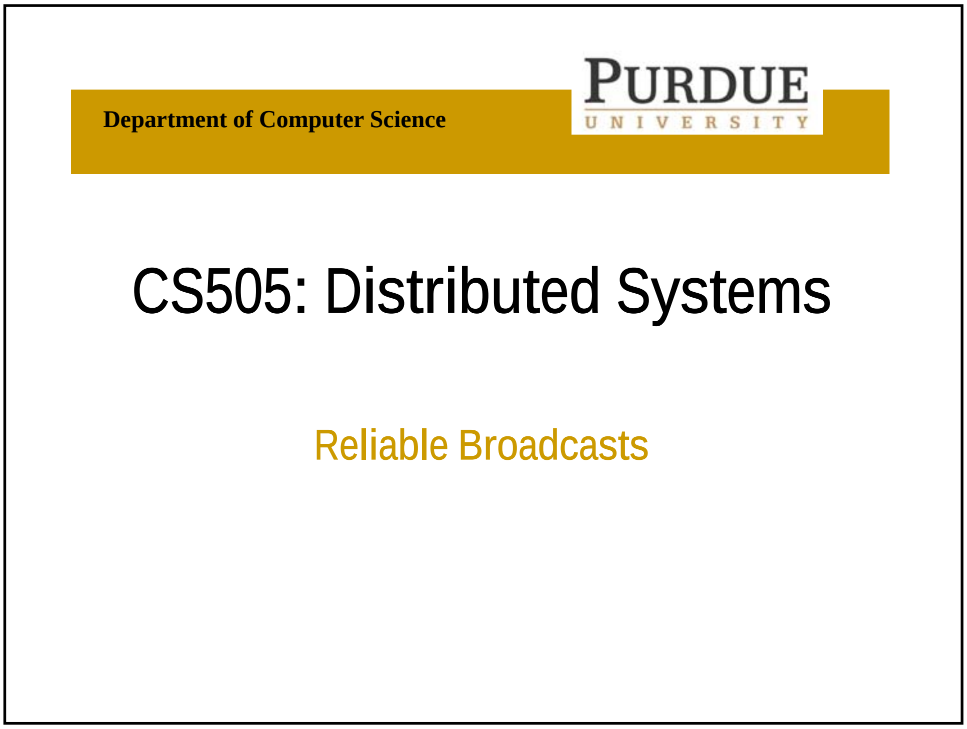
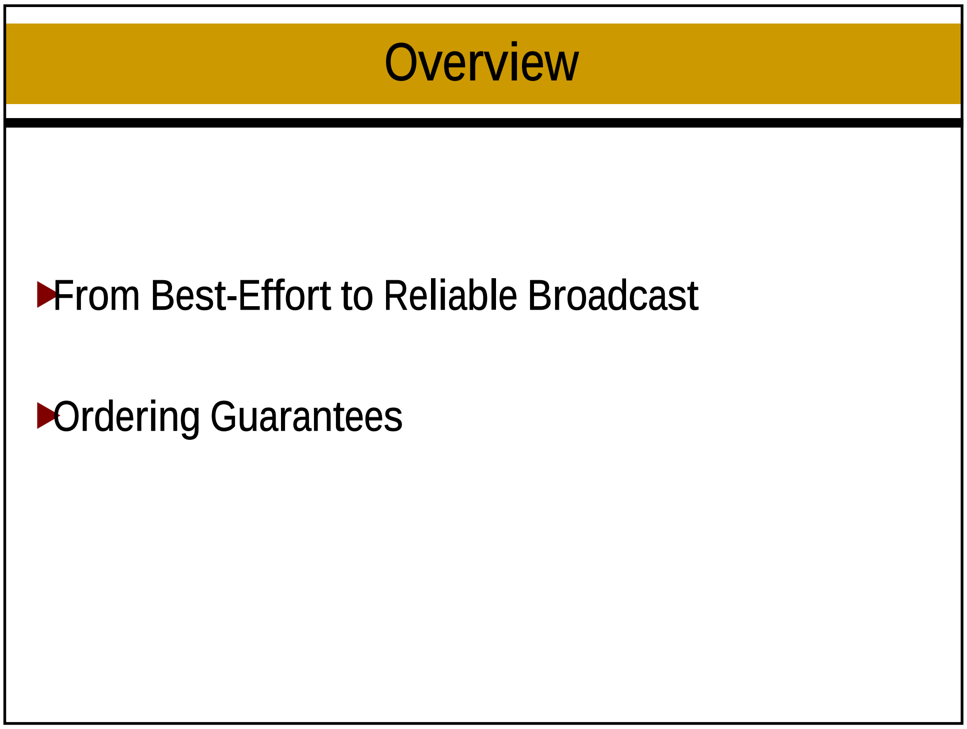


Department of Computer Science

PURDUE UNIVERSITY

CS505: Distributed Systems

Reliable Broadcasts



Overview

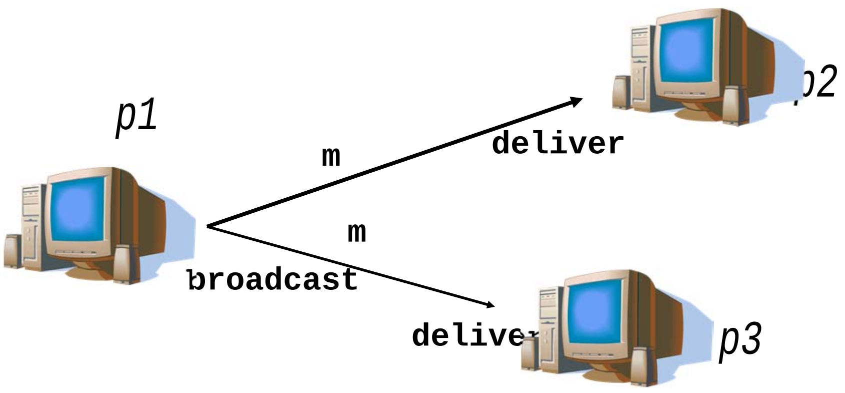
- From Best-Effort to Reliable Broadcast
- Ordering Guarantees

Distributed Systems

- Network provides one-to-one communication primitives
  - Sometimes one-to-many also
    - Membership opaque
    - Fuzzy guarantees
- Need one-to-many communication primitives
  - E.g., replication, peer discovery
  - With reliability guarantees!
    - And possibly ordering

Example: Reliable Broadcast

- Informally
  - A process p_1 wants to **send** a message **`m`** to *several* processes $p_2 \ldots p_n$
- Scenario
  - Chat, mailing list, …
- Assume
  - Asynchronous system
  - Reliable channels
  - Crash-stop failures of processes



p1

m

m

broadcast

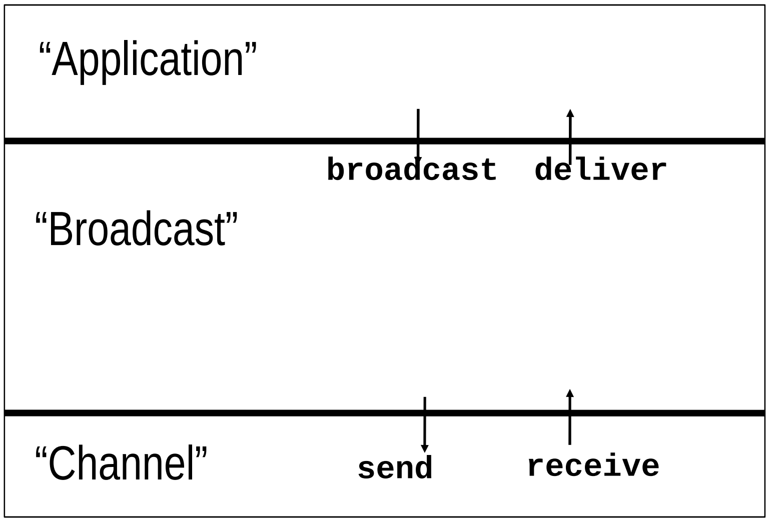
deliver

p2

deliver

p3

Layers



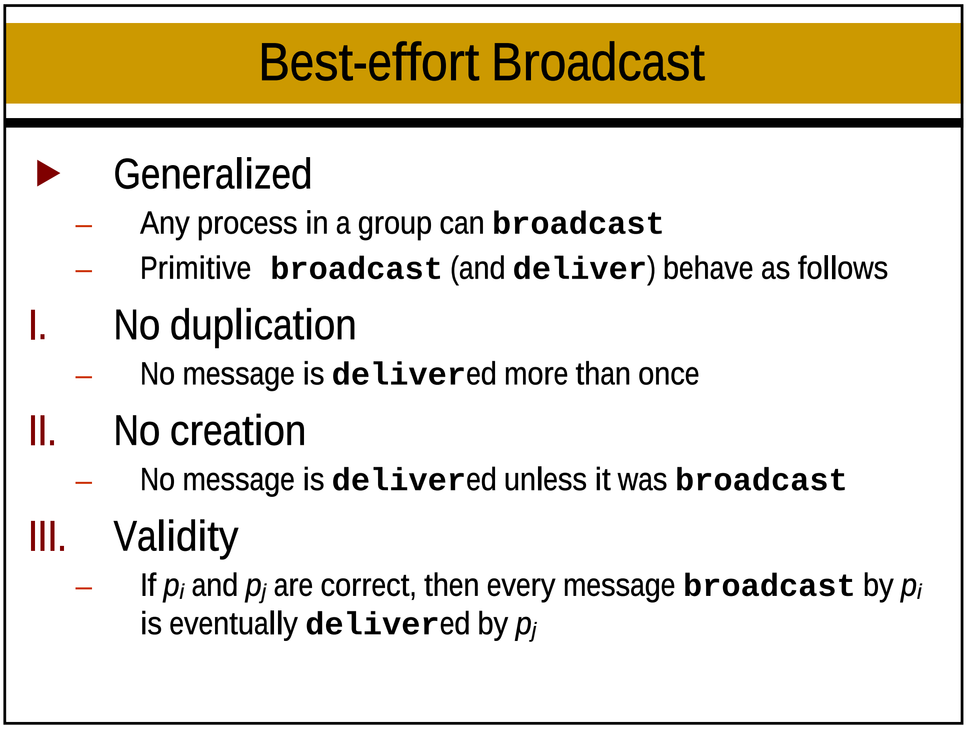
“Application”

broadcast deliver

“Broadcast”

“Channel”

send receive



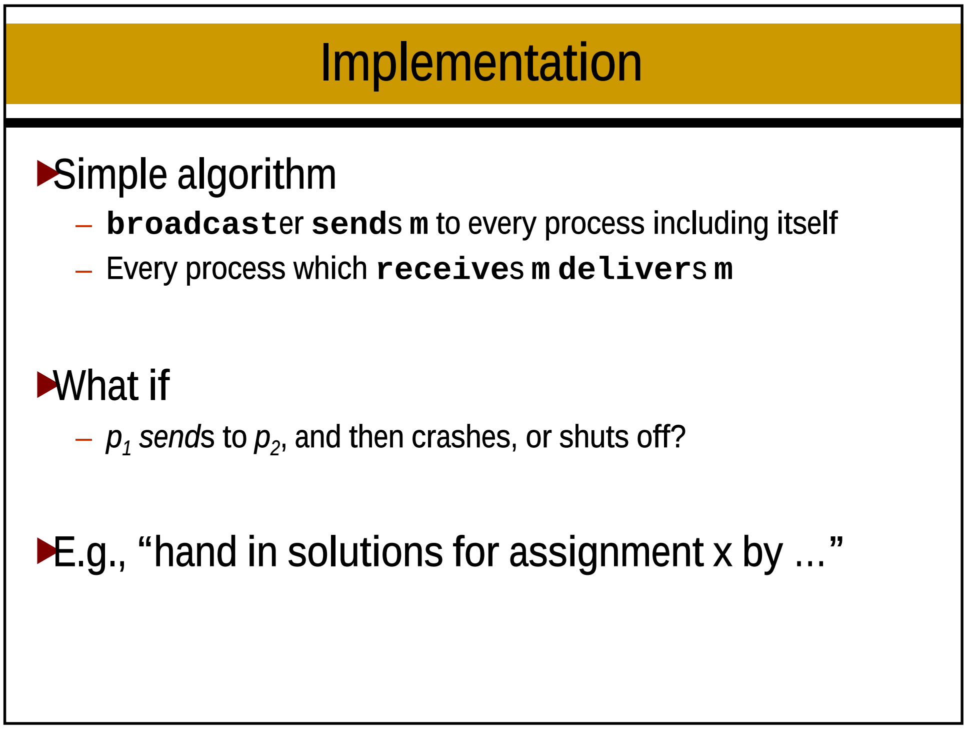
Best-effort Broadcast

- Generalized
  - Any process in a group can **`broadcast`**
  - Primitive **`broadcast`** (and **`deliver`**) behave as follows

I. No duplication
  - No message is **`deliver`**ed more than once

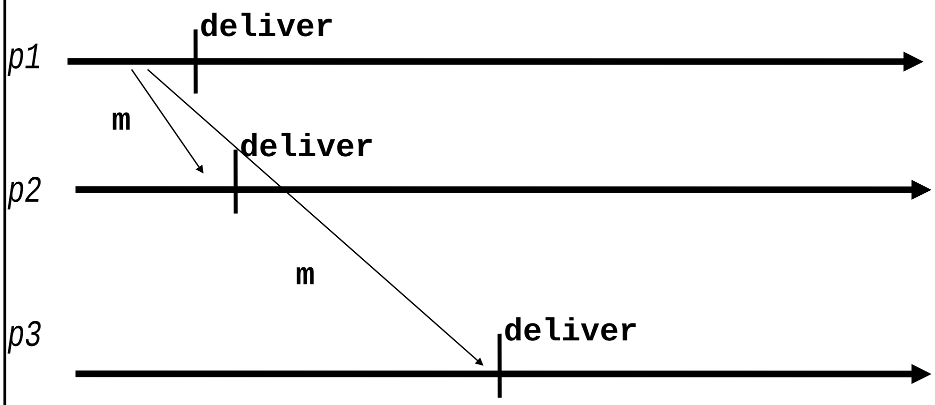
II. No creation
  - No message is **`deliver`**ed unless it was **`broadcast`**

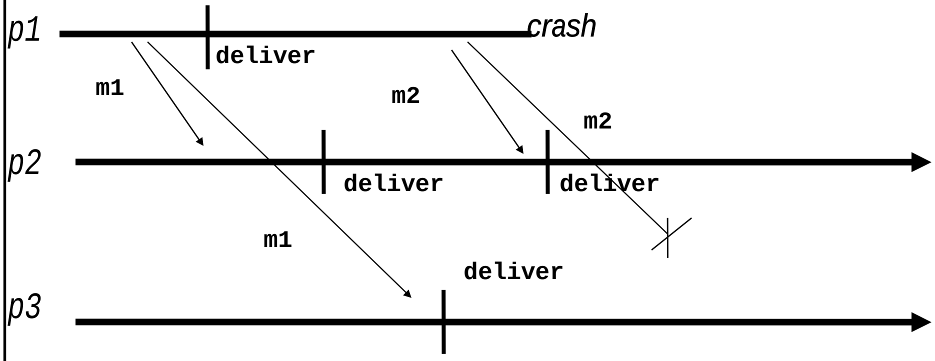
III. Validity
  - If p_i and p_j are correct, then every message **`broadcast`** by p_i is eventually **`deliver`**ed by p_j



Implementation

- Simple algorithm
  - **`broadcast`**er **`send`**s **`m`** to every process including itself
  - Every process which **`receive`**s **`m`** **`deliver`**s **`m`**
- What if
  - p_1 *send*s to p_2, and then crashes, or shuts off?
- E.g., “hand in solutions for assignment x by …”


p1
deliver
m
p2
deliver
m
p3
deliver


p1
crash
deliver
m1
m2
m2
p2
deliver
deliver
m1
deliver
p3

Reliable Broadcast

I. No duplication
   - No message is **`deliver`**ed more than once

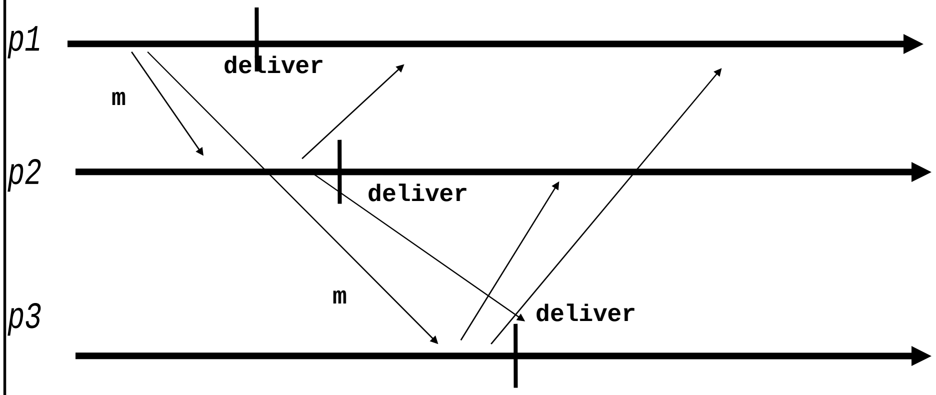
II. No creation
   - No message is **`deliver`**ed unless it was **`broadcast`**

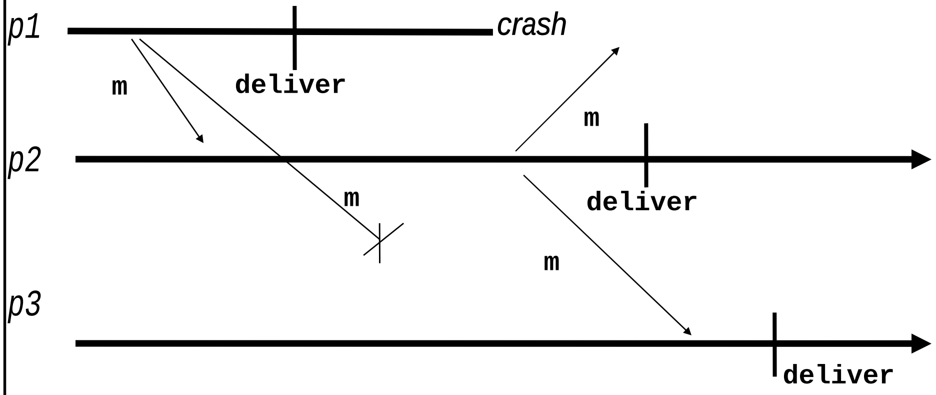
III. Validity
   - If p_i and p_j are correct, then every message **`broadcast`** by p_i is eventually **`deliver`**ed by p_j

IV. Agreement
   - If one correct process **`deliver`**s a message **`m`**, every correct process eventually **`deliver`**s **`m`**

Proposal

- Simple algorithm
  - *p* **`send`**s **`m`** to every other process including itself
  - Every process which **`receive`**s **`m`** for the first time **`send`**s it to every other process (except the sender) and **`deliver`**s it


p1
deliver
m
p2
deliver
m
p3
deliver


p1
crash
m
deliver
m
p2
m
deliver
m
p3
deliver

Correctness?

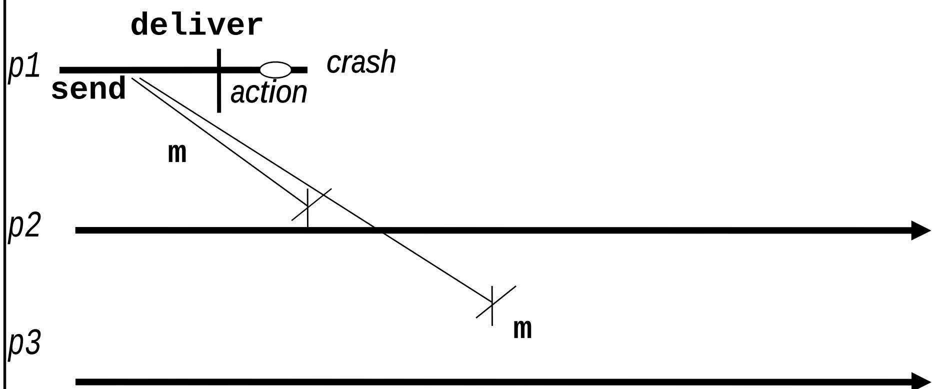
- I. and II. by corresponding properties of reliable channels (I. also by 2nd line of algo)
- By first line of algo, broadcasting process p_i sends to every other process; if it is correct, by Validity of reliable channels every correct process eventually receives the message
- By second line of algo, every correct process p_j which receives the message eventually delivers it
- If some correct process delivers the message, it sends it (before) to all processes, and the correct ones eventually receive and deliver it

Fault Tolerance and Complexity

- How many faults can be tolerated?
- What is the complexity of the algorithm?
  - Messages
  - “Communication steps”

But

- What if a process **`deliver`**s *and then* crashes?
  - **`send`**s possibly haven't completed
  - Not correct?
  - It can initiate next action before crashing that affects entire system
- (General problem)
  - No timing assumptions
  - Algorithm runs terminate *eventually* only
  - *Correct*ness defined with respect to algorithm runs



Uniform Reliable Broadcast

I. No duplication
   - No message is **deliver**ed more than once

II. No creation
   - No message is **deliver**ed unless it was **broadcast**

III. Validity
   - If p_i and p_j are correct, then every message **broadcast** by p_i is eventually **deliver**ed by p_j

V. Uniform agreement
   - If a (correct or not) process **deliver**s a message **m**, every correct process **deliver**s **m**

A Simple Algorithm?

- Avoid that some process **deliver**s and subsequently crashes
  - Can not keep processes from crashing, can not foresee crashes
  - However, can make sure everybody **receive**s message before even thinking about **deliver**ing
  - Processes need acknowledgements from every process before **deliver**ing
    - Every process?

- Uniform Reliable Broadcast
  - Not implementable in asynchronous system
  - Need a *failure detector*

Uniform Properties

- Properties which range over *all* involved processes
  - As opposed to only *correct* ones
- Intuition
  - Correctness is bound by algorithm termination, and eventual (liveness) properties have requirements on correct processes
  - Algorithm termination on individual processes is not same
  - Some processes can terminate their “active” part of the algorithm, move on to subsequent (causally) tasks and fail amidst
    - E.g., message still in buffer of outgoing channel
    - The failure affects also the seemingly terminated previous algorithm
    - Often algorithm runs follow each other
- Sometimes “for free”

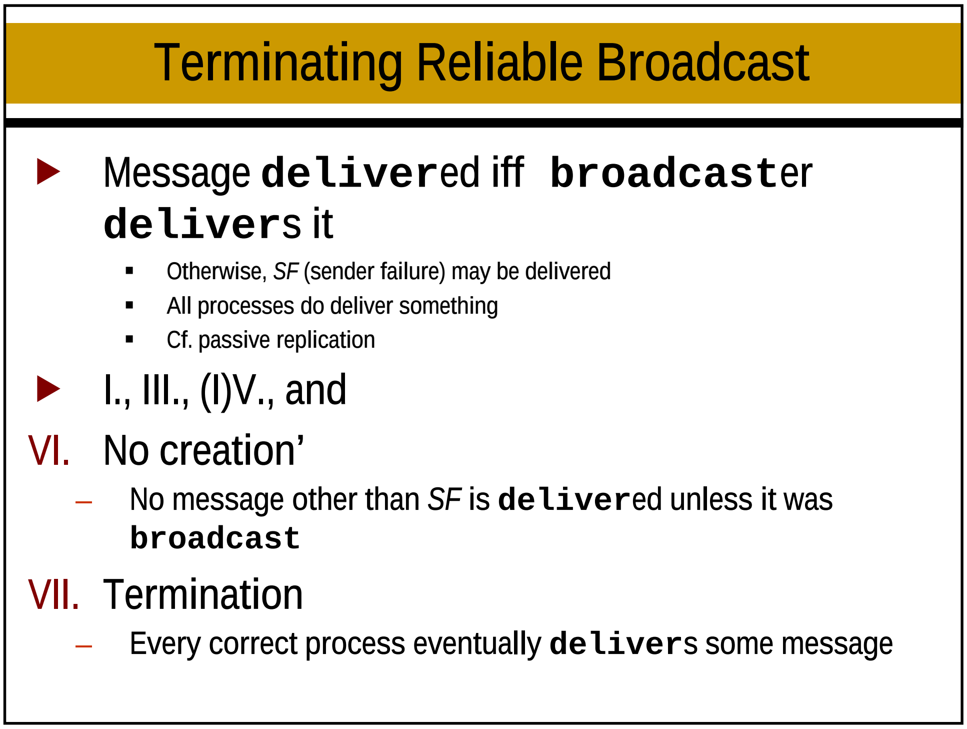
How About

- Uniform variants of:

I. No duplication
   - No message is **`deliver`**ed more than once

II. No creation
   - No message is **`deliver`**ed unless it was **`broadcast`**

- (usually summarized as Integrity)?



Terminating Reliable Broadcast

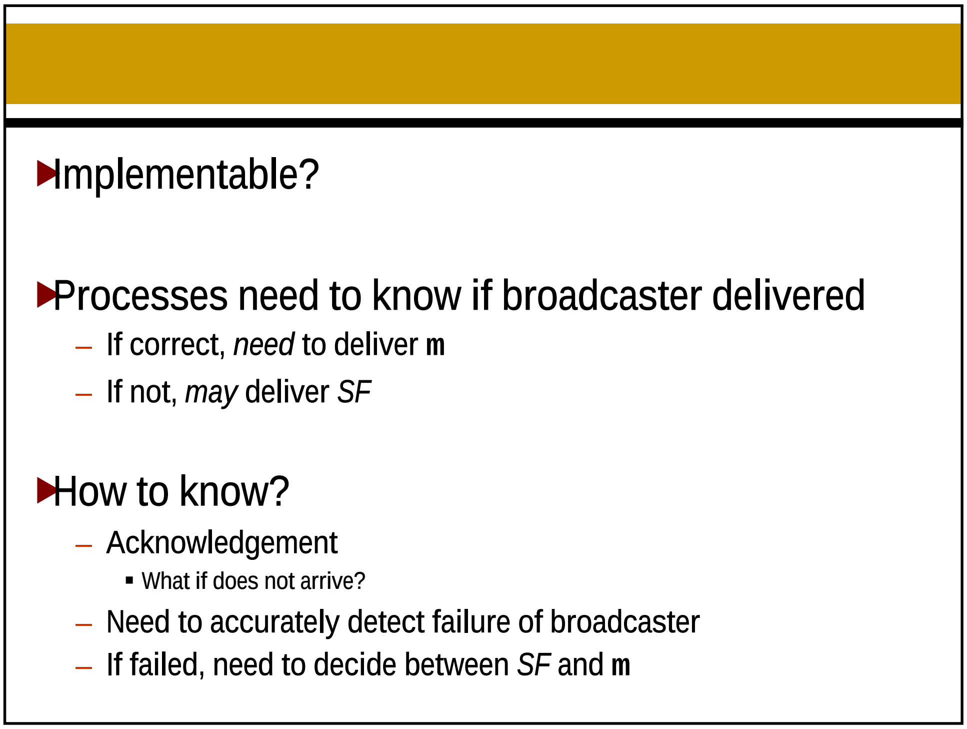
- Message **`delivered`** iff **`broadcaster`** **`delivers`** it
  - Otherwise, *SF* (sender failure) may be delivered
  - All processes do deliver something
  - Cf. passive replication
- I., III., (I)V., and

VI. No creation'

- No message other than *SF* is **`delivered`** unless it was **`broadcast`**

VII. Termination

- Every correct process eventually **`delivers`** some message

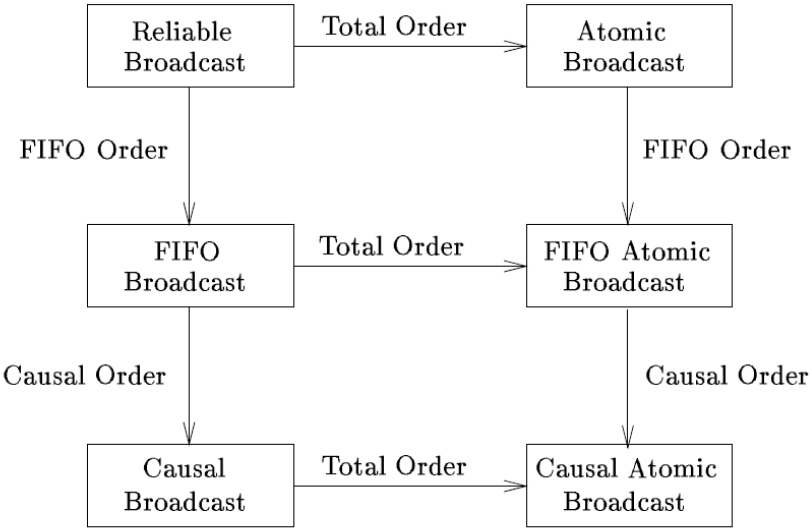


- Implementable?
- Processes need to know if broadcaster delivered
  - If correct, *need* to deliver **`m`**
  - If not, *may* deliver *SF*
- How to know?
  - Acknowledgement
    - What if does not arrive?
  - Need to accurately detect failure of broadcaster
  - If failed, need to decide between *SF* and **`m`**

Ordered Broadcasts

- Concurrency/parallelism underlies distribution
  - Concurrent activities need to be perceived by all processes in the same order
    - Cf. causality relationship
  - Ordering guarantees required depend on application
- FIFO
  - "Messages from same process are **`delivered`** in the order **`broadcast`**"
- Causal Order
  - "Messages **`broadcast`** are **`delivered`** after any messages that causally affected them"
- Total Order
  - "Processes **`deliver`** messages in same order"

Relationships



Reliable Broadcast

Total Order

Atomic Broadcast

FIFO Order

FIFO Order

FIFO Broadcast

Total Order

FIFO Atomic Broadcast

Causal Order

Causal Order

Causal Broadcast

Total Order

Causal Atomic Broadcast

FIFO Reliable Broadcast

- I., II., III., IV., and

VIII. FIFO order

- If a process **broadcasts** a message m_1 before m_2, then no correct process **delivers** m_2 before m_1

- Can we build FIFO Broadcast with Reliable Broadcast?

Proposition

```
msgBag := □
next[p] := 1 for all p

to execute broadcast_F(m):
  broadcast_R(m)              \\ m tagged with sender and seq#


deliver_F(m) occurs as follows:
  upon deliver_R(m) do
    p := sender(m)
    msgBag := msgBag ∗ {m}
    while(□ m'□ msgBag: sender(m') = p and seq#(m) = next[p]do
       deliver_F(m')
       next[p]++
       msgBag := msgBag \ {m'}
```

Uniform FIFO Order

- How about I., II., III., IV., and

IX. Uniform FIFO order

  - If a process **broadcast**s a message m_1 before m_2, then no process (correct or faulty) **deliver**s m_2 before m_1

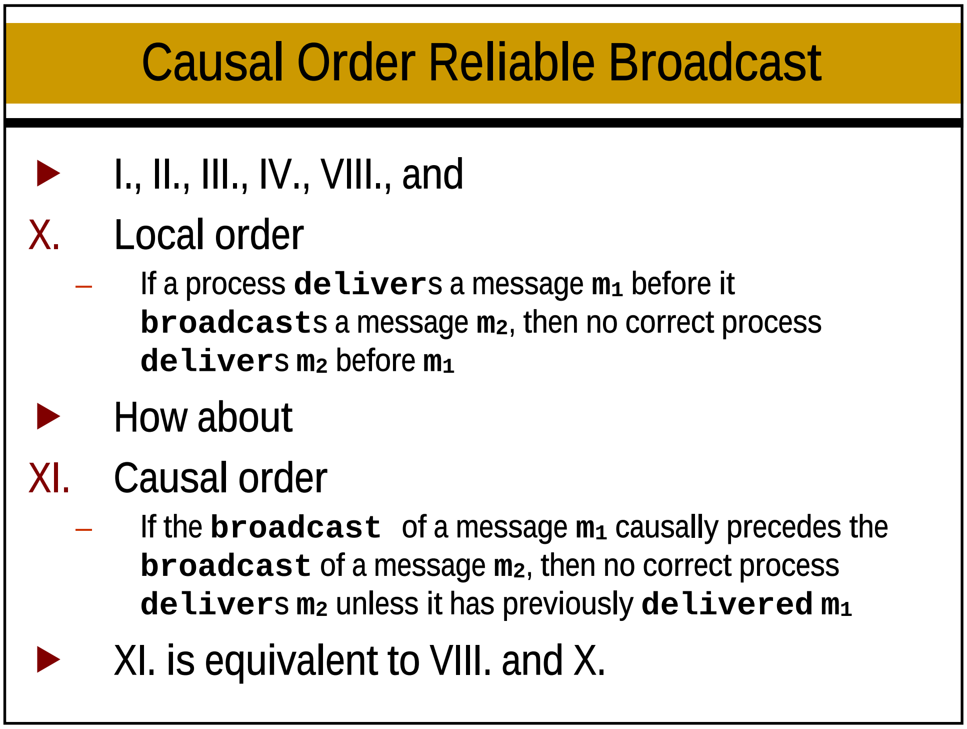
- Implementable?
- Can anyone deliver m_2 from *p* before m_1?

Causal Order Reliable Broadcast

- Causal order (in **broadcast** setting)
- *a* □ *b* ™

1. A process executed both *a* and *b*, and in that order,
2. *a* is a **broadcast(m)** and *b* is a **deliver(m)**, or
3. □ *c: a* □ *c* and *c* □ *b*

- Causal order vs FIFO order?



Causal Order Reliable Broadcast

- I., II., III., IV., VIII., and

X. Local order

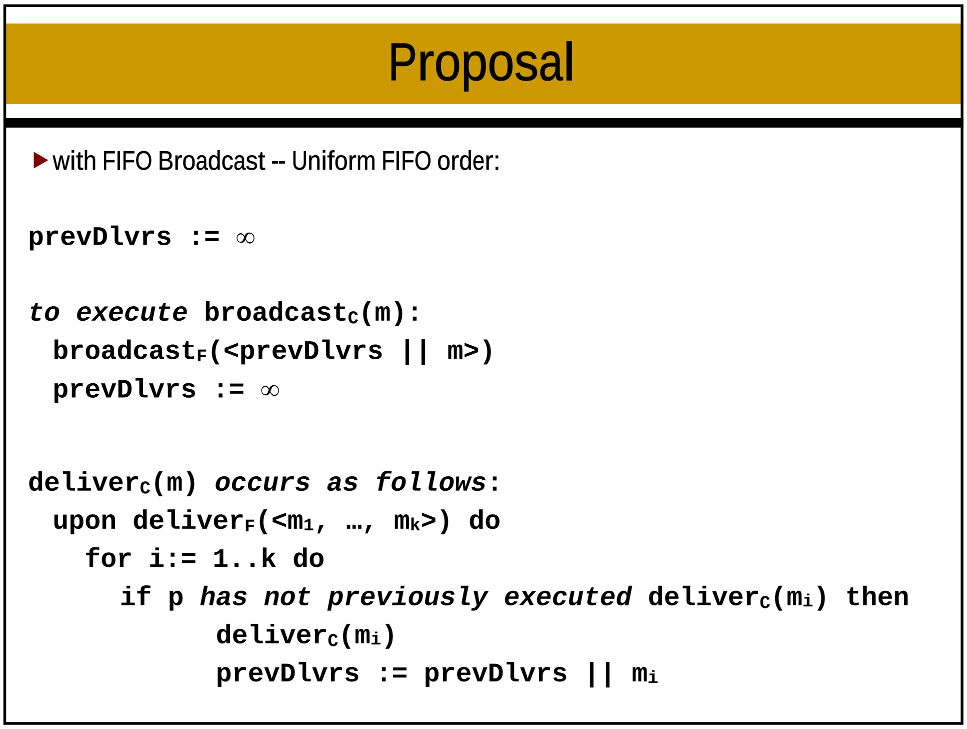
- If a process **delivers** a message m_1 before it **broadcasts** a message m_2, then no correct process **delivers** m_2 before m_1

- How about

XI. Causal order

- If the **broadcast** of a message m_1 causally precedes the **broadcast** of a message m_2, then no correct process **delivers** m_2 unless it has previously **delivered** m_1

- XI. is equivalent to VIII. and X.



Proposal

- with FIFO Broadcast -- Uniform FIFO order:

```
prevDlvrs := ∞

to execute broadcast$_C$(m):
  broadcast$_F$(<prevDlvrs || m>)
  prevDlvrs := ∞


deliver$_C$(m) occurs as follows:
  upon deliver$_F$(<$m_1$, …, $m_k$>) do
    for i:= 1..k do
      if p has not previously executed deliver$_C$($m_i$) then
            deliver$_C$($m_i$)
            prevDlvrs := prevDlvrs || $m_i$
```

Correct?

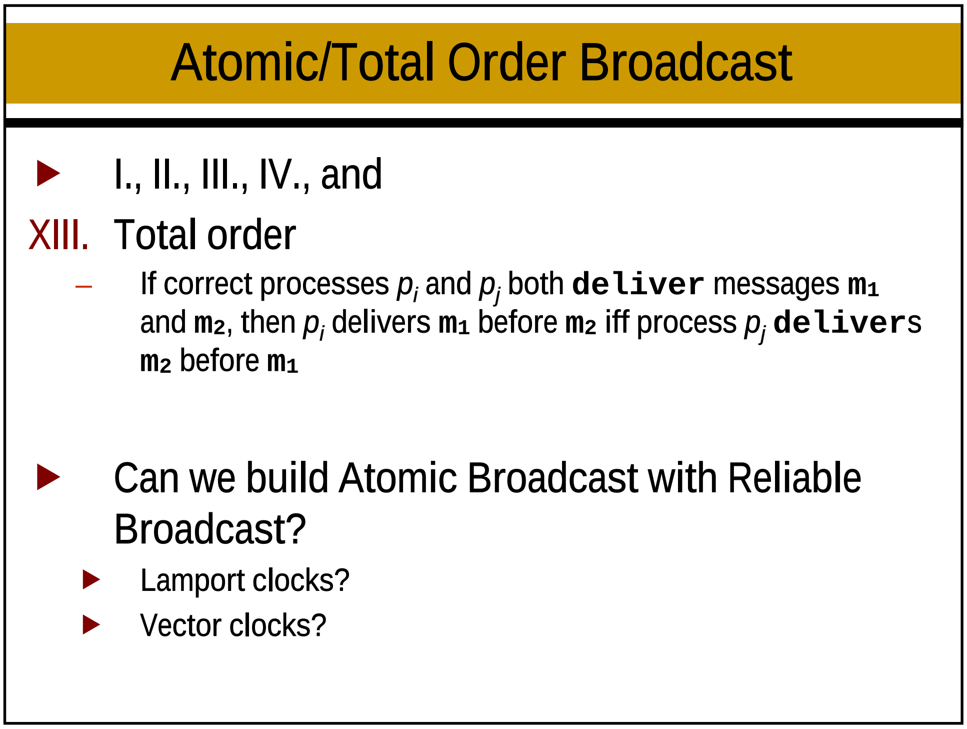
- Why purge **`prevDlvrs`** after a **`broadcast`**?
- Do we need uniform FIFO order?
  - Suppose a faulty process p_i delivers (**`deliver`**$_F$) a message **`m`**$_2$ before a message **`m`**$_1$ (from the same broadcaster)
  - It can broadcast a message after delivering m$_2$, and then fail, ...
    - Remember: it can still be in the process of broadcasting/sending previous message **`m`**$_2$ and/or **`m`**$_1$
  - Failures propagate throughout algorithm runs
    - Particularly in ordered broadcasts, as these relate different messages/runs
- Limitations?
  - Improvements?

Uniform Causal Order

XII. Uniform causal order

- If the **`broadcast`** of a message **`m`**$_1$ causally precedes the **`broadcast`** of a message **`m`**$_2$, then no process (correct or faulty) **`deliver`**s **`m`**$_2$ unless it has previously **`delivered`** **`m`**$_1$

- How about the previous algorithm?
- How about uniform agreement?



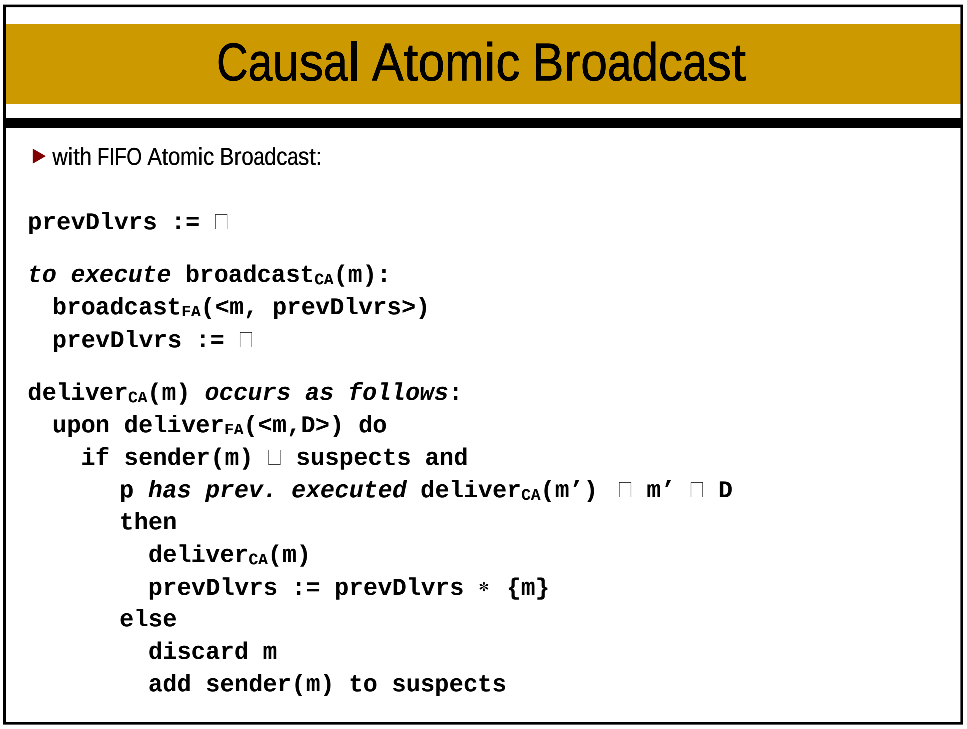
Atomic/Total Order Broadcast

- I., II., III., IV., and

XIII. Total order

– If correct processes p_i and p_j both **deliver** messages m_1 and m_2, then p_i delivers m_1 before m_2 iff process p_j **delivers** m_2 before m_1

- Can we build Atomic Broadcast with Reliable Broadcast?
  - Lamport clocks?
  - Vector clocks?



Causal Atomic Broadcast

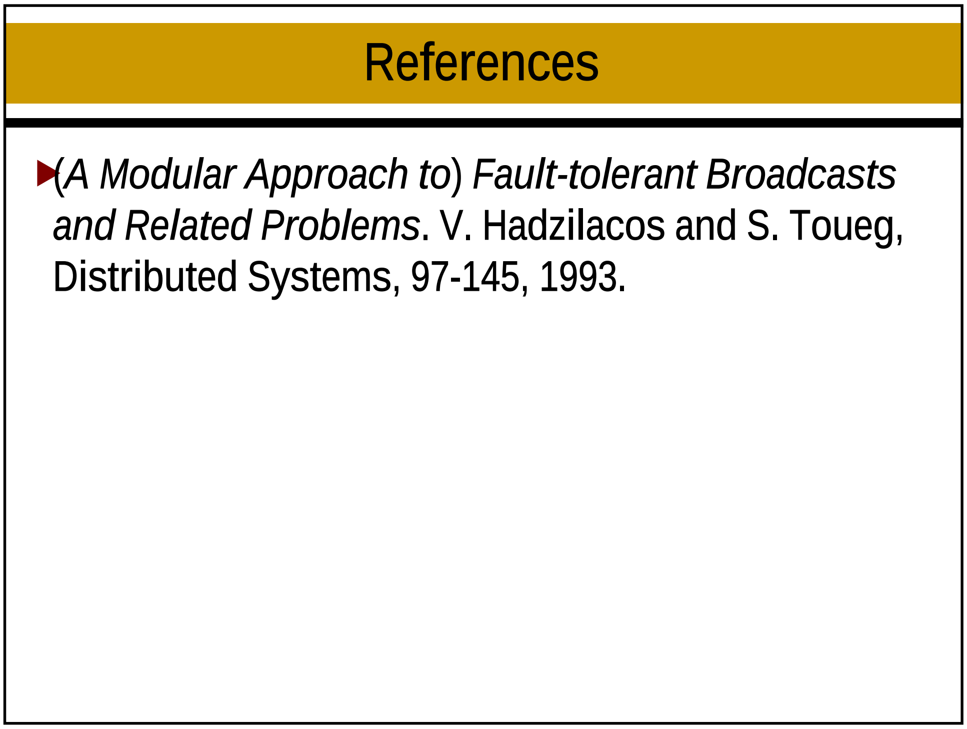
- with FIFO Atomic Broadcast:

```
prevDlvrs := □

to execute broadcast_CA(m):
  broadcast_FA(<m, prevDlvrs>)
  prevDlvrs := □

deliver_CA(m) occurs as follows:
  upon deliver_FA(<m,D>) do
    if sender(m) □ suspects and
       p has prev. executed deliver_CA(m') □ m' □ D
       then
         deliver_CA(m)
         prevDlvrs := prevDlvrs ∗ {m}
       else
         discard m
         add sender(m) to suspects
```

- `suspects?`
  - Process can be faulty, and thus violate XIII.
    - Deliver messages out of order and broadcast before crashing
- Remedy?

Causal vs Total Order

- Interestingly, we can implement causal order in an asynchronous distributed system…
  - … but not total order
- Intuition
  - Causal ordering is defined w.r.t. a given message
    - Only depends on the deliveries preceding the broadcast on the very broadcaster (one process)
    - Ordering is defined a priori, algorithm must then enforce this order
    - (Same goes for FIFO)
  - Total ordering of messages is defined w.r.t. multiple messages from concurrent broadcasters
    - No predefined order, algorithm must "come up" with an order. How about deterministic order?



References

- (*A Modular Approach to*) *Fault-tolerant Broadcasts and Related Problems*. V. Hadzilacos and S. Toueg, Distributed Systems, 97-145, 1993.