Distributed Systems (5DV147)

Mutual Exclusion and Elections

Fall 2013

Processes often need to coordinate their actions

- Which process gets to access a shared resource?
- Has the master crashed? Elect a new one!

Distributed mutual exclusion

Motivation

- Is needed to coordinate access to a shared resource
  - Concurrent access to a shared resource is serialized

    … but the solution need to be based on message passing
- Three basic approaches
  - Token-based
  - Permission-based
  - Quorum-based

Assumptions

- The system is asynchronous, process do not fail, and message delivery is reliable
- N processes `p`$_i$ `(i=1, 2, …, N)` that do not share variables
  - `p`$_i$ access shared resources in a critical section
  - `p`$_i$`'s` are well behaved, finite time on the critical section

```
enter()
resourceAccesses()
exit()
```

Application level protocol for executing a critical section

Fairness

- Absence of starvation
- Order in which process enter critical section
  - No global clocks
  - Happened-before ordering:
    - it is not possible for a process to enter the critical section more than once while another waits to enter.

Essential requirements

<u>safety</u>: at most 1 process may enter the critical section at a time

<u>liveness</u>: requests to enter and exit the critical section eventually succeed

- Freedom of *deadlock* and *starvation*

<u>→ ordering</u>: if a request to enter the critical section *happened-before* another, then access is granted according to that order

Metrics for evaluation of algorithms

- Bandwidth consumed
  - Entry and exit operations
- Client delay
- Throughput of the system
  - Synchronization delay, one process exit and another one enters the critical section

Central Server

Send request to server, oldest process in queue gets access (a *token*), return token when done

- No process has token → reply (enter) immediately
- Otherwise → queue request

Oldest process in the queue gets token after released

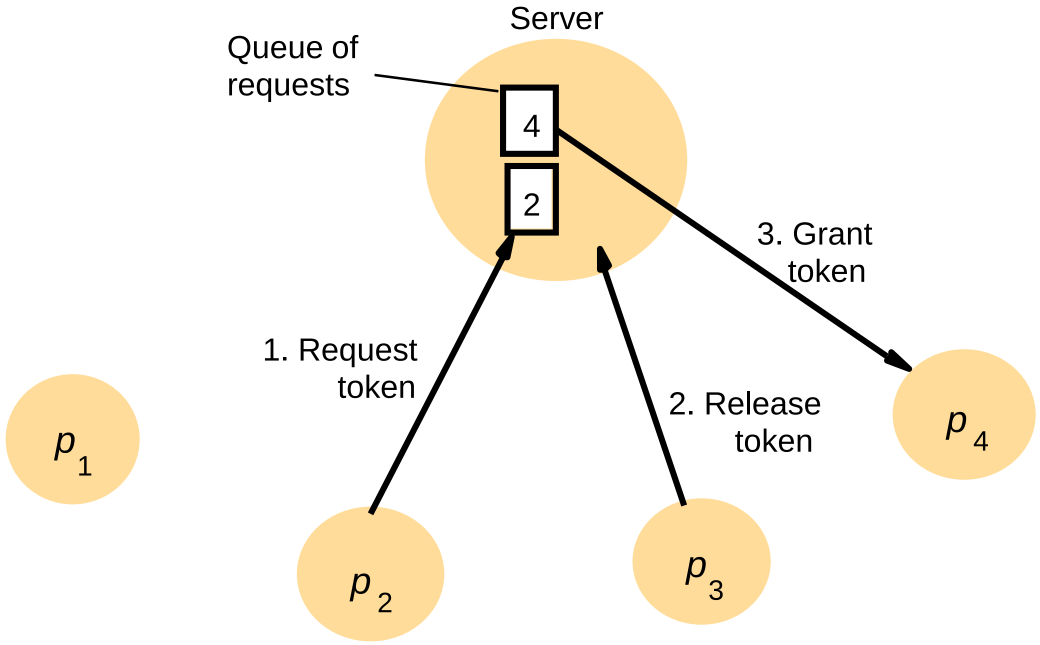


Figure adapted from Instructor's Guide for Coulouris, Dollimore, Kindberg and Blair, Distributed Systems: Concepts and Design Edn. 5 © Pearson Education 2012 – **Figure 15.2**

Properties

Safety? Yes!

Liveness? Yes (as long as server does not crash)

→ ordering? No! Why not?

Performance bottleneck

Single point of failure

Performance

Entering : 2 messages (request + grant)

Exiting : 1 message

Synch and client delay : 2 messages (release + grant)

Ring-based

Token is passed around a ring of processes

- Want access? Wait until token comes, and claim it (then pass the token along)
- Can't use the same token twice

- Can't estimate when a process will see a token
- Recovering from a process crash
  - Receipt acknowledgments

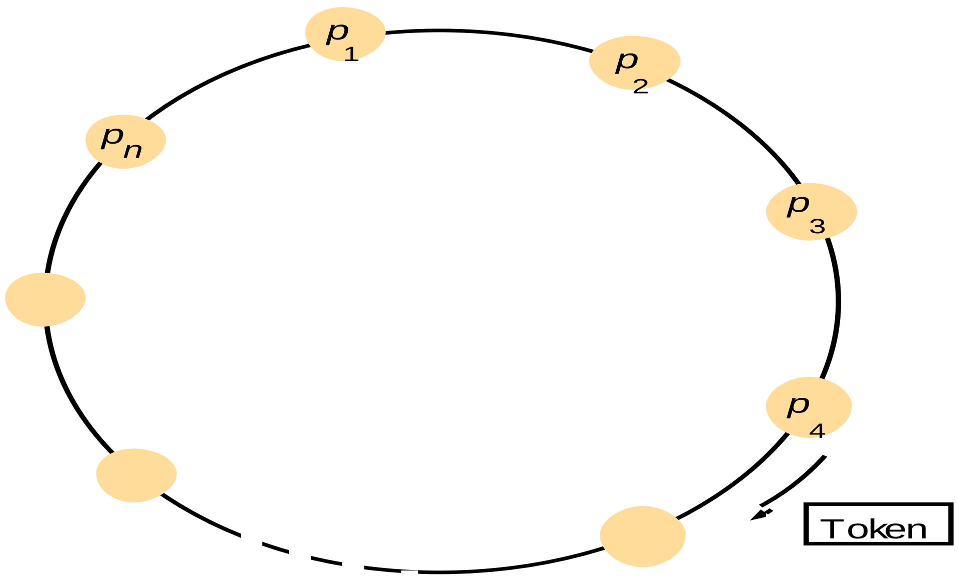


Figure adapted from Instructor's Guide for Coulouris, Dollimore, Kindberg and Blair, Distributed Systems: Concepts and Design Edn. 5 © Pearson Education 2012 – **Figure 15.3**

Properties

Safety? Liveness? Yes (assuming no crashes)

$\rightarrow$ ordering? Not even close!

<u>Performance</u>

Continuously uses network bandwidth

Client delay : between 0 – N messages

Exiting : 1 message

Synchronization delay : between 1 – N messages

Ricart and Agrawala

- Distributed algorithm, no central coordinator
  - Use Lamport timestamps to order requests
- Multicast a request message
  - Enter critical section only when all other processes have given permission
  - Processes work cooperatively to provide access in a fair order
- Use multicast primitive or each process needs a group membership list

Details

Each process

- Has unique process ID
- Has communication channels to the other processes
- Maintains a logical (Lamport) clock
- Has state ∈ `{wanted, held, released}`

Requests are multicasted to group

(process ID and clock value) `<id, value>`

Lowest clock value gets access first

Equal values? Check process ID!

On initialization

state := RELEASED;

To enter the section

state := WANTED;

Multicast *request* to all processes;

T := request's timestamp;

request processing deferred here

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;

Have access or want access and <id, value> is lower than incoming request?

else

reply immediately to p_i;

RELEASED or earlier timestamp

end if

To exit the critical section

state := RELEASED;

reply to any queued requests;

Example

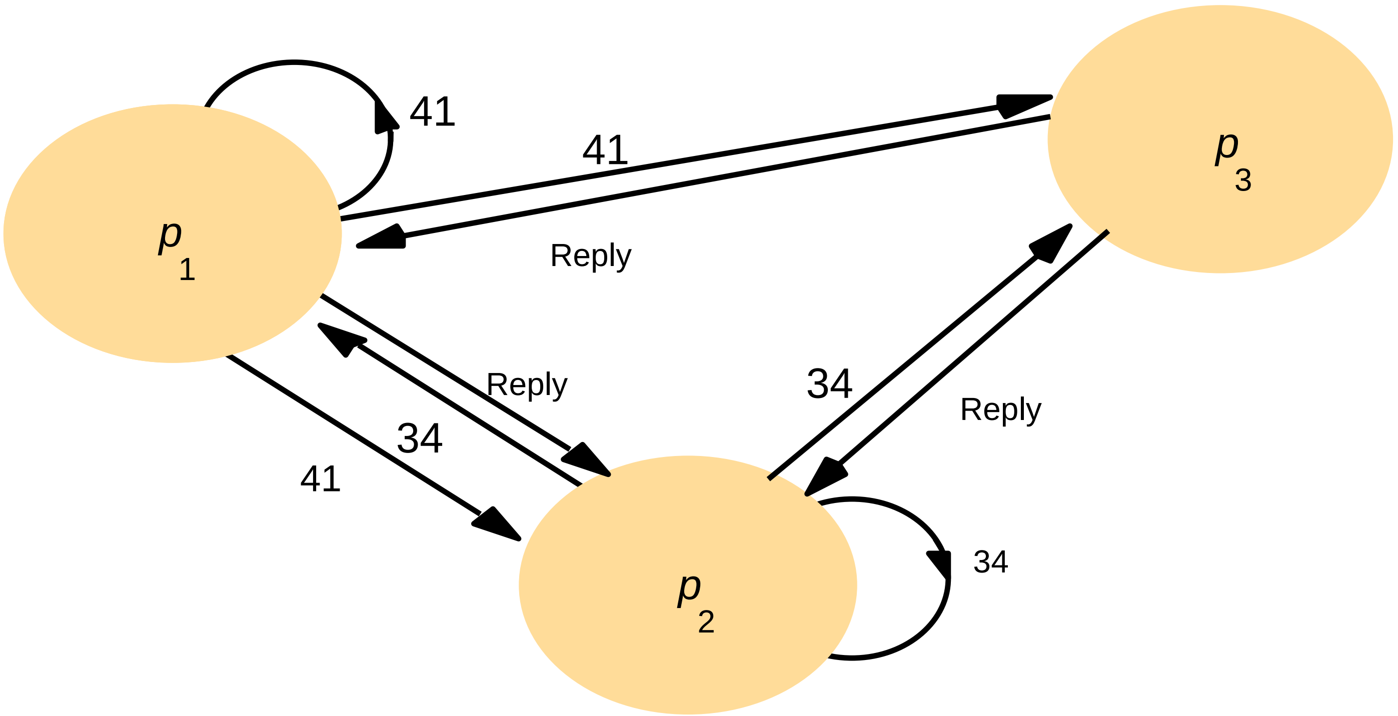


Figure adapted from Instructor's Guide for Coulouris, Dollimore, Kindberg and Blair, Distributed Systems: Concepts and Design Edn. 5 © Pearson Education 2012 – **Figure 15.5**

Properties

Safety? Liveness? → ordering? Yes!

…but every node is a point of failure

<u>Performance</u>

Entering : 2(N-1) messages

- (n-1) multicast request + (n-1) replies

Client delay : 1 round-trip

Synchronization delay : 1 message transmission

Improve performance

- If process wants to re-enter critical section, and no new requests have been made, just do it!
- Grant access using simple majority

Maekawa's voting

Optimization: only ask subset of processes for entry

- Key is how to build the subsets
  - At least one common member in any two voting sets
  - Each process has a voting set of the same size
  - Each process is in as many voting sets as the number of processes in a voting set
  - Works as long as subsets overlap
  - Use matrix of $\sqrt{n}$ by $\sqrt{n}$ and voting sets are the union of rows and columns
- Vote only in one election at a time!

Details

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

Safety? Yes

Liveness? → ordering? No, deadlocks can happen! $V_1=\{p_1,p_2\}$, $V_2=\{p_2,p_3\}$, $V_3=\{p_3,p_1\}$

Comparison of Mutex algorithms

- Central server:
  - simple and error-prone!
  - but otherwise good performance!!
- Ring-based algorithm:
  - also simple, but not single point of failure
- Ricart and Agrawala:
  - completely distributed and decentralized
  - multicast request, access when all have replied (ordered using logical clocks)
- Maekawa's voting algorithm:
  - ask only a subset for access: works if subsets are overlapping

… more comparison

Message loss?

None of the algorithms handle this

Crashing processes?

Ring? No! others? depends (central- not server nor holding or having requested token, Maekawa’s only if crashed process is not in voting set)

Summary

- Control access to shared resources
- Algorithms
  - central server
  - ring-based
  - Ricart and Agrawala
  - Maekawa's voting algorithm

Election algorithms

Motivation

- How to choose a process to play a particular role in the system
- Start with all process in same state
  - One process will reach state *leader*
  - Other process will reach state *lost*

Details

- Any process can call an election but can only call one election at a time
- Each process has the same local algorithm
- The elected process is the one with the largest identifier, identifiers should be unique and totally ordered
- The election must always produce a unique winner

Essential requirements

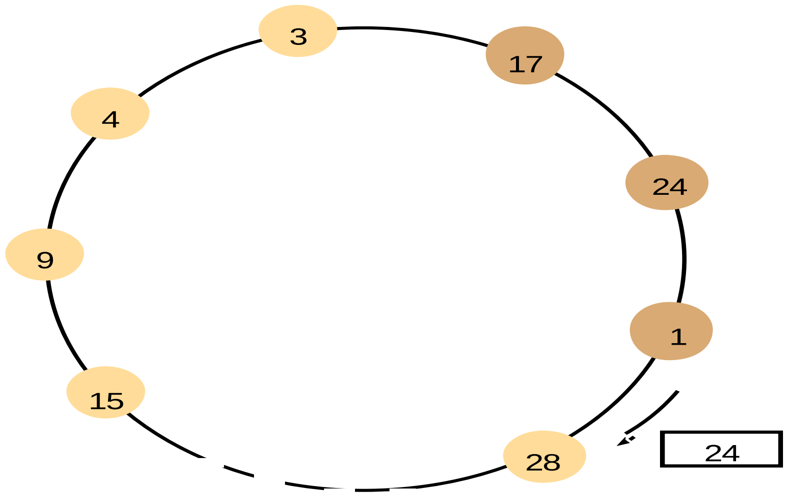
<u>safety</u>: A participant has `elected`$_i$ `= False` or `elected`$_i$ `= P`, where `P` is chosen as the non-crashed process with the highest identifier

<u>liveness</u>: All processes participate and eventually set `elected`$_i$ to not `=False` *or* crash

Ring-based algorithm

- Goal is to elect a single process – the *coordinator*
  - process with the largest identifier
- During election, pass `max(own ID, incoming ID)` to next process
  - If a process receives own `ID`, it must have been highest and may send that it has been elected

Details



- Safety? Liveness? Yes!
- Tolerates no failures (limited use)

Worst case, N-1 messages until reaching peer with largest identifier

+

N messages to complete another circuit

+

N messages advertising the election

3N-1 messages

- The election was started by process 17
- The highest process identifier encountered so far is 24.
- Participant processes are shown in a darker color

Figure adapted from Instructor's Guide for Coulouris, Dollimore, Kindberg and Blair, Distributed Systems: Concepts and Design Edn. 5 © Pearson Education 2012 – **Figure 15.7**

Bully algorithm

Requires:

- Synchronous system
- All processes know of each other (which ones have higher ids)
- Reliable failure detectors
- Reliable message delivery

Allows

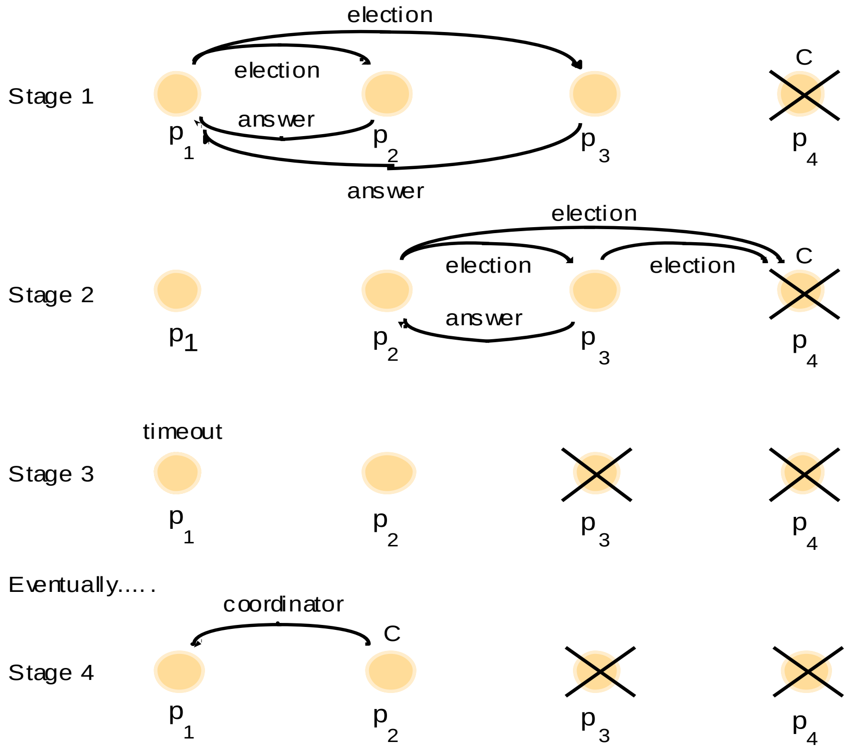
- Crashing processes

Details

- Process P discovers that leader has crashed
  - P sends an Election message to all processes with higher numbers
  - If no one responds, P wins the election and becomes coordinator
  - If one of the higher ups answers, it takes over, P's job is done
- Upon receiving an Election message, the receiving process respond to sender and initiates an election

Example

The election of coordinator p_2, after the failure of p_4 and then p_3



Safety? Not if process IDs can be reused!

Liveness? Yes (if message delivery is reliable)

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Summary

- Election algorithms
  - Seems like a simple problem, but non-trivial solutions are... non-trivial
- Want to read more about non-trivial election algorithms?
  - http://www.sics.se/~ali/teaching/dalg/l06.ppt

Next Lecture

Group communication