Vector Clocks & Distributed snapshots

CS 452

Vector clocks

Precisely represent transitive causal relationships

$T(A) < T(B) \leftrightarrow$ *happens-before*(A, B)

Idea: track events known to each node, *on each node*

Used in practice for eventual and causal consistency

- git, Amazon Dynamo, …

Vector clocks

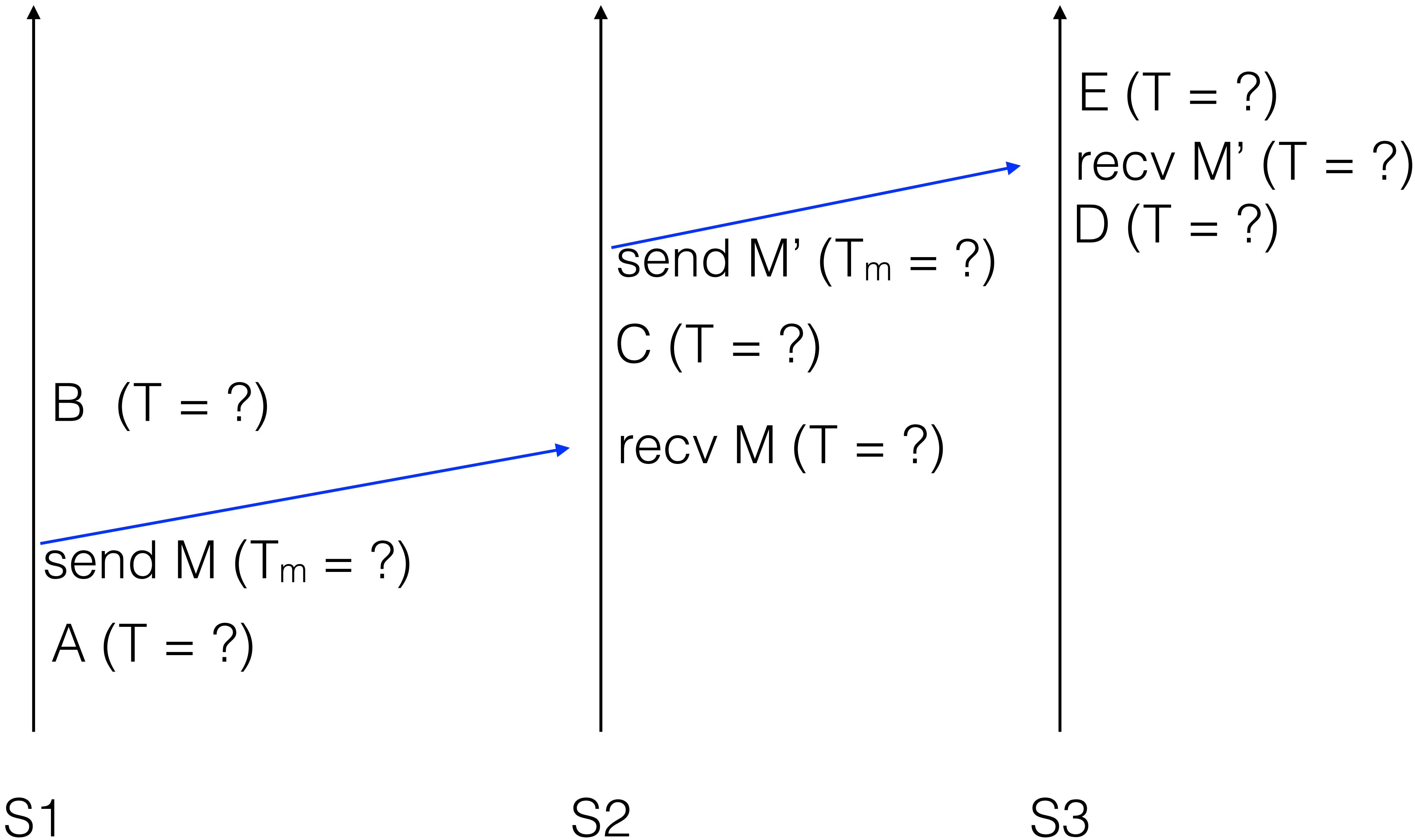
Clock is a vector C, length = # of nodes

On node i, increment C[i] on each event

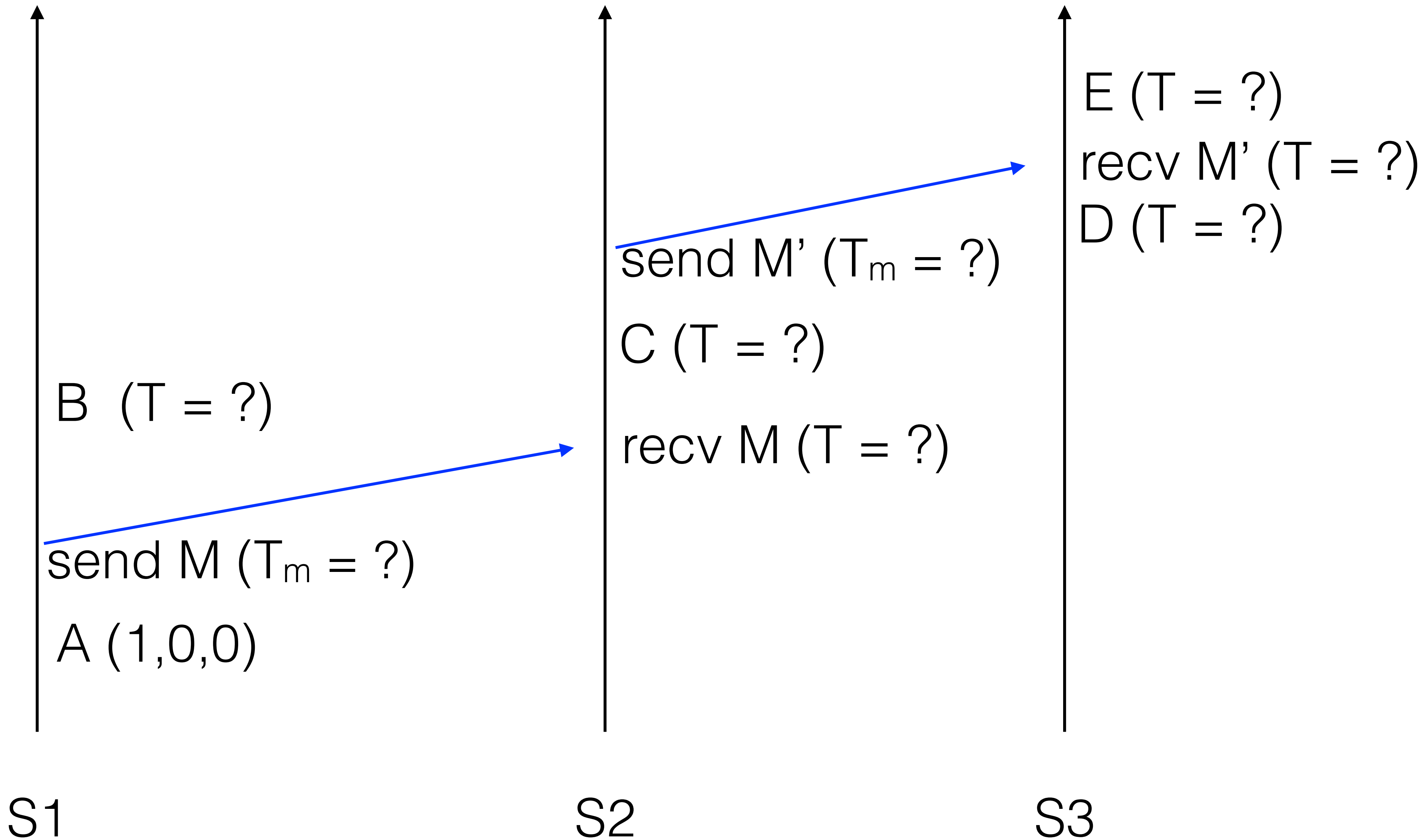
On receipt of message with clock C_m on node i:

- increment C[i]
- for each j != i
  - C[j] = *max*(C[j], C_m[j])

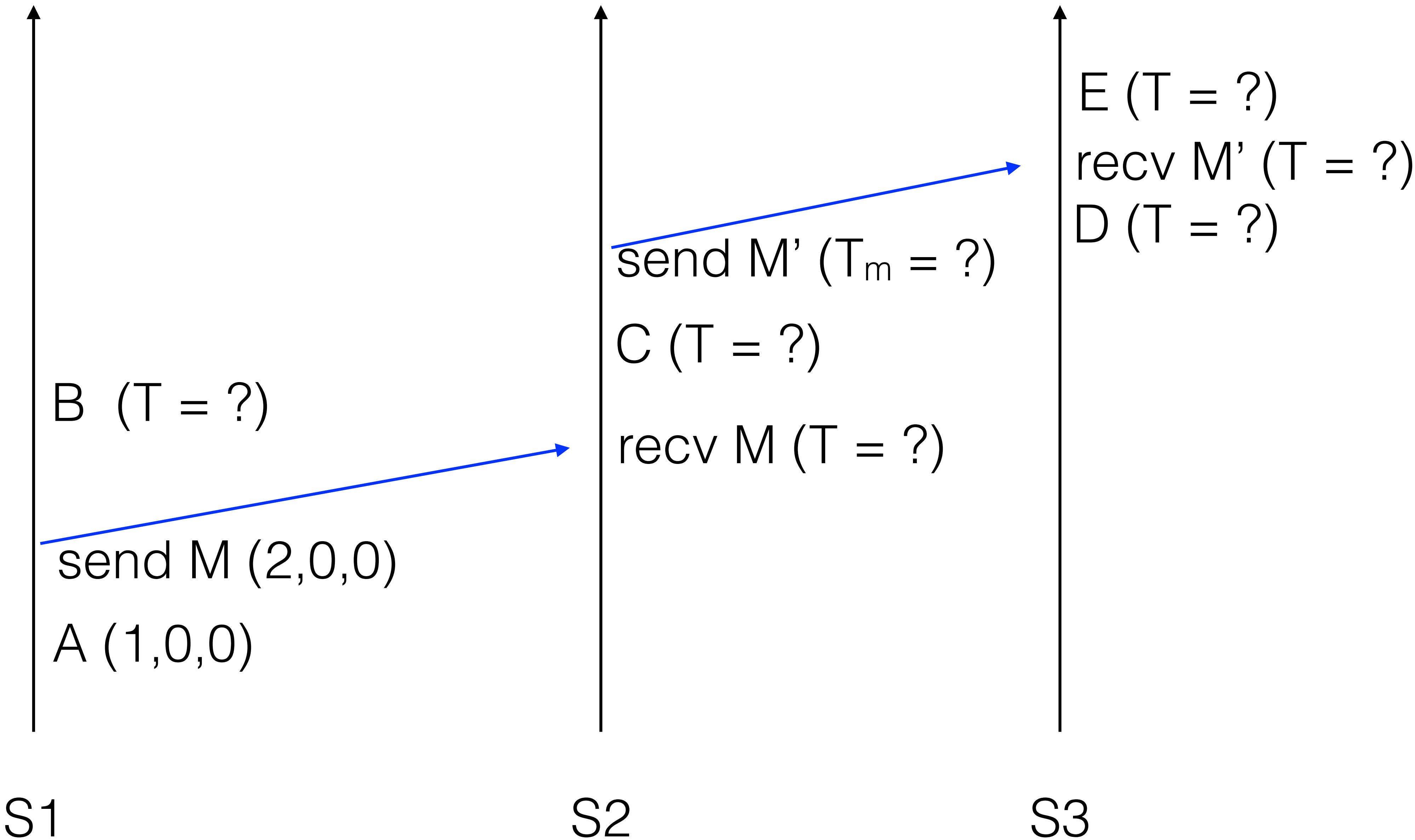
Example



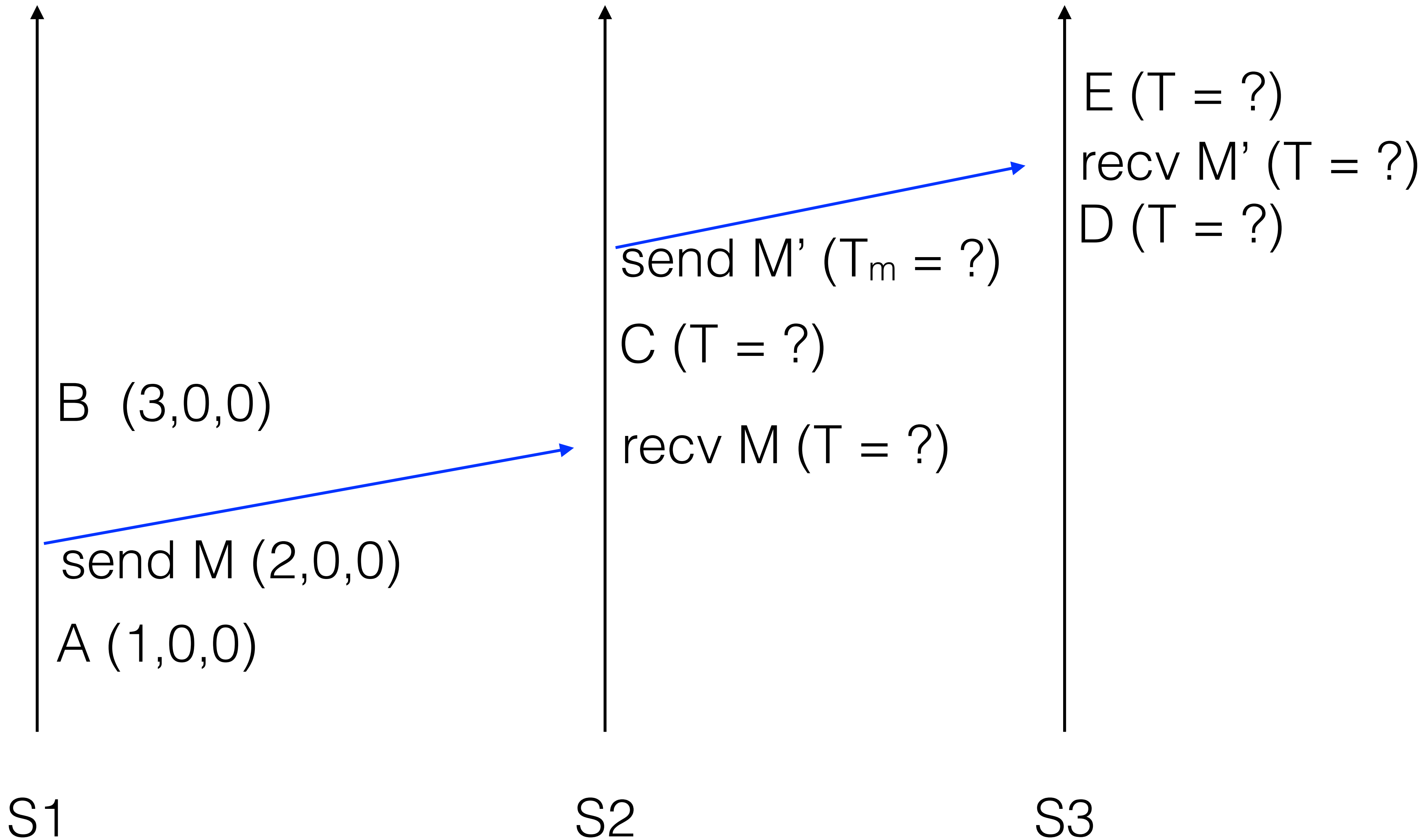
Example



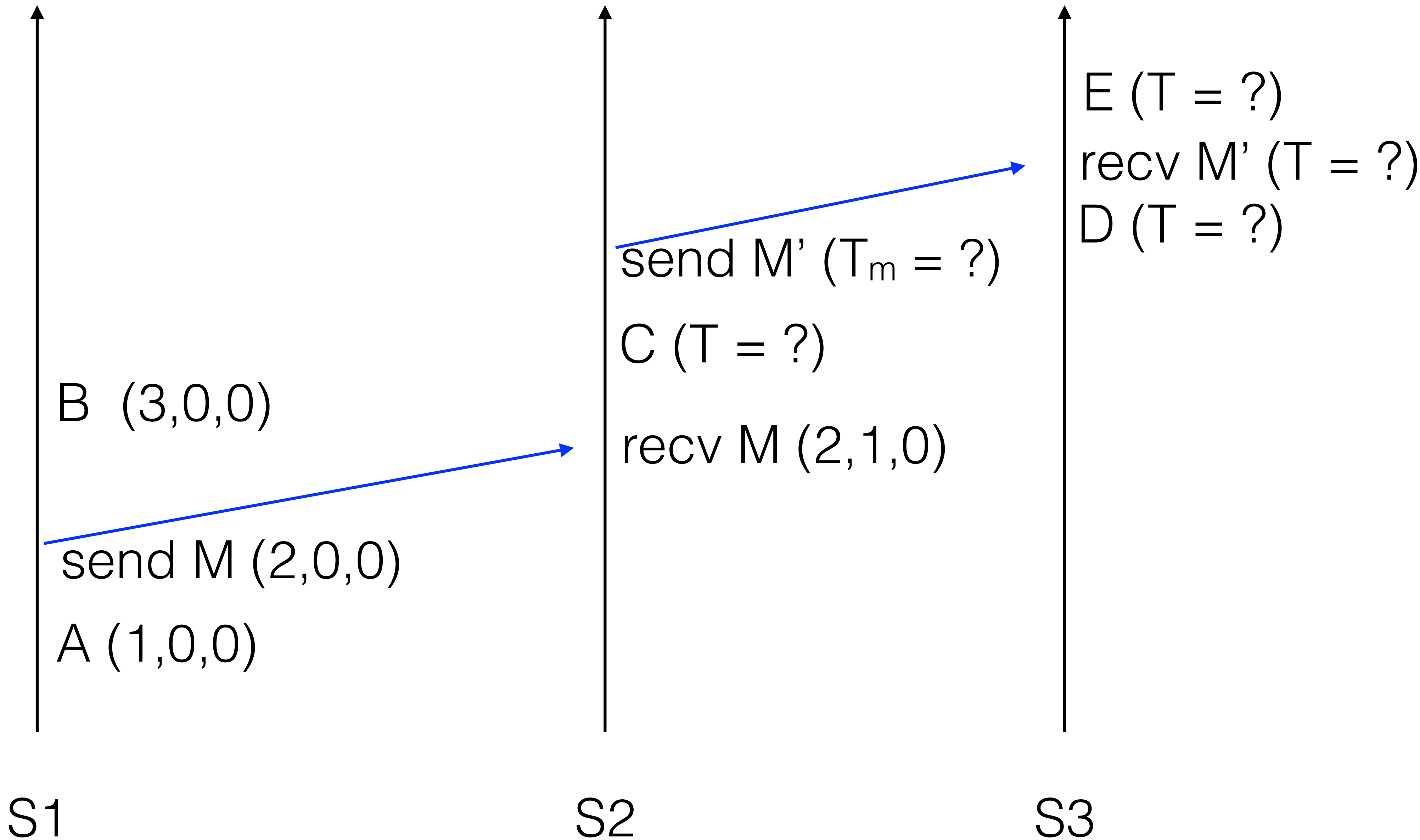
Example



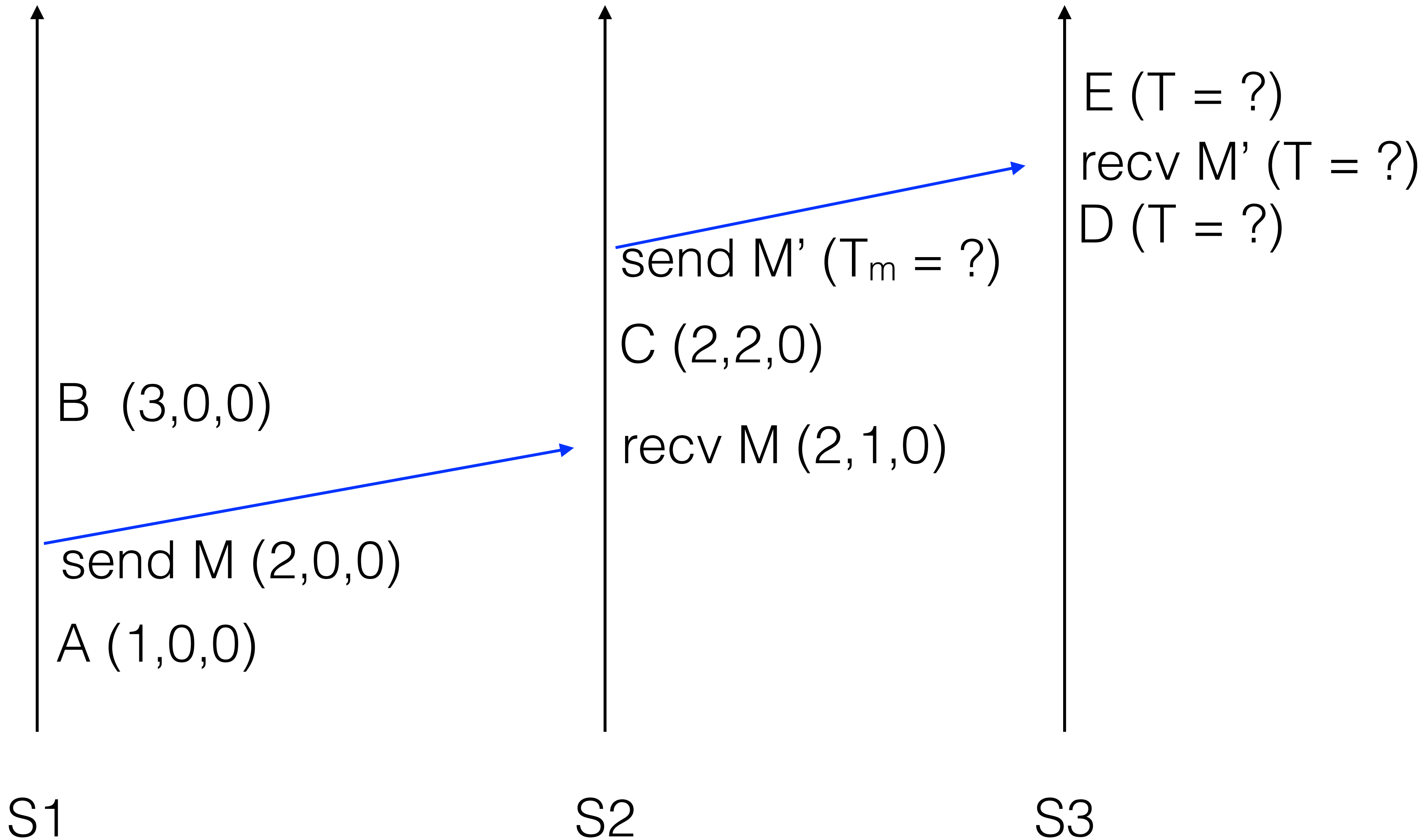
Example



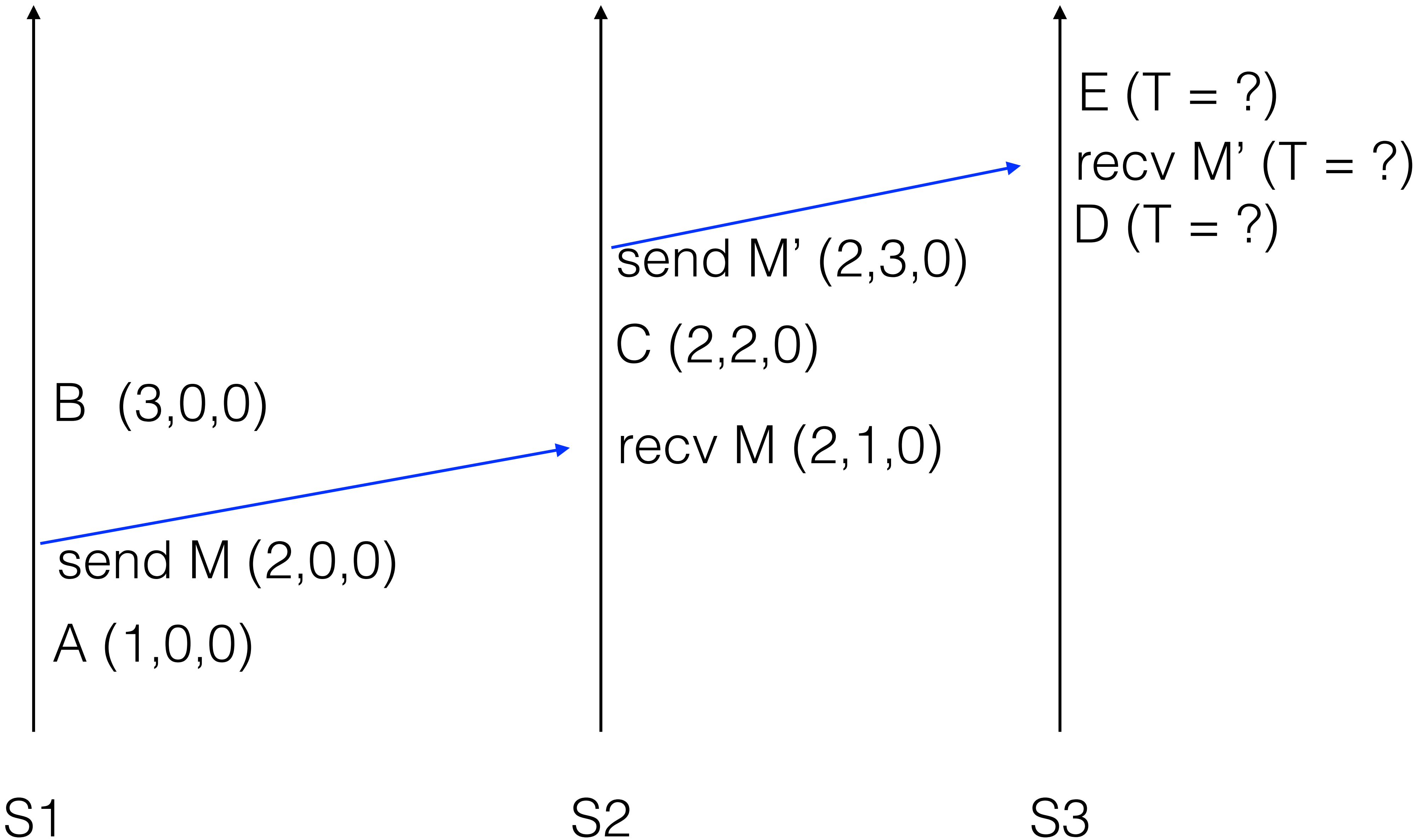
Example



Example

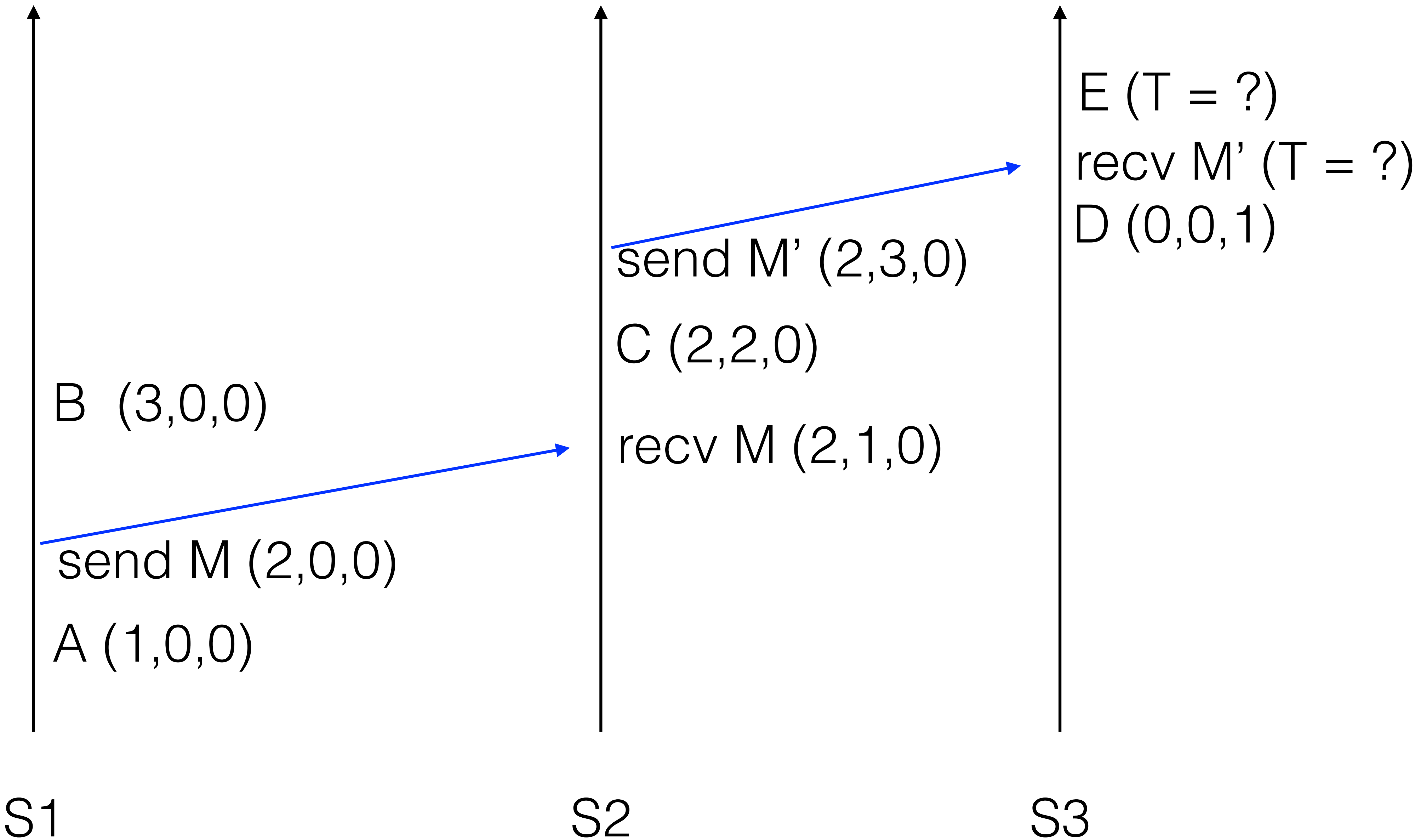

E (T = ?)
recv M' (T = ?)
D (T = ?)
send M' (Tm = ?)
C (2,2,0)
B (3,0,0)
recv M (2,1,0)
send M (2,0,0)
A (1,0,0)
S1
S2
S3

Example

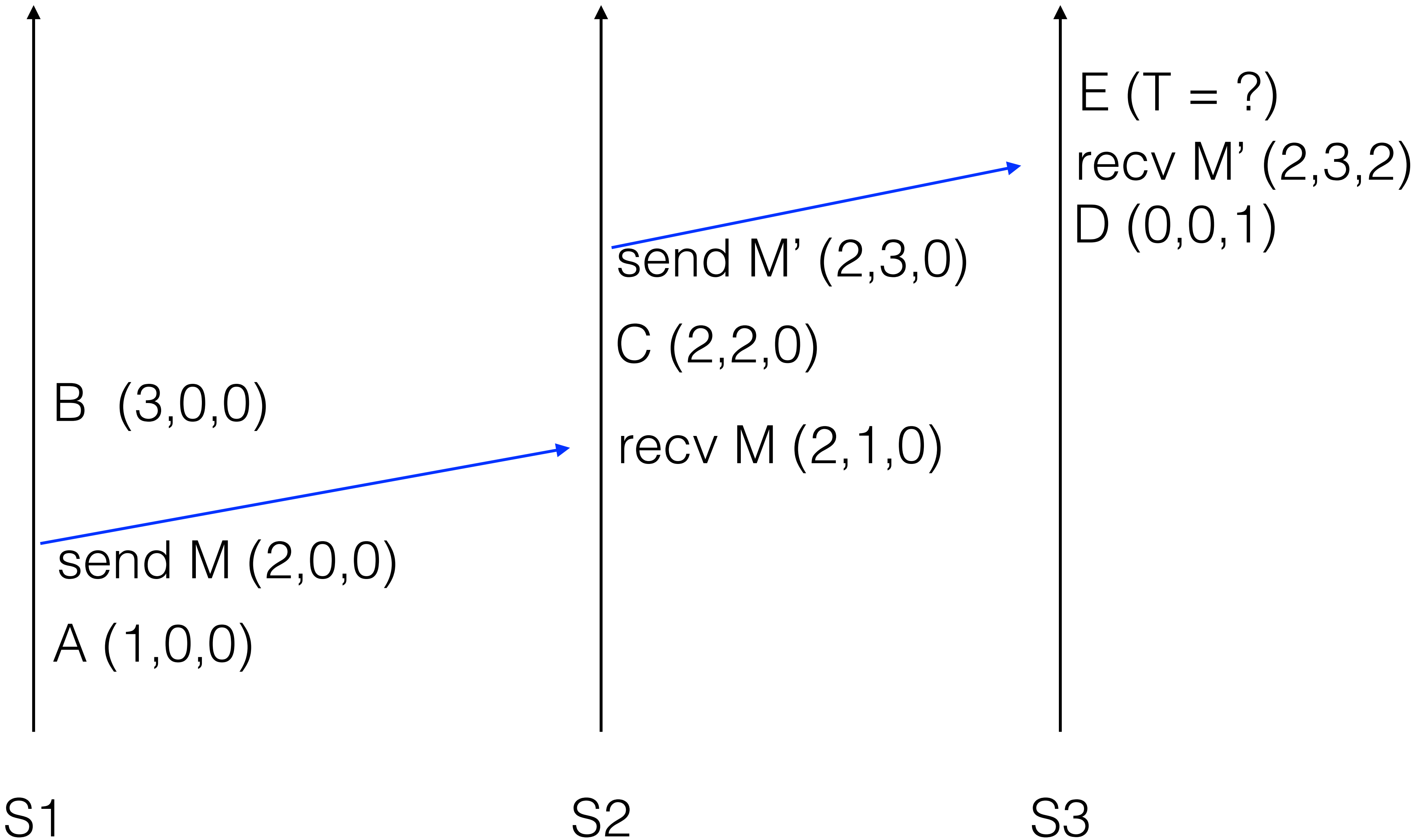


E (T = ?)
recv M’ (T = ?)
D (T = ?)
send M’ (2,3,0)
C (2,2,0)
B (3,0,0)
recv M (2,1,0)
send M (2,0,0)
A (1,0,0)
S1
S2
S3

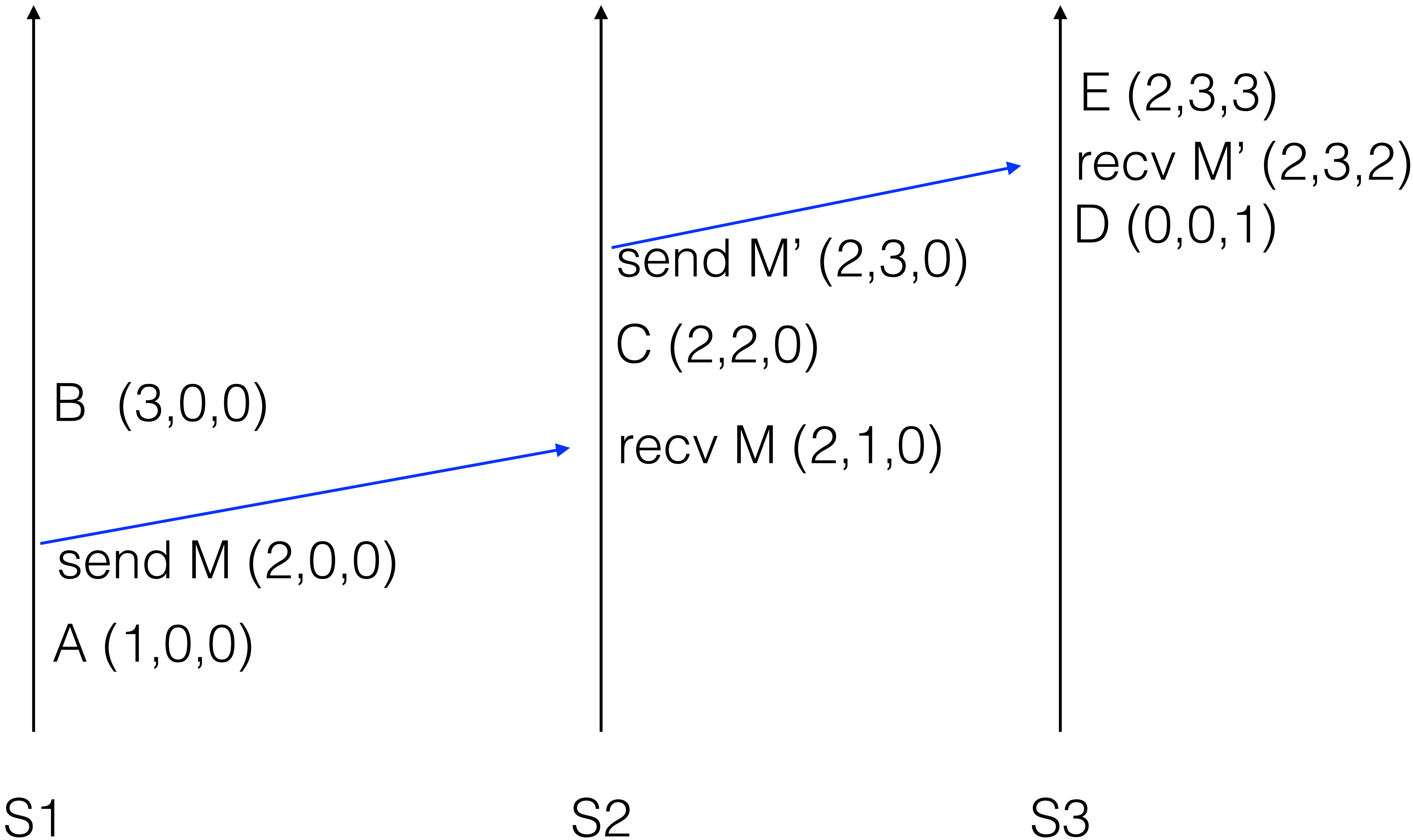
Example


E (T = ?)
recv M’ (T = ?)
D (0,0,1)
send M’ (2,3,0)
C (2,2,0)
B (3,0,0)
recv M (2,1,0)
send M (2,0,0)
A (1,0,0)
S1
S2
S3

Example

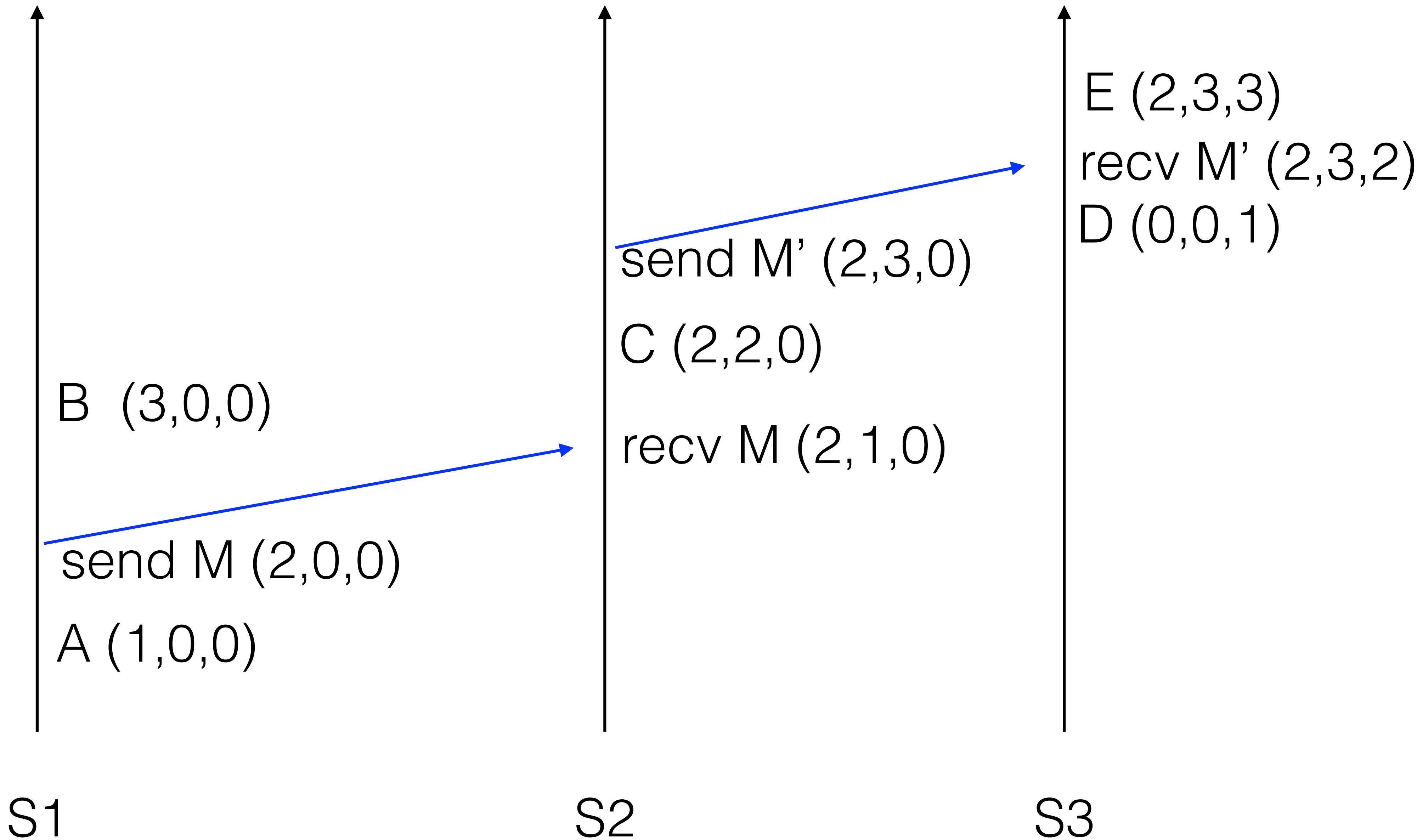

E (T = ?)
recv M’ (2,3,2)
D (0,0,1)
send M’ (2,3,0)
C (2,2,0)
B (3,0,0)
recv M (2,1,0)
send M (2,0,0)
A (1,0,0)
S1
S2
S3

Example



E (2,3,3)
recv M’ (2,3,2)
D (0,0,1)
send M’ (2,3,0)
C (2,2,0)
B (3,0,0)
recv M (2,1,0)
send M (2,0,0)
A (1,0,0)
S1
S2
S3

Example


E (2,3,3)
recv M’ (2,3,2)
D (0,0,1)
send M’ (2,3,0)
C (2,2,0)
B (3,0,0)
recv M (2,1,0)
send M (2,0,0)
A (1,0,0)
S1
S2
S3

Vector Clocks

Compare vectors element by element

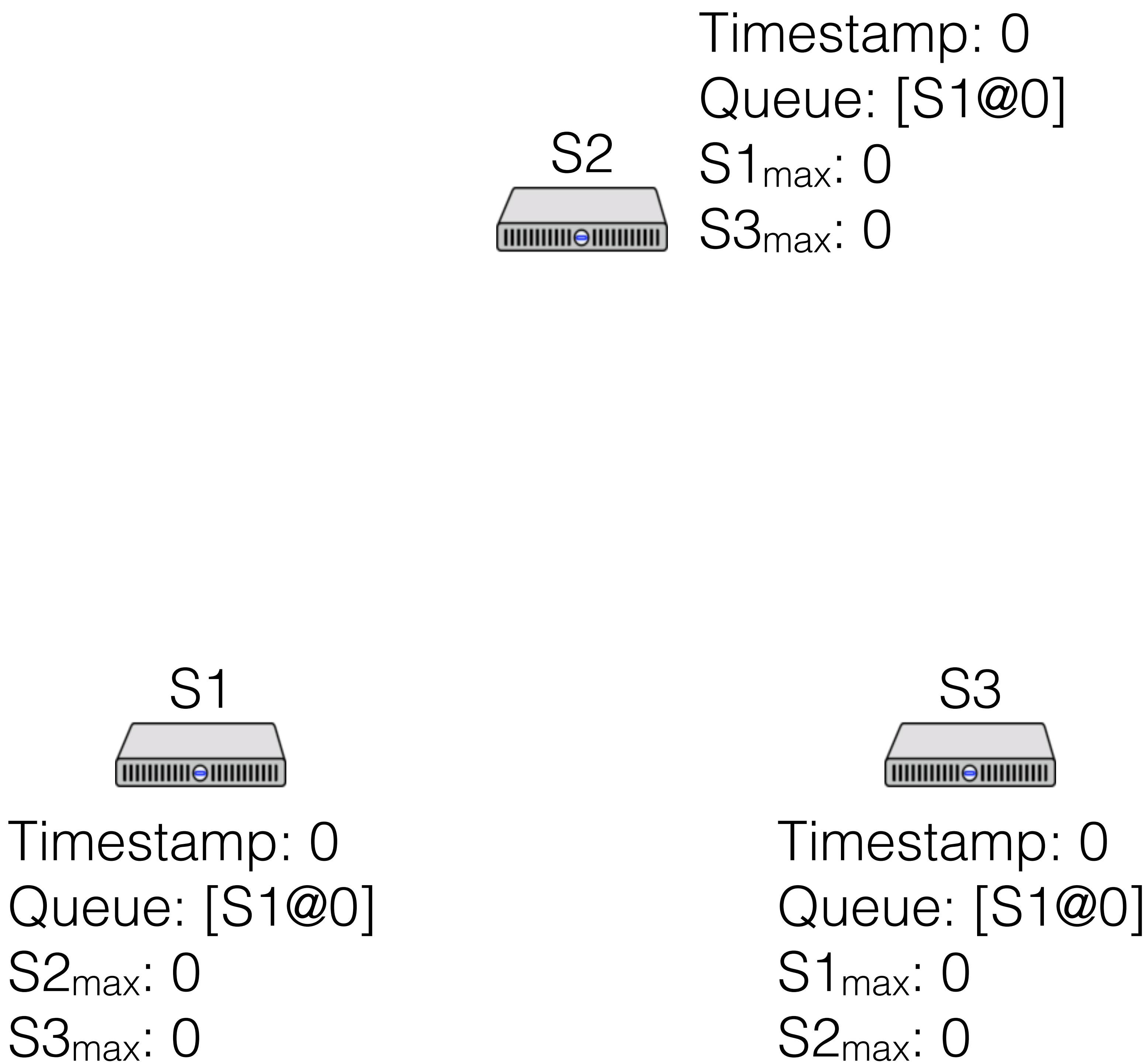
Provided the vectors are not identical,

If $C_x[i] < C_y[i]$ and $C_x[j] > C_y[j]$ for some i, j

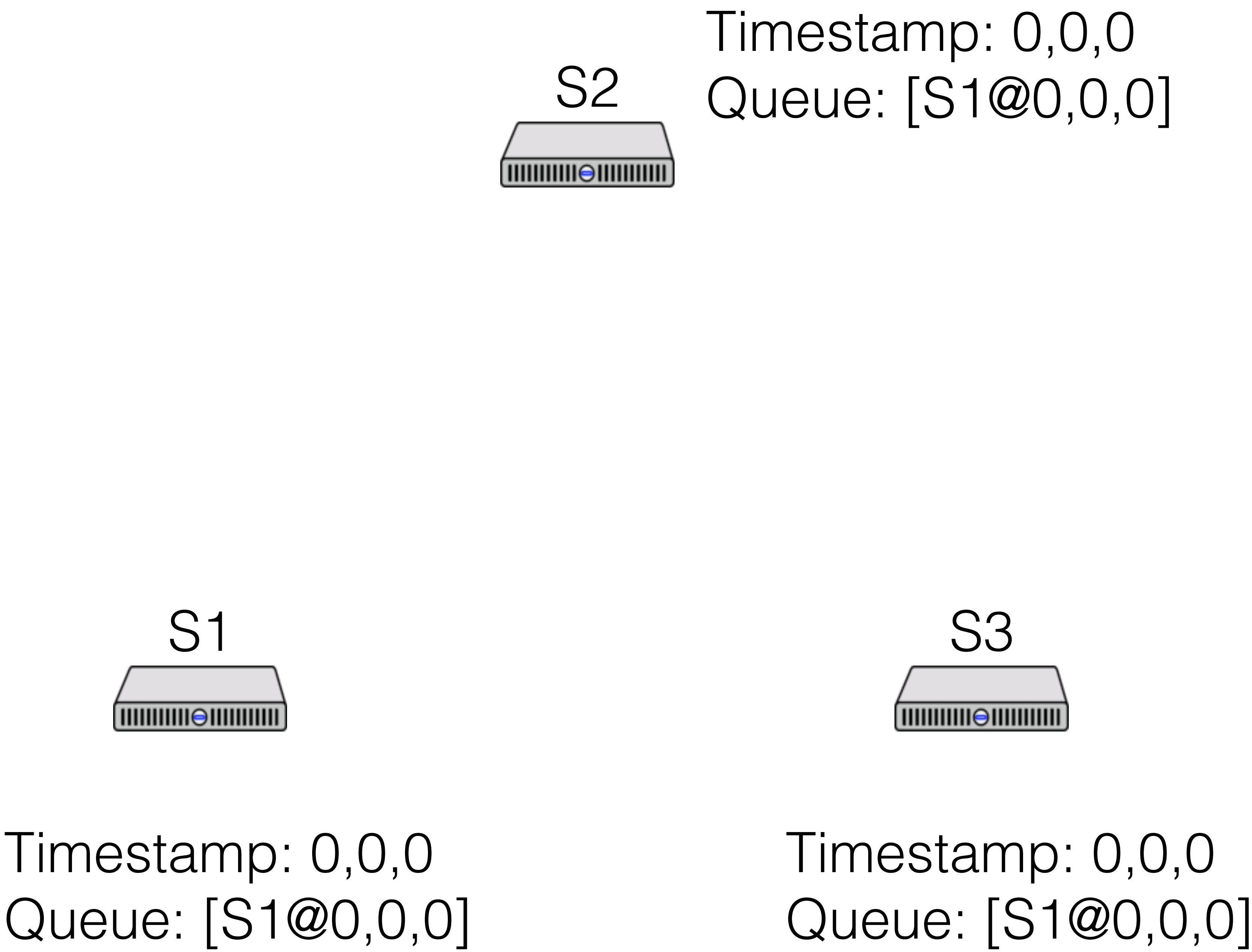
C_x and C_y are concurrent

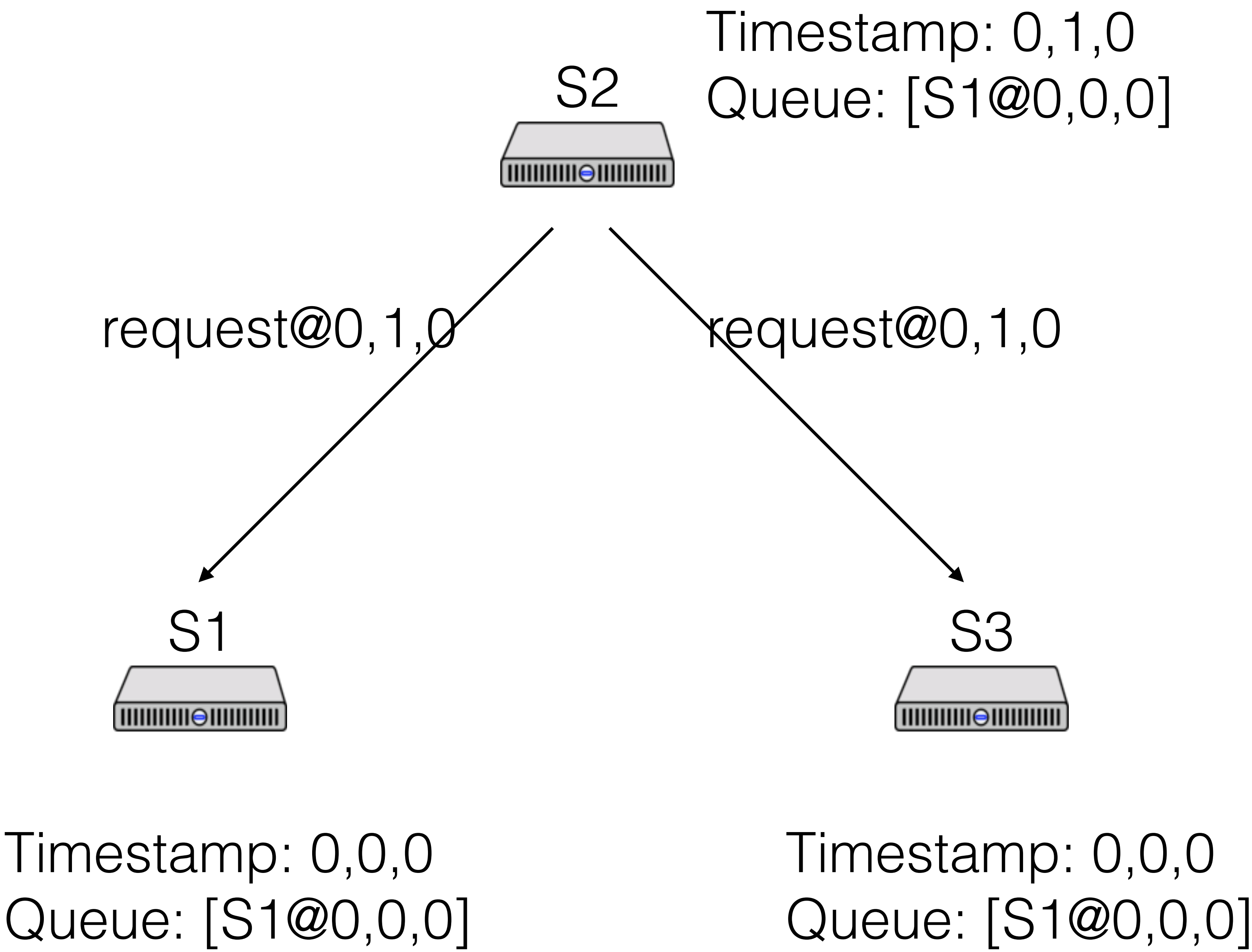
if $C_x[i] <= C_y[i]$ for all i

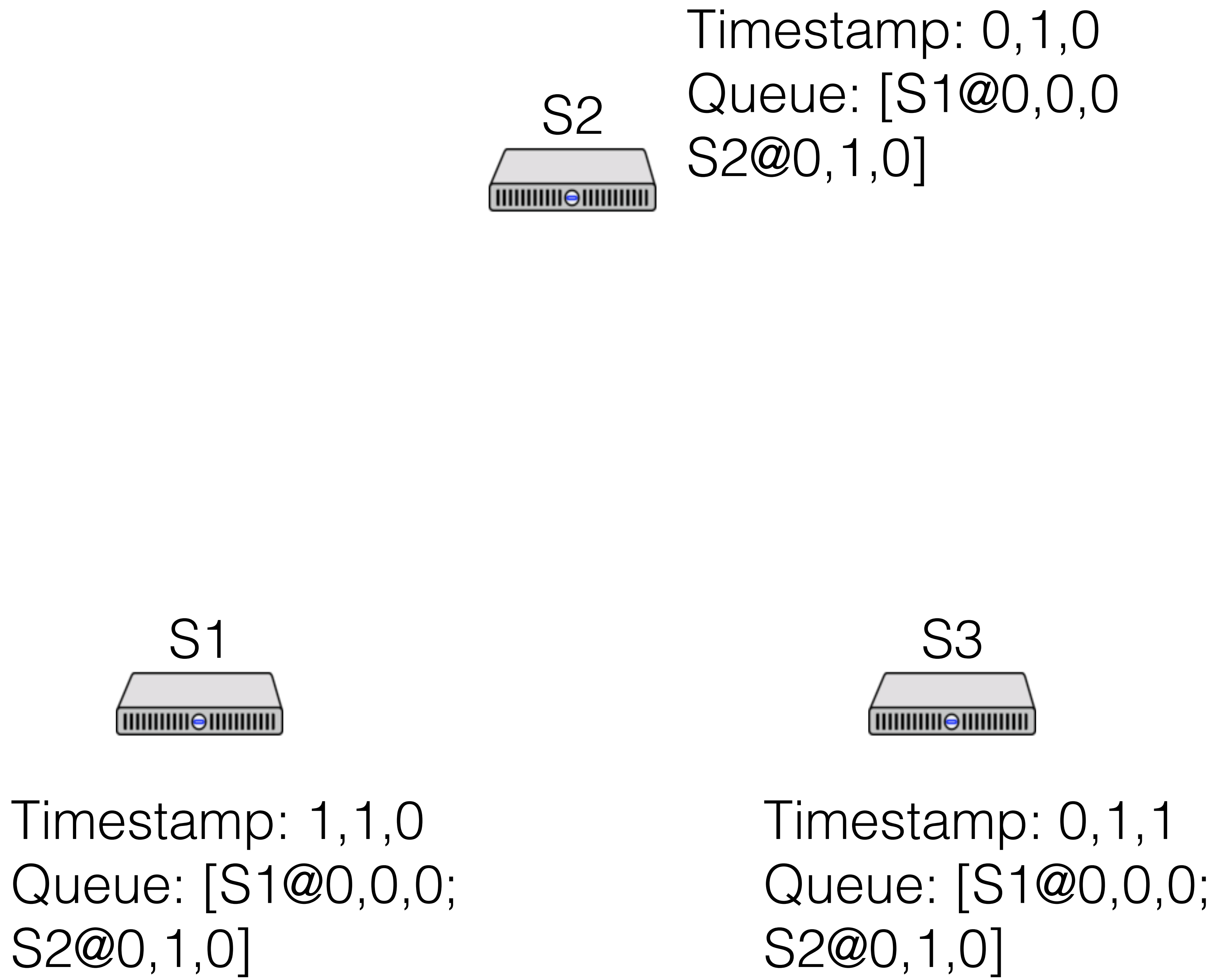
C_x happens before C_y

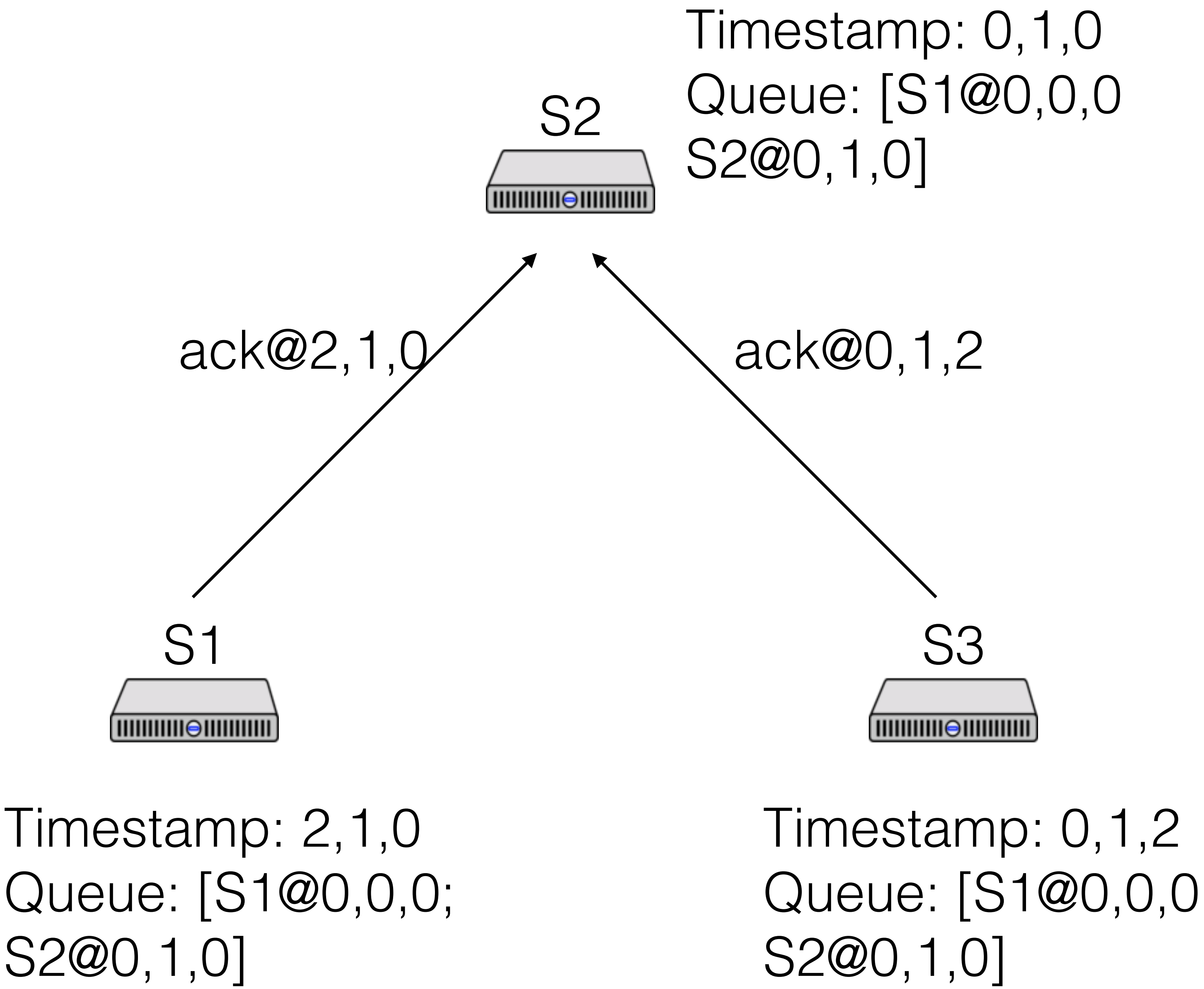


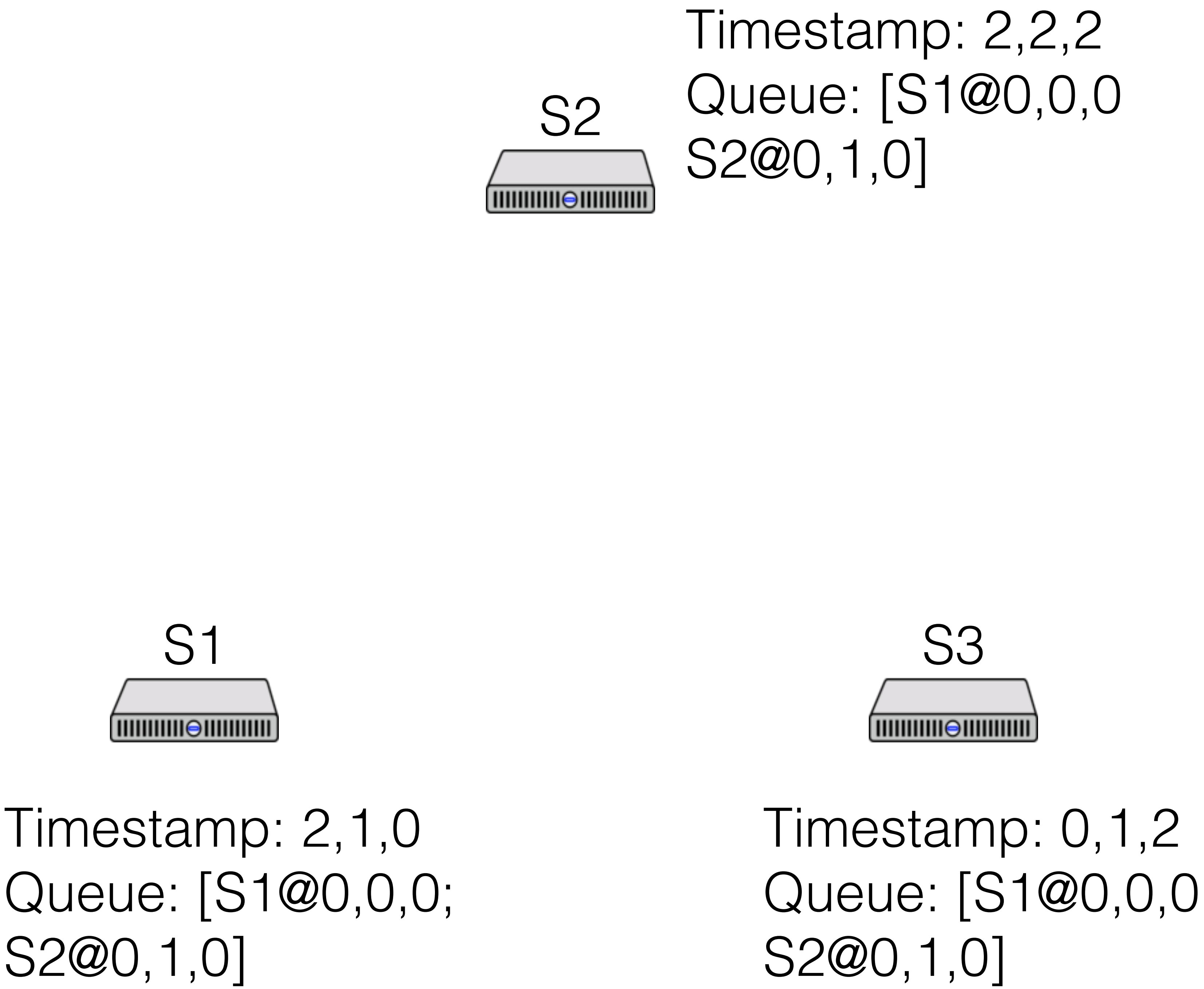
S2
Timestamp: 0
Queue: [S1@0]
$S1_{max}$: 0
$S3_{max}$: 0
S1
Timestamp: 0
Queue: [S1@0]
$S2_{max}$: 0
$S3_{max}$: 0
S3
Timestamp: 0
Queue: [S1@0]
$S1_{max}$: 0
$S2_{max}$: 0

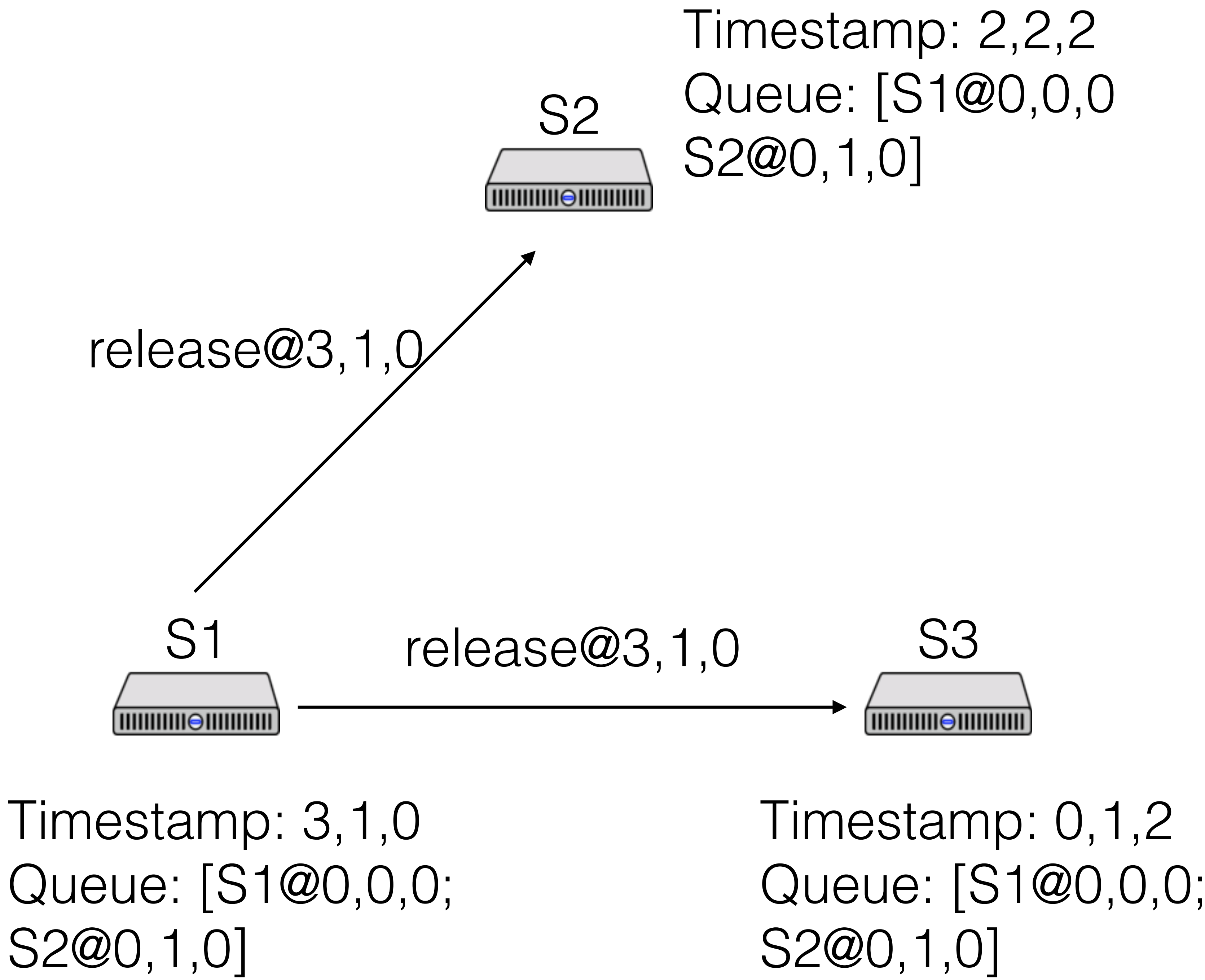

S2
Timestamp: 0,0,0
Queue: [S1@0,0,0]
S1
Timestamp: 0,0,0
Queue: [S1@0,0,0]
S3
Timestamp: 0,0,0
Queue: [S1@0,0,0]

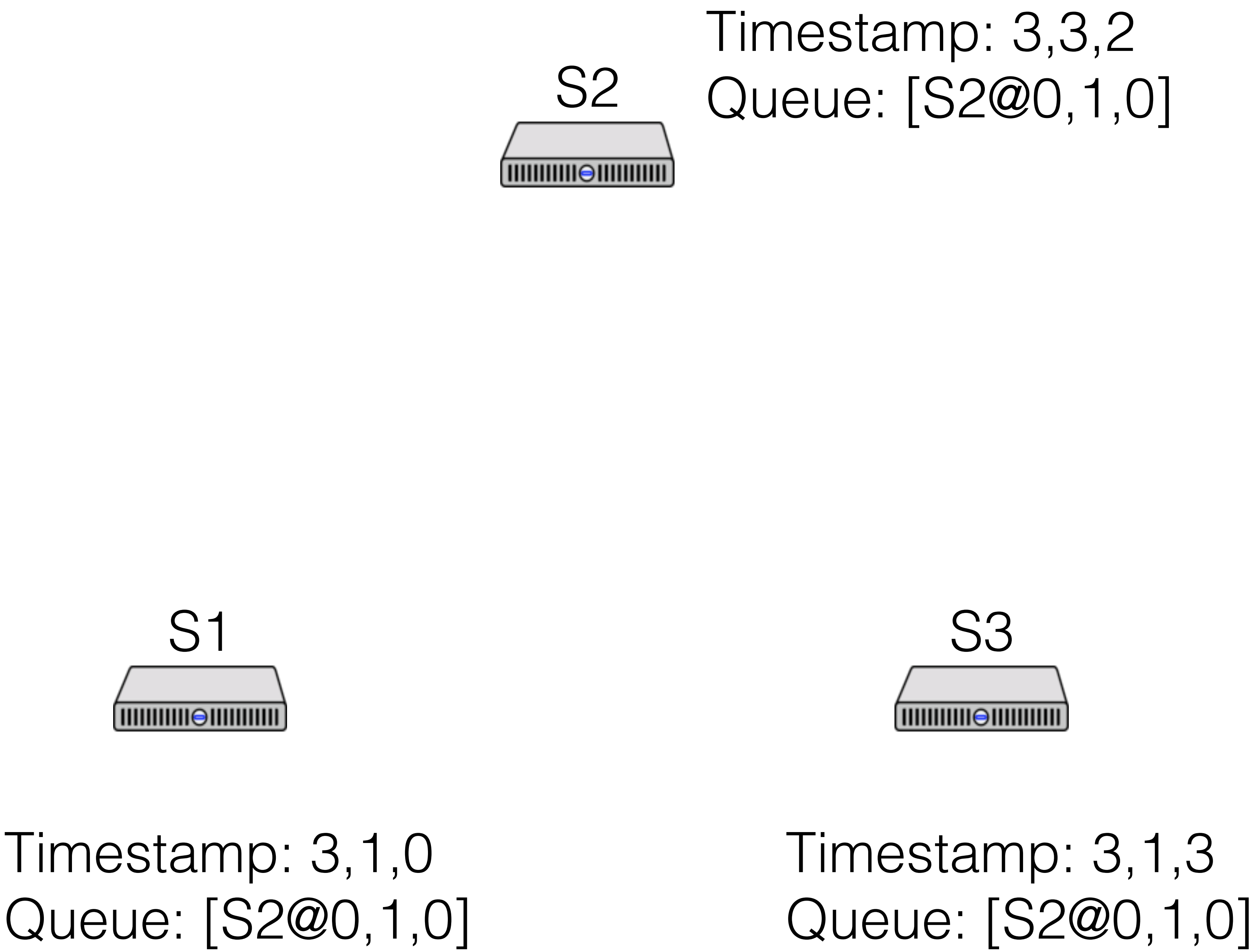

S2
Timestamp: 0,1,0
Queue: [S1@0,0,0]
request@0,1,0
request@0,1,0
S1
S3
Timestamp: 0,0,0
Queue: [S1@0,0,0]
Timestamp: 0,0,0
Queue: [S1@0,0,0]

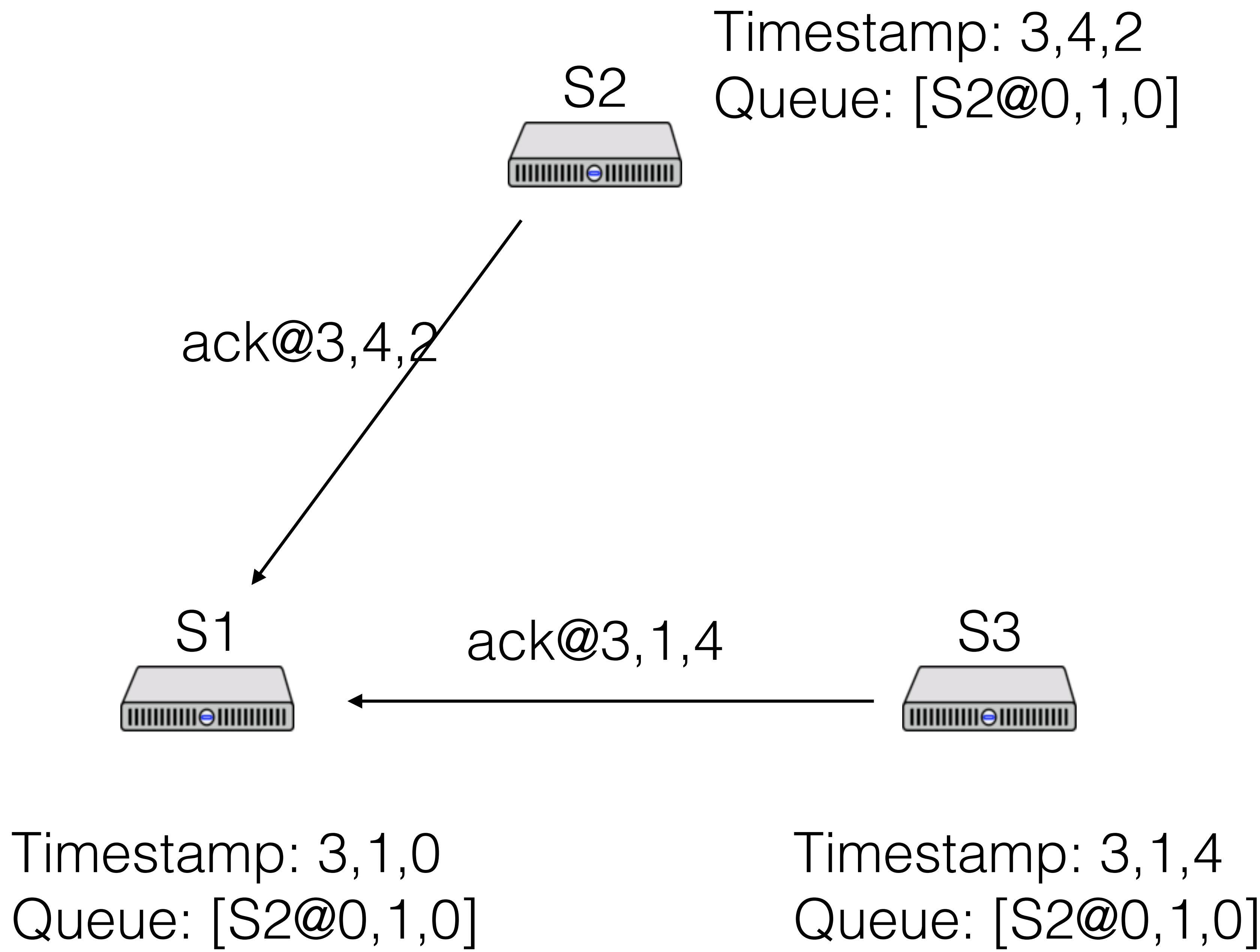

S2
Timestamp: 0,1,0
Queue: [S1@0,0,0
S2@0,1,0]
S1
Timestamp: 1,1,0
Queue: [S1@0,0,0;
S2@0,1,0]
S3
Timestamp: 0,1,1
Queue: [S1@0,0,0;
S2@0,1,0]

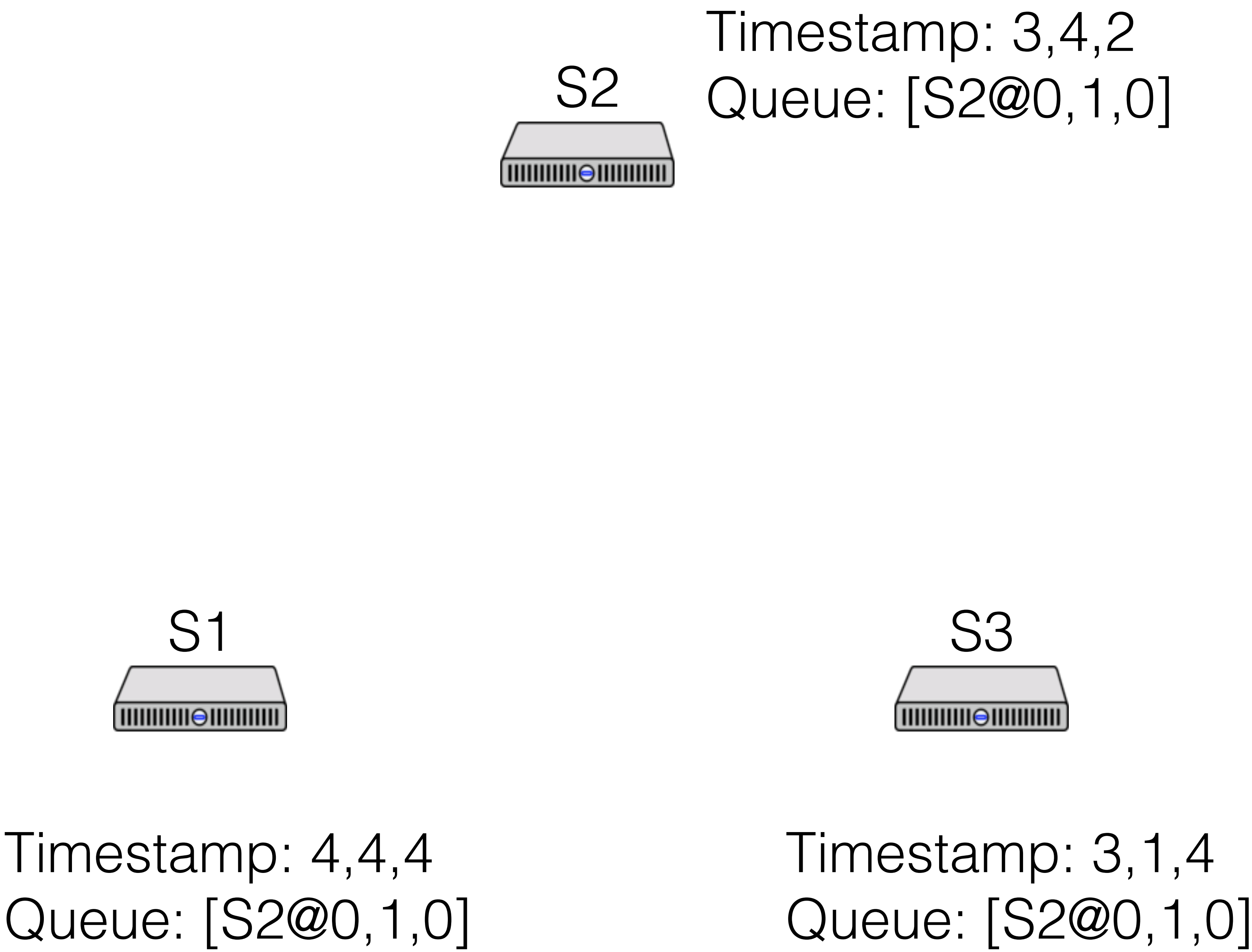

S2
Timestamp: 0,1,0
Queue: [S1@0,0,0
S2@0,1,0]
ack@2,1,0
ack@0,1,2
S1
S3
Timestamp: 2,1,0
Queue: [S1@0,0,0;
S2@0,1,0]
Timestamp: 0,1,2
Queue: [S1@0,0,0;
S2@0,1,0]


S2
Timestamp: 2,2,2
Queue: [S1@0,0,0
S2@0,1,0]
S1
Timestamp: 2,1,0
Queue: [S1@0,0,0;
S2@0,1,0]
S3
Timestamp: 0,1,2
Queue: [S1@0,0,0;
S2@0,1,0]


Timestamp: 2,2,2
Queue: [S1@0,0,0
S2@0,1,0]
S2
release@3,1,0
S1
release@3,1,0
S3
Timestamp: 3,1,0
Queue: [S1@0,0,0;
S2@0,1,0]
Timestamp: 0,1,2
Queue: [S1@0,0,0;
S2@0,1,0]


S2
Timestamp: 3,3,2
Queue: [S2@0,1,0]
S1
Timestamp: 3,1,0
Queue: [S2@0,1,0]
S3
Timestamp: 3,1,3
Queue: [S2@0,1,0]


Timestamp: 3,4,2
Queue: [S2@0,1,0]
S2
ack@3,4,2
S1
ack@3,1,4
S3
Timestamp: 3,1,0
Queue: [S2@0,1,0]
Timestamp: 3,1,4
Queue: [S2@0,1,0]


Timestamp: 3,4,2
Queue: [S2@0,1,0]
S2
S1
S3
Timestamp: 4,4,4
Queue: [S2@0,1,0]
Timestamp: 3,1,4
Queue: [S2@0,1,0]

Some terms

Often useful: states, executions, reachability

- A state is a global state S of the system: states at all nodes + channels

- An execution is a series of states S_i s.t. the system is allowed to transition from S_i to S_{i+1}

- A state S_j is reachable from S_i if, starting in S_i, it's possible for the system to end up at S_j

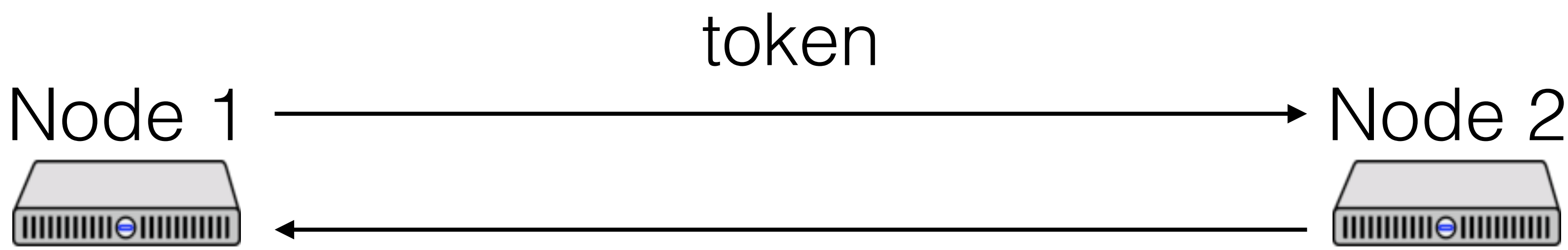
Types of properties: stable properties, invariants

- A property P is stable if

  $P(S_i) \rightarrow P(S_{i+1})$

- A property P is an invariant if it holds on all reachable states

Token conservation system



haveToken: bool

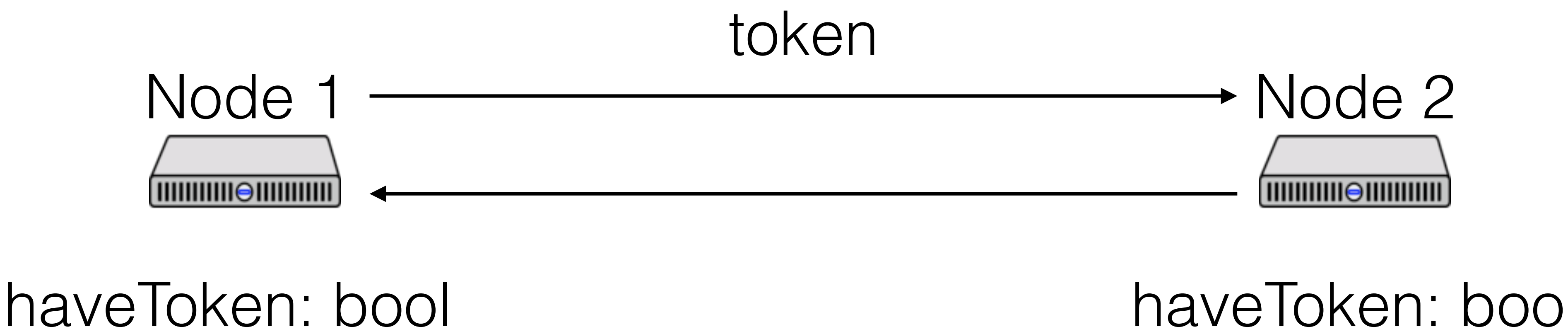
haveToken: bool

In S_0

- No messages
- Node 1 has haveToken = true
- Node 2 has haveToken = false

Nodes can send each other the token or discard the token

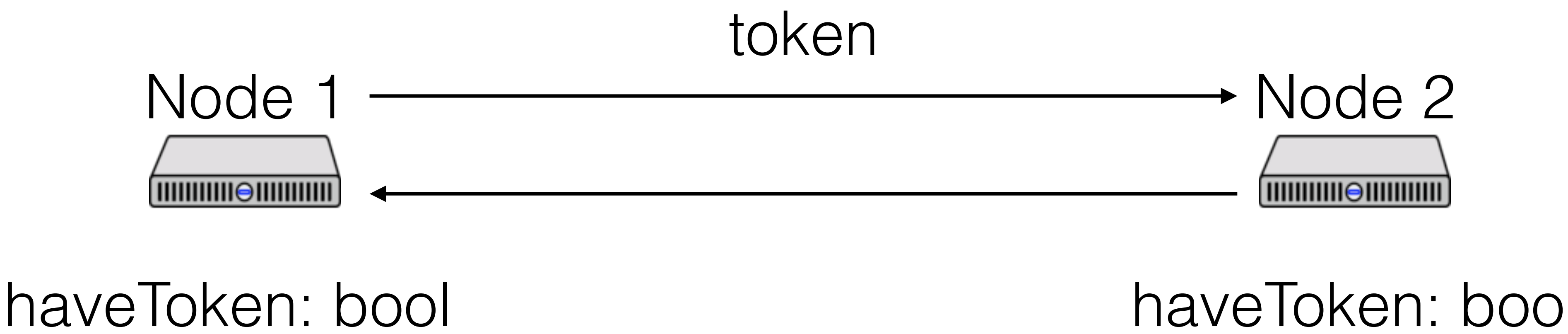
Token conservation system



Invariant: token in at most one place

Stable property: no token

Token conservation system



How can we check the invariant at runtime?

How can we check the stable property at runtime?

Distributed snapshots

Why do we want snapshots?

- Detect stable properties (e.g., deadlock)
- Distributed garbage collection
- Diagnostics (is invariant still true?)

Distributed snapshots

Record global state of the system

- Global state: state of every node, every channel

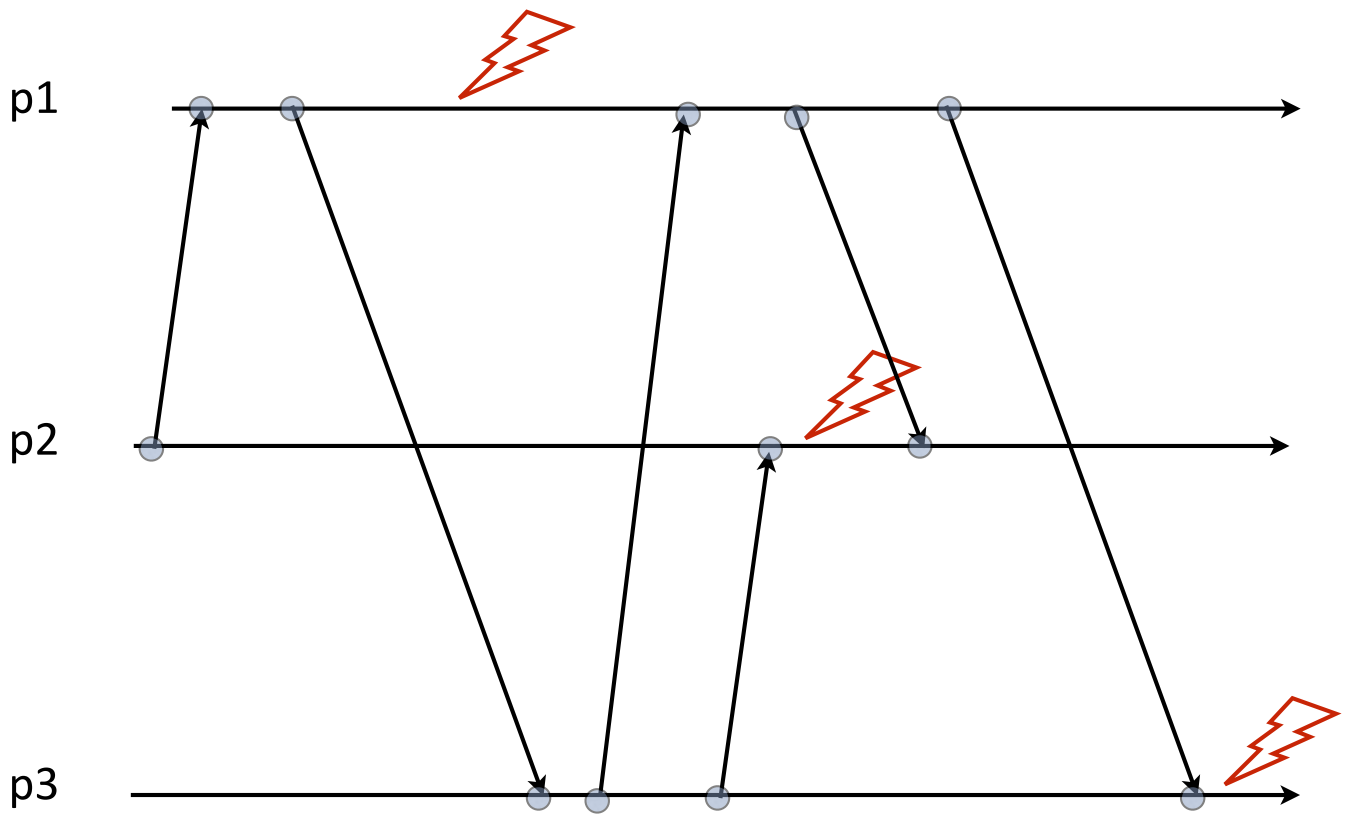
Challenges:

- Physical clocks have skew
- State can't be an instantaneous global snapshot
- State must be consistent

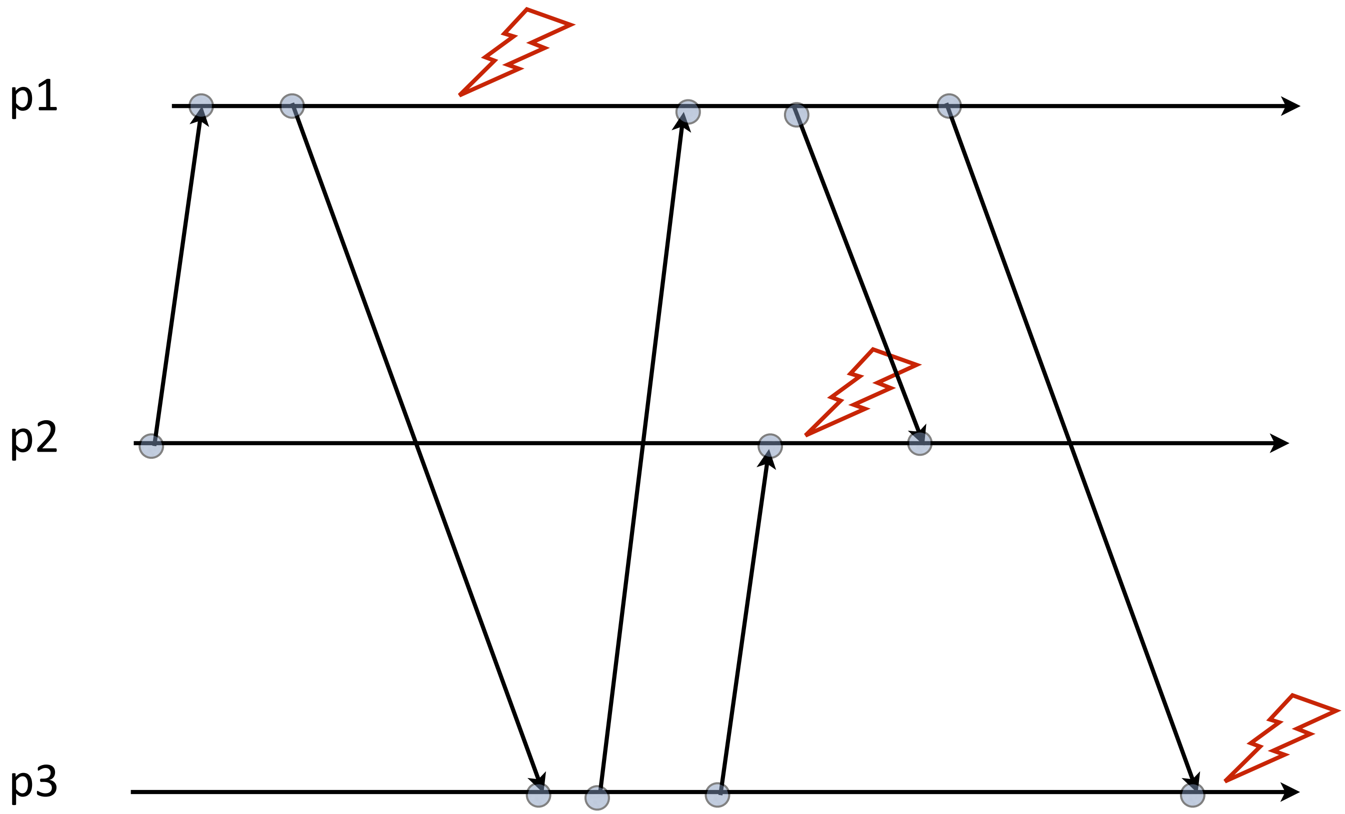
Consistent snapshots

- Consistent global state: causal dependencies are captured
  - If a snapshot of a node includes some events
    - All causally earlier events should be part of snapshots of other nodes

Space Time Diagrams



Cuts

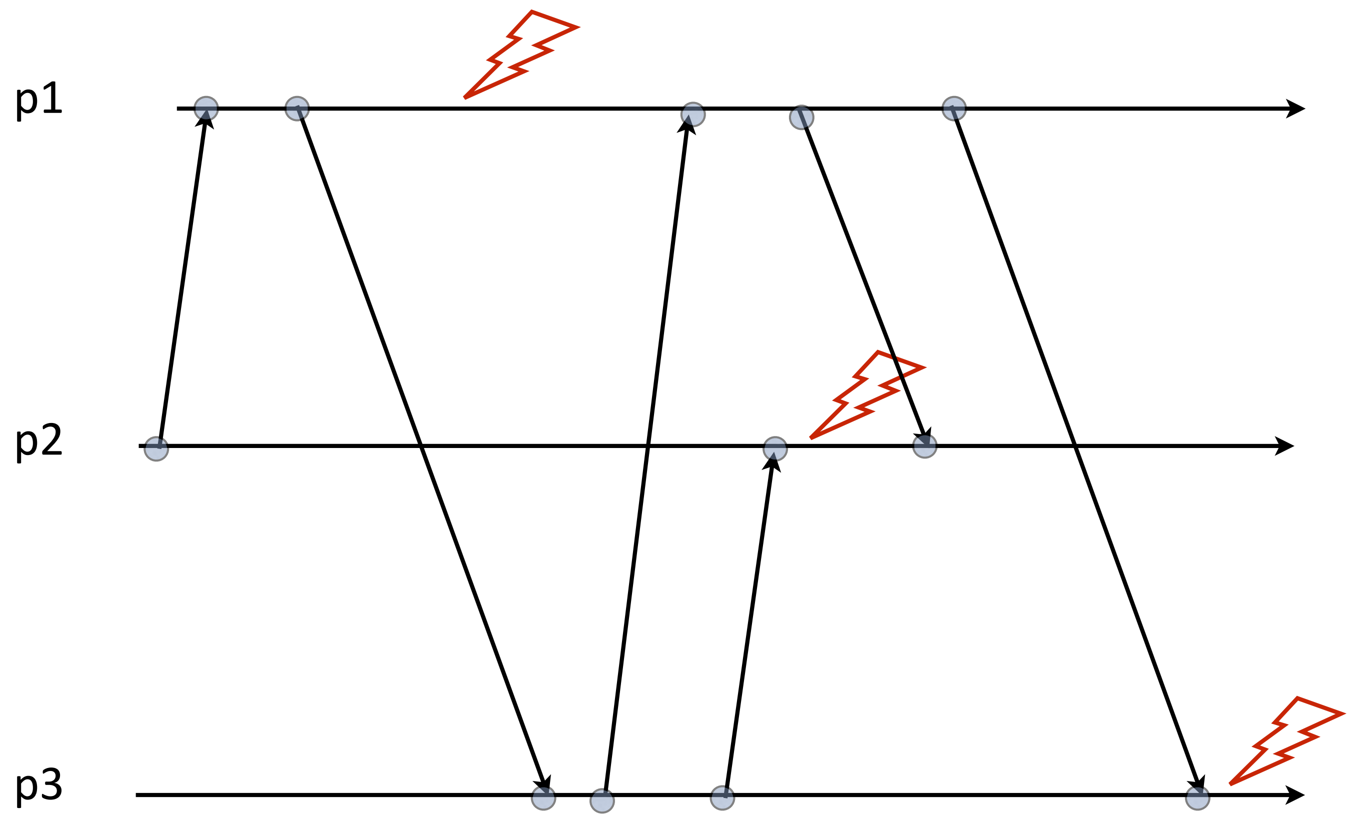


A cut C is a subset of the global history of H

Consistent Cuts

- A cut is consistent if
  - e2 is in the cut and if e1 happens before e2
    - then e1 should also be in the cut
- A consistent global state is one corresponding to a consistent cut

Inconsistent Cut (or global state)



Physical time algorithm

What if we could trust clocks?

Idea:

- Node: “hey, let’s take a snapshot @ noon”
- At noon, everyone records state
- How to handle channels?

Physical time algorithm

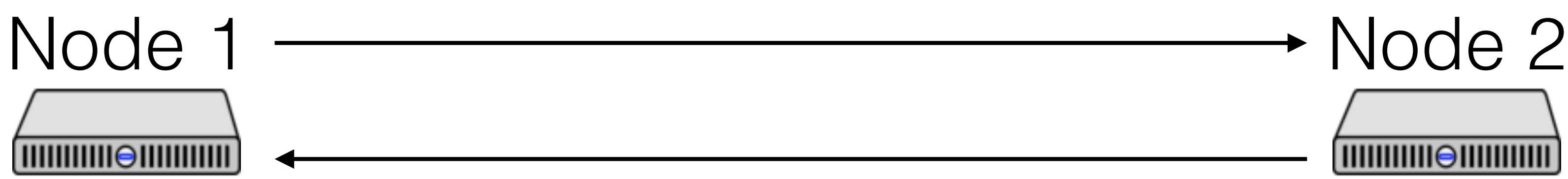
Channels:

- Timestamp all messages
- Receiver records channel state
- Channel state = messages received after noon but sent before noon

Example: is there <= 1 token in the system?

Physical time algorithm

11:59

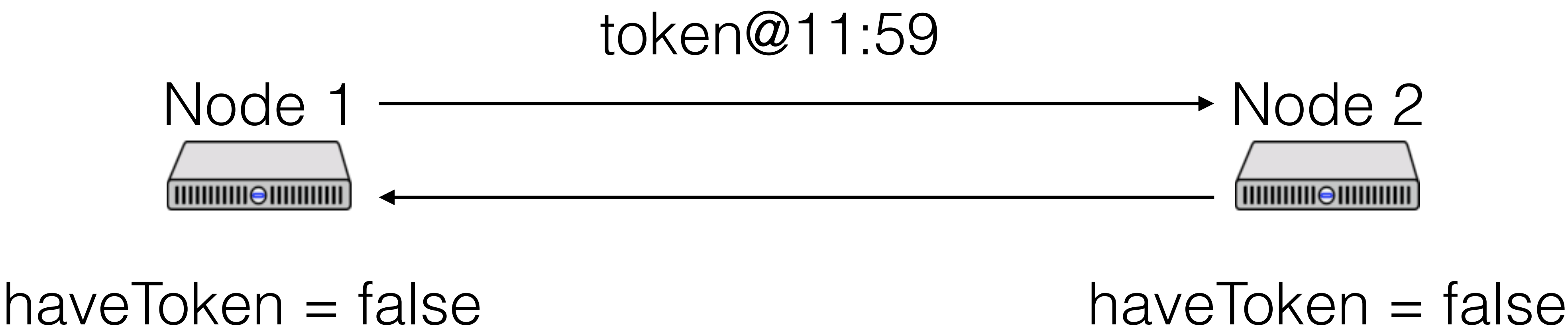


haveToken = true

haveToken = false

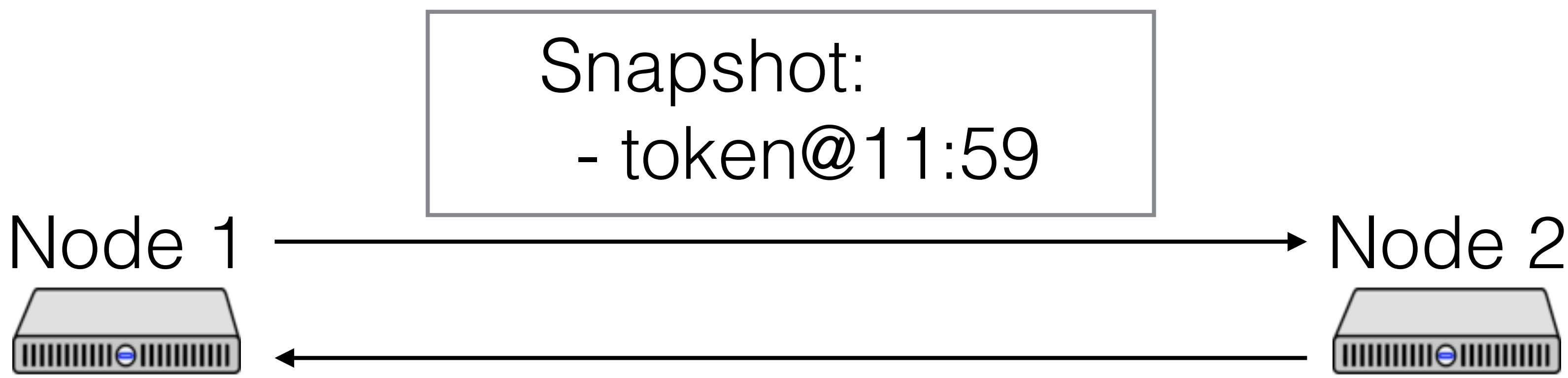
Physical time algorithm

11:59



Physical time algorithm

12:00



haveToken = false

Snapshot:
- haveToken = false

haveToken = false

Snapshot:
- haveToken = false

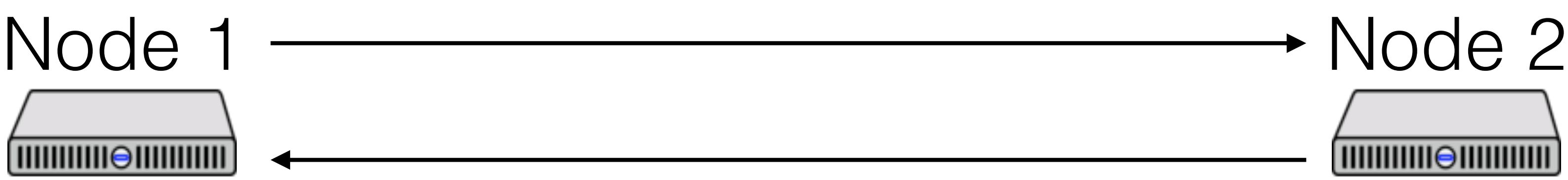
Physical time algorithm

This seems like it works, right?

What could go wrong?

Physical time algorithm

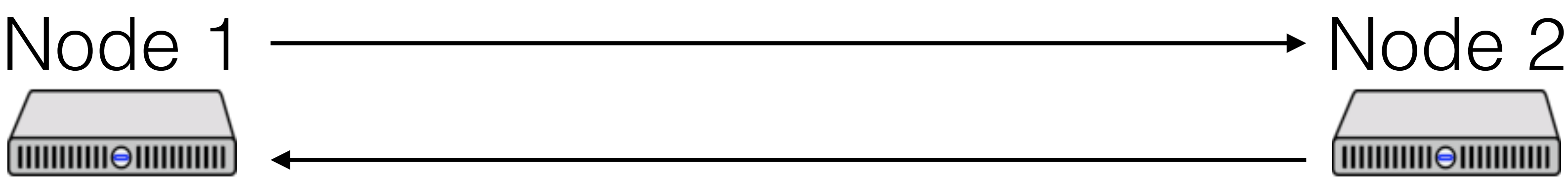
11:59 **11:58**



haveToken = true haveToken = false

Physical time algorithm

12:00 **11:59**

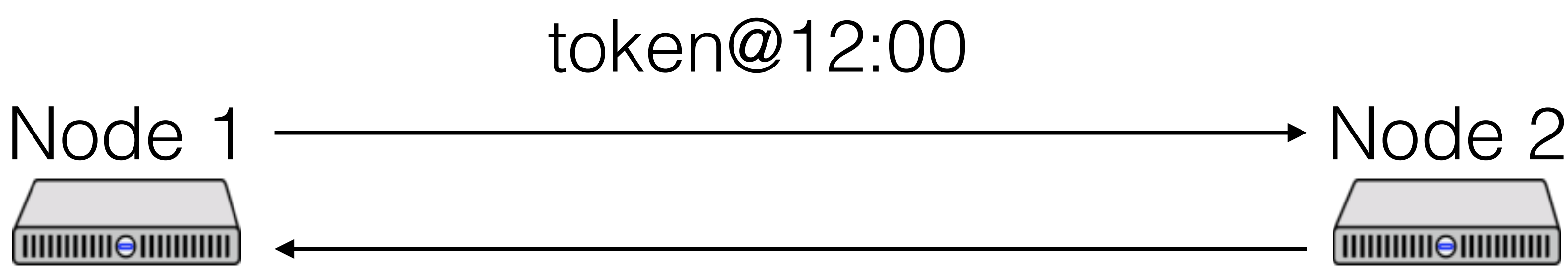


haveToken = true haveToken = false

Snapshot:
- haveToken = true

Physical time algorithm

12:00 **11:59**

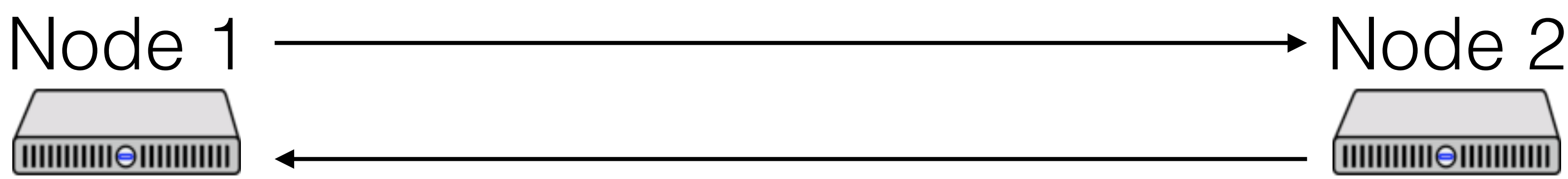


haveToken = false haveToken = false

Snapshot:
- haveToken = true

Physical time algorithm

12:00 **11:59**



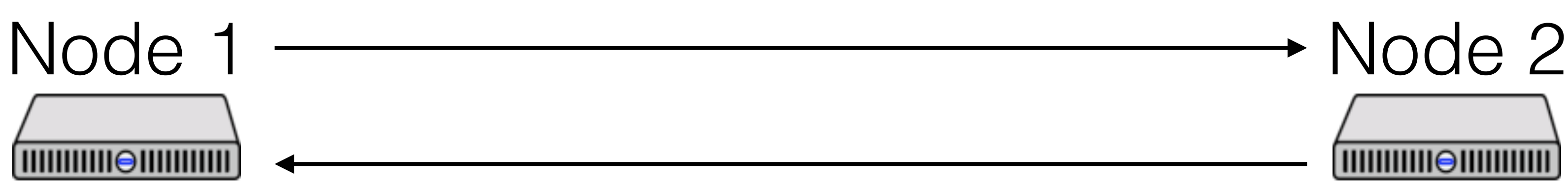
haveToken = false

haveToken = true

Snapshot:
- haveToken = true

Physical time algorithm

12:01 **12:00**



haveToken = false

haveToken = true

Snapshot:
- haveToken = true

Snapshot:
- haveToken = true

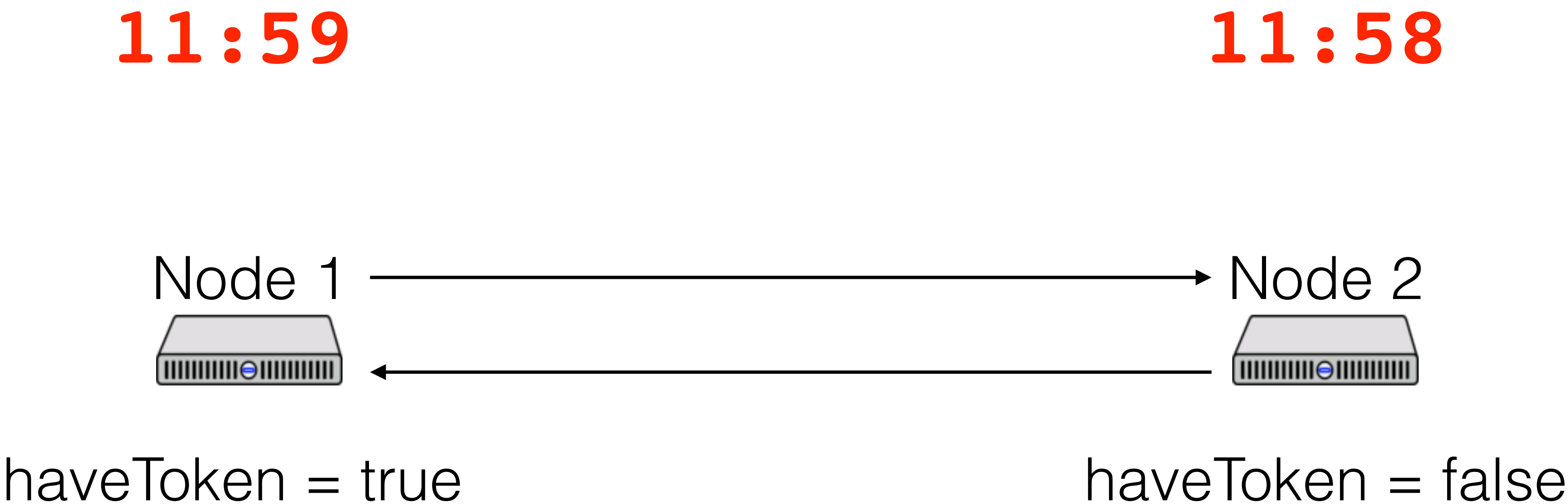
Avoiding inconsistencies

As we've seen, physical clocks aren't accurate enough

Need to use messages to coordinate snapshot

=> make sure Node 2 takes snapshot before receiving any messages sent after Node 1 takes snapshot

Better algorithm



Better algorithm

12:00 **11:59**

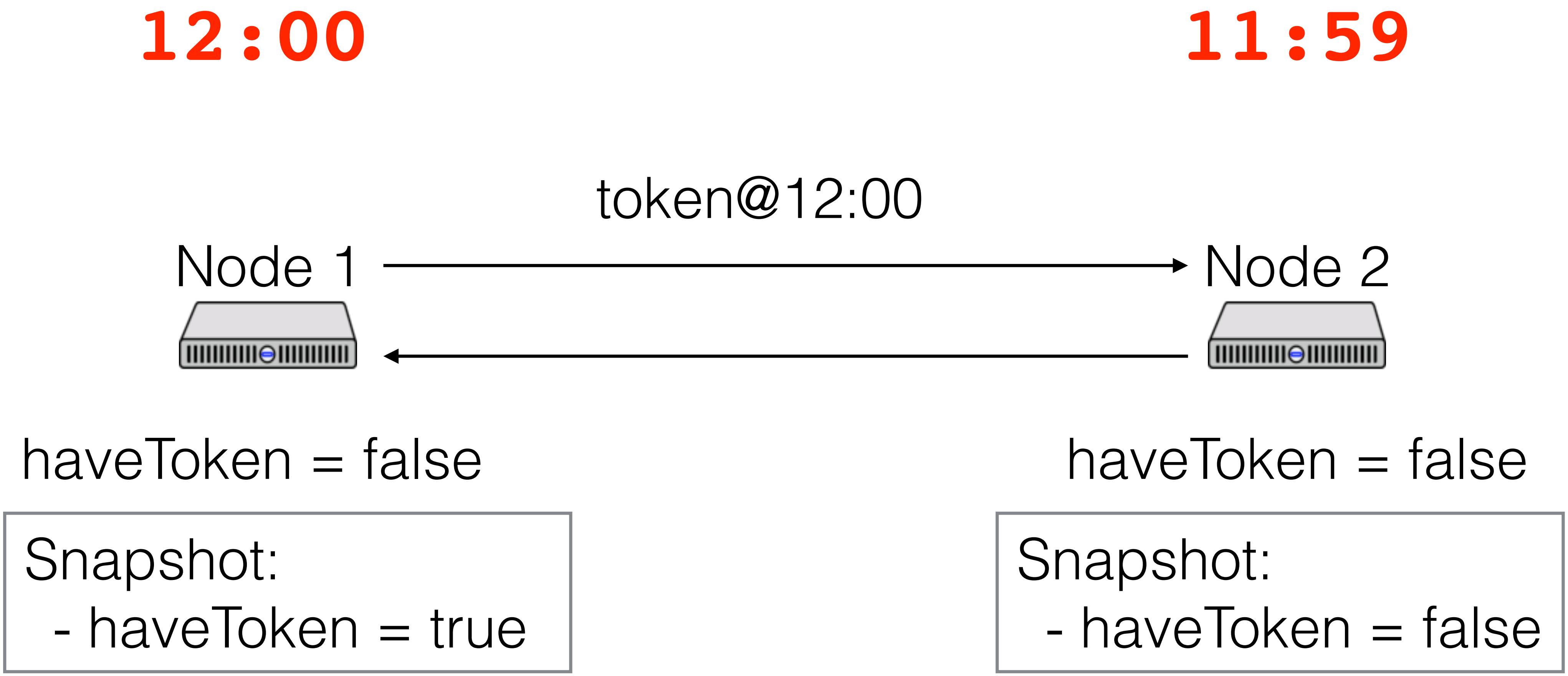
haveToken = true

haveToken = false

Snapshot:
- haveToken = true

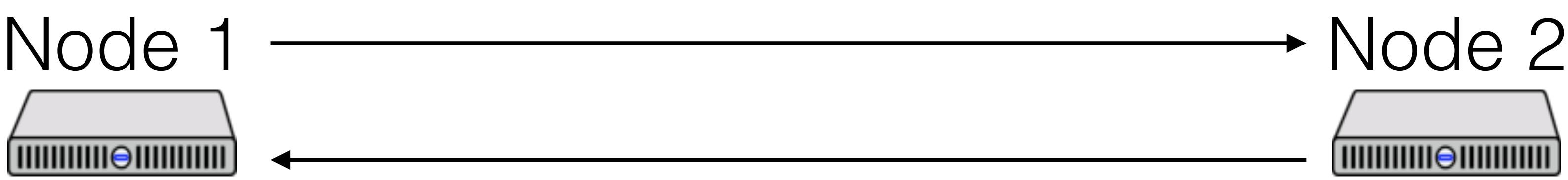
Better algorithm

Better algorithm



Better algorithm

12:00 **11:59**



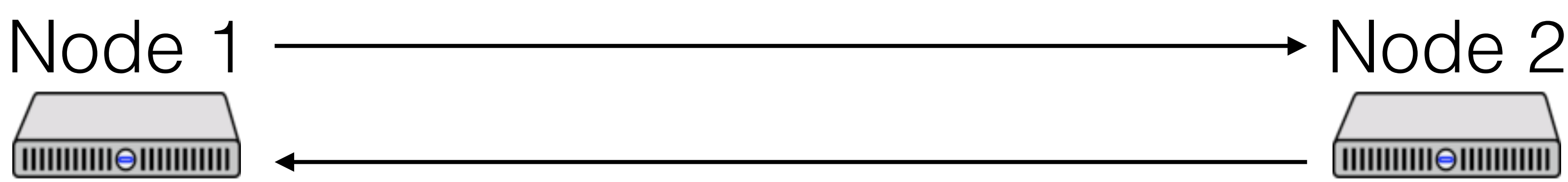
haveToken = false

haveToken = true

Snapshot:
- haveToken = true

Snapshot:
- haveToken = false

Better algorithm



haveToken = false

Snapshot:
- haveToken = true

haveToken = true

Snapshot:
- haveToken = false

Distributed Snapshots

As we've seen, physical clocks aren't accurate enough

Need to use messages to coordinate snapshot

=> make sure Node 2 takes snapshot before receiving any messages sent after Node 1 takes snapshot

Chandy-Lamport Snapshots

At any time, a node can decide to snapshot

- Actually, multiple nodes can

That node:

- Records its current state
- Sends a “marker” message on all channels

When a node receives a marker, snapshot

- Record current state
- Send marker message on all channels

How to record channel state?

Chandy-Lamport Snapshots

Channel state recorded by the receiver

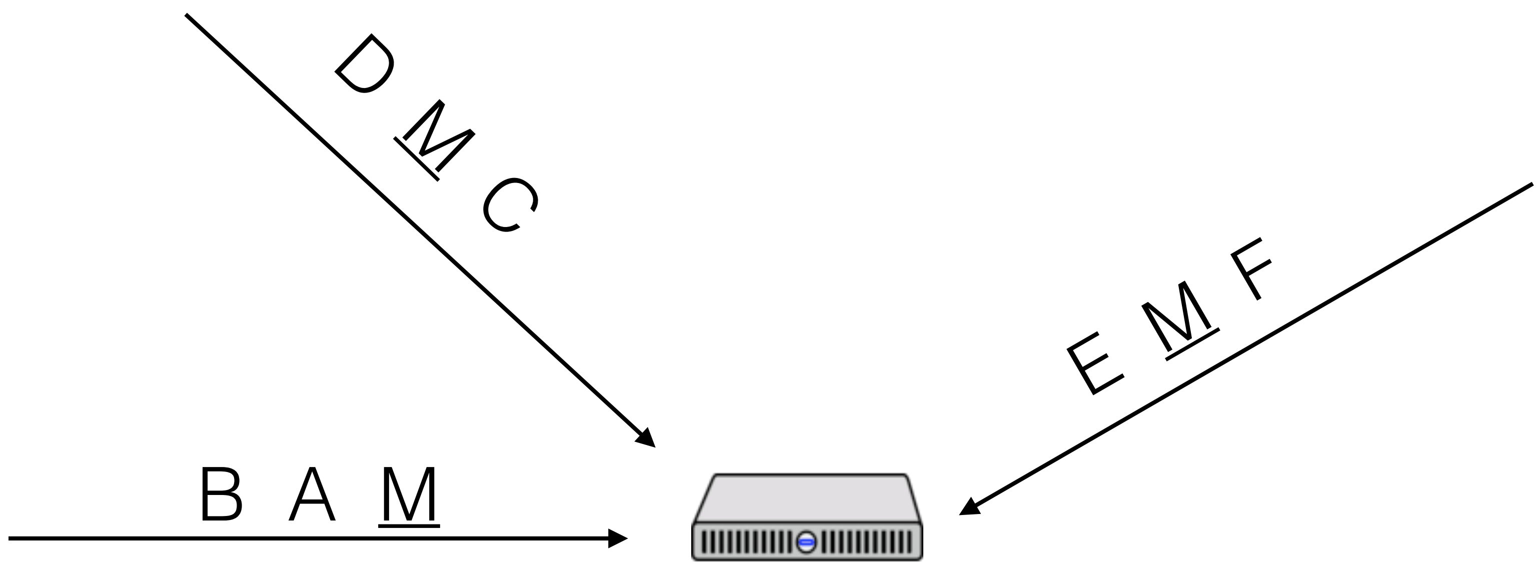
Recorded when marker received on that channel

- Why do we know we'll receive a marker on every channel?

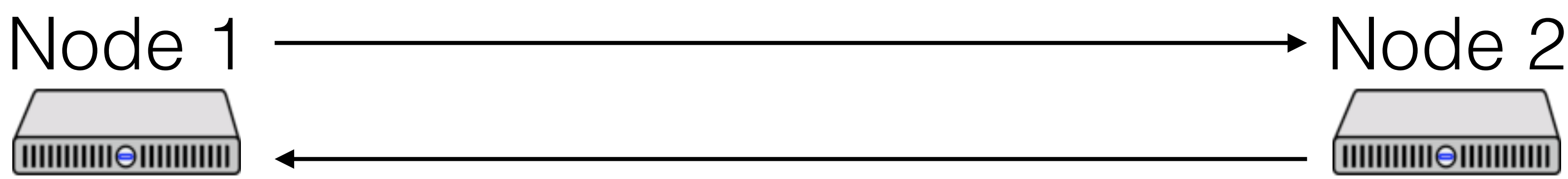
When marker received on channel, record:

- Empty, if this is the first marker
- Messages received on channel since we snapshotted, otherwise

Chandy-Lamport Snapshots



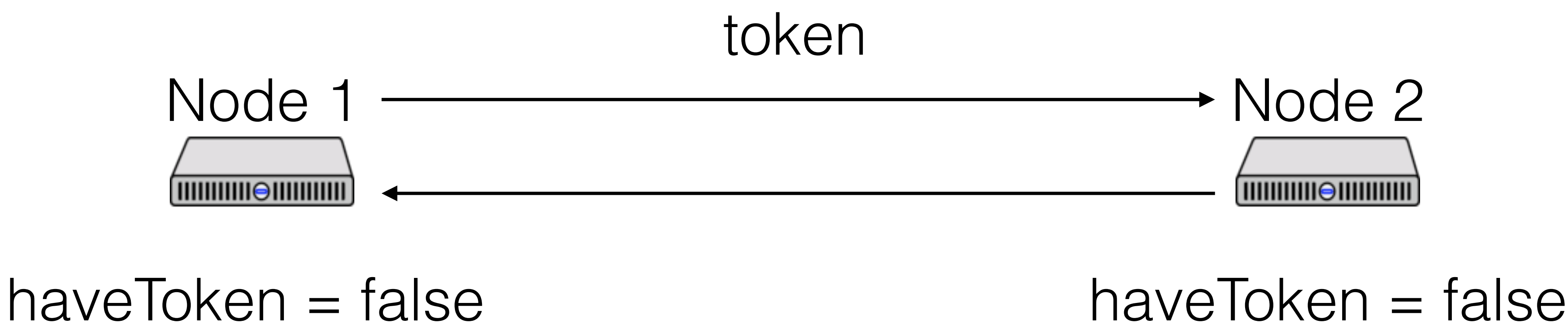
Chandy-Lamport Snapshots



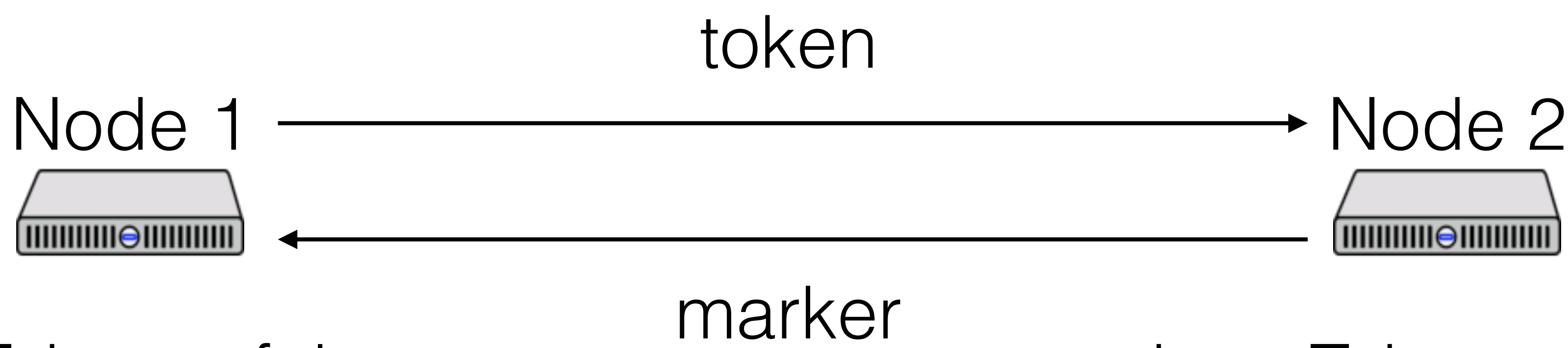
haveToken = true

haveToken = false

Chandy-Lamport Snapshots



Chandy-Lamport Snapshots



haveToken = false

haveToken = false

Snapshot:
- haveToken = false

Chandy-Lamport Snapshots

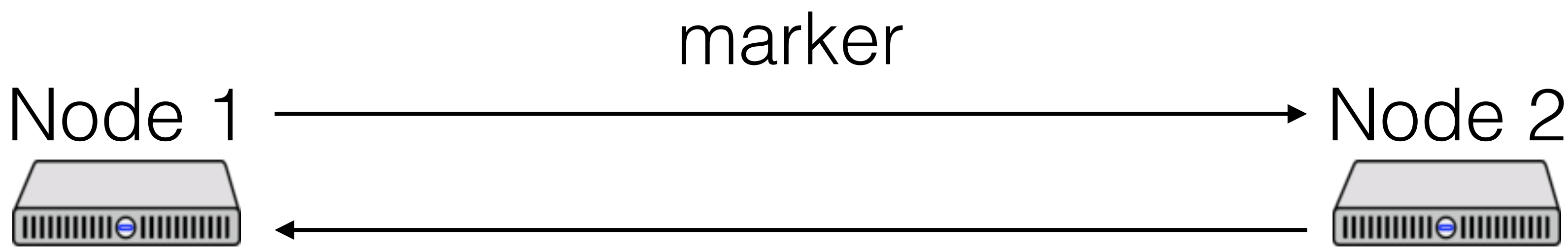
haveToken = false

haveToken = false

Snapshot:
- haveToken = false

Snapshot:
- haveToken = false

Chandy-Lamport Snapshots



haveToken = false

Snapshot:
- haveToken = false

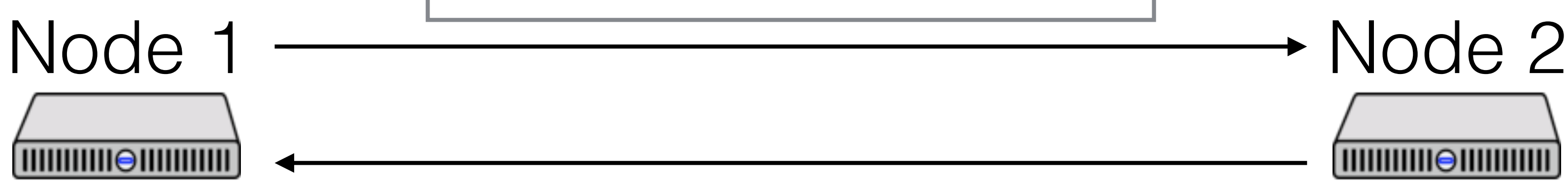
haveToken = true

Snapshot:
- haveToken = false

In-flight:
- token

Chandy-Lamport Snapshots

Snapshot:
- token



haveToken = false

Snapshot:
- haveToken = false

haveToken = true

Snapshot:
- haveToken = false

Chandy-Lamport Snapshots

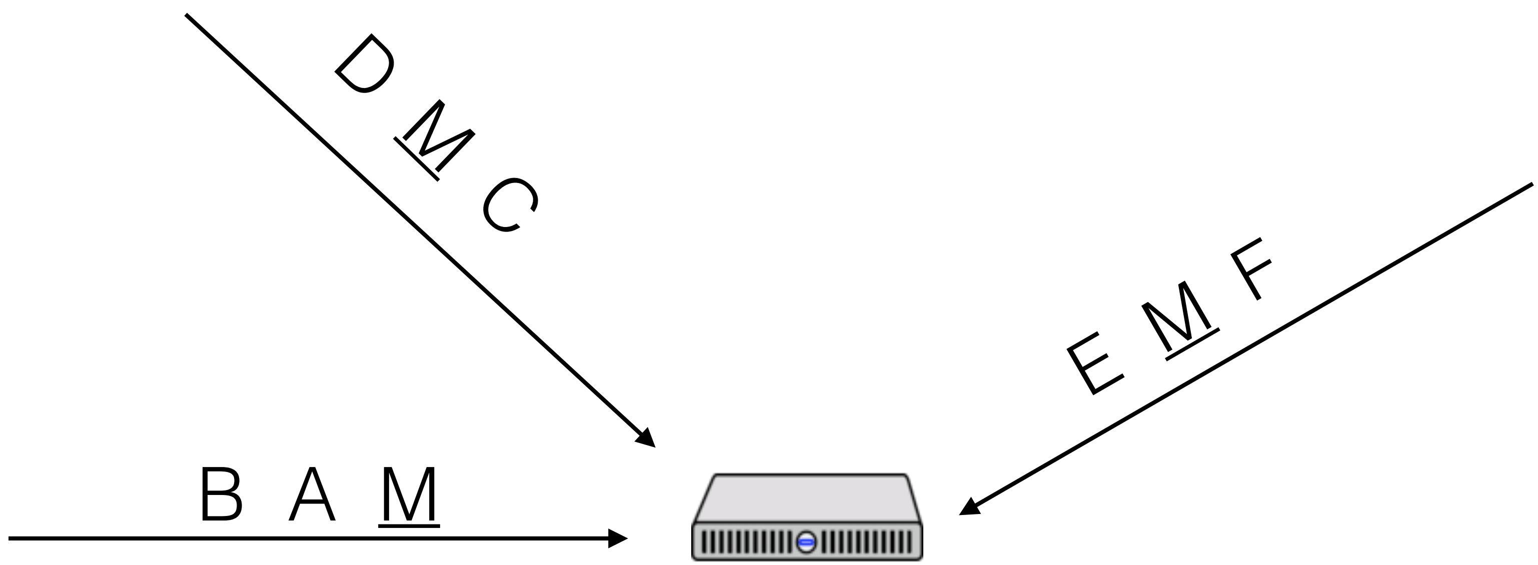
What if multiple nodes initiate the snapshot?

- Follow same rules: send markers on all channels

Intuition:

- All initiators are concurrent
- Concurrent snapshots are ok, as long as we account for messages in flight
- If receive marker before initiating, must snapshot to be consistent with other nodes

Chandy-Lamport Snapshots



Consistent Cut

A cut is the set of events on each node in the system that are included in the snapshot

A consistent cut is a cut that respects causality

If an event is included by any node, all events that “happen before” the event are also included

Which state is snapshotted?

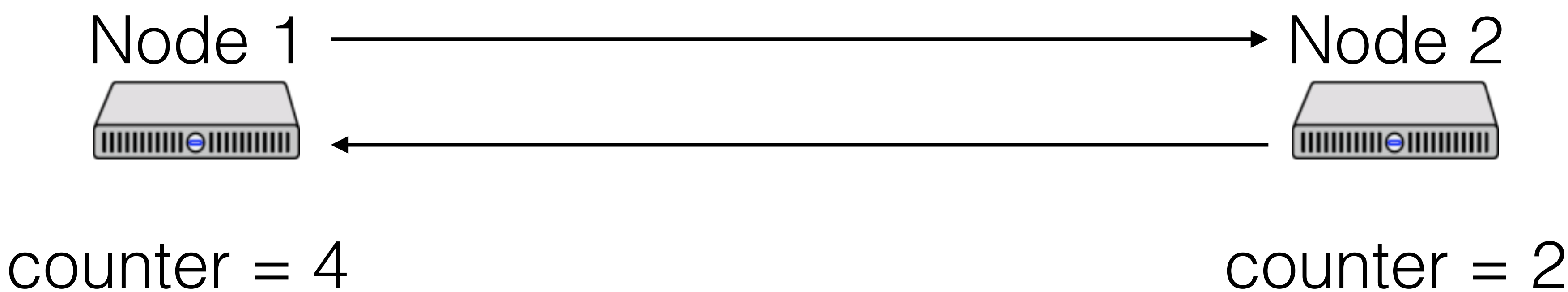
Let's say we have an execution S_0, S_1, …

Some node starts the snapshot in S_b

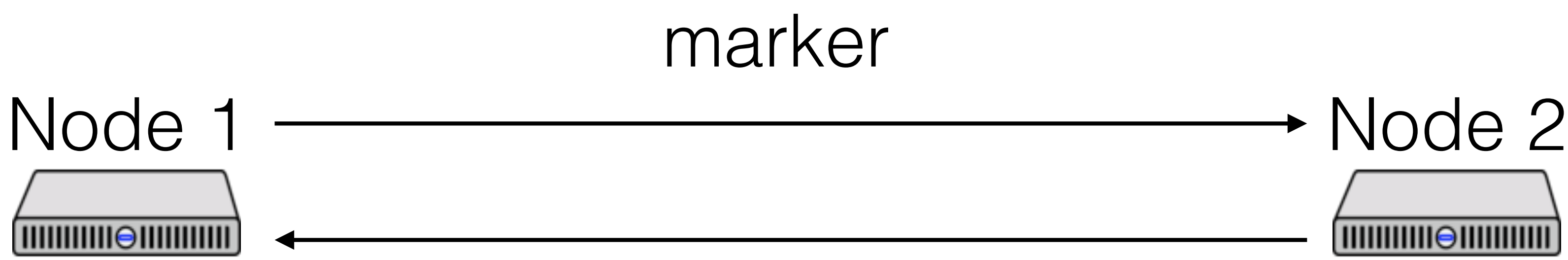
The snapshot finishes in S_e

Which state did we snapshot?

Which state is snapshotted?



Which state is snapshotted?

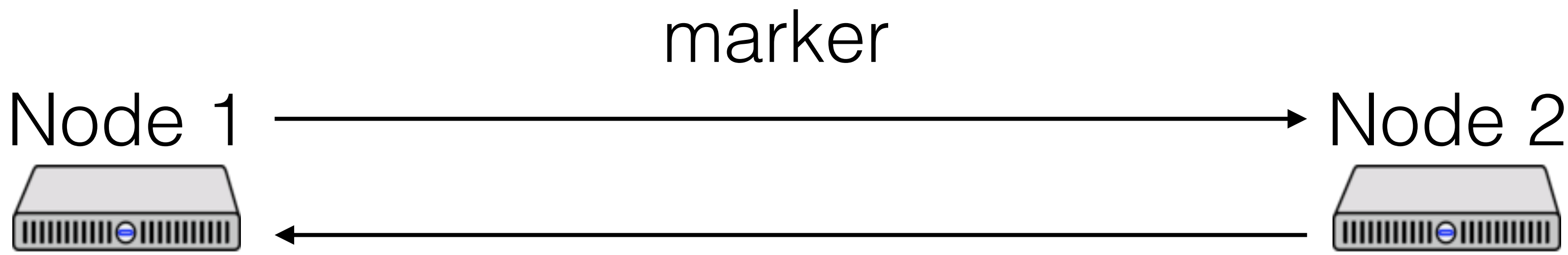


counter = 4

counter = 2

Snapshot:
- counter = 4

Which state is snapshotted?

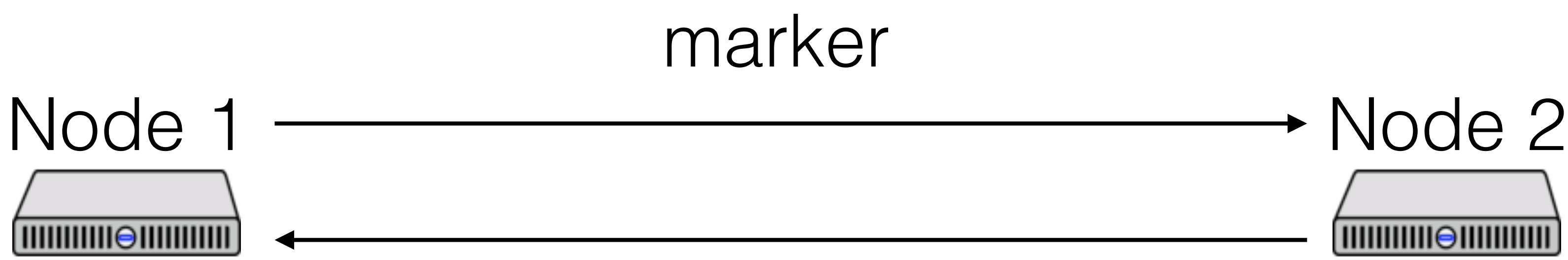


counter = 5

counter = 2

Snapshot:
- counter = 4

Which state is snapshotted?

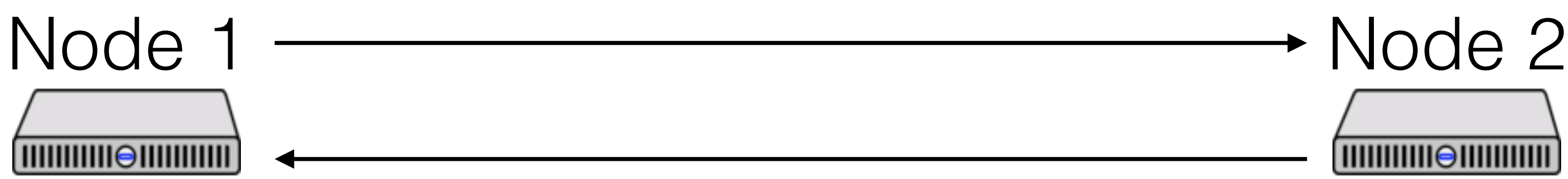


counter = 5

counter = 3

Snapshot:
- counter = 4

Which state is snapshotted?



counter = 5

counter = 3

Snapshot:
- counter = 4

Snapshot:
- counter = 3

Which state is snapshotted?

What *can* we say about this snapshotted state?

Two things:

- Reachable from S_b
- Can reach S_e

Proof is in the paper

- Intuition: state is “consistent” with what actually happened

Stable Properties and Invariants

Recall: a stable property is one that, once true, stays true

An invariant is true of all states

Snapshot represents a reachable state, but it may not represent any actual global state from S_b to S_e

Stable Properties and Invariants

If stable property is *true* in snapshot, we know it *must* still be true in S_e

If stable property is *false* in snapshot, we know it *must* have been false in S_b

If invariant is false in snapshot, we know the invariant is violated in at least one reachable state.

If invariant is true in snapshot, we do *not* know the invariant is true in any other reachable state.