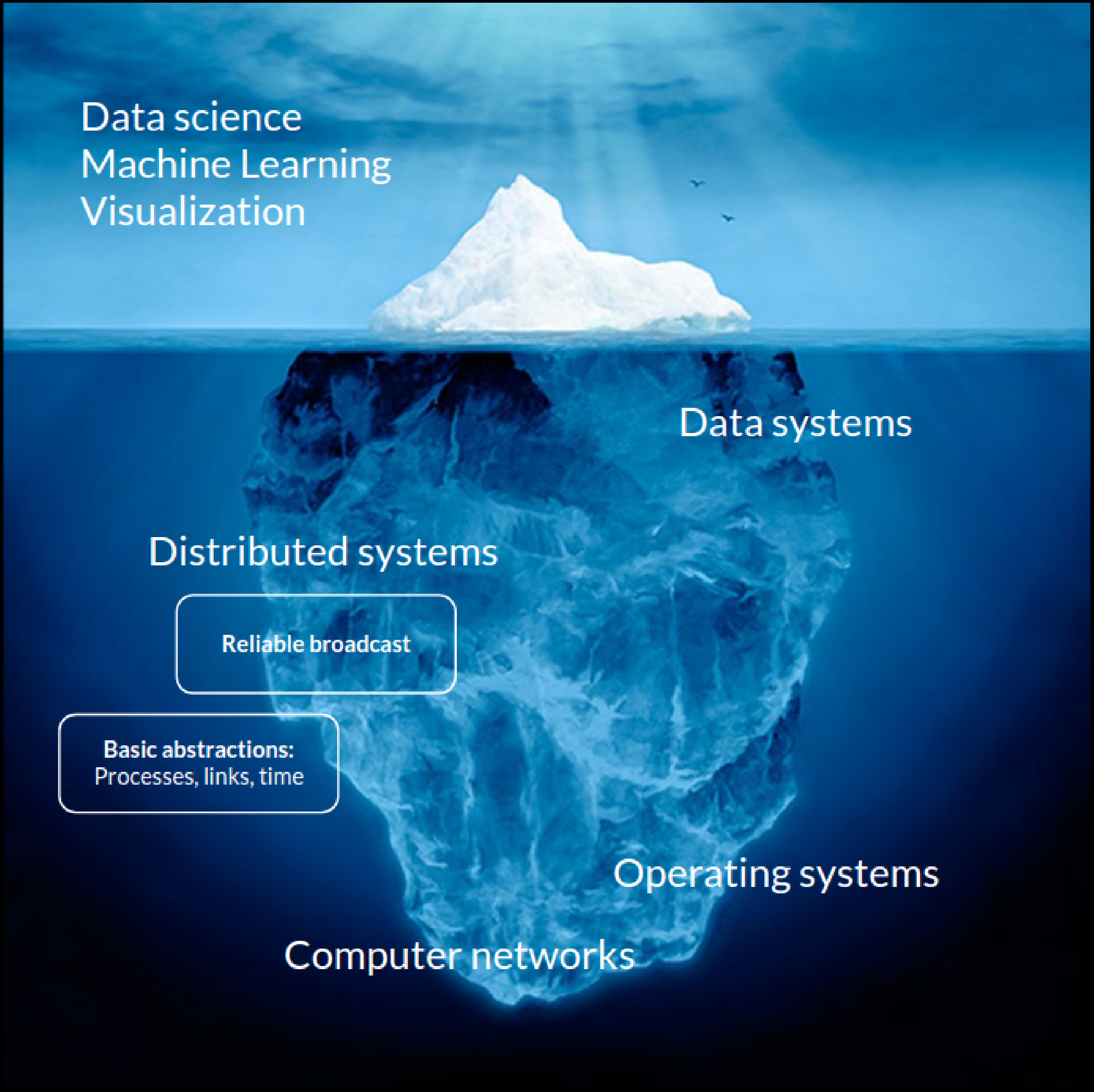
Large-scale Data Systems

Lecture 3: Reliable broadcast

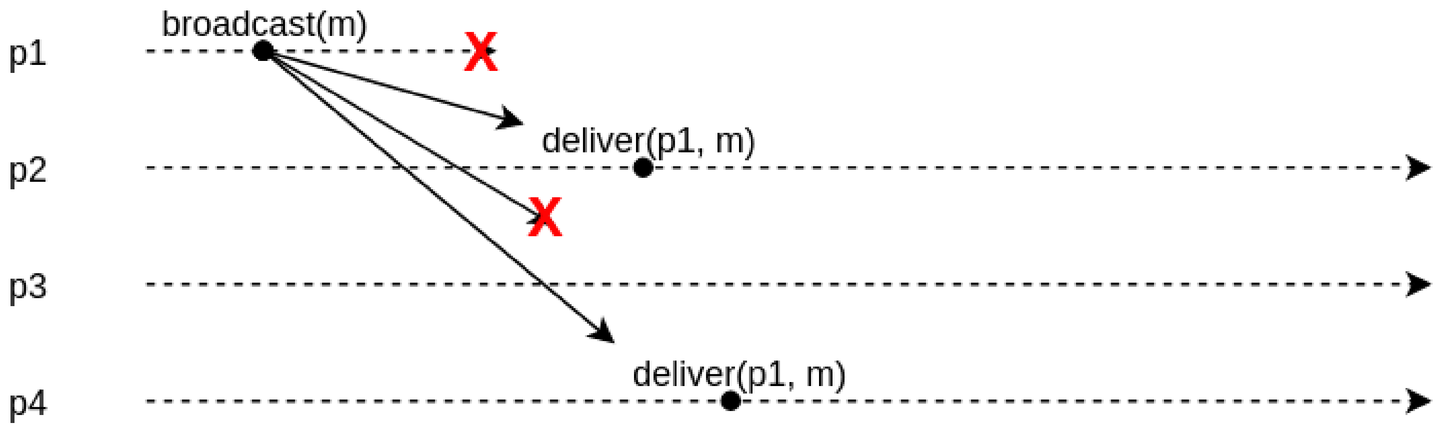
Prof. Gilles Louppe
g.louppe@uliege.be

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?


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: $\langle$ *beb*, *Broadcast* | m $\rangle$: Broadcasts a message m to all processes.

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

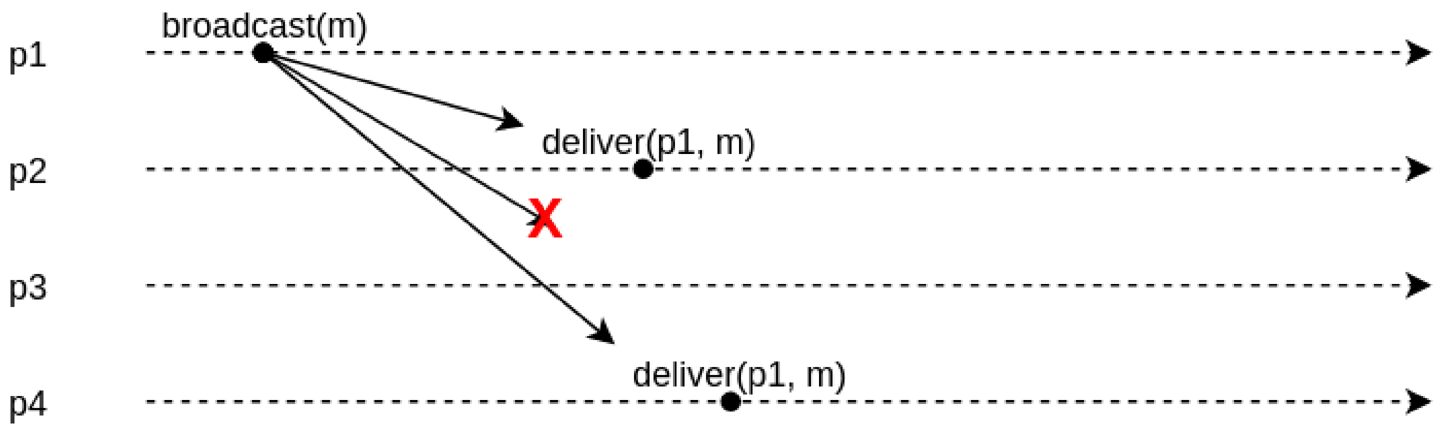
Properties:

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.

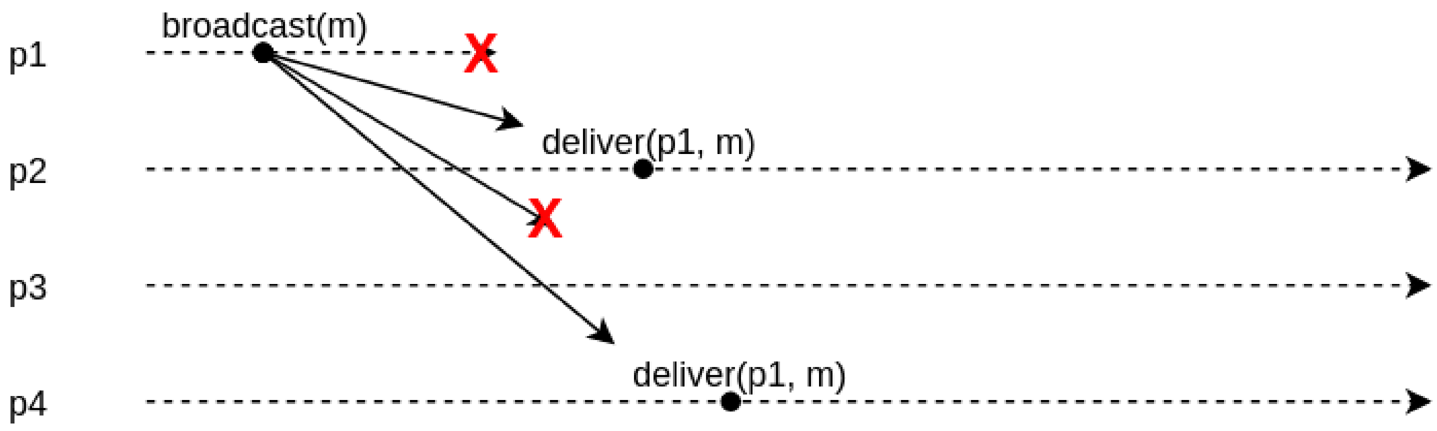
beb example (1)



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*, *Broadcast* | m $\rangle$: Broadcasts a message m to all processes.

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

Properties:

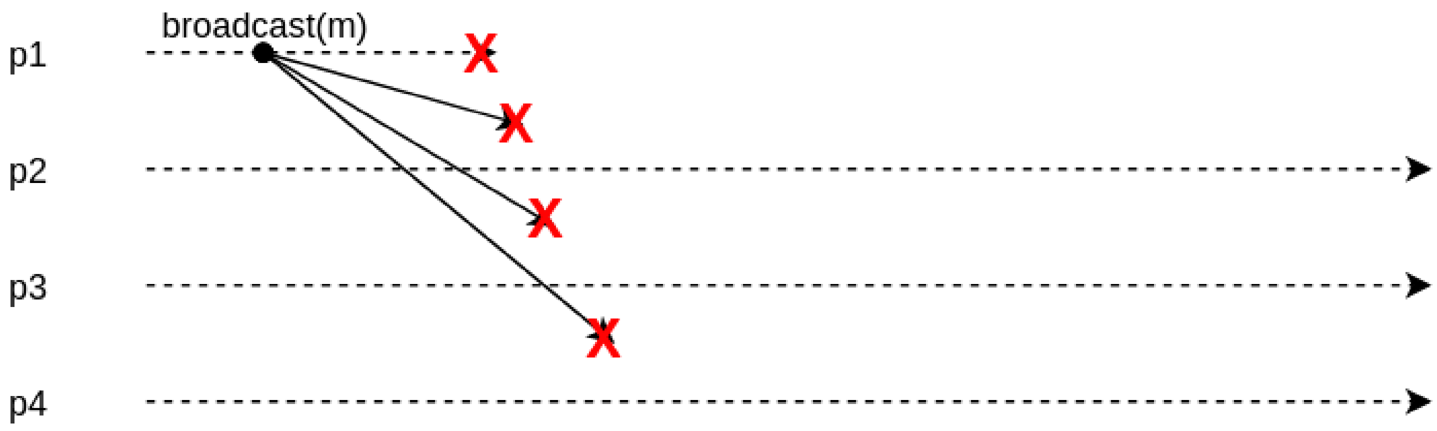
RB1: *Validity:* If a correct process p broadcasts a message m, then p eventually delivers m.

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.

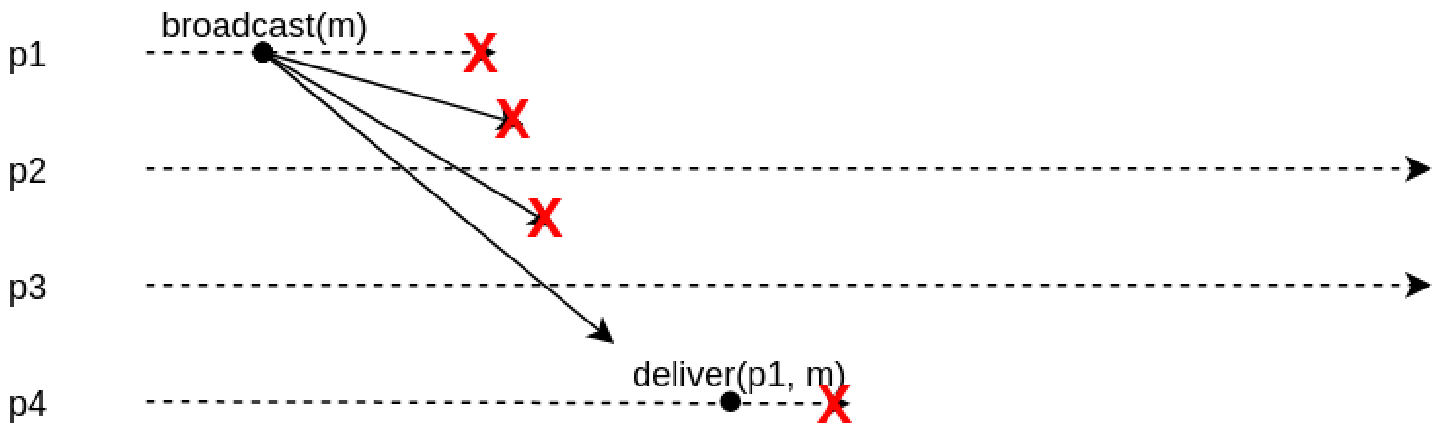
rb example (1)



Exercise

Is this allowed?

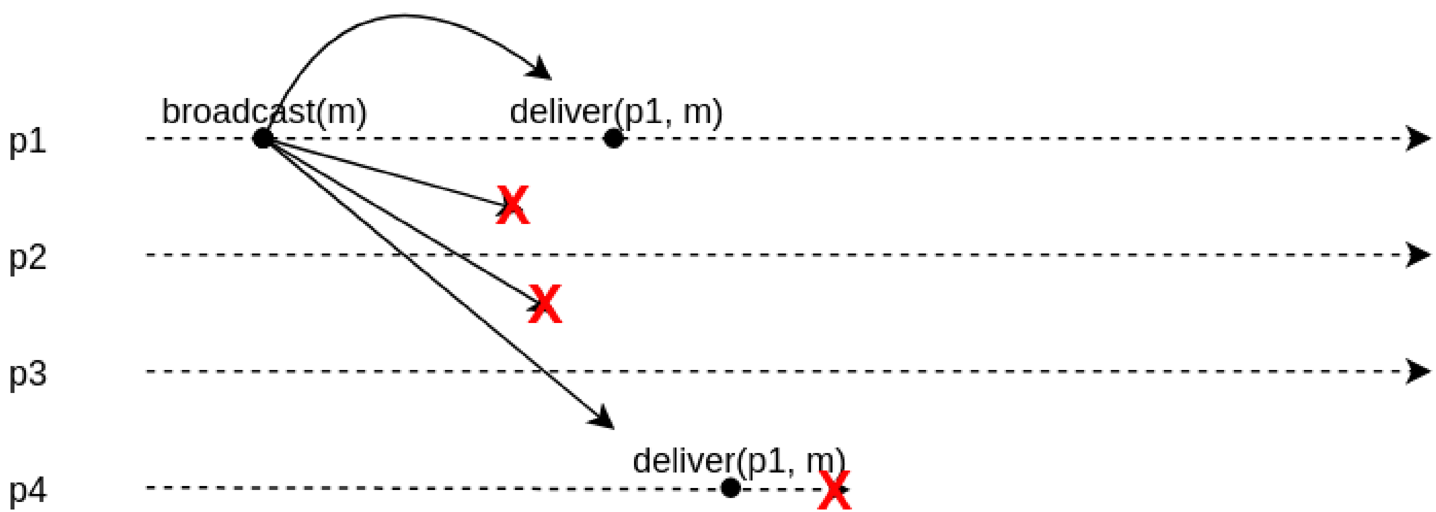
rb example (2)



Exercise

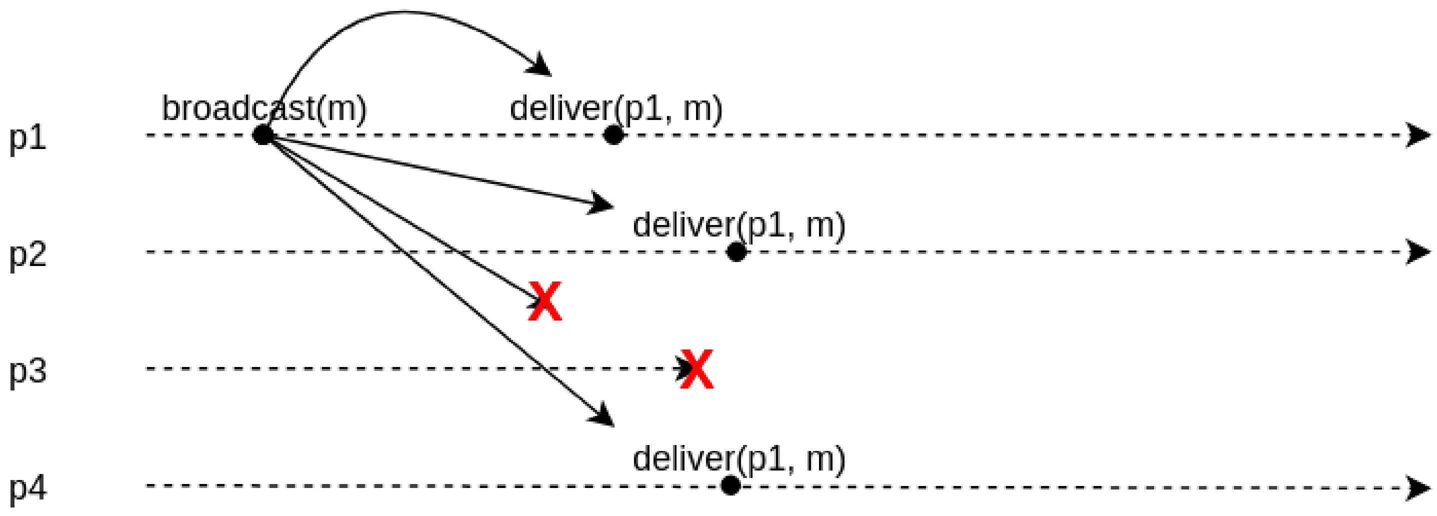
Is this allowed?

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* | m $\rangle$: Broadcasts a message m to all processes.

Indication: $\langle$ *urb*, *Deliver* | 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 $\langle$ *beb*, *Broadcast* | m $\rangle$ **do**
forall $q \in \Pi$ **do**
trigger $\langle$ *pl*, *Send* | q, m $\rangle$;

upon event $\langle$ *pl*, *Deliver* | p, m $\rangle$ **do**
trigger $\langle$ *beb*, *Deliver* | 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** $\mathcal{P}$.

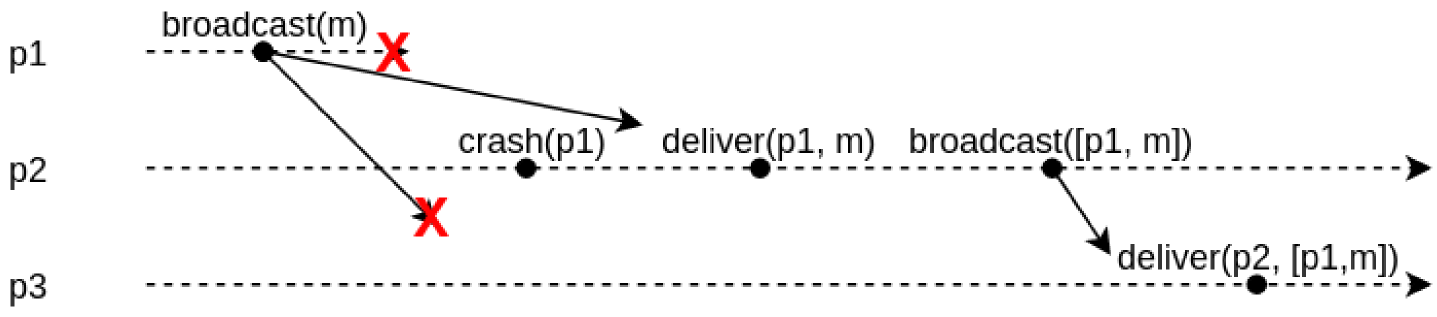
upon event ⟨ *rb*, *Init* ⟩ **do**
    correct := Π;
    from$[p]$:= $[\emptyset]^N$;

upon event ⟨ *rb*, *Broadcast* | m ⟩ **do**
    trigger ⟨ *beb*, *Broadcast* | [DATA, *self*, m] ⟩;

upon event ⟨ *beb*, *Deliver* | p, [DATA, s, m] ⟩ **do**
    if $m \notin$ *from*$[s]$ **then**
        trigger ⟨ *rb*, *Deliver* | s, m ⟩;
        from$[s]$:= *from*$[s] \cup \{m\}$;
        if $s \notin$ *correct* **then**
            trigger ⟨ *beb*, *Broadcast* | [DATA, s, m] ⟩;

upon event ⟨ $\mathcal{P}$, *Crash* | p ⟩ **do**
    correct := *correct* $\setminus \{p\}$;
    forall $m \in$ *from*$[p]$ **do**
        trigger ⟨ *beb*, *Broadcast* | [DATA, p, m] ⟩;

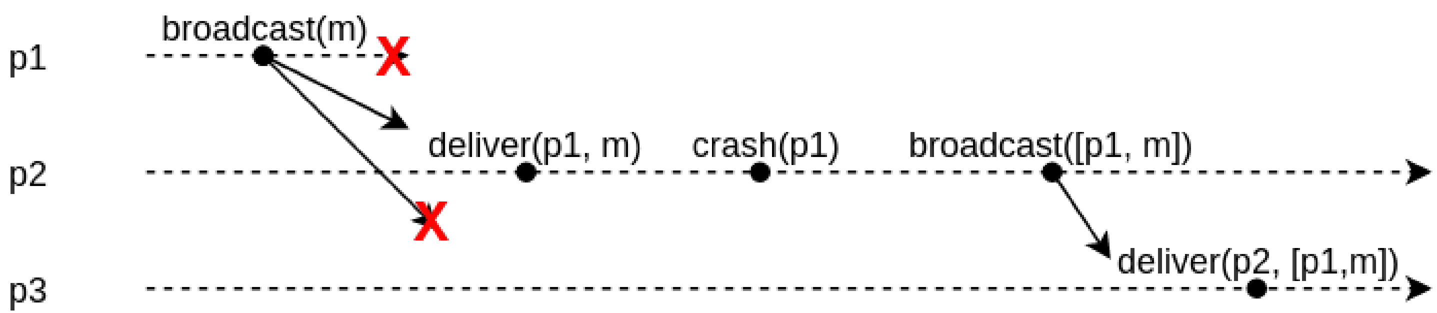
Lazy reliable broadcast example (1)



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* | m $\rangle$ **do**
    trigger $\langle$ *beb*, *Broadcast* | [DATA, *self*, m] $\rangle$;

upon event $\langle$ *beb*, *Deliver* | p, [DATA, s, m] $\rangle$ **do**
    if $m \notin$ *delivered* **then**
        delivered := *delivered* $\cup \{m\}$;
        trigger $\langle$ *rb*, *Deliver* | s, m $\rangle$;
        trigger $\langle$ *beb*, *Broadcast* | [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 $\langle$ *urb*, *Init* $\rangle$ **do**
delivered := $\emptyset$;
pending := $\emptyset$;
correct := Π;
forall m **do** *ack*$[m]$:= $\emptyset$;

upon event $\langle$ *urb*, *Broadcast* | m $\rangle$ **do**
pending := *pending* $\cup$ $\{(self, m)\}$;
trigger $\langle$ *beb*, *Broadcast* | [DATA, *self*, m] $\rangle$;

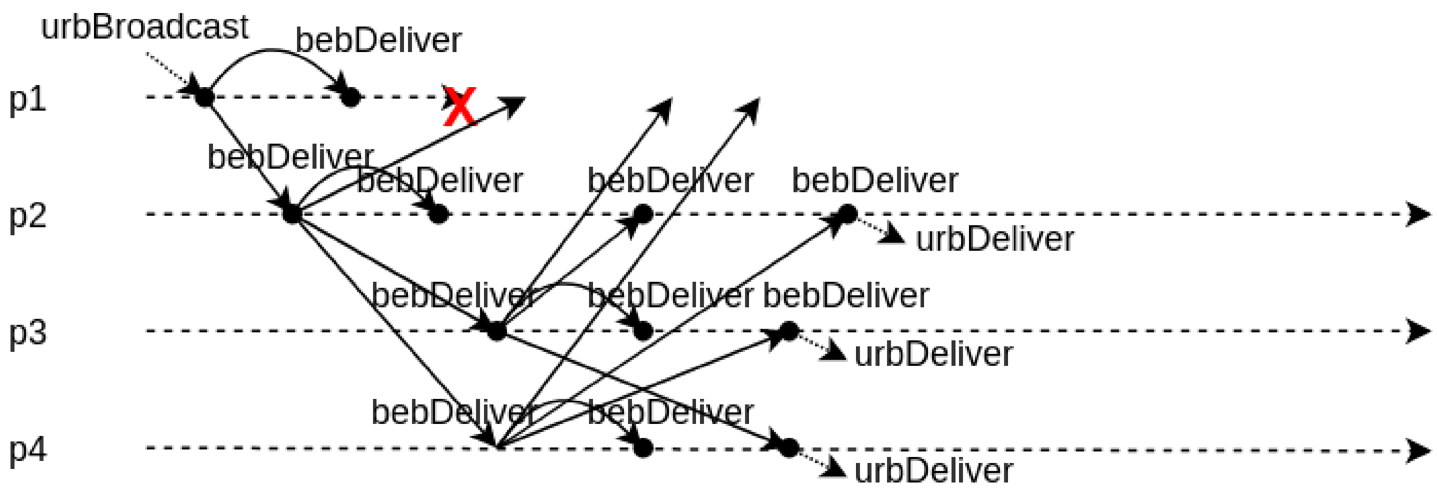
upon event $\langle$ *beb*, *Deliver* | p, [DATA, s, m] $\rangle$ **do**
ack$[m]$:= *ack*$[m]$ $\cup$ $\{p\}$;
if $(s, m) \notin$ *pending* **then**
pending := *pending* $\cup$ $\{(s, m)\}$;
trigger $\langle$ *beb*, *Broadcast* | [DATA, s, m] $\rangle$;

upon event $\langle$ $\mathcal{P}$, *Crash* | p $\rangle$ **do**
correct := *correct* $\setminus$ $\{p\}$;

function *candeliver*(m) **returns** Boolean **is**
return (*correct* $\subseteq$ *ack*$[m]$);

upon exists $(s, m) \in$ *pending* such that *candeliver*$(m) \wedge m \notin$ *delivered* **do**
delivered := *delivered* $\cup$ $\{m\}$;
trigger $\langle$ *urb*, *Deliver* | s, m $\rangle$;

Example



urbBroadcast
bebDeliver
p1
bebDeliver
bebDeliver
bebDeliver
bebDeliver
p2
urbDeliver
bebDeliver
bebDeliver
bebDeliver
p3
urbDeliver
bebDeliver
bebDeliver
p4
urbDeliver

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 $\langle$ *Crash* $\rangle$ events
// triggered by the perfect failure detector, it is the same as Algorithm 3.4.

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

Exercise
Show that this variant is correct.

Causal reliable broadcast

Mathias Verraes
@mathiasverraes

Follow

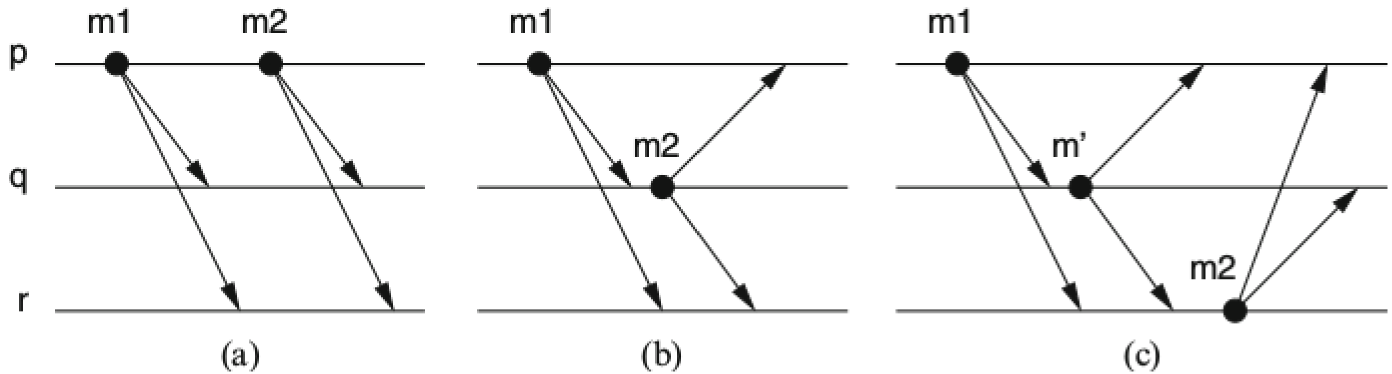
There are only two hard problems in distributed systems: 2. Exactly-once delivery 1. Guaranteed order of messages 2. Exactly-once delivery

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: ⟨ *crb*, *Broadcast* | m ⟩: Broadcasts a message m to all processes.

Indication: ⟨ *crb*, *Deliver* | p, m ⟩: Delivers a message m broadcast by process p.

Properties:

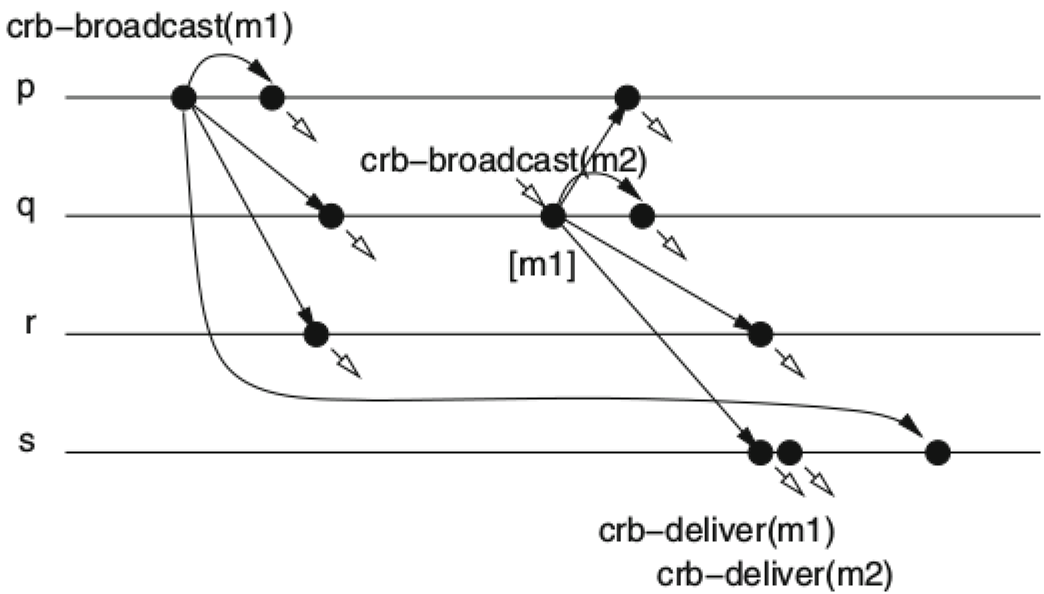
CRB1–CRB4: Same as properties RB1–RB4 in (regular) reliable broadcast (Module 3.2).

CRB5: *Causal delivery:* For any message m_1 that potentially caused a message m_2, i.e., $m_1 \to m_2$, 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 ⟨ crb, Init ⟩ do
    delivered := ∅;
    past := [];

upon event ⟨ crb, Broadcast | m ⟩ do
    trigger ⟨ rb, Broadcast | [DATA, past, m] ⟩;
    append(past, (self, m));

upon event ⟨ rb, Deliver | p, [DATA, mpast, m] ⟩ do
    if m ∉ delivered then
        forall (s, n) ∈ mpast do                         // by the order in the list
            if n ∉ delivered then
                trigger ⟨ crb, Deliver | s, n ⟩;
                delivered := delivered ∪ {n};
                if (s, n) ∉ past then
                    append(past, (s, n));
        trigger ⟨ crb, Deliver | p, m ⟩;
        delivered := delivered ∪ {m};
        if (p, m) ∉ 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*.

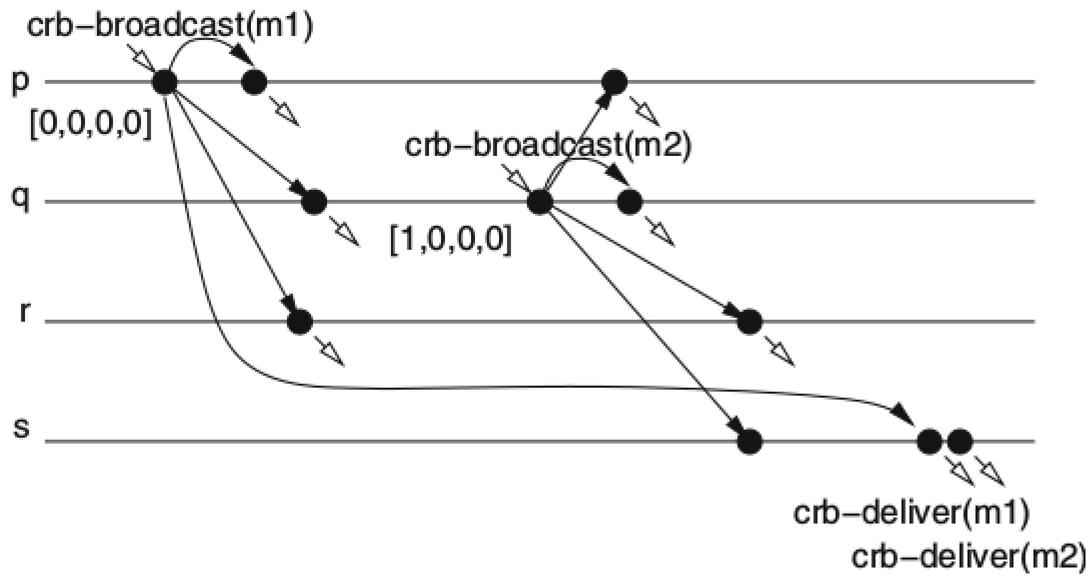
Uses:
ReliableBroadcast, **instance** *rb*.

upon event ⟨ *crb*, *Init* ⟩ **do**
$V := [0]^N$;
lsn := 0;
pending := ∅;

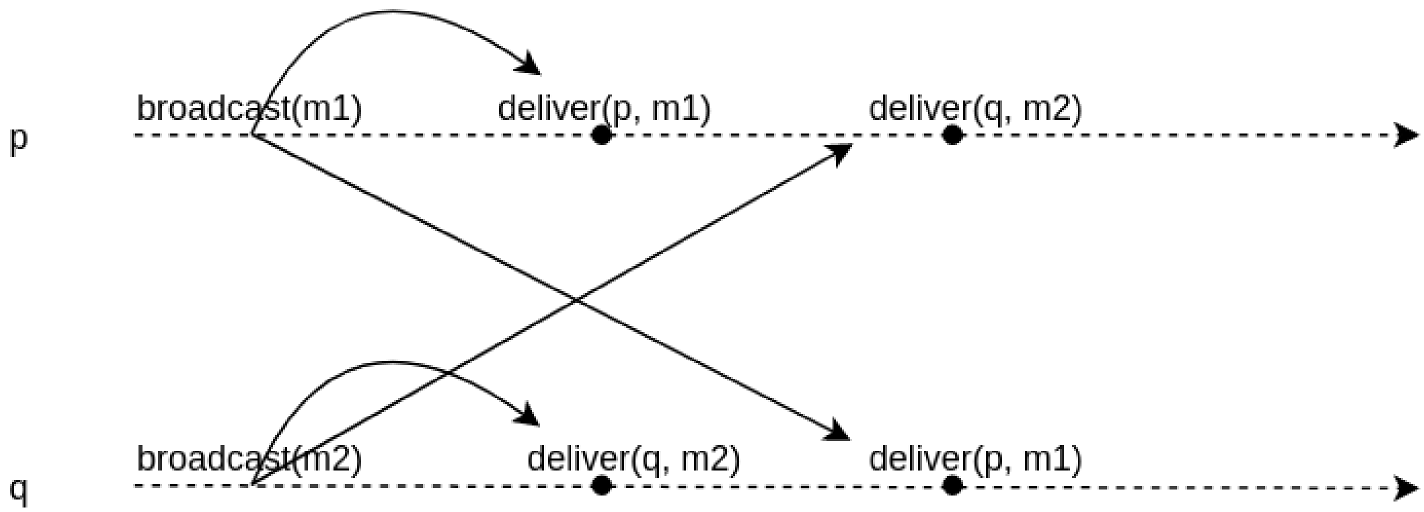
upon event ⟨ *crb*, *Broadcast* | m ⟩ **do**
$W := V$;
W[rank(*self*)] := *lsn*;
lsn := *lsn* + 1;
trigger ⟨ *rb*, *Broadcast* | [DATA, W, m] ⟩;

upon event ⟨ *rb*, *Deliver* | p, [DATA, W, m] ⟩ **do**
pending := *pending* ∪ $\{(p, W, m)\}$;
while exists (p', W', m') ∈ *pending* such that $W' \leq V$ **do**
pending := *pending* \ $\{(p', W', m')\}$;
$V[\text{rank}(p')] := V[\text{rank}(p')] + 1$;
trigger ⟨ *crb*, *Deliver* | p', m' ⟩;

Waiting CB example



Possible execution?



Exercise

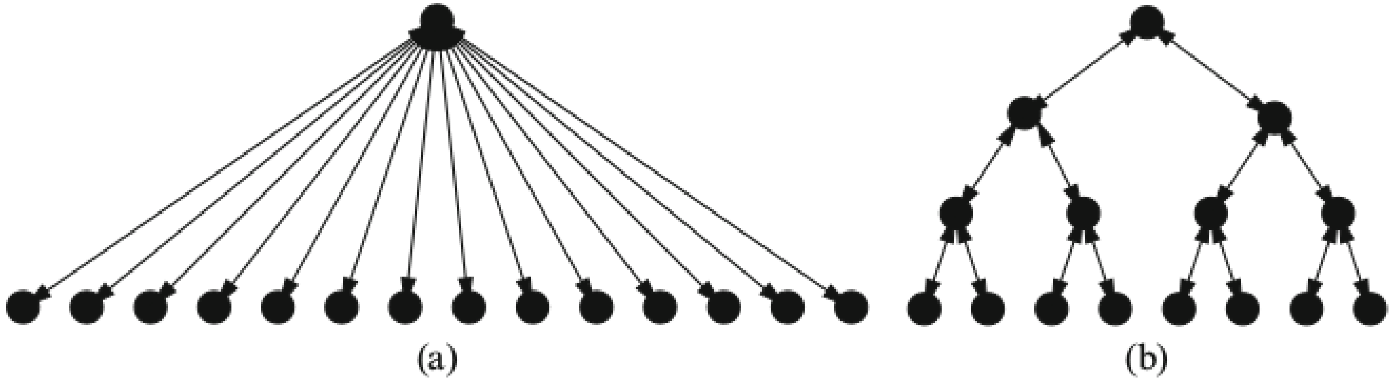
Is this a valid execution? the order of delivery is not the same.

Probabilistic broadcast

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

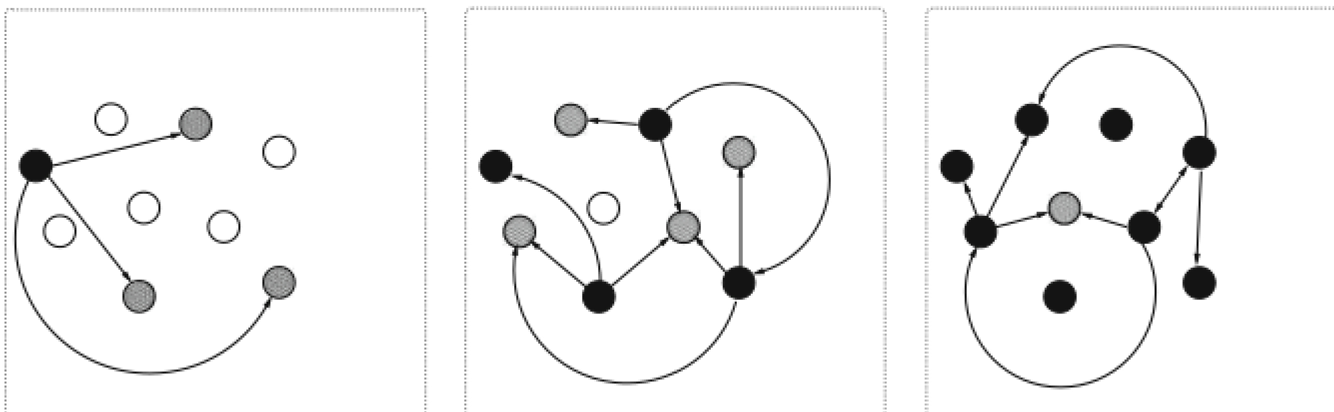
Scalability of reliable broadcast

- 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, *Broadcast* | m $\rangle$: Broadcasts a message m to all processes.

Indication: $\langle$ pb, *Deliver* | 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 ⟨ *pb*, *Init* ⟩ **do**
delivered := ∅;

procedure *gossip*(*msg*) **is**
forall $t \in$ *picktargets*(k) **do trigger** ⟨ *fll*, *Send* | t, *msg* ⟩;

upon event ⟨ *pb*, *Broadcast* | m ⟩ **do**
delivered := *delivered* ∪ $\{m\}$;
trigger ⟨ *pb*, *Deliver* | *self*, m ⟩;
gossip([GOSSIP, *self*, m, *R*]);

upon event ⟨ *fll*, *Deliver* | p, [GOSSIP, s, m, r] ⟩ **do**
if $m \notin$ *delivered* **then**
delivered := *delivered* ∪ $\{m\}$;
trigger ⟨ *pb*, *Deliver* | s, m ⟩;
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.

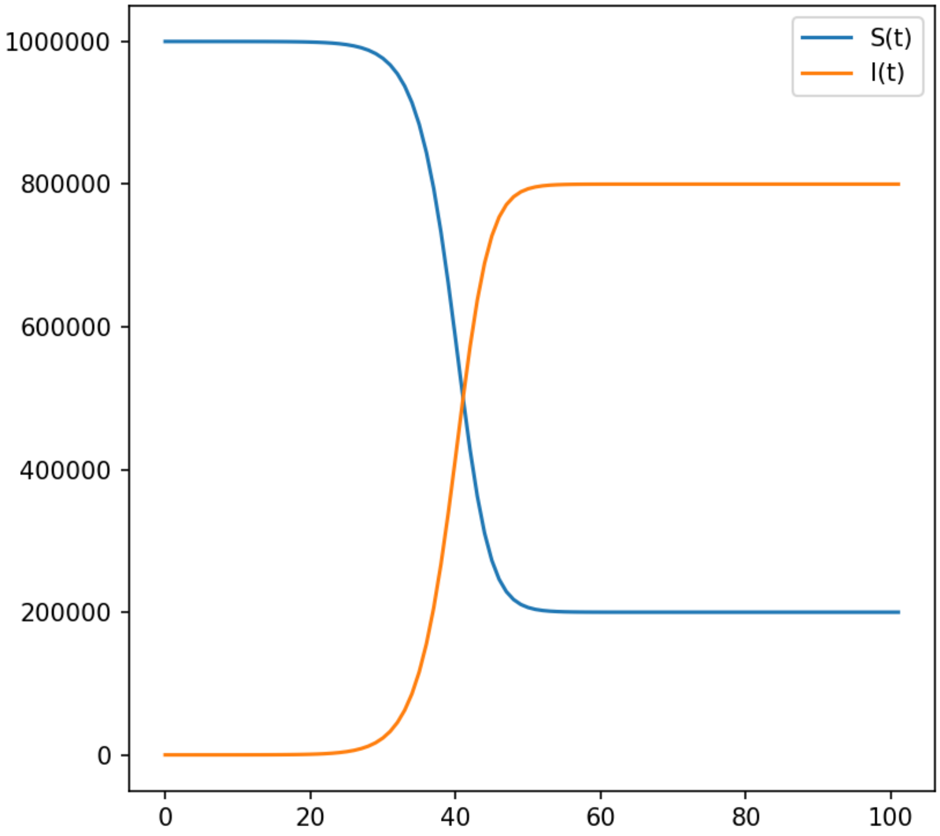
The expected dynamics of the SIS model is given as follows:

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

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

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

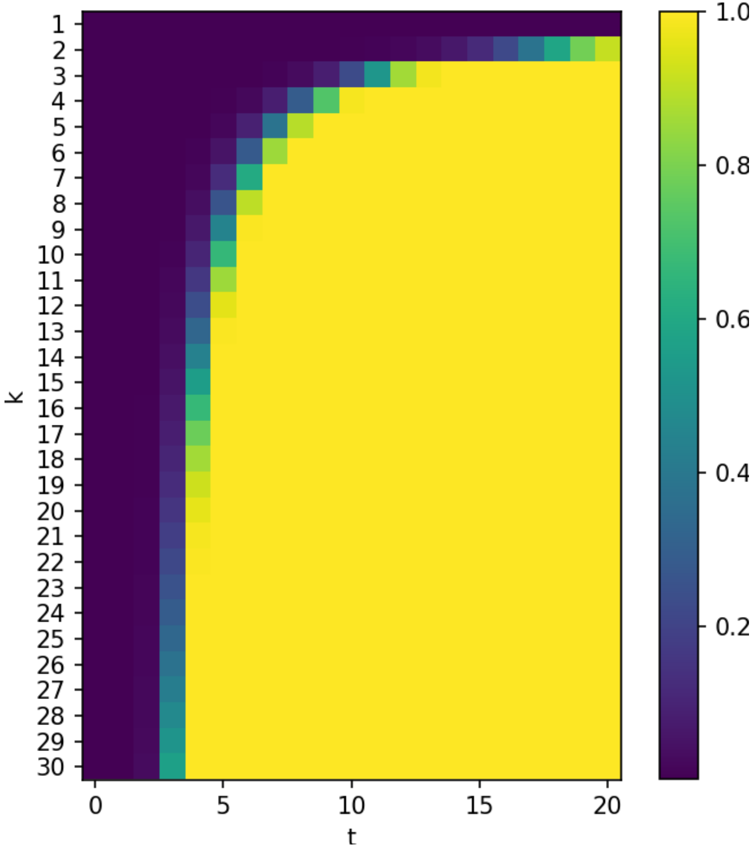
$$(1 - \frac{k}{N})^{I(t)}$$

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

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

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 fll;
    ProbabilisticBroadcast, instance upb.            // an unreliable implementation

upon event ⟨ pb, Init ⟩ do
    next := [1]^N;
    lsn := 0;
    pending := ∅; stored := ∅;

procedure gossip(msg) is
    forall t ∈ picktargets(k) do trigger ⟨ fll, Send | t, msg ⟩;

upon event ⟨ pb, Broadcast | m ⟩ do
    lsn := lsn + 1;
    trigger ⟨ upb, Broadcast | [DATA, self, m, lsn] ⟩;

upon event ⟨ upb, Deliver | p, [DATA, s, m, sn] ⟩ do
    if random([0, 1]) > α then
        stored := stored ∪ {[DATA, s, m, sn]};
    if sn = next[s] then
        next[s] := next[s] + 1;
        trigger ⟨ pb, Deliver | s, m ⟩;
    else if sn > next[s] then
        pending := pending ∪ {[DATA, s, m, sn]};
        forall missing ∈ [next[s], . . . , sn − 1] do
            if no m′ exists such that [DATA, s, m′, missing] ∈ pending then
                gossip([REQUEST, self, s, missing, R − 1]);
        starttimer(Δ, s, sn);
```

Phase 2: recovery

upon event ⟨ *fll*, *Deliver* | p, [REQUEST, q, s, sn, r] ⟩ **do**
  if exists m such that [DATA, s, m, sn] $\in$ *stored* **then**
    trigger ⟨ *fll*, *Send* | q, [DATA, s, m, sn] ⟩;
  else if $r > 0$ **then**
    gossip([REQUEST, $q, s, sn, r - 1$]);

upon event ⟨ *fll*, *Deliver* | p, [DATA, s, m, sn] ⟩ **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 ⟨ *pb*, *Deliver* | s, x ⟩;

upon event ⟨ *Timeout* | s, sn ⟩ **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.

The end.

References

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