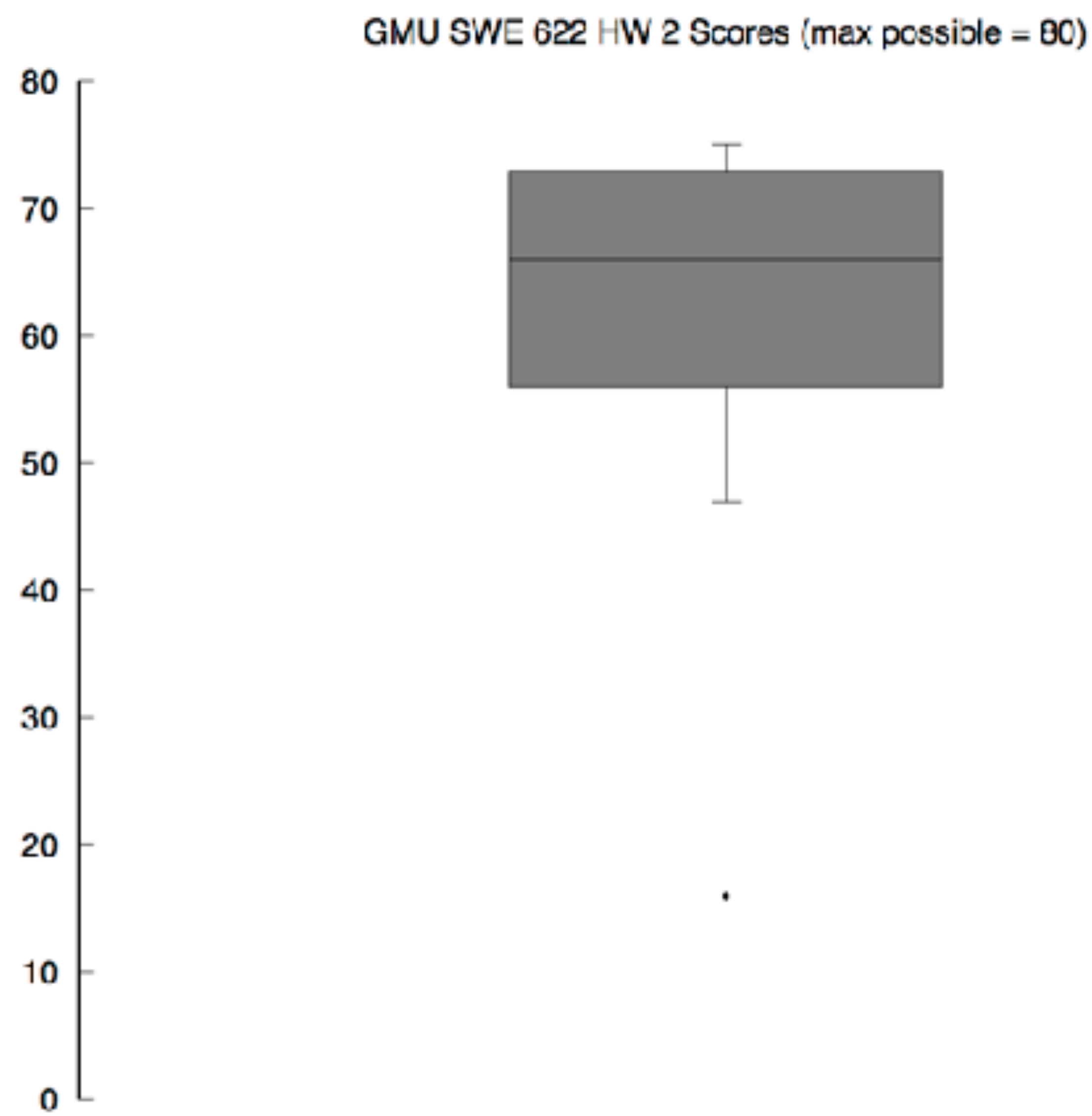
Transactions

SWE 622, Spring 2017
Distributed Software Engineering

Review: HW2



Sequential Consistency: Quiz

- There is some *total order* of operations so that:
- Each CPUs operations appear in order
- All CPUs see results according to that order (read most recent writes)

Sequential Consistency: Quiz

- There is some *total order* of operations so that:
- Each CPUs operations appear in order
- All CPUs see results according to that order (read most recent writes)

P1	W(X) a				
P2		W(X) b			
P3			R(X) b		R(X) a
P4				R(X) b	R(X) a

Sequential Consistency: Quiz

- There is some *total order* of operations so that:
- Each CPUs operations appear in order
- All CPUs see results according to that order (read most recent writes)

P1	W(X) a				
P2		W(X) b			
P3			R(X) b		R(X) a
P4				R(X) b	R(X) a

Sequentially consistent but not strictly consistent.

W(X)b, R(X)b,R(X)b,W(X)a, R(X)a, R(X)a

Sequential Consistency: Quiz

- There is some *total order* of operations so that:
- Each CPUs operations appear in order
- All CPUs see results according to that order (read most recent writes)

Sequential Consistency: Quiz

- There is some *total order* of operations so that:
- Each CPUs operations appear in order
- All CPUs see results according to that order (read most recent writes)

P1	W(X) a				
P2		W(X) b			
P3			R(X) b		R(X) a
P4				R(X) a	R(X) b

Sequential Consistency: Quiz

- There is some *total order* of operations so that:
- Each CPUs operations appear in order
- All CPUs see results according to that order (read most recent writes)

P1	W(X) a				
P2		W(X) b			
P3			R(X) b		R(X) a
P4				R(X) a	R(X) b

Not sequentially consistent

Causal Consistency

Causal Consistency

P1	W(X)a			W(X)c		
P2		R(X)a	W(X)b			
P3		R(X)a			R(X)c	R(X)b
P4		R(X)a			R(X)b	R(x)c

Causal Consistency

P1	W(X)a			W(X)c	
P2		R(X)a	W(X)b		
P3		R(X)a		R(X)c	R(X)b
P4		R(X)a		R(X)b	R(x)c

Causally Consistent. W(X) b and W(X) c are not related, hence could have happened one either order.

Causal Consistency

Causal Consistency

P1	W(X)a				
P2		R(X)a	W(X)b		
P3				R(x)b	R(x)a
P4				R(x)a	R(x)b

Causal Consistency

P1	W(X)a				
P2		R(X)a	W(X)b		
P3				R(x)b	R(x)a
P4				R(x)a	R(x)b

NOT Causally Consistent. X couldn't have been b after it was a

Causal Consistency

P1	W(X)a				
P2		R(X)a	W(X)b		
P3				R(x)b	R(x)a
P4				R(x)a	R(x)b

NOT Causally Consistent. X couldn't have been b after it was a

P1	W(X)a			
P2		W(X)b		
P3			R(x)b	R(x)a
P4			R(x)a	R(x)b

Causal Consistency

P1	W(X)a				
P2		R(X)a	W(X)b		
P3				R(x)b	R(x)a
P4				R(x)a	R(x)b

NOT Causally Consistent. X couldn’t have been b after it was a

P1	W(X)a			
P2		W(X)b		
P3			R(x)b	R(x)a
P4			R(x)a	R(x)b

Causally Consistent. X can be a or b concurrently

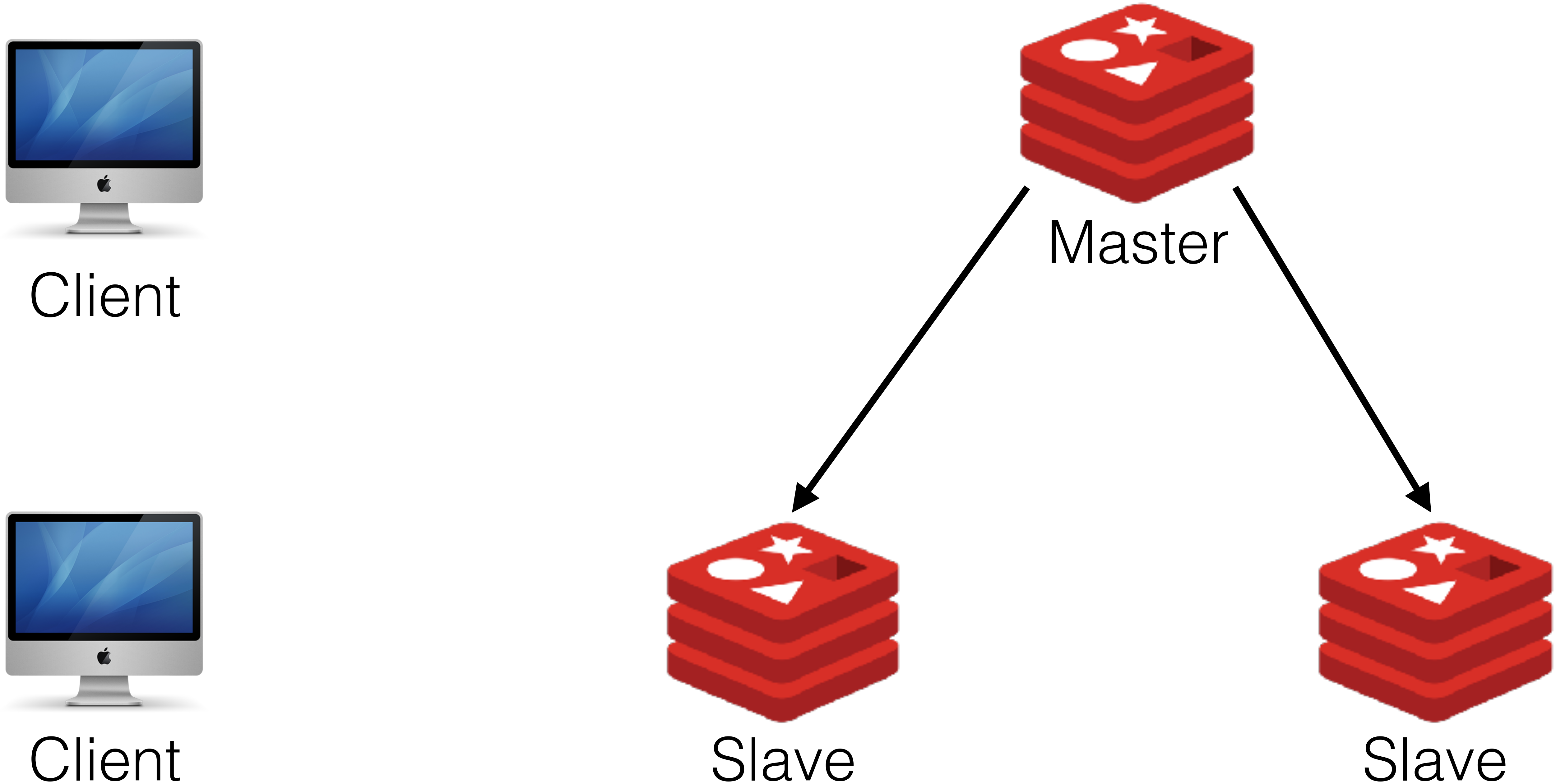
Eventual Consistency

- Allow stale reads, but ensure that reads will **eventually** reflect the previously written values
  - Eventually: milliseconds, seconds, minutes, hours, years…
- Writes are NOT ordered as executed
  - Allows for conflicts. Consider: Dropbox
- Git is eventually consistent

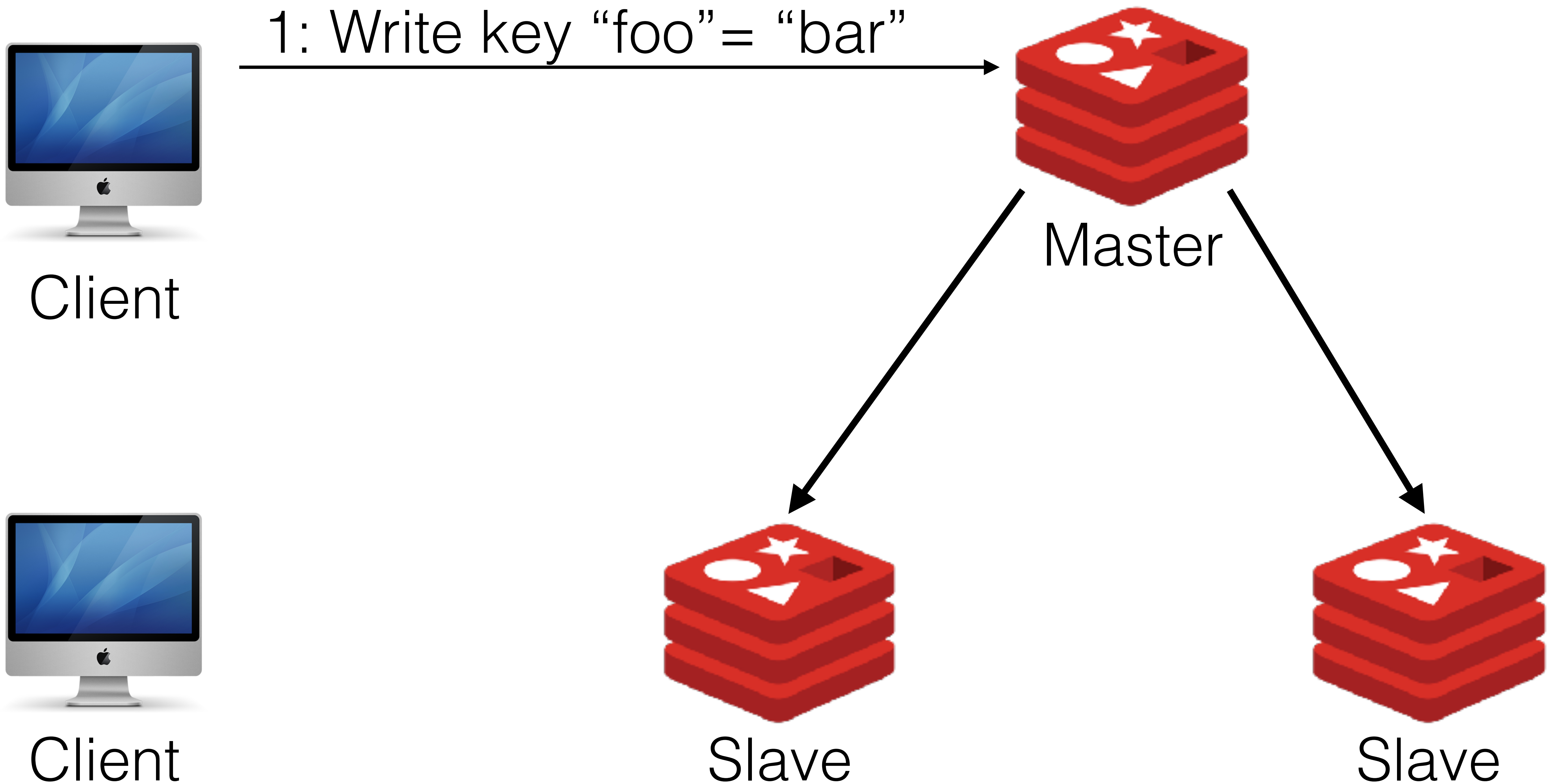
Eventual Consistency

- More concurrency than strict, sequential or causal
  - These require **highly available** connections to send messages, and generate lots of chatter
- Far looser requirements on network connections
  - Partitions: OK!
  - Disconnected clients: OK!
  - Always available!
- Possibility for conflicting writes :(

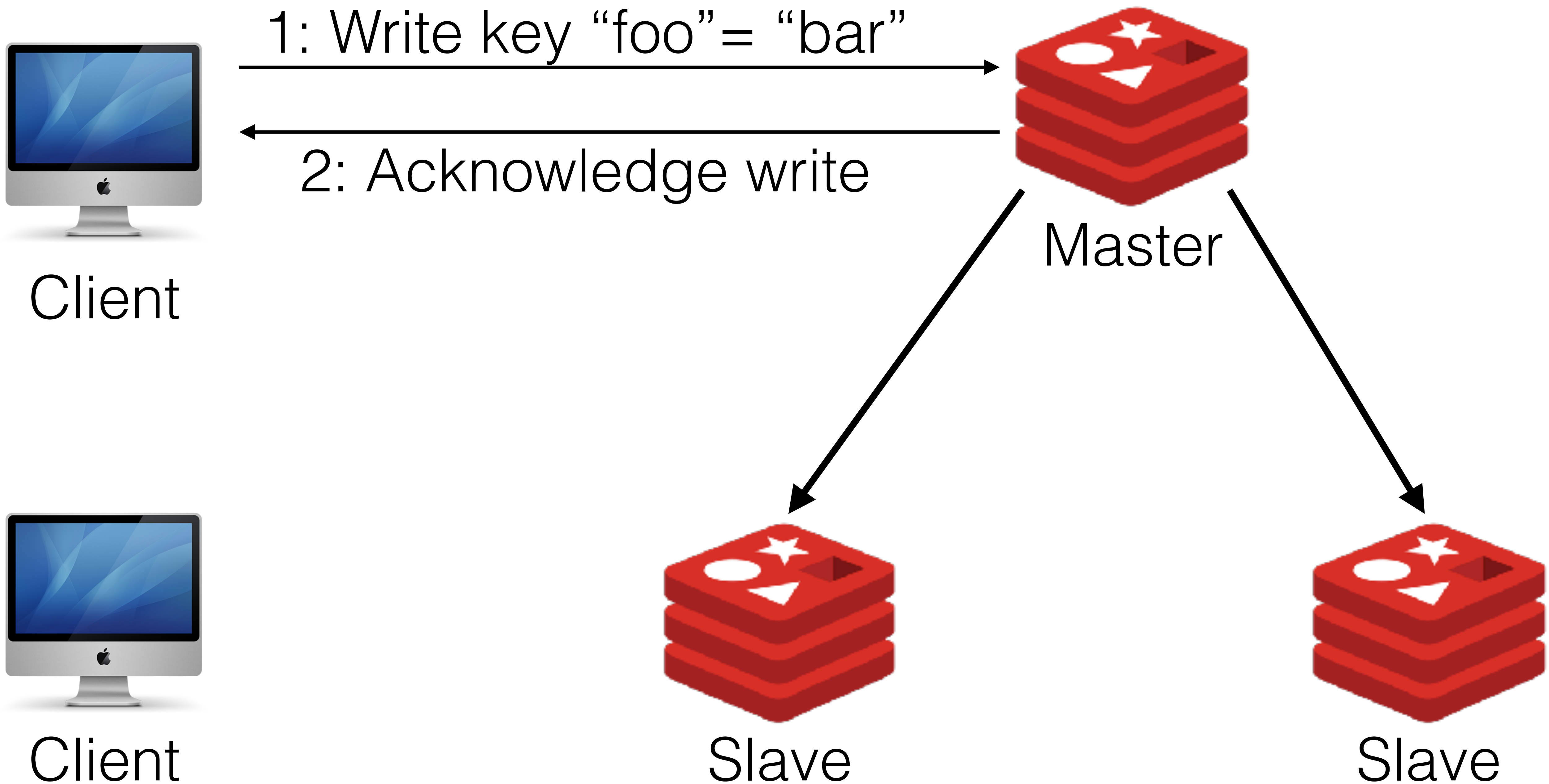
Redis Replication



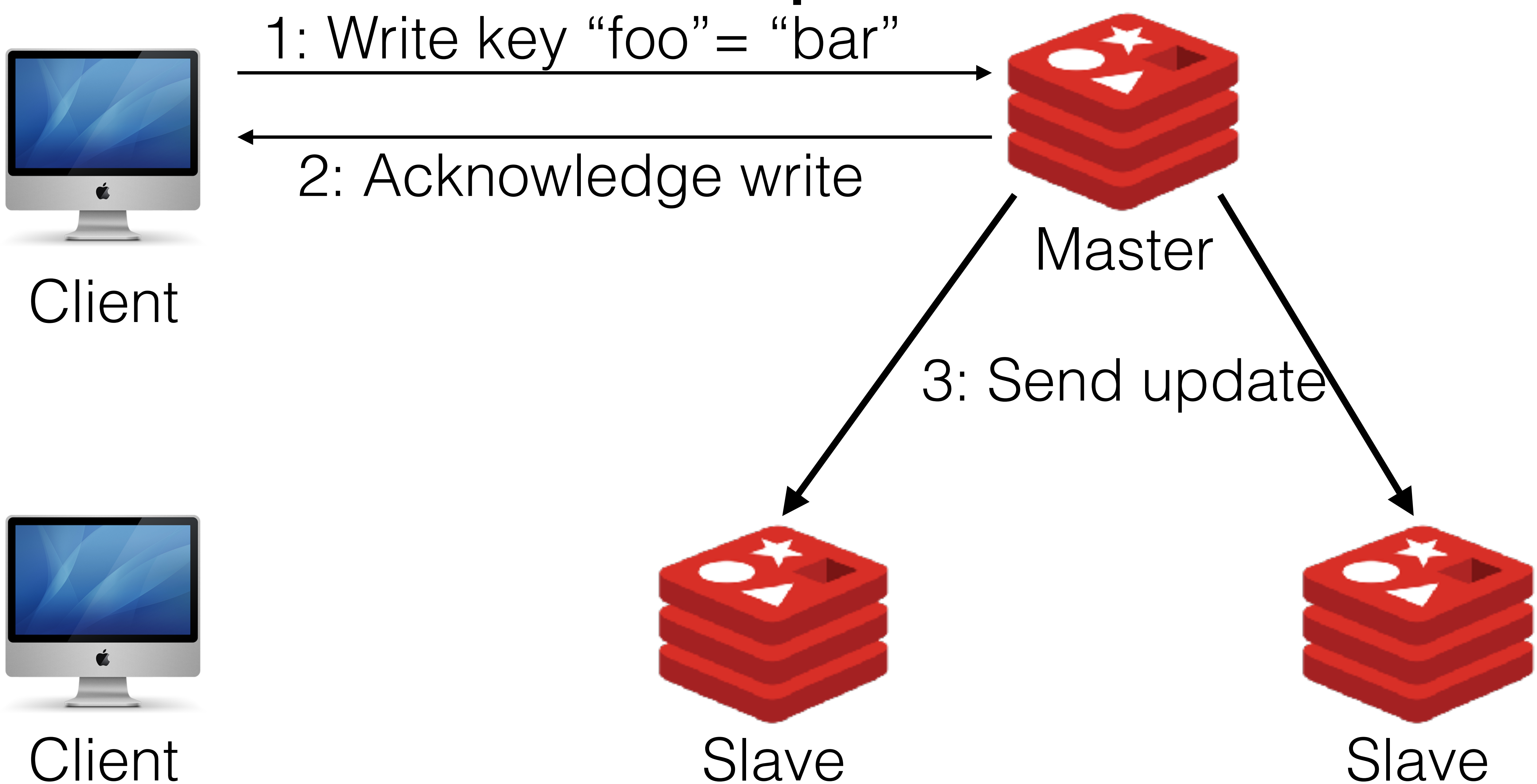
Redis Replication



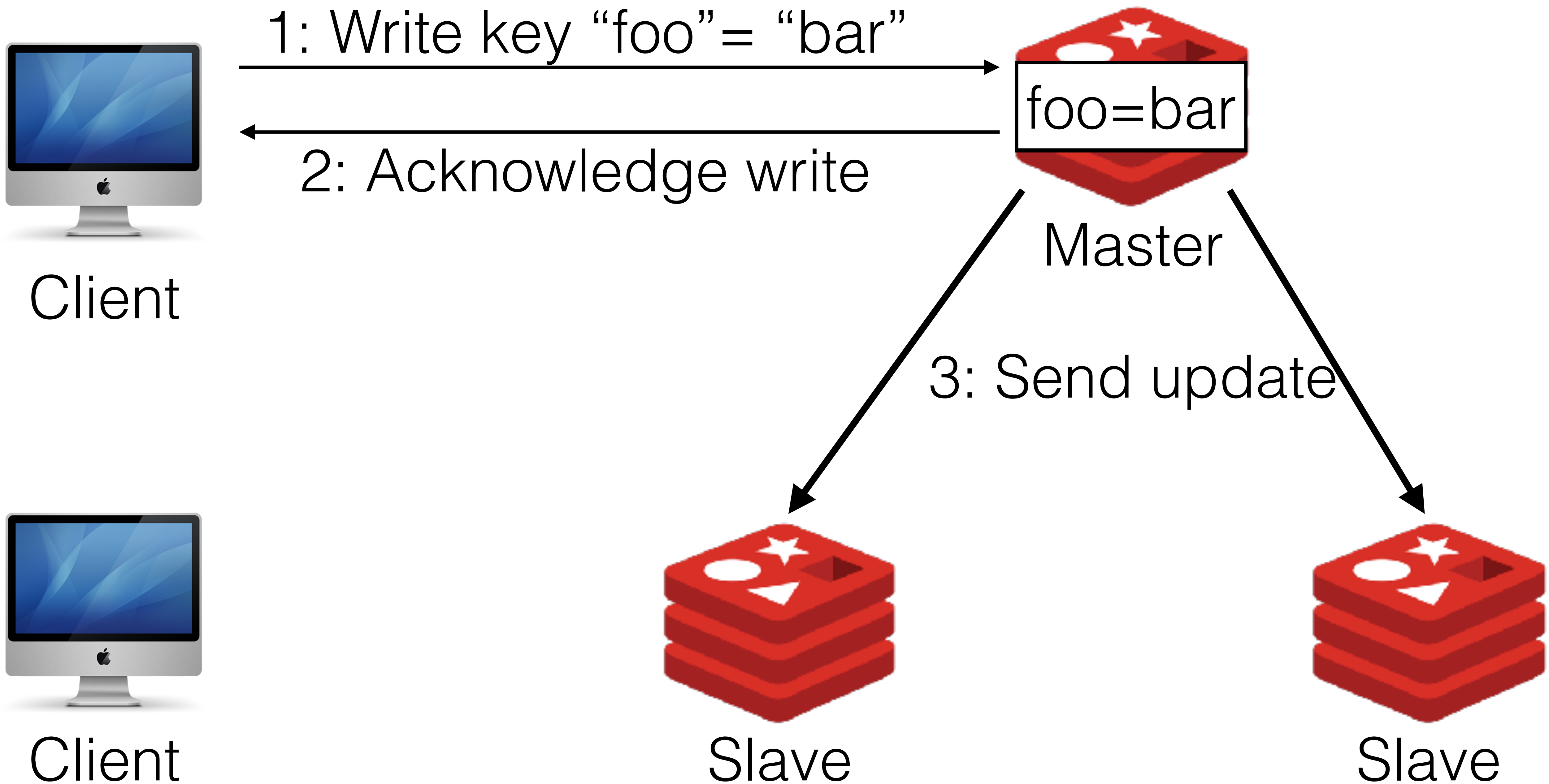
Redis Replication



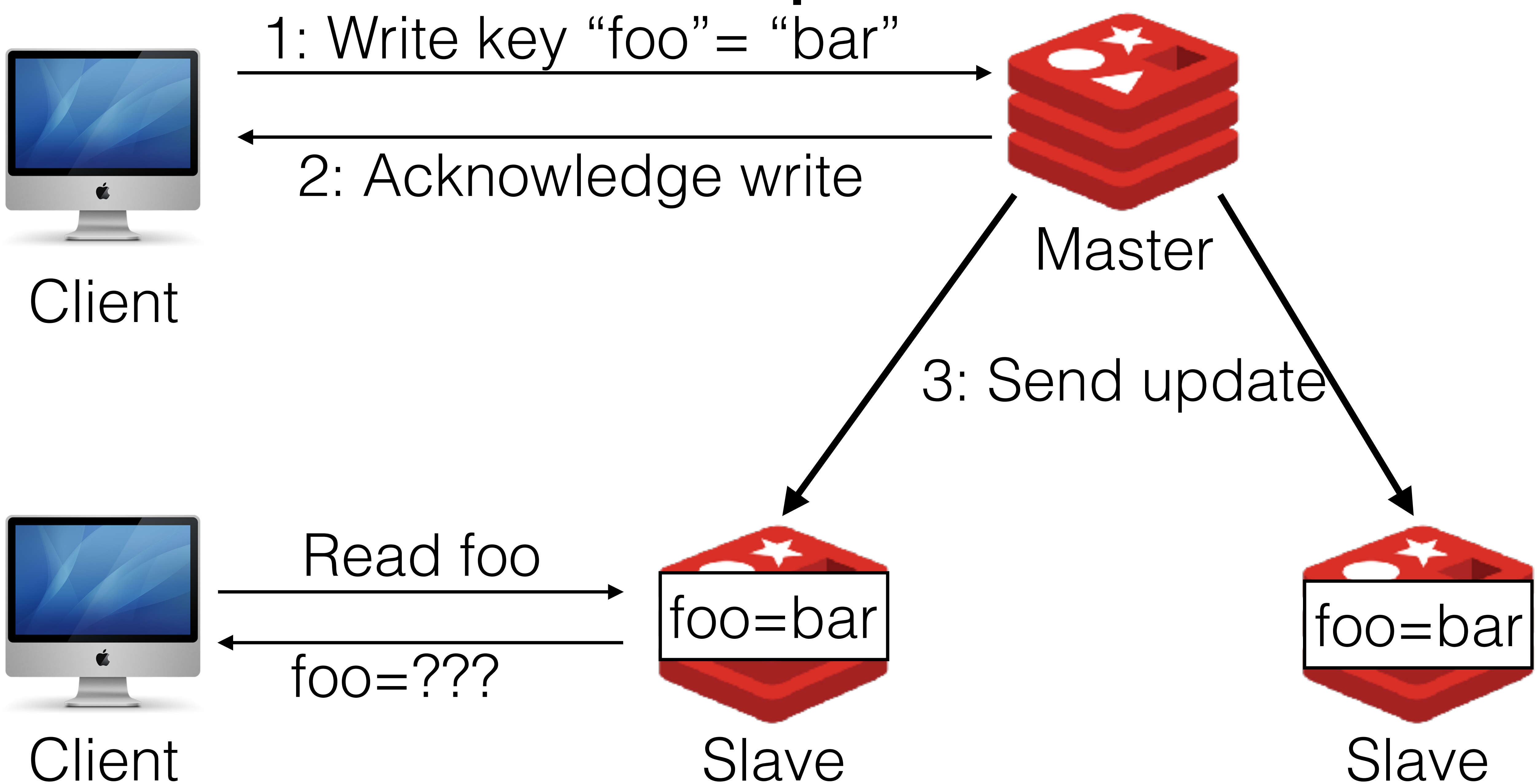
Redis Replication



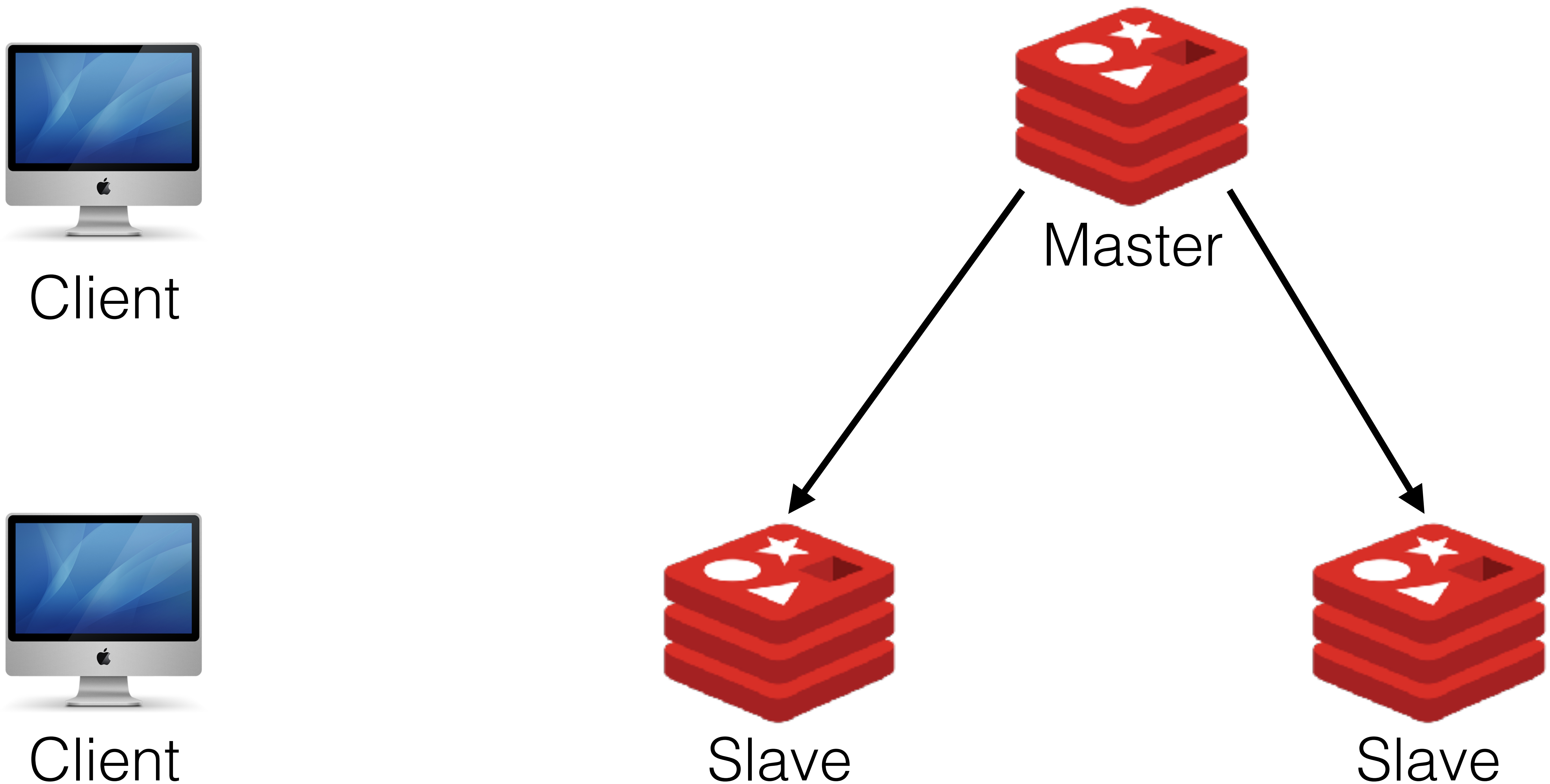
Redis Replication



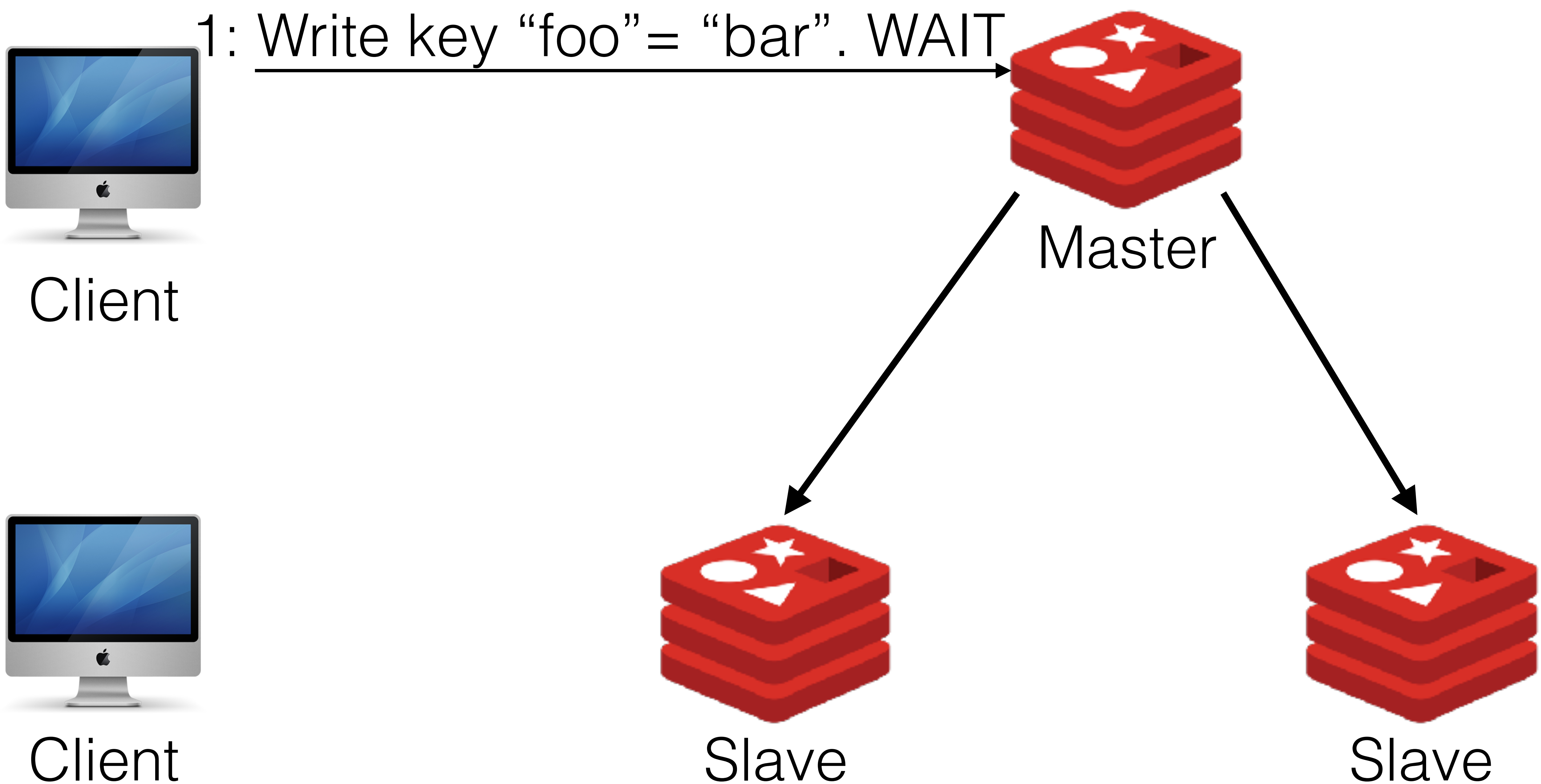
Redis Replication



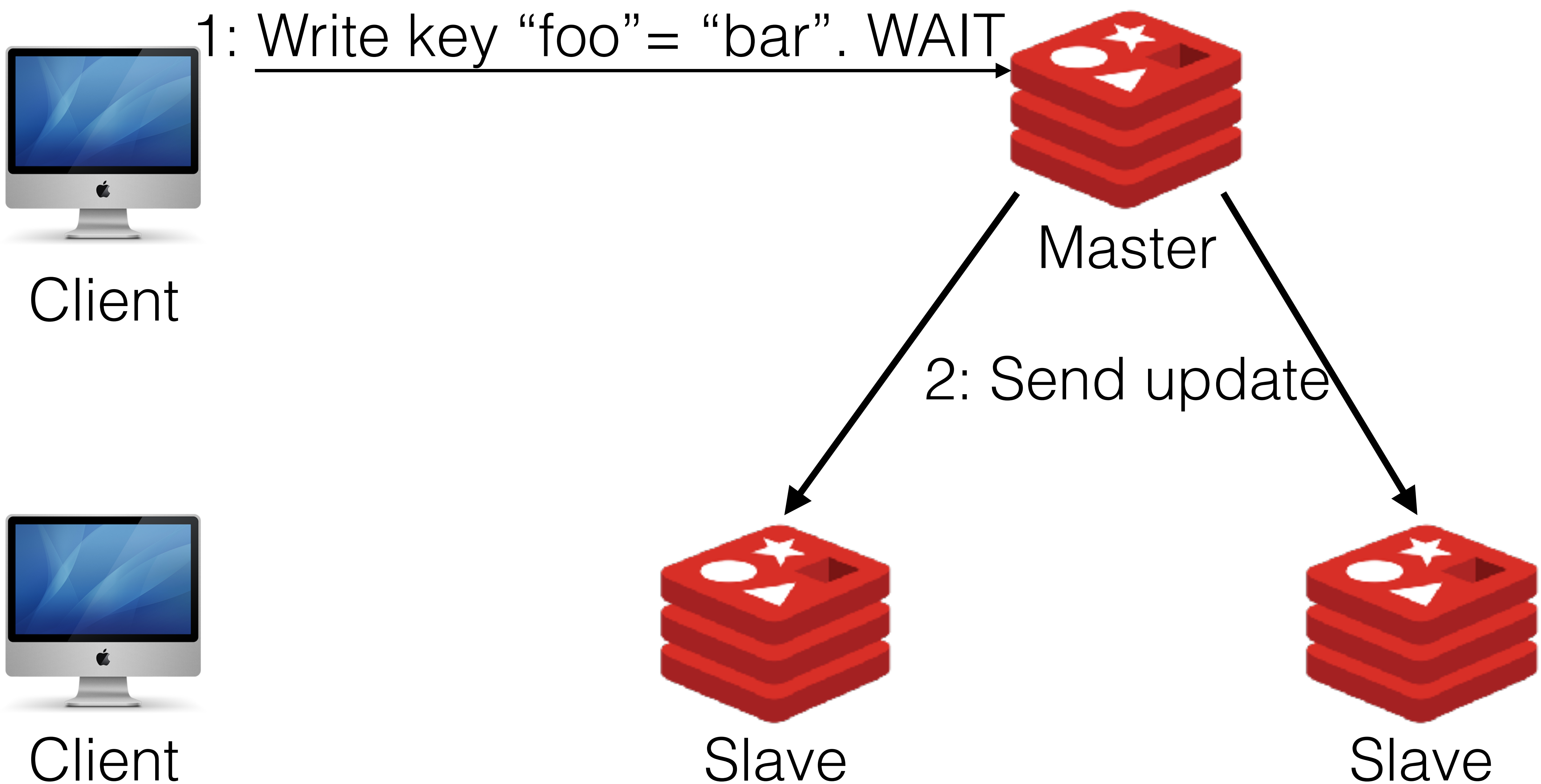
Redis “Wait” command



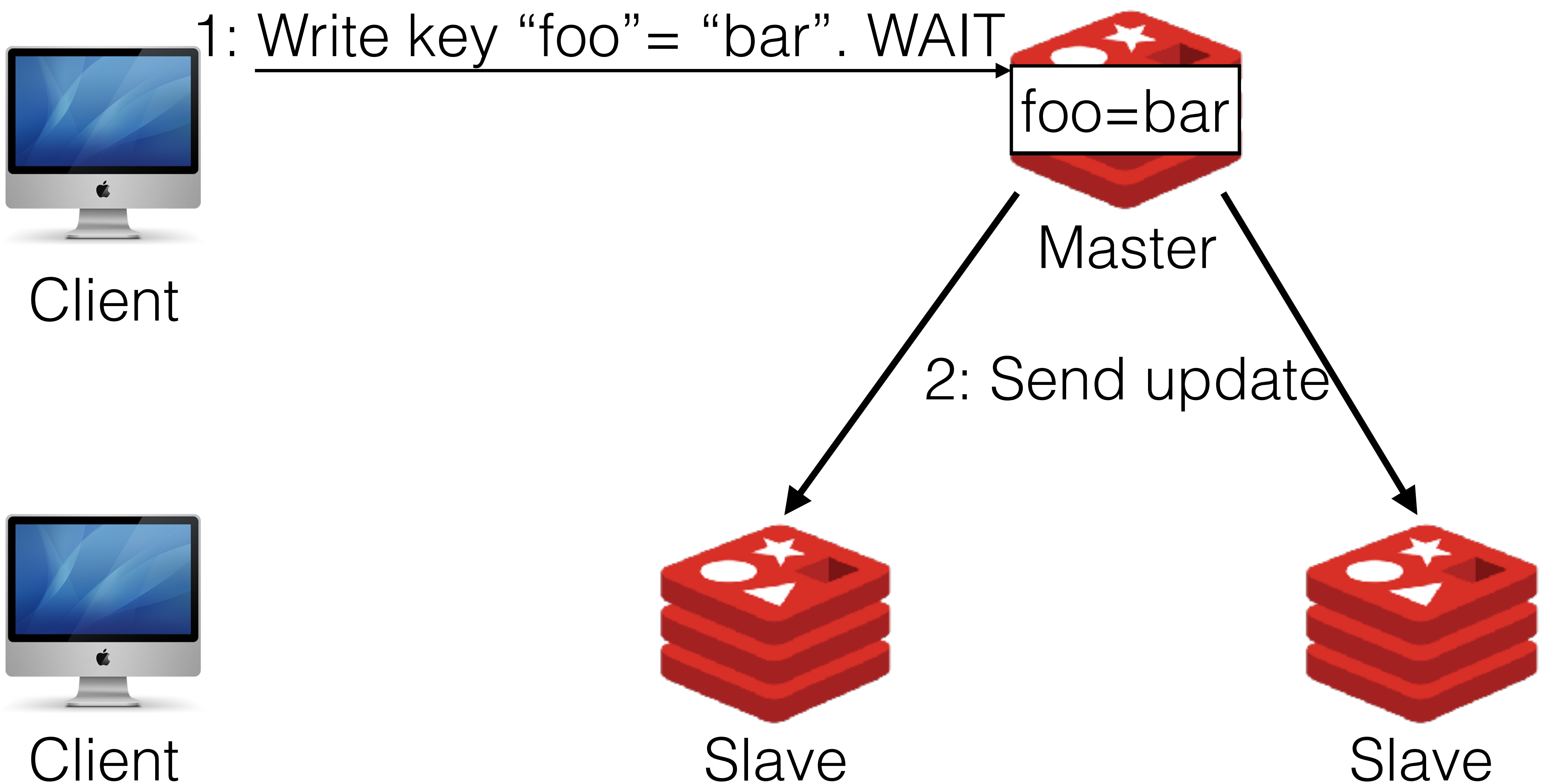
Redis "Wait" command



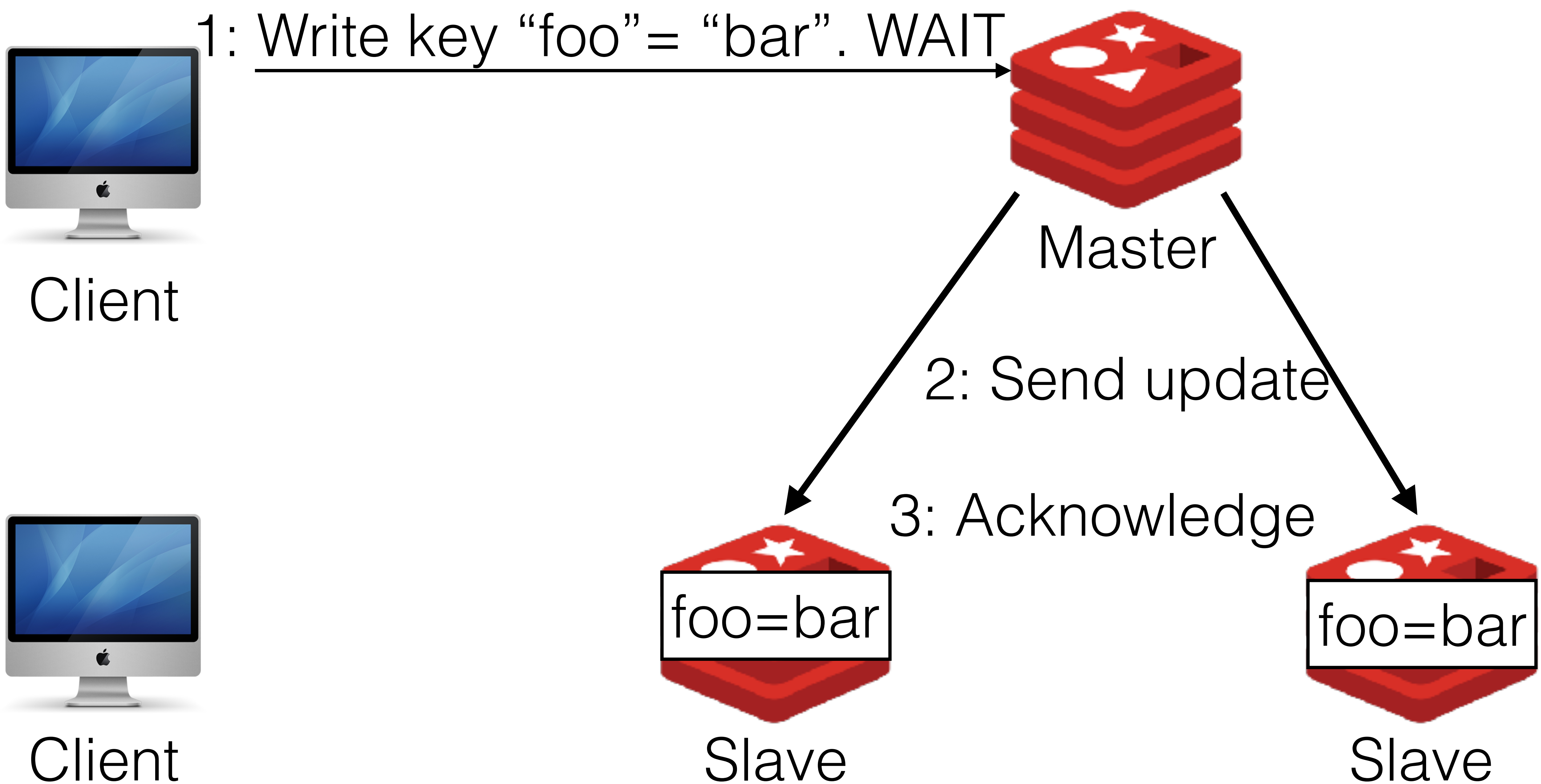
Redis "Wait" command



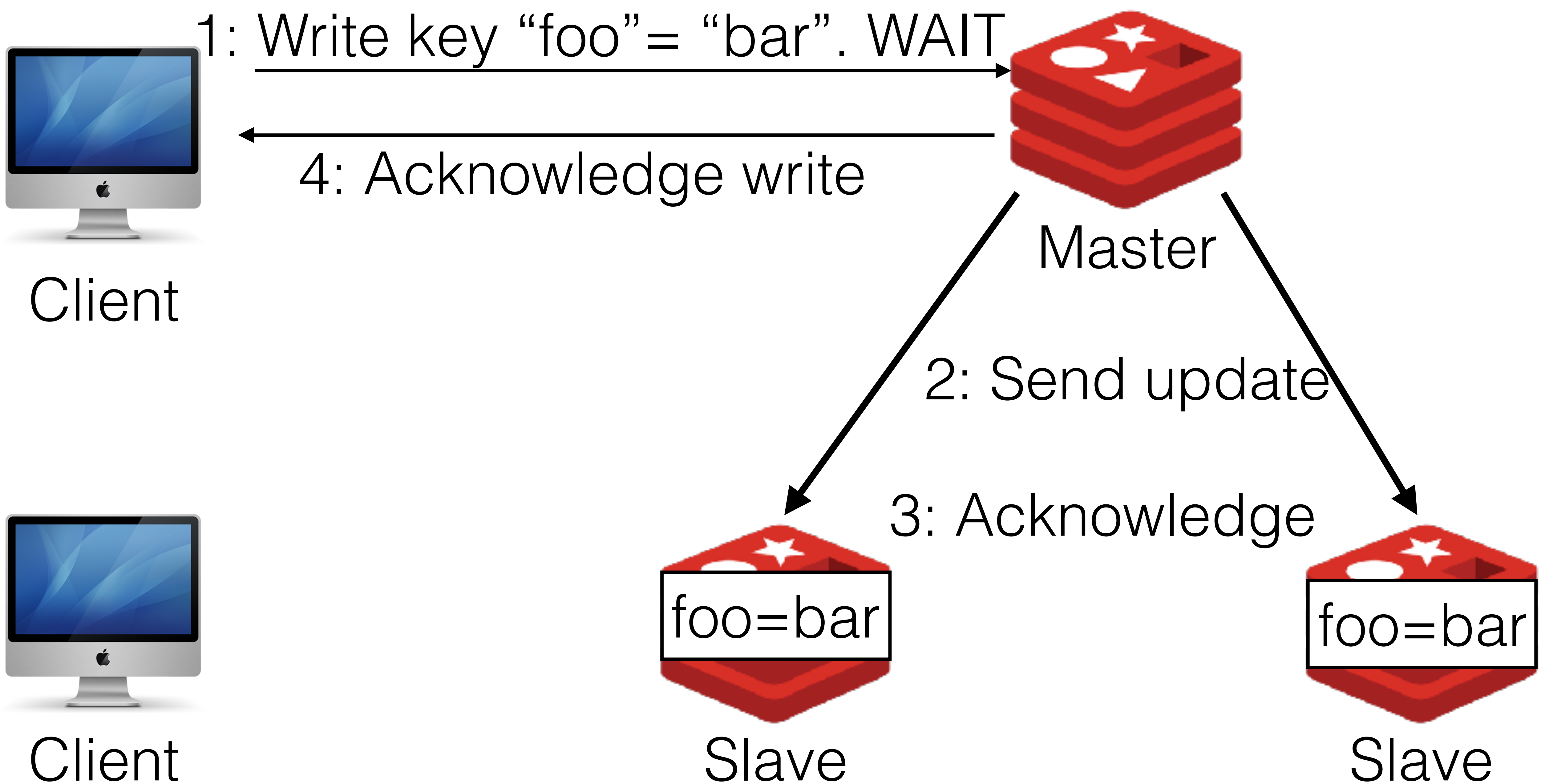
Redis “Wait” command



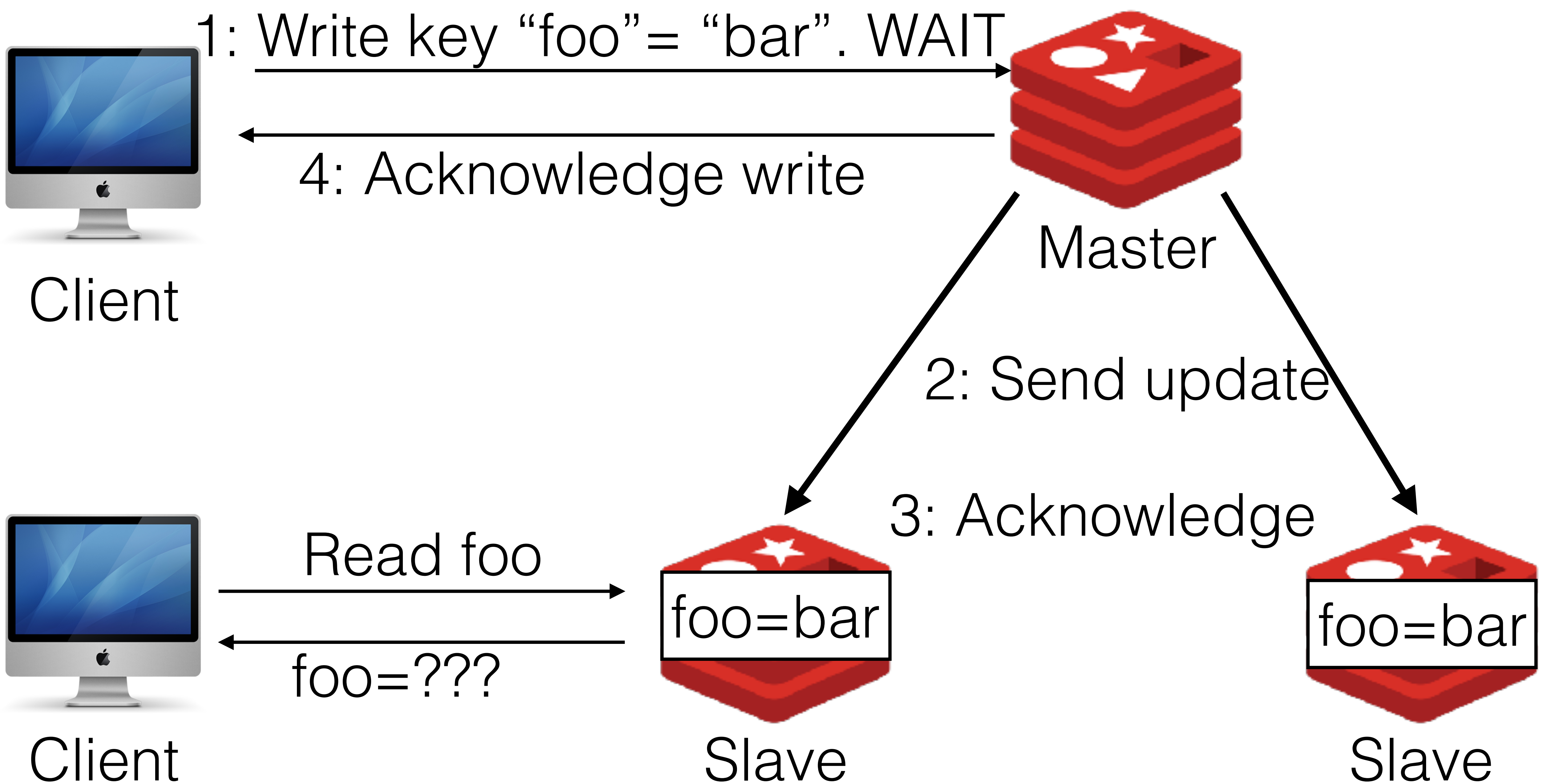
Redis "Wait" command



Redis "Wait" command



Redis "Wait" command



HW3: Replicate Redis

- What happens if Redis fails?
- Solution:
  - Redis has built in replication!
- What consistency guarantees does that provide?
- We want to maintain what we've got.
- You'll use WAIT after writes
- All writes -> master, reads -> slave (note: now each client has its own redis slave)
- Add heartbeat to know how many replicas there are

Today

- Transactions
- 2 Phase Locking
- 2 Phase Commit
- Write Ahead Logging

Transactions

- The past few weeks we've talked about consistency of individual reads/writes
- How can we provide some consistency guarantees **across operations**
- Transaction: unit of work (grouping) of operations
  - Begin transaction
  - Do stuff
  - Commit OR abort

Properties of Transactions

Properties of Transactions

- Traditional properties: ACID

Properties of Transactions

- Traditional properties: ACID
- **Atomicity**: transactions are “all or nothing”

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

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

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

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;
}
```

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;
}
```

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;
}
```

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)

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	P2.balance (200) > 200

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	P2.balance (200) > 200
P1.balance = 200 - 100 = 0	**P1.balance = 200 - 200 = 0**

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	P2.balance (200) > 200
P1.balance = 200 - 100 = 0	**P1.balance = 200 - 200 = 0**
P2.balance = 200 + 100 = 300	

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	P2.balance (200) > 200
P1.balance = 200 - 100 = 0	**P1.balance = 200 - 200 = 0**
P2.balance = 200 + 100 = 300	
return true;	P2.balance = 300 + 200 = 500

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	P2.balance (200) > 200
P1.balance = 200 - 100 = 0	**P1.balance = 200 - 200 = 0**
P2.balance = 200 + 100 = 300	
return true;	P2.balance = 300 + 200 = 500
	return true;

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	P2.balance (200) > 200
P1.balance = 200 - 100 = 0	**P1.balance = 200 - 200 = 0**
P2.balance = 200 + 100 = 300	
return true;	P2.balance = 300 + 200 = 500
	return true;

OK, we know how to solve this one (we need sequential consistency on P1.balance, which we'd get normally given the way the code is written above if balance is volatile)

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;
}
```

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)

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	P2.balance (200) > 200

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	P2.balance (200) > 200
P1.balance = 200 - 100 = 0	

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	P2.balance (200) > 200
P1.balance = 200 - 100 = 0	
P2.balance = 200 + 100 = 300	

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	P2.balance (200) > 200
P1.balance = 200 - 100 = 0	
P2.balance = 200 + 100 = 300	
return true;	P1.balance = 100 - 200 = -100

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	P2.balance (200) > 200
P1.balance = 200 - 100 = 0	
P2.balance = 200 + 100 = 300	
return true;	P1.balance = 100 - 200 = -100
	P2.balance = 300 + 200 = 500

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	P2.balance (200) > 200
P1.balance = 200 - 100 = 0	
P2.balance = 200 + 100 = 300	
return true;	P1.balance = 100 - 200 = -100
	P2.balance = 300 + 200 = 500
	return true;

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	P2.balance (200) > 200
P1.balance = 200 - 100 = 0	
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

```java
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;
    }
}
```

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)

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	

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 = 0	

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 = 0	
P2.balance = 200 + 100 = 300	

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 = 0	
P2.balance = 200 + 100 = 300	
return true;	

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 = 0	
P2.balance = 200 + 100 = 300	
return true;	
	P1.balance <= 200

Transactions: Classic Example

```java
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 = 0	
P2.balance = 200 + 100 = 300	
return true;	
	P1.balance <= 200
	return false;

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 = 0	
P2.balance = 200 + 100 = 300	
return true;	
	P1.balance <= 200
	return false;

Adding a lock: prevents accounts from being overdrawn

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 = 0	
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, to){
        if(from.balance >= amount)
        {
            from.balance = from.balance - amount;
            to.balance = to.balance + amount;
            return true;
        }
        return false;
    }
}
```

Transactions: Classic Example

```
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)**

Transactions: Classic Example

```
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	

Transactions: Classic Example

```
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 = 0	

Transactions: Classic Example

```
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 = 0	
P2.balance = 200 + 100 = 300	

Transactions: Classic Example

```
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 = 0	
P2.balance = 200 + 100 = 300	
return true;	

Transactions: Classic Example

```
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 = 0	
P2.balance = 200 + 100 = 300	
return true;	
	P1.balance <= 200

Transactions: Classic Example

```
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 = 0	
P2.balance = 200 + 100 = 300	
return true;	
	P1.balance <= 200
	return false;

Transactions: Classic Example

```
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 = 0	
P2.balance = 200 + 100 = 300	
return true;	
	P1.balance <= 200
	return false;

Locking on both from, to at same time

Transactions: Classic Example

```
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;
    }
}
```

Transactions: Classic Example

```
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)

Transactions: Classic Example

```
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	

Transactions: Classic Example

```
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 = 0	

Transactions: Classic Example

```
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 = 0	

Transactions: Classic Example

```
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 = 0	
	P1.balance <= 200

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 = 0	
	
	P1.balance <= 200
	return false;

Transactions: Classic Example

```
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 = 0	
	
	P1.balance <= 200
	return false;

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

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;
}
```

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;
}
```

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

Avoiding Deadlocks

- Remember: dining philosophers
- Easiest fix: always acquire locks in the same order
  - E.g., first acquire lock on person with older account, then other person?
- Also: get all locks at same time
  - Not really practical
- Alternatively: timeouts

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

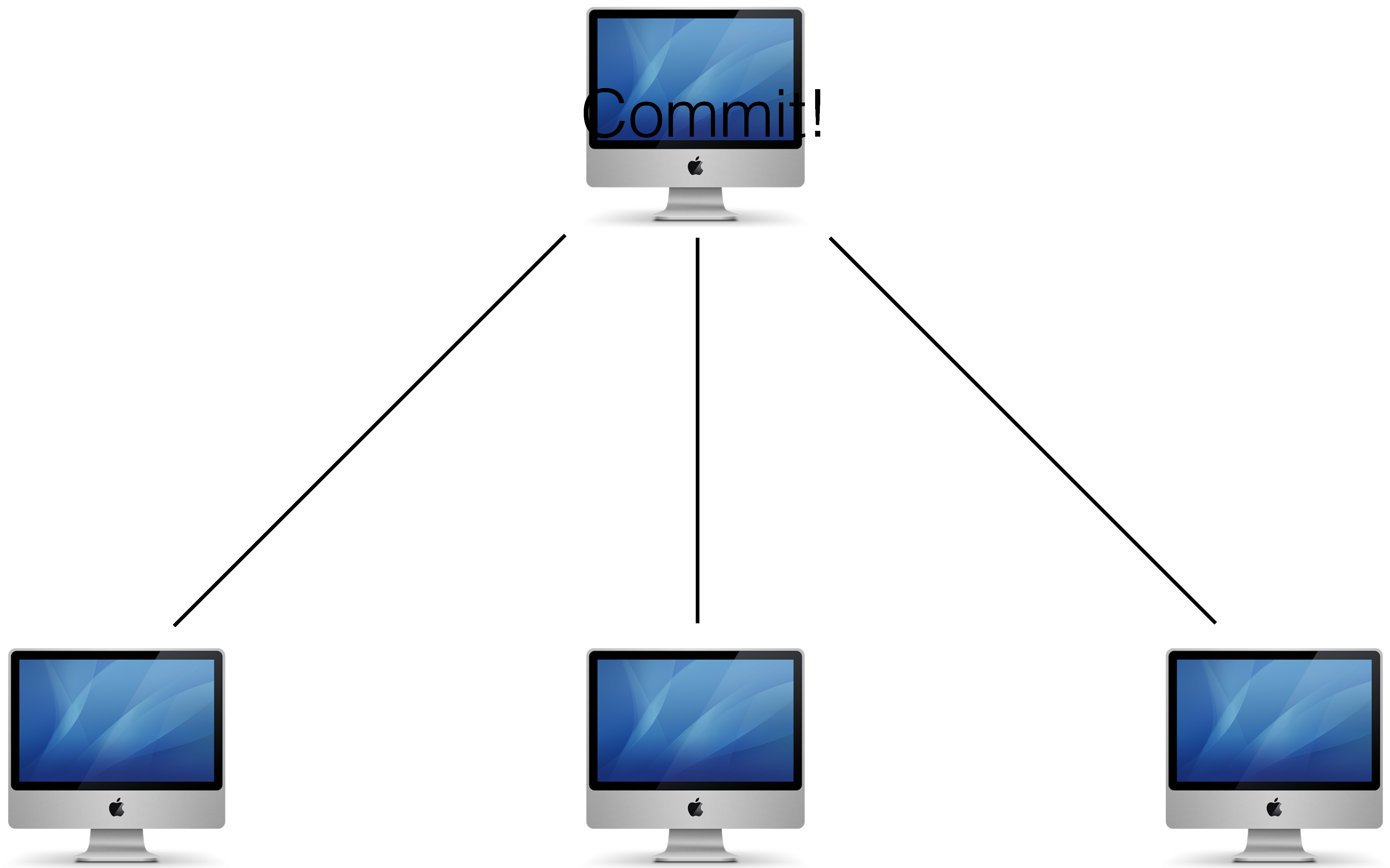
Distributed Transactions

- 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

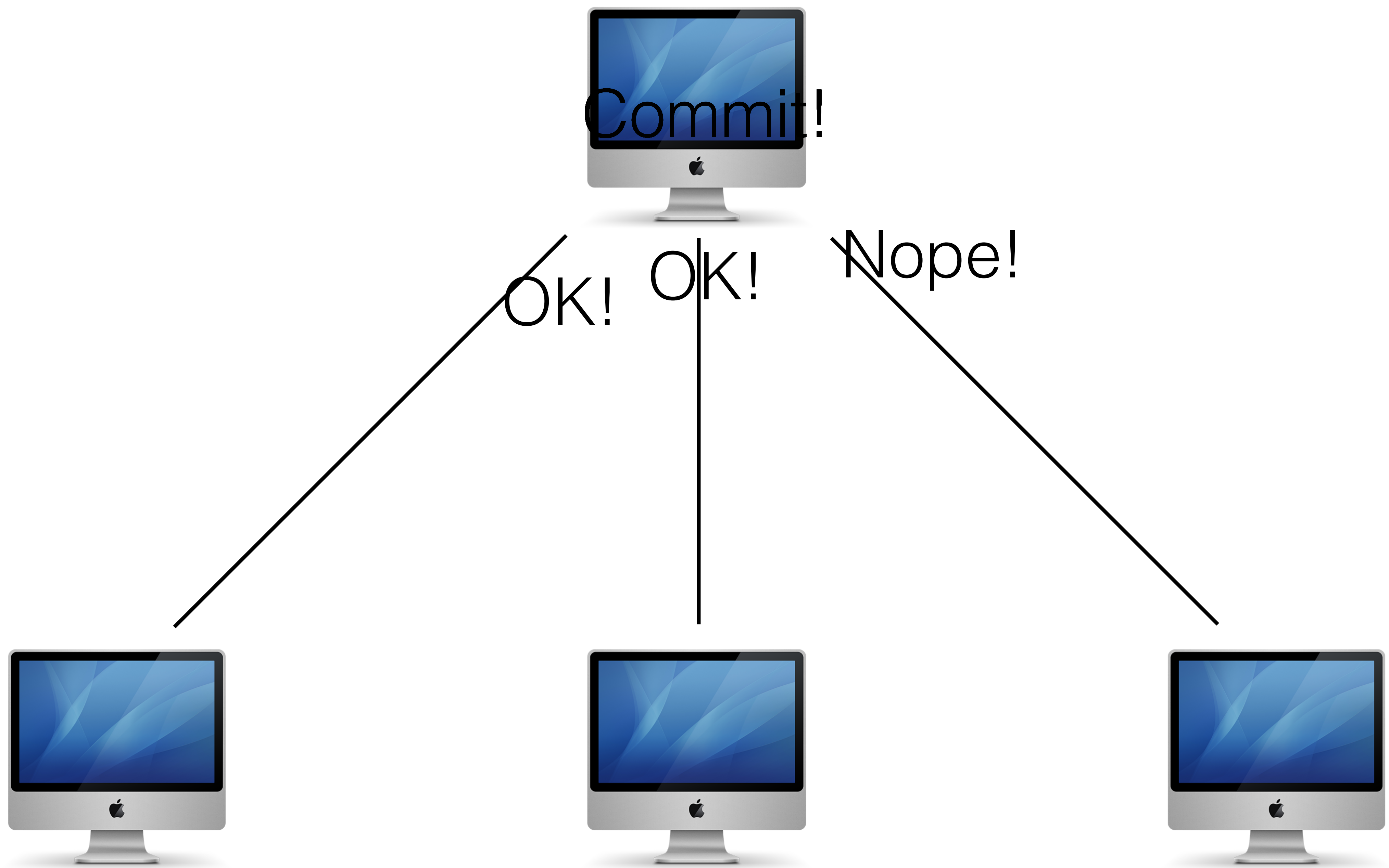
1-Phase Transaction Commit

- Naive protocol: coordinator broadcasts out "commit!" continuously until participants all say "OK!"
- Problem: what happens when a participants fails during commit? How do the other participants know that they shouldn't have really committed and they need to abort?

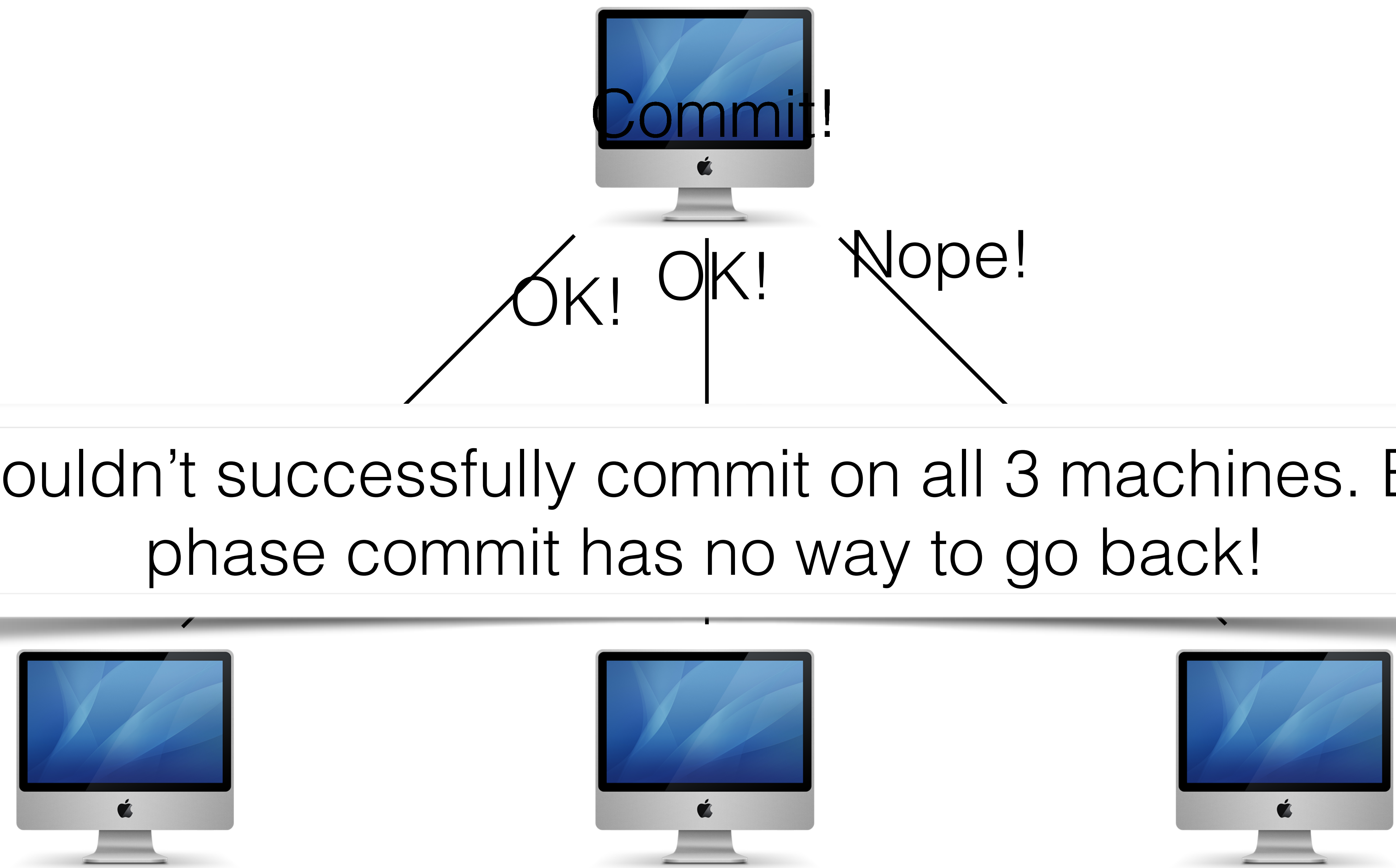
1-Phase Commit



1-Phase Commit



1-Phase Commit



We couldn't successfully commit on all 3 machines. But 1-phase commit has no way to go back!

2-Phase Commit

2-Phase Commit

- Separate the commit into two steps:

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-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

2PC: Voting

2PC: Voting

- Coordinator asks each participant: can you commit for this transaction?

2PC: Voting

- Coordinator asks each participant: can you commit for this transaction?
- Each participant prepares to commit BEFORE answering yes

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

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

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

Coordinator

Transaction state:

prepared

Participant

Local state:

prepared

2PC Event Sequence

Coordinator

Transaction state:

prepared

Can you commit?

Participant

Local state:

prepared

uncertain

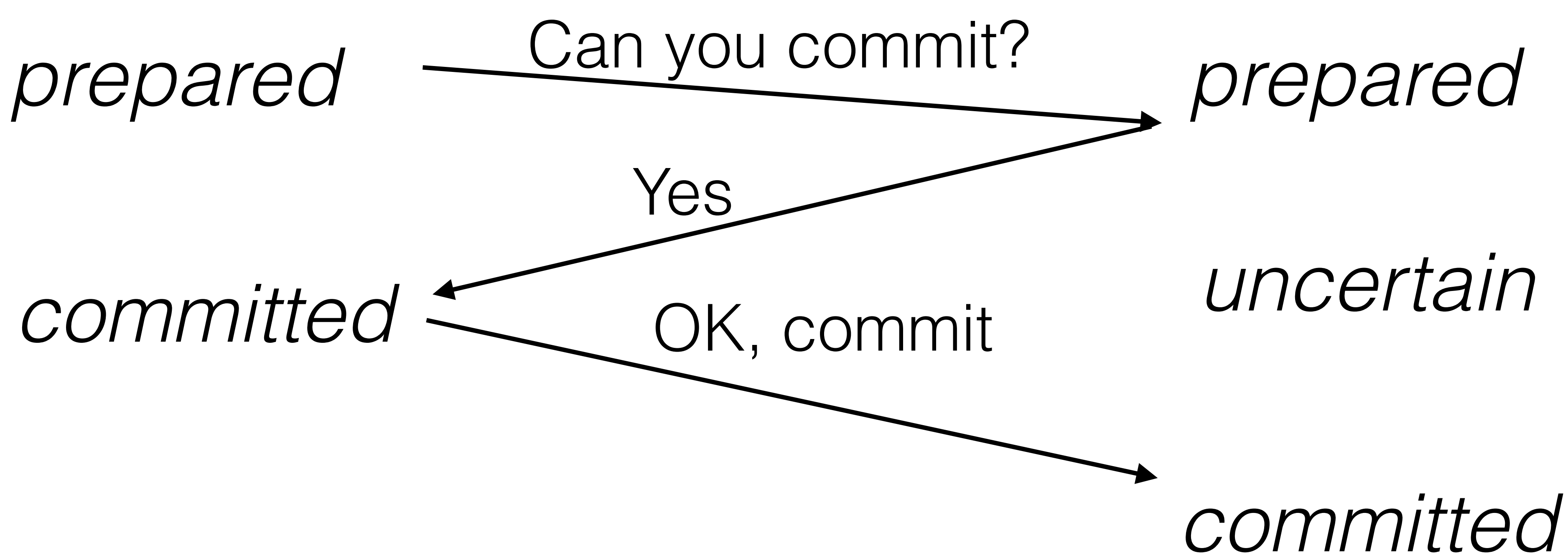
2PC Event Sequence

Coordinator		**Participant**
Transaction state:		**Local state:**
prepared	Can you commit? →	*prepared*
	← Yes	
		uncertain

2PC Event Sequence

Coordinator **Participant**

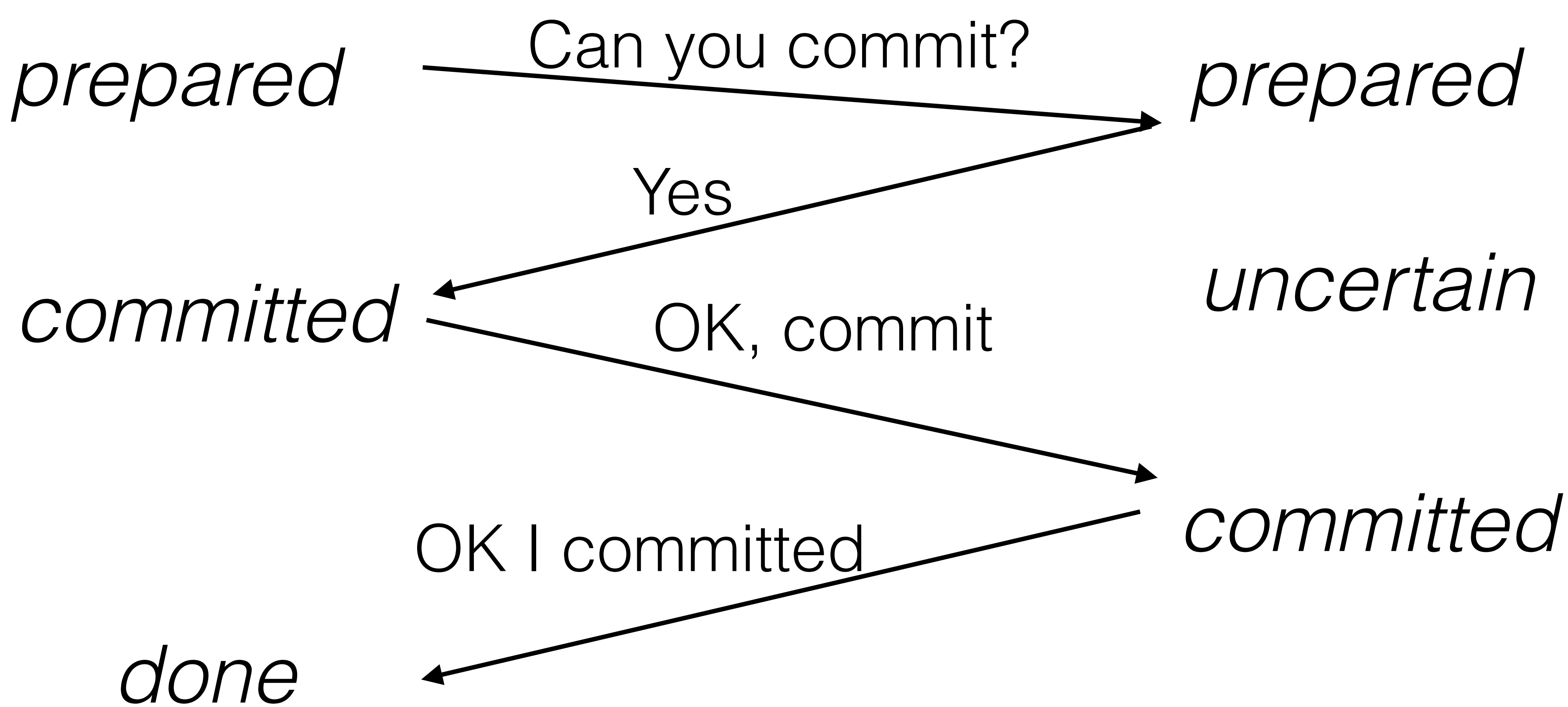
Transaction state: **Local state:**



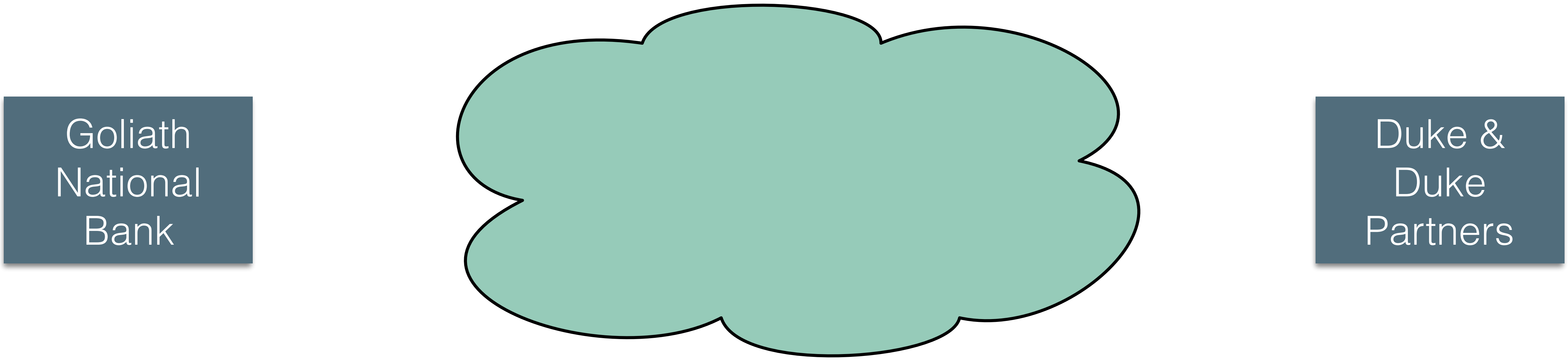
2PC Event Sequence

Coordinator **Participant**

Transaction state: **Local state:**

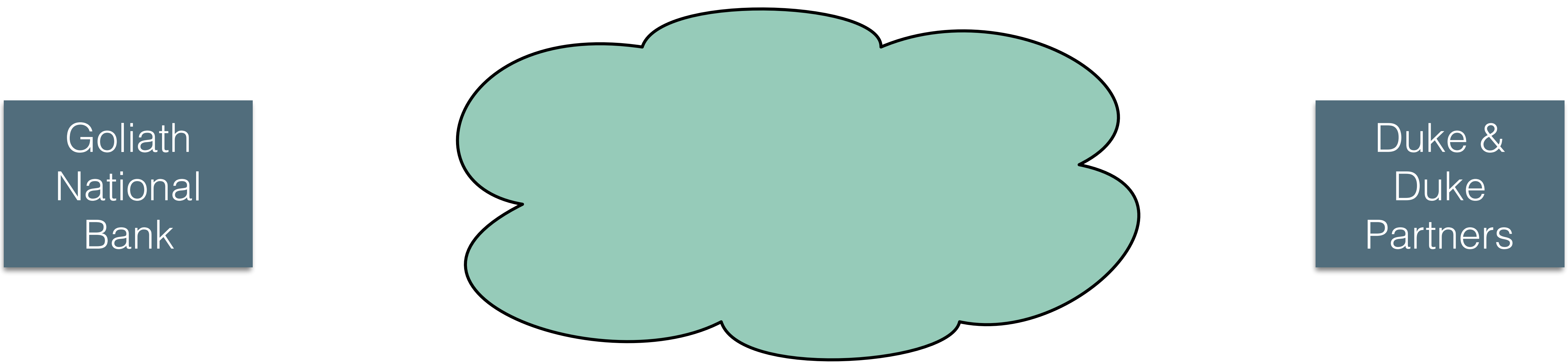


2PC Example



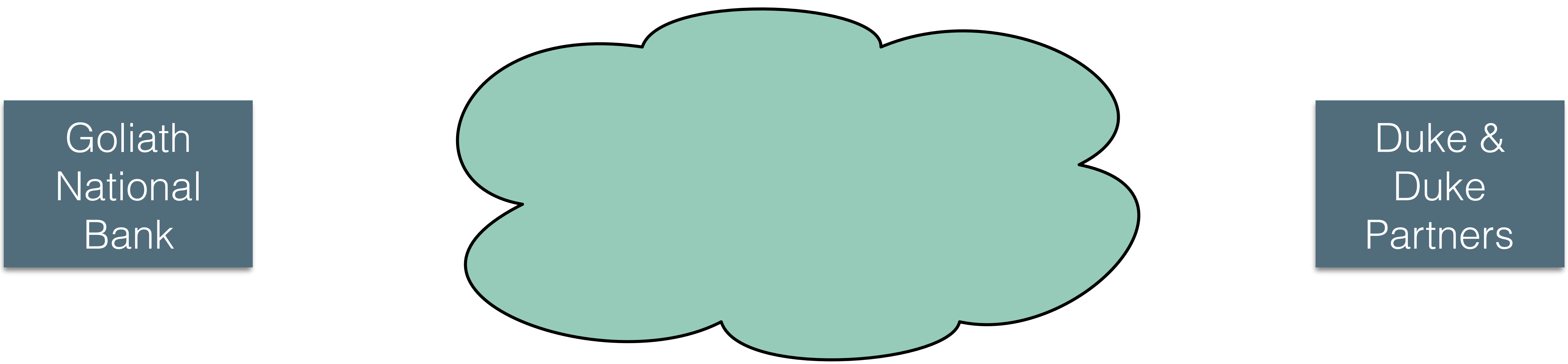
2PC Example

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

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



2PC Example

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

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



Requirements:

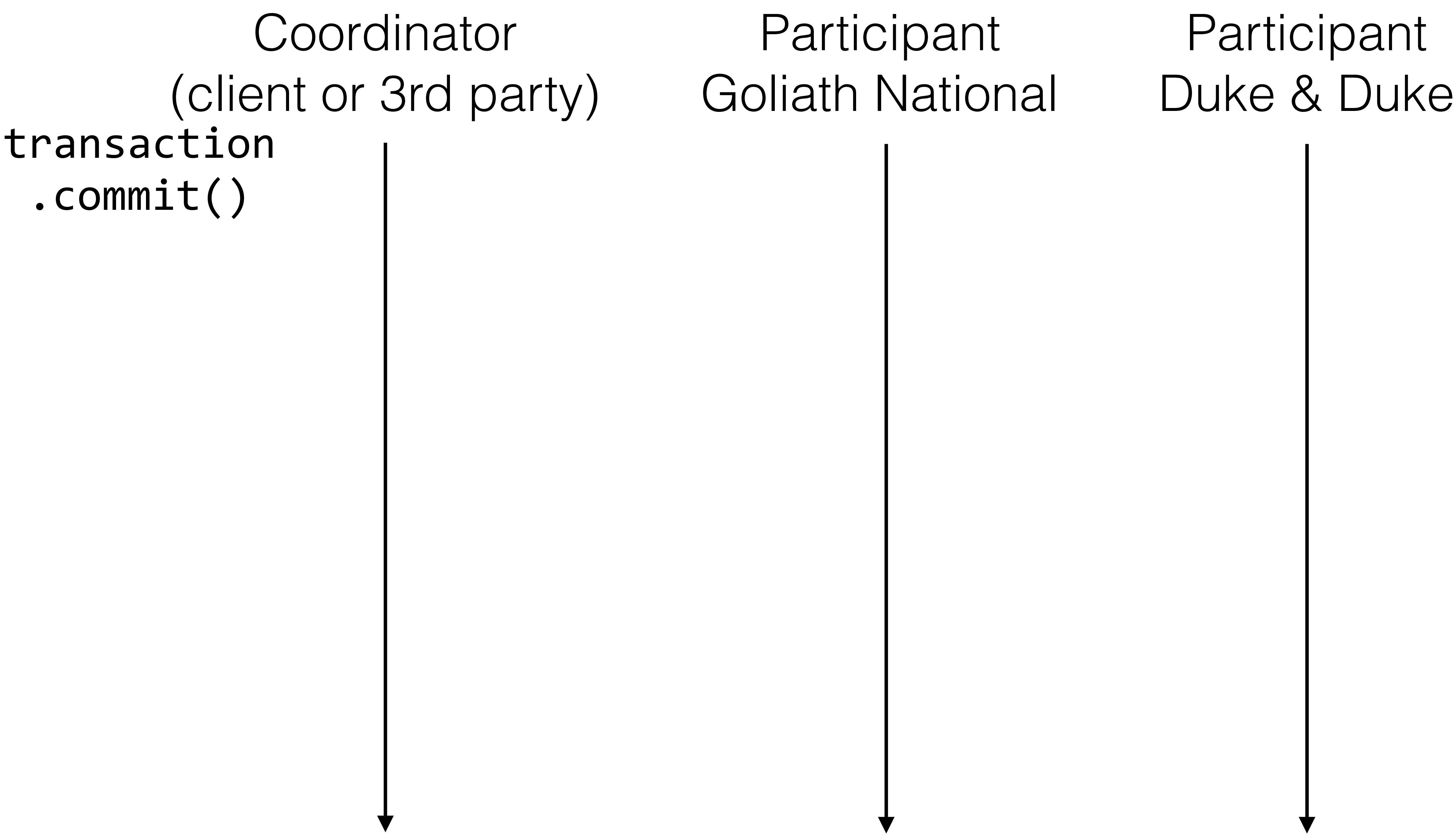
1. Atomicity (transfer happens or doesn't)
2. Concurrency control (serializability)

2PC Example

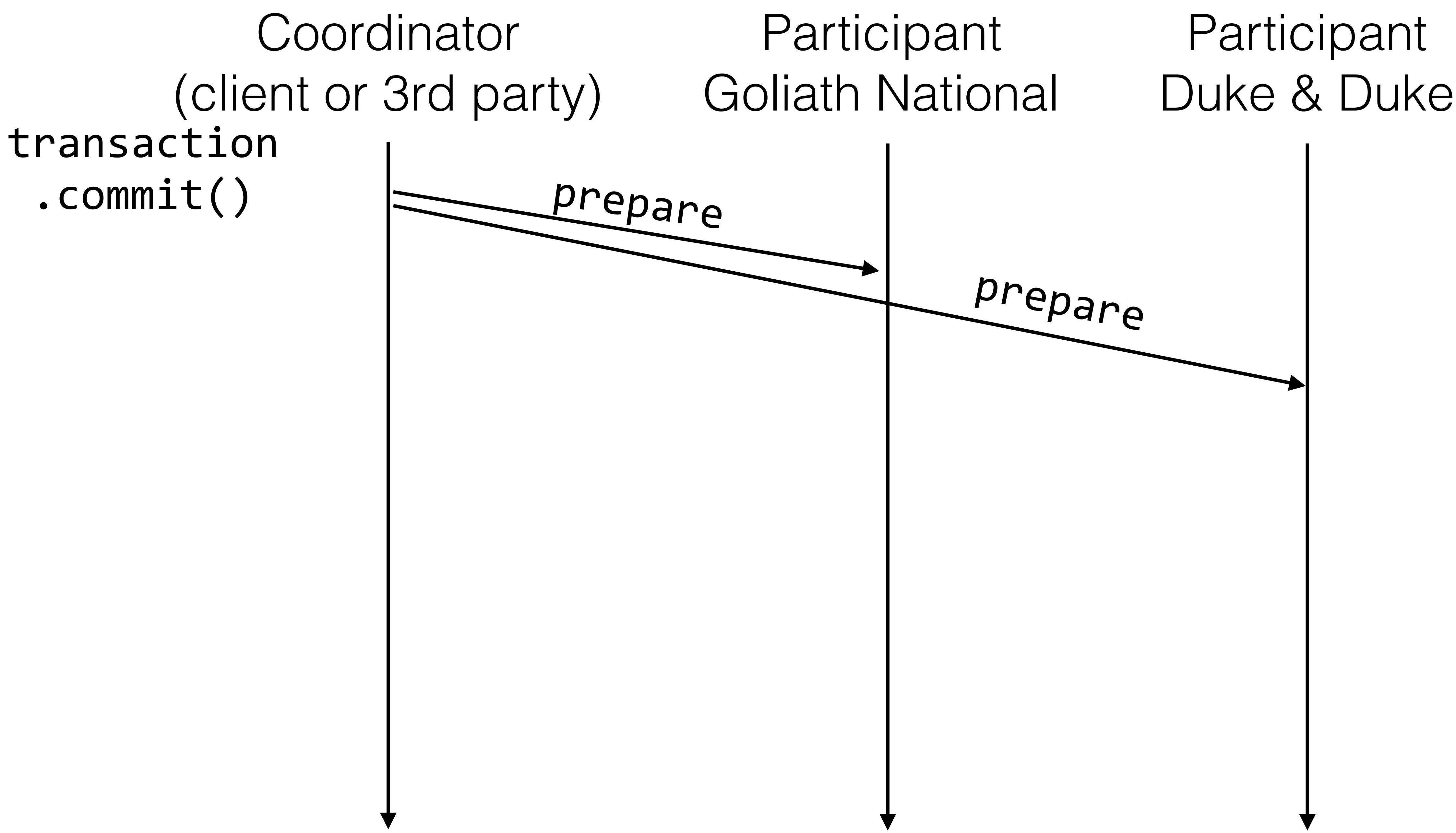
For simplicity, let's assume transfer is:

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

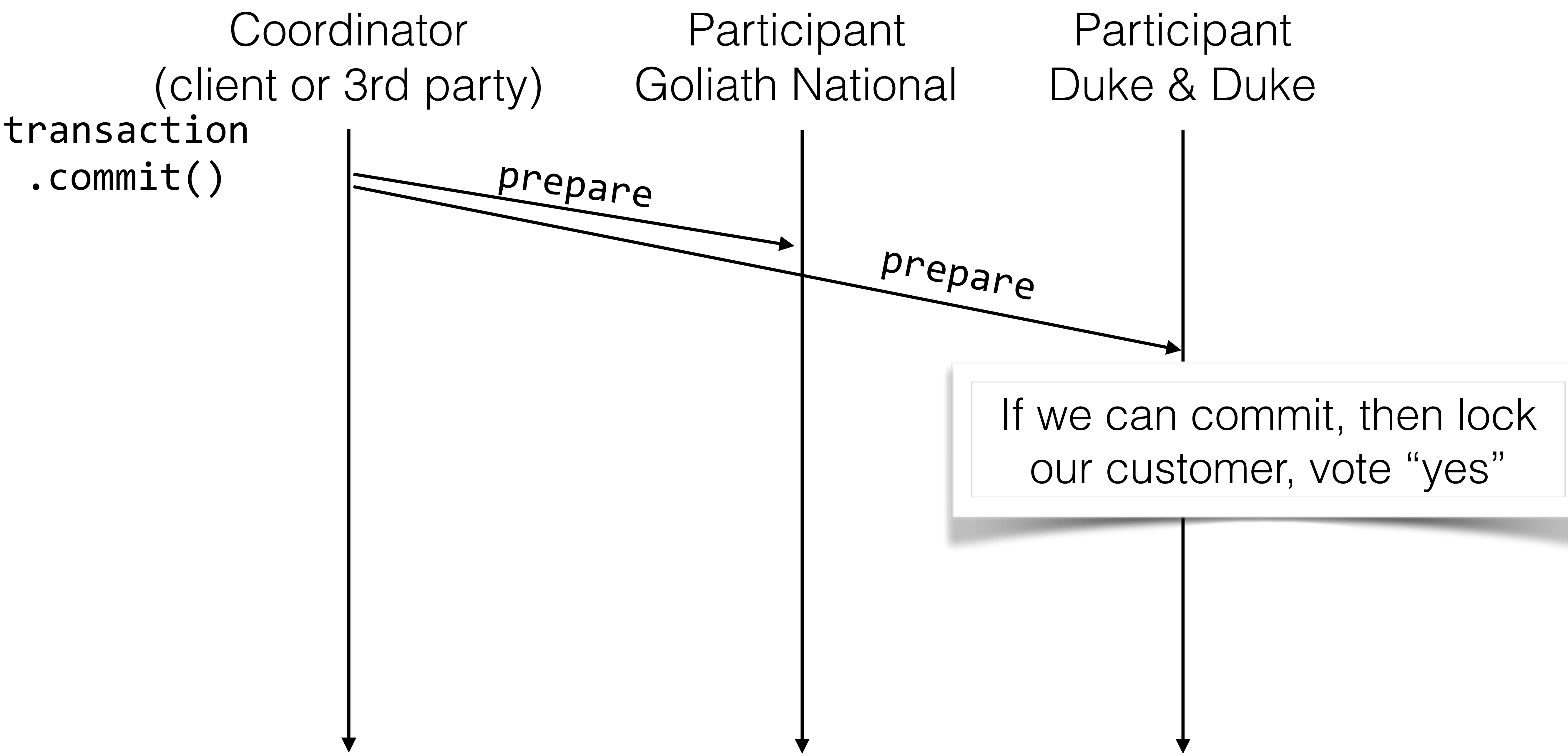
2PC Example


Coordinator
(client or 3rd party)
Participant
Goliath National
Participant
Duke & Duke
transaction
.commit()

2PC Example

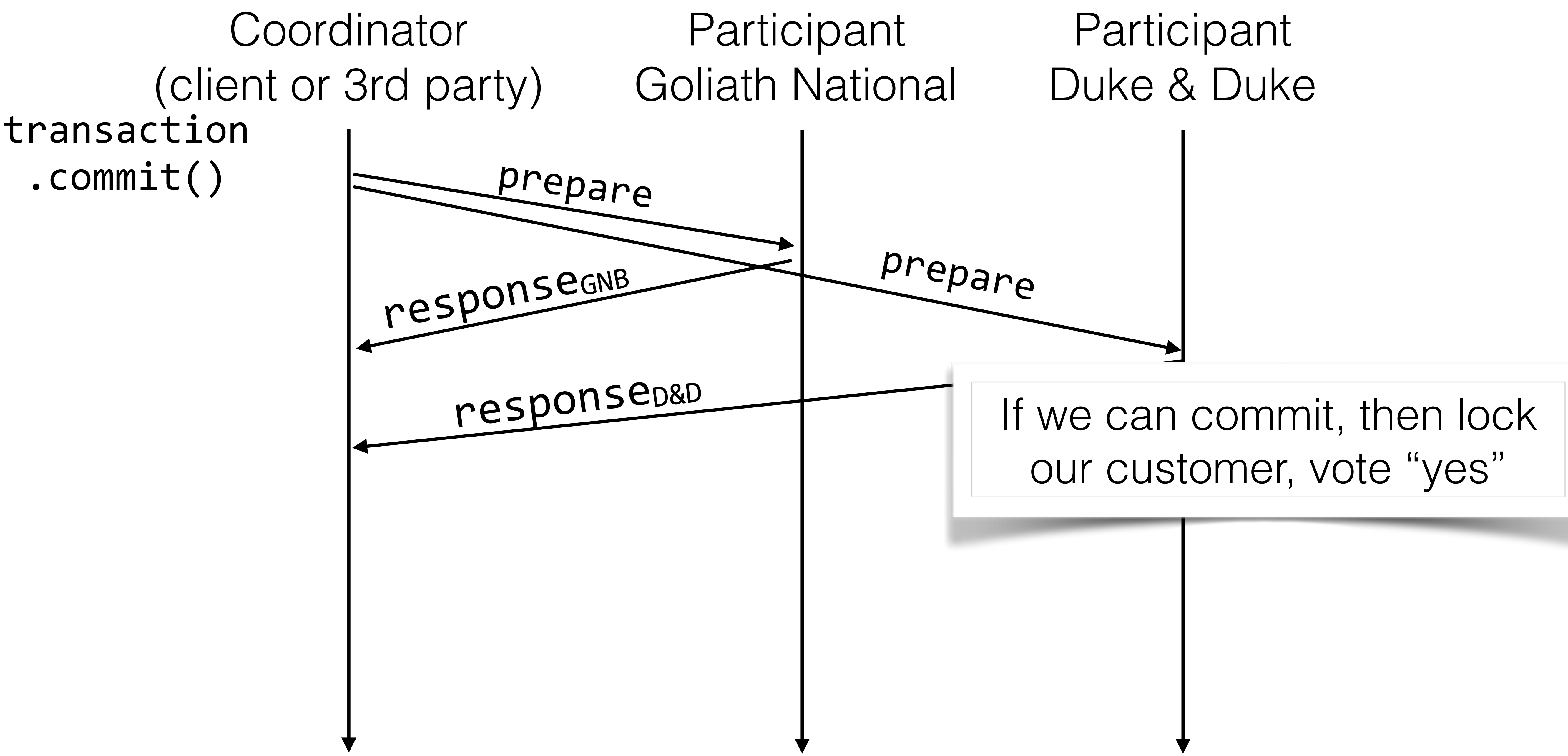

Coordinator
(client or 3rd party)
Participant
Goliath National
Participant
Duke & Duke
transaction
.commit()
prepare
prepare

2PC Example



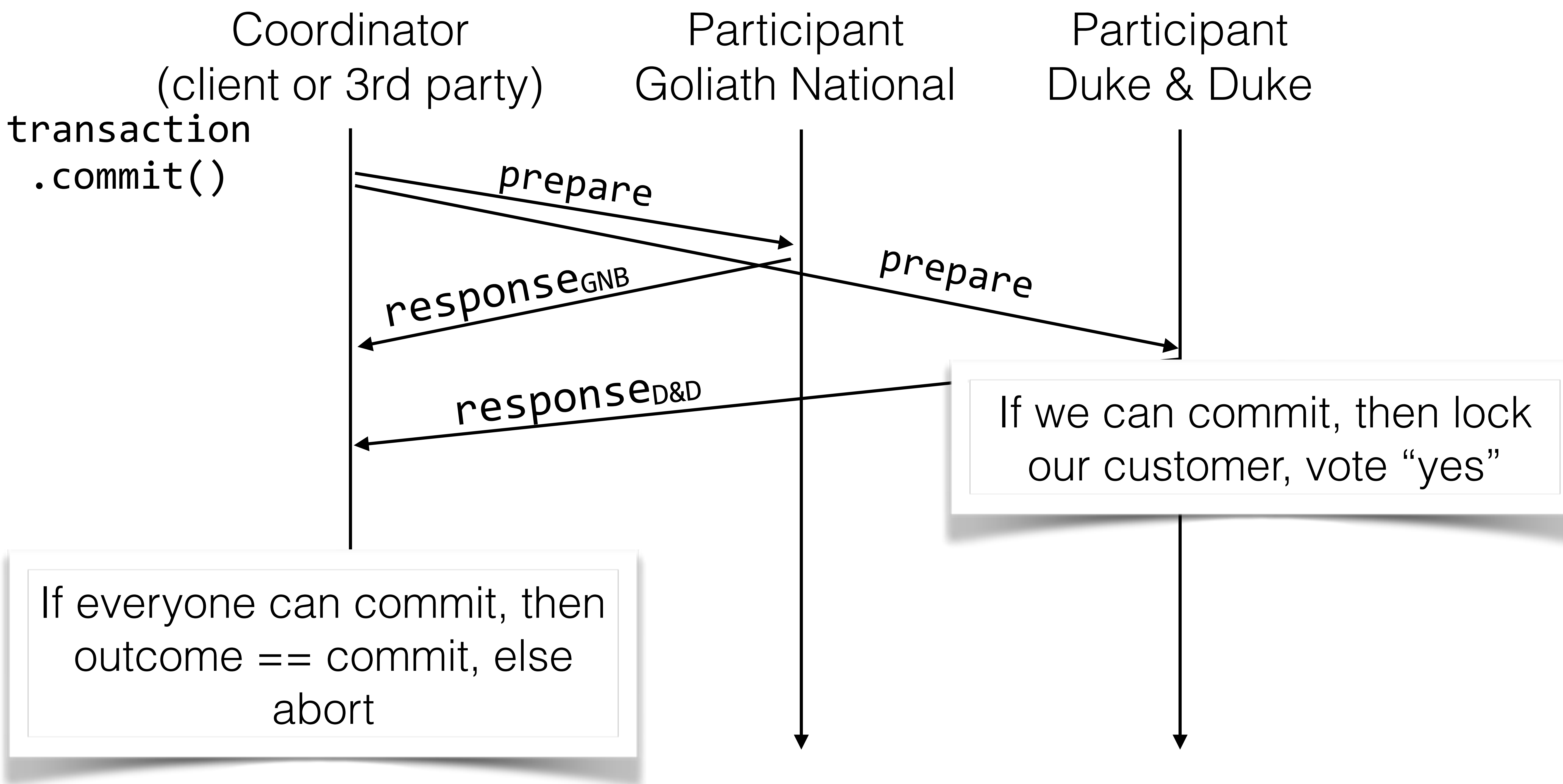
Coordinator
(client or 3rd party)
Participant
Goliath National
Participant
Duke & Duke
transaction
.commit()
prepare
prepare
If we can commit, then lock our customer, vote "yes"

2PC Example

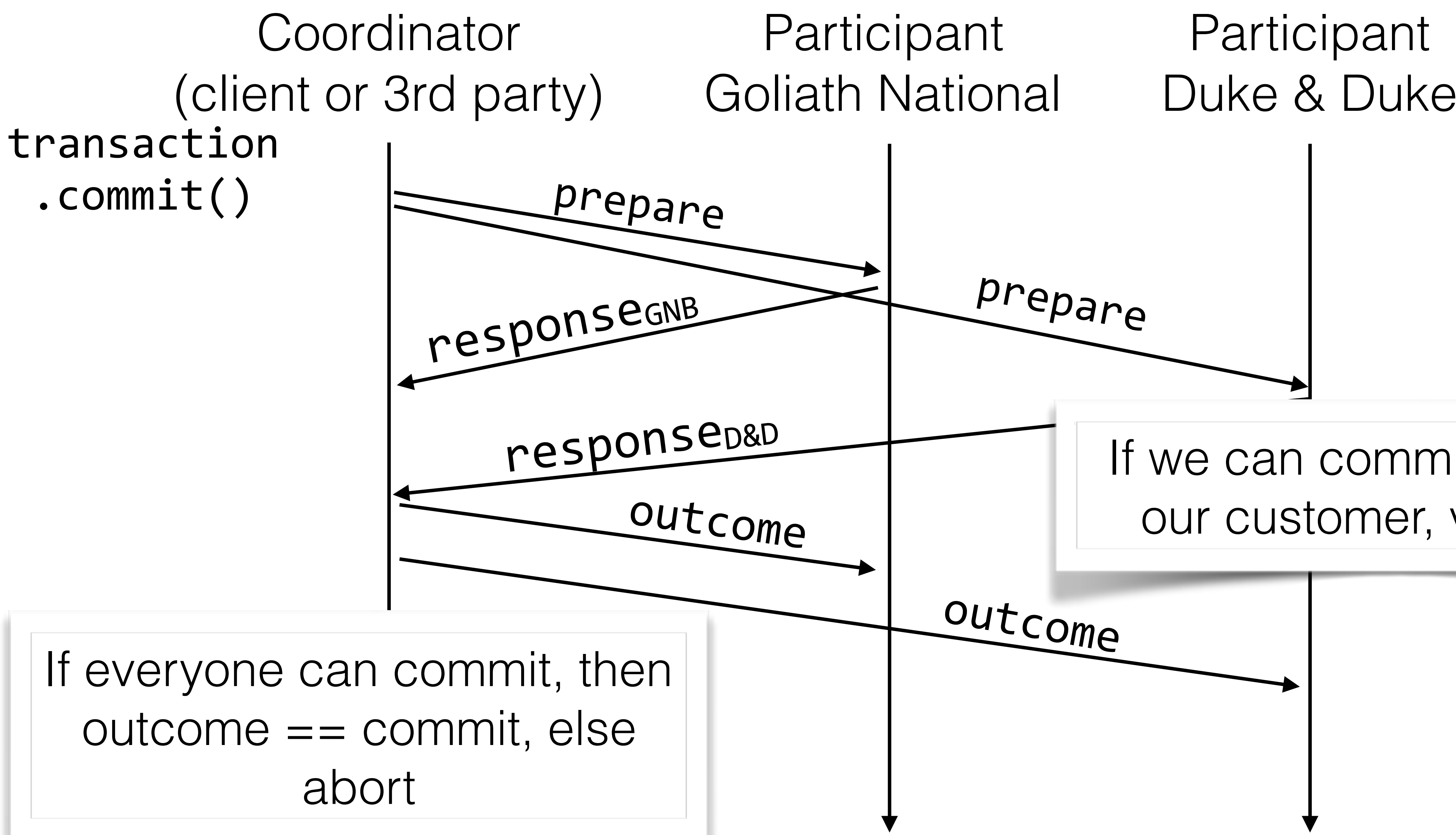


Coordinator
(client or 3rd party)
Participant
Goliath National
Participant
Duke & Duke
transaction
.commit()
prepare
prepare
responseGNB
responseD&D
If we can commit, then lock our customer, vote “yes”

2PC Example


Coordinator
(client or 3rd party)
Participant
Goliath National
Participant
Duke & Duke
transaction
.commit()
prepare
prepare
responseGNB
responseD&D
If we can commit, then lock our customer, vote "yes"
If everyone can commit, then outcome == commit, else abort

2PC Example



If we can commit, then lock our customer, vote "yes"

If everyone can commit, then outcome == commit, else abort

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

Write ahead logging: Begin/commit/abort

- Maintain this big log, with…
- Log Sequence Numbers (LSN) to track entries
- Each record contains an LSN, plus the LSN of the previous transaction
- Transaction ID
- Operation type

Write ahead logging: update records

- Track all information needed to reproduce transaction
  - prevLSN, transactionID, operationType (like begin/commit/abort)
  - Update itself:
    - Update location
    - Old value
    - New value

Recovering From Failure

Recovering From Failure

- Let's assume we can always read the log

Recovering From Failure

- Let's assume we can always read the log
- Analyze the log

Recovering From Failure

- Let’s assume we can always read the log
- Analyze the log
- Redo all transactions starting from beginning

Recovering From Failure

- Let’s assume we can always read the log
- Analyze the log
- Redo all transactions starting from beginning
- Undo uncommitted transactions

Recovering From Failure

- Let's assume we can always read the log
- Analyze the log
- Redo all transactions starting from beginning
- Undo uncommitted transactions
    - We replay all of the transactions for consistency

Recovering From Failure

- Let’s assume we can always read the log
- Analyze the log
- Redo all transactions starting from beginning
- Undo uncommitted transactions
  - We replay all of the transactions for consistency
  - Generalize all operations - don’t need to store the results of operations, just the operations

Write Ahead Logging + Checkpoints

Write Ahead Logging + Checkpoints

- If you have a checkpoint, you can guarantee that all things before that checkpoint have been flushed to disk

Write Ahead Logging + Checkpoints

- If you have a checkpoint, you can guarantee that all things before that checkpoint have been flushed to disk
- Hence, no need to replay log after then

Write Ahead Logging + Checkpoints

- If you have a checkpoint, you can guarantee that all things before that checkpoint have been flushed to disk
- Hence, no need to replay log after then
- Speeds up recovery

Write Ahead Logging + Checkpoints

- If you have a checkpoint, you can guarantee that all things before that checkpoint have been flushed to disk
- Hence, no need to replay log after then
- Speeds up recovery
- Reduces log size

Write Ahead Logging + Checkpoints

- If you have a checkpoint, you can guarantee that all things before that checkpoint have been flushed to disk
- Hence, no need to replay log after then
- Speeds up recovery
- Reduces log size
- Can always build one checkpoint off an old one

Write Ahead Logging + Checkpoints

- If you have a checkpoint, you can guarantee that all things before that checkpoint have been flushed to disk
- Hence, no need to replay log after then
- Speeds up recovery
- Reduces log size
- Can always build one checkpoint off an old one
- Why not always checkpoint?

Recovery in 2PC

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 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

Crash + Reboot Recovery

- Nodes can’t back out once commit is decided

Crash + Reboot Recovery

- Nodes can't back out once commit is decided
- If coordinator crashes just AFTER deciding "commit"
  - Must remember this decision, replay

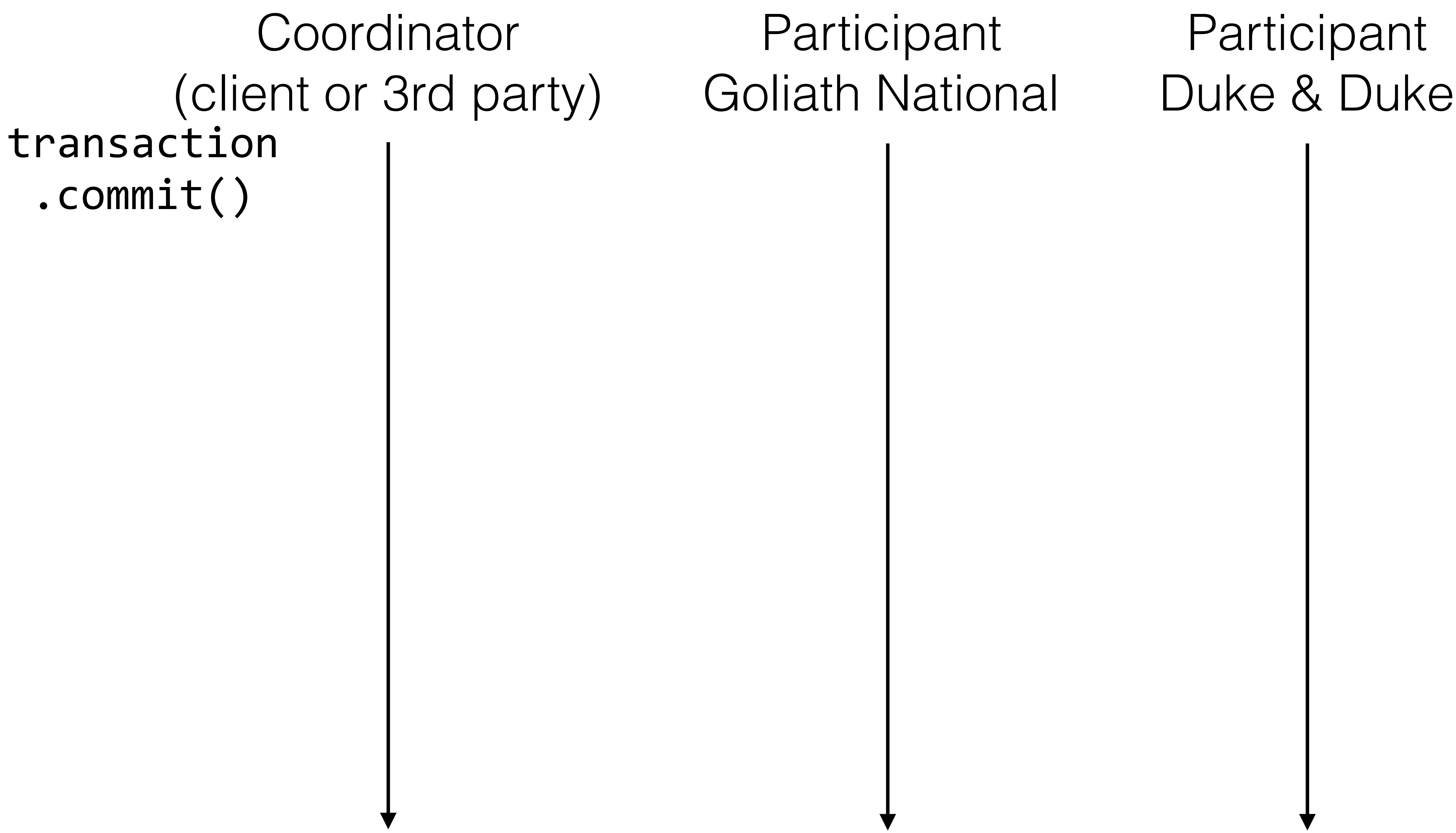
Crash + Reboot Recovery

- 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

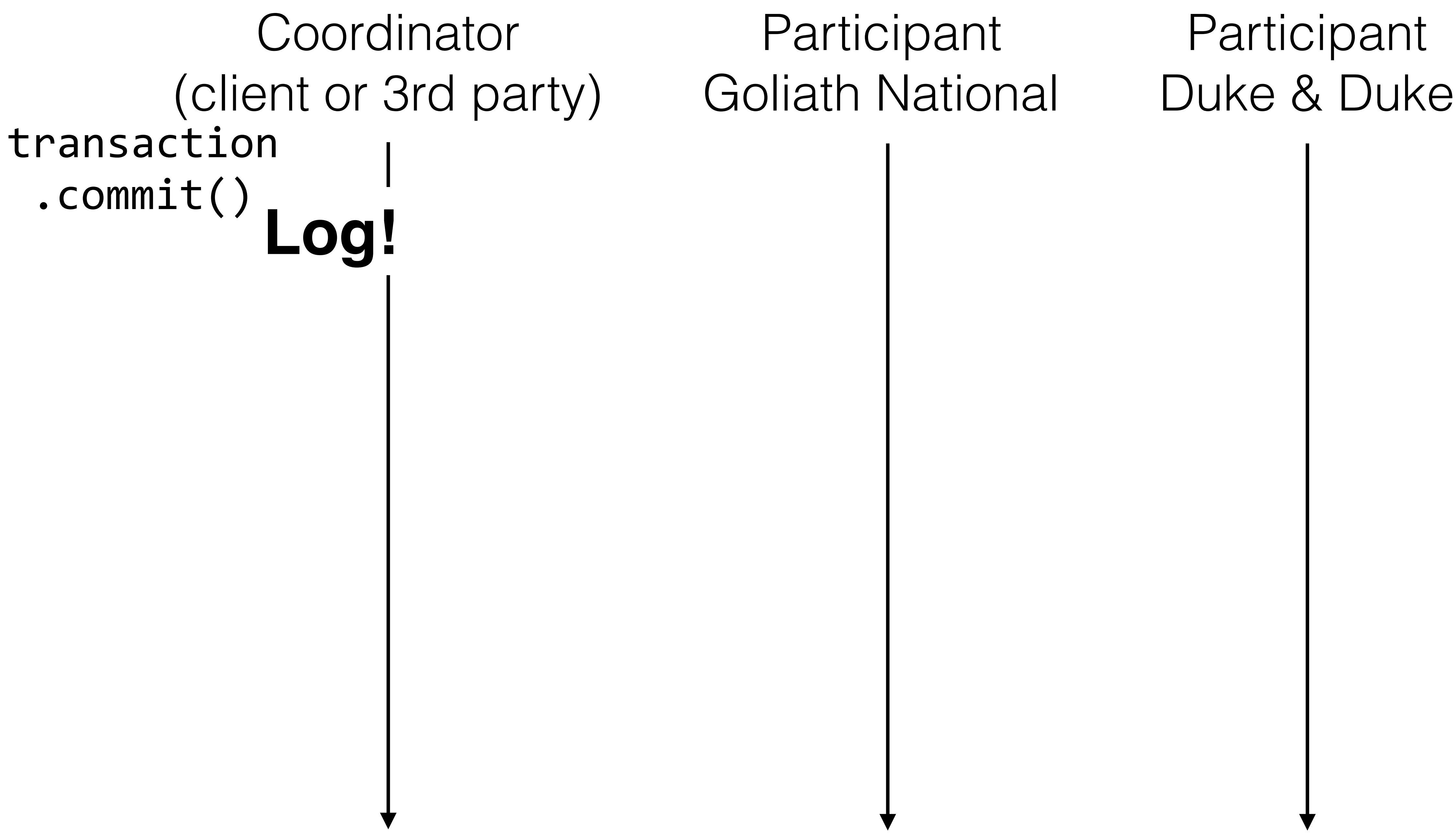
Crash + Reboot Recovery

- 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

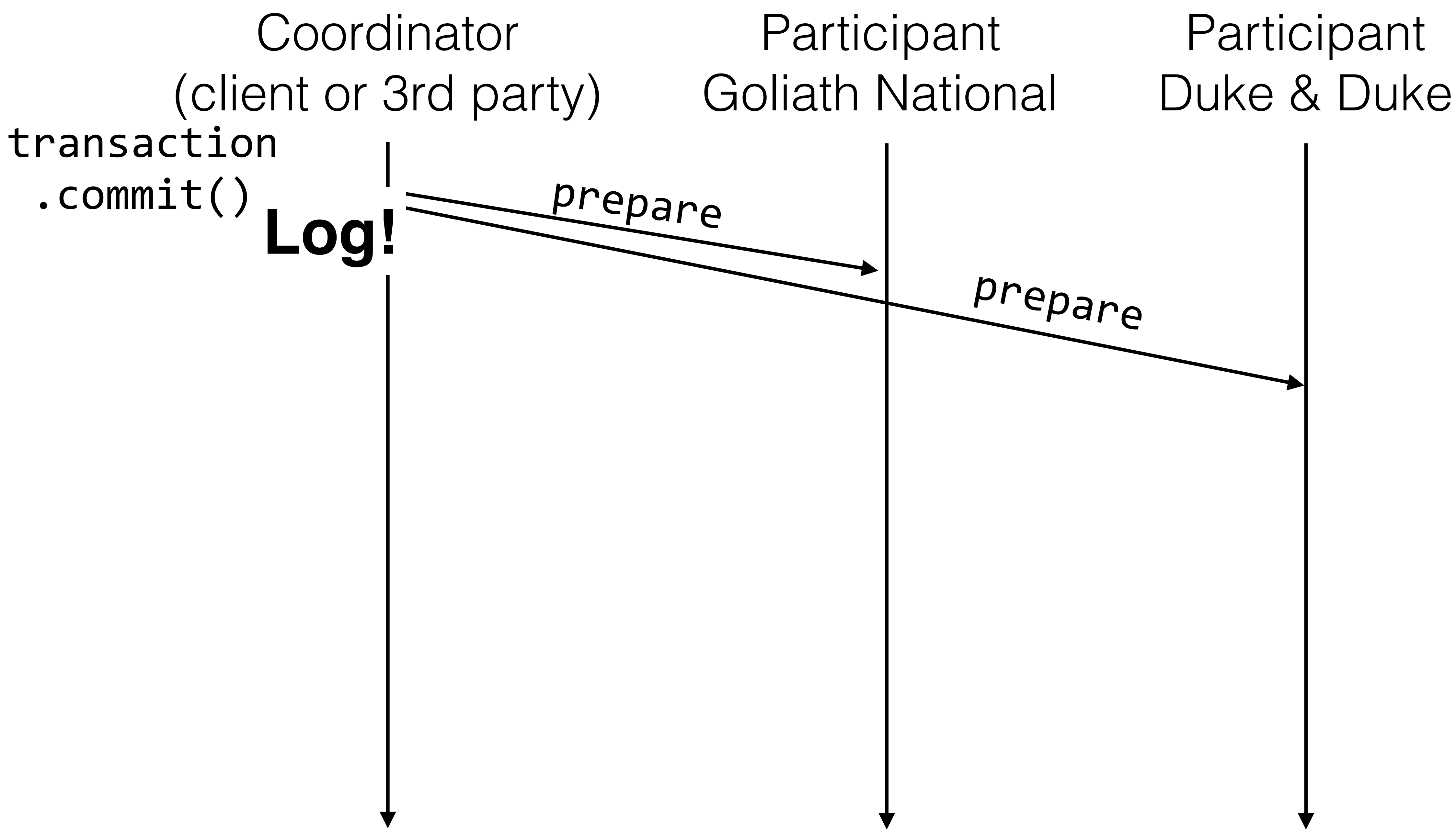
2PC Example with logging



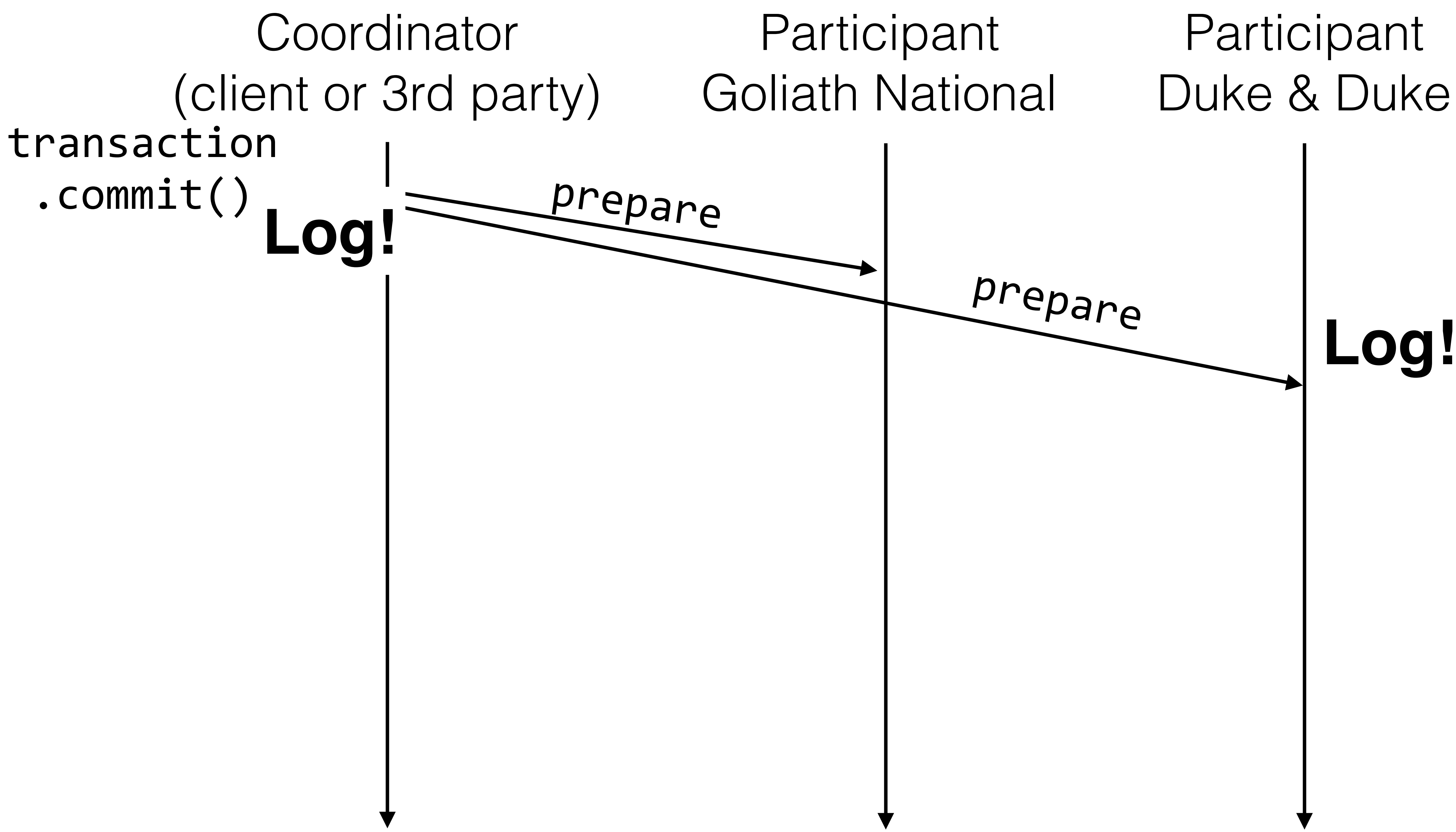
2PC Example with logging



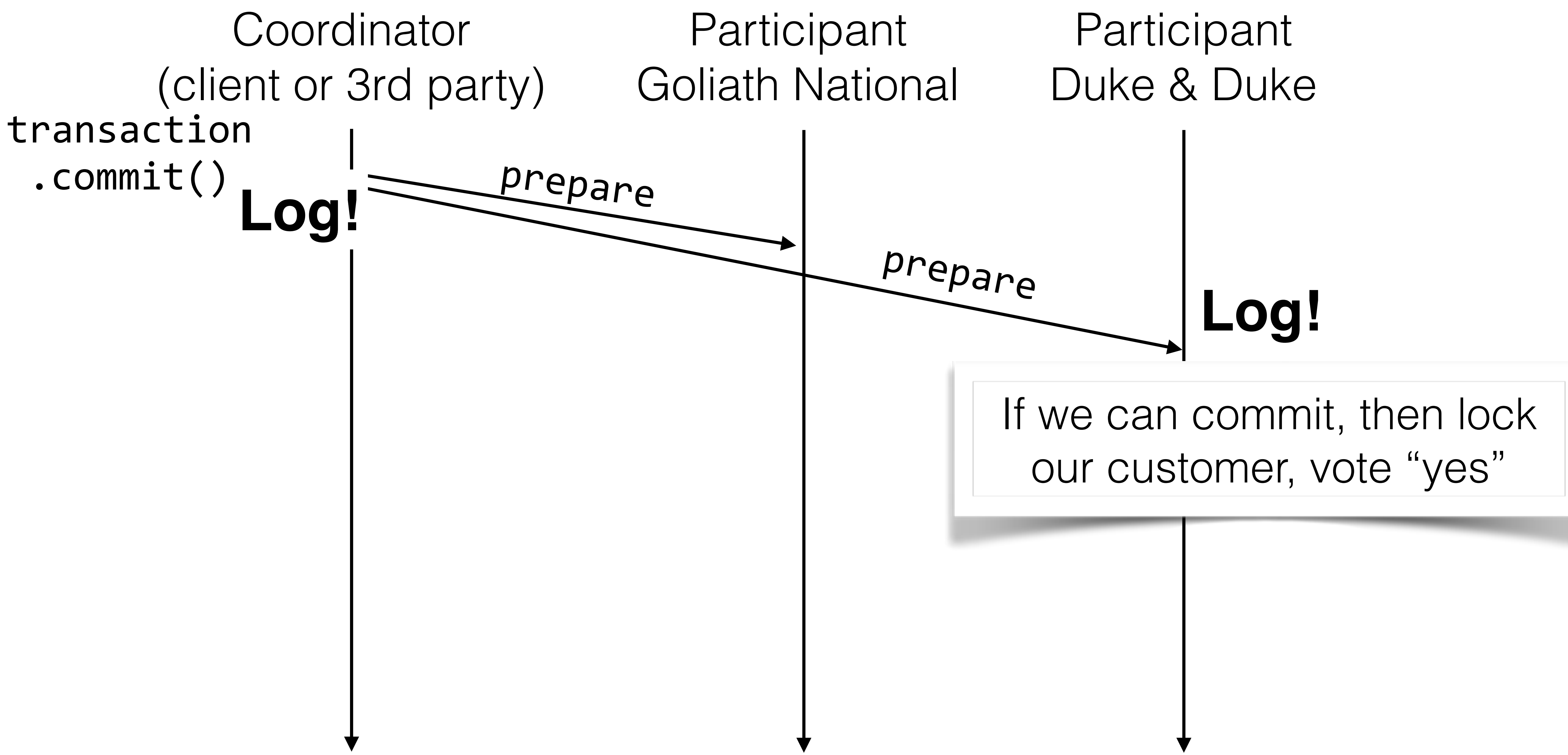
2PC Example with logging



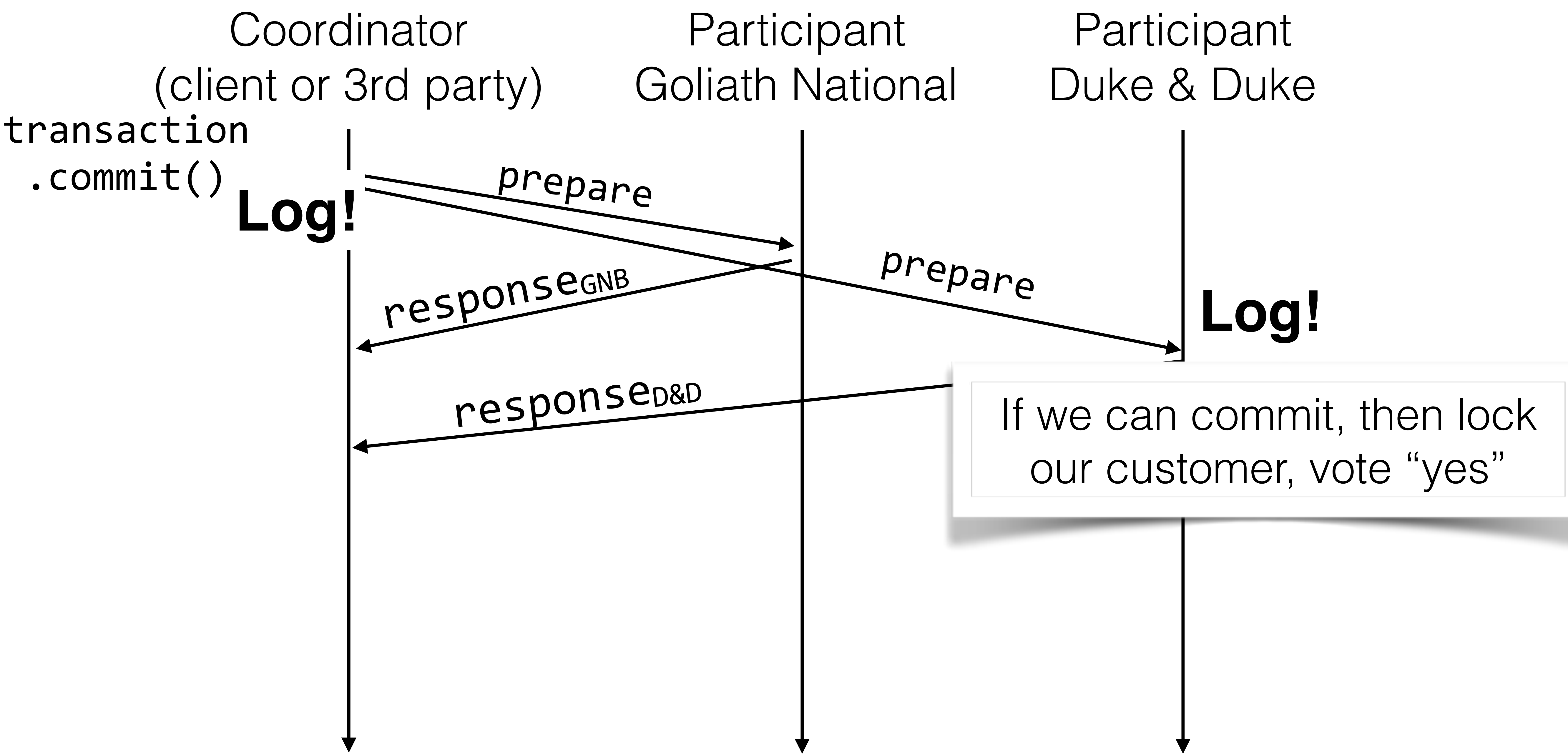
2PC Example with logging



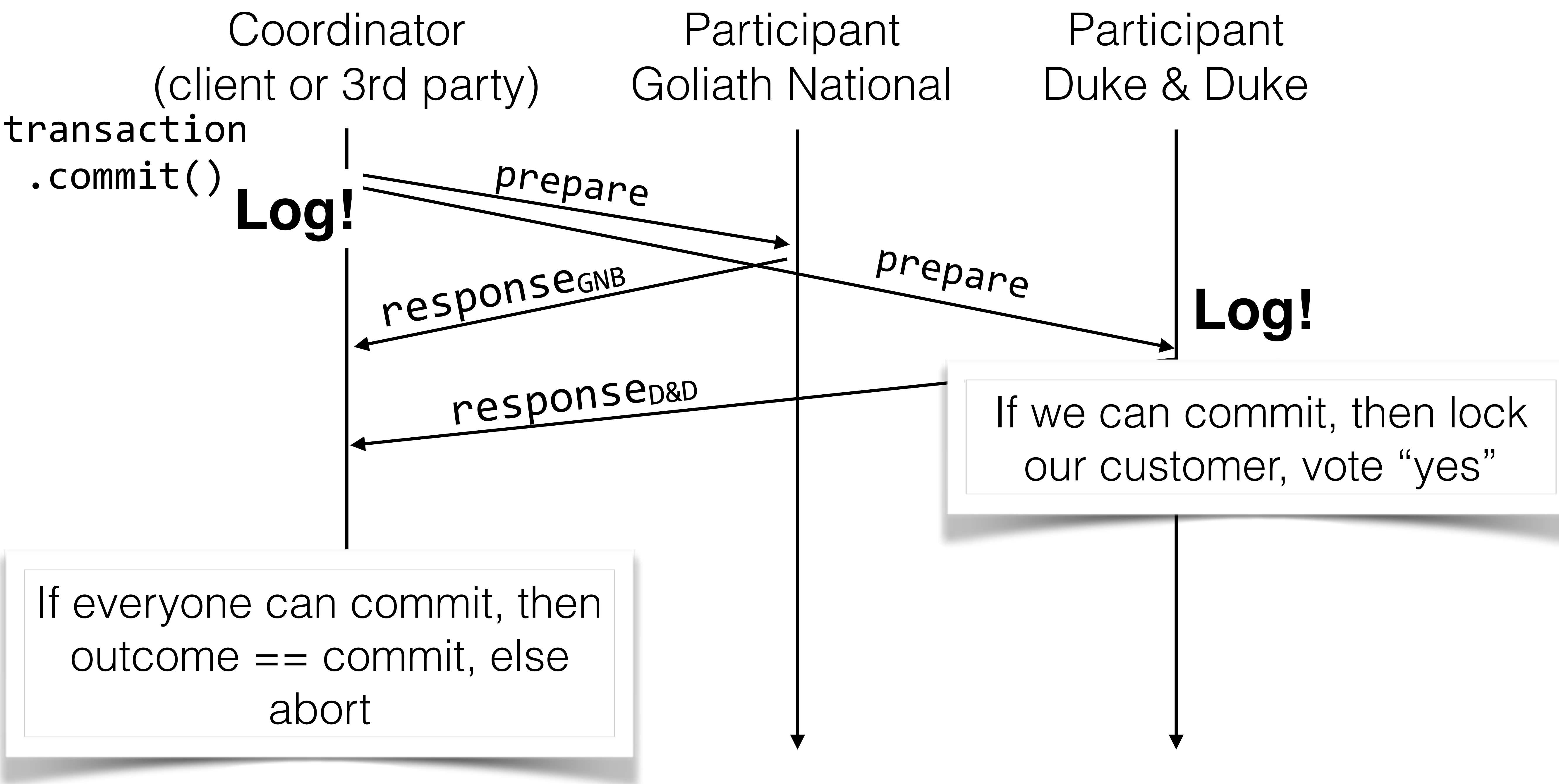
2PC Example with logging



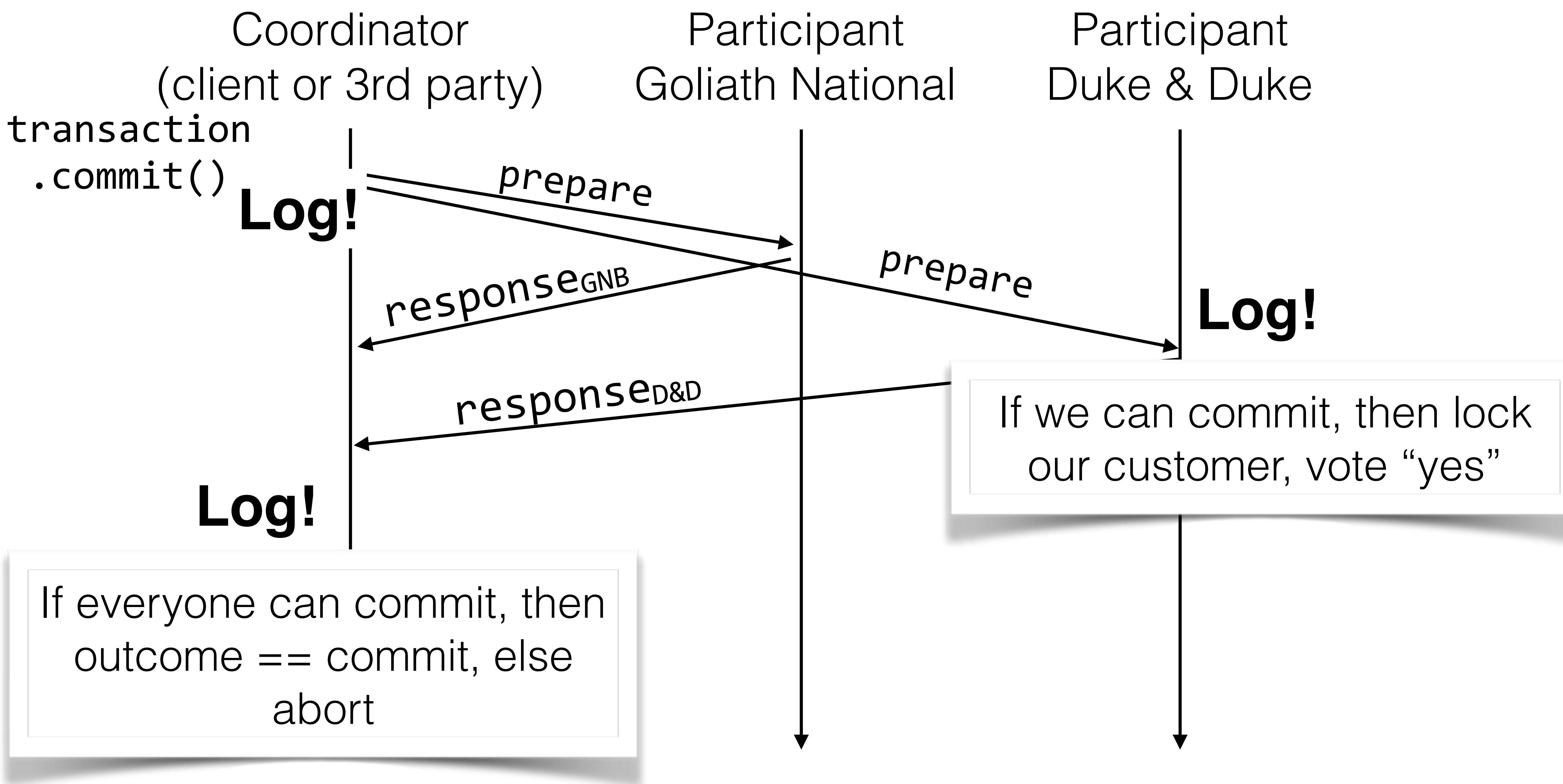
2PC Example with logging



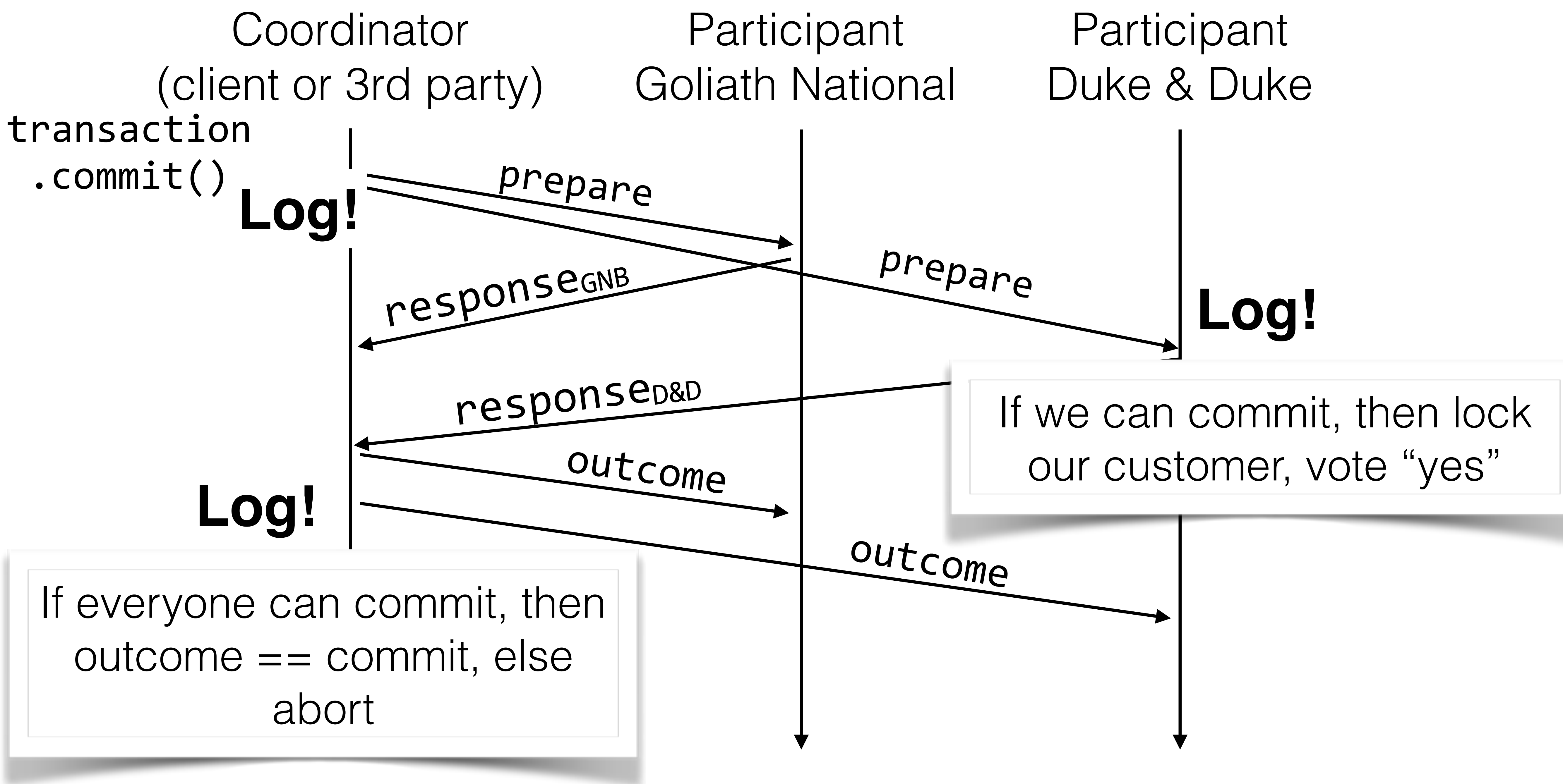
2PC Example with logging



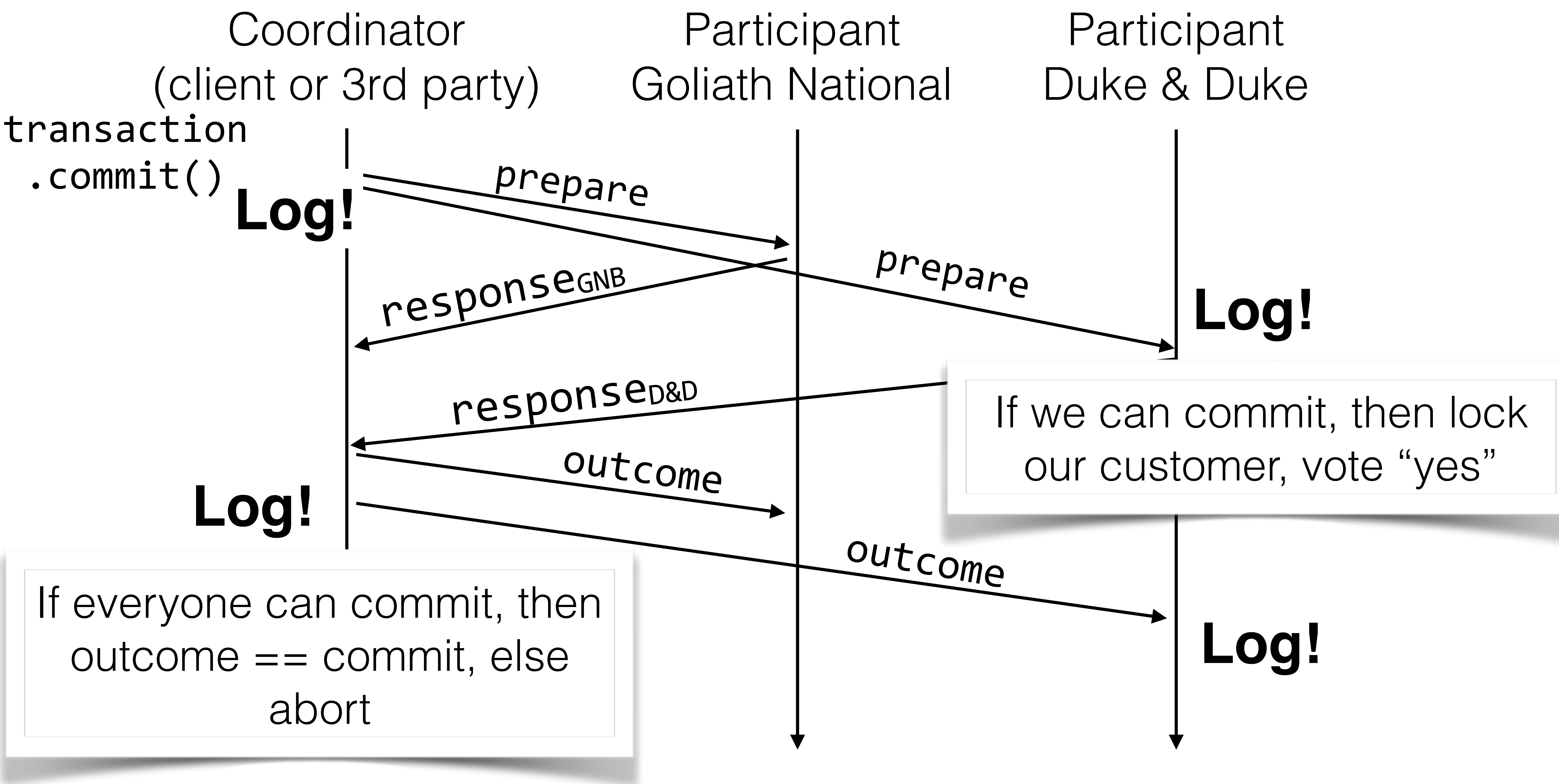
2PC Example with logging



2PC Example with logging



2PC Example with logging



Recovery on Reboot

Recovery on Reboot

- If coordinator finds no “commit” message on disk, abort

Recovery on Reboot

- If coordinator finds no “commit” message on disk, abort
- If coordinator finds “commit” message, commit

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

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

Timeouts in 2PC

- Example:
  - Coordinator times out waiting for Goliath National Bank's response
  - Bank times out waiting for coordinator's outcome message

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

Coordinator Timeouts

- If coordinator times out waiting to hear from a bank

Coordinator Timeouts

- If coordinator times out waiting to hear from a bank
  - Coordinator hasn't sent any commit messages yet

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

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!)

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

Handling Bank Timeouts

- What if the bank doesn't hear back from coordinator?

Handling Bank Timeouts

- What if the bank doesn't hear back from coordinator?
- If bank voted "no", it's OK to 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"

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)

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)

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

Handling Bank Timeouts

- Can resolve SOME timeout problems with guaranteed correctness in event bank voted “yes” to commit

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)

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

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

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

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

2PC Timeouts

- We can solve a lot (but not all of the cases) by having the participants talk to each other

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

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

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

Lab 5: Lock Server

- We're going to build, together, a lock server like from HW2
- Address book example
  - Lock server allows read/write locks on entire list
  - Lock server will allow an entry to be locked by exactly one client at a time
  - Clients will track which locks they have

Lab 5: Lock Server Semantics

- List contents of address book: read lock on list
- Add new entry: write lock on list
- Update entry: write lock on the entry