Week 4: Part 1
Group Communication
Modes of communication

- **One-to-One**
  - **Unicast**
    - 1\(\leftrightarrow\)1
    - Point-to-point
  - **Anycast**
    - 1\(\rightarrow\)nearest 1 of several identical nodes
    - Introduced with IPv6; used with BGP routing protocol

- **One-to-many**
  - **Broadcast**
    - 1\(\rightarrow\)all
  - **Multicast**
    - 1\(\rightarrow\)many = *group communication*
Groups

Groups allow us to deal with a collection of processes as one abstraction

Send a message to one entity
  – Deliver to the entire group

Groups are *dynamic*
  – Created and destroyed
  – Processes can join or leave
    • May belong to 0 or more groups

**Primitives:**
  • `create_group`
  • `delete_group`
  • `join_group`
  • `leave_group`
  • `send_to_group`
  • `query_membership`

*Optional
Design Issues

- **Closed vs. Open**
  - Closed: only group members can send messages

- **Peer vs. Hierarchical**
  - Peer: each member communicates with the entire group
  - Hierarchical: go through coordinator(s)
    - Root coordinator: forwards message to appropriate subgroup coordinators

- **Managing membership & group creation/deletion**
  - Distributed vs. centralized

- **Leaving & joining** — must be synchronous

- **Fault tolerance & message order**
  - Reliable message delivery? What about missing members?
  - Do messages need to be received in the order they were sent?
Failure considerations

The same things bite us with unicast communication

- **Crash failure**
  - Process stops communicating

- **Omission failure** (typically due to network)
  - Send omission: A process fails to send messages
  - Receive omission: A process fails to receive messages

- **Byzantine failure**
  - Some messages are faulty

- **Partitions**
  - The network may get segmented, dividing the group into two or more unreachable sub-groups
Implementing Group Communication Mechanisms
Hardware multicast

If we have hardware support for multicast
- Group members listen on network address

send $addr=m_1$

listen multicast $addr = m_1$

listen multicast $addr = m_1$

listen multicast $addr = m_1$
Diffusion group: send to all clients & then filter
- Software filters incoming broadcast or multicast address
- May need to use auxiliary group ID to identify the group
  (not in the network address header)
Hardware multicast & broadcast

- Ethernet supports both multicast & broadcast
- Limited to local area networks
Software implementation: multiple unicasts

Sender knows group members

- send(a_2)
- send(a_3)
- send(a_5)

listen local addr = a_2
listen local addr = a_3
listen local addr = a_5
Software implementation: hierarchical

Multiple unicasts via group coordinator

- Coordinator knows group members
- Coordinator iterates through group members
- May support a hierarchy of coordinators
Publish-Subscribe (Pub/Sub)

Communication pattern – one of several for group communication

- Publishers & subscribers
  - Publishers: send messages — typically to a topic
  - Subscribers: receive messages that match certain attributes (topics)

- Message broker – service that filters, routes, & queues messages
  (also known as a message bus or event bus)
Publish-Subscribe (Pub/Sub)

The message broker is a service that is responsible for

- Message queuing
- Filtering
- Reliability (of itself and, in some cases, dealing with dead subscribers)
- Delivery guarantees and message ordering
- Scaling to handle message volume and clients
Reliability of multicasts
Unreliable multicast (best effort)

• Basic multicast

• Hope it gets to all the members

• Best-effort delivery
  – The system (computers & network) tries to deliver messages to their destinations but does not retransmit corrupted or lost data
Reliable multicast

- All non-faulty group members will receive the message
  - Assume sender & recipients will remain alive
  - Network may have glitches
    - Try to retransmit undelivered messages … but eventually give up
  - It’s OK if some group members don’t get the message

- Acknowledgements
  - Send message to each group member
  - Wait for acknowledgement from each group member
  - Retransmit to non-responding members
  - Subject to feedback implosion in group communication
    - Feedback implosion = a system sends one message but gets many back in response.
      E.g., send a message to a group of 1,000 members and get back 1,000 acknowledgements.
Optimizing Acknowledgements

- Easiest thing is to wait for an ACK before sending the next message
  - But that incurs a round-trip delay

- Optimizations
  - **Pipelining**
    - Send multiple messages – receive ACKs asynchronously
    - Set timeout – retransmit message for missing ACKs
  - **Cumulative ACKs**
    - Wait a little while before sending an ACK
    - If you receive other messages, then send one ACK for everything
  - **Piggybacked ACKs**
    - Send an ACK along with a return message
  - **Negative ACKs**
    - Use a sequence # on each message
    - Receiver requests retransmission of a missed message
    - More efficient but requires sender to buffer messages indefinitely
    - Need to account for the receiver not sending a negative ACK because it is dead

TCP (not multicast) does the first three of these … but with groups we must do this for each recipient
Atomic multicast

Atomicity – “all or nothing” property

A message sent to a group arrives at all group members
If it fails to arrive at any member, no member will process it

Problems

– Unreliable network
  • Each message should be acknowledged
  • Acknowledgements can be lost
– Recipient might die
– Message sender might die
Achieving atomicity

• General idea
  – Ensure that every recipient acknowledges receipt of the message
  – Only then allow the application to process the message
  – If we give up on a recipient then no recipient can process that received message

• Easier said than done!
  – What if a recipient dies after acknowledging the message?
    • Is it obligated to restart?
    • If it restarts, will it know to process the message?
  – What if the sender (or coordinator) dies partway through the protocol?
Achieving atomicity – example 1

Retry through network failures & system downtime

- Sender & receivers maintain a persistent log
- Each message has a unique ID so we can discard duplicates

Sender
  - Write message to log
  - Send message to all group members
  - Wait for acknowledgement from each group member
  - Write acknowledgement to log
  - If timeout on waiting for an acknowledgement, retransmit to group member

Receiver
  - Log received non-duplicate message to persistent log
  - Send acknowledgement

NEVER GIVE UP!
  - Assume that dead senders or receivers will be rebooted and will restart where they left off
Redefine the group

• If some members failed to receive the message:
  – Remove the failed members from the group
  – Then allow existing members to process the message

• But still need to account for the death of the sender
  – Surviving group members may need to take over to ensure all current group members receive the message

• This is the approach used in virtual synchrony
Message ordering
Good Ordering
Bad Ordering

message $a$

message $b$

order received

$a, b$

$b, a$
Good Ordering

Order received

Process 0

message a

Process 1

message b

a, b
Bad Ordering

Good ordering = consistent order
If a node sends a sequence of messages, all group members will receive the messages in the same order

Bad ordering = Some group members receive the messages in a different order than others
Sending vs. Receiving vs. Delivering

• Multicast receiver algorithm decides when to *deliver* a message to the process.

• A received message may be:
  – **Delivered immediately**
    (put on a delivery queue that the process reads)
  – **Placed on a hold-back queue**
    (because we need to wait for an earlier message)
  – **Rejected/discarded**
    (duplicate or earlier message that we no longer want)
Sending, delivering, holding back

sender

Multicast sending algorithm

send

receiver

deliver

delivery queue

hold-back queue

? discard

message transmission

receive

Multicast receiving algorithm
Global time ordering

• All messages are delivered in exact order sent
• Assumes two events never happen at the exact same time!

• Difficult (impossible) to achieve
• Not viable
Total ordering

- Consistent ordering at all receivers
- All messages are delivered at all group members in the same order
  - They are sorted into the same sequence before being placed on the delivery queue

1. If a process sends $m$ before $m'$
   then any other process that delivers $m'$ will have delivered $m$.

2. If a process delivers $m'$ before $m''$ then every other process will have delivered $m'$ before $m''$.

Implementation:

- Attach **unique totally sequenced message ID**
- Receiver delivers a message to the application only if it has received all messages with a smaller ID
- Otherwise, the message sits in the hold-back queue
Causal ordering

Also known as partial ordering

Messages sequenced by only if they are causally related (e.g., by Lamport or Vector timestamps)

If multicast(G, m) \rightarrow multicast(G, m')
then every process that delivers m' will have delivered m

If message m' is causally dependent on message m,
all processes must deliver m before m'
Causal ordering example

$m_1$ is causally dependent on the receipt of $m_0$
$\Rightarrow m_1$ must be delivered only after $m_0$ has been delivered

$m_0$ and $m_2$ have no causal relationship (they are concurrent)
$\Rightarrow$ Any process can deliver these messages in any order
Causal ordering – implementation

Implementation: $P_a$ receives a message from $P_b$

- Each process keeps a **precedence vector**

- Vector is updated on multicast *send* and *receive* events
  - Each position in the vector = sequence number of latest message from the corresponding group member that causally precedes the event: $[P_0, P_1, P_2, \ldots]$
Causal ordering – implementation

Algorithm

– When $P_a$ sends a message, it increments its own entry and sends the vector

$$V_a[a] = V_a[a] + 1$$

– where $a$ is the index for process $P_a$

Send $V_a$ with the message

– When $P_b$ receives a message from $P_a$

1. Check that the message arrived in sequential order from $P_a$:

$$V_a[a] == V_b[a] + 1 ?$$

2. Check that the message does not causally depend on messages $P_b$ has not received from other processes:

$$\forall i, i \neq a: V_a[i] \leq V_b[i] ?$$

*The sequence # of every other message in $P_a$ must be $\leq$ the corresponding on in $P_b*

*• If both conditions are satisfied, $P_b$ will deliver the message to the application:*

At $P_b$, update the precedence vector: $V_b[a] = V_b[a] + 1$

• Otherwise, *hold the message* until these conditions are satisfied
Causal Ordering: Example

P_2 receives message m_1 from P_1 with V_1=(1,1,0)

1) Is this in sequential order from P_1?
   Compare current V on P_2: V_2=(0,0,0) with received V from P_1, V_1=(1,1,0)
   Yes: V_2[1] = 0, received V_1[1] = 1 ⇒ sequential order – message 1 follows message 0

2) Is V_1[i] ≤ V_2[i] for all other i?
   Compare the same vectors: V_1=(1,1,0) vs. V_2=(0,0,0)
   No, because (V_1[0] = 1) > (V_2[0] = 0)
   – this means P_2 has seen msg #1 from P_0 that P_2 has not yet received

Therefore: hold back m_1 at P_2
Next, $P_2$ receives message $m_0$ from $P_0$ with $V=(1,0,0)$

1. Is $m_0$ in sequential order from $P_0$?
   - Compare current $V$ on $P_2$: $V_2=(0,0,0)$ with received $V$ from $P_0$, $V_0=(1,0,0)$
   - Yes: $V_2[0] = 0$, received $V_0[0] = 1 \Rightarrow$ sequential order

2. Is $V_0[i] \leq V_2[i]$ for all other $i$?
   - Yes. Element 0: $(0 \leq 0)$, Element 1: $(0 \leq 0)$

**Deliver $m_0$ on $P_2$ and update precedence vector on $P_2$ from (0, 0, 0) to (1, 0, 0)**

Now check hold-back queue. Can we deliver $m_1$?
Causal Ordering: Example

Check the message in the hold-back set
(1) Is the held-back message $m_1$ in sequential order from $P_0$?
Compare element 1 on current $V$ on $P_2$: $V_2 = (1, 0, 0)$ with held-back $V$ from $P_0$, $V_0 = (1, 1, 0)$
Yes: (current $V_2[1] = 0$) vs. (received $V_1[1] = 1$) ⇒ sequential
(2) Is $V_0[i] \leq V_2[i]$ for all other $i$?
Now yes. ($V_0[0] = 1 \leq V_2[0] = 1$) and element 2: ($V_0[2] = 0 \leq V_2[2] = 0$)

Deliver $m_1$ on $P_2$ and update the precedence vector on $P_2$: $V_2 = (1, 1, 0)$
Causal Ordering

- Causal ordering can be implemented more efficiently than total ordering:
  - No need for a global sequencer
  - Expect reliable delivery but we may not need to send immediate acknowledgements
Sync ordering

- Messages can be delivered in any order
- Special message type
  - Synchronization primitive = barrier
  - Ensure all pending messages are delivered before any additional (post-sync) messages are accepted

If $m$ is sent with a sync-ordered primitive and $m'$ is multicast, then every process either delivers $m$ before $m'$ or delivers $m'$ before $m$.

Multiple sync-ordered primitives from the same process must be delivered in order.
Single Source FIFO (SSF) ordering

- Messages from the same source are delivered in the order they were sent
  - Message $m$ must be delivered before message $m'$ iff $m$ was sent before $m'$ from the same host

If a process issues a multicast of $m$ followed by $m'$, then every process that delivers $m'$ will have already delivered $m$. 
Unordered multicast

- Messages can be delivered in different order to different members
- Order per-source does not matter
Multicasting considerations

- atomic
- reliable
- unreliable

Message Ordering

- unordered
- Single-Source FIFO
- sync
- causal
- total
- global
The End