Coordination and Agreement

Web Applications and Services

Spring Term

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Contents

- Distributed Mutual Exclusion
- Consensus

Distributed Mutual Exclusion

- Distributed processes need to coordinate their activities
- Mutual exclusion is required, when processes share resources, to prevent interference and ensure consistency
- Shared resources may reside on a server, or a collection of peer processes must coordinate their accesses amongst themselves
- An asynchronous distributed system of N processes $p_i, i = 1, 2, \ldots N$ that do not share variables – communicate through messaging

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Distributed Mutual Exclusion

- Application-level protocol for executing a critical section (CS)
  - `enter()` (may block), `resourceAccess()`, `exit()`
- Essential requirements for mutual exclusion

1. *Safety*: at most one process may execute in the CS at a time
2. *Liveness*: requests to enter and exit the CS <u>eventually succeed</u>
3. *Happened-before ordering:* if one request to enter the CS happened-before another, then entry to the CS is granted in that order

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Distributed Mutual Exclusion

- Requirement 2 (i.e., *liveness*) implies freedom from deadlock and starvation
- Requirement 3 is about fairness: if all requests are related by happened-before ordering, then <u>it is not possible</u> for a process to enter the CS more than once while other waits to enter
- Evaluation criteria
  - number of messages sent for *enter* and *exit* operation
  - synchronisation delay (p_1 exiting and p_2 entering)

Central Server Algorithm

- A process sends a request message to the server and waits for a permission token (i.e., the reply)
- The server replies immediately, if no other process has the token at the time of the request, or queues the request if token is given
- When a process exits the CS, it sends the token back to the server
- If the queue of waiting processes is not empty, the server chooses the oldest entry in the queue, removes it and replies to the corresponding process

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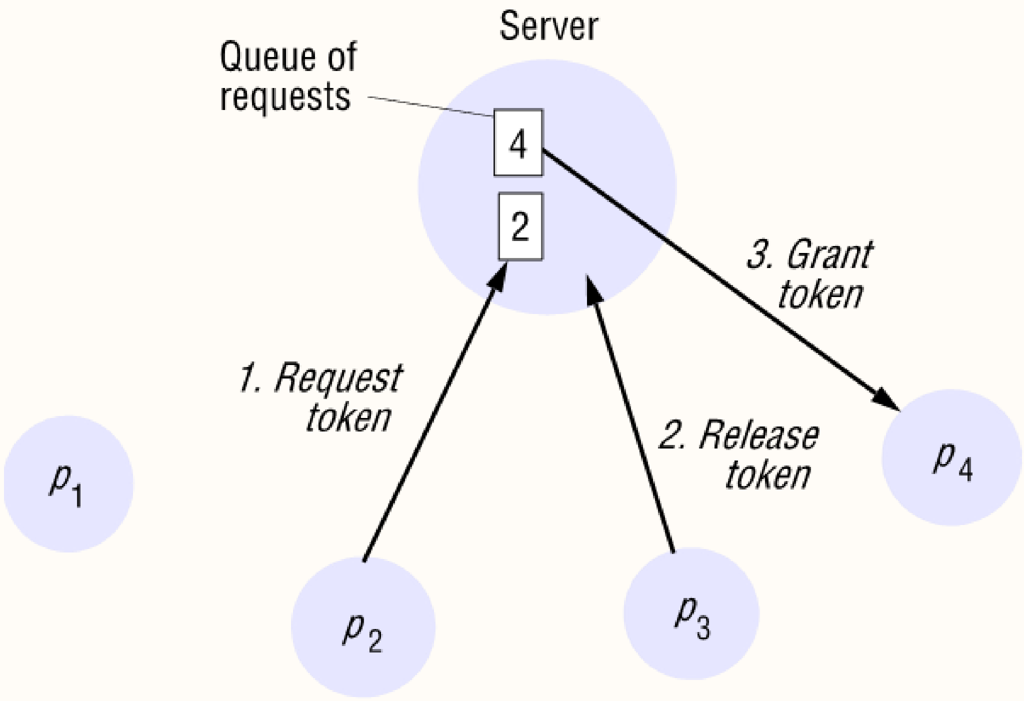
Central Server Algorithm

- *safety* and *liveness* requirements are met
- *happened-before ordering* requirement isn't
- Entering the CS takes two messages
- Exiting the CS takes one message
- Synchronization delay is a round-trip
- Failures?
- How to (s)**elect** the server?



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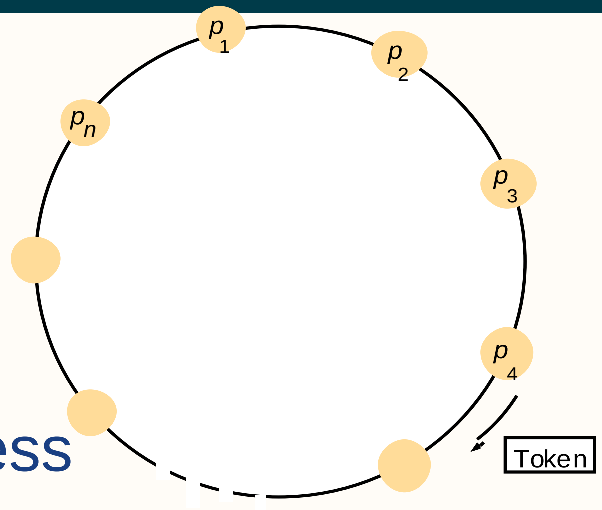
Ring-based Algorithm



- No Central Server
- *N* processes arranged in a logical ring
- Each process has a communication channel to the next process
- A token is passed from process to process in a single direction
- If no access to CS is required, token is passed to next process
- A process that needs access to the CS waits for the token

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Ring-based Algorithm

- Upon exiting the CS, the token is passed to the next process
- *liveness* and *safety* are met but <u>not</u> the *happened-before ordering*
  - Processes exchange messages independently of the rotation of the token
- Bandwidth is constantly consumed
  - Processes send messages around the ring even when no process requires access
- Delay to enter
  - 0 to N messages

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Ring-based Algorithm

- Delay to exit
  - Only 1 message
- Synchronization delay
  - 1 to N messages

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Mutual Exclusion with Multicast and Logical Clocks

- Processes multicast a request message
  - enter only when all the other processes have replied
- Each process keeps a *Lamport Virtual Clock*
  - updated for internal events and when receiving messages
- Messages requesting entry are of the form $< T, p_i >$
- Each process records its state of being outside the CS (*RELEASED*), wanting entry (*WANTED*) or being in the CS (*HELD*) in a variable

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Mutual Exclusion with Multicast and Logical Clocks

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;

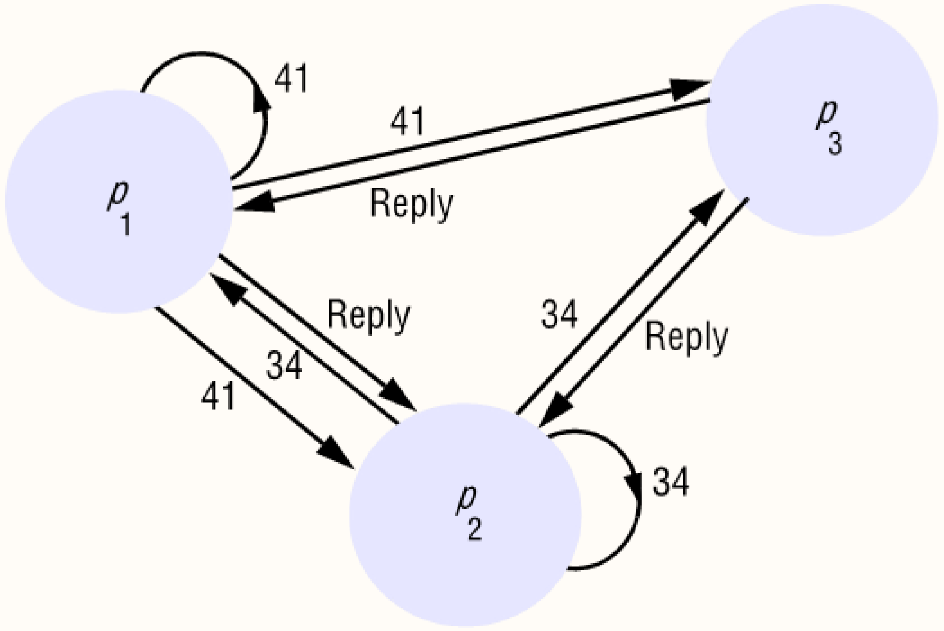
Request processing deferred here

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;

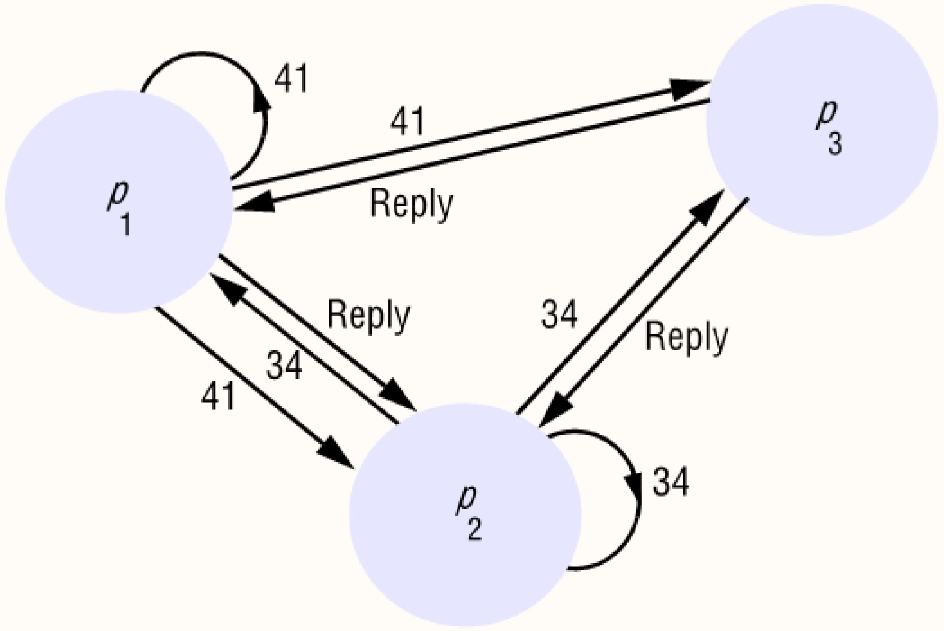
Mutual Exclusion with Multicast and Logical Clocks

- *Safety*
  - If it were possible for two processes to enter the CS at the same time, both of those processes would have to have replied to the other ($< T_i, p_i >$ are causally ordered)
- *Liveness*
  - when exiting the CS, a process replies to all pending requests
- *Happened-before ordering*
  - Lamport Clocks



Mutual Exclusion with Multicast and Logical Clocks

- Delay to enter
  - *2*(N – 1)* messages or *N* if native multicast is supported
- Delay to exit
  - up to *N - 1*
- Synchronization delay
  - 1 message (i.e., one process waits for only 1 message)



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Consensus

- A collection of processes p_i $(i = 1, 2, \ldots N)$ communicating by message passing
- Requirement: consensus can be reached even in the presence of faults
  - communication is reliable
  - processes may fail (crash or Byzantine (i.e., arbitrary) process failures)
    - up to some number f of the N processes are faulty

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Consensus

- To reach consensus, every process p_i begins in the <u>undecided</u> state and proposes a single value v_i, drawn from a set D
- Processes communicate by exchanging values
- In the end, each process sets the value of a decision variable d_i and enters the <u>decided</u> state

Consensus

- The requirements of a consensus algorithm is that the following conditions should hold for its every execution
  - Termination
    - Eventually each correct process sets its decision variable
  - Agreement
    - The decision value of all correct processes is the same
  - Integrity
    - If all correct processes proposed the same value, then any correct process in the decided state has chosen that value

Consensus

- Consensus in the absence of failures is straightforward!
  - Each process reliably multicasts a proposed value and waits for all other values
  - Selects the decided value using an appropriate method (majority, min or max)

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Consensus in a Synchronous System

- Up to f of the N processes may exhibit crash failures. Timeouts are used to detect.

Algorithm for process $p_i \in g$; algorithm proceeds in $f+1$ rounds

On initialization

$Values_i^1 := \{v_i\}$; $Values_i^0 = \{\}$;

In round r $(1 \le r \le f+1)$

B-multicast(g, $Values_i^r - Values_i^{r-1}$); // Send only values that have not been sent

$Values_i^{r+1} := Values_i^r$;

while (in round r)

{

On B-deliver(V_j) *from some* p_j

$Values_i^{r+1} := Values_i^{r+1} \cup V_j$;

}

After $(f+1)$ *rounds*

Assign $d_i = minimum(Values_i^{f+1})$;

Consensus in a Synchronous System

- All correct processes will have all proposed values to decide in the end
- If a process failed while multicasting its value either one or none of the processes will circulate this value
- Termination is obvious, i.e., the system is synchronous
- To check the correctness of the algorithm, we must show that each process arrives at the same set of values at the end of the final round

Consensus in a Synchronous System

- Agreement and integrity will then follow
- Assume that two processes differ in their final set of values
- Some correct process p_i possesses a value v that another correct process p_j doesn't
- <u>Only possible explanation</u>: some other process p_k sent v to p_i and then crashed

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Consensus in a Synchronous System

- But why p_k possesses v but not p_i? Another process crashed in the previous round
- We assumed f crash failures and we have $f + 1$ rounds – a contradiction

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Impossibility in asynchronous systems

- The assumption above was that message exchanges take place in rounds
    - …processes are entitled to timeout and assume that a faulty process has not sent them a message within the round, because the maximum delay has been exceeded
- No algorithm can <u>guarantee</u> to reach consensus in an asynchronous system, even with one process crash failure
  - The proof is beyond the scope of this module

Impossibility in asynchronous systems

- In an asynchronous system, processes can respond to messages at arbitrary times, so a crashed process is indistinguishable from a slow one
- Note the word <u>guarantee</u>!
- Masking faults
- Consensus using failure detectors
  - Ignore processes that are considered failed (even if they are not)
  - Large timeouts

Next Lecture ...

- ✓ Introduction
- ✓ HTTP, Caching, and CDNs
- ✓ Views
- ✓ Templates
- ✓ Forms
- ✓ Models
- ✓ Security
- ✓ Transactions
- ✓ Remote Procedure Call
- ✓ Web Services
- ✓ Time
- ✓ Elections and Group Communication
- ➢ **Coordination and Agreement**

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