Distributed Systems

ECE428

Lecture 11

Adopted from Spring 2021

Today's agenda

- Wrap up Mutual Exclusion
  - Extending Maekawa's algorithm to break deadlocks.

Mutual exclusion in distributed systems

- Classical algorithms for mutual exclusion in distributed systems.
  - Central server algorithm
  - Ring-based algorithm
  - Ricart-Agrawala Algorithm
  - Maekawa Algorithm

Maekawa Algorithm: Actions

- state = Released, voted = false
- enter() at process P*i*:
  - state = Wanted
  - Multicast Request message to all processes in V*i*
  - Wait for Reply (vote) messages from all processes in V*i* (including vote from self)
  - state = Held
- exit() at process P*i*:
  - state = Released
  - Multicast Release to all processes in V*i*

Maekawa Algorithm: Actions (contd.)

- When P*i* receives a Request from P*j*:

  if (state == <u>Held</u> OR voted = true)

      queue Request

  else

      send Reply to P*j* and set voted = true

- When P*i* receives a Release from P*j*:

  if (queue empty)

      voted = false

  else

      dequeue head of queue, say P*k*

      Send Reply *only* to P*k*

      voted = true

Analysis: Maekawa Algorithm

- Safety:
  - When a process P*i* receives replies from all its voting set V*i* members, no other process P*j* could have received replies from all its voting set members V*j.*
- Liveness
  - Not satisfied. Can have deadlock!
- Ordering:
  - Not satisfied.

Breaking deadlocks

- Maekawa algorithm can be extended to break deadlocks.
- Compare Lamport timestamps before replying (like Ricart-Agrawala).
- But is that enough?
  - *System of 6 processes {0,1,2,3,4,5}. 0,1,2 want to enter critical section:*
    - V_0= {0, 1, 2}: 0, 2 send reply to 0, but 1 sends reply to 1;
    - V_1= {1, 3, 5}: 1, 3 send reply to 1, but 5 sends reply to 2;
    - V_2= {2, 4, 5}: 4, 5 send reply to 2, but 2 sends reply to 0;
  - Suppose (L1, P1) < (L0, P0) < (L2, P2).
  - *Deadlock can still happen based on when messages are received.*
    - P5 receives P2's request before P1's, and replies back to P2 first.
- *We need a way to take back the reply.*

Breaking deadlocks

- Say Pi's request has a smaller timestamp than Pj.
- If Pk receives Pj's request after replying to Pi, send fail to Pj.
- If Px receives Pi's request after replying to Pj, send inquire to Pj.
- If Pj receives an inquire and at least one fail, it sends a relinquish to release locks, and deadlock breaks.

Breaking deadlocks

- *System of 6 processes {0,1,2,3,4,5}. 0,1,2 want to enter critical section:*
    - V_0= {0, 1, 2}: 0, 2 send reply to 0, but 1 sends reply to 1;
    - V_1= {1, 3, 5}: 1, 3 send reply to 1, but 5 sends reply to 2;
    - V_2= {2, 4, 5}: 4, 5 send reply to 2, but 2 sends reply to 0;
- Suppose (L1, P1) < (L0, P0) < (L2, P2).
- P2 will send fail to itself when it receives its own request after P0.
- P5 will send inquire to P2 when it receives P1's request.
- P2 will send relinquish to V_2. P5 and P4 will set "voted = false". P5 will reply to P1.
- P1 can now enter CS, followed by P0, and then P2.

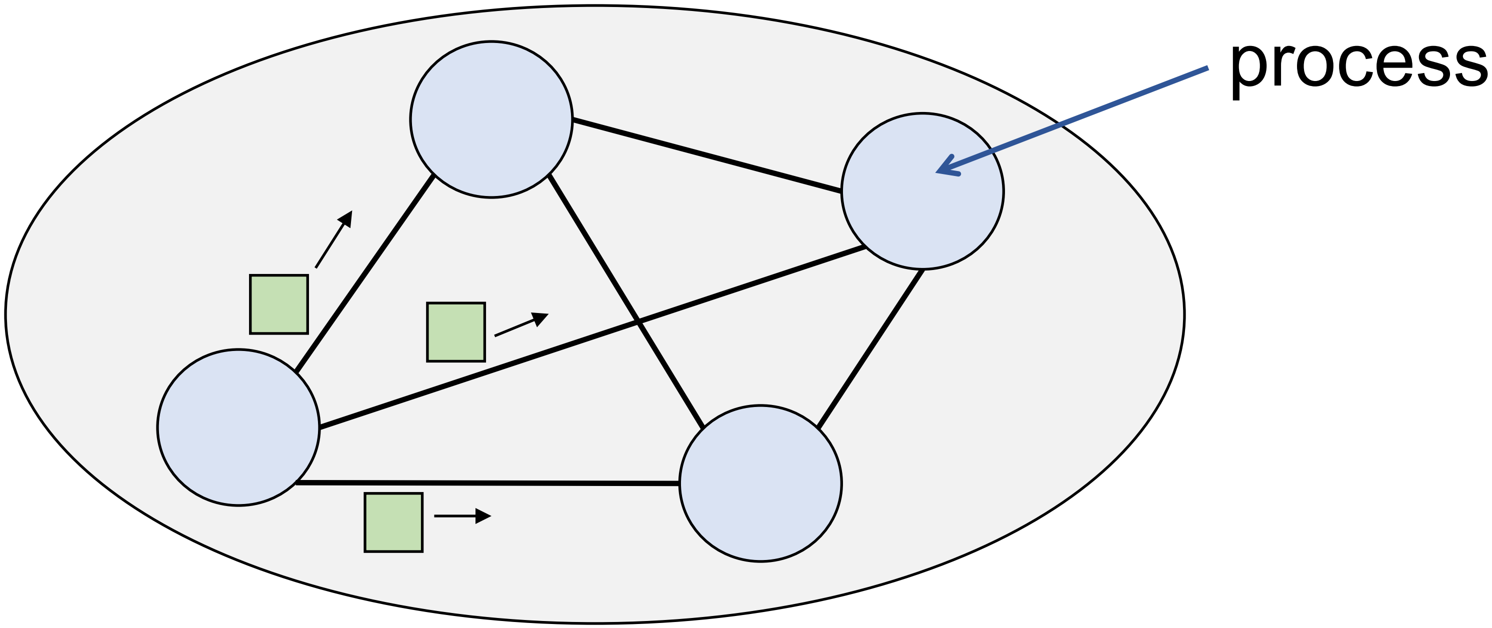
Mutual exclusion in distributed systems

- Classical mutual exclusion in distributed systems
  - Central server algorithm
    - Satisfies safety, liveness, but not ordering.
    - O(1) bandwidth, and O(1) client and synchronization delay.
    - Central server is scalability bottleneck
  - Ring-based algorithm
    - Satisfies safety, liveness, but not ordering.
    - Always uses bandwidth, O(N) client & synchronization delay
  - Ricart-Agrawala algorithm
    - Satisfies safety, liveness, and ordering.
    - O(N) bandwidth, O(1) client and synchronization delay
  - Maekawa algorithm
    - Satisfies safety, but not liveness and ordering.
    - $O(\sqrt{N})$ bandwidth, O(1) client and synchronization delay

Topics for first midterm

- System model and Failures
- Failure Detection
- Clock Synchronization
- Event ordering and Logical Timestamps
- Global Snapshot
- Multicast

What is a distributed system?



Independent components that are connected by a network and communicate by passing messages to achieve a common goal, appearing as a single coherent system.

Relationship between processes

- Two broad categories:

  - Client-server:
    - different roles/responsibilities.

  - Peer-to-peer:
    - similar role/responsibility.
    - run the same program/algorithm.

Key aspects of a distributed system

- Processes must communicate with one another to coordinate actions.
  - Communication channel between each pair of processes.
  - Time taken to transmit a message over a communication channel may vary.

- Different processes (on different computers) have different clocks.
  - These clocks *drift* from real time at different rates.

- Processes and communication channels may fail.

Two ways to model

- Synchronous distributed systems:
  - Known upper and lower bounds on time taken by each step in a process.
  - Known bounds on message passing delays.
  - Known bounds on clock drift rates.

- Asynchronous distributed systems:
  - No bounds on process execution speeds.
  - No bounds on message passing delays.
  - No bounds on clock drift rates.

Types of failure

- Omission: when a process or a channel fails to perform actions that it is supposed to do.
  - Process may crash.
  - Fail-stop: if other processes can detect that the process has crashed.
  - Communication omission: a message sent by process was not received by another.
- Arbitrary (Byzantine) Failures: any type of error, e.g. process executing incorrectly, sending a wrong message, etc.
- Timing Failures: Timing guarantees are not met.
  - Applicable only in synchronous systems.

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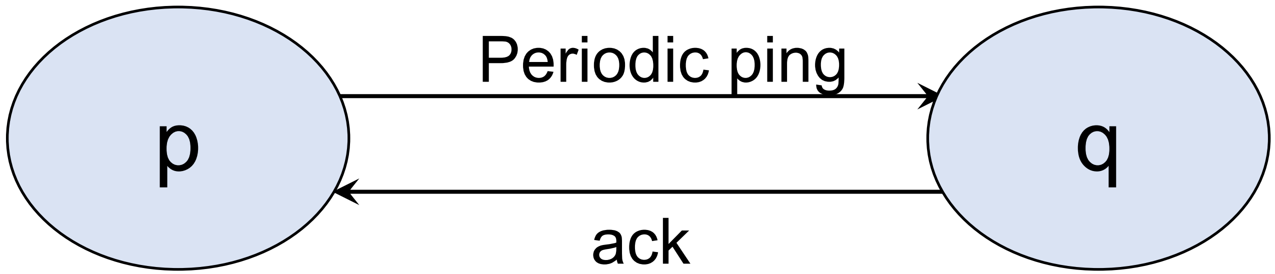
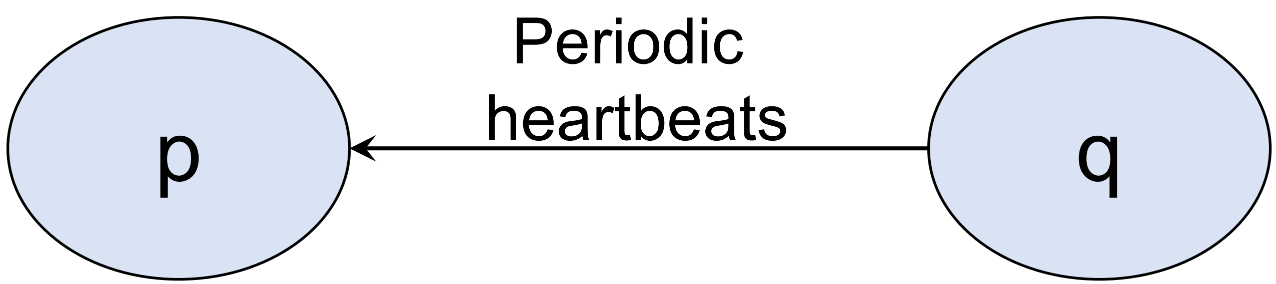
How to detect a crashed process?



p sends pings to q every T seconds (T = period).
If p doesn’t receive an ack after sending a ping within a specified timeout, declare q has failed.



q sends heartbeats to p every T seconds (T = period).
If p doesn’t receive a heartbeat from q for a specified timeout, declare q has failed.

Computing timeout values

- Can precisely compute timeout value in synchronous systems.
  - In the worst case, how long would take to receive an ack after sending a ping?
  - In the worst case, what is the maximum time gap between two consecutive heartbeats?

- Can estimate timeout value based on observed round-trip times in asynchronous systems.

Metrics for evaluating failure detector

- Correctness:
  - Completeness: Every failed process is *eventually* detected.
  - Accuracy: Every detected failure corresponds to a crashed process (no mistakes).

- Performance:
  - Worst-case failure detection time: maximum time gap between when a failure occurs to when it is detected.
  - Bandwidth usage: No. of messages exchanged for failure detection per unit time.

Extending to N processes

- Centralized heartbeat
  - All processes send heartbeats to a central server.
- Ring-based failure detector
  - A process sends heartbeats to its ring successor.
- All-to-all failure detector
  - All processes send heartbeats to each-other.

Trade-off in completeness and bandwidth usage.

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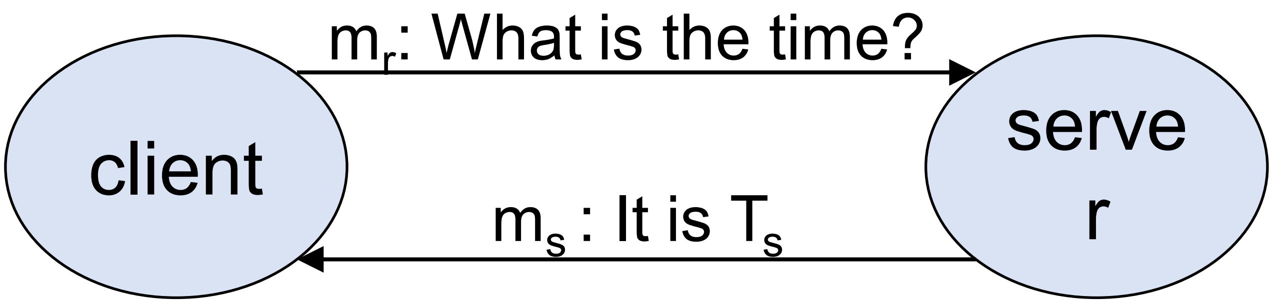
Clock Skew and Drift Rates

- Each process has an internal clock.
- Clocks between processes on different computers differ:
  - Clock skew:
    - relative difference between two clock values.
  - Clock drift rate:
    - change in skew from a perfect reference clock per unit time (measured by the reference clock).

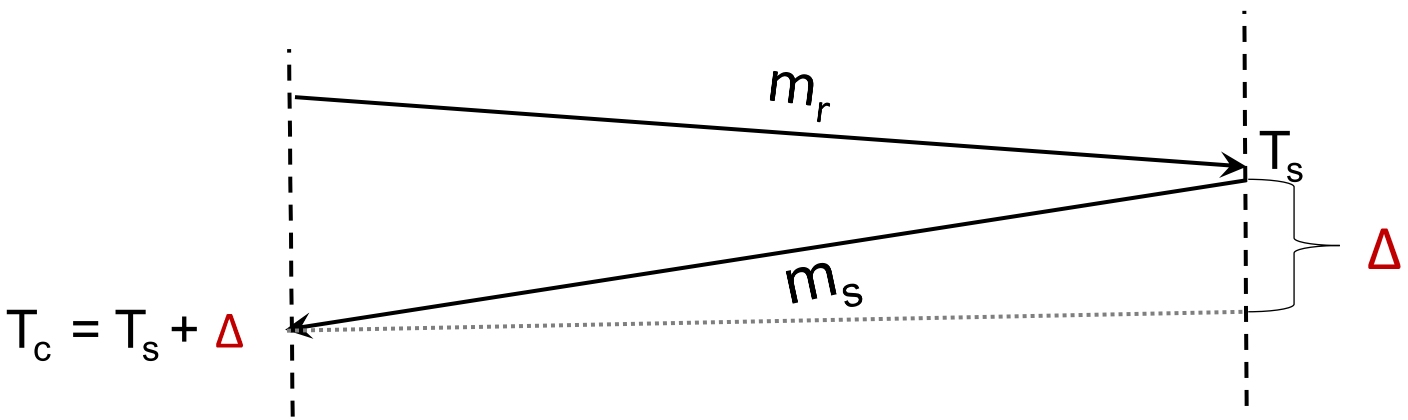
Clock synchronization

- External synchronization
  - Synchronize time with an authoritative clock.
- Internal synchronization
  - Synchronize time internally between all processes in a distributed system.
- Synchronization bound (D) between two clocks A and B over a real time interval I.
  - $|A(t) - B(t)| < D$, for all t in the real time interval I.
  - Skew(A, B) < D during the time interval I.
- *Important metric: worst-case skew right after synchronization.*

Clock Synchronization



What time T_c should client adjust its local clock to after receiving m_s ?



But the value of Δ is unknown.

Clock synchronization

- In a synchronous system:
  - use known maximum and minimum network delays to find the Δ value that results in smallest worst-case skew.

- In asynchronous system:
  - Use observed round-trip time (RTT).
  - Cristian algorithm: Estimates Δ as RTT/2.
    - What is the worst-case skew?

Other clock synchronization protocols

- Berkeley algorithm for internal synchronization.
  - Central server collects and estimates local timestamps, computes updated time as average of estimated local times, and disseminates offsets from updated time.
- Network Time Protocol:
  - External time synchronization service over the Internet.
  - Symmetric mode synchronization:
    - Two servers exchange a pair of messages (A to B and B to A)
    - Estimate offset and accuracy bound using the send and receive timestamps at A and B for both messages.

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Happened-Before Relationship

- *Happened-before* (HB) relationship denoted by $\rightarrow$.
  - $e \rightarrow e'$ means e *happened before* e'.
  - $e \rightarrow_i e'$ means e *happened before* e', as observed by p_i.

- HB rules:
  - If $\exists\, p_i$, $e \rightarrow_i e'$ then $e \rightarrow e'$.
  - For any message m, send(m) $\rightarrow$ receive(m)
  - If $e \rightarrow e'$ and $e' \rightarrow e''$ then $e \rightarrow e''$

- Also called "*causal*" relationship.

Lamport’s Logical Clock

- Logical timestamp for each event that captures the *happened-before* relationship.
- Each process maintains a single integer clock to logically timestamp each event.
- Checkout algorithm to assign Lamport timestamps.
- If $e \rightarrow e'$ then $L(e) < L(e')$.
- What can we conclude if $L(e) < L(e')$?

Vector Clocks

- Each process maintains vector of clocks V_i
  - $V_i[j]$ is the clock for process p_j
- Checkout algorithm to assign vector timestamps.
- Let $V(e) = V$ and $V(e') = V'$
  - $V = V'$, iff $V[i] = V'[i]$, for all $i = 1, \ldots, n$
  - $V \leq V'$, iff $V[i] \leq V'[i]$, for all $i = 1, \ldots, n$
  - $V < V'$, iff $V \leq V'$ & $V \neq V'$
    iff $V \leq V'$ & $\exists$ j such that $(V[j] < V'[j])$
- $e \rightarrow e'$ iff $V < V'$
  - ($e \rightarrow e'$ implies $V < V'$) and ($V < V'$ implies $e \rightarrow e'$)
- $e \parallel e'$ iff ($V \nless V'$ and $V' \nless V$)

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Global snapshot

- State of each process (and each channel) in the system at a given instant of time.
- Difficult to capture a global snapshot of the system.
  - Requires precise clock synchronization across processes.
- *How do we capture global snapshots without precise time synchronization across processes?*
  - Relax the requirement for capturing the state of different processes and channels at the same real time instant.
  - As long as the global state is *consistent*, it is still useful in reasoning about properties of the system.

Notations and Definitions

- For a process p_i , where events e_i^0, e_i^1, … occur:

  history(p_i) = h_i = <e_i^0, e_i^1, … >

  prefix history(p_i^k) = h_i^k = <e_i^0, e_i^1, …,e_i^k >

  s_i^k : p_i's state immediately after k^{th} event.
- For a set of processes <p_1, p_2, p_3, …., p_n>:

  global history: $H = \cup_i (h_i)$

  a cut $C \subseteq H = h_1^{c_1} \cup h_2^{c_2} \cup \ldots \cup h_n^{c_n}$

  the frontier of $C = \{e_i^{c_i}, i = 1,2, \ldots n\}$

  global state S that corresponds to cut $C = \cup_I (s_i^{c_i})$

Notations and definitions

- A cut C is consistent if and only if

$$\forall e \in C \text{ (if } f \rightarrow e \text{ then } f \in C)$$

- A global state S is consistent if and only if it corresponds to a consistent cut.

Notations and definitions

- A run is a total ordering of events in H that is consistent with each h_i's ordering.
- A linearization is a run consistent with happens-before ($\rightarrow$) relation in H.
- Linearizations pass through consistent global states.
- Execution lattice: a way to reason about linearizations and the set of all consistent global states.

Chandy-Lamport Algorithm

- Records a consisted global snapshot
  - identifies a consistent cut.
- Key system assumptions:
  - Two uni-directional communication channels between each ordered process pair : p_j to p_i and p_i to p_j.
  - *Communication channels are FIFO-ordered (first in first out).*
  - No failures (messages are not dropped, process doesn't crash).
- Checkout the algorithm!

Chandy-Lamport Algorithm

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  - identifies a consistent cut.
- Key system assumptions:
  - Two uni-directional communication channels between each ordered process pair : p_j to p_i and p_i to p_j.
  - *Communication channels are FIFO-ordered (first in first out).*
  - No failures (messages are not dropped, process doesn't crash).
- Useful for reasoning about system *properties*.

Liveness

- Liveness = guarantee that something good will happen, eventually
- Examples:
  - A distributed computation will terminate.
  - "Completeness" in failure detectors: the failure will be detected.
  - All processes will eventually decide on a value.
- A global state S_0 satisfies a liveness property P iff:
  - liveness($P(S_0)$) $\equiv \forall L \in$ linearizations from S_0, L passes through a S_L & $P(S_L)$ = true
  - For any linearization starting from S_0, P is true for some state S_L reachable from S_0.

Safety

- Safety = guarantee that something bad will never happen.
- Examples:
  - There is no deadlock in a distributed transaction system.
  - "Accuracy" in failure detectors: an alive process is not detected as failed.
  - No two processes decide on different values.
- A global state S_0 satisfies a safety property P iff:
  - safety(P(S_0)) $\equiv$ $\forall$S reachable from S_0, P(S) = true.
  - For all states S reachable from S_0, P(S) is true.

Stable Global Predicates

- once true, stays true forever afterwards (for stable liveness)
  - True for a state S, true for all states reachable from S.
- once false, stays false forever afterwards (for stable non-safety)
  - False for a state S, false for all states reachable from S.
- *All stable global properties can be detected using the Chandy-Lamport algorithm.*

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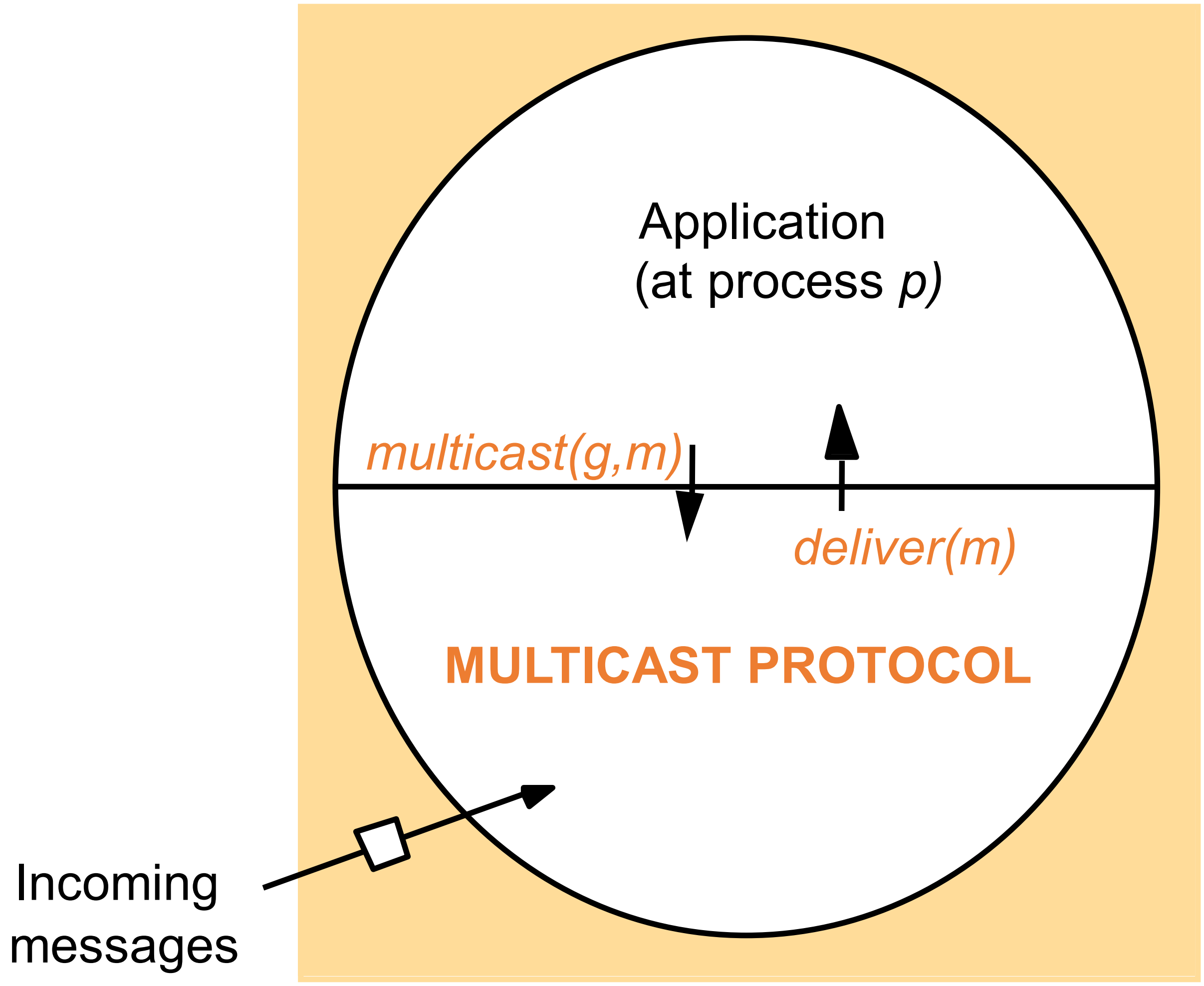
Multicast Protocol



Distinction between when a message arrives at process p's node
vs
when the message is delivered to the application at p.

It is the message delivery that matters!

Basic Multicast (B-Multicast)

- Straightforward way to implement B-multicast:
  - use a reliable one-to-one send (unicast) operation:

    B-multicast(group g, message m):

        for each process p in g, send (p,m).

    receive(m): B-deliver(m) at p.
- Guarantees: message is eventually delivered to the group if:
  - Processes are non-faulty.
  - The unicast "send" is reliable.
  - *Sender does not crash.*
- *Can we provide reliable delivery even after sender crashes?*

Reliable Multicast (R-Multicast)

- Integrity: A *correct* (i.e., non-faulty) process *p* delivers a message *m* at most once.
  - *Assumption: no process sends the same message twice*
- Validity: If a *correct* process multicasts (sends) message *m*, then it will eventually deliver *m* itself.
  - *Liveness for the sender.*
- Agreement: If a *correct* process delivers message *m*, then all other *correct* processes in group(*m*) will eventually deliver *m*.
  - *All or nothing.*
- Validity and agreement together ensure overall liveness: if some correct process multicasts a message *m*, then, all correct processes deliver *m* too.

Implementing R-Multicast

On initialization

    Received := {};

For process p to R-multicast message m to group g

    B-multicast(g,m); ($p \in g$ is included as destination)

On B-deliver(m) at process q with g = group(m)

    if ($m \notin$ Received):

        Received := Received $\cup$ {m};

        if ($q \neq p$): B-multicast(g,m);

        R-deliver(m)

Ordered Multicast

- FIFO ordering: If a correct process issues multicast(g,m) and then multicast(g,m'), then every correct process that delivers m' will have already delivered m
- Causal ordering: If multicast(g,m) → multicast(g,m') then any correct process that delivers m' will have already delivered m.
  - Note that → counts messages multicast delivered to the application, rather than all network messages.
- Total ordering: If a correct process delivers message m before m', then any other correct process that delivers m' will have already delivered m.

HB Relationship for Causal Ordering

- HB rules in causal ordered multicast:
  - If $\exists\, p_i$, $e \rightarrow_i e'$ then $e \rightarrow e'$.
    - If $\exists\, p_i$, multicast(g,m) $\rightarrow_i$ multicast(g,m'), then multicast(g,m) $\rightarrow$ multicast(g,m')
    - If $\exists\, p_i$, delivery(m) $\rightarrow_i$ multicast(g,m'), then delivery(m) $\rightarrow$ multicast(g,m')
  - For any message m, send(m) $\rightarrow$ receive(m)
    - For any *multicast* message m, multicast(g,m) $\rightarrow$ delivery(m)
  - If $e \rightarrow e'$ and $e' \rightarrow e''$ then $e \rightarrow e''$
    - multicast(g,m) $\rightarrow$ delivery(m)
    - delivery(m) $\rightarrow_i$ multicast(g,m')
    - multicast(g,m) $\rightarrow$ multicast(g,m')
- *Application can only see when messages are sent (multicast) and delivered, not when they are received at the protocol.*

Implementing Ordered Multicast

- Basic idea:
  - Sequence number (or vector, in case of causal-ordered multicast) associated which each multicast message.
  - Multicast protocol buffers the message until the conditions for the next expected sequence number/vector are satisfied.
- Two ways to implement total-ordered multicast:
  - Central server based algorithm
  - Decentralized ISIS algorithm
- Checkout algorithms to implement FIFO, Causal, and Total ordered multicasts.

Underlying multicast mechanisms

- Unicast to each process in the group.
- Tree-based multicast.
  - Construct a minimum spanning tree of processes and unicast along the tree.
- Gossip
  - Each process sends a message to ‘b’ random processes.

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Good luck!