Causal Broadcast

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Motivation

- Assume we have a chat application
  - Whatever written is reliably broadcast to group
- If you get the following output, is it ok?

```
[Paris] Are you sure, the lecture is not in room B?
[Lars] Room C at Electrum
[Cosmin] Does anyone know where is the lecture
today?
```

- Cosmin’s message caused Lars’s message,
  - Lars’s message caused Paris’s message

Motivation (2)

- Does uniform reliable broadcast remedy this? [d]

Motivation (3)

- Causal reliable broadcast solves this
  - Deliveries in causal order!

- Causality is same as happened-before relation by Lamport!

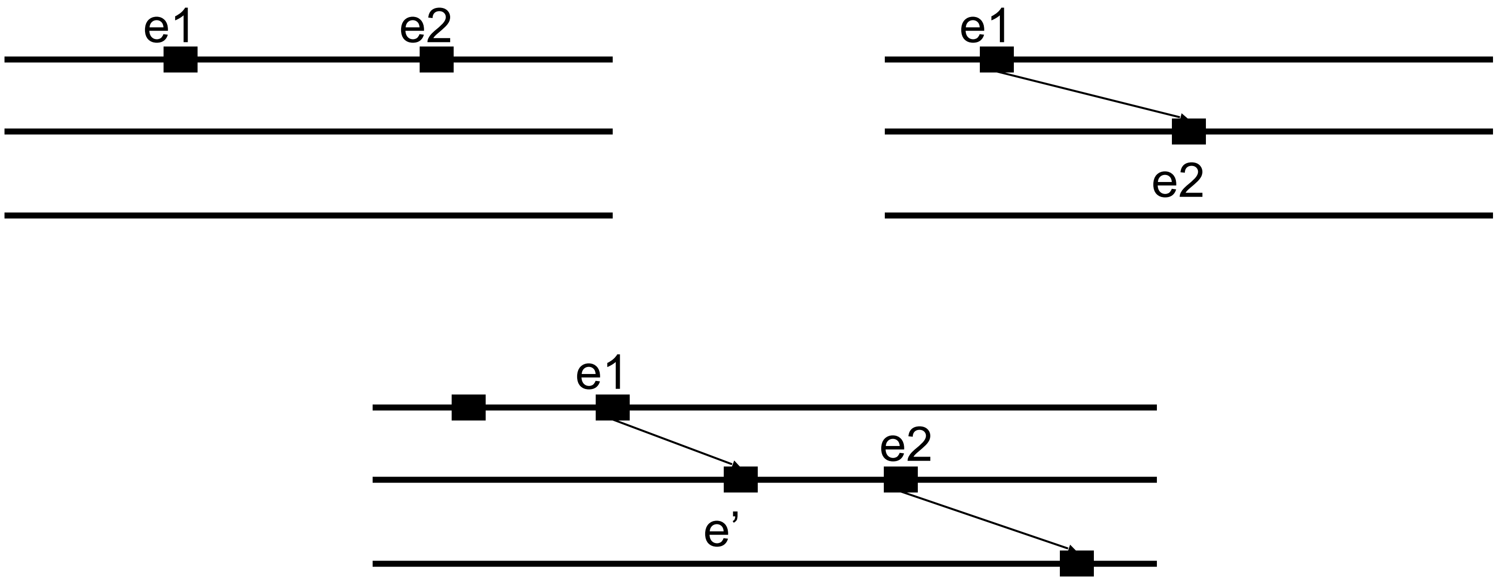
Cause-effect relations in message passing systems

- An event e1 may potentially have caused another event e2 if the following relation, called, *happens-before* and denoted by e1 $\rightarrow$ e2 holds

Happens-before relation

- e1 and e2 occurs at the same process p, and e1 occurs before e2
- e1 is the transmission of a message m at process p and e2 is the reception of the same message at process q
- There exist some event e’ such that e1→e’ and e’→e2

Happens-before relation



Intuitions (1)

- So far, we did not consider ordering among messages; In particular, we considered messages to be independent
- Two messages from the same process might not be delivered in the order they were broadcast
- A message m1 that causes a message m2 might be delivered by some process after m2

Intuitions (2)

- Causal broadcast means
  - Causality between broadcast events is preserved by the corresponding delivery events
  - If broadcast(m1) happens-before broadcast(m2), any delivery(m2) cannot happen-before a delivery(m1)

Causality of Messages

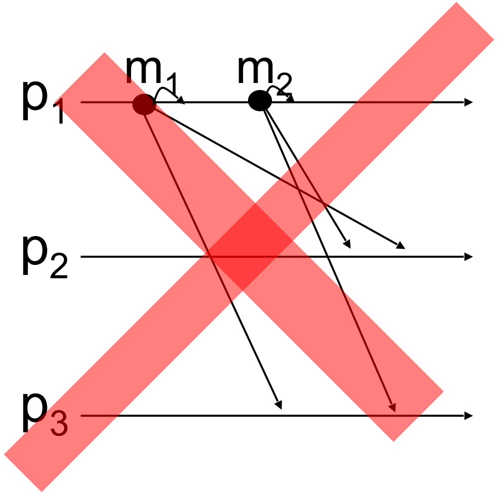
- Let m_1 and m_2 be any two messages:

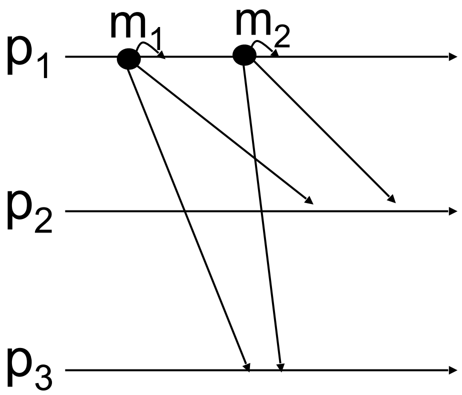
  $m_1 \rightarrow m_2$ (m_1 causally precedes m_2) if

  - ***C1 (FIFO order)*.**
    - Some process p_i broadcasts m_1 before broadcasting m_2
  - ***C2 (Network order)*.**
    - Some process p_i delivers m_1 and later broadcasts m_2
  - ***C3 (Transitivity)*.**
    - There is a message m’ such that $m_1 \rightarrow m'$ and $m' \rightarrow m_2$

Causality

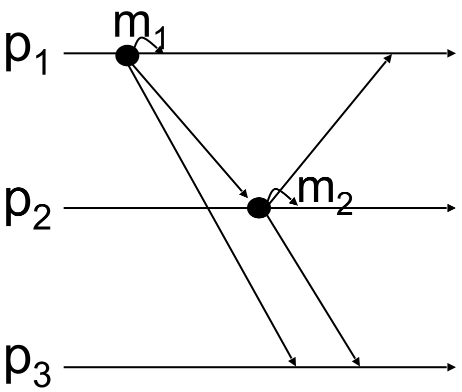
- ***C1 (FIFO order)***.
  - Some process p_i broadcasts m_1 before broadcasting m_2

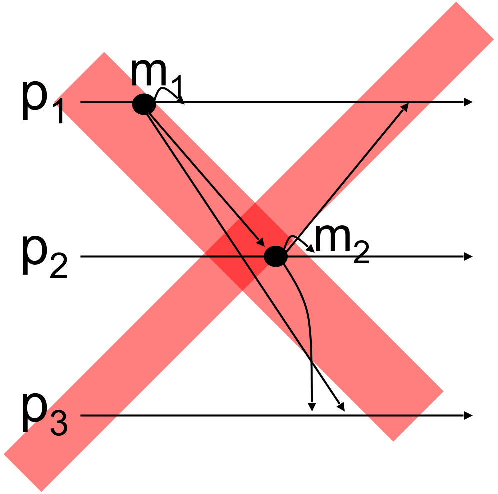




Causality (2)

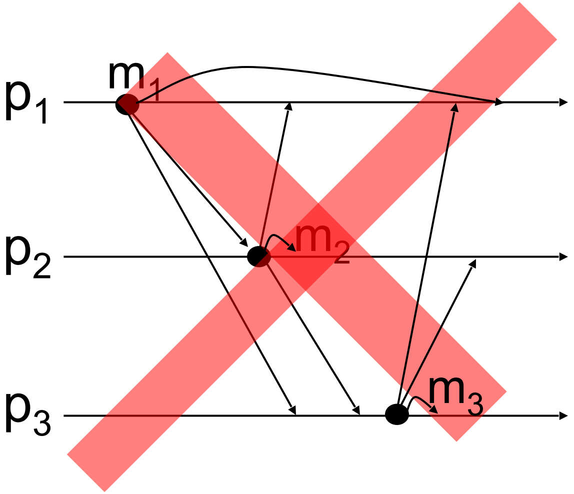
- ***C2 (Network order)***.
  - Some process p_i delivers m_1 and later broadcasts m_2

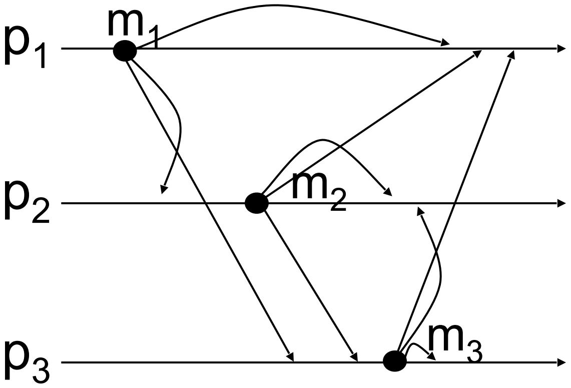




Causality (3)

- ***C3 (Transitivity)***.
  - There is a message m’ such that $m_1 \rightarrow$ m’ and m’ $\rightarrow m_2$





Specification of causal reliable broadcast

Causal Broadcast Interface

- **Module:**
  - Name: CausalOrder (co)
- ***Events***
  - Request: ⟨co Broadcast | m⟩
  - Indication: ⟨co Deliver | src, m⟩
- ***Property:***
  - ***CB***: If node p_i delivers m_1, then p_i must have delivered every message causally preceding (→) m_1 before m_1

Causal Broadcast Interface

- If node p_i delivers m_1, then p_i must have delivered every message causally preceding (→) m_1 before m_1

- Is this useful? How can it be satisfied? [d]
  - It is only safety. Satisfy it by never delivering!

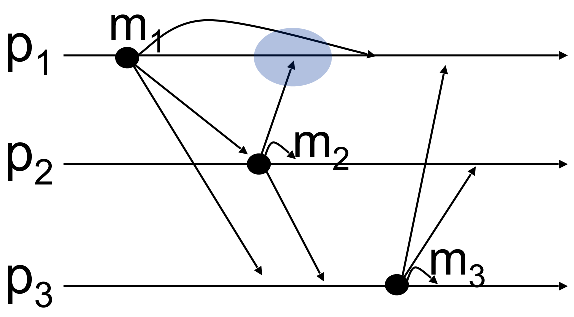
Different Causalities

- ***Property:***
  - ***CB***: If node p_i delivers m_1, then p_i must deliver every message causally preceding ($\rightarrow$) m_1 before m_1
  - ***CB'***: If p_j delivers m_1 and m_2, and $m_1 \rightarrow m_2$, then p_j must deliver m_1 before m_2
- What is the difference? [d]

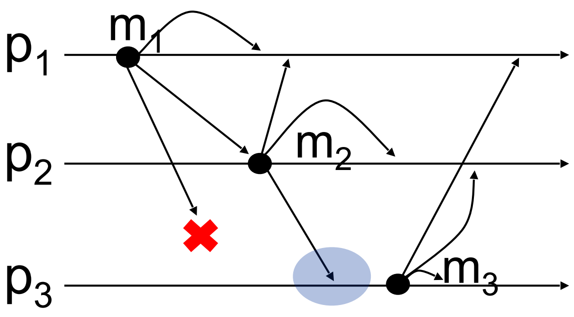
Different Causalities

- ***Property:***
  - ***CB***: If node p_i delivers m_1, then p_i must deliver every message causally preceding ($\rightarrow$) m_1 before m_1
  - ***CB'***: If p_j delivers m_1 and m_2, and $m_1 \rightarrow m_2$, then p_j must deliver m_1 before m_2
- What is the difference? [d]

Violates CB and CB'



Violates CB, not CB'



- Indeed, CB implies CB'

Reliable Causal Broadcast Interface

- **Module:**
  - Name: ReliableCausalOrder (rco)
- ***Events***
  - Request: ⟨rco Broadcast | m⟩
  - Indication: ⟨rco Deliver | src, m⟩
- ***Property:***
  - ***RB1-RB4*** from regular reliable broadcast
  - ***CB***: If node p_i delivers m, then p_i must deliver every message causally preceding ($\rightarrow$) m before m

Uniform Reliable Causal Broadcast

- **Module:**
  - Name: UniformReliableCausalOrder (urco)
- ***Events***
  - Request: ⟨urco Broadcast | m⟩
  - Indication: ⟨urco Deliver | src, m⟩
- ***Property:***
  - ***URB1-URB4*** from uniform reliable broadcast
  - ***CB***: If node p_i delivers m, then p_i must deliver every message causally preceding (→) m before m

Idea reuse…

- Reuse RB for CB

  - Use **reliable broadcast** abstraction to implement **reliable causal broadcast**

  - Use **uniform reliable broadcast** abstraction to implement **uniform causal broadcast**

Implementation of causal reliable broadcast

Towards an implementation

- Main idea
  - Each broadcasted message carries a history
  - Before delivery, ensure causality

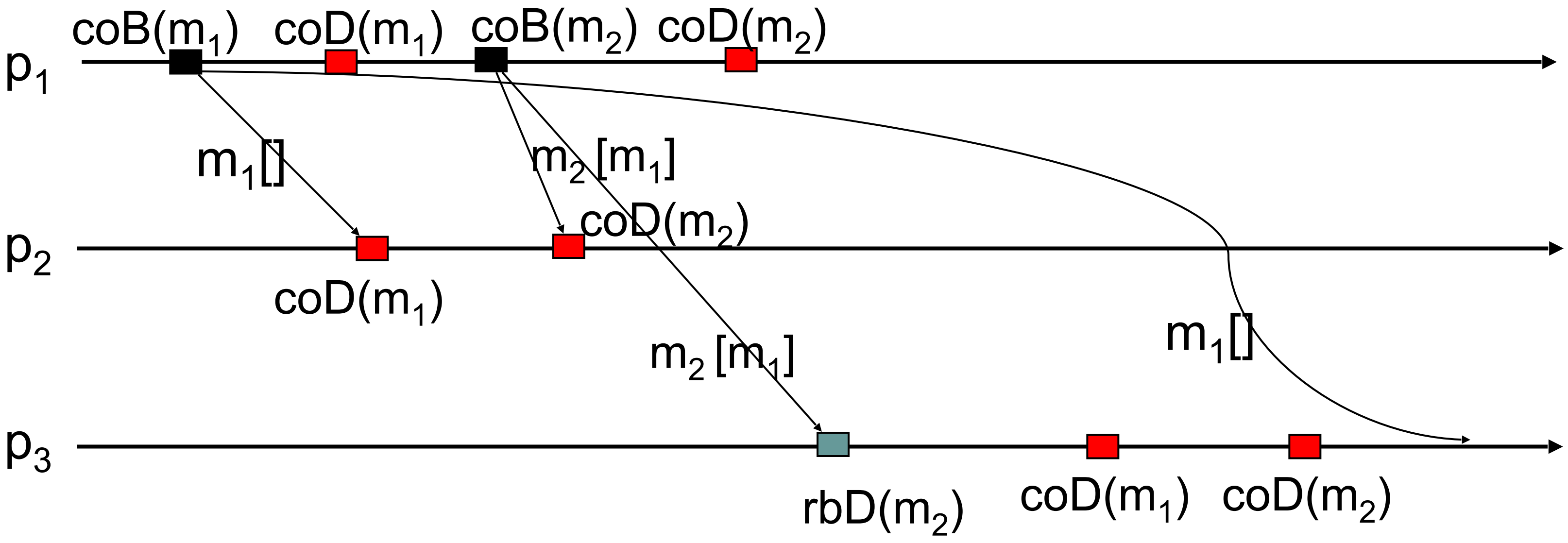
- First algorithm
  - History is set of all causally preceding messages

Fail-Silent No-Waiting Causal Broadcast

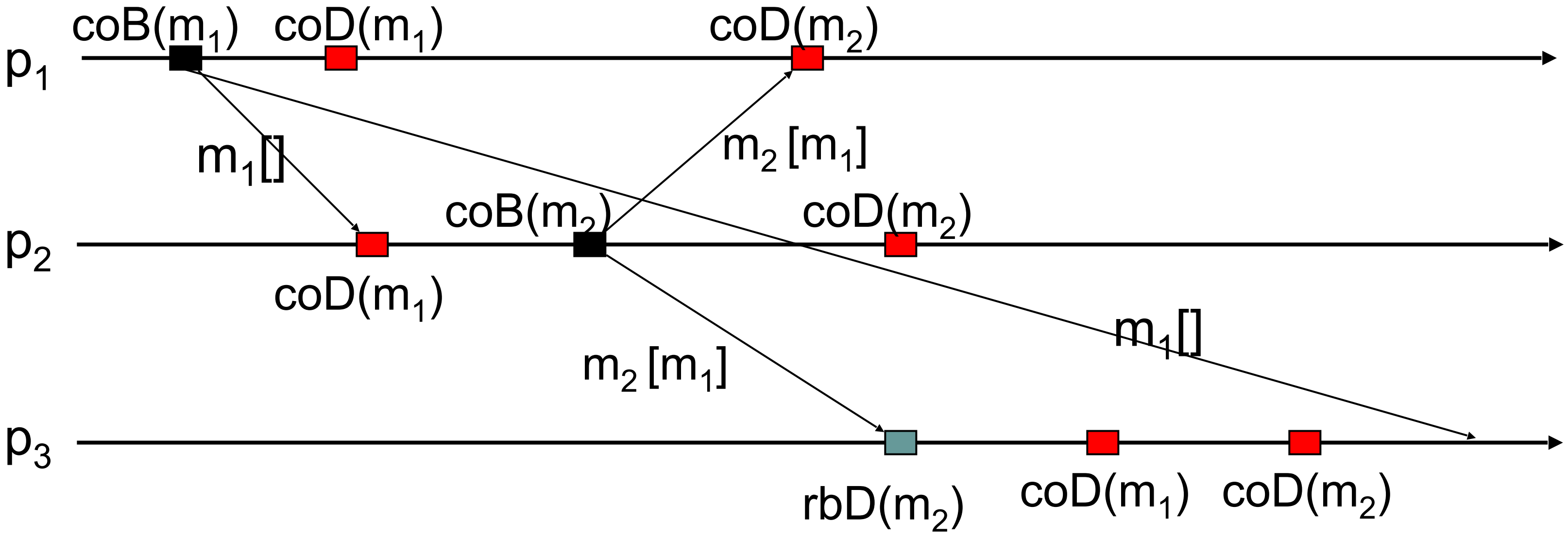
- Each message m carries ordered list of causally preceding messages in **$past_m$**

- Whenever a node rb-Delivers m
  - co-Deliver causally preceding messages in **$past_m$**
  - co-Delivers m
    - Avoid duplicates using **delivered**

Execution (direct override)



Execution (indirect override)



Fail-silent Causal Broadcast Impl

- **Implements:**
  - ReliableCausalOrderBroadcast (rco)
- **Uses:** ReliableBroadcast (rb)
- **upon event** ⟨Init⟩ **do**
  - delivered := ∅; past := nil
- **upon event** ⟨rco Broadcast | m⟩ **do**
  - **trigger** ⟨rb Broadcast | (DATA, past, m)⟩
  - past := append(past, (p_i, m))

Append this message to past history

Fail-silent Causal Broadcast Impl (2)

```
upon event ⟨rb Deliver | pi,(DATA, $past_m$ , m)⟩ do
    if $m \notin$ delivered then
        forall $(s_n,n) \in past_m$ do                      in ascending order
            if $n \notin$ delivered then
                trigger ⟨rco Deliver|$s_n$, n⟩               deliver preceding messages
                delivered := delivered$\cup${n}
                past := append(past, ($s_n$,n))              append to history
        trigger ⟨rco Deliver|$p_i$,m⟩                        deliver current message
        delivered := delivered$\cup${m}
        past := append(past, ($p_i$,m))                      append to history
```

Correctness

- RB1-RB4 follow from use of RB
  - No creation and no duplication still satisfied
  - Validity still satisfied
    - Some messages might be delivered earlier, never later
  - Agreement directly from RB

Correctness

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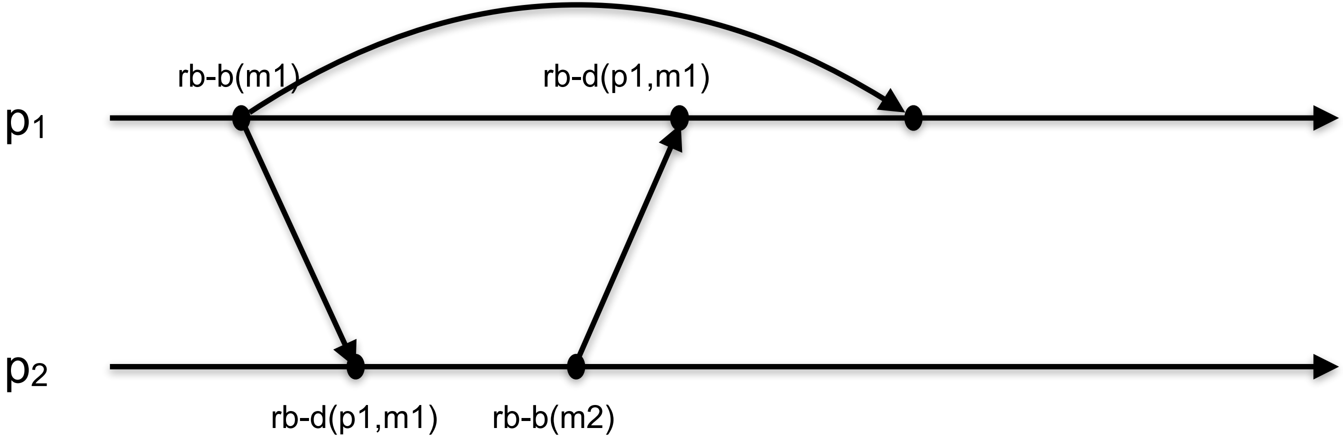


Correctness

- RB1-RB4 follow from use of RB
  - Agreement directly from RB
  - If correct process p_k delivers all correct processes deliver
    - all processes will deliver because of RB agreement either immediately or included in the $past_m$ of previous message m

Correctness of CB

- If process p_i delivers m, then p_i must deliver every message causally preceding ($\rightarrow$) m before m
- This property is an invariant of each execution (or prefix of)
- P is an invariant if P(E) holds for all executions E
- If P(E) is an invariant,
  - P hold for all s_0 in the set of initial states
  - If P holds in execution (prefix) E with final state s_n then P holds after extending E with any transition step (s_n, e_{n+1}, s_{n+1})

Correctness CB

- Each message carries its causal past
  - Each delivery of a message m makes sure that its causal past is delivered before m
- CO by induction on prefixes of executions
  - It is true for empty executions (initial state s_0)
  - Assume it is true for all deliveries of a prefix
    - Then it is true for any extension with one more event

Improving the algorithm

- Disadvantage of algorithm is that the message size (bit complexity) grows
- Useful idea
  - Garbage collect old messages
- Implementation of GC
  - Acknowledge causal delivery of every message m to all processes
  - Use perfect failure detector **P**
    - Determine with **P** when all correct nodes got message m
    - Delete m from past when all correct processes got m

Improving the algorithm

- We use **P**
- Use FIFO reliable broadcast
- It is possible to trim **Past ?**

Causal Broadcast Algorithm using FIFO Broadcast

Causal Broadcast Interface

- **Module:**
  - Name: FIFO-ReliableBroadcast (frb)

- ***Events***
  - Request: ⟨frb Broadcast | m⟩
  - Indication: ⟨frb Deliver | src, m⟩

- ***Property:***
  - ***FIFO delivery***: if p_i broadcasts message m_1 before it broadcasts message m_2, then no correct process delivers m2 unless it has already delivered m1
  - ***RB1-RB4***

Idea of using FIFO reliable broadcast

- Assume we use fifo-rb instead rb
- In the no-waiting algorithm
  - Each process p_i rb-broadcasts the message append($past_m$, m)
  - Assume two consecutive broadcasts by p_i
    - *append($past_{m1}$, m_1)=l_1* and then *append($past_{m2}$, m_2)=l_2*
    - Each correct process delivers l_1 before l_2 by FIFO delivery
    - But l_1 is a prefix of l_2 so p_i needs to only broadcast l_2 - l_1
  - Each p_i needs to keep track only of messages between to consecutive broadcasts

Fail-silent Causal Broadcast Impl

- **Implements:**
  - ReliableCausalOrderBroadcast (rco)
- **Uses:** FIFO-ReliableBroadcast (frb)
- **upon event** ⟨Init⟩ **do**
  - delivered := ∅; l := nil
- **upon event** ⟨rco Broadcast | m⟩ **do**
  - **trigger** ⟨frb Broadcast | (DATA, append(l, m))⟩
  - l := nil

reset l to store only new deliveries

Fail-silent Causal Broadcast Impl (2)

```
upon event ⟨frb Deliver | pi,(DATA, $l_m$)⟩ do
    forall $(s_n, n) \in l_m$ do
    if n $\notin$ delivered then
        trigger ⟨rco Deliver| $s_n$, n⟩
        delivered := delivered $\cup$ {n}
        if $(s_n, n) \notin l$ then
            append($l$, $(s_n, n)$)
```

in ascending order

deliver message

append to local l

- Can we trim the **delivered** set? [d]

Fail-Silent Waiting Algorithm

Towards another implementation

- Main idea
  - Each broadcasted message carries a history
  - Before delivery, ensure causality

- First & Second algorithms
  - History is set of all causally preceding messages
- Third algorithm [d]
  - History is a vector timestamp

Fail-Silent Waiting Causal Broadcast

- Represent past history by vector clock (VC)

- Slightly modify the VC implementation
  - At process p_i
    - VC[i]: number of messages p_i coBroadcasted
    - VC[j], j≠i: number of messages p_i coDelivered from pj

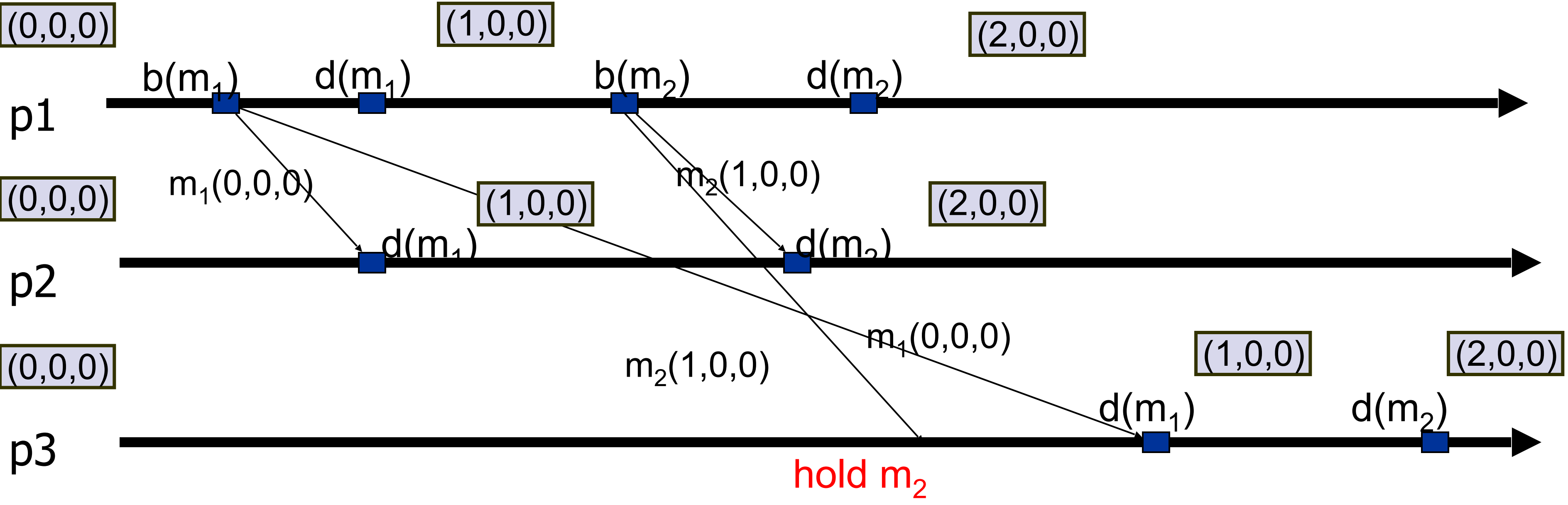
Fail-Silent Waiting Causal Broadcast

- Upon CO broadcast m
  - Piggyback VC and RB-broadcast m
  - $VC_m[r]$ is the number messages causally preceding m from r
- Upon RB delivery of m with attached VC_m compare VC_m with local VC_i
  - Only deliver m once $VC_m \leq VC_i$
  - **Do Not deliver** if $VC_m > VC_i$ or $VC_m \neq VC_i$

Fail-Silent Waiting Causal Broadcast

- Upon RB delivery of m with attached VC_m compare VC_m with local VC_i
  - Only deliver m once $VC_m \leq VC_i$
  - **Do Not deliver** if $VC_m > VC_i$ or $VC_m \neq VC_i$

Execution



(0,0,0)
(1,0,0)
(2,0,0)
b(m$_1$)
d(m$_1$)
b(m$_2$)
d(m$_2$)
p1
m$_1$(0,0,0)
(0,0,0)
(1,0,0)
m$_2$(1,0,0)
(2,0,0)
d(m$_1$)
d(m$_2$)
p2
m$_1$(0,0,0)
(0,0,0)
m$_2$(1,0,0)
(1,0,0)
(2,0,0)
d(m$_1$)
d(m$_2$)
p3
hold m$_2$

Fail-Silent Waiting Causal Implementation

```
• Uses:  ReliableBroadcast (rb)
• upon event ⟨Init⟩ do
    • forall pi ∈ Π do VC[pi] := 0
    • sn := 0
    • Pending := ∅
• upon event ⟨rco Broadcast|m⟩ do
    • W = copy(VC)
    • W[self] := sn
    • trigger ⟨rbBroadcast|(DATA, W, m)⟩
    • sn := sn + 1
```

send m with VC

Increase sn for next broadcast

Fail-Silent Waiting Causal Impl. (2)

```
• upon event ⟨rbDeliver | $p_j$, (DATA, $VC_m$ , m)⟩ do
    • pending := pending ∪ ($p_j$, (DATA, $VC_m$, m))
    • deliver-pending()

• proc deliver-pending()
    • while exists x=($s_m$,(DATA,$VC_m$,m)) ∈ pending s.t. $VC_m \leq VC$ do
        • pending := pending \ ($s_m$, (DATA, $VC_m$, m))
        • VC[ $s_m$ ] := VC[ $s_m$ ] + 1
        • trigger ⟨rcoDeliver | $s_m$, m⟩
```

put on hold

for every message whose VC precedes local VC

Remove on hold deliver and increase local VC

Correctness

- Validity
  - m is co-cast by a correct pi with VC_m equal VC_i at send time or higher only at $VC_i[i]$ by outstanding earlier co-cast not delivered yet
  - By rb-cast validity m is eventually rb-delived at p_i as well as earlier co-casts
  - At delivery time VC_i can only increase, so
  - Eventually $VC_m \leq VC_i$ and m is co-delived

```
upon event ⟨rco Broadcast|m⟩ do
W = copy(VC)
W[self] := sn
trigger ⟨rbBroadcast|(DATA, W, m)⟩
sn := sn + 1
```

Correctness

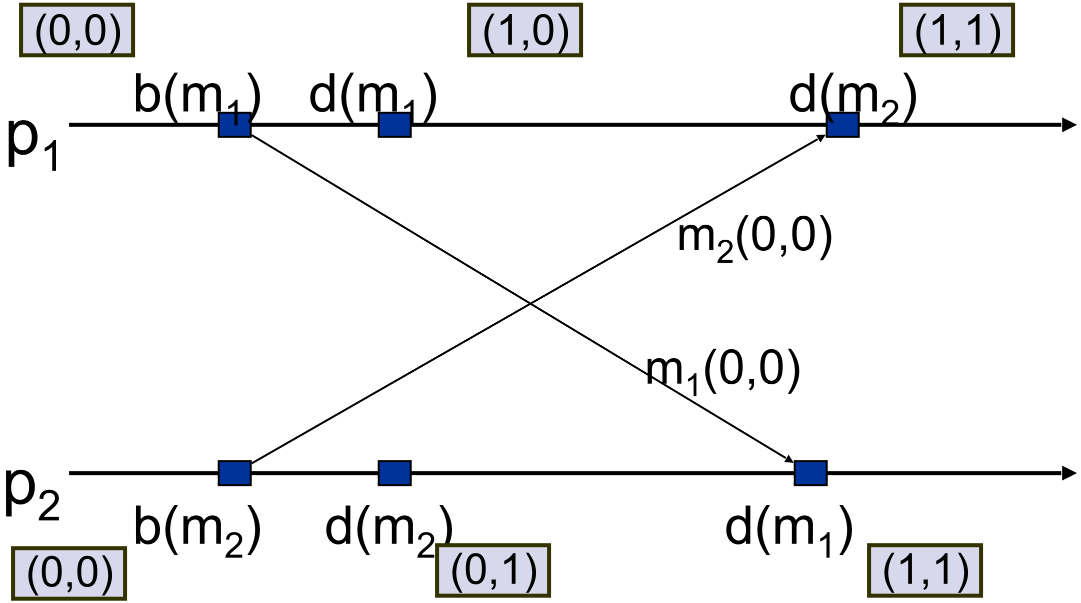
- Agreement
  - Assume m is co-delivered at correct pi
  - pi co-delivered all message causally before m
  - Every correct process rb-delivered m and all causally preceding messages (agreement of RB)
  - Hence every correct process co-deliver m

Correctness

- Causal Order
  - Assume p rb-delivers m, VC_m from q
  - $VC_m[r]$ is the number messages causally preceding m from r
  - VC at p stores the number of messages co-delivered from each process
  - For some r, $VC_m[r] > VC[r]$ implies there is at least one message from r that is causally before m, which is not co-delivered at p
  - P waits to deliver m until $VC_m [r] \leq VC_i [r]$, for all r
  - Hence m is not delivered until all causally preceding messages are delivered

Orderings of Broadcast

Possible execution?



- Delivery order isn’t same!
  - What is wrong? [d]   Nothing, there is no causality.

Other possible orderings

- Other common orderings
  - Single-source FIFO order
  - Total order
  - Causal order

Single-Source FIFO order

- Intuitively
  - Msgs from same node delivered in order sent
- For all messages m_1 and m_2 and all p_i and p_j,
  - if p_i broadcasts m_1 before m_2, and if p_j delivers m_2, then p_j delivers m_1 before m_2
- Caveat
  - This formulation doesn’t require delivery of both messages

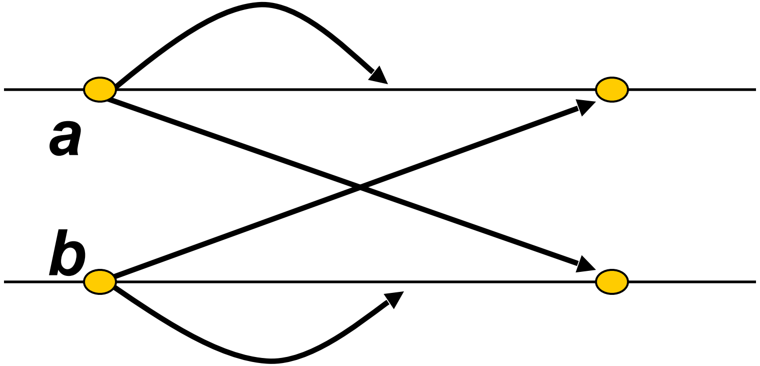
Total Order

- Intuitively
  - Everyone delivers everything in exact same order

- For all messages m_1 and m_2 and all p_i and p_j,
  - if both p_i and p_j deliver both messages, then they deliver them in the same order

- Caveat
  - This formulation doesn’t require delivery of both messages
  - Everyone delivers same order, maybe not send order!

Execution Example (1)

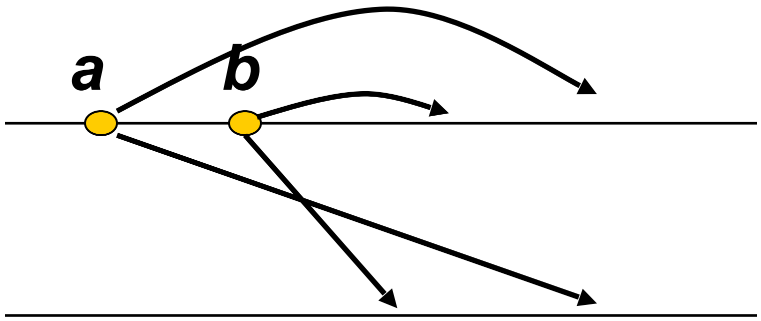


single-source FIFO?**yes**

totally ordered? **no**

causally ordered? **yes**

Execution Example (2)

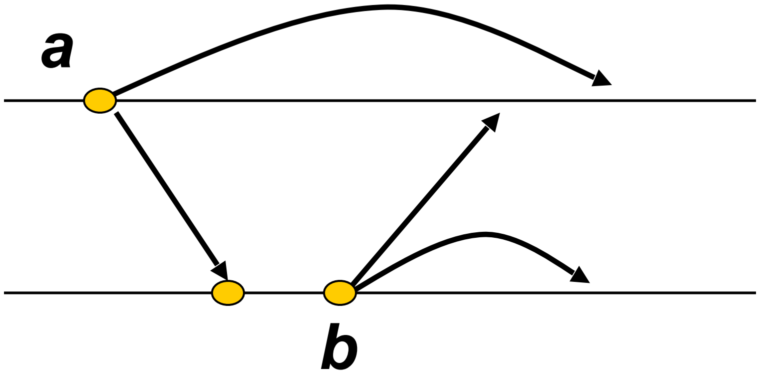


single-source FIFO? **no**

totally ordered? **yes**

causally ordered? **no**

Execution Example (3)



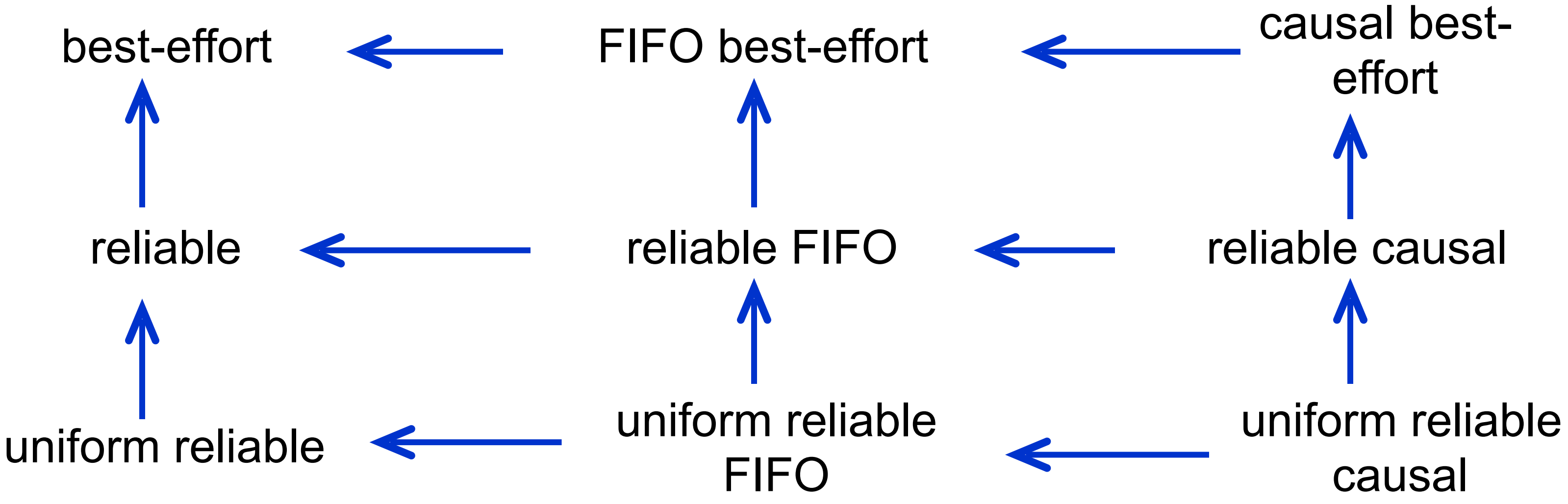
single-source FIFO? **yes**

totally ordered? **no**

causally ordered? **no**

Hierarchy of Orderings

- Stronger implies weaker ordering (→)



best-effort

FIFO best-effort

causal best-effort

reliable

reliable FIFO

reliable causal

uniform reliable

uniform reliable FIFO

uniform reliable causal