Programming Distributed Systems

Fault-tolerance in Message-Passing Distributed Systems

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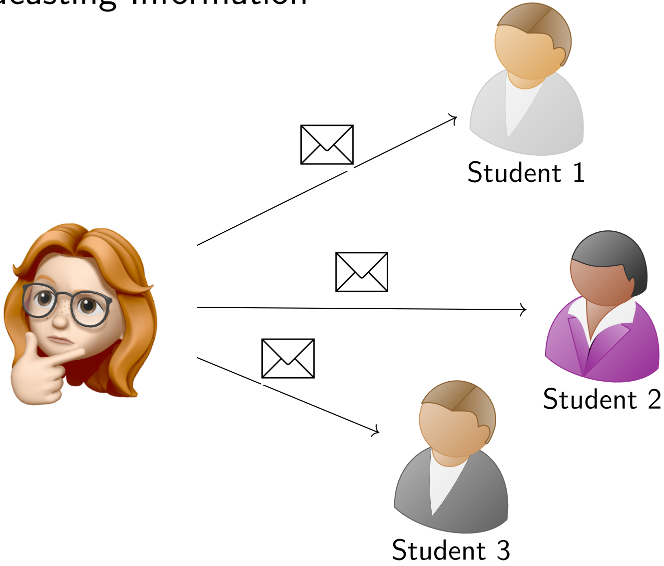
Broadcasting Information



The Need for Distributed Algorithms

- Distributed algorithms are at the core of any distributed systems
- Implemented as middelware between network and application
- Services beyond network protocols (e.g. TCP, UDP)
  - Group communication
  - Shared memory abstractions
  - Replicated state machines

Overview

- Formal models for specifying and analyzing distributed algorithms
- Composability of distributed algorithms
- The Broadcast Problem
  - Best-effort broadcast
  - Reliable broadcast
  - FIFO broadcast
  - Causal broadcast
  - Total-Order broadcast

Goals of this Learning Path

In this learning path, you will learn

- to formally specify safety and liveness properties of several broadcast problem
- to define fault-tolerant algorithms for Best-effort, Reliable, FIFO and Causal Broadcast in an asynchronous system with reliable channels
- to prove the correctness of these algorithms
- to use space-time diagrams to visualize executions
- to implement these algorithms in Erlang

The Broadcast Problem

Informally: A process needs to transmit a message other processes.

`broadcast(m)` $\approx$ `for each` $j \in \{1, \ldots, n\}$ `: send m to` p_j

System model

- Asynchronous system
  - no upper bound on message transfer delay
  - no failure detectors
- Static set of processes $\Pi = \{p_1, \ldots, p_n\}$
  - crash-stop fault model
- Sending and receiving messages through reliable channels (*perfect point-to-point links*)
  - no message loss / creation / modification / duplication
  - bidirectional
  - infinite capacity
- Messages are uniquely identifiable
  - e.g. tag with `<sender, seq_number>`

Only a subset $\Pi' \subseteq \Pi$ receives messages in arbitrary order at distinct, independent time instants.

What is the simplest solution that you can think of?

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Just go ahead and send the message to everyone, one at a time.

Specifying the Broadcast Algorithms

Wait... How do you specify an algorithm for a process again?

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Wait... How do you specify an algorithm for a process again?

⇒ Deterministic I/O automaton with send/receive operations!

- Events: Messages, timers, conditions, ...
- Event-driven interface

```
Upon Event(arg1, arg2, ...) do:
  // local computation
  trigger Event(arg1', arg2',...)
```

- Correctness properties
  - Safety: Nothing bad ever happens
  - Liveness: Something good eventually happens

The Anatomy of a Broadcast Algorithm

For the broadcast algorithms:

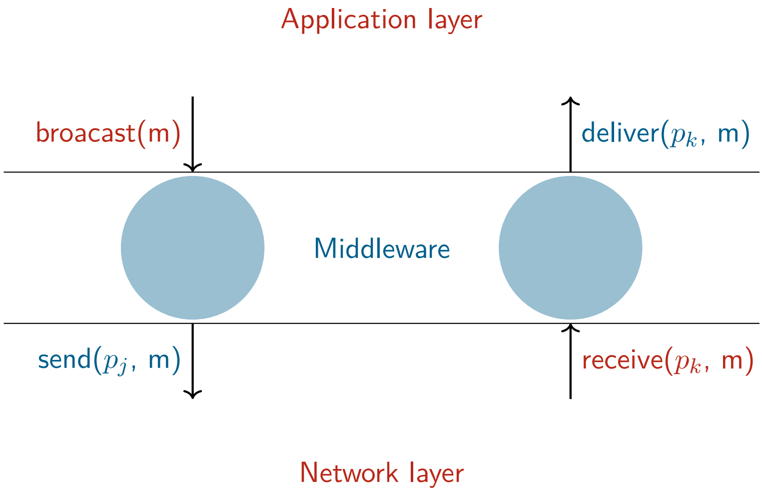
```
Upon Init            do: ...
Upon Broadcast(m)    do: ...
Upon Receive(p_k, m) do: ...
```

- You can trigger an event on another layer:

```
trigger Send(p_j, m)
trigger Deliver(p_k, m)
```

- There is a special event called `Init` for initializing the local state.
- p_j denotes the target process when sending a message
- p_k denotes the process where the message originated from

At Process p_i



Best-effort Broadcast (BEB): Specification

- *BEB-Validity:* If a correct process p_j beb-delivers a message m, then m has previously been beb-broadcast to p_j by some process p_i.
  - No creation, no alteration of messages
- *BEB-Integrity:* A process beb-delivers a message m at most once.
  - No duplication of messages
- *BEB-Termination:* For any two **correct** processes p_i and p_j, every message that has been beb-broadcast by p_i is eventually beb-delivered by p_j.

Best-effort Broadcast: Algorithm

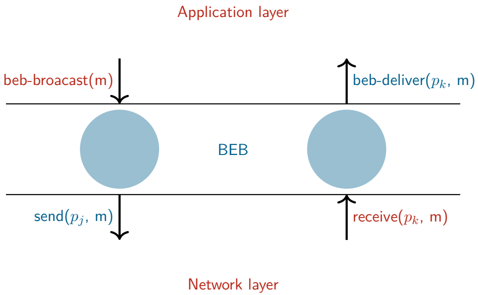
Idea:

- Just go ahead and send the message to every other process.
- When you get one of these messages, you deliver it to the upper layer.
- Intuition: No guarantees if sender crashes

```
State:          --
Upon Init do:   --

Upon beb-broadcast(m) do:
  forall p_j ∈ Π:
    trigger send(p_j, m)

Upon receive(p_k, m) do:
  trigger beb-deliver(p_k, m)
```



Best-effort Broadcast: Correctness

Why does it work?

- BEB-Validity holds because Perfect-Link model guarantees no creation and there is no other way for messages to appear, only through beb-broadcast
- BEB-Integrity holds because Perfect-Link model guarantees no duplication
- BEB-Termination holds because Perfect-Link model guarantees reliable delivery

Perfect-Link Model

- **Reliable Delivery**: Considering two correct processes i and j; if i sends a message m to j, then j eventually delivers m.
- **No Duplication**: No message is delivered by a process more than once.
- **No Creation**: If a correct process j delivers a message m, then m was sent to j by some process i.

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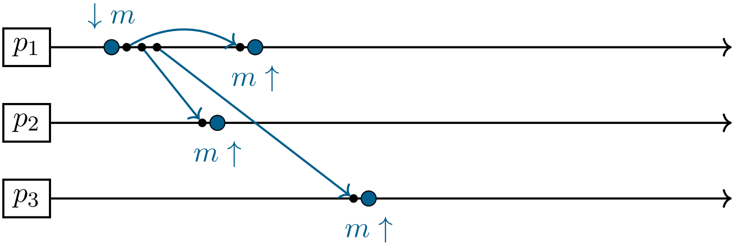
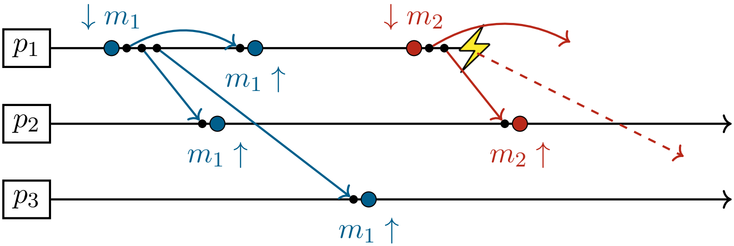
Visualizing Executions with Space-Time Diagrams



- $\downarrow m$ = broadcast message m
- $\uparrow m$ = deliver message m

Best-effort Broadcast: Sender crashes



Limitations of Best-effort Broadcast

What happens if a process fails while sending a message?

- If the sender crashes before being able to send the message to all processes, some process will not deliver the message.
- Even in the absence of communication failures!

Limitations of Best-effort Broadcast

What happens if a process fails while sending a message?

- If the sender crashes before being able to send the message to all processes, some process will not deliver the message.
- Even in the absence of communication failures!

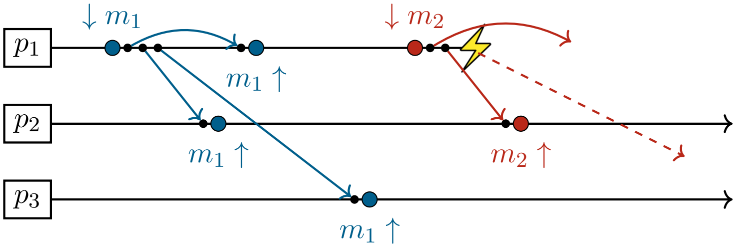
Let's try for a reliable version of broadcast!

- Guarantees that all or none of the correct nodes gets the message
- Even if sender crashes!

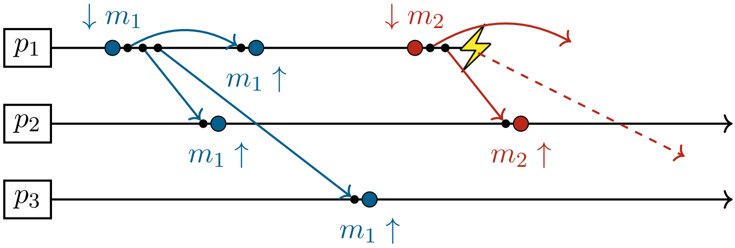
Reliable Broadcast (RB): Specification

- *RB-Validity:* If a correct process p_i rb-delivers a message m, then m has been previously rb-broadcast.
- *RB-Integrity:* A process rb-delivers a message m at most once.
- *RB-Termination-1:* If a correct process p_i rb-broadcasts message m, then p_i rb-delivers the message m.
- *RB-Termination-2:* If a correct process p_i rb-delivers a message m, then each correct process rb-delivers m.

Reliable Broadcast: Scenario 1



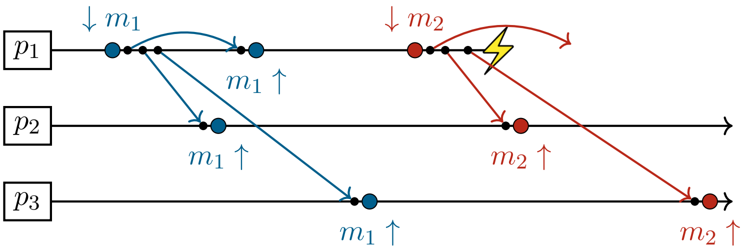
Reliable Broadcast: Scenario 1



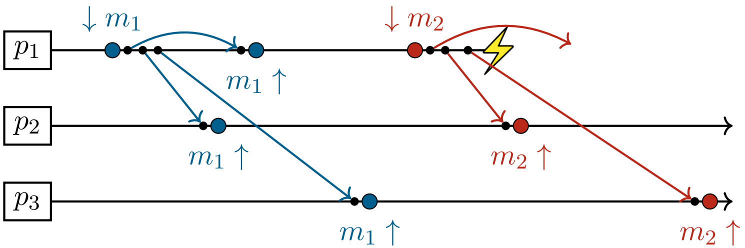
Not possible under Reliable Broadcast: RB-Termination-2 is violated!

If correct process p_2 delivers m, then correct process p_3 must also rb-deliver m.

Reliable Broadcast: Scenario 2

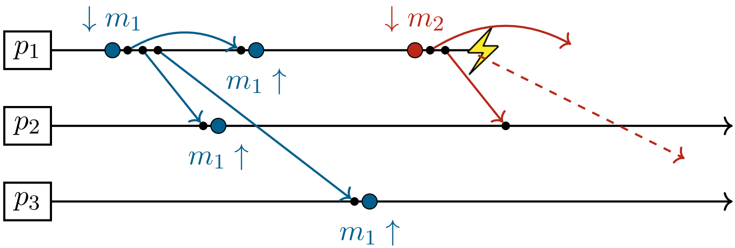


Reliable Broadcast: Scenario 2

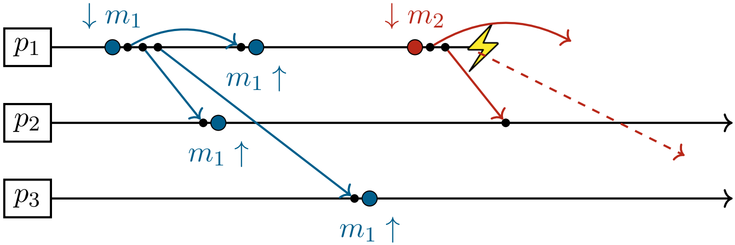


The fact that process p_1 does not deliver m_2 is not a problem, because only correct processes are required to deliver their own messages.

Reliable Broadcast: Scenario 3

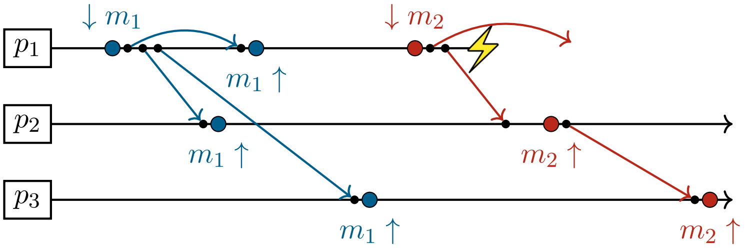


Reliable Broadcast: Scenario 3



The fact that no process delivers m_2 is not a problem, because process p_1 has crashed and no process delivers m_2.

Reliable Broadcast: Idea!



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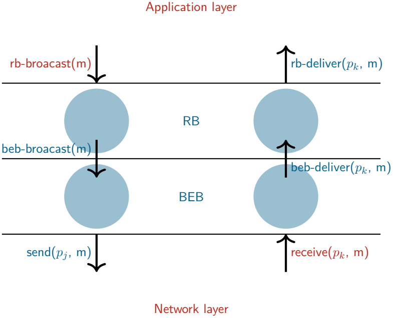
Reliable Broadcast: Algorithm

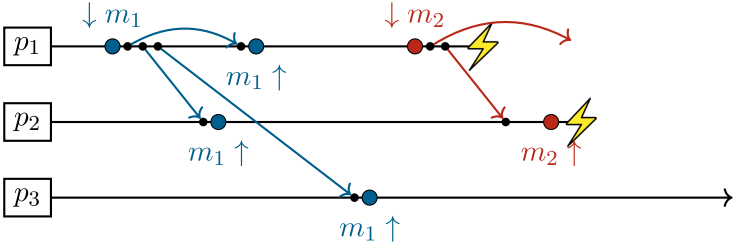
```
State:
  delivered //set of message ids
    that have already been delivered

Upon Init do:
  delivered <- ∅

Upon rb-broadcast(m) do
  m_id <- generateUniqueID(m)
  trigger beb-broadcast([m_id, m])

Upon beb-deliver(p_k, [m_id, m]) do
  if ( m_id ∉ delivered ) then
    delivered <- delivered ∪ {m_id}
    trigger rb-deliver(p_k, m)
    trigger beb-broadcast([m_id, m])
```



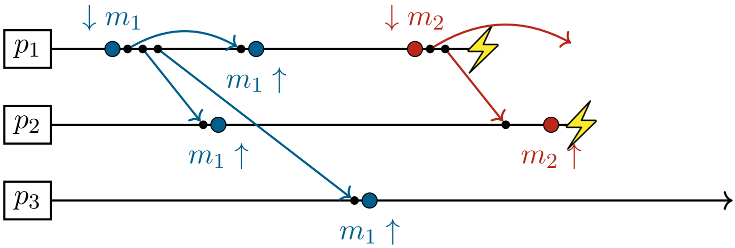
Reliable Broadcast: Correctness

- *RB-Validity:* If a correct process p_i rb-delivers a message m, then m has previously been rb-broadcast.
  - By BEB-Validity.
- *RB-Integrity:* A process rb-delivers a message m at most once.
  - By BEB-Integrity and handling the set of delivered messages.
- *RB-Termination-1:* If a correct process p_i broadcasts message m, then p_i eventually rb-delivers m.
  - By BEB-Termination and handling of the set of delivered messages.
- *RB-Termination-2:* If a correct process p_i rb-delivers a message m, then each correct process rb-delivers m.
  - After rb-delivering m, a correct process forwards m to all processes. By BEB-Termination and p_i being correct, all correct processes will eventually beb-deliver m and hence rb-deliver it.

Reliable Broadcast: Scenario 4



Reliable Broadcast: Scenario 4



The fact that m_2 has been delivered by faulty p_1 and p_2 does not imply that m_2 has to be delivered by p_3 as well. Yet, this situation is not desirable, because two processes deliver something and another one does not.

$\Rightarrow$ Interaction with external world!

Uniform Reliable Broadcast (URB): Specification

- *URB-Validity:* If a correct process p_i urb-delivers a message m, then m was urb-broadcast to p_i by some process p_j.
- *URB-Integrity:* A process p_i urb-delivers a message m at most once.
- *URB-Termination-1*: If a correct process p_i urb-broadcasts a message m, then p_i eventually urb-delivers m.
- *URB-Termination-2*: If a process p_i urb-delivers a message m, then each correct process p_j eventually urb-delivers m.

An Impossibility Result

- n: total number of processes
- t: upper bound on the number of processes that can fail
- Fail-silent system model: crash-stop + perfect point-to-point links

Theorem

There is no algorithm implementing URB under the fail-silent system model if a majority of processes can fail, i.e. if $t \geq n/2$.

Proof sketch

By contradiction.

- Assume there exists algorithm A that implements URB under the fail-silent model for $t \geq n/2$.
- Partition $\Pi = P_1 \cup P_2$ such that
  - $P_1 \cap P_2 = \emptyset$
  - $|P_1| = \lceil n/2 \rceil$ and $|P_2| = \lfloor n/2 \rfloor$ ($|P_1| \geq |P_2|$)
- Consider two executions E_1 and E_2
- Execution E_1:
  - All $p_i \in P_2$ crash initially, all processes in P_1 are correct.
  - $p_x \in P_1$ issues urb-broacast(m) using algorithm A
  - Every process in P_1 urb-delivers m

Proof sketch (2)

- Execution E_2:
  - No $p_i \in P_2$ crashes, and none of them issues urb-broadcast.
  - All processes in P_1 are correct.
  - $p_x \in P_1$ issues urb-broacast(m) using algorithm A
  - Every process in P_1 urb-delivers m and then crashes
  - Now, m is lost and can't be urb-delivered by processes in P_2, because perfect-link model requires sender and receiver to be correct for reliable delivery.
- E_1 and E_2 are indistiguishable by algorithm A.

Uniform Reliable Broadcast for $t < n/2$: Algorithm

```
State:
  delivered //set of message ids that have already been delivered
  pending // set of messages to be delivered
  ack // map m_id to received acknowledgments

Upon Init do:
  delivered, pending <- ∅
  ∀m_id: ack[m_id] = ∅

Upon urb-broadcast(m) do
  m_id <- generateUniqueID(m)
  pending <- pending ∪ {m_id}
  trigger beb-broadcast([self, m_id, m])
```

Uniform Reliable Broadcast for $t < n/2$: Algorithm (2)

```
Upon beb-deliver(p_k, [p_j, m_id, m]) do
  ack[m_id] <- ack[m_id] ∪ {k}
  if ( (p_j, m_id, m) ∉ pending ) then
    pending <- pending ∪ (p_j, m_id, m)
    trigger beb-broadcast([p_j, m_id, m])

Upon exists (p_j, m_id, m) ∈ pending
    with ack[m_id] > n/2 and m_id ∉ delivered
  delivered <- delivered ∪ m_id
  trigger urb-deliver(p_j, m)
```

Uniform Reliable Broadcast: Correctness

- Assume majority of correct processes ($t < n/2$)
- If a process urb-delivers, it got acknowledgement from majority
- In this majority, at least one process p must be correct
- p ensures that all correct processes beb-deliver m
- These correct processes (majority!) will ack and urb-deliver the message

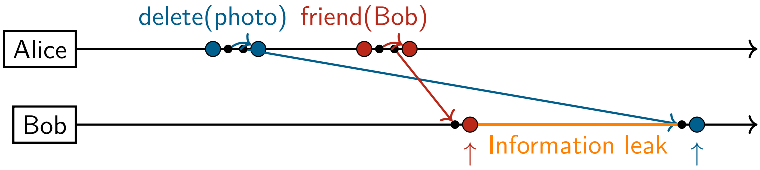
Resilience

- Defined by maximum number of faulty processes an algorithm can handle
- Algorithm for URB under fail-silent model has resilience $< n/2$

Problem: Message ordering

- Given the asynchronous nature of distributed systems, messages may be delivered in *any* order.
- Some services, such as replication, need messages to be delivered in a consistent manner, otherwise replicas may diverge.

FIFO Order

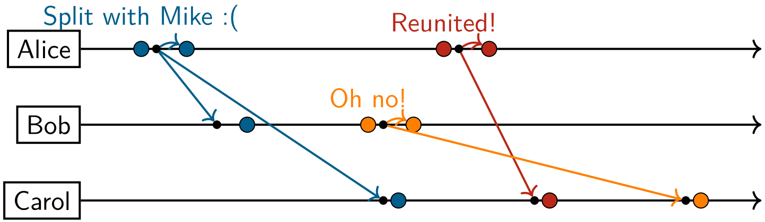


FIFO Property

If a process p broadcasts a message m before the same process broadcasts another message m', then no correct process q delivers m' unless it has previously delivered m.

$$broadcast_p(m) \rightarrow broadcast_p(m') \Rightarrow deliver_q(m) \rightarrow deliver_q(m')$$

Causal Order



Causality Property

If the broadcast of a message m happens-before the broadcast of some message m', then no correct process delivers m' unless it has previously delivered m.

$$broadcast_p(m) \rightarrow broadcast_q(m') \Rightarrow deliver_r(m) \rightarrow deliver_r(m')$$

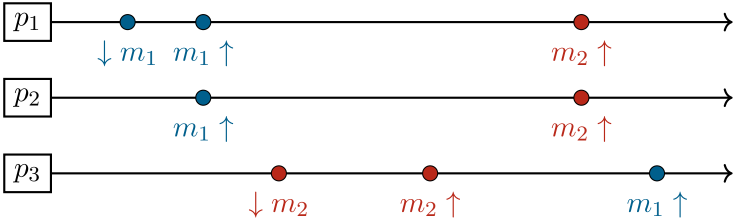
Total Order

Total Order Property

If correct processes p and q both deliver messages m, m', then p delivers m before m' if and only if q delivers m before m'.

$$deliver_p(m) \rightarrow deliver_p(m') \Rightarrow deliver_q(m) \rightarrow deliver_q(m')$$

Message ordering: Quizzzzz



Is this allowed under FIFO Order, Causal Order, Total Order?

(Reliable) FIFO Broadcast (FIFO): Specification

- All properties from reliable broadcast
- *FIFO delivery*: If a process fifo-broadcasts m and later m', then no process fifo-delivers m' unless it already delivered m.

FIFO-Broadcast: Algorithm

```
State:
  next    // array mapping process id to seq numer
  seq     // sequence numbers for broadcast messages
  pending // messages to be delivered
Upon Init do:
  next <- [0, ..., 0]
  seq <- 0
  pending <- ∅
Upon fifo-broadcast(m) do
  m_id <- seq++ // generate next seq number
  trigger rb-broadcast([m_id , m])

Upon rb-deliver(p_k, [m_id, m]) do
  if  m_id = next[p_k] then
    trigger fifo-deliver(p_k, m)
    next[p_k]++
    while exists (p_k, n_id, n) ∈ pending with n_id = next[p_k] do
      trigger fifo-deliver(p_k, n)
      next[p_k]++
      pending <- pending \ {(p_k, n_id, n)}
  else pending <- pending ∪  {(p_k, m_id, m)}
```

(Reliable) Causal Broadcast (RCO): Specification

- All properties from reliable broadcast
- *Causal delivery:* No process p_i delivers a message m' unless p_i has already delivered every message m such that $m \rightarrow m'$.

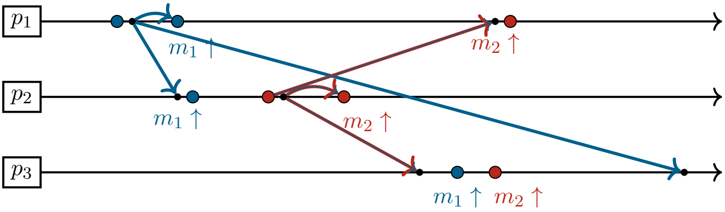
Idea

- Each messages carries $\texttt{past}_m$, an ordered list of messages that causally precede m
- When a process rb-delivers m,
  - it co-delivers first all causally preceding messages in $\texttt{past}_m$
  - it co-delivers m
  - avoiding duplicates using `delivered`

Causal Broadcast (RCO): Algorithm 1 (No-waiting)

```
State:
  delivered //set of messages ids that were already rco-delivered
  past      // ordered list
Upon Init do:
  delivered <- ∅
  past      <- []
Upon rco-broadcast(m) do
  m_id <- generateUniqueID(m)
  trigger rb-broadcast([m_id , past, m])
  past <- past ++ [(self, m_id, m)] // append at the end
Upon rb-deliver(p_k, [m_id, past_m, m]) do
  if ( m_id ∉ delivered ) then
    for (p_j, n_id, n) : past_m do // from old to recent
      if (n_id ∉ delivered ) then
        trigger rco-deliver(p_j, n)
        delivered <- delivered ∪ {n_id}
        if (p_j, n_id, n) ∉ past then
            past <- past ++ [(p_j, n_id, n)]
    trigger rco-deliver(p_k, m)
    delivered <- delivered ∪ {m_id}
    if (p_k, m_id, m) ∉ past then
        past <- past ++ [(p_k, m_id, m)]
```

Causal Broadcast: Scenario 1



Causal Broadcast - Algorithm 1: Correctness

- Validity follows directly from rb-broadcast
- Integrity follows from rb-broadcast and the check before rco-delivering messages from $\texttt{past\_}m$
- Termination follows directly from rb-broadcast and the fact that no waiting occurs
  - Every message is rco-delivered once rb-delivered
- Causal delivery
  - Each message m carries its causal past
  - Causal past is in order delivered before m
  - Proof by induction on trace prefix
    - Initial state
    - For every delivery

Remarks

- Message from causal past of m are delivered before message m (*causal delivery*)
- Message id's could be reused for rb-broadcast
- Size of messages grows linearly with every message that is broadcast since it includes the complete causal past

Idea: Garbage collect the causal past

- If we know when a process fails (i.e., under the fail-stop model), we can remove messages from the causal past.
- When a process rb-delivers a message m, it rb-broadcasts an acknowledgement message to all other processes.
- When an acknowledgement for message m has been rb-delivered by all correct processes, m is removed from $past$
- N^2 additional ack messages for each application message
- Typically, acknowledgements are grouped and processed in batch mode

$\Rightarrow$ Requires still unbounded messages sizes

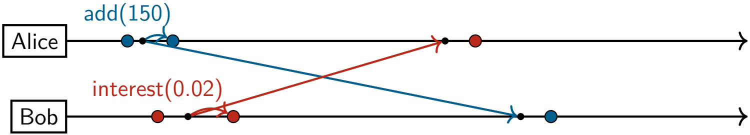
Causal Broadcast (RCO): Algorithm 2 [1]

```
State:
  pending //set of messages that cannot be delivered yet
  VC // vector clock
Upon Init do:
  pending <- ∅
  forall p_i ∈ Π do: VC[p_i] <- 0

Upon rco-broadcast(m) do
  trigger rco-deliver(self, m)
  trigger rb-broadcast(VC, m)
  VC[self] <- VC[self] + 1

Upon rb-deliver(p_k, VC_m, m) do
  if ( p_k ≠ self ) then
    pending <- pending ∪ {(p_k, VC_m, m)}
    while exists (q, VC_{m_q}, m_q) ∈ pending with VC ≥ VC_{m_q} do
        pending <- pending \ {(q, VC_{m_q}, m_q)}
        trigger rco-Deliver(q, m_q)
        VC[q] <- VC[q] + 1
```

Limitations of Causal Broadcast

Example: Replicated database handling bank accounts

- Initially, account A holds 1000 Euro.
- User deposits 150 Euro, triggers broadcast of message $m_1 =$ `'add 150 Euro to A'`
- Concurrently, bank initiates broadcast of message $m_2 =$ `'add 2% interest to A'`
- Diverging state because processes can observe messages in different order



Outlook: Total-order broadcast (aka Atomic Broadcast)

- All processes deliver their messages in the same order
- Replicated services
  - Multiple processes execute the same sequence of commands
  - Replicated State Machines (RSM)
- Impossibile under our assumed system model

Summary

- Composability of distributed algorithms
- Correctness proofs based on properties of underlying level + algorithmic properties
- Different variants of solution to the Broadcast Problem
  - Best-effort broadcast
    - Reliable only if sender is correct
  - Reliable broadcast
    - Reliable independent of whether sender is correct
  - Uniform reliable broadcast
    - Considers also behavior of failed nodes
  - FIFO broadcast
    - Reliable broadcast with FIFO delivery order
  - Causal broadcast
    - Reliable broadcast with causal delivery order
  - Total-order broadcast
    - Reliable and same order of delivery at all nodes

Further reading I

[1] Michel Raynal, André Schiper und Sam Toueg. „The Causal Ordering Abstraction and a Simple Way to Implement it“. In: *Inf. Process. Lett.* 39.6 (1991), S. 343–350. DOI: 10.1016/0020-0190(91)90008-6. URL: https://doi.org/10.1016/0020-0190(91)90008-6.