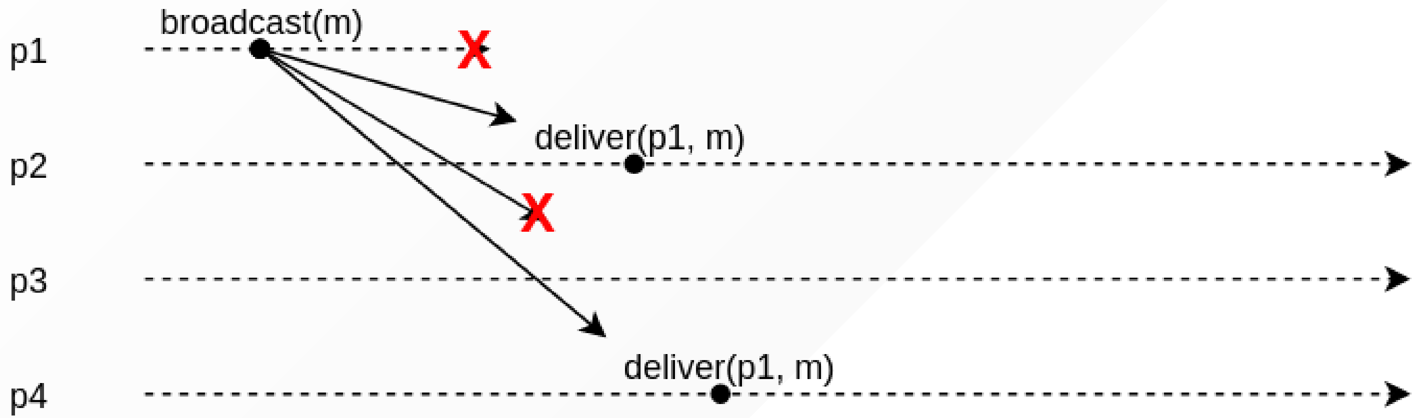
Large-scale Distributed Systems

Lecture 3: Reliable broadcast

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?

Unreliable broadcast



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

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.

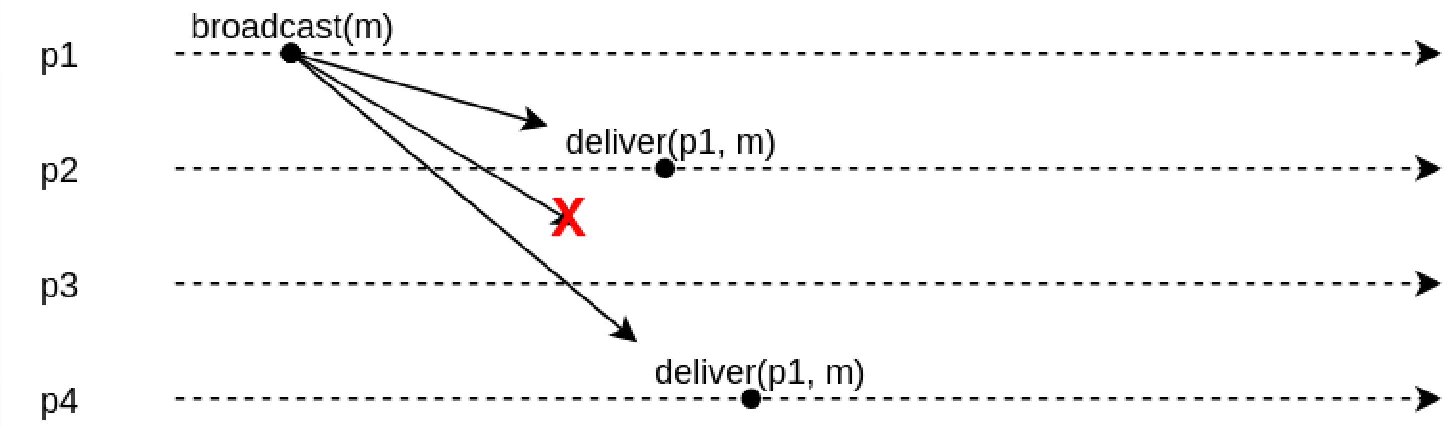
Properties:

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.

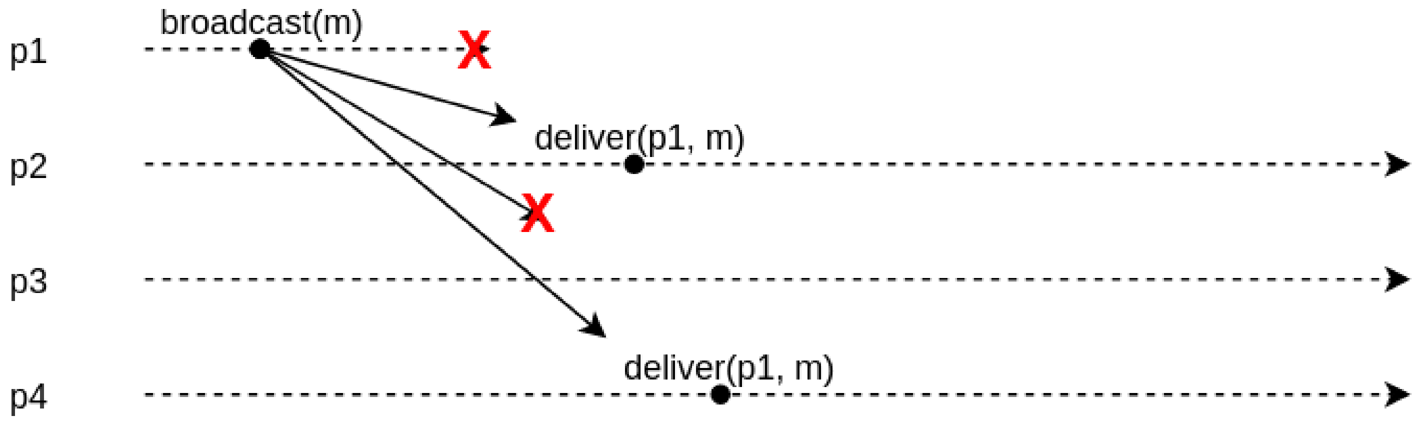
BEB3: *No creation:* If a process delivers a message m with sender s, then m was previously broadcast by process s.

BEB example (1)



[Q] Is this allowed?

BEB example (2)



[Q] Is this allowed?

Reliable broadcast

- 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.

Reliable broadcast

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:

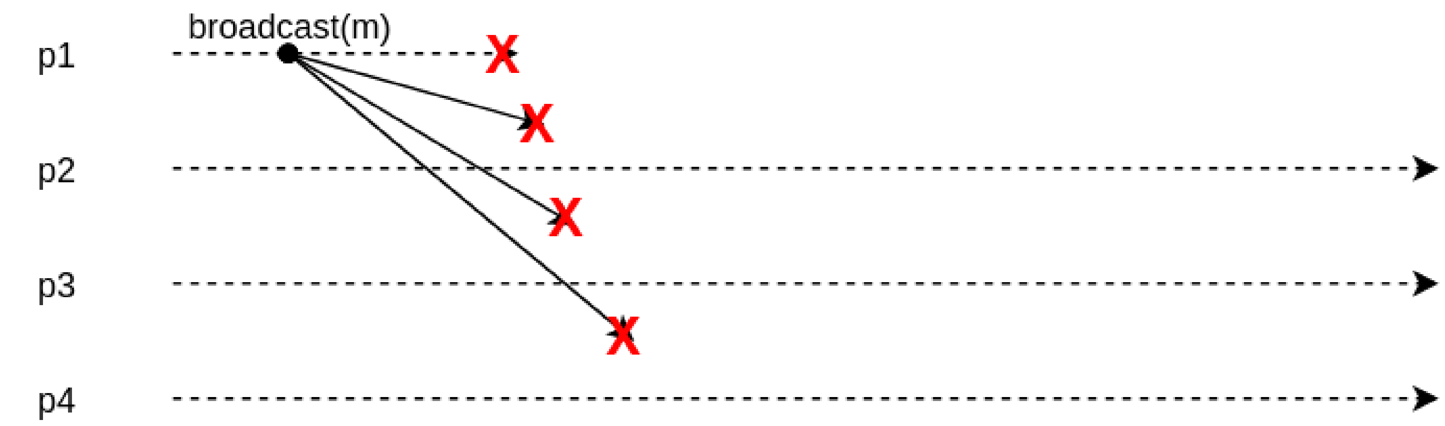
RB1: *Validity:* If a correct process p broadcasts a message m, then p eventually delivers m.

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.

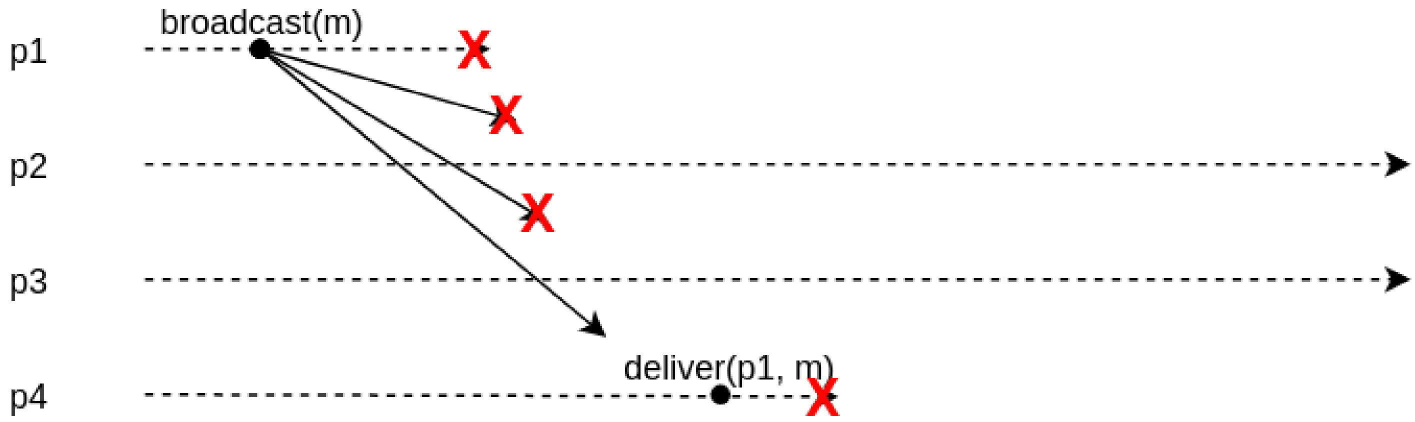
RB4: *Agreement:* If a message m is delivered by some correct process, then m is eventually delivered by every correct process.

RB example (1)



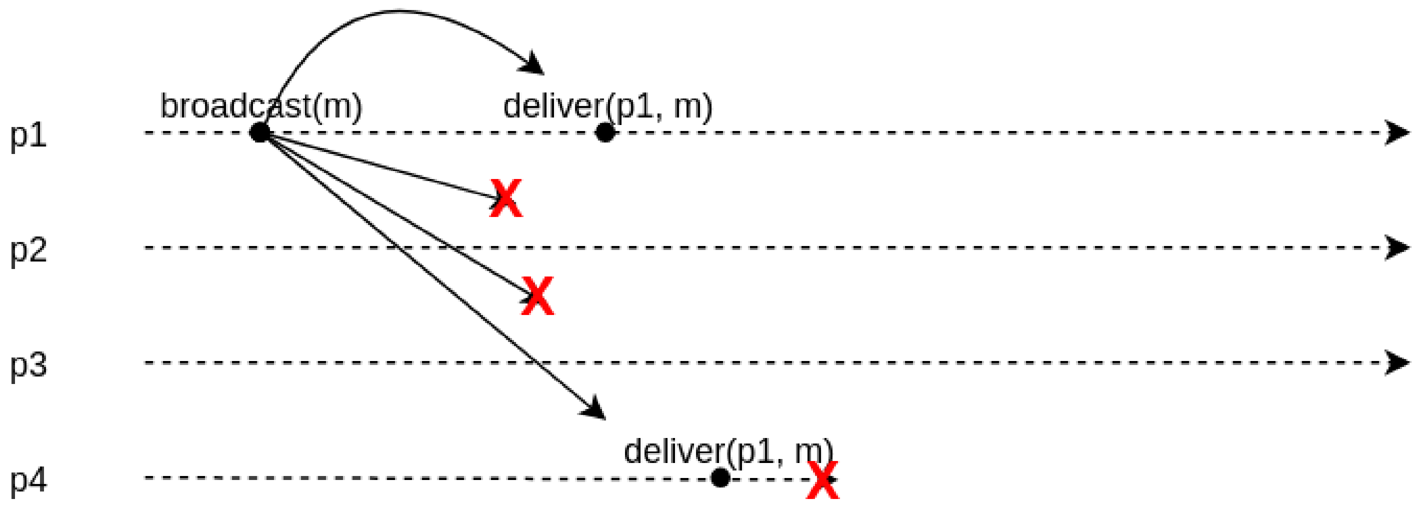
[Q] Is this allowed?

RB example (2)



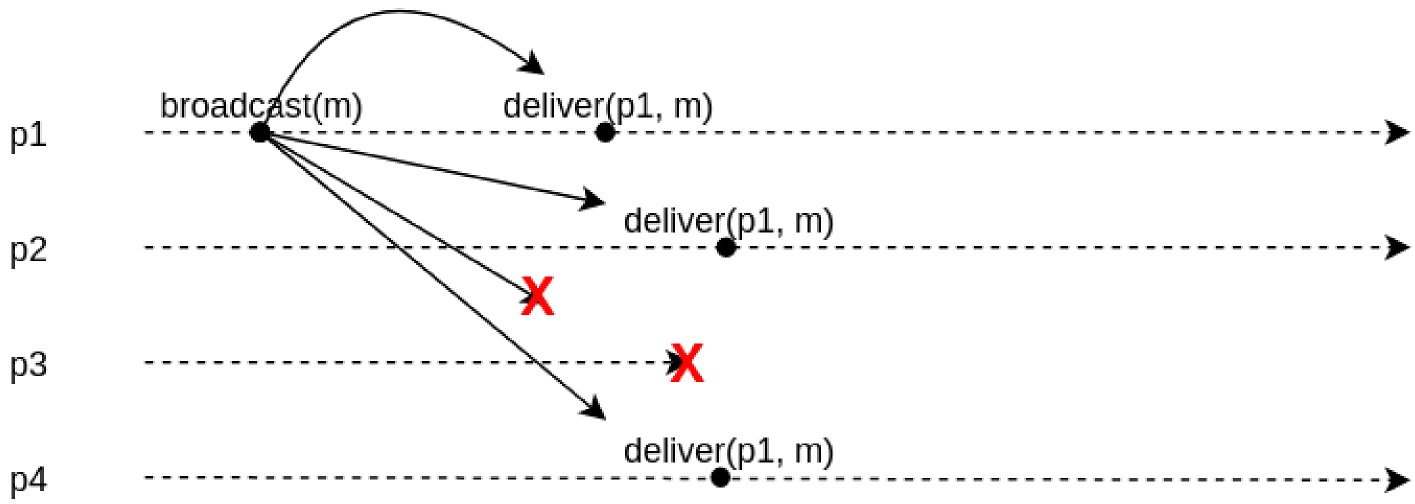
[Q] Is this allowed?

RB example (3)



[Q] Is this allowed?

RB example (4)



[Q] Is this allowed?

Uniform reliable broadcast

- Assume the broadcast enforces
  - Printing a message on paper
  - Withdrawing money from account in variable
- Assume sender broadcasts a message
  - Sender fails
  - No correct node delivers the message
  - Failed nodes deliver the message, is this OK?
- Uniform reliable broadcast ensures that if a message is delivered (by a correct or faulty process), then all correct processes deliver.

Uniform reliable broadcast

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 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.

Lazy reliable broadcast

Implements:
    ReliableBroadcast, **instance** *rb*.

Uses:
    BestEffortBroadcast, **instance** *beb*;
    PerfectFailureDetector, **instance** $\mathcal{P}$.

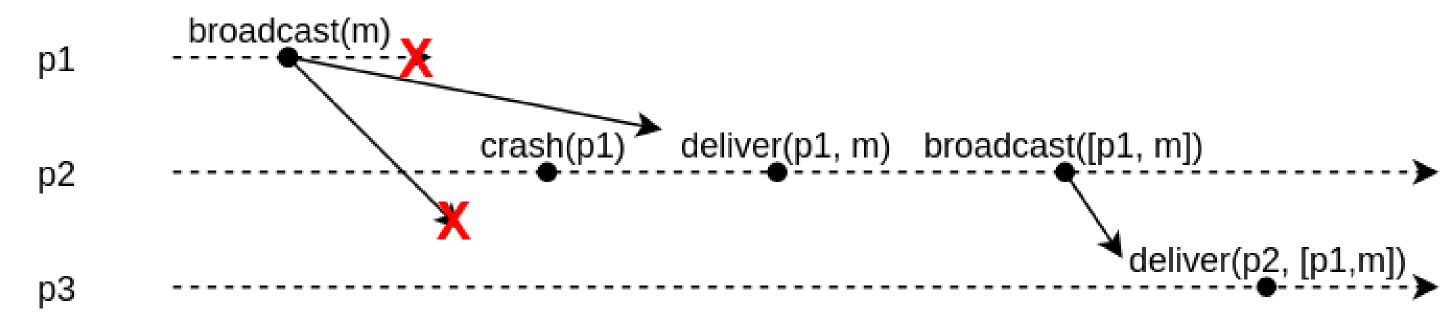
upon event $\langle$ *rb*, *Init* $\rangle$ **do**
    correct := Π;
    from$[p]$:= $[\emptyset]^N$;

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

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

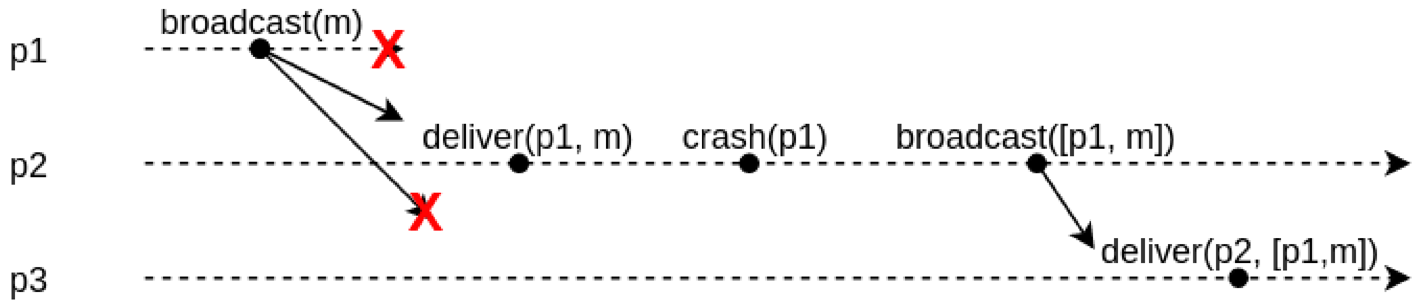
upon event $\langle$ $\mathcal{P}$, *Crash* | p $\rangle$ **do**
    correct := *correct* $\setminus \{p\}$;
    forall $m \in$ *from*$[p]$ **do**
        trigger $\langle$ *beb*, *Broadcast* | [DATA, p, m] $\rangle$;

LRB example (1)



[Q] Which case?

LRB example (2)



[Q] Which case?

Correctness of LRB

Correctness:

- RB1-RB3
  - Satisfied with best-effort broadcast.
- RB4. Agreement
  - 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.
  - Best-effort broadcast all received messages.

Eager reliable broadcast

Implements:
ReliableBroadcast, **instance** *rb*.

Uses:
BestEffortBroadcast, **instance** *beb*.

upon event $\langle$ *rb*, *Init* $\rangle$ **do**
$\quad$ *delivered* $:= \emptyset$;

upon event $\langle$ *rb*, *Broadcast* $\mid m \rangle$ **do**
$\quad$ **trigger** $\langle$ *beb*, *Broadcast* $\mid$ [DATA, *self*, m] $\rangle$;

upon event $\langle$ *beb*, *Deliver* $\mid p$, [DATA, s, m] $\rangle$ **do**
$\quad$ **if** $m \notin$ *delivered* **then**
$\quad\quad$ *delivered* $:=$ *delivered* $\cup \{m\}$;
$\quad\quad$ **trigger** $\langle$ *rb*, *Deliver* $\mid s, m \rangle$;
$\quad\quad$ **trigger** $\langle$ *beb*, *Broadcast* $\mid$ [DATA, s, m] $\rangle$;

[Q] Show that eager reliable broadcast is correct.

Uniformity

Neither Lazy RB nor Eager RB 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] $\rangle$;

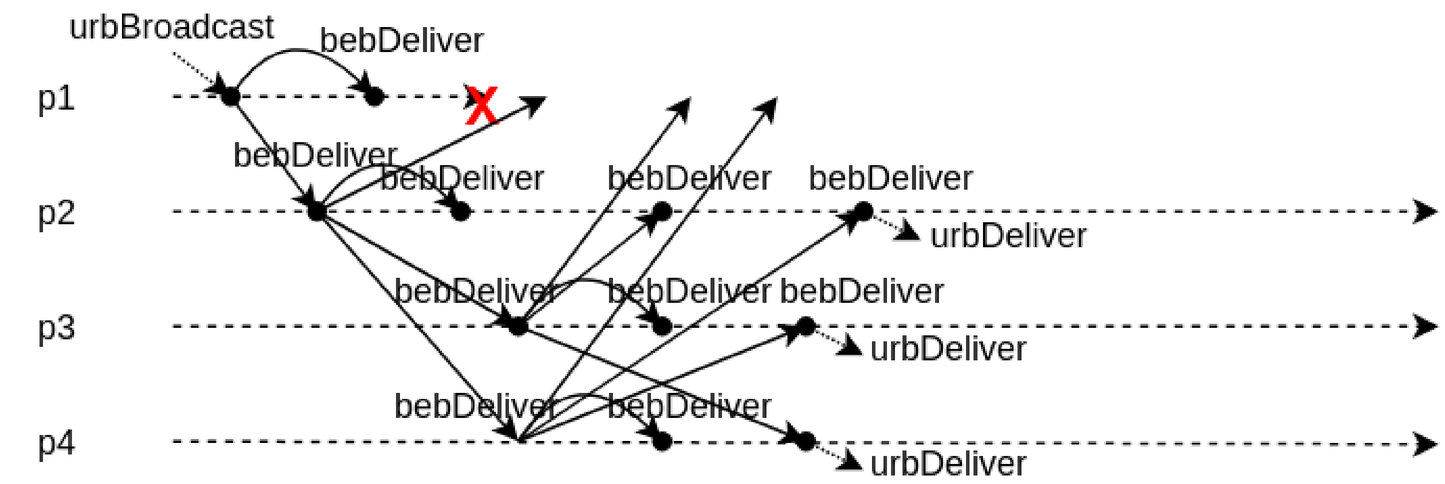
upon event $\langle$ *beb*, *Deliver* | p, [DATA, s, m] $\rangle$ **do**
ack[m] := *ack*[m] $\cup$ {p};
if $(s, m) \notin$ *pending* **then**
pending := *pending* $\cup$ {(s, m)};
trigger $\langle$ *beb*, *Broadcast* | [DATA, s, m] $\rangle$;

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 $\rangle$;

All-ack URB 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.

Correctness of All-ack URB

- URB1. Validity
  - 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
  - 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*.

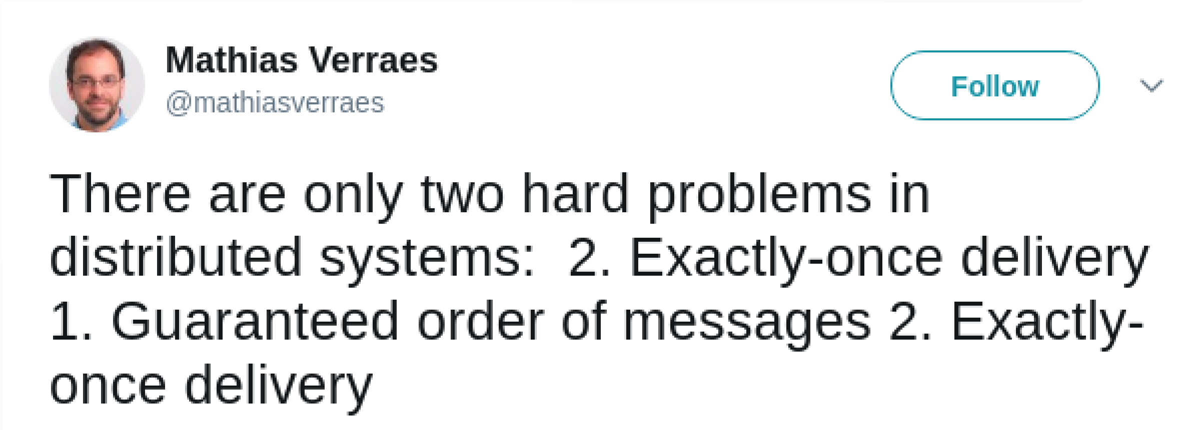
// Except for the function *candeliver*$(\cdot)$ below and for the absence of $\langle$ *Crash* $\rangle$ events
// triggered by the perfect failure detector, it is the same as Algorithm 3.4.

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

[Q] Show that this variant is correct.

Causal reliable broadcast

Motivation


Mathias Verraes
@mathiasverraes
Follow

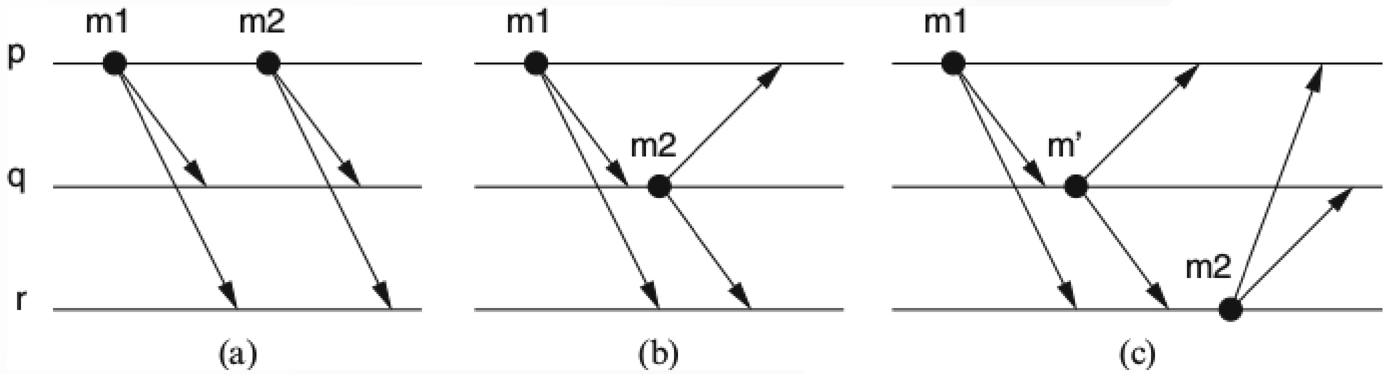
There are only two hard problems in distributed systems: 2. Exactly-once delivery 1. Guaranteed order of messages 2. Exactly-once delivery

Reliable broadcast:

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

[Q] 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

Module:

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

Events:

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

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

Properties:

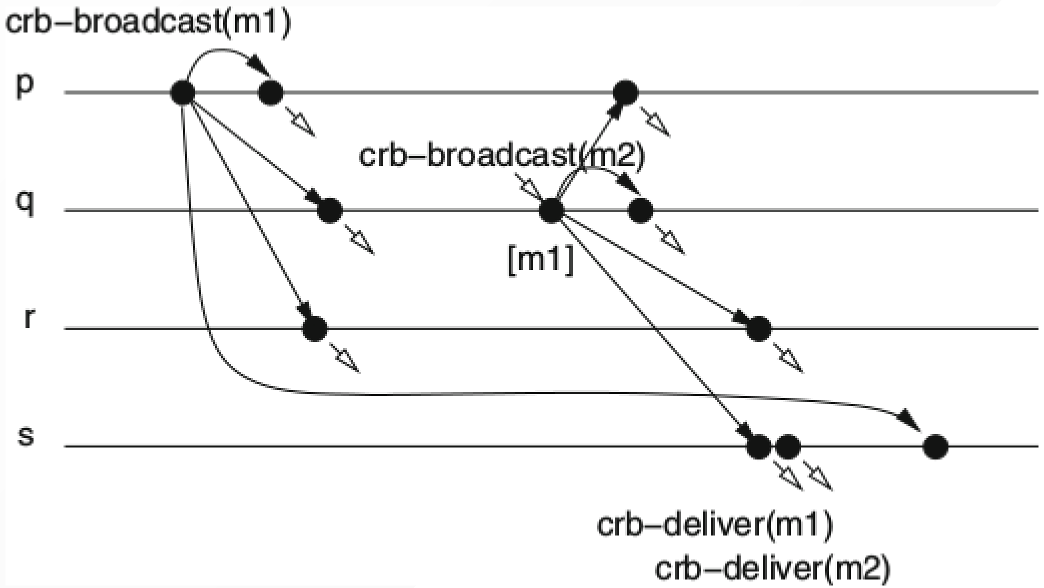
CRB1–CRB4: Same as properties RB1–RB4 in (regular) reliable broadcast (Module 3.2).

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 ⟨ 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



Issue:

- The size of the message grows with time, as messages include their list of causally preceding messages `mpast`.
- Solution 1: Garbage collect old messages.
- Solution 2: History is a vector timestamp!

Waiting causal broadcast

Implements:
    CausalOrderReliableBroadcast, **instance** *crb*.

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

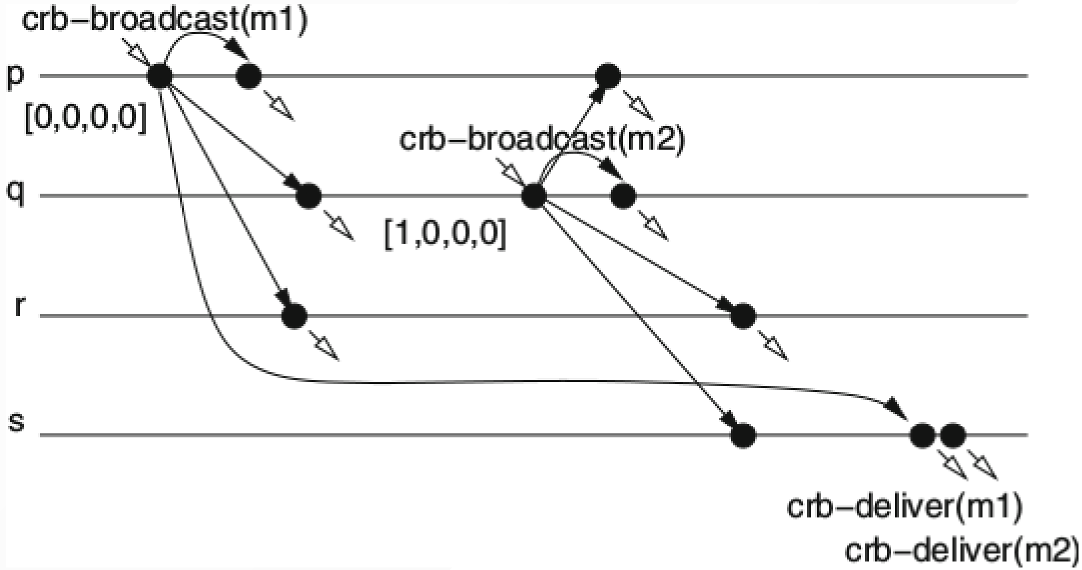
upon event $\langle$ *crb*, *Init* $\rangle$ **do**
    $V := [0]^N$;
    $lsn := 0$;
    $pending := \emptyset$;

upon event $\langle$ *crb*, *Broadcast* | m $\rangle$ **do**
    $W := V$;
    $W[\text{rank}(self)] := lsn$;
    $lsn := lsn + 1$;
    trigger $\langle$ *rb*, *Broadcast* | [DATA, W, m] $\rangle$;

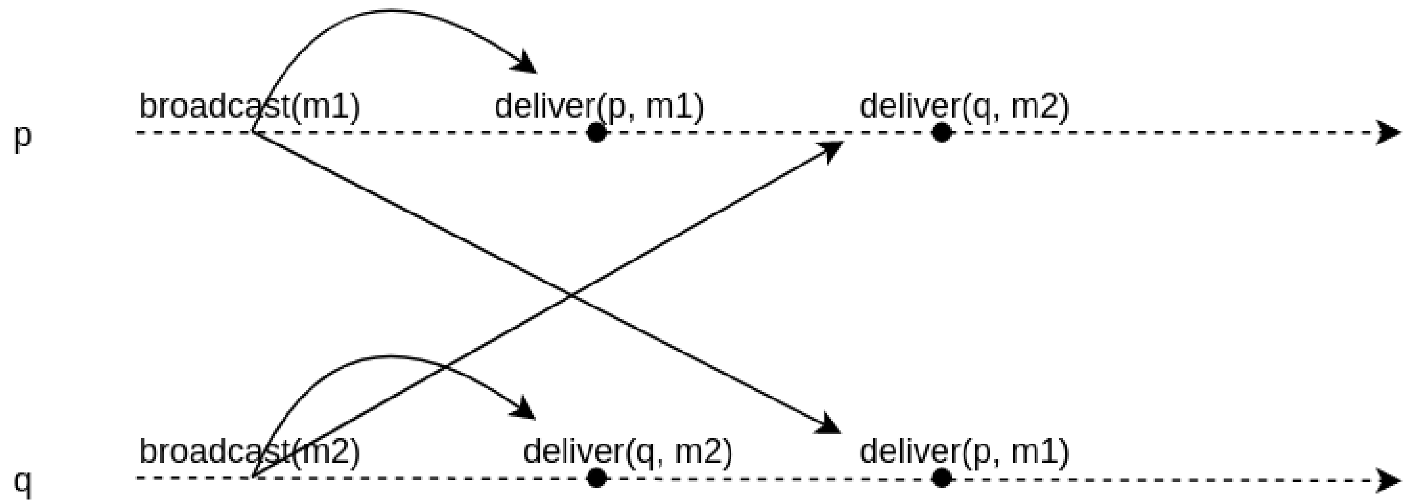
upon event $\langle$ *rb*, *Deliver* | p, [DATA, W, m] $\rangle$ **do**
    $pending := pending \cup \{(p, W, m)\}$;
    while exists $(p', W', m') \in pending$ such that $W' \leq V$ **do**
        $pending := pending \setminus \{(p', W', m')\}$;
        $V[\text{rank}(p')] := V[\text{rank}(p')] + 1$;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

[Q] Show the correctness of the algorithm.

Waiting CB example



Possible execution?



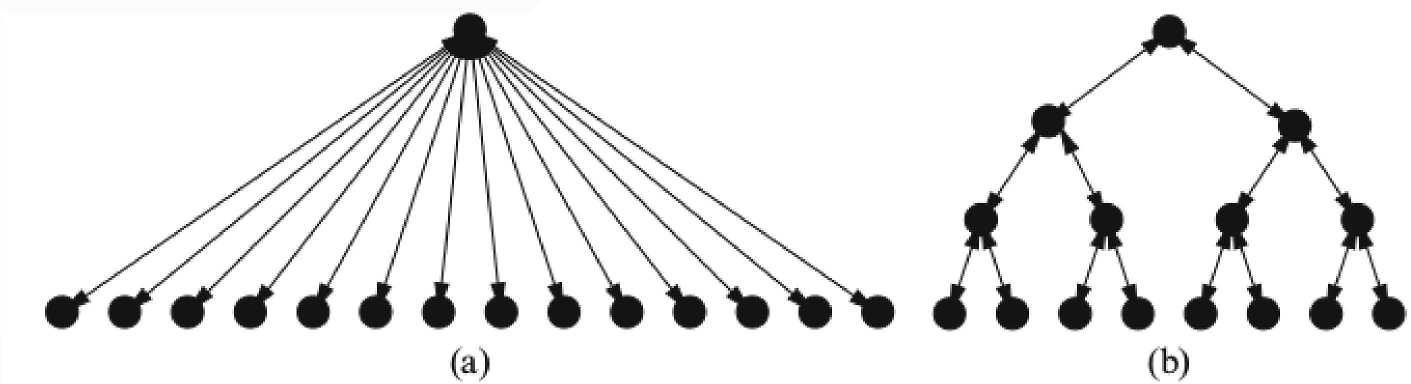
[Q] Is this a valid execution? the order of delivery is not the same.

Probabilistic broadcast

a.k.a. epidemic broadcast or gossip

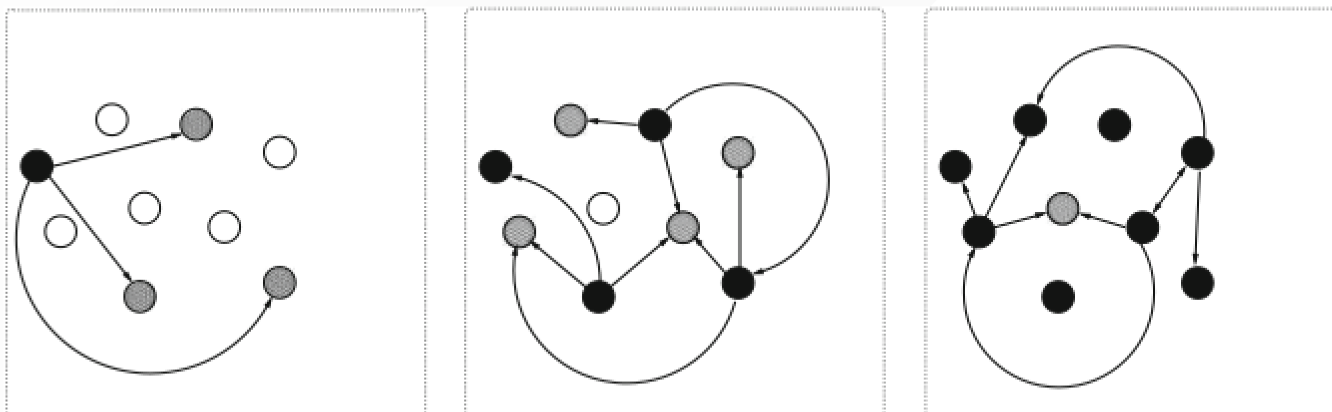
Scalability of reliable broadcast

- 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., uniformally).
  - 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

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**
    $delivered := \emptyset$;

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

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

upon event ⟨ *fll*, *Deliver* | p, [GOSSIP, s, m, r] ⟩ **do**
    if $m \notin delivered$ **then**
        $delivered := delivered \cup \{m\}$;
        trigger ⟨ *pb*, *Deliver* | s, m ⟩;
    if $r > 1$ **then** $gossip([\text{GOSSIP}, s, m, r - 1])$;

The mathematics of epidemics

- Assume an 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 mathematics of epidemics

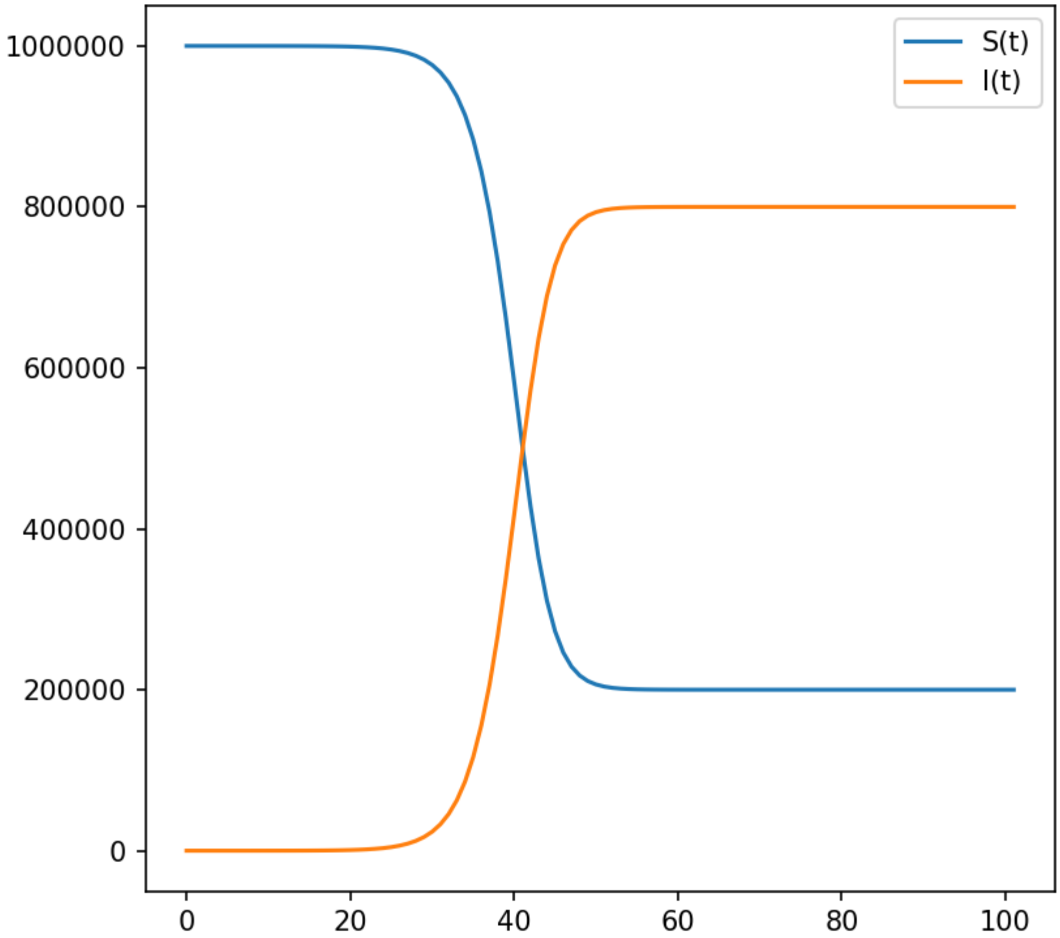
The dynamics of the SIS model is given as follows:

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

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

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.



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

The mathematics of epidemics

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

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

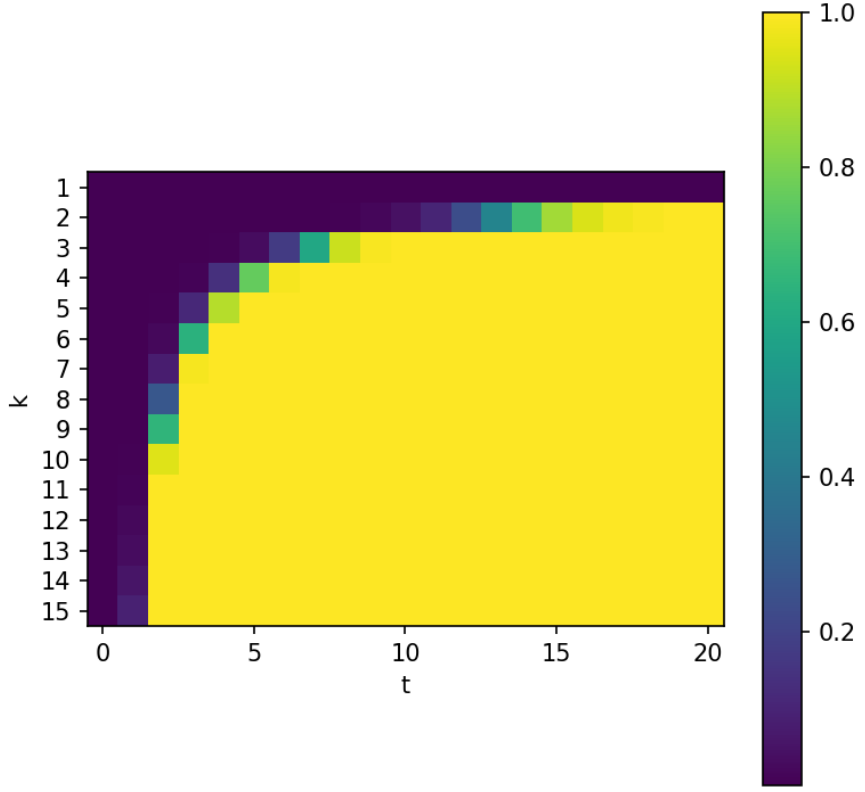
Therefore the probability of having received of one or more gossip messages up to time t, that is to have PB-delivered, is

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

[Q] What if nodes fail? if packets are loss?

Probabilistic validity

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



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

Probabilistic validity

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.

Lazy Probabilistic broadcast

Phase 1: data dissemination

Implements:
  ProbabilisticBroadcast, **instance** *pb*.

Uses:
  FairLossPointToPointLinks, **instance** *fll*;
  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** $\langle$ *fll*, *Send* $|$ t, msg $\rangle$;

upon event $\langle$ *pb*, *Broadcast* $|$ m $\rangle$ **do**
  $lsn := lsn + 1$;
  trigger $\langle$ *upb*, *Broadcast* $|$ $[\text{DATA}, self, m, lsn]$ $\rangle$;

upon event $\langle$ *upb*, *Deliver* $|$ p, $[\text{DATA}, s, m, sn]$ $\rangle$ **do**
  if $random([0, 1]) > \alpha$ **then**
    $stored := stored \cup \{[\text{DATA}, s, m, sn]\}$;
  if $sn = next[s]$ **then**
    $next[s] := next[s] + 1$;
    trigger $\langle$ *pb*, *Deliver* $|$ s, m $\rangle$;
  else if $sn > next[s]$ **then**
    $pending := pending \cup \{[\text{DATA}, s, m, sn]\}$;
    forall $missing \in [next[s], \ldots, sn - 1]$ **do**
      if no m' exists such that $[\text{DATA}, s, m', missing] \in pending$ **then**
        $gossip([\text{REQUEST}, self, s, missing, R - 1])$;
    $starttimer(\Delta, s, sn)$;

Lazy Probabilistic broadcast

Phase 2: recovery

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

upon event $\langle$ *fll*, *Deliver* | 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* | s, x $\rangle$;

upon event $\langle$ *Timeout* | 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.