Ordered Multicast

CSE 486: Distributed Systems

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Causal and Total Orderings

We previously saw these definitions:

Causal ordering preserves the causal relationship between messages.

Formally:
If MSend(m, G) $\rightarrow$ MSend(m', G), then every correct process that delivers m' must have already delivered m.

Total ordering preserves the order of all messages across all processes.

Formally:
If any correct process delivers m before m', then every correct process that delivers m' must have already delivered m.

The ISIS System

The ISIS system defined causally and totally ordered multicast [1, 2].

It uses vector clocks for causal ordering.

Causal ordering is imposed on multicast message delivery only.

It uses a two-phase protocol for total ordering.

Processes cooperatively arrive at a total ordering for each message.

Safety and Liveness

These protocols maintain two properties [1]:

- Safety: The protocol never delivers messages in an order that violates the ordering constraints.
- Liveness: The protocol never delays a message indefinitely.

The latter requires that every message is delivered.

This can be accomplished via, *e.g.*, R_MCast.

ISIS VT Protocol

ISIS defines several protocols for causal ordering.

The VT protocol [1] addresses causal ordering with static group membership.

More complicated ISIS protocols handle:

- Dynamic group membership (processes joining and leaving)
- Overlapping groups with causal relationships
- Causal total ordering

Vector Timestamps

The VT protocol uses vector timestamps.

Every message is transmitted with its timestamp.

These timestamps look just like our FIFO timestamps!

However, vector entries are causally updated like vector clocks.

Messages must be held back if they do not arrive in causal order.

VT Protocol Vector Timestamps

The VT protocol maintains a vector *VT* for:

- Every message *m*: $VT(m) = \langle 1, \ldots, n \rangle$
- Every process *p*: $VT(p) = \langle 1, \ldots, n \rangle$

Each entry in the vector represents process p_i for $0 <= i < n$ processes.

Every process maintains its own vector.

Every process increments only its own timestamp.

VT Protocol Methods

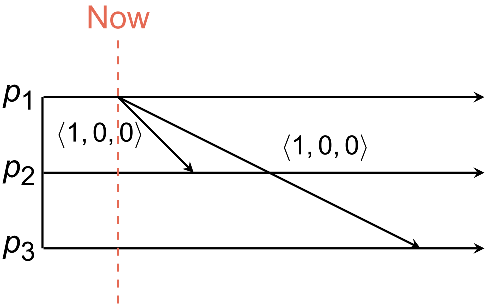
VT_Send(m, G) at p_i:
  Increment $VT(p_i)[i]$
  $VT(m) = VT(p_i)$
  R_MCast($VT(m) \parallel m, G$)

VT_Recv(m) from p_j at $p_i \neq p_j$:
  If $VT(m) = VT(p_i)[j] + 1$ and
  $\forall k \neq j : VT(m)[k] \leq VT(p_i)[k]$:
    VT_Deliver(m)
  Else:
    Hold back m

VT_Deliver(m) from p_j at $p_i \neq p_j$:
  Increment $VT(p_i)[j]$
  Deliver(m)
  Run hold back queue

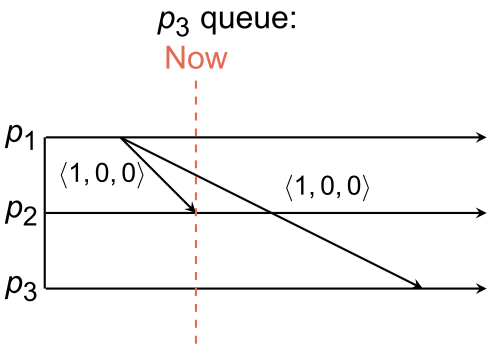
VT Example

p_3 queue:



p_1 sends a message with timestamp $\langle 1, 0, 0 \rangle$.

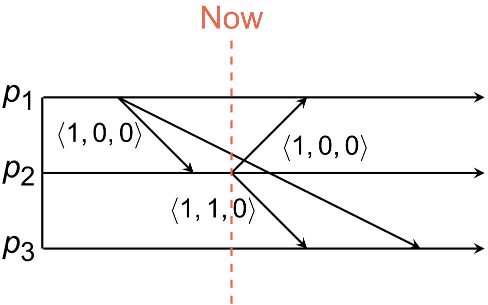
VT Example



p_2 receives and delivers message $\langle 1, 0, 0 \rangle$.

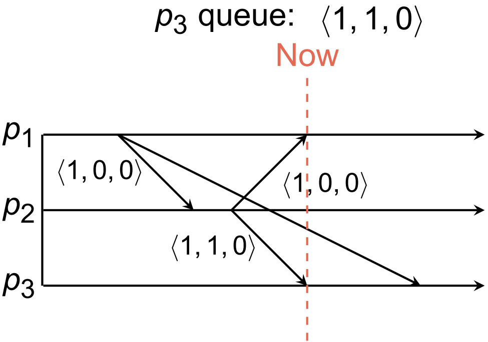
VT Example

p_3 queue:



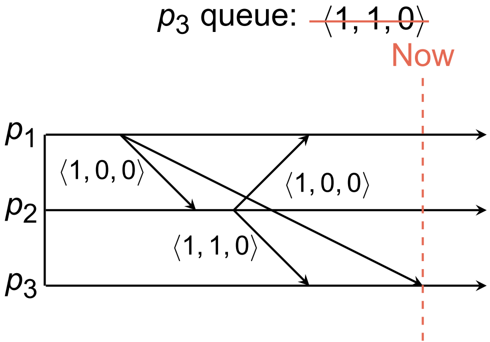
p_2 sends a message $\langle 1, 1, 0 \rangle$.

VT Example



p_1 receives and delivers $\langle 1, 1, 0 \rangle$.
p_3 holds back $\langle 1, 1, 0 \rangle$.

VT Example



p_3 receives and delivers message $\langle 1, 0, 0 \rangle$.
p_3 delivers held back message $\langle 1, 1, 0 \rangle$.

Total Ordering with a Sequencer

Total ordering can be achieved through a sequencer.

Each time a process p_i wants to send a message:

1. p_i sends m to the sequencer
2. The sequencer sends m with FIFO multicast

All messages are received FIFO from the sequencer.

What are the disadvantages of this?

ISIS ABCAST Protocol

The ISIS ABCAST Protocol [2] is totally ordered.

It doesn't require a central sequencer!

It uses a two phase protocol.

Each message is:

- Transmitted without ordering
- Ordered and delivered

Messages are queued but undeliverable until ordered.

The ordering of each message is managed by its sender.

Intuition

Every host p_i in ABCAST maintains a logical clock T_i.

Every message has two associated timestamps:

- A proposed timestamp T_m^p, set when it is transmitted
- An ordered timestamp T_m^o, set when it is deliverable

The ordered timestamp of a message is the maximum clock on all processes when its proposal was received.

The clock ticks for:

- Sending an unordered message
- Receiving an unordered message

ABCAST Phase 1

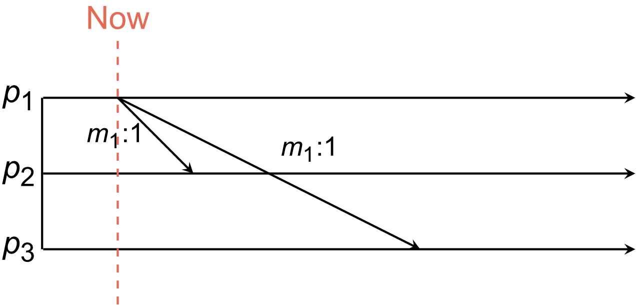
In the first phase of message transmission:

1. Process p_i increments its local clock.
2. Process p_i adds m to its queue as undeliverable at priority $T_m^p = T_i$.
3. Process p_i multicasts m with timestamp T_m^p from its local clock.

Every process $p_j, j \neq i$ eventually receives m and:

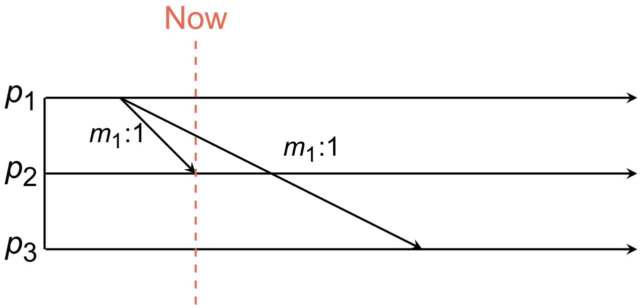
1. p_j sets its local timestamp to MAX(T_j, T_m^p).
2. p_j increments T_j.
3. p_j adds m to its queue as undeliverable at priority T_j.
4. p_j sends an acknowledgment for m with timestamp T_j to p_i.

Phase 1 Example



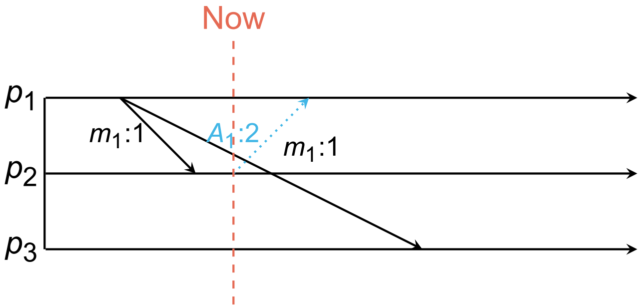
p_1 sends message m_1 with timestamp 1.

Phase 1 Example



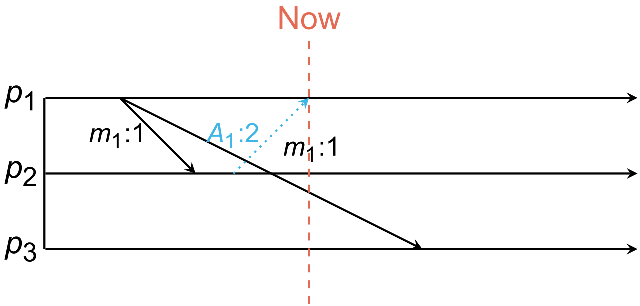
p_2 receives m_1.

Phase 1 Example



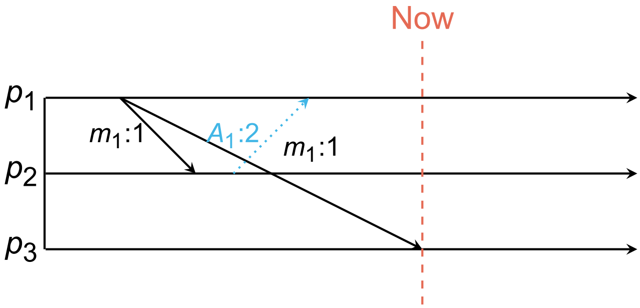
p_2 returns an acknowledgment for m with timestamp 2.

Phase 1 Example



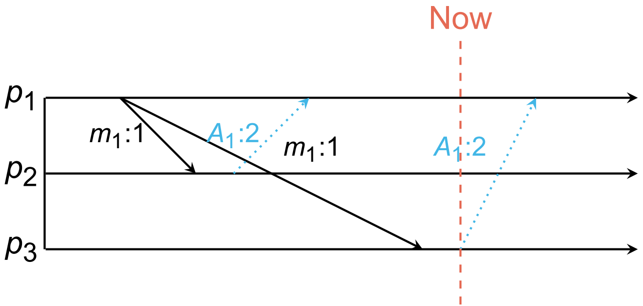
p_1 receives p_2's acknowledgment.

Phase 1 Example



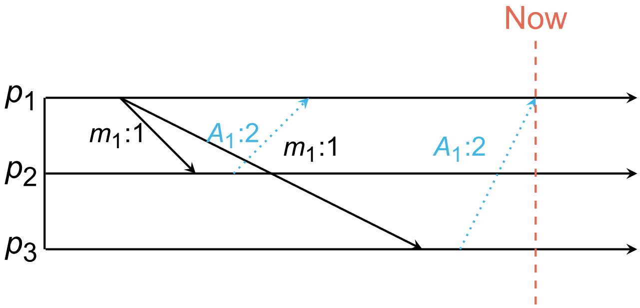
p_3 receives m_1.

Phase 1 Example



p_3 returns an acknowledgment for m with timestamp 2.

Phase 1 Example



p_1 receives p_3's acknowledgment.

ABCAST Phase 2

In the second phase of message m transmission from p_i:

p_i performs the following steps:

1. compute the maximum timestamp T_m^o from all acknowledgments of m
2. multicast the ordered message m with timestamp T_m^o

Each process $p_j, j \neq i$ eventually receives the ordered m and:

1. marks m as deliverable
2. delivers all deliverable messages at the front of its queue

Tie Breaking

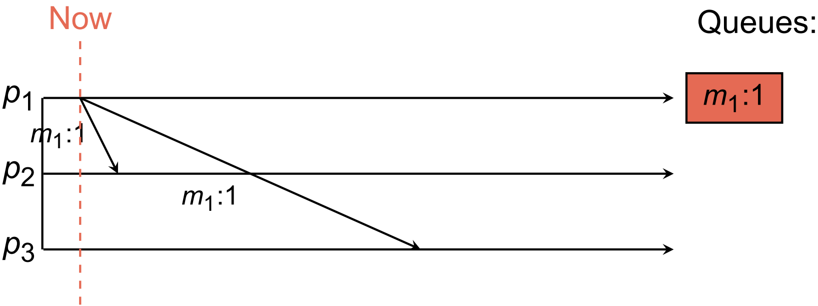
There's one wrinkle:
What if two processes propose the same max timestamp for different messages?

Those messages are tie broken by appending the process ID.

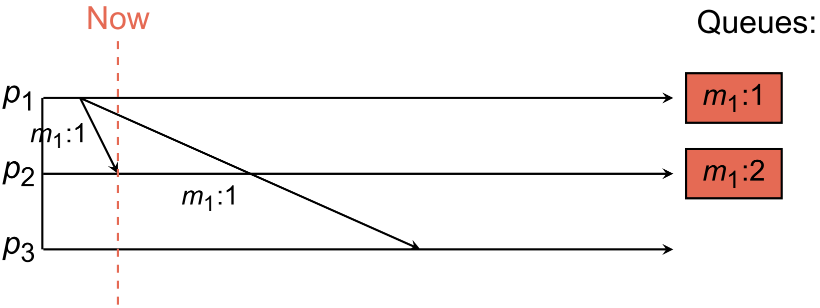
If timestamp $T_i = k$, it is treated as $k.i$; for example:
Timestamp 3 at p_2 is 3.2.

We will elide this suffix when it is irrelevant.

ABCAST Example

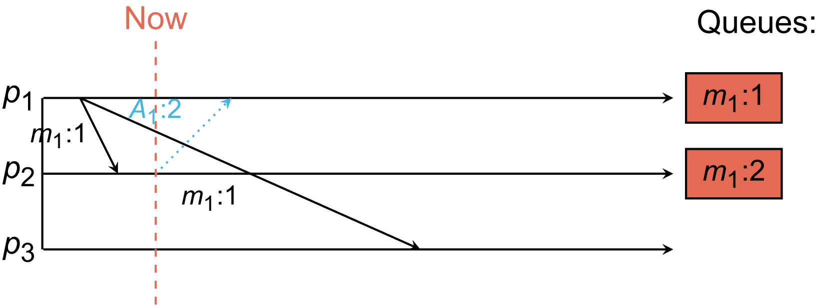


ABCAST Example

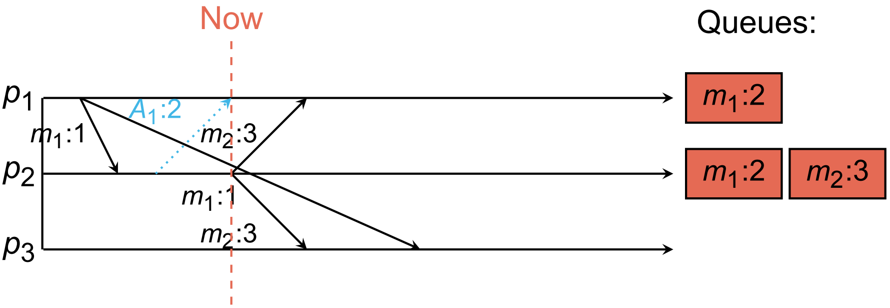


p_2 receives m_1 and enqueues it at priority 2.

ABCAST Example

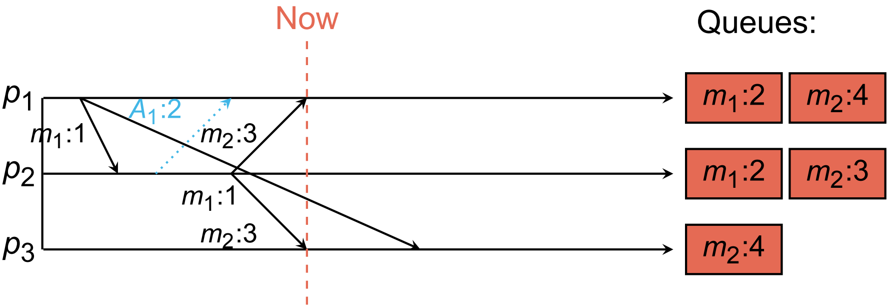


ABCAST Example



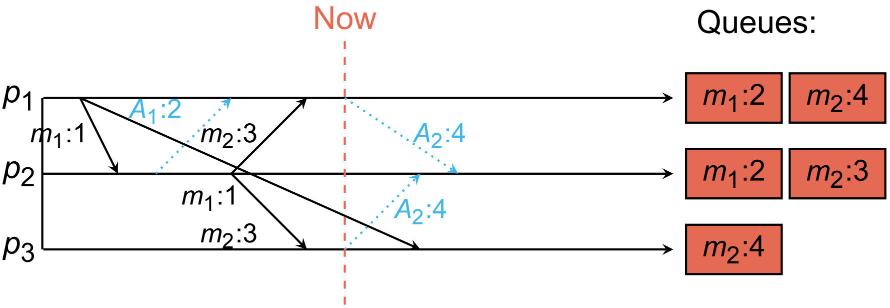
p_1 receives A_1:2 from p_2 and takes the max priority for m_1.
p_2 sends m_2 with $T_2^p = 3$.

ABCAST Example

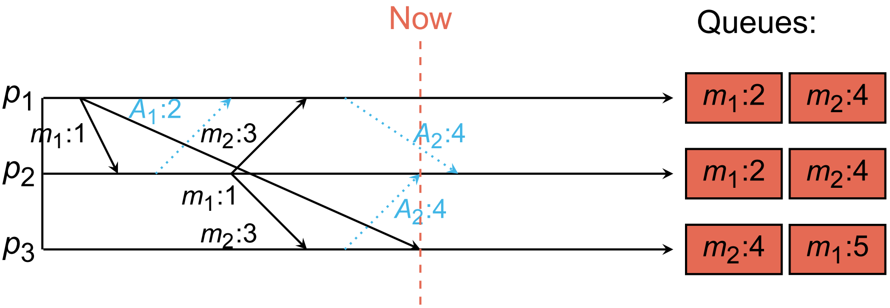


p_1 and p_3 enqueue m_2 with priority 4.

ABCAST Example

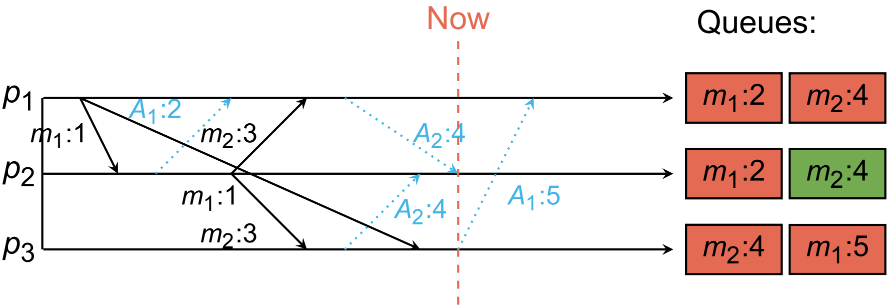


ABCAST Example



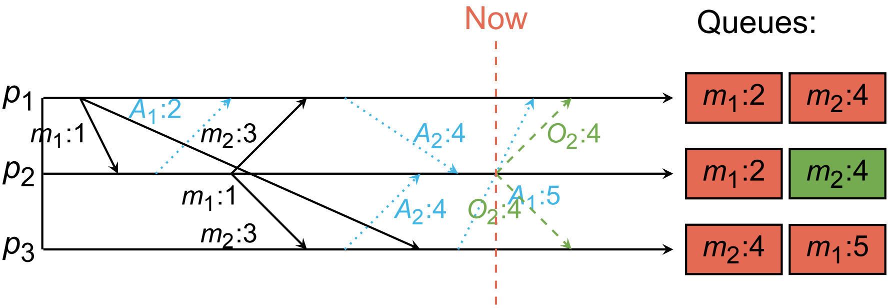
p_2 receives A_2:4 from p_3 and takes the max priority for m_2.
p_3 receives m_1 and enqueues it at priority 5.

ABCAST Example

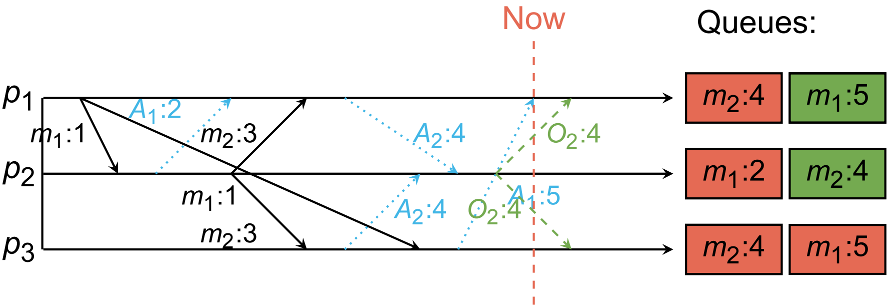


p_2 receives the final ack for m_2 and orders it at 4.

ABCAST Example

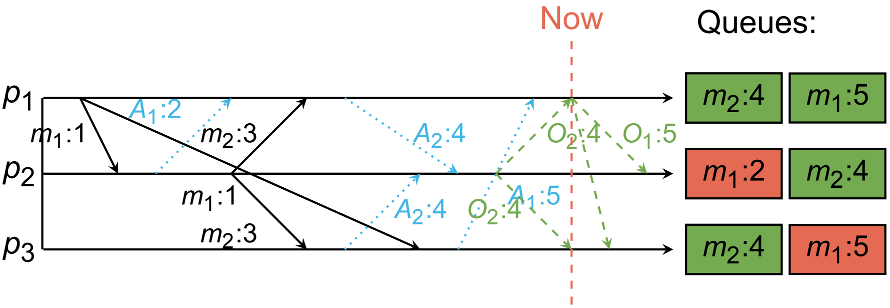


ABCAST Example



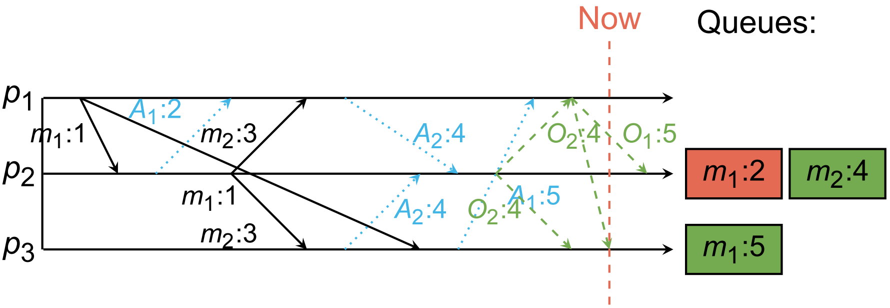
p_1 receives the final ack for m_1 and orders it at 5.

ABCAST Example



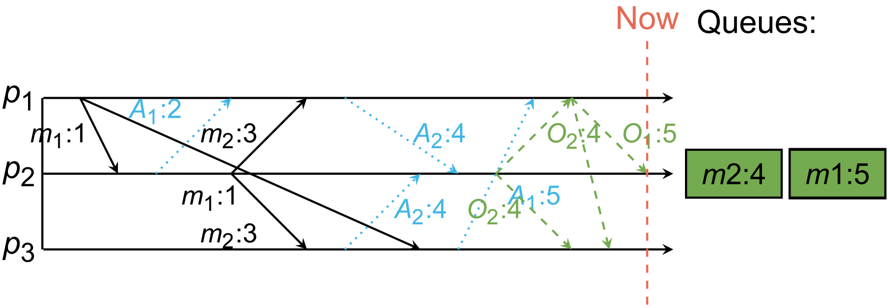
p_1 receives the ordering for m_2 and delivers m_2 then m_1.
p_3 receives the ordering for m_2 and delivers it.

ABCAST Example



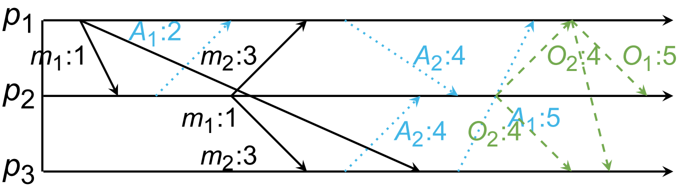
p_3 receives the ordering for m_1 and delivers it.

ABCAST Example



p_2 receives the ordering for m_1 and delivers m_2 then m_1.

ABCAST Example



Queues:

All processes delivered m_2 followed by m_1.

Sketch for Correctness

Why does this work?

Every process knows that *m* will be delivered no earlier than its acknowledged ordering.

The sequencer for *m* takes the maximum observed timestamp.

When a deliverable message is in the queue the local process will never propose an earlier sequence!

Summary

- Safety means constraints will never be violated
- Liveness means every message is eventually delivered
- ISIS provides causally and totally ordered multicast
- The VT protocol uses vector clocks to causally order
- ISIS ABCAST uses distributed sequencing to totally order

References I

Required Readings

[3] Ajay D. Kshemkalyani and Mukesh Singhal. *Distributed Computing: Principles, Algorithms, and Systems*. Chapter 6: 6.6. Cambridge University Press, 2008. ISBN: 978-0-521-18984-2.

Optional Readings

[1] Kenneth Birman, Andre Schiper, and Pat Stephenson. *Fast Causal Multicast*. Tech. rep. Contractor Report 19900012217. National Aeronautics and Space Administration, Apr. 1990. URL: https://ntrs.nasa.gov/citations/19900012217.

References II

[2] Kenneth P. Birman and Thomas A. Joseph. "Reliable Communication in the Presence of Failures". In: vol. 5. 1. Feb. 1987, pp. 47–76. DOI: 10.1145/7351.7478. URL: https://dl-acm-org.gate.lib.buffalo.edu/doi/pdf/10.1145/7351.7478.