# Messaging Order

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# System Model

- We may want to assume as little as possible from the system
- Assumptions for an asynchronous distributed system
  - No global time, nor knowledge of relative speeds
  - Messages may take unbounded time to arrive
  - Messages may be lost, duplicated, reordered
- We want to write algorithms relying on stronger assumptions

Solution: delegate to an underlying messaging algorithm which ensures some guarantees

# Receiving vs delivering messages

- Suppose high-level algorithm $A$, resorting to ...
- ... messaging algorithm $M$
- Algorithm $M$ encapulsates messaging from $A$
- When a message $m$ arrives at a node $n$ we say $n$ received $m$
- Algorithm $M$ may decide it is to soon to handle $m$ to $A$
- It may "quarantine" $m$, i.e., buffer $m$ for some time
- When appropriate, $M$ hands $m$ to $A$
- We say then that $m$ was delivered (to $A$).
- Possible events visible to $A$ are then send(m) and deliver(m)

# Some guarantees

- Reliability; many variations; examples
  - at-most-once
  - at-least-once
  - exactly-once
  - ...
- Order
  - FIFO
  - causal
  - total
- Here we are interested in order guarantees (regardless of reliability)

# Some approaches to ensuring delivery order

- Send set containing also previous messages
  - wastes bandwidth; a bit naive
  - needs protocol to GC messages to avoid growth
- Delay sending
  - waits for ack before sending next message
  - causes delays; prevents pipelining
  - not spatially scalable
- Delay delivery, buffering at receiver
  - best general purpose approach
  - allows pipelining and ack grouping
  - allows spatial scalability (if possible)
- Exploit network topology
  - very interesting if applicable
  - allows scalable designs
  - example: FIFO + spanning tree $\Rightarrow$ Causal

# FIFO order

- For any messages $a$ and $b$, from sender $i$, to receiver $j$:

$$\mathsf{send}_i(a) \rightarrow \mathsf{send}_i(b) \Rightarrow \mathsf{deliver}_j(a) \rightarrow \mathsf{deliver}_j(b)$$

- Simple, cheap, spatially scalable
- Useful basic guarantee, usually the minimum to aim for
- Trivially implemented
  - tag each message with a sequence number
  - receiver buffers messages out of order
  - delivers when next suitable one is received
  - receivers track each sender separately
  - sender keeps a sequence number per receiver ...
  - ... unless messages are broadcast, where one is enough

# Causal order

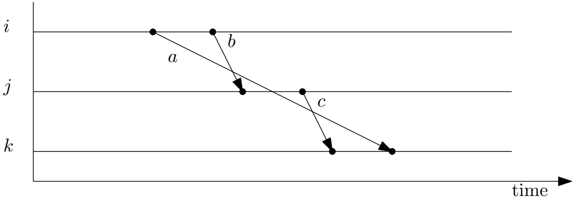
- For any messages $a$ and $b$, from senders $i$ and $j$, to receiver $k$:

$$\mathrm{send}_i(a) \rightarrow \mathrm{send}_j(b) \Rightarrow \mathrm{deliver}_k(a) \rightarrow \mathrm{deliver}_k(b)$$

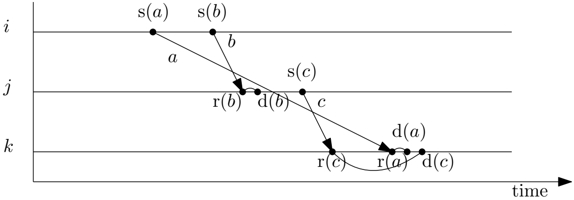
- Includes the case $i = j$; FIFO $<$ causal
- Useful guarantee to obtain causal consistency
- More complex to implement than FIFO
- More difficult to scale with number of nodes than FIFO
- Strongest still spatially scalable delivery order
  - far away nodes do not slow down nearby interactions

# Delaying delivery to achieve causal order

- Violation of causal order, if message $c$ is delivered to $k$ before $a$




- Ensuring causal order by delaying delivery of $c$ after $a$ (s – send, r – receive, d – deliver)



# Detecting causality violation

- First ingredient to ensure causal delivery; the easy part
- Lamport clocks are not enough; provide only "if", not "iff"

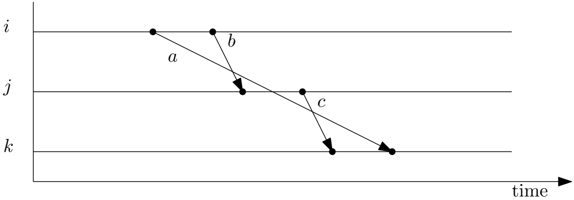
> if causal order has been violated, a message $m$ with clock $L_m$ must have arrived at node $i$ when $L_i > L_m$

- Vector clocks provide "iff", allowing checking for violations

> causal order has been violated if and only if a message $m$ with clock $V_m$ arrives at node $i$ when $V_i > V_m$

# Knowing if messages can still arrive

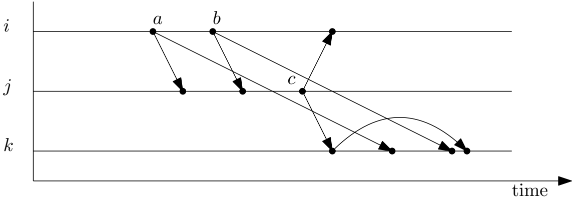
- Second ingredient: knowing if some causally in the past message can still arrive
- Complex and expensive in the general case




- How does node $k$ know when receiving $c$ that node $i$ has previously sent $a$ but it has not yet arrived?
- Less expensive for a common useful case: causal broadcast

# Causal broadcast

- The common scenario: each “send” (cbcast) is to all nodes
- Useful for symmetric data replication




- $c$ carries info that it depends on first two messsages from $i$
- Because each message is for all nodes, when $k$ receives $c$:
  - it knows it has not yet delivered two messages from $i$
  - that they must be delivered before $c$
  - so, it buffers $c$ to be delivered after those messages

# Causal broadcast algorithm

- Each node keeps a vector of integers (or map from node ids)
  - like a vector clock, but updated only on cbcast and deliver
- On cbcast($m$), increment self entry:

  $$V[i] := V[i] + 1$$

  and send vector with message:

  $$\text{for } j \in I \setminus \{i\} : \text{send}(j, m, V)$$

- On receive($j, m, V_m$), i.e., $m$ tagged with $V_m$, buffer $m$ until:

  $$V[j] + 1 = V_m[j] \wedge \forall j \neq i \cdot V_m[j] \leq V[j]$$

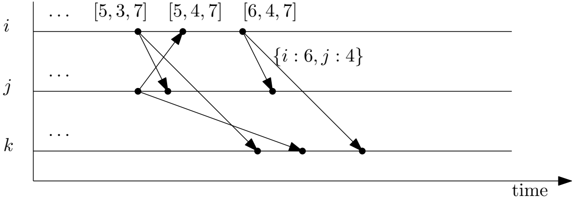
  then increment $j$'s entry:

  $$V[j] := V[j] + 1$$

  and deliver $m$ (and retest other messages in the buffer)

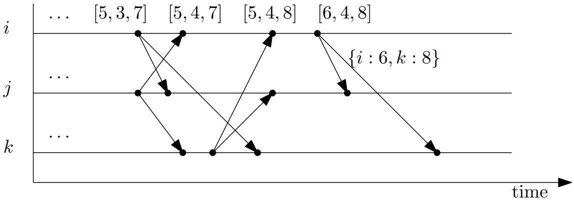
# Causal broadcast – improvements (1)

- Sending the full vector is not really needed
- For each sender, $n+1$ message delivered after message $n$
- We need only send entries that changed since previous cbcast
- For many nodes it can save bandwidth



# Causal broadcast – improvements (2)

- A vector describes transitive dependencies
- My dependencies already wait for their dependencies
- We need only send direct dependencies (direct predecessors)



# Total order

- For any two messages $a$ and $b$ delivered by two nodes $i$ and $j$:

$$\text{deliver}_i(a) \rightarrow \text{deliver}_i(b) \Rightarrow \text{deliver}_j(a) \rightarrow \text{deliver}_j(b)$$

- Does not necessarily respect FIFO or causal;
- But would be silly not to
  - extra cost of getting FIFO pales in comparison
  - would violate basic guarantees, such as monotonic writes
- So, normally we want to respect FIFO and in such case

$$\text{FIFO} < \text{causal} < \text{total}$$

# Total order broadcast

- Total order broadcast useful where a set of replicas needs to apply requests in the same order; a replicated state machine
- Can be implemented by:
  - Lamport clocks based algorithm; generalisation of lock
  - Consensus based, for fault tolerance
- In most contexts this term also implies reliability
- Undesirable spatial scalability properties:
  - minimum delivery time proportional to physical span
  - does not tolerate network partitions
- Undesirable for large scale systems aiming for responsiveness