TÉCNICO LISBOA

Towards a dependable consensus: Broadcast primitives

Highly dependable systems

Lecture 3

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Last lecture: safety and liveness

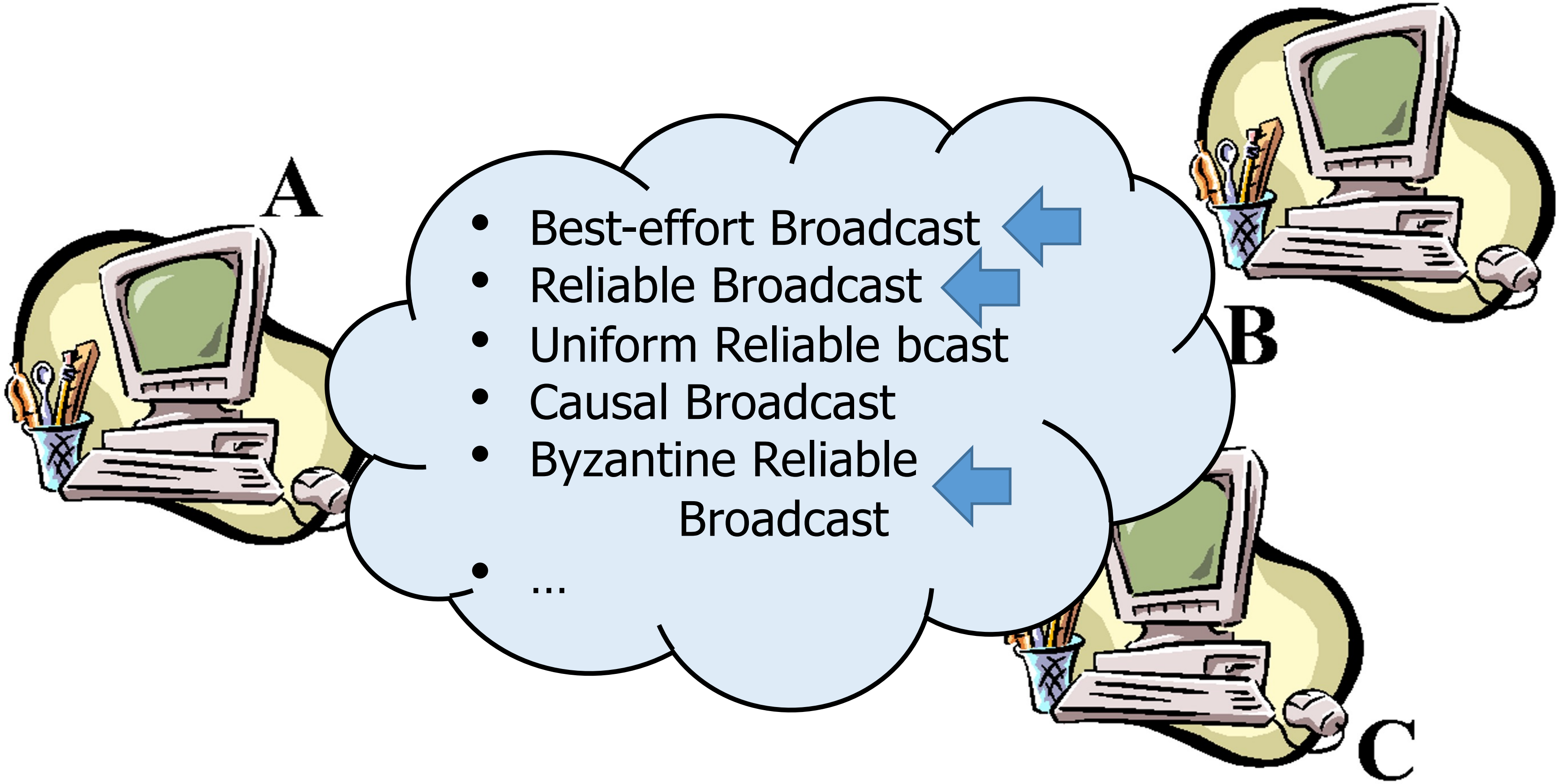
- Given a trace (sequence of outputs) of a distributed system
  - A safety property obeys:
    - If a finite trace does not obey the property, no extension of that trace obeys that property
  - A liveness property obeys:
    - A finite trace that does not obey the property can be extended so that the liveness property is upheld
- Any specification can be expressed in terms of liveness and safety properties

Last lecture - Byzantine Leader Election

- Properties
  - **Eventual succession**: if more than f correct processes that trust some process p complain about p, then every correct process eventually trusts a different process than p
  - **Putsch resistance:** A correct process does not trust a new leader unless at least one correct process has complained against the previous leader
  - **Eventual agreement**: there is a time after which no two correct processes trust different processes

- Eventually every <u>correct</u> process trusts some process that appears to perform its task in the higher-level algorithm.

Broadcast Abstractions



Intuition

- Broadcast is useful per se, for instance, in applications where some processes subscribe to events published by other processes (e.g., stocks)
- But also, a crucial building blocks in other protocols, namely consensus
- The receivers might require some **reliability** guarantees from the broadcast service (we say sometimes quality of service QoS) that the underlying network does not provide

Overview

We shall consider three forms of reliability for a broadcast primitive

- **(1) Best-effort broadcast**
- **(2) Reliable broadcast in the crash fault model**
- **(3) Reliable broadcast in the arbitrary fault model**

- We provide **specifications** and then **algorithms**

Best-effort Broadcast (beb)

- **Events**

  Request: <bebBroadcast, m>

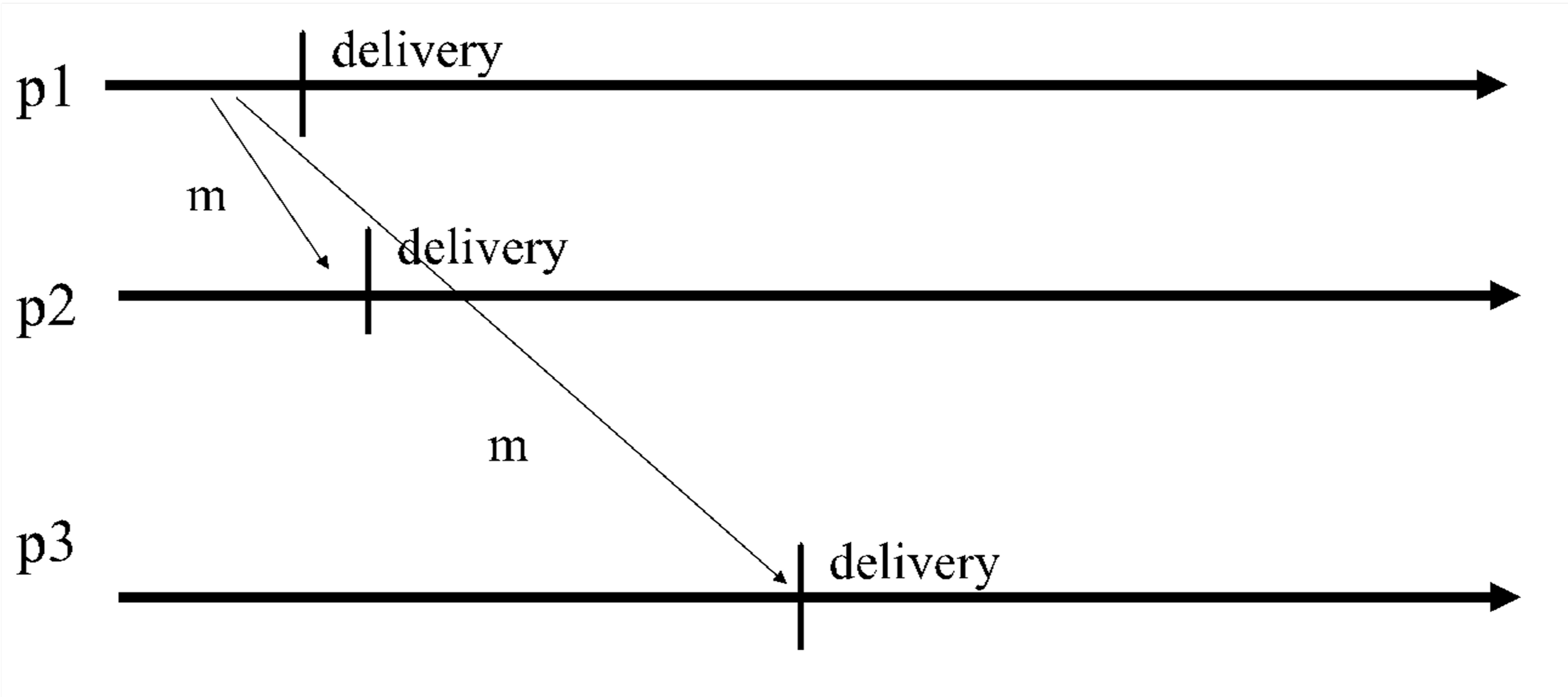
  Indication: <bebDeliver, src, m>

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

Best-effort broadcast (beb)

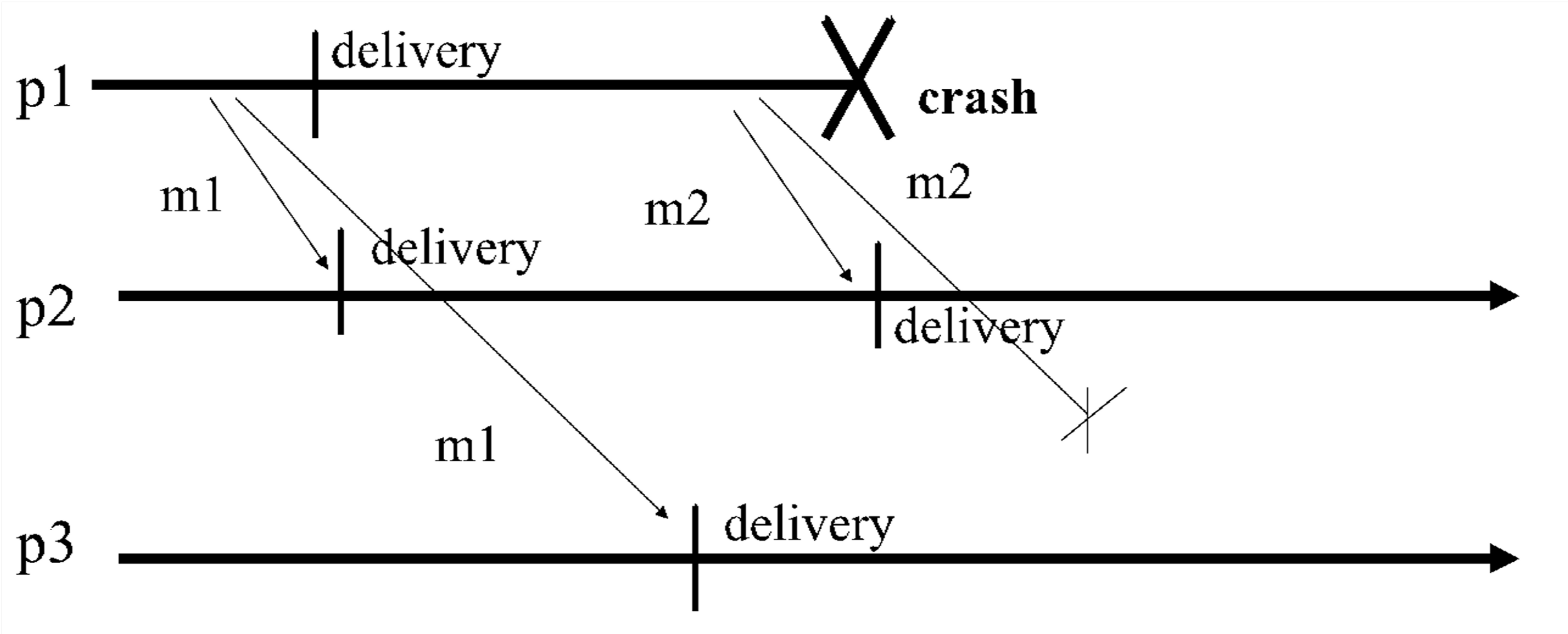
- **Properties**
  - **BEB1. Validity**: If pi and pj are correct, then every message broadcast by pi is eventually delivered by pj
  - **BEB2. No duplication:** No message is delivered more than once
  - **BEB3. No creation:** No message is delivered unless it was broadcast

Best-effort Broadcast



Meets the specification

Best-effort Broadcast



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Algorithm (beb)

- **Implements:** BestEffortBroadcast (beb).
- **Uses:** PerfectLinks (pp2p).

- **upon event** < bebBroadcast, m> **do**
  - **for all** pi∈S **do**
    - **trigger** < pp2pSend, pi, m>;

- **upon event** < pp2pDeliver, pi, m> **do**
  - **trigger** < bebDeliver, pi, m>;

Algorithm (beb)

- **Proof (sketch)**
  - **BEB1. Validity**: By the validity property of perfect links and the very facts that (1) the sender sends the message to all and (2) every correct process that pp2pDelivers a message bebDelivers it
  - **BEB2. No duplication:** By the no duplication property of perfect links
  - **BEB3. No creation:** By the no creation property of perfect links

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Reliable Broadcast (rb)

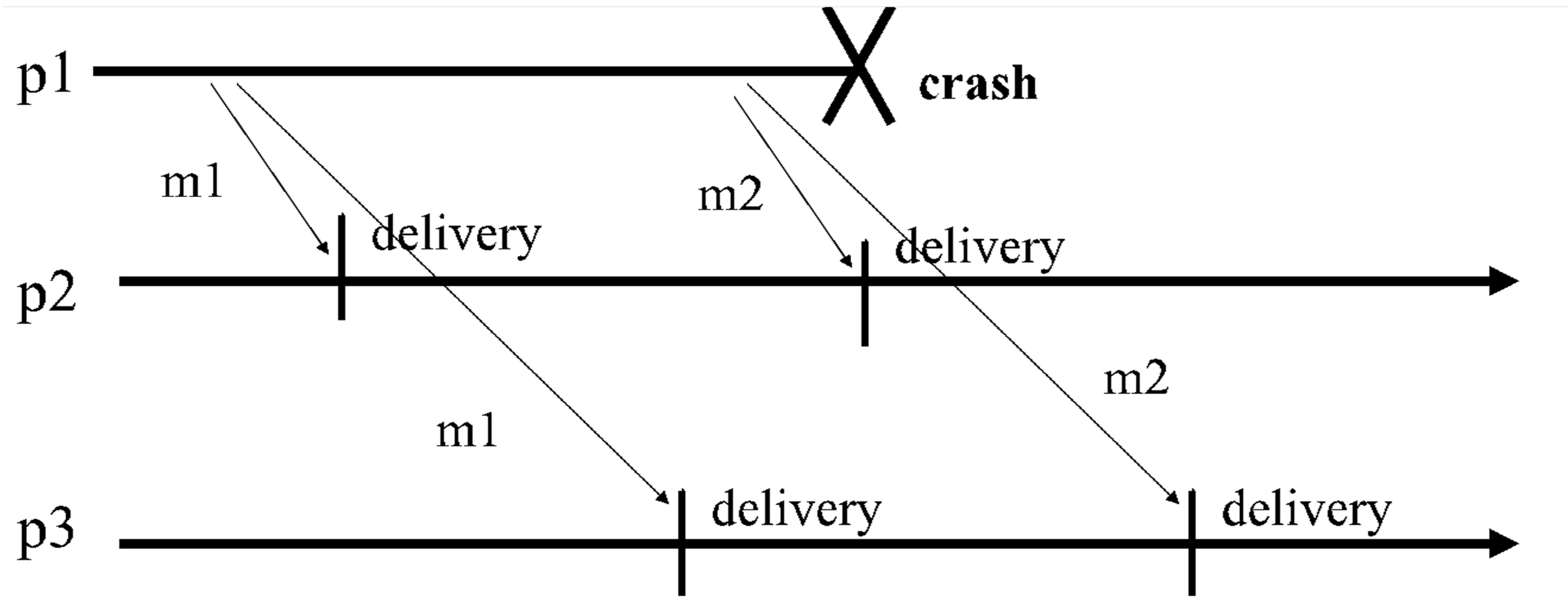
- **Events**
  - Request: <rbBroadcast, m>
  - Indication: <rbDeliver, src, m>

- **Properties: RB1, RB2, RB3, RB4**

Reliable broadcast

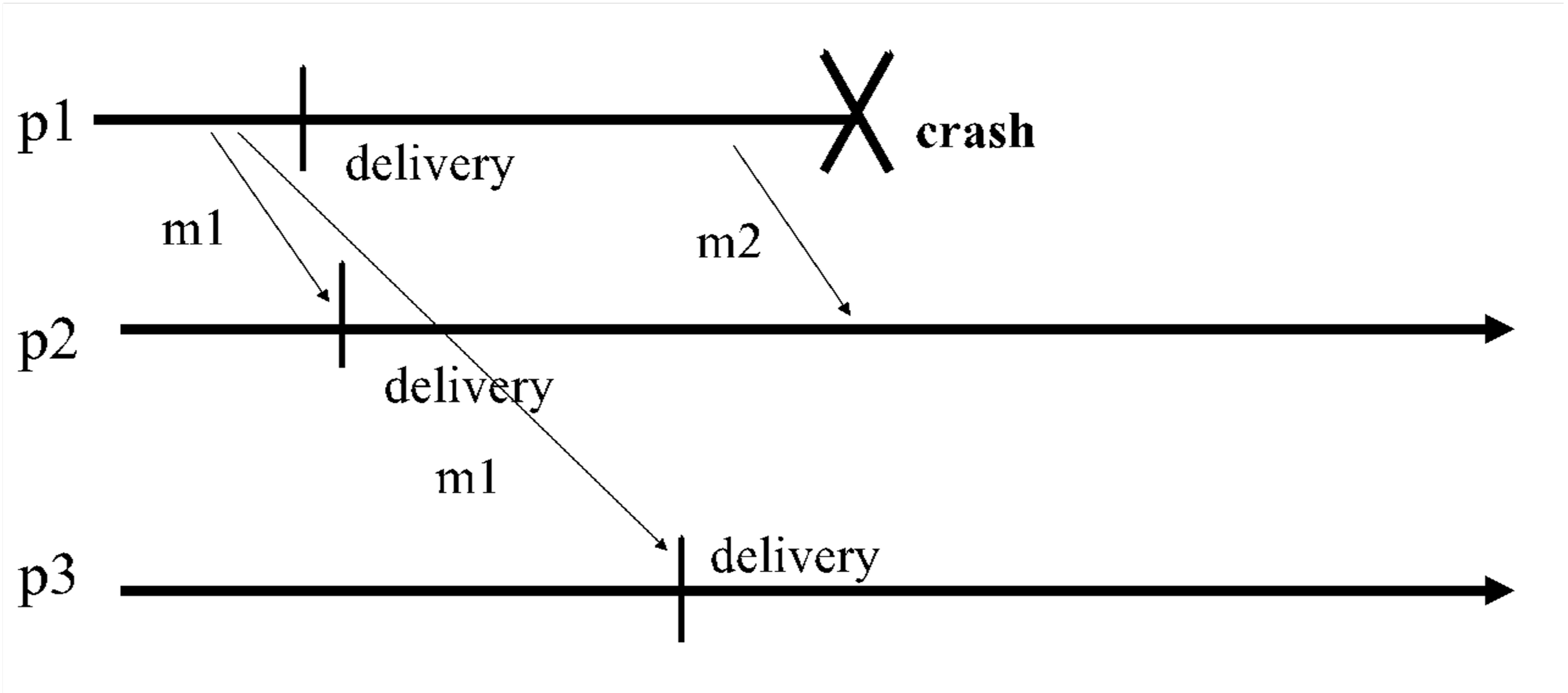
- **Properties**
  - **RB1 = BEB1.**
  - **RB2 = BEB2.**
  - **RB3 = BEB3.**
  - **RB4. Agreement:** For any message m, if a correct process delivers m, then every correct process delivers m

Reliable Broadcast



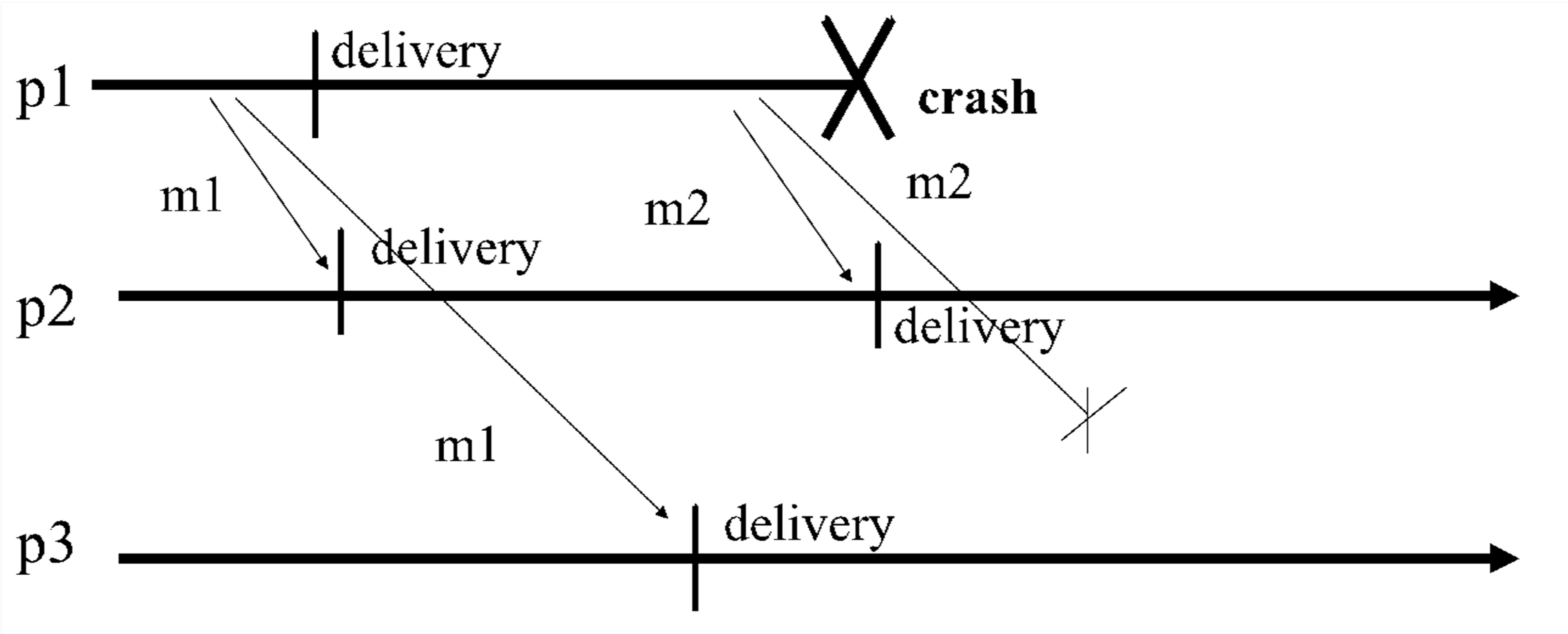
Meets the specification

Reliable Broadcast



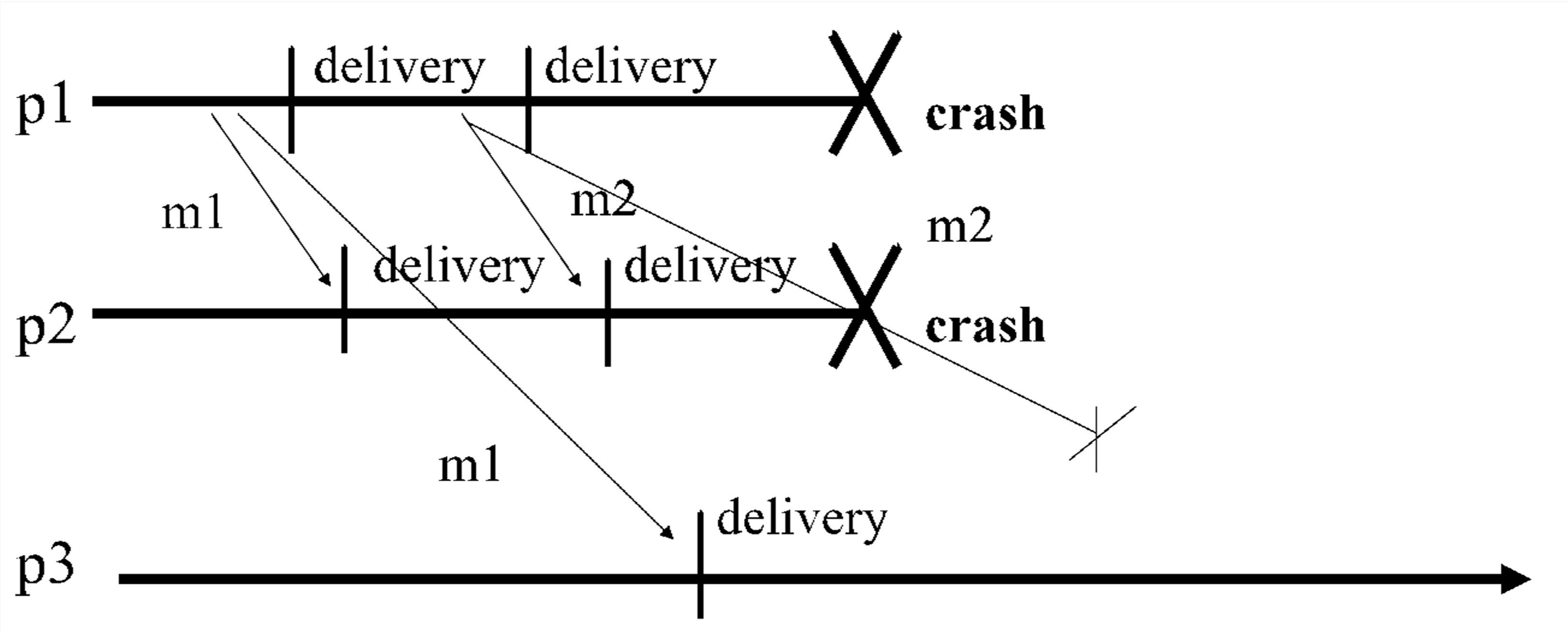
Meets the specification

Reliable Broadcast



Does not meet the specification

Reliable Broadcast



Meets the specification

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Eager Reliable Broadcast

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* | $[\text{DATA}, self, m]$ $\rangle$;

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

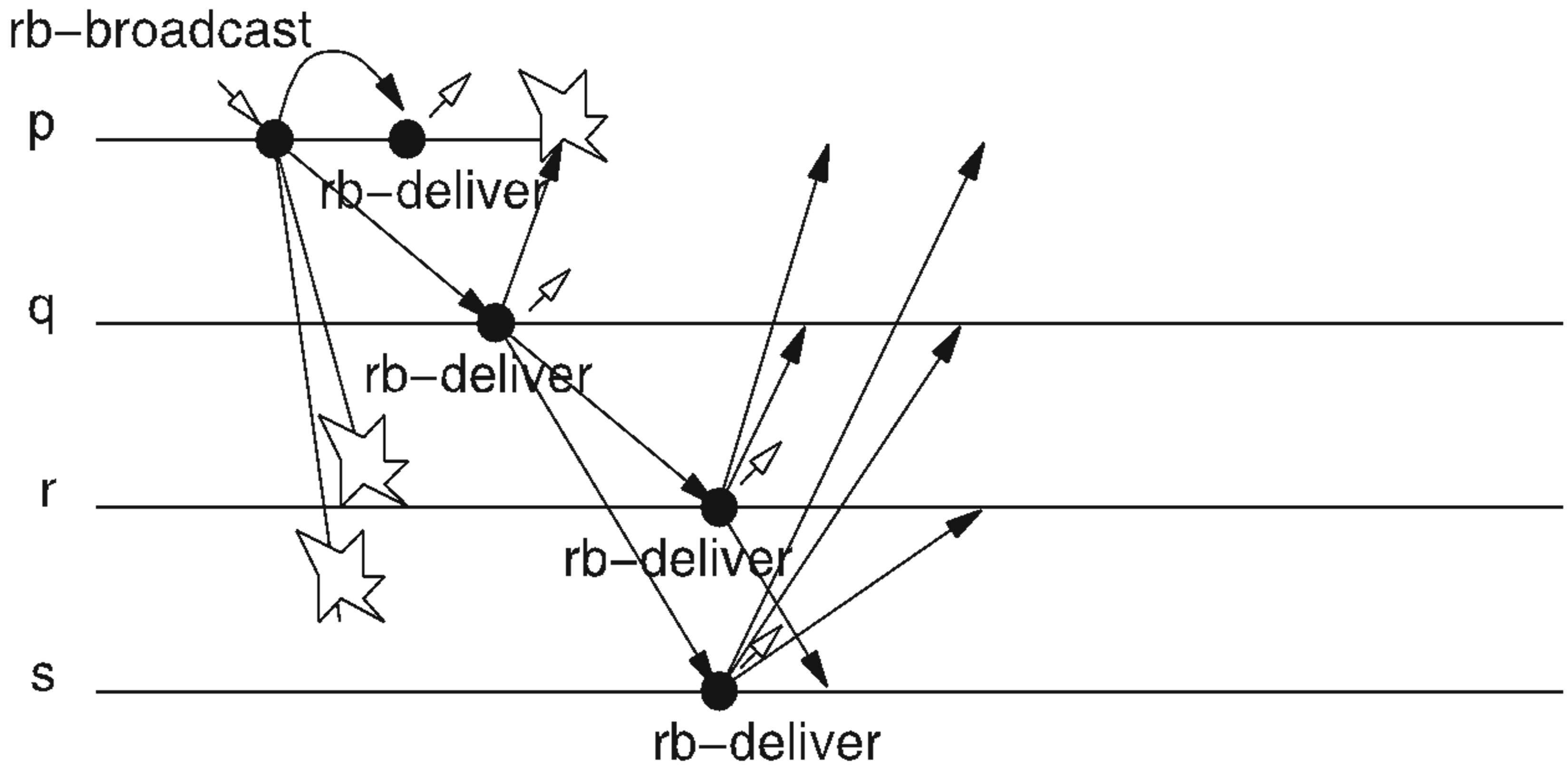
if $m \notin delivered$ **then**

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

trigger $\langle$ *rb*, *Deliver* | s, m $\rangle$;

trigger $\langle$ *beb*, *Broadcast* | $[\text{DATA}, s, m]$ $\rangle$;

Eager Reliable Broadcast



Proof (sketch)

- **RB1. RB2. RB3:** as for the 1st algorithm
- **RB4. Agreement:**
  - every correct process immediately relays every message it *rb*-delivers
  - the *validity* property of the underlying best-effort broadcast primitive ensures that all other correct process will eventually deliver the message.

Note: Does not use a failure detector ⇔
Does not make any synchrony assumptions

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Reliable broadcast in the byzantine model

- A byzantine process may, e.g.:
  - broadcast messages different from the ones sent by applications,
  - forge messages so that they look as originated by other processes
    - violation of the No creation property
  - send different messages to different processes
    - violation of the *agreement* property

Reliable broadcast in the byzantine model

- Authenticated Perfect Links are a useful tool:
  - disallows forging messages as originated from other processes
  - still does not solve the problems above
- Digital signatures can also be helpful:
  - allow any process to verify the authenticity of a message
  - but faulty processes may sign “illegal” msgs
    - e.g., sending two different messages, after having signed them

Byzantine Consistent and Reliable Broadcasts

- We consider two variants of reliable broadcasts in the byzantine model:

  - Byzantine Consistent Broadcast

  - Byzantine Reliable Broadcast

Byzantine Consistent and Reliable Broadcasts

- Byzantine Consistent Broadcast
  - If the sender s is correct then every correct process should later deliver m.
  - If s is faulty, then every correct process delivers the same message, <u>if it delivers one at all.</u>
    - i.e., correct processes are <u>not</u> guaranteed to deliver the same set of messages if sender is faulty
- Byzantine Reliable Broadcast
  - Ensures that if a correct process delivers m, then every correct process delivers m
    - <u>**independently of whether the sender is faulty**</u>

Byzantine Consistent Broadcast: specification

- **BCB1:** *Validity:* If a correct process p broadcasts a msg m, then every correct process eventually delivers m.
- **BCB2:** *No duplication:* Every correct process delivers at most one message.
- **BCB3:** *Integrity:* If some correct process delivers a message m with sender p and process p is correct, then m was previously broadcast by p.

  BCB4: *Consistency:* If some correct process delivers a message m and another correct process delivers a message m′, then m = m′.

Note: "Correct" now means non-Byzantine-faulty

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Byzantine Consistent Broadcast: Algorithms

- Byzantine Consistent Broadcast
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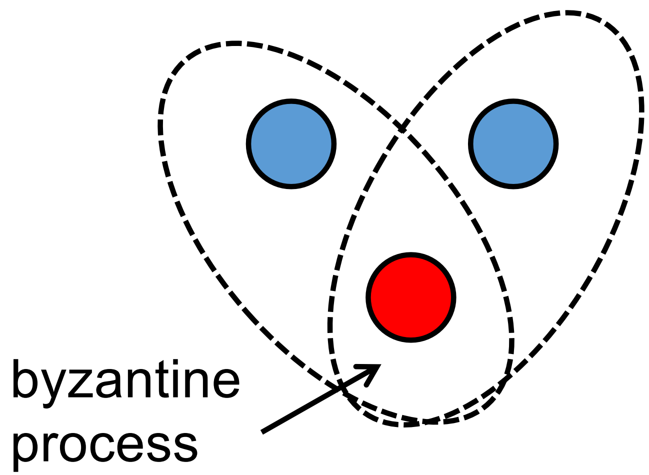
    - i.e., correct processes are <u>not</u> guaranteed to deliver the same set of messages
- Two algorithms:
  - Authenticated Echo Broadcast
    - exchanges a quadratic number of messages
  - Signed Echo Broadcast
    - linear no. of messages but uses digital signatures (costly)
  - Leverage **Byzantine quorums**

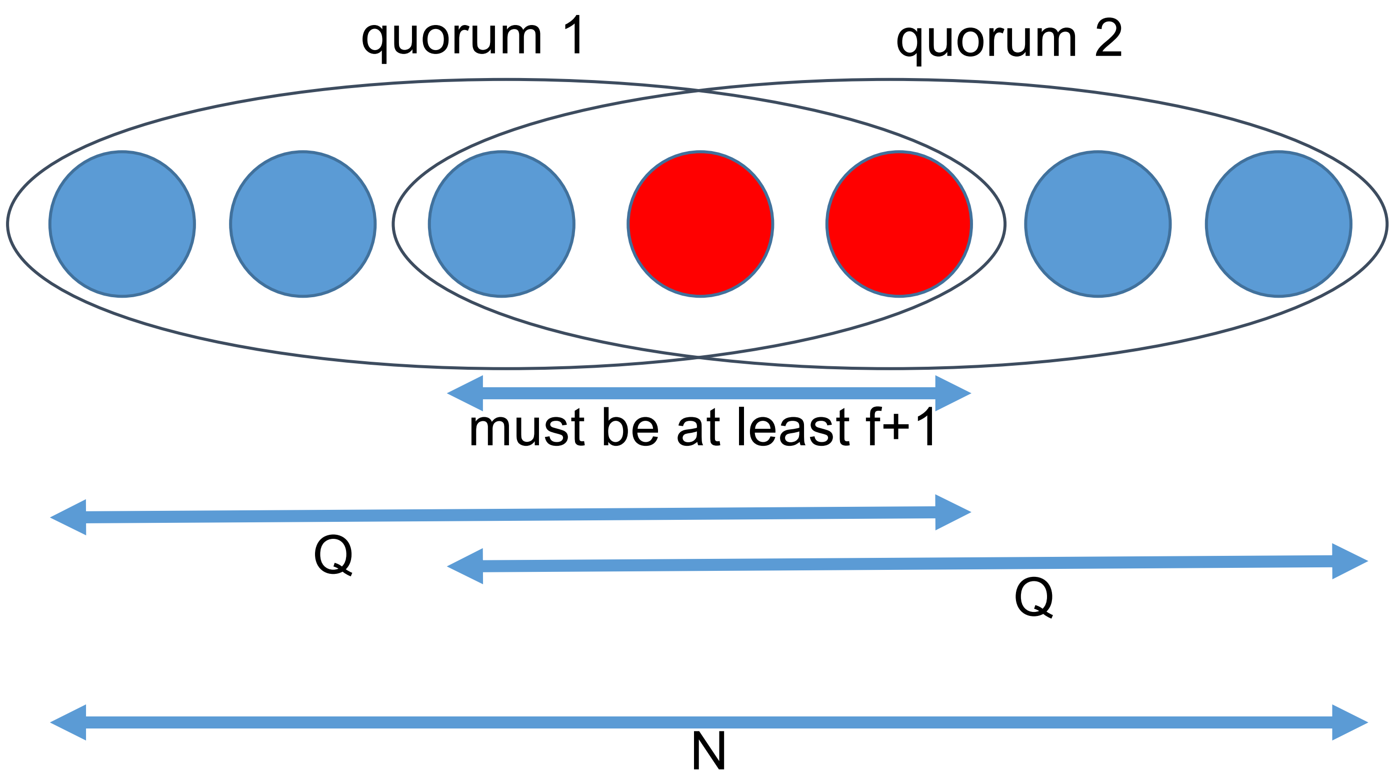
Quorums and Byzantine Quorums

- Quorums are sets of subsets with a specific intersection property:
  - they always overlap in at least one correct process
  - example:
    - majority of processes, assuming f<N/2 **crash failure model**
    - intersection of 2 majority quorums is necessarily a correct process with crash faults
    - no longer true with byzantine faults!



Derivation of Byzantine quorum sizes

- Safety: every pair of quorums must intersect in at least one correct process



Derivation of Byzantine quorum sizes

- $Q + Q – N \geq f+1$
- To simplify, we take the optimal size (no need to intersect more than strictly necessary)
- $2Q – N = f+1$

Derivation of Byzantine quorum sizes

- Liveness: a quorum always needs to be available
- Challenge: f processes may never reply (crashed or deliberately silent)
- Thus quorums can't be larger than $N - f$
- $N - f \geq Q$
- Again, we turn this into an equality (don't use more processes than strictly necessary)
- $N - f = Q$

Solving a system of two equations

- Note that f is a system parameter (constant)

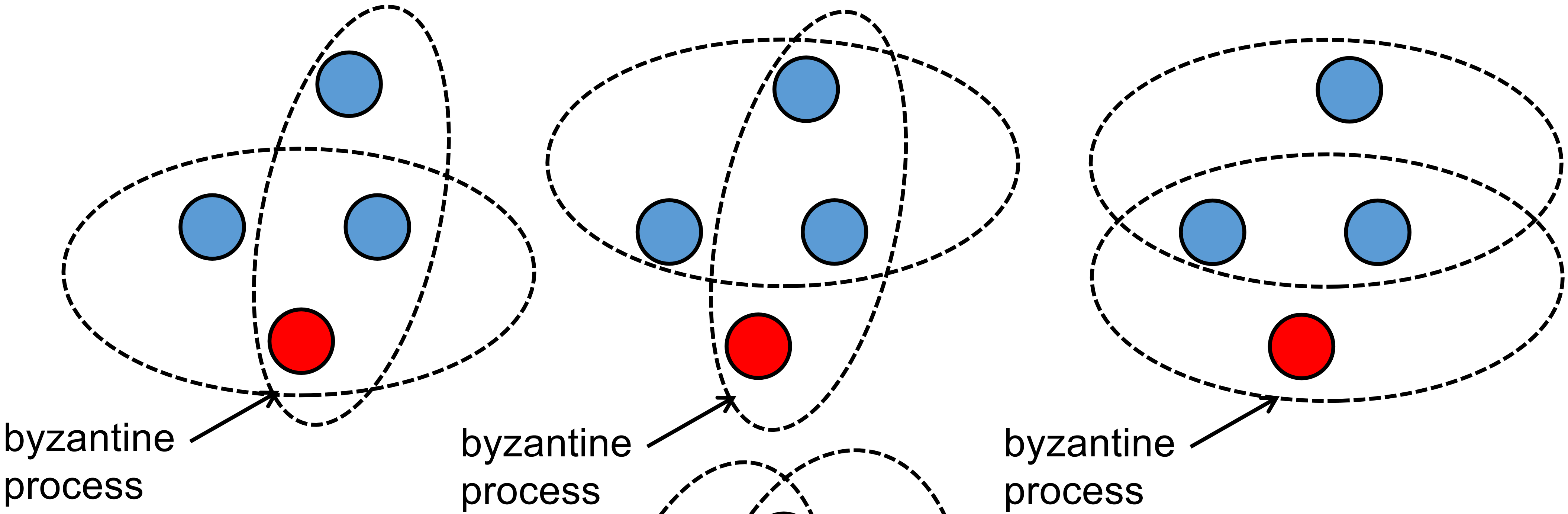
$$\begin{cases} 2Q - N = f+1 \\ N - f = Q \end{cases}$$

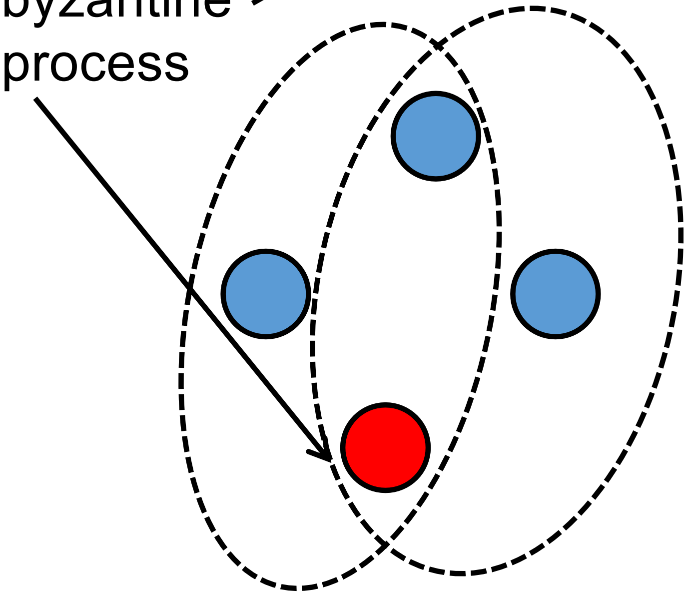
- Thus, solving these equations for N and Q yields:

$$N = 3f+1$$

$$Q = 2f+1$$

Byzantine Quorums: examples





The intersection of any two Byzantine Quorums contains at least a correct process

Acknowledgements

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