Computer Science 425
Distributed Systems

CS 425 / ECE 428

Fall 2013

Indranil Gupta (Indy)

October 3, 2013

Lecture 12

Mutual Exclusion

Reading: Sections 15.2

Why Mutual Exclusion?

- **Bank's Servers in the Cloud: Think of two simultaneous deposits of $10,000 into your bank account, each from one ATM.**
  - 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?

Why Mutual Exclusion?

- **Bank's Servers in the Cloud: Think of two simultaneous deposits of $10,000 into your bank account, each from one ATM.**
  - **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 executing the code that modifies the account entry)**

Mutual Exclusion

- ***Critical section*** **problem: Piece of code (at all clients) for which we need to ensure there is at most one client executing it at any point of time.**
- **Solutions:**
  - **Semaphores, mutexes, etc. in single-node operating systems**
  - **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**

Refresher - Semaphores

- **To synchronize access of multiple threads to common data structures**
- **Semaphore S=1;**

  Allows two operations: wait and signal

  1. wait(S) (or P(S)):

```
while(1){ // each execution of the while loop is atomic
  if (S > 0)
     S--;
     break;
 }
```

  Each while loop execution and S++ are each atomic operations

  – how?

  2. signal(S) (or V(S)):

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

Refresher - Semaphores

- **To synchronize access of multiple threads to common data structures**
- **Semaphore S=1;**

Allows two operations: wait and signal

1. wait(S) (or P(S)):

enter()

```
while(1){ // each execution of the while loop is atomic
  if (S > 0)
    S--;
    break;
}
```

Each while loop execution and S++ are each atomic operations

– how?

2. signal(S) (or V(S)):

exit()

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

How are semaphores used?

One Use: Mutual Exclusion – Bank ATM example

```
semaphore S=1;

ATM1:
    wait(S); // enter
             // critical section
    obtain bank amount;
    add in deposit;
    update bank amount;
    signal(S); // exit
```

```
extern semaphore S;

ATM2
    wait(S); // enter
             // critical section
    obtain bank amount;
    add in deposit;
    update bank amount;
    signal(S); // exit
```

Distributed Mutual Exclusion: Performance Evaluation 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 operation (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)

- These translate into *throughput* -- the rate at which the processes can access the critical section, i.e., x processes per second.

(these definitions more correct than the ones in the textbook)

Assumptions/System Model

- For all the algorithms studied, we make the following assumptions:
  - Each pair of processes is connected by reliable channels (such as TCP).
  - Messages are eventually delivered to recipient in FIFO order.
  - Processes do not fail.

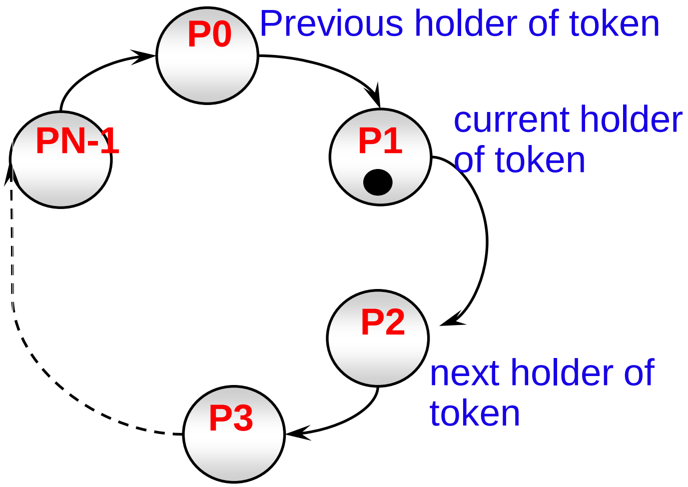
1. Centralized Control of Mutual Exclusion

- **A central coordinator (master or leader)**
  - **Is elected (which algorithm?)**
  - **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 message, which it can give to any process to access CS.**
- **Operations**
  - **To enter a CS Send a request to the coord & wait for token.**
  - **On exiting the CS Send a message to the coord to release the token.**
  - **Upon receipt of a request, if no other process has the token, the coord replies with the token; otherwise, the coord queues the request.**
  - **Upon receipt of a release message, the coord removes the oldest entry in the queue (if any) and replies with a token.**
- **Features:**
  - **Safety, liveness are guaranteed**
  - **Ordering also guaranteed (what kind?)**
  - **Requires 2 messages for entry + 1 messages for exit operation.**
  - **Client delay: one round trip time (request + grant)**
  - **Synchronization delay: 2 message latencies (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 and don't release it.**
  - **To exit the CS, send the token onto your neighbor.**
  - **If a process does not want to enter the CS when it receives the token, it simply forwards the token to the next neighbor.**

- **Features:**
  - **Safety & liveness are guaranteed**
  - **<u>Ordering</u> is not guaranteed.**
  - **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. Timestamp Approach: Ricart & Agrawala

- **Processes requiring entry to critical section multicast a request, and can enter it only when *all* other processes have replied positively.**
- **Messages requesting entry are of the form $<T,p_i>$, where T is the sender's timestamp (from a *Lamport* clock) and p_i the sender's identity (used to break ties in T).**
- **To enter the CS**
  - **set state to wanted**
  - **multicast "request" to all processes (including timestamp) – use R-multicast**
  - **wait until all processes send back "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 & $(T_j, p_j)<(T_i,p_i)$), // lexicographic ordering**

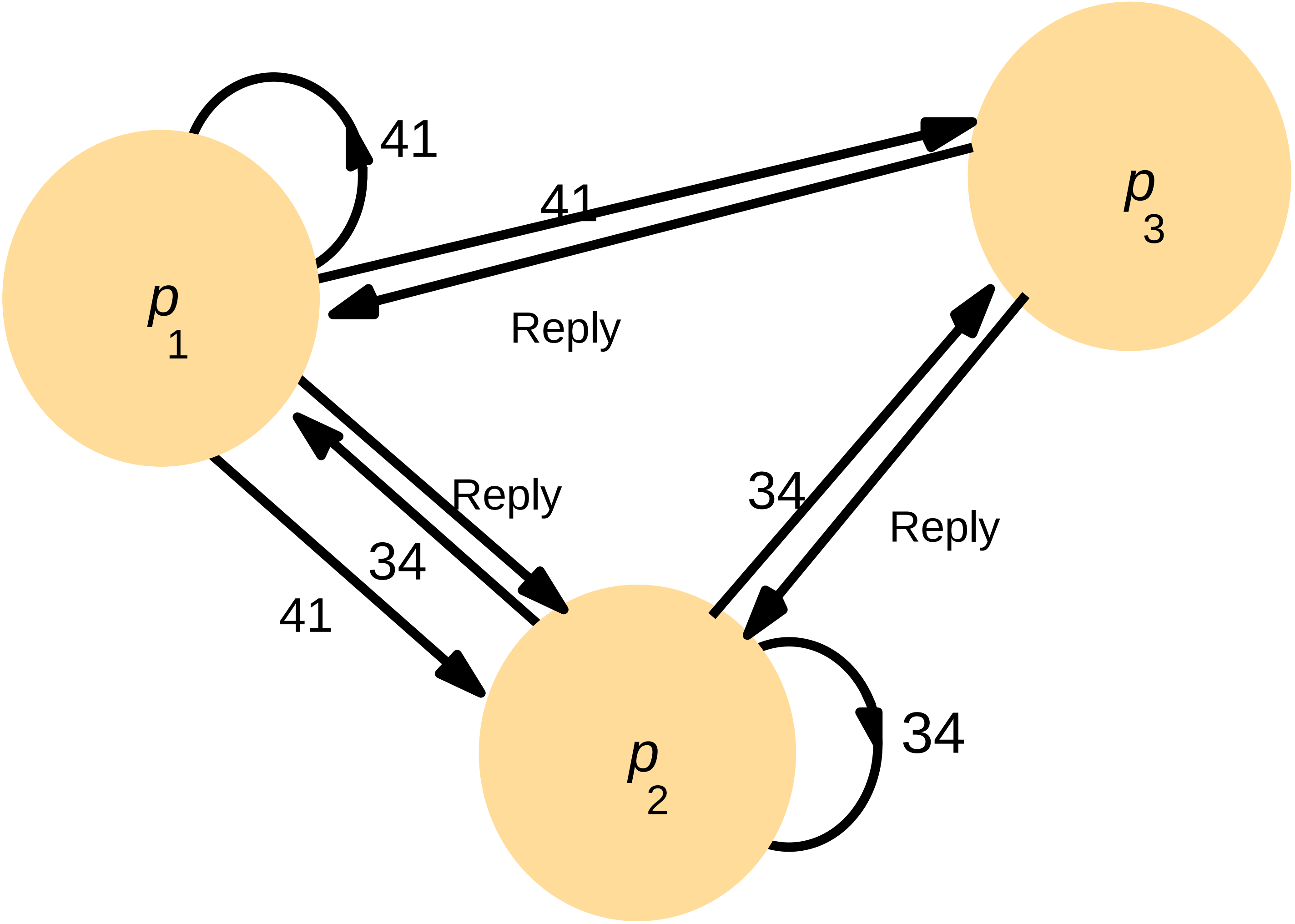
    enqueue request
  - **else "reply" to p_i**
- **On exiting the CS**
  - **change state to release and "reply" to *all* queued requests.**

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;
```

Ricart & Agrawala’s Algorithm



Analysis: Ricart & Agrawala

- Safety, liveness, and ordering (causal) are guaranteed
  - Why?
- Bandwidth: 2(N-1) messages per entry operation
  - N-1 unicasts for the multicast request + N-1 replies
  - N messages if the underlying network supports multicast
  - N-1 unicast messages per exit operation
    - 1 multicast if the underlying network supports multicast
- Client delay: one round-trip time
- Synchronization delay: one message transmission time

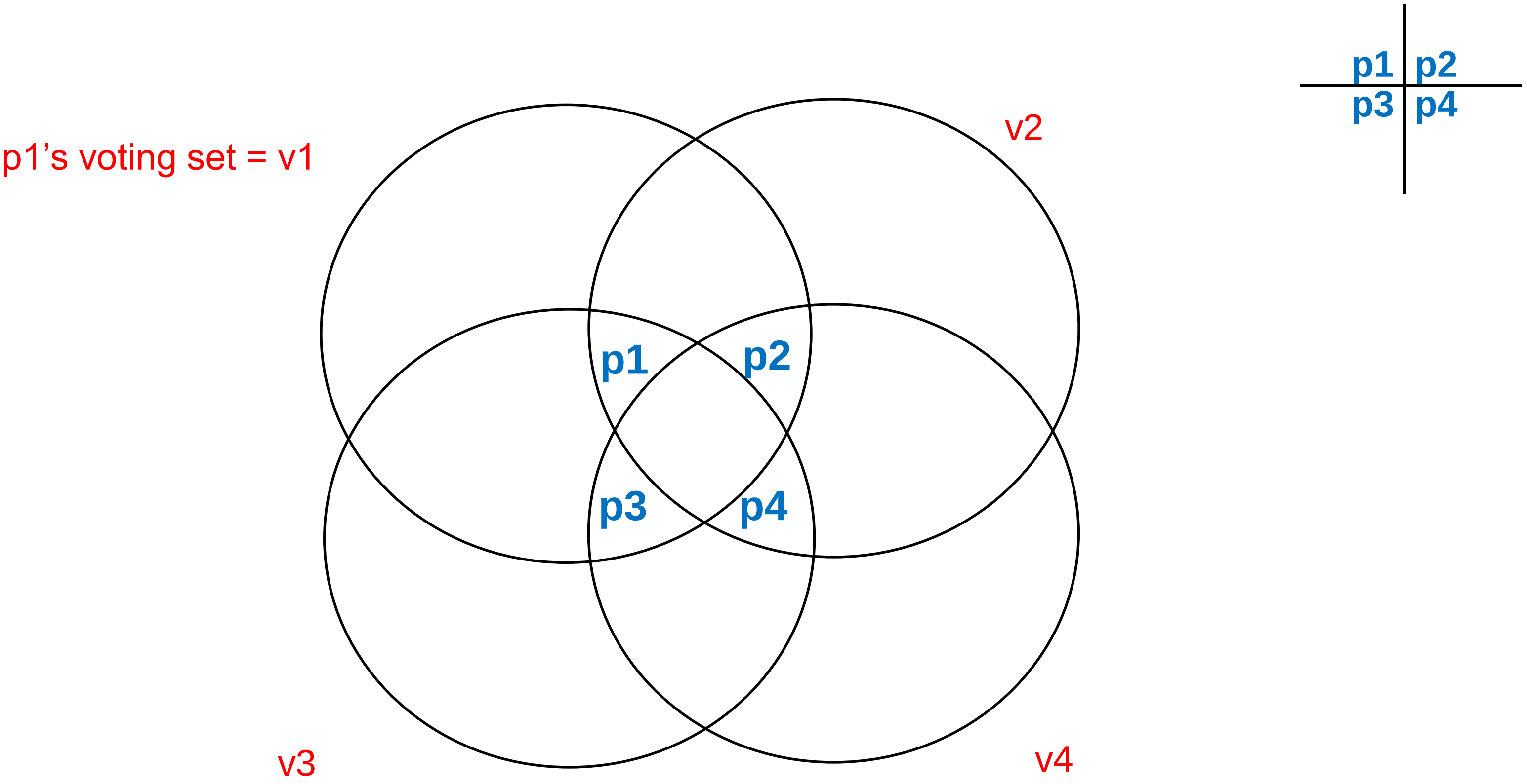
4. Timestamp Approach: Maekawa’s Algorithm

❖ Setup

- ☐ 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
- ☐ Maekawa showed that K=M=√N works best

One way of doing this is to put N processes in a √N by √N matrix and for each p_i, v_i = row + column containing p_i

Maekawa Voting Set with N=4



Timestamp Approach: Maekawa's Algorithm

- **Protocol**
  - ☐ **Each process *p_i* is associated with a *<u>voting set</u>* *v_i* (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**
  - ☐ **May not guarantee liveness (may deadlock)**

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 $V_i \cancel{- \{p_i\}}$;
    Wait until (number of replies received = $(K \cancel{- 1})$);
    state := HELD;
On receipt of a request from $p_i$ at $p_j$ $(i \cancel{\neq j})$
    if (state = HELD or voted = TRUE)
    then
        queue request from $p_i$ without replying;
    else
        send reply to $p_i$;
        voted := TRUE;
    end if
```

Continues on next slide

Maekawa’s Algorithm – Part 2

```
For $p_i$ to exit the critical section
    state := RELEASED;
    Multicast release to all processes in $V_i \cancel{- \{p_i\}}$;
On receipt of a release from $p_i$ at $p_j$ $(\cancel{i \neq j})$
    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 – Analysis

- 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
- Synchronization delay: 2 message transmission times

Summary and Important Announcements

- **Mutual exclusion**
  - **Semaphores review**
  - **Coordinator-based token**
  - **Token ring**
  - **Ricart and Agrawala’s timestamp algo.**
  - **Maekawa’s algo.**

- **MP2 due this Sunday @ 11.59 PM (10/6)**