Lamport Clocks

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Logistics notes

Problem Set 1 due Friday

Chandy-Lamport Snapshots thread up

Today

Lamport Clocks

- Motivation
- Basic ideas
- Mutual exclusion
- State machine replication

Vector clocks

Lamport Clocks

Classic paper in distributed systems, but not really implemented in practice

So, why read it?

- Good example of *reasoning* about systems
- Core ideas are useful—notion of logical time as distinct from physical time
- Causal ordering is important in weak consistency models (eventual consistency!)

Semi-realistic example

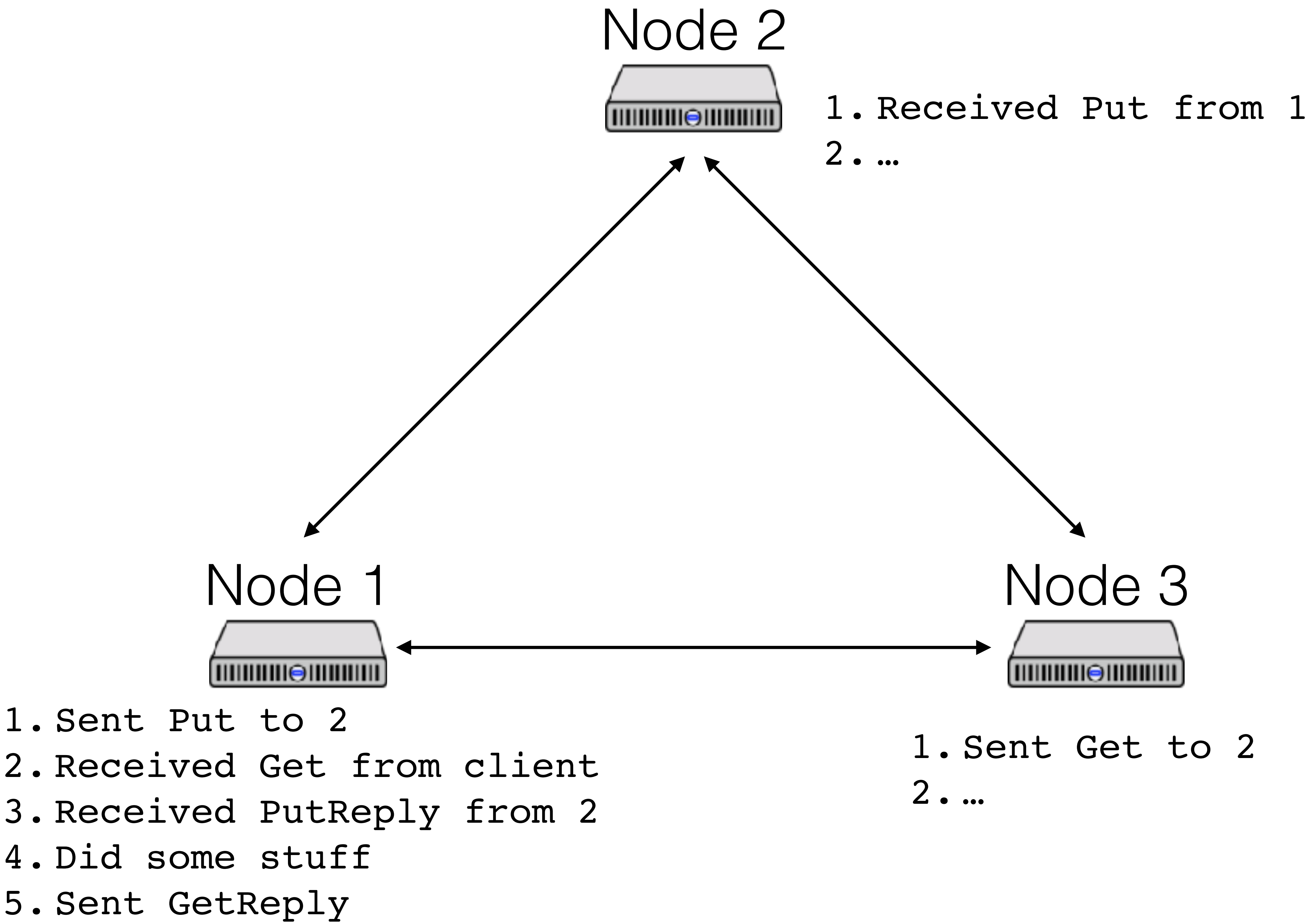
You have a large, complex distributed system

Sometimes, things go wrong—bugs, bad client behavior, etc.

You want to be able to debug!

So, each node produces a log

Semi-realistic example



How do we order these events?

By timestamp, using a physical clock?

- Clock skew is real
- Crystals oscillate at slightly different frequencies
- Typically, ~2s/month skew
- Clock sync relies on communication!

Need a better way of assigning timestamps to events

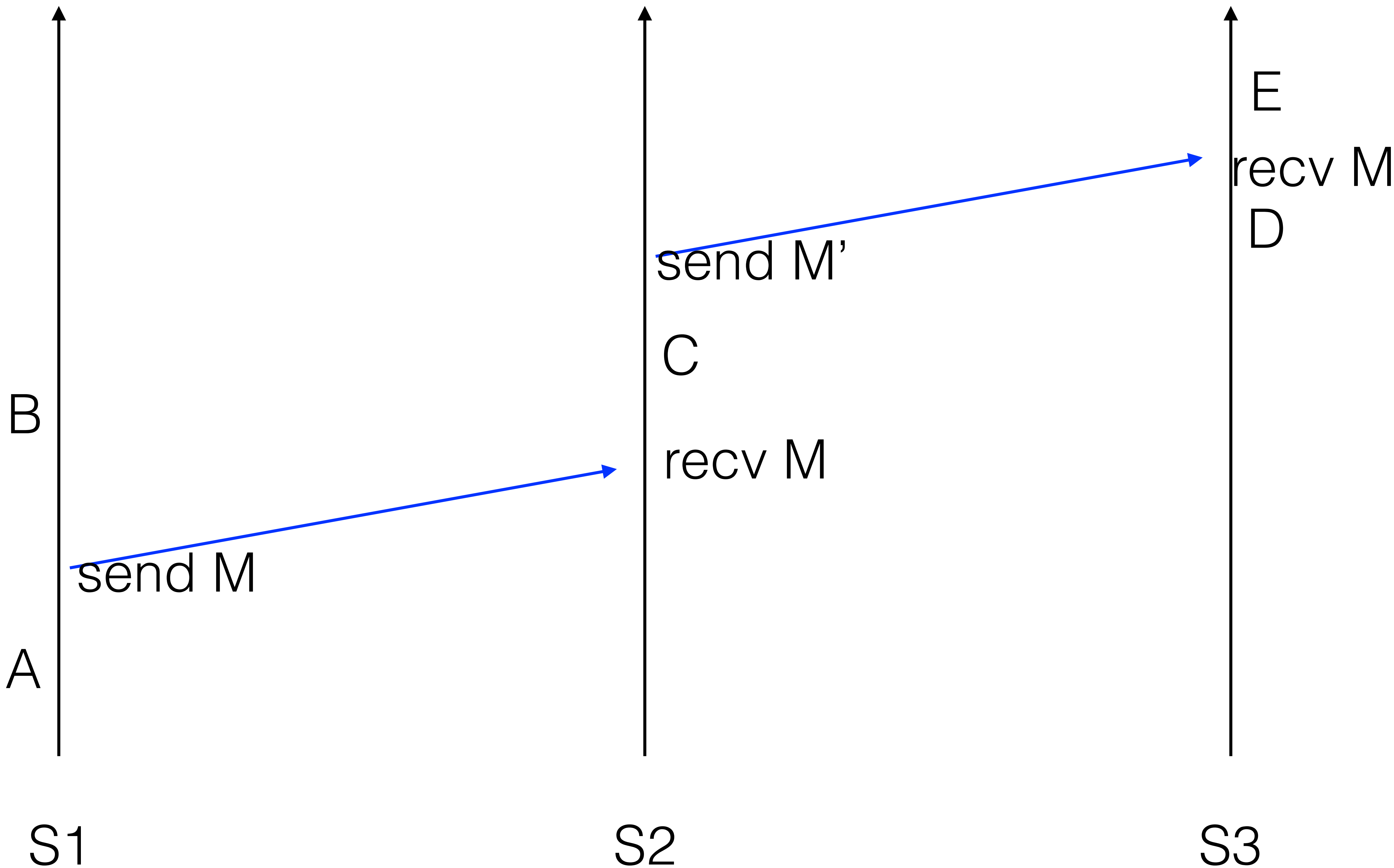
- Globally valid, s.t. it respects causality
- Using only local information

So: what does it mean for *a* to happen before *b*?

Happens-before

1. Happens at same location, earlier
2. Transmission before receipt
3. Transitivity

Example



Goal of a logical clock

happens-before(A, B) -> *T*(A) < *T*(B)

What about the converse?

Logical clock implementation

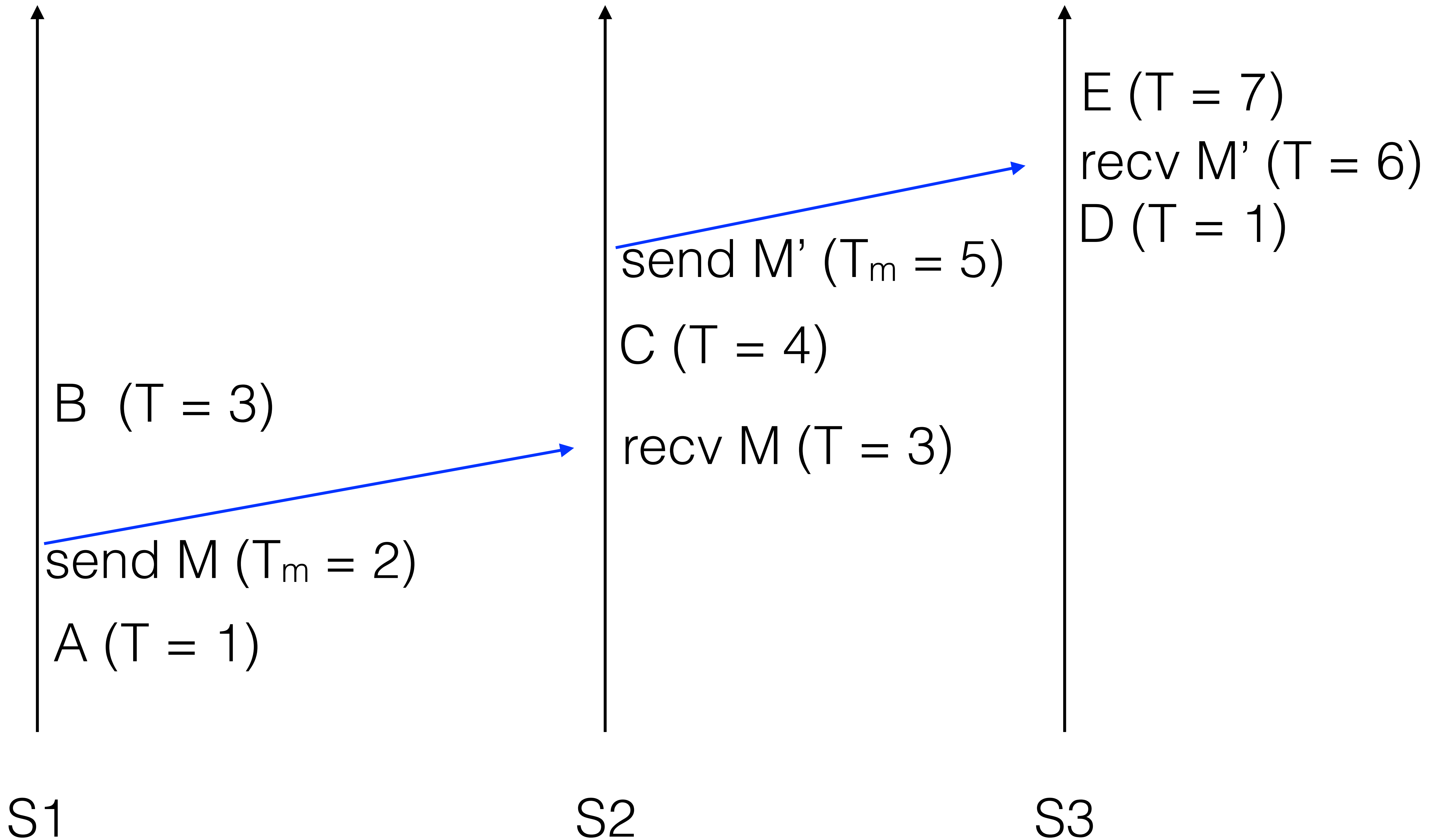
Keep a clock T

Increment T whenever an event happens

Send clock value on all messages as T_m

On message receipt: $T = \mathit{max}(T, T_m) + 1$

Example


E (T = 7)
recv M’ (T = 6)
D (T = 1)
send M’ (T_m = 5)
C (T = 4)
B (T = 3)
recv M (T = 3)
send M (T_m = 2)
A (T = 1)
S1
S2
S3

Mutual exclusion

Use clocks to implement a lock

Goals:

- Only one process has the lock at a time
- Requesting processes eventually acquire the lock, in same order they request it

Assumptions:

- Reliable in-order channels (TCP)
- No failures

Mutual exclusion implementation

Timestamp all messages

Three message types:

- *request*
- *release*
- *acknowledge*

Each node's state:

- A queue of *request* messages, ordered by T_m
- The latest message it has received from each node

Mutual exclusion implementation

On receiving a *request*:

- Record message timestamp
- Add request to queue

On receiving a *release*:

- Record message timestamp
- Remove corresponding request from queue

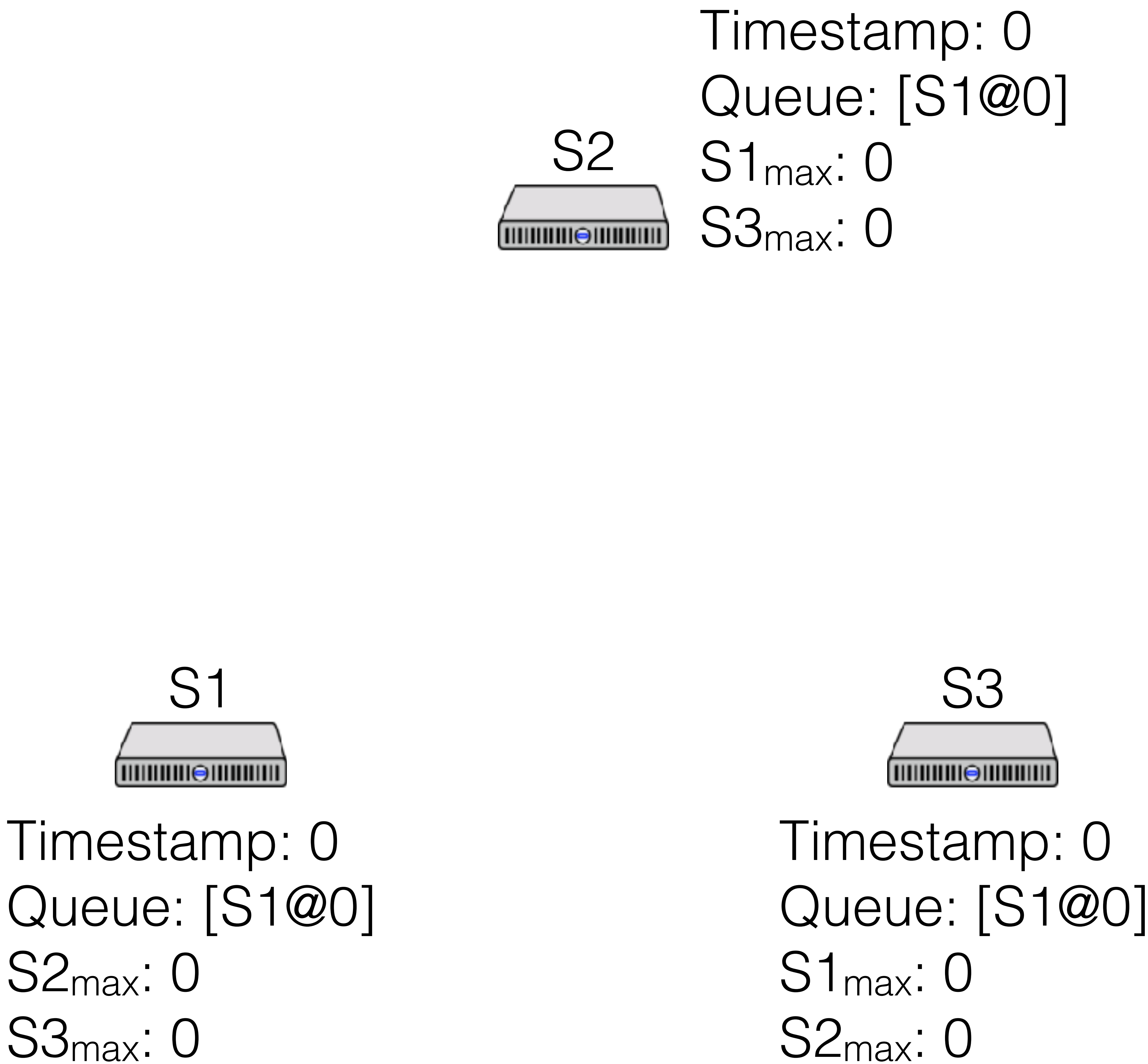
On receiving an *acknowledge*:

- Record message timestamp

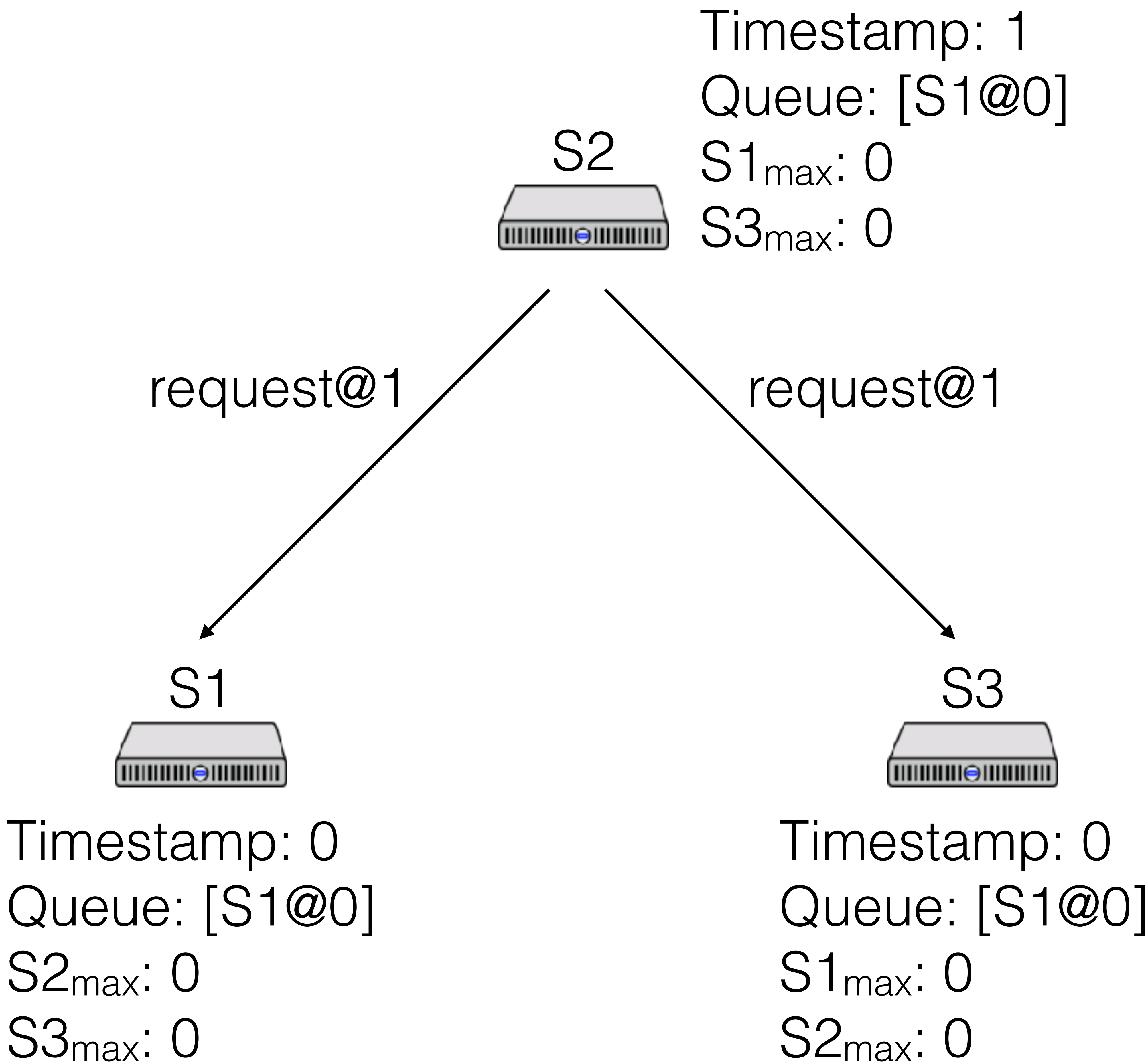
Mutual exclusion implementation

To acquire the lock:

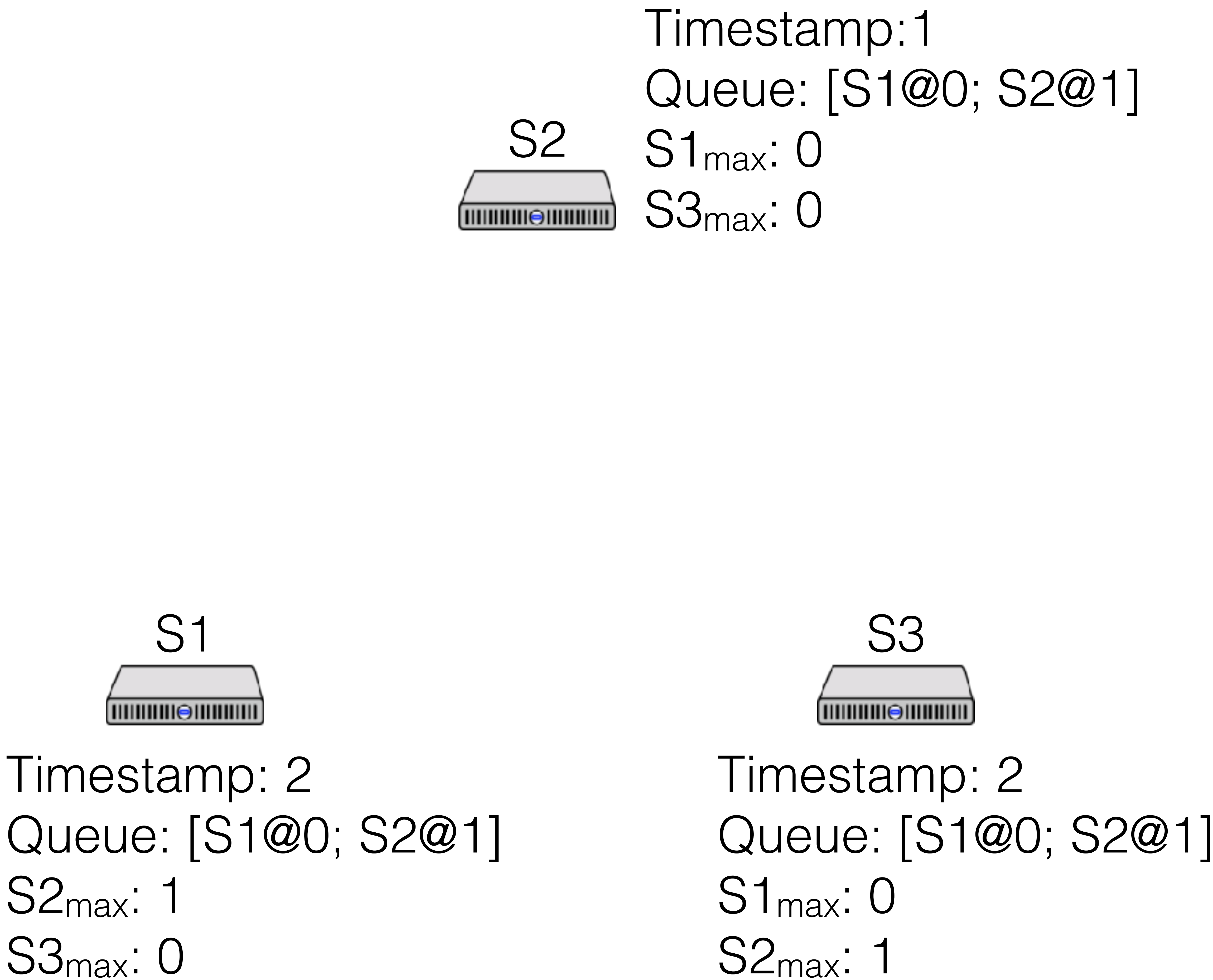
- Send *request* to everyone, including self
- The lock is acquired when:
  - My request is add the head of my queue, and
  - I've received higher-timestamped messages from everyone



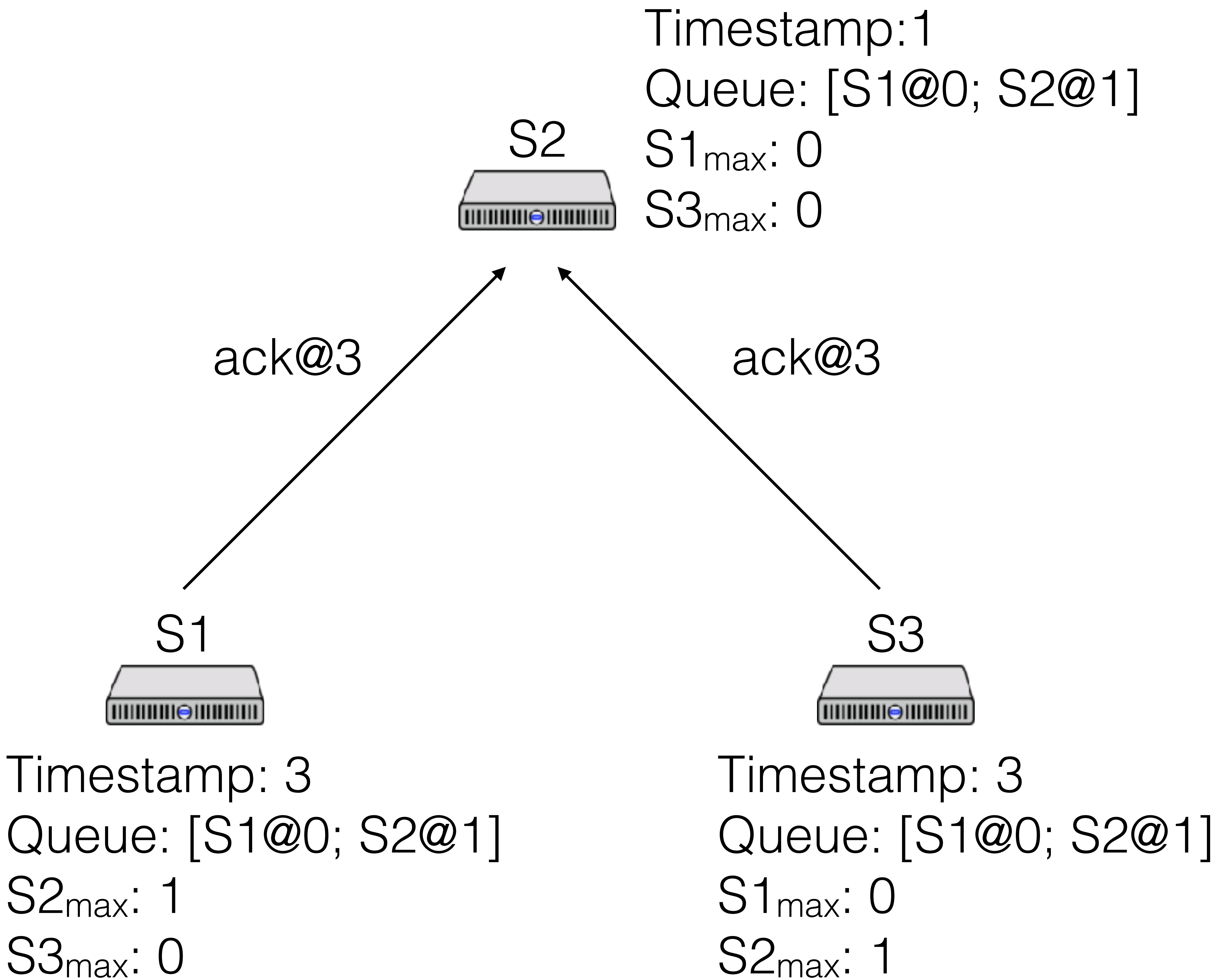
S2
Timestamp: 0
Queue: [S1@0]
$S1_{max}$: 0
$S3_{max}$: 0
S1
Timestamp: 0
Queue: [S1@0]
$S2_{max}$: 0
$S3_{max}$: 0
S3
Timestamp: 0
Queue: [S1@0]
$S1_{max}$: 0
$S2_{max}$: 0



Timestamp: 1
Queue: [S1@0]
S2
S1max: 0
S3max: 0
request@1
request@1
S1
S3
Timestamp: 0
Queue: [S1@0]
S2max: 0
S3max: 0
Timestamp: 0
Queue: [S1@0]
S1max: 0
S2max: 0



S2
Timestamp:1
Queue: [S1@0; S2@1]
$S1_{max}$: 0
$S3_{max}$: 0
S1
Timestamp: 2
Queue: [S1@0; S2@1]
$S2_{max}$: 1
$S3_{max}$: 0
S3
Timestamp: 2
Queue: [S1@0; S2@1]
$S1_{max}$: 0
$S2_{max}$: 1


S2
Timestamp:1
Queue: [S1@0; S2@1]
$S1_{max}$: 0
$S3_{max}$: 0
ack@3
ack@3
S1
Timestamp: 3
Queue: [S1@0; S2@1]
$S2_{max}$: 1
$S3_{max}$: 0
S3
Timestamp: 3
Queue: [S1@0; S2@1]
$S1_{max}$: 0
$S2_{max}$: 1

Timestamp:4
Queue: [S1@0; S2@1]
$S1_{max}$: 3
$S3_{max}$: 3

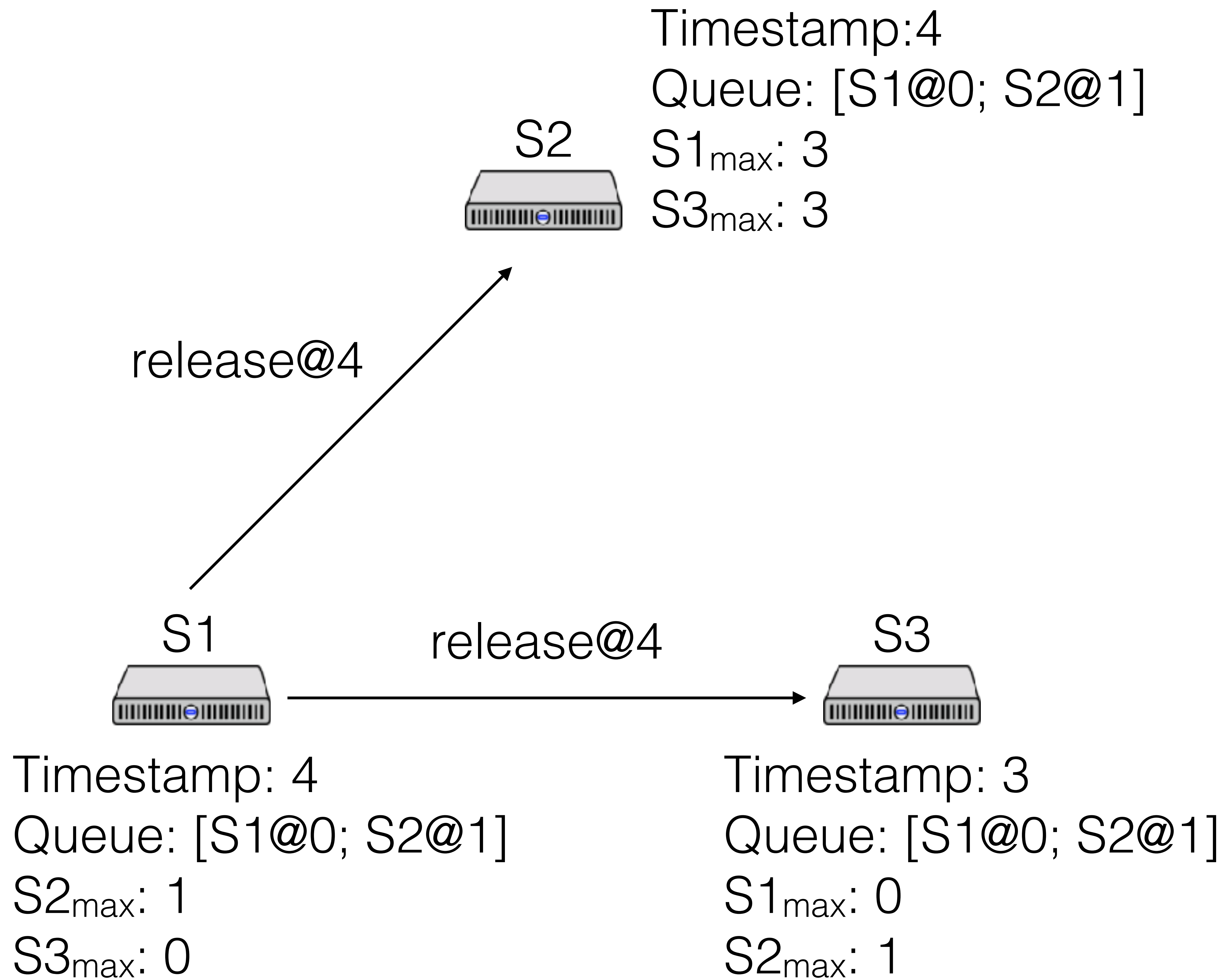
S2

S1

Timestamp: 3
Queue: [S1@0; S2@1]
$S2_{max}$: 1
$S3_{max}$: 0

S3

Timestamp: 3
Queue: [S1@0; S2@1]
$S1_{max}$: 0
$S2_{max}$: 1



Timestamp:4
Queue: [S1@0; S2@1]
S2
$S1_{max}$: 3
$S3_{max}$: 3
release@4
S1
release@4
S3
Timestamp: 4
Queue: [S1@0; S2@1]
$S2_{max}$: 1
$S3_{max}$: 0
Timestamp: 3
Queue: [S1@0; S2@1]
$S1_{max}$: 0
$S2_{max}$: 1

S2

Timestamp:5
Queue: [S2@1]
$S1_{max}$: 4
$S3_{max}$: 3

S1

Timestamp: 4
Queue: [S2@1]
$S2_{max}$: 1
$S3_{max}$: 0

S3

Timestamp: 5
Queue: [S2@1]
$S1_{max}$: 4
$S2_{max}$: 1

State machine replication

We've seen a SMR implementation: Primary/backup

Key question in SMR: what is the order in which ops are executed?

How does this work in Primary/backup?

How to do SMR with Lamport clocks?

Mutual exclusion as SMR

State: queue of processes who want the lock

Commands: P_i *requests*, P_i *releases*

Process a command iff we've seen all commands w/ lower timestamp

What are advantages/disadvantages over P/B?

Vector clocks

Another type of logical clock

Sometimes actually used in practice

- Eventual consistency

Better partial order

- Logical time partially ordered, integers totally
- Want T(A) < T(B) -> *happens-before*(A, B)

Idea: track a timestamp for each node, *on each node*

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:

- increment C[i]
- for each j:
  - $C[j] = max(C[j], C_m[j])$

Vector clocks

Ordering is partial: compare vectors pointwise

Why does *T*(A) < *T*(B) -> *happens-before*(A, B)?

Piazza discussion

What happens when we need to add a process?

Why is coordination necessary for locking?

Events that happened vs. might have happened