CSE 486/586 Distributed Systems

Mutual Exclusion

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Recap: Consensus

- On a synchronous system
  - There's an algorithm that works.
- On an asynchronous system
  - It's been shown (FLP) that it's impossible to guarantee.
- Getting around the result
  - Masking faults
  - Using failure detectors
  - Still not perfect
- Impossibility Result
  - Lemma 1: schedules are commutative
  - Lemma 2: some initial configuration is bivalent
  - Lemma 3: from a bivalent configuration, there is always another bivalent configuration that is reachable.

Why Mutual Exclusion?

- Bank Servers in the Cloud: Think of two simultaneous deposits of $10,000 into your bank account, each from one ATM connected to a different server.
  - Both ATMs read initial amount of $1000 concurrently from the bank's cloud server
  - Both ATMs add $10,000 to this amount (locally at the ATM)
  - Both write the final amount to the server
  - What's wrong?
- The ATMs need mutually exclusive access to your account entry at the server (or to execution of the code that modifies the account entry)

Mutual Exclusion

- Critical section problem
  - Piece of code (at all clients) for which we need to ensure at most one client is executing it at any point of time.
- Solutions:
  - Semaphores, mutexes, *etc.* in single-node OS
  - Message-passing-based protocols in distributed systems:
    - enter() the critical section
    - AccessResource() in the critical section
    - exit() the critical section
- Distributed mutual exclusion requirements:
  - Safety – At most one process may execute in CS at any time
  - Liveness – Every request for a CS is eventually granted
  - Ordering (desirable) – Requests are granted in the order they were made

Mutexes

- Synchronize access to common data structures between multiple threads

  Allows two operations:

```
lock()
  forever: // each loop iteration is atomic
    if lock not in use:
      label lock in use
      break
unlock()
  label lock not in use // atomic
```

Semaphores

- Synchronize access to common data structures between multiple threads

  Initialize with `S = 1`, allows two operations:

  `wait(S)` (or `P(S)`):

```
forever: // each loop iteration is atomic
  if S > 0:
    S--
    break
```

  `signal(S)` (or `V(S)`):

```
S++      // atomic
```

How Are Mutexes Used?

```
mutex L = UNLOCKED

ATM1:
  lock(L) // enter
          // critical section
  obtain bank amount
  add in deposit
  update bank amount
  unlock(L) // exit
```

```
extern mutex L;

ATM2:
  lock(L); // enter
           // critical section
  obtain bank amount;
  add in deposit;
  update bank amount;
  unlock(L); // exit
```

Distributed Mutual Exclusion Performance Criteria

- Bandwidth: the total number of messages sent in each entry and exit operation.
- Client delay: the delay incurred by a process at each entry and exit (when no other process is in, or waiting)
  - (We will prefer mostly the entry operation.)
- Synchronization delay: the time interval between one process exiting the critical section and the next process entering it (when there is only one process waiting)
- Throughput: the rate at which the processes can access the critical section, *i.e.*, *x* processes per second
- (these definitions are more correct than those in the textbook)

Assumptions/System Model

- We make the following assumptions:
  - Each pair of processes is connected by reliable channels.
  - Messages are eventually delivered to recipient's input buffer in FIFO order.
  - Processes do not fail. (why?)
- Four algorithms
  - Centralized control
  - Token ring
  - Ricart and Agrawala
  - Maekawa

1. Centralized Control

- A central coordinator (master or leader)
  - Is elected (next lecture)
  - Grants permission to enter CS & keeps a queue of requests to enter the CS.
  - Ensures only one process at a time can access the CS
  - Has a special token per CS
- Operations (token gives access to CS)
  - Enter: Send a request to the coordinator & wait for token.
  - Exit: Send a message to the coordinator to release the token.
  - Upon receipt of a request, if no other process has the token, the coordinator grants the token; otherwise, it queues the request.
  - Upon receipt of a release message, the coordinator removes the oldest entry in the queue (if any) and grants the token.

1. Centralized Control

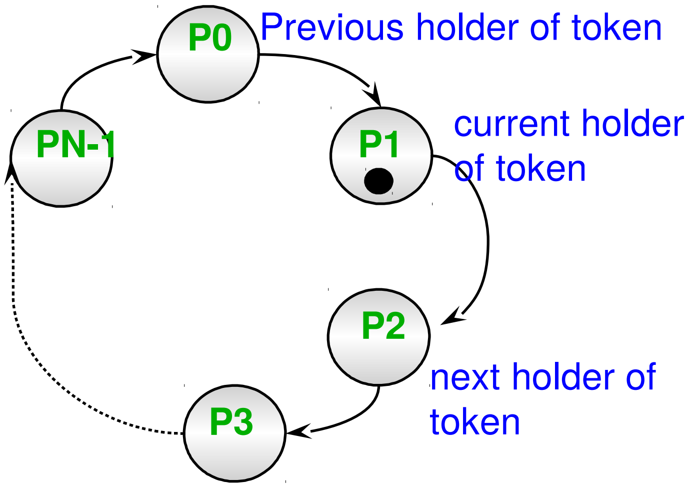
- Safety, liveness, ordering?
- Bandwidth?
  - Requires 3 messages per entry + exit operation.
- Client delay:
  - one round trip time (request + grant)
- Synchronization delay
  - one round trip time (release + grant)
- The coordinator becomes performance bottleneck and single point of failure.

2. Token Ring Approach

- Processes are organized in a logical ring: p_i has a communication channel to $p_{(i+1 \bmod N)}$
- Operations:
  - Only the process holding the token can enter the CS.
  - To enter the critical section, wait passively for the token.
  - When in CS, hold on to the token.
  - To exit the CS, forward the token on.
  - If a process does not want to enter the CS when it receives the token, it forwards the token its neighbor.

2. Token Ring Approach

- Features:
  - Safety & liveness, ordering?
  - Bandwidth: 1 message per exit
  - Client delay: 0 to N message transmissions.
  - Synchronization delay between one process's exit from the CS and the next process's entry is between 1 and N-1 message transmissions.



3. Ricart & Agrawala's Algorithm

- Processes multicast a request to enter a CS
  - Once all processes reply positively, the requester can enter
- Use a Lamport clock and process id for ordering
  - Messages requesting entry are of the form <T,p_i>
    - T is the sender's Lamport clock timestamp
    - p_i is the sender's identity (used to break ties in T)

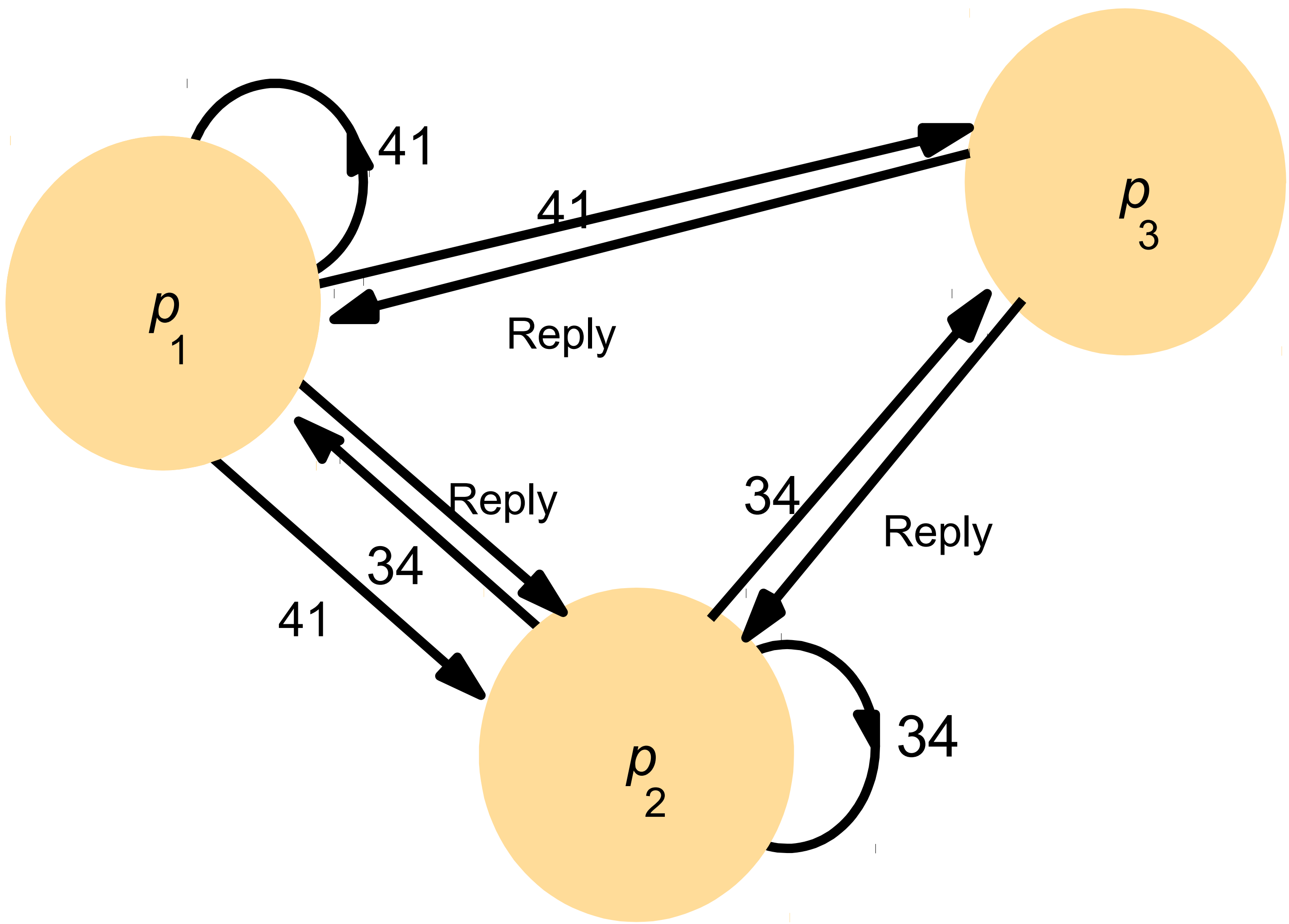
3. Ricart & Agrawala's Algorithm

- To enter the CS
  - set state to *wanted*
  - multicast request to all processes (including timestamp)
  - wait until all processes reply
  - change state to *held* and enter the CS
- On receipt of a request $<T_i, p_i>$ at p_j:
  - if (state = *held*) or (state = *wanted* & $(T_j, p_j)<(T_i,p_i)$), enqueue request
  - else "reply" to pi
- On exiting the CS
  - change state to *release* and reply to all queued requests.

3. Ricart & 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;

3. Ricart & Agrawala's Algorithm

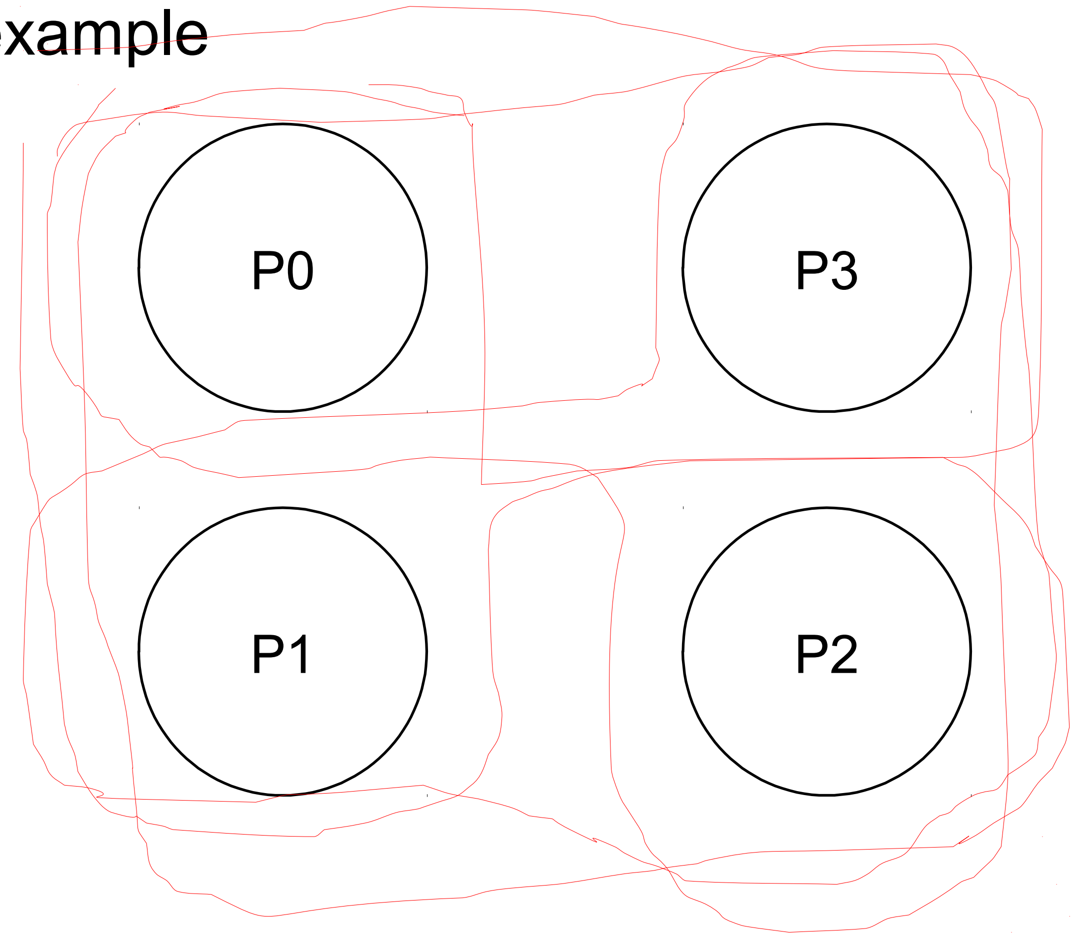


Analysis: Ricart & Agrawala

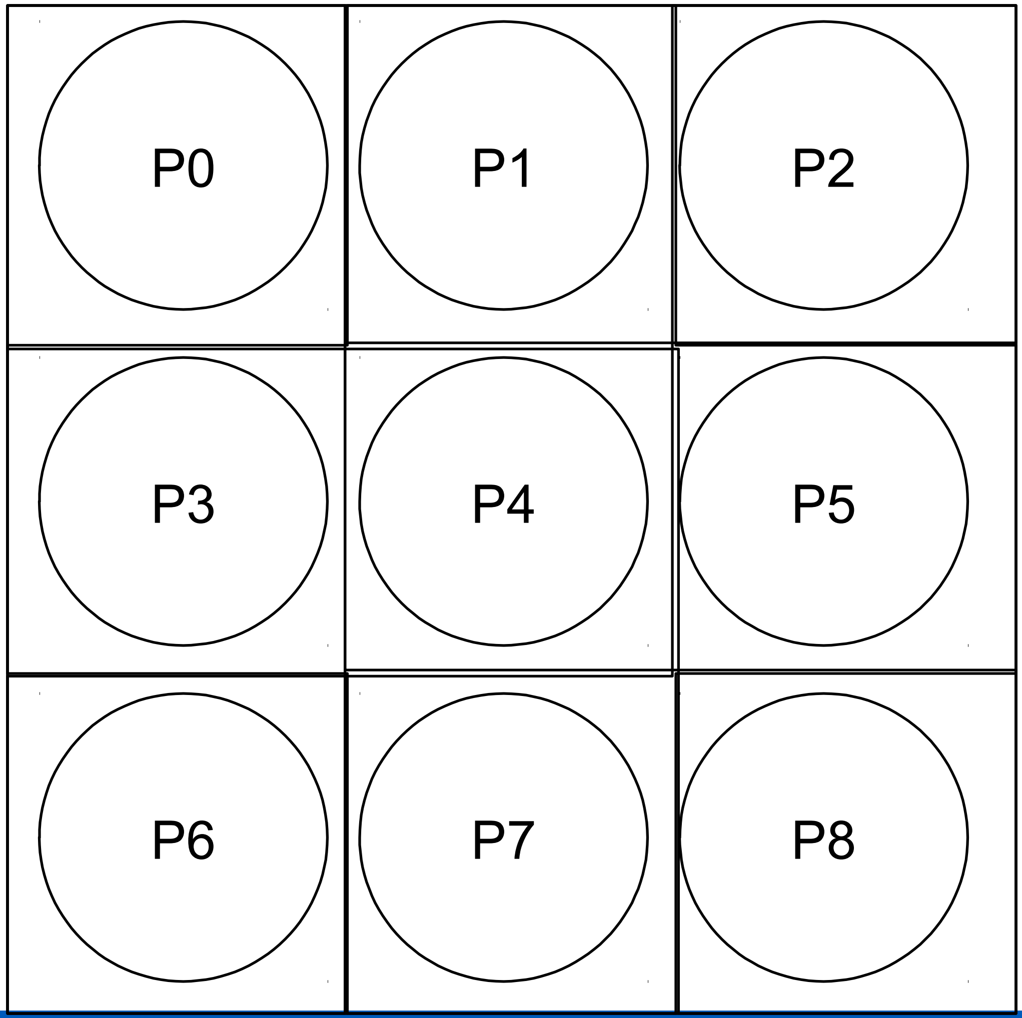
- Safety, liveness, and ordering?
- Bandwidth:
  - 2(N-1) messages per entry operation
  - N-1 unicasts for the multicast request + N-1 replies
  - N-1 unicast messages per exit operation
- Client delay
  - One round-trip time
- Synchronization delay
  - One message transmission time

4. Maekawa's Algorithm

- Simple example



4. Maekawa's Algorithm



4. Maekawa's Algorithm

- Observation: no need to have all peers reply
- A subset of peers is sufficient as long as all subsets overlap.
- Voting set: a subset of processes that grant permission to enter a CS
- Voting sets are chosen so that for any two processes, p_i and p_j, their corresponding voting sets have at least one common process.
  - Each process p_i is associated with a voting set v_i (of processes)
  - Each process belongs to its own voting set
  - The intersection of any two voting sets is non-empty
  - Each voting set is of size K
  - Each process belongs to M other voting sets

4. Maekawa's Algorithm

- Multicasts messages to a (voting) subset of processes
  - To access a critical section, p_i requests permission from all other processes in its own voting set v_i
  - Voting set member gives permission to only one requestor at a time, and queues all other requests
  - Guarantees safety
  - Maekawa showed that $K=M=\sqrt{N}$ works best
  - One way of doing this is to put N processes in a $\sqrt{N}$ by $\sqrt{N}$ matrix and take union of row & column containing p_i as its voting set.

Maekawa's Algorithm – Part 1

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

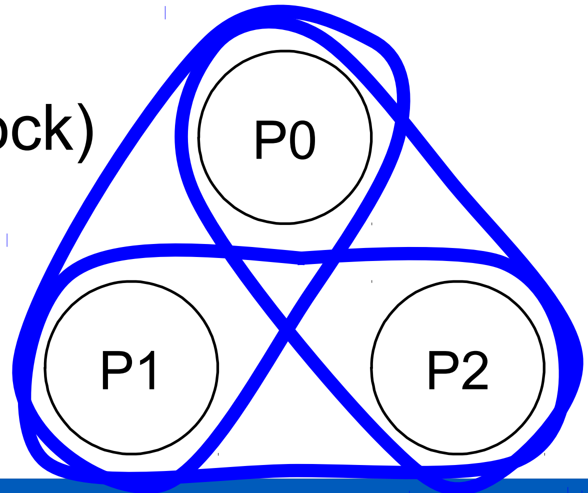
Maekawa's Algorithm – Part 2

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

Maekawa's Algorithm – Analysis

- Bandwidth: 2√N messages per entry, √N messages per exit
  - Better than Ricart and Agrawala's (2(N-1) and N-1 messages)
- Client delay: One round trip time
  - Same as Ricart and Agrawala
- Synchronization delay: One round-trip time
  - Worse than Ricart and Agrawala
- May not guarantee liveness (may deadlock)
  - How?



Summary

- Mutual exclusion
  - Coordinator-based token
  - Token ring
  - Ricart and Agrawala’s timestamp algorithm
  - Maekawa’s algorithm

References

- Textbook section 15.2. **Required Reading.**

Acknowledgements

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