CS 455: Introduction To Distributed Systems [Distributed Mutual Exclusion]

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Frequently asked questions from the previous class survey

- Yes. But *what* really is a second?
  - 1 second ==time for a cesium 133 atom to make 9,192,631,770 transitions
- Even though we are assuming processes do not fail, how would you cope with tokens that are lost in transit?

Topics covered in this lecture

- Distributed Mutual Exclusion
  - Multicast & logical clocks [Agarwala & Ricart]
  - Maekawa's voting based algorithm
- Election algorithms

Requirements for distributed mutual exclusion

- **ME1:** *At most one* process may execute in the critical section at a time
  - **Safety**
- **ME2:** Requests to enter and exit the critical section *eventually succeed*
  - **Liveness:** Freedom from **deadlocks** and **starvation**
- **ME3:** If one request *happened-before* another, then entry to the CS is granted in that order

Evaluation of the algorithms

- **Bandwidth consumed**
  - Proportional to number of messages sent in each entry and exit operation
- **Client delay** incurred by process for each entry or exit operation
- Effect on **throughput** of the system
  - **Synchronization delay** between one process exiting critical section and next process entering it
  - Throughput is greater when synchronization delay is shorter

Mutual Exclusion using Multicast & Logical Clocks {Ricart & Agarwala's Algorithm}

Agarwala & Ricart's algorithm using multicast and logical clocks

- Processes that require entry to a critical section **multicast** a request message
  - *Enter it only when* all other processes have replied to request
- Process' replies to a request are designed to ensure that ME1, ME2, and ME3 are met

The setting

- Processes $p_1, p_2, \ldots, p_N$ have distinct identifiers
- Processes have communication channels to each other
- Each process p_i keeps a Lamport clock
- Messages requesting entry are of the form <T, p_i>
  - T is the sender's timestamp and p_i is the sender's identifier

Each process records its state

- `Released`
  - Outside the critical section
- `Wanted`
  - Wanting entry into the critical section
- `Held`
  - Being in the critical section

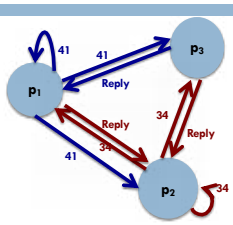
Entering the critical section [1/2]

- If a process requests entry and the state of all other processes is `Released`
  - All processes respond immediately and the entry is granted
- If a process requests entry and some process is in the state `Held`
  - **That holding process will not reply** to requests *until it has finished* with the critical section
  - All other processes respond

Entering the critical section [2/2]

- If two or more processes request entry at the same time?
  - Request with the *lowest timestamp* will be first to collect N-1 replies
  - If the Lamport timestamps are the same?
    - Requests are ordered based on their identifiers
- When a process requests entry?
  - Defers all processes until its own request has been sent

Multicast synchronization



Initial Condition:
p_3 not interested in entering critical section
p_1 and p_2 request entry concurrently
Timestamp of p_1's request: 41
Timestamp of p_2's request: 34

p_2 enters the critical section

Achieving the properties ME1, ME2 and ME3

- If two processes p_i and p_j ($i \neq j$) enter critical section at the same time?
  - Both these processes would have replied to each other; but the pairs $<T_i, p_i>$ are totally ordered
    - So it's impossible
- Requests to enter and exit the critical section *eventually succeed* because requests are served based on timestamps
  - Satisfies ME2 and ME3 (order)

Evaluation of the algorithm

- Gaining entry takes 2(N-1) messages
  - N-1 to multicast the request Followed by N-1 replies
  - Expensive in terms of bandwidth utilization
- Synchronization delay
  - Just one message transmission time
    - Previous algorithms incurred round-trip delays

Some observations [1/2]

- One of the problems with the central server algorithm was that it was a single point of failure
- Here, the single point of failure has been replaced by N points of failure
  - If any process crashes, it will fail to respond to requests
    - This silence is interpreted (incorrectly) as a denial of permission
    - Blocks ALL subsequent processes from entering the critical section
  - Solution: To have timeout mechanisms in place

Some observations [2/2]

- Another problem with the central server algorithm was that making it handle all requests can lead to a bottleneck
- In this setup *all* processes are involved in *all* decisions
- Improvements?
  - Getting permission from *everyone* is an overkill
  - All we need is to prevent two processes from entering the CS at the same time

MAEKAWA'S VOTING ALGORITHM FOR DISTRIBUTED MUTUAL EXCLUSION

Maekawa's solution to distributed mutual exclusion

- In order for a process to enter a critical section it is not necessary for all peers to grant access
  - Obtain permission from **subsets** of peers
  - Subsets used by any two peers **must overlap**
- Candidate process must collect *sufficient votes* to enter critical section

How mutual exclusion is achieved

- Processes at the **intersection of two sets** of voters ensure this
  - Cast votes **for only one** candidate

Voting sets

- There is a voting set V_i associated with *each* process p_i (i=1,2, …, N)

$$V_i \subseteq \{p_1, p_2, ..., p_N\}$$

Voting sets

- The sets V_i are chosen such that, for all $i, j = 1, 2, \ldots, N$

$$p_i \in V_i$$

$$V_i \cap V_j \neq \varnothing$$

$$|V_i| = K$$

To be fair, each process has a voting set of the same size

Each process p_j is contained in M of the voting sets V_i

The optimal solution to the Maekawa's algorithm

$$K \sim \sqrt{N}$$

$$M = K$$

Each process is in **as many of the voting sets** as there are **elements in one of the sets**

Calculation of voting sets

- Is not trivial
- As an approximation
  - Place processes in a $\sqrt{N}$ by $\sqrt{N}$ matrix
  - Voting set V_i is the union of the row and column containing p_i
  - Voting set size is then $\sim 2\sqrt{N}$

Maekawa's voting sets Example

R_1={1, 2, 3}
R_4={1, 4, 5}
R_6={1, 6, 7}
R_2={2, 4, 6}
R_5={2, 5, 7}
R_7={3, 4, 7}
R_3={3, 5, 6}

K=3 *N*=7

R_1={1, 2, 3, 4}
R_5={1, 5, 6, 7}
R_8={1, 8, 9, 10}
R_{11}={1, 11, 12, 13}
R_2={2, 5, 8, 11}
R_6={2, 6, 9, 12}
R_9={2, 7, 10, 13}
R_{10}={3, 5, 10, 12}
R_3={3, 6, 8, 13}
R_9={3, 7, 9, 11}
R_{13}={4, 5, 9, 13}
R_4={4, 6, 10, 11}
R_{12}={4, 7, 8, 12}

K=4 *N*=13

R_1={1, 2, 3, 4, 5}
R_6={1, 6, 7, 9, 9}
R_{10}={1, 10, 11, 12, 13}
R_{14}={1, 14, 15, 16, 17}
R_{18}={1, 18, 19, 20, 21}
R_2={2, 6, 10, 14, 18}
R_7={2, 7, 11, 15, 19}
R_8={2, 8, 12, 16, 20}
R_9={2, 9, 13, 17, 21}
R_{11}={3, 6, 11, 17, 20}
R_3={3, 7, 10, 16, 21}
R_{13}={3, 8, 13, 15, 18}
R_{12}={3, 9, 12, 14, 19}
R_{15}={4, 6, 12, 15, 21}
R_4={4, 7, 13, 14, 20}
R_{17}={4, 8, 10, 17, 19}
R_{16}={4, 9, 11, 16, 18}
R_{19}={5, 6, 13, 16, 19}
R_5={5, 7, 12, 17, 18}
R_{21}={5, 8, 11, 14, 21}
R_{20}={5, 9, 10, 15, 20}

K=5 *N*=21

Source: Maekawa, Mamoru, Arthur E. Oldehoft, and Rodney R. Oldehoft Operating Systems Advanced Concepts., 1987.

Entering the critical section

- To obtain entry into the critical section, each p_i sends request message to all K members of V_i
  - Including itself
- p_i cannot enter critical section till it has received **all** K reply messages

The reply message

- When a process p_j in V_i receives p_i's request message it sends a reply message immediately unless …
  - Its state is HELD
  - It has replied (voted) since it last received a release message

The release message

- To leave the critical section, p_i sends **`release` message** to *all K members* of V_i (incl. itself)
- When a process receives a `release` message?
  - **Removes the head** of its queue of outstanding requests and **sends a reply (vote)** in response to it

Satisfying the safety property

- If it were possible for p_i and p_j to enter the critical section at the same time, then …
  - Processes in $V_i \cap V_j \neq \emptyset$ would have voted for both p_i and p_j
- But a process can make at **most one vote** *between successive receipts of a* `release` *message*
  - So it is impossible for p_i and p_j to both enter the critical section

But the basic algorithm is deadlock prone

- Consider three processes p_1, p_2, and p_3 with $V_1 = \{p_1, p_2\}$, $V_2 = \{p_2, p_3\}$ and $V_3 = \{p_3, p_1\}$
- If 3 processes concurrently request entry to the critical section it is possible for:
  - p_1 to reply to itself and hold-off p_2
  - p_2 to reply to itself and hold-off p_3
  - p_3 to reply to itself and hold-off p_1
  - Each process receives one of two replies; none can proceed

Resolving the deadlock issue

- Processes queue requests in the happened-before order
  - This also allows **ME3** to be satisfied besides **ME2**

Analyzing the performance of the algorithm

- Bandwidth utilization
  - $2\sqrt{N}$ messages per entry into the critical section
  - $\sqrt{N}$ messages per exit
  - Total of $3\sqrt{N}$ is superior to $2(N\text{-}1)$ required by the previous algorithm (Ricart and Agarwala)
    - If $N \geq 3$
- Synchronization delay
  - Round-trip time

Election Algorithms

Election algorithms

- Algorithm for choosing a *unique* process to play a particular role
- When an elected process wants to *retire*, another election is needed

Calling an election

- When a process calls an election it initiates a particular run of the **election algorithm**
- A given process does not call more than one election at a time
  - With N processes there could be N concurrent elections
- At any point a process p_i is either:
  - A participant: Engaged in the election algorithm
  - Non-participant: Not engaged in the election algorithm

The choice of the elected process must be unique

- Even in cases where several processes call the election *simultaneously*
- E.g., 2 processes see a coordinator has failed and they both call elections

The elected process is the one with the largest identifier

- The identifier is any value with the provision that the *identifiers are unique and totally ordered*
- E.g., electing process with the lowest computational load
  - Use $<1/load,\ i>$ as the identifier
  - Process i is used to order identifiers with same load

Managing the identity of the elected process

- Each process p_i *(i=1, 2, …, N)* has a variable $elected_i$
  - Contains identifier of the elected process
- When a process first becomes a participant in an election
  - Set this variable to ⊥ indicating that it is undefined

Requirements for the election algorithm

- **E1** (safety)
  - Participant process has $elected_i = \perp$ or $elected_i = P$
    - P is a non-crashed process at the end of run with the largest identifier
- **E2** (liveness)
  - All processes p_i participate and eventually either set $elected_i \neq \perp$ or crash

Measuring performance of election algorithms

- Network **bandwidth utilization**
  - How many messages are sent?
- **Turnaround time** for the algorithm
  - Number of message transmissions between the initiation and termination of a run

The contents of this slide set are based on the following references

- *Distributed Systems: Concepts and Design.* George Coulouris, Jean Dollimore, Tim Kindberg, Gordon Blair. 5th Edition. Addison Wesley. ISBN: 978-0132143011 [Chapter 15]
- *Distributed Systems: Principles and Paradigms. Andrew S. Tanenbaum and Maarten Van Steen. 2nd Edition. Prentice Hall. ISBN: 0132392275/978-0132392273 [Chapter 6]*