Distributed Systems

CS425/ECE428

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Acknowledgements for some of materials: Indy Gupta and Nikita Borisov
Logistics

- HW1 is due tomorrow at 11:59pm.

- MP1 and HW2 will be released on Thursday, Feb 10\textsuperscript{th}.

- Online midterm on March 10\textsuperscript{th}, Thursday
  - Time: 11:05am-12:05pm (during class hours)
  - More instructions to follow soon.
  - If you have any \textit{unavoidable} conflict, fill up a form I’ll soon share on Campuswire.

- Please make sure you are on CampusWire
  - Reach out to Sanchit (sv4) if you need access.
Recap: Global snapshot

• State of each process (and each channel) in the system at a given instant of time.

• Difficult to capture global state at same instant of time.

• Capture consistent global state.
  • If captured state includes an event $e$, it includes all other events that happened before $e$.

• Chandy-Lamport algorithm captures consistent global state.
Recap: Global snapshot

- **Global system properties (or predicates):** defined for a captured global state. Two categories:
  - Liveness, e.g. has the algorithm terminated?
    - Must be true for *some* state reachable from initial state for all linearizations.
  - Safety, e.g. the system is not deadlocked.
    - Must be true for *all* states reachable from initial state for all linearizations.

- Chandy-Lamport algorithm can capture **stable global properties**:
  - once true, stays true forever afterwards (for stable liveness)
  - once false, stays false forever afterwards (for stable non-safety)
Today’s agenda

• Multicast
  • Chapter 15.4

• Goal: reason about desirable properties for message delivery among a group of processes.
Communication modes

• **Unicast**
  • Messages are sent from exactly one process to one process.

• **Broadcast**
  • Messages are sent from exactly one process to all processes on the network.

• **Multicast**
  • Messages broadcast within a group of processes.
  • A multicast message is sent from any one process to a group of processes on the network.
Where is multicast used?

• Distributed storage
  • Write to an object are multicast across replica servers.
  • Membership information (e.g., heartbeats) is multicast across all servers in cluster.

• Online scoreboards (ESPN, French Open, FIFA World Cup)
  • Multicast to group of clients interested in the scores.

• Stock Exchanges
  • Group is the set of broker computers.

• .......

Communication modes

• **Unicast**
  - Messages are sent from exactly **one** process to **one** process.
    - *Best effort*: if a message is delivered it would be intact; no reliability guarantees.
    - *Reliable*: guarantees delivery of messages.
    - *In order*: messages will be delivered in the same order that they are sent.

• **Broadcast**
  - Messages are sent from exactly **one** process to **all** processes on the network.

• **Multicast**
  - Messages broadcast within a group of processes.
  - A multicast message is sent from any **one** process to the **group** of processes on the network.
  - *How do we define (and achieve) reliable or ordered multicast?*
What we are designing in this class?

Application (at process $p$)

$\text{multicast}(g, m)$

$\text{deliver}(m)$

MULTICAST PROTOCOL

Incoming messages

One process $p$
What we are designing in this class?

Application (at process $p$)

- $\text{multicast}(g,m)$
- $\text{deliver}(m)$

MULTICAST PROTOCOL

One process $p$

Incoming messages
Basic Multicast (B-Multicast)

• Straightforward way to implement B-multicast:
  • use a reliable one-to-one send (unicast) operation:
    \[
    \text{B-multicast(group } g, \text{ message } m): \\
    \quad \text{for each process } p \text{ in } g, \text{ send } (p,m). \\
    \text{receive}(m): \text{B-deliver}(m) \text{ at } p.
    \]

• Guarantees: message is eventually delivered to the group if:
  • Processes are non-faulty.
  • The unicast “send” is reliable.
  • \textit{Sender does not crash}.

• \textit{Can we provide reliable delivery even after sender crashes?}
  • What does this mean?
Reliable Multicast (R-Multicast)

- **Integrity**: A *correct* (i.e., non-faulty) process $p$ delivers a message $m$ at most once.
  - Assumption: no process sends *exactly* 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 the 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.
Reliable Multicast (R-Multicast)

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  - Assumption: no process sends exactly 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 the other *correct* processes in group($m$) will eventually deliver $m$ too.
  - All or nothing.
  
  What happens if a process initiates B-multicasts of a message but fails after unicasting to a subset of processes in the group?

**Agreement is violated! R-multicast not satisfied.**

- 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

Application (at process \( p \))

MULTICAST PROTOCOL

\[ \text{multicast}(g, m) \]

\[ \text{deliver}(m) \]

Incoming messages
Implementing R-Multicast

Incoming messages

Application (at process p)

R-multicast(g,m)  \rightarrow  R-deliver(m)

B-multicast(g,m)  \rightarrow  B-deliver(m)
Implementing R-Multicast

On initialization

\[ \text{Received} := \{\}\; \]

For process \( p \) to R-multicast message \( m \) to group \( g \)

\[ \text{B-multicast}(g,m); \; (p \in g \text{ is included as destination}) \]

On B-deliver(\( m \)) at process \( q \) in \( g = \text{group}(m) \)

\[ \text{if } (m \notin \text{Received}) : \]

\[ \text{Received} := \text{Received} \cup \{m\}; \]

\[ \text{if } (q \neq p) : \text{B-multicast}(g,m); \]

\[ \text{R-deliver}(m) \]
Reliable Multicast (R-Multicast)

- **Integrity:** A correct (i.e., non-faulty) process $p$ delivers a message $m$ at most once.
  - Assumption: no process sends exactly 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 the other correct processes in group$(m)$ will eventually deliver $m$.
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Ordered Multicast

• Three popular flavors implemented by several multicast protocols:
  1. FIFO ordering
  2. Causal ordering
  3. Total ordering
1. FIFO Order

- Multicasts from each sender are delivered in the order they are sent, at all receivers.
- Don’t care about multicasts from different senders.

- More formally
  - 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.
FIFO Order: Example

M1:1 and M1:2 should be delivered in that order at each receiver. Order of delivery of M3:1 and M1:2 could be different at different receivers.
2. Causal Order

- Multicasts whose send events are causally related, must be delivered in the same causality-obeying order at all receivers.

- More formally
  - If $\text{multicast}(g,m) \rightarrow \text{multicast}(g,m')$ then any correct process that delivers $m'$ will have already delivered $m$.
  - $\rightarrow$ is Lamport’s happens-before
  - $\rightarrow$ is induced only by multicast messages in group $g$, and when they are delivered to the application, rather than all network messages.
HB Relationship for Causal Ordering

- HB rules in causal ordered multicast:
  - If \( \exists p_i, e \rightarrow_i e' \) then \( e \rightarrow e' \).
    - If \( \exists p_i, \text{multicast}(g,m) \rightarrow_i \text{multicast}(g,m') \), then \( \text{multicast}(g,m) \rightarrow \text{multicast}(g,m') \)
    - If \( \exists p_i, \text{delivery}(m) \rightarrow_i \text{multicast}(g,m') \), then \( \text{delivery}(m) \rightarrow \text{multicast}(g,m') \)
    - ...
  - For any message \( m \), \( \text{send}(m) \rightarrow \text{receive}(m) \)
HB Relationship for Causal Ordering

- HB rules in causal ordered multicast:
  - If $\exists p_i, e \rightarrow_i e'$ then $e \rightarrow e'$.
    - If $\exists p_i, \text{multicast}(g,m) \rightarrow_i \text{multicast}(g,m')$, then $\text{multicast}(g,m) \rightarrow \text{multicast}(g,m')$
    - If $\exists p_i, \text{delivery}(m) \rightarrow_i \text{multicast}(g,m')$, then $\text{delivery}(m) \rightarrow \text{multicast}(g,m')$
    - ...
  - For any message $m$, $\text{send}(m) \rightarrow \text{receive}(m)$
    - For any multicast message $m$, $\text{multicast}(g,m) \rightarrow \text{delivery}(m)$
  - If $e \rightarrow e'$ and $e' \rightarrow e''$ then $e \rightarrow e''$
    - $\text{multicast}(g,m) \rightarrow \text{delivery}(m)$
    - $\text{delivery}(m) \rightarrow \text{multicast}(g,m')$
    - $\text{multicast}(g,m) \rightarrow \text{multicast}(g,m')$
  - Application can only see when messages are sent (multicast) and delivered, not when they are received at the protocol.
M3:1 \rightarrow M3:2, M1:1 \rightarrow M2:1, M1:1 \rightarrow M3:1\text{ and so should be delivered in that order at each receiver.}

M3:1 \text{ and M2:1} \text{ are concurrent and thus ok to be delivered in any (and even different) orders at different receivers.}
Where is causal ordering useful?

• Group = set of your friends on a social network.

• A friend sees your message $m$, and she posts a response (comment) $m'$ to it.
  • If friends receive $m'$ before $m$, it wouldn’t make sense
  • But if two friends post messages $m''$ and $n''$ concurrently, then they can be seen in any order at receivers.

• A variety of systems implement causal ordering:
  • social networks, bulletin boards, comments on websites, etc.
Causal vs FIFO

• Causal Ordering ⇒ FIFO Ordering

• Why?
  • If two multicasts M and M’ are sent by the same process P, and M was sent before M’, then M ⇒ M’.
  • Then a multicast protocol that implements causal ordering will obey FIFO ordering since M ⇒ M’.

• Reverse is not true! FIFO ordering does not imply causal ordering.
Example

Does this satisfy FIFO order?

P1

M1:1

M1:2

M3:1

P2

P3

P4

Time
Example

Does this satisfy FIFO order? Yes
Example

Does this satisfy causal order?
Does this satisfy causal order?

No
M1:1 is delivered at P3 after M3:1’s multicast.

Does this satisfy causal order?

Yes
Example

Does this satisfy causal order? No
Example

Does this satisfy FIFO order?

No
3. Total Order

- Ensures all processes deliver all multicasts in the same order.
- Unlike FIFO and causal, this does not pay attention to order of multicast sending.
- Formally
  - If a correct process delivers message $m$ before $m'$ (independent of the senders), then any other correct process that delivers $m'$ will have already delivered $m$. 

A reliable totally ordered multicast is also known as "atomic multicast".
The order of receipt of multicasts is the same at all processes. M1:1, then M2:1, then M3:1, then M3:2. May need to delay delivery of some messages.
Causal vs Total

• Total ordering does not imply causal ordering.

• Causal ordering does not imply total ordering.
Hybrid variants

• We can have hybrid ordering protocols:
  • Causal-total hybrid protocol satisfies both Causal and total orders.
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\((g,m) \rightarrow multicast(g,m')\) then any correct process that delivers \(m'\) will have already delivered \(m\).
  - Note that \(\rightarrow\) counts messages **delivered** to the application, rather than all network messages.

- **Total ordering:** If a correct process delivers message \(m\) before \(m'\) (independent of the senders), then any other correct process that delivers \(m'\) will have already delivered \(m\).
Example

Does this satisfy causal (and FIFO) order? Yes
Example

Does this satisfy total order?
No
Example

Does this satisfy total order? Yes
Summary

• Multicast is an important communication mode in distributed systems.

• Applications may have different requirements:
  • Reliability
  • Ordering: FIFO, Causal, Total
  • Combinations of the above.
Next Question

How do we implement ordered multicast?