Programming Distributed Systems

02 Broadcast

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Overview

- Formalism for specifying distributed algorithms
- Composability of distributed algorithms
- The Broadcast Problem
  - Best-effort broadcast
  - Reliable broadcast
  - Causal broadcast
Motivation
The Broadcast Problem

Informally: A process needs to transmit the same message \( m \) to \( N \) other processes.

Assumptions

- Complete set of processes in the system is known a-priori
- Perfect-Point-2-Point Link Abstraction
- Asynchronous system (no rounds, no failure detection)
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 problem

Wait... How do you specify an algorithm for a process again?
Specifying the broadcast problem

Wait... How do you specify an algorithm for a process again?
⇒ Deterministic I/O automaton!
The Anatomy of an Algorithm

- Event driven interface

\begin{verbatim}
Upon Init do: ...
Upon Broadcast(m) do: ...
Upon Receive(p, m) do: ...
\end{verbatim}

- You can trigger an event on another layer:

\begin{verbatim}
trigger Send(q, m)
trigger Deliver(p, m)
\end{verbatim}

- There is a special event called \texttt{Init} for initializing the local state.
- \texttt{q} denotes the target process when sending a message
- \texttt{p} denotes the process where the message originated from
Best-effort Broadcast (BEB): Specification

- **BEB1 (Best-Effort Validity):** For any two correct processes $i$ and $j$, every message broadcast by $i$ is eventually delivered by $j$.
- **BEB2 (No Duplication):** No message is delivered more than once.
- **BEB3 (No Creation):** If a correct process $j$ delivers a message $m$, then $m$ was broadcast to $j$ by some process $i$. 
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.

_State:_

--- // could be omitted

_Upon Init do:_

--- // could be omitted

_Upon beb-Broadcast(m) do:_

forall \( q \in \Pi \):

trigger Send(q, m);

_Upon Receive(p, m) do:_

trigger beb-Deliver(p, m);
Best-effort Broadcast: Correctness

Why does it work?

- BEB1 holds because Perfect-Point-2-Point links guarantee reliable delivery (PL1)
- BEB2 holds due to PL2, BEB3 holds due to PL3
Best-effort Broadcast: Scenario 1

Process A

Process B

Process C
Best-effort Broadcast: Scenario 2

- Process A
  - $m_1$
- Process B
  - $m_1$
- Process C
  - $m_1$
  - $m_2$
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!
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Let’s try for a stronger version of broadcast . . .
Reliable Broadcast (RB): Specification

- **RB1 (Validity):** If a correct process $i$ broadcasts message $m$, then $i$ eventually delivers the message.
- **RB2 (No Duplications):** No message is delivered more than once.
- **RB3 (No Creation):** If a correct process $j$ delivers a message $m$, then $m$ was broadcast to $j$ by some process $i$.
- **RB4 (Agreement):** If a message $m$ is delivered by some correct process $i$, then $m$ is eventually delivered by every correct process $j$. 

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Reliable Broadcast (RB): Scenario 1

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Reliable Broadcast (RB): Scenario 1

Not possible under Reliable Broadcast: RB4 is violated!
Reliable Broadcast (RB): Scenario 2

The fact that process A does not deliver $m_2$ is not a problem, because only correct processes are required to deliver their own messages (RB1).
Reliable Broadcast (RB): Scenario 2

The fact that process A does not deliver $m_2$ is not a problem, because only correct processes are required to deliver their own messages (RB1).
Reliable Broadcast (RB): Scenario 3

The fact that no process delivers $m_2$ is not a problem, because process A is faulty (RB1) and no process delivers $m_2$ (RB4).
Reliable Broadcast (RB): Scenario 3

The fact that no process delivers $m_2$ is not a problem, because process $A$ is faulty (RB1) and no process delivers $m_2$ (RB4).
Reliable Broadcast (RB): Scenario 4
Reliable Broadcast (RB): Algorithm

**State:**
- delivered //set of message ids that were already delivered

**Upon Init do:**
- delivered $\leftarrow \emptyset$

**Upon rb-Broadcast(m) do**
- trigger rb-Deliver(self, m);
- $m_{id} \leftarrow \text{generateUniqueID}(m)$;
- delivered $\leftarrow$ delivered $\cup \{m_{id}\}$;
- trigger beb-Broadcast([$m_{id}$, m]);

**Upon beb-Deliver(p, [$m_{id}$, m]) do**
- if ($m_{id} \notin$ delivered) then
  - delivered $\leftarrow$ delivered $\cup \{m_{id}\}$;
  - trigger rb-Deliver(p, m);
  - trigger beb-Broadcast([$m_{id}$, m]);

**Why is this algorithm correct?**
Reliable Broadcast (RB): Correctness

- **RB1 (Validity):** If a correct process $i$ broadcasts message $m$, then $i$ eventually delivers the message.
  - Delivering the message is the first step when handling rb-Broadcast.
- **RB2 (No Duplications):** No message is delivered more than once.
  - By handling the set of delivered messages.
- **RB3 (No Creation):** If a correct process $j$ delivers a message $m$, then $m$ was broadcast to $j$ by some process $i$.
  - By BEB3.
- **RB4 (Agreement):** If a message $m$ is delivered by some correct process $i$, then $m$ is eventually delivered by every correct process $j$.
  - Before rb-Delivering $m$, a correct process forwards $m$ to all processes. By BEB1 and $p$ being correct, all correct processes will eventually receive $m$ and rb-Deliver it.
The fact that $m_2$ has been delivered by faulty A and B does not imply that $m_2$ has to be delivered by C as well. Yet, this situation is not desirable, because two processes deliver something and another one does not. ⇒ Interaction with external world!
The fact that $m_2$ has been delivered by faulty $A$ and $B$ does not imply that $m_2$ has to be delivered by $C$ as well. Yet, this situation is not desirable, because two processes deliver something and another one does not.

⇒ Interaction with external world!
Uniform Reliable Broadcast - Specification

- **URB1 (Validity):** If a correct process $i$ broadcasts message $m$, then $i$ eventually delivers the message.
- **URB2 (No Duplications):** No message is delivered more than once.
- **URB3 (No Creation):** If a correct process $j$ delivers a message $m$, then $m$ was broadcast to $j$ by some process $i$.
- **URB4 (Uniform Agreement):** If a message $m$ is delivered by some correct process $i$, then $m$ is eventually delivered by every correct process $j$. 
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

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 $m$.

$$\text{broadcast}_p(m) \rightarrow \text{broadcast}_p(m') \Rightarrow \text{deliver}_q(m) \rightarrow \text{deliver}_q(m')$$
Causal Order

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

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?
Summary

- Composability of distributed algorithms by stacking algorithms
- Correctness proofs based on properties of underlying level + algorithmic properties
- Different variants of solution to the Broadcast Problem
  - Best-effort broadcast
  - Reliable broadcast
  - Uniform reliable broadcast
  - Causal broadcast ($\Rightarrow$ next lecture)
  - [Uniform causal broadcast]
Joe Armstrong († 20 April 2019)

“Make it work, then make it beautiful, then if you really, really have to, make it fast. 90% of the time, if you make it beautiful, it will already be fast. So really, just make it beautiful.”

— Joe Armstrong

Checkout Joe’s thesis[1] for lots of wisdom on building distributed systems!

Sketch by David Neal (http://reverentgeek.com/)
Further reading I