# Consistency in Distributed Systems

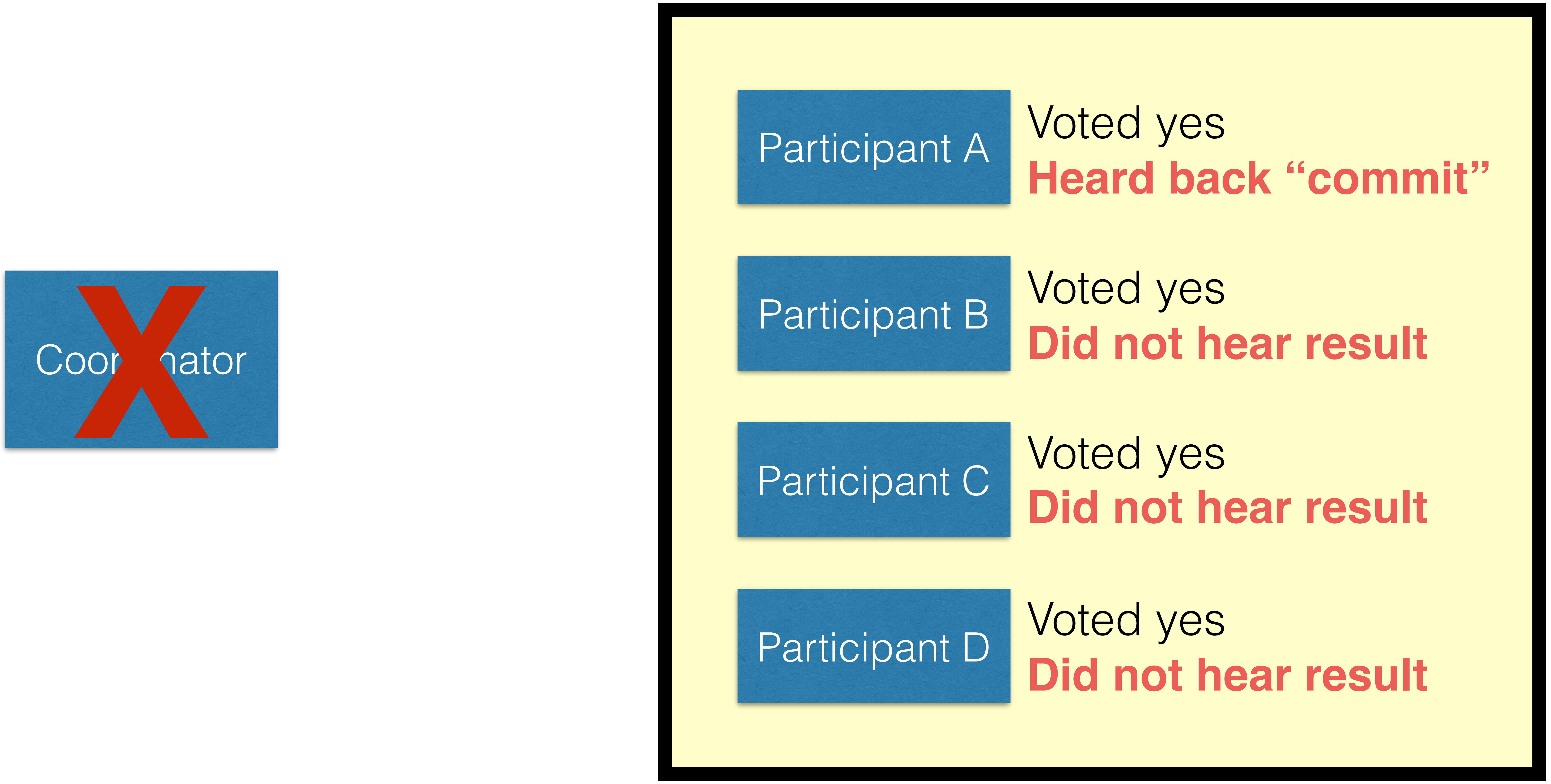
CS 475, Spring 2019
Concurrent & Distributed Systems

GEORGE MASON UNIVERSITY

# Review: Transactions
# 2PC, 3PC

# Digging Deeper into 2PC Failures

**If they can talk to each other, we know we can commit (good)**



# Digging Deeper into 2PC Failures

**If they can talk to each other, we know that we can all abort (good)**

~~Coordinator~~

Participant A
Voted no
**Did not hear result**

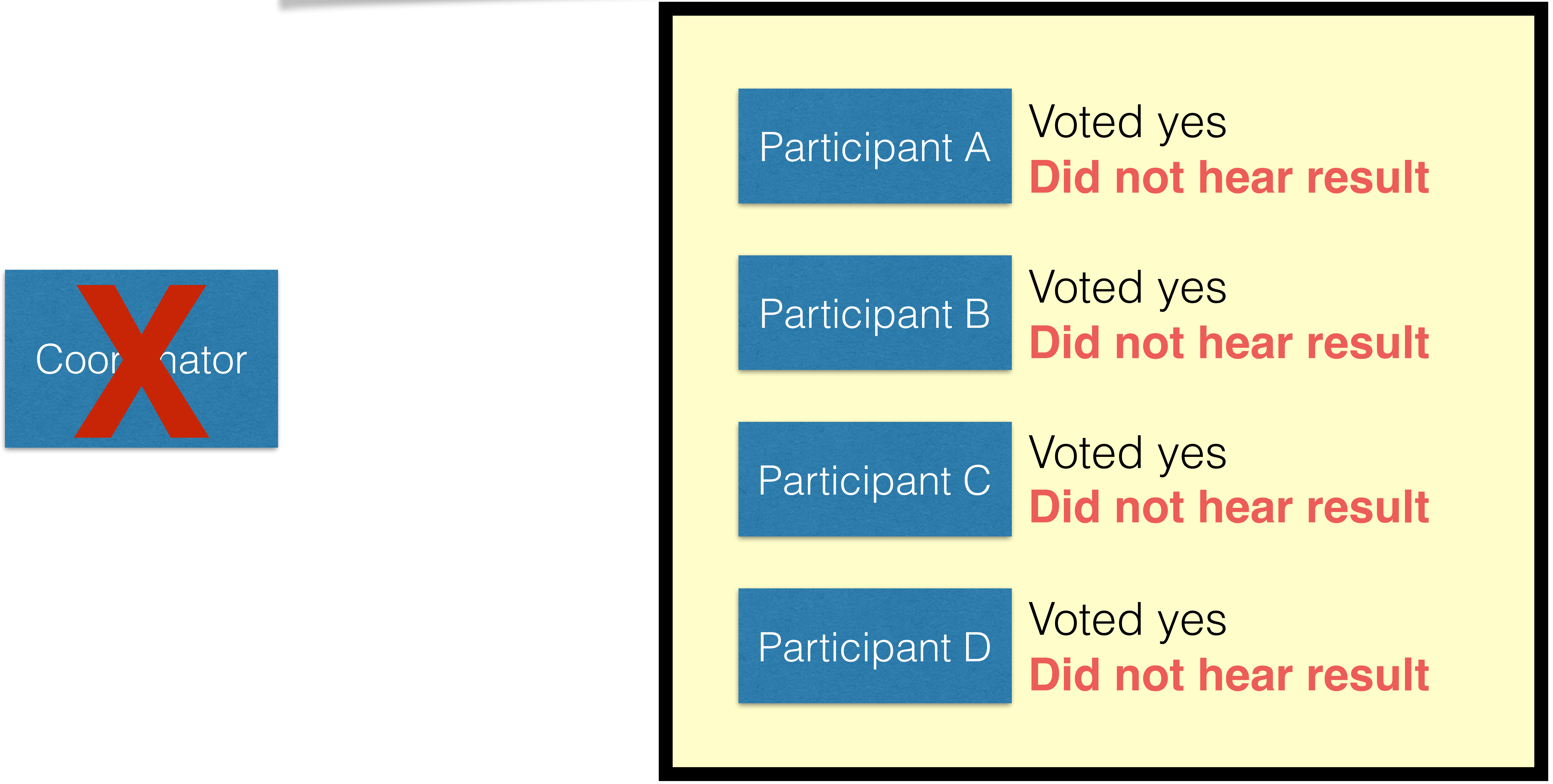
Participant B
Voted yes
**Did not hear result**

Participant C
Voted yes
**Did not hear result**

Participant D
Voted yes
**Did not hear result**

# Digging Deeper into 2PC Failures

**If they can talk to each other, we do not know if we can commit/abort (who knows what the coordinator will do?)**

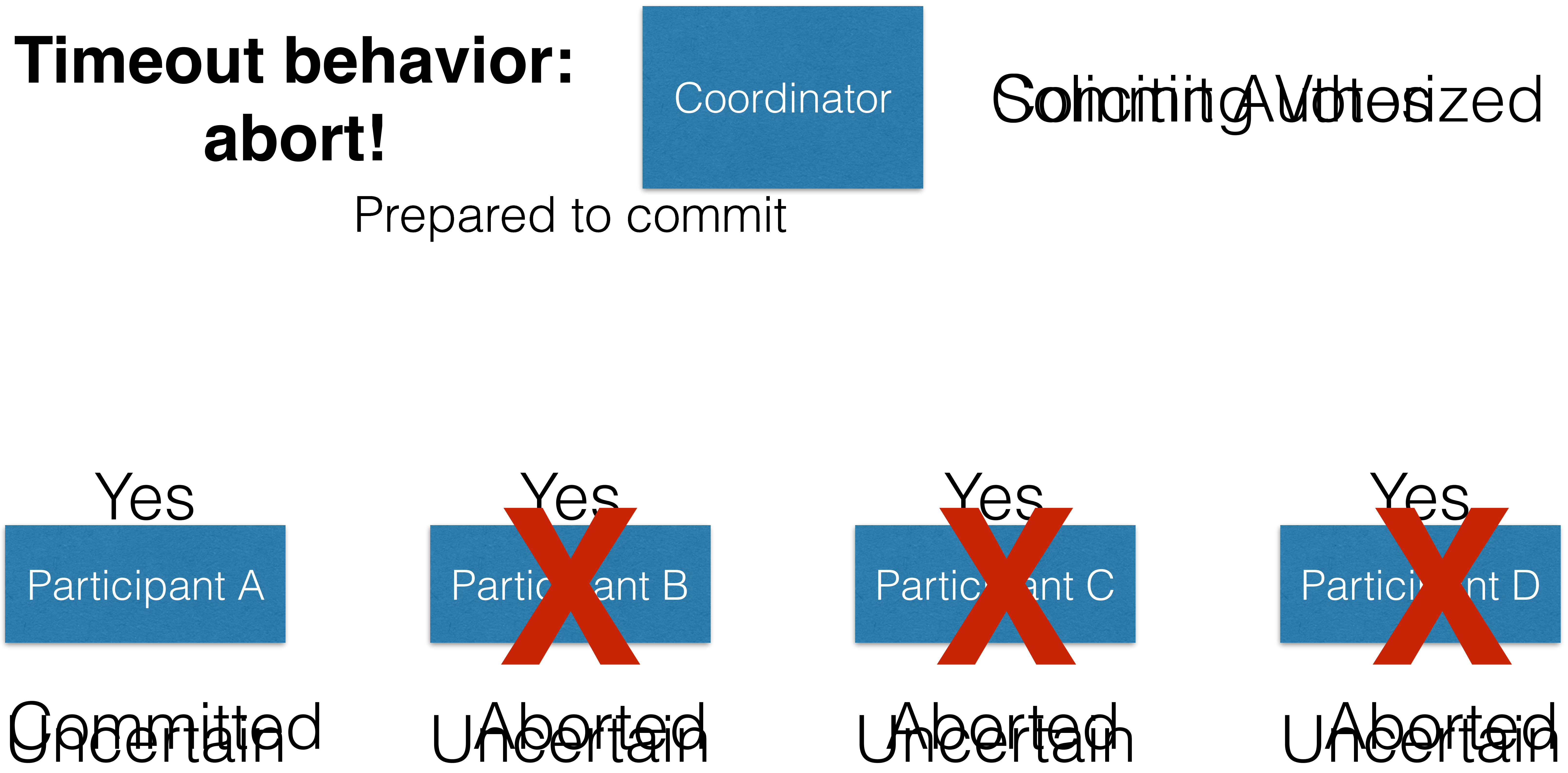


# 3 Phase Commit

- Goal: Avoid blocking on node failure
- How?
  - Think about how 2PC is better than 1PC
    - 1PC means you can never change your mind or have a failure after committing
    - 2PC **still** means that you can't have a failure after committing (committing is irreversible)

# Safety in Crashes

**Timeout behavior: abort!**




**Crashed: do not commit or abort. When recovers, asks coordinator what to do**

# Partitions

**Implication: if networks can delay arbitrarily, 3PC does not guarantee safety!!!!**

**Timeout behavior: abort**

Coordinator

Soliciting Votes
Commit Authorized

Prepared to commit

**Network Partition!!!**

Yes Yes Yes Yes

Participant A | Participant B | Participant C | Participant D

Uncertain / Committed | Uncertain / Aborted | Uncertain / Aborted | Uncertain / Aborted

**Timeout behavior: Commit!**

**Timeout behavior: abort**

# FLP - Intuition

- Why can’t we make a protocol for consensus/agreement that can tolerate both partitions and node failures?
- To tolerate a partition, you need to assume that **eventually** the partition will heal, and the network will deliver the delayed packages
- But the messages might be delayed **forever**
- Hence, your protocol would not come to a result, until **forever** (it would not have the **liveness** property)

# Partitions

Insight: There is a “majority” partition here (B,C,D)
The “minority” know that they are not in the majority (A can only talk to Coordinator, knows B, C, D might exist)

Coordinator

Soliciting Votes / Commit Authorized

Prepared to commit

**Network Partition!!!**

| Participant A | Participant B | Participant C | Participant D |
| --- | --- | --- | --- |
| Yes | Yes | Yes | Yes |
| Uncertain / Committed | Uncertain / Aborted | Uncertain / Aborted | Uncertain / Aborted |

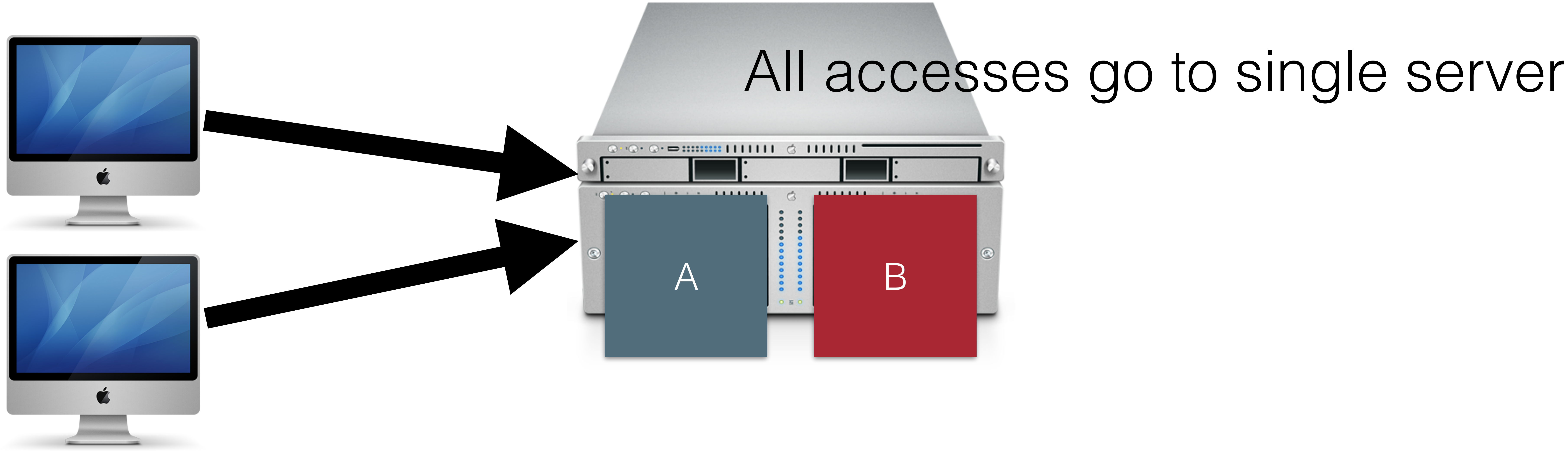
**Timeout behavior: Commit!**

**Timeout behavior: abort**

# Today

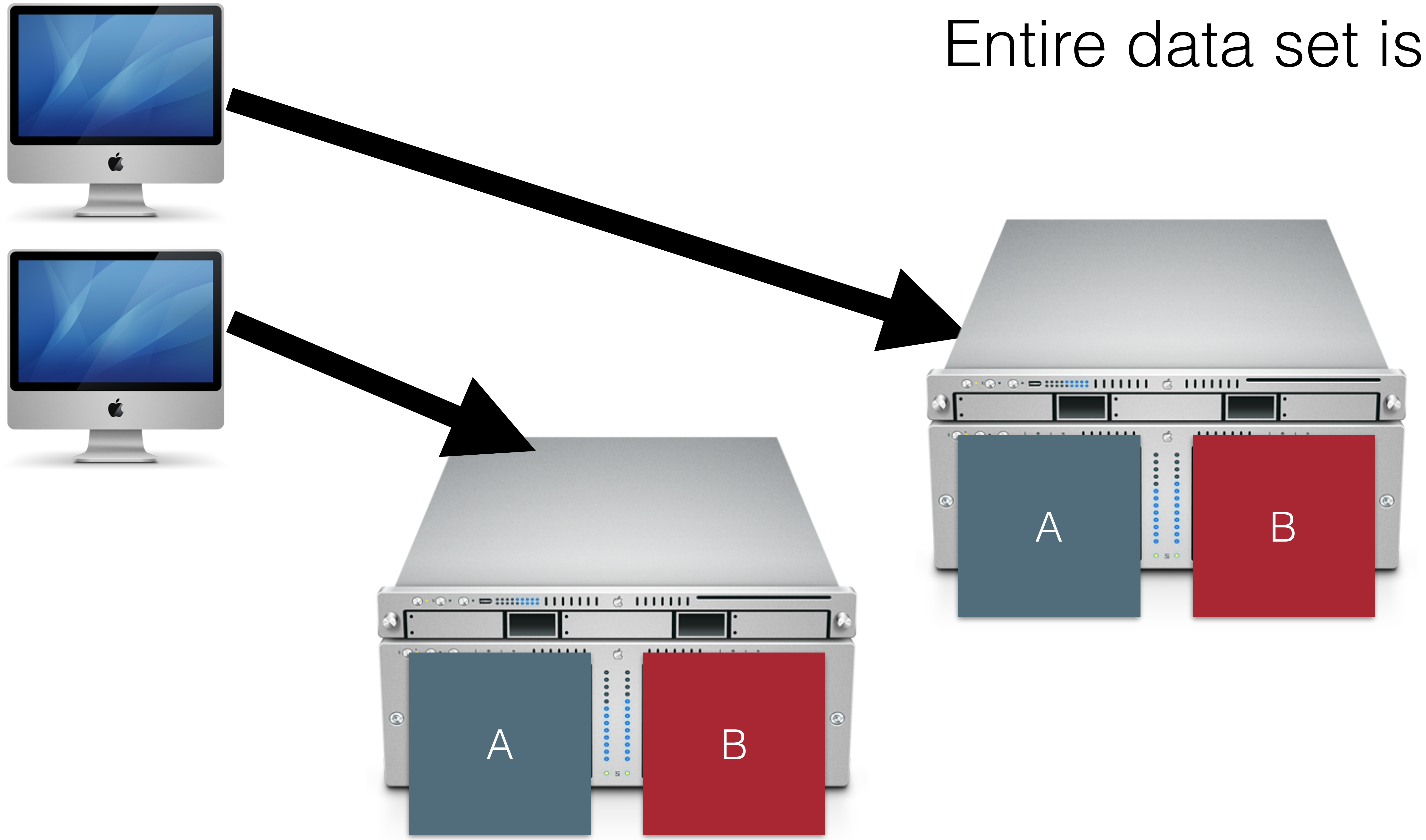
- Consistency in distributed systems
- Ivy - a consistent replicated datastore
- Reminders:
  - HW3 graded by end of week
  - HW4 is out!

# Recurring Solution in Distributed Systems: Replication



# Recurring Solution in Distributed Systems: Replication

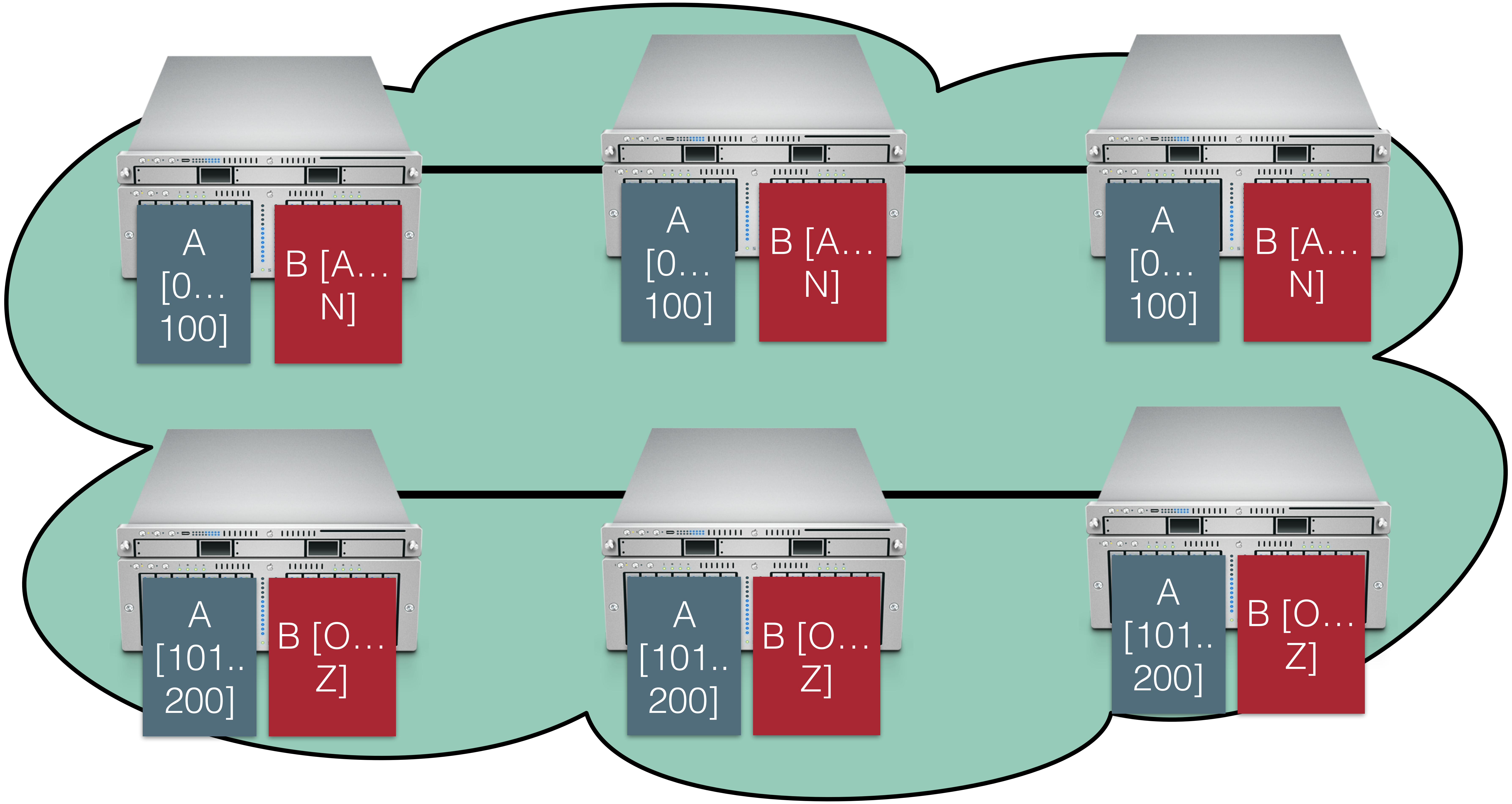
Entire data set is copied



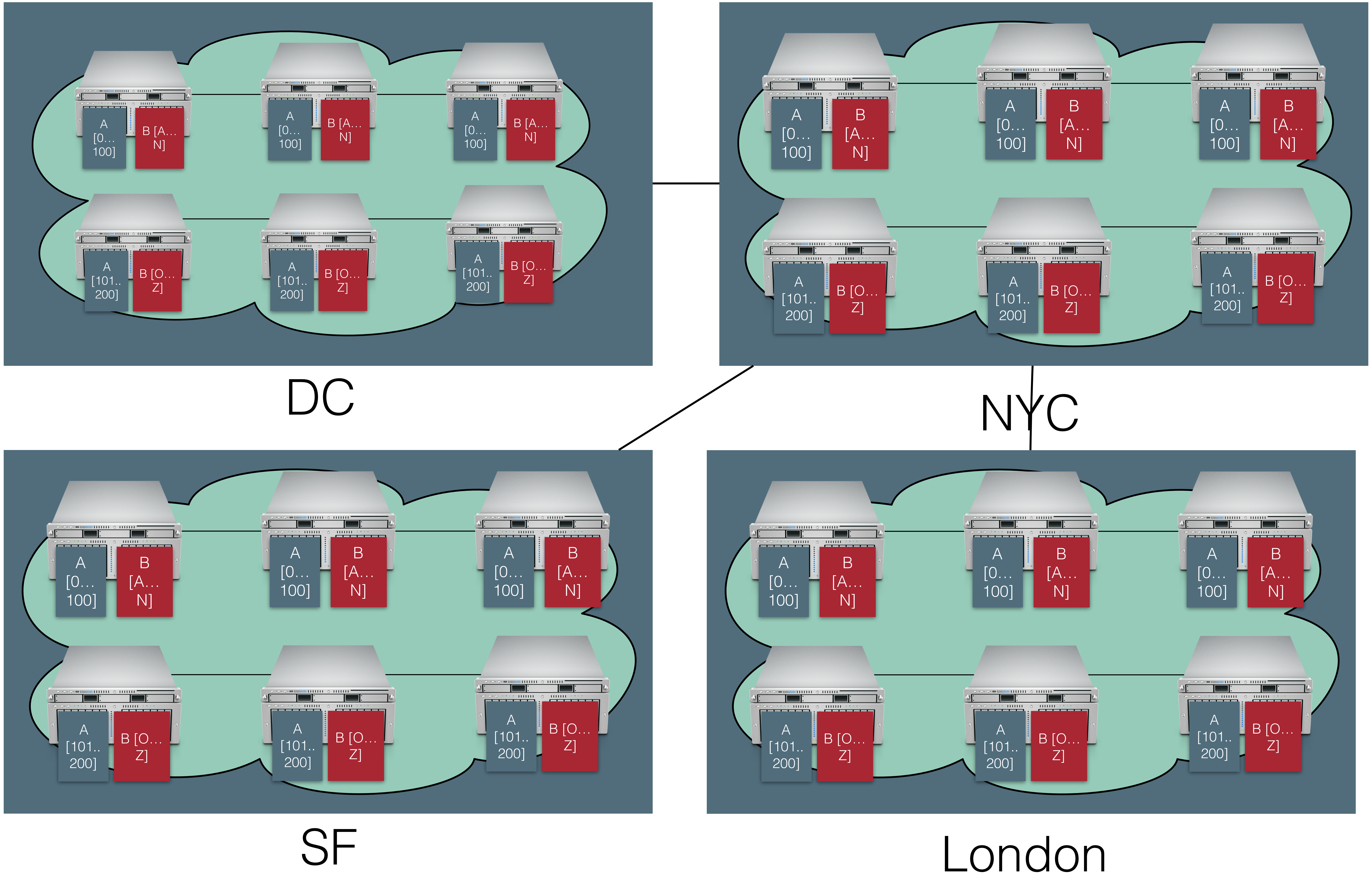
# Recurring Solution in Distributed Systems: Replication

- Improves performance:
  - Client load can be evenly shared between servers
  - Reduces latency: can place copies of data nearer to clients
- Improves availability:
  - One replica fails, still can serve all requests from other replicas

# Partitioning + Replication

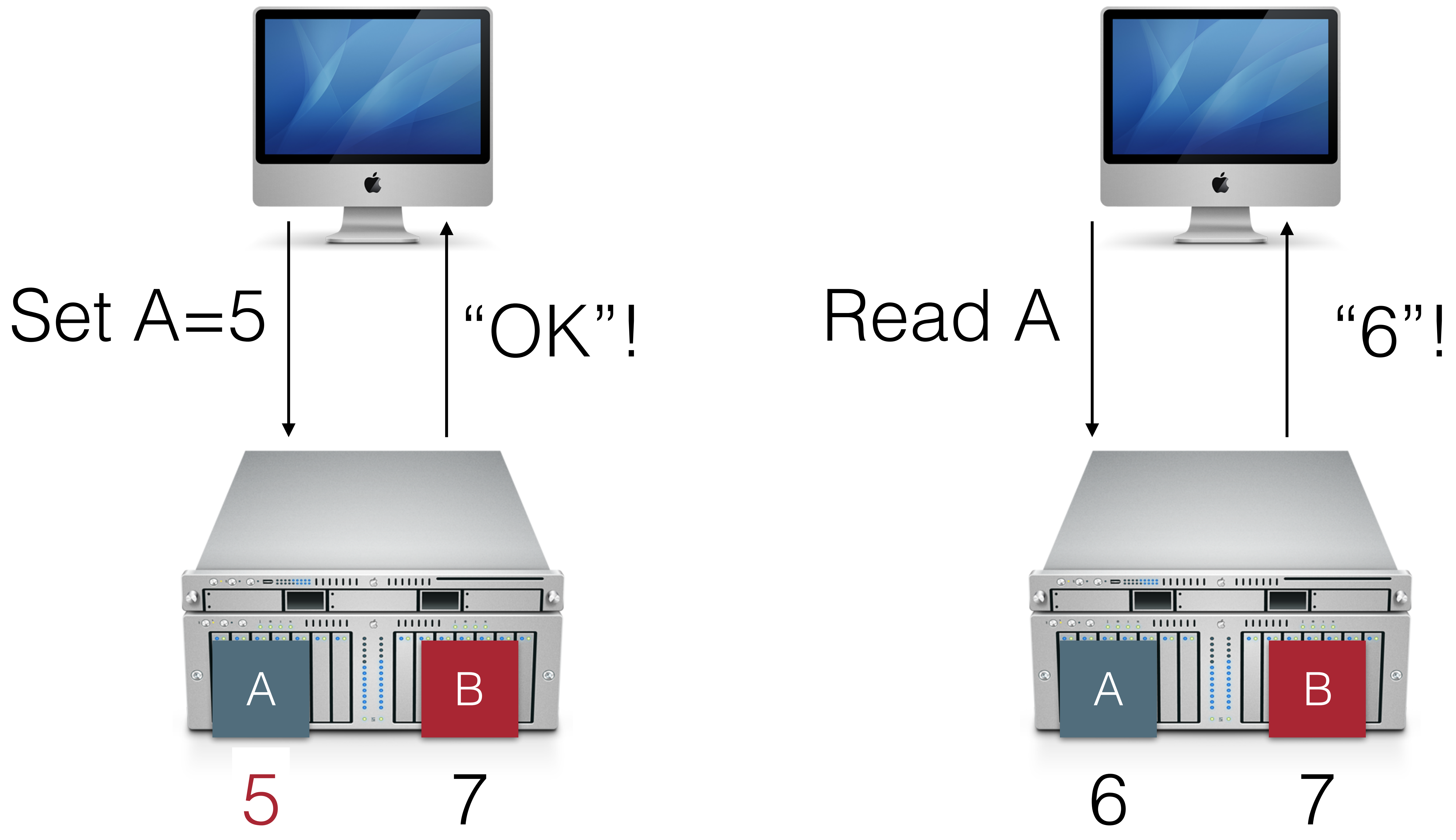


# Partitioning + Replication



# Recurring Problem: Replication

- Replication solves some problems, but creates a huge new one: consistency

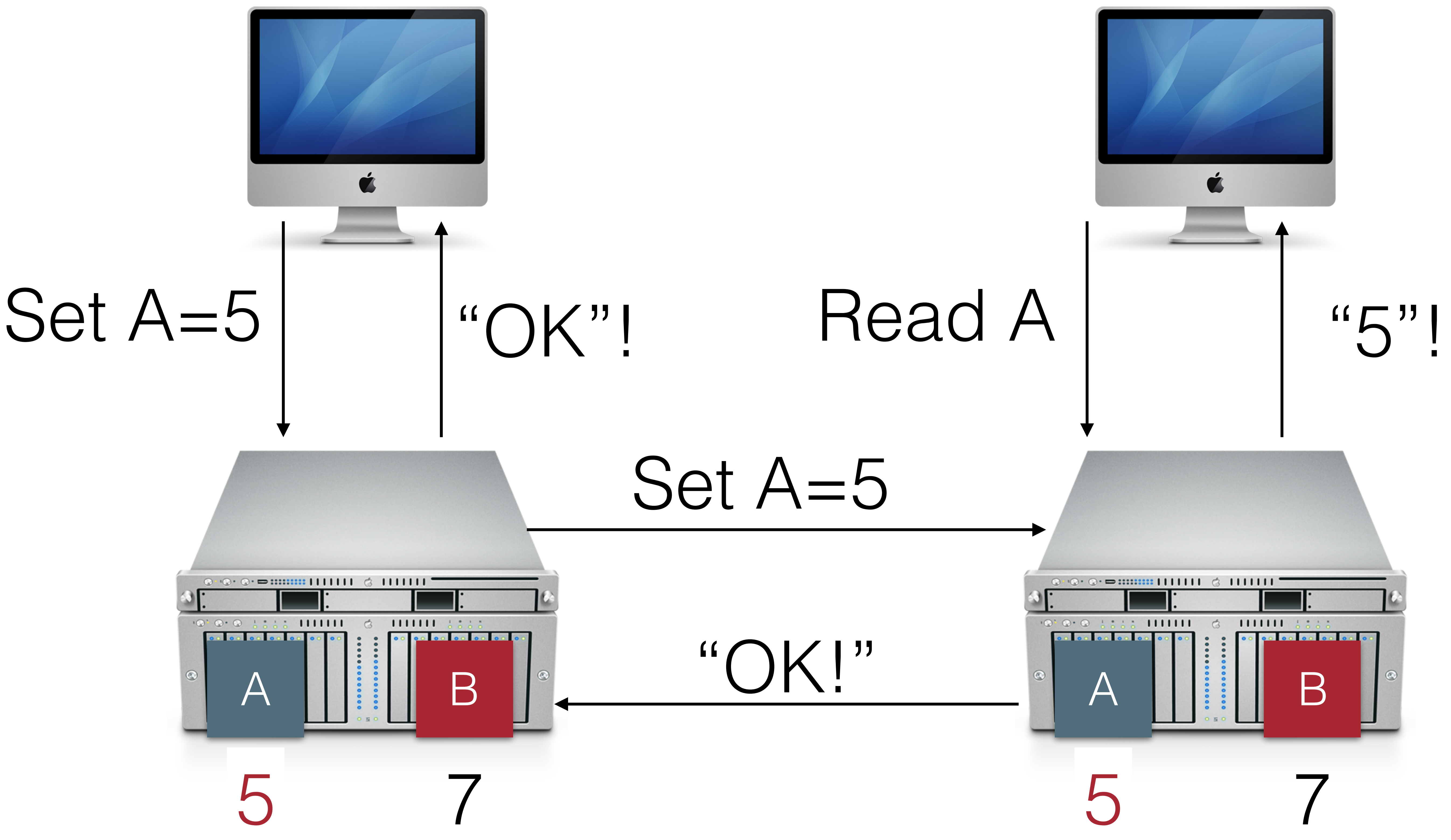



OK, we obviously need to actually do something here to replicate the data… but what?

# Consistency

- The problem of consistency arrises whenever some data is replicated
- That data exists in (at least) two places at the same time
- What is a "valid" state?

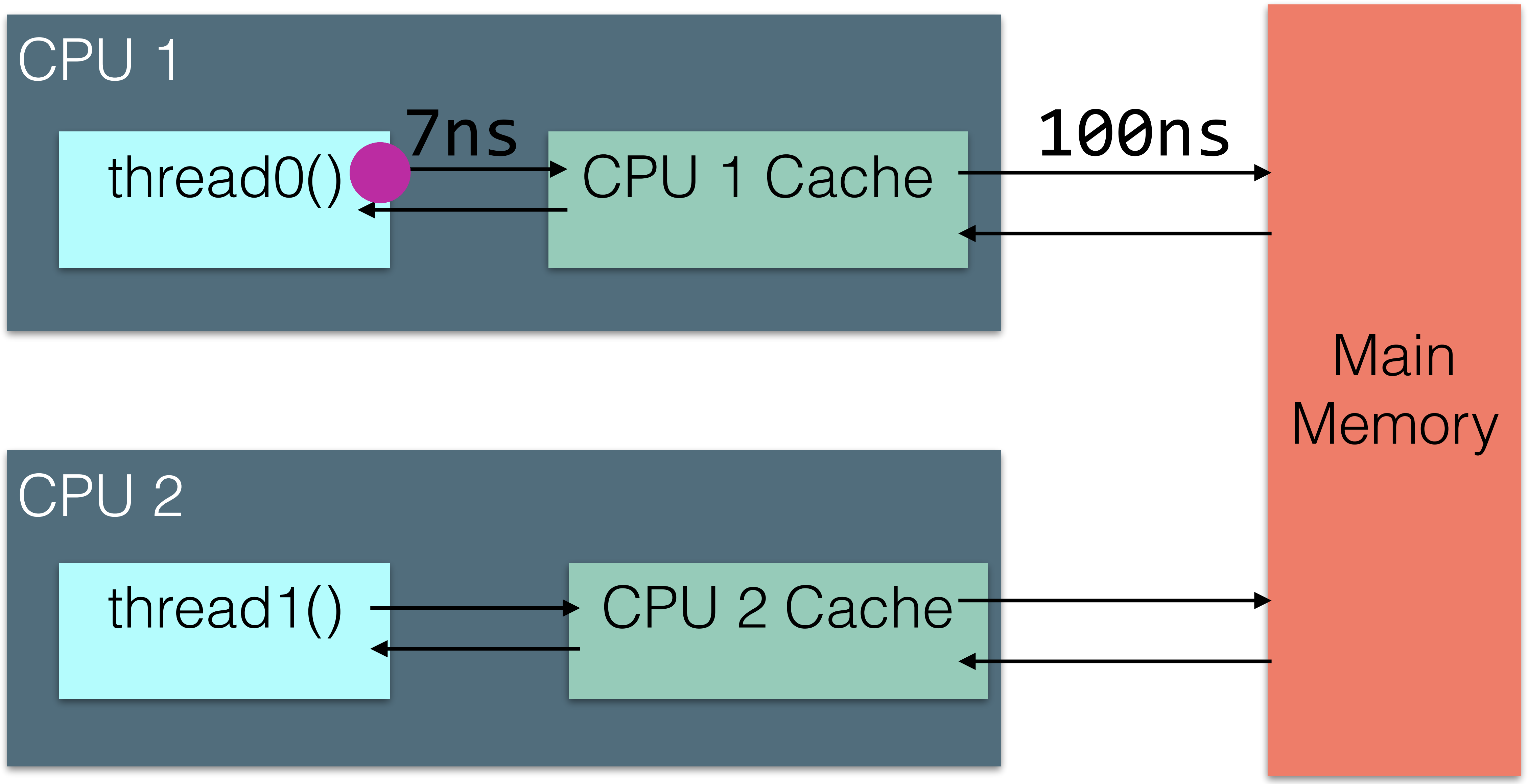
# Consistency



# Consistency

- Why do we think the prior slide was consistent?
  - Whenever we read, we see the most recent writes
- Even programs running **on a single computer** have to obey some consistency model
  - We talked about: linearizability, sequential consistency
  - Remember that consistency comes at a price

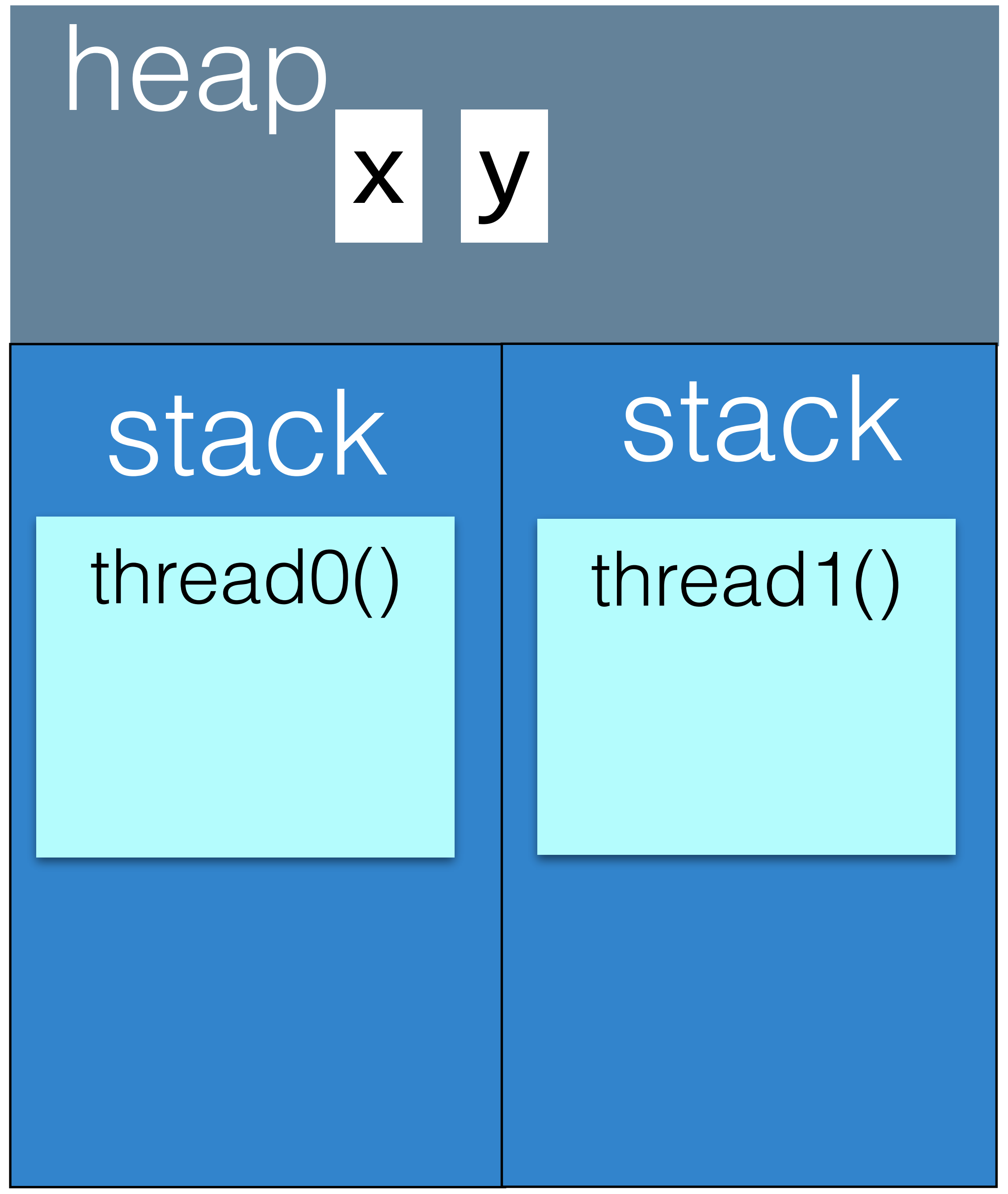
# Java Memory Model



# Quiz: What’s the output?

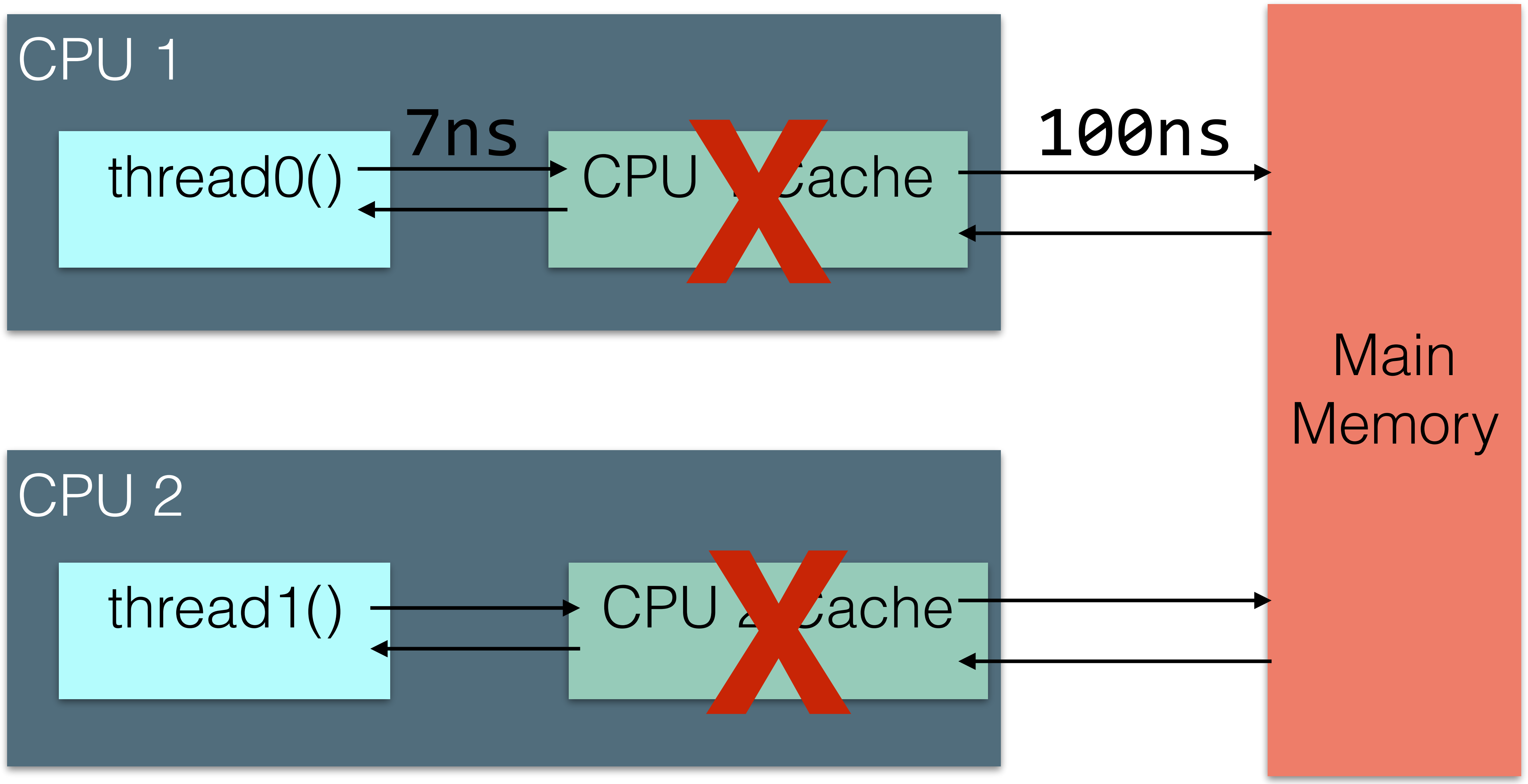
```
class MyObj {
 volatile int x = 0;
 volatile int y = 0;

 void thread0()
 {
  x = 1;
  if(y==0)
       System.out.println(“OK");
 }
 void thread1()
 {
  y = 1;
  if(x==0)
       System.out.println(“OK");
 }
}
```




`Volatile` keyword: no per-thread caching of variables

# Volatile Keyword



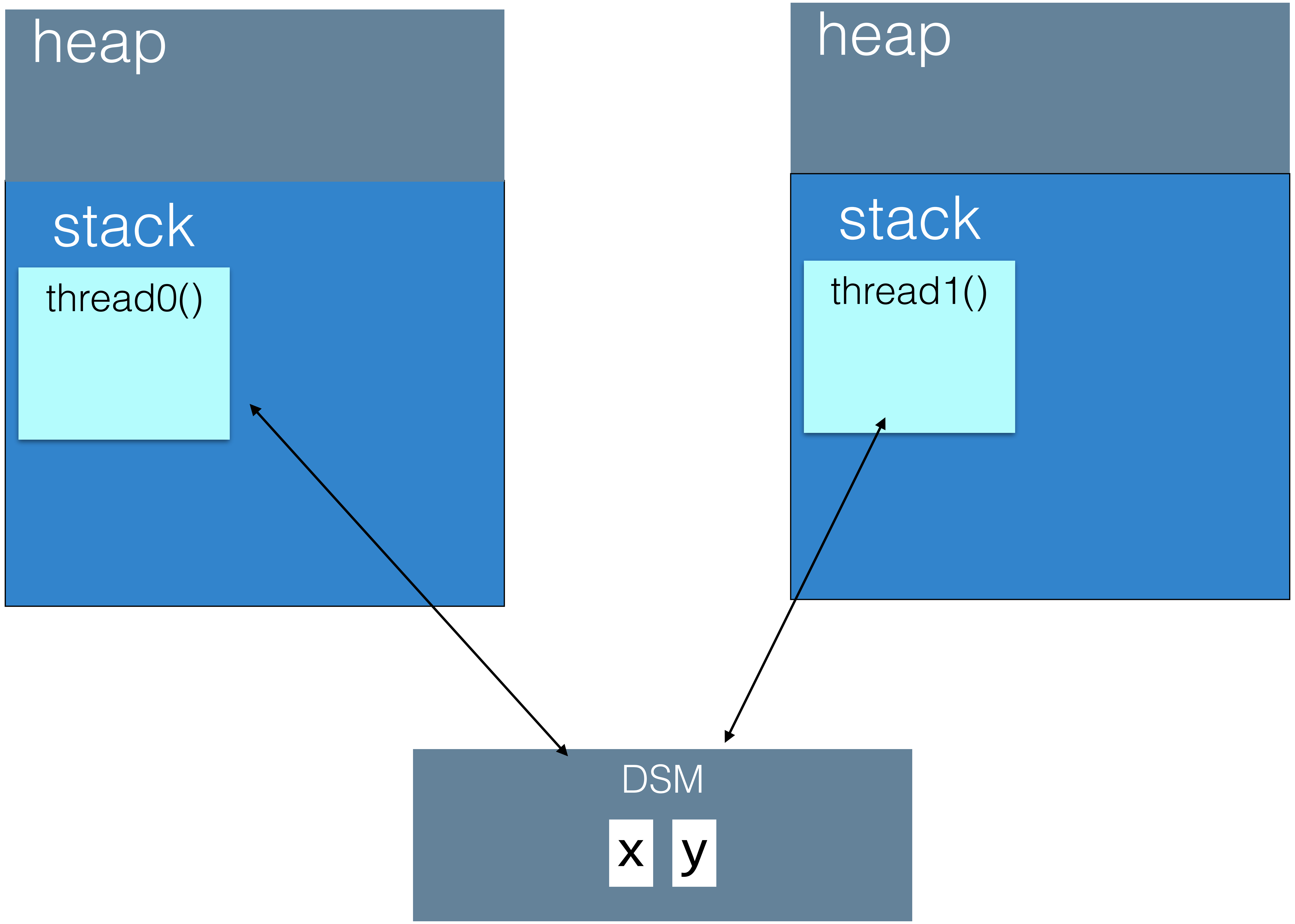
# Consistency

- This is a consistency model!
    - Constraints on the system state that are observable by applications
- "When I write y=1, any future reads must say y=1"
    - … except in Java, if it's a non-volatile variable
- Clearly, this often comes at a cost (see simple example with `volatile`…)

# Sequential Consistency

- Strict consistency is often not practical
  - Requires globally synchronizing clocks
- Sequential consistency gets close, in an easier way:
  - 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)

# Distributed Shared Memory



# Naïve DSM

- Assume each machine has a complete copy of memory
- Reads from local memory
- Writes broadcast update to other machines, then immediately continue

```
class Machine1 {
 DSMInt x = 0;
 DSMInt y = 0;

 static void main(String[] args)
 {
  x = 1;
  if(y==0)
      System.out.println("OK");
 }
}
```

```
class Machine2 {
 DSMInt x = 0;
 DSMInt y = 0;

 static void main(String[] args)
 {
  y = 1;
  if(x==0)
      System.out.println("OK");
 }
}
```

# Naïve DSM

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 DSMInt x = 1
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 static void main(String[] args)
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 }
}
```

```
class Machine2 {
 DSMInt x = 0;
 DSMInt y = 1

 static void main(String[] args)
 {
  y = 1;
  if(x==0)
      System.out.println("OK");
 }
}
```

# Naïve DSM

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```
class Machine1 {
 DSMInt x = 1
 DSMInt y = 0;

 static void main(String[] args)
 {
  x = 1;
  if(y==0)
       System.out.println("OK");
 }
}
```

**Is this correct?**

```
ne2 {
 = 0;
 DSMInt y = 1

 static void main(String[] args)
 {
  y = 1;
  if(x==0)
       System.out.println("OK");
 }
}
```

# Naïve DSM

- Gets even more funny when we add a third host
  - Many more interleaving possible
- Definitely not sequentially consistent
- Who is at fault?
  - The DSM system?
  - The app?
  - **The developers of the app, if they thought it would be sequentially consistent.**

# Sequentially Consistent DSM

- How do we get this system to behave similar to Java’s volatile keyword?
- We want to ensure:
  - Each machine’s own operations appear in order
  - All machines see results according to some total order (each read sees the most recent writes)
- We can say that some observed runtime ordering of operations can be “explained” by a sequential ordering of operations that follow the above rules

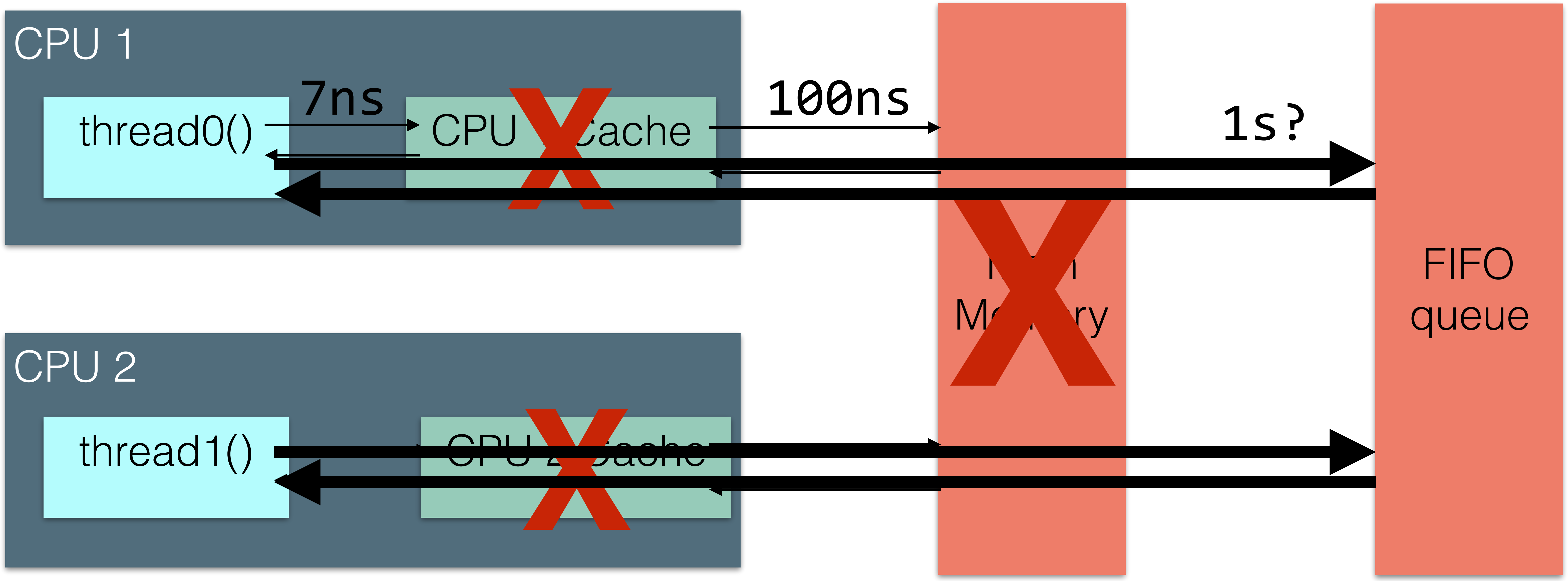
# Sequentially Consistent DSM

- Each node must see the most recent writes before it reads that same data
- Performance is not great:
  - Might make writes expensive: need to wait to broadcast and ensure other nodes heard your new value
  - Might make reads expensive: need to wait to make sure that there are no pending writes that you haven't heard about yet

# Sequentially Consistent DSM

- Each processor issues requests in the order specified by the program
  - Can’t issue the next request until previous is finished
- Requests to an individual memory location are served from a single FIFO queue
  - Writes occur in single order
  - Once a read observes the effect of a write, it’s ordered behind that write

# Sequentially Consistent DSM

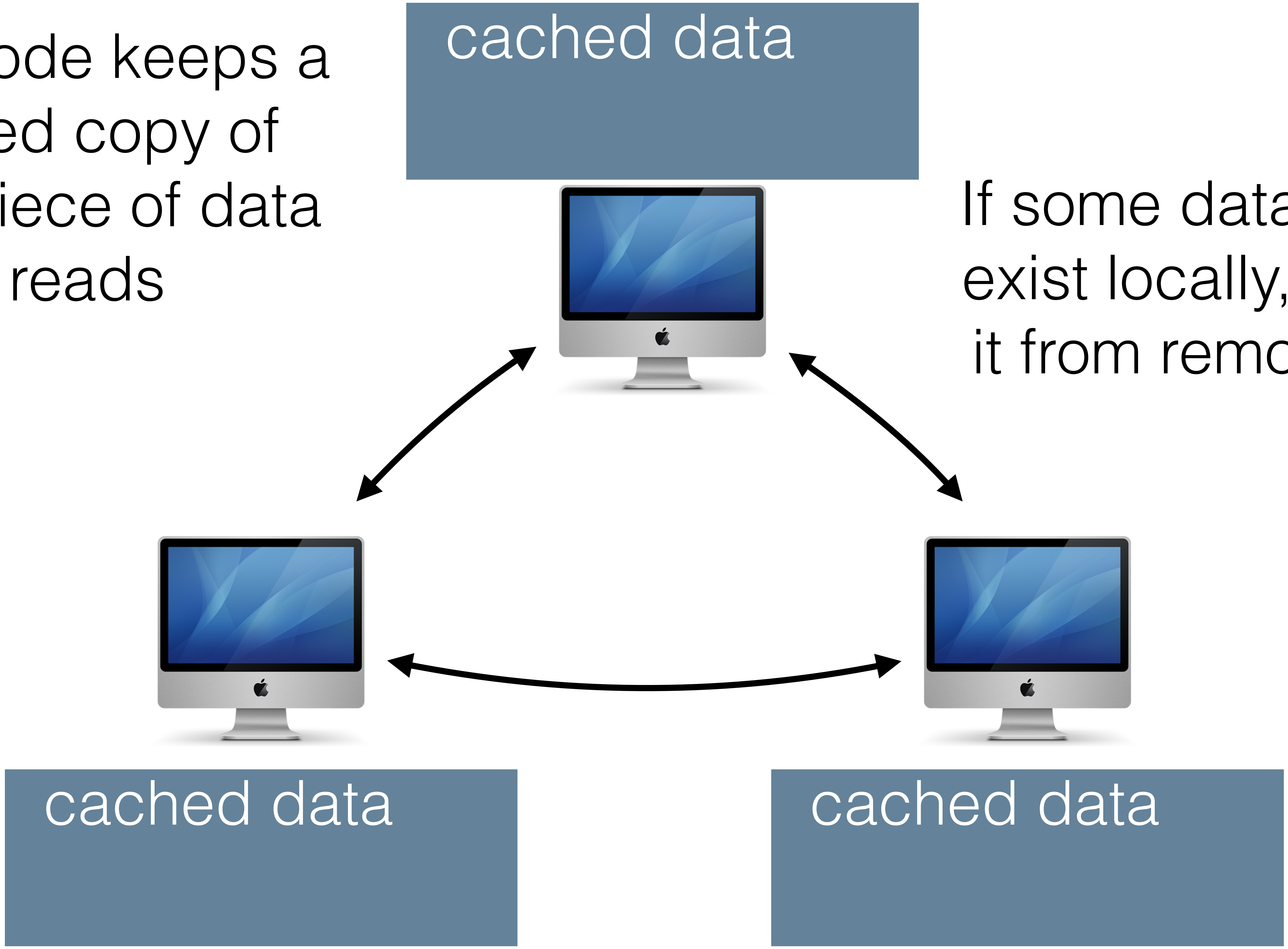


# Ivy DSM

- **I**ntegrated shared **V**irtual memory at **Y**ale
- Provides shared memory across a group of workstations
- Might be easier to program with shared memory than with message passing
  - Makes things look a lot more like one huge computer with hundreds of CPUs instead of hundreds of computers with one CPU

# Ivy Architecture

Each node keeps a cached copy of each piece of data it reads




If some data doesn't exist locally, request it from remote node

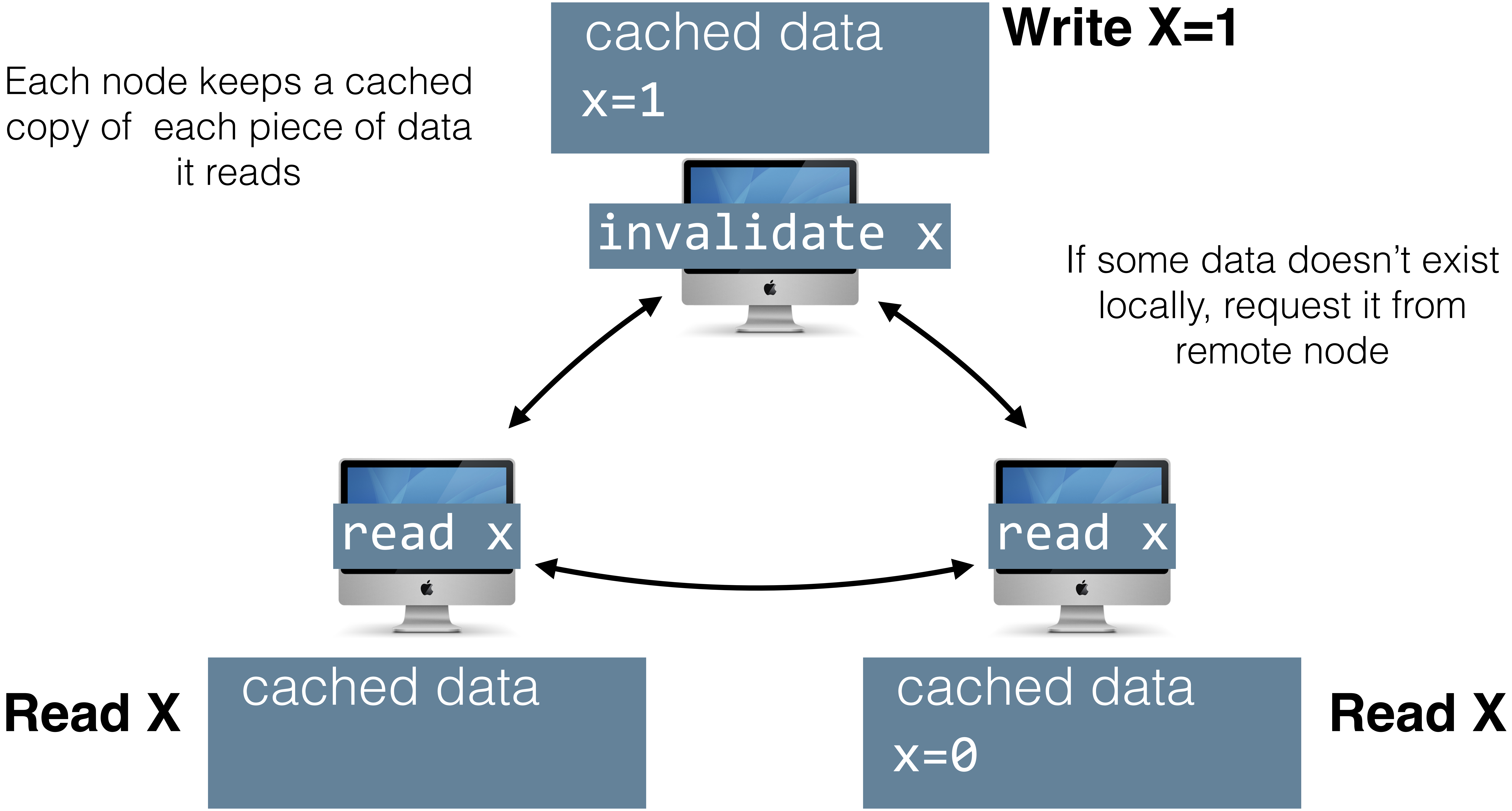
# Ivy provides sequential consistency

- Support multiple readers, single writer semantics
- Write invalidate update protocol
- If I write some data, I must tell everyone who has cached it to get rid of their cache

# Ivy Architecture

Each node keeps a cached copy of each piece of data it reads

If some data doesn't exist locally, request it from remote node



# Ivy Implementation

- Ownership of data moves to be whoever last wrote it
- There are still some tricky bits:
  - How do we know who owns some data?
  - How do we ensure only one owner per data?
  - How do we ensure all cached data are invalidated on writes?
- Solution: Central manager node

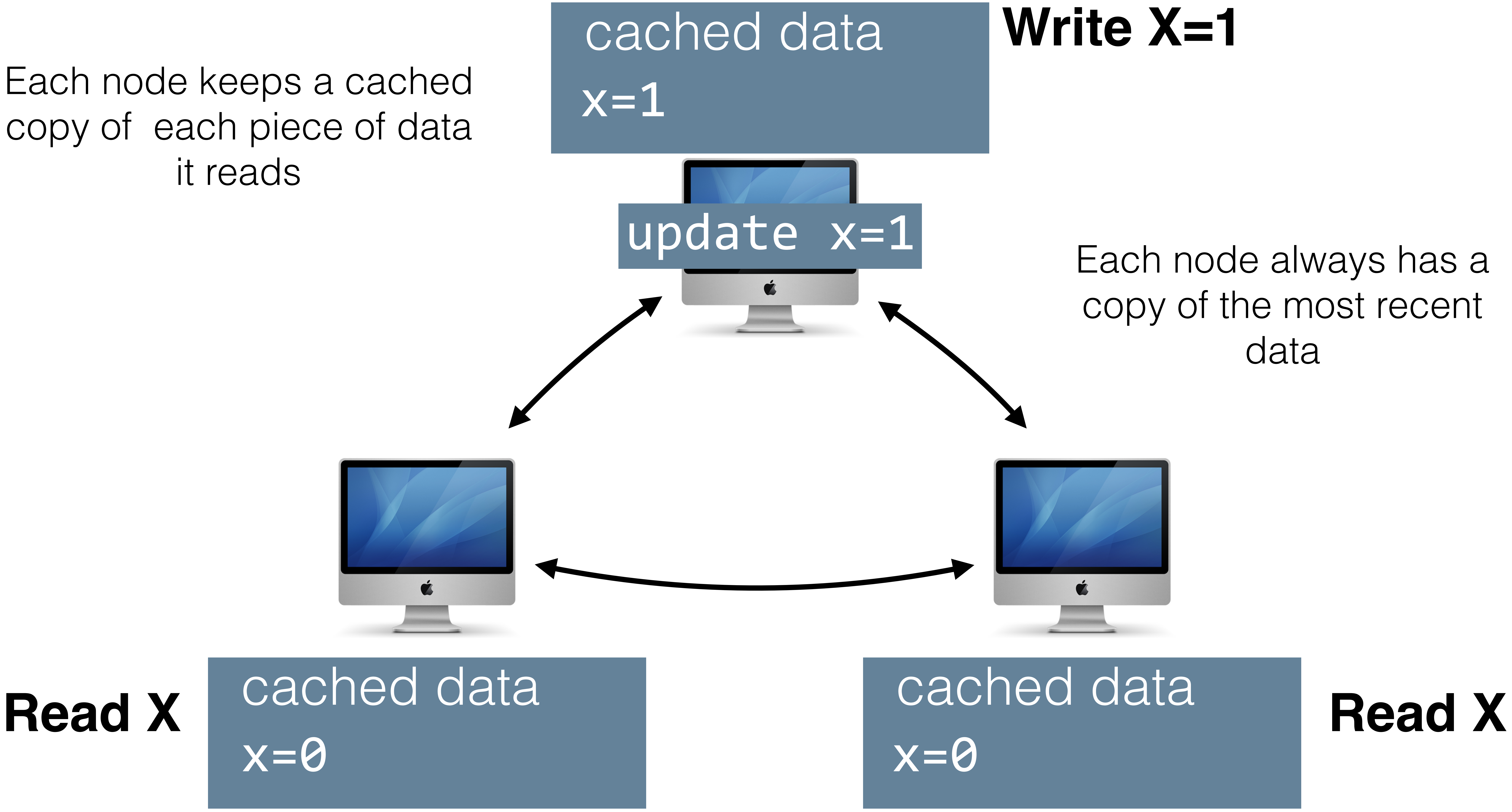
# Ivy invariants

- Every piece of data has exactly one current owner
- Current owner is guaranteed to have a copy of that data
- If the owner has write permission, no other copies can exist
- If owner has read permission, it's guaranteed to be identical to other copies
- Manager node knows about all of the copies
- Sounds a lot like HW4? :)

# HW4 Architecture

Each node keeps a cached copy of each piece of data it reads

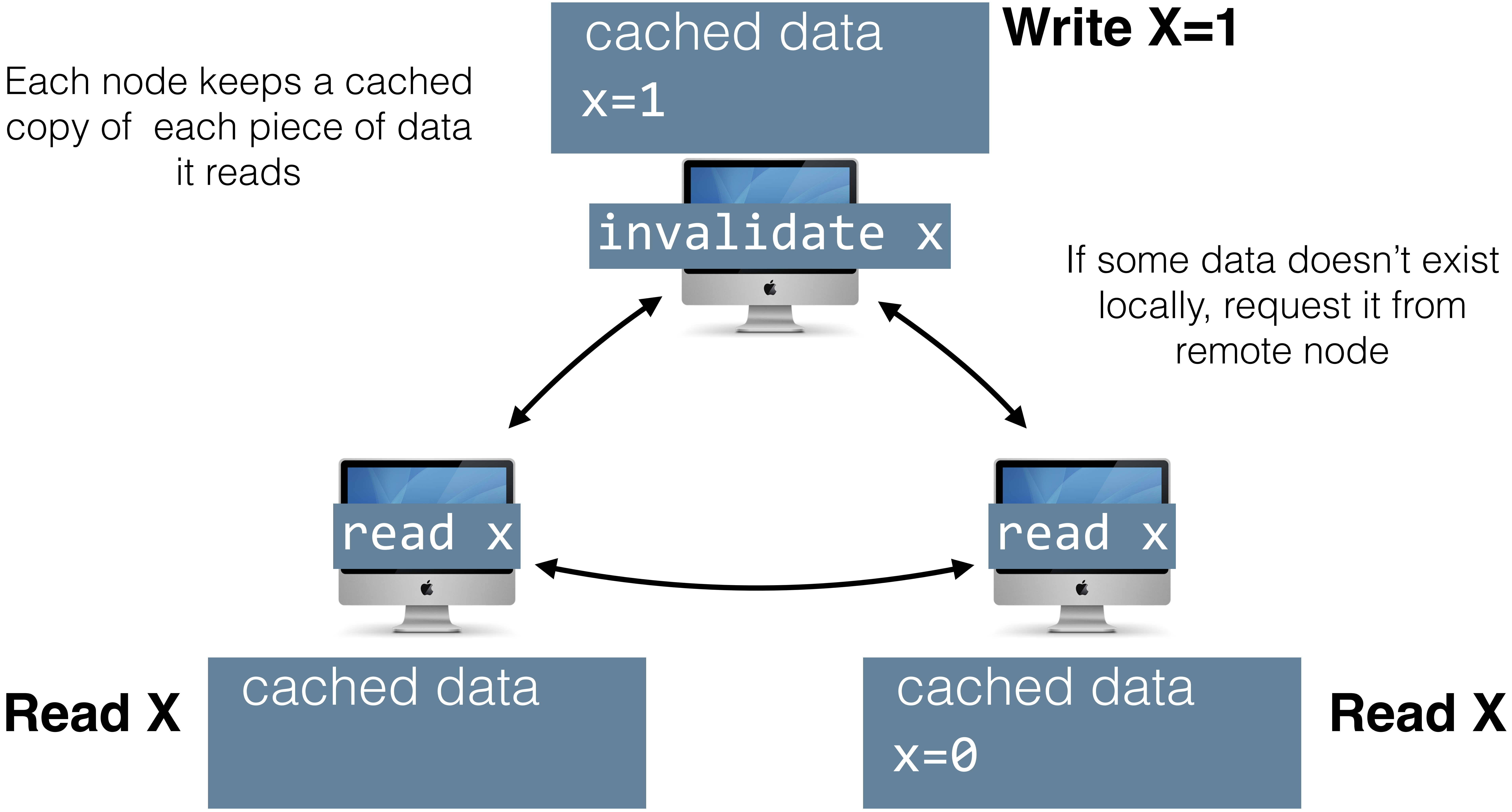
Each node always has a copy of the most recent data



# Ivy Architecture

Each node keeps a cached copy of each piece of data it reads

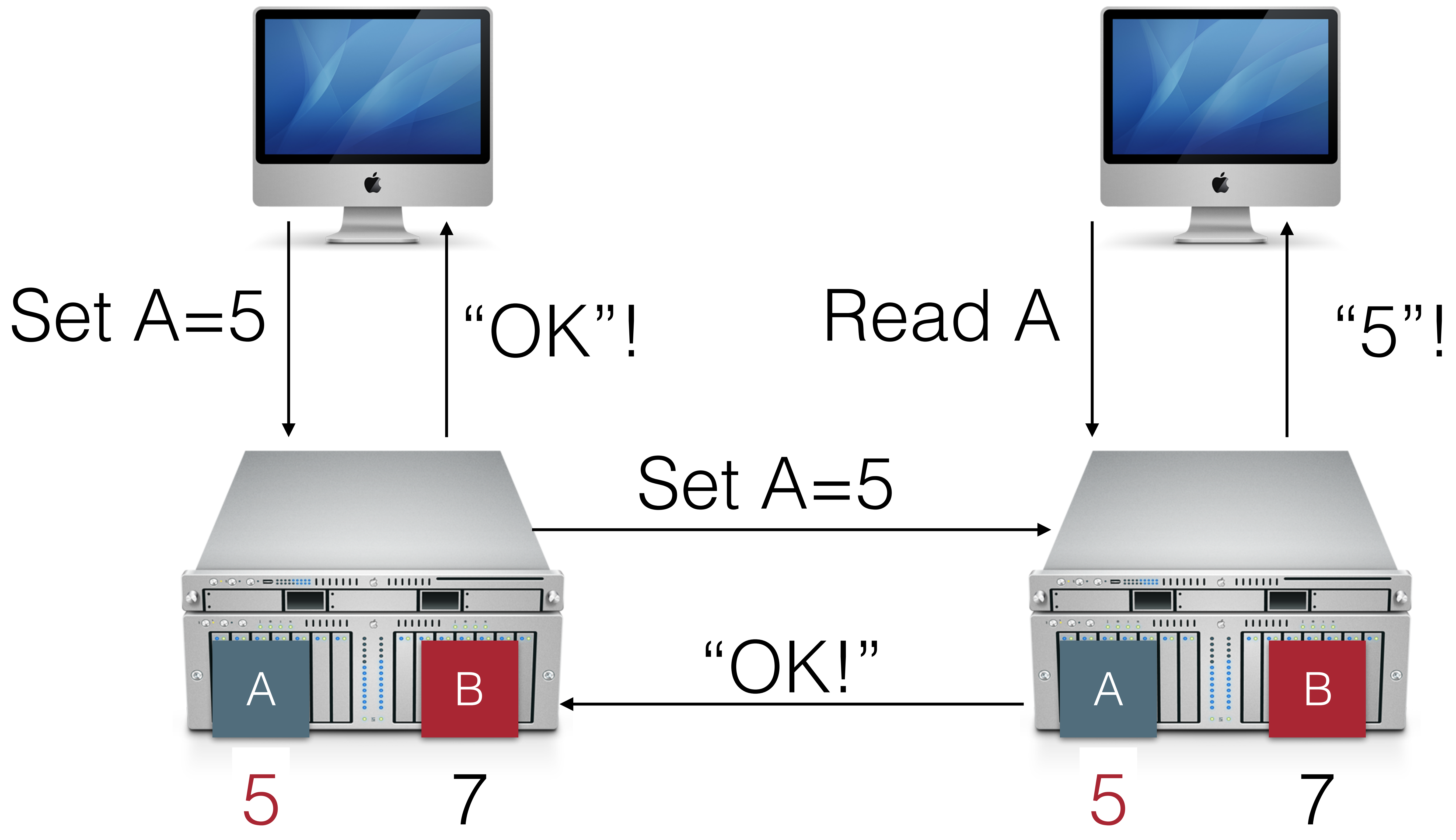
If some data doesn't exist locally, request it from remote node



# Ivy vs HW4

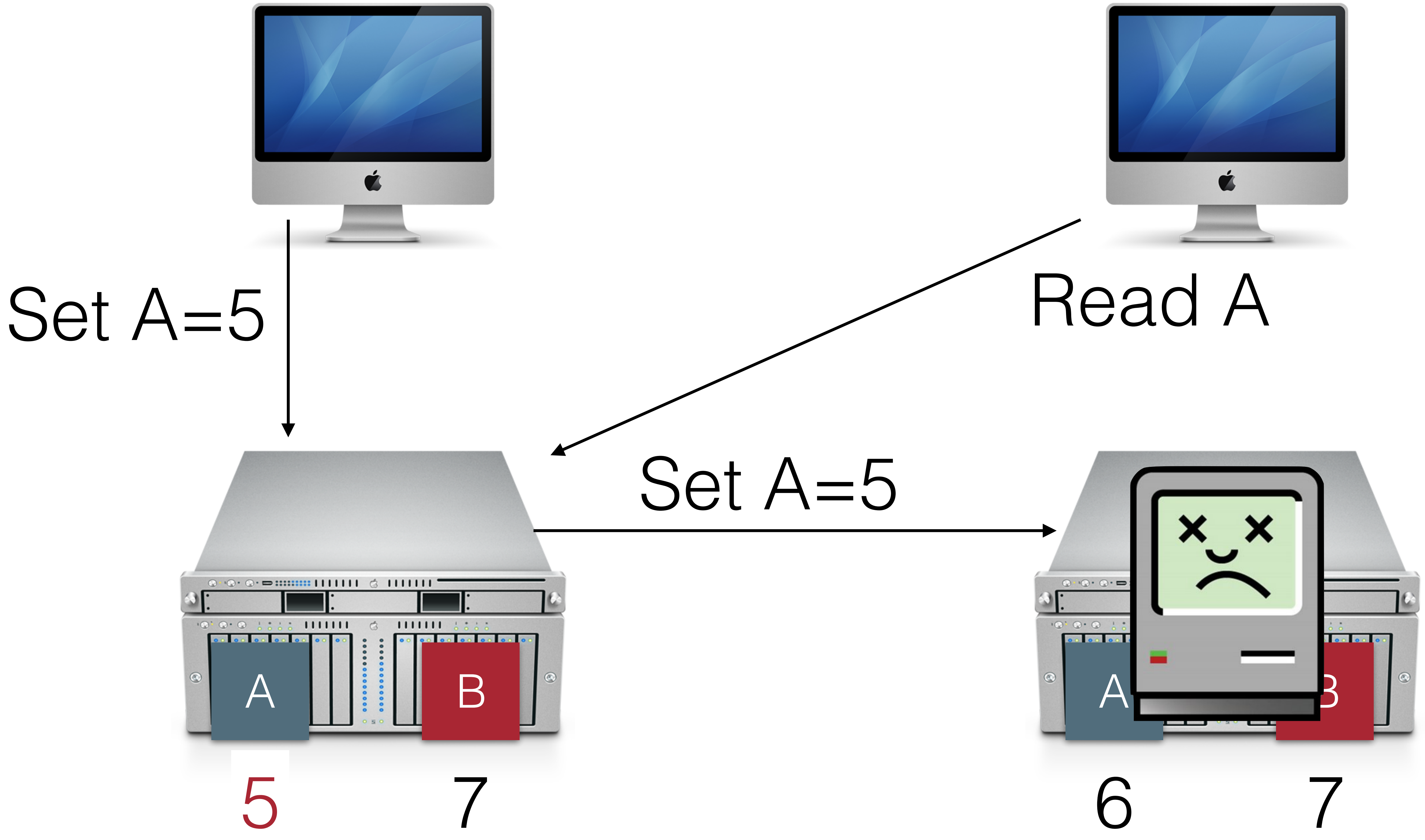
- Ivy never copies the actual values until a replica reads them (unlike HW4)
  - Invalidate messages are probably smaller than the actual data!
- Ivy only sends update (invalidate) messages to replicas who have a copy of the data (unlike HW4)
  - Maybe most data is not actively shared
- Ivy requires the lock server to keep track of a few more bits of information (which replica has which data)
- With near certainty Ivy is a lot faster :)

# Sequential Consistency

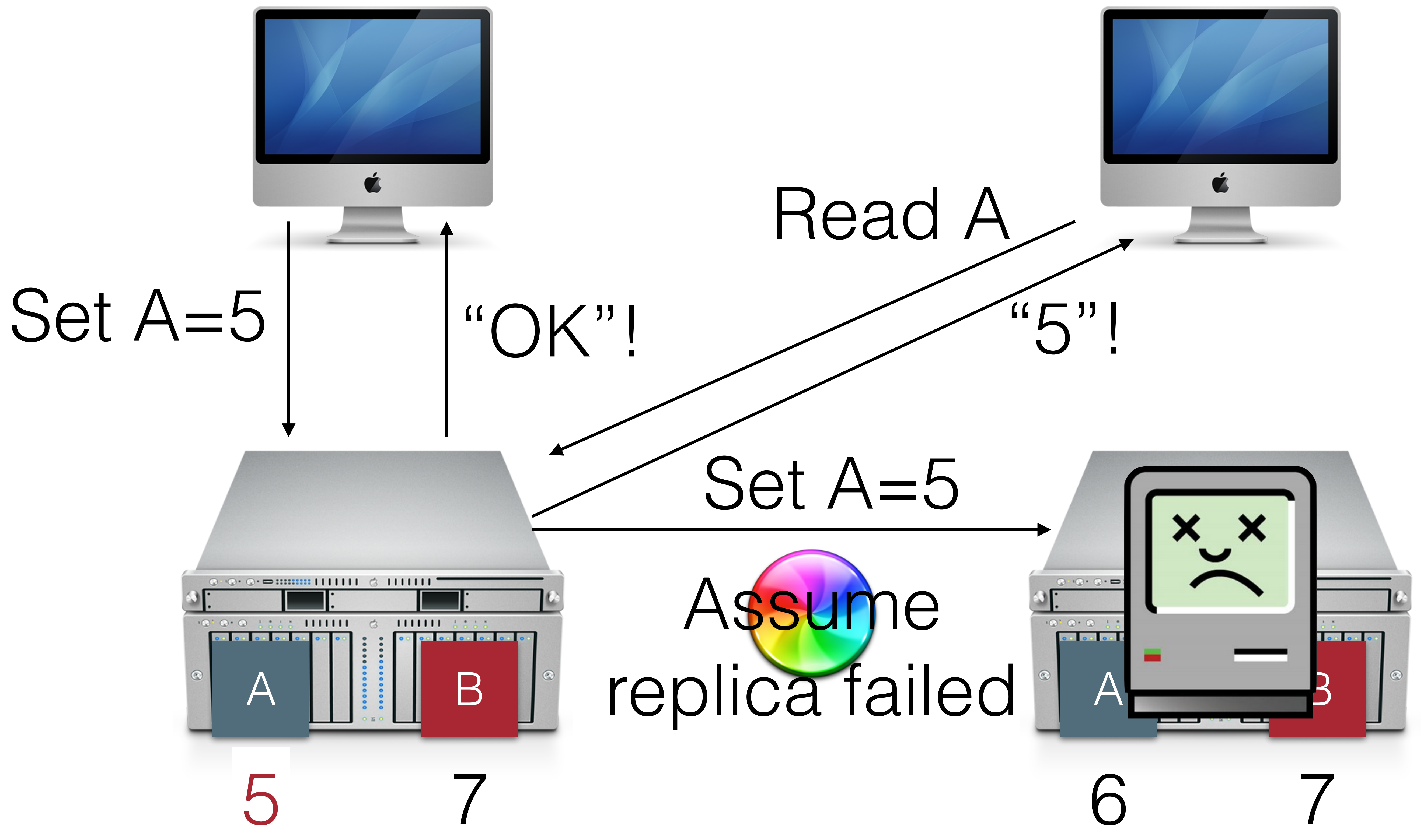


# Availability

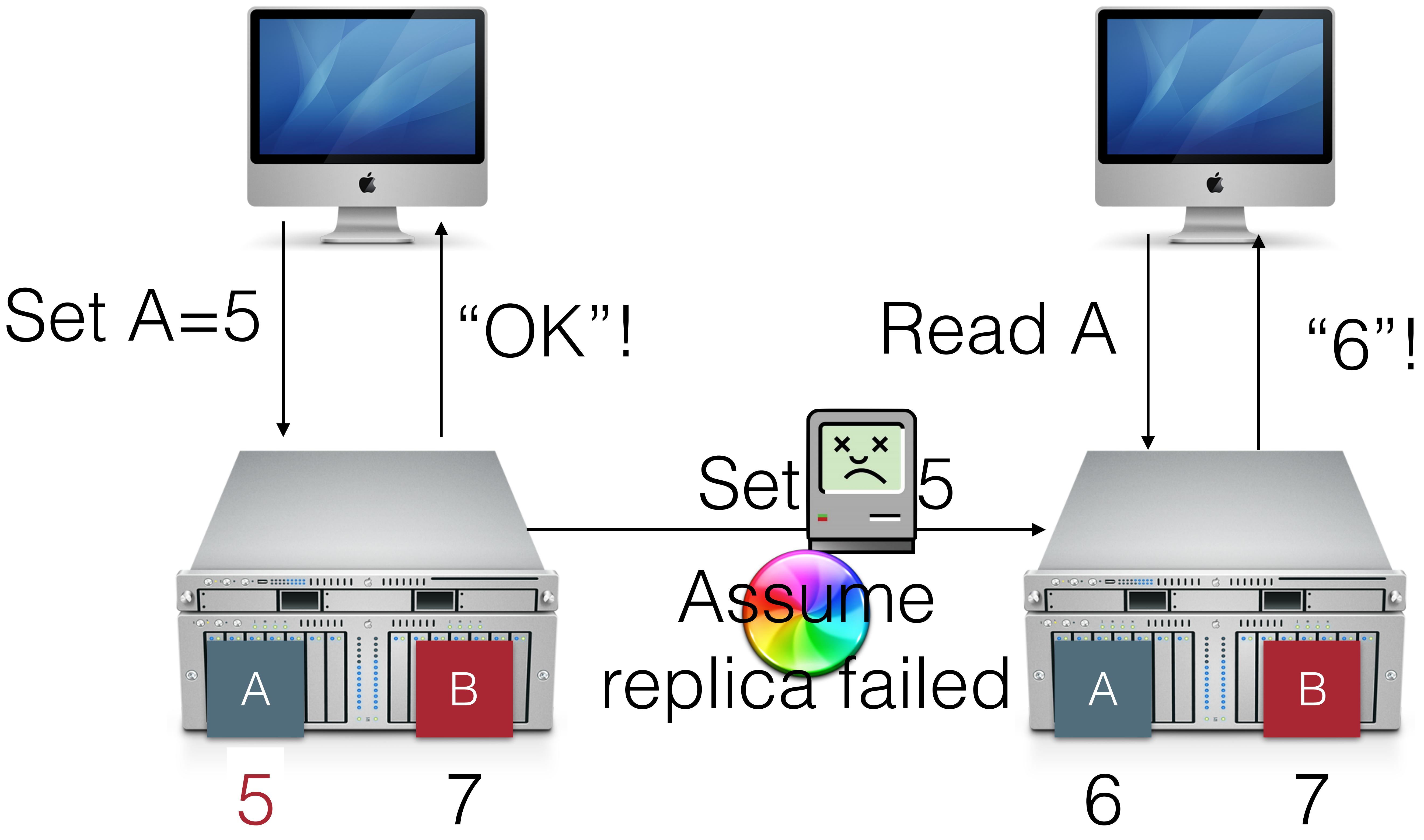
- Our protocol for sequential consistency does NOT guarantee that the system will be available!



# Consistent + Available

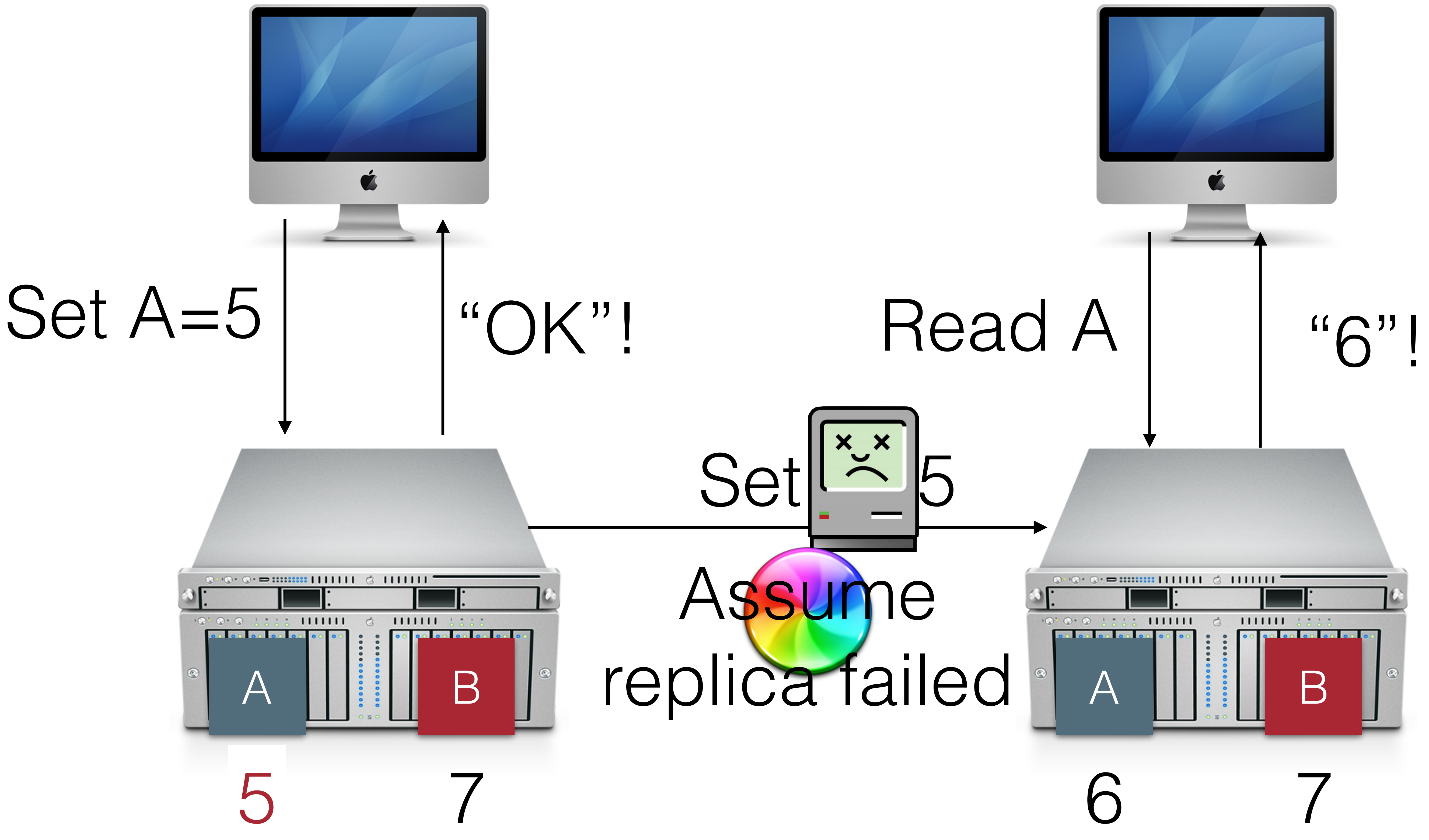


# Still broken...



# Network Partitions

- The communication links between nodes may fail arbitrarily
- But other nodes might still be able to reach that node



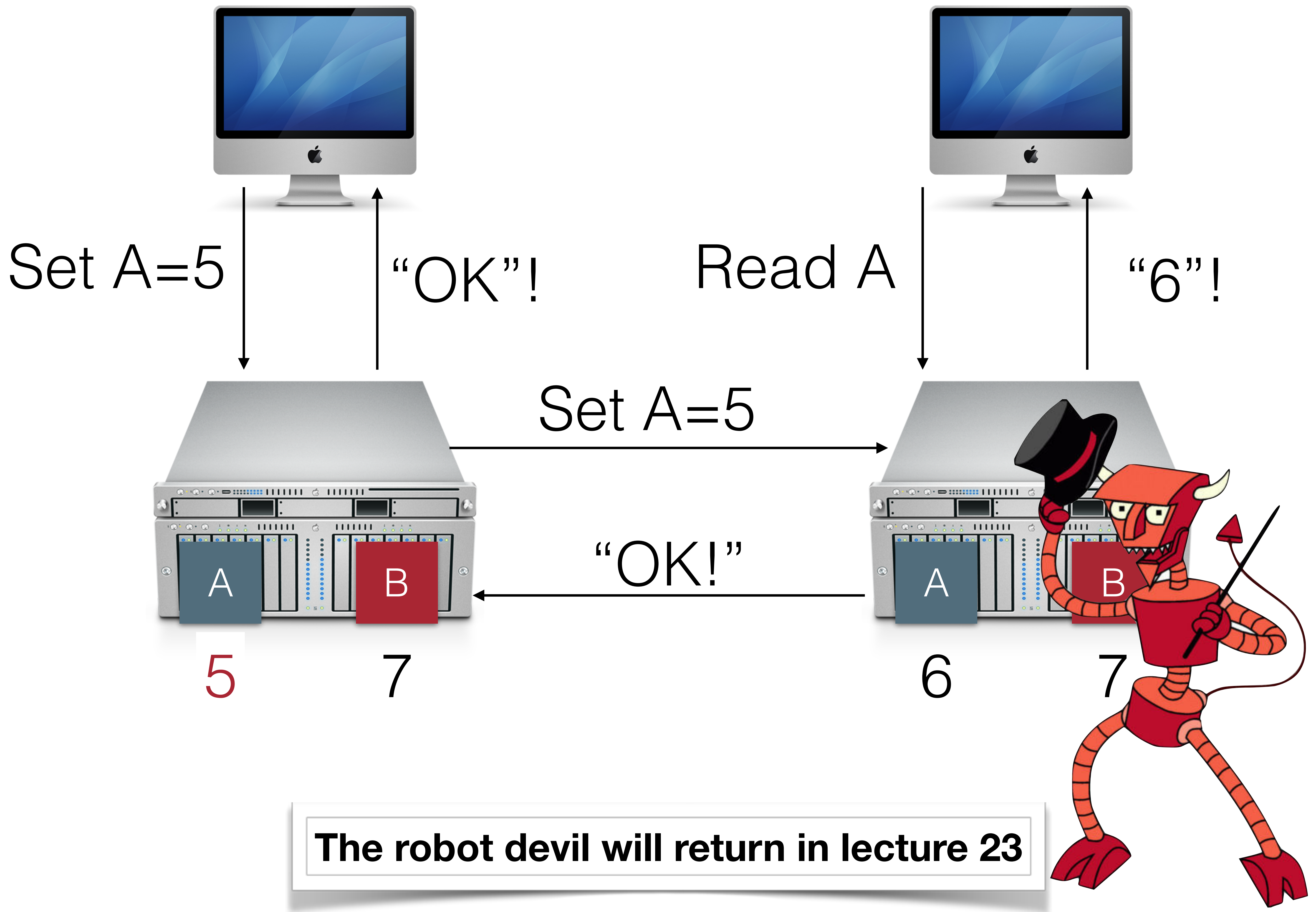
# CAP Theorem

- Pick two of three:
  - Consistency: All nodes see the same data at the same time (strong consistency)
  - Availability: Individual node failures do not prevent survivors from continuing to operate
  - Partition tolerance: The system continues to operate despite message loss (from network and/or node failure)
- **You can not have all three, ever***
  - If you relax your consistency guarantee (we'll talk about in a few weeks), you might be able to guarantee THAT…

# CAP Theorem

- C+A: Provide strong consistency and availability, assuming there are no network partitions
- C+P: Provide strong consistency in the presence of network partitions; minority partition is unavailable
- A+P: Provide availability even in presence of partitions; no strong consistency guarantee

# Still broken...




The robot devil will return in lecture 23