COEN6731 Distributed Software Systems

Week 2: Coordination, Agreement, and Paxos

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Today's outline

The consensus problem

Network assumptions

Failure assumptions

Paxos

The consensus problem

Let’s go to the beach!

Let’s go get some food!

Let’s go see a movie!

The consensus problem

Let’s go to the beach!

Let’s go get some food!

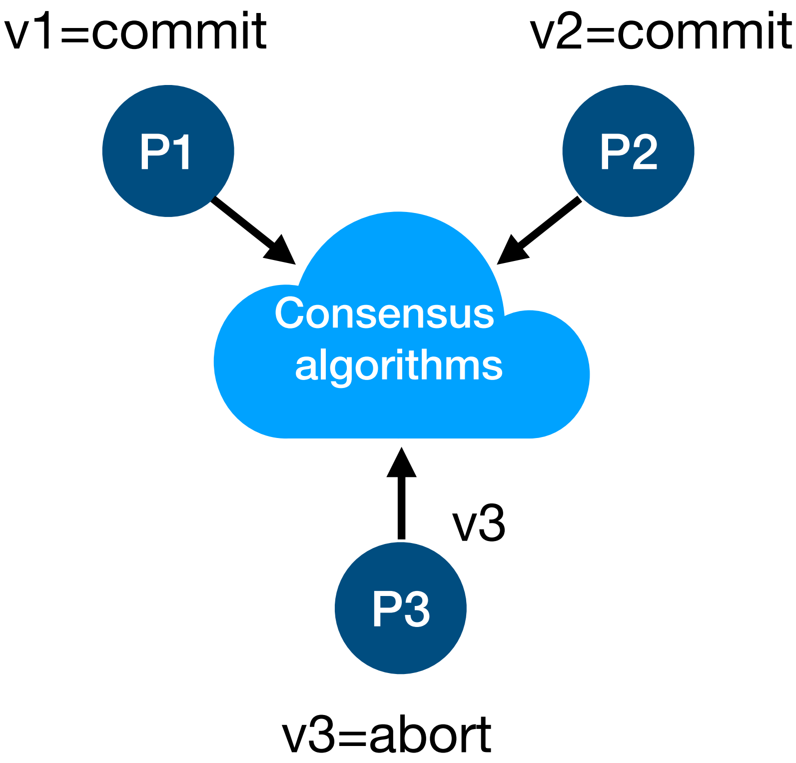
Let’s go see a movie!

What’s important in reaching agreement?

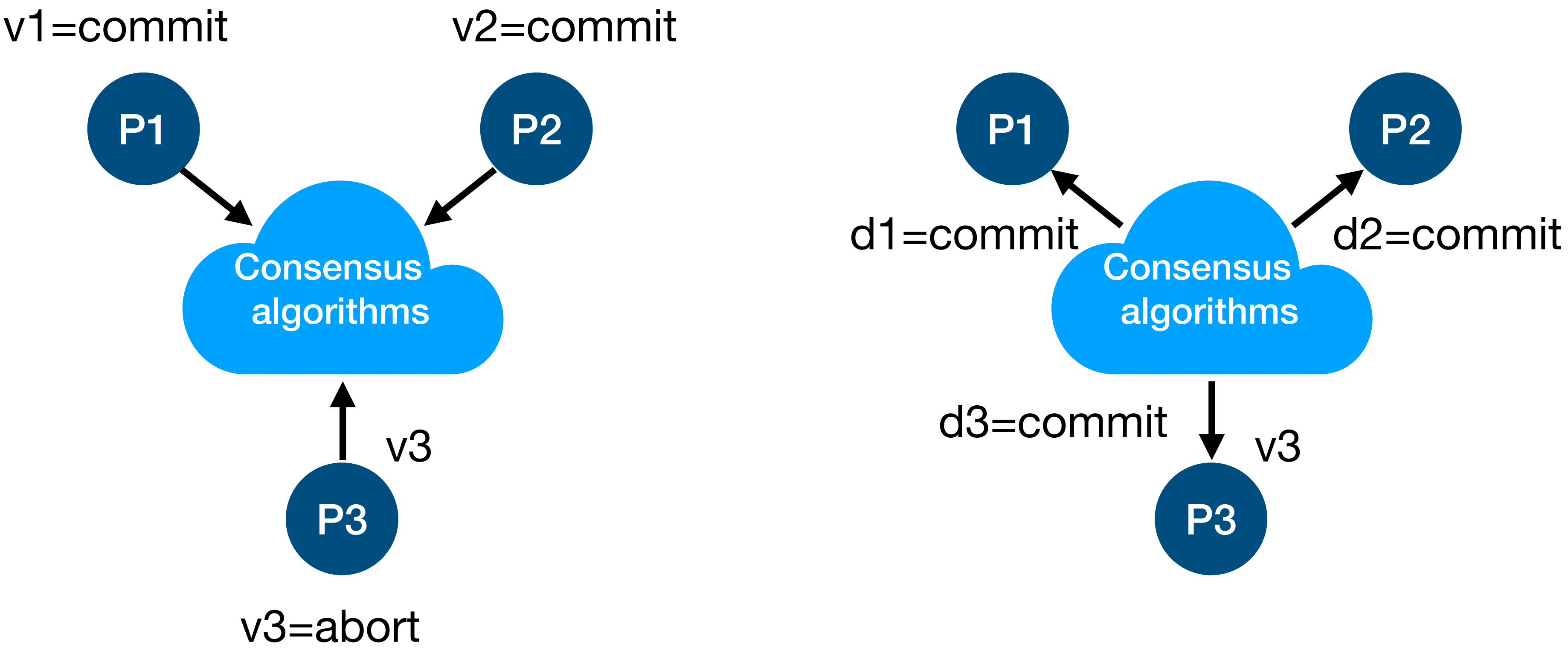
1. Agree on the activities
2. Agree on the order of activities

The happened-before relation of activities

Consensus in distributed systems



Consensus in distributed systems



Formally, the consensus problem

- To reach consensus, every process p_i begins in the **undecided** state and **proposes** a single value v_i, drawn from a set D $(i = 1,2,\ldots,N)$.
- Processes communicate with one another, exchanging values.
- Each process then sets the value of a **decision variable**, d_i.
- After that, each process enters the **decided** state, where d_i $(i = 1,2,\ldots,N)$ do not change

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In short, all correct processes commit the **same value** in the **same order**

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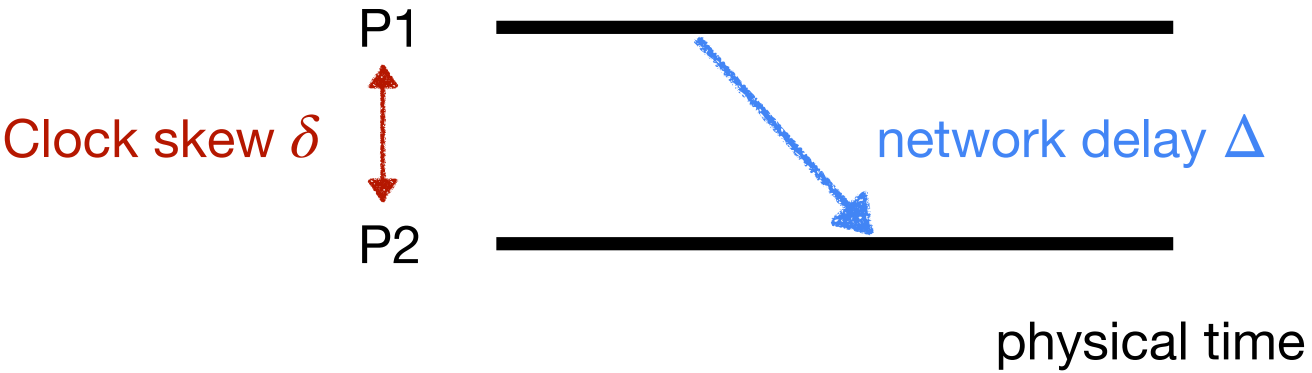
System model: network synchrony

- Synchronous
- Asynchronous
- Partially synchronous



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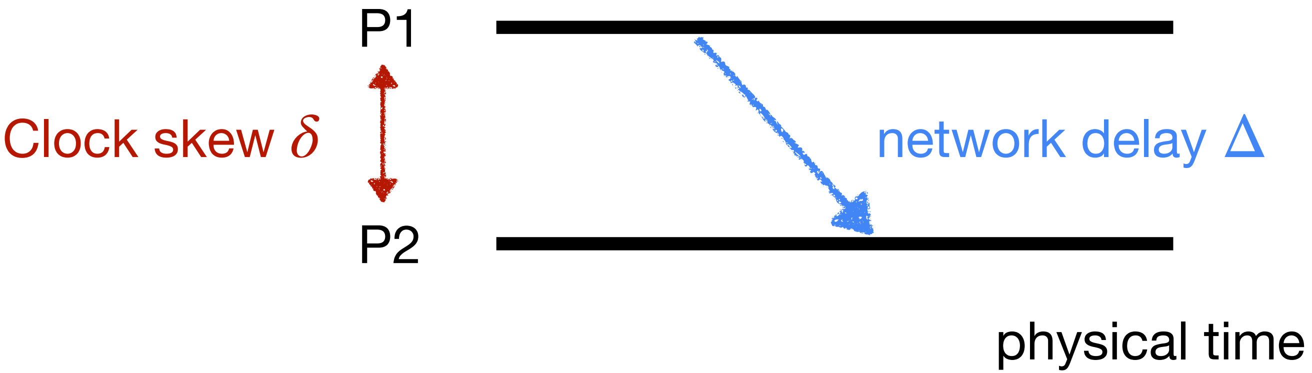
Synchronous:

Both δ and Δ have a fixed upper bound



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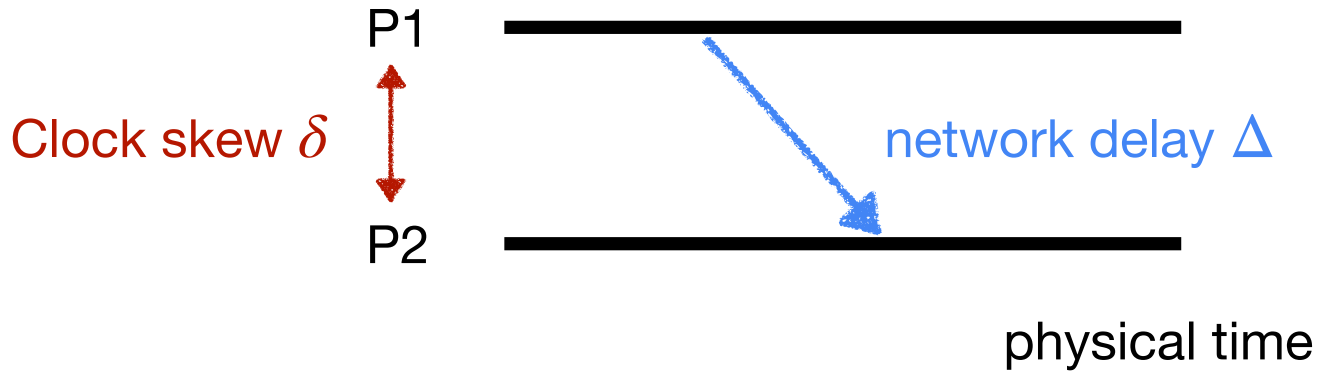

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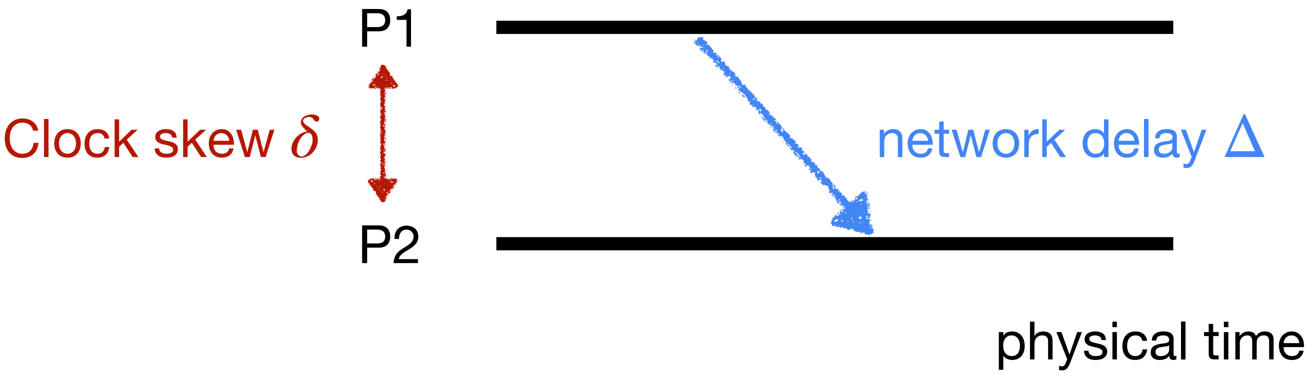
Asynchronous:
No fixed upper bound for message delivery or clock skew (i.e., δ does not exist, or Δ does not exist)



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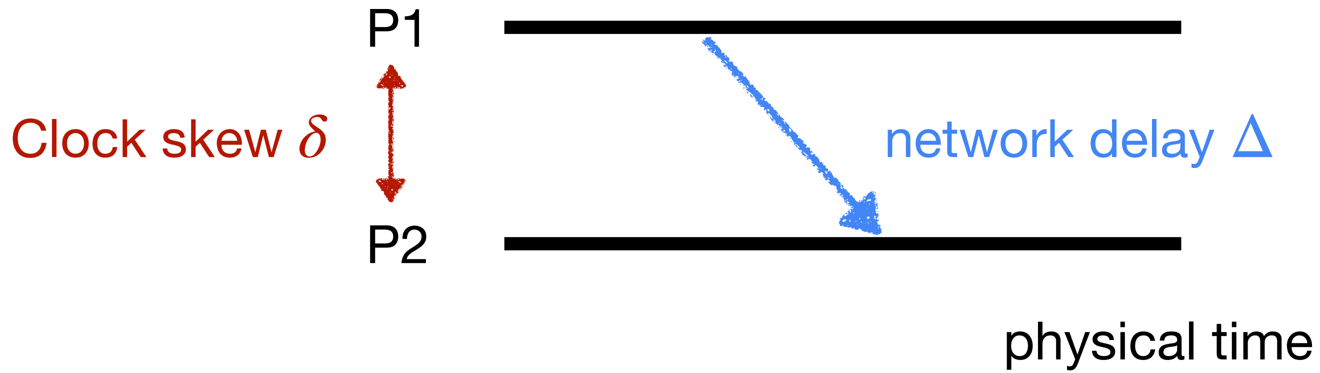

System model: network synchrony

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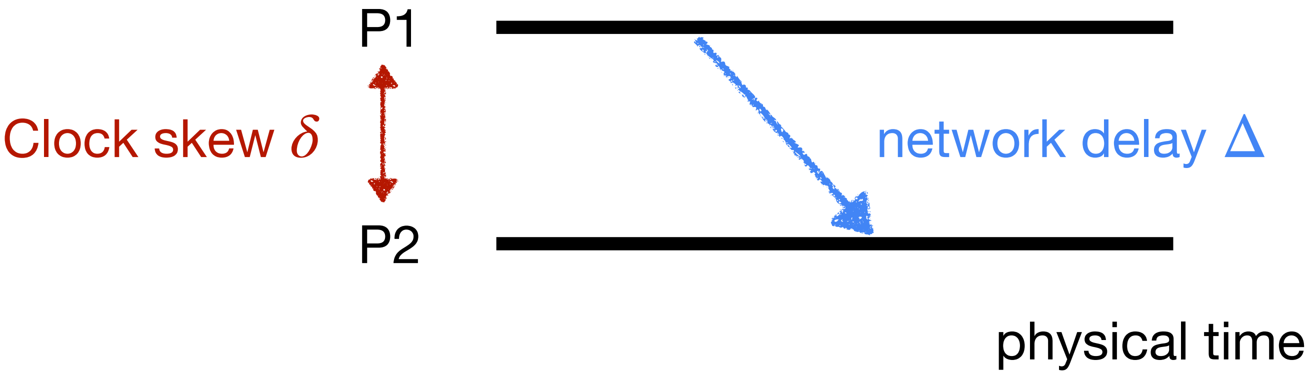
Partially synchronous:
Communication among servers can have a global stabilization time (GST), unknown to processors.

1. δ and Δ both exist but unknown, or
2. δ and Δ are known after GST



chalk talk

Let’s design a simple consensus algorithm

- Assume processes cannot fail
- Synchronous network
- We’d like to have:

Termination: Eventually each correct process sets its decision variable

Agreement: Decision value of all correct processes is the same; if p_i and p_j are correct and ahem entered the decided state, then $d_i = d_j (i, j = 1,2,\ldots,N)$

Integrity/Validity: If the correct processes all proposed the same value, then any correct process in the decided state has chosen that value.

Service properties

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Something cannot happen

Safety

No two correct nodes decide differently

Service properties

Termination: Eventually each correct process sets its decision variable

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Something cannot happen

Safety

No two correct nodes decide differently

Liveness

Nodes eventually decide

Something must happen

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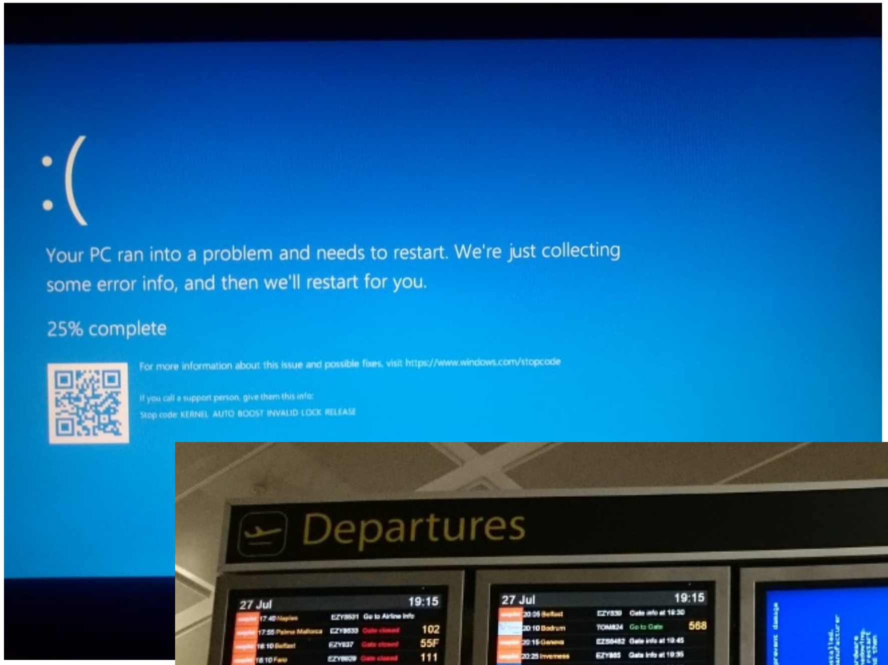
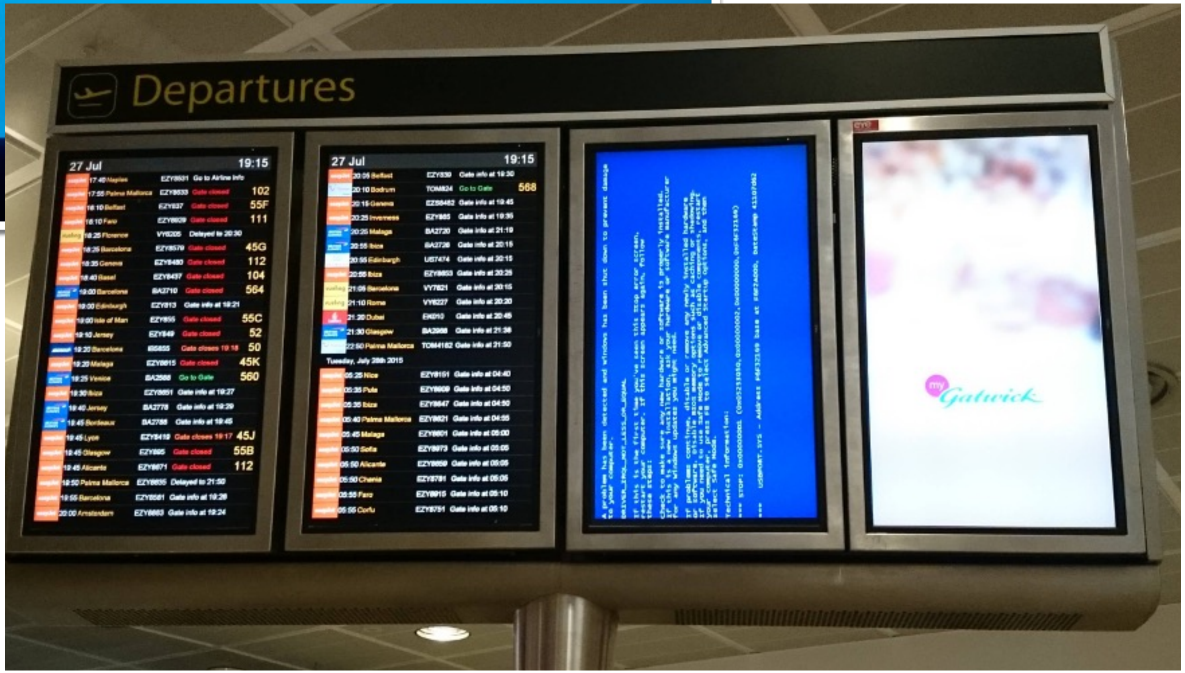
Faults…



:(
Your PC ran into a problem and needs to restart. We're just collecting some error info, and then we'll restart for you.
25% complete
For more information about this issue and possible fixes, visit https://www.windows.com/stopcode
If you call a support person, give them this info:
Stop code: KERNEL AUTO BOOST INVALID LOCK RELEASE

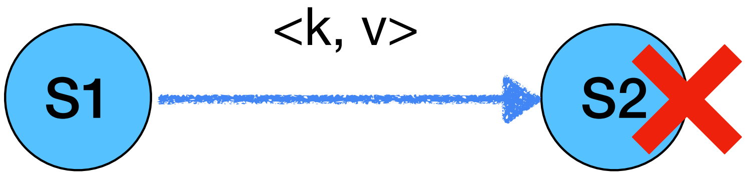


Departures
27 Jul
19:15
27 Jul
19:15

Coca-Cola

Family of faults

- Crash faults
- Omission faults
  - Send omission
  - Receive omission
- Timing faults



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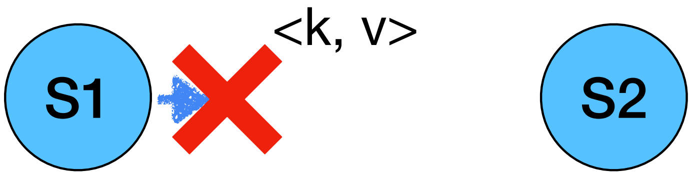

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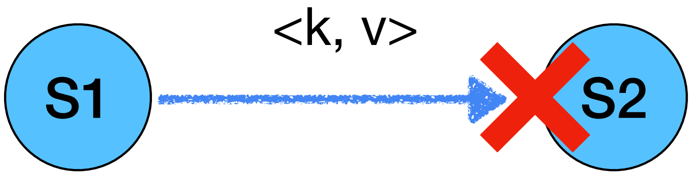

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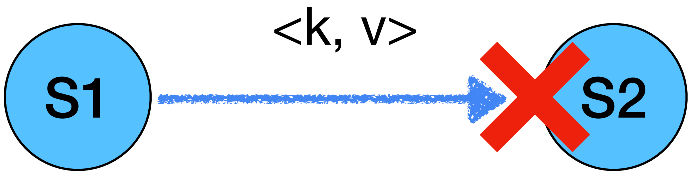

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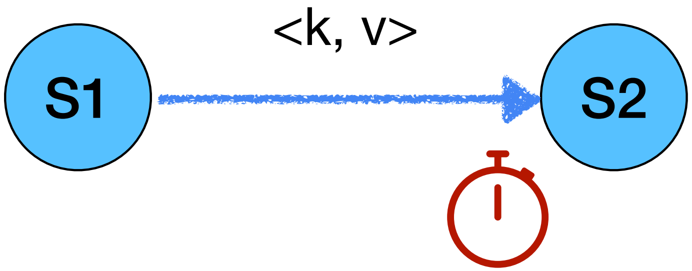


```
if timer.timeout:
   proceed without v
```

Family of faults

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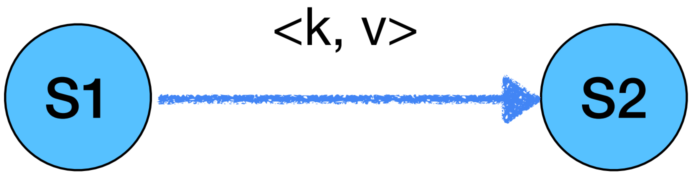
Worst thing that can happen:
S2 does not have the value



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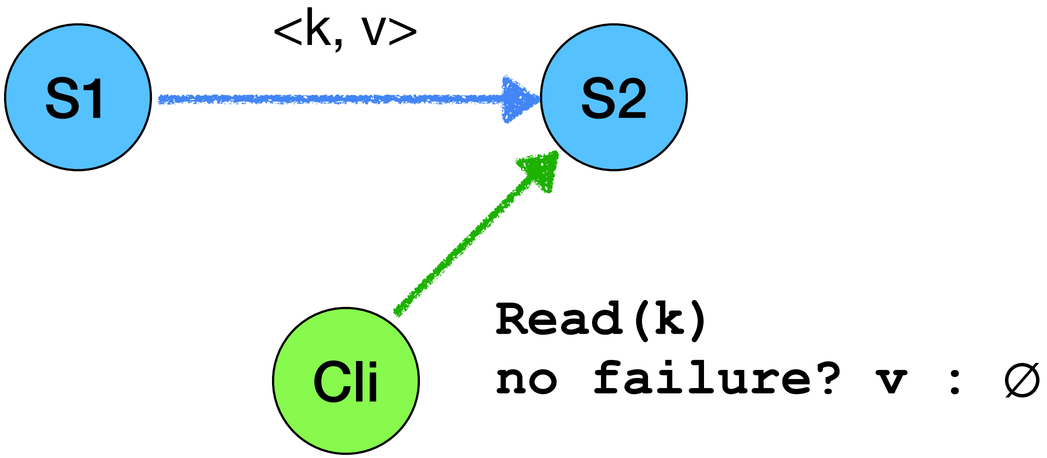

Family of faults

Benign faults

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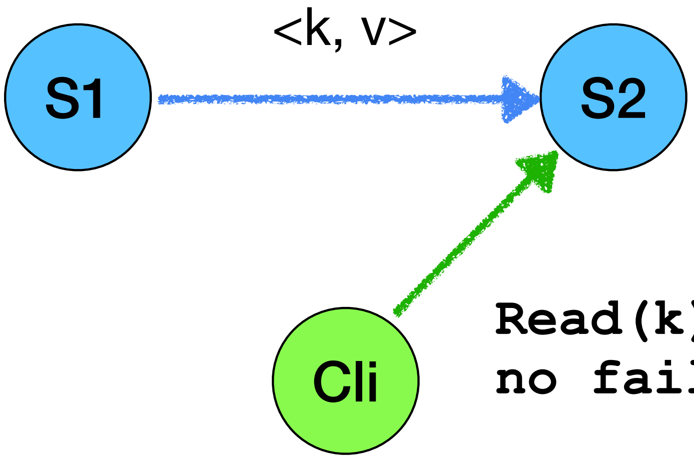


```
Read(k)
no failure? v : ∅
```

Family of faults

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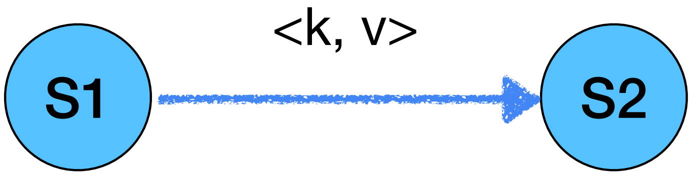

Byzantine faults

- Any arbitrary behaviour, e.g.,
  - Stop responding
  - Send erroneous values

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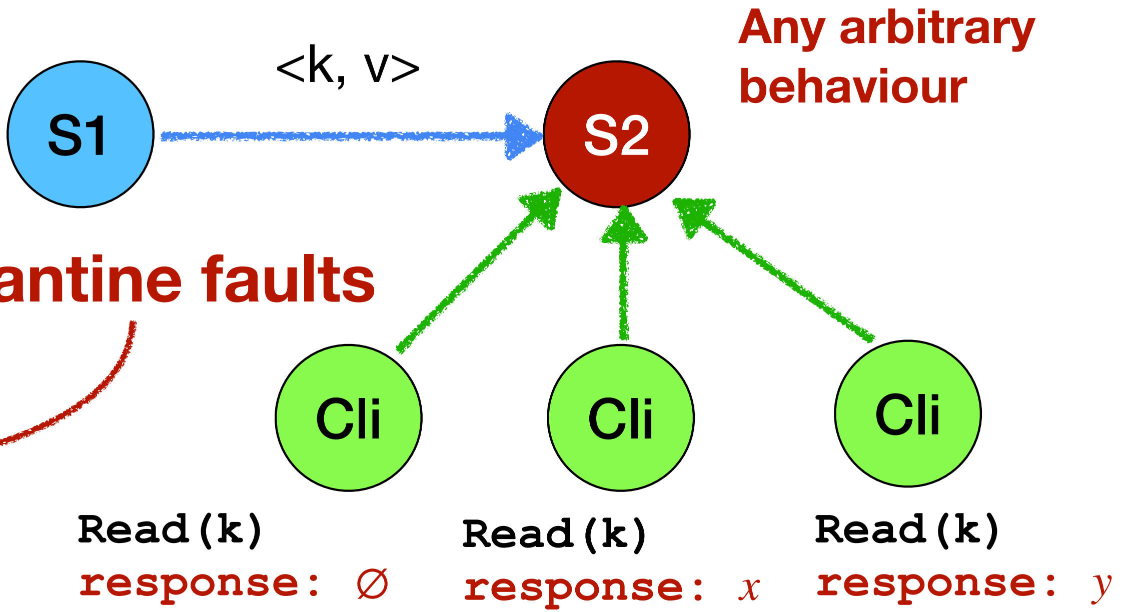

Family of faults

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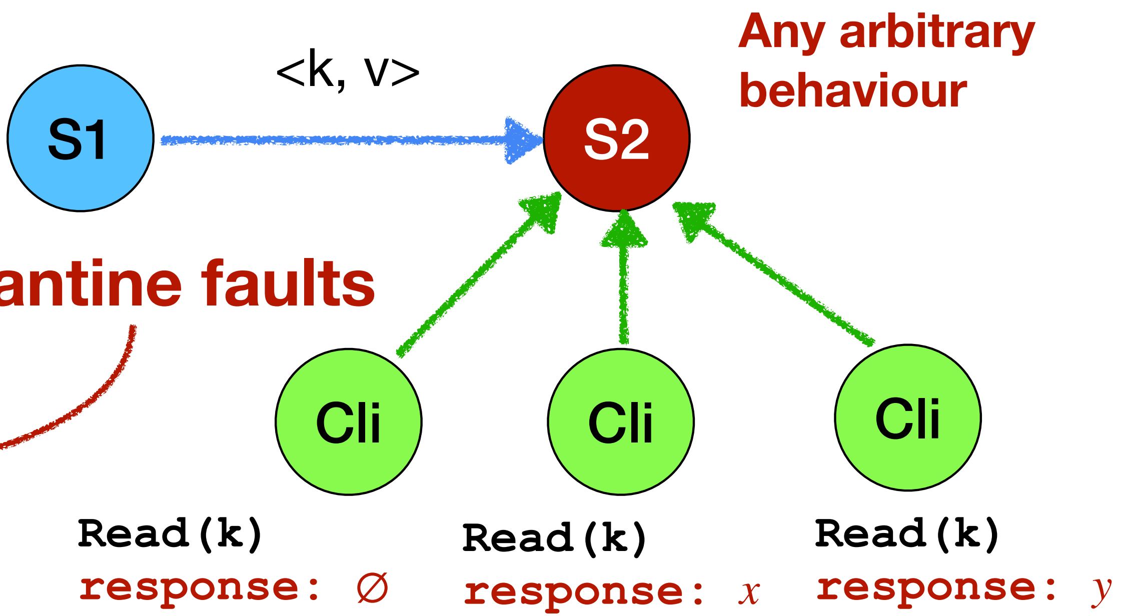
Worst thing that can happen:
Any behaviour that can do the most harm



Byzantine faults

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Family of faults: summary

Fault tolerance

Benign faults

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- Timing faults

- Crash fault tolerance (CFT) algorithms
    - Paxos, ViewStamped Replication, Raft [ATC'13]
- Applications (everything distributed):
    - File systems: HDFS and GFS
    - Databases: Google Spanner and etcd
    - Coordination: Chubby and Zookeeper

Byzantine faults

- Any arbitrary behaviour, e.g.,
    - Stop responding
    - Send erroneous values

- Byzantine fault tolerance (BFT) algorithms
    - PBFT [OSDI'99], HotStuff [PODC'21], Pompe [OSDI'22]
- Applications (safety critical):
    - Unreliable hardware: Airplanes
    - Blockchains: Facebook Diem, Microsoft CCF

Algorithms we will talk about

- Paxos: <- Today's topic
  - How to choose a value under **benign failures**
- Raft [ATC'14]:
  - How to replicate log under **benign failures**?
- PBFT [OSDI'99]:
  - How to replicate log under **Byzantine (arbitrary) failures**?

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Paxos

- Papers:
  - Lamport L. The part-time parliament[J]. ACM Transactions on Computer Systems (TOCS), 1998, 16(2): 133-169.
  - Lamport L. Paxos made simple[J]. ACM Sigact News, 2001, 32(4): 18-25.
- System model
  - Asynchronous
  - CFT: tolerating benign faults (non-Byzantine)

Fundamental #1: Server roles

Proposers (leader)

- receive client requests
- propose received requests
- coordinate consensus process for its proposed requests

Acceptors (follower)

- respond to requests from proposers
- validate states of requests
- store chosen values and state of the process

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Learners (subscriber)

- want to know which value is chosen
- subscribe to acceptors
  - one or a few learners communicate with acceptors
  - propagate the message among learners

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According to the application that uses Paxos,
a server can be a proposer, an acceptor, or both

Fundamental #2: Proposals

- Each proposal has a unique number (proposal number)
  - Higher number take a priority over lower numbers
  - Similar to Lamport clock, proposers can increase a proposal number

Fundamental #3: Phases

Prepare phase
(Phase 1)

Phase 1. (a) A proposer selects a proposal number n and sends a *prepare* request with number n to a majority of acceptors.

(b) If an acceptor receives a *prepare* request with number n greater than that of any *prepare* request to which it has already responded, then it responds to the request with a promise not to accept any more proposals numbered less than n and with the highest-numbered proposal (if any) that it has accepted.

Accept phase
(Phase 2)

Phase 2. (a) If the proposer receives a response to its *prepare* requests (numbered n) from a majority of acceptors, then it sends an *accept* request to each of those acceptors for a proposal numbered n with a value v, where v is the value of the highest-numbered proposal among the responses, or is any value if the responses reported no proposals.

(b) If an acceptor receives an *accept* request for a proposal numbered n, it accepts the proposal unless it has already responded to a *prepare* request having a number greater than n.

Proposers

(1) Choose new proposal number *n*.
(2) Broadcast Prepare(*n*) to all servers.

(4) When responses received from majority, if any *acceptedValue* returned, replace value with *acceptedValue* for highest *acceptedProposal*.

(5) Broadcast Accept(*n*, *value*) to all servers

(7) When responses received from majority:
-> Any rejections (result > n) : go to (1)
-> Otherwise, value is chosen

Acceptors

(3) Respond to Prepare(*n*):
-> If n > *minProposal*, then *minProposal* = *n*
-> Return (*acceptedProposal*, *acceptedValue*)

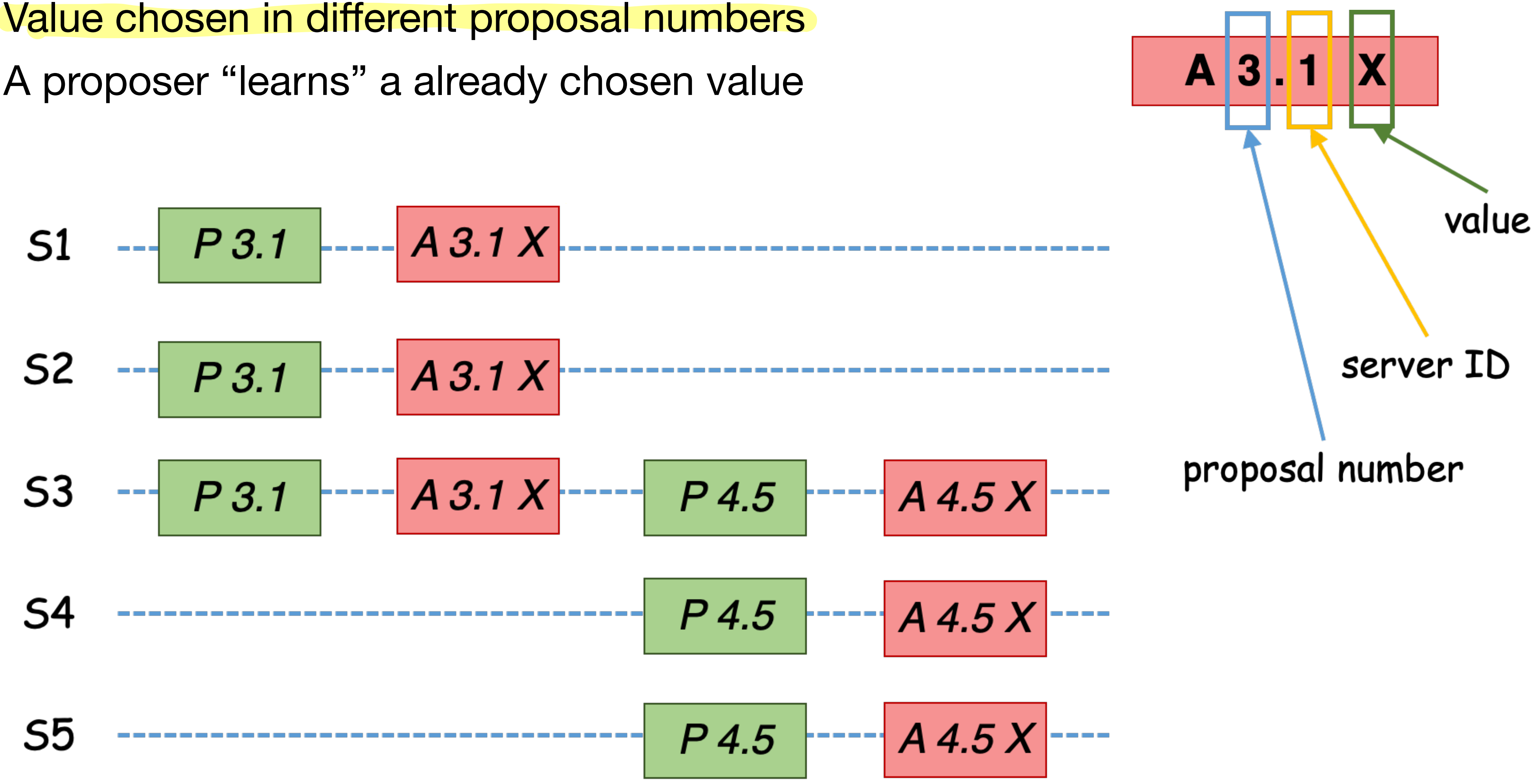
(6) Respond to Accept(*n*, *value*):
-> If *n* >= *minProposal* then
acceptedProposal = *minProposal* = *n*;
acceptedValue = *value*;
-> Return (minProposal)

Acceptors must record *minProposal*, *acceptedProposal*, and *acceptedValue* on stable storage (disk).

From Dr. Diego Ongaro's Paxos lecture

Value chosen in different proposal numbers

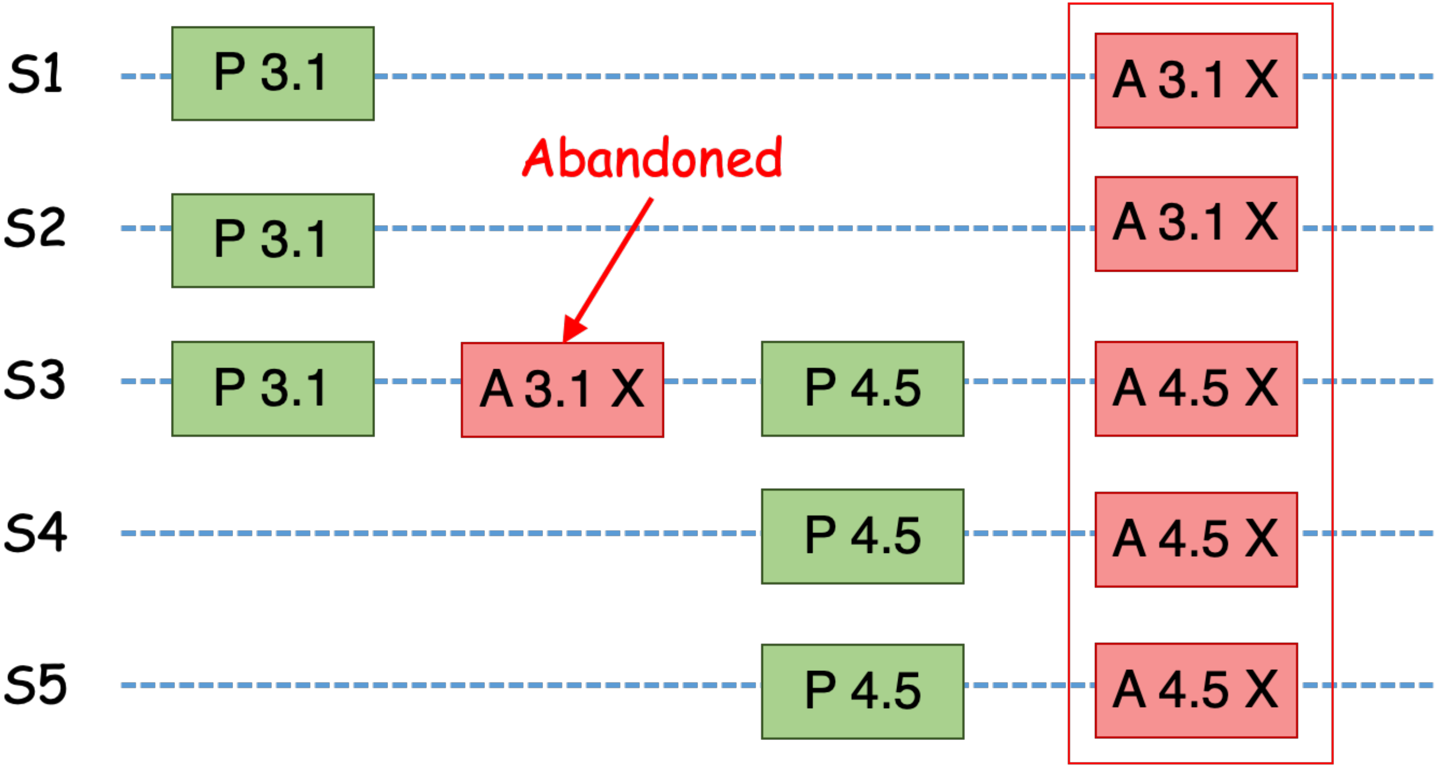
A proposer "learns" a already chosen value



From Dr. Diego Ongaro's Paxos lecture

Value chosen in different proposal numbers

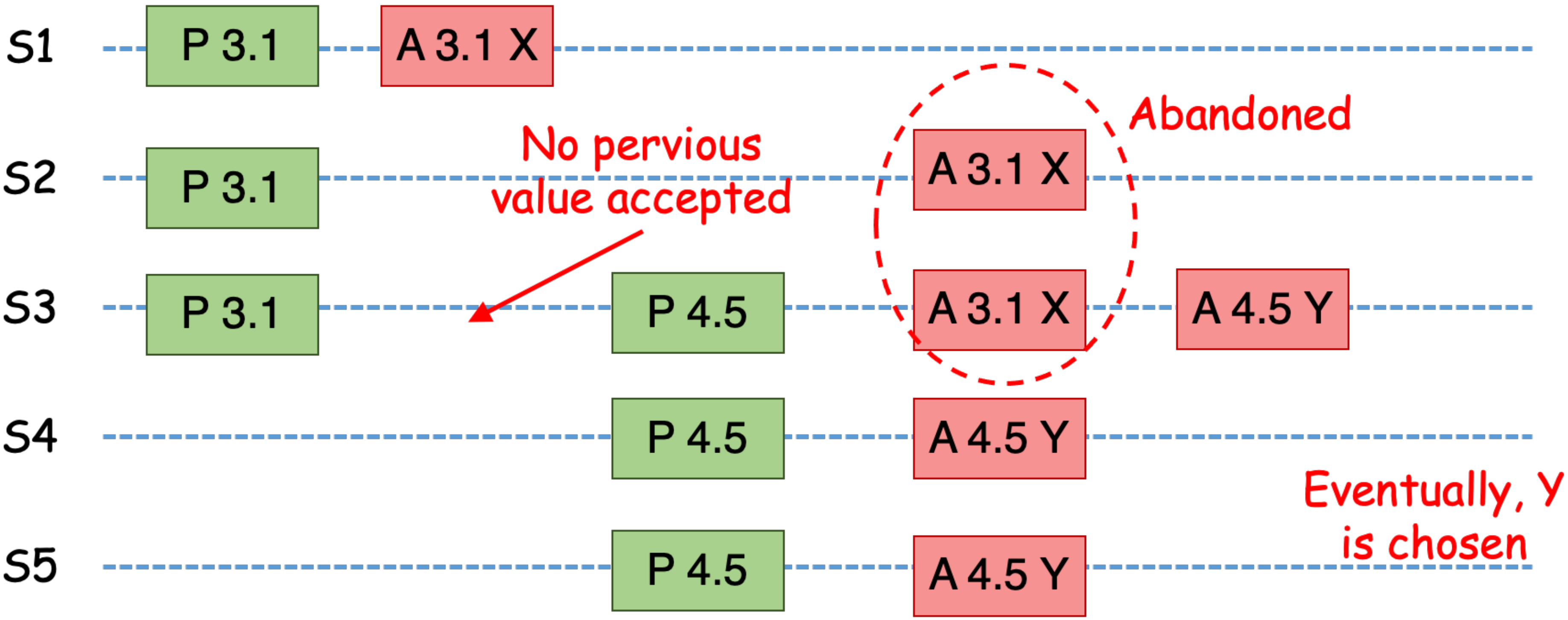
A proposer “learns” a not chosen value



From Dr. Diego Ongaro's Paxos lecture

A new value is chosen in different proposal numbers

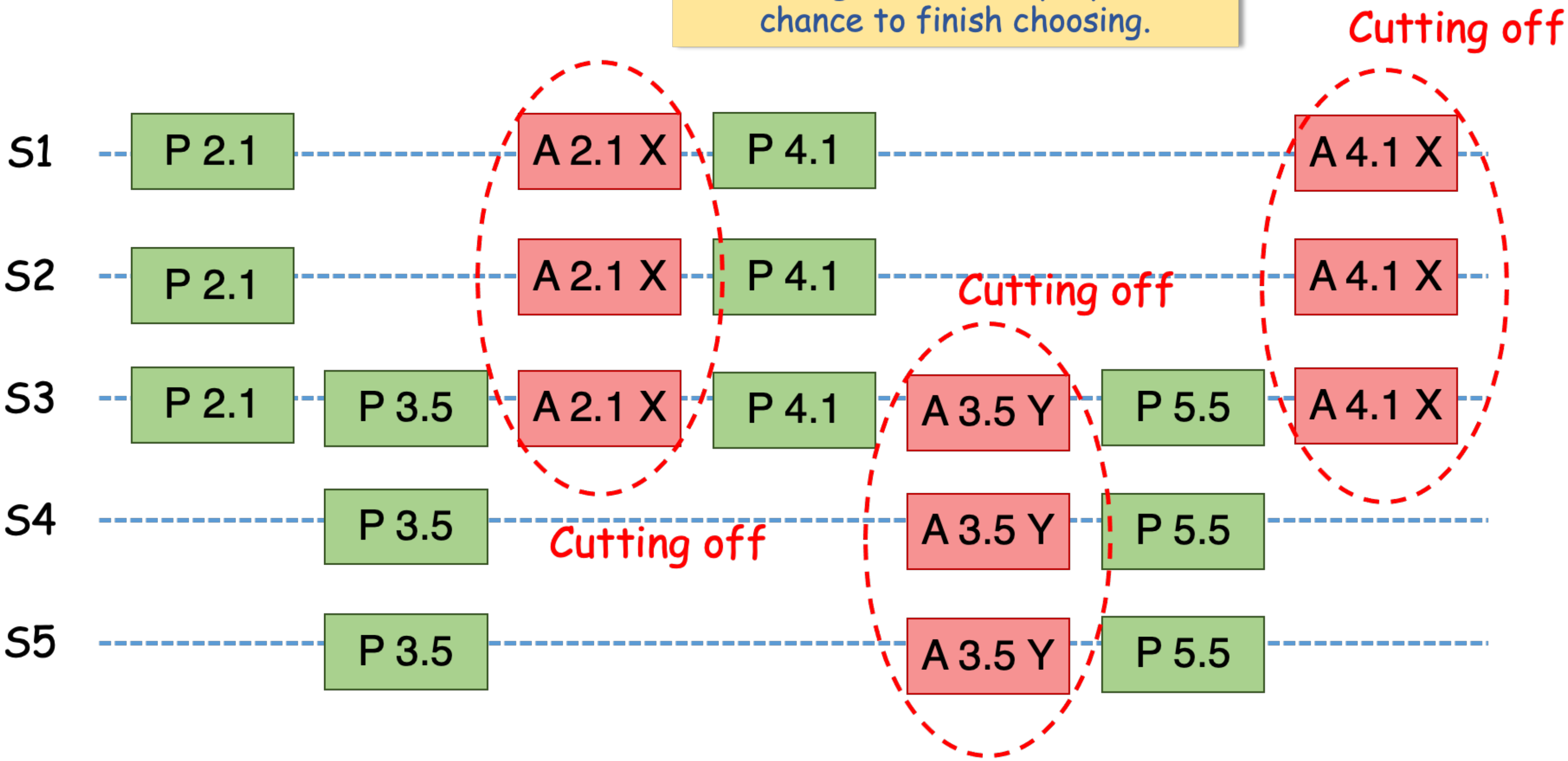
A proposer does not see an unchosen value



From Dr. Diego Ongaro's Paxos lecture

Livelock

Hint:
=> one solution:
Randomized delay before restarting. Give other proposers a chance to finish choosing.



Summary of Paxos

- Anyone can be a proposer/leader
  - Advantages?
  - Disadvantages?
- Only proposer knows which value has been chosen
- If other servers want to know, must execute Paxos with their own proposal
- Competing proposers can cause a livelock

Worksheet