Mutual Exclusion in a Distributed Environment (Review)

- Mutual exclusion
  - Centralized algorithms
    - Central physical clock
    - Central coordinator
  - Distributed algorithms
    - Time-based event ordering
      - Lamport's algorithm (logical clocks)
      - Ricart & Agrawala's algorithm (" ")
      - Suzuki & Kasimi's algorithm (broadcast)
    - Token passing
      - Le Lann's token-ring algorithm (logical ring)
      - Raymond's tree algorithm (logical tree)
    - Sharing K identical resources
      - Raymond's extension to Ricart & Agrawala's time-based algorithm
  - Atomic transactions (later in course)
- Related — self-stabilizing algorithms, election, agreement, deadlock

Suzuki and Kasami's Broadcast Algorithm (1985)

- Overview:
  - If a thread wants to enter the critical section, and it does not have the token, it broadcasts a *request* message to all other sites in the token's request set
  - The thread that has the token will then send it to the requesting thread
    - However, if it's in the critical section, it gets to finish before sending the token
  - A thread holding the token can continuously enter the critical section until the token is requested
  - Request vector at thread *i* :
    - RN_i [*k*] contains the largest sequence number received from thread *k* in a *request* message
  - Token consists of vector and a queue:
    - LN[*k*] contains the sequence number of the latest executed request from thread *k*
    - Q is the queue of requesting thread

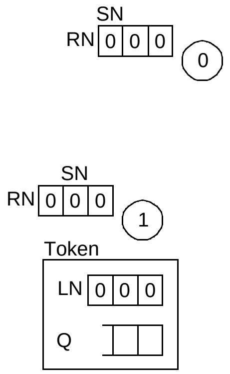
Suzuki and Kasami's Broadcast Algorithm (cont.)

- Requesting the critical section (CS):
  - When a thread *i* wants to enter the CS, if it does not have the token, it:
    - Increments its sequence number *sn* and its request vector RN_i [*i*] to RN_i [*i*]+1
    - Sends a *request* message containing new *sn* to all threads in that CS's request set
  - When a thread *k* receives the *request* message, it:
    - Sets RN_k [*i*] to MAX(RN_k [*i*], *sn* received)
      - If *sn* < RN_k [*i*], the message is outdated
    - If thread *k* has the token and is not in the CS (i.e., is not using it),
and if RN_k [*i*] == LN[*i*]+1 (indicating an outstanding request)
it sends the token to thread *i*
- Executing the CS:
  - A thread enters the CS when it has acquired the token

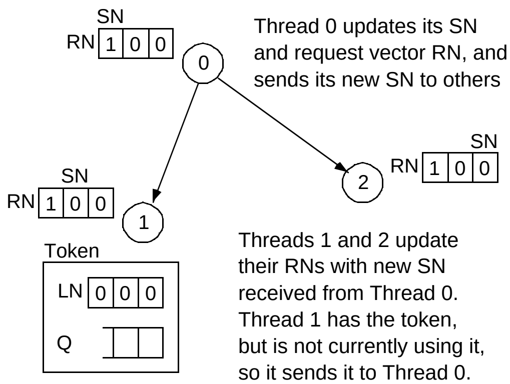
Suzuki and Kasami's Broadcast Algorithm (cont.)

- Releasing the CS:
  - When a thread *i* leaves the CS, it:
    - Sets LN[*i*] of the token equal to RN_i [*i*]
      - Indicates that its request RN_i [*i*] has been executed
    - For every thread *k* whose ID is not in the token queue Q, it appends its ID to Q if RN_i [*k*] == LN[*k*]+1
      - Indicates that thread *k* has an outstanding request
    - If the token queue Q is nonempty after this update, it deletes the thread ID at the head of Q and sends the token to that thread
      - Gives priority to others' requests
      - Otherwise, it keeps the token
- Evaluation:
  - 0 to N messages required to enter CS
    - No messages if thread holds the token
    - Otherwise N–1 requests, 1 reply

Suzuki and Kasami's Broadcast Algorithm (cont.)



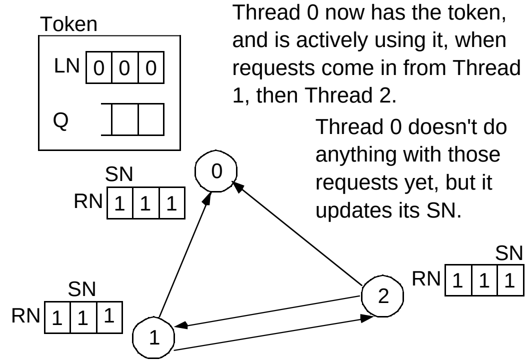
Thread 0 decides it wants to get into the CS



Thread 0 updates its SN and request vector RN, and sends its new SN to others

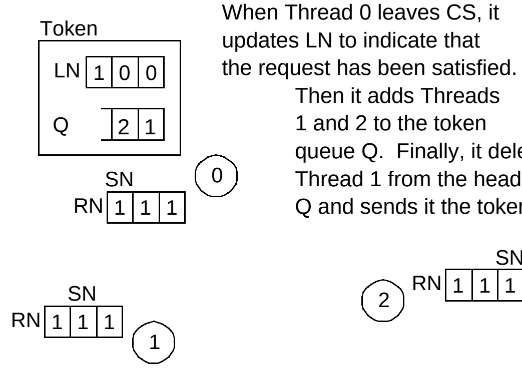
Threads 1 and 2 update their RNs with new SN received from Thread 0. Thread 1 has the token, but is not currently using it, so it sends it to Thread 0.

Suzuki and Kasami's Broadcast Algorithm (cont.)



Thread 0 now has the token, and is actively using it, when requests come in from Thread 1, then Thread 2.

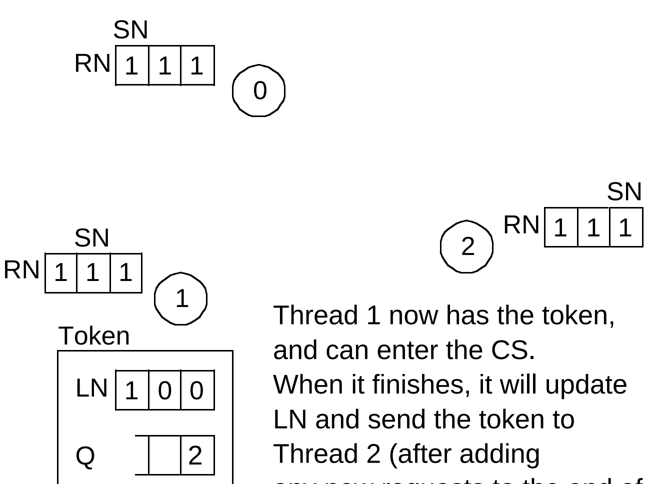
Thread 0 doesn't do anything with those requests yet, but it updates its SN.



When Thread 0 leaves CS, it updates LN to indicate that the request has been satisfied.

Then it adds Threads 1 and 2 to the token queue Q. Finally, it deletes Thread 1 from the head of Q and sends it the token.

Suzuki and Kasami's Broadcast Algorithm (cont.)

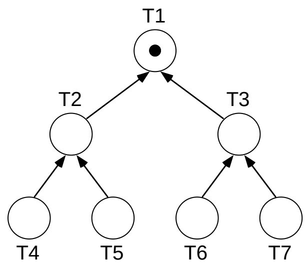


Thread 1 now has the token, and can enter the CS. When it finishes, it will update LN and send the token to Thread 2 (after adding any new requests to the end of the token queue Q).

Token-Ring Algorithm (Le Lann, 1977 ?)

- Processes are arranged in a logical ring
- At start, process 0 is given a *token*
  - Token circulates around the ring in a fixed direction via point-to-point messages
  - When a process acquires the token, it has the right to enter the critical section
    - After exiting CS, it passes the token on
- Evaluation:
  - N–1 messages required to enter CS
  - Not difficult to add new processes to ring
  - With unidirectional ring, mutual exclusion is fair, and no process starves
  - ✘ Not very fault-tolerant
  - ✘ Difficult to detect when token is lost
  - ✘ Doesn't guarantee "happened-before" order of entry into critical section

Raymond's Tree Algorithm (1989)



- Overview:
  - Threads are arranged as a *logical* tree
    - Edges are directed toward the thread that holds the token (called the "holder", initially the root of tree)
  - Each thread has:
    - A variable *holder* that points to its neighbor on the directed path toward the holder of the token
    - A FIFO queue called *request_q* that holds its requests for the token, as well as any requests from neighbors that have requested but haven't received the token
      - If *request_q* is non-empty, that implies the node has already sent the request at the head of its queue toward the holder

Raymond's Tree Algorithm (cont.)

- Requesting the critical section (CS):
  - When a thread wants to enter the CS, but it does not have the token, it:
    - Adds its request to its *request_q*
    - If its *request_q* was empty before the addition, it sends a *request* message along the directed path toward the holder
      - If the *request_q* was not empty, it's already made a request, and has to wait
  - When a thread in the path between the requesting thread and the holder receives the *request* message, it
    - < same as above >
  - When the holder receives a *request* message, it
    - Sends the token (in a message) toward the requesting thread
    - Sets its *holder* variable to point toward that thread (toward the new holder)

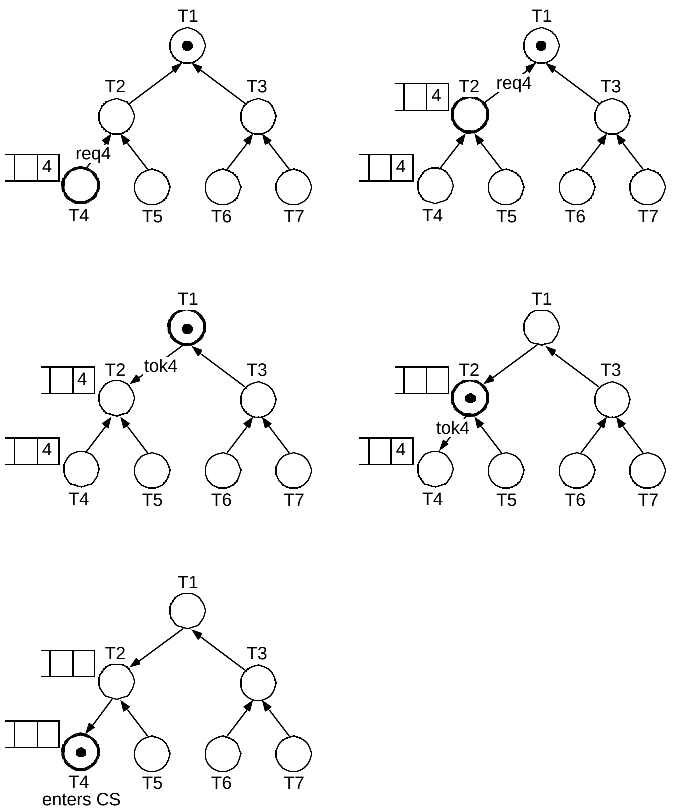
Raymond's Tree Algorithm (cont.)

- Requesting the CS (cont.):
  - When a thread in the path between the holder and the requesting thread receives the token, it
    - Deletes the top entry (the most current requesting thread) from its *request_q*
    - Sends the token toward the thread referenced by the deleted entry, and sets its *holder* variable to point toward that thread
    - If its *request_q* is not empty after this deletion, it sends a *request* message along the directed path toward the new holder (pointed to by the updated *holder* variable)
- Executing the CS:
  - A thread can enter the CS when it receives the token ***and*** its own entry is at the top of its *request_q*
    - It deletes the top entry from the *request_q*, and enters the CS

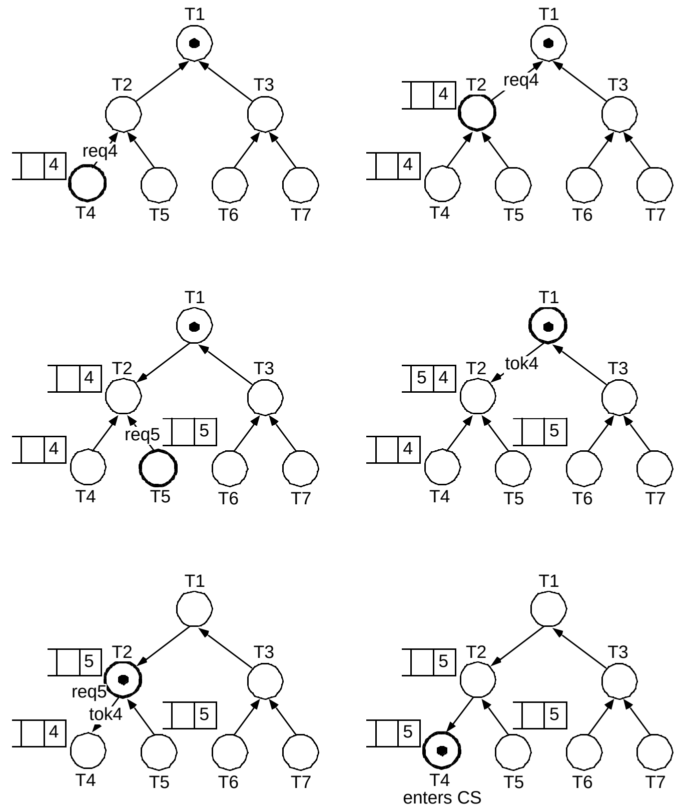
Raymond's Tree Algorithm (cont.)

- Releasing the CS:
  - When a thread leaves the CS
    - If its *request_q* is not empty (meaning a thread has requested the token from it), it:
      - Deletes the top entry from its *request_q*
      - Sends the token toward the thread referenced by the deleted entry, and sets its *holder* variable to point toward that thread
    - If its *request_q* is not empty after this deletion (meaning more than one thread has requested the token from it), it sends a *request* message along the directed path toward the new holder (pointed to by the updated *holder* variable)
- Evaluation:
  - ✔ On average, $O(\log N)$ messages required to enter CS
    - Average distance between any two nodes in a tree with N nodes is $O(\log N)$

Raymond's Tree Algorithm (cont.)



Raymond's Tree Algorithm (cont.)



Election Algorithms

- In a distributed system, many algorithms require a permanent or temporary leader:
  - Distributed mutual exclusion:
    - Central coordinator algorithm requires a coordinator
    - Token-ring algorithm, Suzuki-Kasami's broadcast algorithm, and Raymond's tree algorithm require an initial token holder
  - Distributed deadlock detection — maintainer of a global wait-for graph
- If leader fails, must *elect* a new leader
  - Election algorithms assume there is a unique priority number for each thread
  - Goal: elect the highest-priority thread as the leader, tell all active threads
  - Second goal: allow a recovered leader to re-establish control (or at least, to identify the current leader)

Garcia-Molina's Bully Algorithm (1993)

- 3 types of messages:
  - *Election* —announce an election
  - *Answer* — acknowledge election msg.
  - *Coordinator* — announce new coordinator
- The election:
  - A thread begins an election when it notices the coordinator has failed
    - To do so, it sends *election* messages to all threads with a higher priority
  - It then awaits an *answer* message (from a live thread with a higher priority)
    - If none arrives within a certain time, it declares itself the coordinator, and sends a *coordinator* message to all threads with a lower priority
    - If an *answer* message does arrive, it waits a certain time for a *coordinator* message to arrive from the new coordinator
      - If none arrives, it begins another election

Garcia-Molina's Bully Algorithm (cont.)

- Result of the election:
  - If a thread receives a *coordinator* message, it accepts the new coordinator
- Participating in an election:
  - If a thread receives an *election* message:
    - It sends back an answer message
    - It begins another election (with its higher-ups) unless it has already begun one
- Failed threads:
  - When one restarts, it begins an election
    - Unless it knows it has the highest priority, in which case it just sends out *coordinator* messages to re-establish control
- Evaluation:
  - N–2 messages in best case
  - *O*(N^2) messages in worst case

Garcia-Molina's Bully Algorithm (cont.)