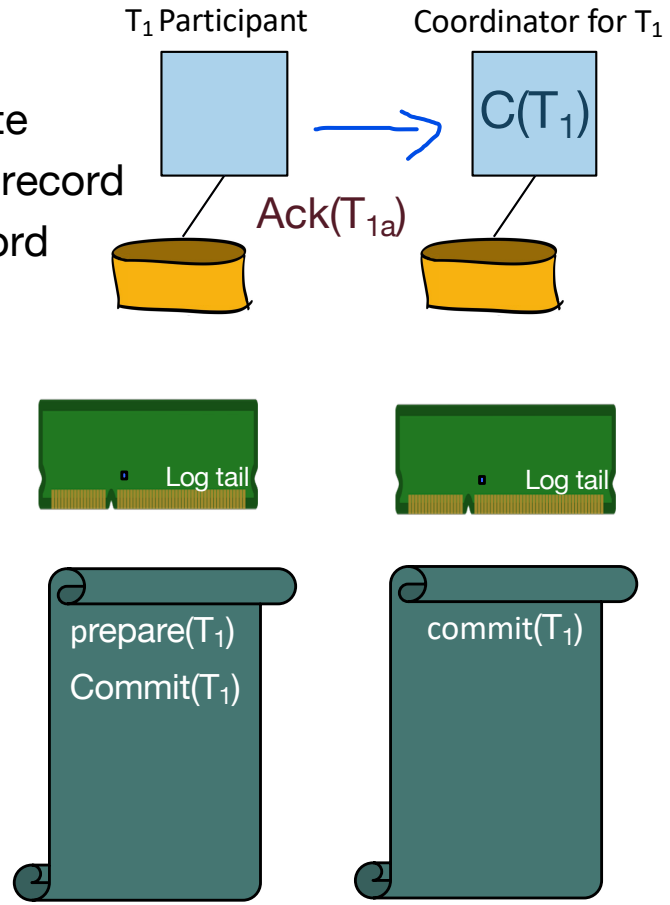
One More Time, With Logging, Part 13

- **Phase 2:**
- Coordinator broadcasts result of vote
- Participants generate commit/abort record
- **Participants flush commit/abort record**
- Participants respond with Ack
- Coordinator generates end record
- Coordinator flushes end record



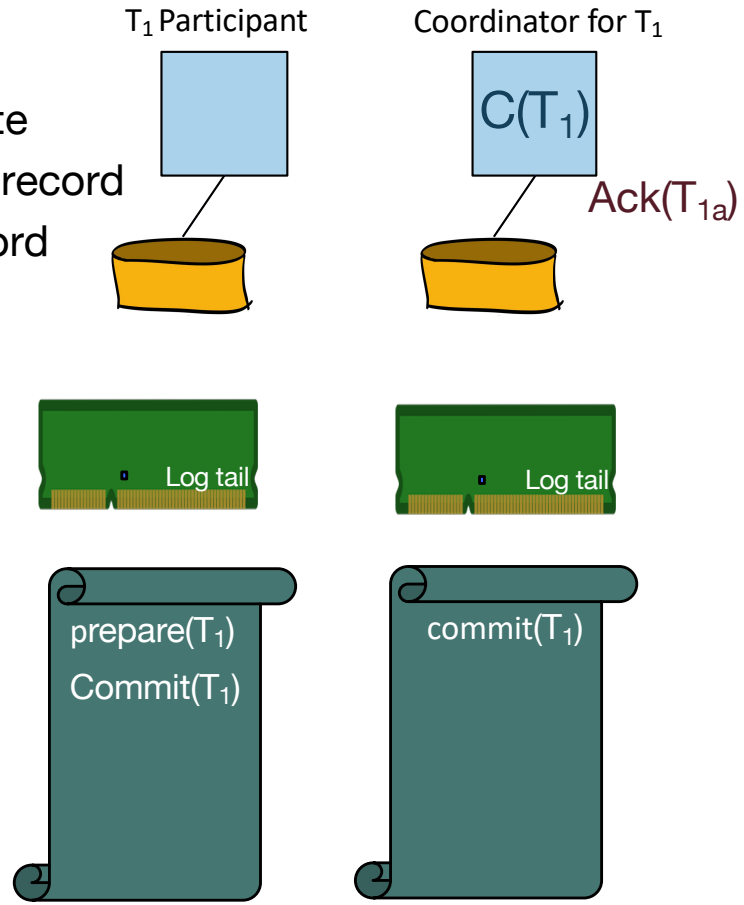
One More Time, With Logging, Part 14

- **Phase 2:**
- Coordinator broadcasts result of vote
- Participants generate commit/abort record
- Participants flush commit/abort record
- **Participants respond with Ack**
- Coordinator generates end record
- Coordinator flushes end record



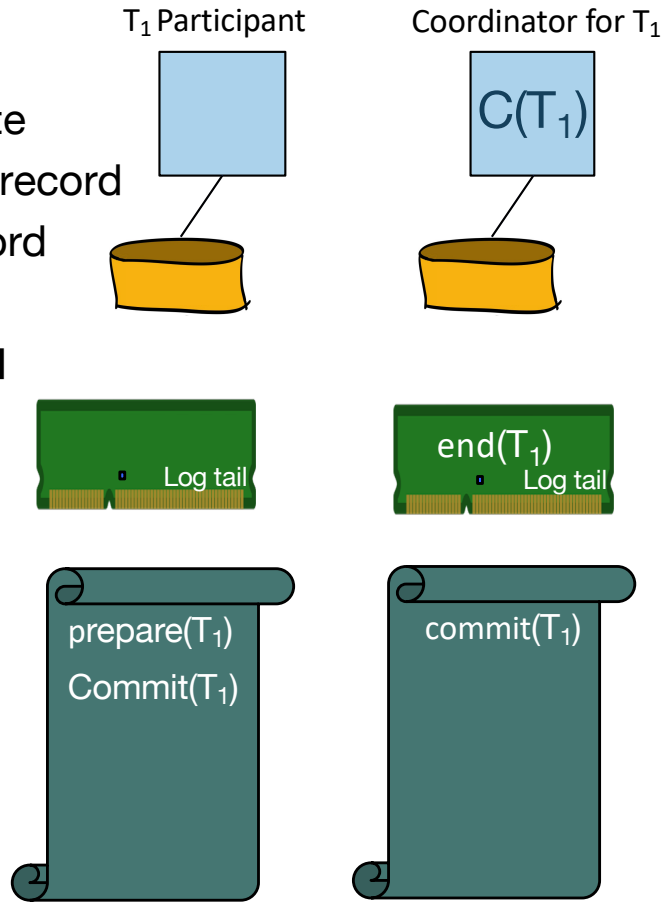
One More Time, With Logging, Part 15

- **Phase 2:**
- Coordinator broadcasts result of vote
- Participants generate commit/abort record
- Participants flush commit/abort record
- **Participants respond with Ack**
- Coordinator generates end record
- Coordinator flushes end record



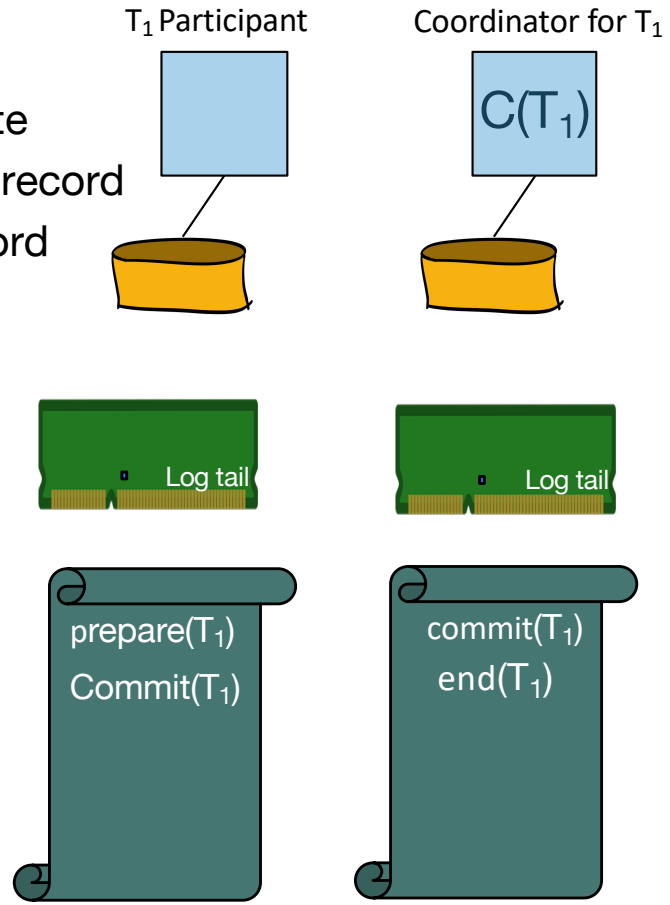
One More Time, With Logging, Part 16

- **Phase 2:**
- Coordinator broadcasts result of vote
- Participants generate commit/abort record
- Participants flush commit/abort record
- Participants respond with Ack
- **Coordinator generates end record**
- Coordinator flushes end record

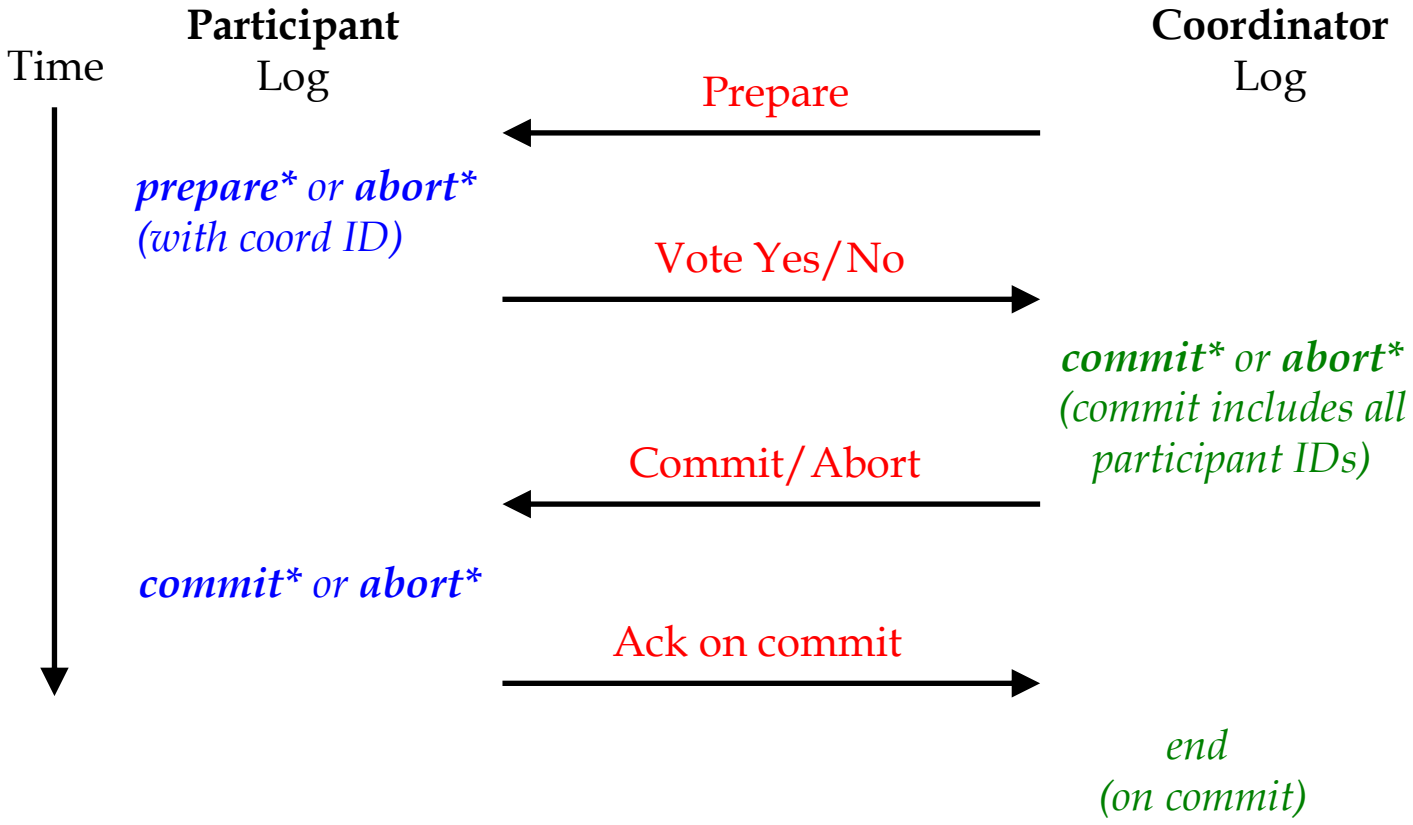


One More Time, With Logging, Part 17

- **Phase 2:**
- Coordinator broadcasts result of vote
- Participants generate commit/abort record
- Participants flush commit/abort record
- Participants respond with Ack
- Coordinator generates end record
- **Coordinator flushes end record**



2PC In a Nutshell

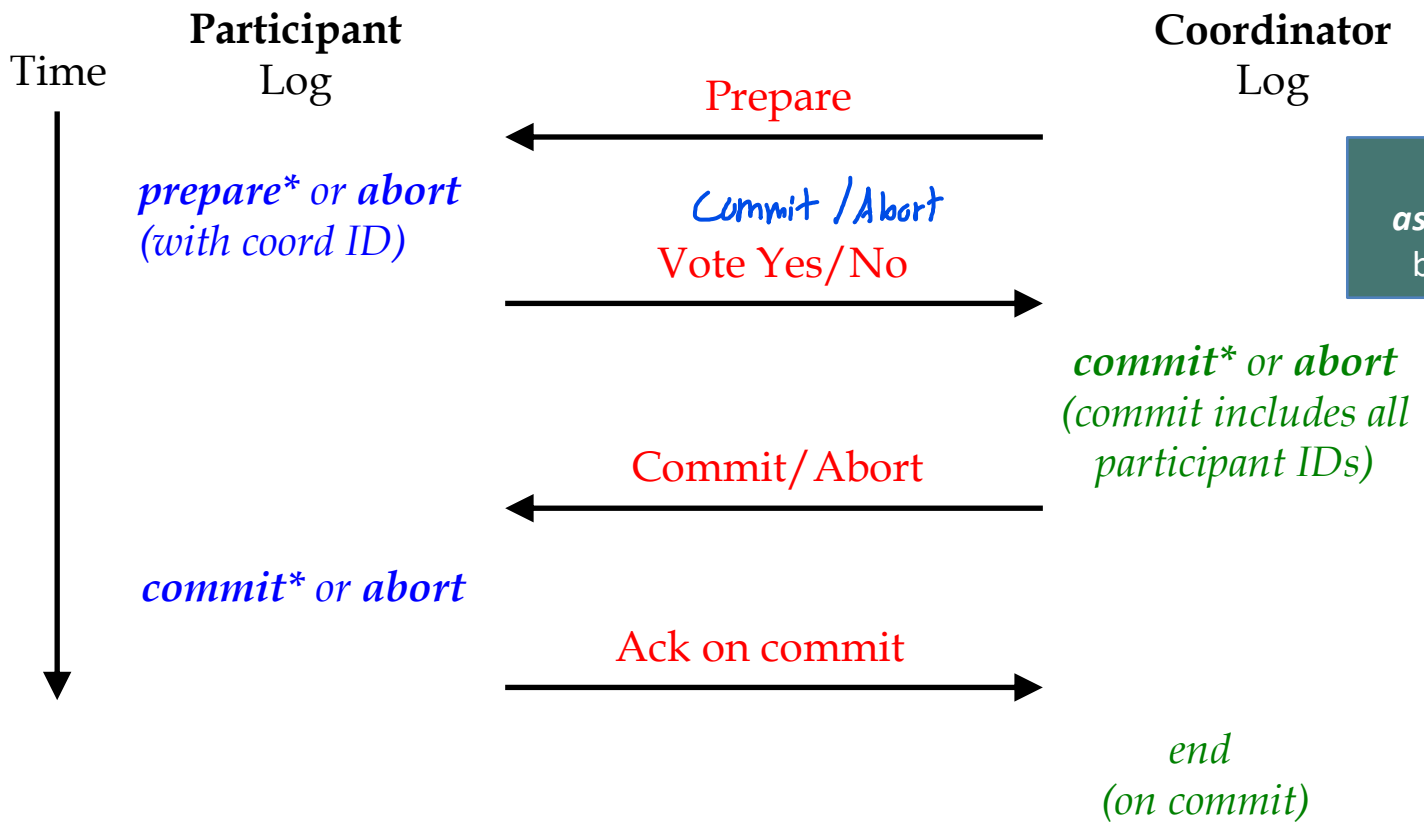


NOTE
asterisk*: wait for log flush before sending next msg

Presumed Abort

- Previous scheme needs prepare / abort / commit logged before sending msgs
- Presumed abort: Don't flush abort records to log before sending next msg

Don't need b/c if txn logs lack commit, we presume it aborted

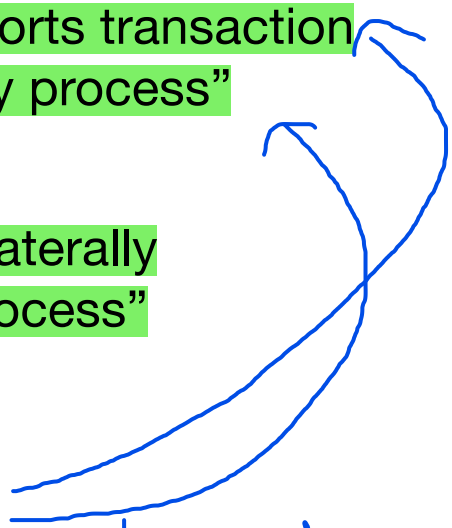


NOTE
asterisk*: wait for log flush before sending next msg

Recovery and 2PC

Failure Handling

- Assume everybody recovers eventually
  - Big assumption!
  - Assume short downtimes!
- Coordinator notices a Participant is down?
  - If participant hasn't voted yet, coordinator aborts transaction
  - If waiting for a commit Ack, hand to "recovery process"
- Participant notices Coordinator is down?
  - If it hasn't yet logged prepare, then abort unilaterally
  - If it has logged prepare, hand to "recovery process"
- Note
  - Thinking a node is "down" may be incorrect!

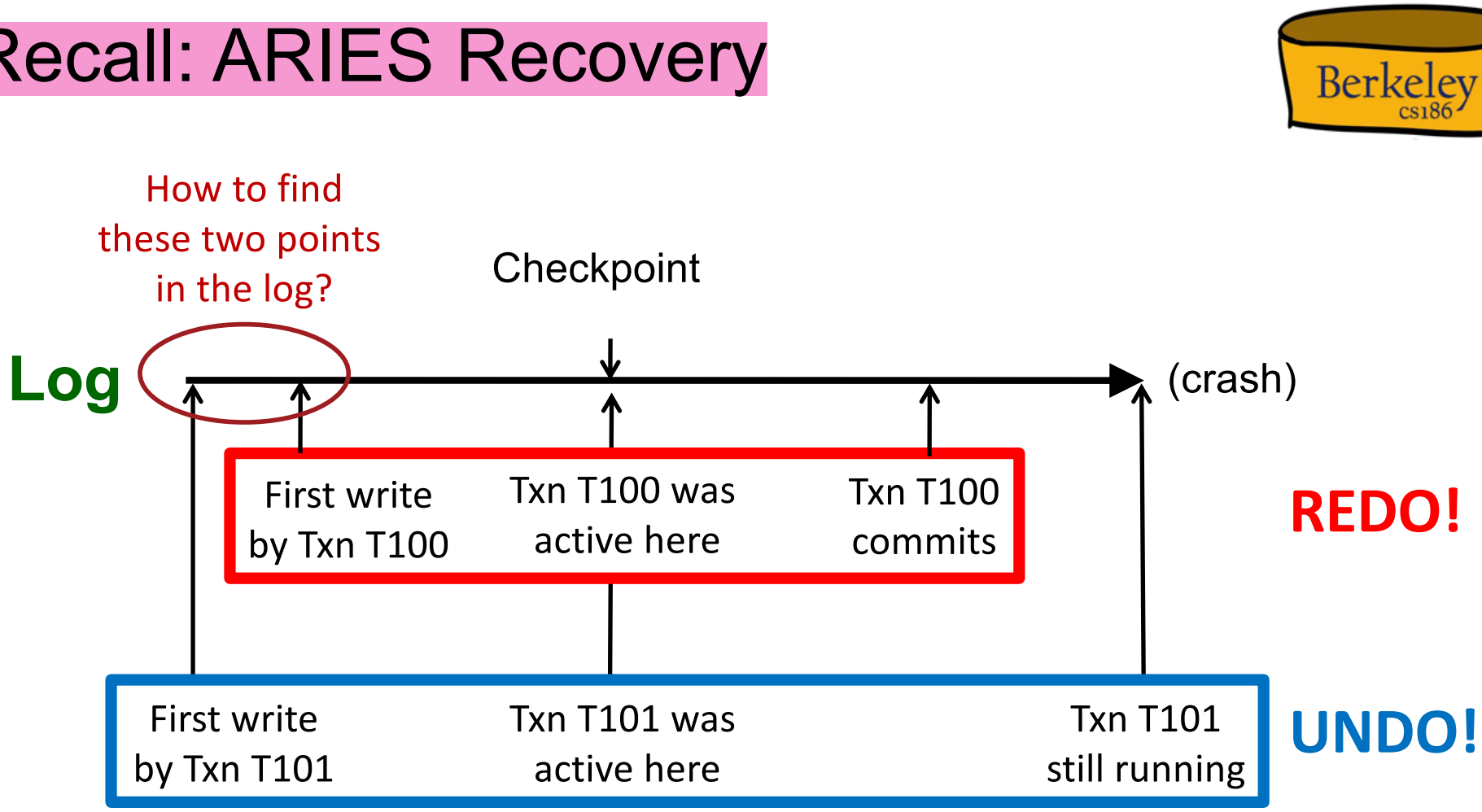


may just be lagging behind

Integration with ARIES Recovery

- On recovery
  - Assume there's a "Recovery Process" at each node
  - It will be given tasks to do by the Analysis phase of ARIES
  - These tasks can run in the background (asynchronously)
- Note: multiple roles on a single node
  - Coordinator for some xacts, Participant for others

Recall: ARIES Recovery



Recall: ARIES Recovery

Recovery from a system crash is done in 3 passes:

1. **Analysis pass**
   - Recreate list of dirty pages and active transactions
2. **Redo pass**
   - Redo all operations, even for those that were incomplete before crash
   - Goal is to replay DB to the state at the moment of the crash
3. **Undo pass**
   - Unroll effects of all incomplete transactions at time of crash
   - Log changes during undo in case of another crash during undo

Integration with ARIES Recovery

- Recall transaction table states
  - Running, Committing, Aborting

- Same goal as before: recover the state of txns at crash
  - Caveat: 2PC introduces a new phase

prepare phases before commit

Integration with ARIES: Participant Analysis

- On seeing Prepare log record
  - Change state to committing
  - Tell recovery process to ask coordinator recovery process for status
  - When coordinator responds, recovery process handles commit/abort as usual
- On seeing Commit or Abort log record
  - Process the same way as single node ARIES
  - Send Ack back to coordinator when done as usual

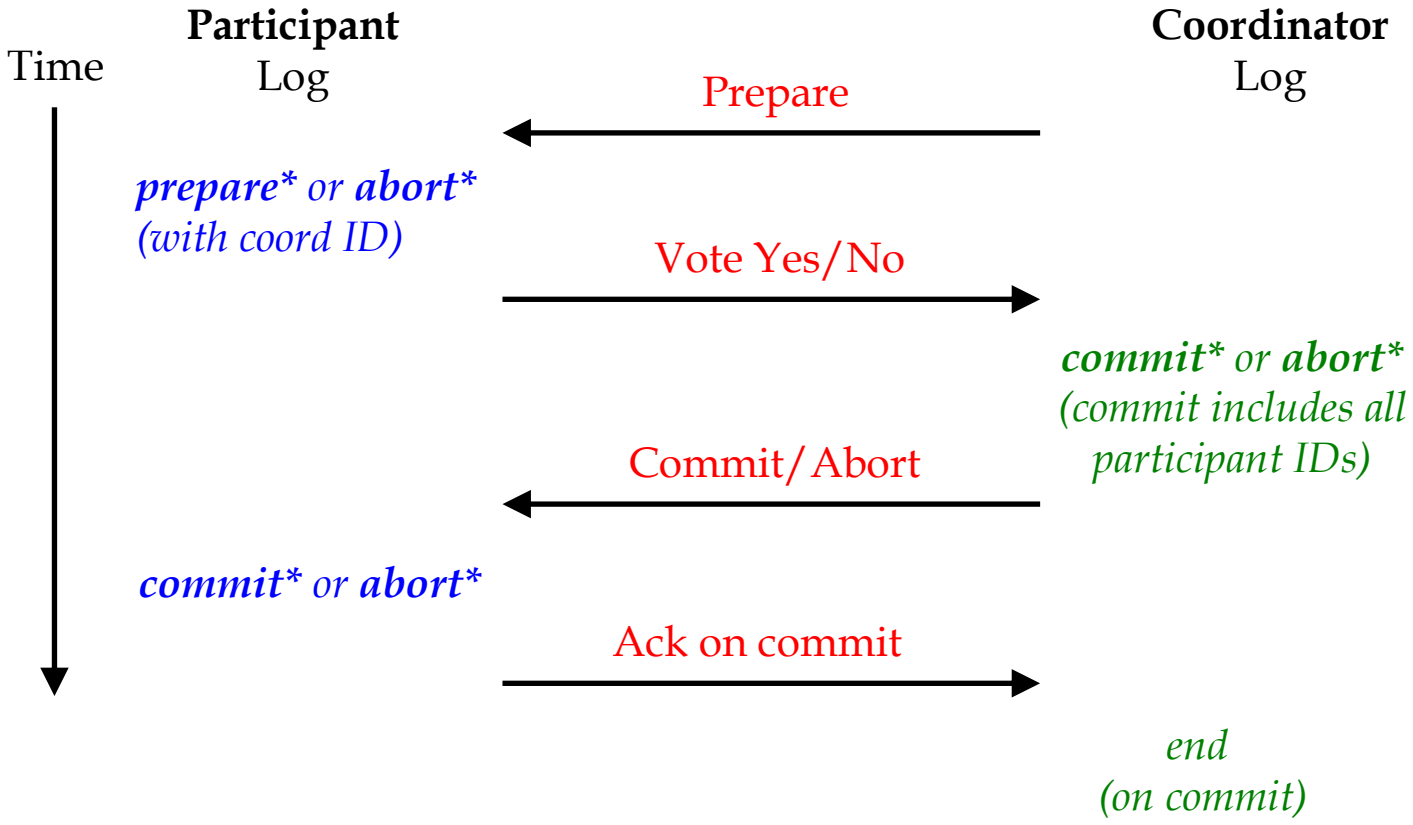
Integration with ARIES: Coordinator Analysis

- On seeing Commit/Abort log record
  - Change state to committing/aborting respectively
  - Tell recovery process to send commit/abort msgs to participants
  - Once all participants ack commit, recovery process writes End record
- If at end of analysis there's no 2PC log records for xact X
  - This means we have not enter phase 2 or txn has aborted (if presumed abort)
  - Simply set to Aborting locally, and let ToUndo handle it.
  - Same for participant and coordinator

How Does Recovery Process Work?

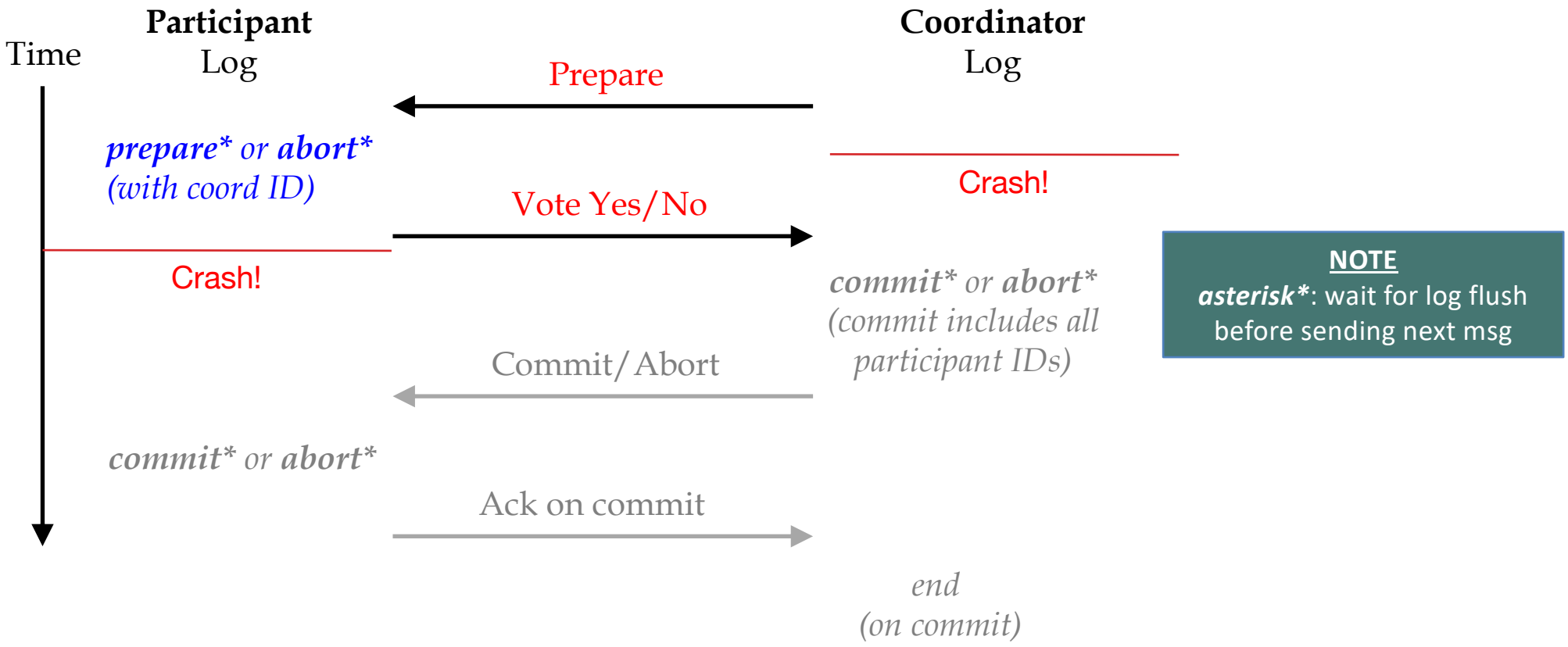
- Coordinator recovery process gets inquiry from a "prepared" participant
  - If transaction table at coordinator says aborting/committing
    - send appropriate response and continue protocol on both sides
  - If transaction table at coordinator says nothing: send ABORT
    - Only happens if coordinator had also crashed before writing commit/abort
    - Inquirer does the abort on its end

2PC In a Nutshell



NOTE
asterisk*: wait for log flush before sending next msg

2PC In a Nutshell



Recovery: Think it through

- What happens when coordinator recovers?
  - With "commit" and "end"? **Nothing**
  - With just "commit"? **Rerun Phase 2!**
  - With "abort"? **Nothing (Presumed Abort)**

Commit iff coordinator logged a commit

- What happens when participant recovers:
  - With no prepare/commit/abort? **Nothing (Presumed Abort)**
  - With "prepare" & "commit"? **Send Ack to coordinator.**
  - With just "prepare"? **Send inquiry to Coordinator**
  - With "abort"? **Nothing (Presumed Abort)**

2PC + Strict 2PL

- Ensure point-to-point messages are densely ordered
  - 1,2,3,4,5…
  - Dense per (sender/receiver/XID)
  - Receiver can detect anything missing or out-of-order
  - Receiver buffers message k+1 until [1..k] received
  - Effect: receiver handles messages in order
- Commit:
  - When a participant processes Commit request, it has all the locks it needs
  - Flush log records and drop locks atomically
- Abort:
  - Its safe to abort autonomously, locally: no cascade.
  - Write abort to log, flush if not presumed abort (otherwise don't flush)
  - Perform local Undo, drop locks atomically

Availability Concerns

- What happens while a node is down?
  - Other nodes may be in limbo, holding locks
  - So certain data is unavailable
  - This may be bad...
- Dead Participants? Respawned by coordinator
  - Recover from log
  - And if the old participant comes back from the dead, just ignore it and tell it to recycle itself
- Dead Coordinator?
  - This is a problem!
  - 3-Phase Commit was an early attempt to solve it
  - Paxos Commit provides a more comprehensive solution
    - Gray+Lamport paper! Out of scope for this class.

Summing Up

- Distributed Databases
  - A central aspect of Distributed Systems
- Partitioning provides Scale-Up
- Can also partition lock tables and logs
- But need to do some global coordination:
  - Deadlock detection: easy
  - Commit: trickier
- Two-phase commit is a classic distributed consensus protocol
  - Logging/recovery aspects unique:
    - many distributed protocols gloss over
  - But 2PC is unavailable on any single failure
  - This is bad news for scale-up,
    - because odds of failure go up with #machines
  - Paxos Commit (Gray+Lamport) addresses that problem