Distributed Systems

11. Distributed Commit Protocols

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Atomic Transactions

Transaction

- An operation composed of a number of discrete steps.

- All the steps must be completed for the transaction to be **committed**. The results are made permanent.
- Otherwise, the transaction is **aborted** and the state of the system reverts to what it was before the transaction started.
  - **rollback** = reverting to a previous state

Example

Buying a house:

– Make an offer
– Sign contract
– Deposit money in escrow
– Inspect the house
– Critical problems from inspection?
– Get a mortgage
– Have seller make repairs
– Commit: sign closing papers & transfer deed
– Abort: return escrow and revert to pre-purchase stat

All or nothing property

Basic Operations

Transaction primitives:

- *Begin transaction*: mark the start of a transaction
- *End transaction*: mark the end of a transaction – no more tasks
- *Commit transaction*: make the results permanent
- *Abort transaction*: kill the transaction, restore old values
- Read/write/compute data (modify files or objects)
  - But data will have to be restored if the transaction is aborted.

Another Example

Book a flight from Newark, New Jersey to Inyokern, California. No non-stop flights are available:

Transaction begin

1. Reserve a seat for Newark to Denver (EWR→DEN)
2. Reserve a seat for Denver to Los Angeles (DEN→LAX)
3. Reserve a seat for Denver to Inyokern (LAX→IYK)

Transaction end

If there are no seats available on the LAX→IYK leg of the journey, the transaction is *aborted* and reservations for (1) and (2) are undone.

Properties of transactions: ACID

- Atomic
  - The transaction happens as a single indivisible action. Everything succeeds or else the entire transaction is rolled back. Others do not see intermediate results.
- Consistent
  - A transaction cannot leave the database in an inconsistent state. E.g., total amount of money in all accounts must be the same before and after a “transfer funds” transaction.
- Isolated (Serializable)
  - Transactions cannot interfere with each other or see intermediate results If transactions run at the same time, the final result must be the same as if they executed in some serial order.
- Durable
  - Once a transaction commits, the results are made permanent.

Distributed Transactions

Transaction that updates data on two or more systems

Challenge

Handle machine, software, & network failures while preserving transaction integrity

Distributed Transactions

Each computer runs a **transaction manager**

- Responsible for subtransactions on that system
- Performs *prepare*, *commit*, and *abort* calls for subtransactions

Every subtransaction must agree to commit changes before the overall transaction can complete

Commits Among Subtransactions = Consensus

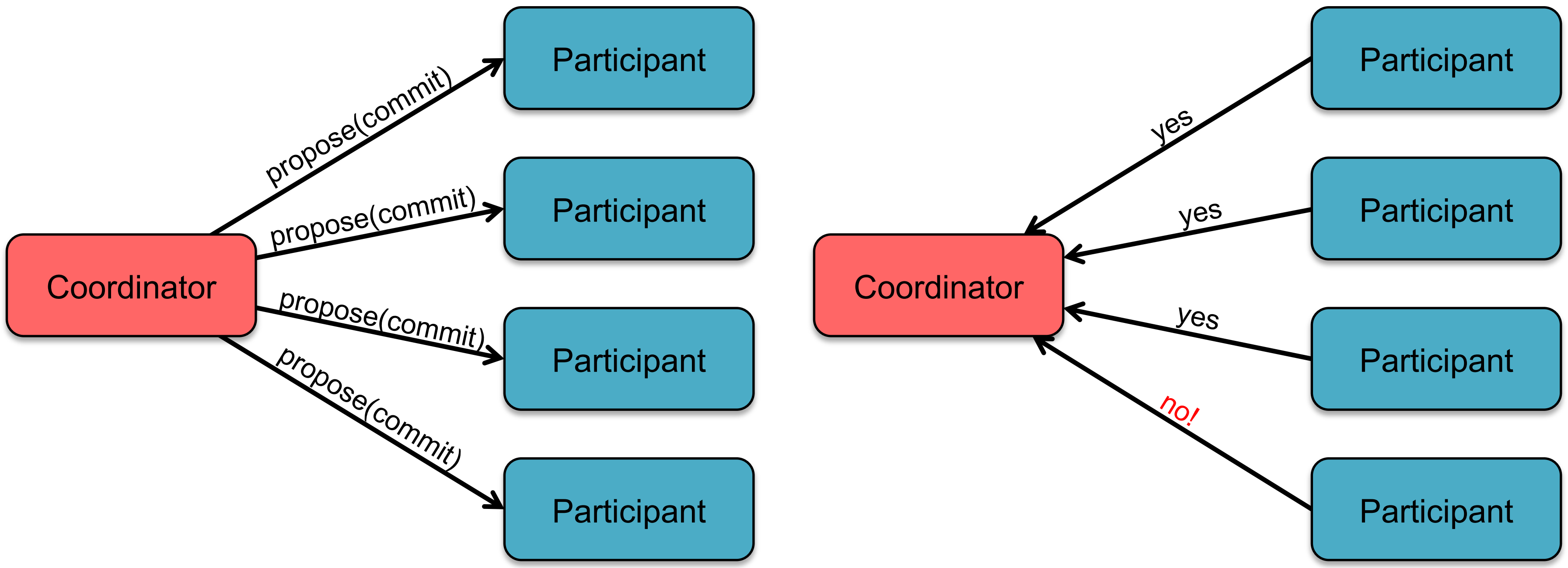
- Remember consensus?
  - Agree on a value proposed by at least one process

- BUT – here we need unanimous agreement to commit

- The coordinator proposes to commit a transaction
  - **All** participants agree ⇒ all participants then commit
  - **Not all** participants agree ⇒ all participants then abort

Two-Phase Commit Protocol

Two-Phase Commit Protocol



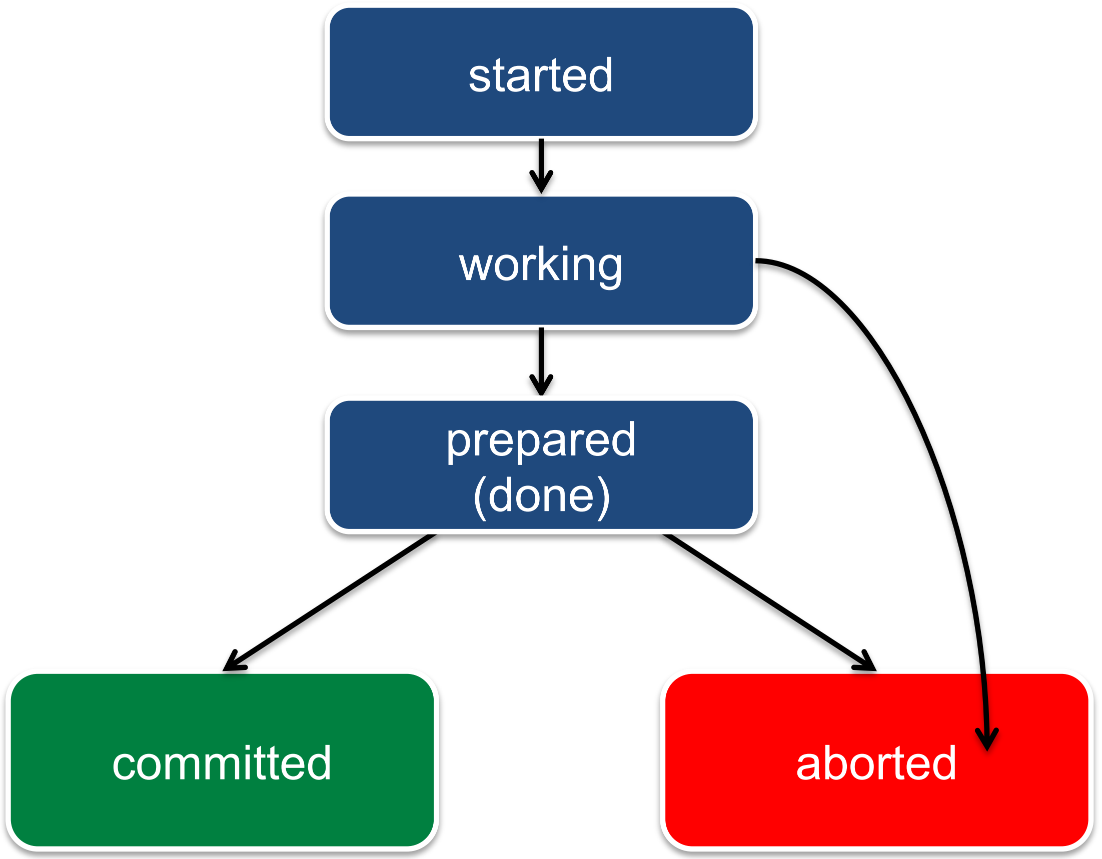
Two-phase commit protocol

Goal:

Reliably agree to commit or abort a collection of sub-transactions

- All processes in the transaction will agree to commit or abort
- Consensus: all processes agree on whether or not to commit
- One transaction manager is *elected* as a **coordinator** – the rest are **participants**
- Assume:
  - **write-ahead log** in stable storage
  - No system dies forever
  - Systems can always communicate with each other

Transaction States

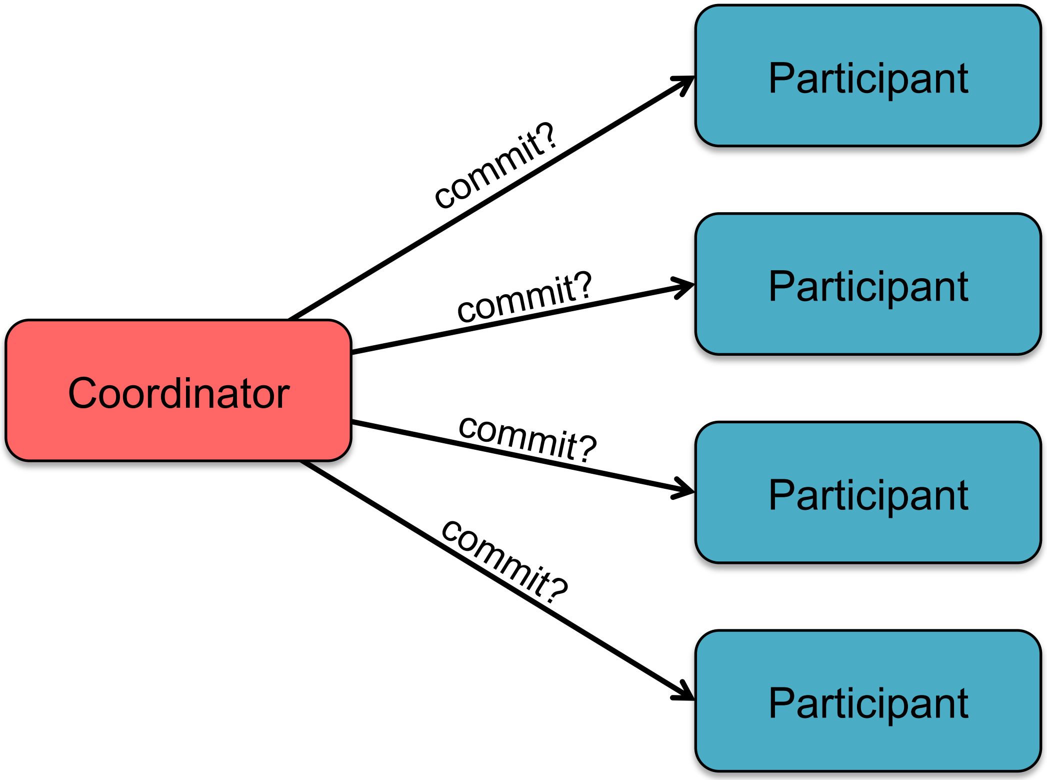


When a participant enters the ***prepared*** state, it contacts the coordinator to start the commit protocol to commit the entire transaction

Two-Phase Commit Protocol

Phase 1: Voting Phase

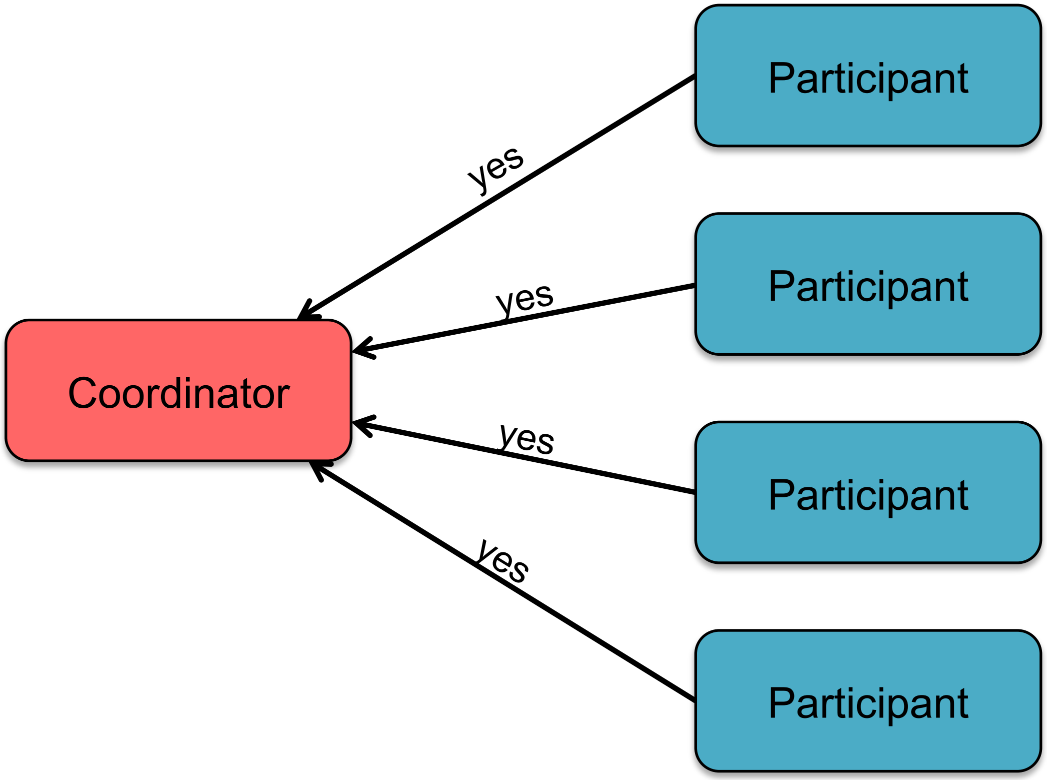
Get commit agreement from *every* participant



Two-Phase Commit Protocol

Phase 1: Voting Phase

Get commit agreement from *every* participant

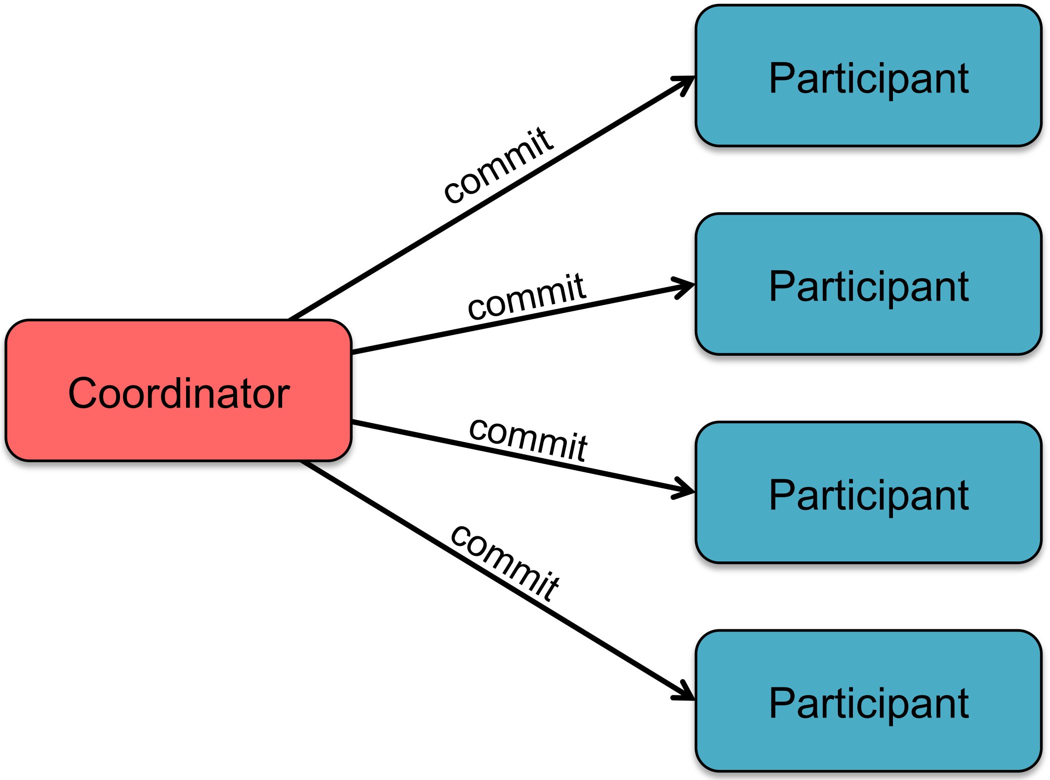


A single "no" response means that we will have to abort the transaction

Two-Phase Commit Protocol

Phase 2: Commit Phase

Send the results of the vote to every participant

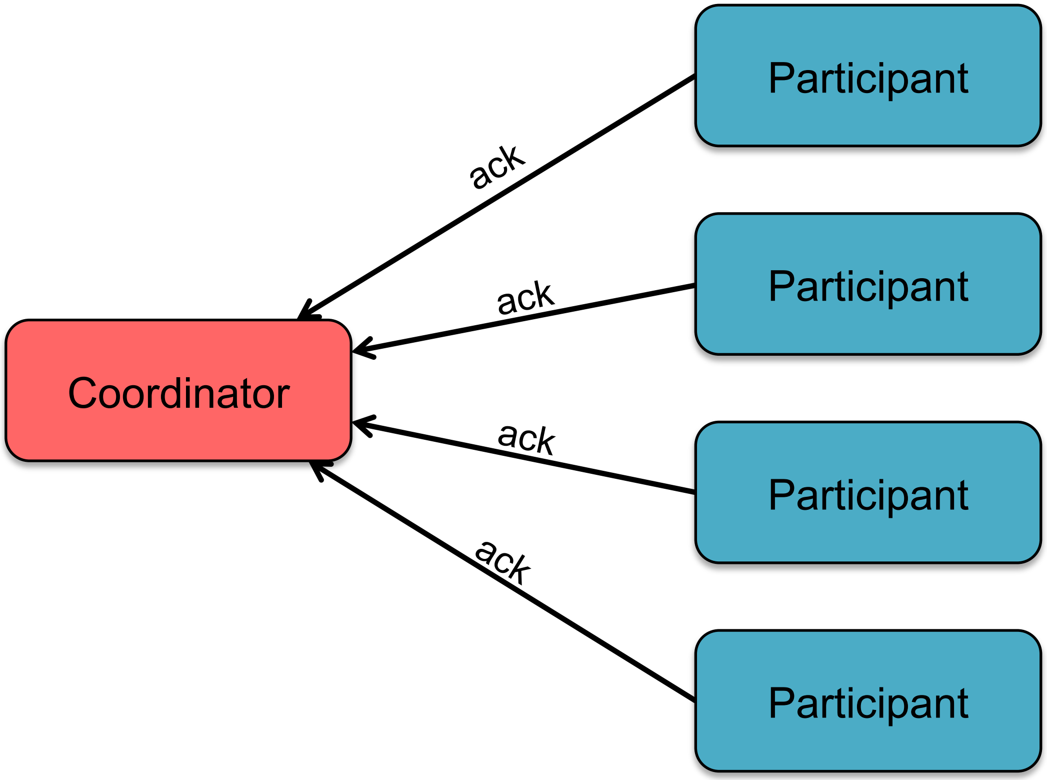


Send *abort* if any participant voted “no”

Two-Phase Commit Protocol

Phase 2: Commit Phase

Get “I have committed” acknowledgements from *every* participant



Dealing with failure

- 2PC assumes a *fail-recover* model
  - Any failed system will eventually recover
- A recovered system cannot change its mind
  - If a node agreed to commit and then crashed, it must be willing and able to commit upon recovery
- Each system will use a write-ahead (transaction) log
  - Keep track of where it is in the protocol (and what it agreed to)
  - As well as values to enable commit or abort (rollback)
  - This enables fail-recover

Two-Phase Commit Protocol: Phase 1

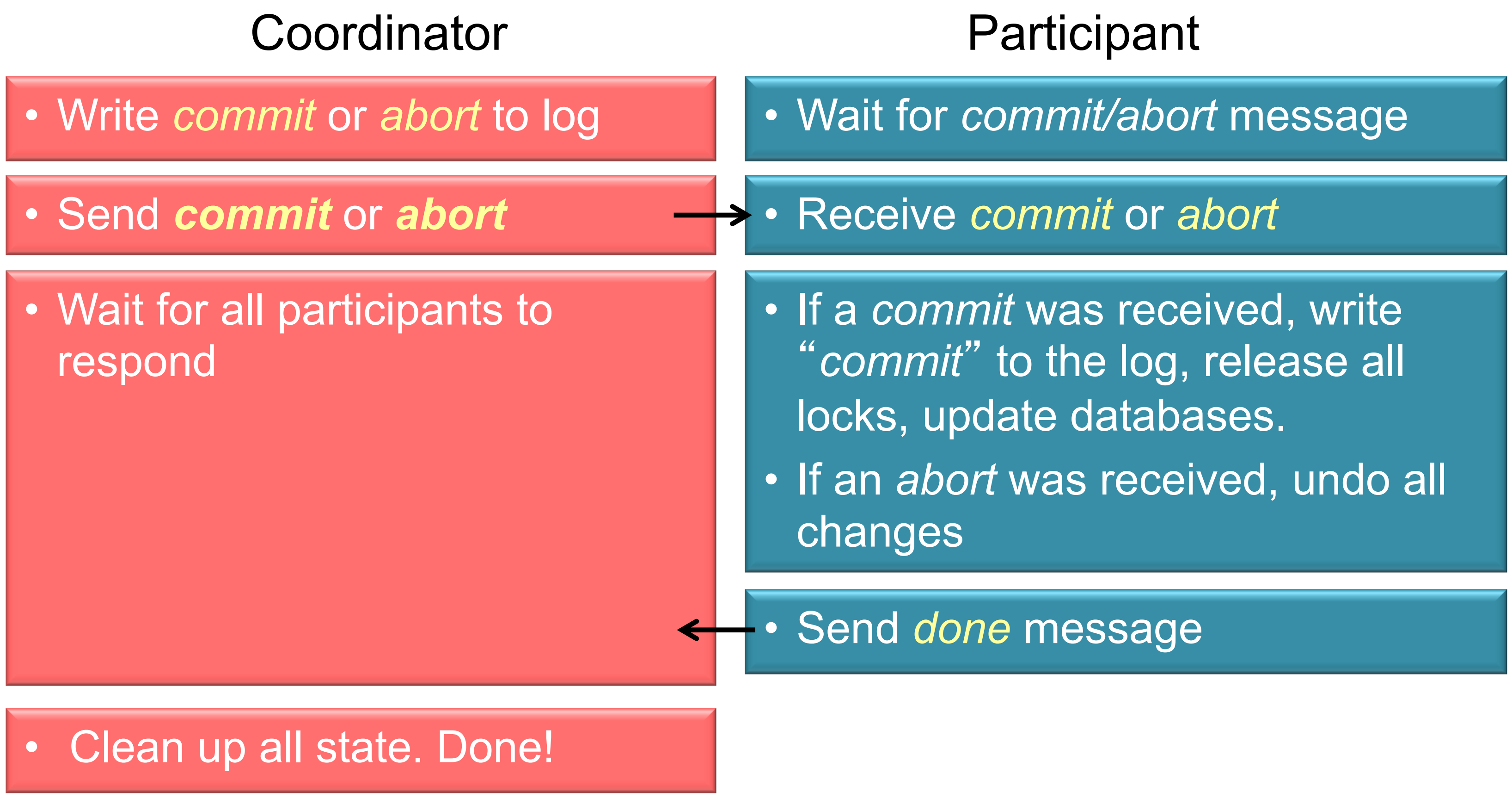
1. Voting Phase

Coordinator		Participant
		• Work on transaction
• Write ***prepare to commit*** to log		• Wait for message from coordinator
• Send ***CanCommit?*** message	→	• Receive the ***CanCommit?*** message
• Wait for all participants to respond		• When ready, write ***agree to commit*** or ***abort*** to the log
	←	• Send *agree to commit* or *abort* to the the coordinator

Get distributed agreement: the coordinator asked each participant if it will commit or abort and received replies from each coordinator.

Two-Phase Commit Protocol: Phase 2

2. Commit Phase



Coordinator	Participant
• Write *commit* or *abort* to log	• Wait for *commit/abort* message
• Send ***commit*** or ***abort*** →	• Receive *commit* or *abort*
• Wait for all participants to respond	• If a *commit* was received, write "*commit*" to the log, release all locks, update databases. • If an *abort* was received, undo all changes
←	• Send *done* message
• Clean up all state. Done!	

Tell *all participants* to *commit* or *abort*
Get everyone's response that they're done.

Consensus

- Validity property
  - Aborts in every case except when every process agrees to commit
  - The final value (commit or not) has been voted on by at least one process
- Uniform Agreement property
  - Every process decides on the value proposed by the coordinator if and only if they are instructed to do so by the coordinator in phase 2
- Integrity property
  - Every process proposes only a single value (commit or abort) and does not change its mind.
- Termination property
  - Every process is guaranteed to make progress and eventually return a vote to the coordinator.

Dealing with failure

Failure during Phase 1 (voting)

Coordinator dies

Some participants may have responded; others have no clue

⇒ Coordinator restarts voting: checks log; sees that voting was in progress

Participant dies

The participant may have died before or after sending its vote to the coordinator

⇒ If the coordinator received the vote, it waits for other votes and go to phase 2

⇒ Otherwise: wait for the participant to recover and respond (keep querying it)

Dealing with failure

Failure during Phase 2 (commit/abort)

Coordinator dies

Some participants may have been given commit/abort instructions

⇒ Coordinator restarts; checks log; informs all participants of chosen action

Participant dies

The participant may have died before or after getting the commit/abort request

⇒ Coordinator keeps trying to contact the participant with the request

⇒ Participant recovers; checks log; gets request from coordinator

- If it committed/aborted, acknowledge the request
- Otherwise, process the commit/abort request and send back the acknowledgement

Adding a recovery coordinator

- Another system can take over for the coordinator
  - Could be a participant that detected a timeout to the coordinator
- Recovery node needs to find the state of the protocol
  - Contact ALL participants to see how they voted
  - If we get voting results from all participants
    - We know that Phase 1 has completed
    - If all participants voted to commit ⇒ send *commit* request
    - Otherwise send *abort* request
  - If ANY participant states that it has *not* voted
    - We know that Phase 1 has *not* completed
    - ⇒ Restart the protocol
- But … if any participant node also crashes, we're stuck!
  - Have to wait for recovery

What's wrong with the 2PC protocol?

Biggest problem: it's a blocking protocol with failure modes that require all systems to recover eventually

- If the coordinator crashes, participants have no idea whether to commit or abort
  - A recovery coordinator helps
- If a coordinator AND a a participant crashes
  - The system has no way of knowing the result of the transaction
  - It might have committed for the crashed participant – hence all others must block

The protocol cannot pessimistically abort because some participants may have already committed

When a participant gets a commit/abort message, it does not know if every other participant was informed of the result

Three-Phase Commit Protocol

Three-Phase Commit Protocol

- Same setup as the two-phase commit protocol:
  - Coordinator & Participants

- Add timeouts to each phase that result in an abort

- Propagate the result of the commit/abort vote to each participant *before* telling them to act on it
  - This will allow us to recover the state if any participant dies

Three-Phase Commit Protocol

Split the second phase of 2PC into two parts:

2a. "*Precommit*" (*prepare to commit*) phase

- Send *Prepare* message to all participants when it received a *yes* from all participants in phase 1
- Participants can prepare to commit but cannot do anything that cannot be undone
- Participants reply with an acknowledgement
- Purpose: *let every participant know the state of the result of the vote so that state can be recovered if anyone dies*

2b. "*Commit*" phase (same as in 2PC)

- If coordinator gets ACKs for all *prepare* messages
  - It will send a *commit* message to all participants
- Else it will abort – send an *abort* message to all participants

Three-Phase Commit Protocol: Phase 1

Phase 1: *Voting phase*

- Coordinator sends *CanCommit?* queries to participants & gets responses
- Purpose: Find out if everyone agrees to commit

- [!] It the coordinator gets a *timeout* from any participant, or *any* NO replies are received
  - Send an *abort* to all participants

- [!] If a participant times out waiting for a request from the coordinator
  - It aborts itself (assume coordinator crashed)

- Else continue to phase 2

We can abort if the participant and/or coordinator dies

Three-Phase Commit Protocol

Phase 2: *Prepare to commit phase*

- Send a ***prepare*** message to all participants.
  Get *OK* messages from **all** participants
  - We need to hear from all before proceeding so we can be sure the state of the protocol can be properly recovered if the coordinator dies
- Purpose: let all participants know the decision to commit
- [!] If a participant times out: assume it crashed; send *abort* to all participants

Phase 3: *Finalize phase*

- Send ***commit*** messages to participants and get responses from all
- [!] If participant times out: *contact any other participant* and move to that state (*commit* or *abort*)
- [!] If coordinator times out: that's ok – we know what to do

3PC Recovery

If the coordinator crashes

A recovery node can query the state from any available participant

Possible states that the participant may report:

Already committed

- That means that *every* other participant has received a *Prepare to Commit*
- Some participants may have committed

  ⇒ Send *Commit* message to all participants (just in case they didn't get it)

Not committed but received a *Prepare* message

- That means that all participants agreed to commit; some may have committed
- Send *Prepare to Commit* message to all participants (just in case they didn't get it)
- Wait for everyone to acknowledge; then commit

Not yet received a *Prepare* message

- This means no participant has committed; some may have agreed
- Transaction can be aborted or the commit protocol can be restarted

3PC Weaknesses

Main weakness of 3PC

- May have problems when the network gets partitioned
  - Partition A: nodes that received *Prepare* message
    - Recovery coordinator for A: allows commit
  - Partition B: nodes that did not receive *Prepare* message
    - Recovery coordinator for B: aborts
  - Either of these actions are legitimate as a whole
    - But when the network merges back, the system is inconsistent

- Not good when a crashed coordinator recovers
  - It needs to find out that someone took over and stay quiet
  - Otherwise it will mess up the protocol, leading to an inconsistent state

3PC coordinator recovery problem

- Suppose
  - a coordinator sent a *Prepare* message to all participants
  - all participants acknowledged the message
  - BUT the coordinator died before it got all acknowledgements
- A recovery coordinator queries a participant
  - Continues with the commit: Sends *Prepare, gets ACKs, sends Commit*
- Around the same time…*the original coordinator recovers*
  - Realizes it is still missing some replies from the *Prepare*
  - Gets timeouts from some and decides to send an *Abort* to all participants
- Some processes may commit while others abort!

- 3PC works well when servers crash (fail-stop model)
- **3PC is not resilient against fail-recover environments**

Paxos Commit

What about Paxos?

- Interface to Paxos
  - Client proposes a value and sends it to the Paxos leader (proposer)
  - Acceptors cooperate to choose a proposed value

- What does Paxos consensus offer?
  - Total ordering of proposals
  - Fault tolerance: proposal is accepted if a **majority** of acceptors accept it
    - There is always enough data available to recover the state of proposals
  - Is provably resilient in asynchronous networks

- Paxos-based commit is a generalization of 2PC
  - Use multiple coordinators to avoid blocking if the coordinator fails
  - Set if acceptors and leader (proposers) act as the coordinator
  - Run a consensus algorithm on the commit/abort decision of **EACH** participant

What do we want to do?

- Each participant tries to get its chosen value (”*prepare*” or “*abort*”) accepted by the majority of *acceptors*
- All instances of Paxos share the same leader and same set of acceptors
- Leader
  - Chosen via election algorithm
  - Coordinates the commit algorithm
  - Not a single point of failure – we can elect a new one; acceptors store state

How do we do it?

- Some participant decides to begin to commit
  - Sends a message to the Leader
- Leader:
  - Sends a *prepare* message to each participant
- Each participant now sends a prepare or aborted message to its instance of Paxos (same leader for all participants)
  - “Prepare” or “Abort” is sent to majority of acceptors
  - Result is sent to the leader
- Leader tracks all instances of Paxos
  - Commit iff every participant’s instance of Paxos chooses “prepared”
  - Tell each participant to commit or abort

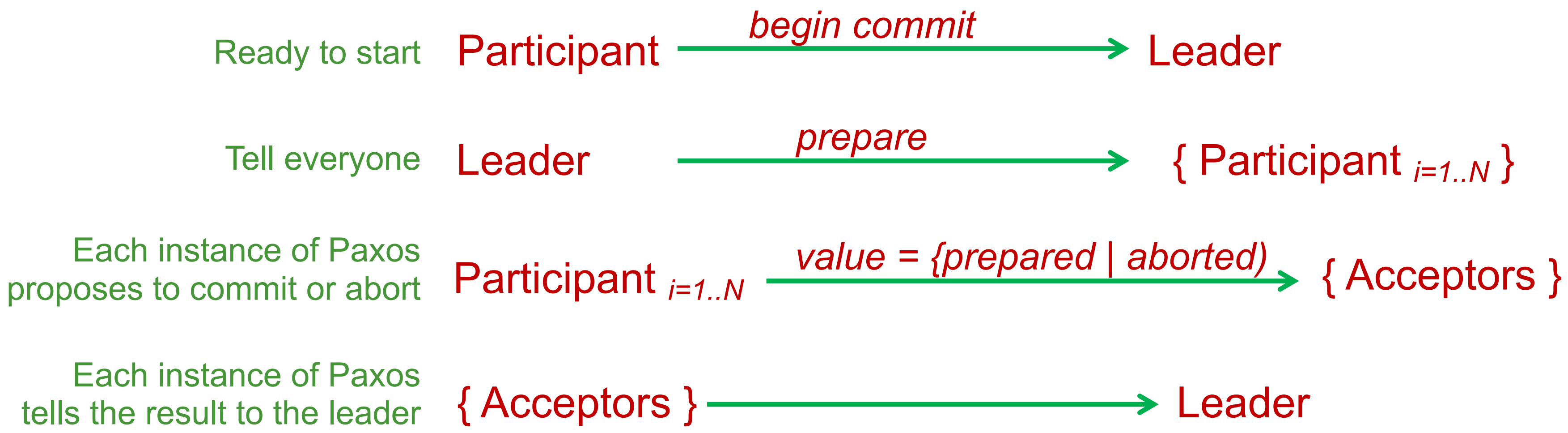
Paxos for Commit Fault-tolerant Coordinator

The cast:

– One instance of Paxos per participant (*N* participants)

– Set of *2F+1* acceptors and a leader play the role of the coordinator

- We can withstand the failure of *F* acceptors
- Leader = proposer elected to be in charge



Ready to start
Participant
begin commit
Leader
Tell everyone
Leader
prepare
{ Participant $_{i=1..N}$ }
Each instance of Paxos proposes to commit or abort
Participant $_{i=1..N}$
value = {prepared | aborted)
{ Acceptors }
Each instance of Paxos tells the result to the leader
{ Acceptors }
Leader

- A leader will get at least *F+1* messages for each instance
- Commit *iff* every participant's instance of Paxos chooses *Prepared*
- Paxos commit = 2PC if one acceptor

Virtual Synchrony vs. Transactions vs. Paxos

- Virtual Synchrony
  - Fastest & most scalable
  - State machine replication: multicast messages to the entire group
  - Focuses on group membership management & reliable multicasts
- Two-Phase & Three-Phase Commit
  - Most expensive – requires extensive use of stable storage
  - 2PC efficient in terms of # of messages
  - Designed for transactional activities
  - Not suitable for high speed messaging
- Paxos
  - General purpose fault-tolerant consensus algorithm
  - Performance limited by its two-phase protocol
  - Useful for fault-tolerant replication & elections
  - Paxos commit overcomes dead coordinator problems of 2PC and 3PC

Scaling & Consistency

Reliance on multiple systems affects availability

- One database with 99.9% availability
  - 8 hours, 45 minutes, 35 seconds downtime per year
- If a transaction uses 2PC protocol and *requires* two databases, each with a 99.9% availability:
  - Total availability = (0.999*0.999) = 99.8%
  - 17 hours, 31 minutes, 12 seconds downtime per year
- If a transaction requires 5 databases:
  - Total availability = 99.5%
  - 1 day, 19 hours, 48 minutes, 0 seconds downtime per year

Scaling Transactions

- Transactions require locking part of the database so that everyone sees consistent data at all times
  - Good on a small scale.
    - Low transaction volumes: getting multiple databases consistent is easy
  - Difficult to do efficiently on a huge scale
- Add replication – processes can read any replica
  - But all replicas must be locked during updates to ensure consistency
- Risks of not locking:
  - Users run the risk of seeing stale data
  - The "I" of ACID may be violated
    - E.g., two users might try to buy the last book on Amazon

Delays hurt

- The delays to achieve consistency can hurt business
- Amazon:
  - 0.1 second increase in response time costs 1% of sales
- Google:
  - 0.5 second increase in latency causes traffic to drop by 20%
- Latency is due to lots of factors
  - OS & software architecture, computing hardware, tight vs loose coupling, network links, geographic distribution, …
  - We're only looking at the problems caused by the tight software coupling due to achieving the ACID model

http://highscalability.com/latency-everywhere-and-it-costs-you-sales-how-crush-it

http://www.julianbrowne.com/article/viewer/brewers-cap-theorem

Eric Brewer's CAP Theorem

Three core requirements in a shared data system:

1. **Atomic, Isolated Consistency**
   – Operations must appear totally ordered and each is isolated
2. **Availability**
   – Every request received by a non-failed node must result in a response
3. **Partition Tolerance**: tolerance to network partitioning
   Messages between nodes may be lost

No set of failures less than total failure is allowed to cause the system to respond incorrectly*

CAP Theorem: when there is a network partition, you cannot guarantee both availability & consistency

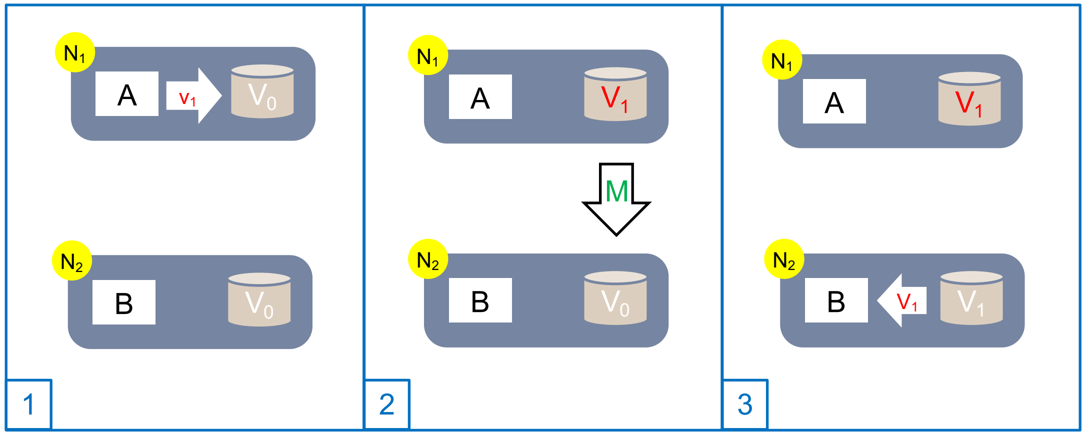
Commonly (not totally accurately) stated as
you can have at most two of the three: C, A, or P

*goo.gl/7nsj1R

Example: Partition

Life is good

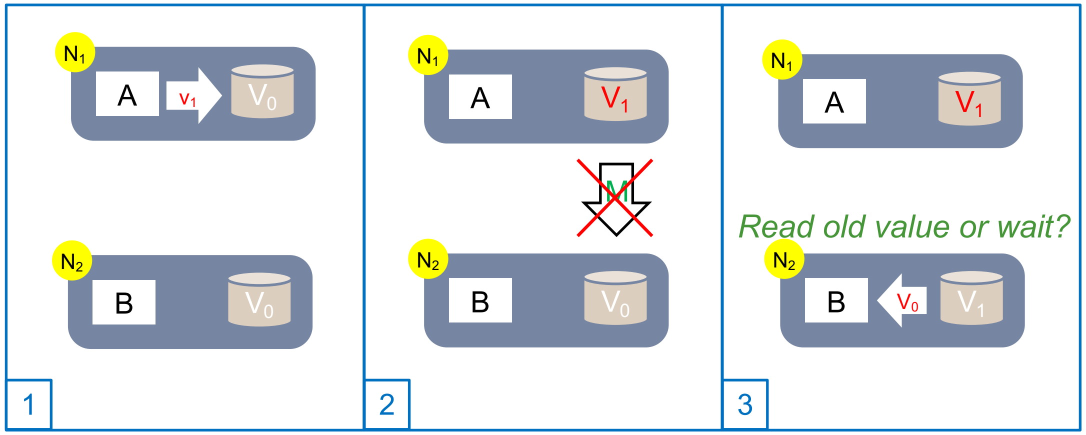
A writes v_1 on N_1.
v_1 propagates to N_2.
B reads v_1 on N_2.



Network partition occurs

A writes v_1 on N_1.
v_1 cannot propagate to N_2.
B reads v_0 on N_2.

Do we want to give up consistency or availability?



From: http://www.julianbrowne.com/article/viewer/brewers-cap-theorem

Giving up one of {C, A, P}

- **Ensure partitions never occur**
  - Put everything on one machine or a cluster in one rack: high availability clustering
  - Use two-phase commit or three phase commit
  - **Scaling suffers**
- **Give up availability** [system is consistent & can handle partitioning]
  - Lock data: have services wait until data is consistent
  - Classic ACID distributed databases (also 2PC)
  - **Response time suffers**

We really want partition tolerance & high availability for a distributed system!

- **Give up consistency** [system is available & can handle partitioning]
  - ***Eventually consistent*** data
  - Use expirations/leases, queued messages for updates
  - Examples: DNS, web caching, Amazon Dynamo, Cassandra, CouchDB
  - Often not as bad as it sounds!

Partitions will happen

- With distributed systems, we expect partitions to occur
  - Maybe not full failure but high latency can act like a failure
  - The CAP theorem says we have a tradeoff between availability & consistency
- We'd like availability and consistency
  - We get availability via replication
  - We get consistency with atomic updates
    1. *Lock all copies before an update*
    2. *Propagate updates*
    3. *Unlock*
- We can choose high availability
  - Allow reads before all nodes are updated (avoid locking)
- or choose consistency
  - Enforce proper locking of nodes for updates

Eventual Consistency

- Traditional database systems want ACID
  - But scalability is a problem
    (lots of transactions in a distributed environment)
- Give up *Consistent* and *Isolated*
  in exchange for *high availability* and *high performance*
  - Get rid of locking in exchange for multiple versions
  - Incremental replication
- BASE:
  - Basically Available
  - Soft-state
  - Eventual Consistency
- Consistency model
  - If no updates are made to a data item, *eventually* all accesses to that item will return the last updated value

ACID vs. BASE

ACID

- Strong consistency
- Isolation
- Focus on *commit*
- Nested transactions
- Availability can suffer
- Pessimistic access to data (locking)

BASE

- Weak (eventual) consistency: stale data at times
- High availability
- Best effort approach
- Optimistic access to data
- Simpler model (but harder for app developer)
- Faster

From Eric Brewer's PODC Keynote, July 2000
http://www.cs.berkeley.edu/~brewer/cs262b-2004/PODC-keynote.pdf

A place for BASE

- ACID is neither dead nor useless
  - Many environments require it
  - It's safer – the framework handles ACID for you

- BASE has become common for large-scale web apps where replication & fault tolerance is crucial
  - eBay, Twitter, Amazon
  - Eventually consistent model not always surprising to users
    - Cellphone usage data
    - Banking transactions (e.g., fund transfer activity showing up on statement)
    - Posting of frequent flyer miles

But … the app developer has to worry about update conflicts and reading stale data

… and programmers often write buggy code

The end