Distributed Systems
分布式系统

Group Communication

群组通信

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)

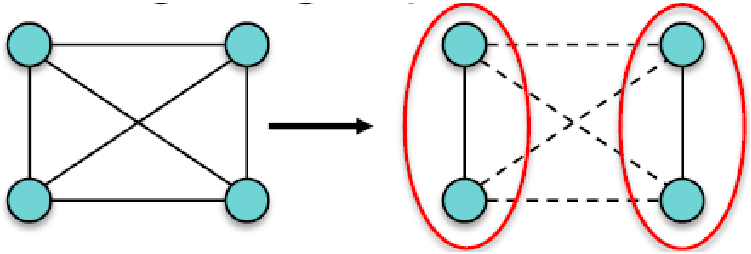
Design Issues

- 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 (容错性）
  - 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



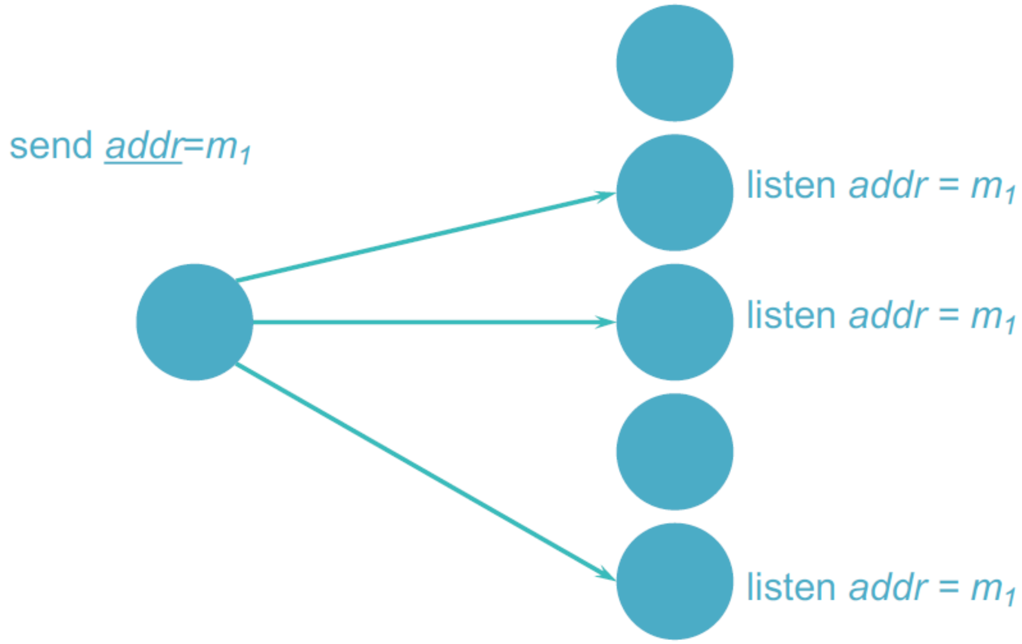
Implementing Group Communication Mechanisms

组播方法实现

Hardware multicast

If we have hardware support for multicast

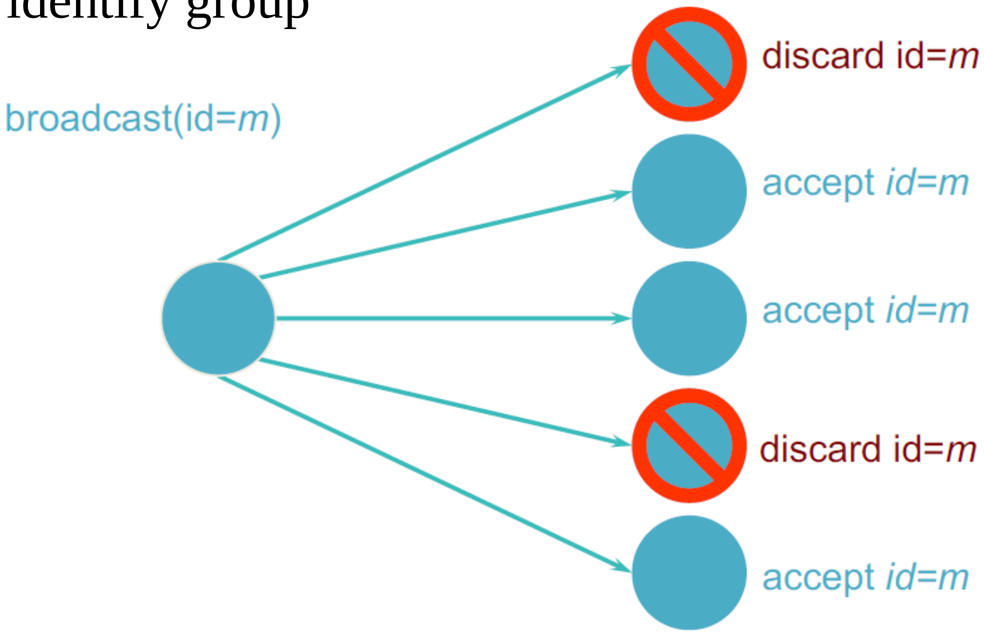
- Group members listen on network address



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

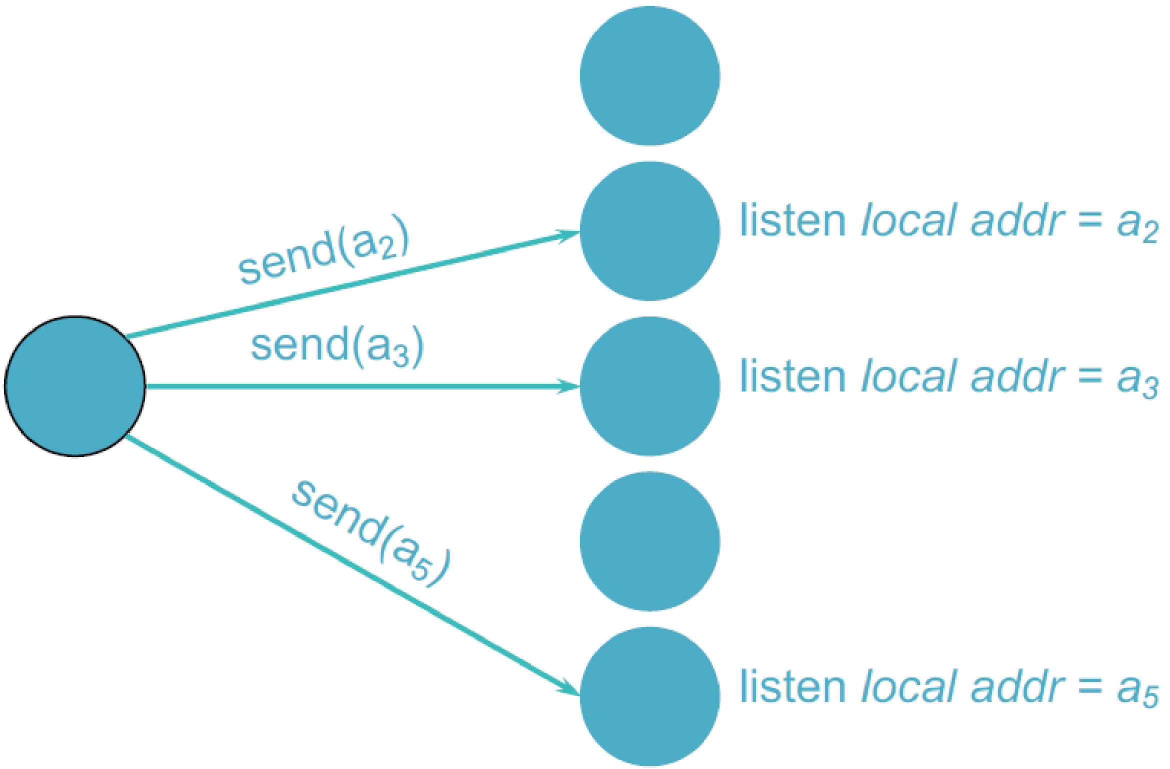


Hardware multicast & broadcast

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

Software implementation: multiple unicasts

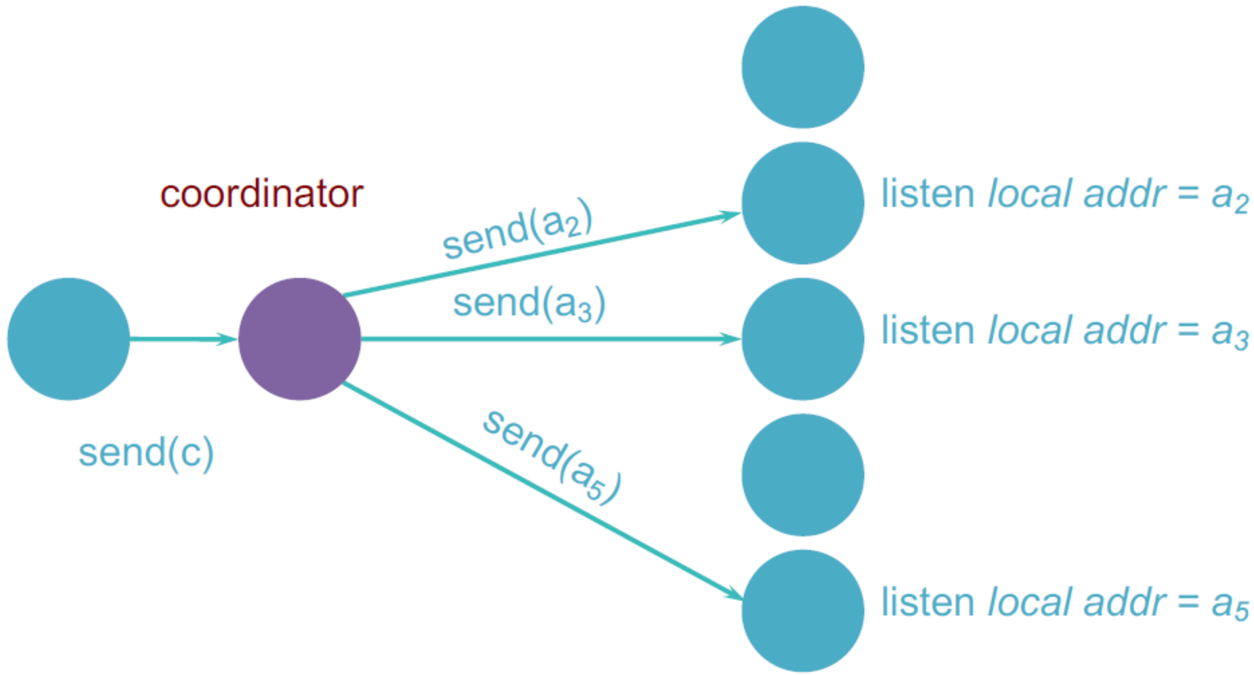
Sender knows group members



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 组播可靠性

Atomic multicast

Atomicity （原子性）

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

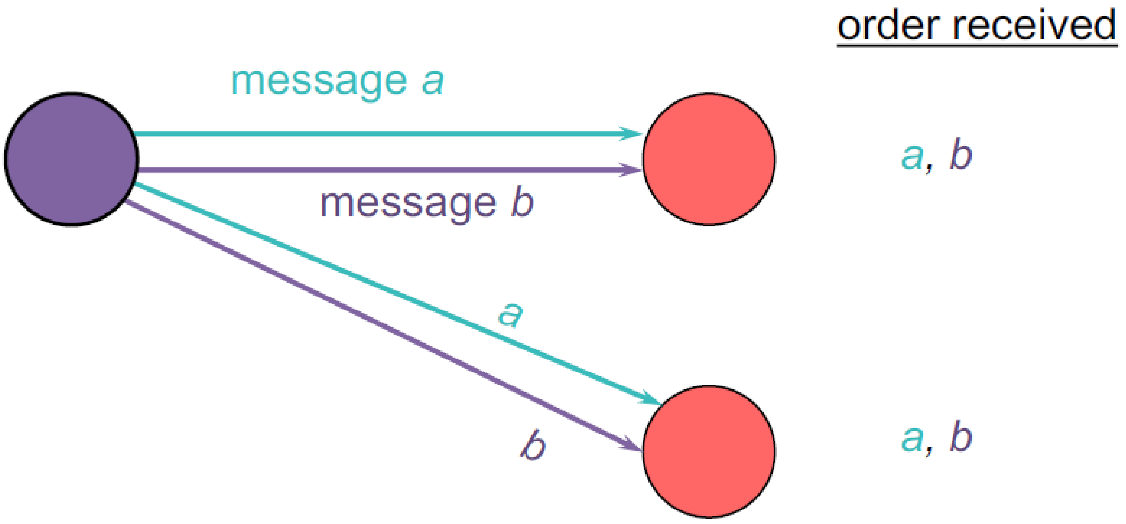
...but now we have to do this for each recipient

Unreliable multicast (best effort)

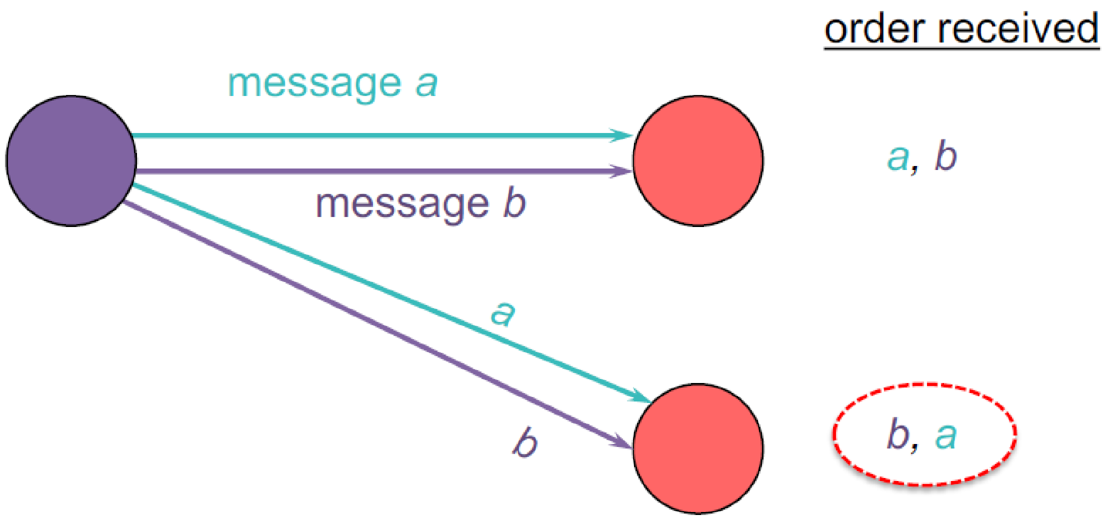
- Basic multicast
- Hope it gets there

Message ordering 消息顺序

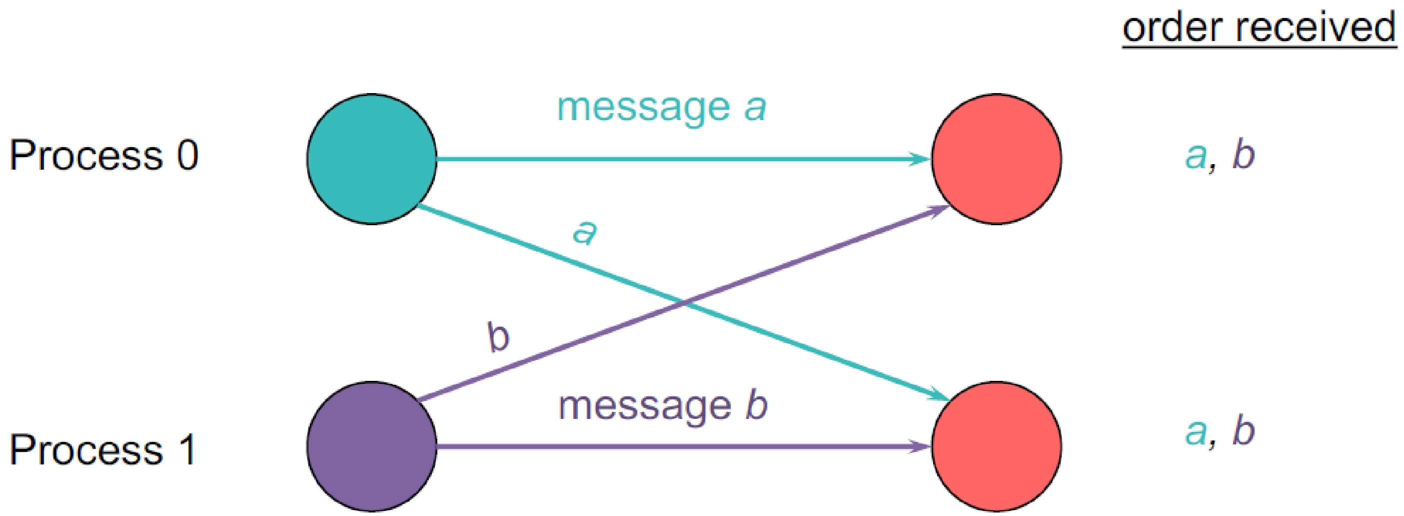
Good Ordering



Bad Ordering



Good Ordering



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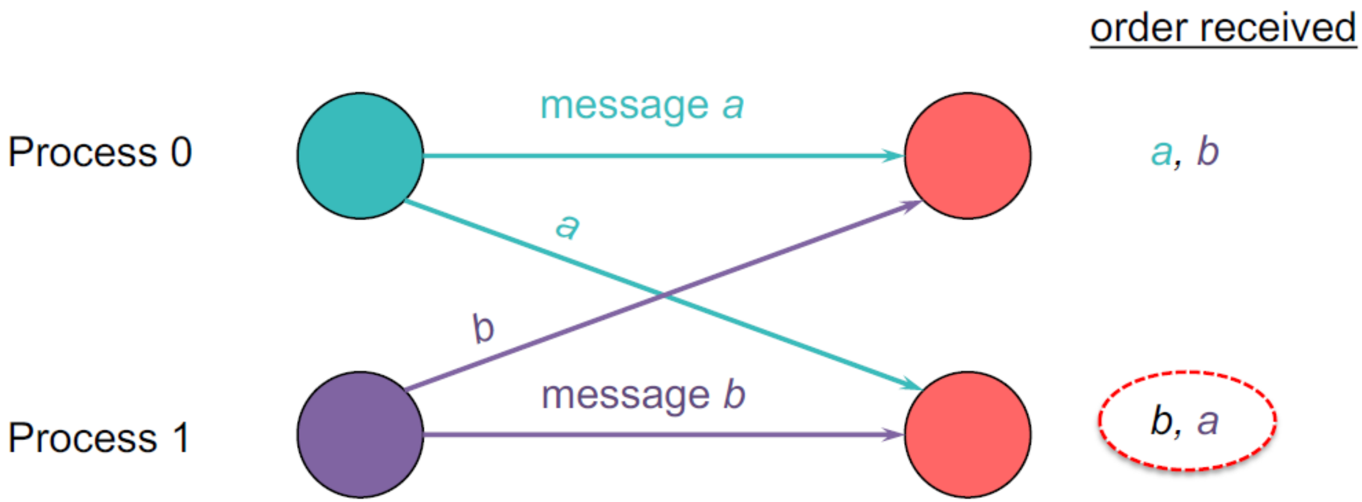


Sending vs. Receiving vs. Delivering

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

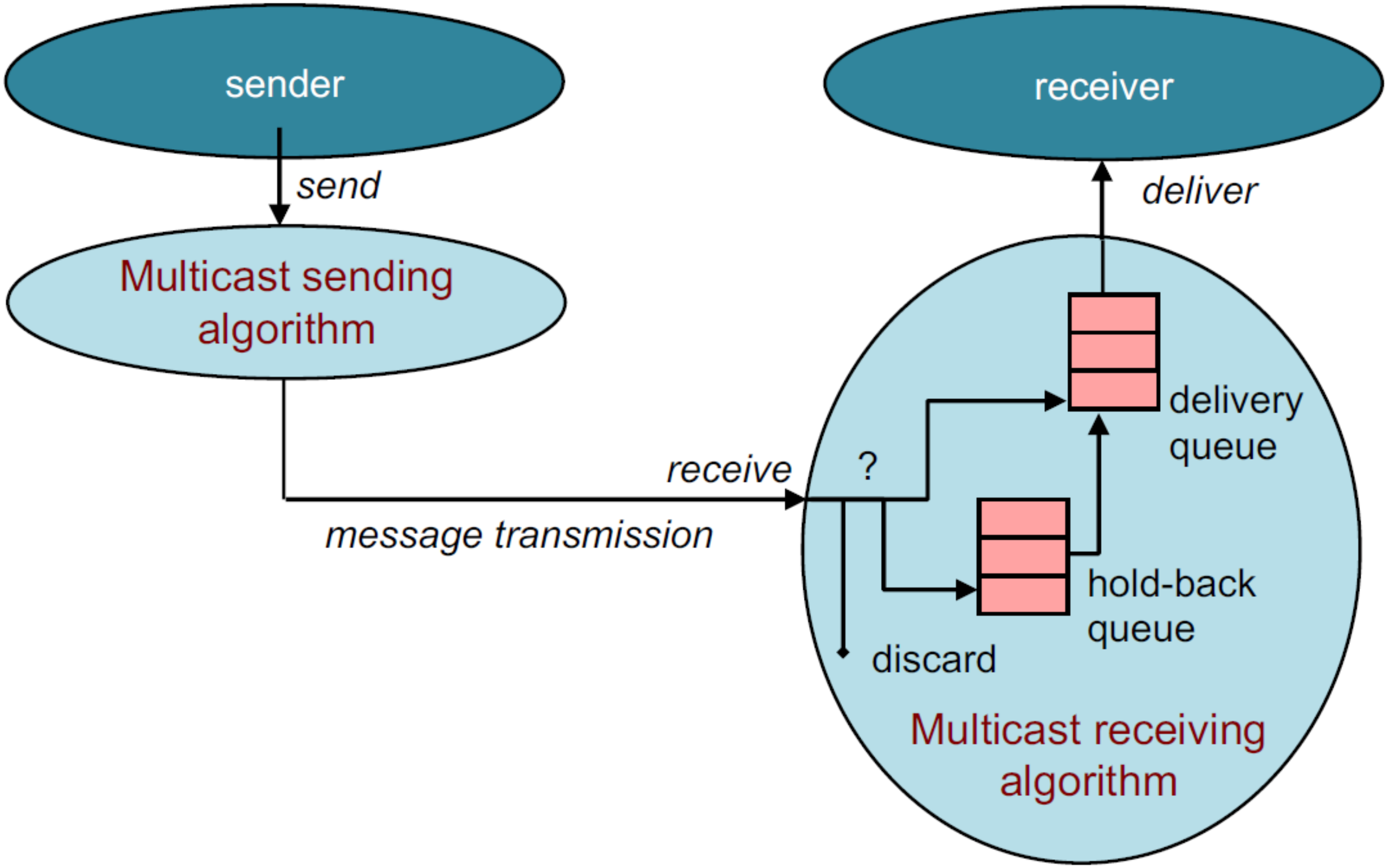
- A received message may be:
  - **Delivered immediately**

  (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 （全序）

- 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 *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

Causal ordering

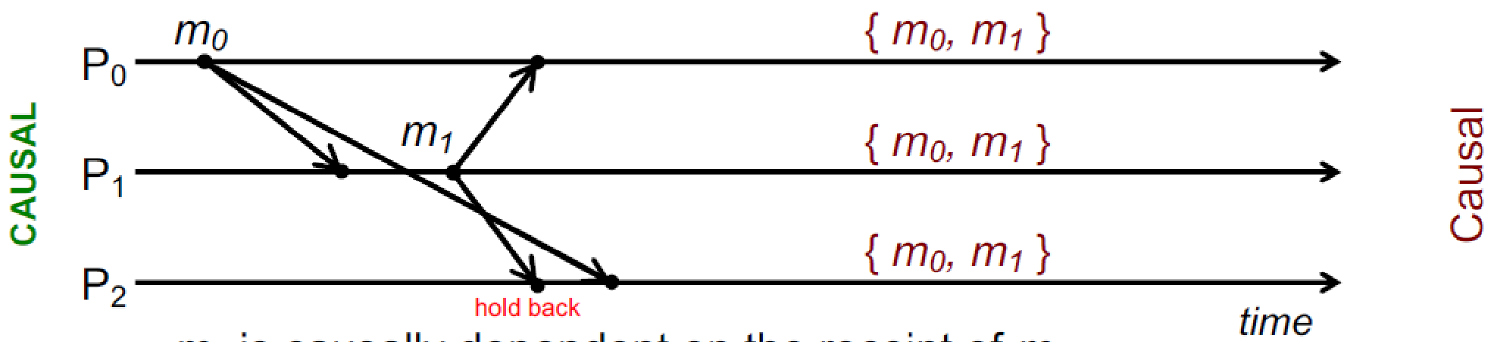
- Also known as partial ordering 偏序
  - Messages sequenced by Lamport or Vector timestamps

If multicast(G, m) $\rightarrow$ multicast(G, m')

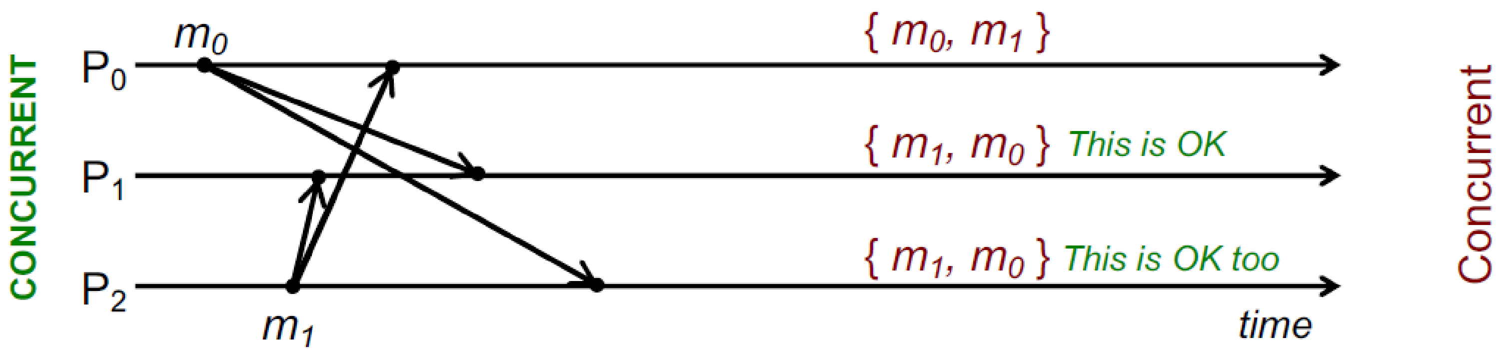
then *every* process that delivers m' will have delivered m

- 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.
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.

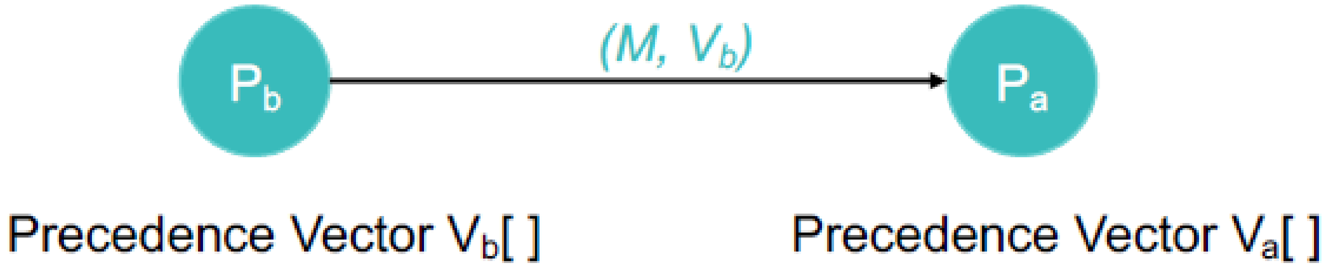
Causal ordering –implementation

Implementation: Pa receives a message from Pb

- 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 Pa **sends** a message, it increments its own entry and sends the vector

$Va[a] = Va[a] + 1$ – where *a* is the index for process Pa

Send Va with the message

– When Pb **receives** a message from Pa

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

$Va[a] == Vb[a] + 1$?

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

$\forall i, i \neq a$: $Va[i] \leq Vb[i]$?

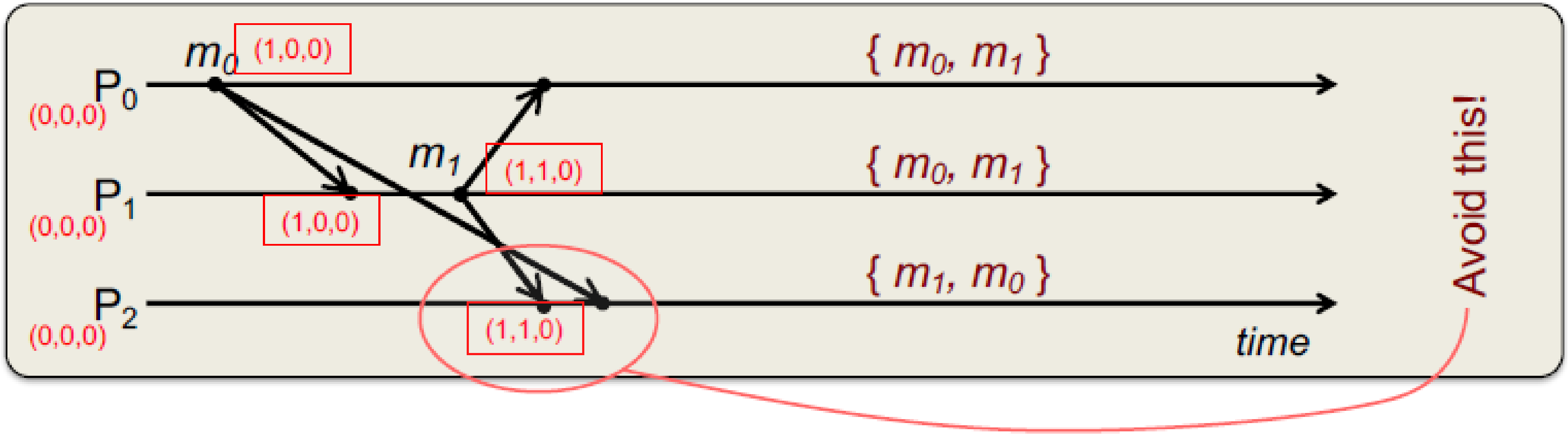
The sequence # of every other message must be ≤ the one Pb has.

- If both conditions are satisfied, Pa will deliver the message to the application

At Pa, update the precedence vector: $Va[a] = Va[a]+1$

- 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 FIFO order from P1?

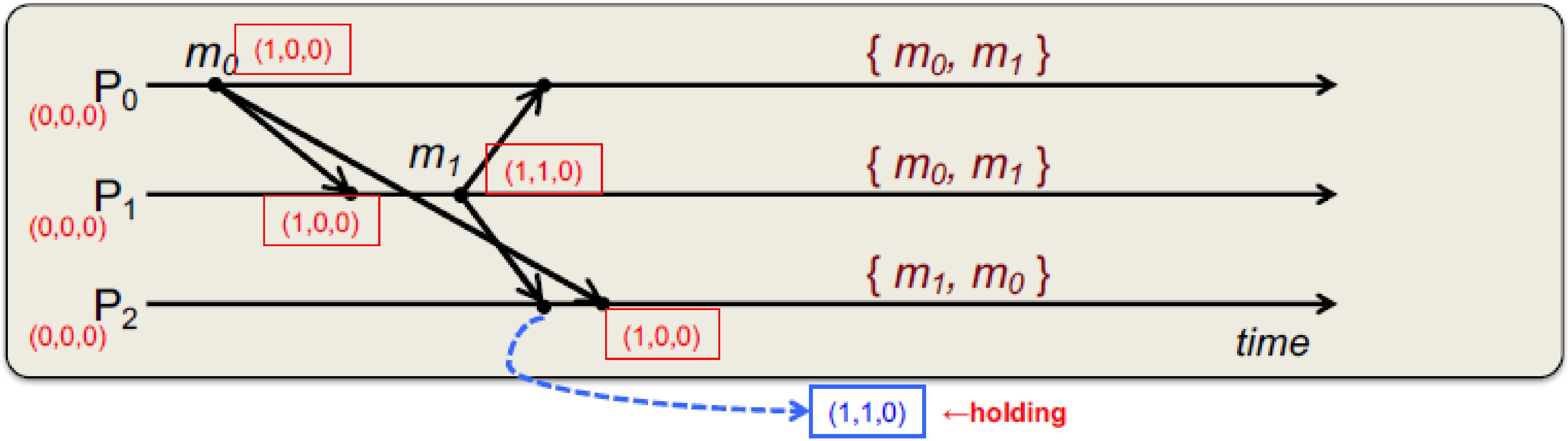
Compare current V on P_2 : V_2 **=(0,0,0)** with received V from P_1 , V_1 **=(1,1,0)**

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_2 **=(1,1,0)**

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

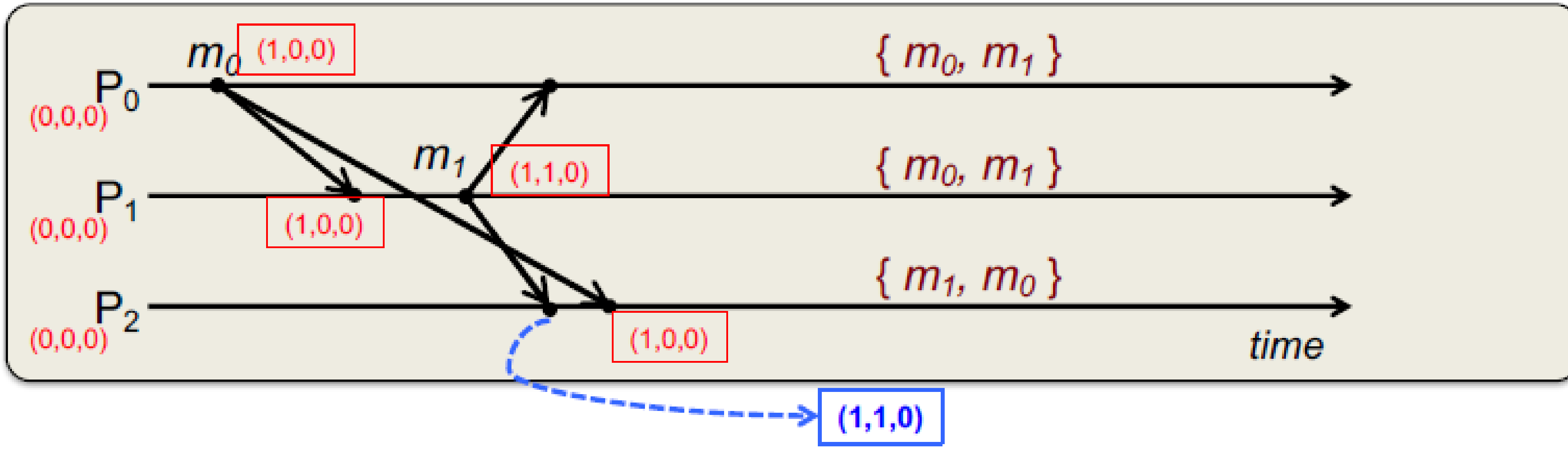
(2) Is $V_0[i] \leq V_2[i]$ for all other i?

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: $\mathbf{V_2=(1,0,0)}$ with held-back V from P_0, $\mathbf{V_1=(1,1,0)}$

Yes: (current $\mathbf{V_2[1] = 0}$) vs. (received $\mathbf{V_1[1] = 1}$) $\Rightarrow$ **sequential**

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

Now yes. $\mathbf{(V_0[0] = 1) \leq (V_2[0] = 1)}$ and element 2: $\mathbf{(V_0[2] = 0) \leq (V_2[2] = 0)}$

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

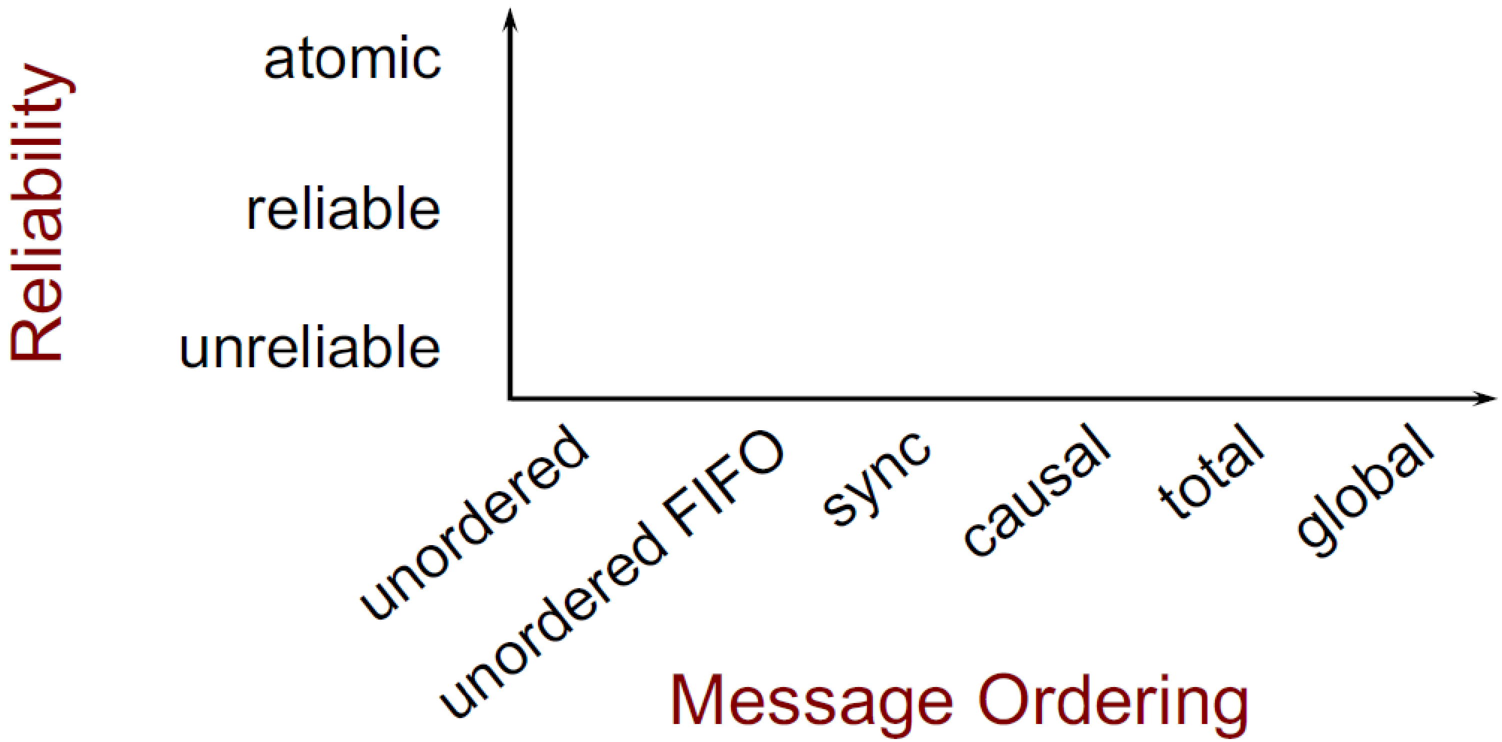
If a process issues a multicast of *m* followed by *m'*, then *every process* that delivers *m'* will have already delivered *m*.

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 因特网组管理协议

- 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

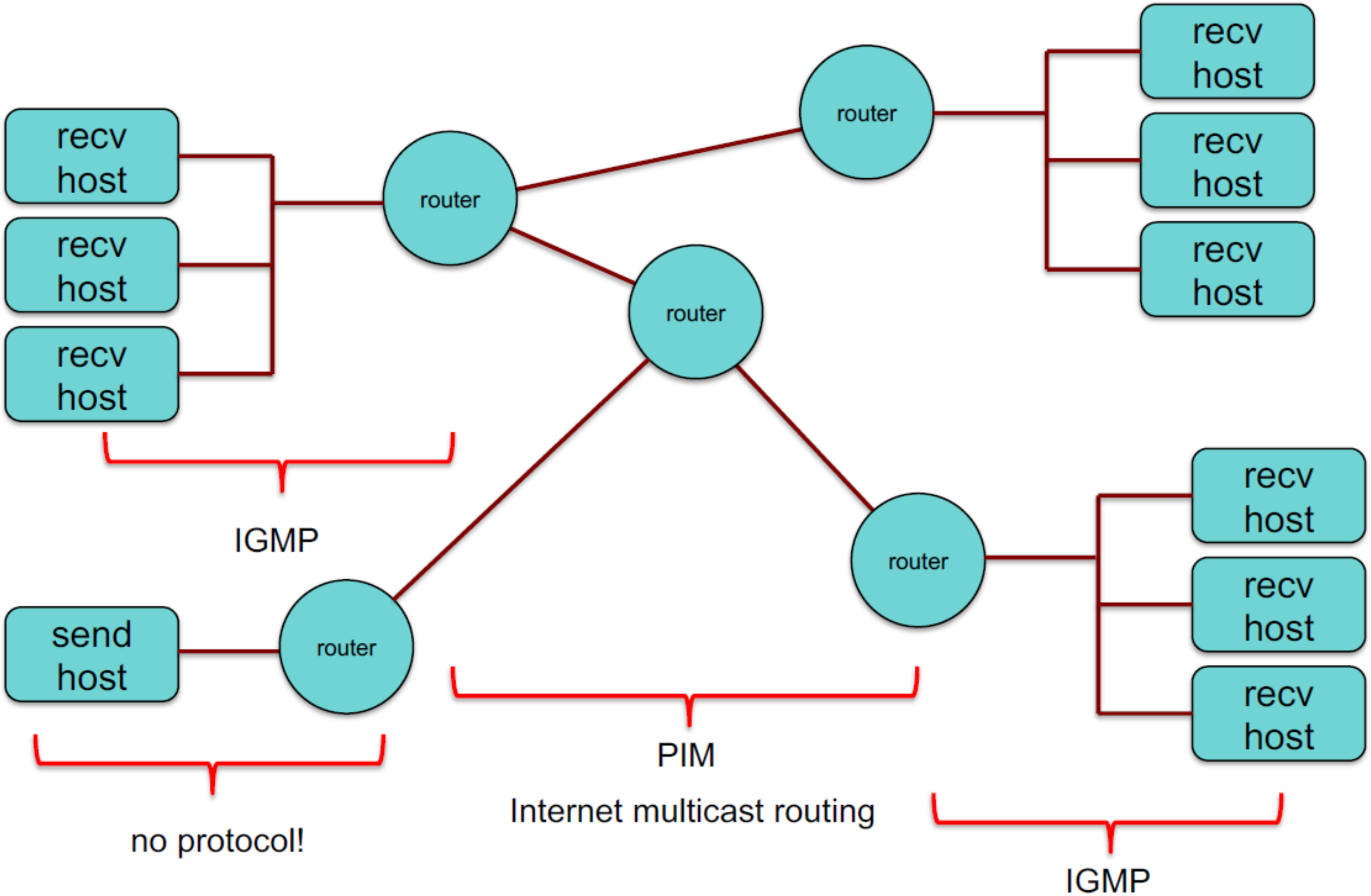
Multicast Forwarding

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 独立组播协议
  - Multicast Routing Protocol for delivering packets across routers
  - Topology discovery is handled by other protocols
  - Two forms:
    1. Dense Mode (PIM-DM) 密集模式
    2. Sparse Mode (PIM-SM) 稀疏模式

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

（逆向路径转发）

  - 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 $\Rightarrow$ 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