Vector Clocks & Distributed snapshots

CS 452

Vector clocks

Precisely represent transitive causal relationships

T(A) < *T*(B) <-> *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

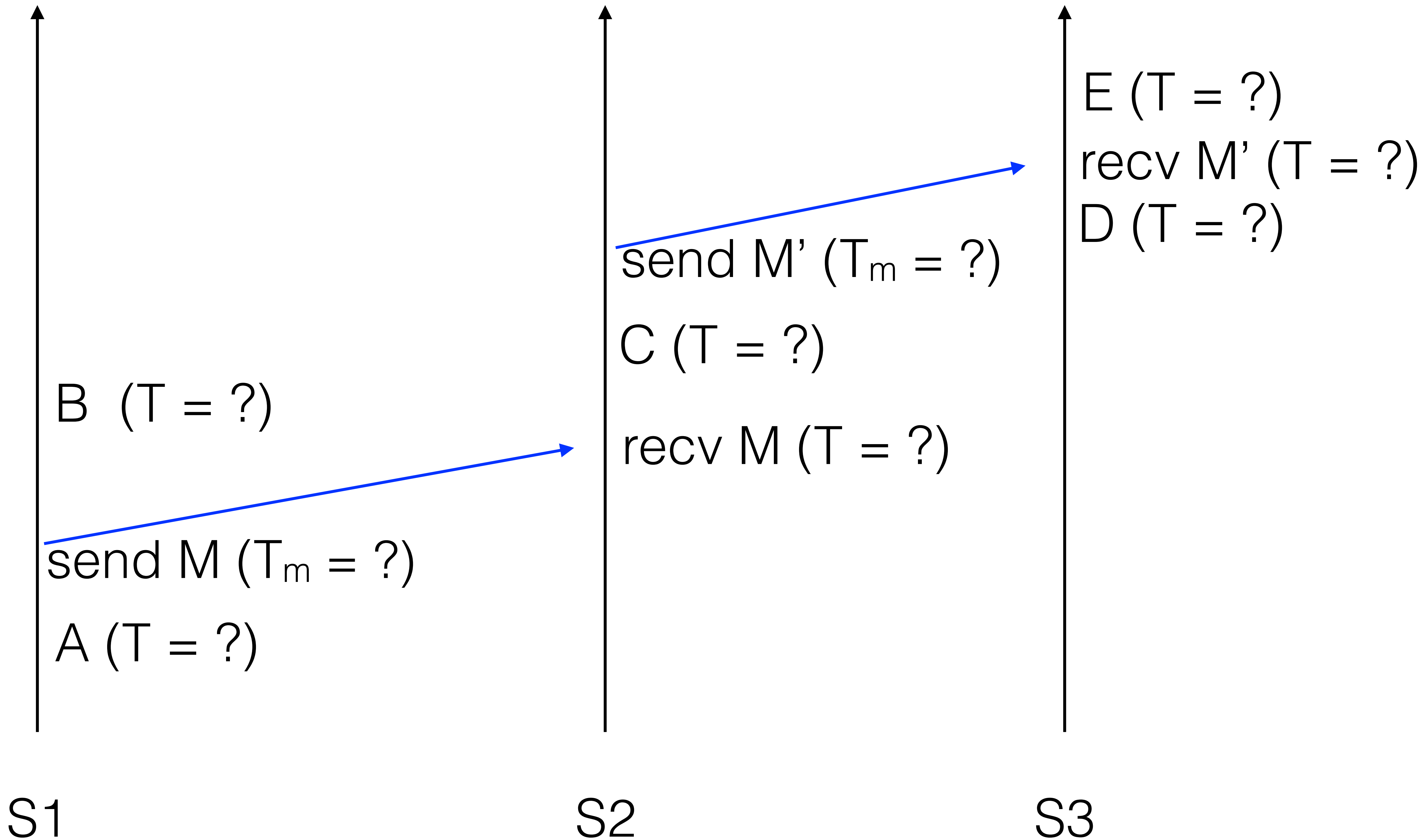
Clock is a vector C, length = # of nodes

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

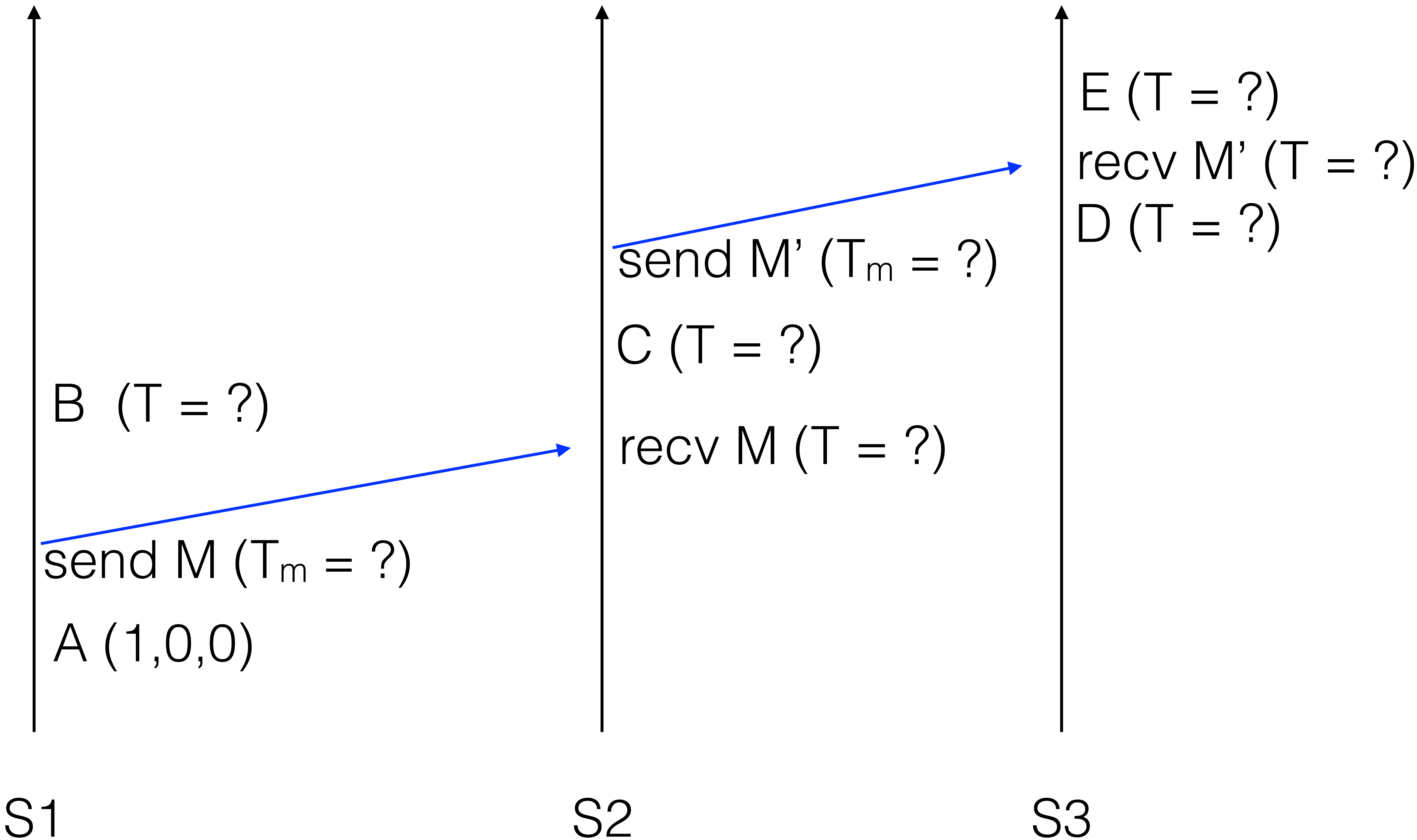
On receipt of message with clock C_m on node i:

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

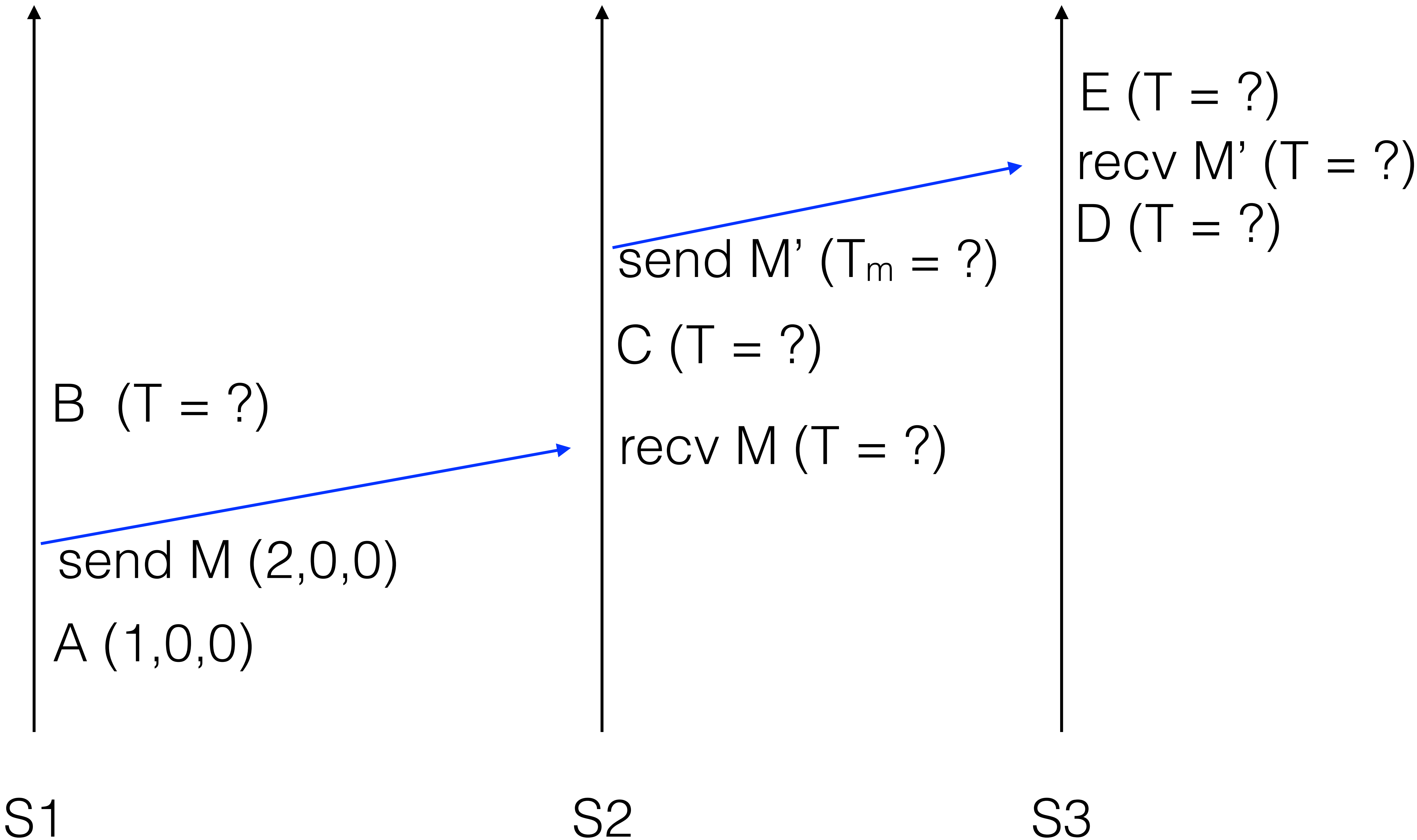
Example



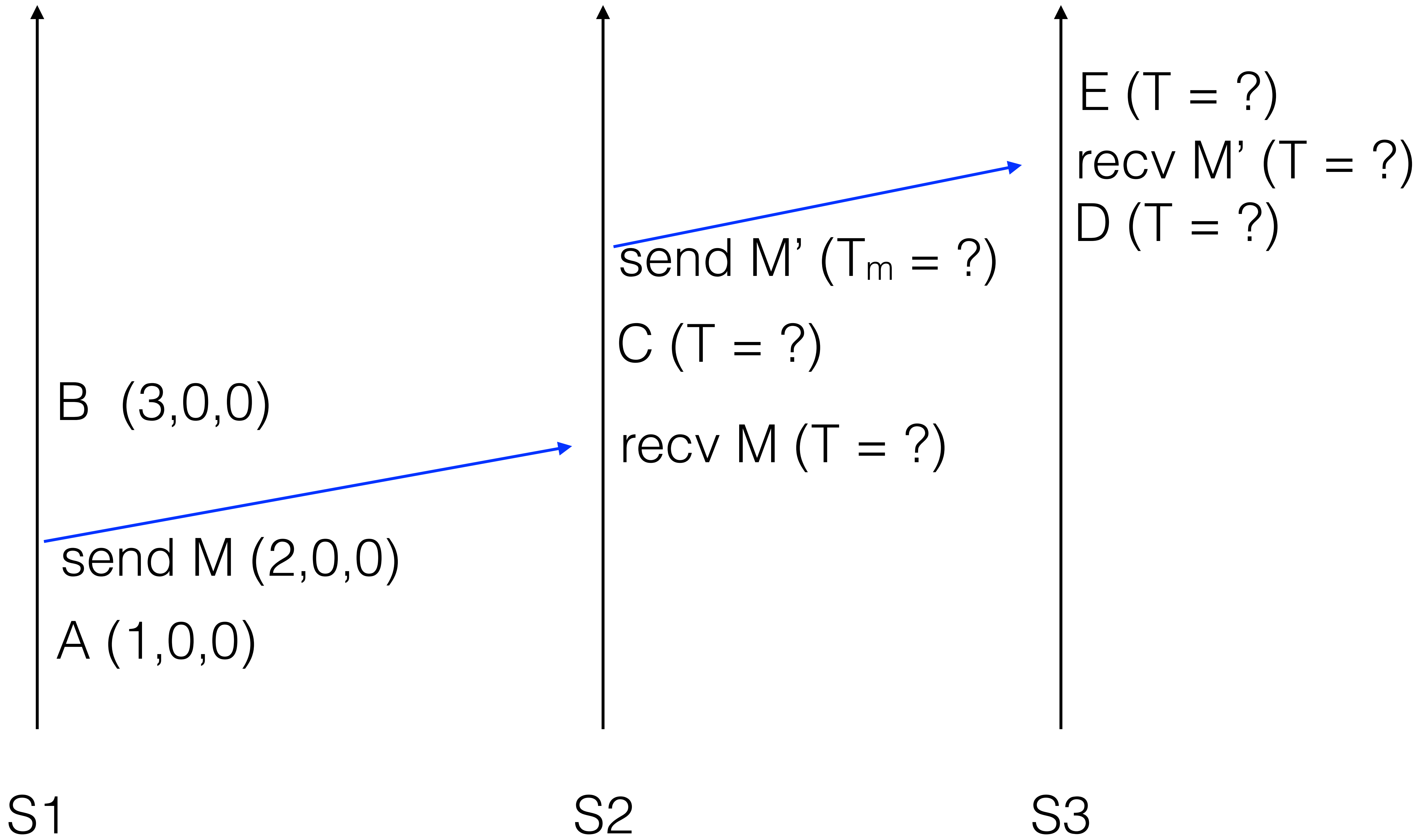
Example



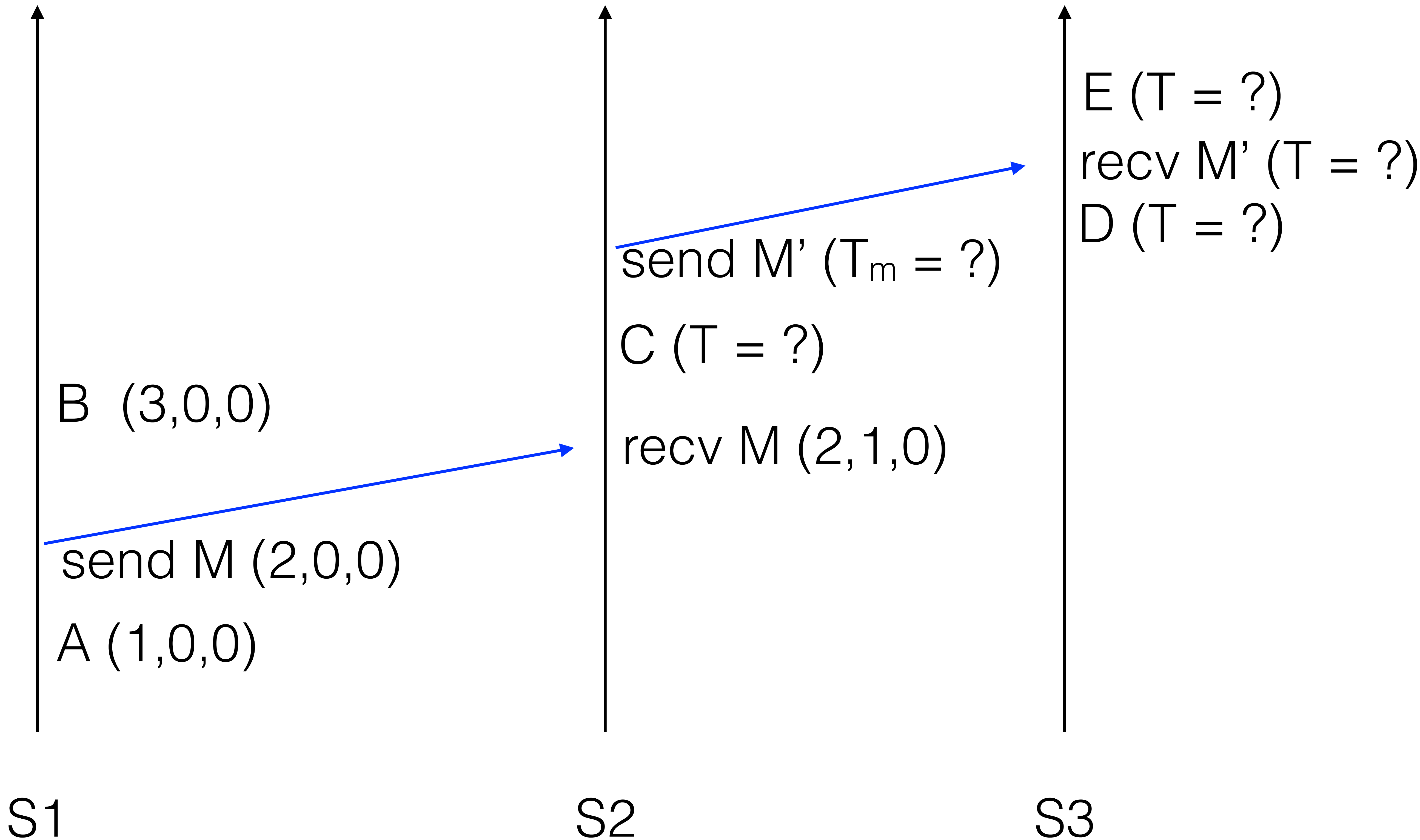
Example



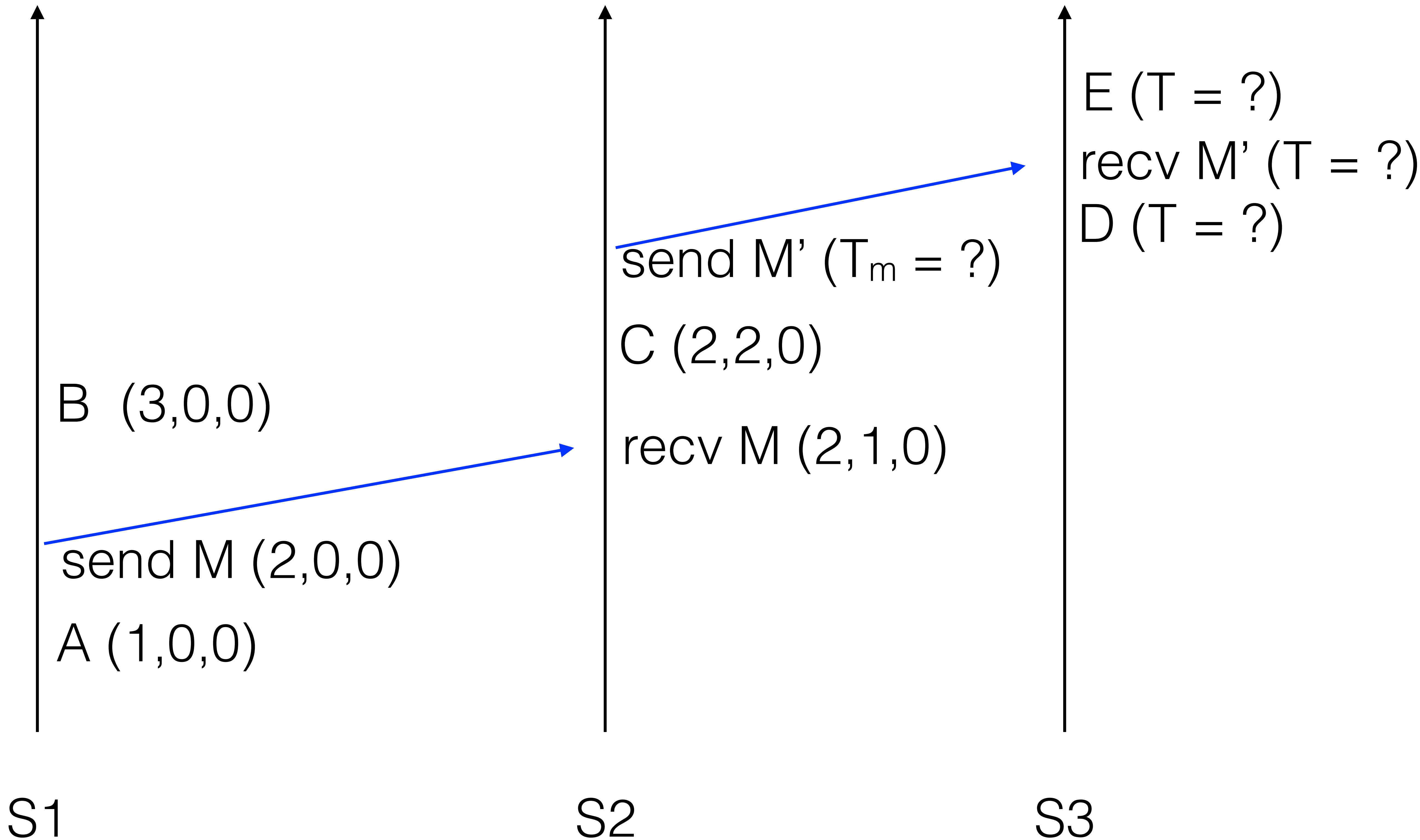
Example



Example

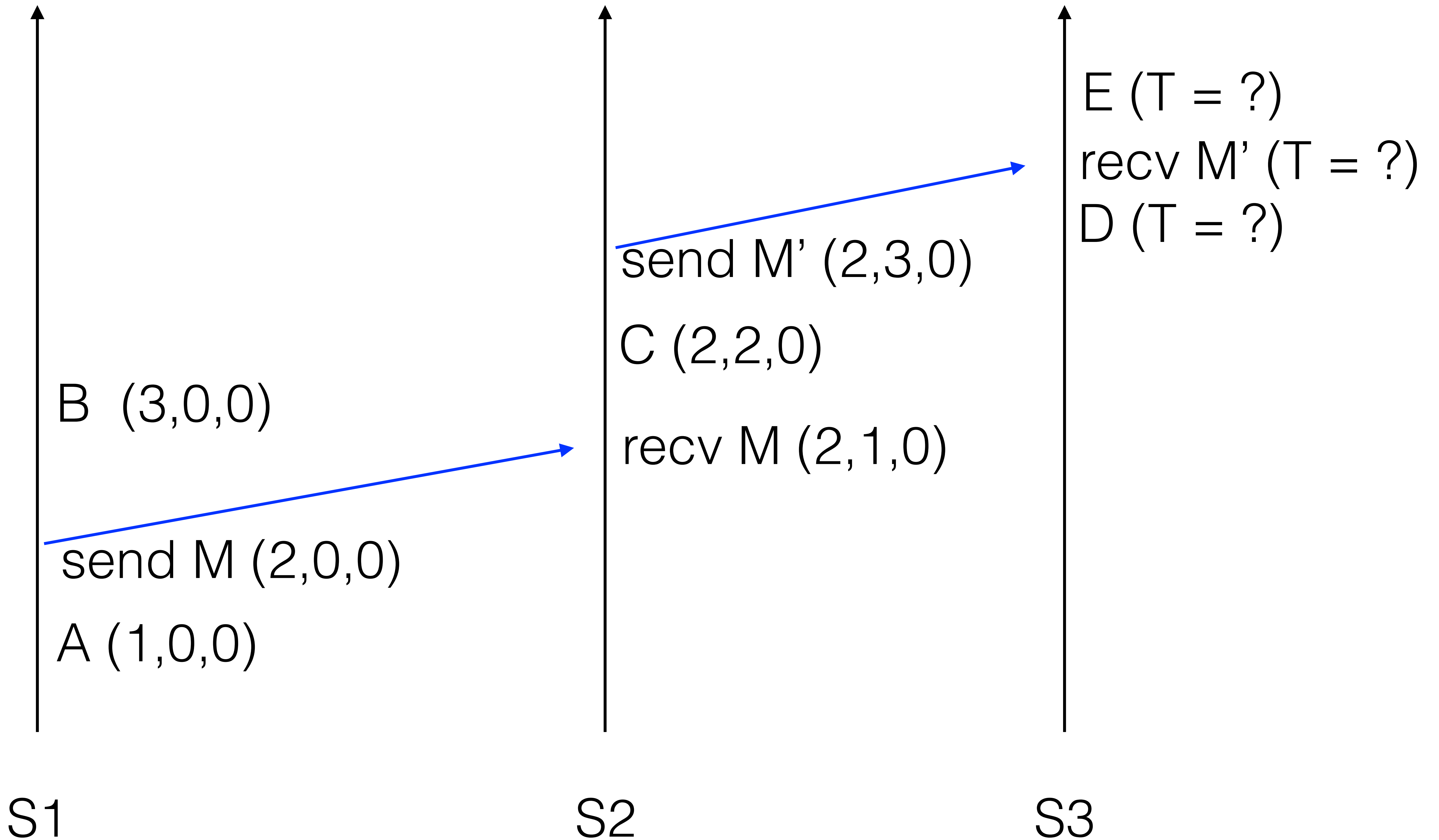


Example



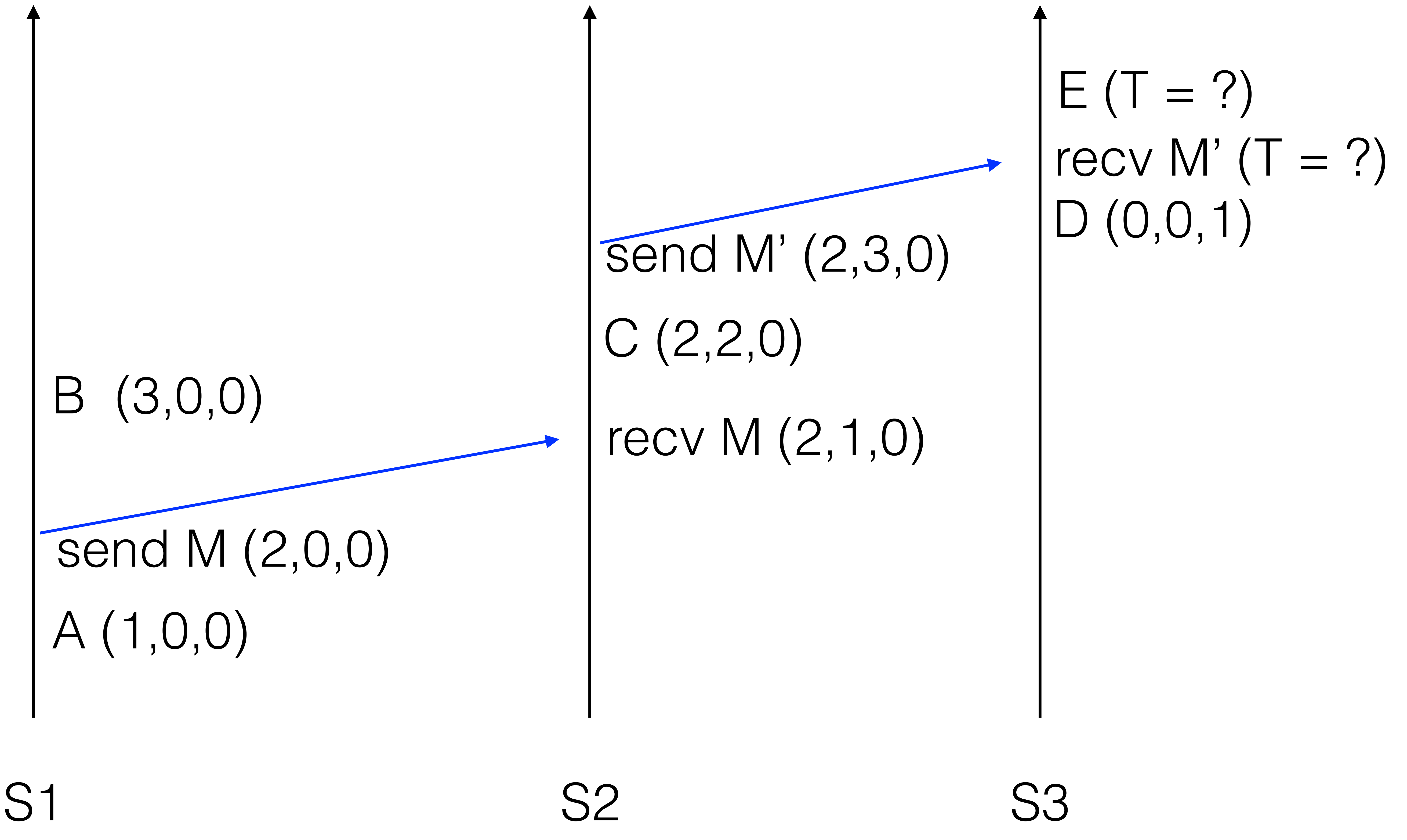
E (T = ?)
recv M' (T = ?)
D (T = ?)
send M' (T_m = ?)
C (2,2,0)
B (3,0,0)
recv M (2,1,0)
send M (2,0,0)
A (1,0,0)
S1
S2
S3

Example



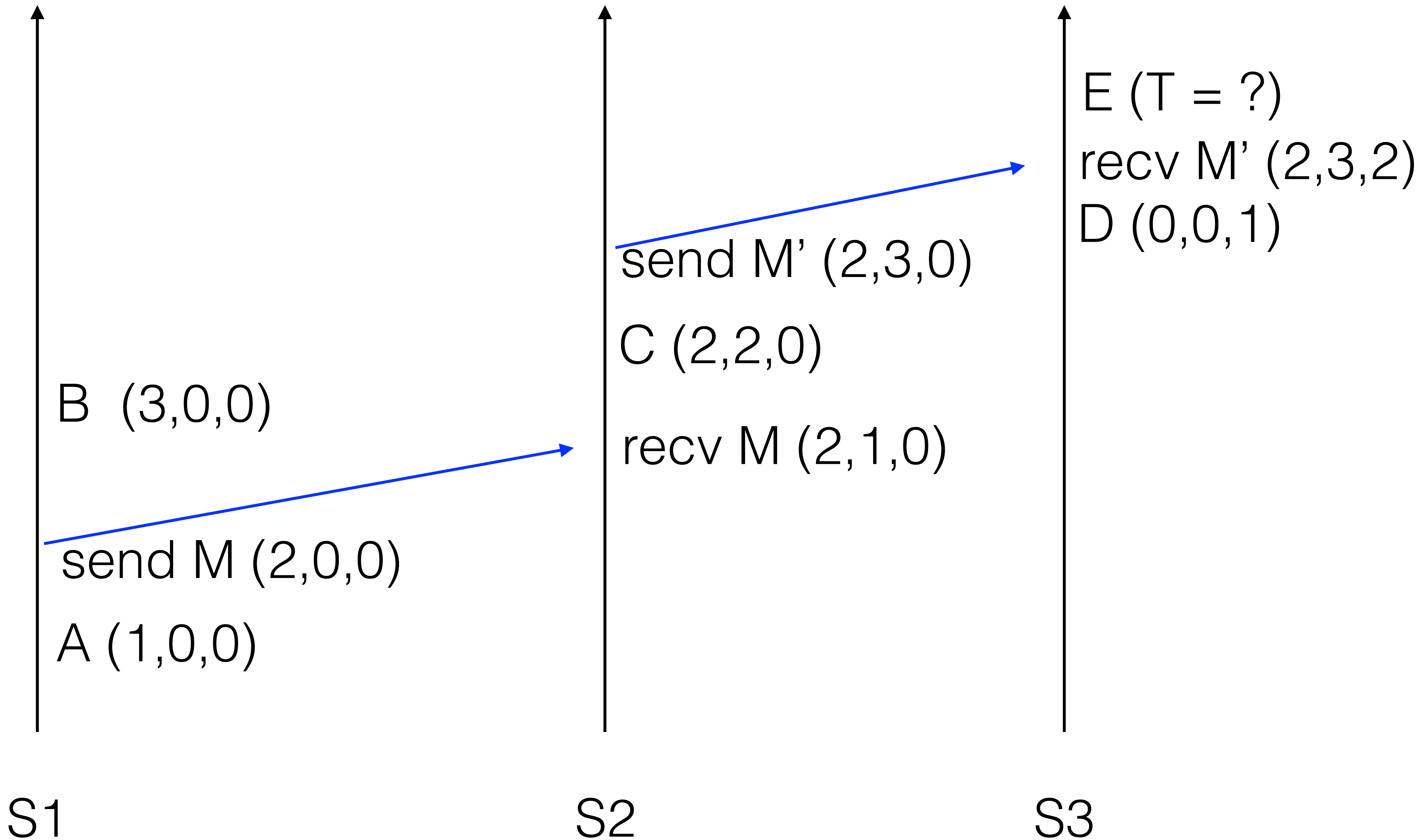
E (T = ?)
recv M' (T = ?)
D (T = ?)
send M' (2,3,0)
C (2,2,0)
B (3,0,0)
recv M (2,1,0)
send M (2,0,0)
A (1,0,0)
S1
S2
S3

Example



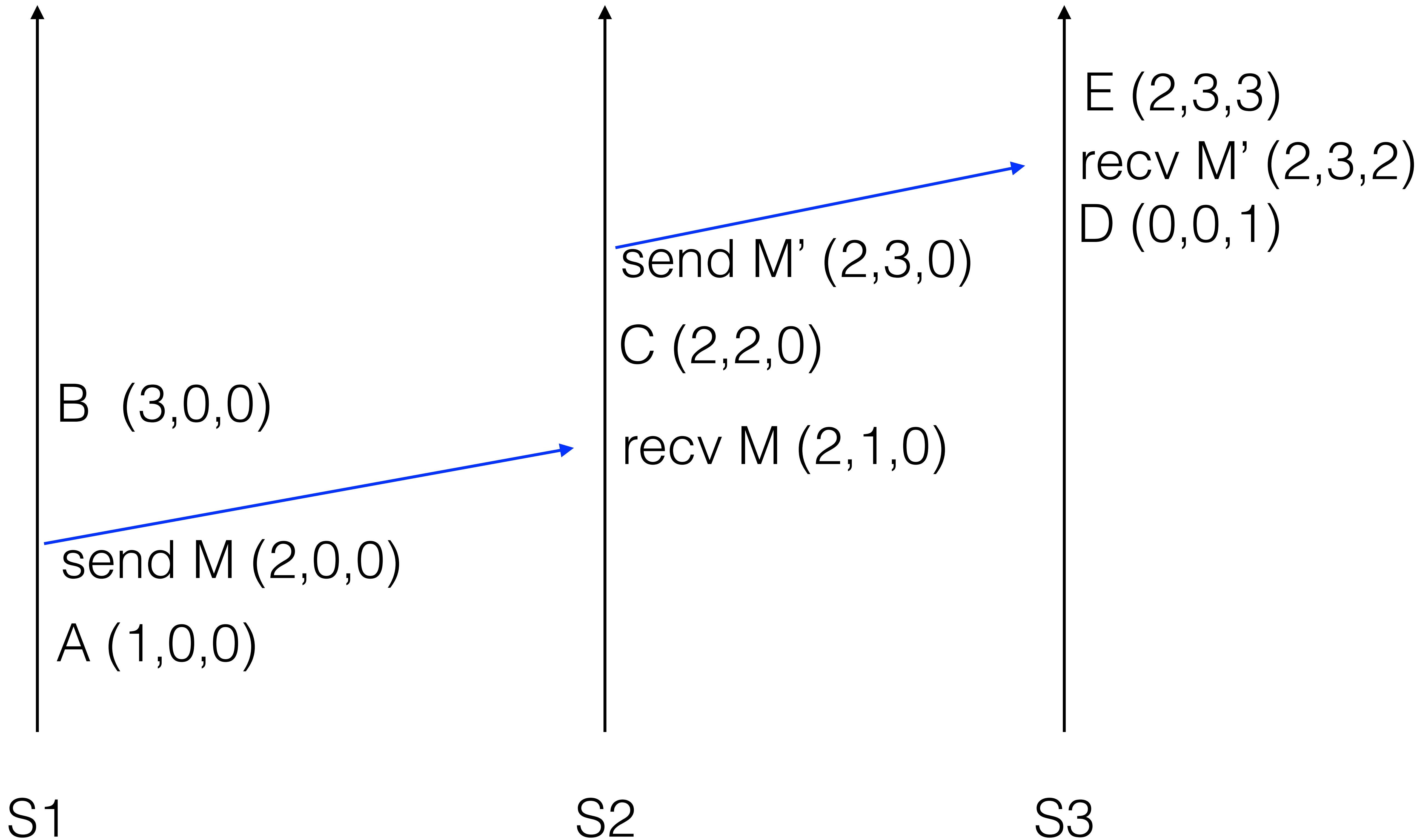
E (T = ?)
recv M’ (T = ?)
D (0,0,1)
send M’ (2,3,0)
C (2,2,0)
B (3,0,0)
recv M (2,1,0)
send M (2,0,0)
A (1,0,0)
S1
S2
S3

Example

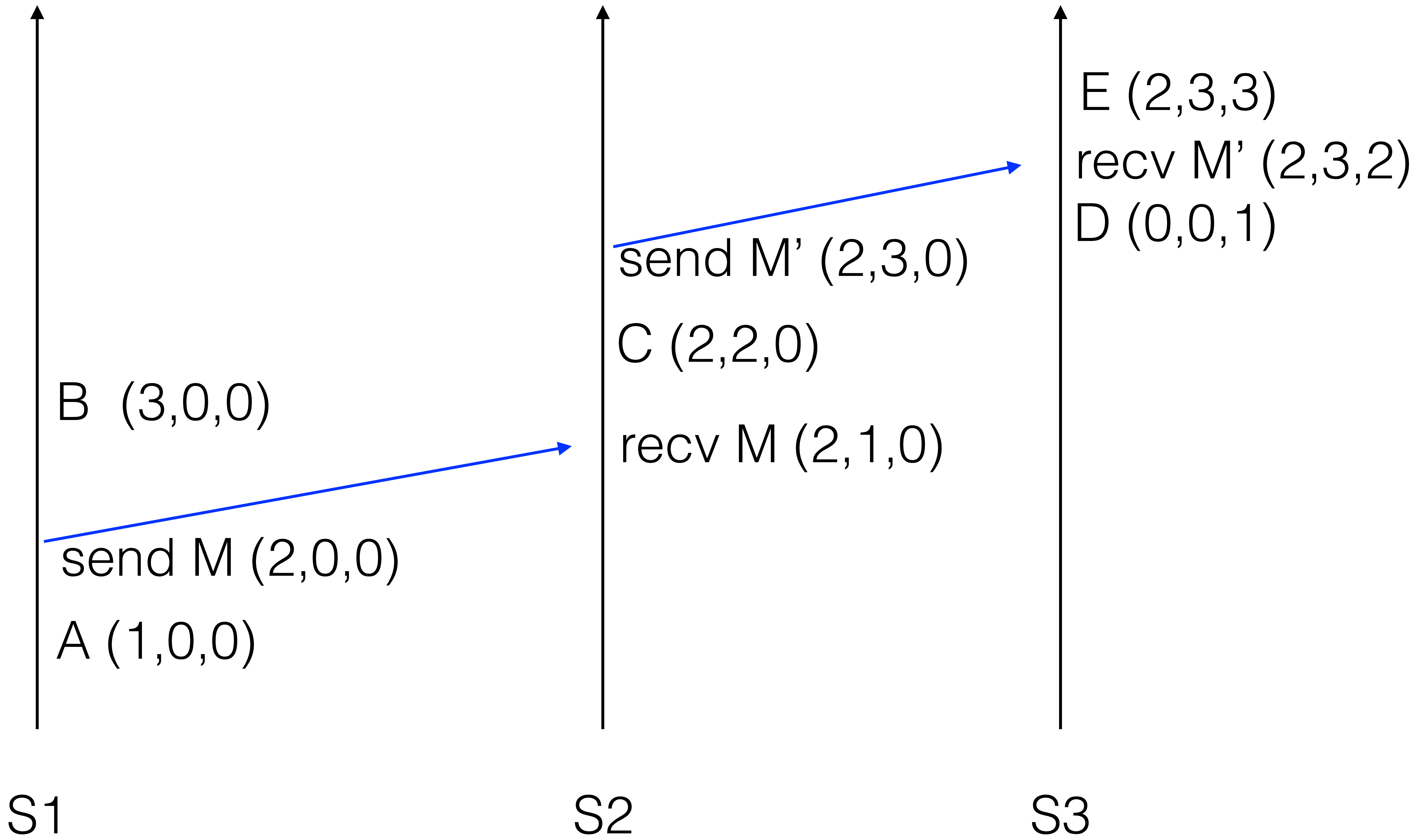


E (T = ?)
recv M’ (2,3,2)
D (0,0,1)
send M’ (2,3,0)
C (2,2,0)
B (3,0,0)
recv M (2,1,0)
send M (2,0,0)
A (1,0,0)
S1
S2
S3

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

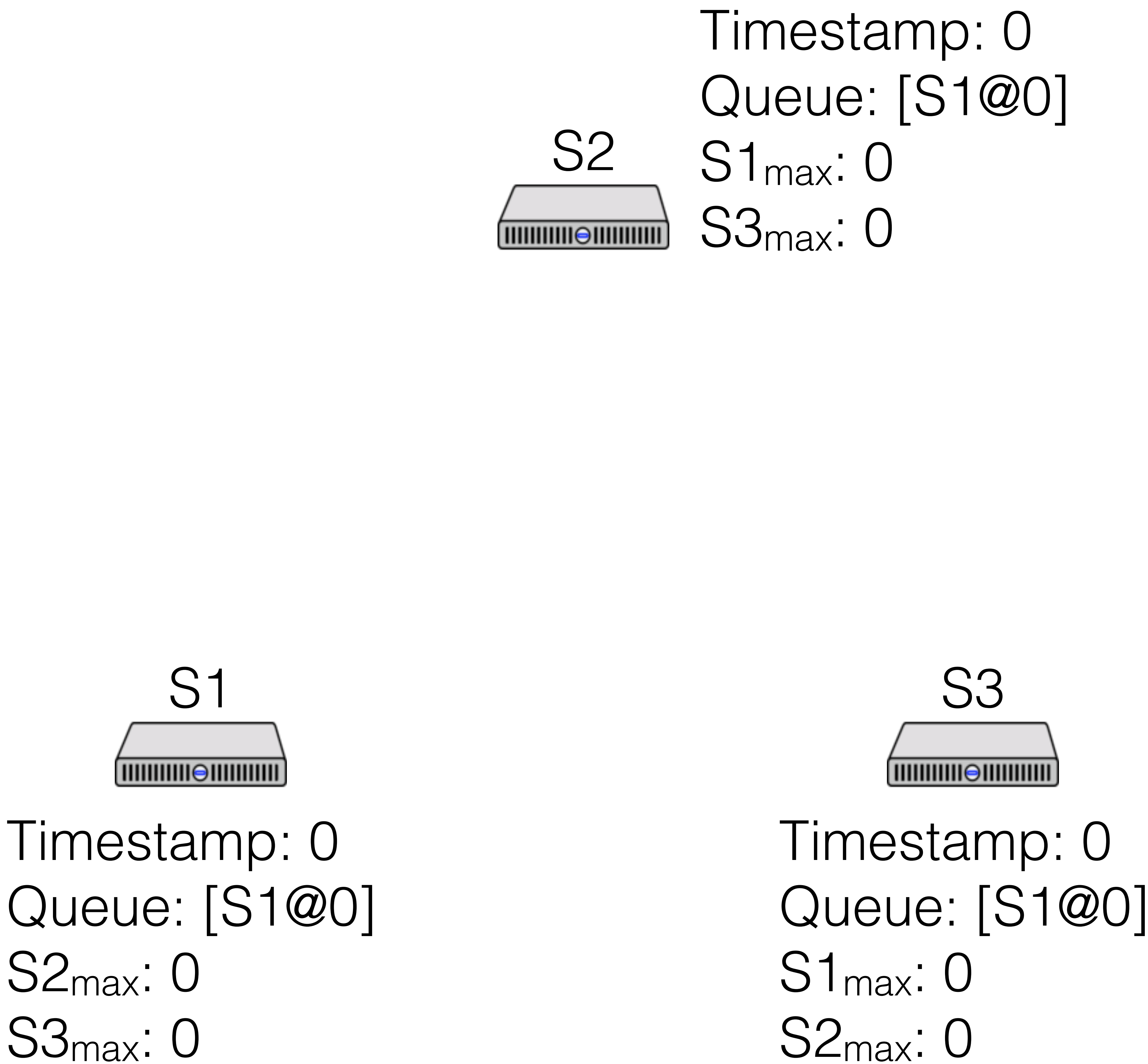
Provided the vectors are not identical,

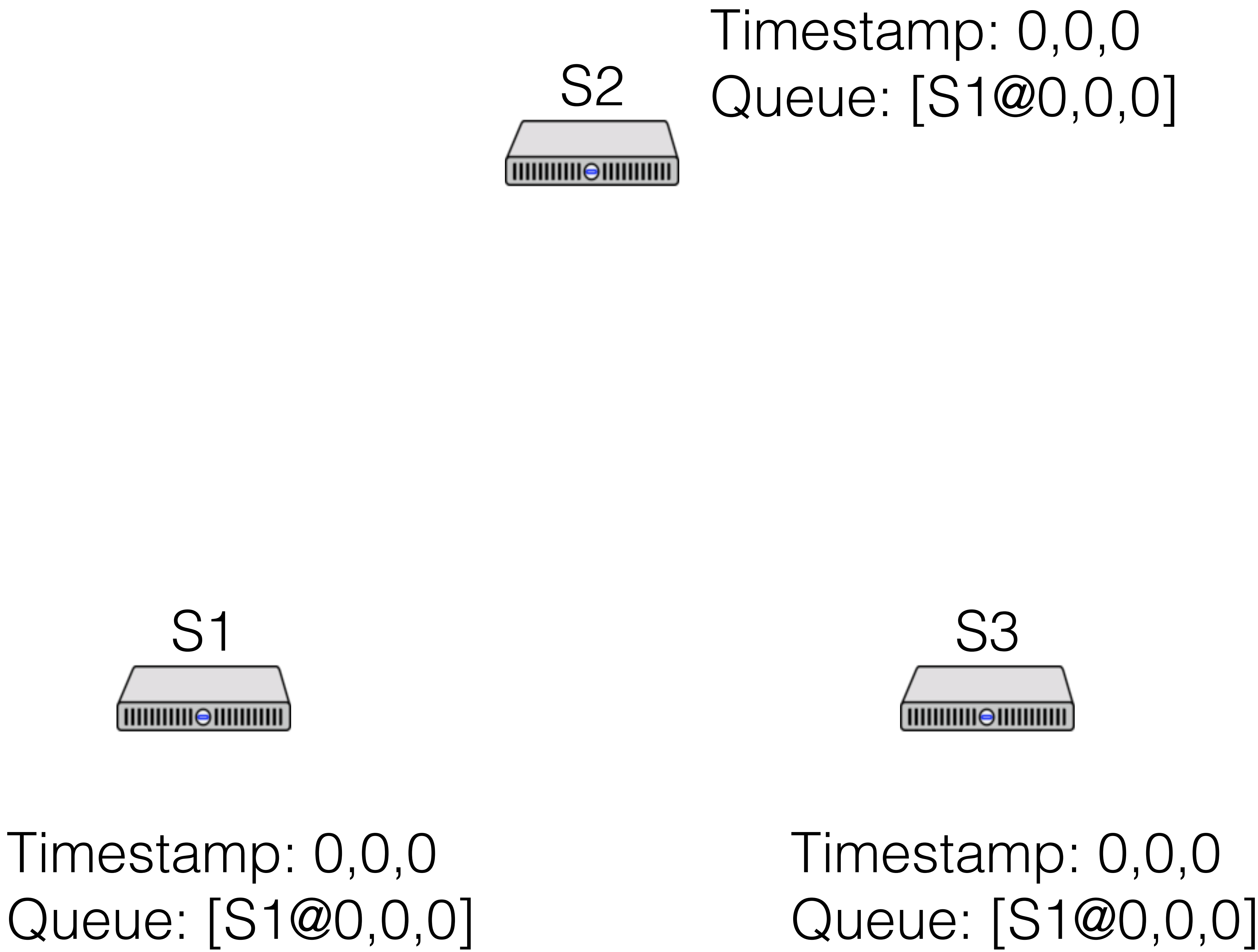
If $C_x[i] < C_y[i]$ and $C_x[j] > C_y[j]$ for some i, j

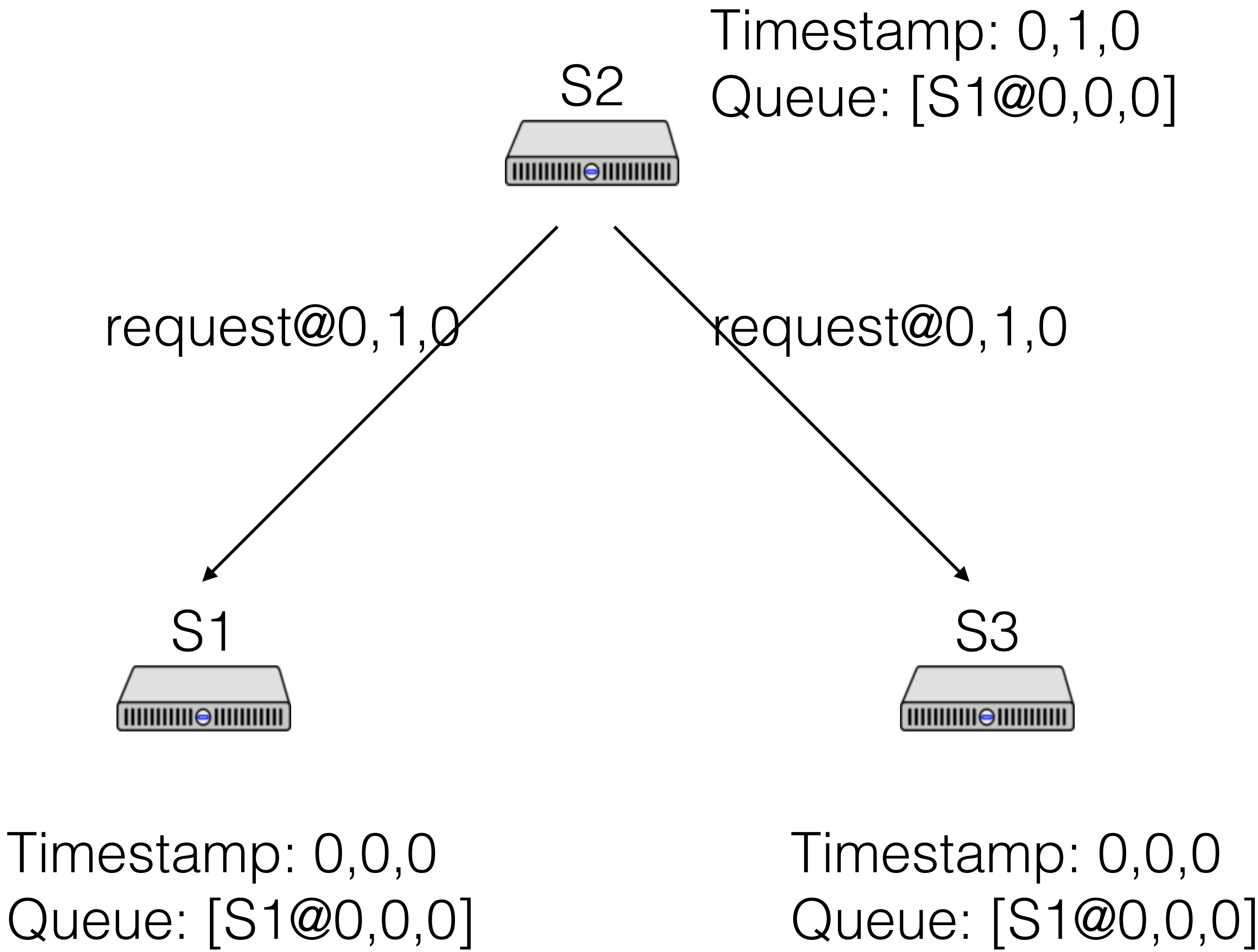
C_x and C_y are concurrent

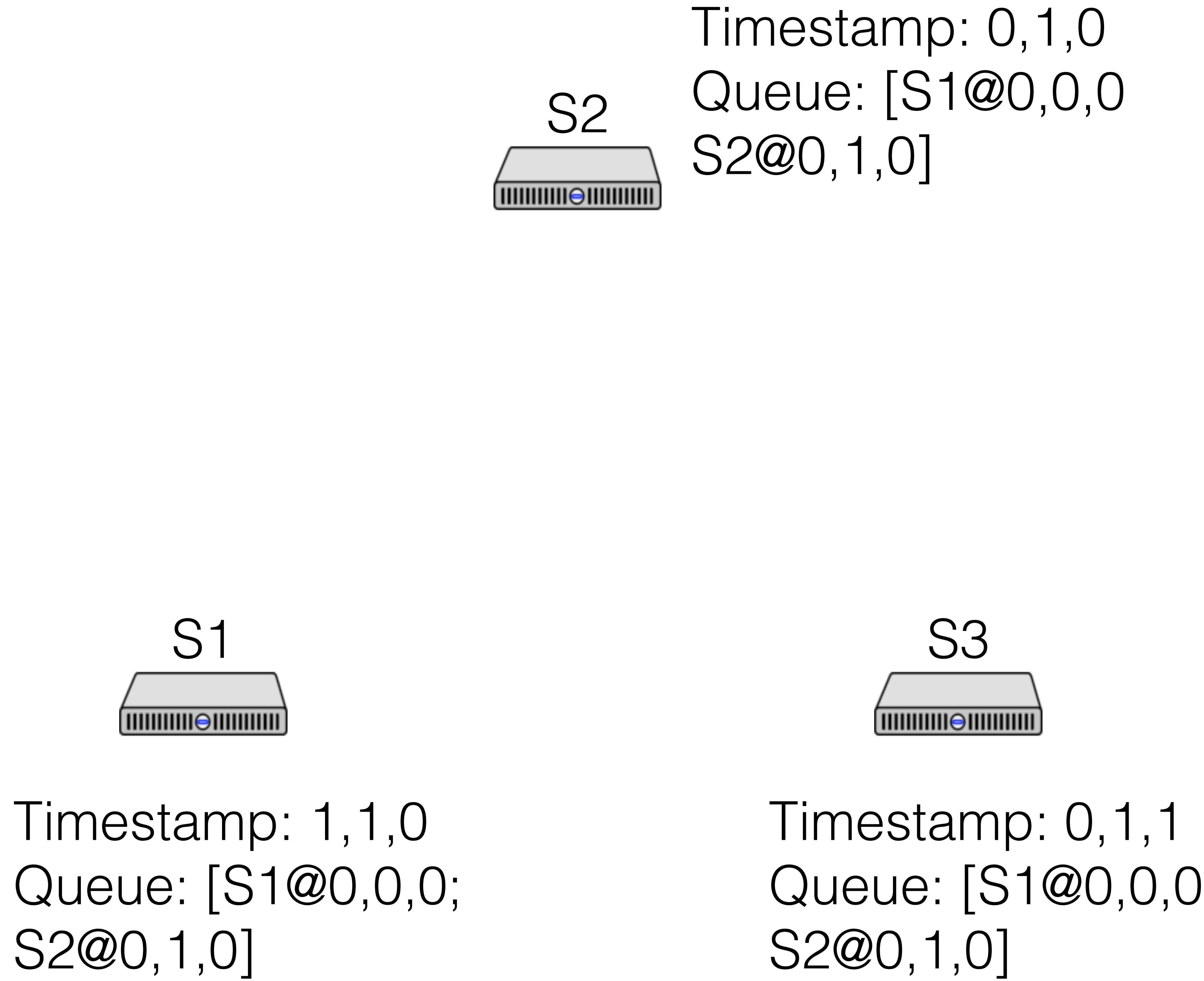
if $C_x[i] <= C_y[i]$ for all i

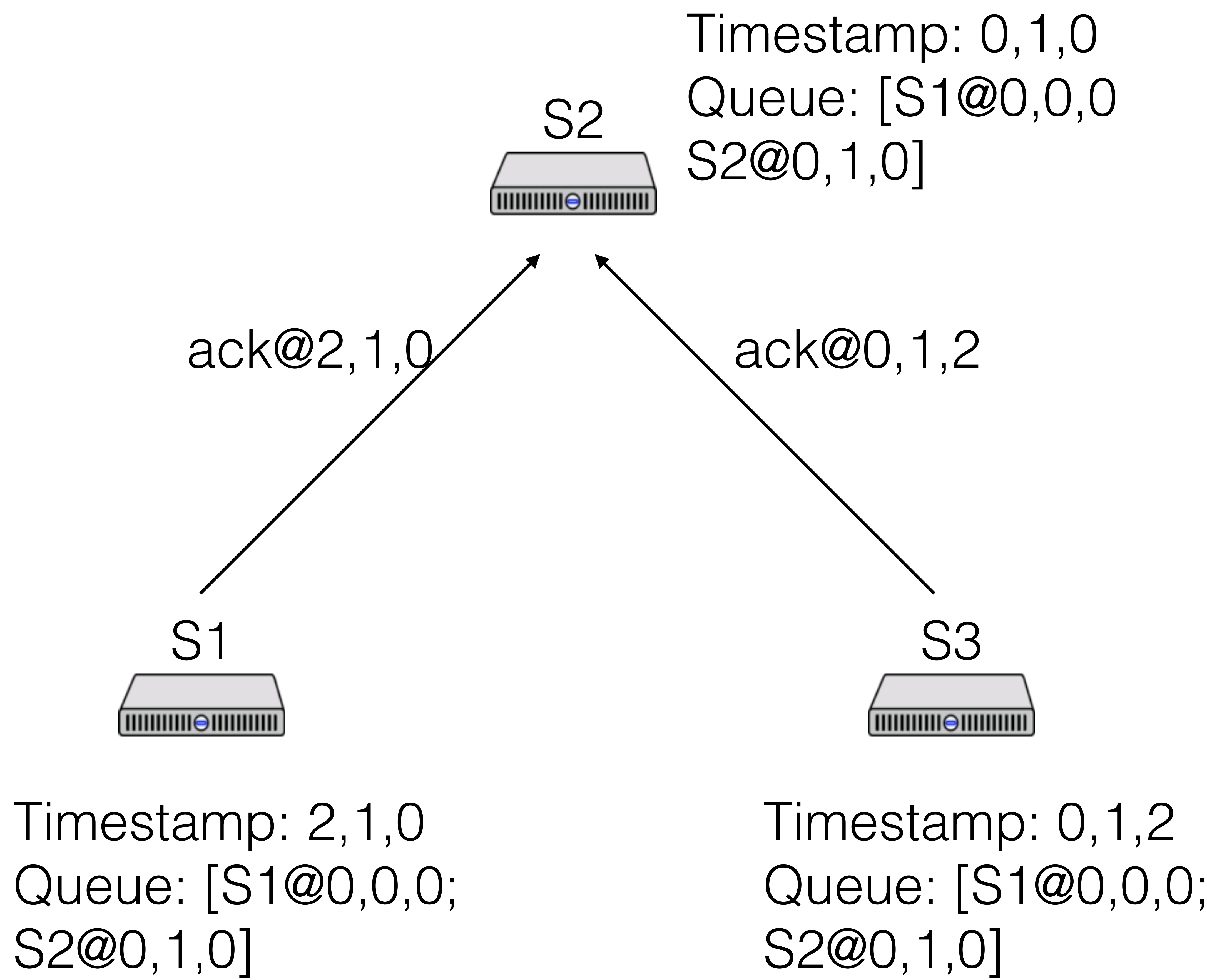
C_x happens before C_y

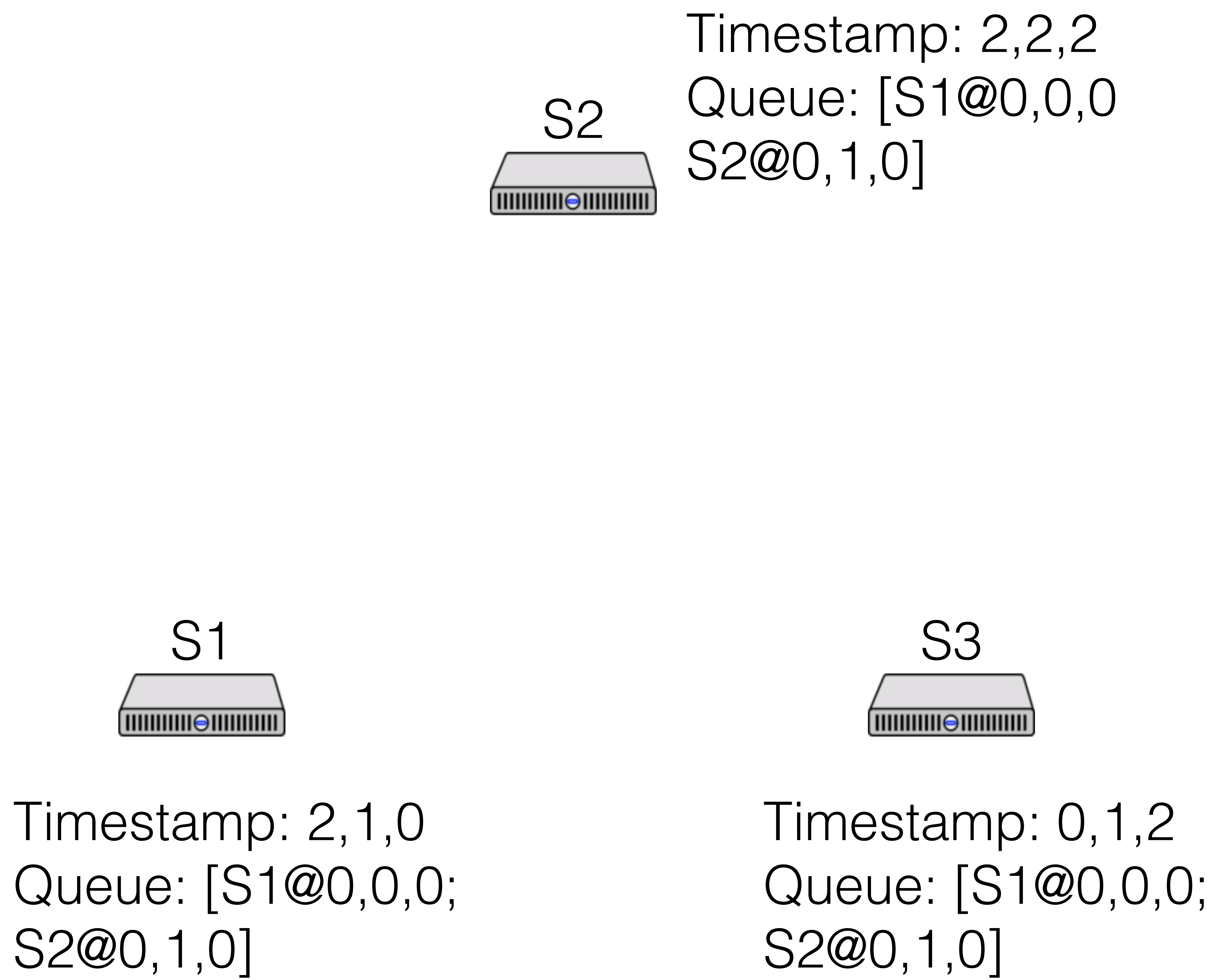

S2
Timestamp: 0
Queue: [S1@0]
$S1_{max}$: 0
$S3_{max}$: 0
S1
Timestamp: 0
Queue: [S1@0]
$S2_{max}$: 0
$S3_{max}$: 0
S3
Timestamp: 0
Queue: [S1@0]
$S1_{max}$: 0
$S2_{max}$: 0

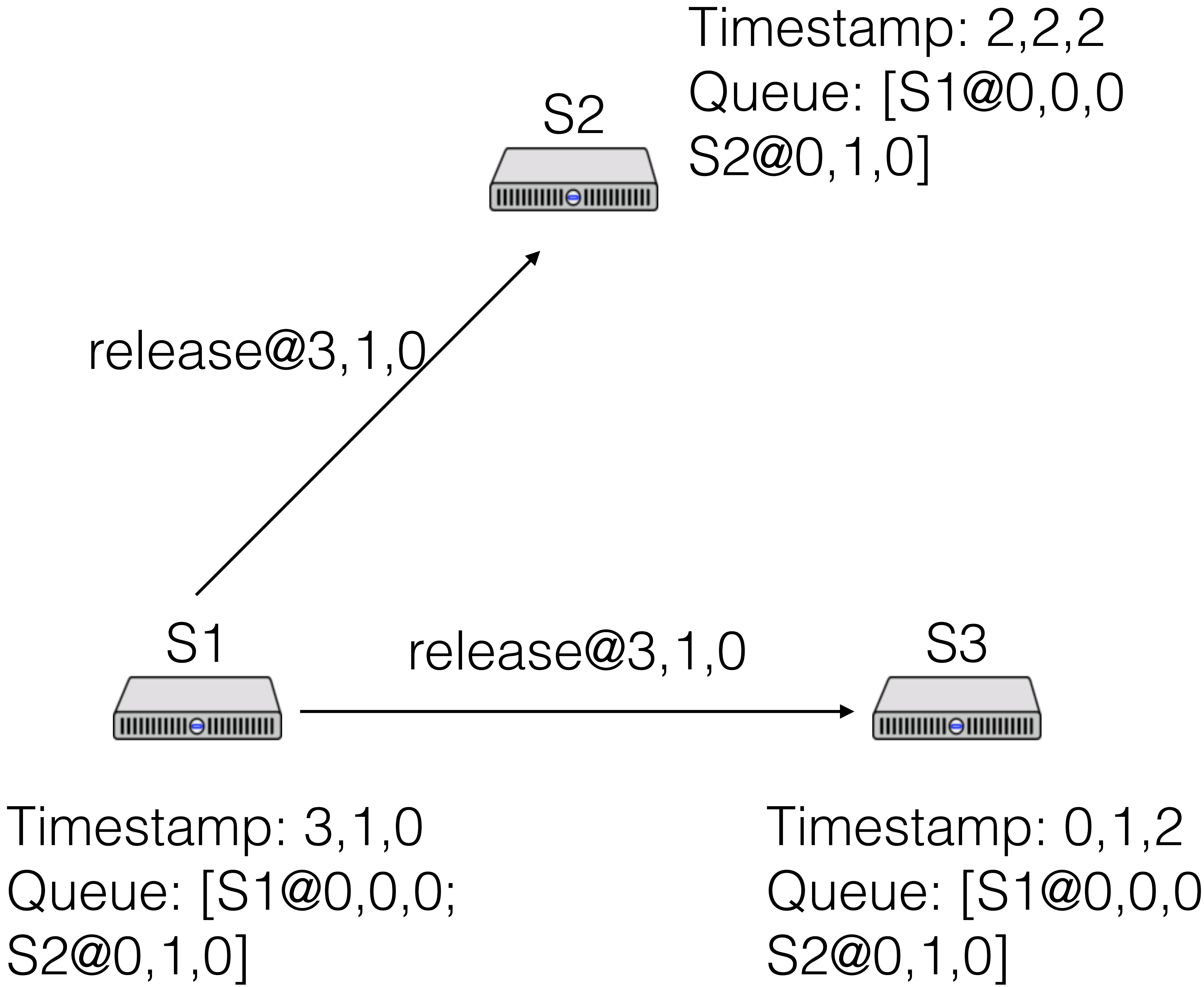

S2
Timestamp: 0,0,0
Queue: [S1@0,0,0]
S1
Timestamp: 0,0,0
Queue: [S1@0,0,0]
S3
Timestamp: 0,0,0
Queue: [S1@0,0,0]

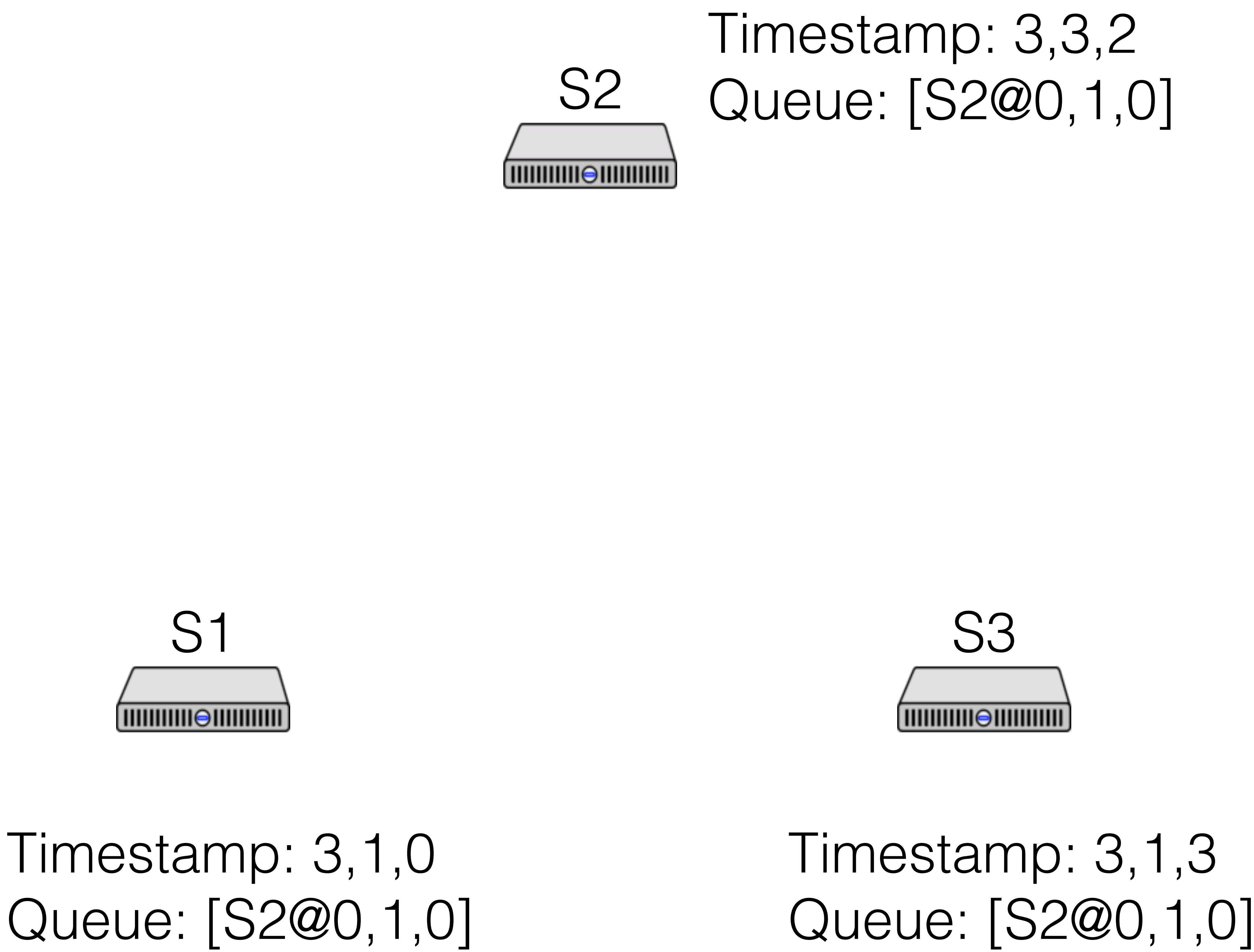

S2
Timestamp: 0,1,0
Queue: [S1@0,0,0]
request@0,1,0
request@0,1,0
S1
S3
Timestamp: 0,0,0
Queue: [S1@0,0,0]
Timestamp: 0,0,0
Queue: [S1@0,0,0]

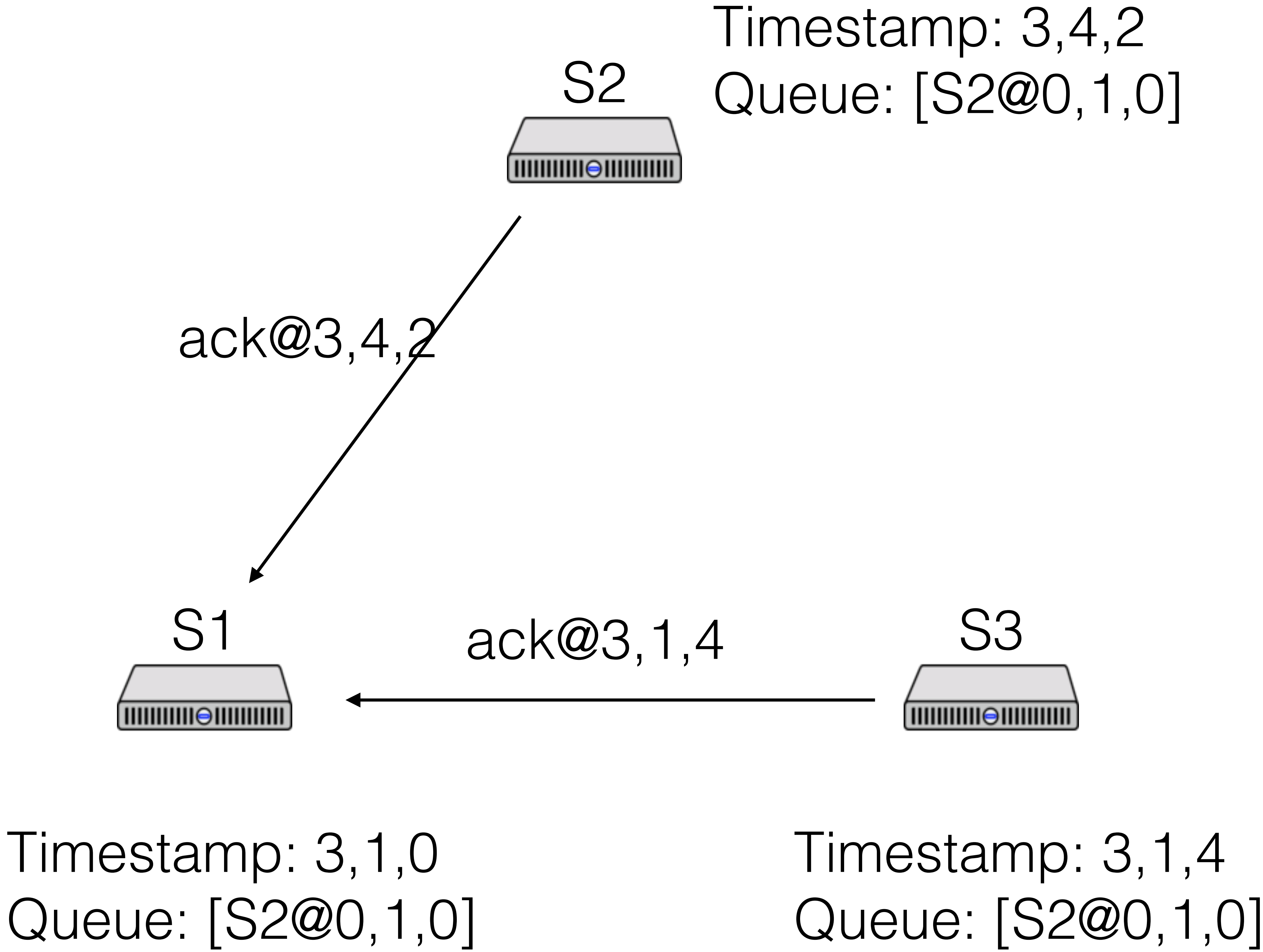

S2
Timestamp: 0,1,0
Queue: [S1@0,0,0
S2@0,1,0]
S1
Timestamp: 1,1,0
Queue: [S1@0,0,0;
S2@0,1,0]
S3
Timestamp: 0,1,1
Queue: [S1@0,0,0;
S2@0,1,0]

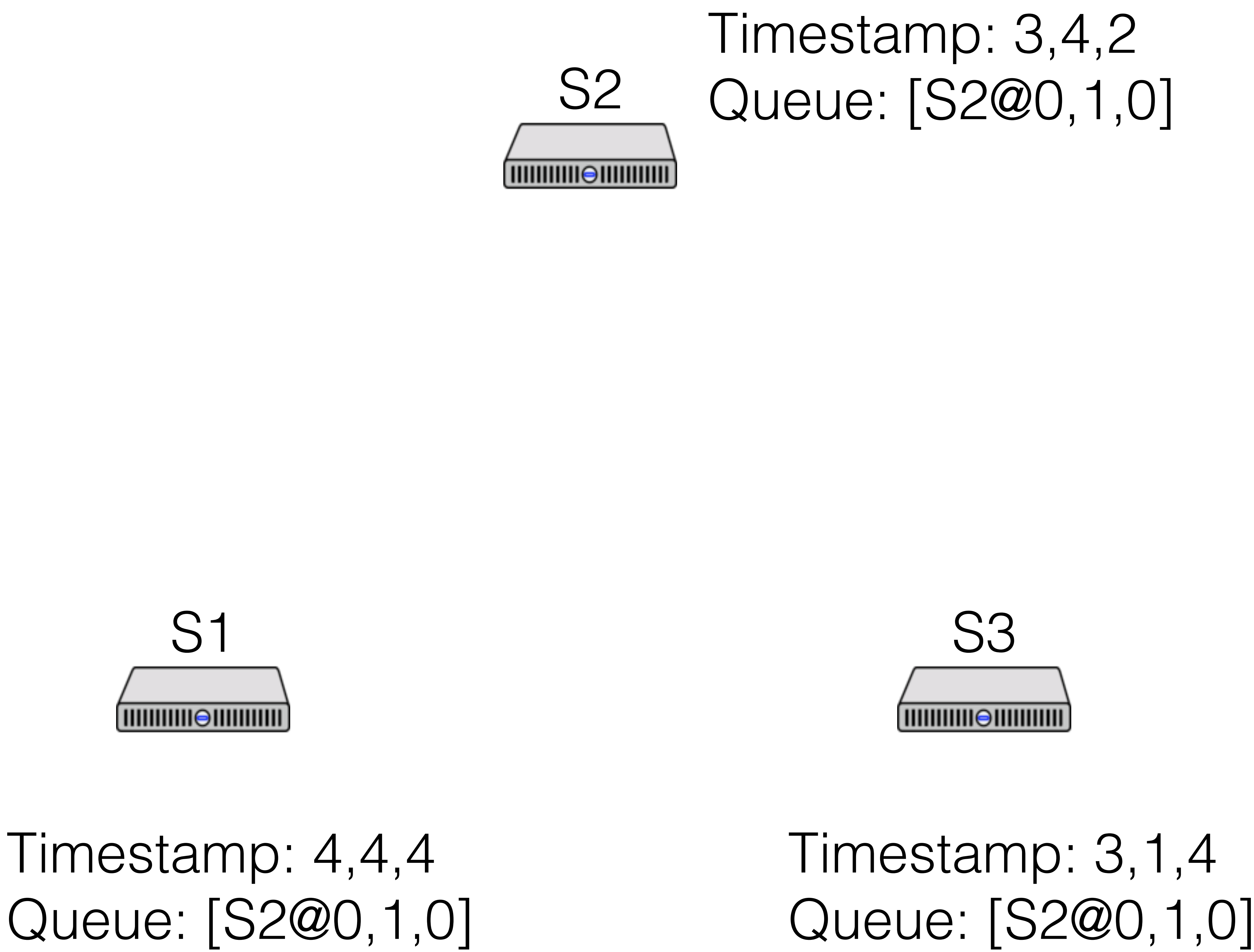

S2
Timestamp: 0,1,0
Queue: [S1@0,0,0
S2@0,1,0]
ack@2,1,0
ack@0,1,2
S1
S3
Timestamp: 2,1,0
Queue: [S1@0,0,0;
S2@0,1,0]
Timestamp: 0,1,2
Queue: [S1@0,0,0;
S2@0,1,0]


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]


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


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

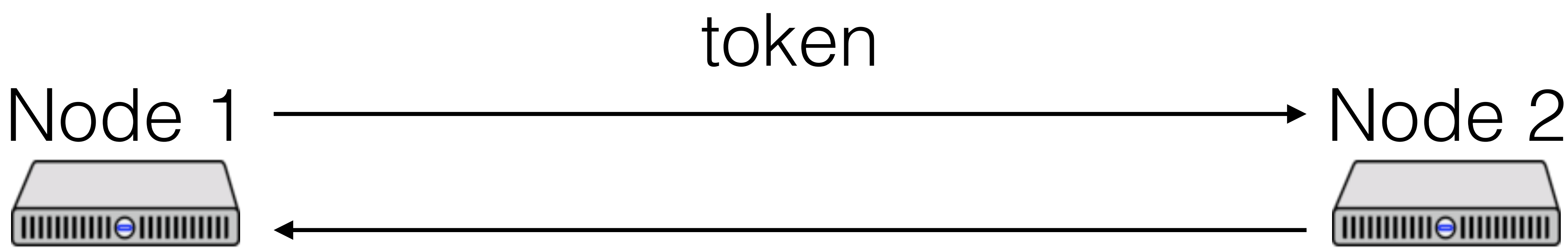
Types of properties: stable properties, invariants

- 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

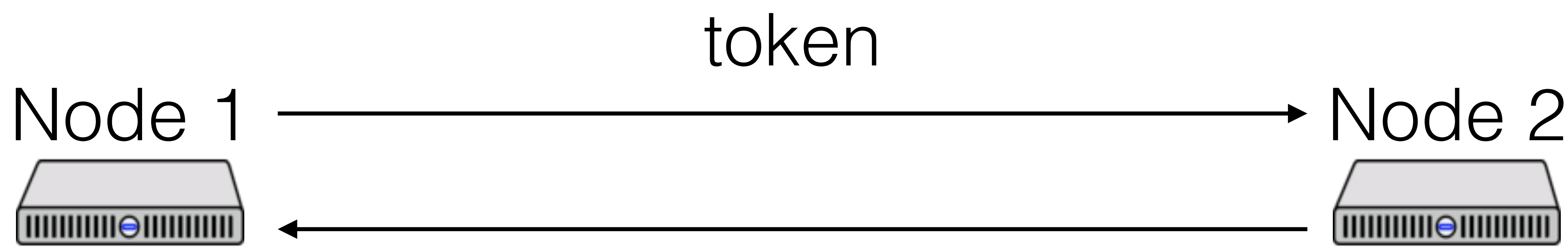
haveToken: bool

In S_o

- 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



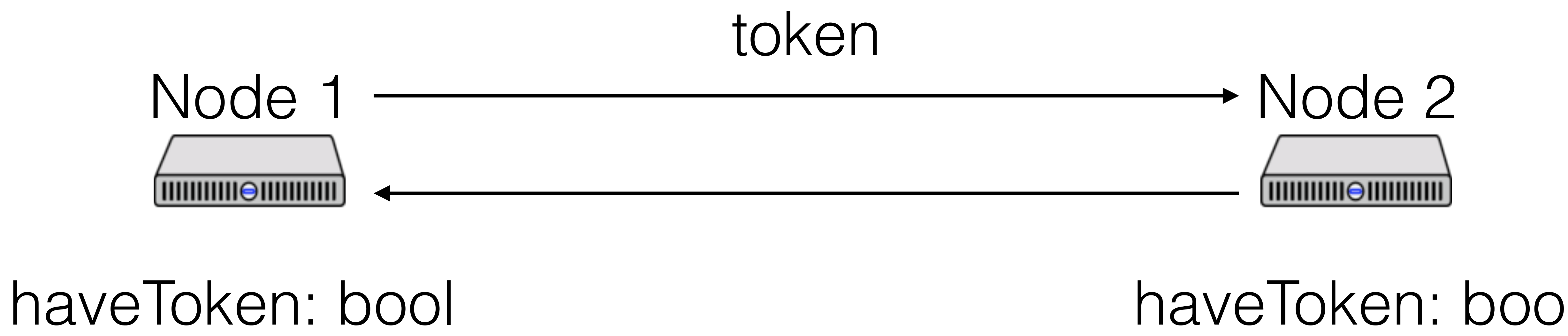
haveToken: bool

haveToken: bool

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?

- Checkpoint and restart
- 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

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

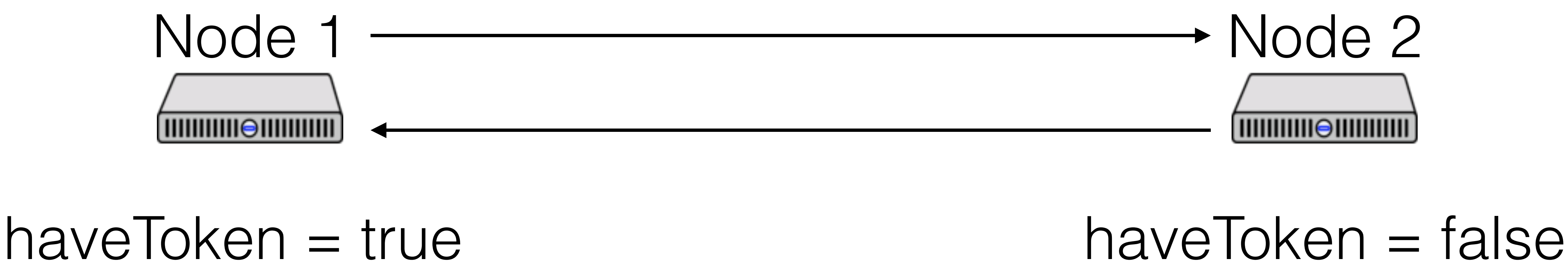
Channels:

- 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?

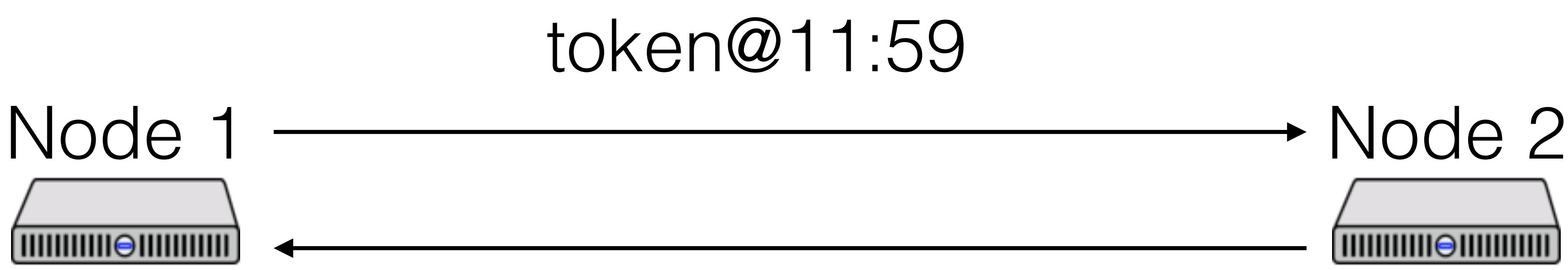
Physical time algorithm

11:59



Physical time algorithm

11:59

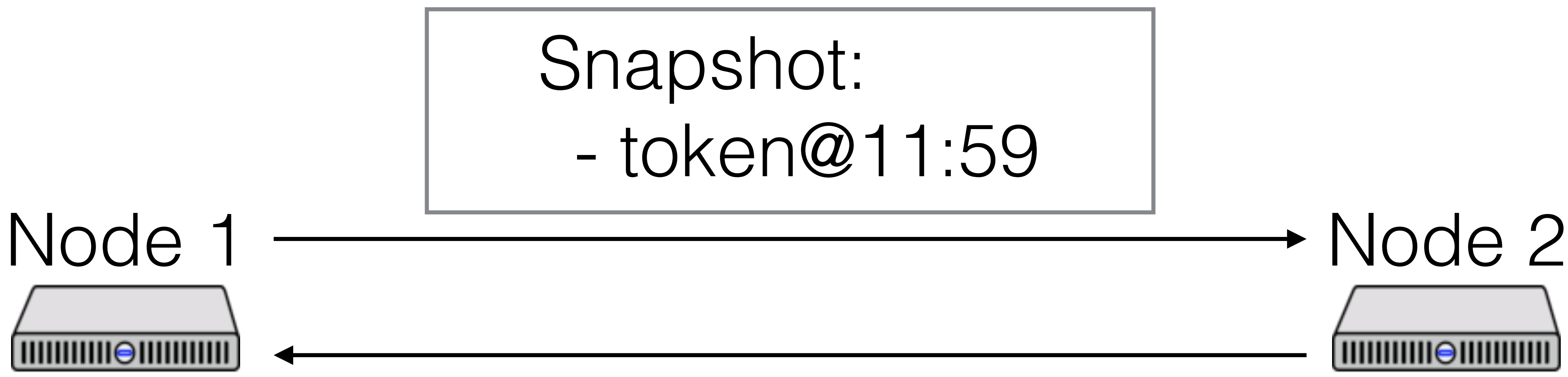


haveToken = false

haveToken = false

Physical time algorithm

12:00



haveToken = false

Snapshot:
- haveToken = false

haveToken = false

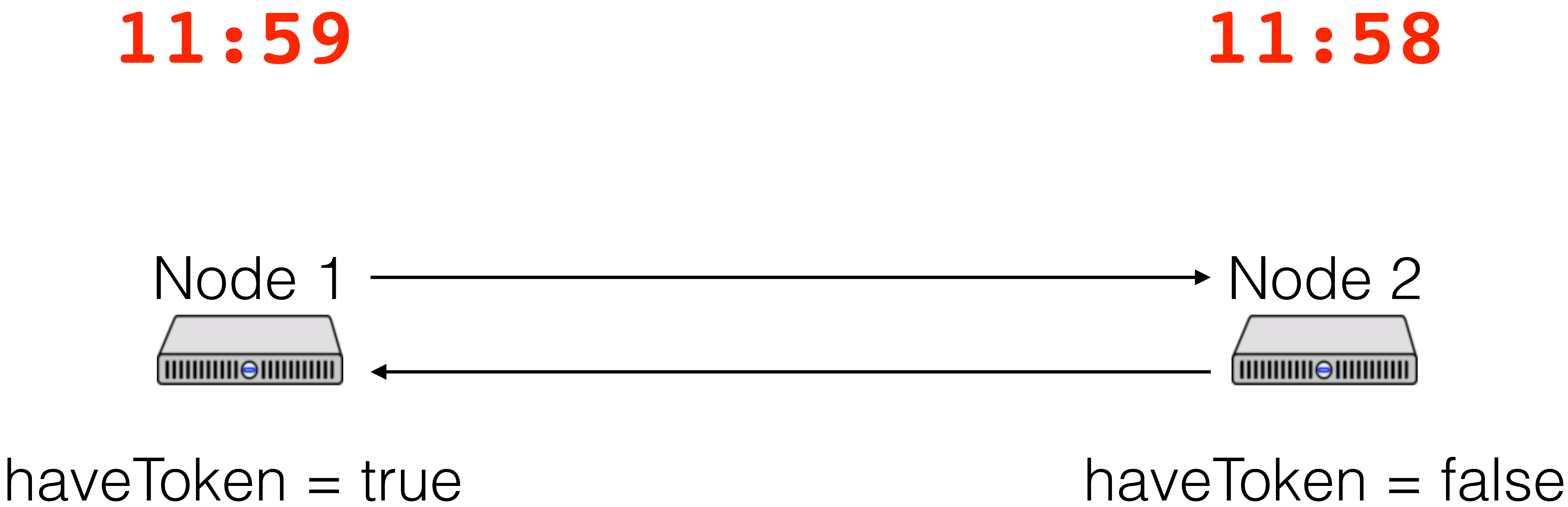
Snapshot:
- haveToken = false

Physical time algorithm

This seems like it works, right?

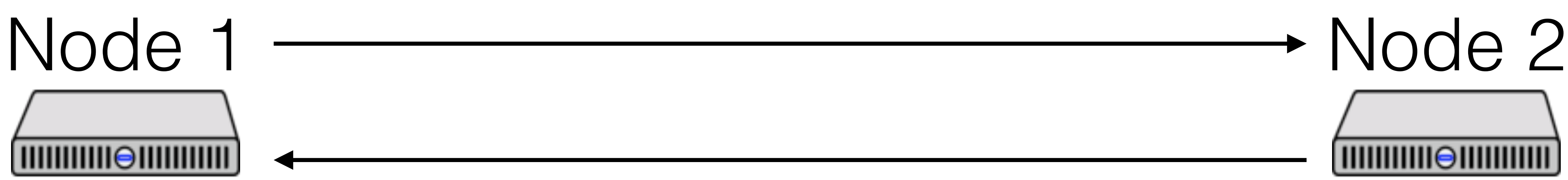
What could go wrong?

Physical time algorithm



Physical time algorithm

12:00 **11:59**

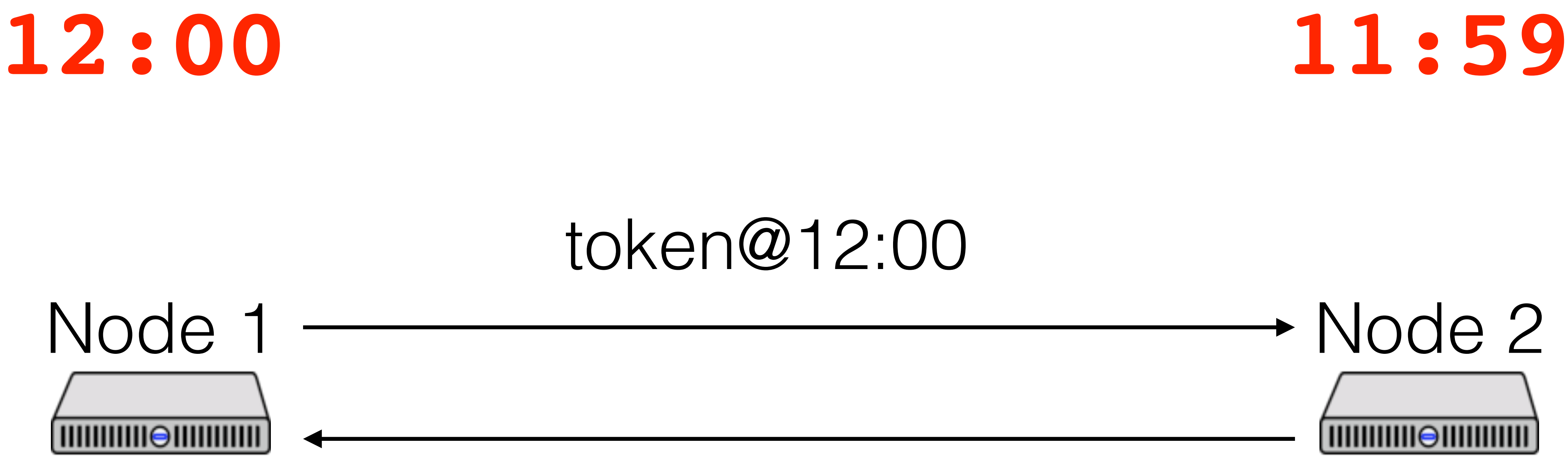


haveToken = true

haveToken = false

Snapshot:
- haveToken = true

Physical time algorithm



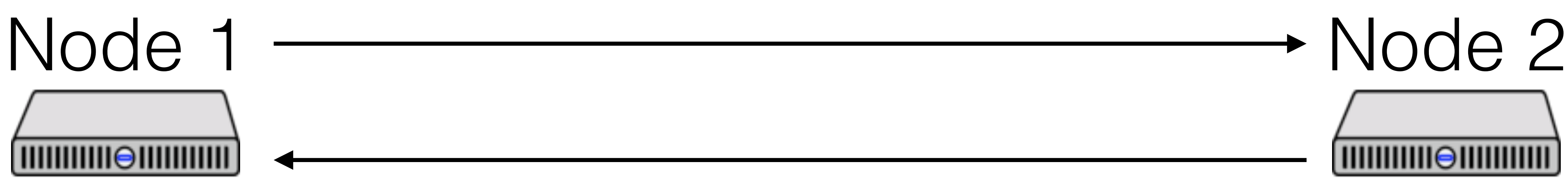
haveToken = false

haveToken = false

Snapshot:
- haveToken = true

Physical time algorithm

12:00 **11:59**



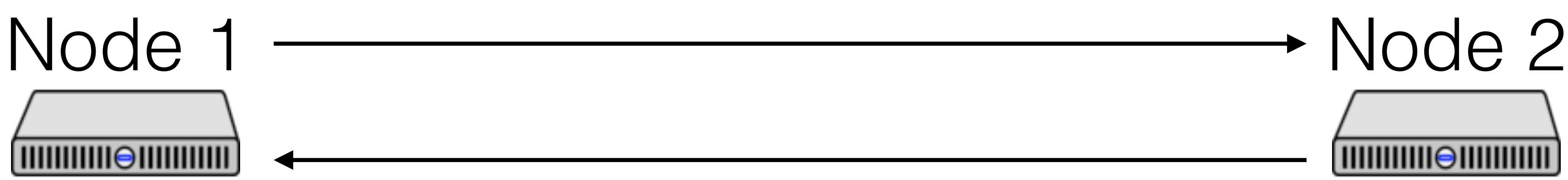
haveToken = false

haveToken = true

Snapshot:
- haveToken = true

Physical time algorithm

12:01 **12:00**



haveToken = false

Snapshot:
- haveToken = true

haveToken = true

Snapshot:
- haveToken = true

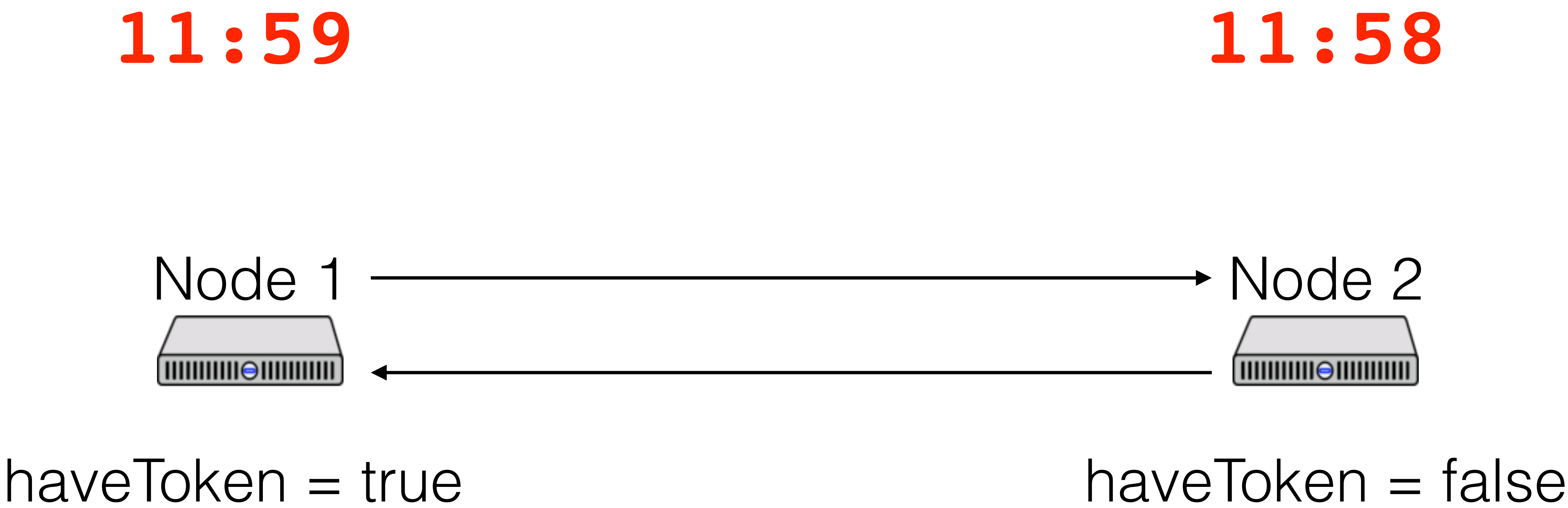
Avoiding inconsistencies

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**

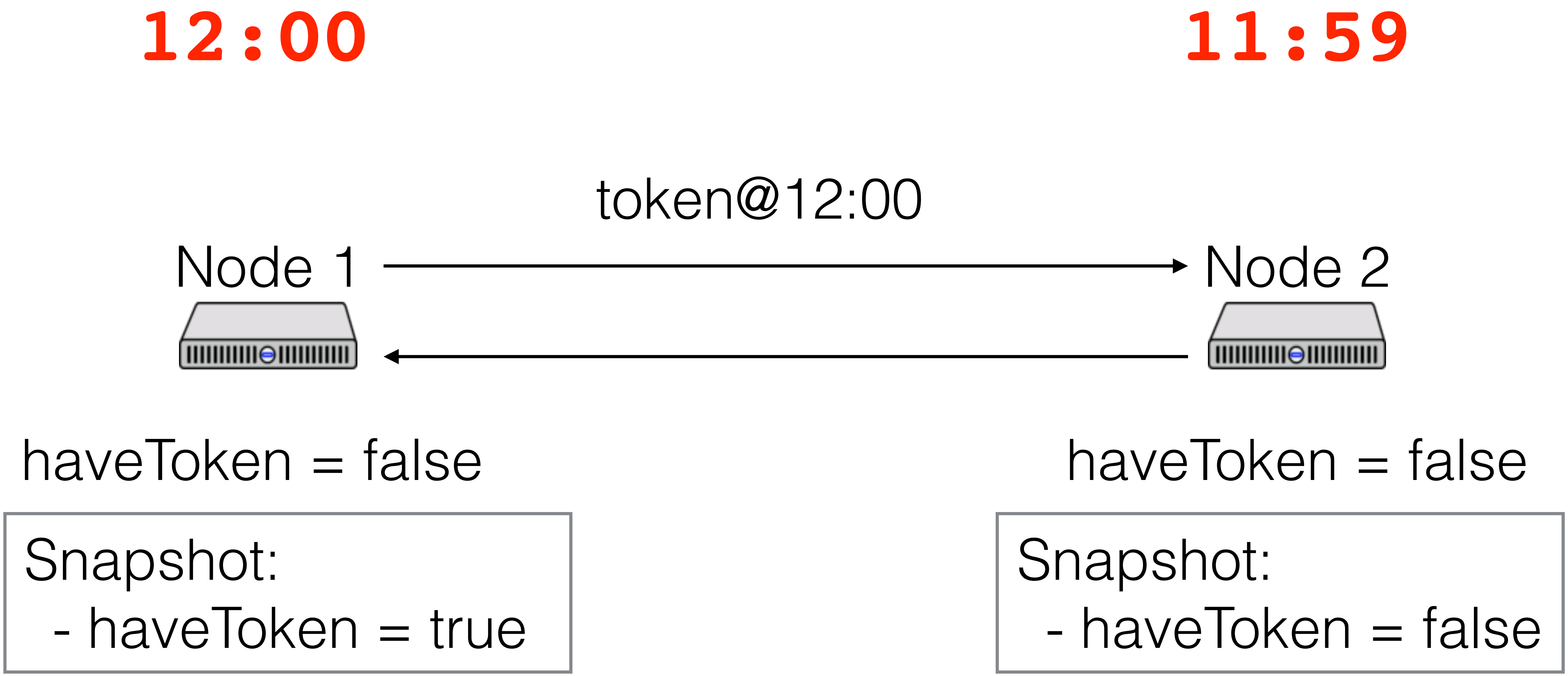
haveToken = true

haveToken = false

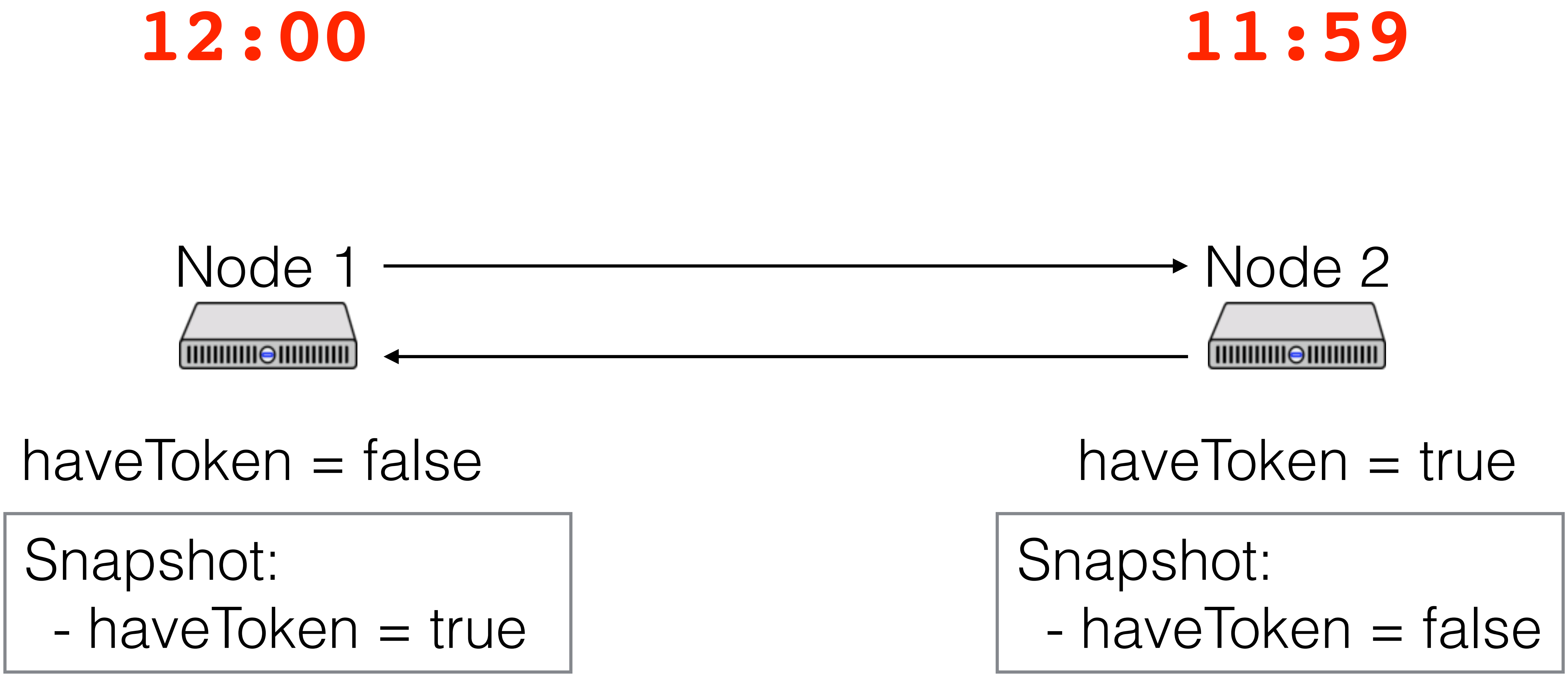
Snapshot:
- haveToken = true

Better algorithm

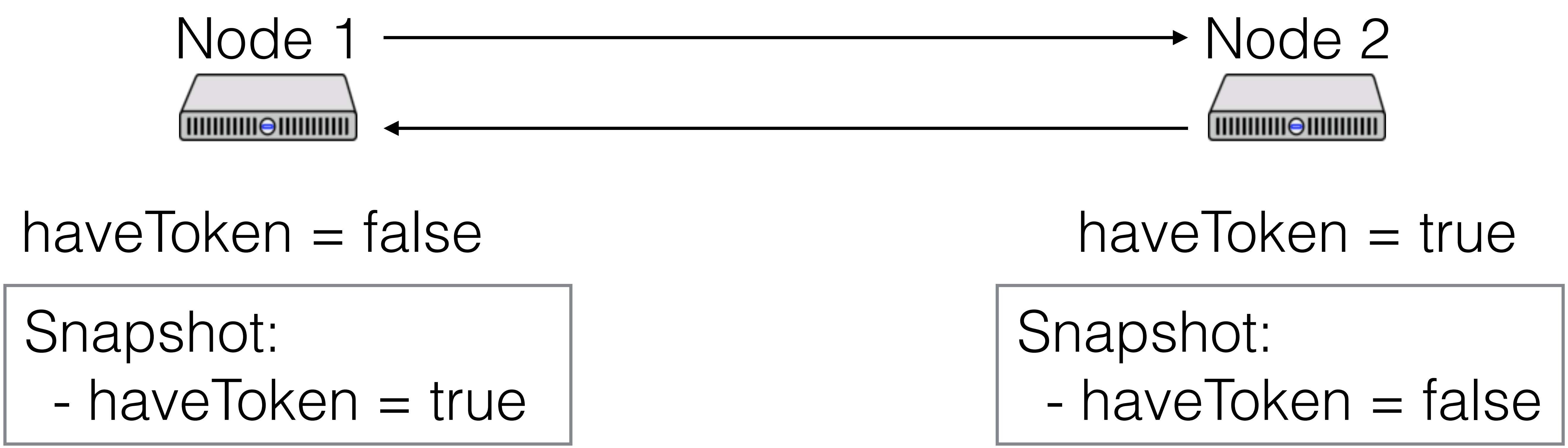
Better algorithm



Better algorithm



Better algorithm



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

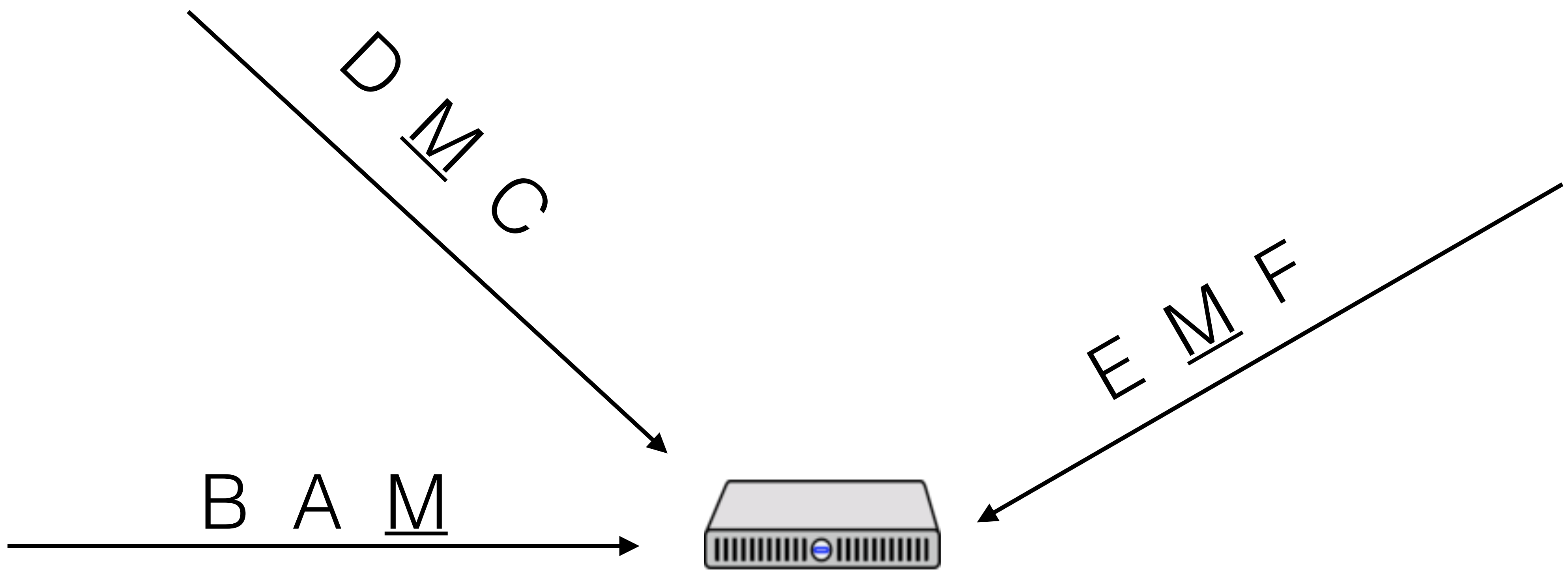
Recorded when marker received on that channel

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

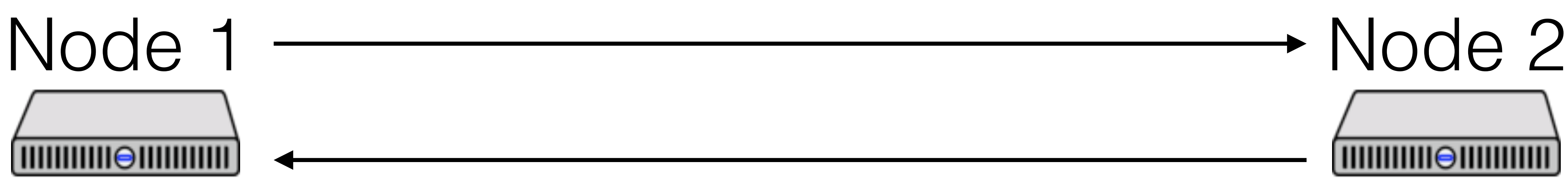
When marker received on channel, record:

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

Chandy-Lamport Snapshots



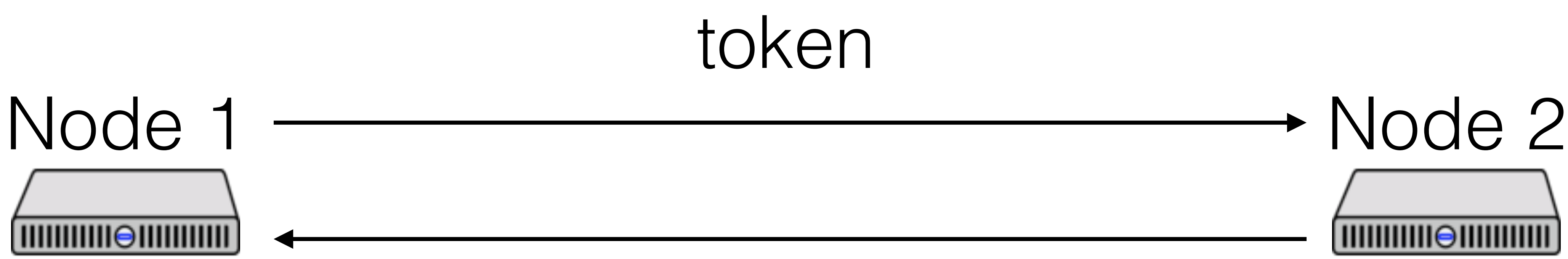
Chandy-Lamport Snapshots



haveToken = true

haveToken = false

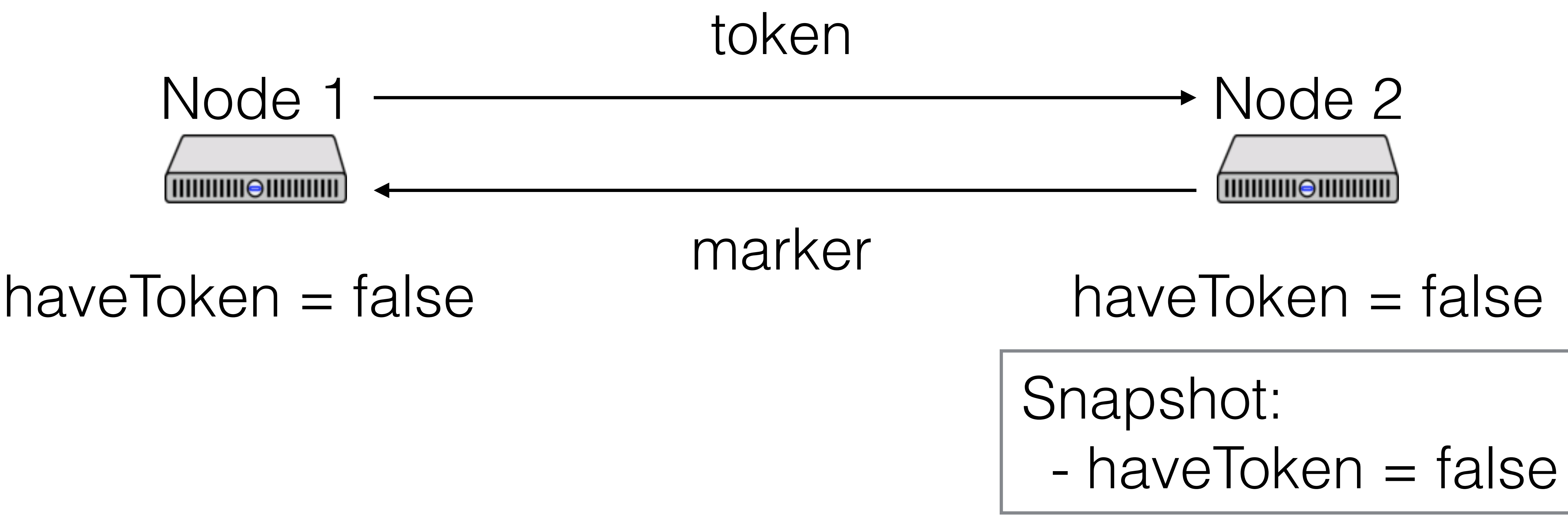
Chandy-Lamport Snapshots



haveToken = false

haveToken = false

Chandy-Lamport Snapshots



Chandy-Lamport Snapshots

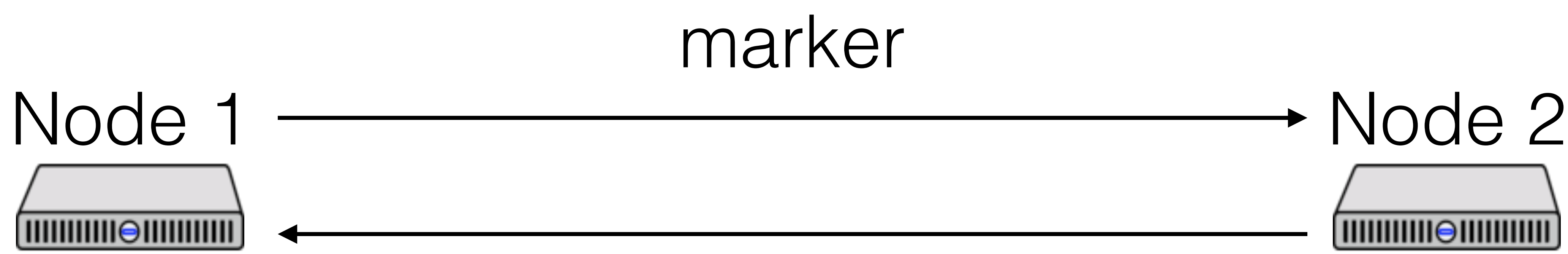
haveToken = false

Snapshot:
- haveToken = false

haveToken = false

Snapshot:
- haveToken = false

Chandy-Lamport Snapshots



haveToken = false

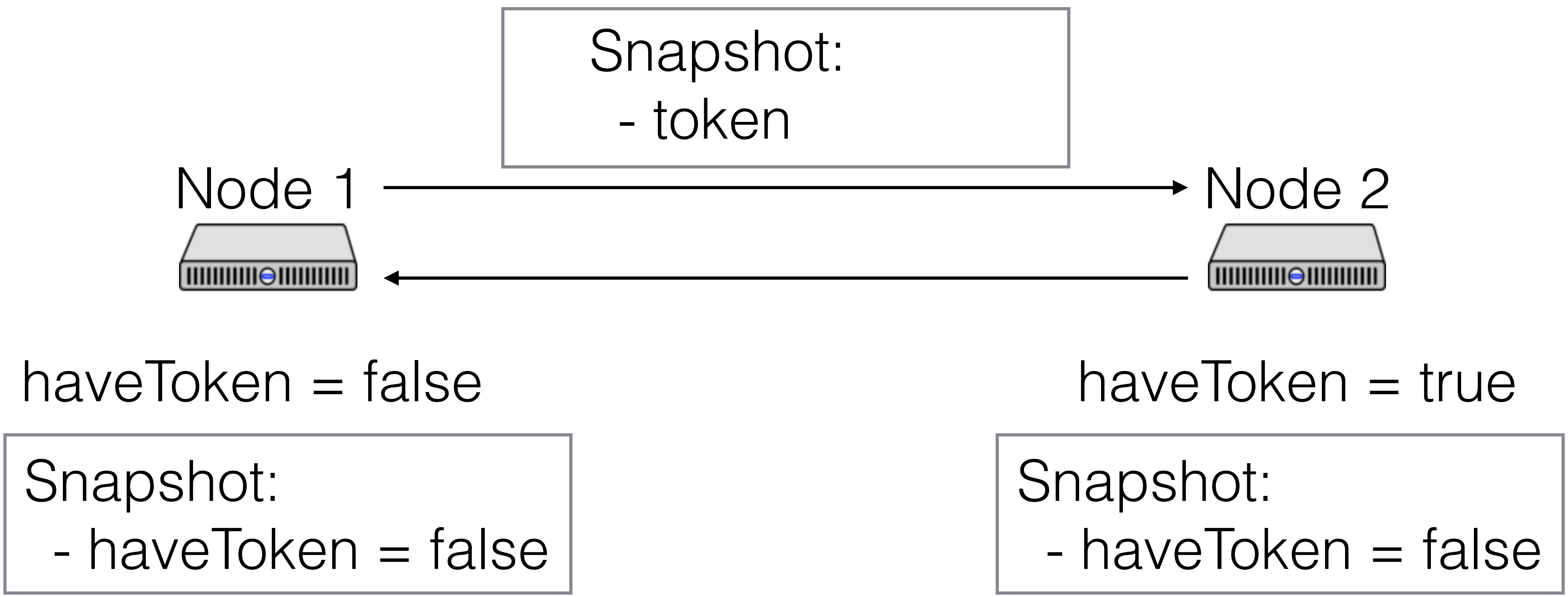
Snapshot:
- haveToken = false

haveToken = true

Snapshot:
- haveToken = false

In-flight:
- token

Chandy-Lamport Snapshots



Chandy-Lamport Snapshots

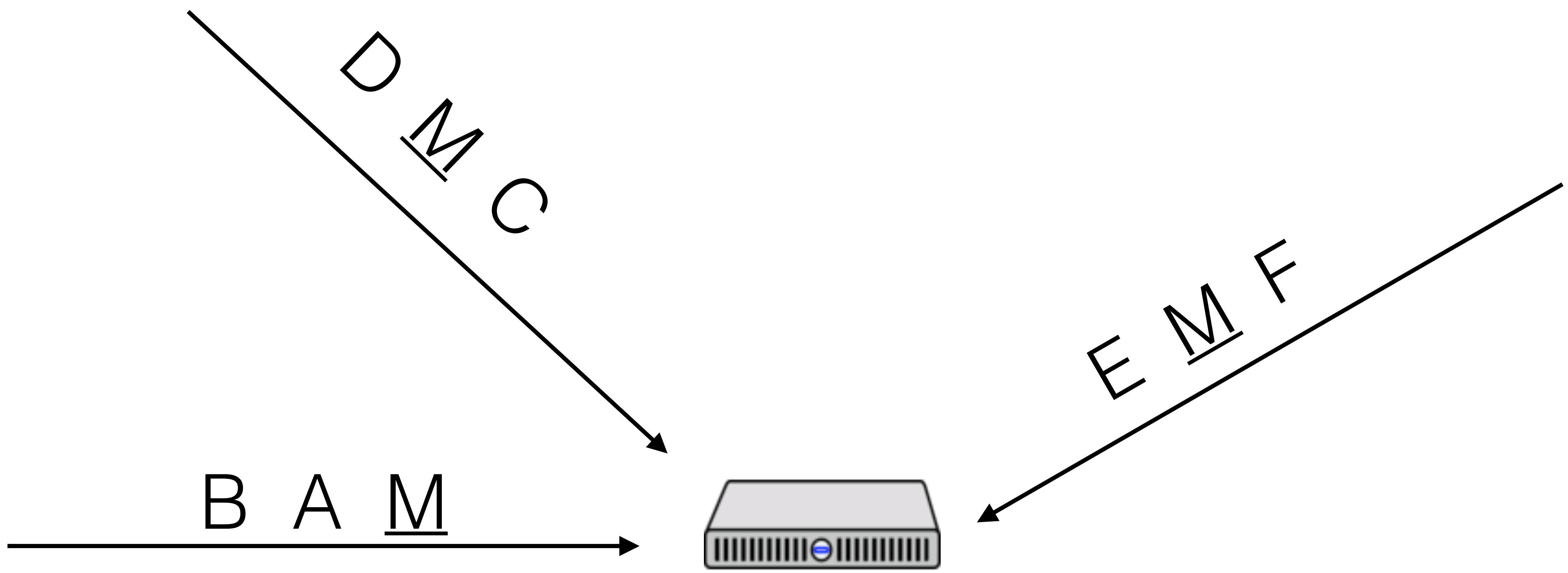
What if multiple nodes initiate the snapshot?

- 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?

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.