Distributed Algorithms
Reliable Broadcast

Alberto Montresor

University of Trento, Italy

2016/04/26

Contents

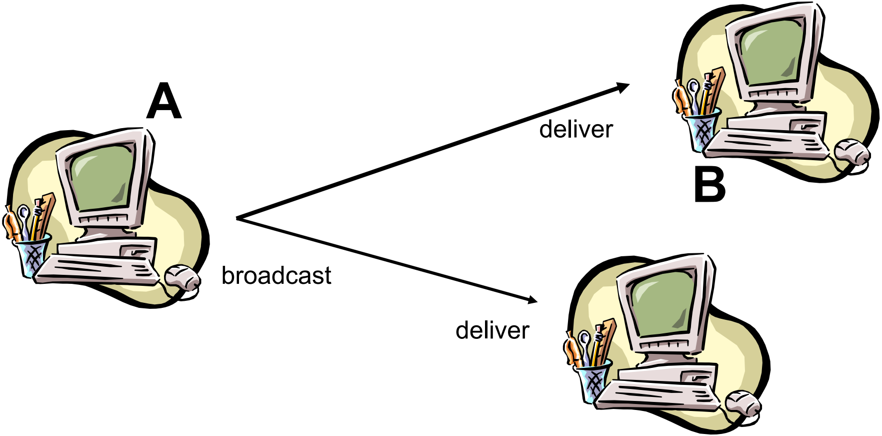
Introduction

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

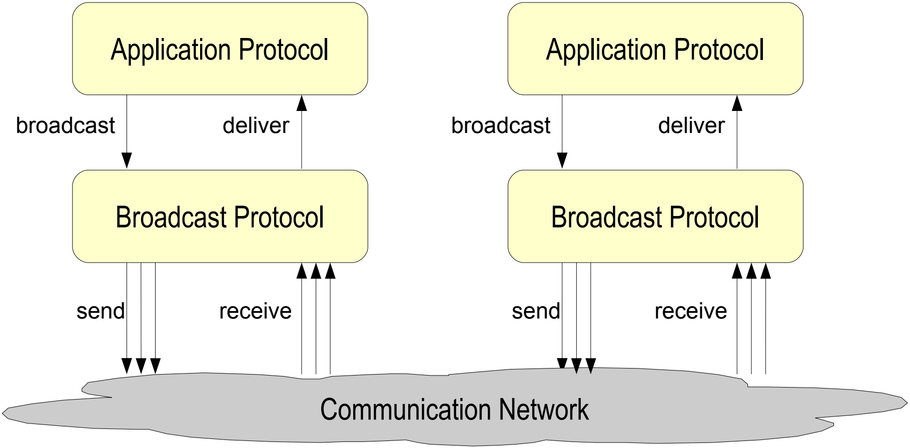
Examples

- 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



Application Protocol

Application Protocol

broadcast

deliver

broadcast

deliver

Broadcast Protocol

Broadcast Protocol

send

receive

send

receive

Communication Network

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
  - ...

Best-effort broadcast – Specification

Definition (BEB1 – Validity)

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

Definition (BEB2 – Uniform Integrity)

m is 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 $q \in \Pi$ 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

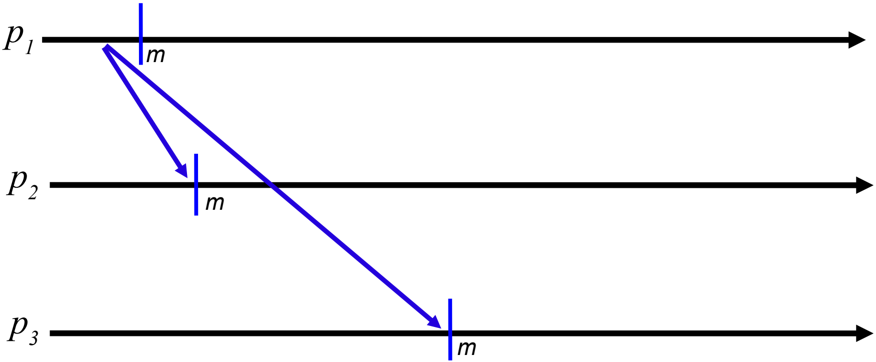
Best-effort broadcast – Proof

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

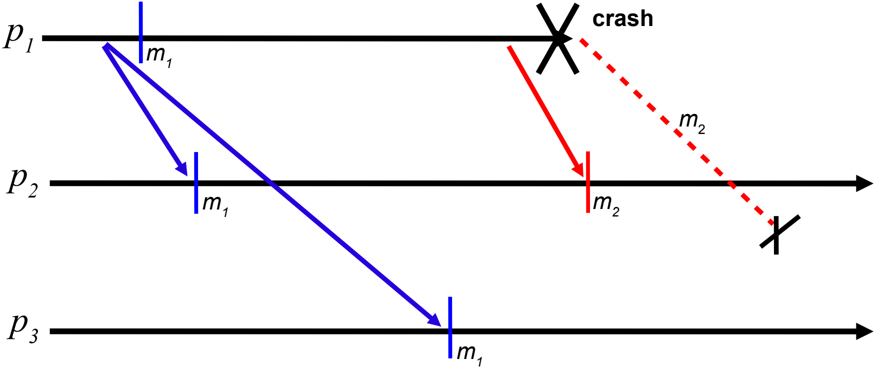
- BEB1 - Validity: By the Validity property of Perfect Channels and the very facts that
    1. the sender sends the message to all
    2. every correct process that receives a message B-delivers it
- BEB2 – Uniform Integrity: By the Integrity property of Perfect Channels

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)

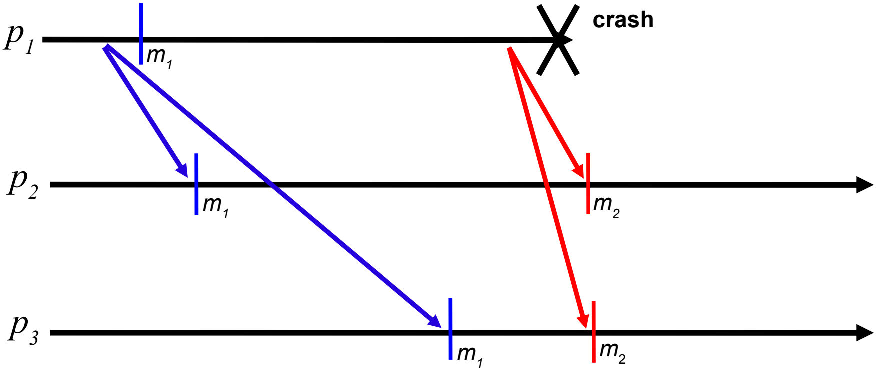
m is delivered by a process at most once, and only if it was previously broadcast

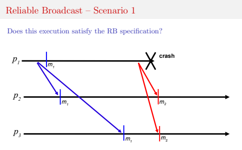
Definition (RB3 – Agreement)

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

Reliable Broadcast – Scenario 1

Does this execution satisfy the RB specification?





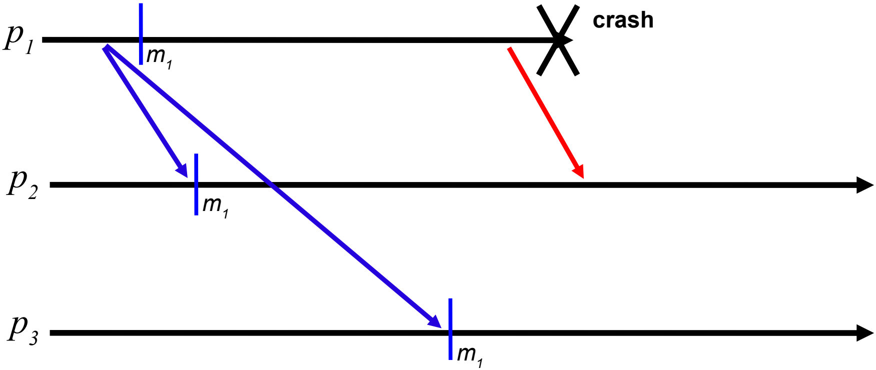
Reliable Broadcast – Scenario 1

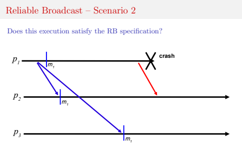
Does this execution satisfy the RB specification?

Obviously yes – the fact that process p_1 does not deliver m is not a problem, because Validity only requires correct processes to deliver their own messages.

Reliable Broadcast – Scenario 2

Does this execution satisfy the RB specification?





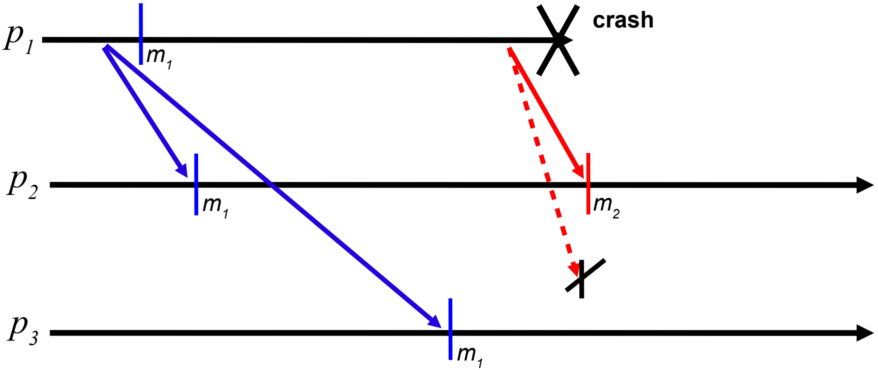
Reliable Broadcast – Scenario 2

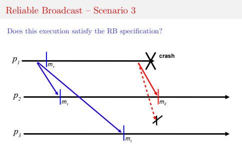
Does this execution satisfy the RB specification?

Obviously yes – the fact that no process delivers m is not a problem, because process p_1 is faulty and Validity does not apply; and nobody delivers m, so Agreement does not apply.

Reliable Broadcast – Scenario 3

Does this execution satisfy the RB specification?





Reliable Broadcast – Scenario 3

Does this execution satisfy the RB specification?

Obviously no – Agreement is not satisfied.

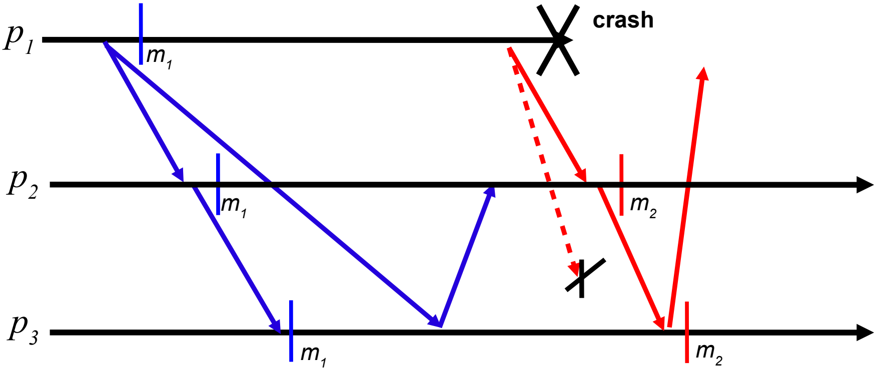
Reliable Broadcast – Algorithm v.1

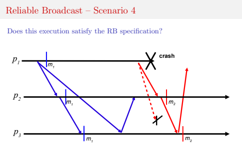
Reliable broadcast protocol executed by p

```
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 – Scenario 4

Does this execution satisfy the RB specification?

Yes, because before R-delivering the message, p_2 forwards it to all other processes.

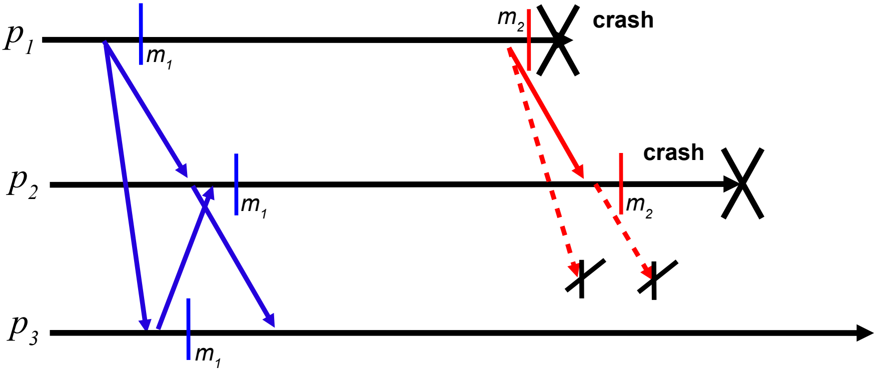
Reliable Broadcast – Proof

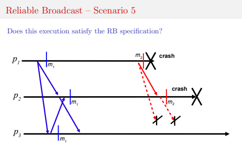
Algorithm v.1 implements Reliable Broadcast.

- RB1 – Validity: *If a correct process broadcasts m, then it eventually delivers m*
  By the code implementing R-broadcast.
- RB2 – 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.
- RB3 – 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*

Reliable Broadcast – Scenario 5

Does this execution satisfy the RB specification?




Reliable Broadcast – Scenario 5

Does this execution satisfy the RB specification?

Yes, because the fact that m_1 has been delivered by p_1 and p_2, which are not correct, does not imply that m_1 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.

Uniform Reliable Broadcast – Specification

Definition (URB1 – Validity)

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

Definition (URB2 – Uniform Agreement)

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

Definition (URB3 — Uniform Integrity)

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

Uniform Reliable Broadcast – Proof

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

- **URB1**, **URB2**: As **RB1**, **RB2**
- **RB3 – 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

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.

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

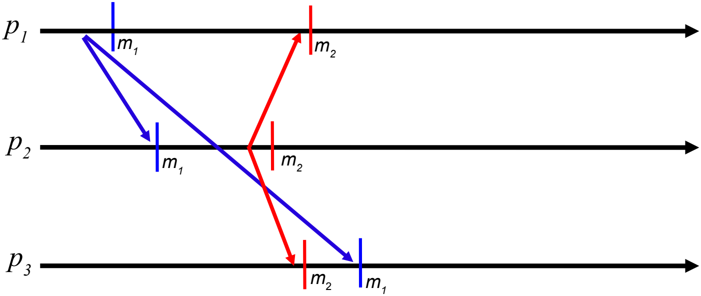
$$broadcast_p(m) \rightarrow broadcast_p(m') \Rightarrow deliver_q(m) \rightarrow deliver_q(m')$$

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? No!

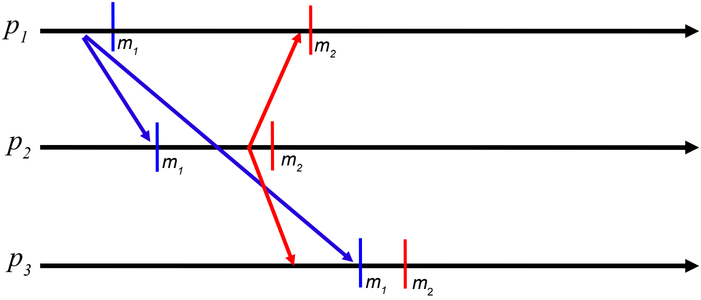


Definition (Causal Order)

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? Yes!

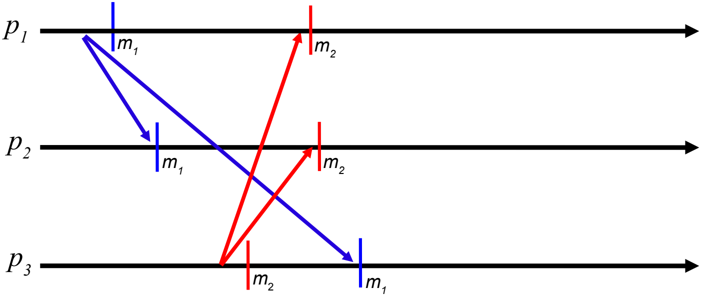


Definition (Causal Order)

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? Yes!



Message ordering

Problem

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

Example

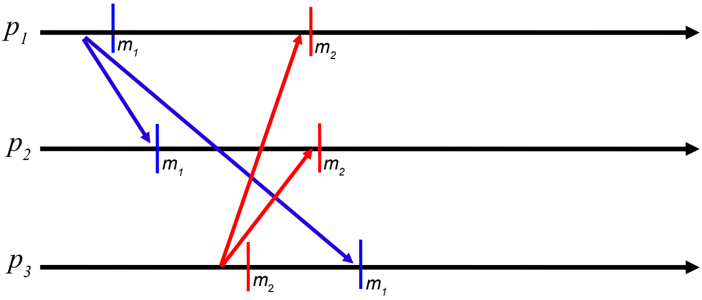
- Consider a replicated database with two copies of a bank account
- Initially, $account = 1000\$$
- A user deposits 150$ triggering a broadcast of $m_1 = \{\text{add } 150\$ \text{ to } account\}$
- At the same time the bank initiates a broadcast of $m_2 = \{\text{add } 2\% \text{ interest to } account\}$
- 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? No!

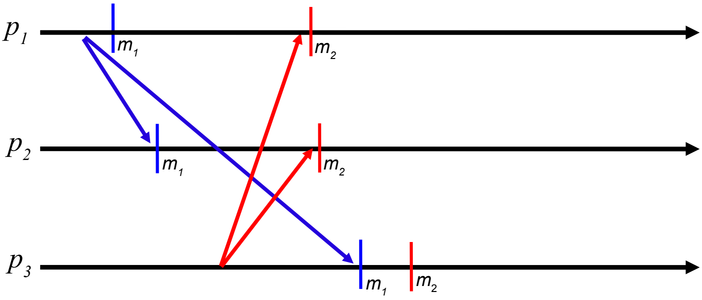


Definition (Total Order)

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? Yes!



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

$$\mathit{broadcast}_p(m) \to \mathit{broadcast}_p(m') \Rightarrow \mathit{deliver}_q(m) \to \mathit{deliver}_q(m')$$

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

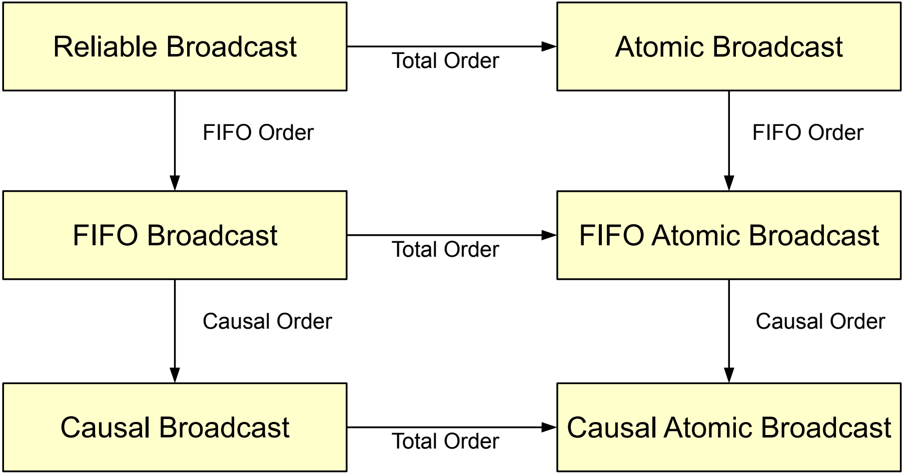
$$\mathit{broadcast}_p(m) \to \mathit{broadcast}_q(m') \Rightarrow \mathit{deliver}_r(m) \to \mathit{deliver}_r(m')$$

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'

$$\mathit{deliver}_p(m) \to \mathit{deliver}_p(m') \Rightarrow \mathit{deliver}_q(m) \to \mathit{deliver}_q(m')$$

A modular approach to Broadcast



Reliable Broadcast

Total Order

Atomic Broadcast

FIFO Order

FIFO Order

FIFO Broadcast

Total Order

FIFO Atomic Broadcast

Causal Order

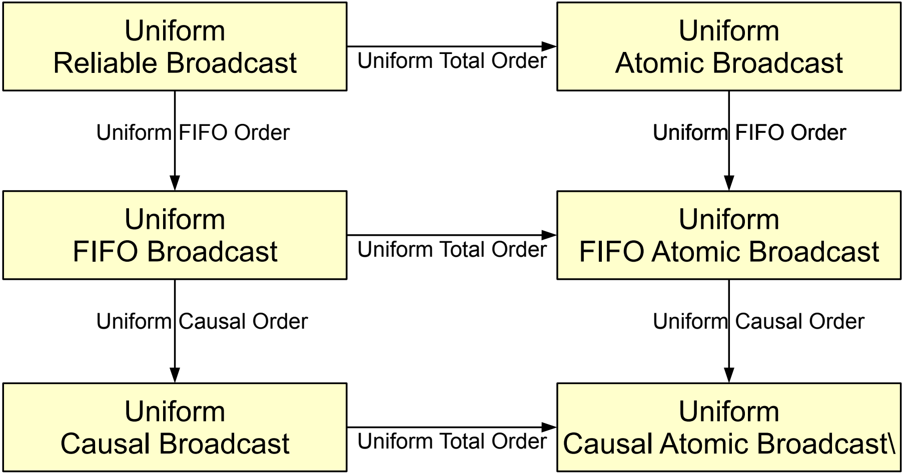
Causal Order

Causal Broadcast

Total Order

Causal Atomic Broadcast

A modular approach to Broadcast



Uniform
Reliable Broadcast

Uniform Total Order

Uniform
Atomic Broadcast

Uniform FIFO Order

Uniform FIFO Order

Uniform
FIFO Broadcast

Uniform Total Order

Uniform
FIFO Atomic Broadcast

Uniform Causal Order

Uniform Causal Order

Uniform
Causal Broadcast

Uniform Total Order

Uniform
Causal Atomic Broadcast\

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 A that solves problem A into an algorithm 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

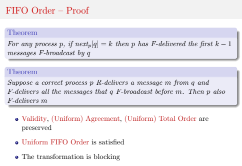
Theorem

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



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

Claim 2 – Proof If m' is the last message delivered from $\mathsf{sender}(m)$, let k be equal to $\mathsf{seqn}(m')$. By claim 1, $next_p[q] = k+1$ and by definition, $\mathsf{seqn}(m) = k+1$. Thus m will be delivered as the next message.

Validity – Proof

- To F-broadcast m, a correct process p R-broadcasts it.
- It will eventually R-deliver m (Validity of RB)
- Suppose m is the first message p R-delivers, but not F-delivers For claim 2, it will eventually F-deliver m. Absurd.

Uniform FIFO Order – Proof

- Suppose a process p F-delivers a message m F-broadcast by q.
- Let $\mathsf{seqn}(m) = k$.
- By the algorithm, just before F-delivering m, $next_p[q] = k$.
- By Claim 1, p has already F-delivered all the $k-1$ messages that q F-broadcast before m, as wanted.

Causal Order - Algorithm

Two transformations:

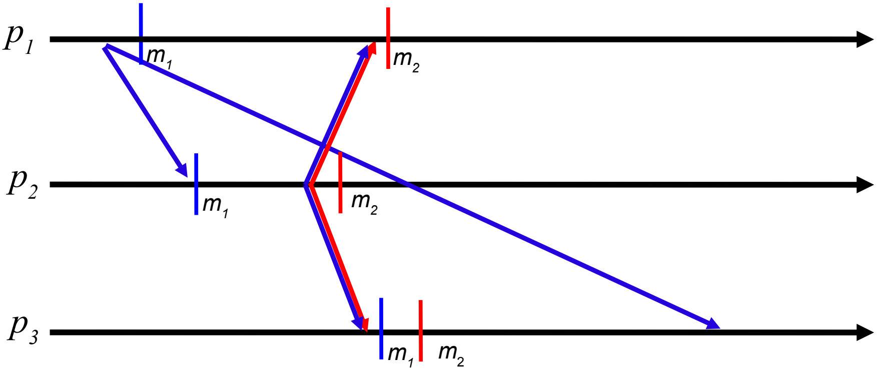
- Both based on FIFO Reliable Broadcast
- One is non-blocking
    - Each message is tagged with “recent history”
    - When a message is F-delivered, all the causal messages that have been F-delivered are locally delivered
    - Does this recall anything?
- One blocking
    - Based on vector clocks

Causal Order - Algorithm 1

Causal Order Transformation executed by process p

```
upon initialization do
    SET delivered ← ∅                % Messages already C-delivered
    SEQUENCE recent ← ⟨⟩ % Messages C-delivered since last C-broadcast

upon C-broadcast($m$) do
    F-broadcast($recent||m$)
    recent ← ⟨⟩

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

Causal Order - Algorithm 1



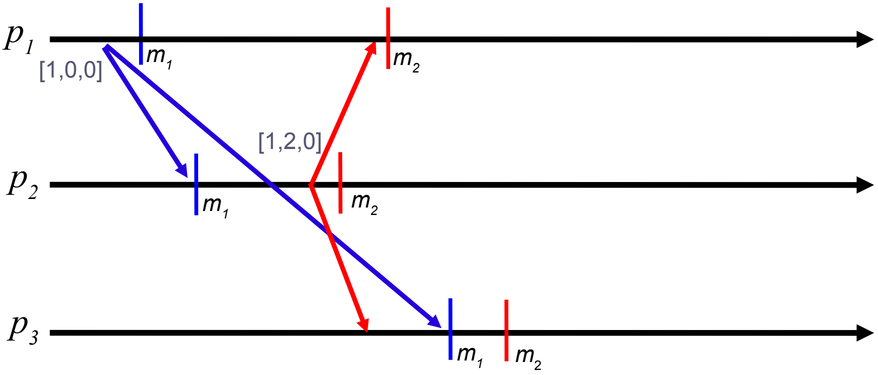
Causal Order – Proof

- 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
    F-broadcast($\langle m, VC \rangle$)

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

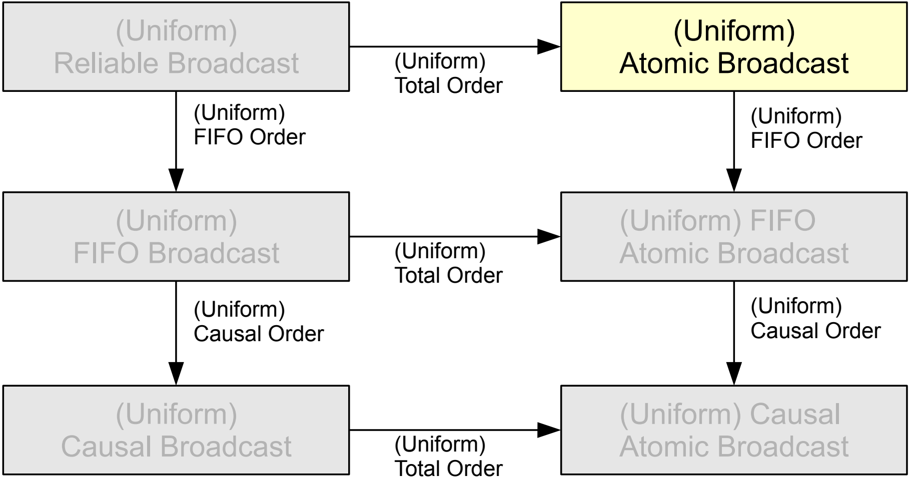
Causal Order - Algorithm 2



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



(Uniform) Reliable Broadcast

(Uniform) Atomic Broadcast

(Uniform) FIFO Broadcast

(Uniform) FIFO Atomic Broadcast

(Uniform) Causal Broadcast

(Uniform) Causal Atomic 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

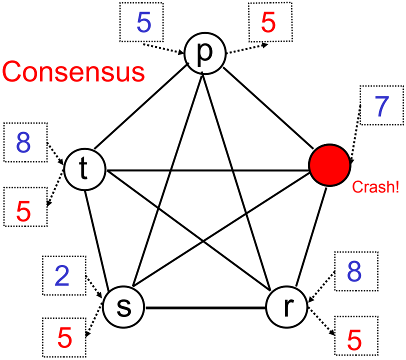
Atomic Broadcast, Algorithm 1

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 $decided \leftarrow$ false

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

upon A-deliver($v$) do
    if not $decided$ then
        $decided \leftarrow$ 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 decide_s(S) do
    $unordered \leftarrow unordered - S$
    foreach $m \in S$ do
        A-deliver($m$)                % In some deterministic order
    $delivered \leftarrow delivered \cup S$
    $s \leftarrow s + 1$
    $wait \leftarrow$ false

upon $unordered \neq \emptyset$ and not $wait$ do
    $wait \leftarrow$ true
    propose_s($unordered$)
```

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 (2nd ed.)*. Addison-Wesley, 1993.

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