# Coordination and Agreement

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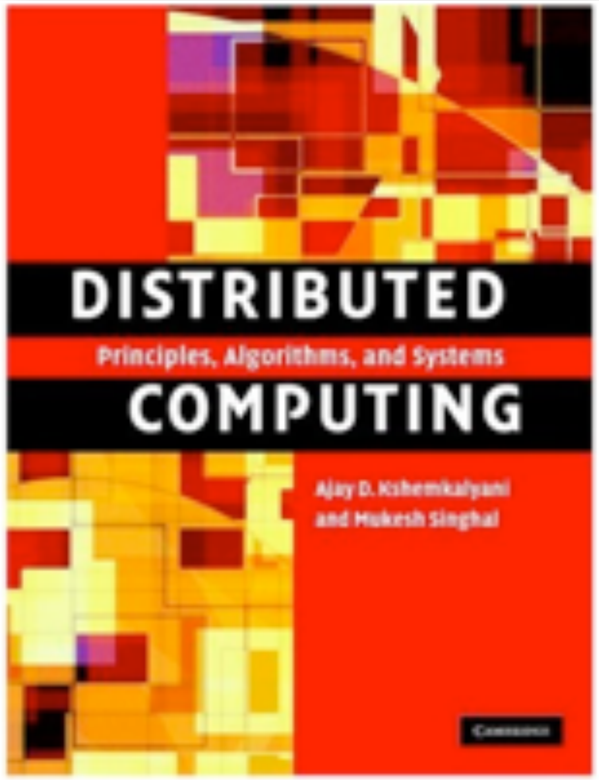
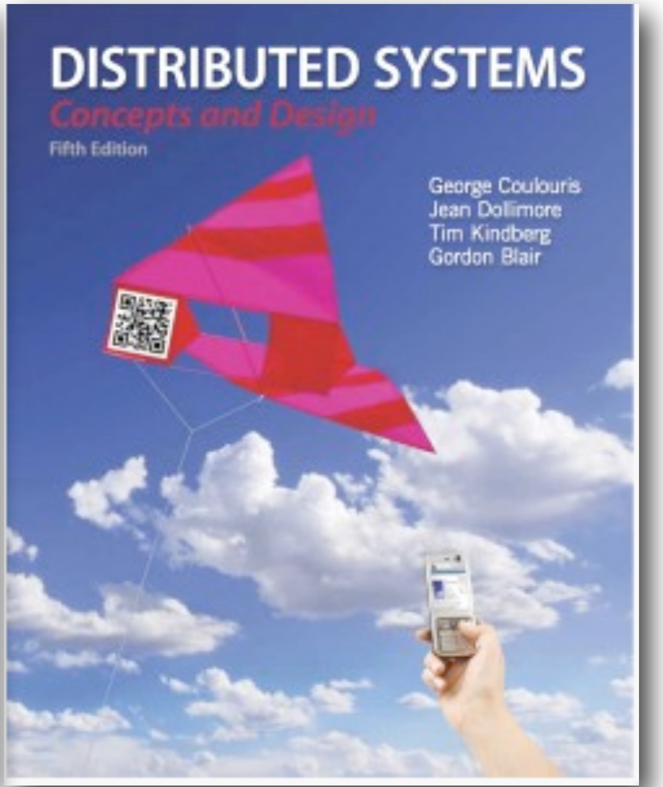


# AIM: Coordination and/or Agreement

**Collection of algorithms** whose goals vary but which share an aim that is fundamental in distributed systems:

***for a set of distributed processes***

***to coordinate their actions***

***and/or***

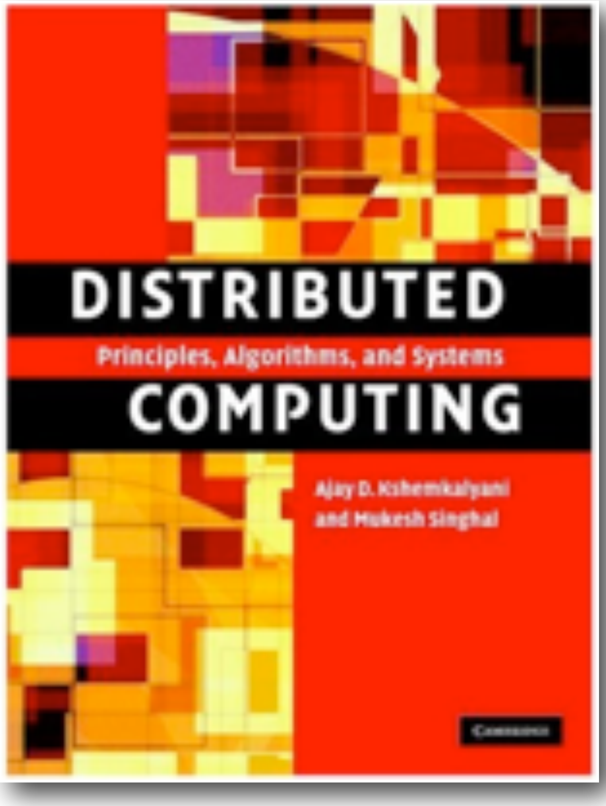
***to agree on one or more values***

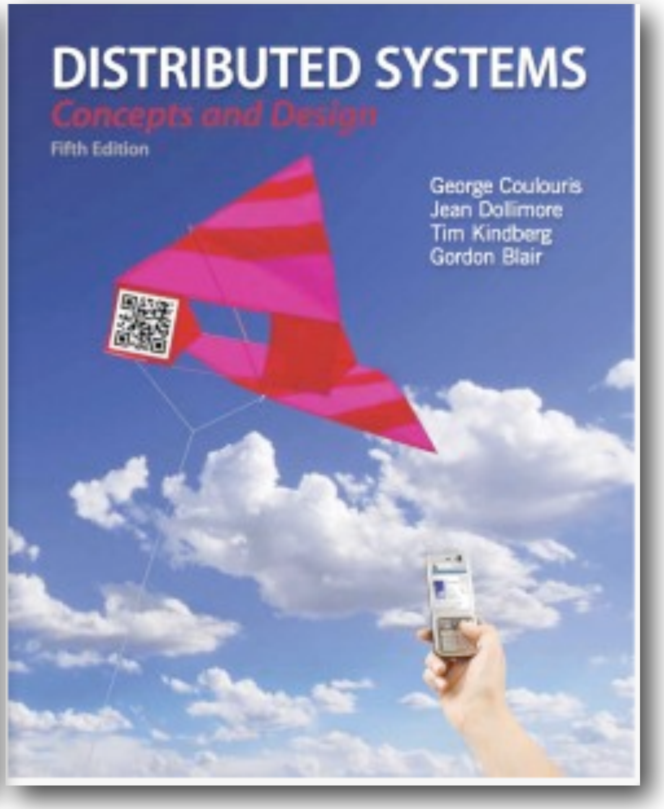
# Failure Assumptions

- Each pair of processes is connected by reliable channels
  - A reliable channel *eventually* delivers a message to the recipient's input buffer
- No process failure implies a threat to the other processes' ability to communicate
  - None of the processes depends upon another to forward messages

# Distributed Mutual Exclusion

## Problem and requirements



# Problem: Coordinate Access to Shared Resources

- Distributed processes often need to **coordinate** their activities

- If a collection of processes share a resource (or collection of resources), then **mutual exclusion** is required **to prevent interference and ensure consistency when accessing the resources**

- Critical Section (CS) problem in the domain of operating systems:

**AT ANY MOMENT,**
**AT MOST ONE PROCESS CAN STAY IN ITS CS!**

# Why Is CS More Complex in Distributed Systems?

- In a distributed system, neither
  - shared variables (semaphores) nor
  - facilities supplied by a single local kernel

  can be used to solve the problem!

- We require a ***distributed* mutual exclusion**: one that is **based solely on message passing**, in a context of
  - unpredictable message delays
  - no complete knowledge of the state of the system

# Model (Without Failures)

- We consider a system of N processes $p_i$, $i = 1,\dots,N$ that do not share variables
- The processes access common resources, but they must do so in a critical section
- The system is asynchronous
- Processes do not fail
- Message delivery is reliable: any message sent is eventually delivered intact, exactly once
- Client processes are well-behaved and spend a finite time accessing resources within their CSs

# Critical Section (CS)

- The application-level protocol for executing a **CS** is as follows:
  - enter(): enter a critical section - block if necessary
  - resourceAccess(): access shared resources in critical section
  - exit(): leave critical section - other processes may now enter

# Requirements for ME

- A **mutual exclusion algorithm** should satisfy the following properties:
  - **[ME1] Safety**: at most one process can execute in the CS at a time
  - **[ME2] Liveness**: requests to enter and exit the CS eventually succeed
  - **[ME3] Ordering**: if one request to enter the CS *happened-before* another, then entry to the CS is granted in that order
- ***Safety is absolutely necessary*** (**CORRECTNESS** property)
- The other two properties are considered important in ME algorithms

# On ME Requirements: **Liveness**

- **[ME2] Liveness**: requests to enter and exit the CS eventually succeed

  Implies freedom from both **deadlock** and **starvation**

  - **Deadlock**: involve two or more processes becoming stuck indefinitely while attempting to enter or exit the critical section, by virtue of their mutual interdependence

  - Even without a deadlock, a poor algorithm might lead to **starvation**: the indefinite postponement of entry for a process that has requested it

- The **absence of starvation** is a **FAIRNESS condition**

# On ME Requirements: **Ordering**

- **[ME3] Ordering**: if one request to enter the CS happened-before another, then entry to the CS is granted in that order

N.B.:

***If*** a solution grants entry to the CS in happened-before order and

***if*** all the requests are related by happened-before

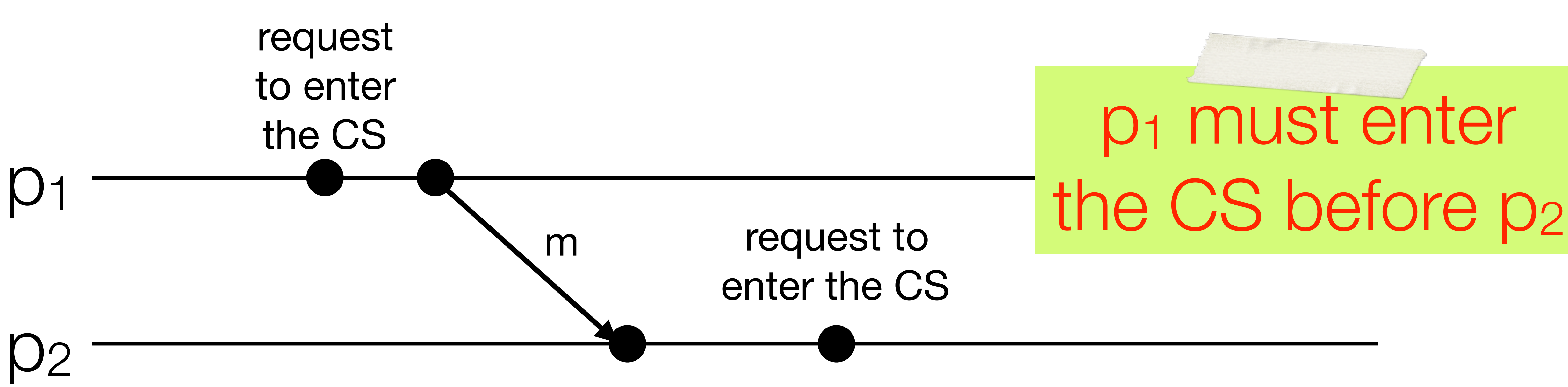
***then***

**it is not possible for a process to enter the CS more than once while another waits to enter**

*Happened-before ordering of CS requests implies liveness*

# [Ordering] Example

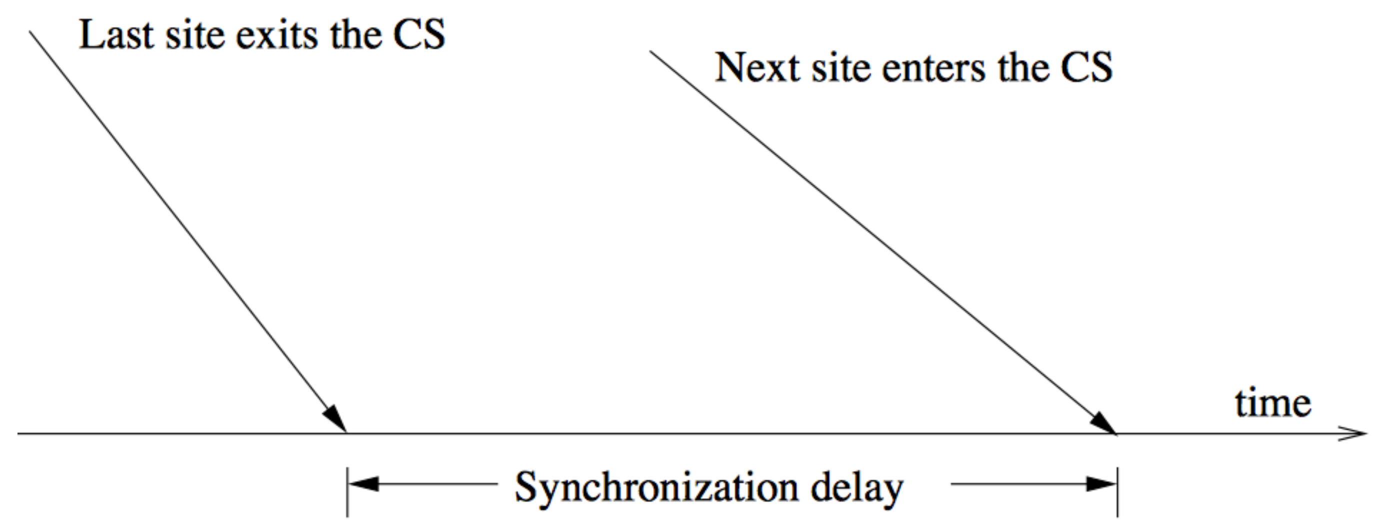
- A multi-threaded process may continue with other processing while a thread waits to be granted entry to a CS
  - During this time, it might send a message to another process, which consequently also tries to enter the CS
  - ME3 specifies that the first process be granted access before the second



# Performance Criteria

- The **bandwidth** consumed, which is proportional to **the number of messages sent in each *entry* and *exit* operation**
- The **client delay** incurred by a process **at each *entry* and *exit* operation**
- **Throughput of the system**: **the rate at which the collection of processes as a whole can access the CS**, given that some communication is necessary between successive processes

$$\text{throughput} = \frac{1}{(E + SD)}$$




E = average CS execution time

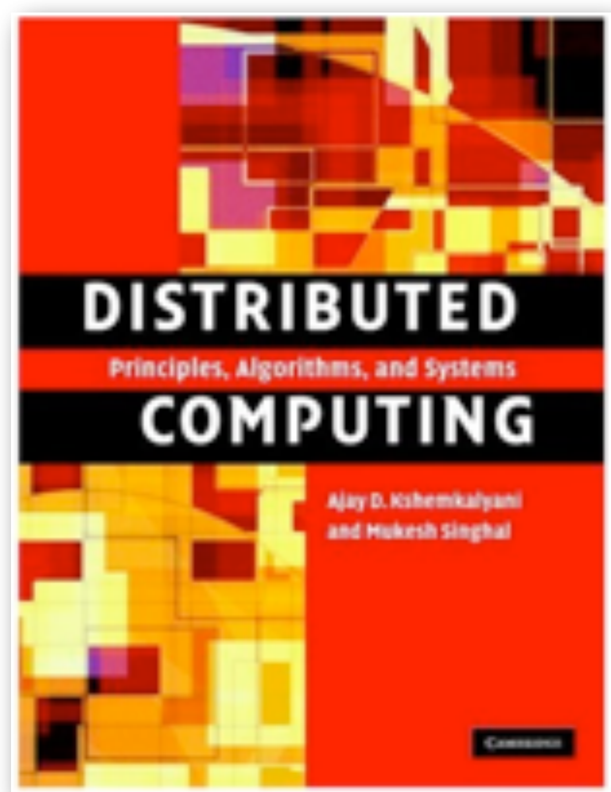
SD (synchronization delay) = delay between one process exiting the CS and the next process entering it

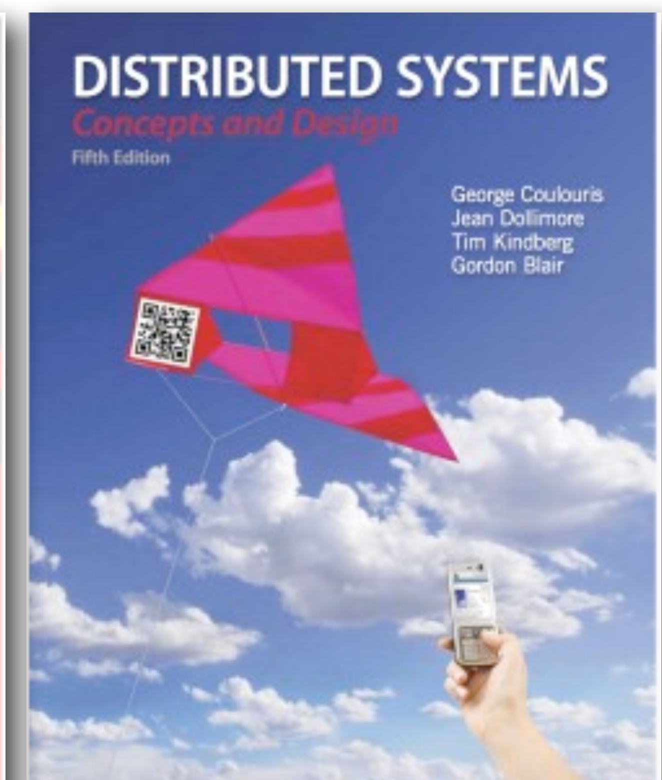
# Design of Distributed ME Algorithms

- Complex because these algorithms have to deal with
  - unpredictable message delays
  - incomplete knowledge of the system state
- 3 **basic approaches**:
  - **Token based approaches**
  - **Non-token based approaches**
    - **Quorum based approaches**

# Distributed Mutual Exclusion

## Token based algorithms

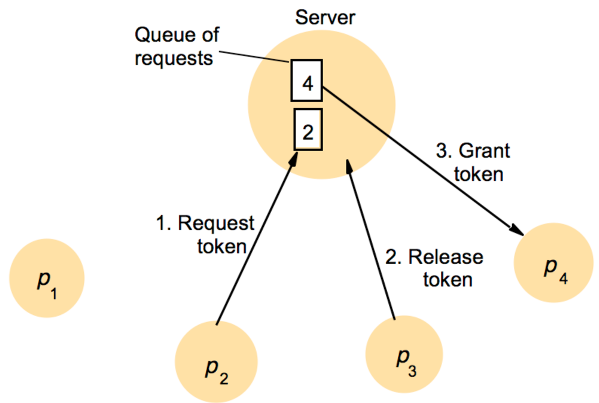


# [Distributed ME] Token Based Algorithms

- A unique token (PRIVILEGE msg) is shared among the processes
- A process is allowed to enter its CS if it possesses the token
- The process continues to hold the token until the execution of the CS is over
- Mutual exclusion is ensured because the **TOKEN IS UNIQUE**
- The algorithms based on this approach essentially differ in the way a process carries out the search for the token

# The Central Server Algorithm



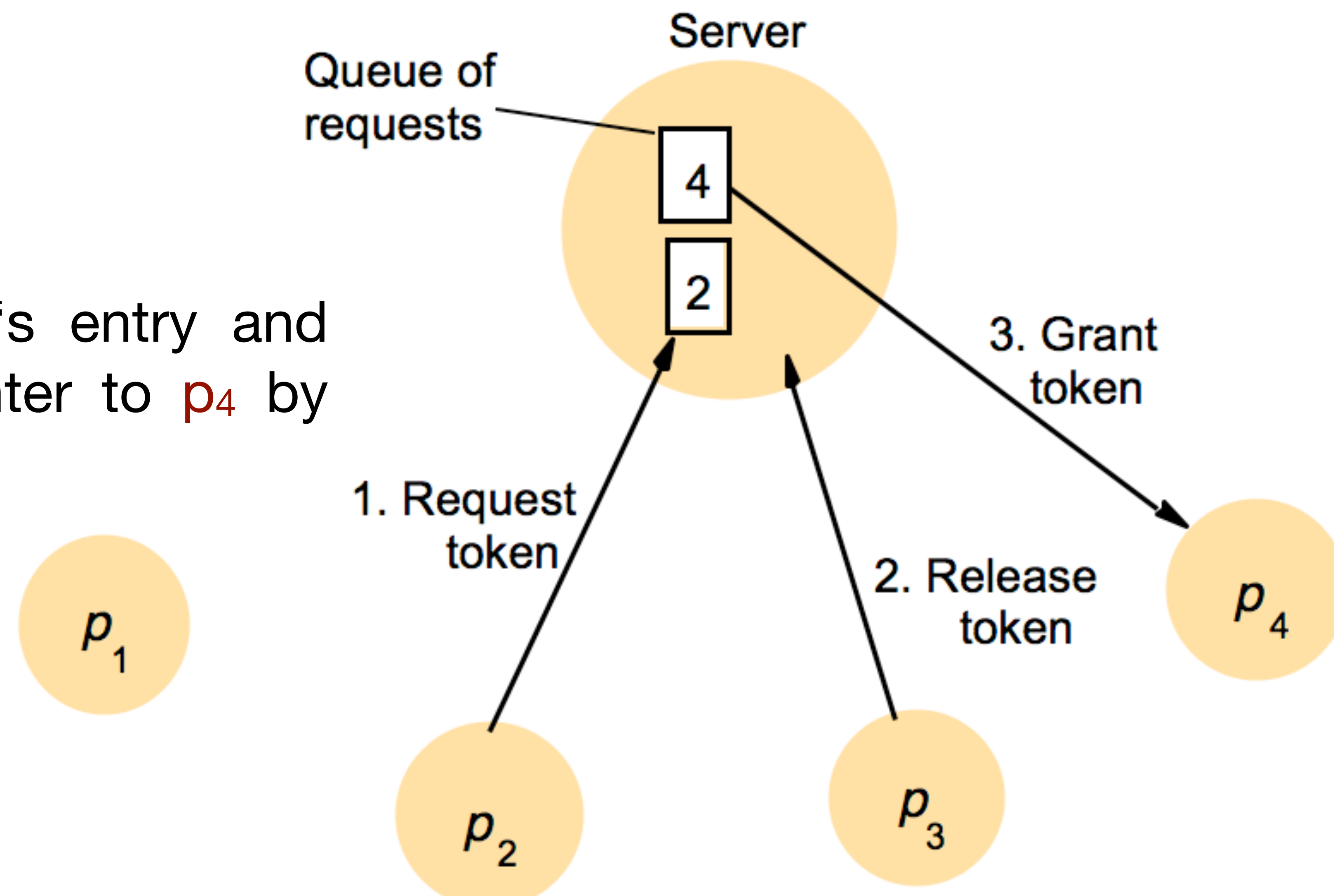

- Simplest way to achieve mutual exclusion: a server grants permission to enter the CS

- To enter a CS, a process sends a requests to the server and awaits a reply from it
- The reply constitutes a token signifying permission to enter the CS
- If no other process has the token at the time of the request then the server replies immediately, granting the token
- If the token is currently held by another process, then the server does not reply but queues the request
- On exiting the CS, a message is sent to the server, giving it back the token
- If the queue of waiting process is not empty, then the server chooses the oldest entry in the queue, removes it and replies to the corresponding process
- The chosen process then holds the token

**Algorithm**

# [The Central Server Algorithm] Example

- Process $p_1$ does not currently require entry to the CS
- Process $p_2$'s request has been appended to the queue, which already contained $p_4$'s request
- Process $p_3$ exits the CS
- The server removes $p_4$'s entry and grants permission to enter to $p_4$ by replying to it



# Performance of the Central Server Algorithm

- Entering the CS:
  - It takes 2 messages: a *request* followed by a *grant*
  - It delays the requesting process (client) by the time for this round-trip
- Exiting the CS:
  - It takes 1 *release* message
  - Assuming asynchronous message passing, this does not delay the exiting process
- Synchronization delay: time taken for a round-trip (a *release* msg to the server, followed be a *grant* msg to the next process to enter the CS)
- The server may become a performance bottleneck for the system as a whole

# Homework

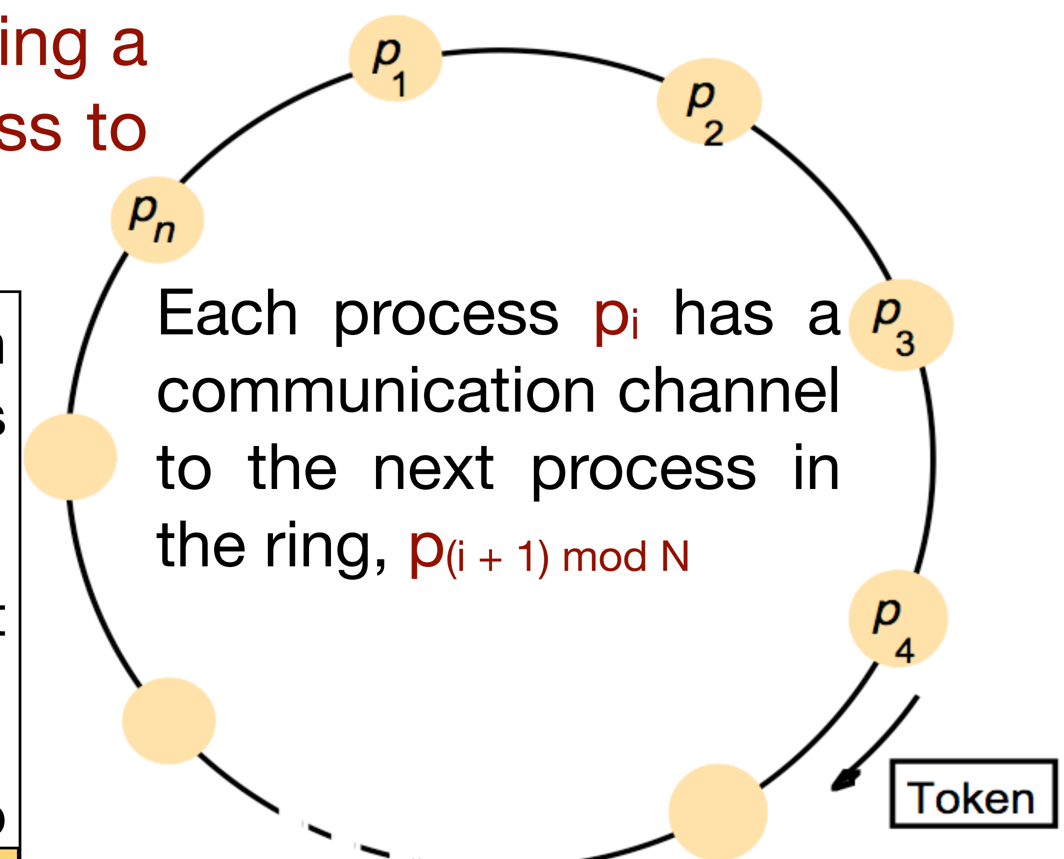
- Basic: given the assumption that no failures occur, informally discuss why
  - safety and liveness conditions [ME1 and ME2] are met by the Central Server algorithm
  - the algorithm does **not** satisfy the ordering property [ME3]
    - hint: describe a situation in which two requests are not processed in happened-before order
- Advanced: **prove** the above statements

# A Ring-Based Algorithm

- Logical ring: one of the simplest ways to arrange a ME between N processes **without requiring an additional process**

  The ring topology may be unrelated to the physical interconnections between the underlying computers

- Basic idea: exclusion is conferred by obtaining a token in the form of a message from process to process in a *single direction around the ring*




- If a process does not require to enter the CS when it receives the token, then it immediately forwards the token to its neighbour
- A process that requires the token waits until it receives it, but retains it
- To exit the CS, the process sends the token on to its neighbour

**Algorithm**

# Performance of the Ring-Based Algorithm

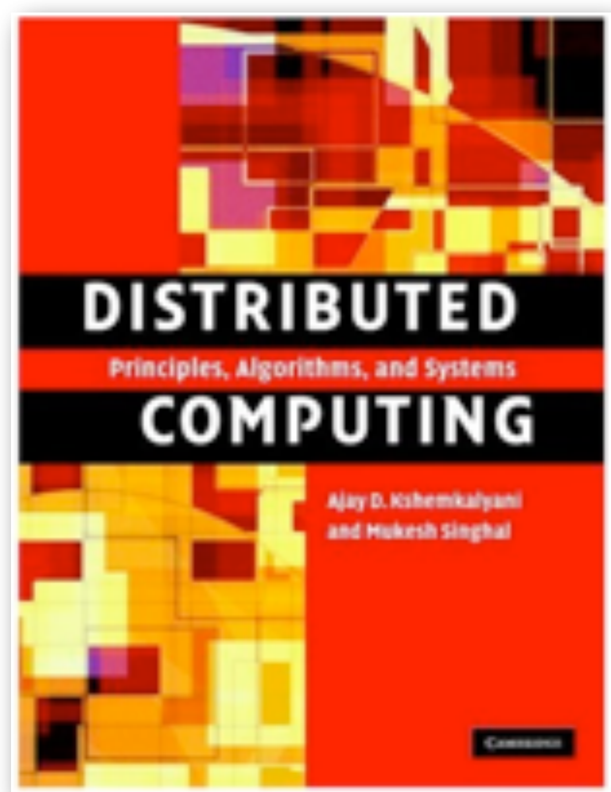
- The algorithm continuously consumes network bandwidth, except when a process is inside the critical section
  - The processes send messages around the ring even when no process requires entry to the CS
- The delay experienced by a process requesting entry to the CS is between 0 messages (when it has just received the token) and N messages (when it has just passed on the token)
- To exit the CS requires only one message
- The synchronization delay between one process's exit from the CS and the next process's entry is anywhere from 1 to N message transmissions

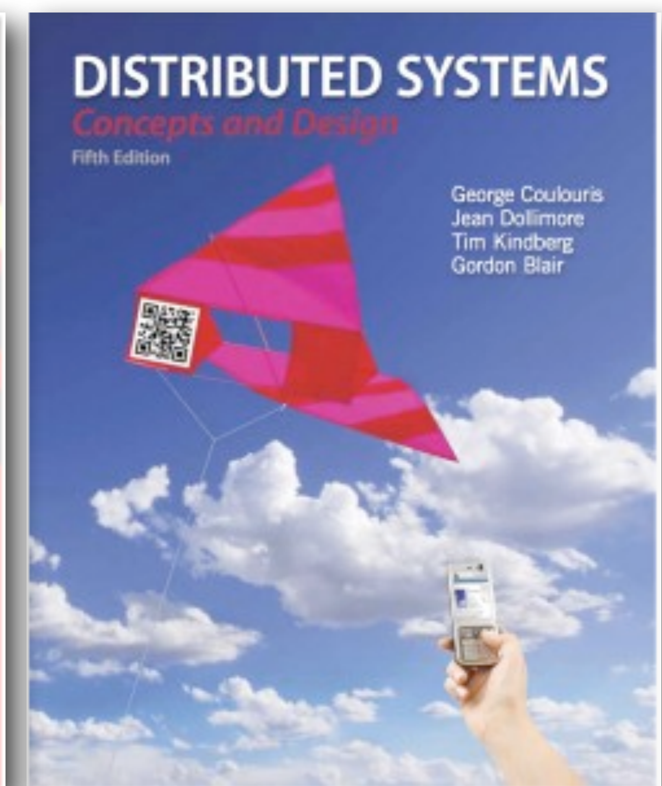
# Homework

- Basic: given the assumption that no failures occur, informally discuss why
  - the safety and liveness conditions [ME1 and 2] are met by the Ring-Based algorithm
  - the algorithm does not necessarily satisfy the ordering property [ME3]
    - hint: give an example execution of the algorithm to show that processes are not necessarily granted entry to the critical section in happened-before order
- Advanced: **prove** the above statements

# Distributed Mutual Exclusion

## Non-token based algorithms



# [Distributed ME] Non-token Based Algorithms

- Two or more successive **rounds of messages** are exchanged among the processes to determine which process will enter the CS next

- **A process enters the CS when an assertion**, defined on its local variables, **becomes *true***

- **Mutual exclusion is enforced because the assertion becomes true *only at one site at any given time***

# Lamport's Algorithm

- Requires communication channels to deliver messages in **FIFO order**
- Satisfies conditions ME1, ME2 and ME3
- Based on Lamport **logical clocks**: **timestamped** requests for entering the CS
- Every process $p_i$ keeps a queue, **request_queue$_i$**, which contains **mutual exclusion requests ordered by their timestamps**
- **IDEA**: the algorithm executes CS requests in the **increasing order of timestamps**
- Timestamp: **(clock value, id of the process)**

# Timestamp: (clock value, id of the process)?

Why does the algorithm need the id of the sending process in the timestamp?

# Extension of Happened-Before Relation (→)

- → defines a partial ordering of events in the system

CR1: If ∃ process $p_i$ such that $e \rightarrow_i e'$, then $L_i(e) < L_i(e')$

CR2: If $a$ is the sending of a message by $p_i$ and $b$ is the receipt of the same message by $p_j$, then $L_i(a) < L_j(b)$

CR3: If $e$, $e'$, $e''$ are three events such that $L(e) < L(e')$ and $L(e') < L(e'')$ then $L(e) < L(e'')$

- A **total ordering** ⇒ requires the further rule:

**Timestamps totally ordered!!**
Example: (1, 1) < (1, 2)

CR4: $a$ (in $p_i$) ⇒ $b$ (in $p_j$) if and only if

either $L_i(a) < L_j(b)$
or $L_i(a) = L_j(b) \wedge p_i < p_j$

for some suitable ordering < of the processes

# Lamport's Algorithm [1978]

**Requesting the CS**

Process $p_i$ updates its local clock and timestamps the request (**$ts_i$**)
Process $p_i$ broadcasts a **REQUEST($ts_i$, i)** to all the other processes
Process $p_i$ places the request on **$request\_queue_i$**

**On Receiving REQUEST($ts_i$, i) from a process $p_i$**

Process $p_j$ places $p_i$'s request on **$request\_queue_j$**

Process $p_j$ returns a timestamped REPLY msg to $p_i$

**Executing the CS**

Process $p_i$ enters the CS when the following two conditions hold:

- L1: $p_i$ has received a msg with timestamp larger than **($ts_i$, i)** from all other processes
- L2: $p_i$'s request is at the top of **$request\_queue_i$**

**Releasing the CS**

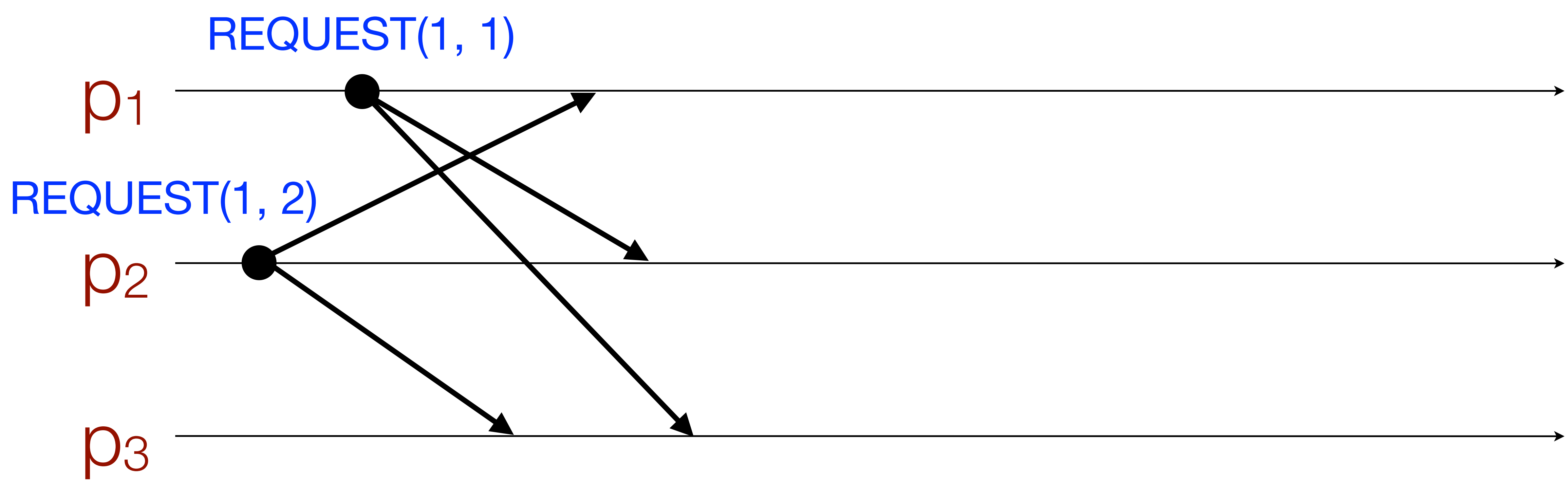
Process $p_i$ removes its request from the top of **$request\_queue_i$**
Process $p_i$ broadcasts a timestamped **RELEASE** msg to all other processes

**On Receiving RELEASE from a process $p_i$**

Process $p_j$ removes $p_i$'s request from its request queue **$request\_queue_j$**

# The Algorithm in Action: Entering a CS

- $p_1$ and $p_2$ send out REQUEST messages for the CS to the other processes

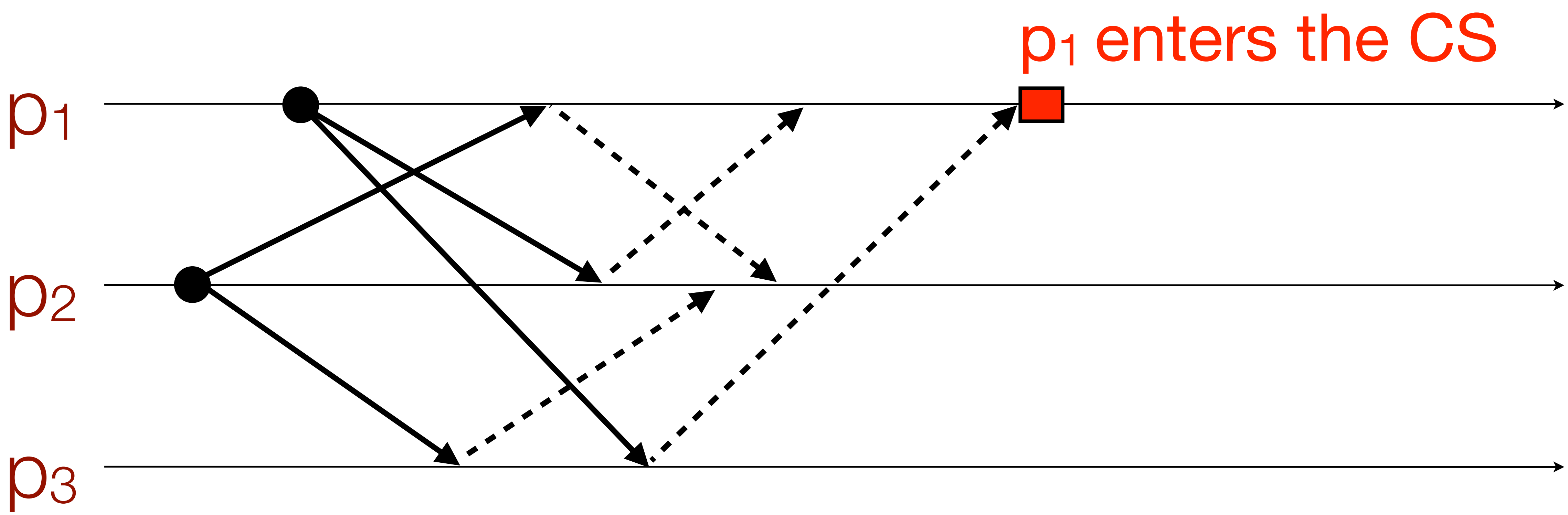



request_queue₁ (1, 1)

request_queue₂ (1, 2)

# The Algorithm in Action: Entering a CS

- Both $p_1$ and $p_2$ have received timestamped REPLY msgs from all processes

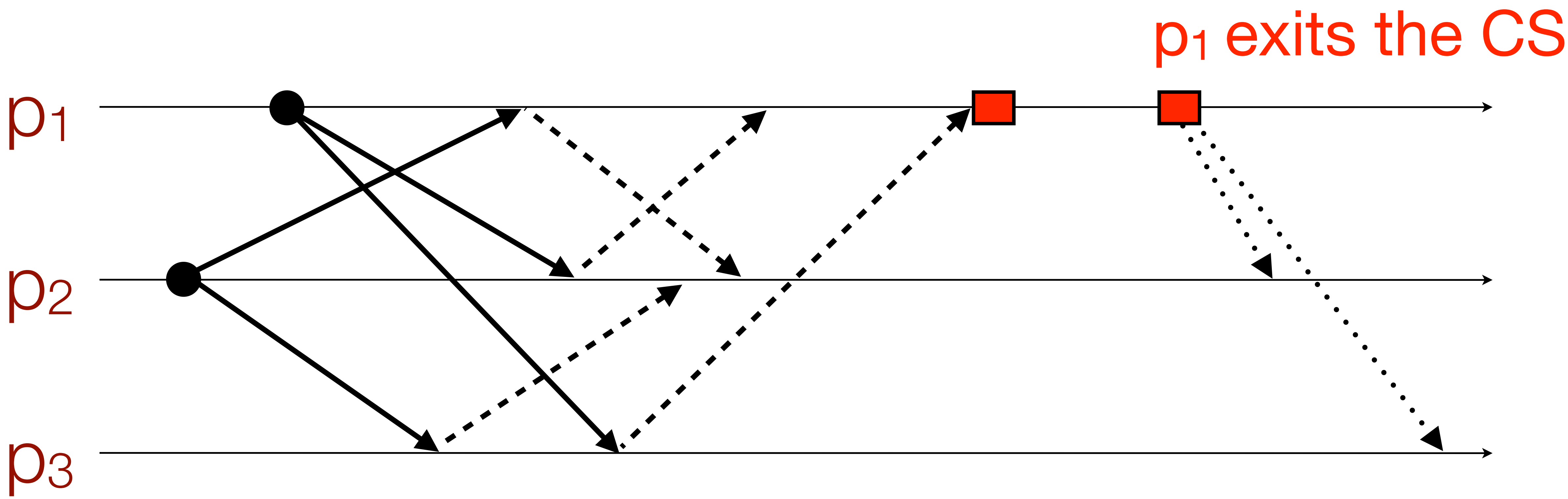



| | | |
|---|---|---|
| $request\_queue_1$ | (1, 1) | (1, 2) |
| $request\_queue_2$ | (1, 1) | (1, 2) |

- L1: $p_1$ has received a msg with timestamp larger than (1, 1) from all other processes
- L2: $p_1$'s request is at the top of $request\_queue_1$

# The Algorithm in Action: Exiting a CS

- $p_1$ exits and sends RELEASE msgs to all other processes

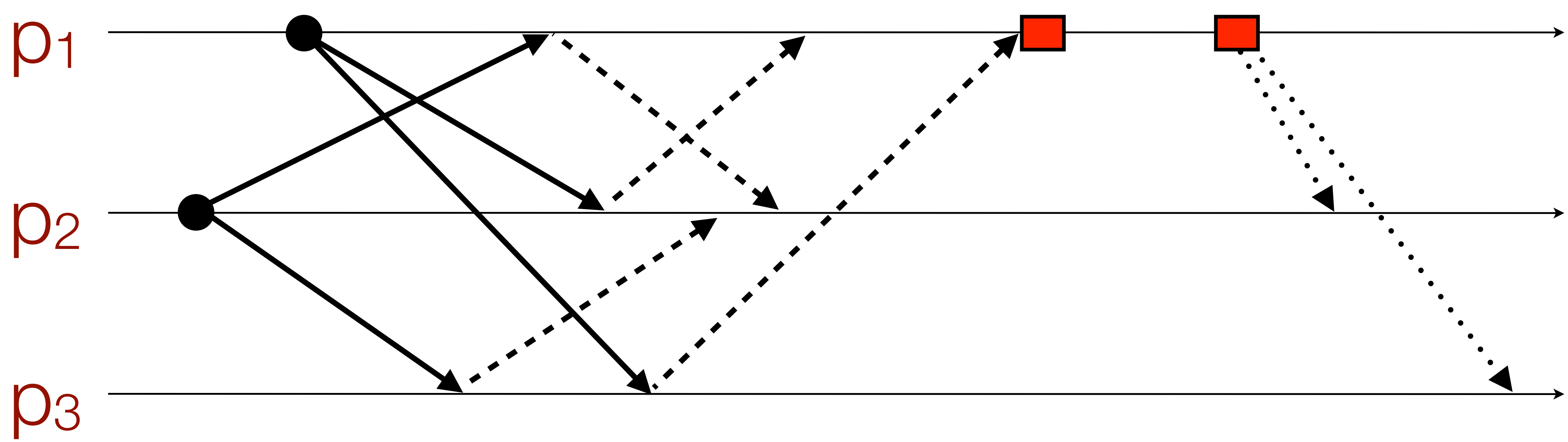



request_queue$_1$ | (1, 2) |

request_queue$_2$ | (1, 2) | (1, 1) |

# The Algorithm in Action: Exiting a CS

- $p_1$ exits and sends RELEASE msgs to all other processes




request_queue$_1$ (1, 2)

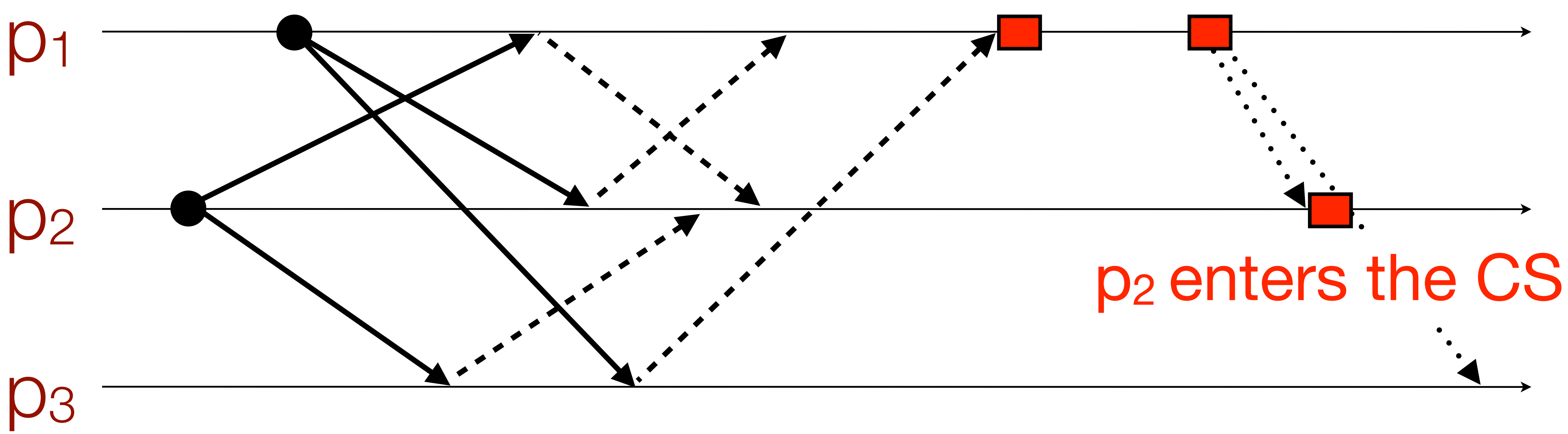
request_queue$_2$ (1, 2)

**On Receiving RELEASE from process $p_1$**

- Process $p_2$ removes $p_1$'s request from its request queue request_queue$_2$

# The Algorithm in Action: $p_2$ enters the CS...

- $p_1$ exits and sends RELEASE msgs to all other processes

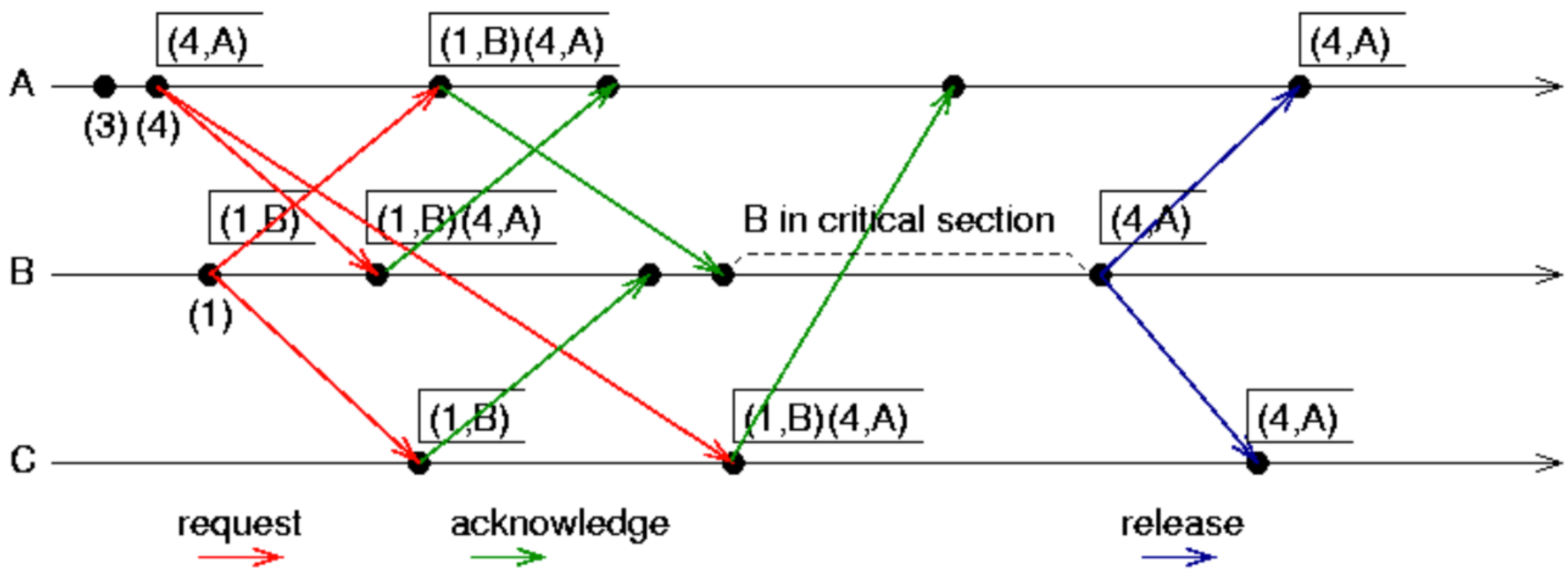



request_queue$_1$ (1, 2)

request_queue$_2$ (1, 2)

- L1: $p_2$ has received a msg with timestamp larger than (1, 2) from all other processes
- L2: $p_2$'s request is at the top of request_queue$_2$

# Another Example



# Correctness Theorem

*Lamport's algorithm achieves mutual exclusion (property ME1)*

Proof [by contradiction]:

- suppose two processes $p_i$ and $p_j$ are executing the CS concurrently

➡ L1 and L2 must hold at both sites concurrently

➡ at some instant in time, say t, both $p_i$ and $p_j$ have their own requests at the top of their request_queue and condition L1 holds at them

- Without loss of generality, assume that $(ts_i, i) < (ts_j, j)$
- From L1 and FIFO property, at instant t the request of $p_i$ must be in $request\_queue_j$ when $p_j$ was executing its CS

➡ $p_j$'s own request is at the top of $request\_queue_j$ when a smaller timestamp request, $(ts_i, i)$ from $p_i$, is present in the queue - a contradiction!!

$request\_queue_j$ | $(ts_j, j)$ | ... | $(ts_i, i)$ | ...

# Fairness Theorem

*Lamport's algorithm is fair (that is, the requests for CS are executed in the order of their timestamps)*

Proof [by contradiction]:

- without loss of generality, suppose a $p_i$'s request has a smaller timestamp than the request of another site $p_j$ and $p_j$ is able to execute the CS before $p_i$

➡ for $p_j$ to execute the CS, it has to satisfy L1 and L2, which implies that:

  - at some instant in time, say t, $p_j$ has its own request at the top of its queue
  - $p_j$ has also received a message with timestamp larger than the timestamp of its request from all other processes, including $p_i$

- by assumption, request queue of a process is ordered by timestamps
- according to our assumption $p_i$ has lower timestamp

➡ So $p_i$'s request must be placed ahead of the $p_j$'s request in the $request\_queue_j$ - a contradiction!

# Performance of Lamport's Algorithm

- For each CS execution, the algorithm requires
  - (N - 1) REQUEST messages
  - (N - 1) REPLY messages
  - (N - 1) RELEASE messages
- Thus, the algorithm requires 3(N - 1) messages per CS invocation
- The client delay in requesting entry is a round-trip time
- The synchronization delay is 1 msg transmission (average message delay)

# Homework

- Advanced: why does Lamport's algorithm require communication channels to deliver messages in **FIFO order**?

# Ricart and Agrawala's Idea [1981]

- Basic idea:
  - processes that require entry to a CS multicast a request message
  - processes can enter the CS only when all the other processes have replied to this message
  - node $p_j$ does **not** need to send a REPLY to node $p_i$ if $p_j$ has a request with timestamp lower than the request of $p_i$ (since $p_i$ cannot enter before $p_j$ anyway in this case)
- **Does NOT require communication channels to be FIFO**

# Ricart and Agrawala's Algorithm [1981]

- Each process $p_i$ keeps a Lamport clock, updated according to LC1 and LC2
- Messages requesting entry are of the form <T, $p_i$>, where T is the sender's timestamp and $p_i$ is the sender's identifier
- Every process records its state of being outside the CS (RELEASED), wanting entry (WANTED) or being in the CS (HELD) in a variable *state*

# Ricart and Agrawala's Algorithm [1981]

**On initialization**
state := RELEASED;

**To enter the Critical 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**

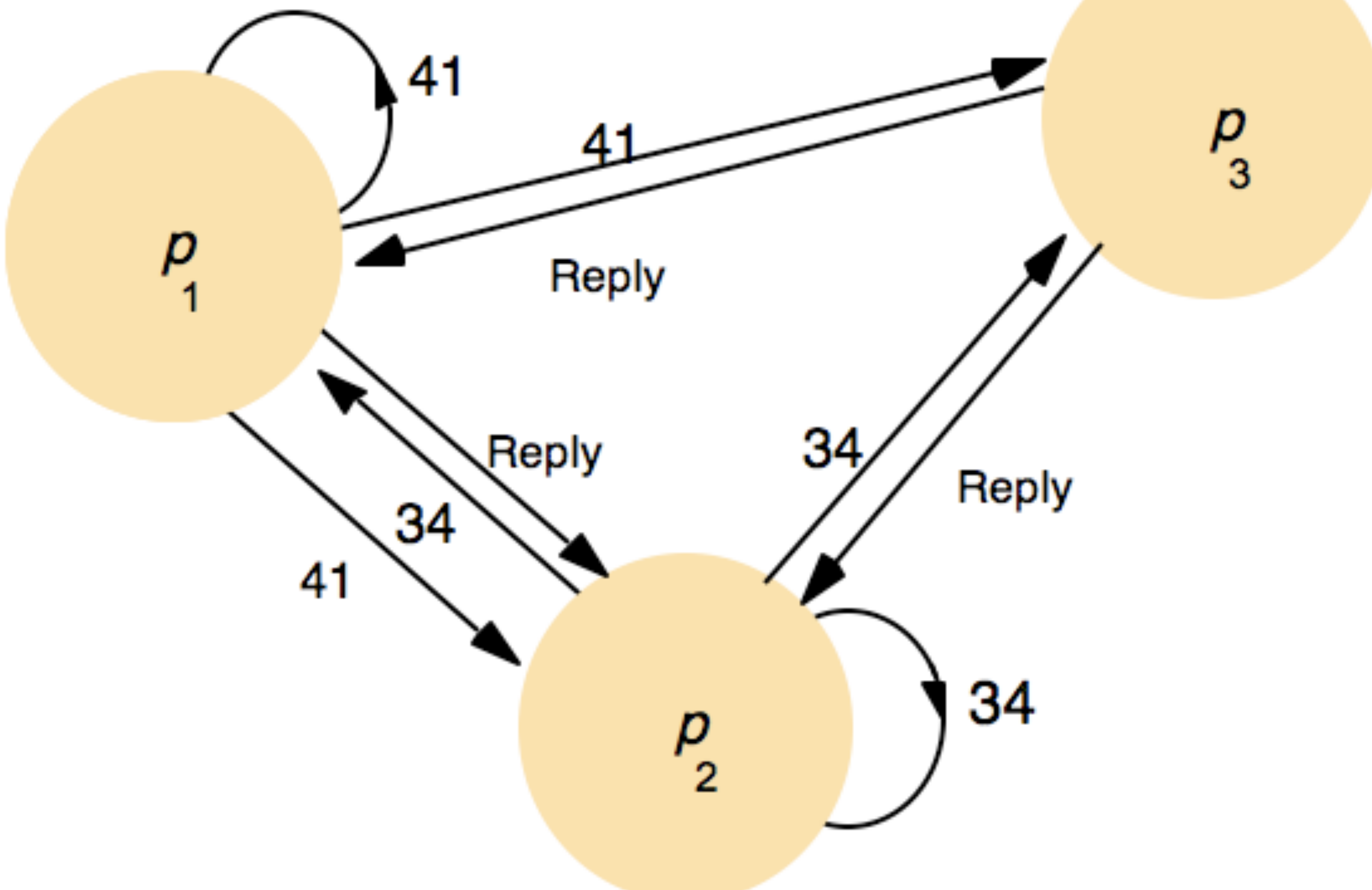
**To exit the Critical Section**
state := RELEASED;
reply to any queued requests;

If two or more processes request entry at the same time, then whichever process's request bears the lowest timestamp will be the first to collect N-1 replies, granting it entry next.

In case of equal timestamps, the requests are ordered according to the process identifiers.

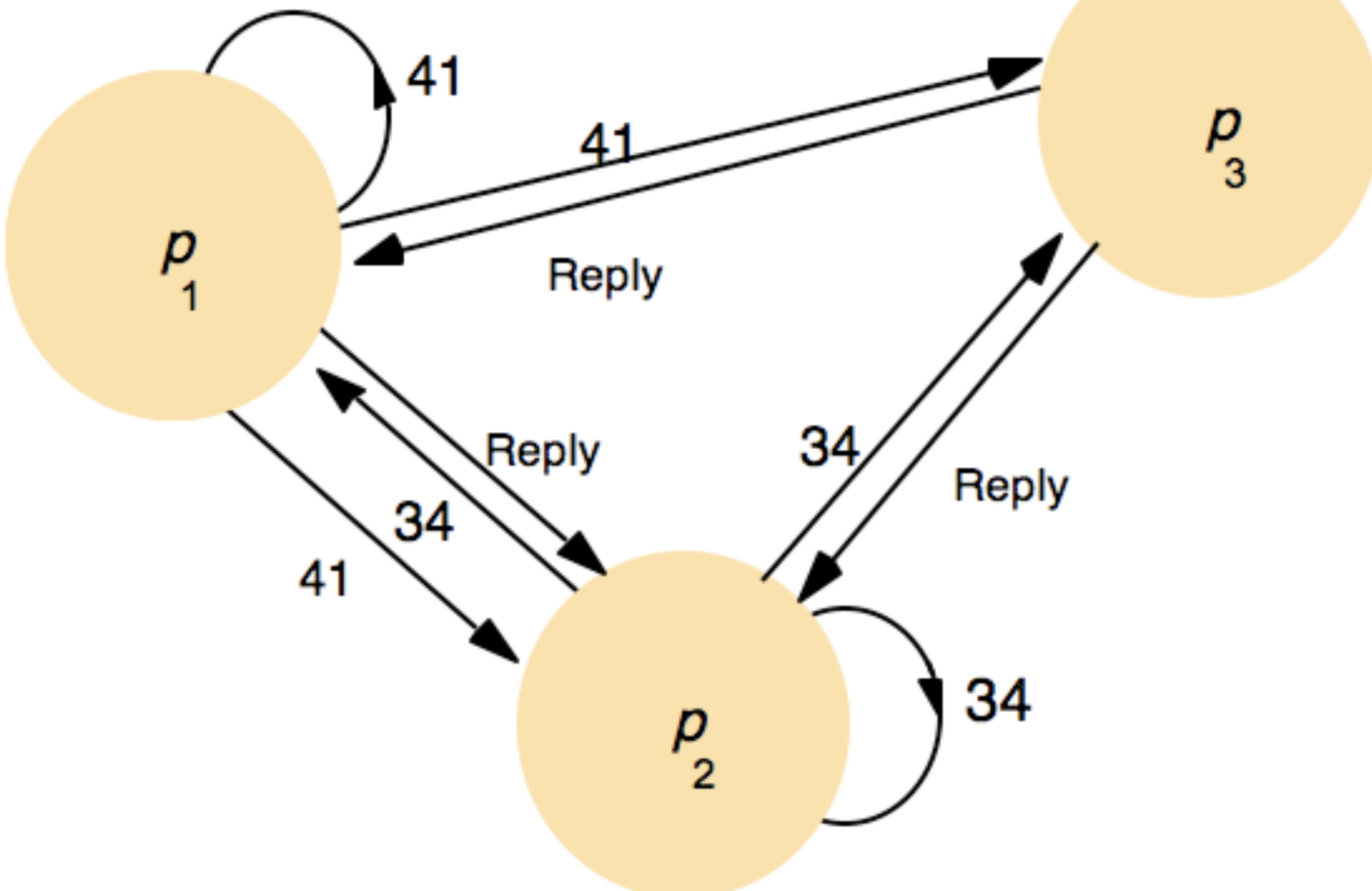
# [Ricart and Agrawala's Algorithm] Example

- $p_3$ not interested in entering the CS
- $p_1$ and $p_2$ request it concurrently



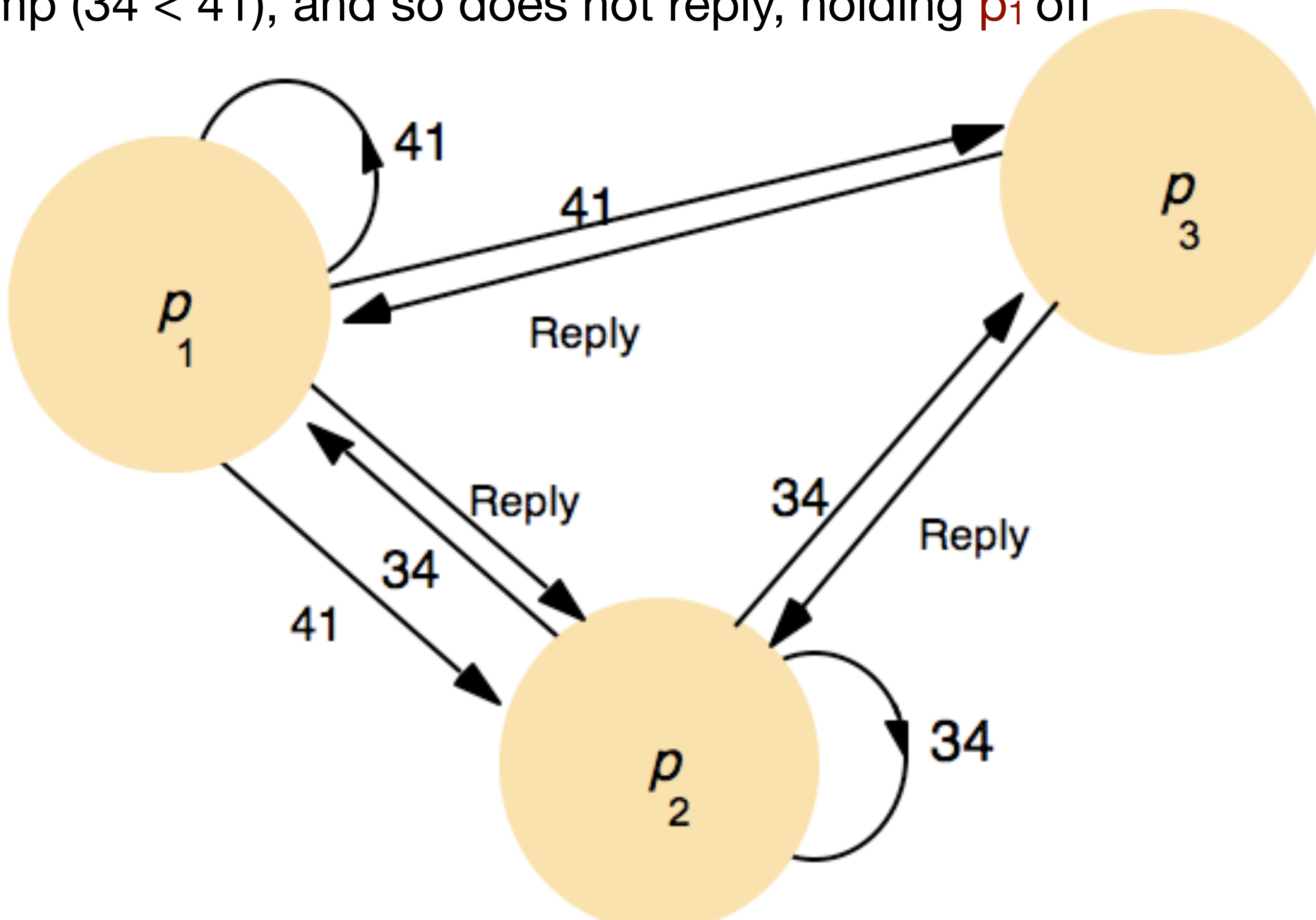
# [Ricart and Agrawala's Algorithm] Example

- The timestamp of $p_1$'s request is 41, that of $p_2$ is 34.
- When $p_3$ receives their requests, it replies immediately



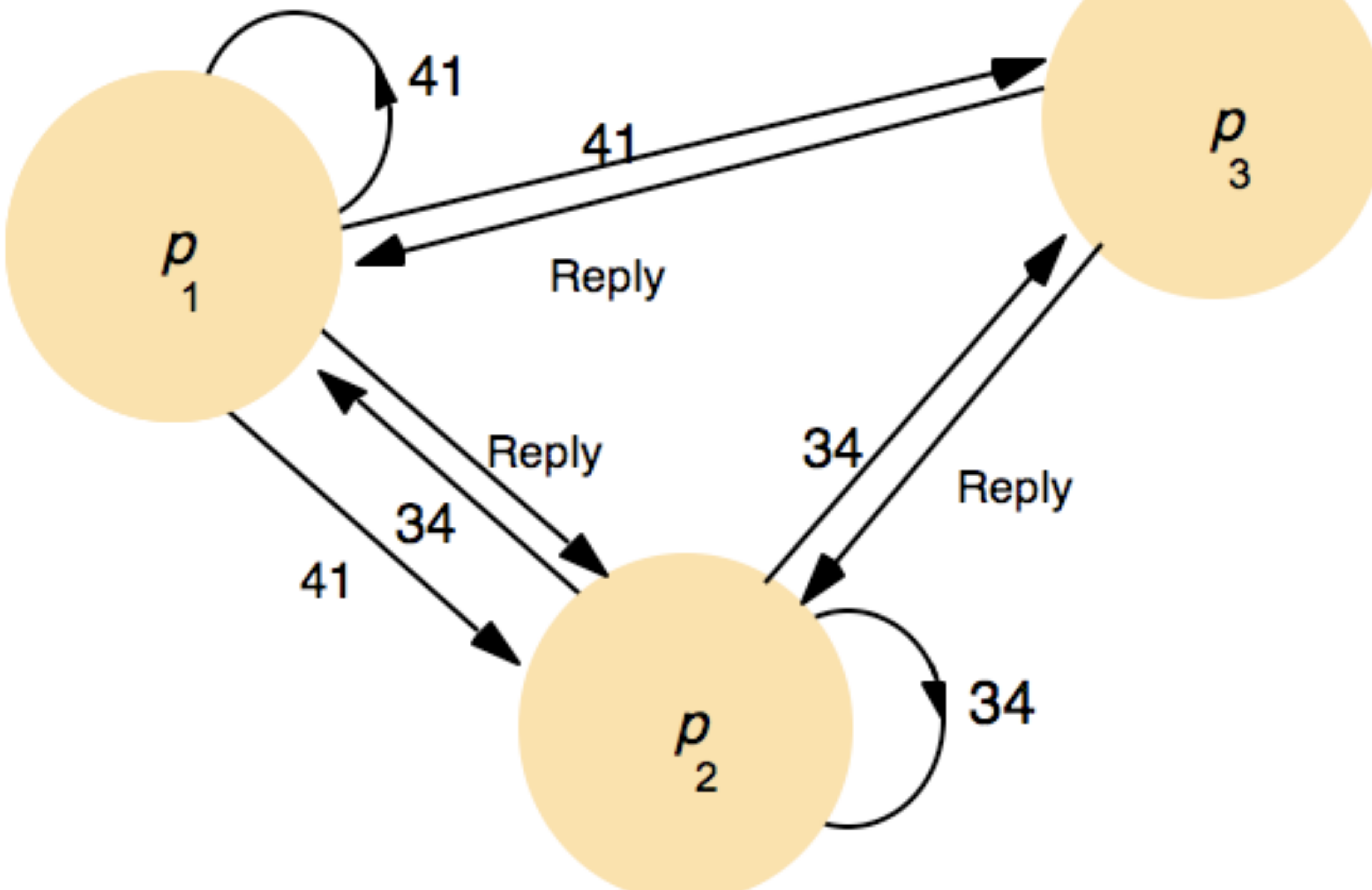
# [Ricart and Agrawala's Algorithm] Example

- When $p_2$ receives $p_1$'s request, it finds its own request has the lower timestamp (34 < 41), and so does not reply, holding $p_1$ off



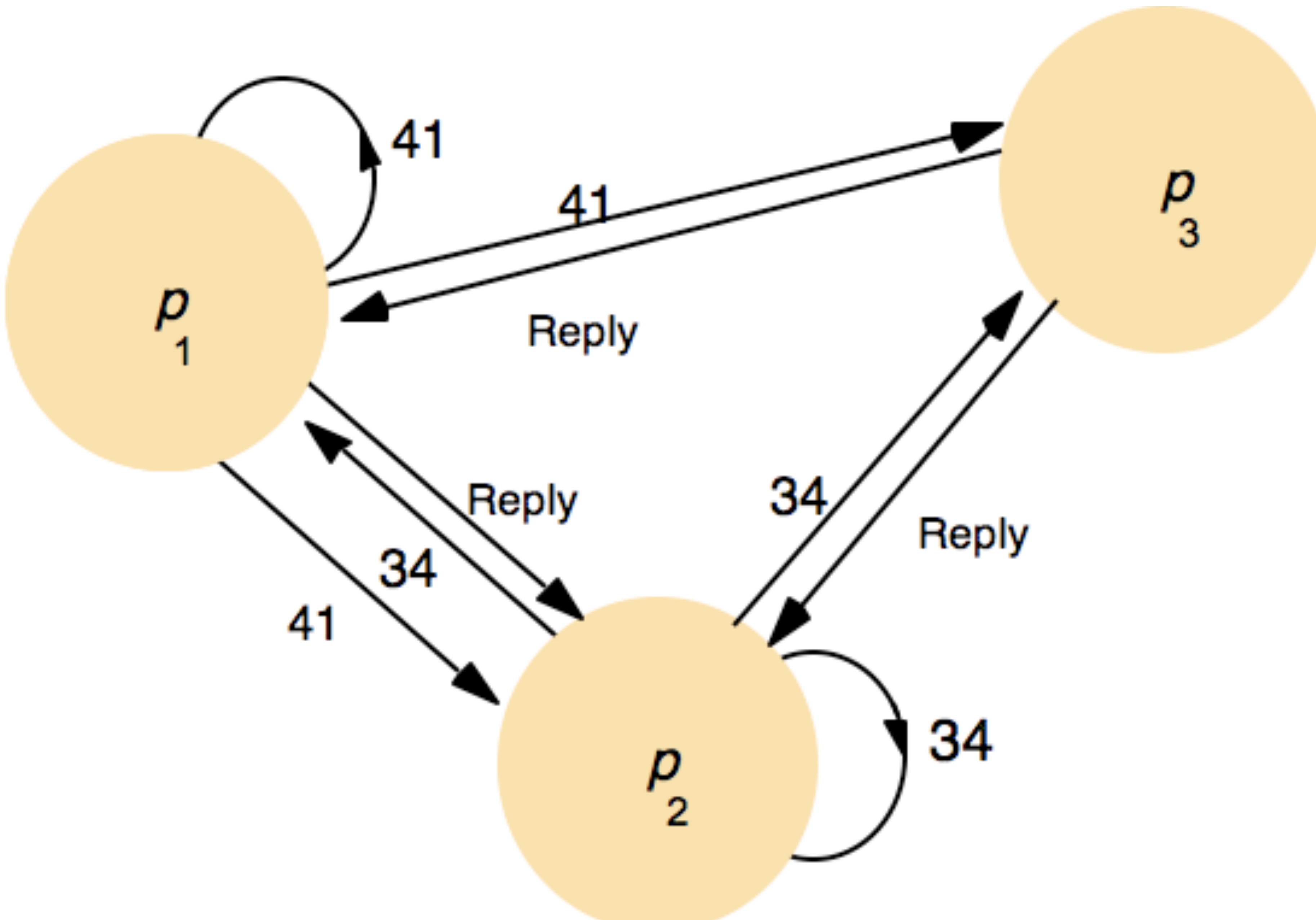
# [Ricart and Agrawala's Algorithm] Example

- However, $p_1$ finds that $p_2$'s request has a lower timestamp than that of its own request (34 < 41) and so replies immediately



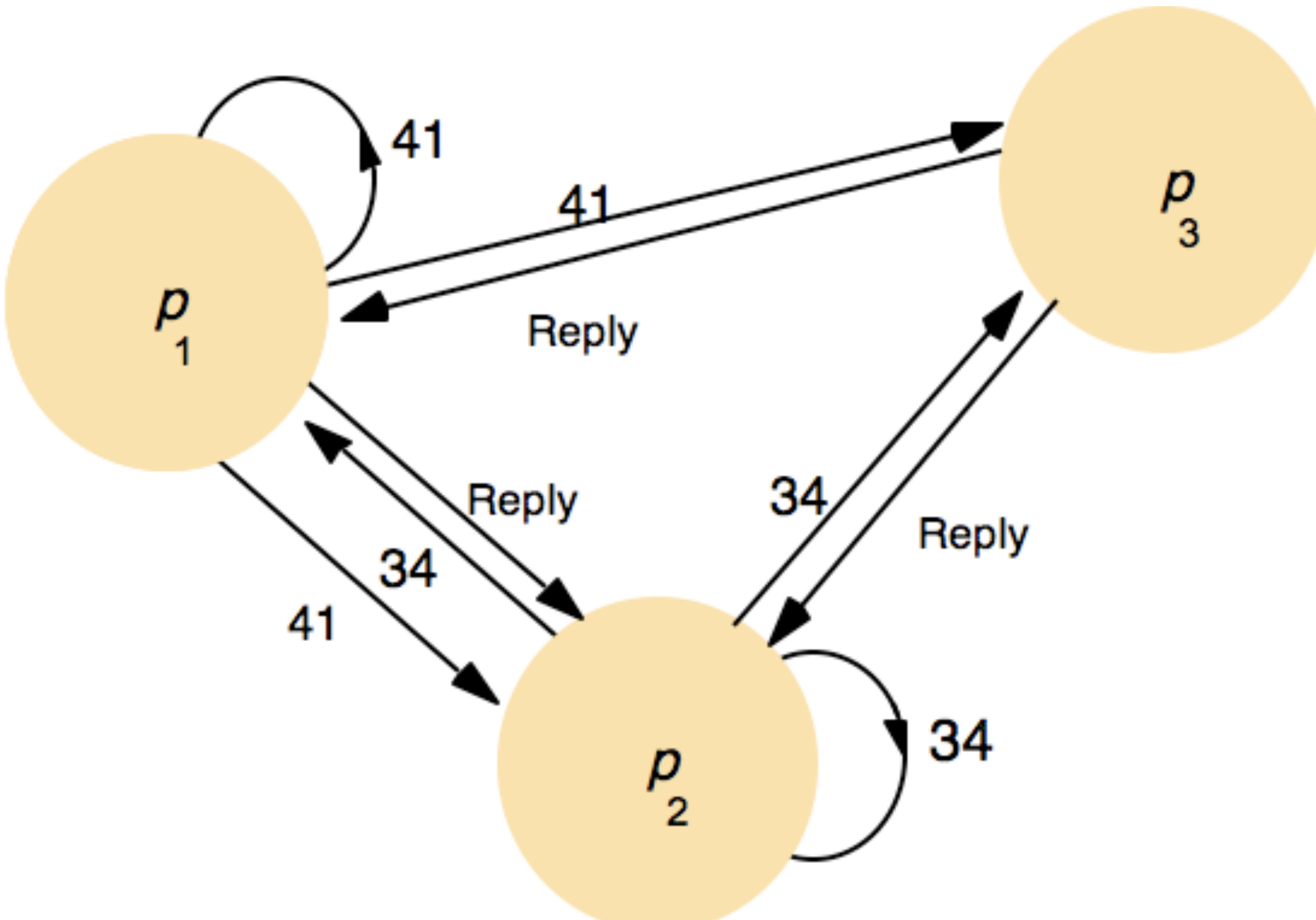
# [Ricart and Agrawala's Algorithm] Example

- On receiving the 2nd reply, $p_2$ can enter the CS



# [Ricart and Agrawala's Algorithm] Example

- When $p_2$ exits the CS, it will reply to $p_1$'s request and so grant it entry



# Performance of the Ricart-Agrawala's Algorithm

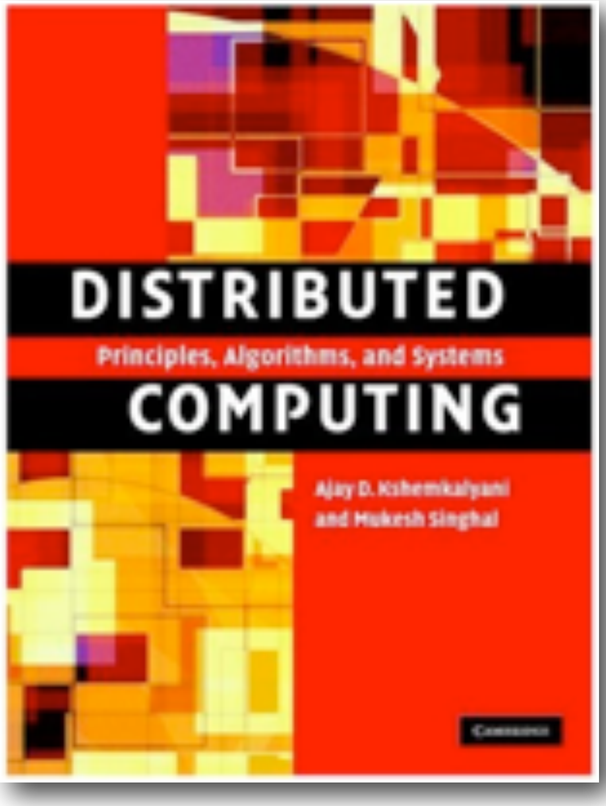
- Gaining entry takes 2(N-1) messages:
  - N-1 to multicast the request
  - followed by N-1 replies
- The client delay in requesting entry is a round-trip time
- The synchronization delay is 1 message transmission time
- Ricart and Agrawala refined the algorithm so that it requires N messages to obtain entry in the worst (and common) case
  [Raynal, M. (1988). *Distributed Algorithms and Protocols*. Wiley]

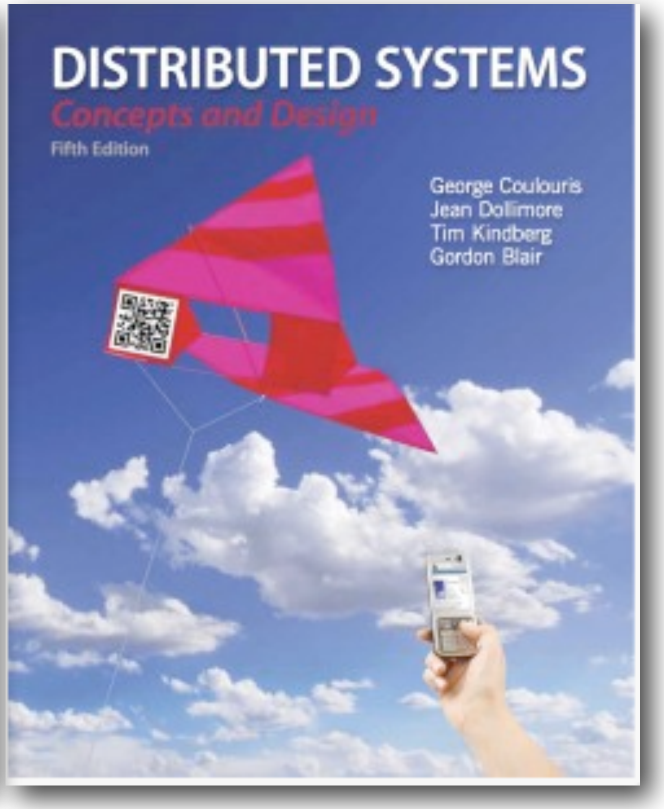
# Homework

- Ricart and Agrawala's Algorithm: prove that the algorithm achieves the safety property ME1
  - hint: proof by contradiction
- Verify, in a similar way, that the algorithm also meets requirements ME2 and ME3.

# Distributed Mutual Exclusion

## Quorum-Based ME Algorithms



# Quorum-Based Algorithms

- Each process requests permission to execute the CS from a subset of processes (QUORUM)

- The quorums are formed in such a way that when two processes concurrently request access to the CS
    - at least one process receives both the requests
    - this process is responsible to make sure that only one request executes the CS at any time

# Quorum-Based Mutual Exclusion Algorithms

- Idea:
  - processes vote for one another to enter the CS
  - a process can vote only one process per session
  - a "candidate" process must collect sufficient votes to enter the CS
    - a process does **NOT** need permission from ALL other processes, but only from a **SUBSET of the processes (QUORUM)**
- Intersection property: for every quorum $V_i$, $V_j \subseteq \{p_1, p_2, ..., p_N\}$, $V_i \cap V_j \neq \emptyset$
  - Example: {2, 5, 7} and {5, 7, 9} are suitable quorums, {1, 2, 3} and {5, 7, 9} are not suitable quorums
- Algorithms basically differ in *how the quorum is constructed*

# Simple Quorum-Based ME Algorithm

- A simple protocol works as follows:
  - let $p_i$ be a process in quorum $V_i$
  - if $p_i$ wants to invoke mutual exclusion, it requests permission from all processes in its quorum $V_i$
    (every process does the same to invoke mutual exclusion)
  - due to the Intersection property, quorum $V_i$ contains at least one process that is common to any other quorums
  - these common processes send permission (i.e., vote) to only one process at any time
  - Thus, mutual exclusion is guaranteed

# Maekawa's Algorithm: Quorums

- The quorums are constructed to satisfy the following conditions:

M1 $\forall i \; \forall j : i \neq j, 1 \leq i, j \leq N$, then $V_i \cap V_j \neq \emptyset$

M2 $\forall i : 1 \leq i \leq N$, then $p_i \in V_i$

necessary for correctness

M3 $\forall i : 1 \leq i \leq N$, then $|V_i| = K$

M4 any process $p_j$ is contained in K number of $V_i$s, $1 \leq i, j \leq N$

desiderable features

- Optimal solution: $N = K(K - 1) + 1$, which gives $K = \sqrt{N}$

# Maekawa's Algorithm [1985]

**On initialization**
state := RELEASED;
voted := FALSE;

**For $p_i$ to enter the critical section**
state := WANTED;
Multicast REQUEST to all processes in $V_i$;
Wait until (number of replies received = K);
state := HELD;

**On receipt of a REQUEST from $p_i$ at $p_j$**
**if** (state = HELD or voted = TRUE)
**then**
queue request from $p_i$ without replying;
**else**
send REPLY to $p_i$;
voted := TRUE;
**end if**

**For $p_i$ to exit the critical section**
state := RELEASED;
Multicast RELEASE to all processes in $V_i$;

**On receipt of a RELEASE from $p_i$ at $p_j$**
**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**

# Correctness Theorem

- *Maekawa's algorithm achieves mutual exclusion.*

- Proof: homework

# Performance of Maekawa's Algorithm

- The size of each quorum is $\sqrt{N}$

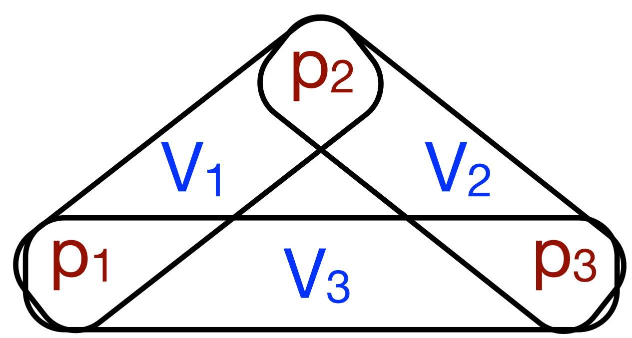
➡ The bandwidth utilization is $3\sqrt{N}$ messages per CS execution

  - $2\sqrt{N}$ messages per entry to the CS ($\sqrt{N}$ REQUEST and $\sqrt{N}$ REPLY)
  - $\sqrt{N}$ messages per exit

- The client delay in requesting entry is a round-trip time
- The synchronization delay is a round-trip time

# A Problematic Scenario

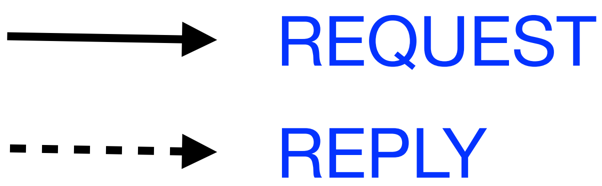
- Consider processes $p_1$, $p_2$ and $p_3$ with $V_1 = \{p_1, p_2\}$, $V_2 = \{p_2, p_3\}$, $V_3 = \{p_1, p_3\}$

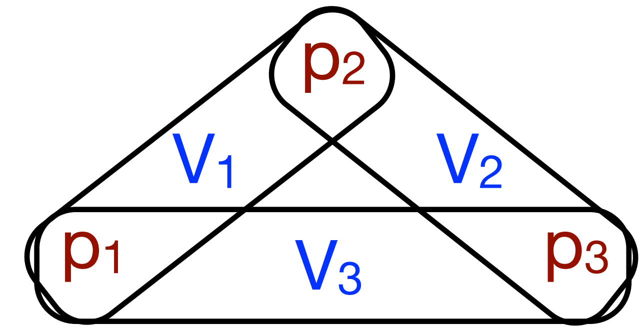


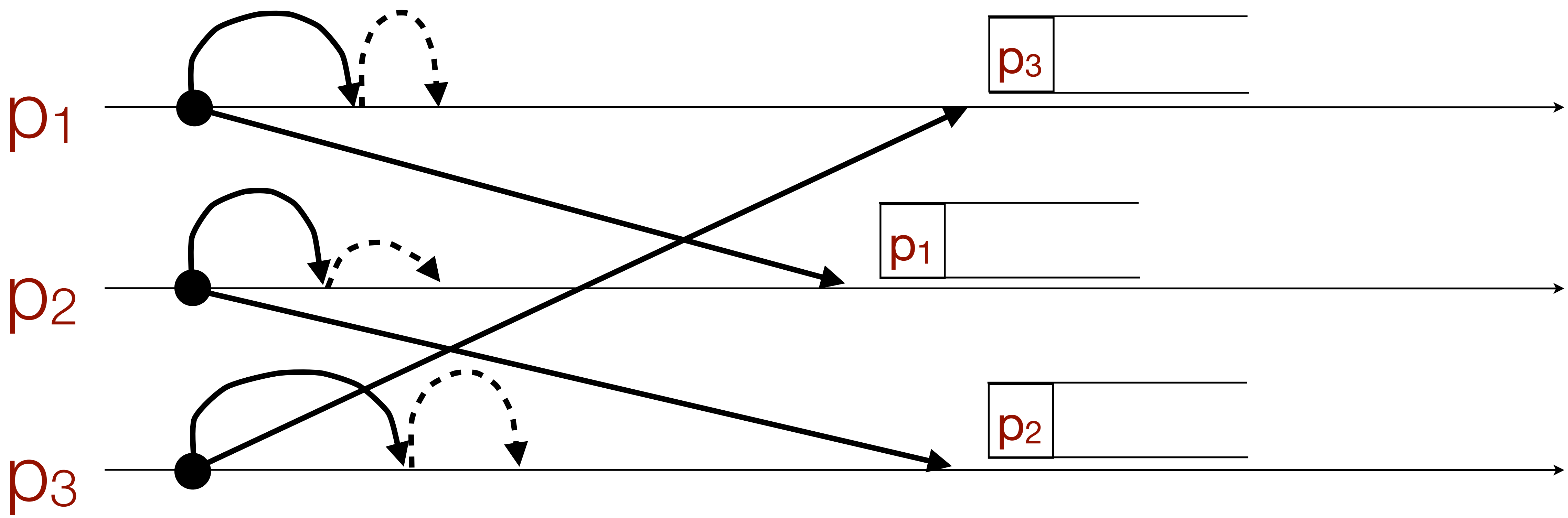

- If the processes *simultaneously* request entry to the CS, then the following scenario is possible:
  - $p_1$ is a candidate in $V_1$, waiting for $p_2$'s REPLY
  - $p_2$ is a candidate in $V_2$, waiting for $p_3$'s REPLY
  - $p_3$ is a candidate in $V_3$, waiting for $p_1$'s REPLY

DEADLOCK!

# Deadlock Scenario




- Each process has received one out of two replies, and none can proceed!

# Solving the Deadlock Problem

- Intuition: Maekawa's algorithm can deadlock because a process is exclusively locked by other processes and requests are not prioritised by their timestamps

- The algorithm can be adapted so that it becomes deadlock-free

- IDEA: in the adapted protocol, processes queue outstanding requests in happened-before order, so that requirements ME3 is also satisfied

- See paper:

  B. Sanders.
  **The Information Structure of Distributed Mutual Exclusion Algorithms**
  *ACM Transactions on Computer Systems*, Vol. 5, No. 3, pp. 284-99, 1987.

# Fault Tolerance

- What happens when messages are lost?
- What happens when a process crashes?

➡ None of the algorithms would tolerate the loss of messages, *if the channels were unreliable*

- Ring-based algorithm: cannot tolerate a crash failure of any single process
- Central server algorithm: can tolerate the crash failure of a client process that neither holds nor has requested the token
- Ricart-Agrawala algorithm: can be adapted to tolerate the crash failure of such a process, by taking it to grant all requests implicitly
- Maekawa's algorithm: can tolerate some process crash failures: if a crashed process is not in a voting set that is required, then its failure will not affect the other processes