Distributed Systems 2
Reliable Broadcast

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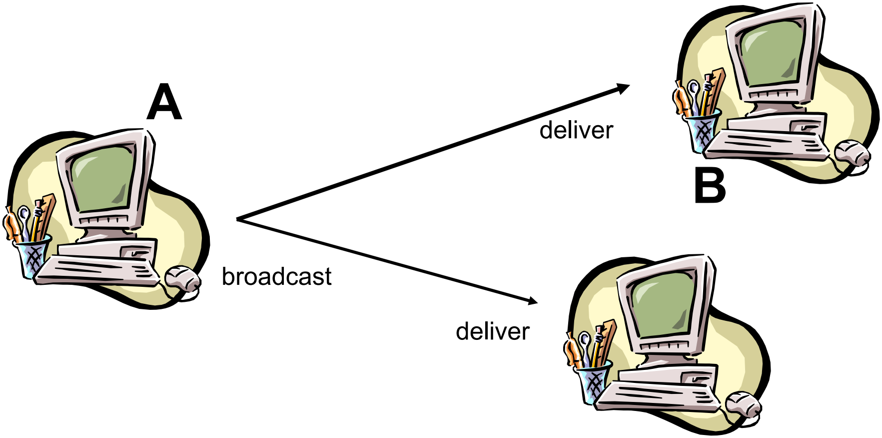
Introduction

Efficient techniques are required, capable of supporting consistent behavior between system components in spite of failures.

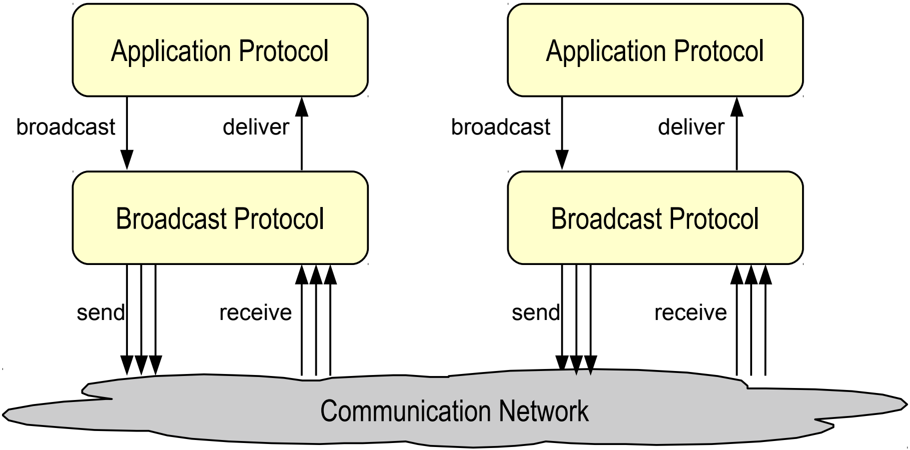
Examples

- Reliable Broadcast/Multicast protocols:
  Ensure reliable message delivery to all participants
- Agreement protocols:
  Ensure all participants to have a consistent system view
- Commit protocols:
  Implement atomic behavior in transactional types of systems

Broadcast



Broadcast Protocol Layering



Basic assumptions (1)

- System is asynchronous
  - No bounds on messages and process execution delays
- Processes fail by crashing
  - stop executing actions after the crash
  - We do not consider Byzantine failures
- Correct/Faulty
  - A process that does not fail in a run is correct in that run
  - Otherwise, the process is faulty

Basic assumptions (2)

We will consider two failure models for communication:

No Failures

- Validity: If p sends a message to q, and q is correct, then q will eventually receive m
- Integrity: No message is delivered to a process more than once, and only if it has been sent previously

Perfect Channels

- Validity: If p sends a message to q, and p,q are correct, then q will eventually receive m
- Integrity: No message is delivered to a process more than once, and only if it has been sent previously

What kind of underlying network?

- Complete graph
  - Every process can communicate with every other process
  - A routing substrate realizes this abstraction
- Point-to-point
  - Every process can communicate with a subset of processes (its neighbors)
  - Routing is not implemented at the send/receive level (we may implement it at the level of our protocols)

Different flavors of broadcast

- Reliability
  - **B**est-effort
  - **R**eliable
  - **U**niform **R**eliable
- Ordering
  - **FIFO**
  - **C**asual
  - **A**tomic
  - **FIFO A**tomic
  - **Causal A**tomic
- Time bounds
  - **T**imed **R**eliable
- Primitives
  - R-Broadcast
  - F-Broadcast
  - C-Broadcast
  - ...

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Best-effort broadcast – Specification

Definition (BEB1 – Validity)

If p and q are correct, then every message B-broadcast by p is eventually B-delivered by q

Definition (BEB2 – Uniform Integrity)

m is B-delivered by a process at most once, and only if it was previously broadcast

Best-effort broadcast – Algorithm

Best-effort broadcast protocol executed by p

```
upon B-broadcast(m) do
    foreach q ∈ Π do
        send m to q

upon receive(m) do
    B-deliver(m)
```

Notation – Send to all

foreach $q \in \Pi$ **do**
  send m **to** q

is equivalent to **send** m **to** Π

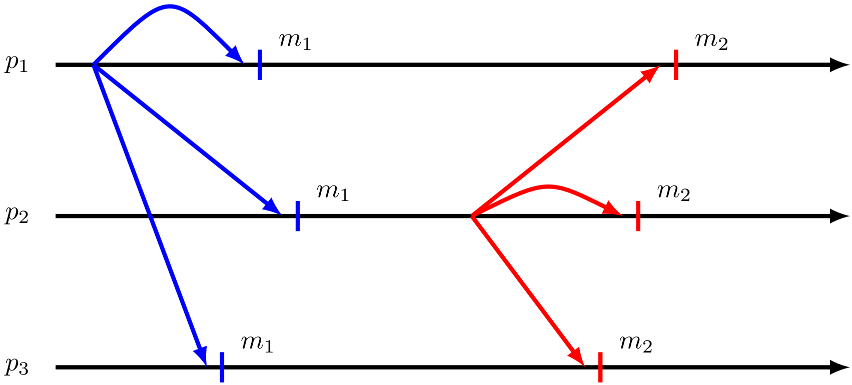
Best-effort broadcast – Proof

We can show that the protocol works with *Perfect Channels*:

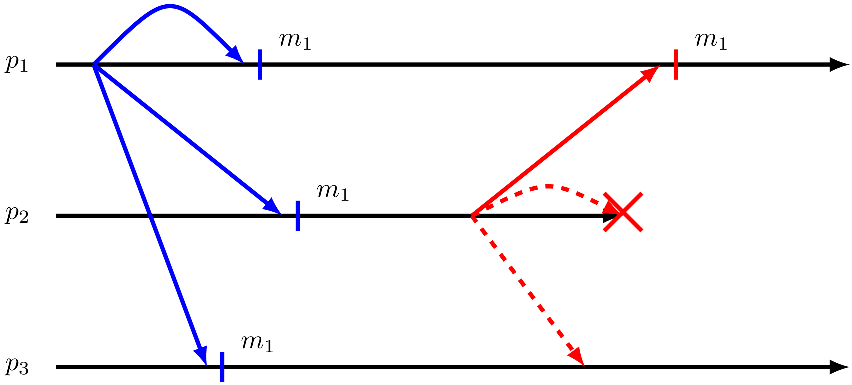
- BEB1 - Validity: By the Validity property of Perfect Channels and the very facts that
  1. the sender sends the message to all
  2. every correct process that receives a message B-delivers it
- BEB2 – Uniform Integrity: By the Integrity property of Perfect Channels

Clearly, it will work also with No Failures

Best-effort broadcast – Example



Best-effort broadcast – Example



Best-effort broadcast – Problem

What happens if the sender fails?

- Even in the absence of communication failures:
  - if the sender crashes before being able to send the message to all
  - some processes will not deliver the message

What we do?

- First we revise the specification of broadcast
- Then we implement the new specification

Reliable Broadcast – Specification

Definition (RB1 – Validity)

If a correct process broadcasts m, then it eventually delivers m

Definition (RB2 – Uniform Integrity)

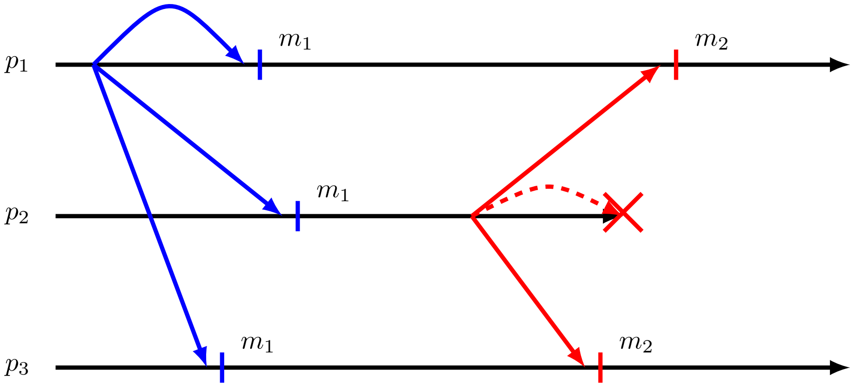
m is delivered by a process at most once, and only if it was previously broadcast

Definition (RB3 – Agreement)

If a correct process delivers m, then all correct processes eventually deliver m

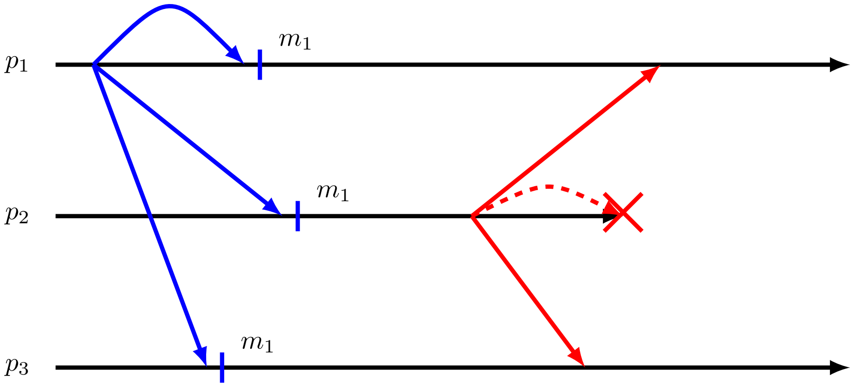
Reliable Broadcast – Scenario 1

Does this execution satisfy the RB specification?



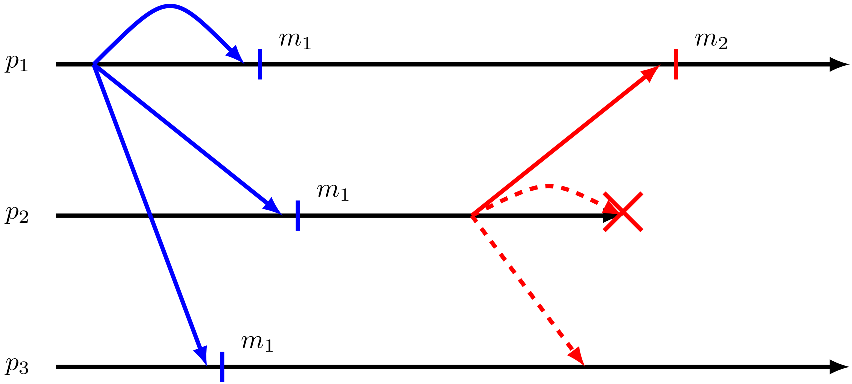
Reliable Broadcast – Scenario 2

Does this execution satisfy the RB specification?



Reliable Broadcast – Scenario 3

Does this execution satisfy the RB specification?



Reliable Broadcast – Algorithm v.1

Reliable broadcast protocol executed by p

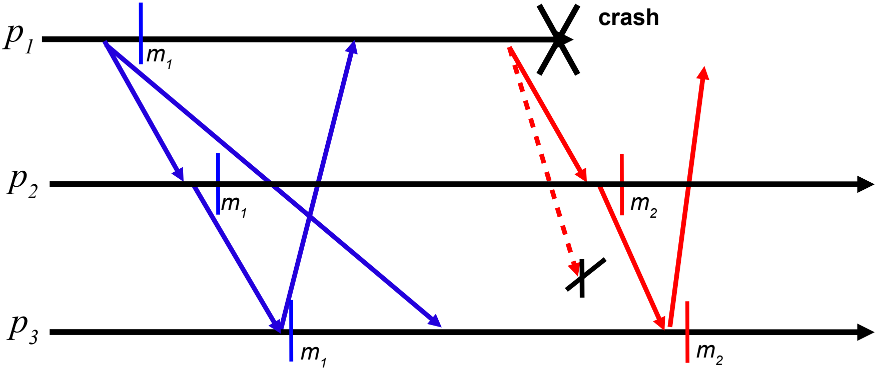
upon initialization **do**
  SET *delivered* $\leftarrow \emptyset$ % Messages already delivered

upon R-broadcast(m) **do**
  send m **to** $\Pi - \{p\}$
  R-deliver(m)
  $delivered \leftarrow delivered \cup \{m\}$

upon receive(m) *from* q **do**
  if not $m \in delivered$ **then**
    send m **to** $\Pi - \{p, q\}$
    R-deliver(m)
    $delivered \leftarrow delivered \cup \{m\}$

Reliable Broadcast – Scenario 4

Does this execution satisfy the RB specification?



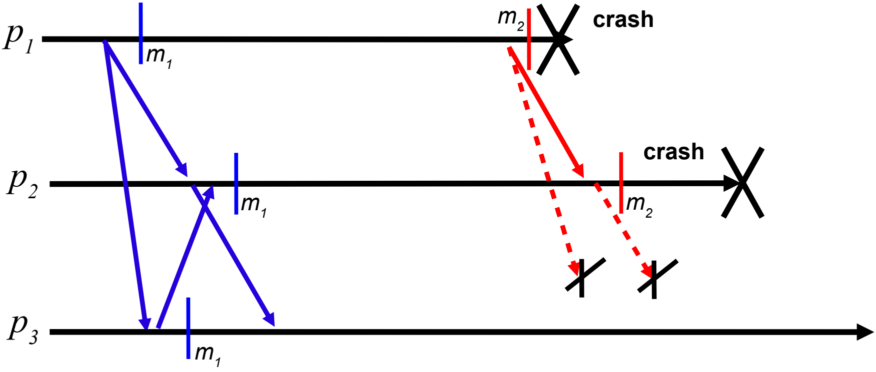
Reliable Broadcast – Proof

Algorithm v.1 implements Reliable Broadcast.

- RB1 – Validity: *If a correct process broadcasts m, then it eventually delivers m*
  By the code implementing R-broadcast.
- RB2 – Uniform Integrity: *m is delivered by a process at most once, and only if it was previously broadcast*
  By the Integrity of Perfect Channels and the use of variable *delivered*
- RB3 – Agreement: *If a correct process delivers m, then all correct processes eventually deliver m*
  Before R-delivering m, a correct process p forwards m to all processes. By Validity of Perfect Channels and the fact that p is correct, all correct processes will eventually receive m and R-deliver it.

Reliable Broadcast – Scenario 5

Does this execution satisfy the RB specification?



Uniform Reliable Broadcast – Specification

Definition (URB1 – Validity)

If a correct process broadcasts m, then it eventually delivers m

Definition (URB2 — Uniform Integrity)

m is delivered by a process at most once, and only if it was previously broadcast

Definition (URB3 – Uniform Agreement)

If a ~~correct~~ process delivers m, then all correct processes eventually deliver m

Uniform Reliable Broadcast – Proof

Algorithm v.1 implements Uniform Reliable Broadcast...
... but under different assumptions!

- **URB1**, **URB2**: As **RB1**, **RB2**
- **URB3 – Uniform Agreement**: If a process delivers m, then all correct processes eventually deliver m
  - Before R-delivering m, a process forwards m to all processes.
  - ~~By Validity of Perfect Channels, all correct processes will eventually receive m and R-deliver it~~
  - In the absence of communication failures, all correct processes will eventually receive m and R-deliver it

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Message ordering

Problem

- 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.

Solution

We describe a collection of ordering policies and we show how to implement them in a modular way.

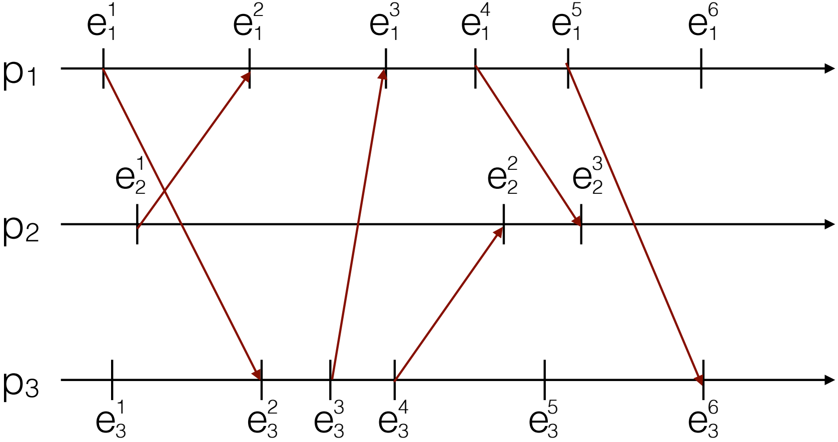
Happen-Before

Definition (Happen-before)

We say that an event e happens-before an event e', and write $e \to e'$, if one of the following three cases is true:

1. $\exists p_i \in \Pi : e = e_i^r, \quad e' = e_i^s, \quad r < s$
   (e and e' are executed by the same process, e before e')
2. $e = \mathit{send}(m, *) \wedge e' = \mathit{receive}(m)$
   (e is the send event of a message m and e' is the corresponding receive event)
3. $\exists e'' : e \to e'' \to e'$)
   (in other words, $\to$ is transitive)

Space-Time Diagram of a Distributed Computation



Message ordering

Definition (FIFO Order)

If a process p broadcasts a message m before it broadcast a message m', the no correct process delivers m' unless it has previously delivered m

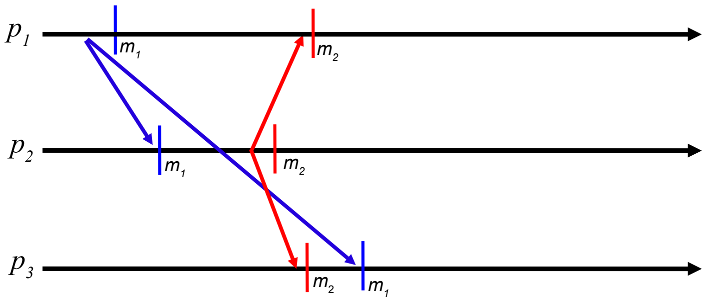
$$broadcast_p(m) \rightarrow broadcast_p(m') \Rightarrow deliver_q(m) \rightarrow deliver_q(m')$$

Definition (Causal Order)

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

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

Is this causal?



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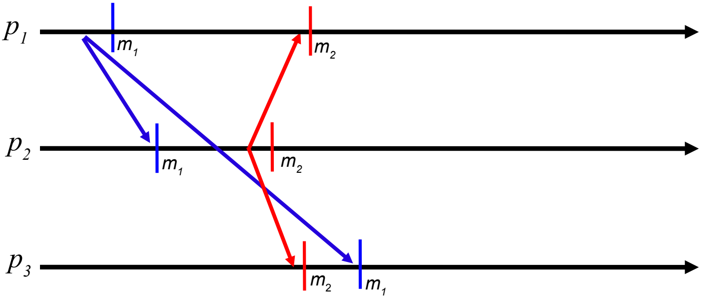
Is this causal? No!



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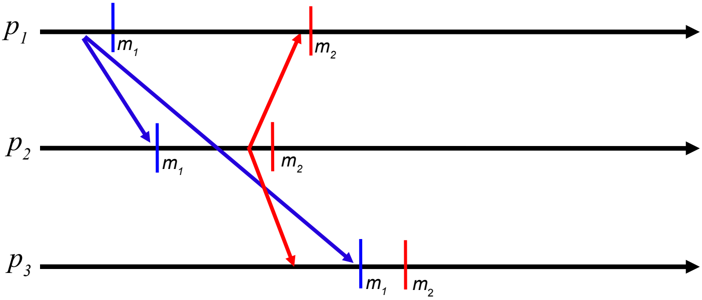

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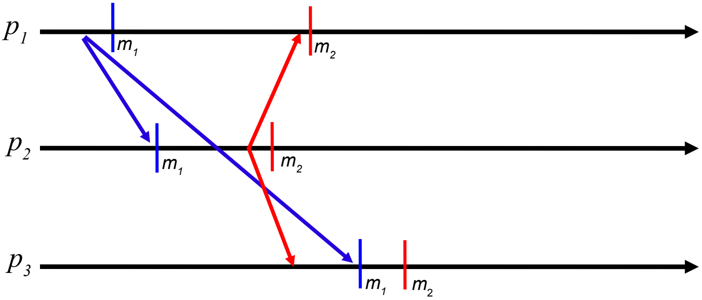
Is this causal? Yes!



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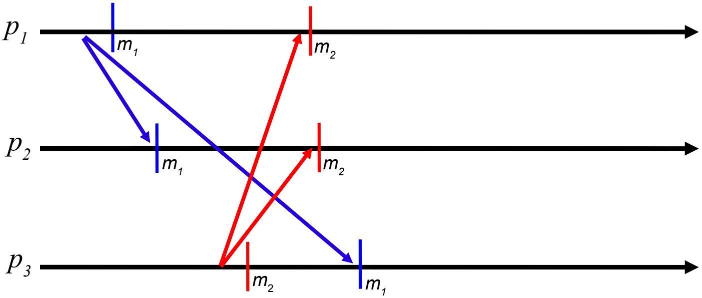

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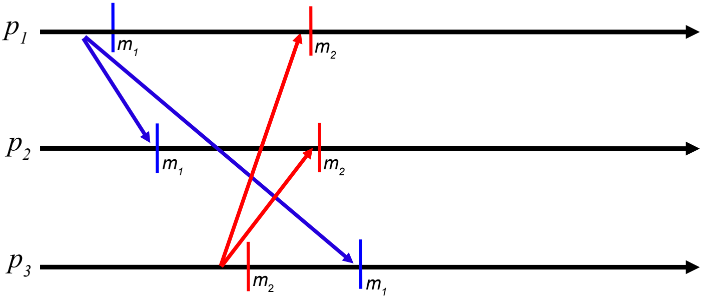


Message ordering

Problem

Causal Broadcast does not impose any order on messages not causally related

Example

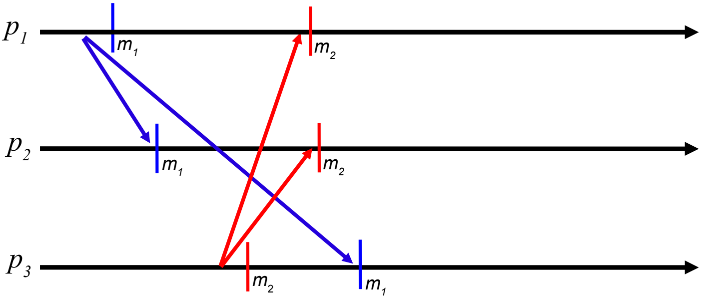
- Consider a replicated database with two copies of a bank account
- Initially, $account = 1000\$$
- A user deposits 150$ triggering a broadcast of $m_1 = \{\text{add } 150\$ \text{ to } account\}$
- At the same time the bank initiates a broadcast of $m_2 = \{\text{add } 2\% \text{ interest to } account\}$
- Causal Broadcast allows two processes to deliver these updates in different order, creating inconsistency

Definition (Total Order)

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'

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

Is this totally ordered?



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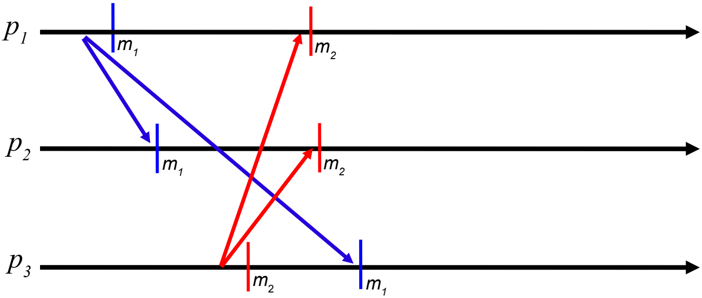

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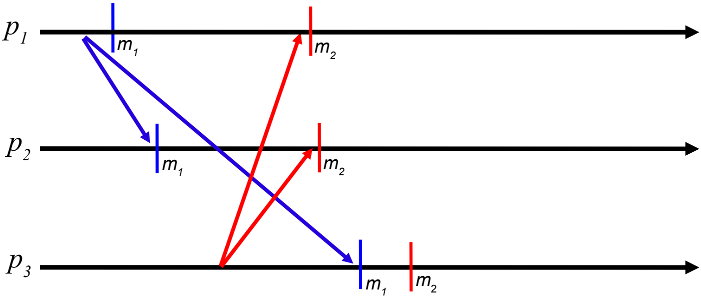

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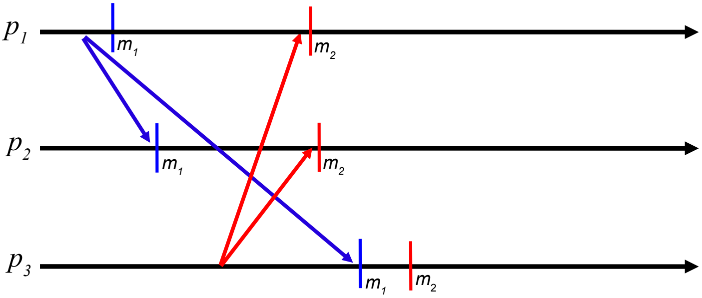


Uniform Versions

Definition (Uniform FIFO Order)

If a process p broadcasts a message m before it broadcast a message m', then no ~~correct~~ process delivers m' unless it has previously delivered m

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

Definition (Uniform Causal Order)

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

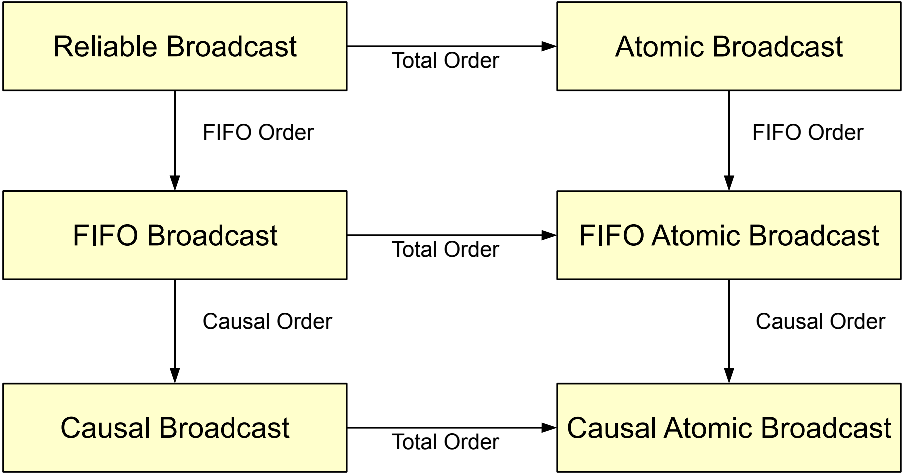
$$broadcast_p(m) \rightarrow broadcast_q(m') \Rightarrow deliver_r(m) \rightarrow deliver_r(m')$$

Definition (Uniform Total Order)

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'

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

A modular approach to Broadcast



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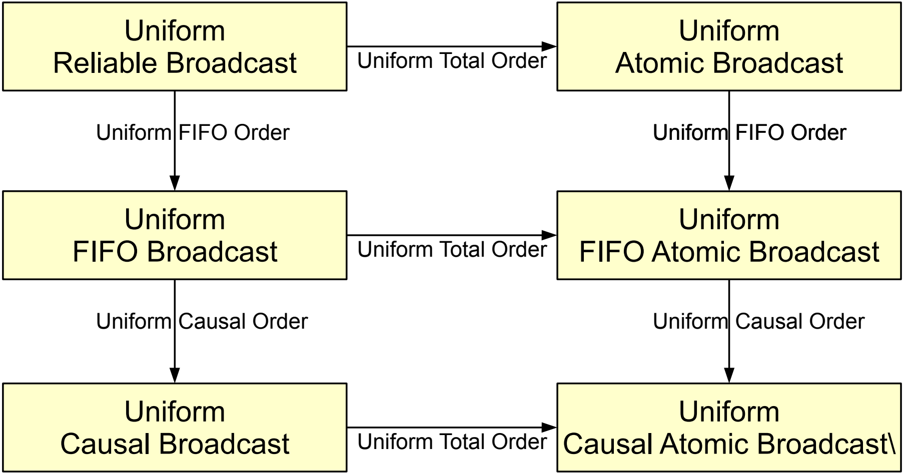


Transformation

Informal definition

A broadcast transformation is an algorithm that takes a weaker broadcast algorithm and transform it into a stronger version

Definition (Transformation)

A transformation from problem A to problem B is an algorithm $T_{A \to B}$ that converts any algorithm $\mathcal{A}$ that solves problem A into an algorithm $\mathcal{B}$ that solves problem B

Definition (Preservation)

A transformation $T_{A \to B}$ preserves property P if it converts any algorithm for A into an algorithm that solves problem B and also satisfies P

Transformation

- Properties of weakest RB must be preserved
  - Uniform Integrity: preserved in all transformations
    - No message is created
    - Messages are tagged to avoid re-delivery
  - Validity, (Uniform) Agreement:
    - To be proved case by case
- To add Total Order:
  - We cannot start from a simple reliable broadcast
  - We need stronger assumptions

Transformation

Definition (Blocking transformation)

A transformation of one broadcast algorithm into another is blocking if the resulting broadcast algorithm has a run in which a process delays the delivery of a message for a later time.

Example

FIFO Order

FIFO Order – Algorithm

FIFO Order Transformation executed by process p

upon initialization **do**
  Set $buffer \leftarrow \emptyset$
  integer[ ] $next \leftarrow$ **new integer**$[1 \ldots |\Pi|]$
  foreach $q \in \Pi$ **do** $next[q] \leftarrow 1$

upon F-broadcast(m) **do**
  R-broadcast(m)

upon R-deliver(m) **do**
  $buffer \leftarrow buffer \cup \{m\}$
  while $\exists m' \in buffer$: sender(m') = sender(m) **and**
      seqn$(m') = next[q]$ **do**
    F-deliver(m')
    $next[q] \leftarrow next[q] + 1$
    $buffer \leftarrow buffer - \{m'\}$

FIFO Order – Proof

Theorem

For any process p, if $next_p[q] = k$ *then p has F-delivered the first* $k-1$ *messages F-broadcast by q*

Theorem

Suppose a correct process p R-delivers a message m from q and F-delivers all the messages that q F-broadcast before m. Then p also F-delivers m

- Validity, (Uniform) Agreement, (Uniform) Total Order are preserved
- Uniform FIFO Order is satisfied
- The transformation is blocking

Causal Order - Algorithm

Two transformations:

- Both based on FIFO Reliable Broadcast
- One is non-blocking
  - Each message is tagged with "recent history"
  - When a message is F-delivered, all the causal messages that have been F-delivered are locally delivered
  - Does this recall anything?
- One blocking
  - Based on vector clocks

Causal Order - Algorithm 1

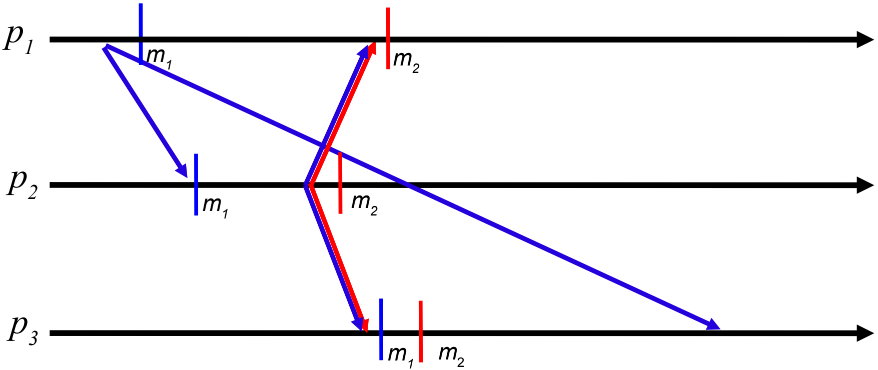
Causal Order Transformation executed by process p

upon initialization **do**
- SET *delivered* $\leftarrow \emptyset$ % Messages already C-delivered
- SEQUENCE *recent* $\leftarrow \langle\rangle$ % Messages C-delivered since last C-broadcast

upon C-broadcast(m) **do**
- F-broadcast($recent || m$)
- $recent \leftarrow \langle\rangle$

upon F-deliver($\langle m_1, \ldots, m_k \rangle$) **do**
- **for** $i \leftarrow 1$ **to** k **do**
  - **if not** $m_i \in delivered$ **then**
    - $delivered \leftarrow delivered \cup \{m_i\}$
    - $recent \leftarrow recent || m_i$
    - C-deliver(m_i)

Causal Order - Algorithm 1



Causal Order – Proof

- Validity, (Uniform) Agreement, (Uniform) Total Order are preserved
- Uniform Causal Order is satisfied
- The transformation is non-blocking

Causal Order - Algorithm 2

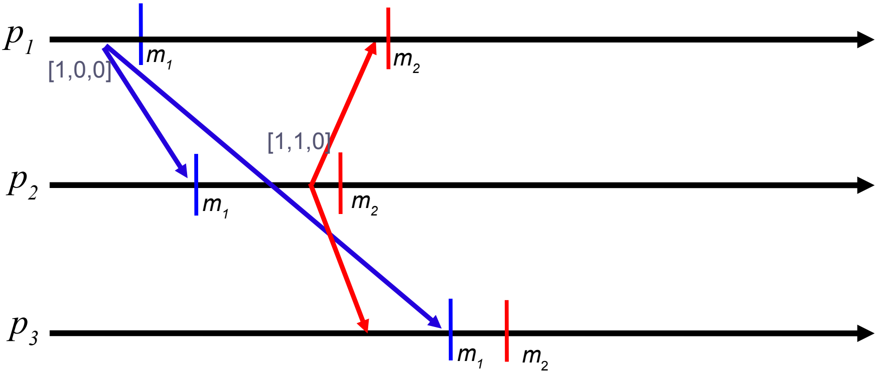
Causal Order Transformation executed by process p

upon initialization **do**
    SET $buffer \leftarrow \emptyset$ % Messages to be delivered
    integer[] $VC \leftarrow \{0, \ldots, 0\}$ % Vector clock

upon C-broadcast(m) **do**
    $VC[p] \leftarrow VC[p] + 1$
    F-broadcast($\langle m, VC \rangle$)

upon F-deliver($\langle m, TS \rangle$) **do**
    $buffer \leftarrow buffer \cup \{\langle m, TS \rangle\}$
    while $\exists \langle m', TS' \rangle \in buffer : VC[\text{sender}(m')] = TS'[\text{sender}(m')] - 1 \wedge$
        $\forall s \neq \text{sender}(m') : VC[s] \geq TS'[s]$ **do**
        C-deliver(m')
        $VC[\text{sender}(m')] \leftarrow TS'[\text{sender}(m')]$
        $buffer \leftarrow buffer - \{m\}$

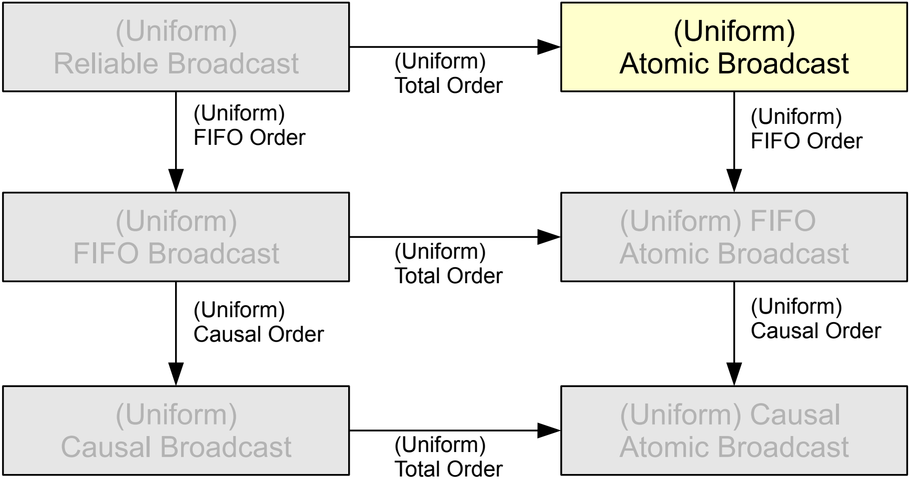
Causal Order - Algorithm 2



Causal Order – Proof

- Validity, (Uniform) Agreement, (Uniform) Total Order are preserved
- Uniform Causal Order is satisfied
- The transformation is blocking

A modular approach to Broadcast



Atomic Broadcast

There are three approaches:

1. We add synchronous assumptions to our system
2. We show that the Atomic Broadcast problem is equivalent to the Consensus problem
   - There is an algorithm $T_{Consensus \rightarrow AtomicBroadcast}$
   - There is an algorithm $T_{AtomicBroadcast \rightarrow Consensus}$
3. Through a coordinator (actual implementation, see later in group communication)

Timed Reliable Broadcast

Definition ((Uniform) Real-Time Δ-Timeliness)

There is a known constant Δ such that if a message m is broadcast at real-time t, then no correct (any) process delivers m after real-time $t + \Delta$

Definition ((Uniform) Local-Time Δ-Timeliness)

There is a known constant Δ such that no correct (any) process delivers m after local time $TS(m) + \Delta$ on p's clock, where $TS(m)$ is the timestamp obtained by the local clock of the sender

Note

(Uniform) Real-Time Δ-Timeliness $\Rightarrow$
(Uniform) Local-Time Δ-Timeliness

Atomic Broadcast, Algorithm 1

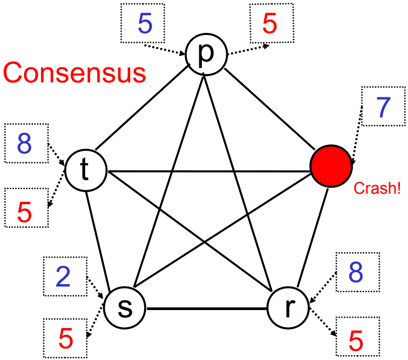
Total Order Transformation executed by process p

upon A-broadcast(m) **do**
- T-broadcast(m)

upon T-deliver(m) **do**
- **schedule** A-deliver(m) **at time** $TS(m) + \Delta$

Consensus

In the (Uniform) Consensus problem, the processes propose values and need to decide (agree) on one of these values



Definition (Uniform Validity)

Any value decided is a value proposed

Definition ((Uniform) Agreement)

No two correct (any) processes decide differently

Definition (Termination)

Every correct process eventually decides

Definition (Uniform Integrity)

Every process decides at most once

From Atomic Broadcast to Consensus

Transformation executed by process p

```
upon initialization do
    boolean decided ← false

upon propose(v) do
    A-broadcast(v)

upon A-deliver(v) do
    if not decided then
        decided ← true
        decide(u)
```

From Consensus to Atomic Broadcast

Transformation executed by process p

```
upon initialization do
    SET unordered ← ∅              % Messages to be ordered
    SET delivered ← ∅              % Messages already delivered
    boolean wait ← false           % true when Consensus is running
    integer s ← 1                  % Consensus protocol identifier

upon A-broadcast(m) do
    R-broadcast(m)

upon R-deliver(m) do
    if not m ∈ delivered then
        unordered ← unordered ∪ {m}
```

From Consensus to Atomic Broadcast

Transformation executed by process p

upon $\mathsf{decide}_s(S)$ **do**

- $\mathit{unordered} \leftarrow \mathit{unordered} - S$
- **foreach** $m \in S$ **do**
  - $\mathsf{A\text{-}deliver}(m)$ % In some deterministic order
- $\mathit{delivered} \leftarrow \mathit{delivered} \cup S$
- $s \leftarrow s + 1$
- $\mathit{wait} \leftarrow$ **false**

upon $\mathit{unordered} \neq \emptyset$ **and not** wait **do**

- $\mathit{wait} \leftarrow$ **true**
- $\mathsf{propose}_s(\mathit{unordered})$

Conclusions

Summary

Consensus and total order broadcast are equivalent problems in an asynchronous system with crashes and Perfect Channels

- Consensus can be obtained from total order broadcast
- Total order broadcast can be obtained from Consensus

Problem

But in this way, we have moved the problem from Atomic Broadcast to Consensus.
Next step: can we solve Consensus?

Reading Material

- V. Hadzilacos and S. Toueg. A modular approach to fault-tolerant broadcasts and related problems.

  In S. Mullender, editor, *Distributed Systems (2^{nd} ed.)*. Addison-Wesley, 1993.

  http://www.disi.unitn.it/~montreso/ds/papers/FTBroadcast.pdf