# Distributed Systems

## 07. Group Communication & Multicast

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# Modes of communication

- One-to-One
  - Unicast
    - 1↔1
    - Point-to-point
  - Anycast
    - 1→nearest 1 of several identical nodes
    - Introduced with IPv6; used with BGP routing protocol
- One-to-many
  - Multicast
    - 1→many
    - group communication
  - Broadcast
    - 1→all

# Groups

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

## Send message to one entity

– Deliver to entire group

## Groups are *dynamic*

– Created and destroyed

– Processes can join or leave

- May belong to 0 or more groups

## Primitives

*join_group, leave_group, send_to_group, query_membership* (sometimes)

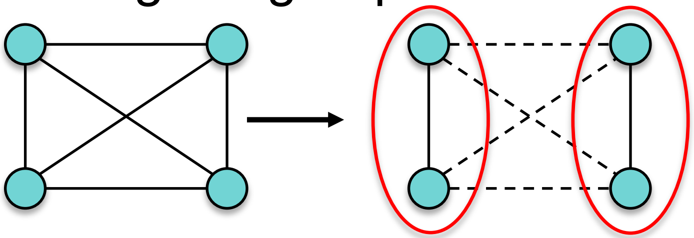
# Design Issues

- Closed vs. Open
  - Closed: only group members can sent 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
  - Reliable message delivery? What about missing members?

# 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
- Partition failure
  - The network may get segmented, dividing the group into two or more unreachable sub-groups

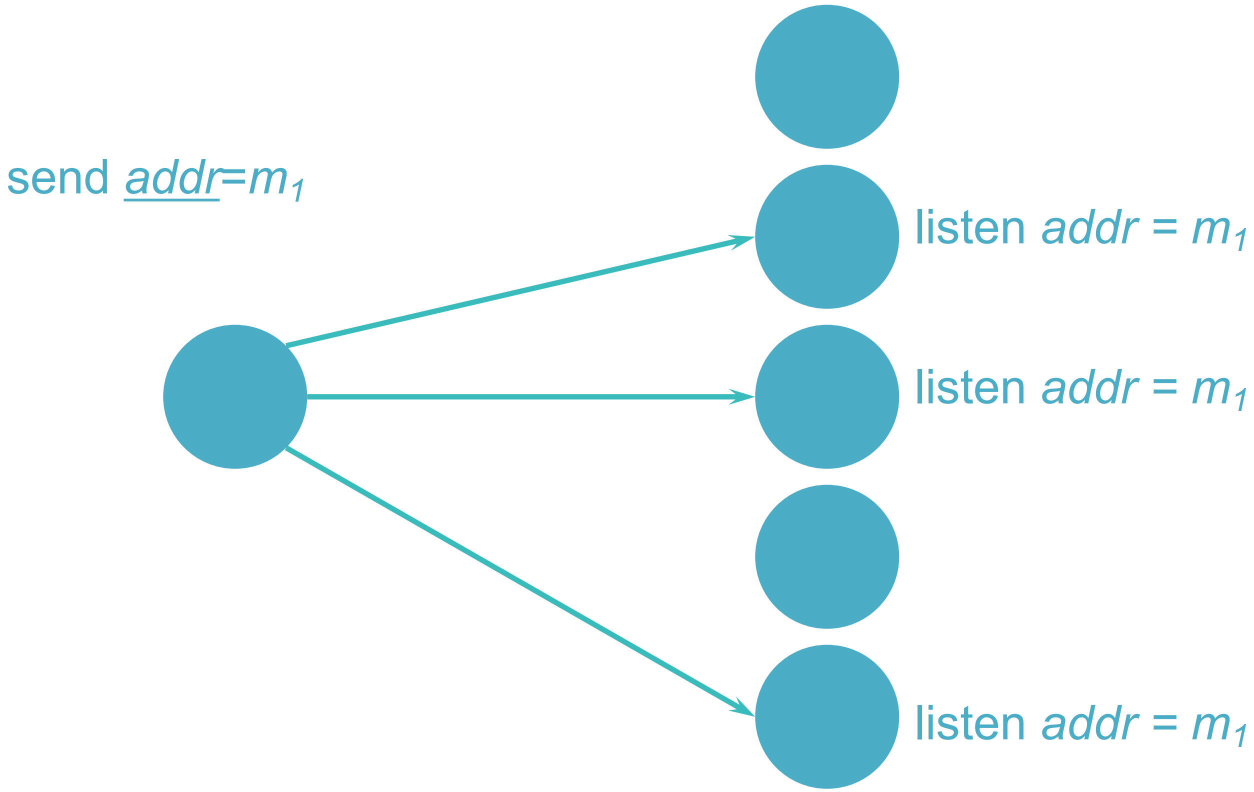


# Implementing Group Communication Mechanisms

# Hardware multicast

If we have hardware support for multicast

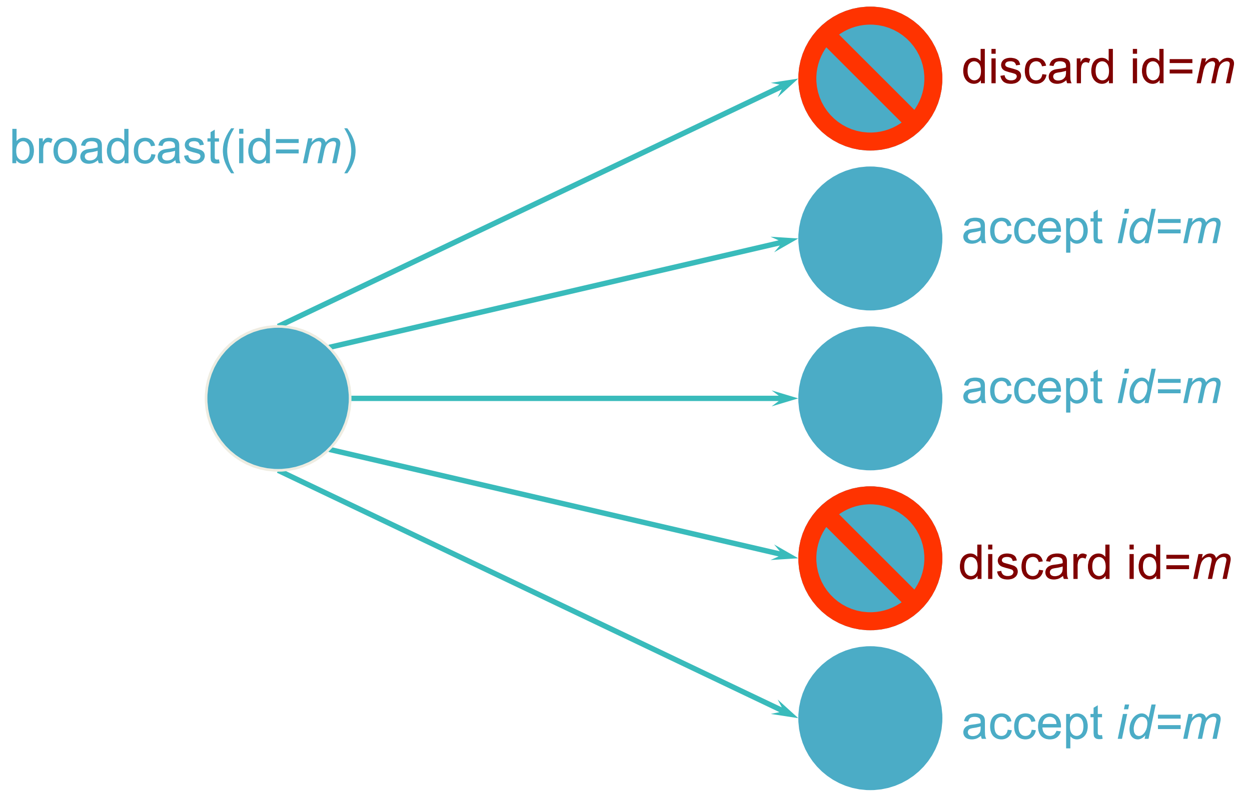
– Group members listen on network address



# Broadcast

Diffusion group: send to all clients & then filter

- Software filters incoming multicast address
- May use auxiliary address (not in the network address header) to identify group

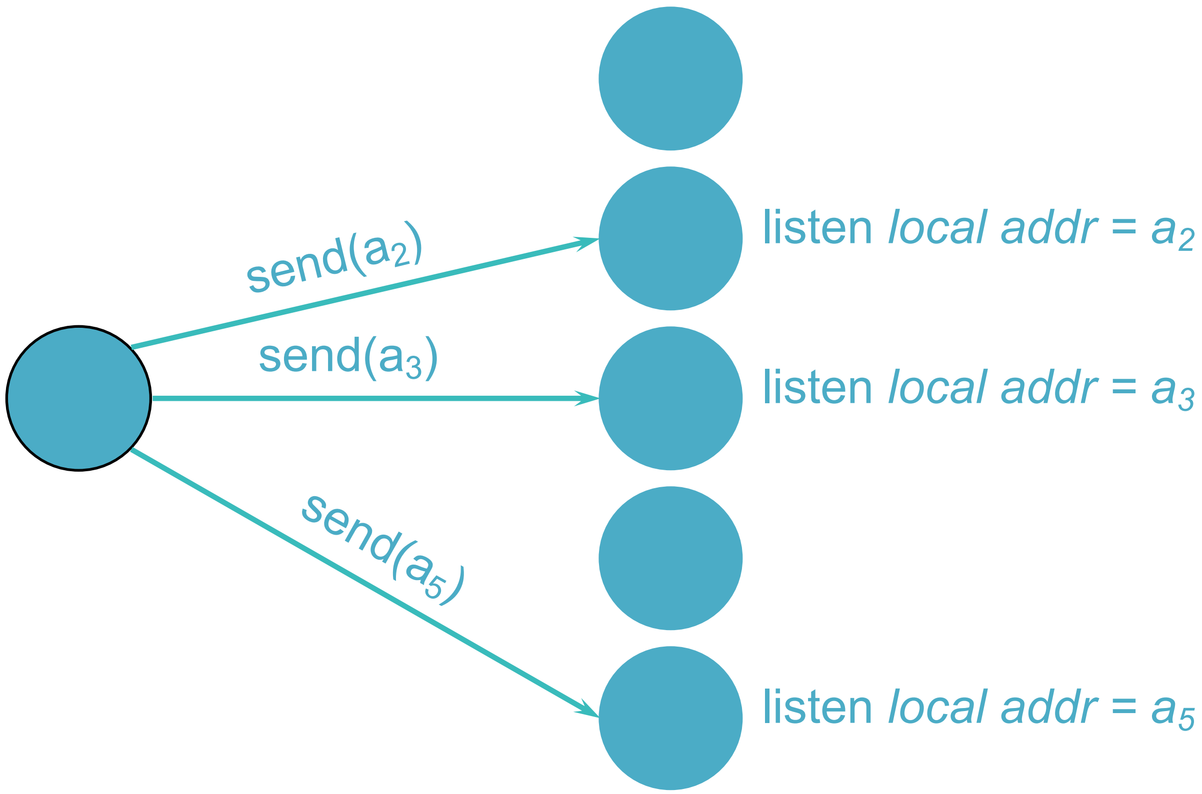


# Hardware multicast & broadcast

- Ethernet supports both multicast & broadcast
- Limited to local area networks

# Software implementation: multiple unicasts

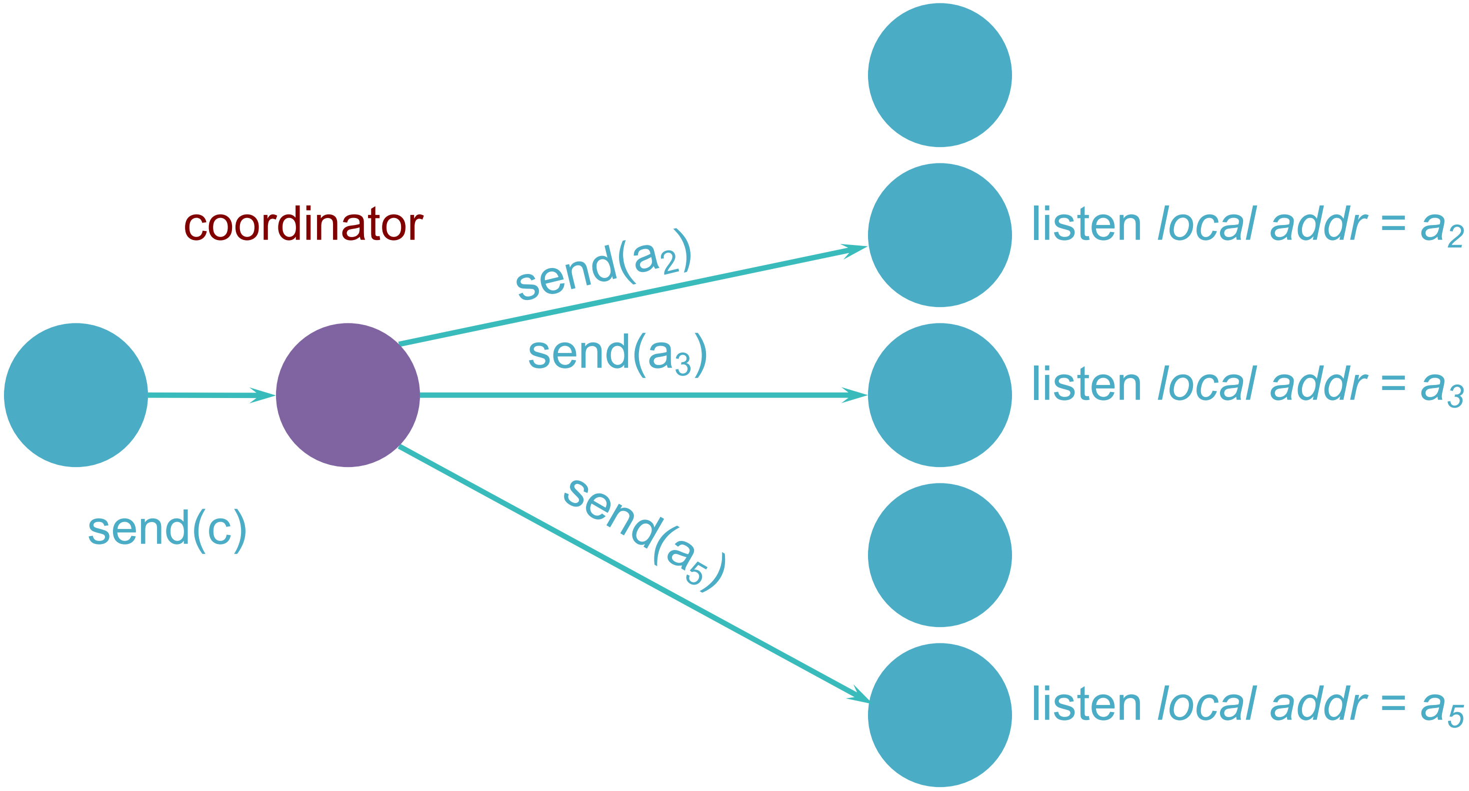
Sender knows group members



# Software implementation: hierarchical

Multiple unicasts via group coordinator

- Coordinator knows group members
- Coordinator iterates through group members
- May support a hierarchy of coordinators



# Reliability of multicasts

# Atomic multicast

## Atomicity

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

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

<u>Retry through network failures & system downtime</u>

- Sender & receivers maintain a persistent log
- Each message has a unique ID so we can discard duplicates
- Sender
  - Send message to all group members
  - Write message to log
  - 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

# Achieving atomicity – example 2

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

# 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**

# 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 others, 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
- TCP does the first three of these

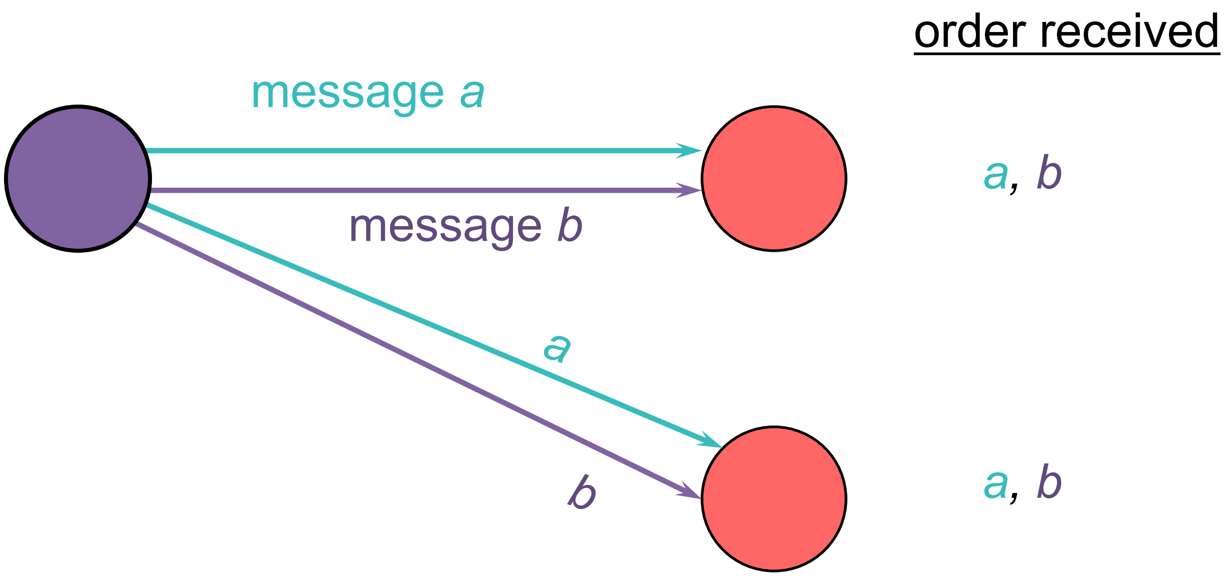
  … but now we have to do this for each recipient

# Unreliable multicast (best effort)

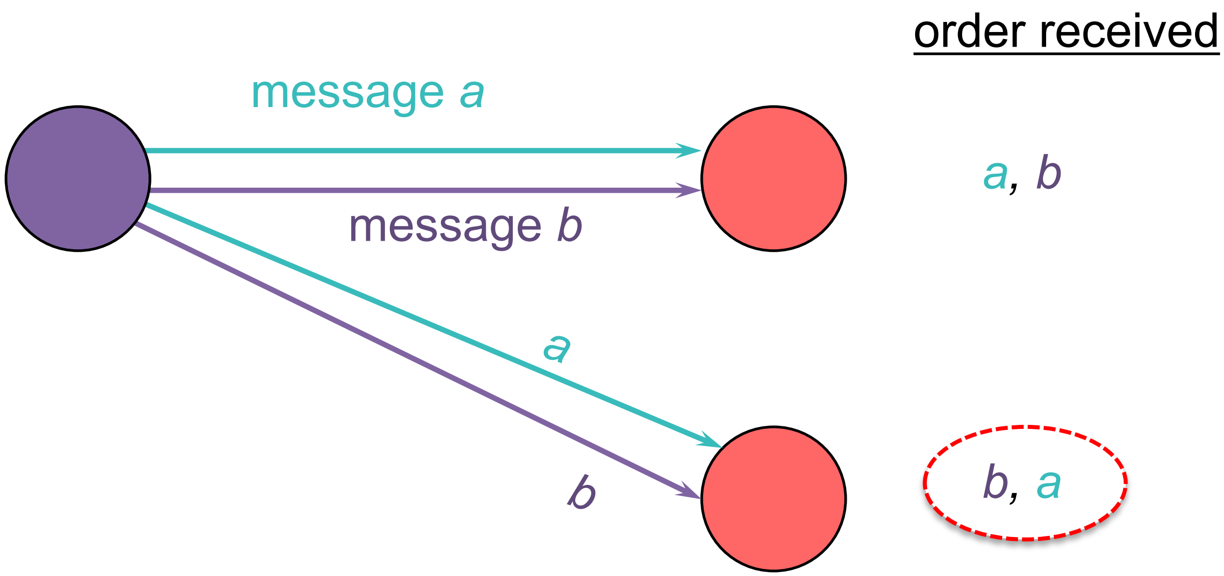
- Basic multicast
- Hope it gets there

# Message ordering

# Good Ordering



# Bad Ordering



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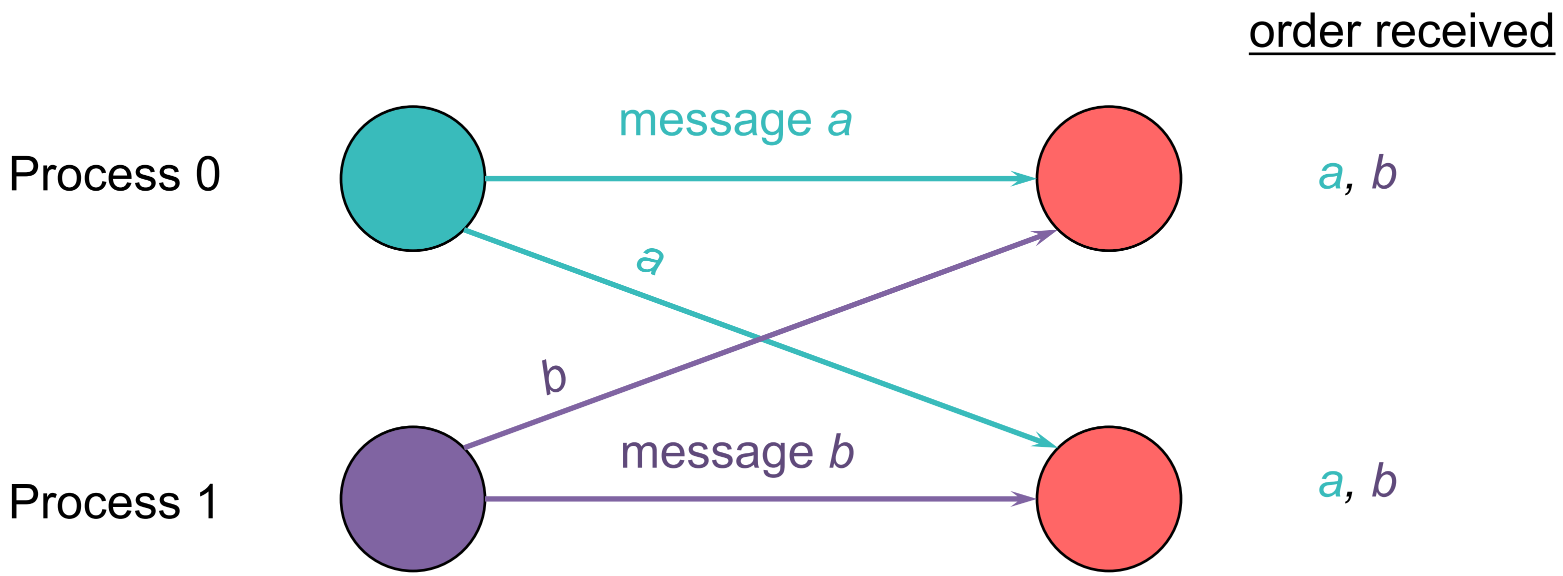

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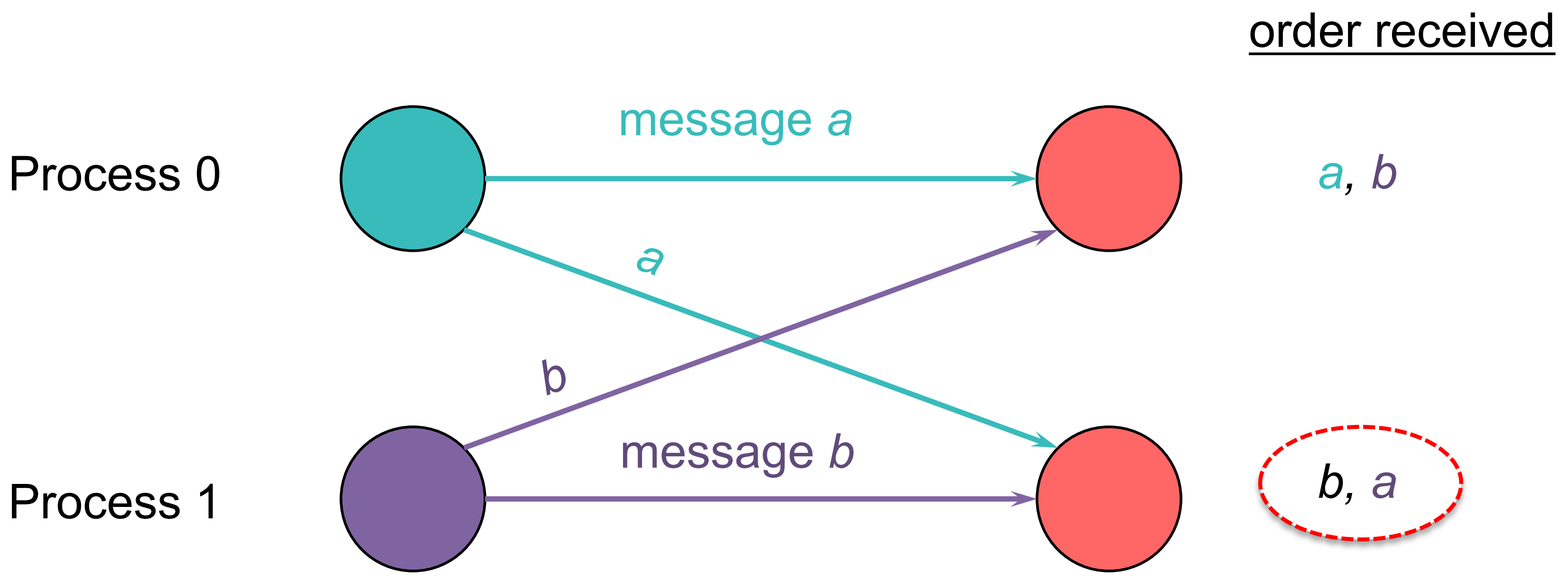
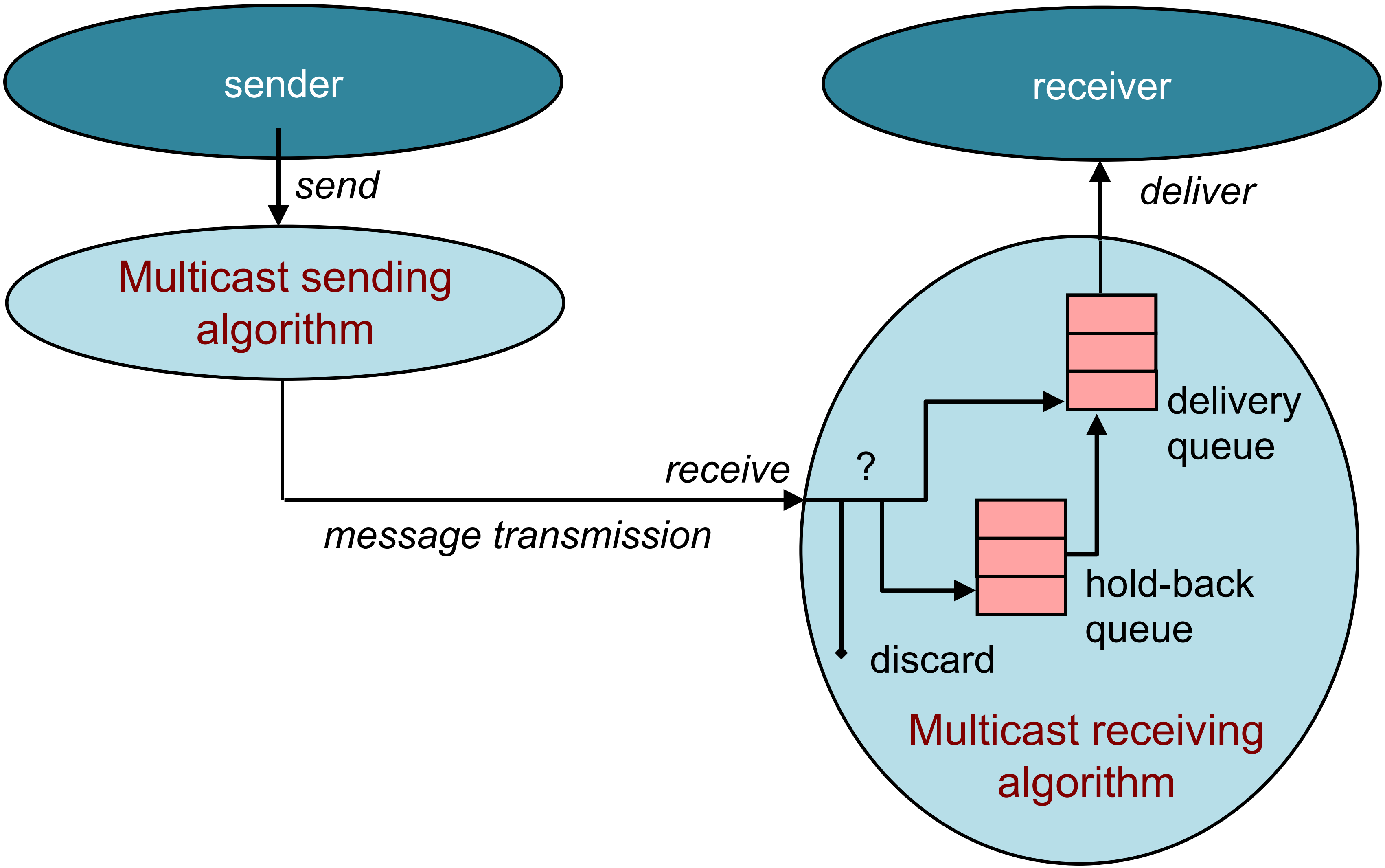


# Sending vs. Receiving vs. Delivering

- 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



# 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 in the same order in the delivery queue

1. If a process sends *m* before *m'*
   then <u>*any*</u> 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

# Causal ordering

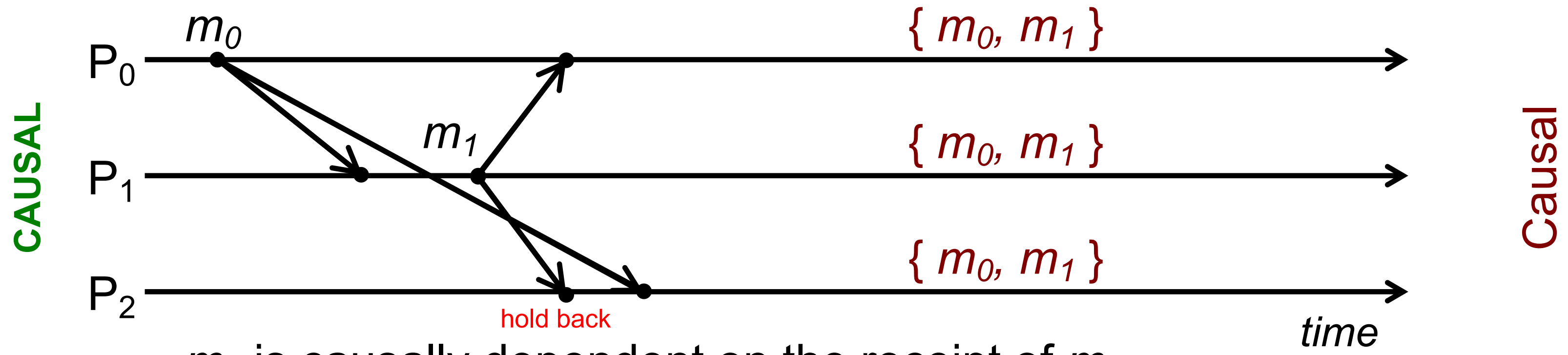
- Also known as partial ordering
  - Messages sequenced by Lamport or Vector timestamps

If multicast($G$, $m$) → multicast($G$, $m'$)

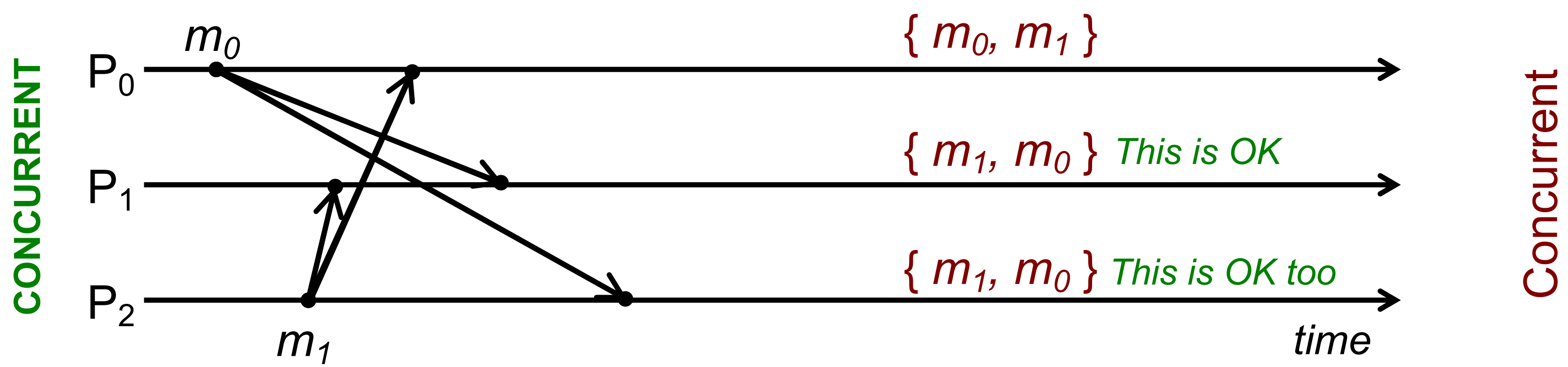
then *every* process that delivers $m'$ will have delivered $m$

- 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 $m_0$.
Hence, $m_1$ must be delivered after $m_0$ has been delivered.

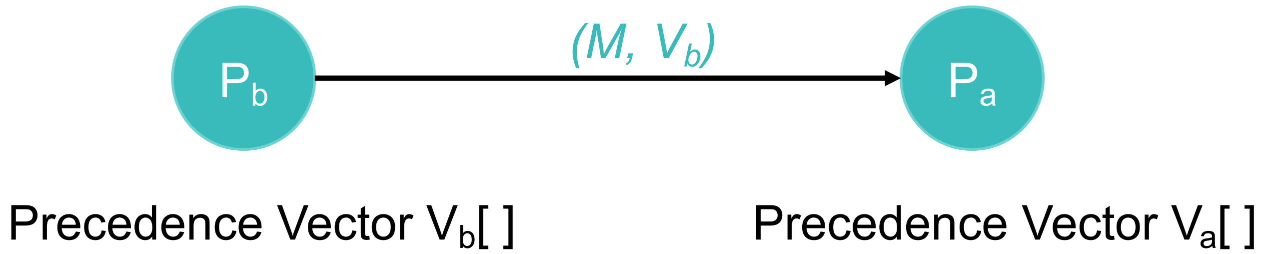



$m_0$ and $m_1$ have no causal relationship (they are concurrent).
Any process can deliver them in any order.

# Causal ordering – implementation

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

- Each process keeps a **precedence vector** (similar to vector timestamp)
- Vector is updated on multicast *send* and *receive* events
  - Each entry = # of latest message from the corresponding group member that causally precedes the event



# Causal ordering – implementation

Algorithm

- When $P_b$ **sends** a message, it increments its own entry and sends the vector

  $V_b[b] = V_b[b] + 1$

  Send $V_b$ with the message

- When $P_a$ **receives** a message from $P_b$
  - Check that the message arrived in FIFO order from $P_b$:

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

  - Check that the message does not causally depend on something $P_a$ has not seen:

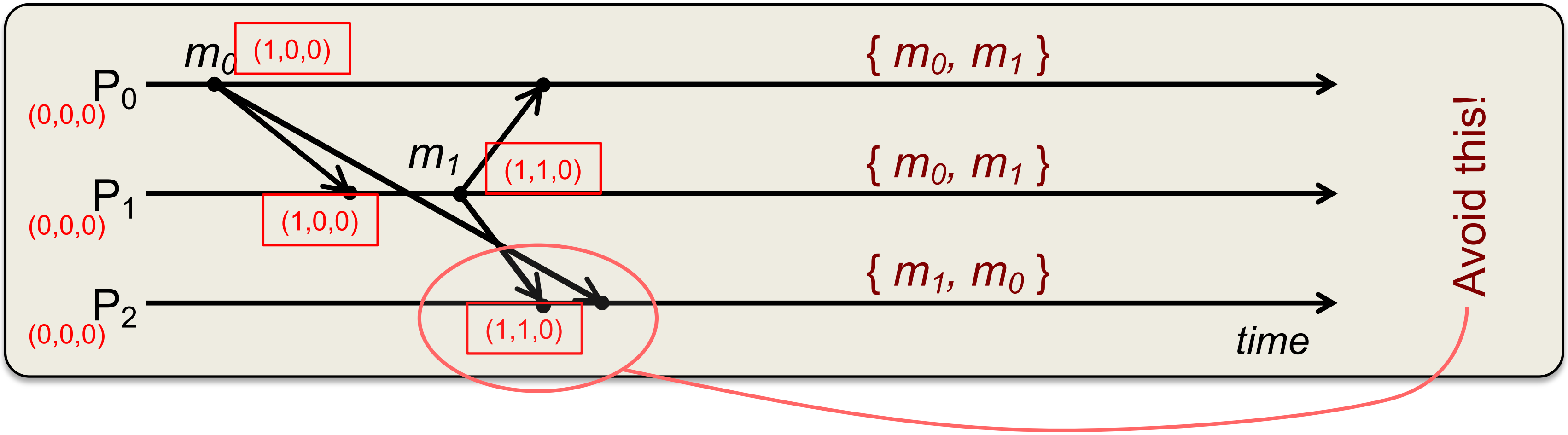
    $\forall i, i \neq b$: $V_b[i] \leq V_a[i]$ ?

  - If both conditions are satisfied, $P_a$ will deliver the message

    At $P_a$, update $V_a[b] = V_a[b]+1$

  - Otherwise, *hold the message* until the 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 FIFO 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 $V_1[1] = 1 \Rightarrow$ sequential order

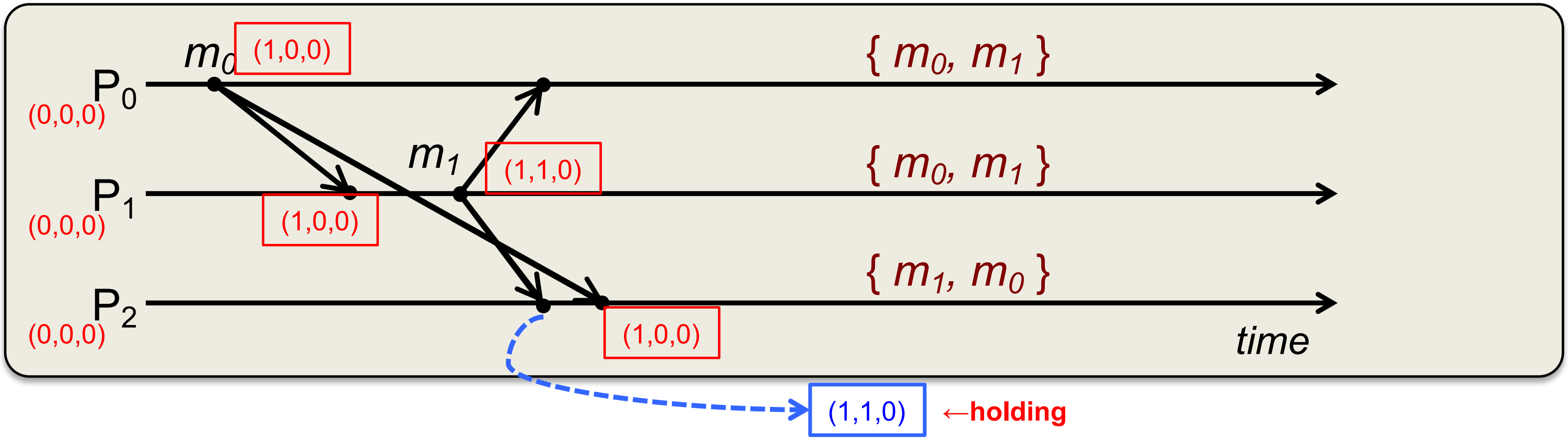
(2) Is $V_1[i] \leq V_2[i]$ for all other i?

Compare the same vectors: **$V_2$=(0,0,0) vs. $V_1$=(1,1,0)**

No. $(V_1[0] = 1) > (V_2[0] = 0)$

Therefore: hold back $m_1$ at $P_2$

# Causal Ordering: Example




$P_2$ receives message $m_0$ from $P_0$ with V=(1,0,0)

(1) Is this in FIFO order from $P_0$?

Compare current V on $P_2$: $V_2$=(0,0,0) with received V from $P_2$, $V_2$=(1,0,0)

Yes: $V_2[0] = 0$, received $V_1[0] = 1 \Rightarrow$ sequential

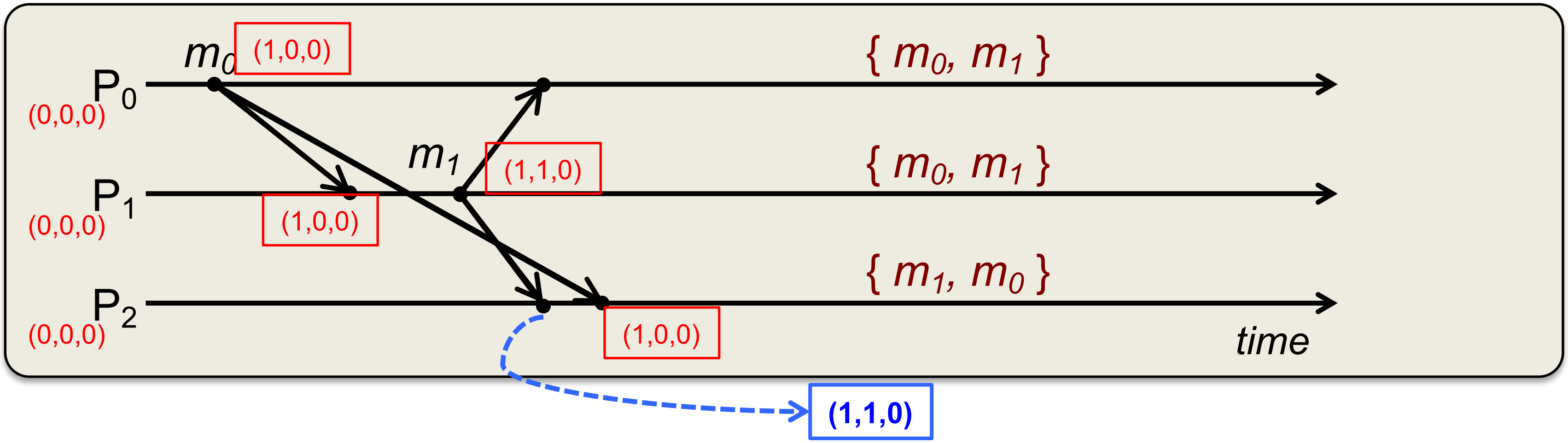
(2) Is $V_0[i] \leq V_2[i]$ for all other i?

Yes. $(0 \leq 0)$, $(0 \leq 0)$.

**Deliver $m_0$. Update precedence vector from (0, 0, 0) to (1, 0, 0)**

Now check hold-back queue. Can we deliver $m_1$?

# Causal Ordering: Example




(1) Is the held-back message $m_1$ in FIFO order from $P_0$?

Compare current V on $P_2$: **$V_2$=(1,0,0)** with held-back V from $P_0$, **$V_1$=(1,1,0)**

Yes: (current **$V_2$[1] = 0**) vs. (received **$V_1$[1] = 1**) ⇒ **sequential**

(2) Is $V_0[i] \le V_2[i]$ for all other i?

Now yes. **($V_0$[0] = 1) ≤ ($V_2$[0] = 1)** and element 2: **($V_0$[2] = 0) ≤ ($V_2$[2] = 0)**

Deliver $m_1$.

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 arrive in any order
- Special message type
  - Synchronization primitive
  - 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*.

# Single Source FIFO (SSF) ordering

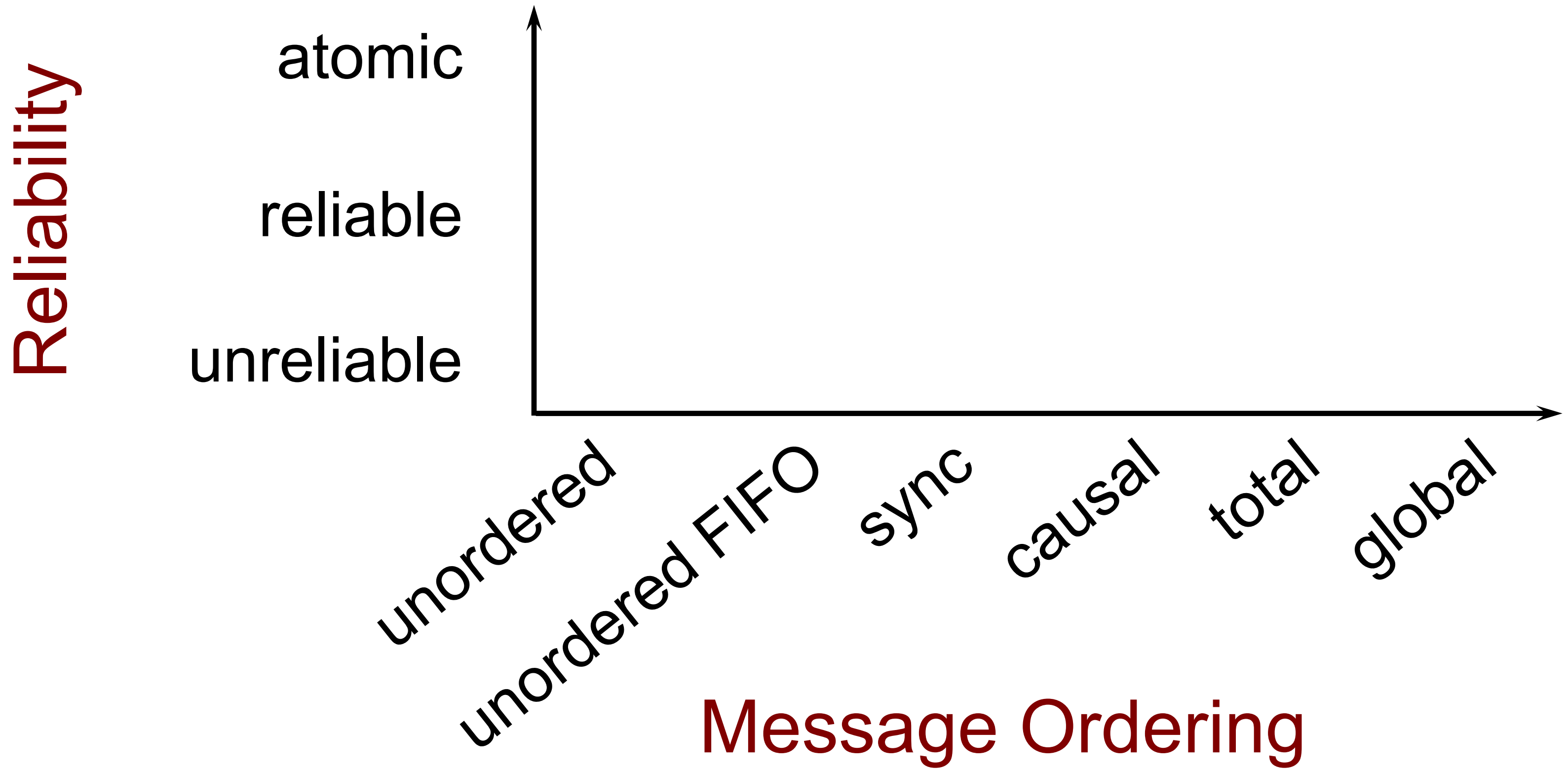
If a process issues a multicast of *m* followed by *m'*, then *every process* that delivers *m'* will have already delivered *m*.

# Unordered multicast

- Messages can be delivered in different order to different members

- Order per-source does not matter.

# Multicasting considerations



# IP multicast routing

# IP multicast routing

- Deliver messages to a subset of nodes
  - Send to a **multicast address**
- How do we identify the recipients?
  - Enumerate them in the header?
    - What if we don't know?
    - What if we have thousands of recipients?
- Use a **special address** to identify a group of receivers
  - A copy of the packet is delivered to all receivers associated with that group
  - IPv4: Class D multicast IP address
    - 32-bit address that starts with 1110
      (224.0.0.0/4 = 224.0.0.0 – 239.255.255.255 )
  - IPv6: 128-bit address with high-order bits 8 bits all 1
  - **Host group** = set of machines listening to a particular multicast address
    - A copy of the message is delivered to all receivers associated with that group

# IP multicasting

- Can span multiple physical networks
- Dynamic membership
  – Machine can join or leave at any time
- No restriction on number of hosts in a group
- Machine does not need to be a member to send messages
- Efficient: Packets are replicated only when necessary
- Like IP, no delivery guarantees

# IP multicast addresses

- Addresses chosen arbitrarily for an application
- Well-known addresses assigned by IANA

**Internet Assigned Numbers Authority**

IPv4 addresses: http://www.iana.org/assignments/multicast-addresses/multicast-addresses.xml

IPv6 addresses: https://www.iana.org/assignments/ipv6-multicast-addresses/ipv6-multicast-addresses.xhtml

- Similar to ports – service-based allocation
  - For ports, we have:
    - FTP: port 21, SMTP: port 25, HTTP: port 80
  - For multicast, we have:

| | |
|---|---|
| 224.0.0.1: | all systems on this subnet |
| 224.0.0.2: | all multicast routers on subnet |
| 224.0.23.173: | Philips Health |
| 224.0.23.52: | Amex Market Data |
| 224.0.12.0-63: | Microsoft & MSNBC |
| FF02:0:0:0:0:0:0:9: | RIP routers |

# IGMP

- Internet Group Management Protocol (IGMP)
  - Operates between a host and its attached router
  - Goal: *allow a router to determine to which of its networks to forward IP multicast traffic*
  - IP protocol (IP protocol number 2)
- Three message types
  - Membership_query
    - Sent by a router to all hosts on an interface to determine the set of all multicast groups that have been joined by the hosts on that interface
  - Membership_report
    - Host response to a query or an initial join or a group
  - Leave_group
    - Host indicates that it is no longer interested
    - Optional: router infers this if the host does not respond to a query

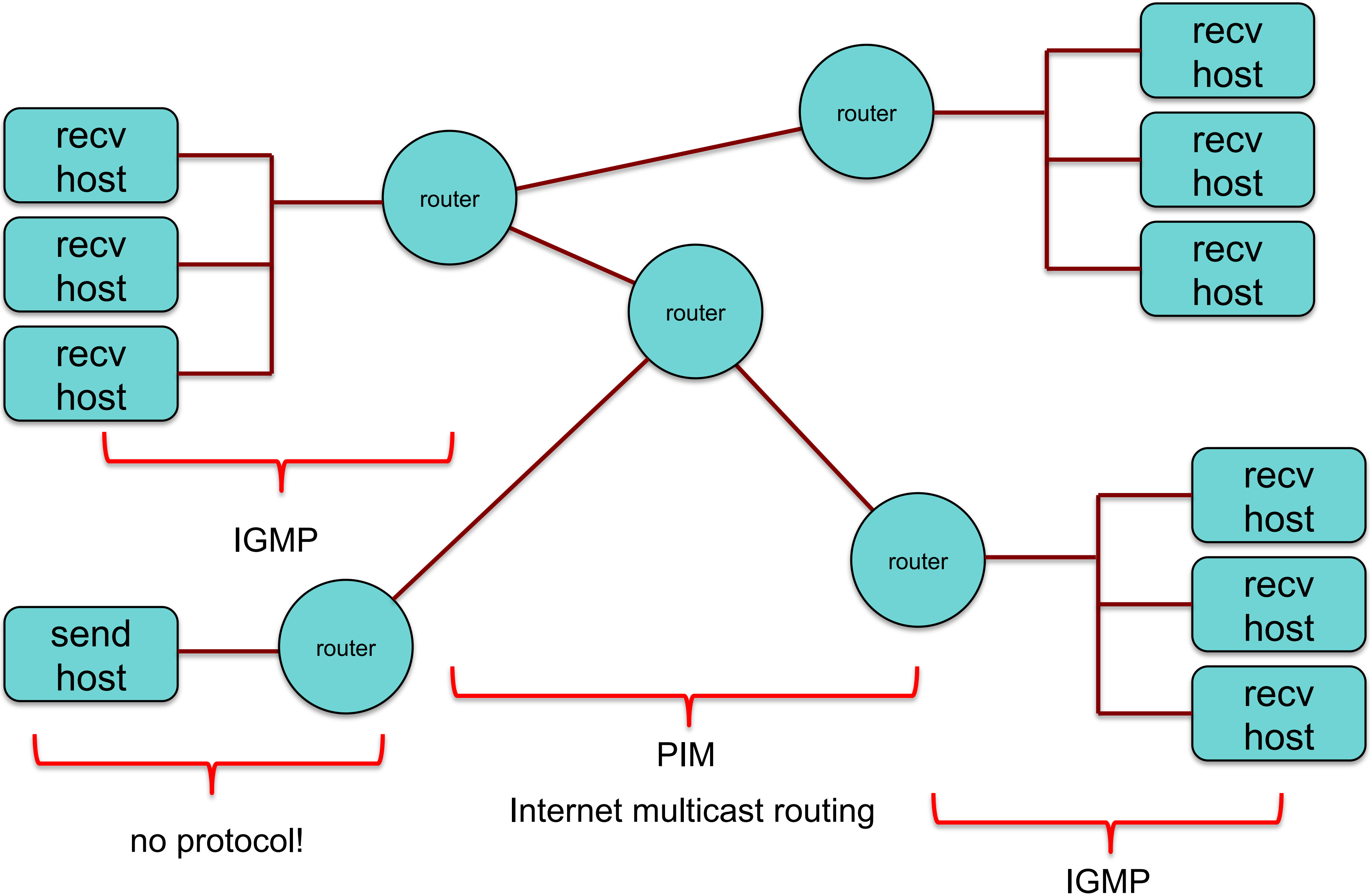
# Multicast Forwarding

IGMP allows a host to *subscribe* to receive a multicast stream

What about the source?

- There is no protocol for the source!
- It just sends one message to a class D address
- Routers have to do the work

# IGMP & Wide-Area Multicast Routing



# Multicast Forwarding

- IGMP: Internet Group Management Protocol
  - Designed for routers to talk with hosts on directly connected networks
- PIM: Protocol Independent Multicast
  - Multicast Routing Protocol for delivering packets across routers
  - Topology discovery is handled by other protocols
  - Two forms:
    1. Dense Mode (PIM-DM)
    2. Sparse Mode (PIM-SM)

# Flooding: Dense Mode Multicast (PIM-DM)

- Relay multicast packet to all connected routers
  - Use a spanning tree and reverse path forwarding (RPF) to avoid loops
  - Feedback & cut off if there are no interested receivers on a link
    - A router sends a *prune* message.
    - Periodically, routers send messages to refresh the prune state
  - Flooding is initiated by the sender's router

- Reverse path forwarding (RPF): avoid routing loops
  - Packet is duplicated & forwarded ONLY IF it was received via the link that is the shortest path to the sender
  - Shortest path is found by checking the router's forwarding table to the source address

# Flooding: Dense Mode Multicast

- Advantage:
  - Simple
  - Good if the packet is desired in most locations
- Disadvantage:
  - wasteful on the network, wasteful extra state & packet duplication on routers

# Sparse Mode Multicast (PIM-SM)

- Initiated by the routers at each receiver
- Each router needs to ask for a multicast feed with a PIM *Join* message
  - Initiated by a router at the destination that gets an IGMP *join*
  - Rendezvous Point: meeting place between receivers & source
    - *Join* messages propagate to a defined ***rendezvous point*** (**RP**)
    - Sender transmits only to the rendezvous point
    - RP announcement messages inform edge routes of rendezvous points
  - A *Prune* message stops a feed
- Advantage
  - Packets go only where needed
  - Creates extra state in routers only where needed

# IP Multicast in use

- Initially exciting:
  - Internet radio, NASA shuttle missions, collaborative gaming
- But:
  - Few ISPs enabled it
  - For the user, required tapping into existing streams (not good for on-demand content)
  - Industry embraced unicast instead

# IP Multicast in use: IPTV

- IPTV has emerged as the biggest user of IP multicast
  - Cable TV networks have migrated (or are migrating) to IP delivery

- Cable TV systems: aggregate bandwidth ~ 4.5 Gbps
  - Video streams: MPEG-2 or MPEG-4 (H.264)
  - MPEG-2 HD: ~30 Mbps ⇒ 150 channels = ~4.5 Gbps
  - MPEG-4 HD: ~6-9 Mbps; DVD quality: ~2 Mbps

- Multicast
  - Reduces the number of servers needed
  - Reduces the number of duplicate network streams

# IP Multicast in use: IPTV

- Multicast allows one stream of data to be sent to multiple subscribers using a single address
- IGMP from the client
  - Subscribe to a TV channel
  - Change channels
- Use unicast for video on demand

# The end