Coordination

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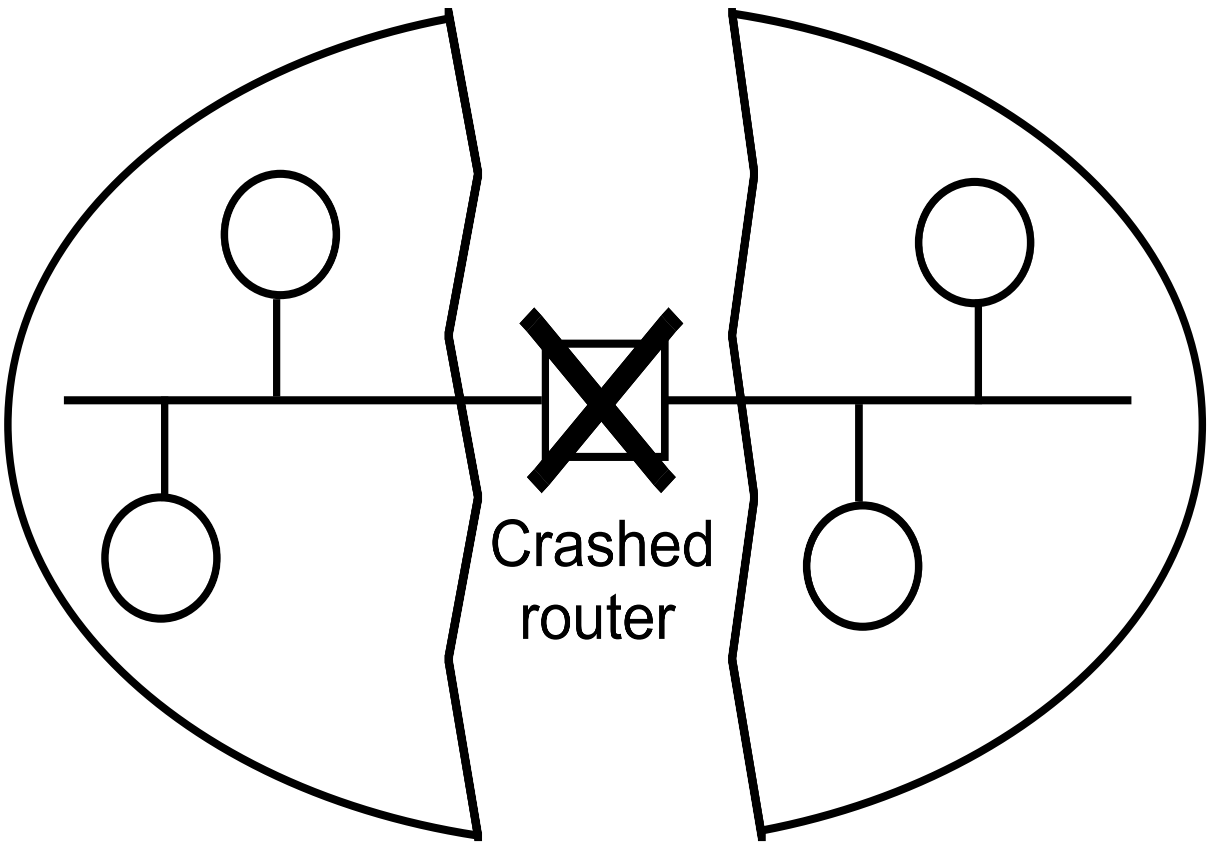
based on www.cdk4.net and
www.cs.uic.edu/~ajayk/DCS-Book

Failure assumptions and detection

- We assume reliable channels:
  - No network partitions
  - Asymmetric communication (p send to q, but not viceversa)
  - Intransitive communication (p send to q, q send to r, does not mean p sends to r)
- We have failure detectors
  - Reliable vs. unreliable
  - Suspected vs. unsuspected failures
  - Use of timeouts for suspected failures

A network partition



Distributed mutual exclusion

- Critical section problem as in OS
- Distributed mutual exclusion (message based)
- Does one have file locking in NFS? (Unix *lockd*)

- Algorithms for mutual exclusion:
  - P_i i=1…N process that do not share variables
  - One single critical section
  - Asynchronous at-most-once message passing
  - Process do not crash

Types

- Token based approaches
- Non-Token based approaches
- Quorum-based approaches

Distributed mutual exclusion

Operations for critical section:

`enter()` `resourceAccess()` `exit()`

Requirements

1. *Safety*: at most one process may execute their critical section
2. *Liveness/Progress*: requests to enter critical section eventually succeed (no deadlocks nor starvation)
3. *Ordering/Fairness*: requests for entering critical sections are served with an ordering policy (usually FIFO)

Performance of Algorithms

- **Message Complexity:** in the number of exchanged messages by N processes

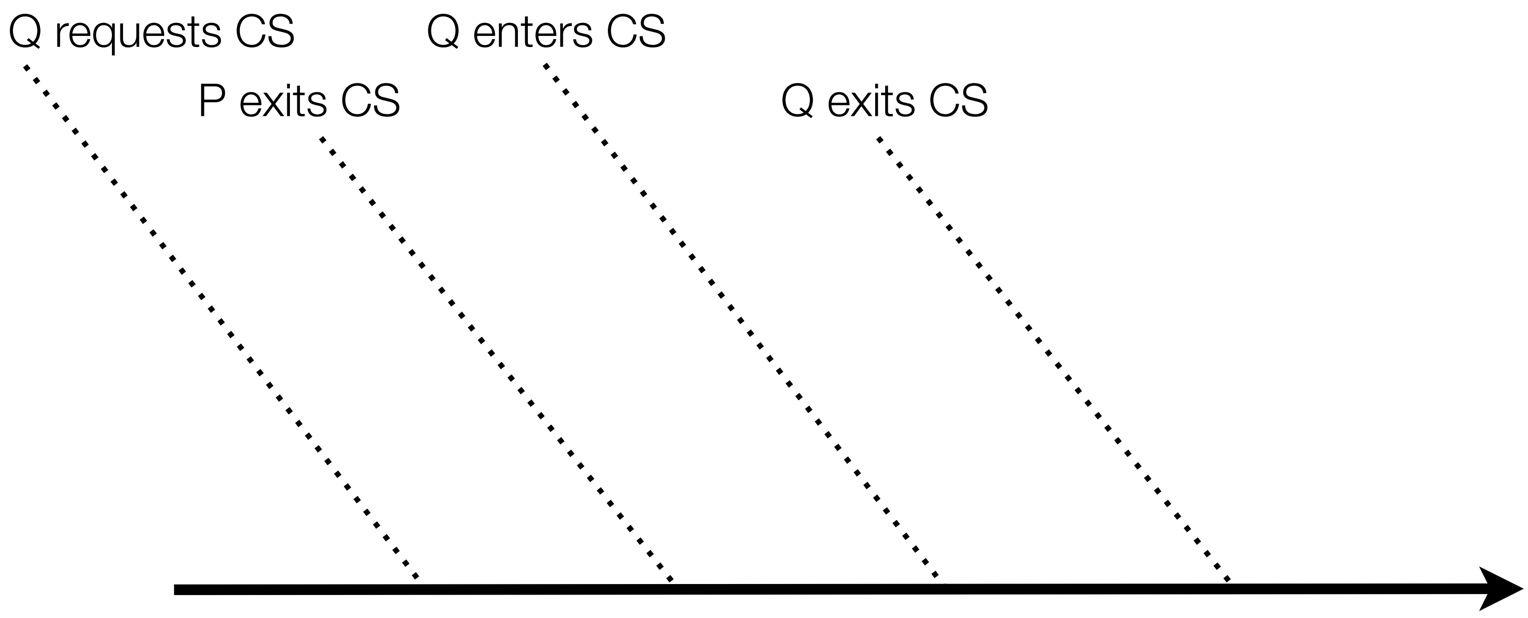
- **Synchronization Delay (SD):** time for next P to enter a CS once the current holder leaves it. T is the average message delay.

- **Response Time:** time between CS request and end of CS execution

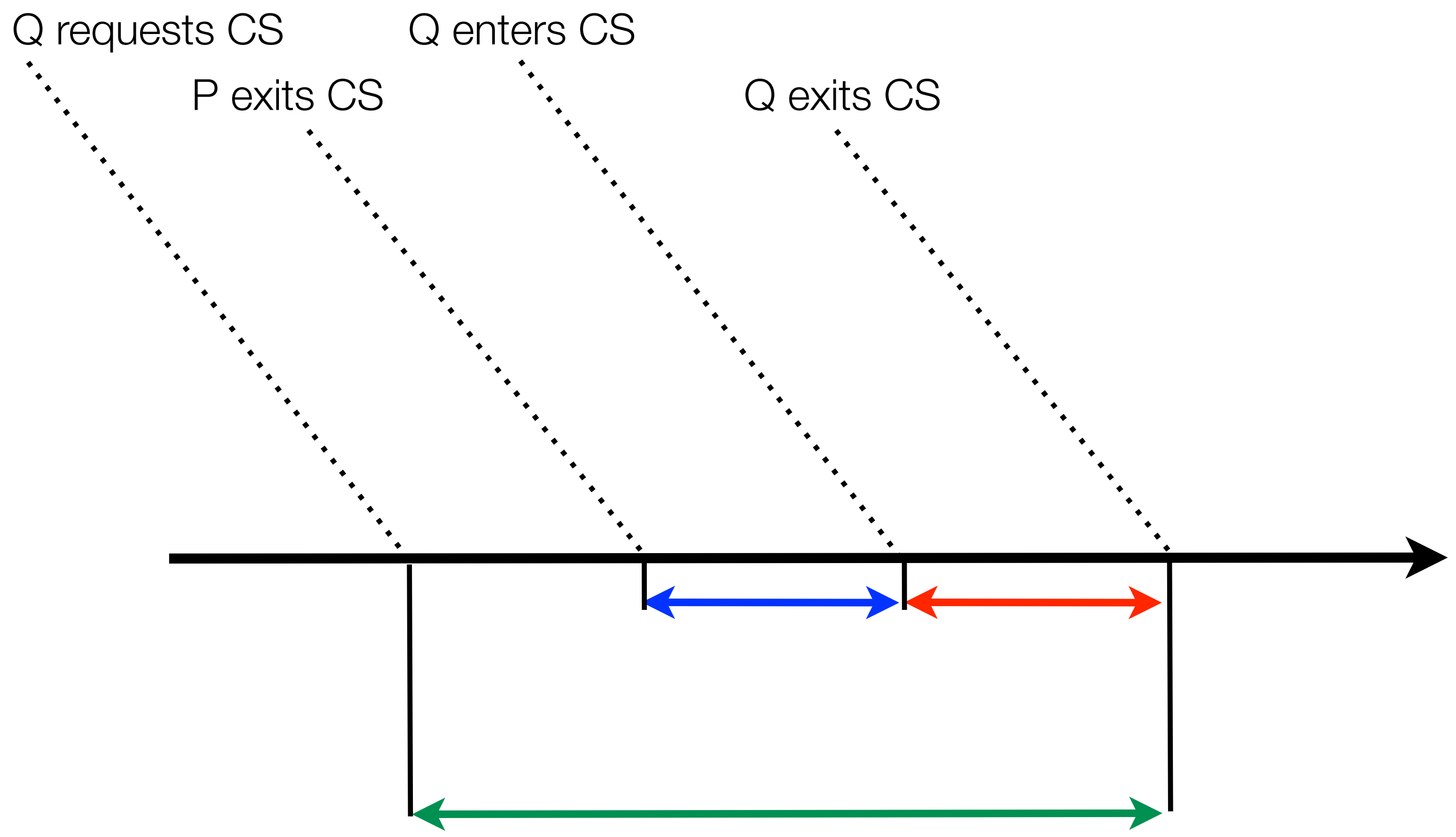
- **System Throughput:** rate at which CS requests are executed $= \frac{1}{SD + E}$
  where E is the average CS execution time

Low vs high load performance **AND** Best and worst case performances

Performance illustration



Performance illustration



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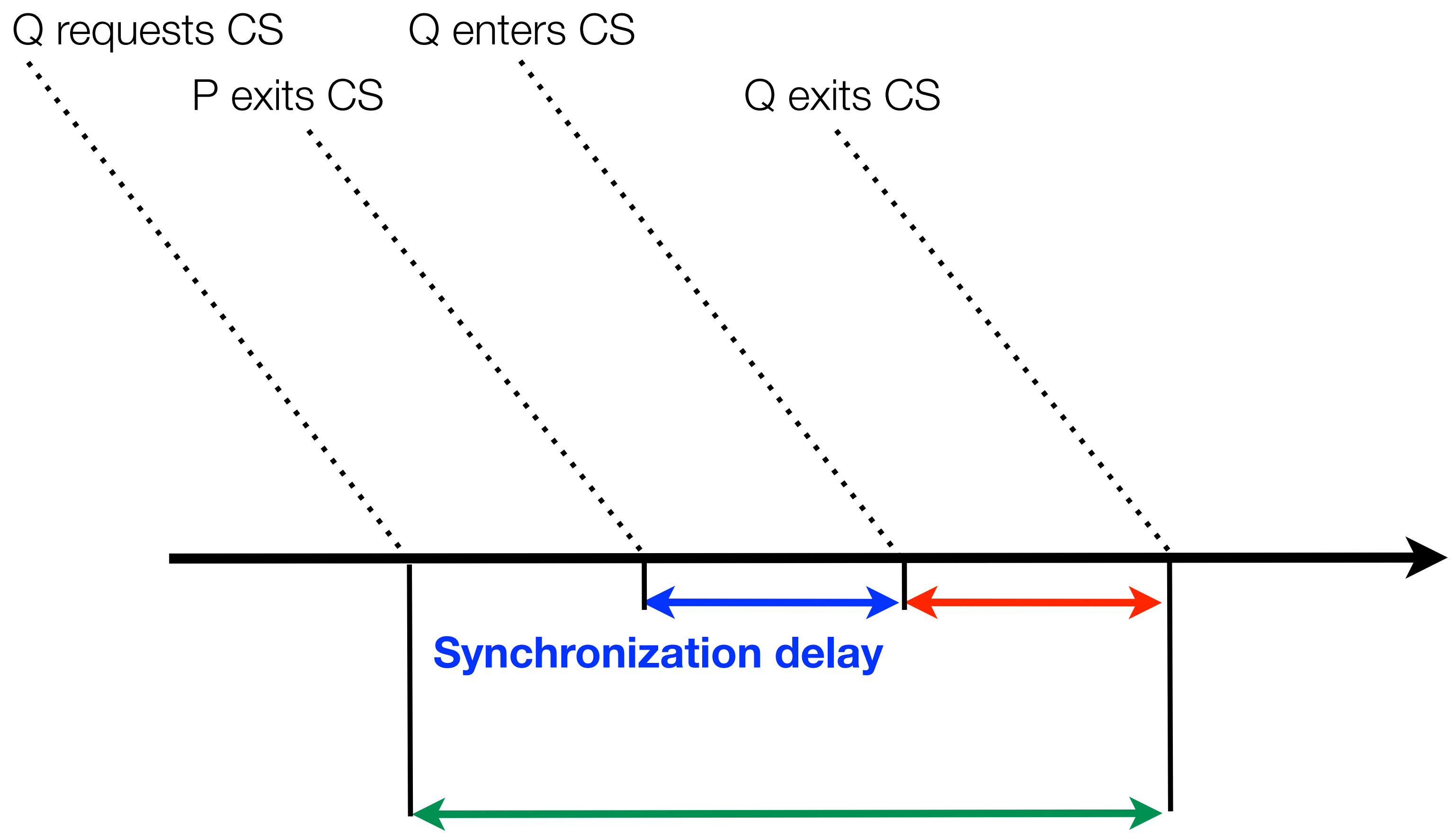

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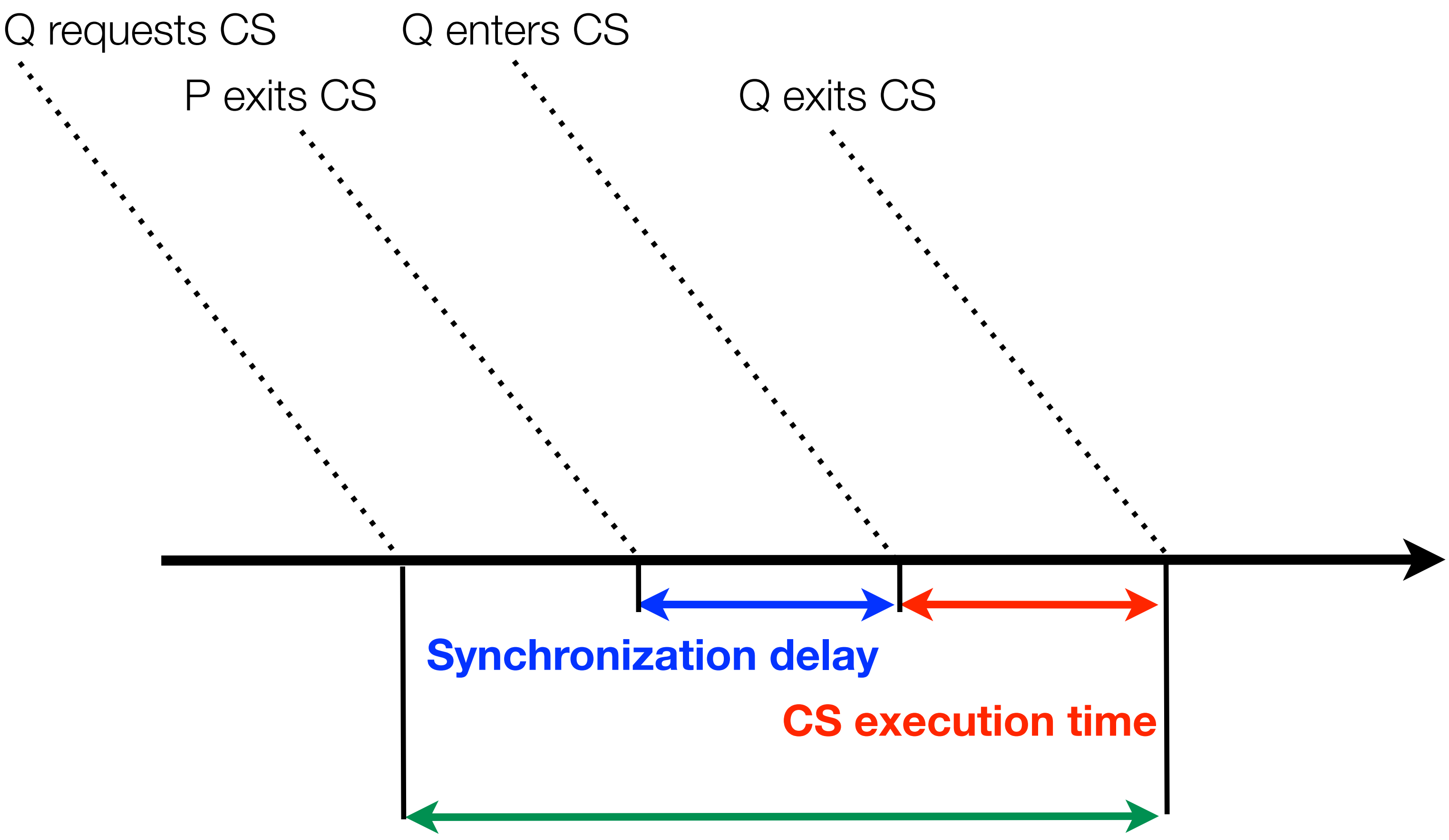

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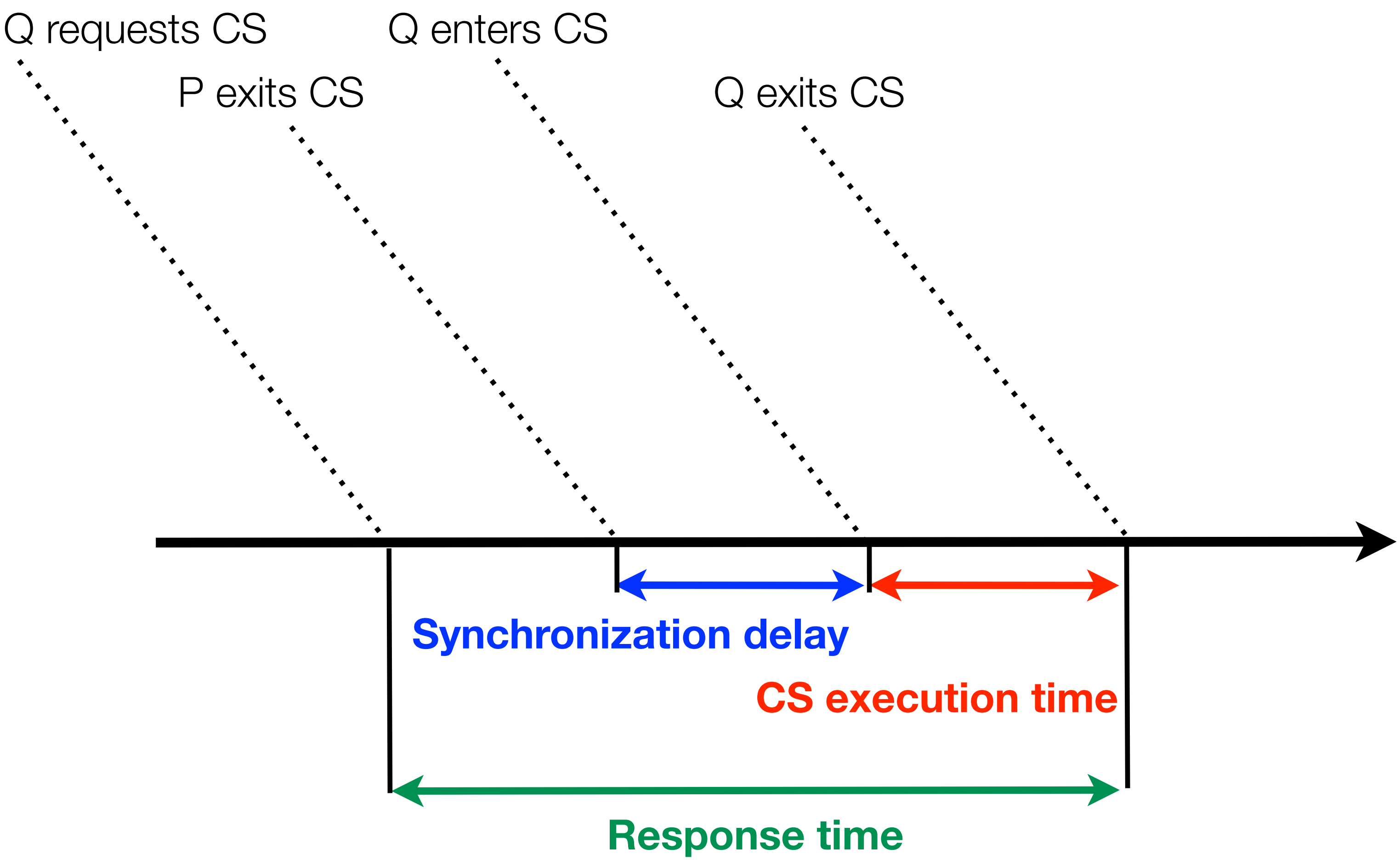
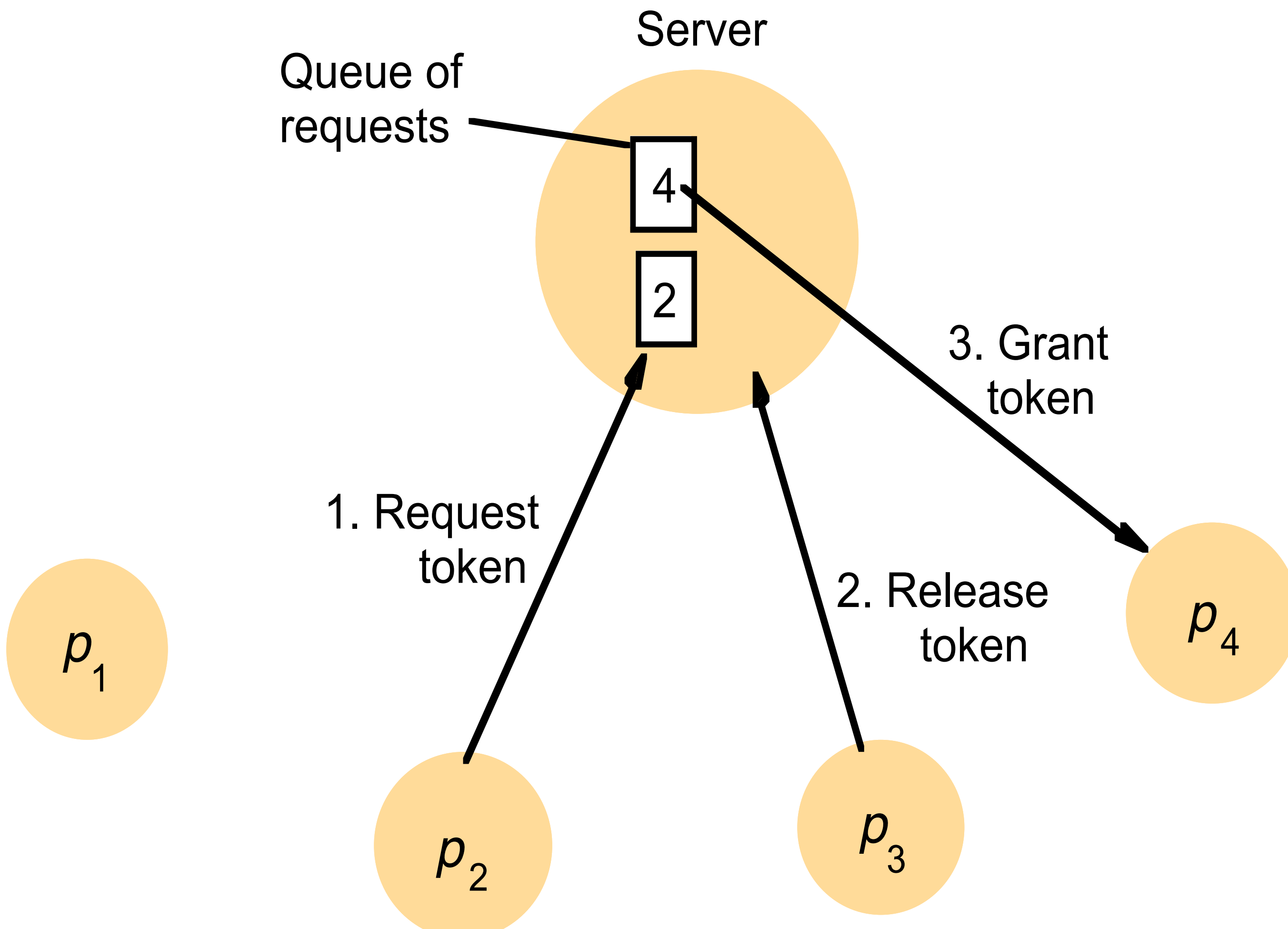


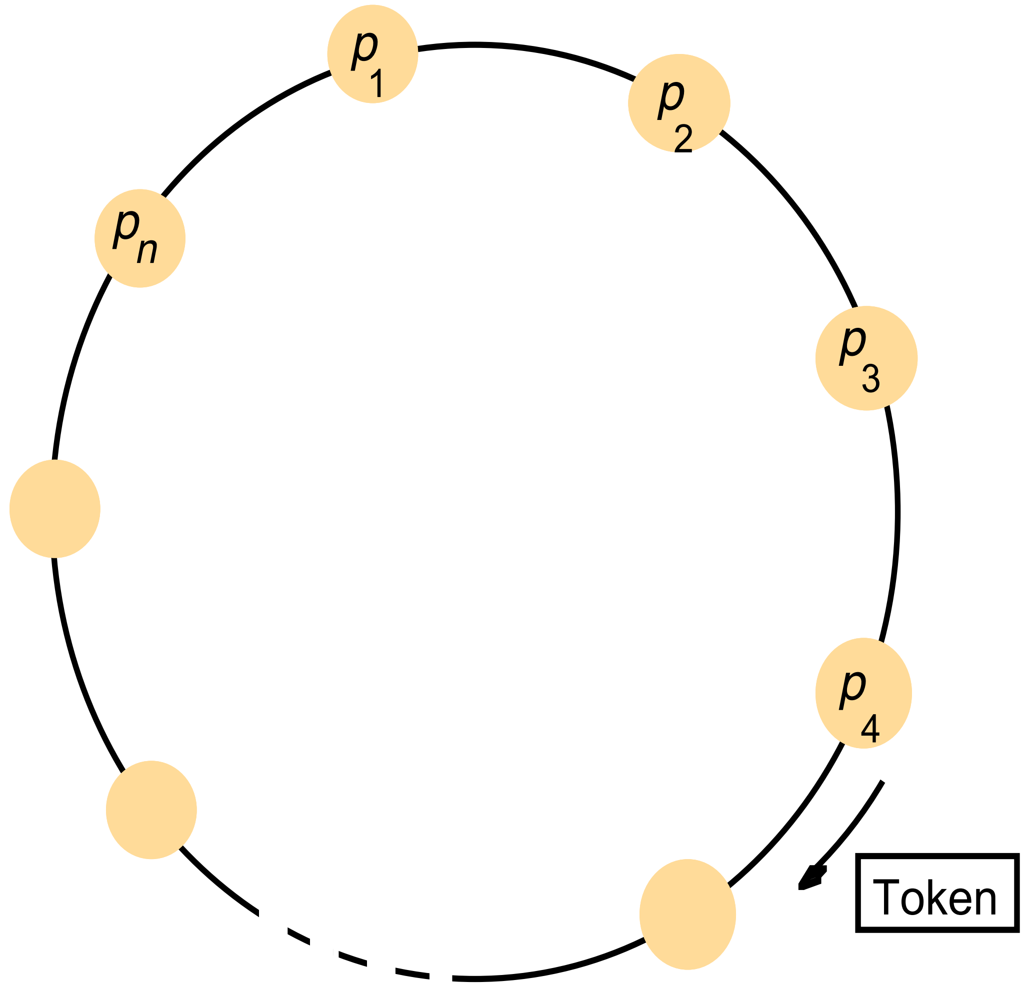
Central server algorithm (token based)



Properties

- Safety and progress are guaranteed, what about ordering?
- Bandwidth: 2 messages for request+1 for release
- The server may become a bottleneck

Ring algorithm (token based)



Ring Algorithm

- What is the message complexity, sync delay, response time, throughput of the algorithm?
- Are safety, progress and ordering guaranteed?

Lamport's Algorithm (non-token based)

- P_i Request:
  - Broadcast *request*(ts_i, *i*) and put request in $request\_queue_i$

- P_j Receives it:
  - place request on $request\_queue_j$ and reply with a timestamp

- P_i enters CS when:
  - It has received a message with larger timestamp than (ts_i, *i*) from all others
  - P_i request is at the top of $request\_queue_i$

- P_i exists CS:
  - remove from $request\_queue_i$ and broadcast *release*
  - each process removes the request from the queue upon *release* receipt

Assumes FIFO channels

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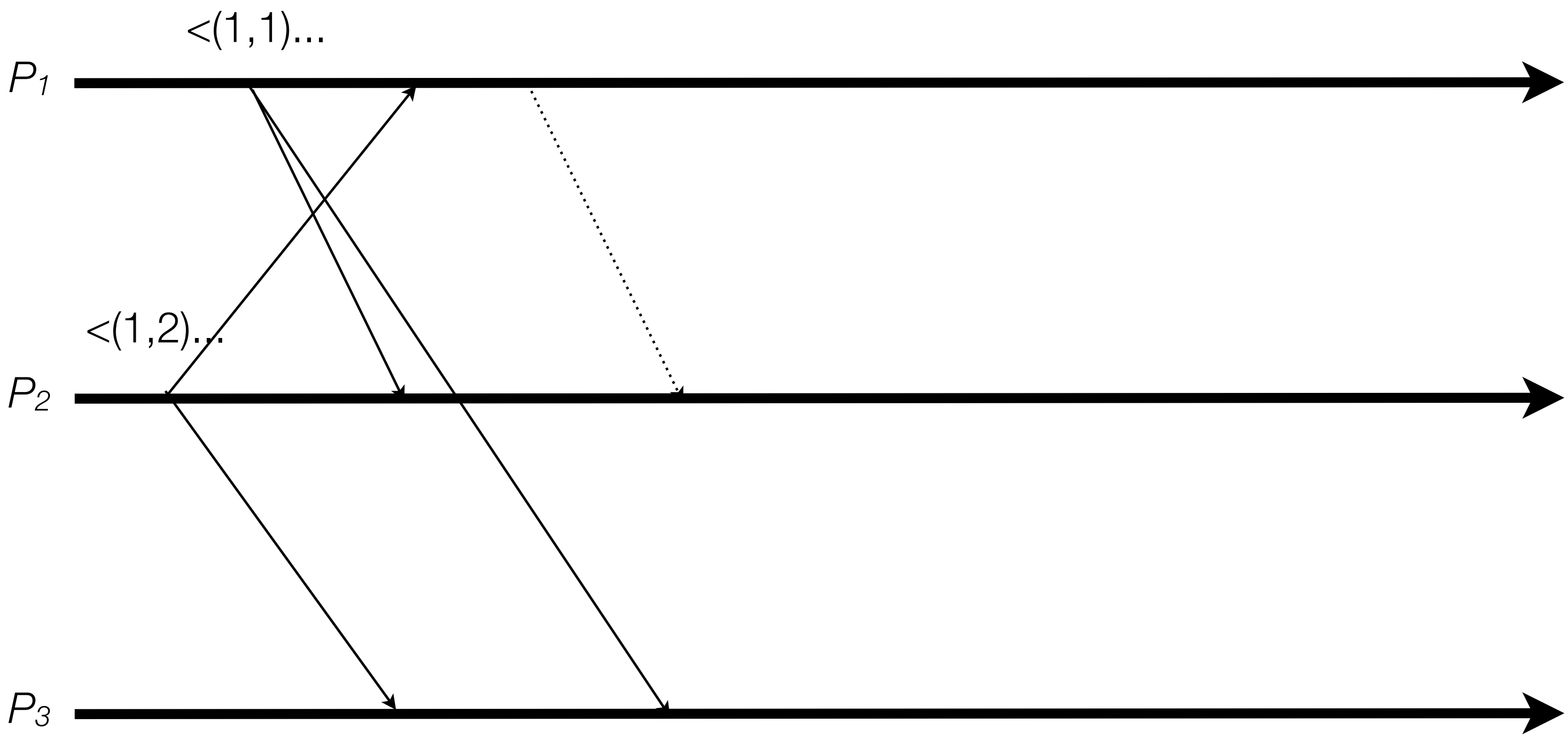

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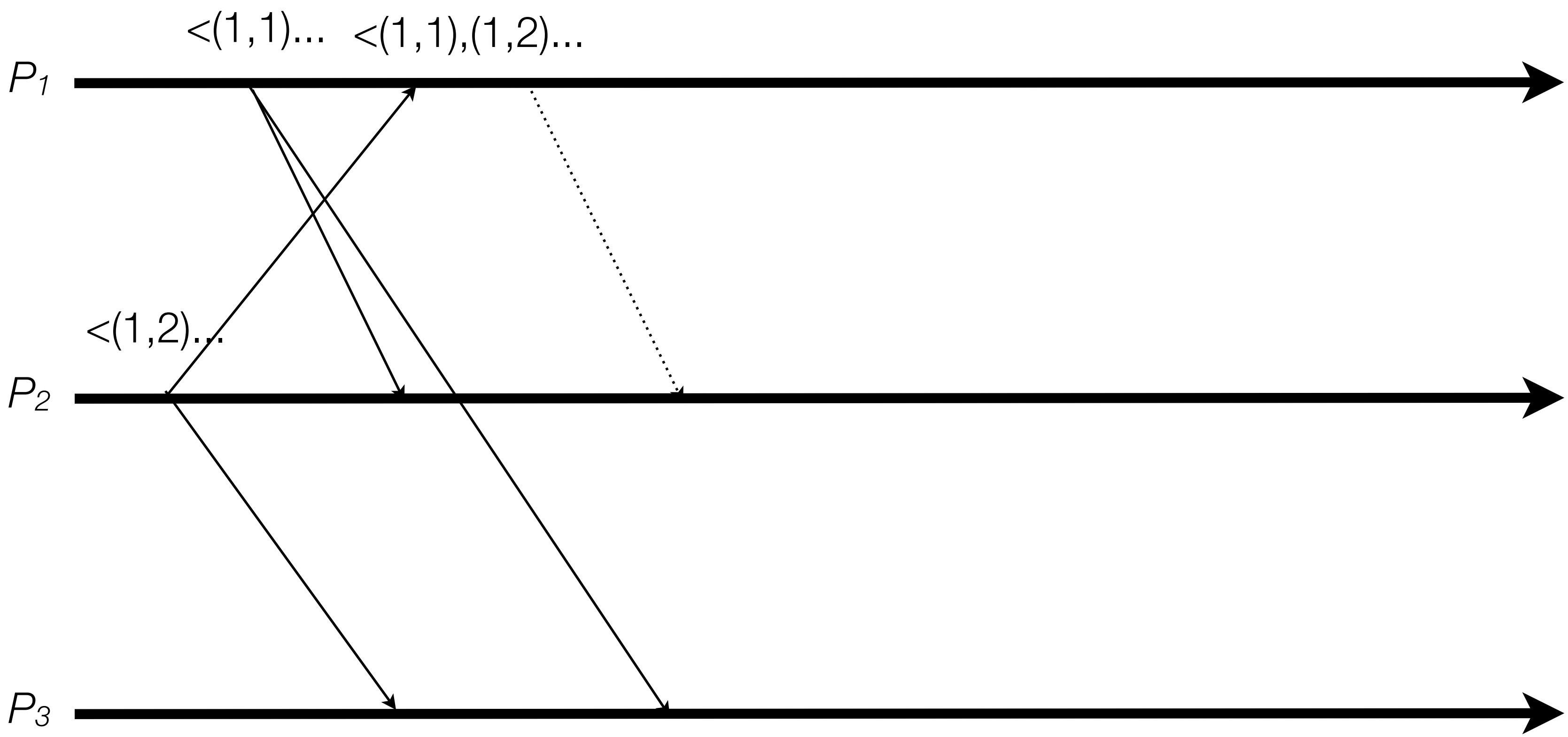

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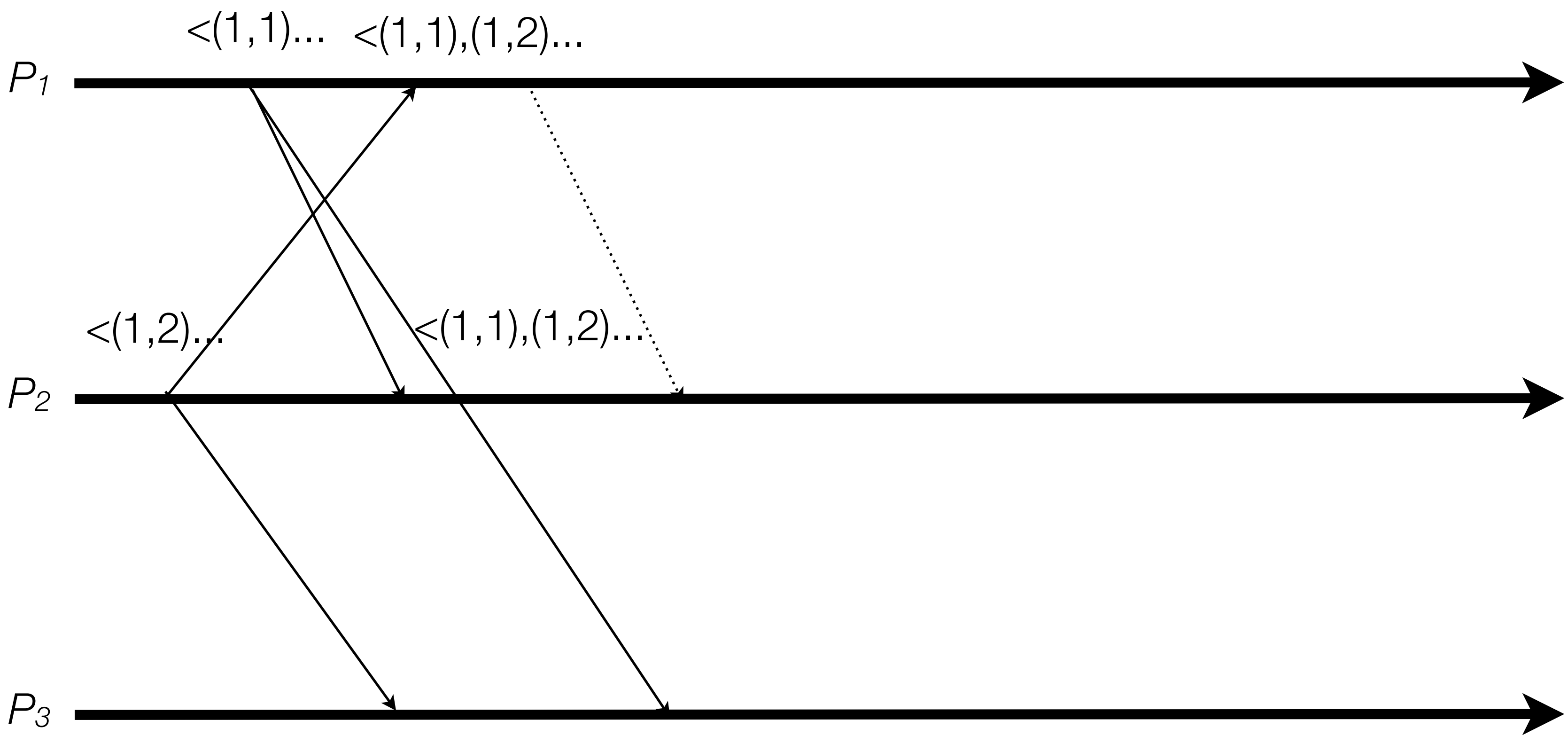

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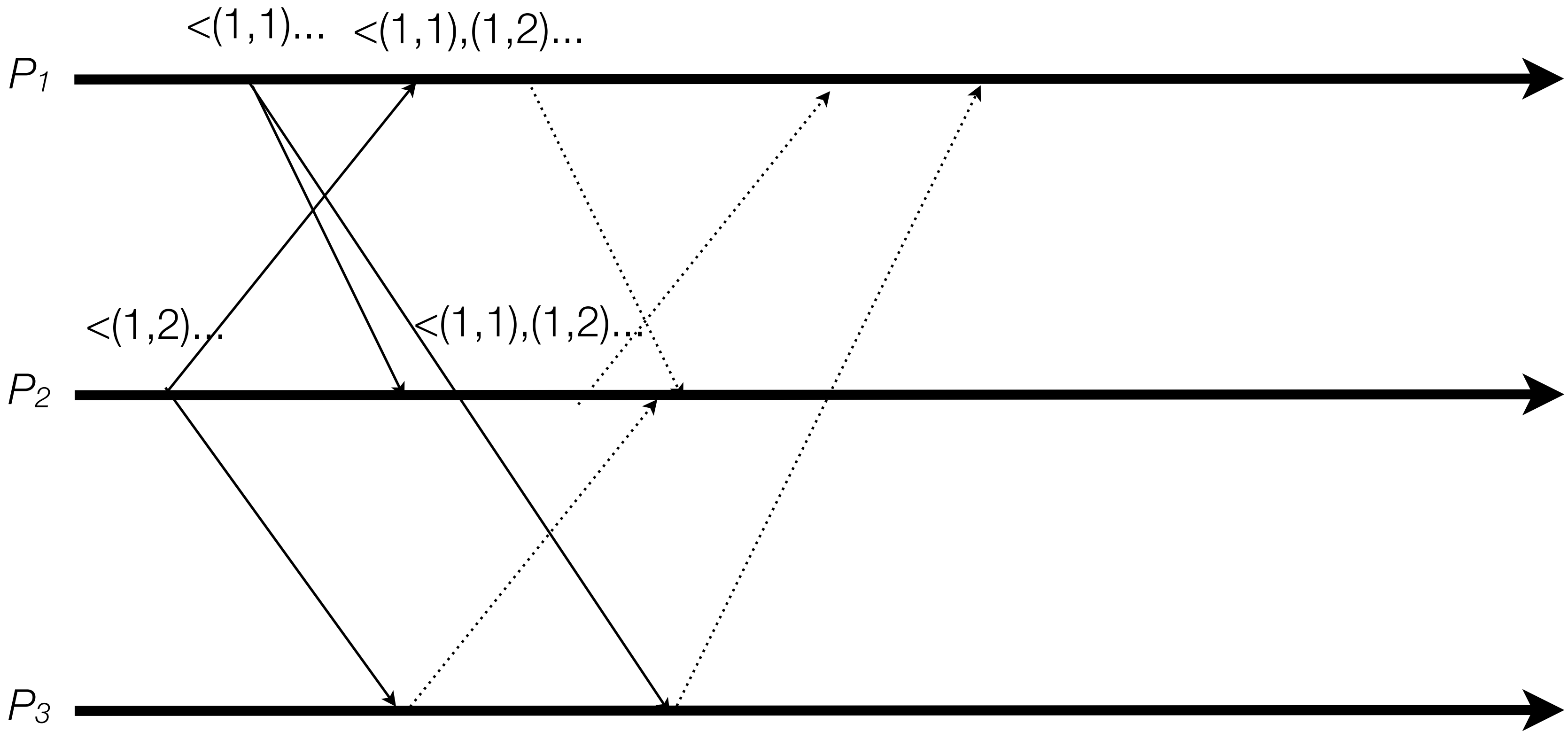

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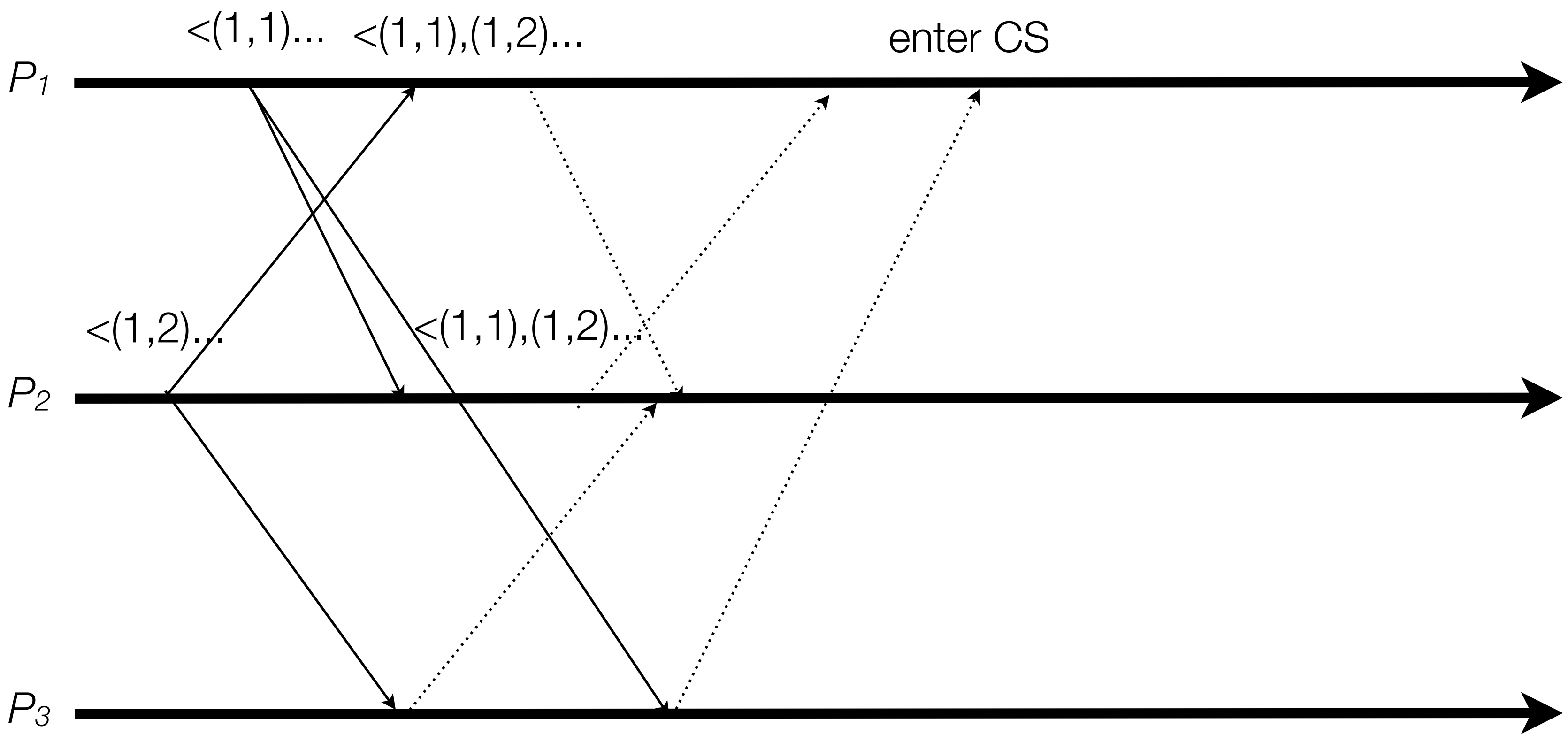

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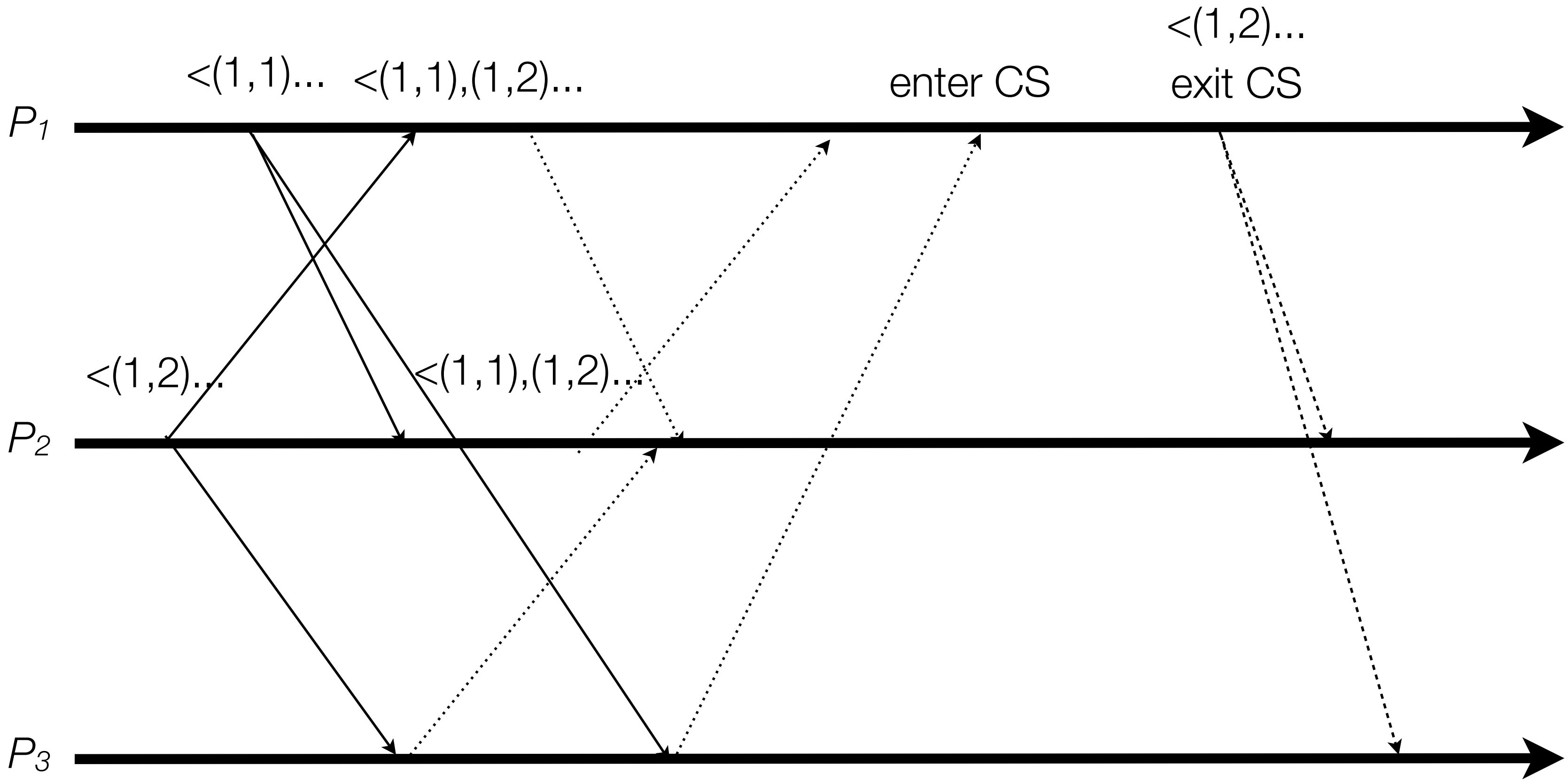

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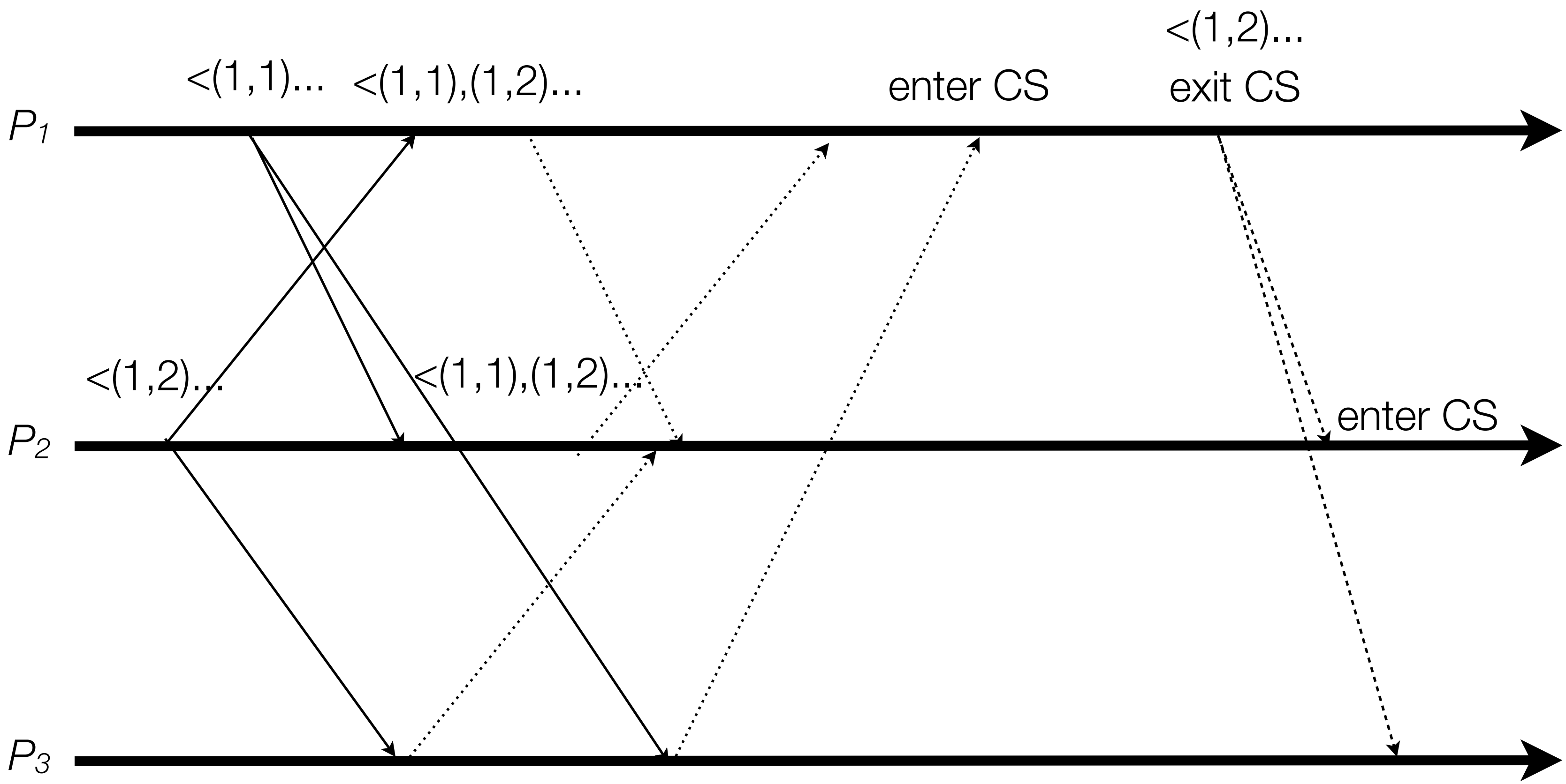

Lamport Algorithm

- Correctness
- Liveliness
- Fairness

(proof by contradiction looking at the conditions that must hold for P_i to enter the CS and the properties of logical clocks)

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3(N-1) per CS invocation, Sync delay is T

Ricart and Agrawala’s algorithm

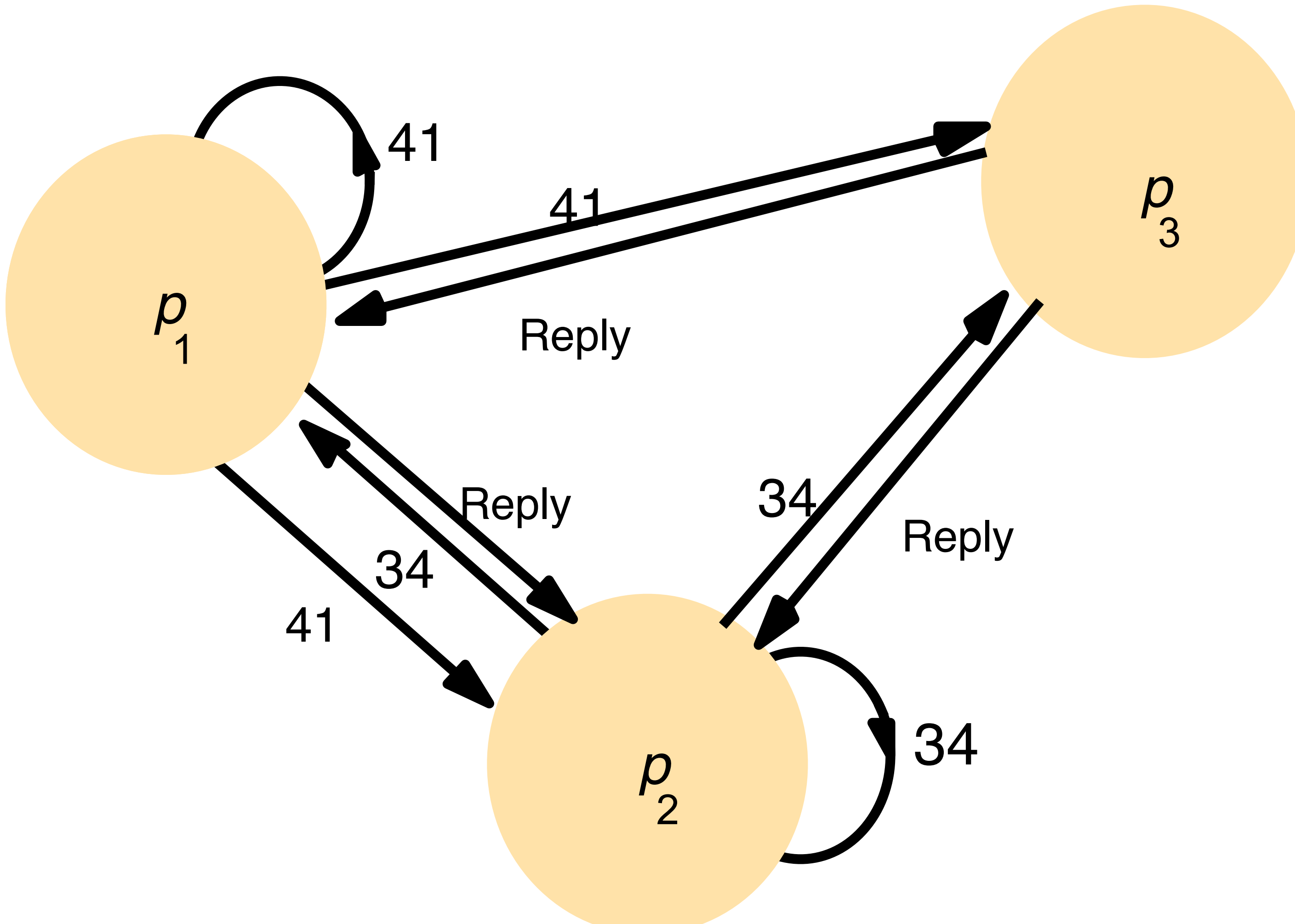
- N peer process synchronize using multicast
- Replies to all message
- Does not require FIFO channels
- Using Lamport’s logical clock

Ricart and Agrawala's algorithm

On initialization
    state := RELEASED;
To enter the section
    state := WANTED;
    Multicast *request* to all processes;
    T := request's timestamp;
    Wait until (number of replies received = $(N - 1)$);
    state := HELD;

On receipt of a request $<T_i, p_i>$ *at* p_j $(i \neq j)$
    if (*state* = HELD or (*state* = WANTED *and* $(T, p_j) < (T_i, p_i)$))
    then
        queue *request* from p_i without replying;
    else
        reply immediately to p_i;
    end if
To exit the critical section
    state := RELEASED;
    reply to any queued requests;

Example



Ricart and Agrawala's algorithm

- Safety, progress and fairness are met
  - (proof by contradiction)

- High bandwidth consumption:
  - 2(N-1) message passed
- Client delay
  - A round trip time of a message
- Sync delay is T

Maekawa's algorithm (Quorum based)

- It is not necessary to have replies of all peers, one can use a voting mechanism
- A voting set V_i associated with each process

  $V_i \subseteq \{p_1, p_2, \ldots, p_N\}$

  For all i and j

  - $p_i \in V_i$
  - $V_i \cap V_j \neq \emptyset$ there is at least a common member
  - $|V_i| = K$ all voting sets are of the same size
  - Each process is contained in M of the voting sets

Maekawa's algorithm – part 1

On initialization

state := RELEASED;

voted

For p_i to enter the critical section

state := WANTED;

Multicast *request* to all processes in $V_i - \{p_i\}$;

Wait until (number of replies received = $(K - 1)$);

state := HELD;

On receipt of a request from p_i at p_j $(i \neq j)$

if (*state* = HELD *or voted* = TRUE)

then

queue *request* from p_i without replying;

else

send *reply* to p_i;

voted := TRUE;

end if

Maekawa's algorithm – part 2

For p_i to exit the critical section

state := RELEASED;

Multicast *release* to all processes in $V_i - \{p_i\}$;

On receipt of a release from p_i at p_j $(i \neq j)$

if (queue of requests is non-empty)

then

remove head of queue – from p_k, say;

send *reply* to p_k;

voted := TRUE;

else

voted := FALSE;

end if

Maekawa’s algorithm

- Optimal solution is with K close to $\sqrt{N}$ and M=K
- How to decide who to put in the voting sets?
- Safety property satisfied, but not progress and ordering
- Using a timestamped queue, the problem can be solved
- Bandwidth = $3\sqrt{N}$ (2 per entry and 1 for exit)
- Client delay = roundtrip time of a message

Agarwal-El Abbadi Algorithm (Quorum based)

- Using Tree quorums
- Trees are <u>complete binary</u> ones (any node can be a root to build the tree)
- 2^k leaves in the tree with k ~ O(log n)
- Algorithm starts with a defined root
- A quorum set is a path root-leaf

Agarwal-El Abbadi Algorithm (Quorum based)

```
quorumSet GetQuorum(tree, networkHierarchy)
    var left,right,quorumSet
    if (tree is empty) then
        return {}
    elseif GrantsPermission (tree↑.Node) then
        return ((tree↑.Node) ∪ GetQuorum(tree↑.LeftChild))
        OR
        return ((tree↑.Node) ∪ GetQuorum(tree↑.RightChild))
        else
            left←GetQuorum(tree↑.left)
            right←GetQuorum(tree↑.right)
            if (left or right are empty) then
                return error
            else
                return (left ∪ right)
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FAILED TO FIND A PATH E.G. DUE TO NODE FAILURE

TAKE TREE↑.NODE CHILDREN IN THE QUORUM/PATH

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FAILED TO FIND A PATH E.G. DUE TO NODE FAILURE

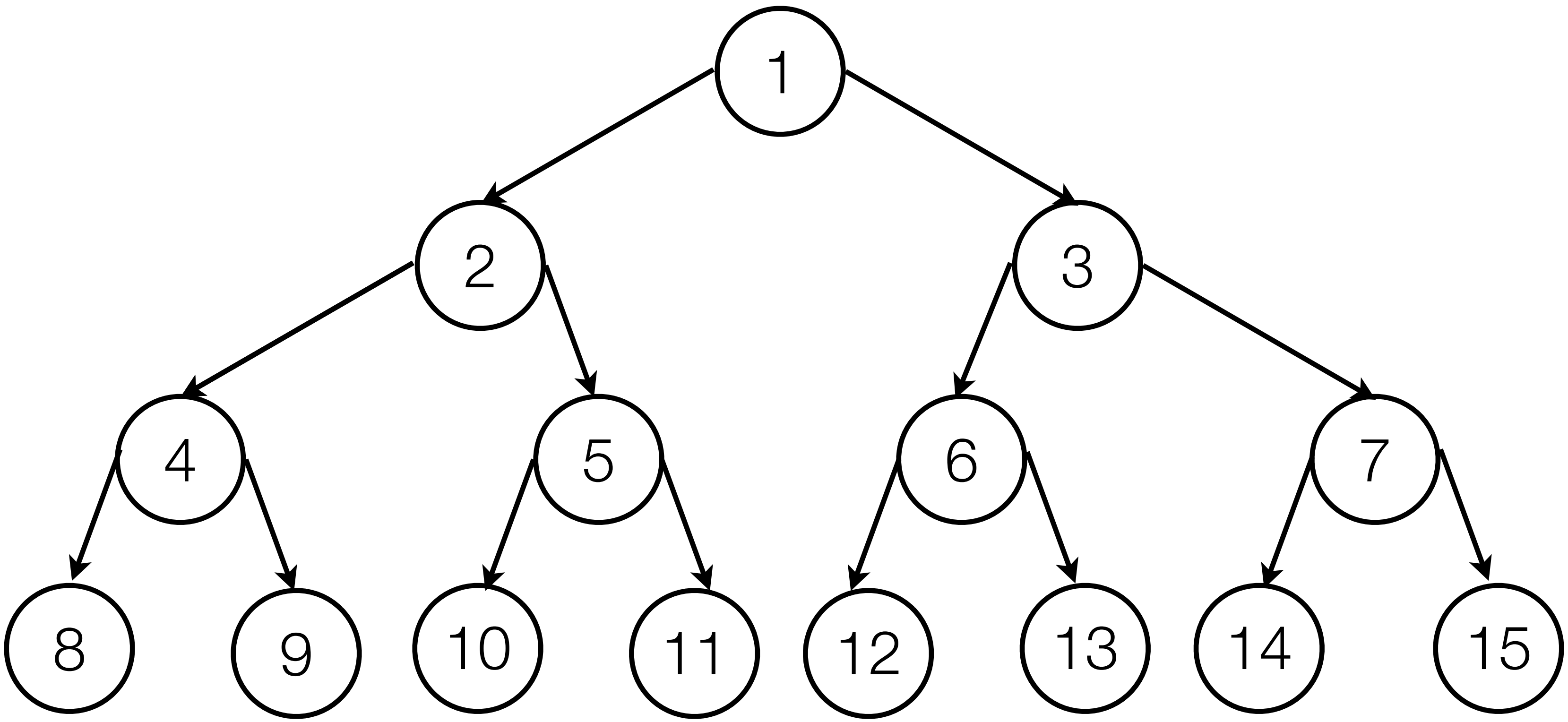
TAKE TREE↑.NODE CHILDREN IN THE QUORUM/PATH

IF LEAF IS DOWN, NO QUORUM CAN BE FORMED

Performance

- best case log n
- worst case O((n+1)/2)
- can tolerate up to n-log n failures

Example



Quorum sets: 1-2-4-8 1-2-4-9 1-2-5-10 1-2-5-11 etc.

If 2 fails: 1-4-8-5-10 1-4-9-5-11 1-4-9-5-10 etc.

Mutual exclusion with tree quorum sets

1. P send *request* to all members of the quorum sets it belongs to
2. Each process stores requests in a *queue*
3. Each site replies to the head of its *queue* only
4. If a site gets replies from all members of its quorum sets it enters the CS
5. Existing the CS, it sends a *relinquish* message, all members remove the request from their queues
6. If a request arrives with a timestamp smaller than the head of the queue, an *inquiry* message is sent to the process at the head of the queue and the process waits for a *yield* or a *relinquish* message
7. Upon receipt of an *inquiry* message: if it has received all replies, it ignores it; otherwise it sends a *yield* message to the sender
8. Upon receipt of a *yield* message, the sender's request is put at the head of the queue and a reply is sent

Mutual exclusion with tree quorum sets

- Correct whenever the quorum sets are built with the Intersection property (such as quorum trees)

- **Example.**
  - Given the sets: 1-2-3   2-4-5   4-1-6
  - Suppose 3, 5 and 6 want to enter CS
  - They send messages to {1,2},{2,4} and {1,4}, respectively
  - At 2, request of 3 arrives before that of 5, then 2 acks 3 and rejects 5
  - At 1, request 3 arrives before that of 6, then 1 acks 3 and rejects 6
  - 3 can enter safely the CS