CS4740
CLOUD COMPUTING

Agreement

Prof. Chang Lou, UVA CS, Fall 2025

AGREEMENT

- A set of nodes in a DS often need to agree on something: a decision, the value of a variable, order of events,...
- Example: ATM machine
  - ATM front-end and banking service need to agree on whether to commit or abort my cash withdrawal.

GAME: GREEN CUP, RED CUP

- Three students stand in a line
  - Cup on the head decides the role. Green: **Leader**, Red: **Follower**
  - Can only see the color of cups in front of them
  - Cannot talk with each other or turn around
  - Cannot move in the first 30 seconds
- **Win**: Leader gives me a high-five within one minute after start.
- **Lose**: Leader didn't give me a high-five in time, or followers take moves instead
- Can you design a protocol to win?

TWO TYPES OF AGREEMENT

- **Consensus**: participants need to agree on a value, but they are willing and capable to accept any value.
- **Atomic commitment**: participants need to agree on a value, but they have specific constraints on whether they can accept any particular value.

- Give some examples?

QUIZ

- Question:
  - Decision of when to meet is likely ??? problem.
  - Decision of which zoom link to meet at is likely ??? problem.
- Answer:
  - Decision of when to meet is likely an atomic commitment problem.
  - Decision of which zoom link to meet at is likely a consensus problem.

EXAMPLES – WHICH TYPE IS EACH?

- Lamport's distributed mutual exclusion protocol: nodes agree on who has the lock at any time. ← ???
- ATM example from RPC lecture: ATM front-end and banking service need to agree on whether to commit or abort my cash withdrawal. ← ???
- In Lab1, you design a MapReduce system that all workers agree whether they are in the map or reduce phase. ← ???

EXAMPLES – WHICH TYPE IS EACH?

- Lamport's distributed mutual exclusion protocol: nodes agree on who has the lock at any time. ← Consensus
- ATM example from RPC lecture: ATM front-end and banking service need to agree on whether to commit or abort my cash withdrawal. ← Atomic commitment
- In Lab1, you design a MapReduce system that all workers agree whether they are in the map or reduce phase. ← Consensus

AGREEMENT IS "HARD"

- In the asynchronous system model, it is impossible to guarantee agreement in finite time under all failure scenarios.
- The consensus problem can be approached in practice: there exist protocols to solve consensus under vast majority of plausible failure scenarios.
- That's not the case for atomic commitment: if each participant has their own constraints, then you can't tolerate any one participant's failure.
- In that sense, atomic commitment is "even harder" than consensus.

REMAINDER OF THIS CLASS

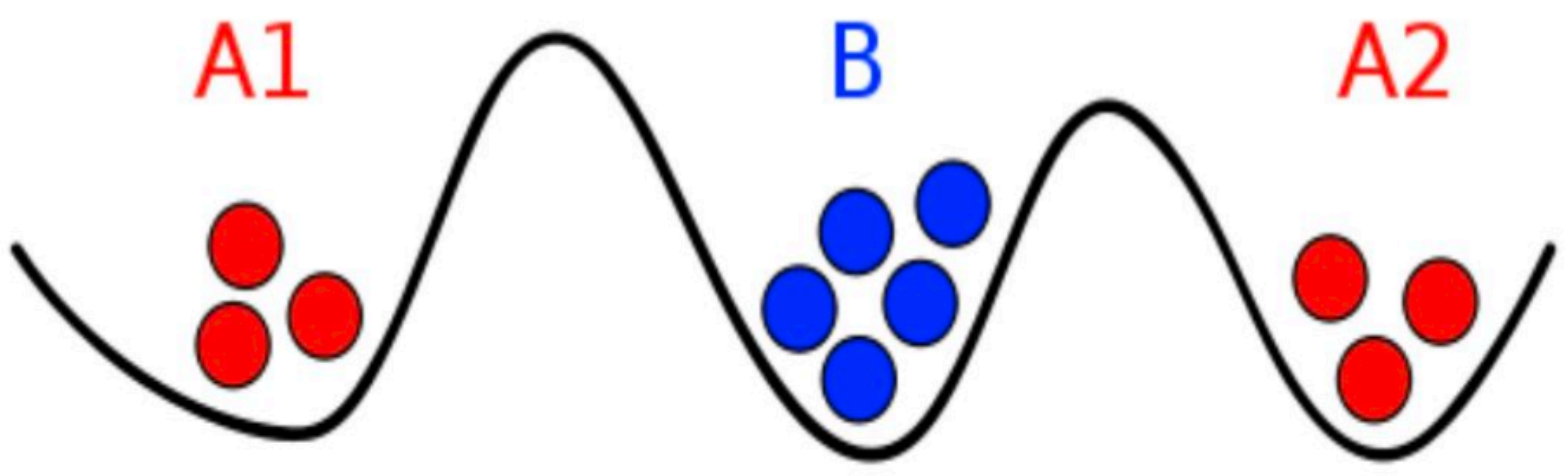
- Focus on two "impossibilities":
  - **FLP**: impossible to have deterministic one-crash-robust consensus with asynchronous communication
  - **CAP**: impossible to achieve consistency, availability and partition-tolerance all

THE FLP IMPOSSIBILITY RESULT

Fischer, Lynch, and Paterson (FLP), 1985

– In an asynchronous system (unordered messages, unbounded communication delays, unbounded processing delays), no protocol can guarantee consensus within a finite amount of time if even a single process can fail by stopping. [FLP-1985]

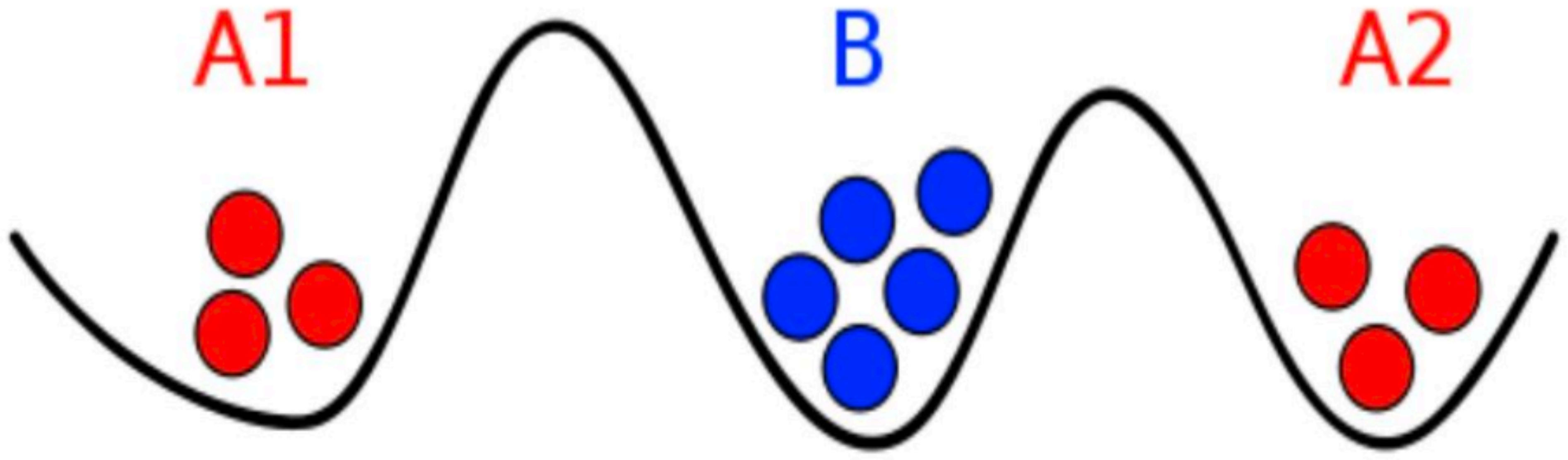
THE TWO-GENERALS PROBLEM



- Two armies, A1 and A2, want to attack a fortified city, B.
- Both armies must attack at the same time to succeed.
- The armies can communicate through messengers, but those can be captured or delayed, so msg. delivery is unreliable.

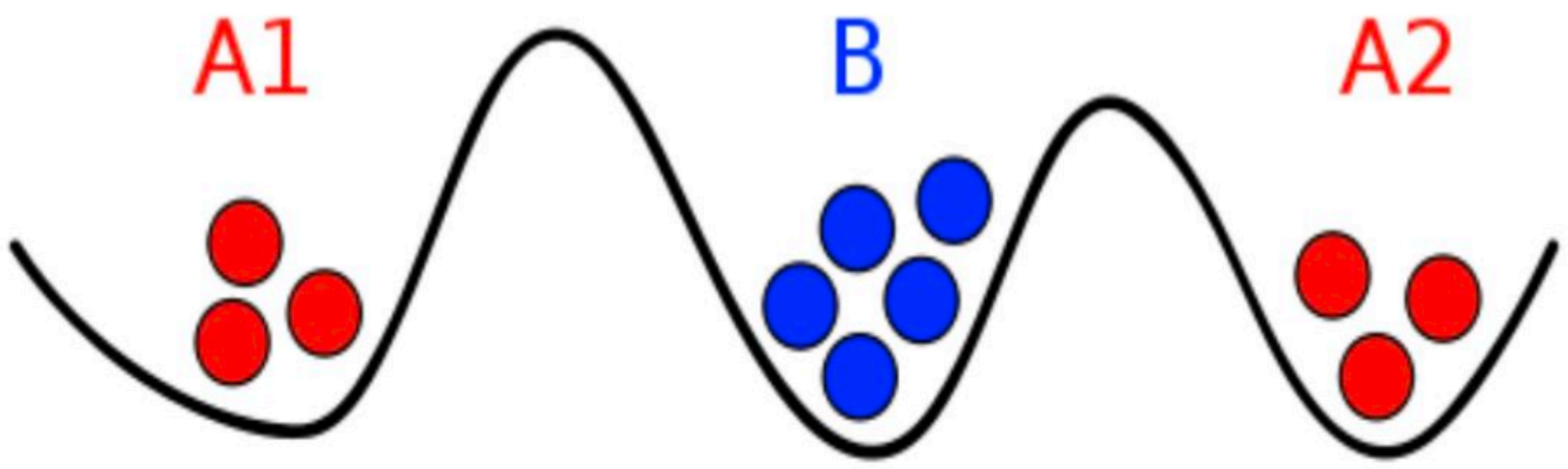
THE TWO-GENERALS PROBLEM

- Three requirements for a solution:
  - Consistency: both armies decide to attack at the same time.
  - Termination: each army decides to attack after a finite number of messages.
  - Validity: the time to attack was proposed by one of the armies.



CASE 1: KNOWN DELAYS, RELIABLE DELIVERY (SYNCHRONOUS SYSTEM MODEL)

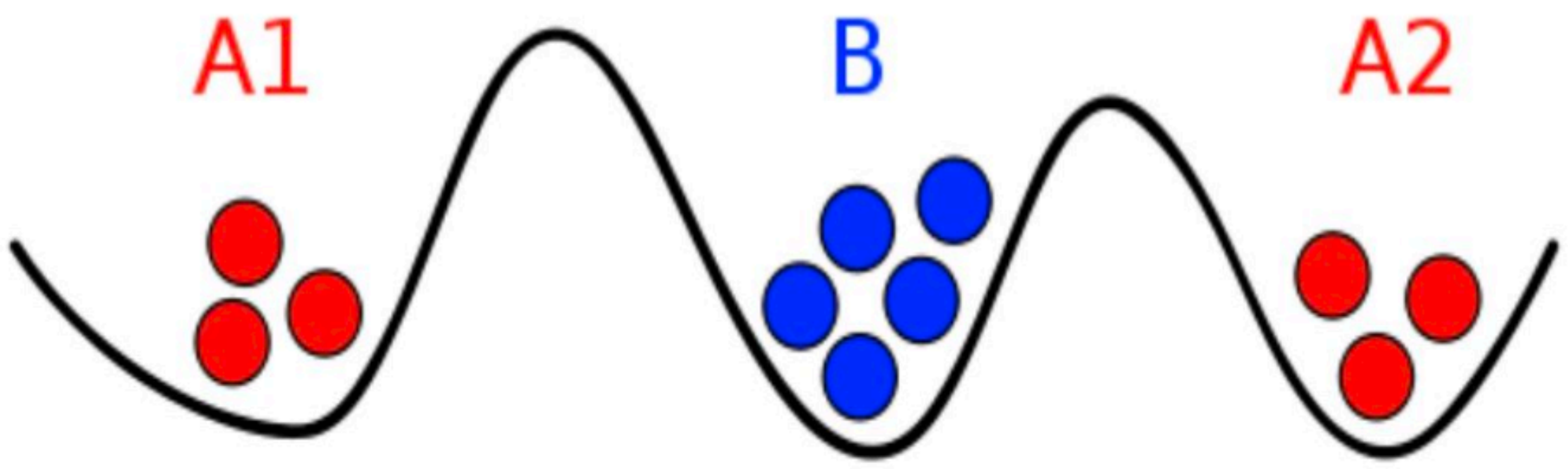
- Protocol:
  - Pre-agree on either A1 or A2 generals proposing the time to attack. Say A1 is the one to propose. A2 will be the one to accept.
  - A1 sets the time of attack to communication delay + some extra time to account for A2's preparation for response.



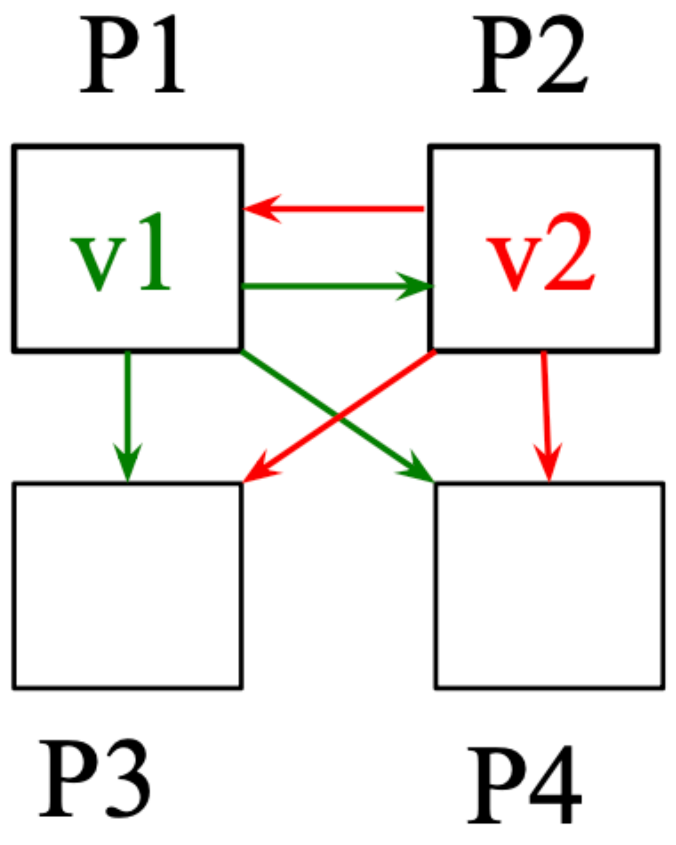
- **So problem is solvable in synchronous networks.**

CASE 2: UNKNOWN DELAYS / UNRELIABLE DELIVERY (ASYNCHRONOUS SYSTEM MODEL)

- Sketch:
  - Need Acks in the protocol.
  - But Acks can be delayed/lost too.
  - Therefore I need more Acks.
  - Therefore, one general can never be sure the other will attack.
  - So they can't be guaranteed to reach agreement.
- Achieving consistency, termination, and validity in the asynchronous model is provably impossible.



CONSENSUS PROBLEM FORMULATION



- A collection of processes, Pi.
- They propose values Vi (e.g., time to attack, client update, lock requests, ...), and send messages to others to exchange proposals.
- Different processes may propose different values, and they can all accept any of the proposed values.
- Only one of the proposed values, V, will be "chosen" and eventually all processes learn that one chosen value.

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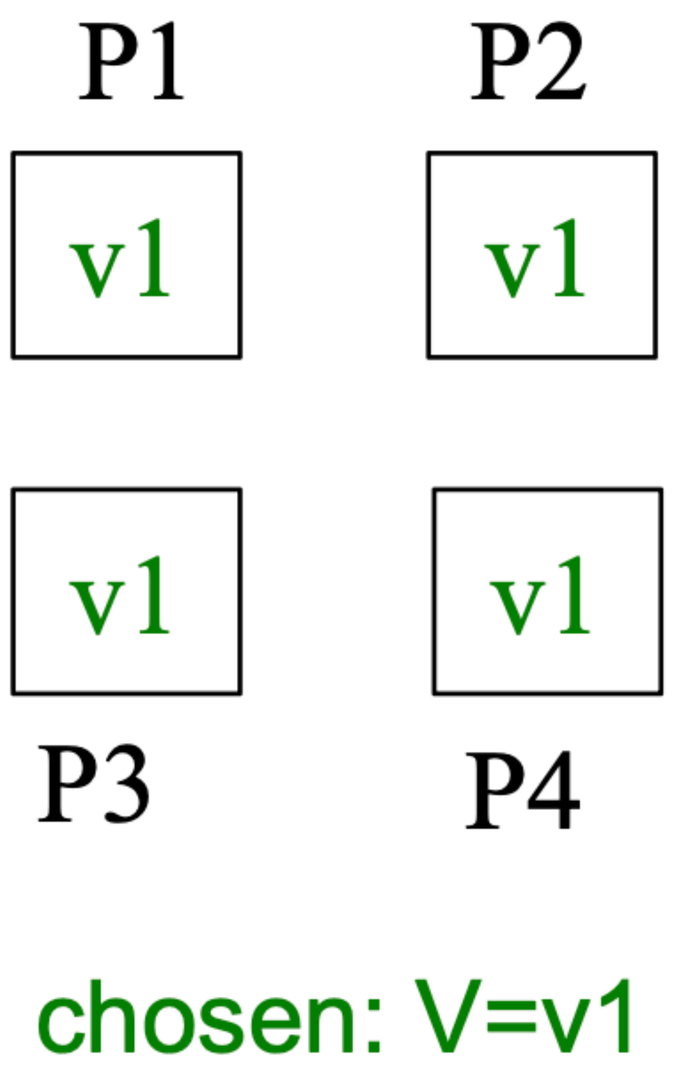

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  - validity:

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  - validity: the chosen value was proposed by one of the nodes.

CONSENSUS IS IMPOSSIBLE

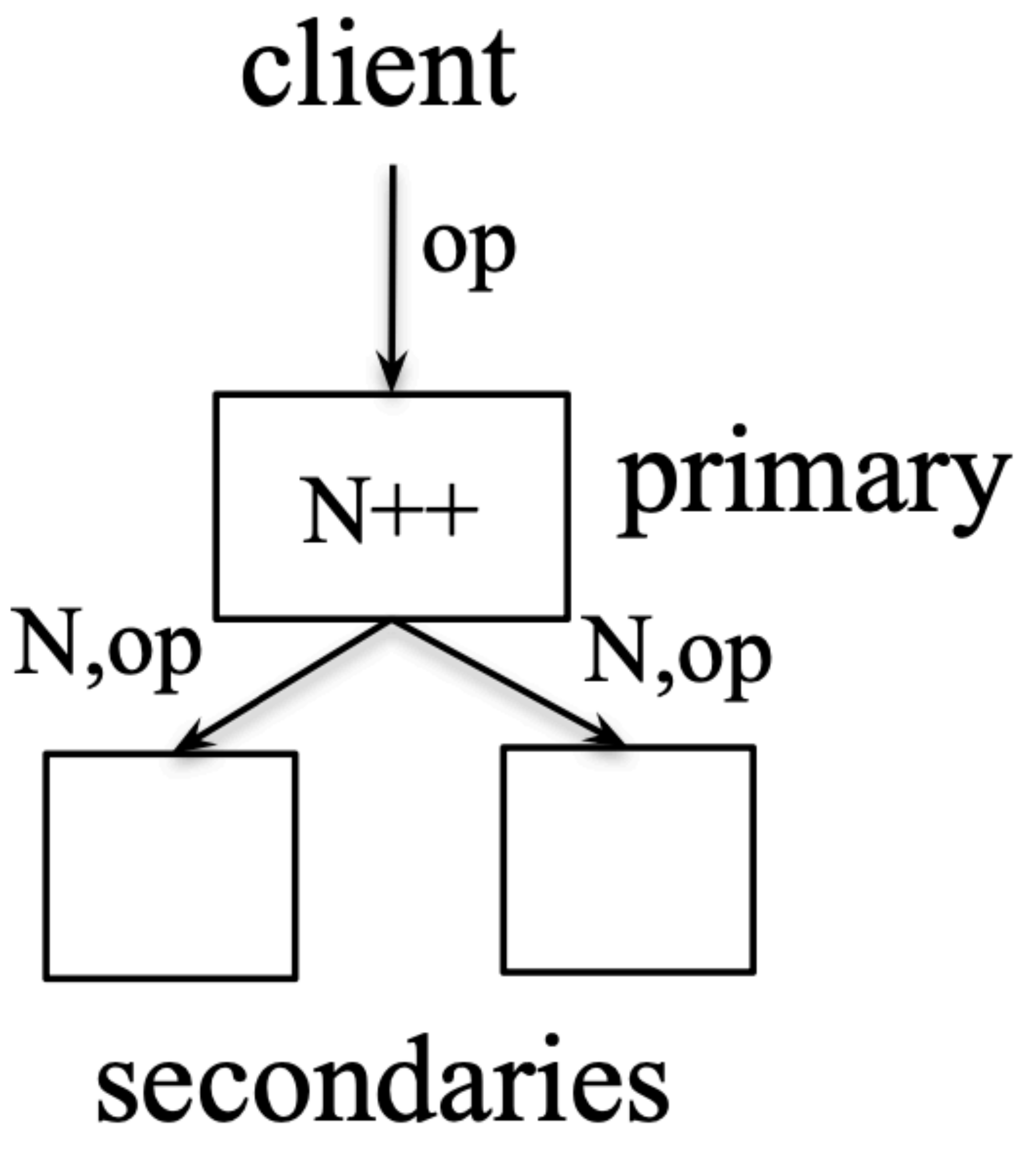
- But, we achieve consensus all the time…

FLP'S STRONG ASSUMPTIONS

- Deterministic actions at each node
  - Randomized algorithms can achieve consensus
- Asynchronous network communication
  - Synchronous or even partial synchrony is sufficient
- All "runs" must eventually achieve consensus
  - In practice, many "runs" achieve consensus quickly
  - In practice, "runs" that never achieve consensus happen vanishingly rarely
  - Both are true with good system designs

CONSENSUS IS PERVASIVE IN DS

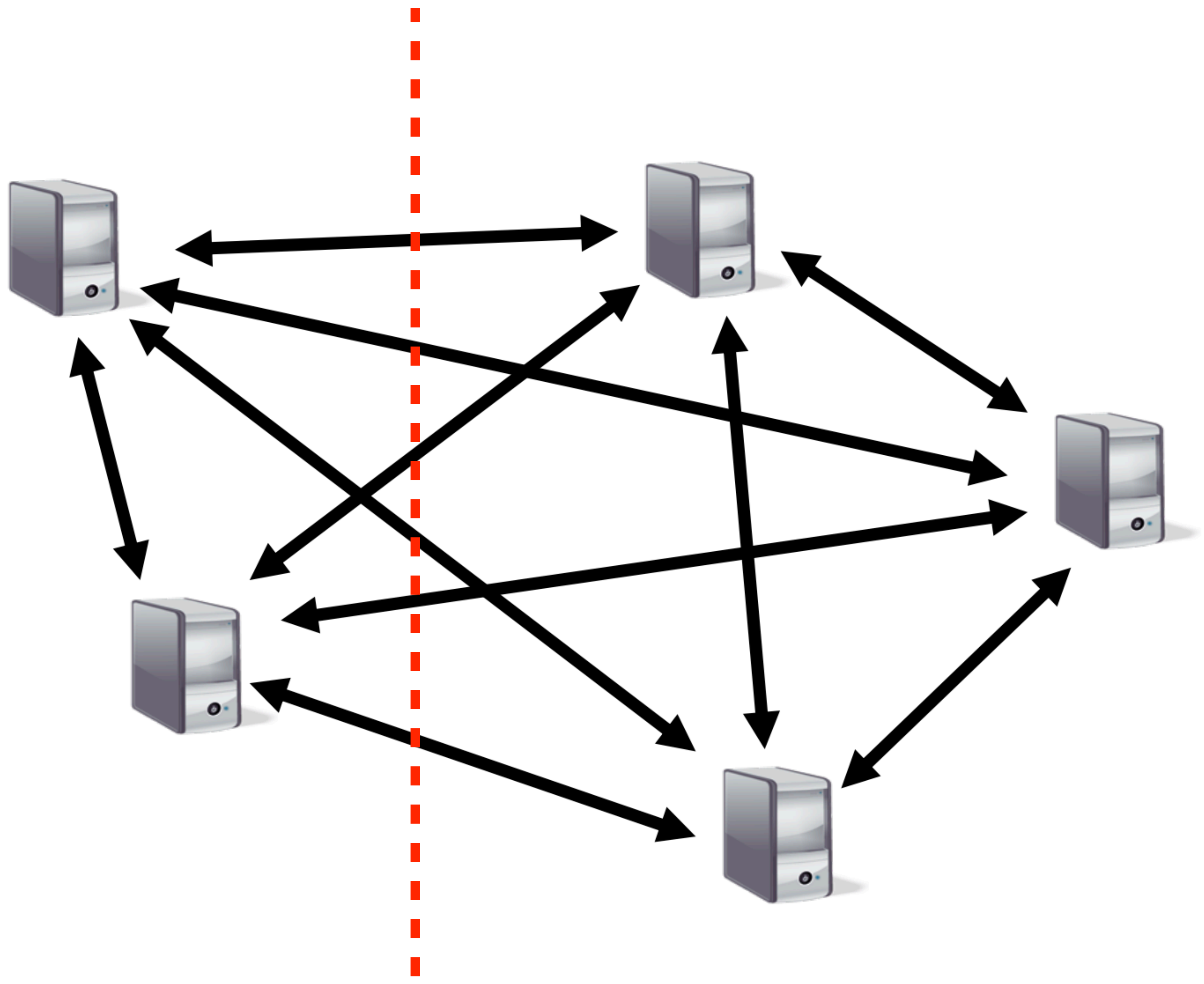
- Agreeing on order of updates to replicated DB.
  - One solution is primary/secondaries replication
  - There are several replicas, one is primary.
  - Reads and writes are accepted only by primary, which establishes an order for all operations before forwarding them to secondaries.
  - Multiple variants exist, but they all reduce to one core consensus question: how to choose the primary? A.k.a. leader election.



IMPOSSIBILITY #2

- Reaching an agreement, when there's a partition

NETWORK PARTITIONS DIVIDE SYSTEMS



FUNDAMENTAL TRADEOFF?

- Replicas appear to be a single machine, but lose availability during a network partition
- or
- All replicas remain available during a network partition but do not appear to be a single machine

CAP THEOREM PREVIEW

- You cannot achieve all three of:
  - Consistency
  - Availability
  - Partition-Tolerance
- Partition Tolerance => Partitions Can Happen
- Availability => All Sides of Partition Continue
- Consistency => Replicas Act Like Single Machine
  - Specifically, Linearizability

CAP THEOREM

– Assume to contradict that Algorithm A provides all of CAP

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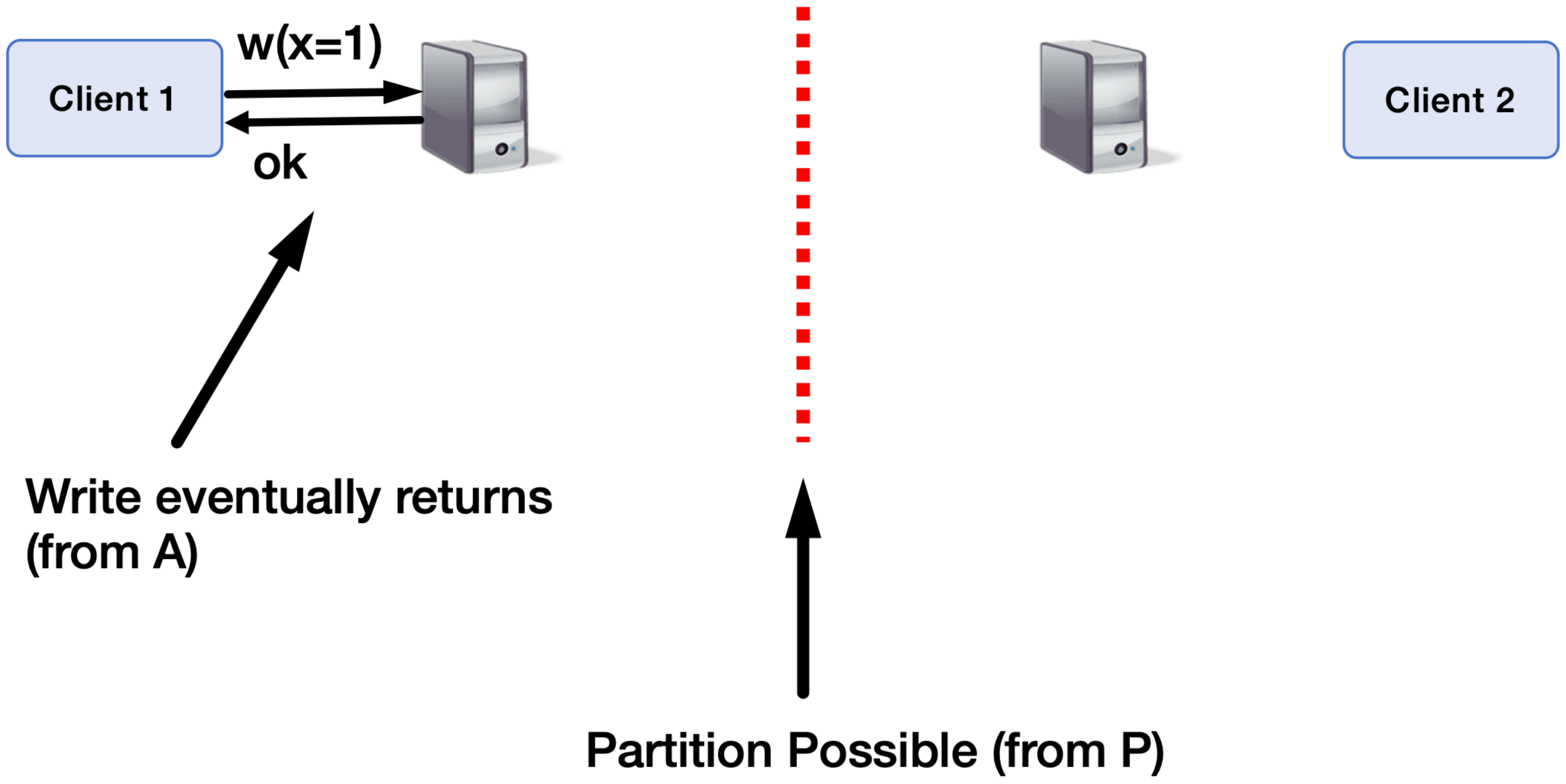

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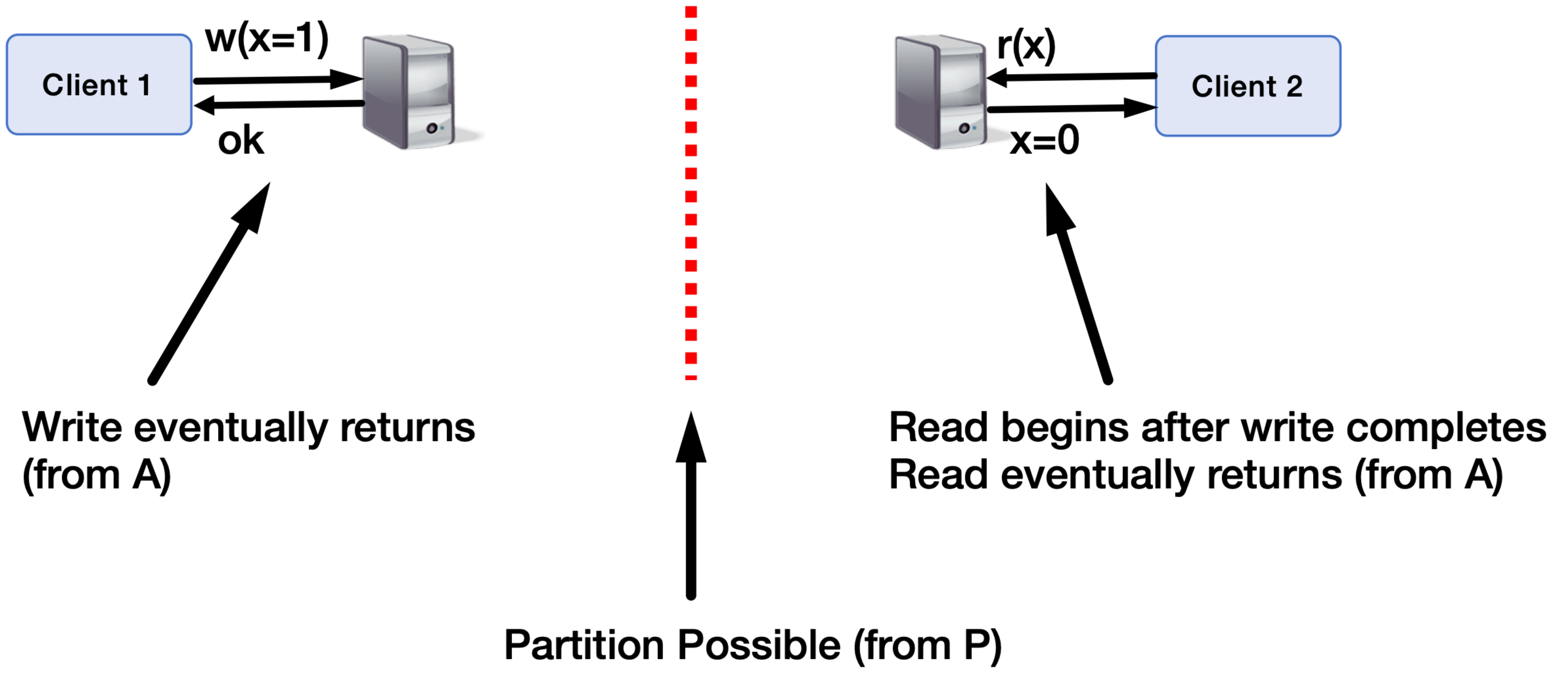

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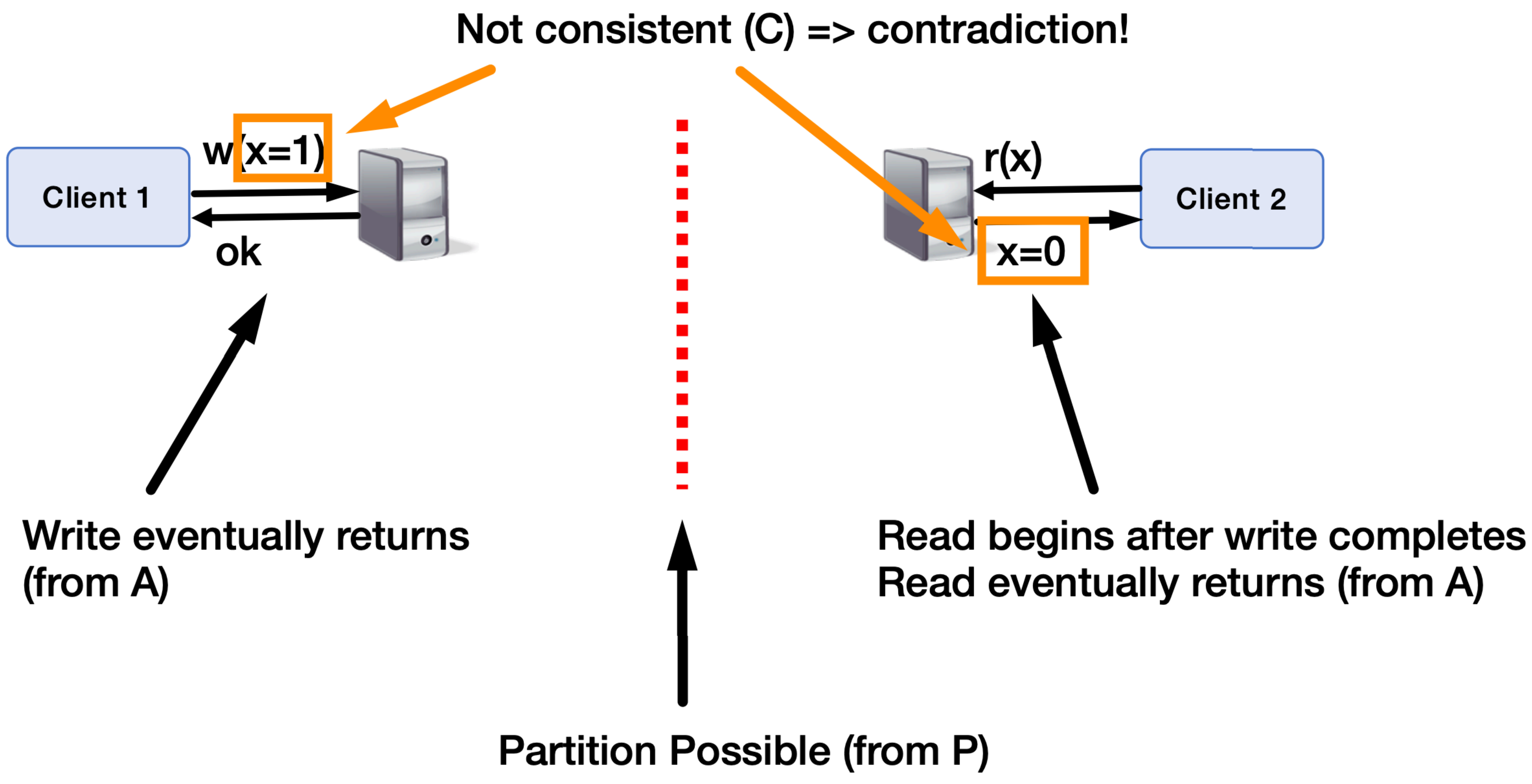
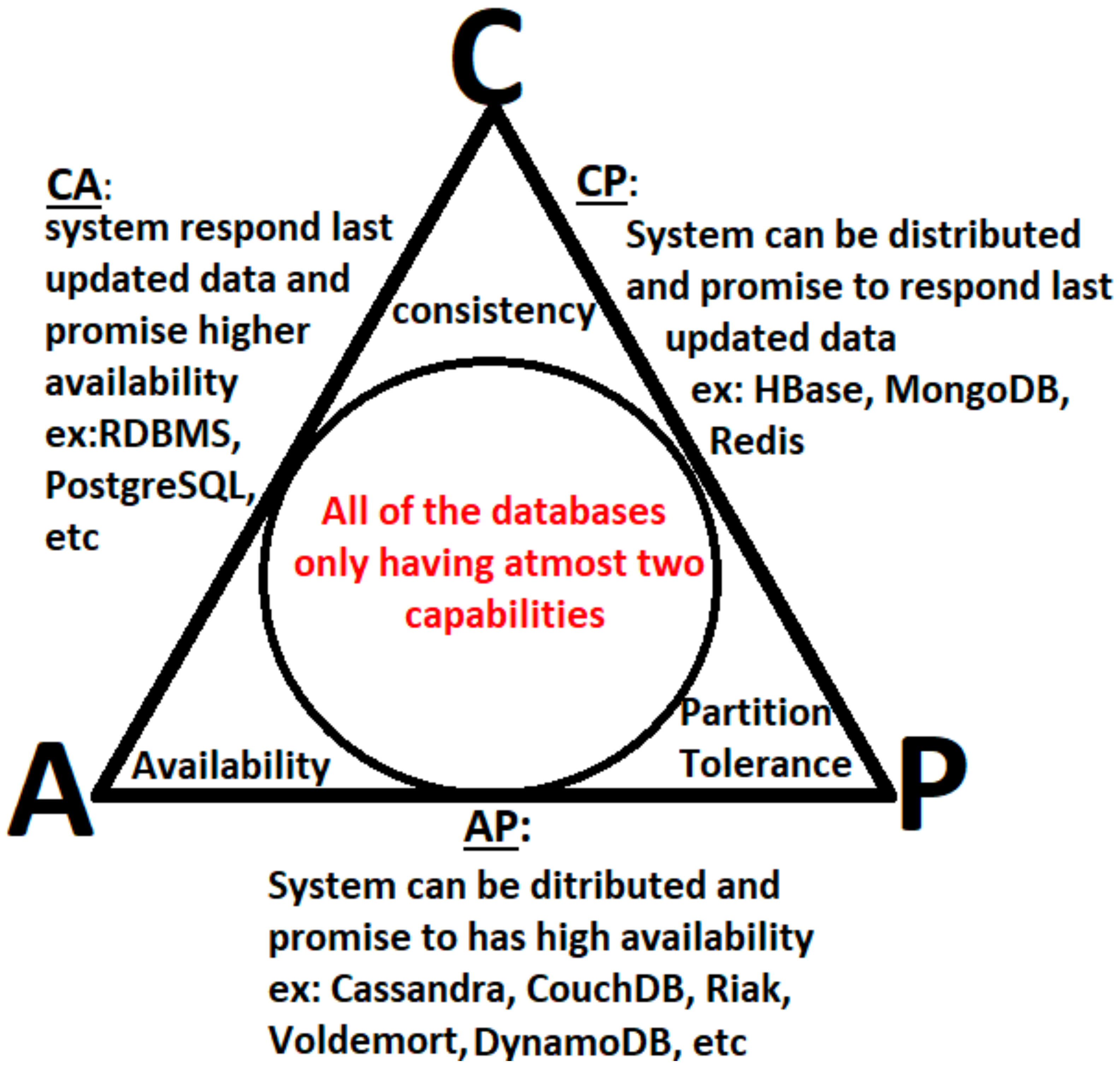


CAP CONJECTURE

– Popular interpretation: 2-out-of-3



CAP INTERPRETATION PART 1

- Cannot “choose” no partitions
  - 2-out-of-3 interpretation doesn’t make sense
  - Instead, availability OR consistency?
- That is: Fundamental tradeoff between availability and consistency
  - When designing system must choose one or the other, both are not possible

CAP INTERPRETATION PART 2

- It is a theorem, with a proof, that you understand!
- Cannot “beat” CAP Theorem
- Can engineer systems to make partitions extremely rare, however, and then just take the rare hit to availability (or consistency)

TAKEAWAYS

- Impossibility results are very useful
  - Avoids wasting effort trying to achieve impossible
  - Tells us the best-possible systems we can build!
- Today: two "impossiblilities"
  - FLP: async systems, infinite time
  - CAP: consistency, availability, partition-tolerance
- Next class: **Two-phase Commit (2PC)**

University of Virginia

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