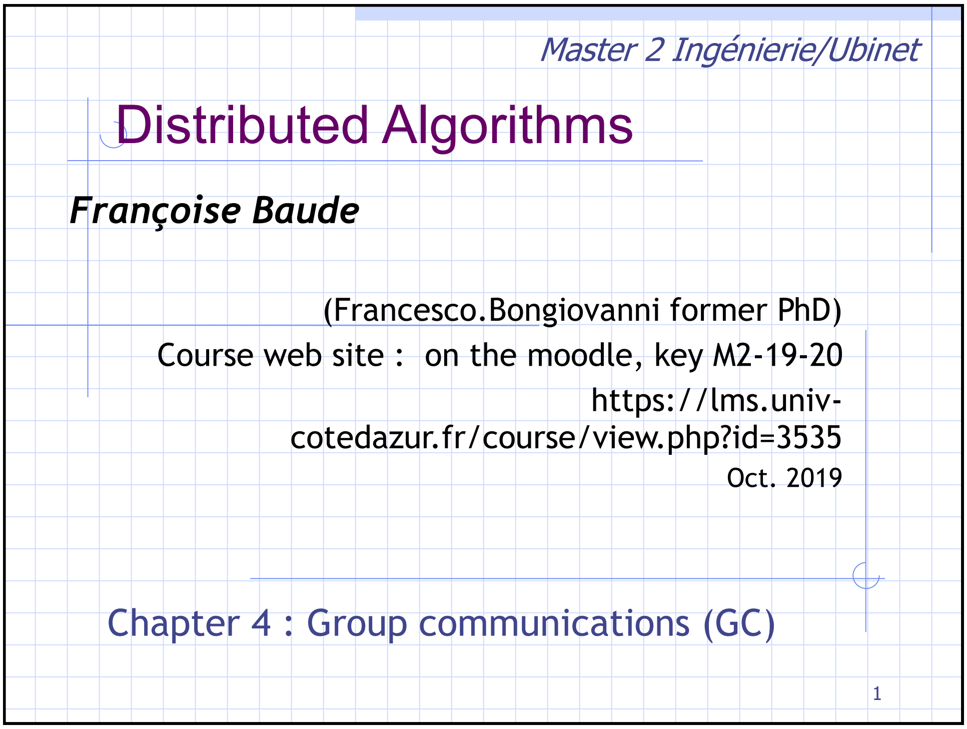


Master 2 Ingénierie/Ubinet

Distributed Algorithms

Françoise Baude

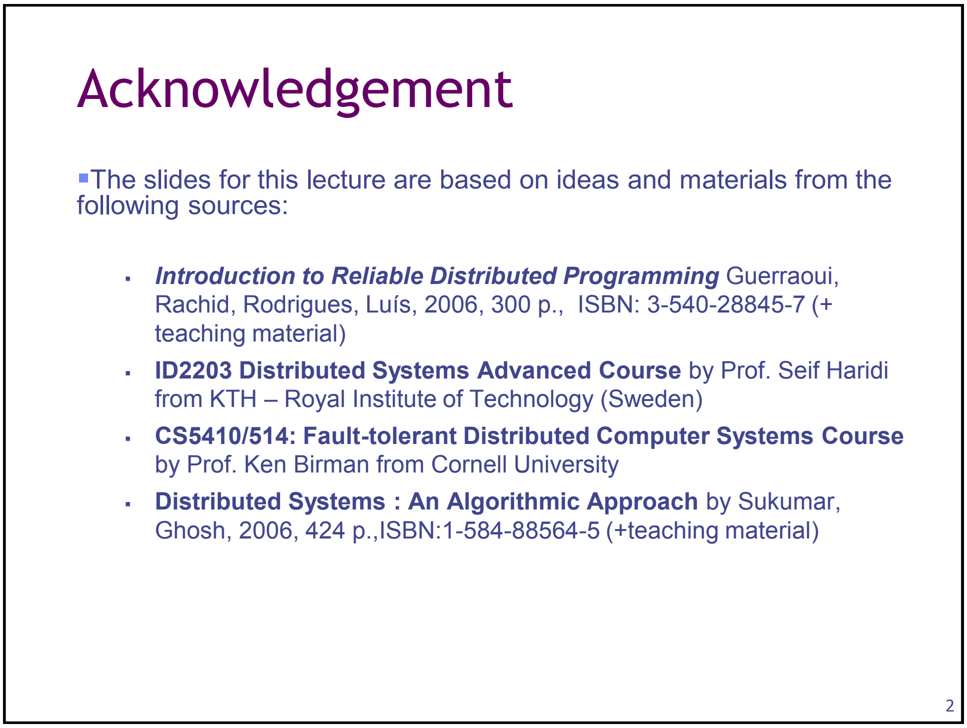
(Francesco.Bongiovanni former PhD)

Course web site : on the moodle, key M2-19-20

https://lms.univ-cotedazur.fr/course/view.php?id=3535

Oct. 2019

Chapter 4 : Group communications (GC)



Acknowledgement

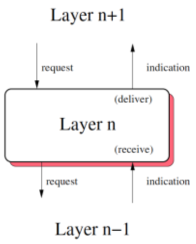
- The slides for this lecture are based on ideas and materials from the following sources:
  - ***Introduction to Reliable Distributed Programming*** Guerraoui, Rachid, Rodrigues, Luís, 2006, 300 p., ISBN: 3-540-28845-7 (+ teaching material)
  - **ID2203 Distributed Systems Advanced Course** by Prof. Seif Haridi from KTH – Royal Institute of Technology (Sweden)
  - **CS5410/514: Fault-tolerant Distributed Computer Systems Course** by Prof. Ken Birman from Cornell University
  - **Distributed Systems : An Algorithmic Approach** by Sukumar, Ghosh, 2006, 424 p.,ISBN:1-584-88564-5 (+teaching material)

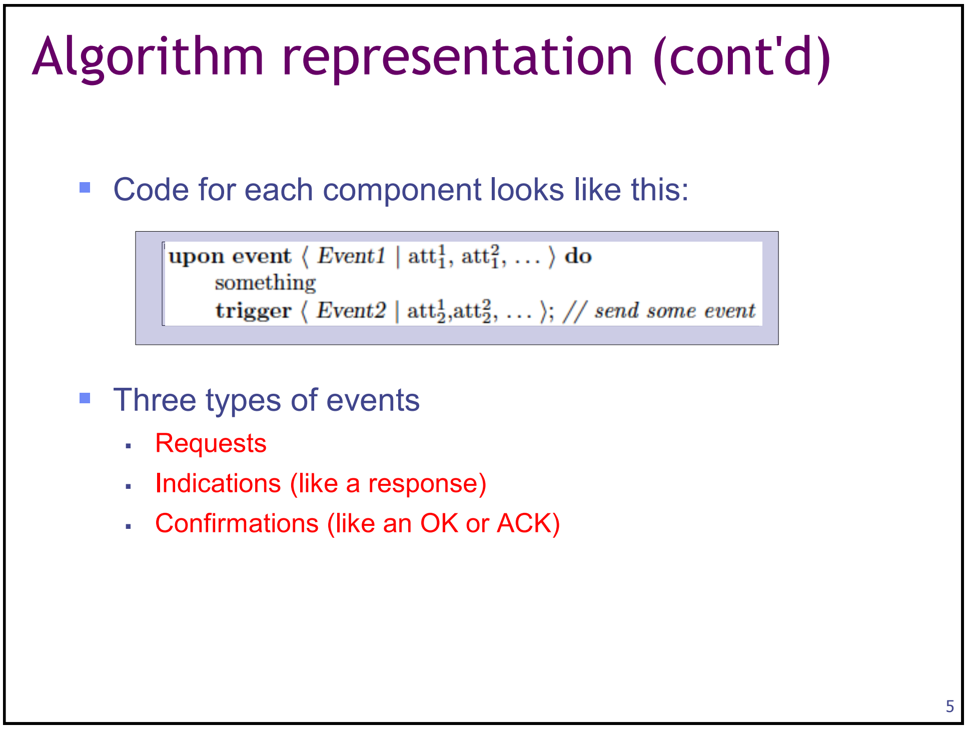
Outline

1. Definition, motivation
2. Basic GC abstraction
   - Best Effort Bcast
   - Causal Order and Total Order Bcast
3. Reliability – small glance at reliable GC
   - Reliable Bcast
   - Reliable causal Bcast

Algorithm representation

- Event-based component (or module) model
  - Nodes in the model execute programs
    - Each program consists of a set of modules (forming a software stack)
- Modules interact via events



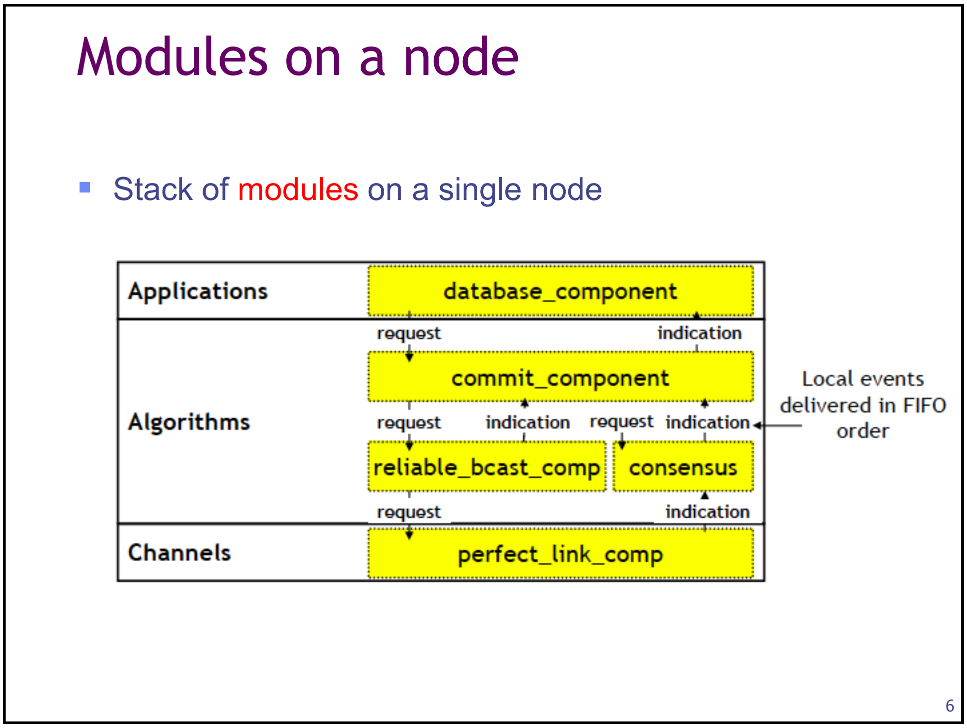


Algorithm representation (cont'd)

- Code for each component looks like this:

```
upon event ⟨ Event1 | $att_1^1$, $att_1^2$, ... ⟩ do
    something
    trigger ⟨ Event2 | $att_2^1$,$att_2^2$, ... ⟩; // send some event
```

- Three types of events
  - Requests
  - Indications (like a response)
  - Confirmations (like an OK or ACK)



Modules on a node

- Stack of modules on a single node

Local events delivered in FIFO order

Channels as modules

- Channels are modules
  - Request event:
    - Send to destination some message (with data)

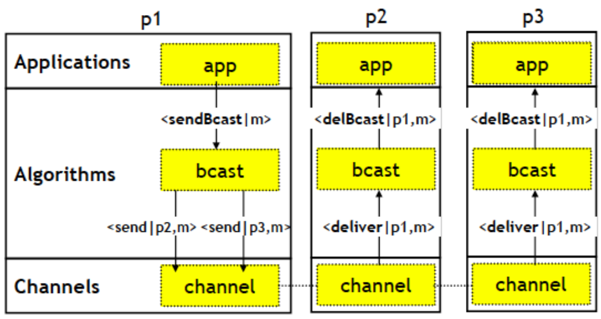
trigger <*send* | *dest*, [data1, data2, …] >

  - Indication event:
    - Deliver from source some message (with data)

upon event <*send* | *src*, [data1, data2, …] > do

Example

- Application uses a Broadcast module
  - Which uses a channel module to broadcast



A little reminder…

- Correctness in distributed systems expressed in terms of *safety* and *liveness* properties
  - Safety
    - *States that a property that is violated at time t should never be satisfied again after that time. Say another way, during the lifetime of the algorithm, only safe things happen*

      « nothing bad will happen»
  - Liveness
    - *States that a property should eventually hold*
    - *« eventually something good happens»*

- Lamport, L. A simple approach to specifying concurrent systems. Commun. ACM 32, 32-45 (1989).

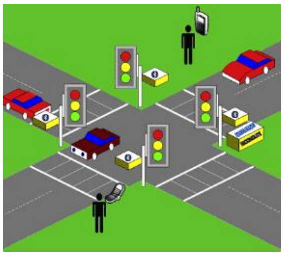
- Lamport, L. Specifying Systems. (Addison-Wesley: 2002).

Correctness example

- Correctness of **YOU** in this course
  - Safety
    - You should never fail the exam
  - Liveness
    - You should eventually take the exam
    - You should eventually pass the exam !!!

Correctness example (2)

- Correctness of a traffic light
- at intersection
  - Safety
    - Only one direction should have a green light
  - Liveness
    - Every direction should eventually get a green light



Distributed algorithms abstractions

- Abstracting computers
  - => processes
- Abstracting communications
  - =>link (or channels)
- Abstracting time
  - => failure detector (*for a latter course but will be slightly introduced here*)

Model and assumptions

- Specification needs to specify the model
  - Assumptions needed for the algorithm to be correct
- Model includes assumptions on:
  - Failure behavior of processes and channels
  - Timing behavior of processes and channels

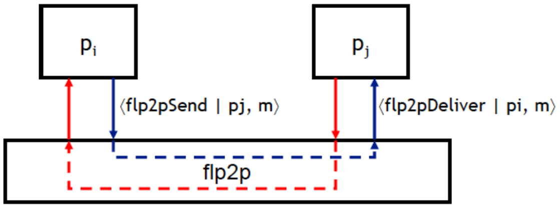
Node failures

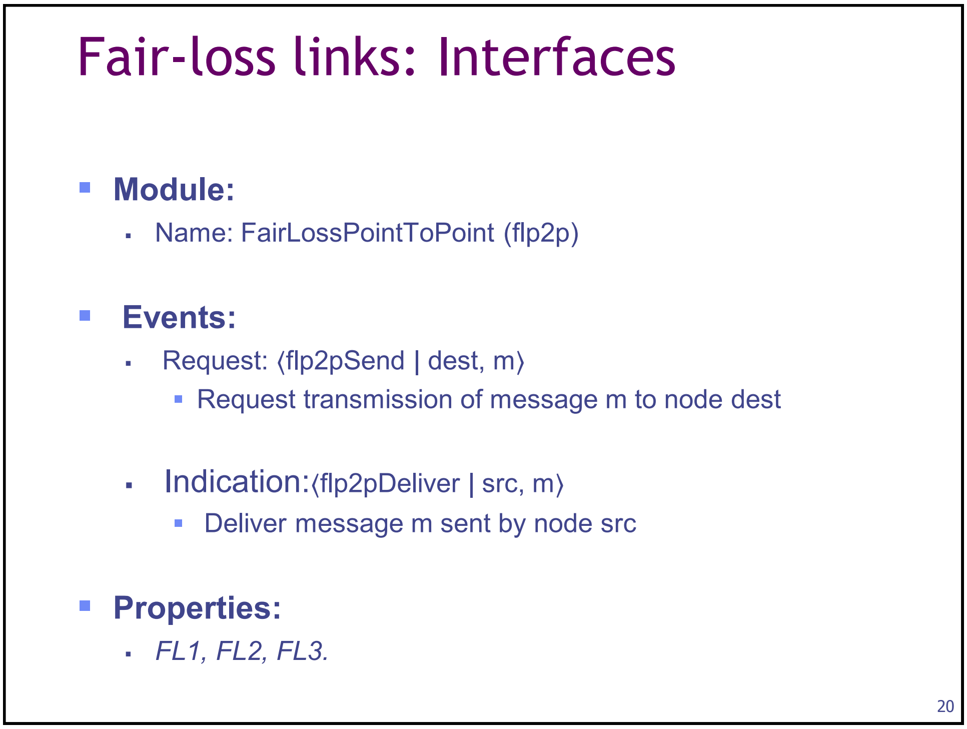
- Node may fail in 4 ways:
  - Crash-stop
  - Omissions
  - Crash-recovery
  - Byzantine / arbitrary
  - (these models are covered in details in another lecture)
- Nodes that don't fail in an execution are correct

Channel failures modes

- Fair-Loss Links
  - Channels delivers any message sent with non-zero probability (no network partitions)
- Stubborn Links (“tétu”)
  - Channels delivers any message sent infinitely many times
- Perfect Links
  - Channels that deliver any message sent exactly once

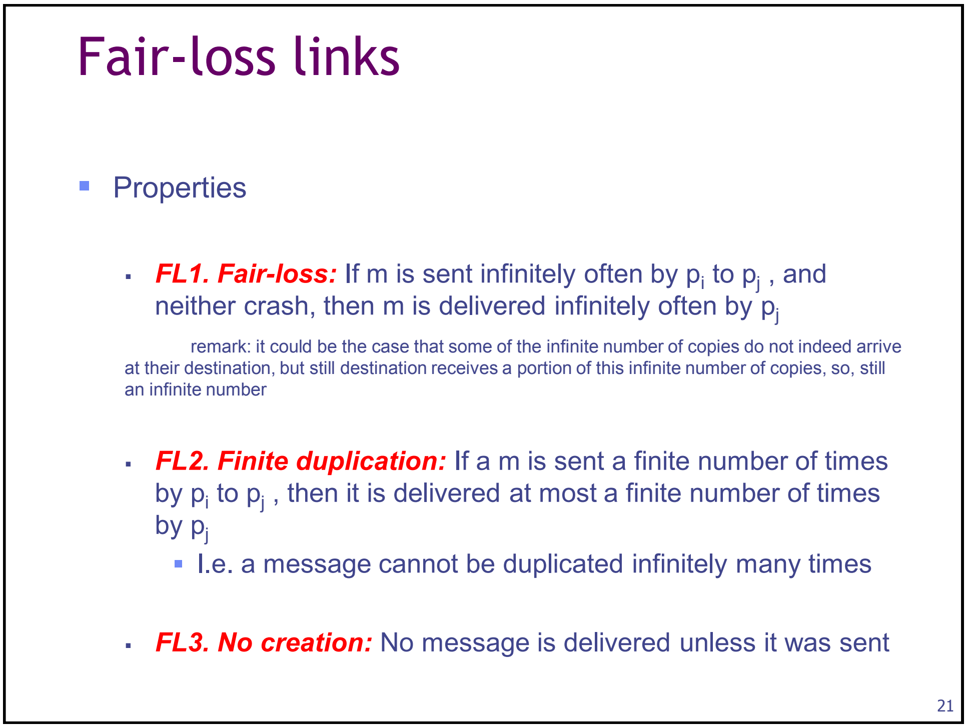
Fair-loss links





Fair-loss links: Interfaces

- **Module:**
  - Name: FairLossPointToPoint (flp2p)
- **Events:**
  - Request: ⟨flp2pSend | dest, m⟩
    - Request transmission of message m to node dest
  - Indication:⟨flp2pDeliver | src, m⟩
    - Deliver message m sent by node src
- **Properties:**
  - *FL1, FL2, FL3.*



Fair-loss links

- Properties
  - ***FL1. Fair-loss:*** If m is sent infinitely often by p_i to p_j , and neither crash, then m is delivered infinitely often by p_j

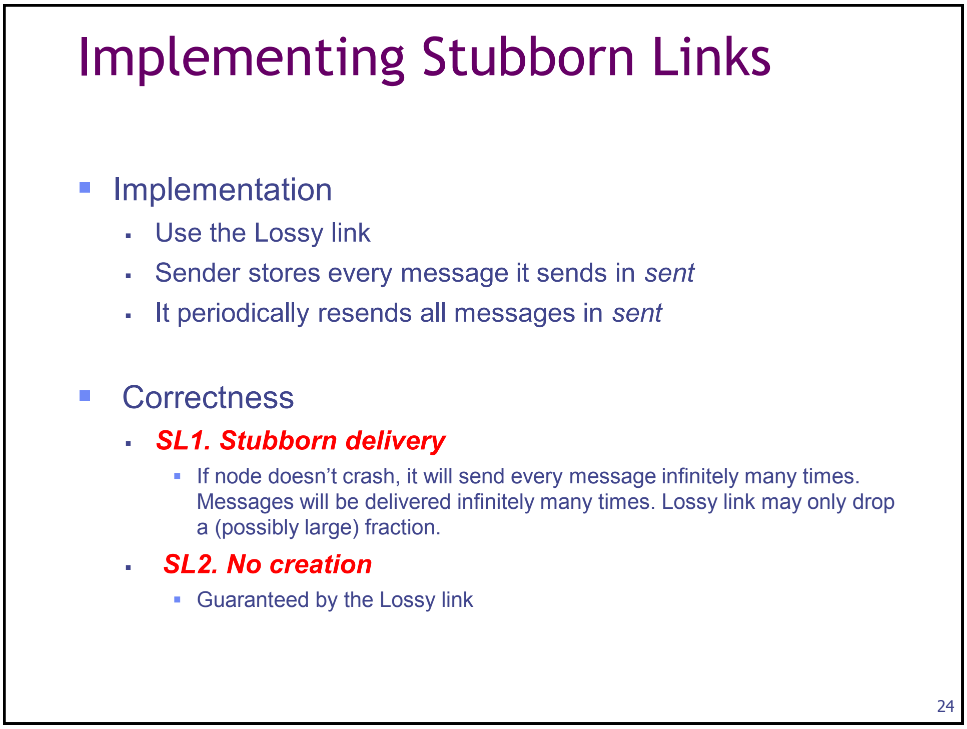
    remark: it could be the case that some of the infinite number of copies do not indeed arrive at their destination, but still destination receives a portion of this infinite number of copies, so, still an infinite number
  - ***FL2. Finite duplication:*** If a m is sent a finite number of times by p_i to p_j , then it is delivered at most a finite number of times by p_j
    - I.e. a message cannot be duplicated infinitely many times
  - ***FL3. No creation:*** No message is delivered unless it was sent

Stubborn links: Interface

- **Module:**
  - Name: StubbornPointToPoint (sp2p)
- **Events:**
  - Request: ⟨sp2pSend | dest, m⟩
    - Request the transmission of message m to node dest
  - Indication:⟨sp2pDeliver src, m⟩
    - deliver message m sent by node src
- **Properties:**
  - *SL1, SL2*

Stubborn links

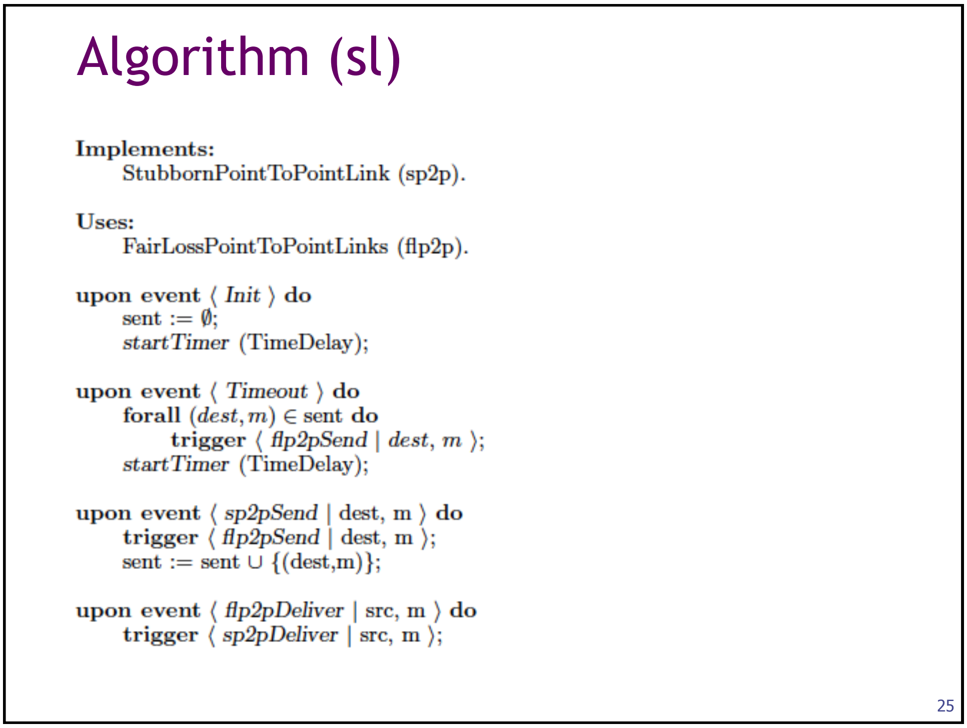
- Properties
  - ***SL1. Stubborn delivery:*** if a node pi sends a message m to a correct node p_j, and p_i does not crash, then p_j delivers m an infinite number of times
  - ***SL2. No creation:*** if a message m is delivered by some node p_j, then m was previously sent by some node p_i



Implementing Stubborn Links

- Implementation
  - Use the Lossy link
  - Sender stores every message it sends in *sent*
  - It periodically resends all messages in *sent*

- Correctness
  - ***SL1. Stubborn delivery***
    - If node doesn't crash, it will send every message infinitely many times. Messages will be delivered infinitely many times. Lossy link may only drop a (possibly large) fraction.
  - ***SL2. No creation***
    - Guaranteed by the Lossy link



Algorithm (sl)

```
Implements:
    StubbornPointToPointLink (sp2p).

Uses:
    FairLossPointToPointLinks (flp2p).

upon event ⟨ Init ⟩ do
    sent := ∅;
    startTimer (TimeDelay);

upon event ⟨ Timeout ⟩ do
    forall (dest, m) ∈ sent do
        trigger ⟨ flp2pSend | dest, m ⟩;
    startTimer (TimeDelay);

upon event ⟨ sp2pSend | dest, m ⟩ do
    trigger ⟨ flp2pSend | dest, m ⟩;
    sent := sent ∪ {(dest,m)};

upon event ⟨ flp2pDeliver | src, m ⟩ do
    trigger ⟨ sp2pDeliver | src, m ⟩;
```

Perfect Links: Interface

- **Module:**
  - Name: PerfectPointToPoint (pp2p)
- **Events:**
  - Request: ⟨pp2pSend | dest, m⟩
    - Request the transmission of message m to node dest
  - Indication: ⟨pp2pDeliver | src, m⟩
    - deliver message m sent by node src
- **Properties:**
  - *PL1, PL2, PL3*

Perfect links aka Reliable links

- Properties
  - ***PL1. Reliable Delivery:*** If neither p_i nor p_j crashes, then every message sent by p_i to p_j is eventually delivered by p_j
  - ***PL2. No duplication:*** Every message is delivered at most once
  - ***PL3. No creation:*** No message is delivered unless it was sent

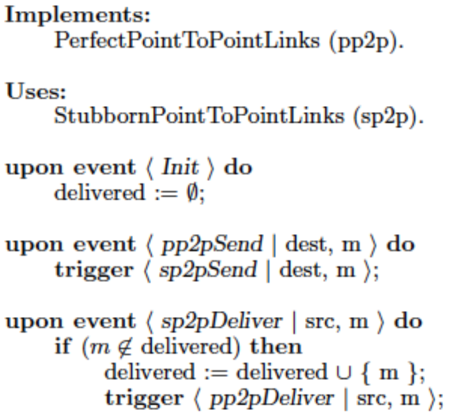
Perfect links aka Reliable links

- Question : Which one is safety/liveness/neither ?

Perfect link implementation

- Implementation
  - Use Stubborn links
  - Receiver keeps log of all received messages in Delivered
    - Only deliver (call pp2pDeliver) messages that weren't delivered before
- Correctness
  - ***PL1. Reliable Delivery***
    - Guaranteed by Stubborn link. In fact the Stubborn link will deliver it infinite number of times
  - ***PL2. No duplication***
    - Guaranteed by our log mechanism
  - ***PL3. No creation***
    - Guaranteed by Stubborn link (and its lossy link?)

Algorithm (pl)



```
Implements:
    PerfectPointToPointLinks (pp2p).

Uses:
    StubbornPointToPointLinks (sp2p).

upon event ⟨ Init ⟩ do
    delivered := $\emptyset$;

upon event ⟨ pp2pSend | dest, m ⟩ do
    trigger ⟨ sp2pSend | dest, m ⟩;

upon event ⟨ sp2pDeliver | src, m ⟩ do
    if ($m \notin$ delivered) then
        delivered := delivered $\cup$ { m };
        trigger ⟨ pp2pDeliver | src, m ⟩;
```

Default assumptions

- We assume perfect links (aka reliable) most of the lecture (unless specified otherwise)
  - Roughly, reliable links ensure messages exchanged between correct processes are delivered exactly once
- NB. Messages are uniquely identified and
  - the message identifier includes the sender’s identifier
  - i.e. if “same” message sent twice, it’s considered as two different messages

GC - Definition

- A *group* = a collection of *users* or *objects* sharing a common interest
- Multicast, broadcast (special case of multicast)
- Purpose :
  - The purpose of introducing groups is to allow processes to deal with collections of processes as a single abstraction. Thus, a process can send a message to a group of servers without having to know how many there are or where they are.

GC - Motivation

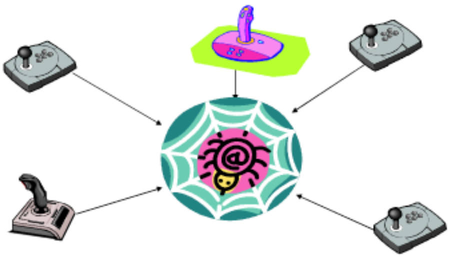
- From client-server to multi-participant systems
- Intuition:
  - distributed applications become bigger and more complex
    => interactions no longer limited to bilateral relationships
- Broadcast is useful for
  - applications where some processes subscribe to events published by other processes(e.g., stocks), and require some reliability guarantees from the broadcast service (we say sometimes quality of service–QoS) that the underlying network does not provide
- Broadcast is also useful for (database) replication
  - And is necessary in particular for a master, to maintain a global distributed state of slaves

GC - Motivation (cont'd)

- Who Needs Group Communication?
  - Highly available servers (client-server)
    - eg. cluster of J2EE servers
  - Database Replication
    - Fault tolerance by replicating the database nodes (State Machine Replication – SRM)
  - Multimedia Conferencing
    - eg Visio conf systems
  - Coordinated replicated services
    - eg. Name service for management of a cluster
      - ZooKeeper, using “Zab”: leader-based atomic broadcast protocol to maintain backup servers consistent replicated state
  - Online Games
  - …

GC - Motivation (cont'd)

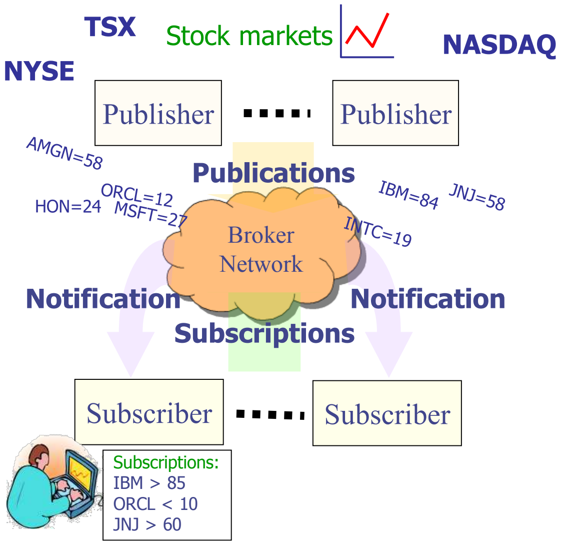
- Online game



- Fault-tolerance, order

GC - Motivation (cont'd)

- Example: Stock Market



TSX

Stock markets

NASDAQ

NYSE

Publisher ..... Publisher

AMGN=58

Publications

IBM=84 JNJ=58

ORCL=12

HON=24 MSFT=27

INTC=19

Broker Network

Notification

Notification

Subscriptions

Subscriber ..... Subscriber

Subscriptions:
IBM > 85
ORCL < 10
JNJ > 60

GC - Motivation (cont'd)

	Unreliable	Reliable
Unicast	UDP	TCP
Multicast	IP Multicast	???

- IP Multicast is not activated everywhere on the Internet...

Basic broadcast abstractions

Best effort broadcast (beb Bcast)

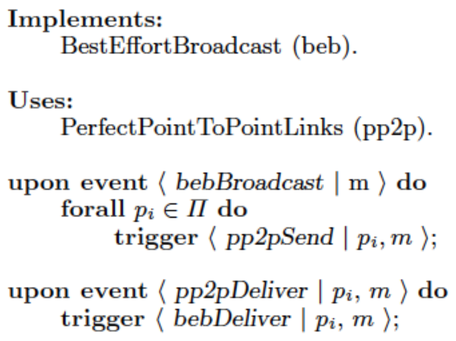
- Best effort Bcast
  - **Intuition:** everything is perfect unless sender crash
  - **Module:**
    - Name: BestEffortBroadcast (beb).
  - **Events:**
    - ***Request:*** < bebBroadcast | m >: Used to broadcast message m to all processes.
    - ***Indication:* <** bebDeliver | src, m > : Used to deliver message m broadcast by process src.
  - **Properties:**
    - ***BEB1,BEB2,BEB3***

Beb Bcast

- **Properties:**
  - ***BEB1:*** Best-effort validity: For any two processes p_i and p_j,If pi and p_j are correct, then every message broadcast by p_i is eventually delivered by p_j .
  - ***BEB2:*** No duplication: No message is delivered more than once.
  - ***BEB3:*** No creation: If a message m is delivered by some process p_j, then m was previously broadcast by some process p_i.

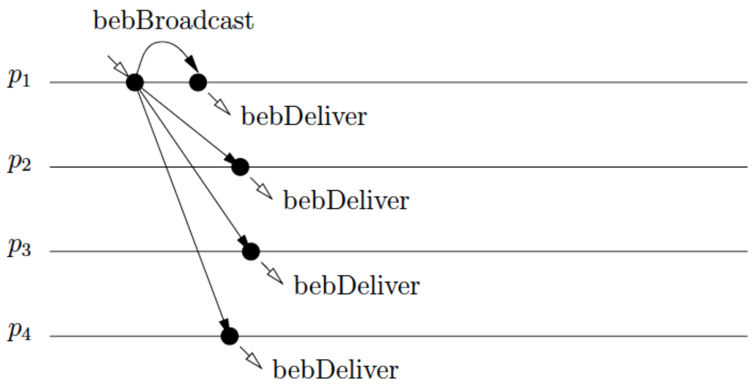
Algorithm (beb bcast)

- Basic bcast



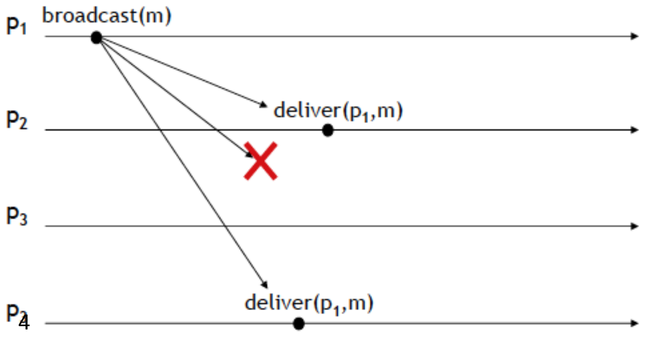
```
Implements:
    BestEffortBroadcast (beb).

Uses:
    PerfectPointToPointLinks (pp2p).

upon event ⟨ bebBroadcast | m ⟩ do
    forall $p_i \in \Pi$ do
        trigger ⟨ pp2pSend | $p_i, m$ ⟩;

upon event ⟨ pp2pDeliver | $p_i$, $m$ ⟩ do
    trigger ⟨ bebDeliver | $p_i$, $m$ ⟩;
```

Beb example (1)



Beb example (2)

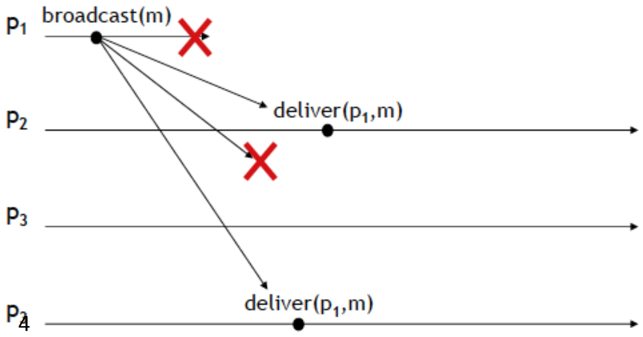
- Is this allowed ? Ie, does Beb algo could behave like that?
  - No because P1 not failed, so in the Beb mode, it should succeed to deliver m to P3 (violates BEB1)



Beb example (3)

- Is this allowed ? Ie, does Beb algo could behave like that?
  - Yes because P1 is not correct, so in the Beb mode, it is not a problem that it could not deliver m to P3 (does not violate BEB1)

STA COSA NON SUCCEDE



Causal Order Bcast

- Motivation
  - Assume a chat application
    - Whatever written is broadcasted to a group
- If you get the following output, is it ok?

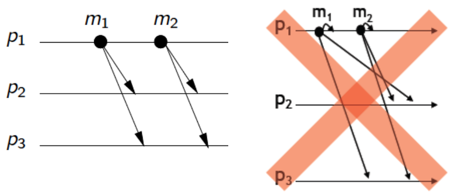
[FBon]	Are you sure? Not in room 411 ?
[Mr Y]	Room 515, 5th floor at CS dept
[Mr X]	Does anyone know where the lecture is today?

- Mr X's message caused Mr Y's message
  - Mr Y's message caused FBon's message

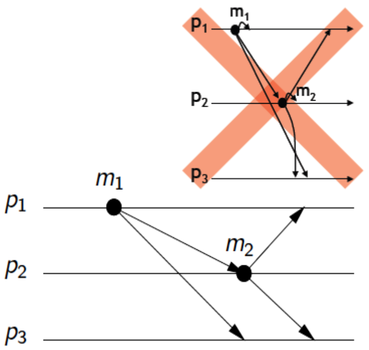
Causality recalled, in context of GC

- Let m_1 and m_2 be any two messages:
  - $m_1 \to m_2$ (m_1 causally precedes m_2) if
  - ***C1 (FIFO order).***
    - Some process p_i broadcasts m_1 before broadcasting m_2
  - ***C2 (Network order).***
    - Some process p_i delivers m_1 and later broadcasts m_2
  - ***C3 (Transitivity).***
    - There is a message m' such that $m_1 \to$ m' and m' $\to m_2$

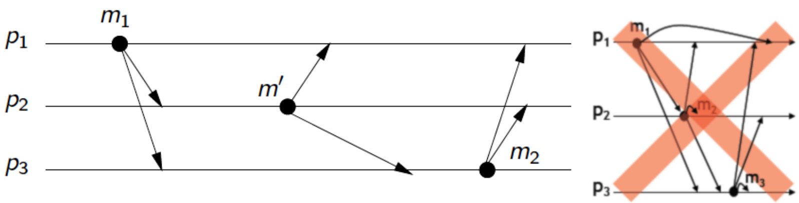
Causal Order bcast



C1 (FIFO order).



C2 (Network order).



C3 (Transitivity).

CO Bcast interface

- Module:
  - Name: CausalOrder (co)
- Events
  - Request: ⟨coBroadcast | m⟩
  - Indication: ⟨coDeliver | src, m⟩
- Property:
  - **CB: *causal delivery:*** If node p_i delivers m_1, then p_i must have delivered every message causally preceding (→) m_1 before m_1

Why Causal broadcast is difficult to design/implement **in the presence of faults** ?

- Exo: Come up with a simple Causal Order Broadcast algorithm using **best-effort bcast**…

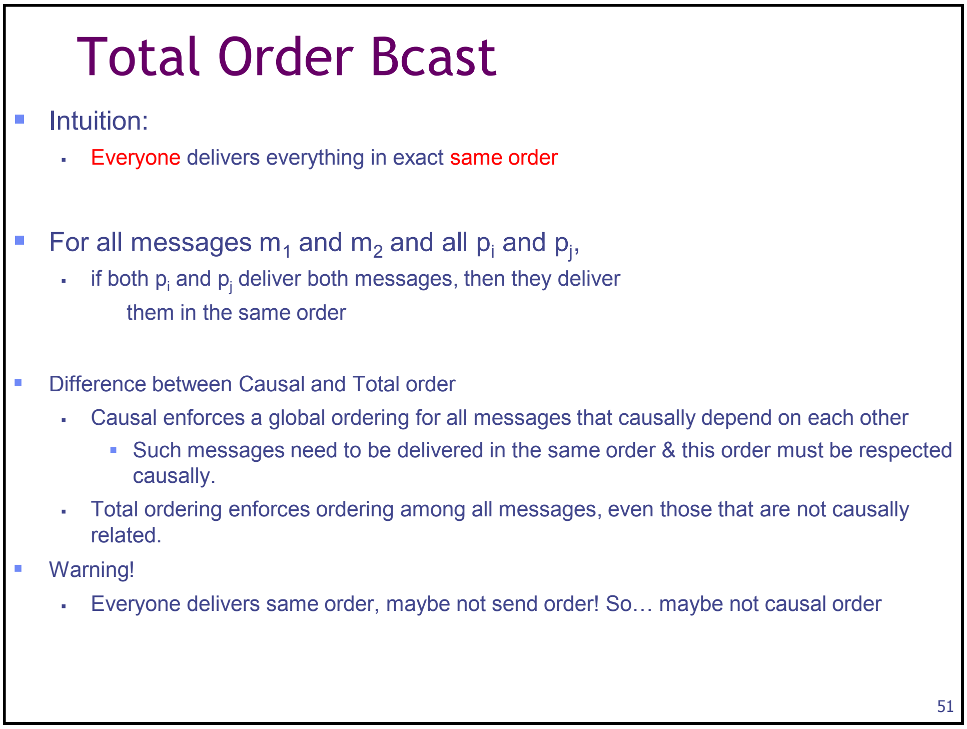
Impossible!: it refers to FLP theorem =>

Because of the use of BEB: impossible to know that a message from the past is missing for ever because not transmitted by the crashed emitter process, or simply in transit.

FLP tells us: Impossible to decide / to agree (consensus); any protocol for consensus (or equivalently ordered bcast) is blocking in an asynchronous system with faults. Only way is to “handle” possible faults

So, if you deliver m, but later you receive an ancestor of m that was delayed, you violate CB property

=> Draw an illustrative example with 3 processes, and one fails

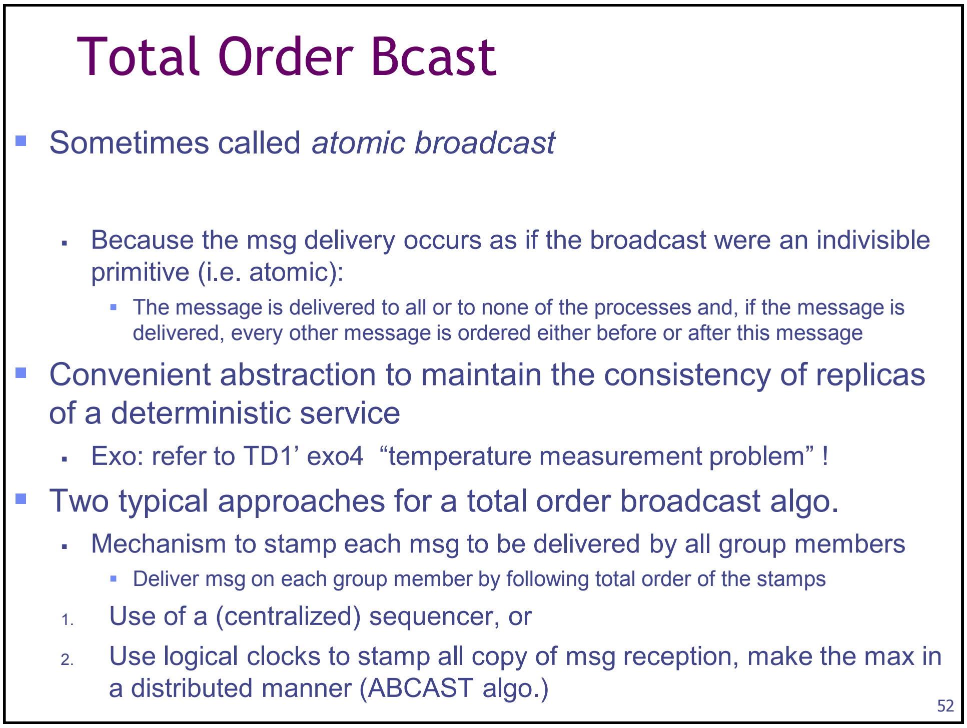


Total Order Bcast

- Intuition:
  - Everyone delivers everything in exact same order

- For all messages m_1 and m_2 and all p_i and p_j,
  - if both p_i and p_j deliver both messages, then they deliver them in the same order

- Difference between Causal and Total order
  - Causal enforces a global ordering for all messages that causally depend on each other
    - Such messages need to be delivered in the same order & this order must be respected causally.
  - Total ordering enforces ordering among all messages, even those that are not causally related.
- Warning!
  - Everyone delivers same order, maybe not send order! So… maybe not causal order



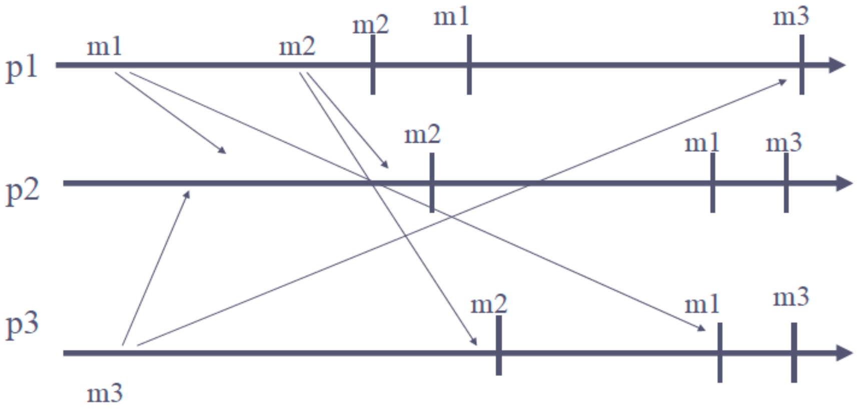
Total Order Bcast

- Sometimes called *atomic broadcast*

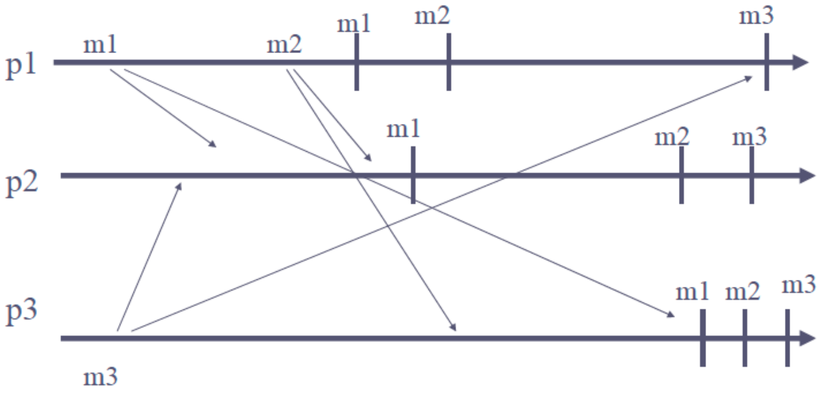
  - Because the msg delivery occurs as if the broadcast were an indivisible primitive (i.e. atomic):
    - The message is delivered to all or to none of the processes and, if the message is delivered, every other message is ordered either before or after this message
- Convenient abstraction to maintain the consistency of replicas of a deterministic service
  - Exo: refer to TD1' exo4 "temperature measurement problem" !
- Two typical approaches for a total order broadcast algo.
  - Mechanism to stamp each msg to be delivered by all group members
    - Deliver msg on each group member by following total order of the stamps

  1. Use of a (centralized) sequencer, or
  2. Use logical clocks to stamp all copy of msg reception, make the max in a distributed manner (ABCAST algo.)

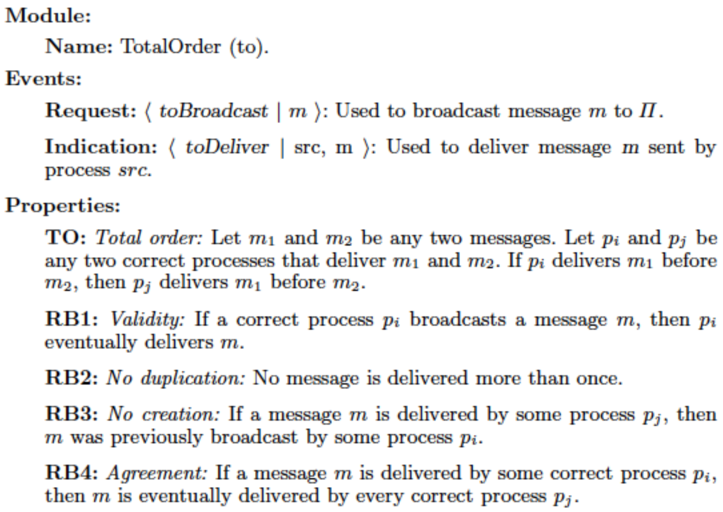
Total Order Bcast



Total Order Bcast



Total Order Bcast (using reliable bcast see next): properties



Module:

Name: TotalOrder (to).

Events:

Request: ⟨ *toBroadcast* | m ⟩: Used to broadcast message m to Π.

Indication: ⟨ *toDeliver* | src, m ⟩: Used to deliver message m sent by process src.

Properties:

TO: *Total order:* Let m_1 and m_2 be any two messages. Let p_i and p_j be any two correct processes that deliver m_1 and m_2. If p_i delivers m_1 before m_2, then p_j delivers m_1 before m_2.

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

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

RB3: *No creation:* If a message m is delivered by some process p_j, then m was previously broadcast by some process p_i.

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

A tour into reliable broadcast abstractions

Reliable GC

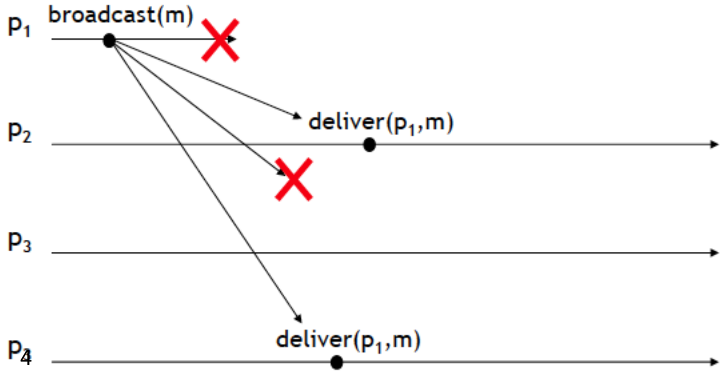
- Why do we need reliable communication primitives ?
  - Network primitives are not enough...
  - Reliable applications need underlying services stronger than network protocols (TCP,UDP...)

Reliable GC (cont'd)

- Network protocols aren't enough...
  - Communications
    - Reliability guarantees (eg TCP) only offered for one-to-one communication (client-server)
    - How to do group communication?
  - High level services
    - Sometimes one-to-one communications is not enough
    - There is a need for reliable high-level services

Reliable Bcast

- Unreliable broadcast



Reliable Bcast

- BEB gives no guarantees if sender crashes

  BEB1: For any 2 processes pi and pj,If pi and pj are correct, then every message broadcast by pi is eventually delivered by pj

- Reliable Broadcast Intuition
  - Same as BEB, + specific actions to give reliability property
  - If sender crashes:
    - ensure *all or none* of the correct nodes get msg

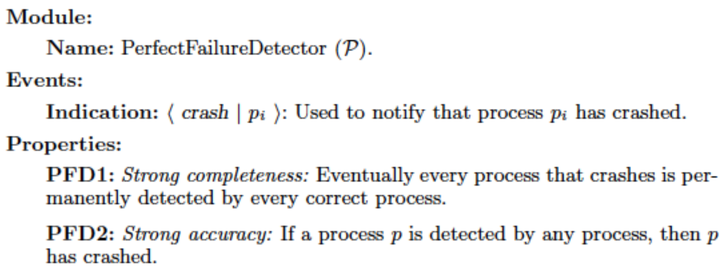
Failure Detector

- But first...a word on Failure Detectors (FD)
  - Abstracting time
  - FD provide information (not necessary fully accurate) about which processes have crashed
  - Use failure detectors to encapsulate timing assumptions
    - Black box giving suspicions regarding node failures
    - Accuracy of suspicions depends on model strength
    - (Failure Detection discussed in details in another course)

Failure Detector

- Typical Implementation of a Failure Detector
  - Periodically exchange heartbeat messages
  - Timeout based on worst case msg round trip
  - If timeout, then suspect node
  - If recv msg from suspected node, revise suspicion and increase time-out
- Two important requirements
  - 1.Completeness requirements
    - Requirements regarding actually crashed nodes
      - When do they have to be detected?
  - 2. Accuracy requirements
    - Requirements regarding actually alive nodes
      - When are they allowed to be suspected?

Perfect Failure Detector



Module:

Name: PerfectFailureDetector ($\mathcal{P}$).

Events:

Indication: $\langle$ *crash* | p_i $\rangle$: Used to notify that process p_i has crashed.

Properties:

PFD1: *Strong completeness:* Eventually every process that crashes is permanently detected by every correct process.

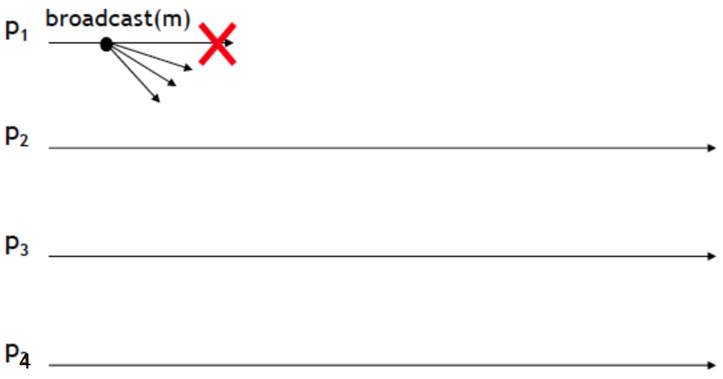
PFD2: *Strong accuracy:* If a process p is detected by any process, then p has crashed.

Reliable Bcast

- Module:
  - Name: (regular)ReliableBroadcast (rb).
- Events:
  - Request: <rbBroadcast | m >: Used to broadcast message m.
  - Indication: < rbDeliver | src,m> : Used to deliver message m broadcast by process src.
- Properties:
  - ***RB1=Beb1:*** *Validity*: If a correct process p_i broadcasts a message m, then p_i eventually delivers m.
  - ***RB2=Beb2:*** *No duplication*: No message is delivered more than once.
  - ***RB3=Beb3:*** *No creation*: If a message m is delivered by some process p_j, then m was previously broadcast by some process p_i.
  - ***RB4:*** *Agreement*: If a message m is delivered by some correct process p_i,then m is eventually delivered by every correct process p_j .

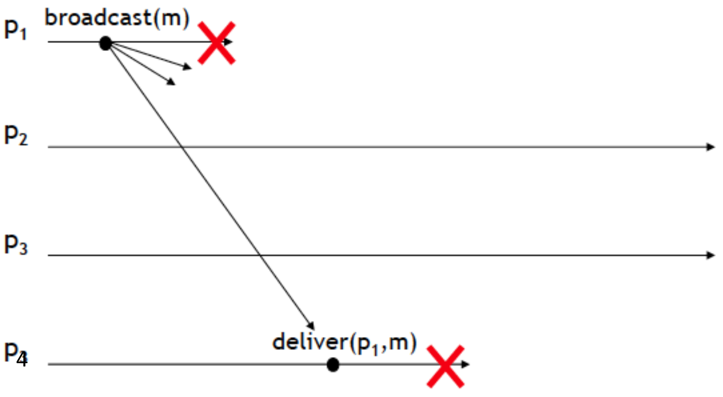
Reliable Bcast – example 1

- Is this allowed ?



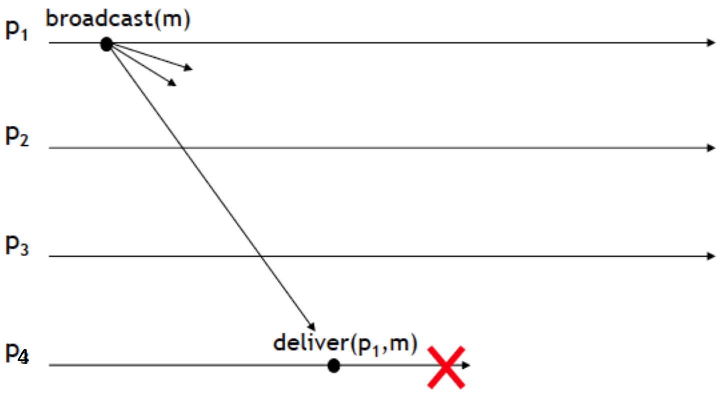
Reliable Bcast – example 2

- Is this allowed ?

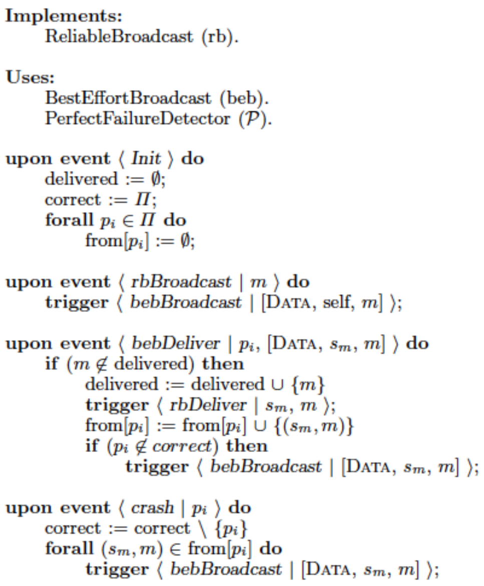


Reliable Bcast – example 3

- Is this allowed ?



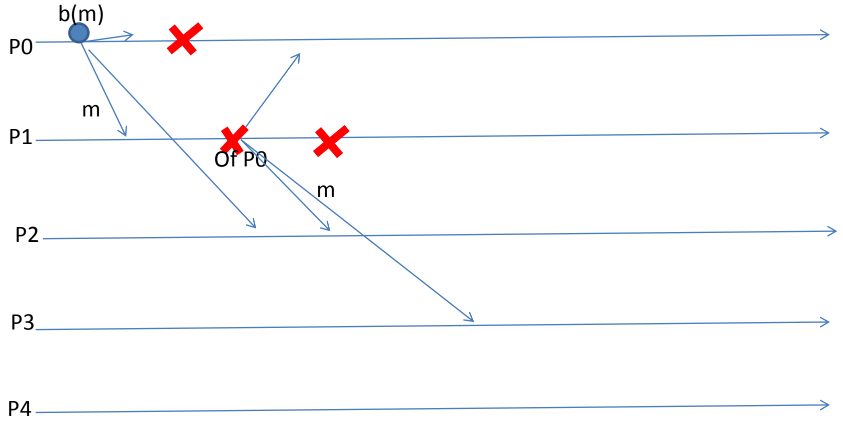
Algorithm (RBcast)



```
Implements:
    ReliableBroadcast (rb).

Uses:
    BestEffortBroadcast (beb).
    PerfectFailureDetector ($\mathcal{P}$).

upon event ⟨ Init ⟩ do
    delivered := $\emptyset$;
    correct := $\Pi$;
    forall $p_i \in \Pi$ do
        from[$p_i$] := $\emptyset$;

upon event ⟨ rbBroadcast | $m$ ⟩ do
    trigger ⟨ bebBroadcast | [DATA, self, $m$] ⟩;

upon event ⟨ bebDeliver | $p_i$, [DATA, $s_m$, $m$] ⟩ do
    if ($m \notin$ delivered) then
        delivered := delivered $\cup$ {$m$}
        trigger ⟨ rbDeliver | $s_m$, $m$ ⟩;
        from[$p_i$] := from[$p_i$] $\cup$ {($s_m$, $m$)}
        if ($p_i \notin$ correct) then
            trigger ⟨ bebBroadcast | [DATA, $s_m$, $m$] ⟩;

upon event ⟨ crash | $p_i$ ⟩ do
    correct := correct \ {$p_i$}
    forall ($s_m$, $m$) $\in$ from[$p_i$] do
        trigger ⟨ bebBroadcast | [DATA, $s_m$, $m$] ⟩;
```

- Fail-stop model

Initial Time-space diagram for exercice 1: continue the simulation



Reliable Bcast plus uniformity

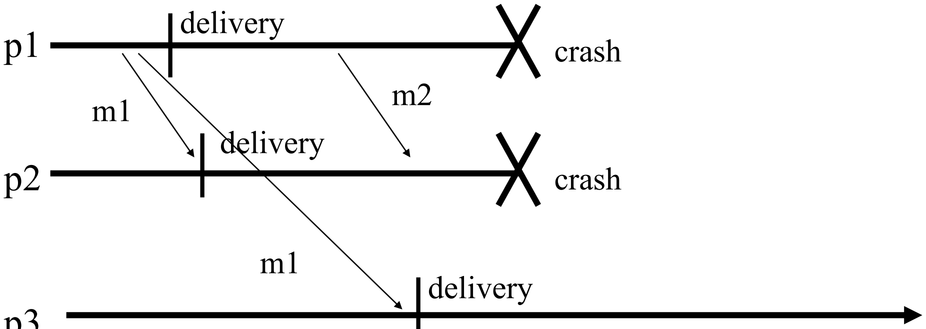
- BEB gives no guarantees if sender crashes

  BEB1: For any 2 processes pi and pj,If pi and pj are correct, then every message broadcast by pi is eventually delivered by pj

- Reliable Broadcast Intuition
  - Same as BEB, + specific actions to give reliability property
  - If sender crashes:
    - ensure *all or none* of the correct nodes get msg
    - What about the msg delivery on the sender and other processes even if crashed ?
      - A *property* (e.g. agreement) is *uniform* if faulty processes satisfy it as well
      - In practice: uniformity ensures that effect of an action (here, msg delivery) visible from the external world (not easily "cancellable") is the same on every (remaining correct) node. (e.g. bank account credit on a replica, even if fails afterwards, must be propagated to all correct replica!)
    - *URB. Uniform Agreement:* For any message m, if a process delivers m, then every correct process delivers m.
      - Then the Reliable bcast algo is also Uniform -URB
    - NB: In this course, we only focus on (non uniform) bcast algorithms

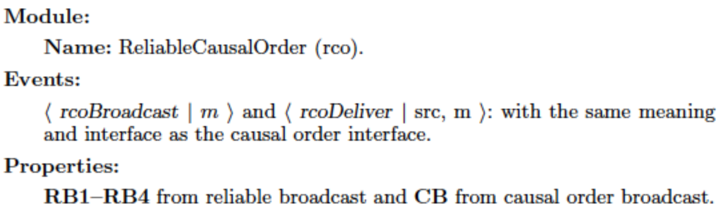
70

Uniform reliable broadcast



- P1 has delivered m1, so p3 must do so, and p2 also (as not yet crashed on the picture!)
- P1 has not delivered m2, so p3 is not obliged to deliver m2, nor p2
- Assume no comm failure: on R-bcast, not only forward m to all but also RB-deliver m

Reliable Causal Order Bcast



Module:

Name: ReliableCausalOrder (rco).

Events:

⟨ *rcoBroadcast* | *m* ⟩ and ⟨ *rcoDeliver* | src, m ⟩: with the same meaning and interface as the causal order interface.

Properties:

RB1–RB4 from reliable broadcast and CB from causal order broadcast.

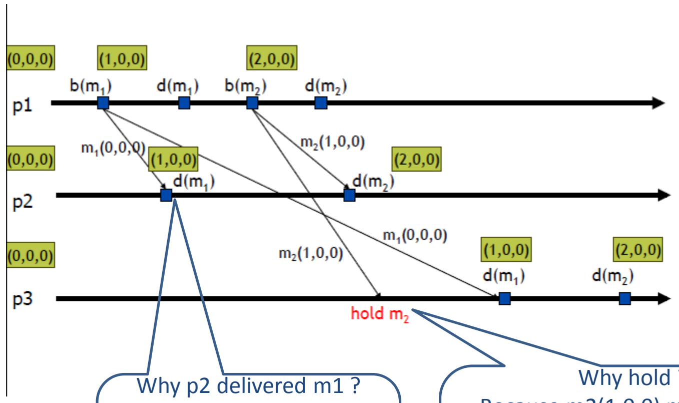
CB: If node p_i delivers m_1, then p_i must have delivered every message causally preceding (→) m_1 before m_1

- Main idea
  - Each broadcasted message carries a history
  - Before delivery, ensure causality

Reliable Causal Order Bcast Algo with Vector Clock

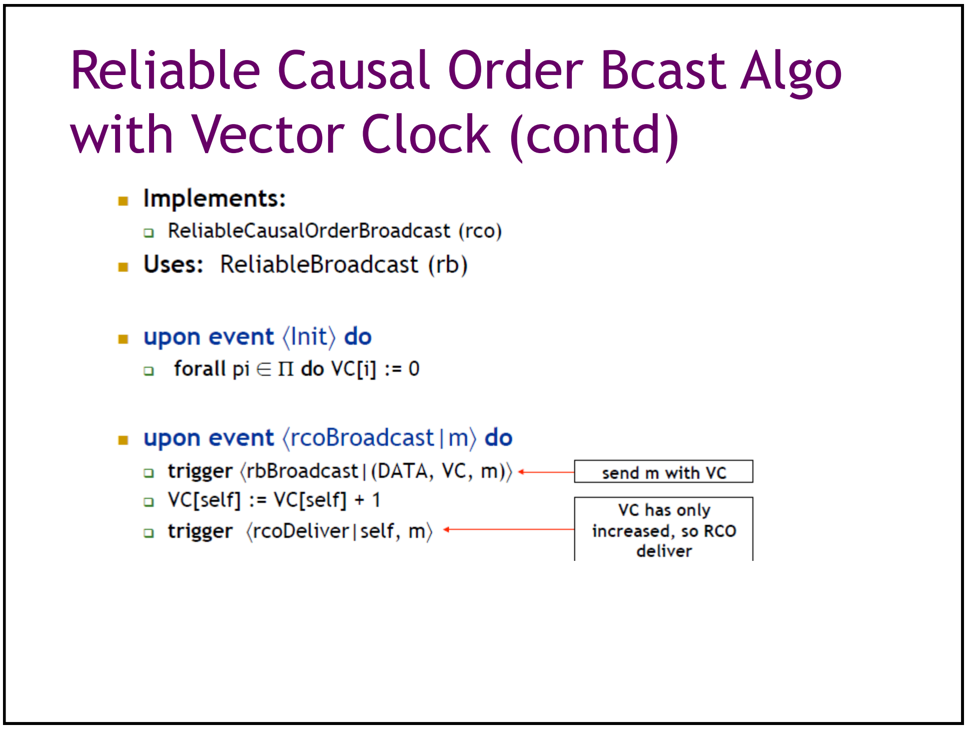
- Represent past history by vector clock (VC)
- Slightly modify the VC implementation
  - At node p_i
    - VC[i]: number of messages p_i coBroadcasted
    - VC[j], $j \neq i$: number of messages p_i coDelivered from p_j
- Upon CO broadcast m
  - Piggyback VC and RB broadcast m
- Upon RB delivery of m with attached VC_m compare VC_m with local VC_i
  - Only deliver m once VC_m precedes ($\leq$) VC_i

Execution



Why p2 delivered m1 ?
because VCm1<=VCp2
After P2 delivered m1, why VC[1] on P2 ==1 ?
Because p2 codelivered 1 message from P1.

Why hold ?
Because m2(1,0,0) means it is a causal consequence of 1 message delivered on P1, but p3 has not yet delivered (nor received:=)) this message. Can see this, as p3' clock (000) < m2 ' (100)



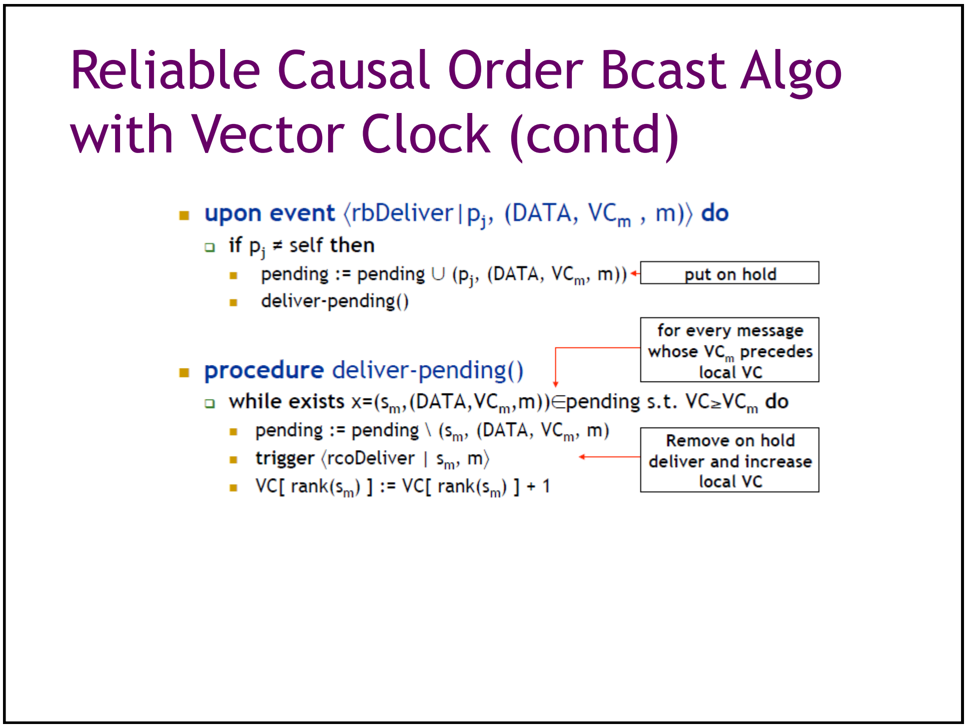
Reliable Causal Order Bcast Algo with Vector Clock (contd)

- **Implements:**
  - ReliableCausalOrderBroadcast (rco)
- **Uses:** ReliableBroadcast (rb)

```
upon event ⟨Init⟩ do
    forall pi $\in \Pi$ do VC[i] := 0

upon event ⟨rcoBroadcast | m⟩ do
    trigger ⟨rbBroadcast | (DATA, VC, m)⟩
    VC[self] := VC[self] + 1
    trigger ⟨rcoDeliver | self, m⟩
```

send m with VC

VC has only increased, so RCO deliver



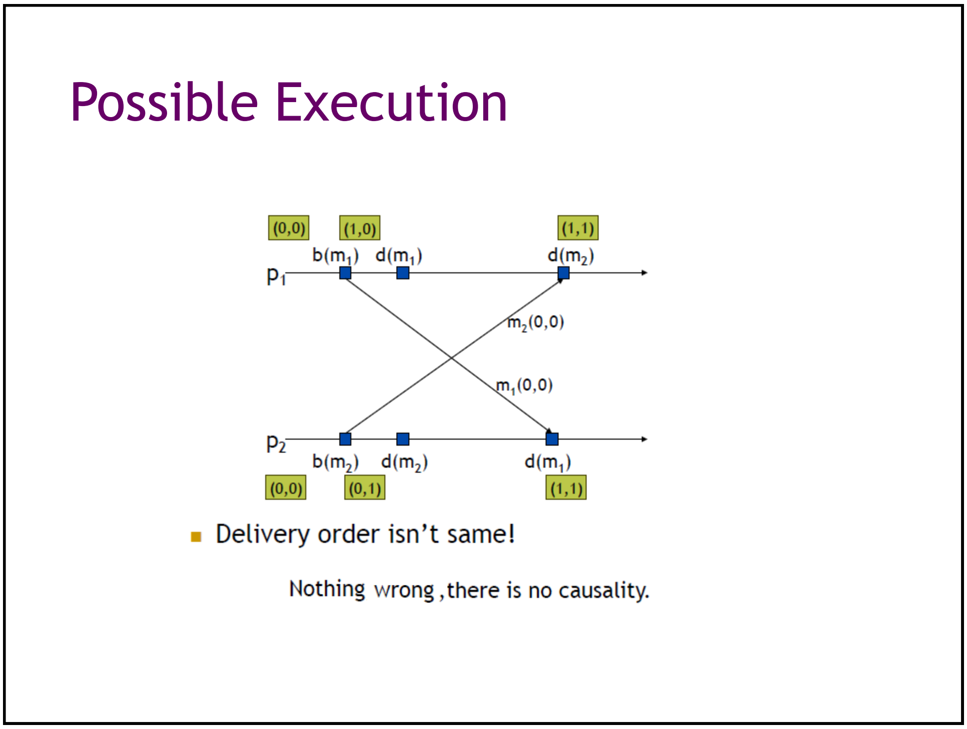
Reliable Causal Order Bcast Algo with Vector Clock (contd)

```
upon event ⟨rbDeliver | $p_j$, (DATA, $VC_m$ , m)⟩ do
    if $p_j \neq$ self then
        pending := pending $\cup$ ($p_j$, (DATA, $VC_m$, m))
        deliver-pending()

procedure deliver-pending()
    while exists x=($s_m$,(DATA,$VC_m$,m))$\in$pending s.t. $VC \geq VC_m$ do
        pending := pending \ ($s_m$, (DATA, $VC_m$, m)
        trigger ⟨rcoDeliver | $s_m$, m⟩
        VC[ rank($s_m$) ] := VC[ rank($s_m$) ] + 1
```

put on hold

for every message whose VC_m precedes local VC

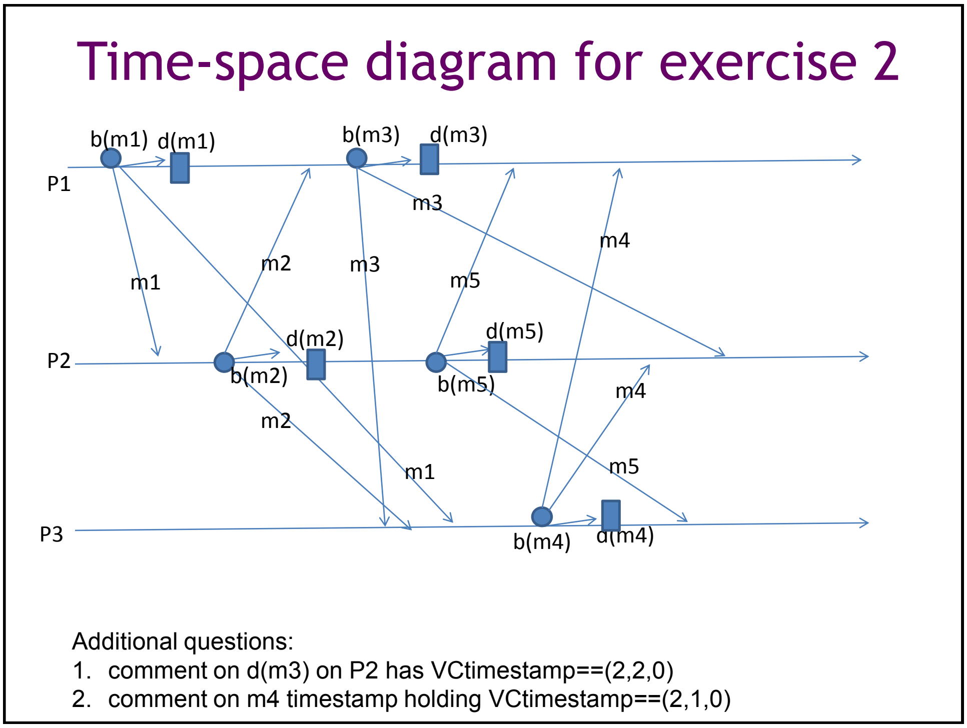
Remove on hold deliver and increase local VC



Possible Execution

- Delivery order isn't same!

Nothing wrong ,there is no causality.



Time-space diagram for exercise 2

Additional questions:

1. comment on d(m3) on P2 has VCtimestamp==(2,2,0)
2. comment on m4 timestamp holding VCtimestamp==(2,1,0)

Consensus vs. Group Comm ?

Decide of a value among propositions, eg updating replicated variable A

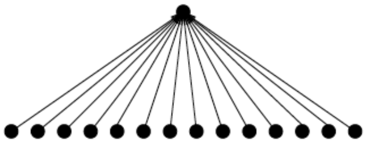
- All non failed nodes must agree the same
- To avoid node failures, need to suspect node crash
- Decision value per value
- Ordering among decided values can be
  - Total
    - Eg RSM any sequence A:=5;read A; A:=7
  - And FIFO (eg as in Zookeeper' AB: primary order FIFO)

Decide to deliver m, a msg broadcasted, on each node

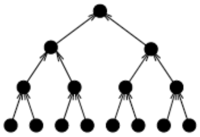
- All correct nodes must deliver the message
- Same: use PFD to be informed about nodes crash
- Decision msg per msg
- Ordering among delivered messages can be
  - FIFO
  - Causal
  - **Total**

Scalability issues of Reliable Bcast

- The *Ack implosion* problem

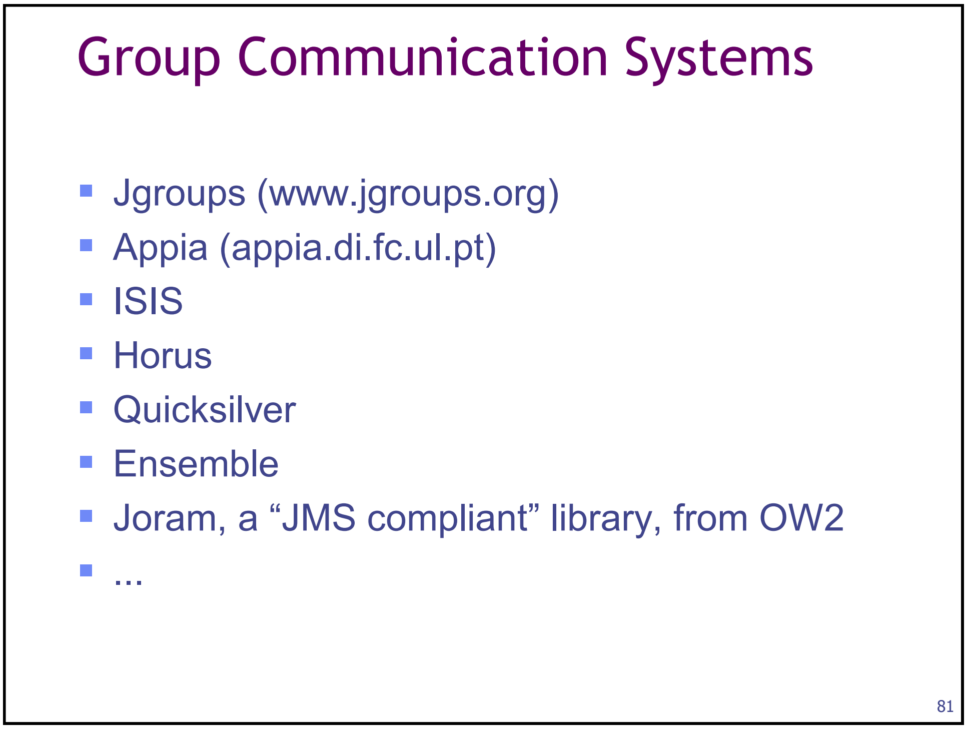


- One way to circumvent it: using an *ack tree*



- Other mechanisms can also be used to circumvent this limitation
  - Epidemic dissemination (or *probabilistic broadcast*)

80



Group Communication Systems

- Jgroups (www.jgroups.org)
- Appia (appia.di.fc.ul.pt)
- ISIS
- Horus
- Quicksilver
- Ensemble
- Joram, a “JMS compliant” library, from OW2
- ...