

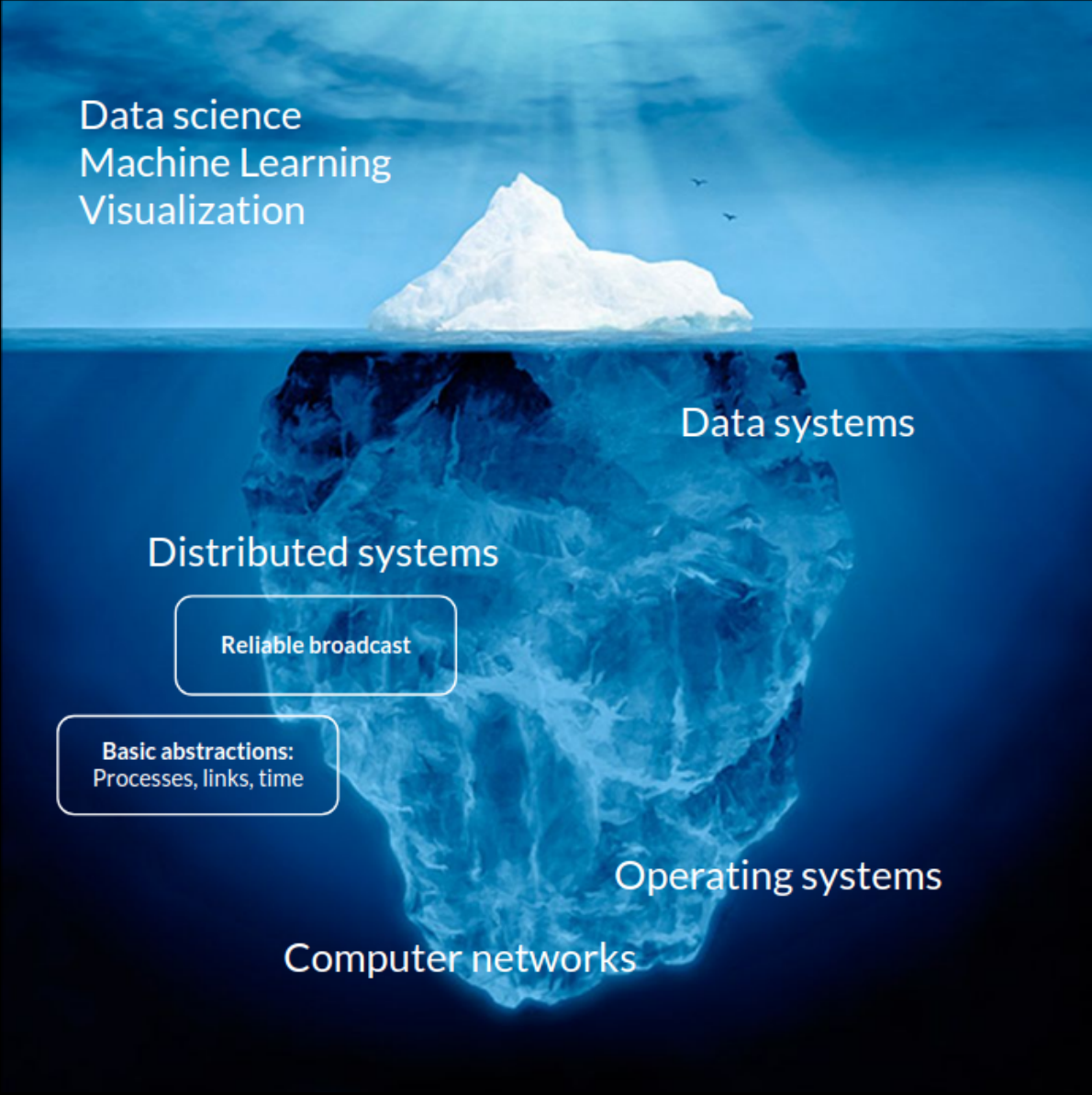
Large-scale Data Systems

Lecture 3: Reliable broadcast

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Today

- How do you talk to **multiple machines** at once?
- What if some of them **fail**?
- Can we guarantee that correct nodes all receive the same messages?
- What about **ordering**?
- What about **performance**?

An iceberg floating in a blue ocean under a blue sky with a few birds. The tip of the iceberg is above the water, while the much larger base is submerged. The layers of the iceberg are labeled with text. The top layer (above water) is labeled 'Data science', 'Machine Learning', and 'Visualization'. The submerged part is divided into several layers: 'Data systems' (top submerged), 'Distributed systems' (middle submerged), 'Operating systems' (lower submerged), and 'Computer networks' (bottom submerged). Two callout boxes are present: one labeled 'Reliable broadcast' pointing to a part of the 'Distributed systems' layer, and another labeled 'Basic abstractions: Processes, links, time' pointing to the bottom of the iceberg.

Data science
Machine Learning
Visualization

Data systems

Distributed systems

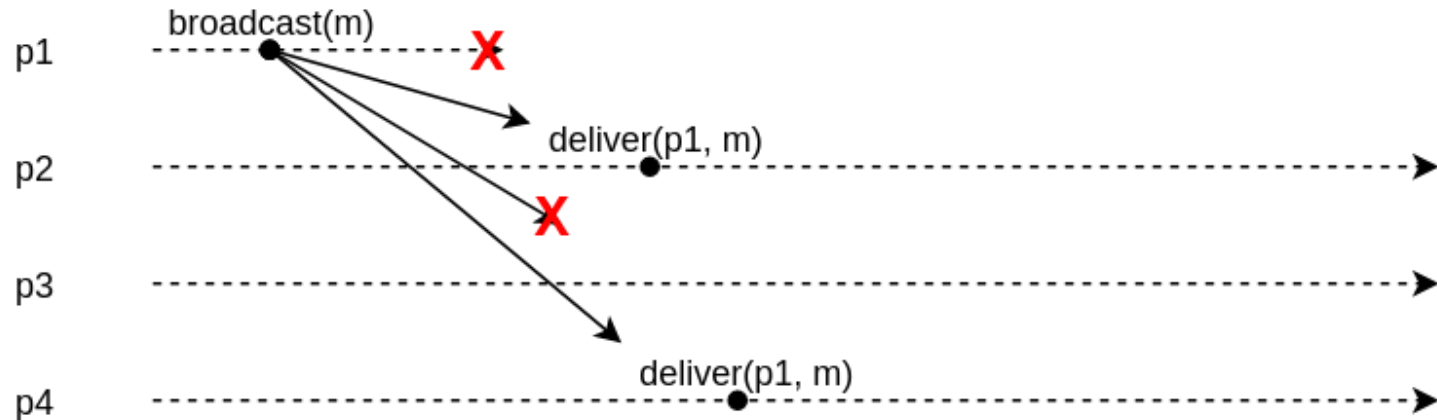
Reliable broadcast

Basic abstractions:
Processes, links, time

Operating systems

Computer networks

Unreliable broadcast



Constraints

- The sender may fail.
- Recipients may fail.
- Packets might get lost.
- Packets may take long to travel.

How do we define a **reliable** broadcast service?

Reliable broadcast abstractions

Reliable broadcast abstractions

- **Best-effort broadcast**
 - Guarantees reliability only if sender is correct.
- **Reliable broadcast**
 - Guarantees reliability independent of whether sender is correct.
- **Uniform reliable broadcast**
 - Also considers the behavior of failed nodes.
- **Causal reliable broadcast**
 - Reliable broadcast with causal delivery order.

Best-effort broadcast (*beb*)

Module:

Name: BestEffortBroadcast, **instance** *beb*.

Events:

Request: $\langle \textit{beb}, \textit{Broadcast} \mid m \rangle$: Broadcasts a message m to all processes.

Indication: $\langle \textit{beb}, \textit{Deliver} \mid p, m \rangle$: Delivers a message m broadcast by process p .

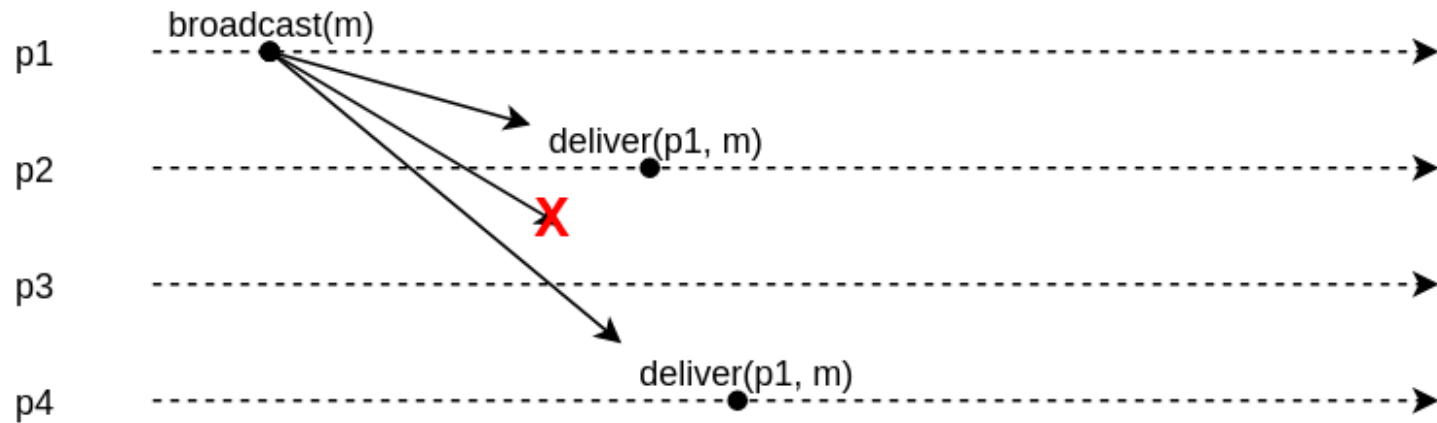
Properties:

BEB1: *Validity*: If a correct process broadcasts a message m , then every correct process eventually delivers m .

BEB2: *No duplication*: No message is delivered more than once.

BEB3: *No creation*: If a process delivers a message m with sender s , then m was previously broadcast by process s .

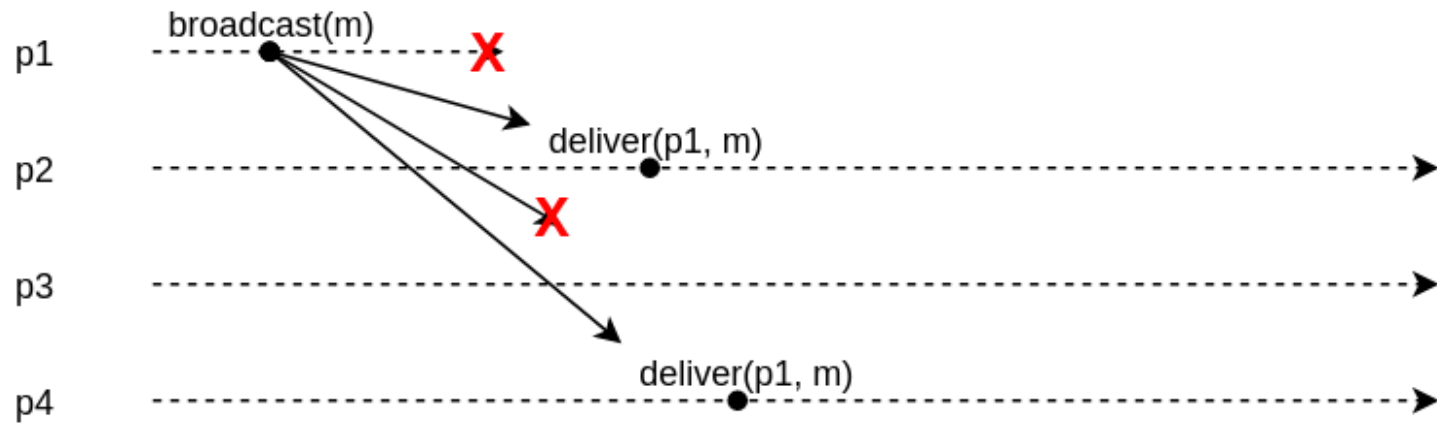
beb example (1)



Exercise

Is this allowed?

beb example (2)



Exercise

Is this allowed?

Reliable broadcast (*rb*)

- Best-effort broadcast gives no guarantees if **sender crashes**.
- **Reliable broadcast:**
 - Same as best-effort broadcast +
 - If sender crashes, ensure **all or none** of the correct node deliver the message.

Module:

Name: ReliableBroadcast, **instance** *rb*.

Events:

Request: $\langle rb, \text{Broadcast} \mid m \rangle$: Broadcasts a message *m* to all processes.

Indication: $\langle rb, \text{Deliver} \mid p, m \rangle$: Delivers a message *m* broadcast by process *p*.

Properties:

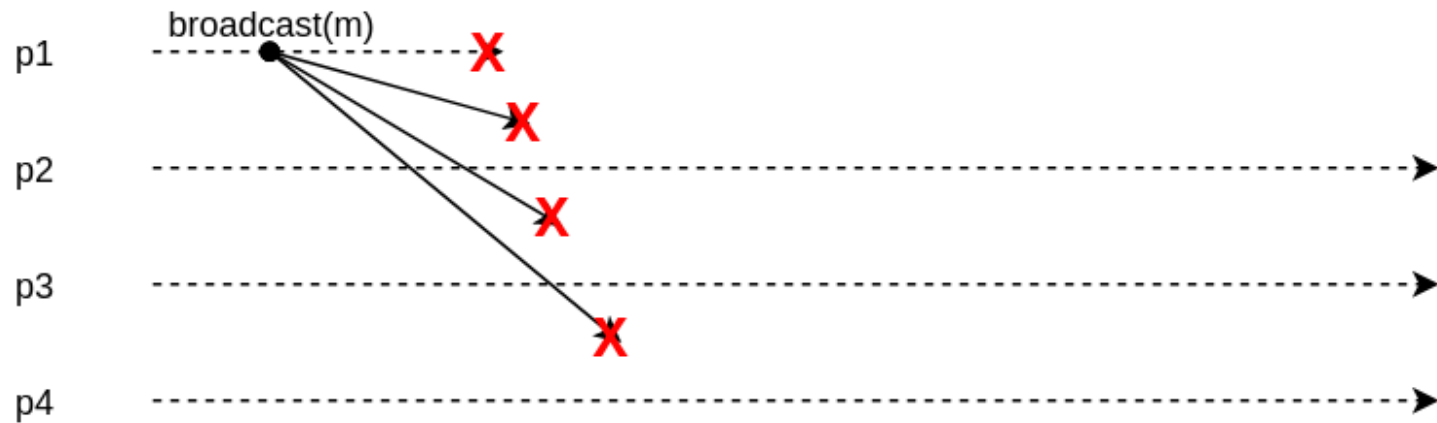
RB1: Validity: If a correct process *p* broadcasts a message *m*, then *p* eventually delivers *m*.

RB2: No duplication: No message is delivered more than once.

RB3: No creation: If a process delivers a message *m* with sender *s*, then *m* was previously broadcast by process *s*.

RB4: Agreement: If a message *m* is delivered by some correct process, then *m* is eventually delivered by every correct process.

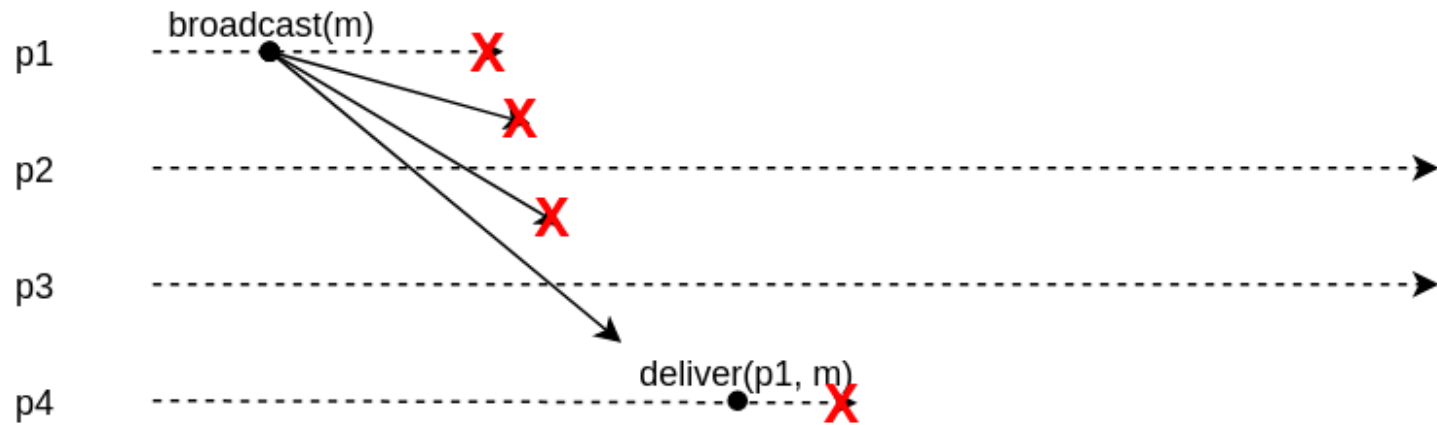
rb example (1)



Exercise

Is this allowed?

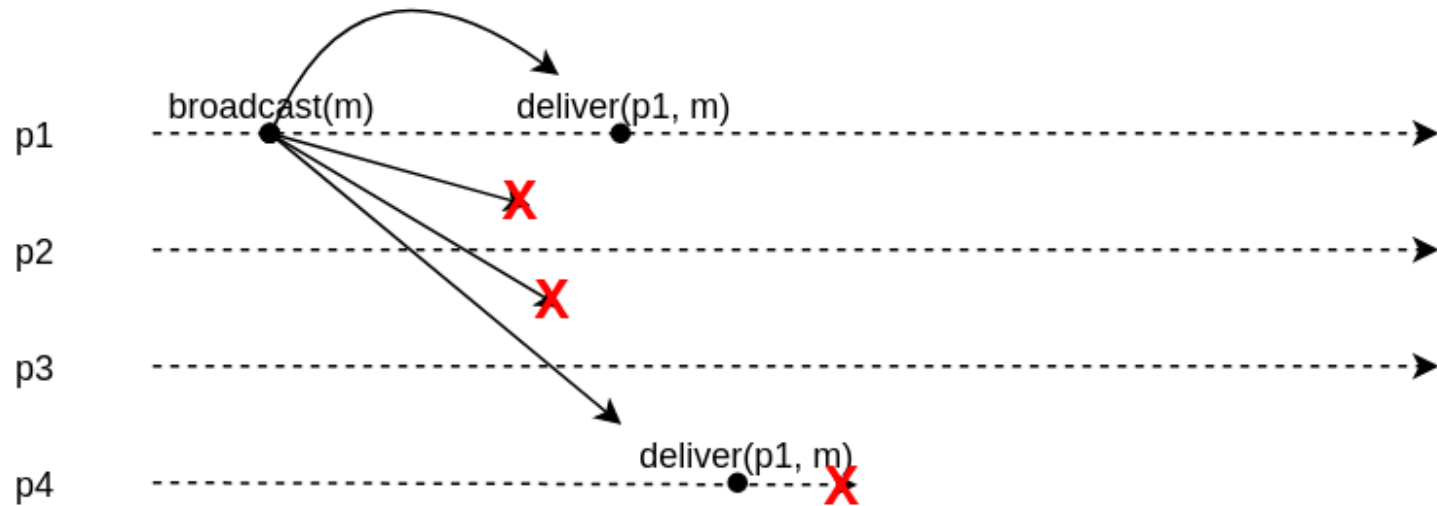
rb example (2)



Exercise

Is this allowed?

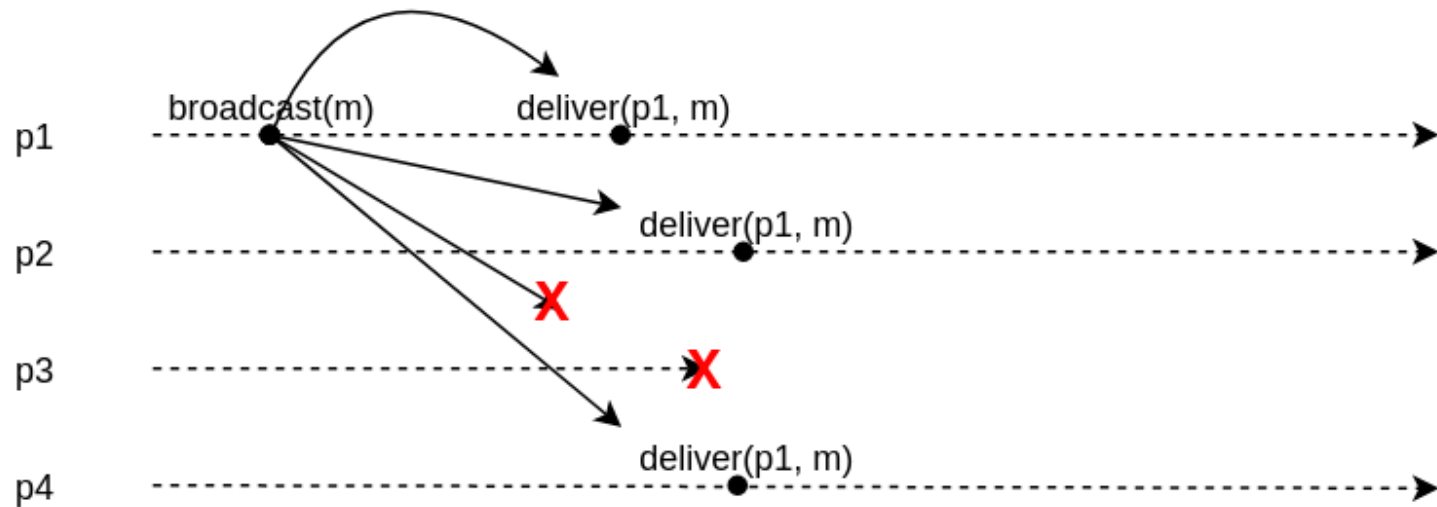
rb example (3)



Exercise

Is this allowed?

rb example (4)



Exercise

Is this allowed?

Uniform reliable broadcast (*urb*)

- Assume sender broadcasts a message
 - Sender fails
 - No correct node delivers the message
 - Failed nodes deliver the message
- Is this OK?
 - A process that delivers a message and later crashes may bring the application into a inconsistent state.
- **Uniform** reliable broadcast ensures that if a message is delivered, by a correct or a **faulty** process, then all correct processes deliver.

Module:

Name: UniformReliableBroadcast, **instance** *urb*.

Events:

Request: $\langle urb, Broadcast \mid m \rangle$: Broadcasts a message *m* to all processes.

Indication: $\langle urb, Deliver \mid p, m \rangle$: Delivers a message *m* broadcast by process *p*.

Properties:

URB1–URB3: Same as properties RB1–RB3 in (regular) reliable broadcast (Module 3.2).

URB4: *Uniform agreement*: If a message *m* is delivered by some process (whether correct or faulty), then *m* is eventually delivered by every correct process.

Implementations

Basic broadcast

Implements:

BestEffortBroadcast, **instance** *beb*.

Uses:

PerfectPointToPointLinks, **instance** *pl*.

upon event $\langle \textit{beb}, \textit{Broadcast} \mid m \rangle$ **do**

forall $q \in \Pi$ **do**

trigger $\langle \textit{pl}, \textit{Send} \mid q, m \rangle$;

upon event $\langle \textit{pl}, \textit{Deliver} \mid p, m \rangle$ **do**

trigger $\langle \textit{beb}, \textit{Deliver} \mid p, m \rangle$;

Correctness:

- **BEB1. Validity**: If a correct process p broadcasts m , then every correct process eventually delivers m .
 - If sender does not crash, every other correct node receives message by perfect channels.
- **BEB2+3. No duplication + no creation**
 - Guaranteed by perfect channels.

Lazy reliable broadcast

- Assume a **fail-stop** distributed system model.
 - i.e., crash-stop processes, perfect links and a perfect failure detector.
- To broadcast m :
 - best-effort broadcast m
 - Upon `bebDeliver`:
 - Save message
 - `rbDeliver` the message
- If sender s crashes, detect and relay messages from s to all.
 - case 1: get m from s , detect crash of s , redistribute m
 - case 2: detect crash of s , get m from s , redistribute m .
- Filter duplicate messages.

Implements:

ReliableBroadcast, **instance** *rb*.

Uses:

BestEffortBroadcast, **instance** *beb*;

PerfectFailureDetector, **instance** \mathcal{P} .

upon event $\langle rb, Init \rangle$ **do**

correct := Π ;

from[*p*] := $[\emptyset]^N$;

upon event $\langle rb, Broadcast \mid m \rangle$ **do**

trigger $\langle beb, Broadcast \mid [DATA, self, m] \rangle$;

upon event $\langle beb, Deliver \mid p, [DATA, s, m] \rangle$ **do**

if $m \notin from[s]$ **then**

trigger $\langle rb, Deliver \mid s, m \rangle$;

from[*s*] := *from*[*s*] $\cup \{m\}$;

if $s \notin correct$ **then**

trigger $\langle beb, Broadcast \mid [DATA, s, m] \rangle$;

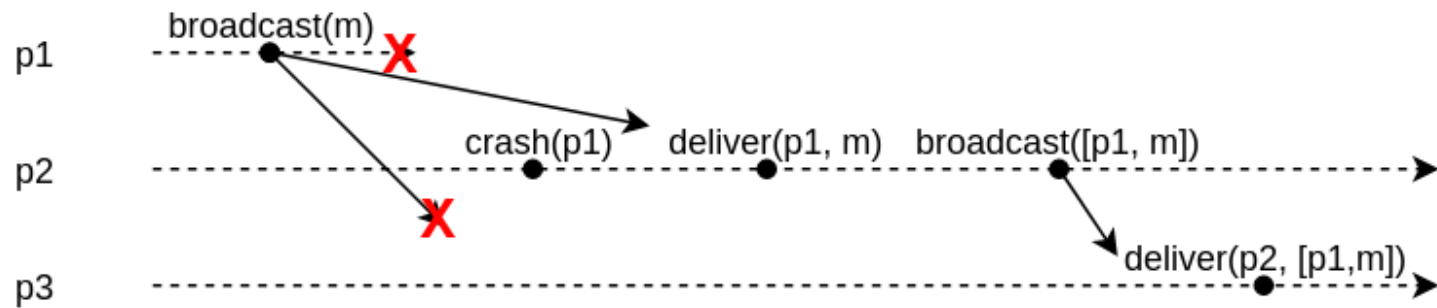
upon event $\langle \mathcal{P}, Crash \mid p \rangle$ **do**

correct := *correct* $\setminus \{p\}$;

forall $m \in from[p]$ **do**

trigger $\langle beb, Broadcast \mid [DATA, p, m] \rangle$;

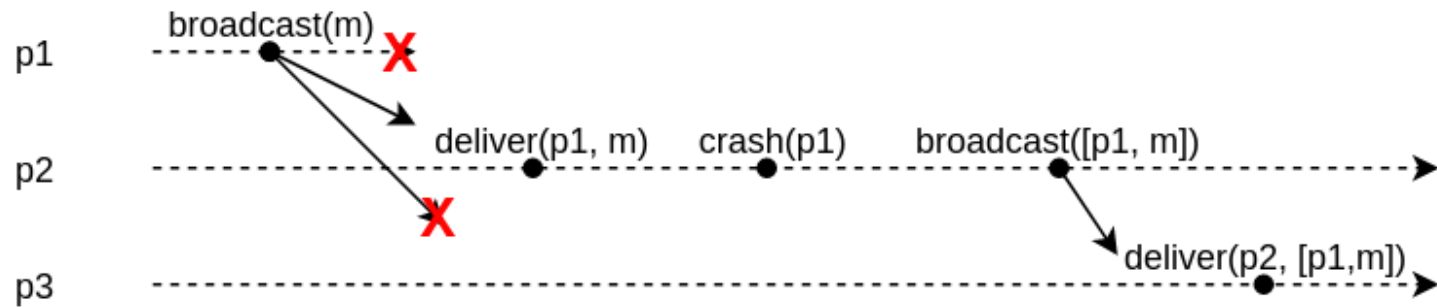
Lazy reliable broadcast example (1)



Exercise

Which case?

Lazy reliable broadcast example (2)



Exercise

Which case?

Correctness of lazy reliable broadcast

- RB1-RB3
 - Satisfied with best-effort broadcast.
- RB4. Agreement: If a message m is delivered by some correct process, then m is eventually delivered by every correct process.
 - When correct p_j delivers m broadcast by p_i
 - if p_i is correct, BEB ensures correct delivery
 - if p_i crashes,
 - p_j detects this (because of completeness of the PFD)
 - p_j uses BEB to ensure (BEB1) every correct node gets m .

Eager reliable broadcast

- What happens if we use instead an **eventually** perfect failure detector?
 - Only affects performance, not correctness.
- Can we modify Lazy RB to not use a perfect failure detector?
 - Assume all nodes have failed.
 - BEB broadcast all received messages.

Implements:

ReliableBroadcast, **instance** *rb*.

Uses:

BestEffortBroadcast, **instance** *beb*.

upon event $\langle rb, Init \rangle$ **do**

delivered := \emptyset ;

upon event $\langle rb, Broadcast \mid m \rangle$ **do**

trigger $\langle beb, Broadcast \mid [DATA, self, m] \rangle$;

upon event $\langle beb, Deliver \mid p, [DATA, s, m] \rangle$ **do**

if $m \notin delivered$ **then**

delivered := *delivered* $\cup \{m\}$;

trigger $\langle rb, Deliver \mid s, m \rangle$;

trigger $\langle beb, Broadcast \mid [DATA, s, m] \rangle$;

Exercise

Show that eager reliable broadcast is correct.

Uniformity

Neither Lazy reliable broadcast nor Eager reliable broadcast ensure **uniform** agreement.

E.g., sender *p* immediately RB delivers and crashes. Only *p* delivered the message.

Strategy for uniform agreement

- Before delivering a message, we need to ensure all correct nodes have received it.
- Messages are **pending** until all correct nodes get it.
 - Collect acknowledgements from nodes that got the message.
- Deliver once all correct nodes acked.

All-ack uniform reliable broadcast

Implements:

UniformReliableBroadcast, **instance** *urb*.

Uses:

BestEffortBroadcast, **instance** *beb*.

PerfectFailureDetector, **instance** \mathcal{P} .

upon event $\langle \textit{urb}, \textit{Init} \rangle$ **do**

delivered := \emptyset ;

pending := \emptyset ;

correct := Π ;

forall *m* **do** *ack*[*m*] := \emptyset ;

upon event $\langle \textit{urb}, \textit{Broadcast} \mid m \rangle$ **do**

pending := *pending* $\cup \{(self, m)\}$;

trigger $\langle \textit{beb}, \textit{Broadcast} \mid [\textit{DATA}, self, m] \rangle$;

upon event $\langle \textit{beb}, \textit{Deliver} \mid p, [\textit{DATA}, s, m] \rangle$ **do**

ack[*m*] := *ack*[*m*] $\cup \{p\}$;

if $(s, m) \notin \textit{pending}$ **then**

pending := *pending* $\cup \{(s, m)\}$;

trigger $\langle \textit{beb}, \textit{Broadcast} \mid [\textit{DATA}, s, m] \rangle$;

upon event $\langle \mathcal{P}, \textit{Crash} \mid p \rangle$ **do**

correct := *correct* $\setminus \{p\}$;

function *candeliver*(*m*) **returns** Boolean **is**

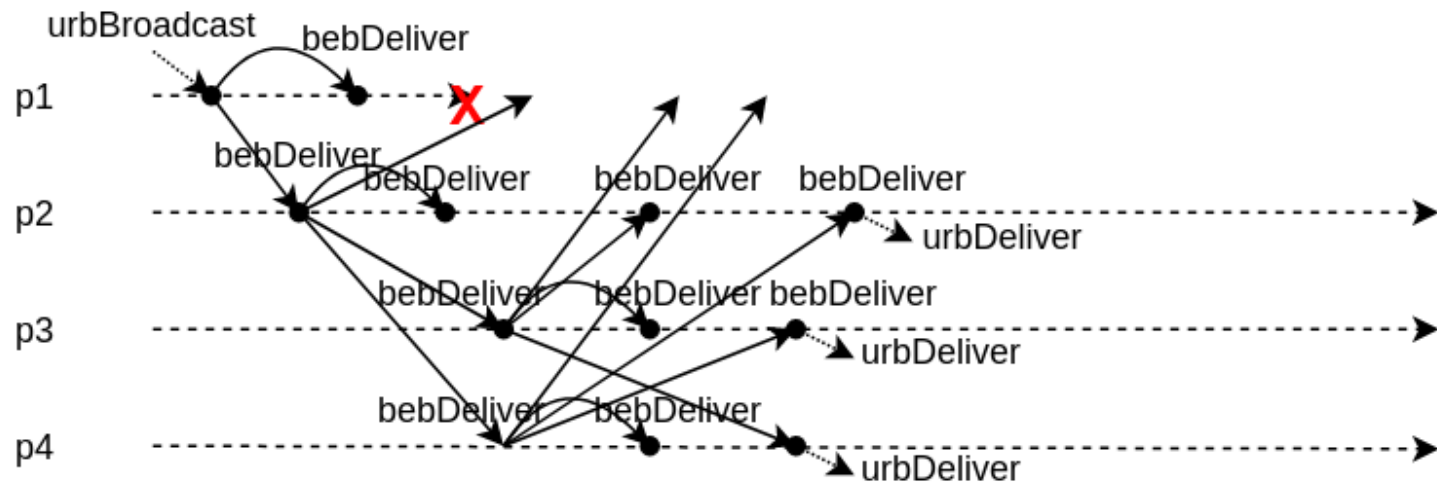
return (*correct* $\subseteq \textit{ack}[m]$);

upon exists $(s, m) \in \textit{pending}$ such that *candeliver*(*m*) $\wedge m \notin \textit{delivered}$ **do**

delivered := *delivered* $\cup \{m\}$;

trigger $\langle \textit{urb}, \textit{Deliver} \mid s, m \rangle$;

Example



Correctness of All-ack URB

Lemma. If a correct node p BEB delivers m , then p eventually URB delivers m .

Proof:

- A correct node p BEB broadcasts m as soon as it gets m .
- By BEB1, every correct node gets m and BEB broadcasts m .
- Therefore p BEB delivers from every correct node by BEB1.
- By completeness of the perfect failure detector, p will not wait for dead nodes forever.
 - `canDeliver` becomes true and p URB delivers m .

- **URB1. Validity:** If a correct process p broadcasts m , then p delivers m
 - If sender is correct, it will BEB delivers m by validity (BEB1)
 - By the lemma, it will therefore eventually URB delivers m .
- **URB2. No duplication**
 - Guaranteed because of the `delivered` set.
- **URB3. No creation**
 - Ensured from best-effort broadcast.
- **URB4. Uniform agreement:** If a message m is delivered by some process (correct or faulty), then m is eventually delivered by every correct process
 - Assume some node (possibly failed) URB delivers m .
 - Then `canDeliver` was true, and by accuracy of the failure detector, every correct node has BEB delivered m .
 - By the lemma, each of the nodes that BEB delivered m will URB deliver m .

urb for fail-silent

- All-ack URB requires a perfect failure detector (fail-stop).
- Can we implement URB in *fail-silent*, without a perfect failure detector?
- **Yes**, provided a majority of nodes are correct.

Implements:

UniformReliableBroadcast, **instance** *urb*.

Uses:

BestEffortBroadcast, **instance** *beb*.

// Except for the function *candeliver*(\cdot) below and for the absence of $\langle \text{Crash} \rangle$ events
// triggered by the perfect failure detector, it is the same as Algorithm 3.4.

function *candeliver*(m) **returns** Boolean **is**
return $\#(\text{ack}[m]) > N/2$;

Exercise

Show that this variant is correct.

Causal reliable broadcast



Mathias Verraes

@mathiasverraes

Follow



There are only two hard problems in distributed systems:

1. Guaranteed order of messages
2. Exactly-once delivery

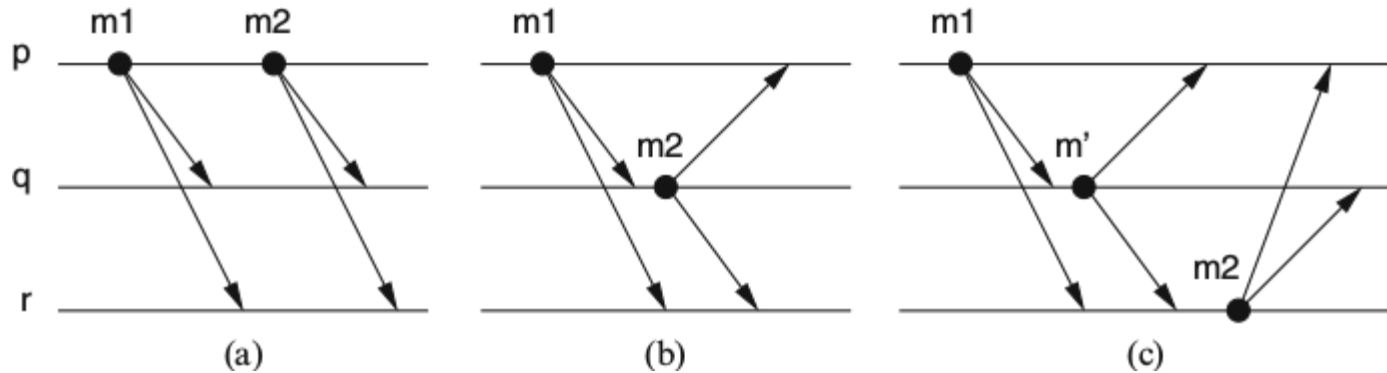
Reliable broadcast:

- Exactly-once delivery: **guaranteed** by the properties of RB.
- Order of message? **Not guaranteed!**

Exercise

Does uniform reliable broadcast remedy this?

Causal order of messages



A message m_1 may have caused another message m_2 , denoted $m_1 \rightarrow m_2$ if any of the following relations apply:

- (a) some process p broadcasts m_1 before it broadcasts m_2 ;
- (b) some process p delivers m_1 and subsequently broadcasts m_2 ; or
- (c) there exists some message m' such that $m_1 \rightarrow m'$ and $m' \rightarrow m_2$.

Causal broadcast (*crb*)

Module:

Name: CausalOrderReliableBroadcast, **instance** *crb*.

Events:

Request: $\langle \text{crb}, \text{Broadcast} \mid m \rangle$: Broadcasts a message m to all processes.

Indication: $\langle \text{crb}, \text{Deliver} \mid p, m \rangle$: Delivers a message m broadcast by process p .

Properties:

CRB1–CRB4: Same as properties RB1–RB4 in (regular) reliable broadcast (Module 3.2).

CRB5: *Causal delivery*: For any message m_1 that potentially caused a message m_2 , i.e., $m_1 \rightarrow m_2$, no process delivers m_2 unless it has already delivered m_1 .

No-waiting causal broadcast

Implements:

CausalOrderReliableBroadcast, **instance** *crb*.

Uses:

ReliableBroadcast, **instance** *rb*.

upon event $\langle crb, Init \rangle$ **do**

delivered := \emptyset ;

past := [];

upon event $\langle crb, Broadcast \mid m \rangle$ **do**

trigger $\langle rb, Broadcast \mid [DATA, past, m] \rangle$;

append(*past*, (*self*, *m*));

upon event $\langle rb, Deliver \mid p, [DATA, mpast, m] \rangle$ **do**

if $m \notin delivered$ **then**

forall $(s, n) \in mpast$ **do**

// by the order in the list

if $n \notin delivered$ **then**

trigger $\langle crb, Deliver \mid s, n \rangle$;

delivered := *delivered* $\cup \{n\}$;

if $(s, n) \notin past$ **then**

append(*past*, (*s*, *n*));

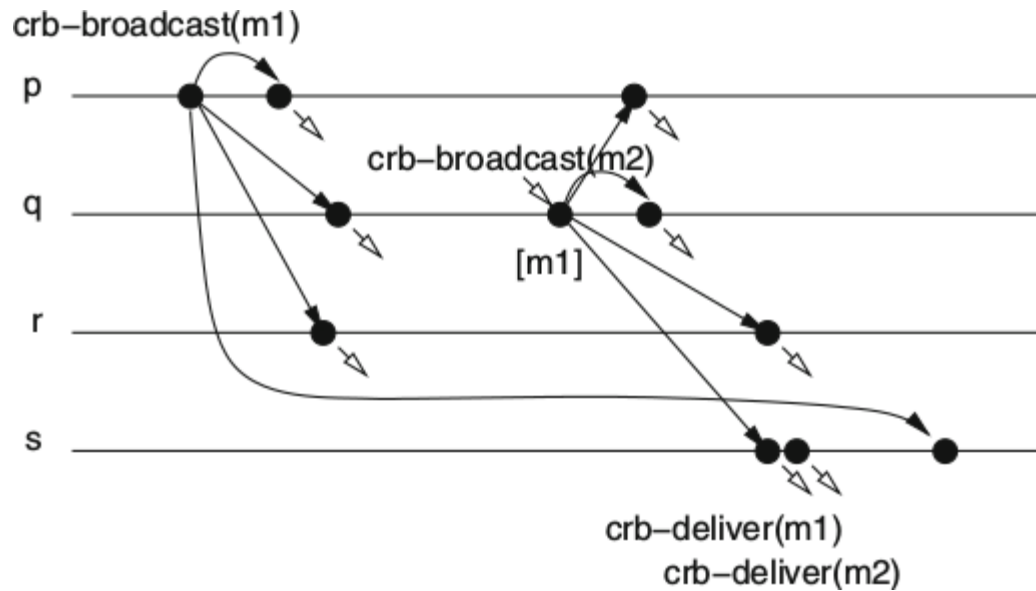
trigger $\langle crb, Deliver \mid p, m \rangle$;

delivered := *delivered* $\cup \{m\}$;

if $(p, m) \notin past$ **then**

append(*past*, (*p*, *m*));

No-waiting CB example



- The size of the message **grows with time**, as messages include their list of causally preceding messages `mpast`.
- Solution 1: **Garbage collect** old messages by sending acknowledgements of delivery to all nodes and purging messages that have been acknowledged from all.
- Solution 2: History is a **vector timestamp**!

Waiting causal broadcast

Implements:

CausalOrderReliableBroadcast, **instance** *crb*.

Uses:

ReliableBroadcast, **instance** *rb*.

upon event $\langle crb, Init \rangle$ **do**

$V := [0]^N$;

$lsn := 0$;

$pending := \emptyset$;

upon event $\langle crb, Broadcast \mid m \rangle$ **do**

$W := V$;

$W[rank(self)] := lsn$;

$lsn := lsn + 1$;

trigger $\langle rb, Broadcast \mid [DATA, W, m] \rangle$;

upon event $\langle rb, Deliver \mid p, [DATA, W, m] \rangle$ **do**

$pending := pending \cup \{(p, W, m)\}$;

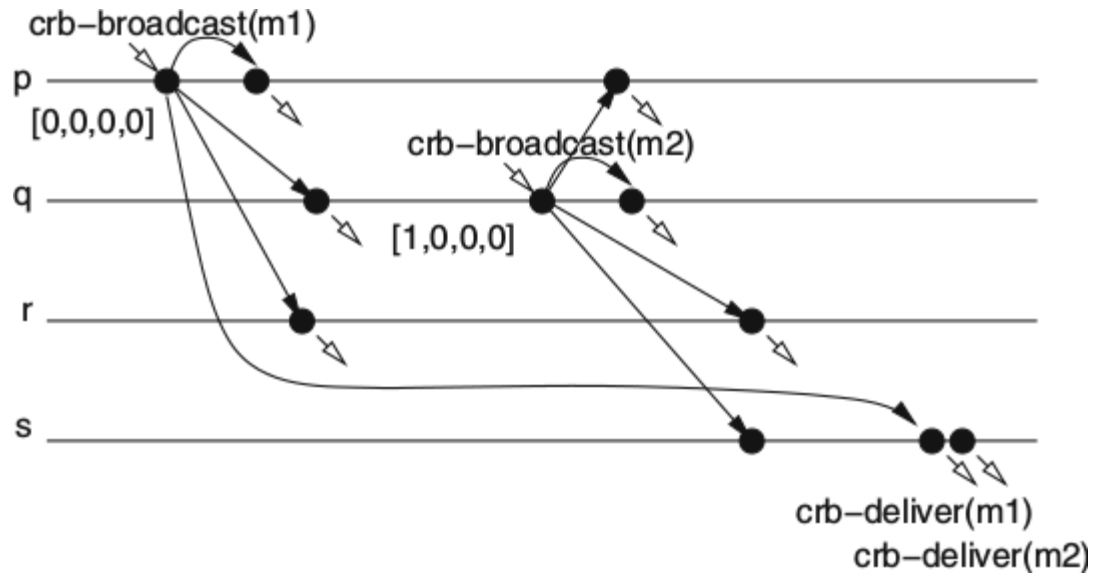
while exists $(p', W', m') \in pending$ such that $W' \leq V$ **do**

$pending := pending \setminus \{(p', W', m')\}$;

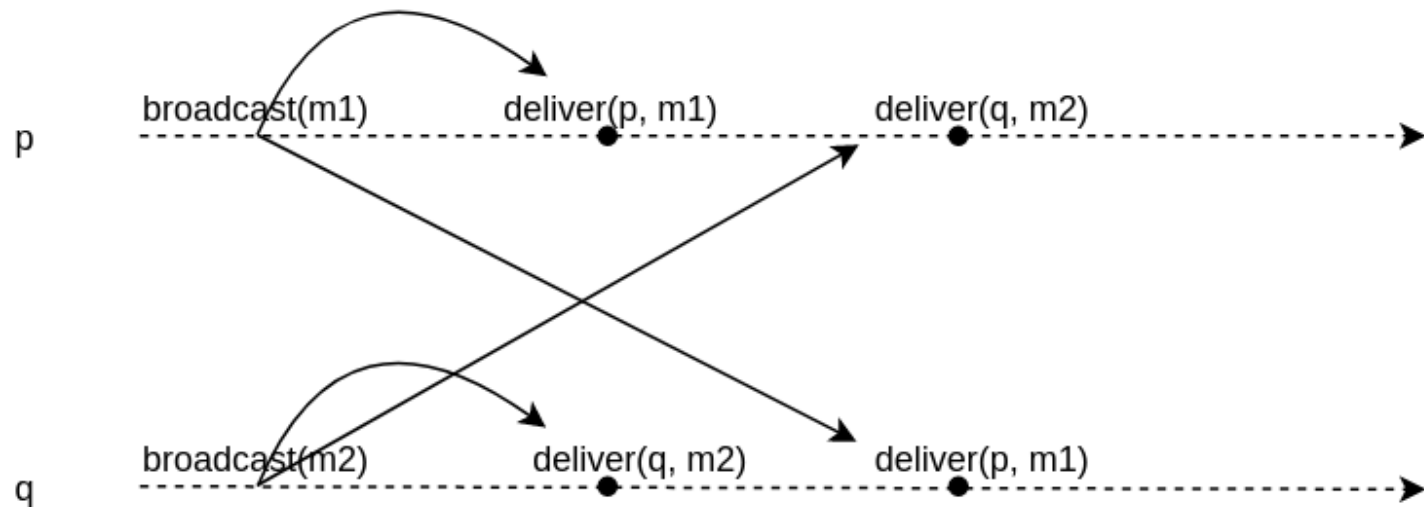
$V[rank(p')] := V[rank(p')] + 1$;

trigger $\langle crb, Deliver \mid p', m' \rangle$;

Waiting CB example



Possible execution?



Exercise

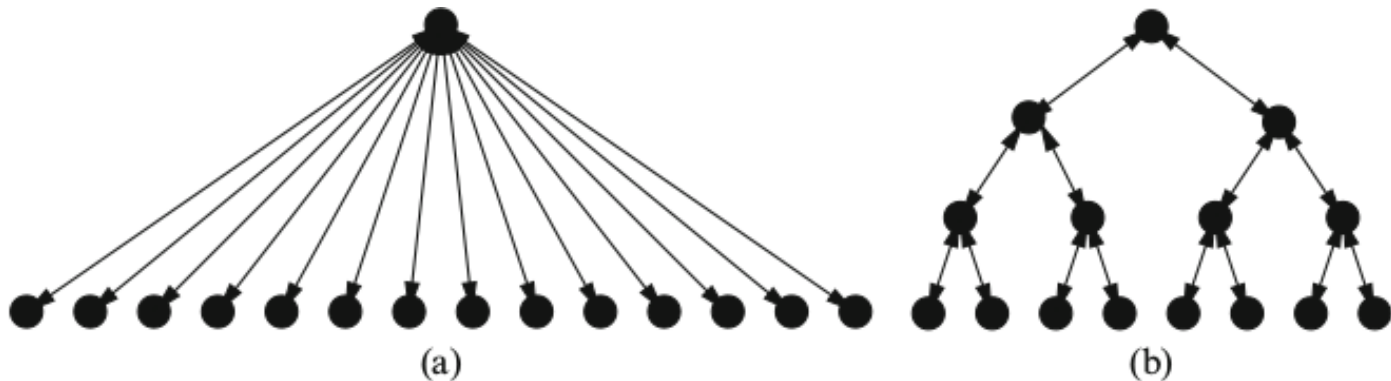
Is this a valid execution? the order of delivery is not the same.

Probabilistic broadcast

(a.k.a. epidemic broadcast or gossiping.)

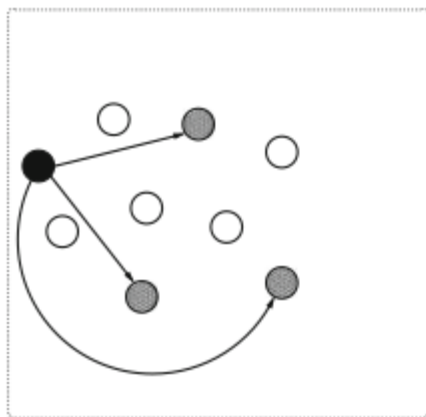
Scalability of reliable broadcast

- In order to broadcast a message, the sender needs
 - to send messages to all other processes,
 - to collect some form of acknowledgement.
 - $O(N^2)$ are exchanged in total.
 - If N is large, this can become overwhelming for the system.
- Bandwidth, memory or processing resources may limit the number of messages/acknowledgements that may be sent/collected.
- Hierarchical schemes reduce the total number of messages.
 - This reduces the load of each process.
 - But increases the latency and fragility of the system.

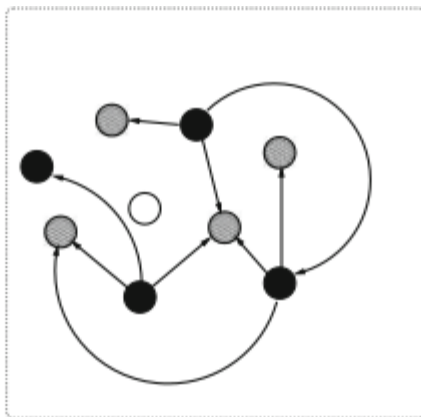


Epidemic dissemination

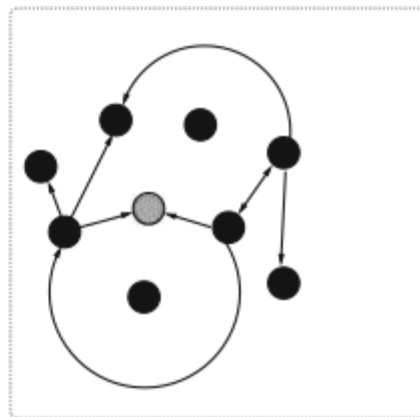
- Nodes infect each other through messages sent in **rounds**.
 - The **fanout k** determines the number of messages sent by each node.
 - Recipients are drawn **at random** (e.g., uniformly).
 - The **number of rounds** is limited to R .
- Total number of messages is usually less than $O(N^2)$.
- No node is overloaded.



(a) round 1



(b) round 2



(c) round 3

Probabilistic broadcast (*pb*)

Module:

Name: ProbabilisticBroadcast, **instance** *pb*.

Events:

Request: $\langle pb, \text{Broadcast} \mid m \rangle$: Broadcasts a message m to all processes.

Indication: $\langle pb, \text{Deliver} \mid p, m \rangle$: Delivers a message m broadcast by process p .

Properties:

PB1: Probabilistic validity: There is a positive value ε such that when a correct process broadcasts a message m , the probability that every correct process eventually delivers m is at least $1 - \varepsilon$.

PB2: No duplication: No message is delivered more than once.

PB3: No creation: If a process delivers a message m with sender s , then m was previously broadcast by process s .

Eager probabilistic broadcast

Implements:

ProbabilisticBroadcast, **instance** *pb*.

Uses:

FairLossPointToPointLinks, **instance** *fll*.

upon event $\langle pb, Init \rangle$ **do**

delivered := \emptyset ;

procedure *gossip*(*msg*) **is**

forall $t \in \text{picktargets}(k)$ **do trigger** $\langle fll, Send \mid t, msg \rangle$;

upon event $\langle pb, Broadcast \mid m \rangle$ **do**

delivered := *delivered* $\cup \{m\}$;

trigger $\langle pb, Deliver \mid self, m \rangle$;

gossip([GOSSIP, *self*, *m*, *R*]);

upon event $\langle fll, Deliver \mid p, [GOSSIP, s, m, r] \rangle$ **do**

if $m \notin delivered$ **then**

delivered := *delivered* $\cup \{m\}$;

trigger $\langle pb, Deliver \mid s, m \rangle$;

if $r > 1$ **then** *gossip*([GOSSIP, *s*, *m*, $r - 1$]);

The mathematics of epidemics

Assume a virus using a distributed system to propagate, with human hosts as nodes.

Setup

- Initial population of N individuals.
- At any time t ,
 - $S(t)$ = the number of susceptible individuals,
 - $I(t)$ = the number of infected individuals.
- $I(0) = 1$
- $S(0) = N - 1$
- $S(t) + I(t) = N$ for all t .

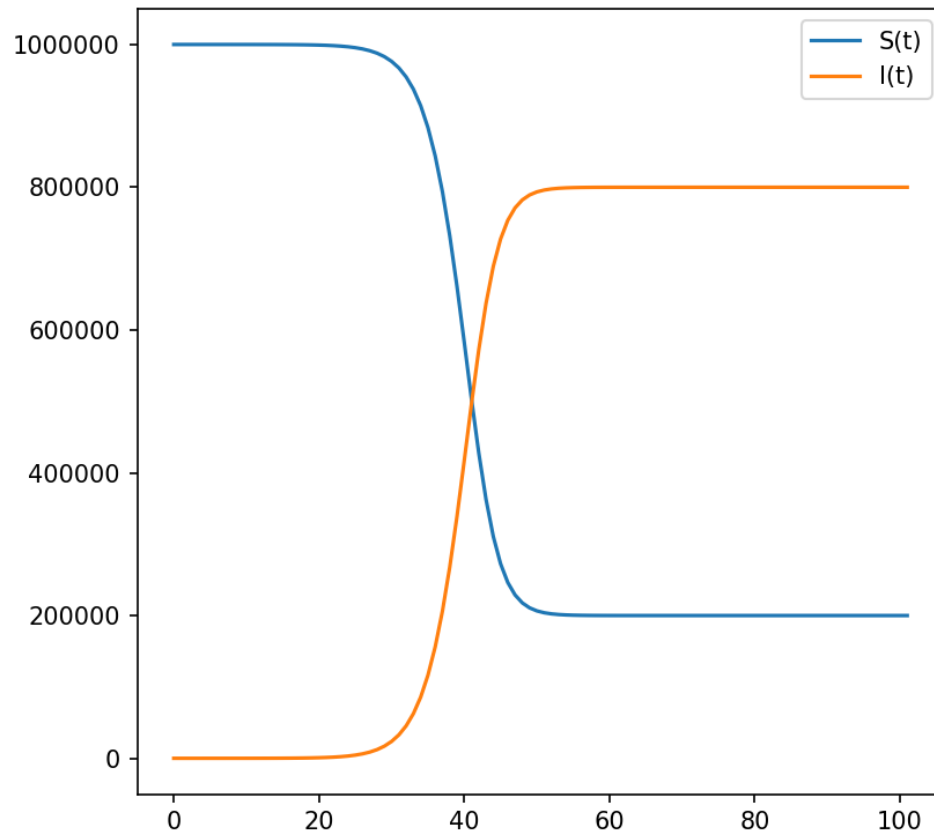
The expected dynamics of the SIS model is given as follows:

$$S(t + 1) = S(t) - \frac{\alpha \Delta t}{N} S(t) I(t) + \gamma \Delta t I(t)$$

$$I(t + 1) = I(t) + \frac{\alpha \Delta t}{N} S(t) I(t) - \gamma \Delta t I(t)$$

where

- α is the contact rate with whom infected individuals make contact per unit of time.
- $\frac{S(t)}{N}$ is the proportion of contacts with susceptible individuals for each infected individual.
- γ is the probability for an infected individual to recover and switch to the pool of susceptibles.



$$N = 1000000, \alpha = 5, \gamma = 0.5, \Delta t = 0.1$$

In eager reliable broadcast,

- $\alpha = k$
 - An infected node selects k nodes among N to send its messages.
- $\gamma = 1$
 - An infected node immediately recovers.

Probabilistic validity

At time t , the probability of not receiving a message is

$$\left(1 - \frac{k}{N}\right)^{I(t)}$$

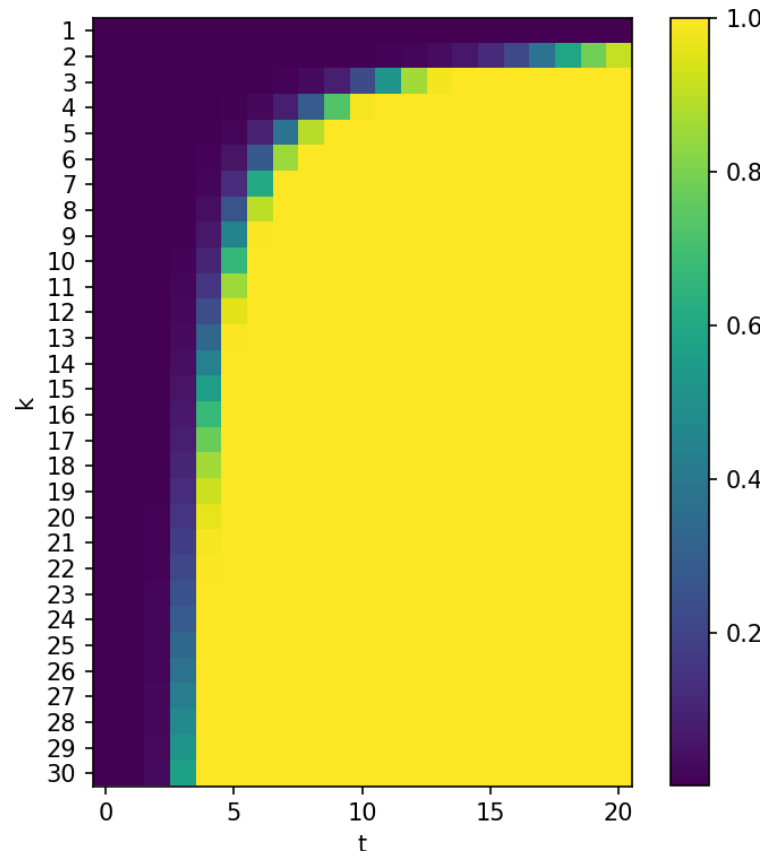
Therefore the probability of having received of one or more gossip messages up to time t , that is to have PB-delivered, is

$$p(\text{delivery}) = 1 - \left(1 - \frac{k}{N}\right)^{\sum_{t_i=0}^t I(t_i)}$$

Exercise

What if nodes fail? if packets are loss?

$$p(\text{delivery}|k, t)$$



$$N = 1000000, \gamma = 1.0$$

From this plot, we observe that:

- Within only a few rounds (**low latency**), a large fraction of nodes receive the message (**reliability**)
- Each node has transmitted no more than kR messages (**lightweight**).

Lazy Probabilistic broadcast

- Eager probabilistic broadcast consumes **considerable resources** and causes many **redundant transmissions**.
 - in particular as r gets larger and almost all nodes have received the message once.
- Assume **a stream of messages** to be broadcast.
- Broadcast messages in **two phases**:
 - **Phase 1 (data dissemination)**: run probabilistic broadcast with a large probability ϵ that reliable delivery fails. That is, assume a constant fraction of nodes obtain the message (e.g., $\frac{1}{2}$).
 - **Phase 2 (recovery)**: upon delivery, detect omissions through sequence numbers and initiate retransmissions with gossip.

Phase 1: data dissemination

Implements:

ProbabilisticBroadcast, **instance** *pb*.

Uses:

FairLossPointToPointLinks, **instance** *fl*;

ProbabilisticBroadcast, **instance** *upb*.

// an *unreliable* implementation

upon event $\langle pb, Init \rangle$ **do**

$next := [1]^N$;

$lsn := 0$;

$pending := \emptyset$; $stored := \emptyset$;

procedure *gossip*(*msg*) **is**

forall $t \in picktargets(k)$ **do trigger** $\langle fl, Send \mid t, msg \rangle$;

upon event $\langle pb, Broadcast \mid m \rangle$ **do**

$lsn := lsn + 1$;

trigger $\langle upb, Broadcast \mid [DATA, self, m, lsn] \rangle$;

upon event $\langle upb, Deliver \mid p, [DATA, s, m, sn] \rangle$ **do**

if $random([0, 1]) > \alpha$ **then**

$stored := stored \cup \{[DATA, s, m, sn]\}$;

if $sn = next[s]$ **then**

$next[s] := next[s] + 1$;

trigger $\langle pb, Deliver \mid s, m \rangle$;

else if $sn > next[s]$ **then**

$pending := pending \cup \{[DATA, s, m, sn]\}$;

forall $missing \in [next[s], \dots, sn - 1]$ **do**

if no m' **exists such that** $[DATA, s, m', missing] \in pending$ **then**

$gossip([REQUEST, self, s, missing, R - 1])$;

$starttimer(\Delta, s, sn)$;

Phase 2: recovery

```
upon event  $\langle fl, Deliver \mid p, [REQUEST, q, s, sn, r] \rangle$  do  
  if exists  $m$  such that  $[DATA, s, m, sn] \in stored$  then  
    trigger  $\langle fl, Send \mid q, [DATA, s, m, sn] \rangle$ ;  
  else if  $r > 0$  then  
     $gossip([REQUEST, q, s, sn, r - 1])$ ;  
  
upon event  $\langle fl, Deliver \mid p, [DATA, s, m, sn] \rangle$  do  
   $pending := pending \cup \{[DATA, s, m, sn]\}$ ;  
  
upon exists  $[DATA, s, x, sn] \in pending$  such that  $sn = next[s]$  do  
   $next[s] := next[s] + 1$ ;  
   $pending := pending \setminus \{[DATA, s, x, sn]\}$ ;  
  trigger  $\langle pb, Deliver \mid s, x \rangle$ ;  
  
upon event  $\langle Timeout \mid s, sn \rangle$  do  
  if  $sn > next[s]$  then  
     $next[s] := sn + 1$ ;
```

Summary

- Reliable multicast enable group communication, while ensuring **validity** and (uniform) **agreement**.
- Causal broadcast extends reliable broadcast with **causal ordering** guarantees.
- **Probabilistic broadcast** enable low-latency, reliable and lightweight group communication.

References

- Allen, Linda JS. "Some discrete-time SI, SIR, and SIS epidemic models." Mathematical biosciences 124.1 (1994): 83-105.