Transactions & Two Phase Commit

CS 475, Fall 2019

Concurrent & Distributed Systems

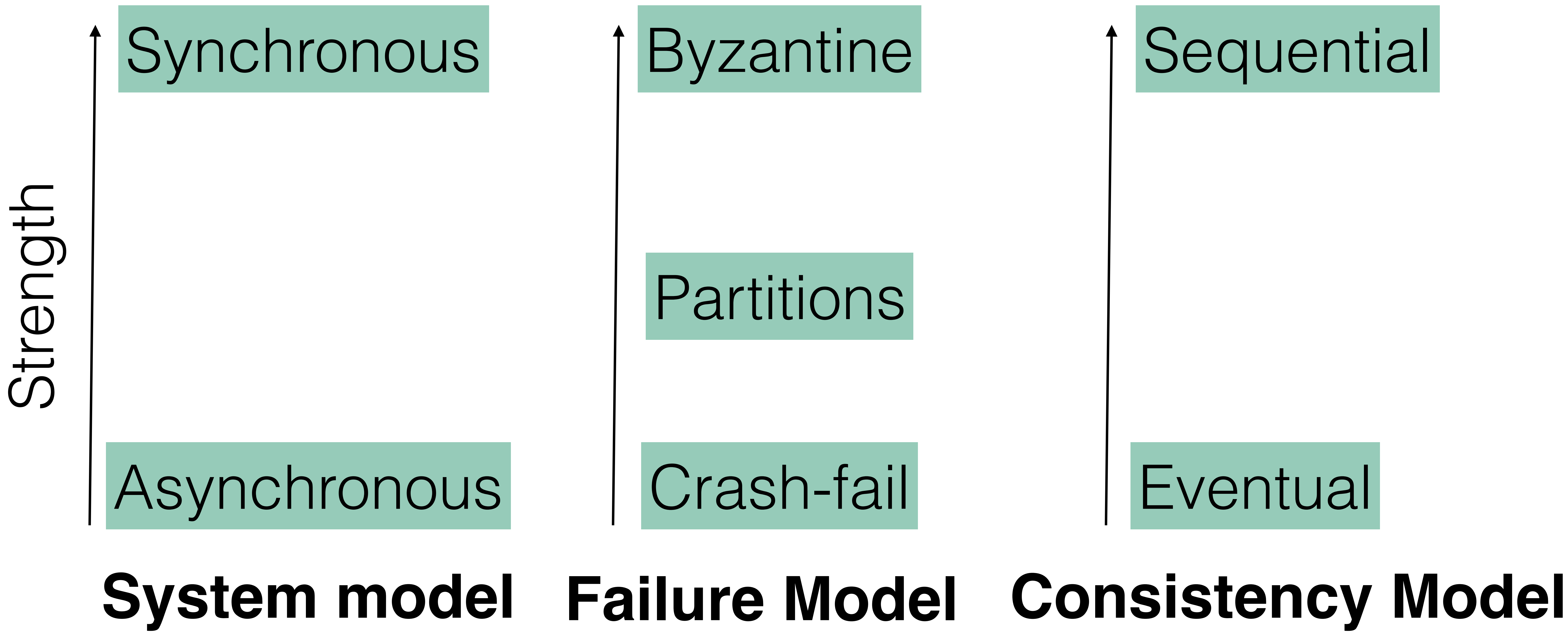
GEORGE MASON UNIVERSITY

Designing and Building Distributed Systems

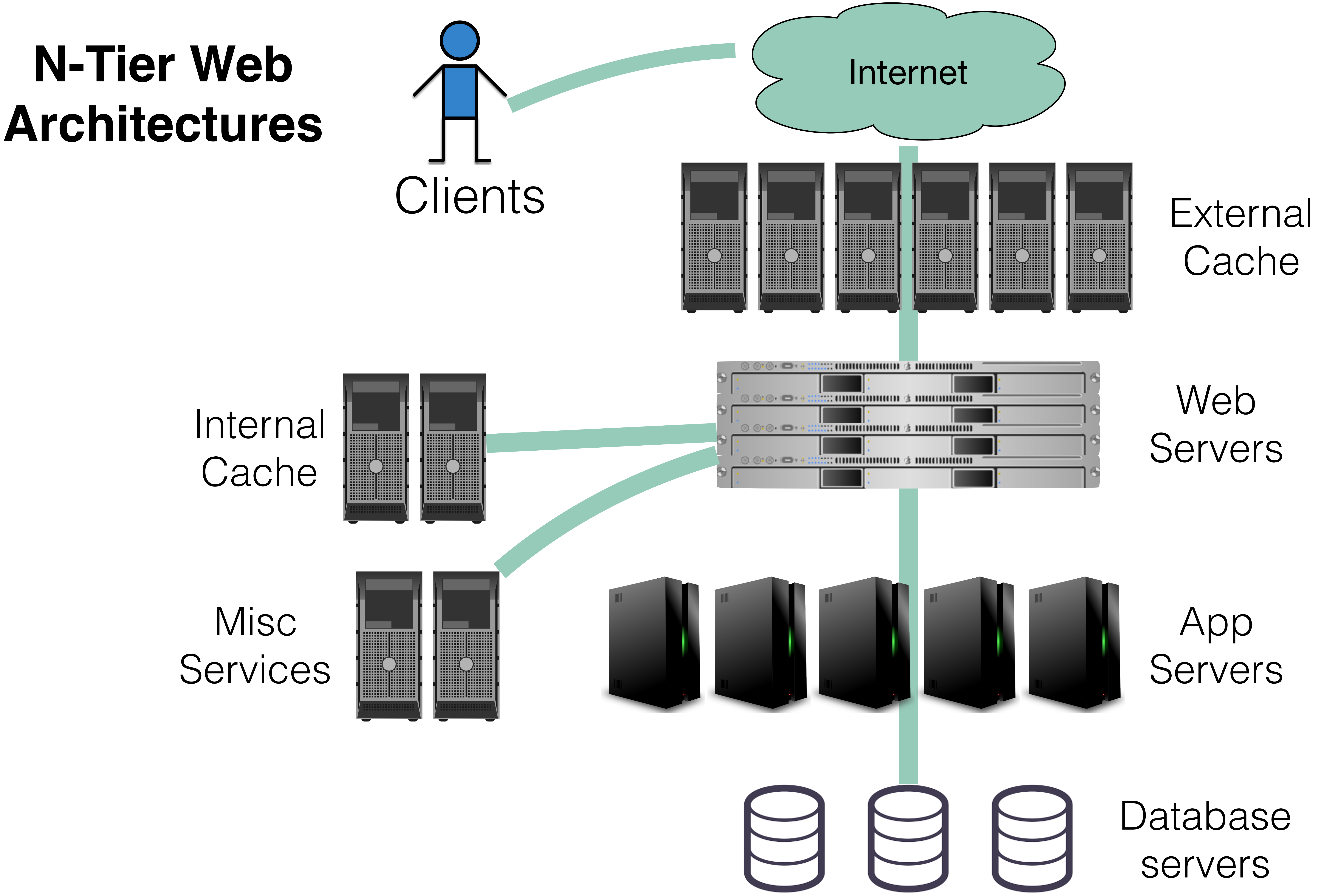
To help design our algorithms and systems, we tend to leverage abstractions and models to make assumptions

Generally: Stronger assumptions -> worse performance

Weaker assumptions -> more complicated



Real Architectures



Today

- First discussion of fault tolerance, in the context of transactions
- Agreement and transactions in distributed systems

Transactions

```
boolean transferMoney(Person from, Person to, float
amount){
    if(from.balance >= amount)
    {
        from.balance = from.balance - amount;
        to.balance = to.balance + amount;
        return true;
    }
    return false;
}
```

What can go wrong here?

Transactions: Classic Example

```
boolean transferMoney(Person from, Person to, float amount){
    if(from.balance >= amount)
    {
        from.balance = from.balance - amount;
        to.balance = to.balance + amount;
        return true;
    }
    return false;
}
```

transferMoney(P1, P2, 100)	**transferMoney(P1, P2, 200)**
P1.balance (200) >= 100	P1.balance (200) >= 200
P1.balance = 200 - 100 = 100	
P2.balance = 200 + 100 = 300	
return true;	P1.balance = 100 - 200 = -100
	P2.balance = 300 + 200 = 500
	return true;

What's wrong here?
Need isolation (prevent overdrawing)

Transactions: Classic Example

```
boolean transferMoney(Person from, Person to, float amount){
    synchronized(from){
        if(from.balance >= amount)
        {
            from.balance = from.balance - amount;
            to.balance = to.balance + amount;
            return true;
        }
        return false;
    }
}
```

transferMoney(P1, P2, 100)	**transferMoney(P1, P2, 200)**
P1.balance (200) >= 100	
P1.balance = 200 - 100 = 100	
P2.balance = 200 + 100 = 300	
return true;	
	P1.balance < 200
	return false;

Adding a lock: prevents accounts from being overdrawn

But: shouldn't we lock on `to` **also?**

Transactions: Classic Example

```
boolean transferMoney(Person from, Person to, float amount){
    synchronized(from){
        if(from.balance >= amount)
        {
            from.balance = from.balance - amount;
            to.balance = to.balance + amount;
            return true;
        }
        return false;
    }
}
```

transferMoney(P1, P2, 100)	**transferMoney(P2, P1, 100)**
P1.balance (200) >= 100	P2.balance (200) > = 100
	P2.balance = 200 - 100 = 100
P1.balance = 200 - 100 = 100	**P1.balance = 200 + 100 = 300**
P2.balance = 200 + 100 = 300	return true;
return true;	

Need to lock on both!

Transactions: Classic Example

```java
boolean transferMoney(Person from, Person to, float amount){
    synchronized(from, to){
        if(from.balance >= amount)
        {
            from.balance = from.balance - amount;
            to.balance = to.balance + amount;
            return true;
        }
        return false;
    }
}
```

transferMoney(P1, P2, 100)	**transferMoney(P1, P2, 200)**
P1.balance (200) >= 100	
P1.balance = 200 - 100 = 100	
	
	P1.balance < 200
	return false;

Problem: `P1.balance` was deducted `P2.balance` not incremented! ("Atomicity violation")

Transactions

- How can we provide some consistency guarantees **across operations**
- Transaction: unit of work (grouping) of operations
  - Begin transaction
  - Do stuff
  - Commit OR abort
- Why distributed transactions?
  - Data might be huge, spread across multiple machines
  - Scale performance up
  - Replicate data to tolerate failures

Properties of Transactions

- Traditional properties: ACID
- **Atomicity**: transactions are “all or nothing”
- **Consistency**: Guarantee some basic properties of data; each transaction leaves the database in a valid state
- **Isolation**: Each transaction runs as if it is the only one; there is some valid serial ordering that represents what happens when transactions run concurrently
- **Durability**: Once committed, updates cannot be lost despite failures

Concurrency control: Consistency & Isolation

2-phase locking

- Simple solution for isolation
- Phase 1: acquire locks (all that you might need)
- Phase 2: release locks
  - You can't get any more locks after you release any
  - Typically: locks released when you say "commit" or "abort"

NOT 2-phase locking

```
boolean transferMoney(Person from, Person to, float amount){
      from.lock();
      if(from.balance >= amount)
      {
          from.balance = from.balance - amount;
          from.unlock();
          to.lock();
          to.balance = to.balance + amount;
          to.unlock();
          return true;
      }
      else
          from.unlock();
      return false;
}
```

Invalid: other transactions could read an inconsistent system state at this point!

2-phase locking

```
boolean transferMoney(Person from, Person to, float amount){
      from.lock();
      if(from.balance >= amount)
      {
         from.balance = from.balance - amount;
         to.lock();
         to.balance = to.balance + amount;
         to.unlock();
         from.unlock();
         return true;
      }
      else
         from.unlock();
      return false;
}
```

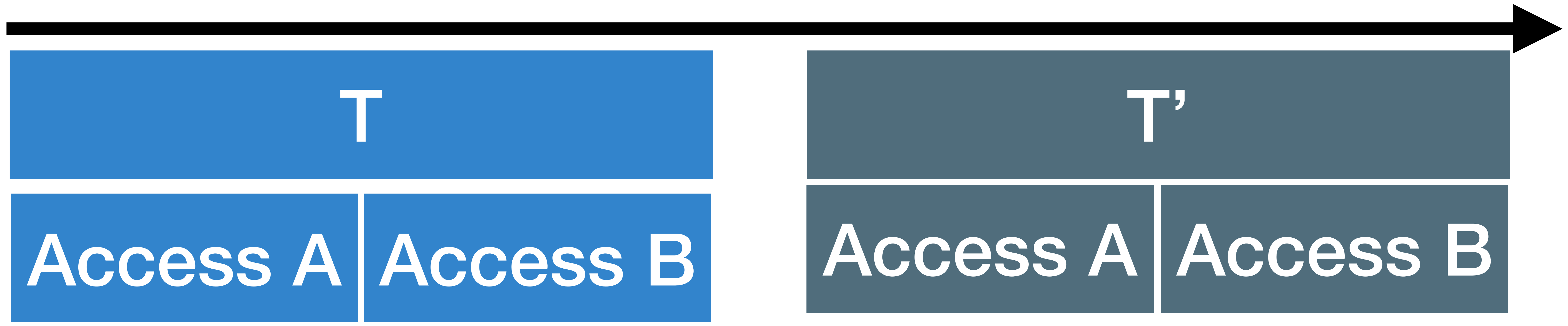
Might deadlock if one transaction gives from P1->P2, other P2->P1

Serializability

- Ideal isolation semantics
- Slightly stronger than sequential consistency
- Definition: execution of a set of transactions is equivalent to *some* serial order
  - Two executions are equivalent if they have the same effect on program state and produce the same output
  - Just like sequential consistency, but the outcome must be equivalent to an ordering where *nothing* happens concurrently, no re-ordering of events between multiple transactions.

2-Phase Locking Ensures Serializability of Transactions

- Allows serializability to be considered at the level of transactions, which might include multiple variables
- If a transaction T accesses variables A and B, and T’ accesses variables A and B, then either:



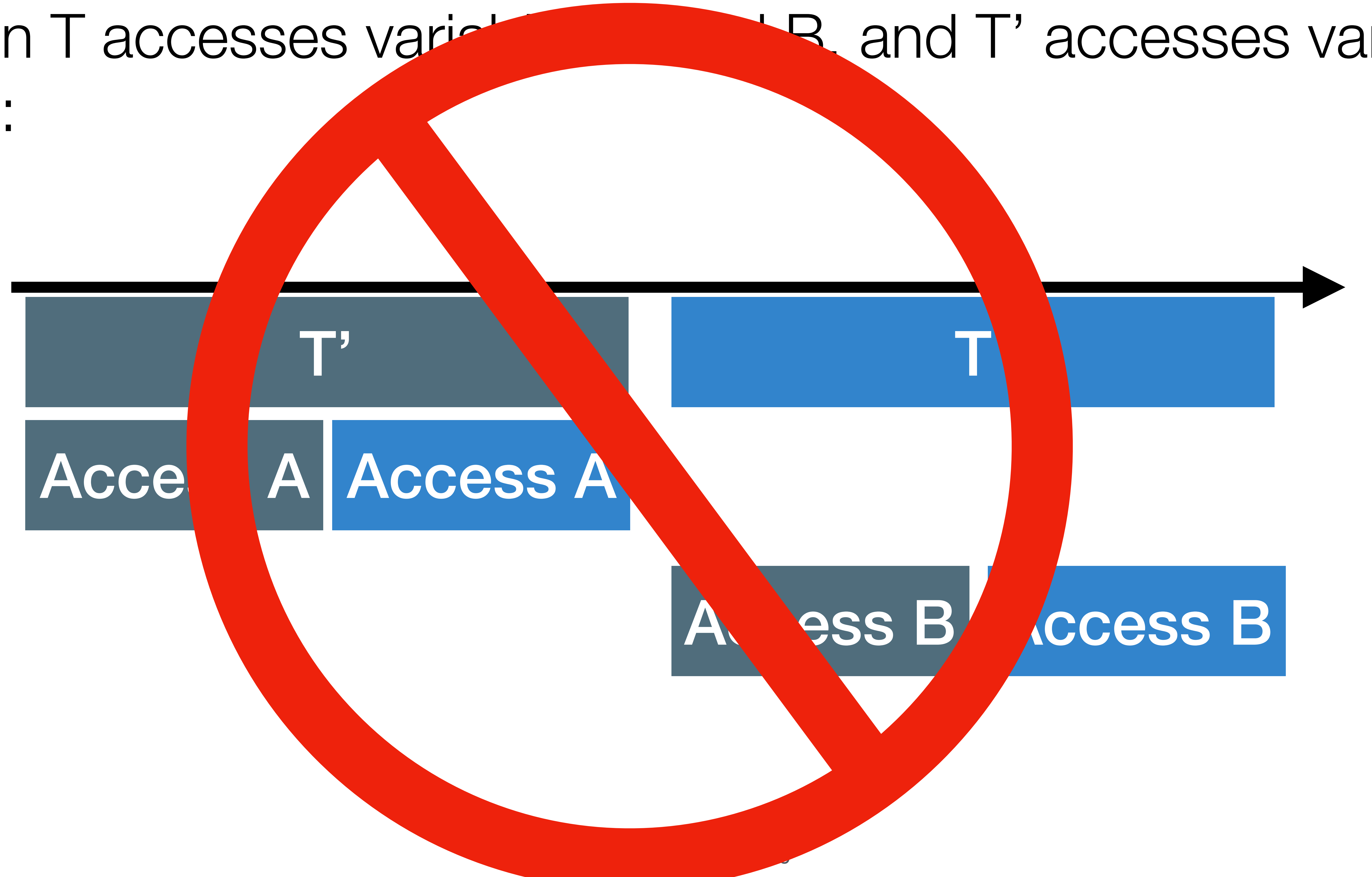
2-Phase Locking Ensures Serializability of Transactions

- Allows serializability to be considered at the level of transactions, which might include multiple variables
- If a transaction T accesses variables A and B, and T’ accesses variables A and B, then either:

2-Phase Locking Ensures Serializability of Transactions

Individual variable accesses are sequentially consistent, but transactions are not serializable!

- If a transaction T accesses vari… B, and T’ accesses variables A and B, then either:



Proof of Serializability - 2PL

- Proof by contradiction
- Is it possible for T -> T’ and T’ -> … -> T? (different order for A and B)
- What would have happened?
  - 1. T releases lock of A
  - 2. T’ acquires lock of A
  - 3. T’ releases lock of B
  - 4. T acquires lock of B
- Hence, 1->2, 3->4
- But, required by 2PL: 4->1, 2->3 (or vv)
- Putting this together would be: 4->1->2, 2->3->4 aka a contradiction

Transactions Might Effect Things You Don't Lock

Employee	Salary
Bob	100
Herbert	100
Larry	100
Jon	100

Transaction 1: Update employees, set salary = salary*1.1

Transaction 2: Hire Carol, Hire Mike

Transactions Might Effect Things You Don't Lock

Employee	Salary
Bob	100
Herbert	100
Larry	100
Jon	100

Transaction 1: Update employees, set salary = salary*1.1

Transaction 2: Hire Carol, Hire Mike

Can run concurrently: no overlapping locks!

Transactions Might Effect Things You Don't Lock

Employee	Salary
Bob	100
Herbert	100
Larry	100
Jon	100
Carol	100

Transaction 1: Update employees, set salary = salary*1.1

Transaction 2: Hire Carol, Hire Mike

Can run concurrently: no overlapping locks!

Transactions Might Effect Things You Don't Lock

Employee	Salary
Bob	110
Herbert	110
Larry	110
Jon	110
Carol	110

Transaction 1: Update employees, set salary = salary*1.1

Transaction 2: Hire Carol, Hire Mike

Can run concurrently: no overlapping locks!

Transactions Might Effect Things You Don't Lock

Employee	Salary
Bob	110
Herbert	110
Larry	110
Jon	110
Carol	110
Mike	100

Transaction 1: Update employees, set salary = salary*1.1

Transaction 2: Hire Carol

Solution to prevent this: Transaction 1 must always acquire some lock to prevent *any* other transaction from touching the data!
Or: ignore this problem and accept the consequences

No half measures: How do we ensure the **entire** transaction happens, or none? (Atomicity, Durability)

If the machine crashes?

If the machine can't commit?

Fault Recovery

- How do we recover transaction state if we crash?
- Goal:
  - Committed transactions are not lost
  - Non-committed transactions either continue where they were or aborted
- Plan:
  - Consider local recovery
  - Then distributed issues

Write-ahead logging

- Maintain a complete log of all operations INDEPENDENT of the actual data they apply to
  - E.g. Transaction boundaries and updates
- Transaction operations considered provisional until commit is logged to disk
  - Log is authoritative and permanent

Distributing Transactions

- System model: data stored in multiple locations, multiple servers participating in a single transaction. One server pre-designated “coordinator”
- Failure model: messages can be delayed or lost, servers might crash, but have persistent storage to recover from

Distributed Transactions

- Coordinator: Begins a transaction
  - Assigns a unique transaction ID
  - Responsible for commit + abort
  - In principle, any client can be the coordinator, but all participants need to agree on who is the coordinator
- Participants: everyone else who has the data used in the transaction

Agreement

- In distributed systems, we have multiple nodes that need to all agree that some object has some state
- Examples:
  - The value of a shared variable
  - Who owns a lock
  - Whether or not to commit a transaction

Agreement Generally

- Most distributed systems problems can be reduced to this one:
  - Despite being separate nodes (with potentially different views of their data and the world)…
  - All nodes that store the same object O must apply all updates to that object in the same order (consistency)
  - All nodes involved in a transaction must either commit or abort their part of the transaction (atomicity)
- Easy?
  - … but nodes can restart, die or be arbitrarily slow
  - … and networks can be slow or unreliable too

Properties of Agreement

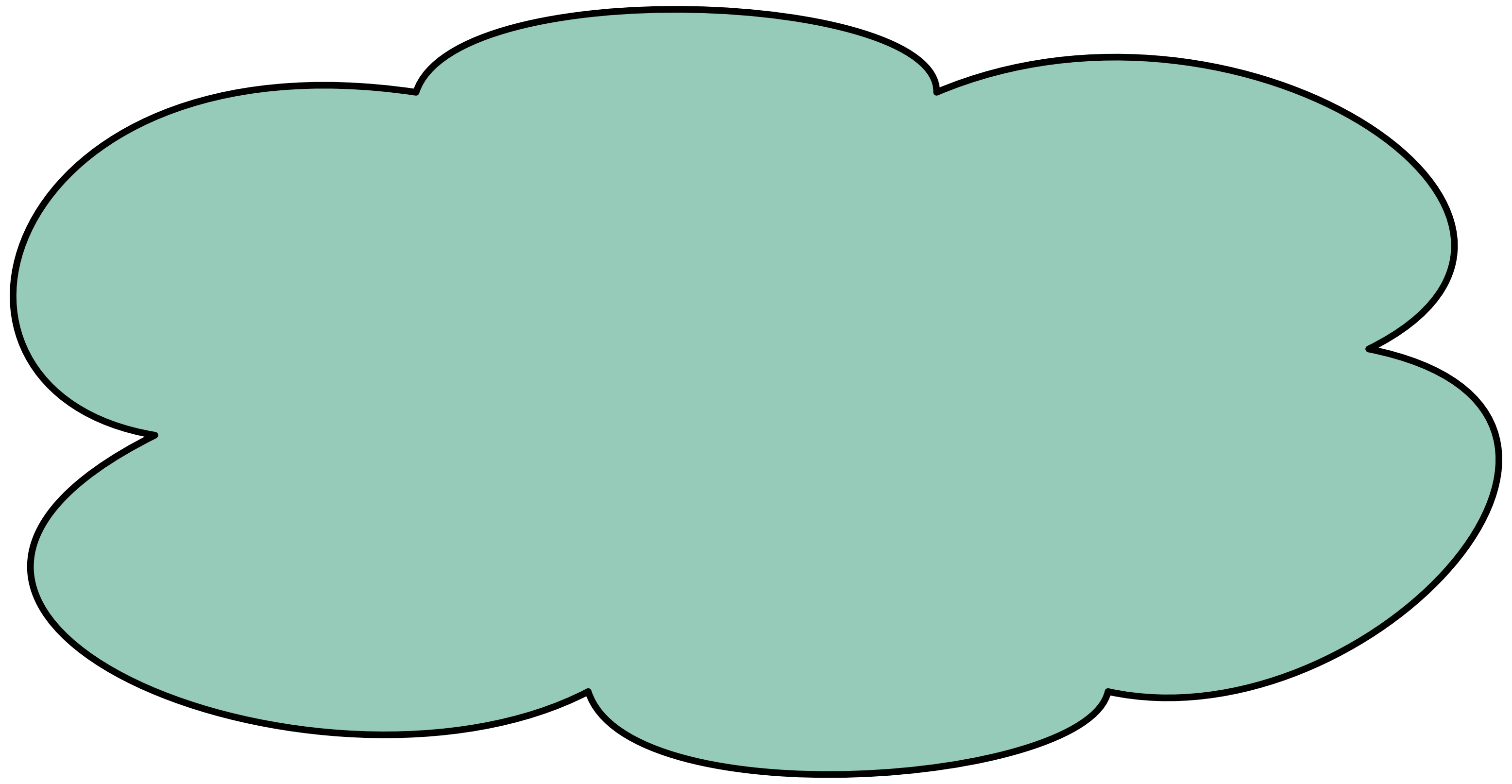
- 2 kinds of properties, just like for mutual exclusion:
- Safety (correctness)
  - All nodes agree on the same value (which was proposed by some node)
- Liveness (fault tolerance, availability)
  - If less than N nodes crash, the rest should still be OK

Distributed Transactions

```
transferMoney("from": Barney@Goliath National,
    "to": Mortimer@ Duke&Duke, "amount"=$1)
    Initially: Barney.balance= $10000, Mortimer.balance=$10000
```

Goliath National Bank

```
transferMoney:
add(Mortimer,1)
add(Barney,-1)
```



Duke & Duke Partners

```
auditRecords:
tmp1 = get(Mortimer)
tmp2 = get(Barney)
print tmp1, tmp2
```

What can we hope for if these two actions happen at once?

10,000 printed twice, or:
10,001 and 9,999
(Atomicity of the transfer)

Distributed Transactions

```
transferMoney("from": Barney@Goliath National,
    "to": Mortimer@ Duke&Duke, "amount"=$1)
    Initially: Barney.balance= $10000, Mortimer.balance=$10000
```

Goliath National Bank

transferMoney:

```
add(Mortimer,1)
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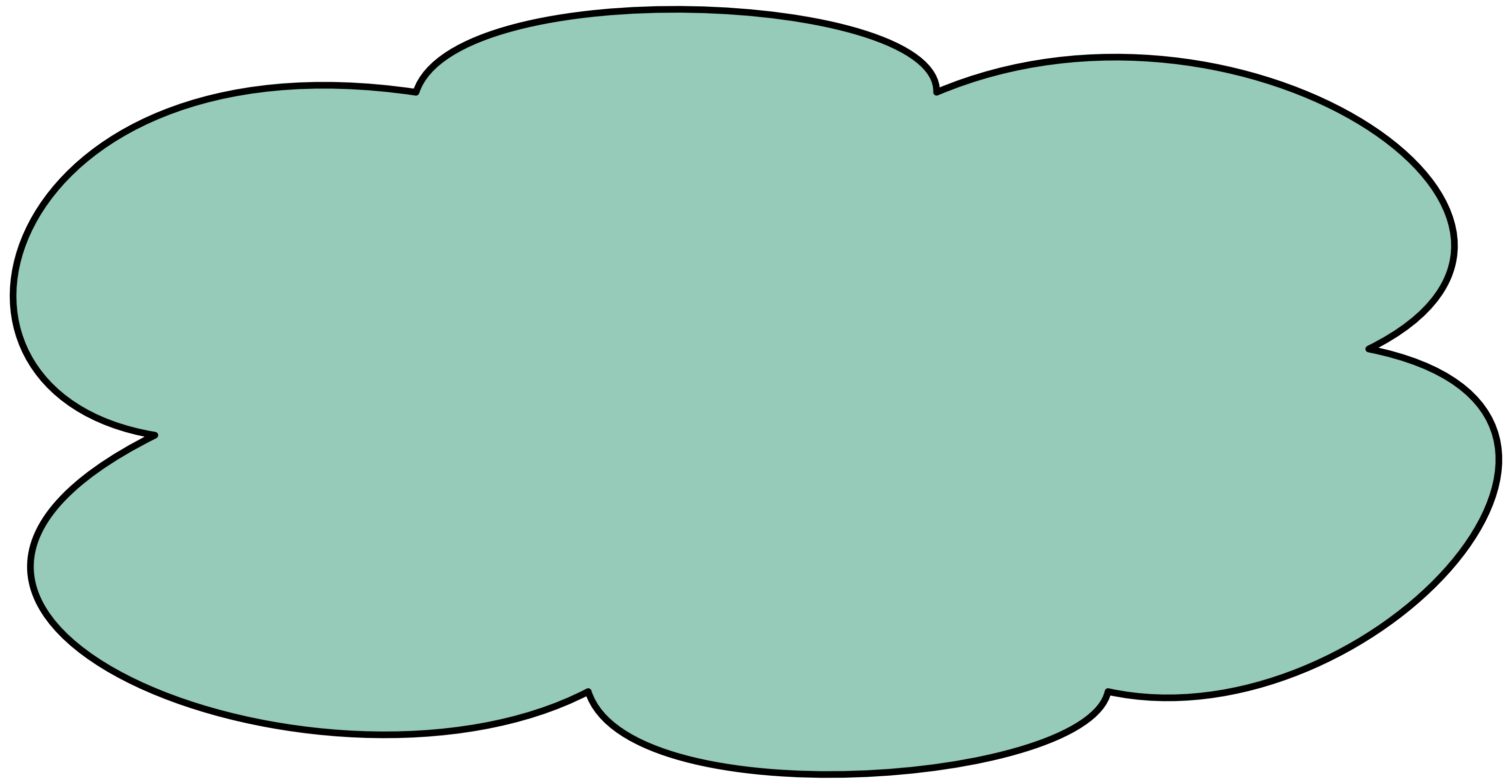


Duke & Duke Partners

auditRecords:

```
tmp1 = get(Mortimer)
tmp2 = get(Barney)
print tmp1, tmp2
```

...But why is this hard? What can go wrong?

auditRecords is interleaved with transferMoney?

Server or network failure on either end

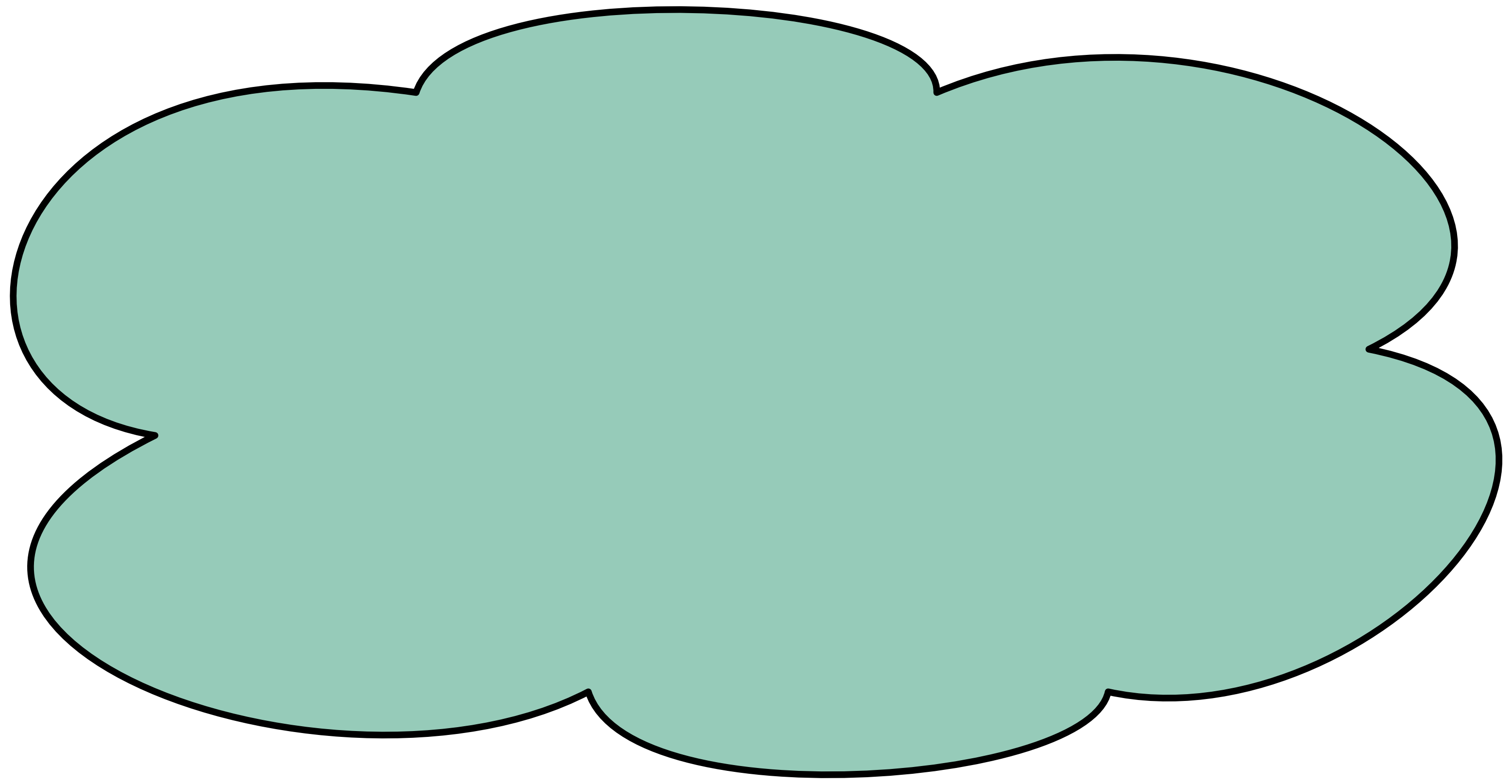
Mortimer or Barney's account might not even exist

Distributed Transactions

- We can easily solve our transfer problem by making this two transactions!
- Client tells the transaction system when to start/end each transaction
- System arranges transactions to ensure our ACID properties
- Today’s focus: how do we build that transaction system?

Goliath National Bank

```
transferMoney:
begin_transaction()
add(Mortimer,1)
add(Barney,-1)
end_transaction()
```



Duke & Duke Partners

```
auditRecords:
begin_transaction()
tmp1 = get(Mortimer)
tmp2 = get(Barney)
print tmp1, tmp2
end_transaction()
```

Distributed Transactions

- Will focus much more on how to abort - because more can go wrong:
    - Abort must undo any in-progress modifications
    - Voluntary abort - some client validation fails (e.g. bank account doesn't exist)
    - Abort might come from failure (server or network crash)
    - System might deadlock and need to abort
- Two big components, just like non-distributed transactions:
    - Concurrency control (2 phase locking, just like non-distributed)
    - Atomic commit

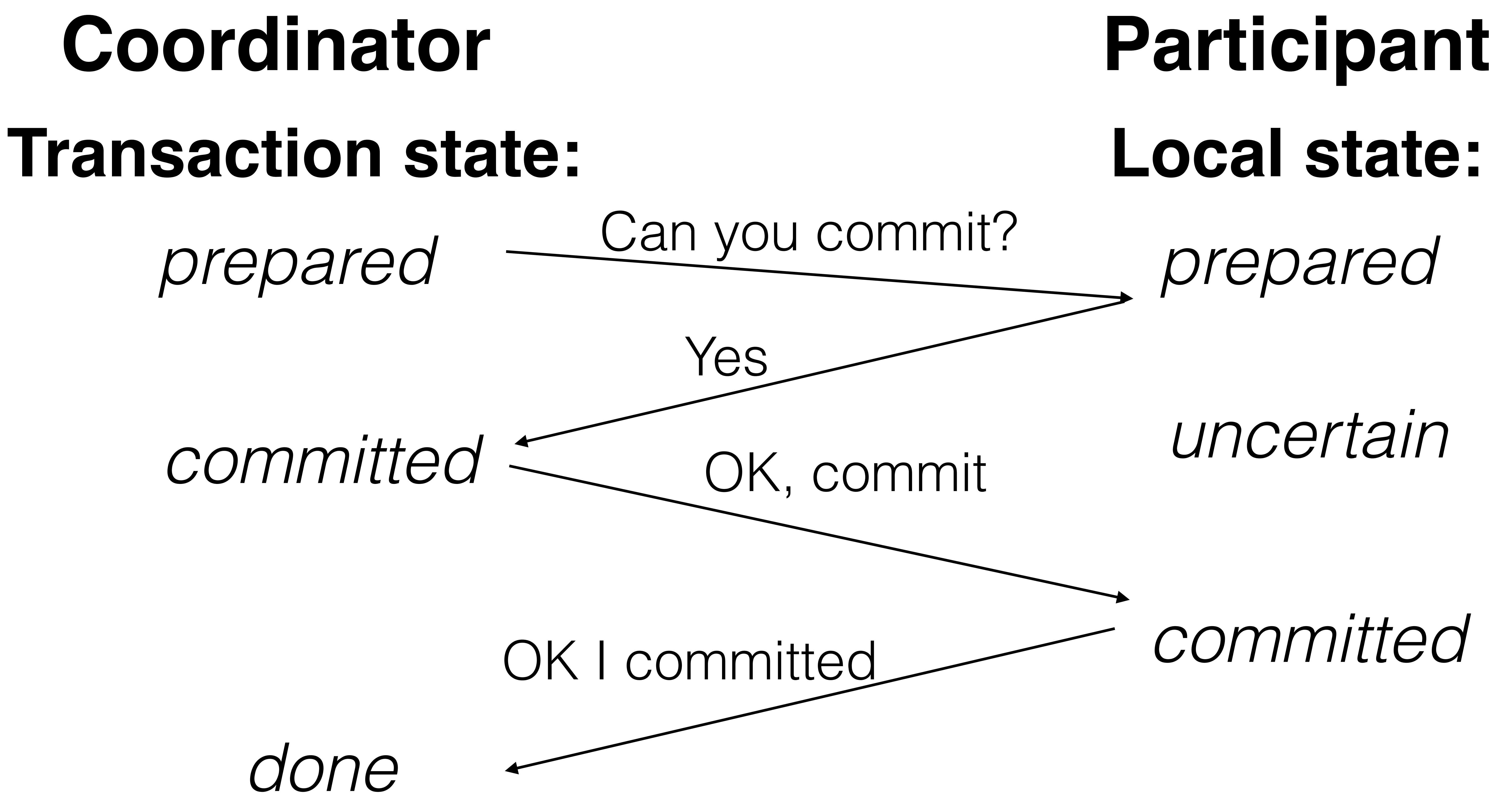
2-Phase Commit

- Separate the commit into two steps:
- 1: Voting
  - Each participant prepares to commit and votes of whether or not it can commit
- 2: Committing
  - Once voting succeeds, every participant commits or aborts
- Assume that participants and coordinator communicate over RPC

2PC: Voting

- Coordinator asks each participant: can you commit for this transaction?
- Each participant prepares to commit BEFORE answering yes
  - e.g. save transaction to disk for later recovery
  - Can not abort after saying yes
- Outcome of transaction is unknown until the coordinator receives all votes and says “do abort” or “do commit”

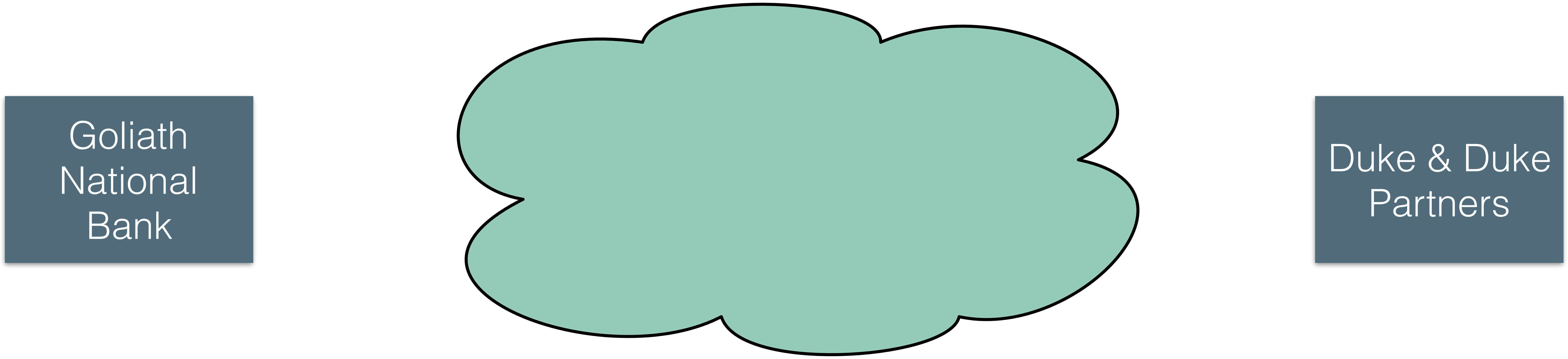
2PC Event Sequence



2PC Example

```
transferMoney(“from”: Barney@Goliath National,
    “to”: Mortimer@ Duke&Duke, “amount”=$1)

Initially: Barney.balance= $10000, Mortimer.balance=$10000
```



Requirements:

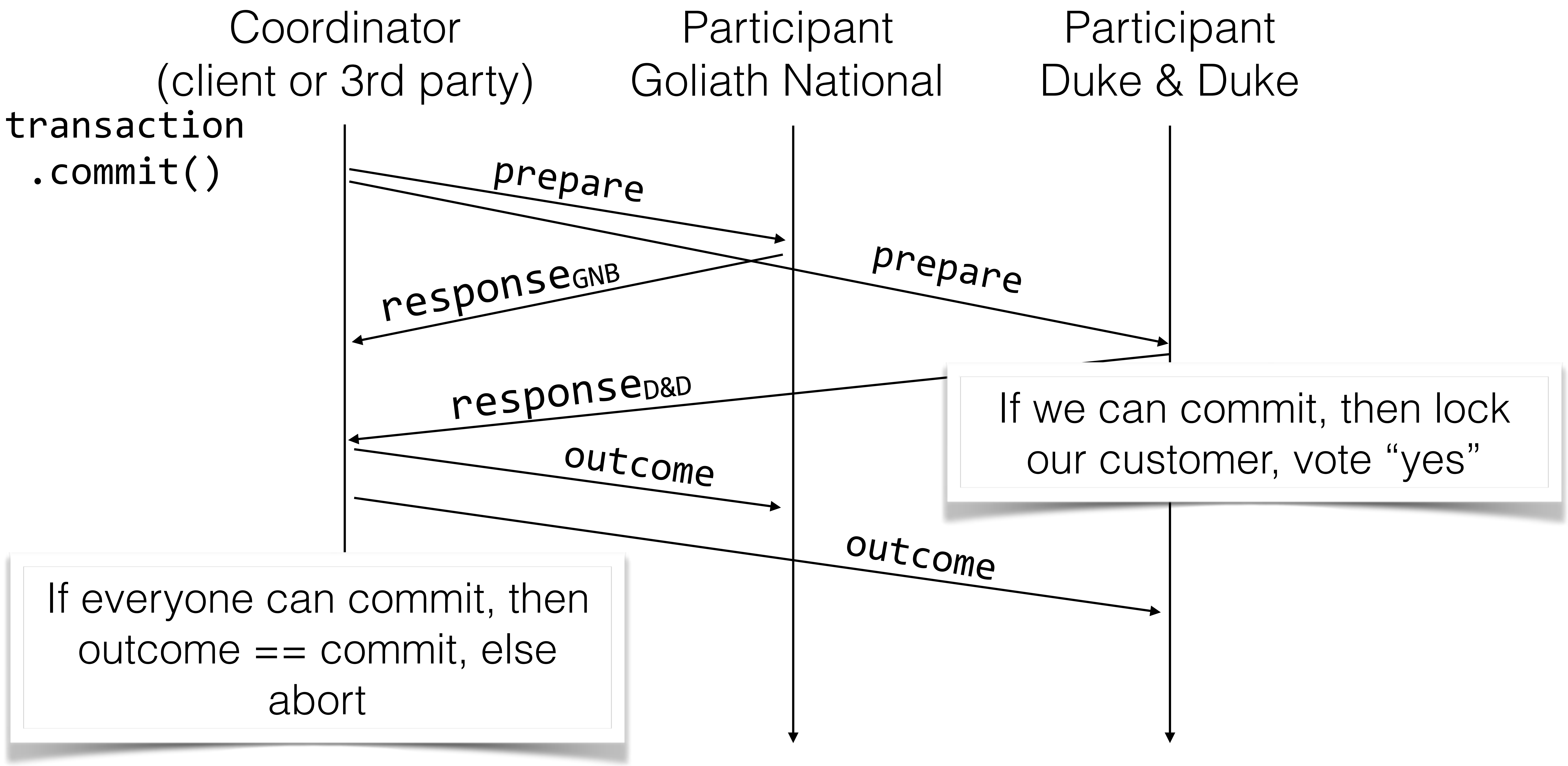
1. Atomicity (transfer happens or doesn’t)
2. Concurrency control (serializability)

2PC Example

For simplicity, let's assume transfer is:

```
int transfer(src, dst, amt) {
    transaction = begin();
    src.bal -= amt;
    dst.bal += amt;
    return transaction.commit();
}
```

2PC Example



Coordinator
(client or 3rd party)
Participant
Goliath National
Participant
Duke & Duke
transaction
.commit()
prepare
prepare
response$_{GNB}$
response$_{D\&D}$
outcome
outcome
If we can commit, then lock our customer, vote “yes”
If everyone can commit, then outcome == commit, else abort

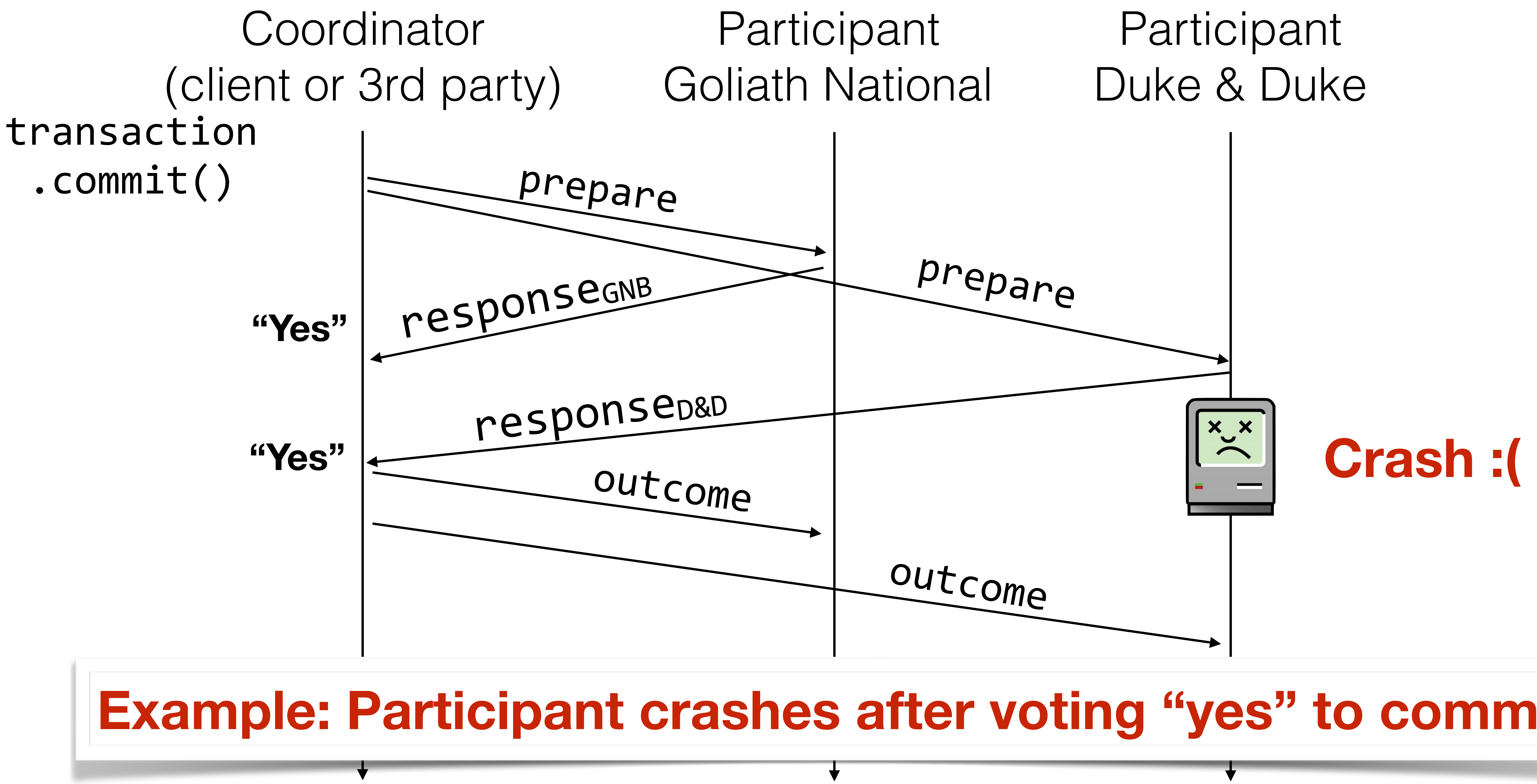
2PC Correctness (Safety)

- Remember the two kinds of properties we want to get:
  - Safety (correctness)
    - All nodes agree on the same value (which was proposed by some node)
  - Liveness (fault tolerance, availability)
    - If less than N nodes crash, the rest should still be OK
- As presented so far, 2PC guarantees safety, because no participant can proceed with the commit

Fault Recovery

- How do we recover transaction state if we crash?
- Goal:
  - Committed transactions are not lost
  - Non-committed transactions either continue where they were or aborted
- First: lay out various failure modes and discuss intuitions for solutions
  - Crashes for participant and coordinator; timeouts for same
- Then: formalize a policy for recovery in 2PC

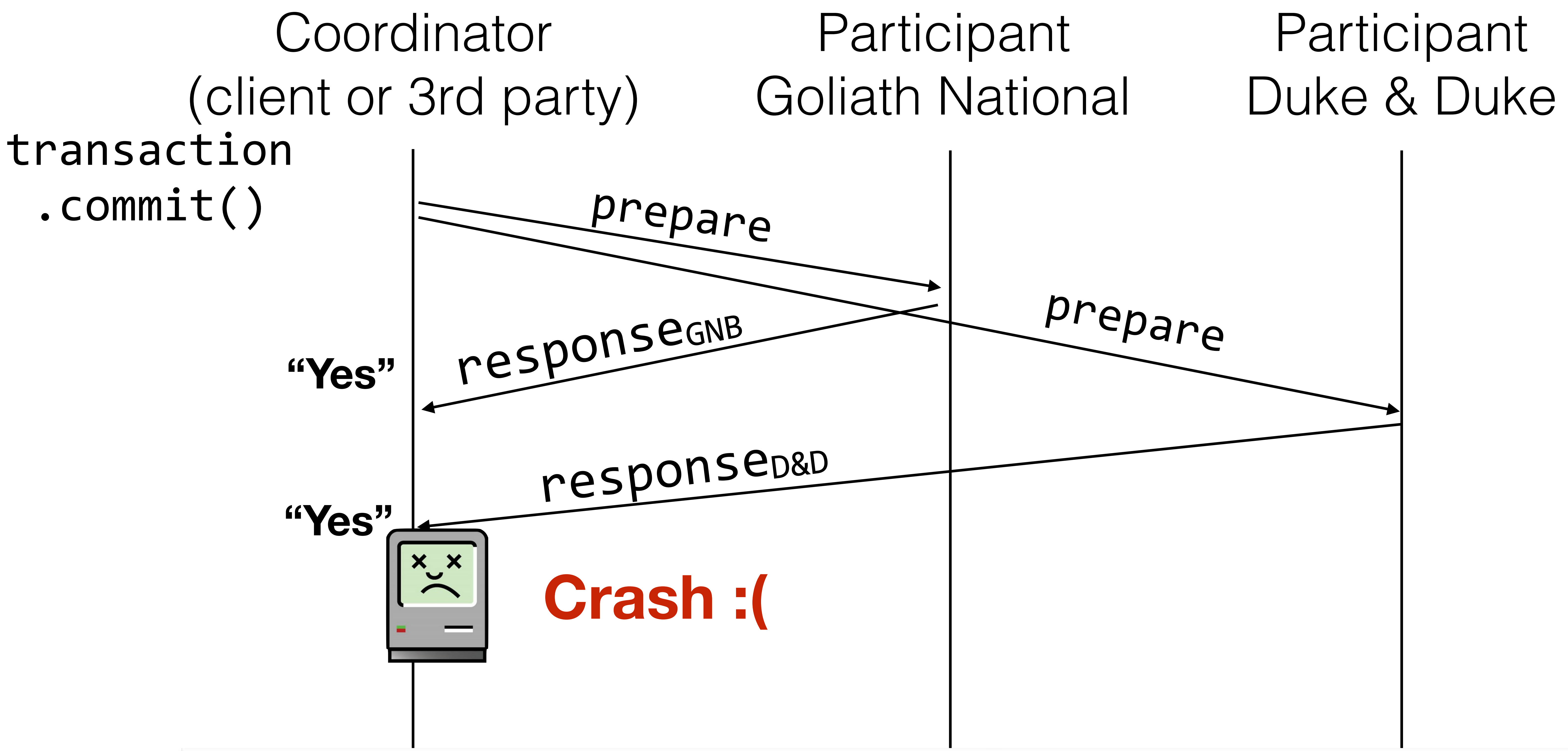
Fault Recovery Example



Example: Participant crashes after voting "yes" to commit

Solution: Participants must keep track of transaction status on persistent storage for recovery on reboot

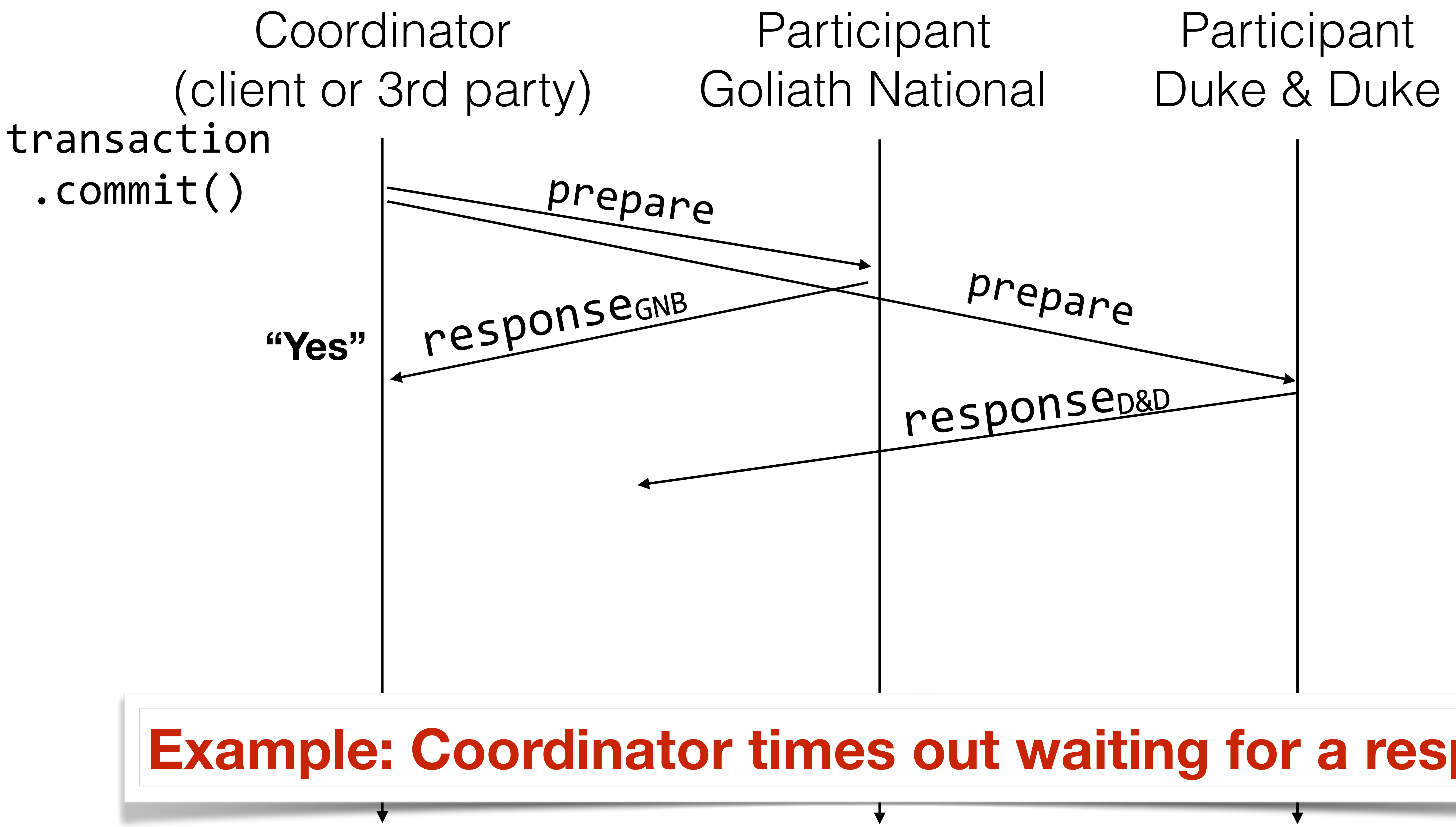
Fault Recovery Example



Example: Coordinator crashes after receiving votes

Solution: Coordinator must keep track of transaction status on persistent storage for recovery on reboot

Fault Recovery Example



Example: Coordinator times out waiting for a response

Solution: Coordinator can default to “abort” on timeout

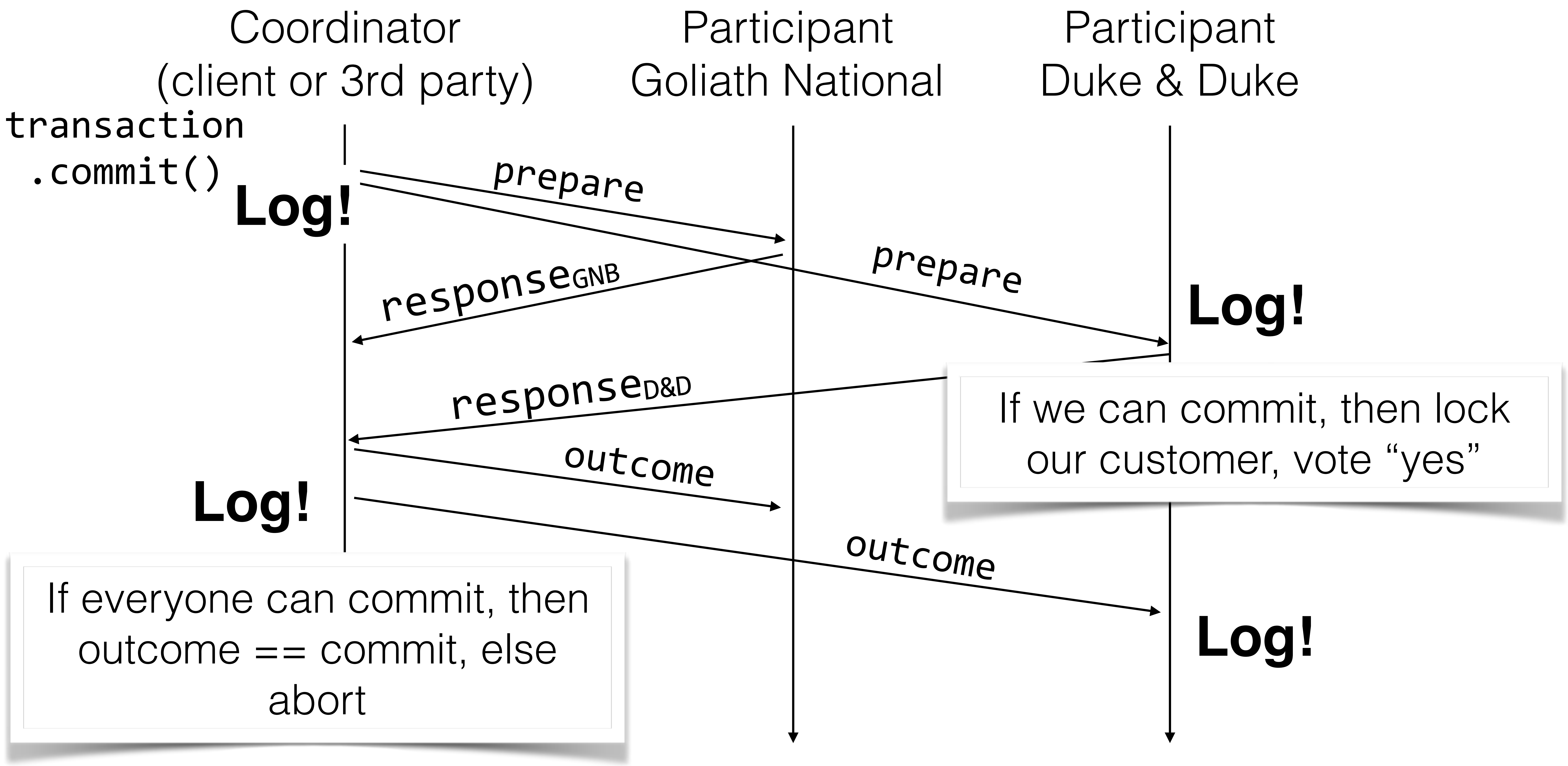
Recovery in 2PC

- What to log?
  - State changes in protocol
  - Participants: prepared; uncertain; committed/aborted
  - Coordinator: prepared; committed/aborted; done
  - These messages are idempotent - can be repeated
- Recovery depends on failure
  - Crash + reboot + recover
  - Timeout + recover

Crash + Reboot Recovery

- Nodes can’t back out once commit is decided
- If coordinator crashes just AFTER deciding “commit”
  - Must remember this decision, replay
- If participant crashes after saying “yes, commit”
  - Must remember this decision, replay
- Hence, all nodes need to log their progress in the protocol

2PC Example with logging



Recovery on Reboot

- If coordinator finds no “commit” message on disk, abort
- If coordinator finds “commit” message, commit
- If participant finds no “yes, ok” message, abort
- If participant finds “yes, ok” message, then replay that message and continue protocol

Timeouts in 2PC

- Example:
  - Coordinator times out waiting for Goliath National Bank's response
  - Bank times out waiting for coordinator's outcome message
- Causes?
  - Network
  - Overloaded hosts
  - Both are very realistic…

Coordinator Timeouts

- If coordinator times out waiting to hear from a bank
  - Coordinator hasn’t sent any commit messages yet
  - Can safely abort - send abort message
  - Preserves correctness, sacrifices performance (maybe didn’t need to abort!)
  - If either bank decided to commit, it’s fine - they will eventually abort

Handling Bank Timeouts

- What if the bank doesn't hear back from coordinator?
- If bank voted "no", it's OK to abort
- If bank voted "yes"
  - It can't decide to abort (maybe both banks voted "yes" and coordinator heard this)
  - It can't decide to commit (maybe other bank voted yes)
- Does bank just wait for ever?

Handling Bank Timeouts

- Can resolve SOME timeout problems with guaranteed correctness in event bank voted “yes” to commit
- Bank asks other bank for status (if it heard from coordinator)
- If other bank heard “commit” or “abort” then do that
- If other bank didn’t hear
  - but other voted “no”: both banks abort
  - but other voted “yes”: no decision possible!

2PC Timeouts

- We can solve a lot (but not all of the cases) by having the participants talk to each other
- But, if coordinator fails, there are cases where everyone stalls until it recovers
- Can the coordinator fail?… yes
- We’ll come back to this “discuss amongst yourselves” kind of transactions next week

2PC Summary

- Guarantees safety, but not liveness - there are situations in which the protocol can stall indefinitely
- Recovery requires considerable logging
- Relatively few messages required though, for each transaction (low latency)