Advanced Course
Distributed Systems

Reliable Broadcast

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Course Topics

- Intro to Distributed Systems
- Basic Abstractions and Failure Detectors
- Reliable and Causal Order Broadcast
- Distributed Shared Memory
- Consensus (Paxos, Raft, etc.)
- Dynamic Reconfiguration
- Time Abstractions and Interval Clocks (Spanner etc.)
- Consistent Snapshotting (Stream Data Management)
- Distributed ACID Transactions (Cloud DBs)

Quorums

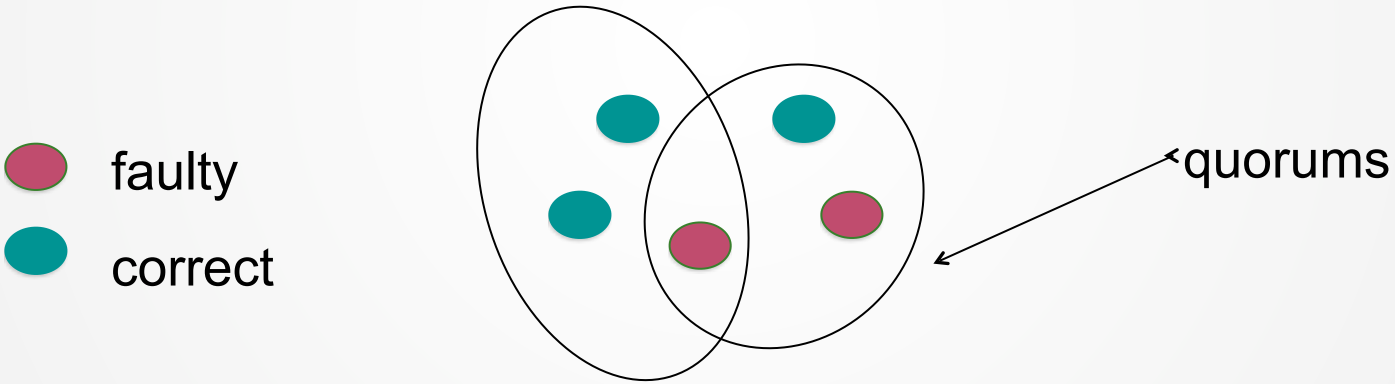
QUORUMS

- For N crash-stop processes
- Quorum is **<u>any set of majority of processes</u>**
- i.e., a set with at least $\lfloor N/2 \rfloor + 1$ processes

- The algorithms will rely on a majority of processes will not fail
  - $f < N/2$ (f is the max number of faulty processes)
- f is the resilience of the algorithm

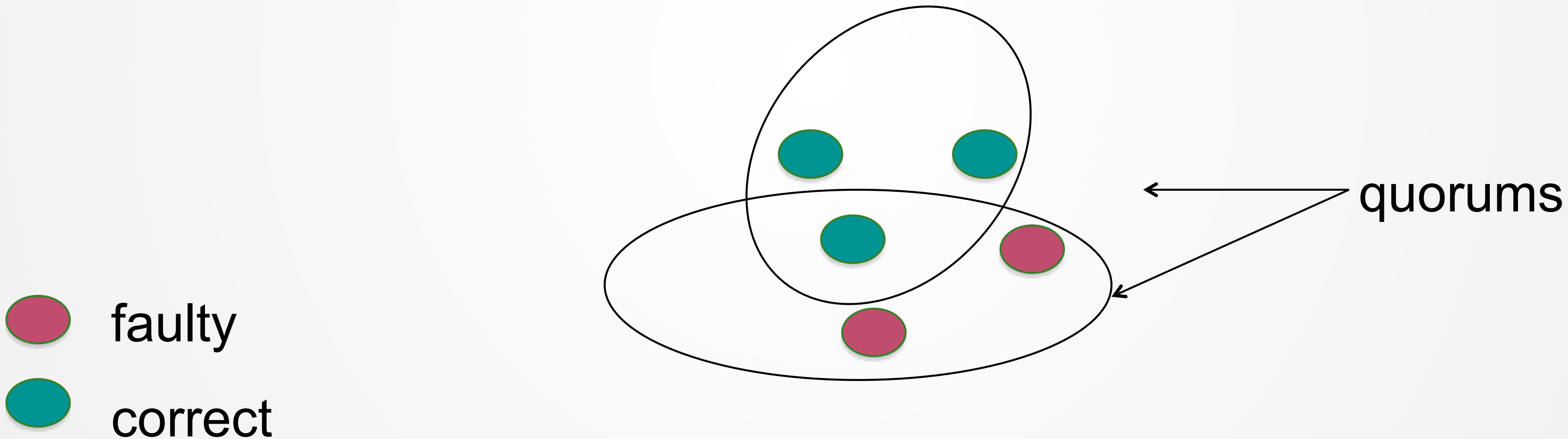
Quorums crash-stop/recovery model - F < N/2

Two quorums always intersect in at least ONE process



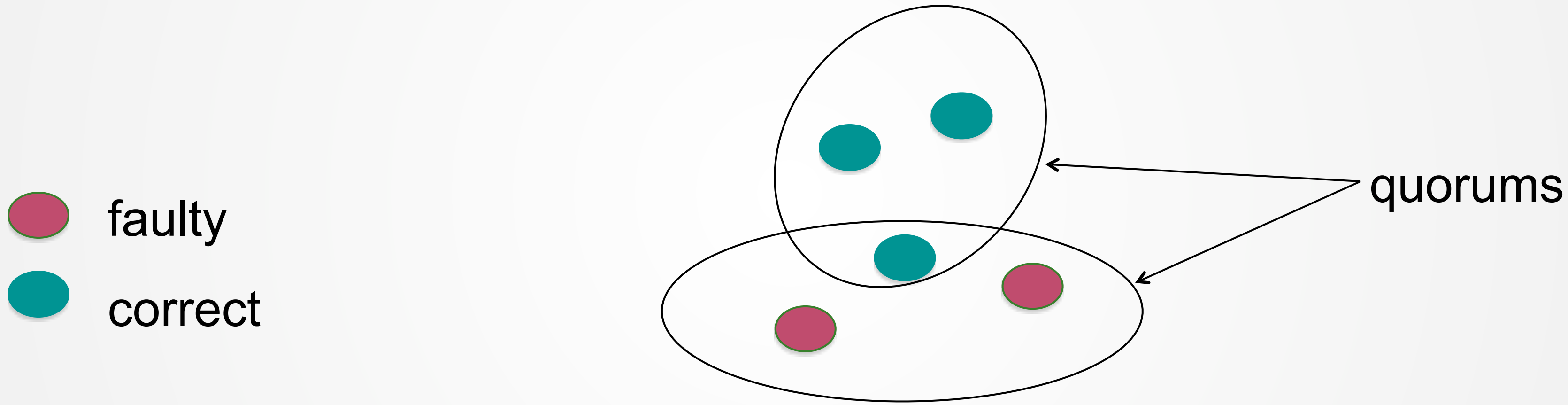
QUORUMS CRASH-STOP/RECOVERY MODEL - F < N/2

There is at least ONE quorum with only correct processes



Quorums crash-stop/recovery model - F < N/2

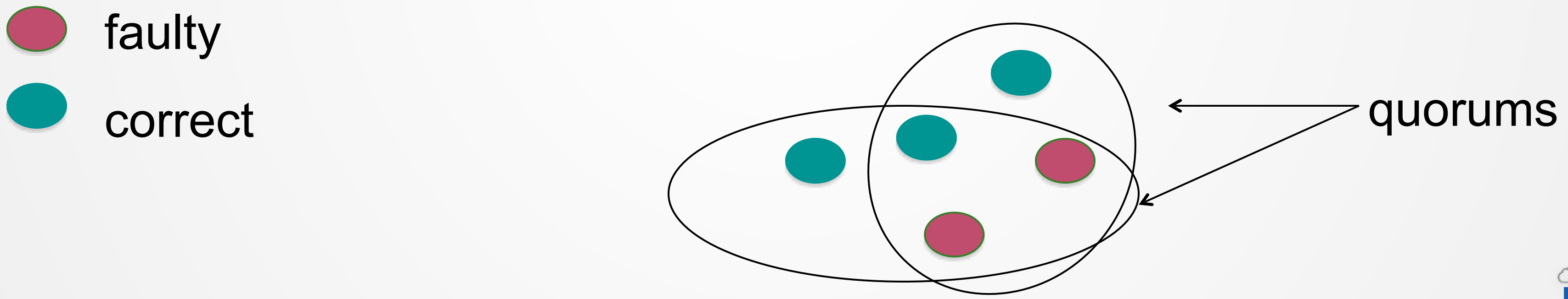
There is at least ONE correct process in each quorum



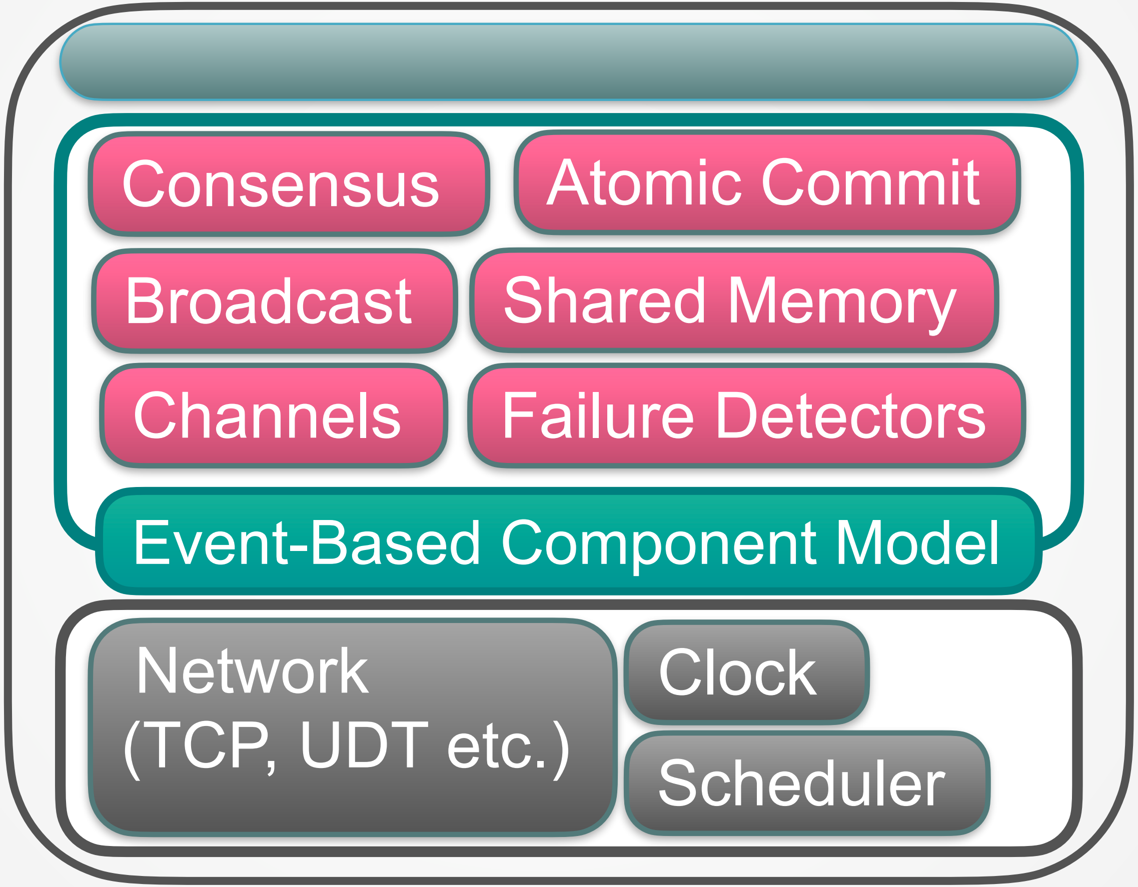
QUORUMS

Quorums used in Fail-Silent and Fail-Noisy algorithms

A process never waits for messages from more than $\lfloor N/2 \rfloor + 1$ (different) processes



LET'S DEFINE OUR BUNDLES



Let's Make Some Bundles

Fail-Stop	Fail-Silent	Fail-Noisy
Perfect FD (P)	Perfect Link (pl)	Eventually Perfect FD (◊P)
Perfect Link (pl)		Perfect Link (pl)
Crash-Stop Failure Model	Crash-Stop Failure Model	Crash-Stop Failure Model
Synchronous Model	**Asynchronous Model**	**Partially Synchronous Model**

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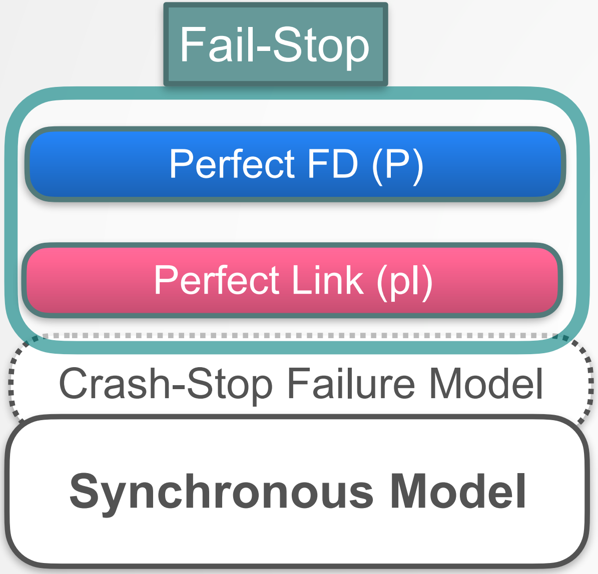
THE FAIL-STOP



- **How we work with it**

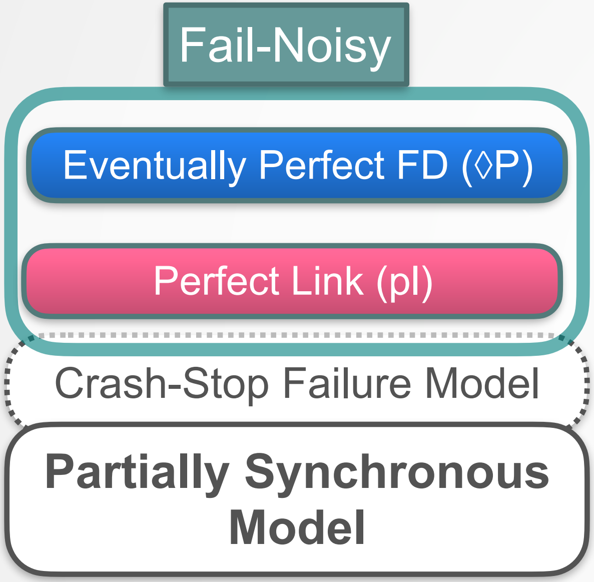
- Local algorithms can **track the set of correct processes at any time.**
- Without violating liveness properties: use
  - Request/Reply protocols.
  - Wait for **correct** processes to reply.

The Fail-Silent

- **How we work with it**

- Failure detection is impossible.
- **Correctness assumptions**: a majority of processes are always correct.
- Protocols work with **majority quorums**.
  - Expect at least $\lceil n/2 \rceil + 1$ responses.

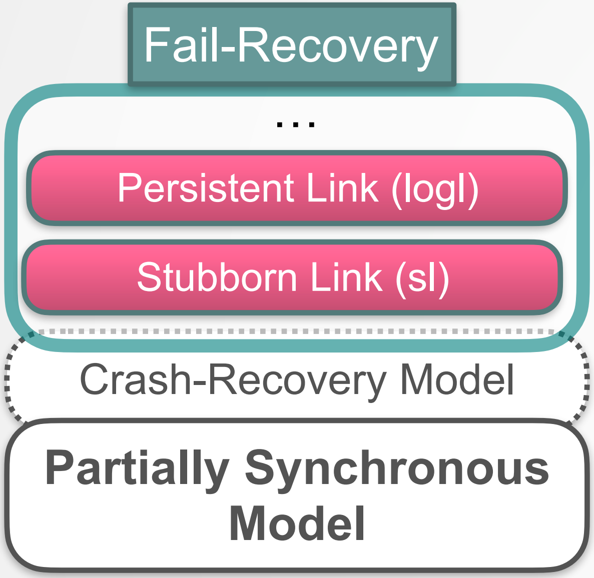
The Fail-Noisy



- **Key ideas:**
- To guarantee safety properties any algorithm has to assume the failure detector can be **inaccurate.**
- Eventual strong accuracy is only used to guarantee **liveness.**

  Quorum-based ideas also apply here.

A Fail-Recovery Bundle



- **Key ideas:**

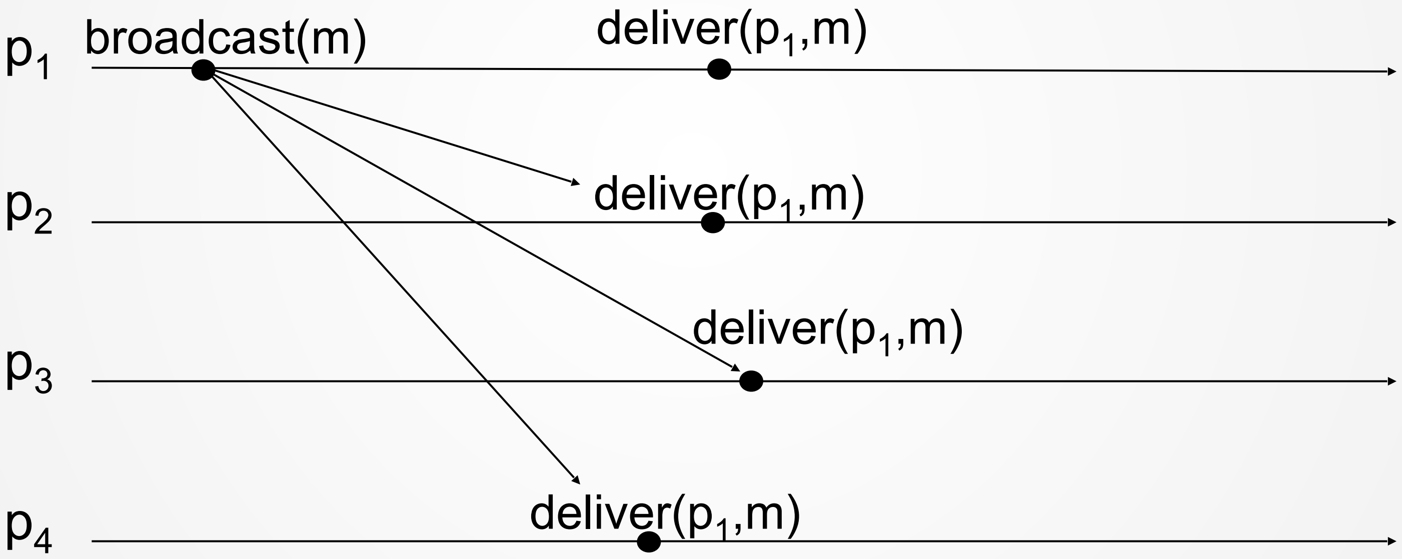
- Relies often on a **persistent memory** to store and retrieve critical information
- After recovery a process may contact other process to retrieve up to date state information

- Some algorithms **relax** the reliability conditions on channels allowing message loss/duplication/reordering

Broadcast Abstractions

BROADCAST SERVICES

Send a message to a group of processes



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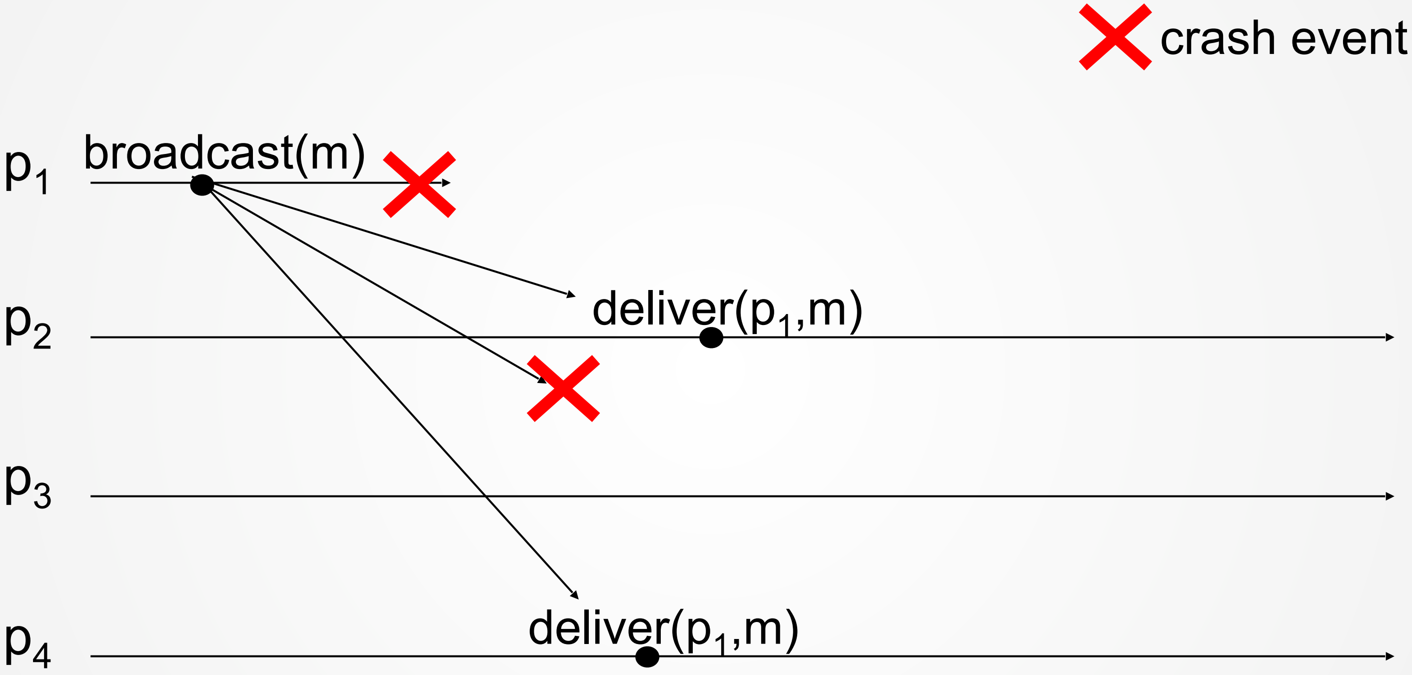
Unreliable Broadcast



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 behaviour of failed nodes
- **FIFO reliable broadcast**
  - Reliable broadcast with FIFO delivery order
- **Causal reliable broadcast**
  - Reliable broadcast with causal delivery order

Reliable Broadcast Abstractions

- **Probabilistic reliable broadcast**
  - Guarantees reliability with high probability
  - Scales to large number of nodes

- **Total order (atomic) reliable broadcast**
  - Guarantees reliability and same order of delivery

Specification of Broadcast Abstractions

Best-effort broadcast (beb)

- ***Instance beb***
- ***Events***
  - Request: ⟨beb Broadcast | m⟩
  - Indication: ⟨beb Deliver | src, m⟩

- ***Properties: BEB1, BEB2, BEB3***

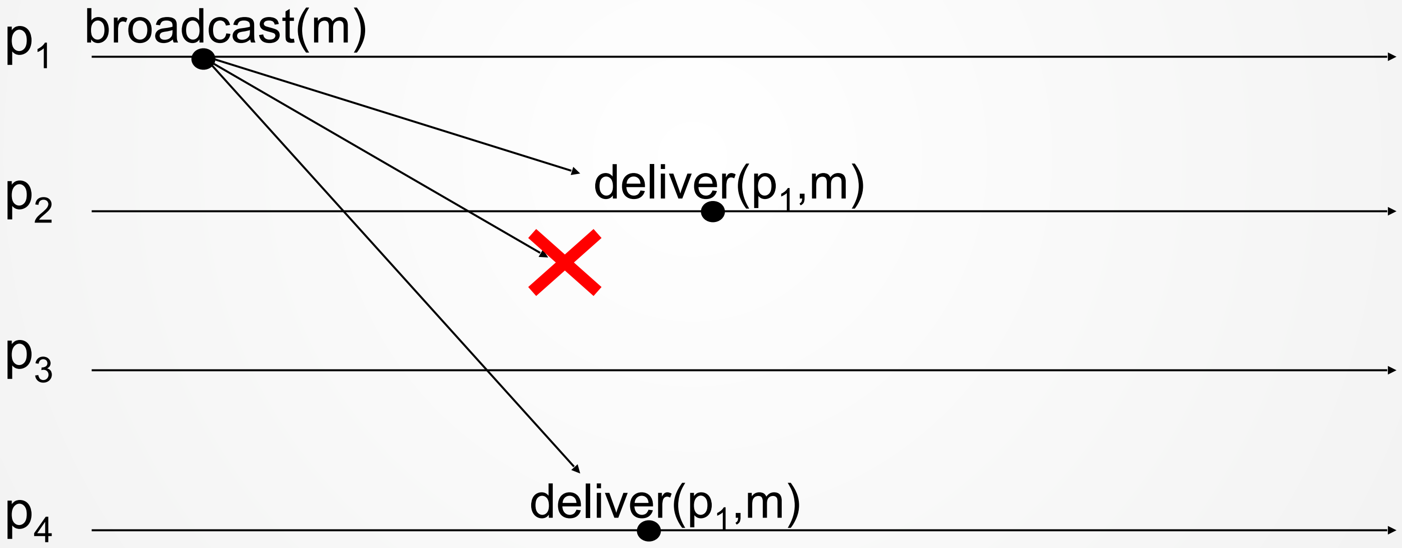
BEST-EFFORT BROADCAST (BEB)

- ***Intuitively***: everything perfect unless sender crash

- ***Properties***
  - ***BEB1. Best-effort-Validity***: If p_i and p_j are correct, then any broadcast by p_i is eventually delivered by p_j
  - ***BEB2. No duplication***: No message delivered more than once
  - ***BEB3. No creation***: No message delivered unless broadcast

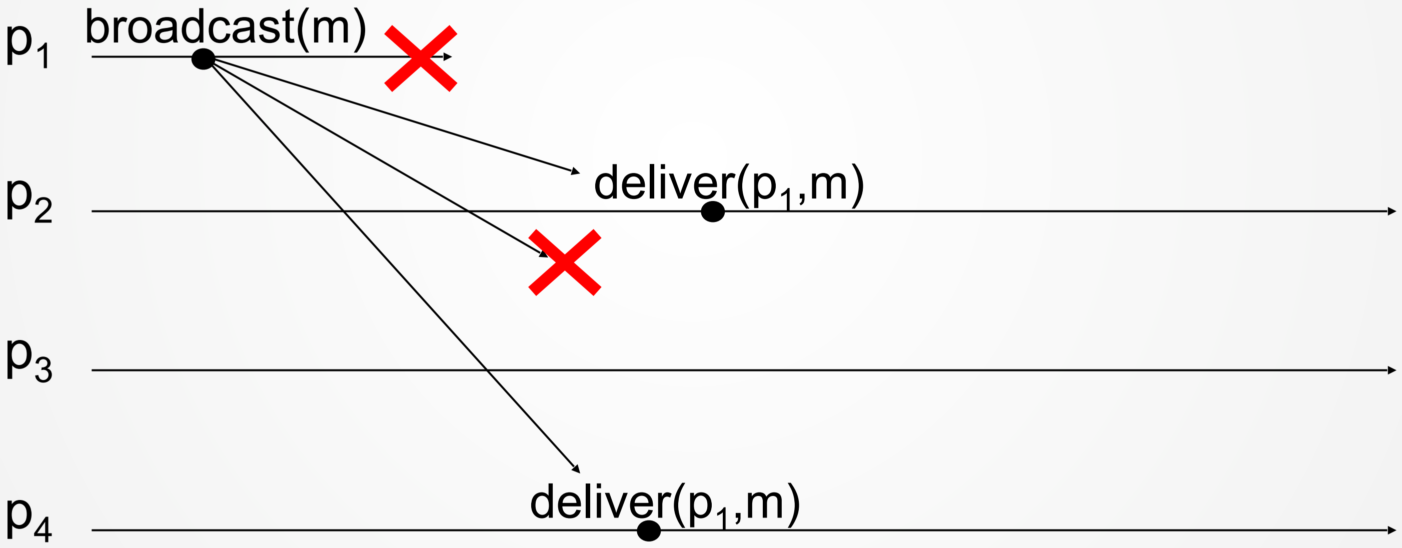
BEB EXAMPLE

Is this allowed? No



BEB Example (2)

Is this allowed? Yes



RELIABLE BROADCAST

- BEB gives no guarantees if sender crashes
  - Strengthen to give guarantees if sender crashes

- Reliable Broadcast Intuition
  - Same as BEB, plus
  - If sender crashes:
    - ensure *all or none* of the correct nodes get msg

Reliable Broadcast (rb)

Instance rb

Events

Request: ⟨rb Broadcast | m⟩

Indication: ⟨rb Deliver | src, m⟩

Properties: RB1, RB2, RB3, RB4

Reliable Broadcast Properties

- **Properties**
  - **RB1 = BEB1. Validity**
  - **RB2 = BEB2. No duplication**
  - **RB3 = BEB3. No creation**

  - **RB4. Agreement.**
    - If a **correct process delivers** m, then every correct process delivers m

REFINING CORRECTNESS

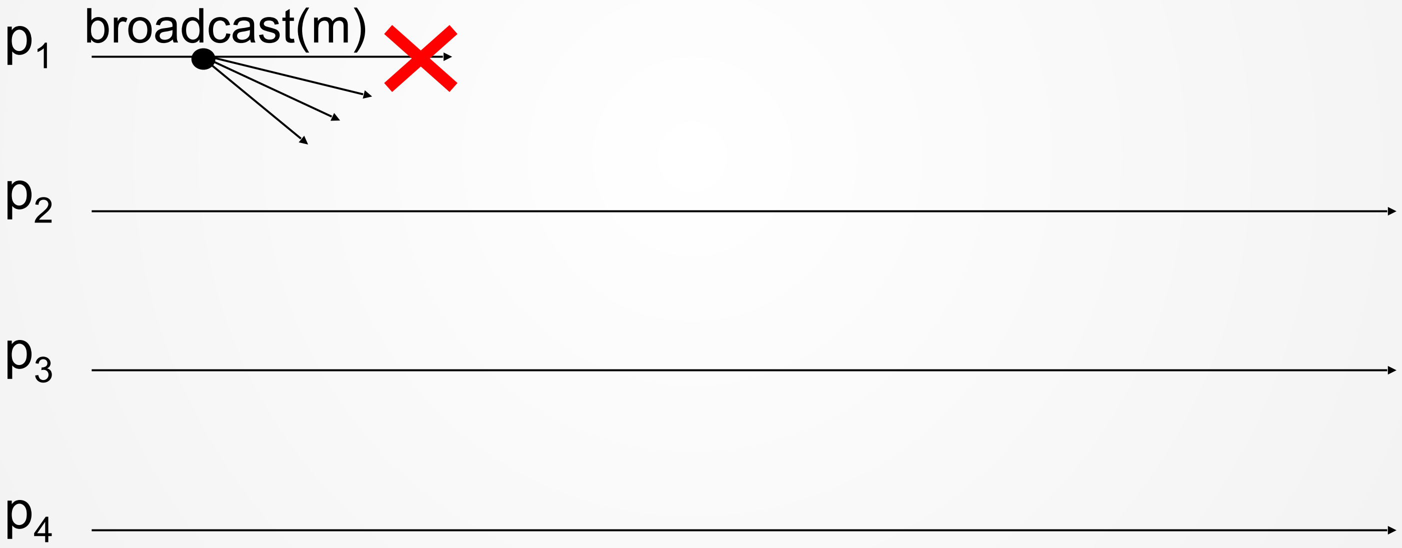
Can weaken RB1 without any effect

Old Validity ←equivalent with→ **New Validity**

Old Validity	New Validity
RB1 = BEB1 Validity ❑ If p_i and p_j are **correct**, then any broadcast by p_i is eventually delivered by p_j	***RB1 Validity.*** ❑ If **correct** p_i broadcasts m, p_i itself eventually delivers m
RB2 = BEB2. No duplication	***RB2 = BEB2. No duplication***
RB3 = BEB3. No creation	***RB3 = BEB3. No creation***
RB4. Agreement. ❑ If a **correct node delivers** m, then every correct node delivers m	***RB4. Agreement.*** ❑ If a **correct node delivers** m, then every correct process delivers m

RB Example

Is this allowed? Yes



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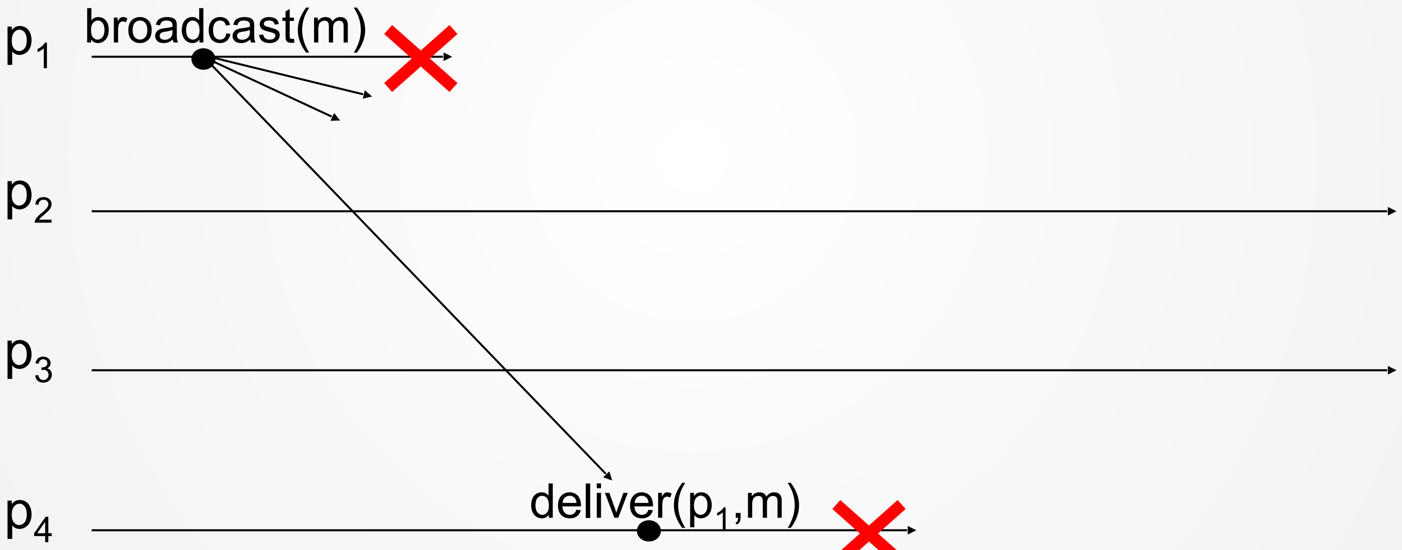
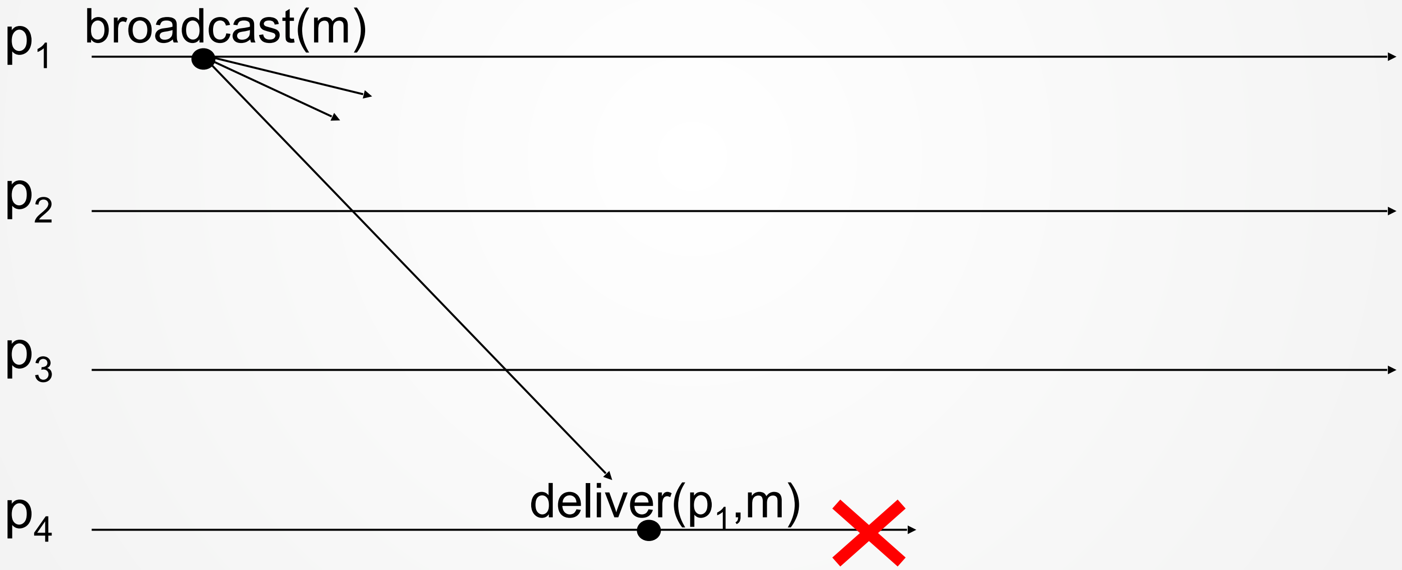
RB Example

Is this allowed? Yes



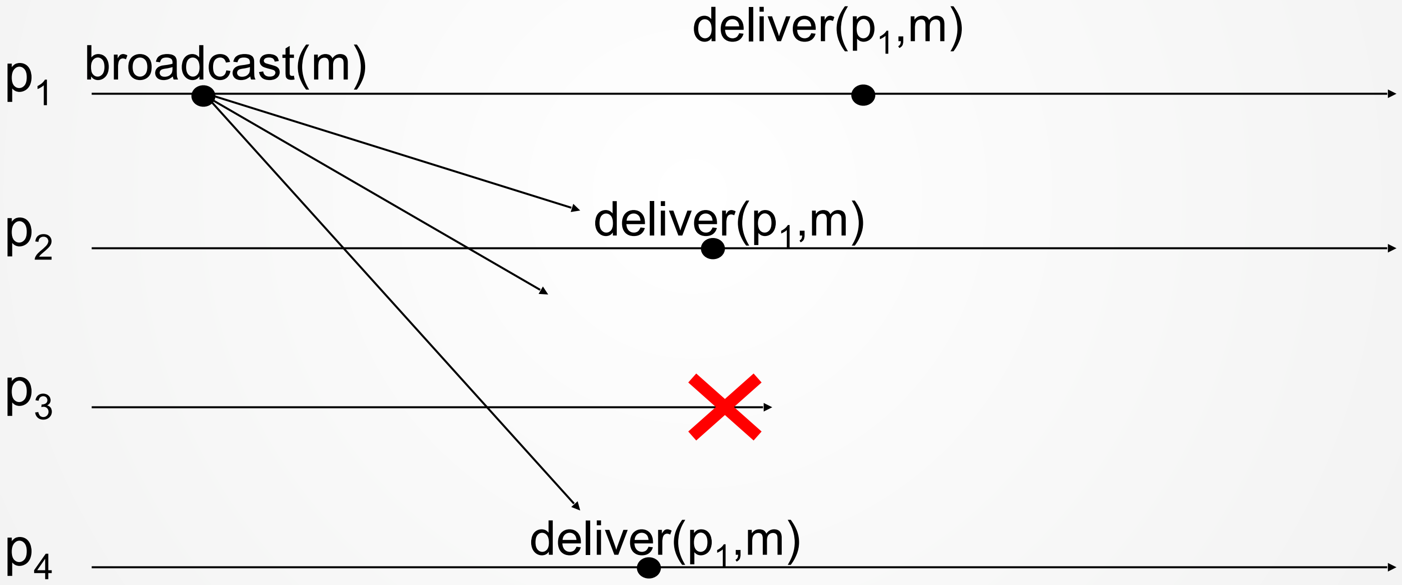
RB EXAMPLE

Is this allowed? No



RB Example

Is this allowed? Yes



Uniform Reliable Broadcast

- Assume sender broadcasts message
  - Sender fails
  - No correct process delivers message
  - Some failed processes deliver message
- Assume the broadcast enforces
  - Printing a message on paper
  - Withdrawing money from account
- Uniform reliable broadcast intuition
  - If a failed node delivers, everyone must deliver…
  - At least correct nodes, we cannot revive the dead…

Uniform broadcast (URB)

Events

Request: ⟨urb Broadcast | m⟩

Indication: ⟨urb Deliver | src, m⟩

Properties:

URB1

URB2

URB3

URB4

Uniform Broadcast Properties

Properties

Wanted: Dead & Alive!

URB1 = RB1.

URB2 = RB2.

URB3 = RB3.

URB4. Uniform Agreement: For any message m, if **a process delivers** m, then every correct process delivers m

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Broadcast Abstractions

Implementation of Broadcast Abstractions

IMPLEMENTING BEB

- Use Perfect channel abstraction
  - Upon ⟨beb Broadcast | m⟩ send message m to all processes (for-loop)
- Correctness
  - If sender doesn't crash, every other correct process receives message by perfect channels (Validity)
  - No creation & No duplication already guaranteed by perfect channels

Fail-Stop

Lazy Reliable Broadcast

FAIL-STOP: LAZY RELIABLE BROADCAST

- Requires perfect failure detector (**P**)

- To broadcast m:
  - best-effort broadcast m
  - When get **beb** Deliver
    - Save message, and
    - **rb** Deliver message

- If sender s crash, detect & relay msgs from s to all
  - **case 1**: get m from s, detect crash s, redistribute m
  - **case 2**: detect crash s, get m from s, redistribute m

- Filter duplicate messages before delivery

FAIL-STOP: LAZY RELIABLE BROADCAST

If sender s crashes, detect & relay msgs from s to all

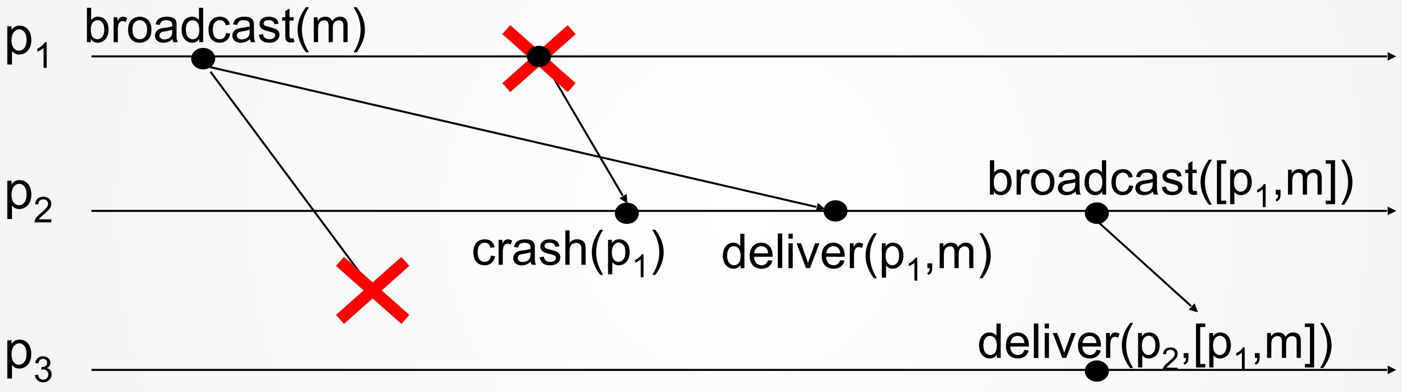
case 1: get m from s, detect crash s, redistribute m

case 2: detect crash s, get m from s, redistribute m

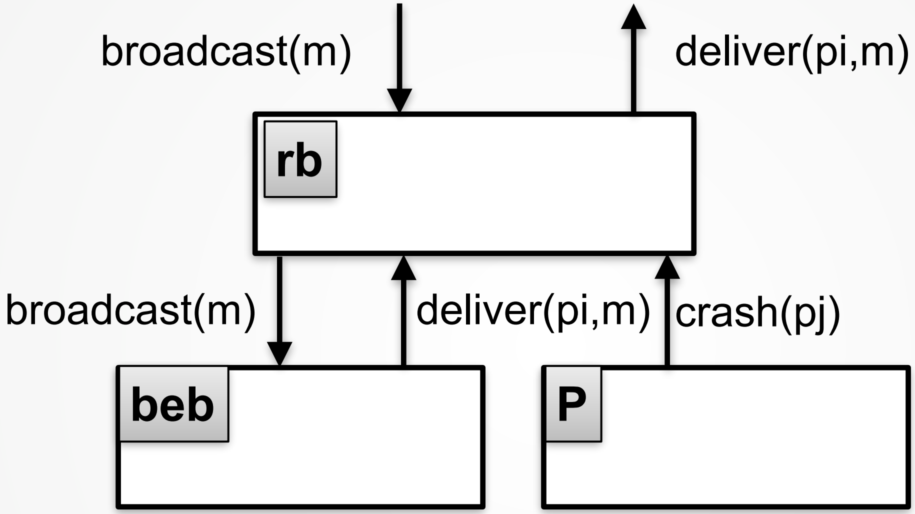
Why case 2? [d]

Lazy Reliable Broadcast

Case 2



FAIL-STOP LAZY RELIABLE BROADCAST



Lazy Reliable Broadcast

Implements: ReliableBroadcast (rb)

Uses:

BestEffortBroadcast (beb)
PerfectFailureDetector (P)

upon event ⟨Init⟩ **do**

delivered := ∅
correct := Π
forall $p_i \in \Pi$ **do** from[p_i] := ∅

for filtering duplicates

storage for saved messages

upon event ⟨rb Broadcast | m⟩ **do**

trigger ⟨beb Broadcast | (DATA, self, m)⟩

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Lazy Reliable Broadcast (2)

upon event ⟨crash | p_i⟩ **do**

correct := correct \ {p_i}

forall $(s_m, m) \in from[p_i]$ **do**

trigger ⟨beb Broadcast | (DATA, s_m ,m)⟩

Case 1: redistribute anything we have from failed node

upon event ⟨beb Deliver | p_i, (DATA, s_m , m)⟩ **do**

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

delivered := delivered ∪ {m}

$from[p_i] := from[p_i] \cup \{ (s_m, m)\}$

trigger ⟨rb Deliver | s_m , m⟩

if pi $\notin$ correct **then**

trigger ⟨beb Broadcast |(DATA, s_m, m) ⟩

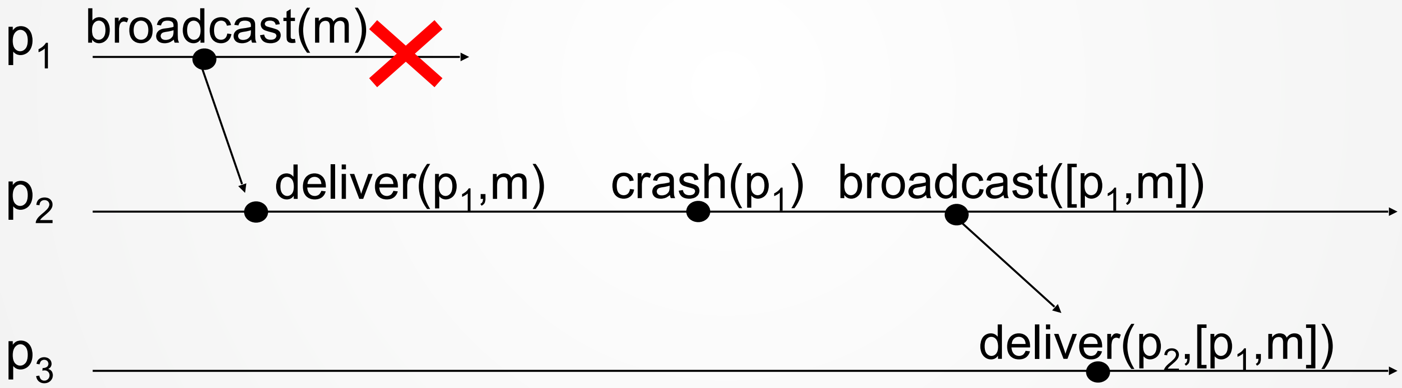
Avoid duplicates

Store for future

Case 2: redistribute

RB EXAMPLE

Which case? **Case 1**



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CORRECTNESS OF LAZY RB

- ***RB1-RB3*** satisfied by BEB
- Need to prove ***RB4***
  - If a **correct node delivers** m, then every correct node delivers m
- Assume Correct p_k delivers message bcast by p_i
  - If p_i is correct, BEB ensures correct delivery
  - If p_i crashes,
    - p_k detects this (completeness)
    - p_k uses BEB to ensure (BEB1) every correct node gets it

Measuring Performance

MESSAGE COMPLEXITY

- The number of messages required to terminate an operation of an abstraction

- Lazy reliable broadcast
  - The number of messages initiated by broadcast(m)
  - Until a deliver(src, m) event is issued at each process

- Bit complexity
  - Number of bits sent, if messages can vary in size

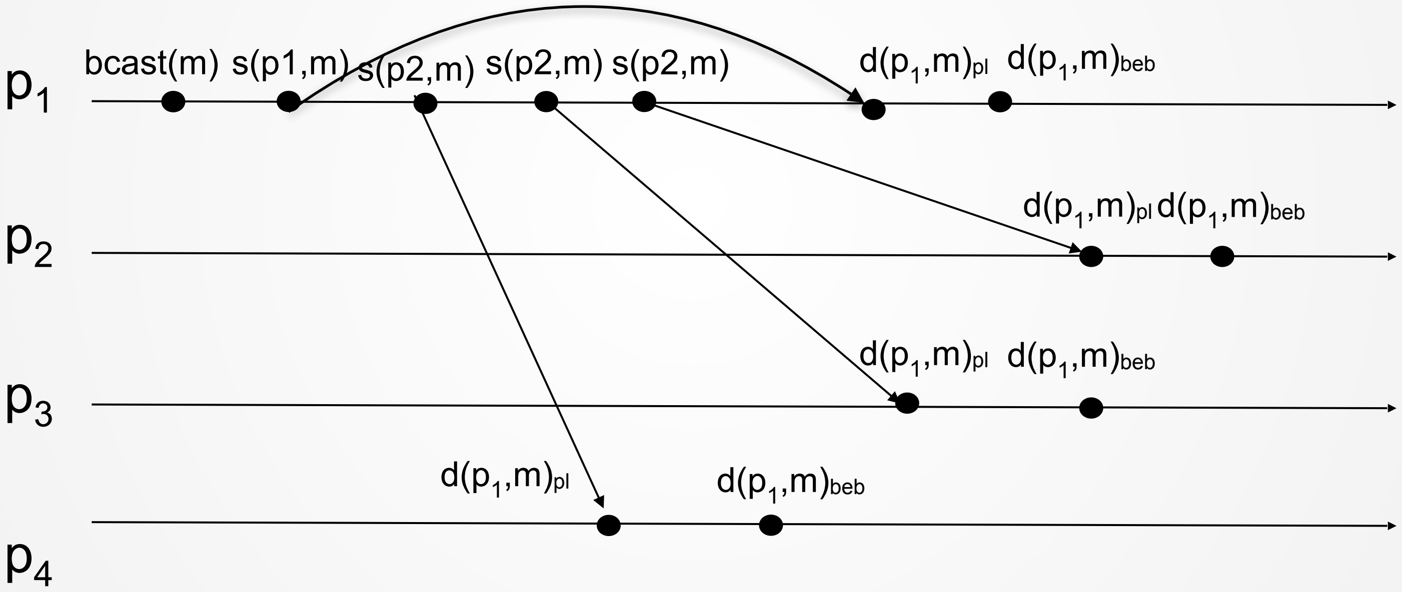
TIME COMPLEXITY ~ #ROUNDS

- **One time unit** in an Execution E is the **longest** message delay in E
- **Time Complexity is** Maximum time taken by any execution of the algorithm under the assumptions
  - A process can execute any finite number of actions (events) in **zero** time
  - The time between send$(m)_{i,j}$ and deliver$(m)_{i,j}$ is **at most one** time unit
- In most algorithms we study we assume all communication steps takes one time unit. We also call this a **round or step.**

BEST EFFORT BROADCAST

Takes **one time unit** from broadcast$(m)_p$ to last deliver(p,m)

We also call it one **communication step / round.**



COMPLEXITY OF LAZY RELIABLE BROADCAST

- Assume N processes
- Message complexity
  - Best case: O(N) messages
  - Worst case: O(N^2) messages
- Time complexity
  - Best case: 1 time unit
  - Worst case: 2 time units

Fail-Silent

Eager Reliable Broadcast

Eager Reliable Broadcast

What happens if we replace P with ◊P? [d]

- Only affects performance
- Only affects correctness
- No effect
- Affects performance and correctness

Eager Reliable Broadcast

Can we modify Lazy RB to not use P? [d]

- Just assume all processes failed
- BEB Broadcast as soon as you get a msg

Eager Reliable Broadcast

Uses: BestEffortBroadcast (beb)

upon event ⟨Init⟩ **do**

delivered := $\emptyset$

upon event ⟨rb Broadcast | m⟩ **do**

delivered := delivered $\cup$ {m}
trigger ⟨rb Deliver | self , m⟩
trigger ⟨beb Broadcast | (DATA, self, m)⟩

Immediately deliver

Immediately BEB broadcast

upon event ⟨beb Deliver |p_i, (DATA, s_m , m)⟩ **do**

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

delivered := delivered $\cup$ {m}
trigger ⟨rb Deliver | s_m , m⟩
trigger ⟨beb Broadcast | (DATA, s_m, m)⟩

Immediately deliver

Immediately BEB broadcast

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CORRECTNESS OF EAGER RB

- ***RB1-RB3*** satisfied by BEB
- Need to prove ***RB4***
  - If a **correct process delivers** m, then every correct node delivers m

- Assume correct p_k delivers message bcast by p_i
  - p_k uses BEB to ensure (BEB1) every correct process gets it

Uniform Reliable Broadcast

UNIFORMITY

- Is the proposed algorithm also uniform? [d]

- Uniformity necessitates
  - If a **failed process** delivers a message m
    - then every correct node delivers m

UNIFORMITY

- No.
  - Sender p immediately RB delivers and crashes
  - Only p delivered message
- **upon event** ⟨rb Broadcast | m⟩ **do**
  - delivered := delivered ∪ {m}
  - **trigger** ⟨rb Deliver | self , m⟩
  - **trigger** ⟨beb Broadcast | (DATA, self, m)⟩

UNIFORM EAGER RB

- Necessary condition for uniform RB delivery
  - All correct processes will get the msg
  - How do we know the correct processes got msg? [d]

- Messages are pending until all correct processes get it
  - Collect acks from processes that got msg

Use vector ***ack*[*m*]** at p_i: the set of processes that acked m

- Deliver once all correct processes acked
  - **Use perfect FD**
  - **function canDeliver**(m):
    - **return** correct $\subseteq$ ack[m]

UNIFORM EAGER RB IMPLEMENTATION

- **upon event** ⟨urb Broadcast | m⟩ **do**
  - pending := pending ∪ {(self, m)}
  - **trigger** ⟨beb Broadcast | (DATA, self, m)⟩

remember sent messages

- **upon event** ⟨beb Deliver | pi, (DATA, s_m, m)⟩ **do**
  - ack[m] := ack[m] ∪ {pi}
  - **if** (s_m , m) ∉ pending **then**
    - pending := pending ∪ (s_m, m)
    - **trigger** ⟨beb Broadcast | (DATA, s_m , m)⟩

p_i obviously got m

avoid resending

- **Upon exists** (s_m,m)∈pending **s.t.**
  - **canDeliver(m) and** m ∉ delivered **do**
    - delivered := delivered ∪ {m}
    - **trigger** ⟨urb Deliver | s_m, m⟩

deliver when all correct nodes have acked

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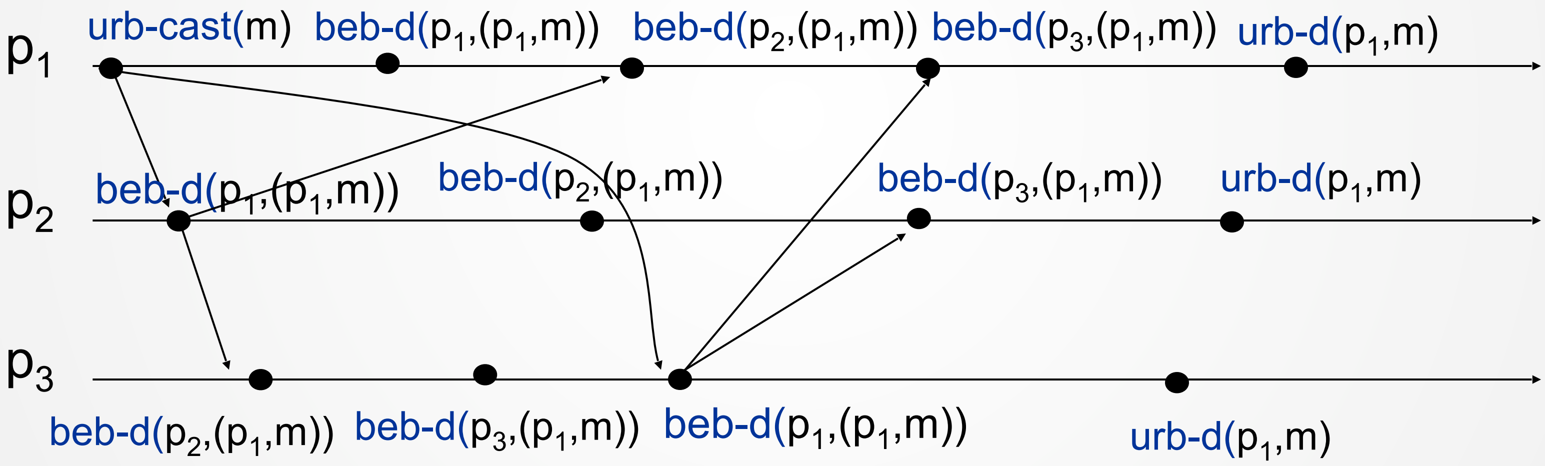
URB Eager Algorithm Example



Correctness of Uniform RB

- No creation from BEB
- No duplication by using ***delivered*** set
- **Lemma**
  - If a **correct** process p_i bebDelivers m, then p_i eventually urbDelivers m
- **Proof**
  - Correct process p_i bebBroadcasts m as soon as it gets m
    - By BEB1 every correct process gets m and bebBroadcasts m
    - p_i gets bebDeliver(m) from every correct process by BEB1
    - By completeness of **P**, it will not wait for dead nodes forever
      - **canDeliver(m)** becomes true and p_i delivers m

Correctness of Uniform RB

Validity

If sender s is correct, it'll by validity (BEB1) bebDeliver m

By the lemma, it will eventually urbDeliver(m)

Correctness of Uniform RB

- Uniform agreement
  - Assume some process (possibly failed) URB delivers m
    - Then canDeliver(m) was true,

    by **accuracy** of P **every** correct process has BEB delivered m
  - By lemma each of the nodes that BEB delivered m will URB deliver m

Uniform Broadcast

Fail-Silent

How useful is the uniform algorithm?

- Strong failure detectors necessary for URB?
  - No, we'll provide RB for fail-silent model

- Assume a majority of correct nodes
  - Majority = $\lfloor n/2 \rfloor + 1$, i.e. 6 of 11, 7 of 12…
- Every node eagerly BEB broadcast m
  - URB deliver m when received m from a majority

MAJORITY-ACK UNIFORM RB

- Same algorithm as uniform eager RB
  - Replace one function
  - **function** canDeliver(m)
    - **return** |ack[m]|>n/2

majority has acknowledged m

- Agreement (main idea)
  - If a process URB delivers, it got ack from majority
  - In that majority, one node, p, must be correct
  - p will ensure all correct processes BEB deliver m
    - The correct processes (majority) will ack and URB deliver

MAJORITY-ACK UNIFORM RB

Validity

- If correct sender sends m
  - All correct nodes BEB deliver m
  - All correct nodes BEB broadcast
  - Sender receives a majority of acks
  - Sender URB delivers m

RESILIENCE

- The maximum number of faulty processes an algorithm can handle
- The Fail-Silence algorithm
    - Has resilience less than N/2
- The Fail-Stop algorithm
    - Has resilience = N – 1