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 network 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 hand over m to A
- It may "quarantine" m, i.e., buffer m for some time
- When appropriate, M hands m over 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 only in order guarantees (assume there are no failures)

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

Semantic happens-before

- Will use $\rightarrow$ for $\xrightarrow{\text{hb}}$, the semantic happens-before

$$\text{hb} \doteq (\text{so} \cup \text{vis})^{+}$$

- Session order as before, relating ops from same process
- Operations/events provided by messaging algorithm:
  - $\text{send}_i(j, m)$: send message m to j, at process i
  - $\text{deliver}_i(m)$: deliver message m, at process i
- With visibility given by:

$$\text{send}_i(j, m) \xrightarrow{\text{vis}} \text{deliver}_j(m)$$

FIFO order

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

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

- 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

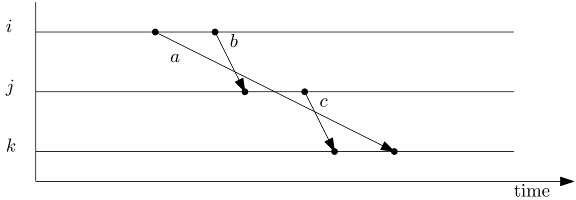
- For any messages a and b, from senders i and j, to receiver k:

$$\text{send}_i(k, a) \rightarrow \text{send}_j(k, b) \Rightarrow \text{deliver}_k(a) \rightarrow \text{deliver}_k(b)$$

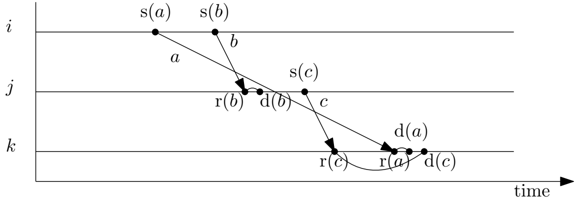
- Includes the case $i = j$; FIFO $<$ causal
- Useful guarantee to obtain causal consistency
- More complex to implement than FIFO
- More difficult to scale with number of nodes than FIFO
- Strongest still spatially scalable delivery order
  - far away nodes do not slow down nearby interactions

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"

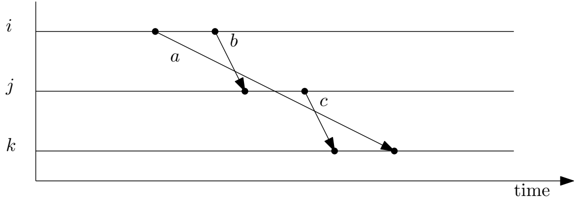
> if causal order has been violated, a message m with clock L_m must have arrived at node i when $L_i > L_m$

- 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

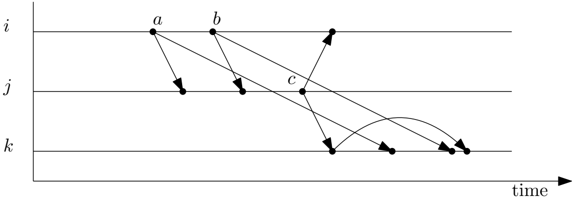
- Second ingredient: knowing if some message causally in the past can still arrive
- Complex and expensive in the general case



- 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 version vector (or map from ids to ints)
  - like a vector clock, but updated only on cbcast and deliver
- On $\text{cbcast}_i(m)$, node i increments self entry:

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

  and sends vector with message:

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

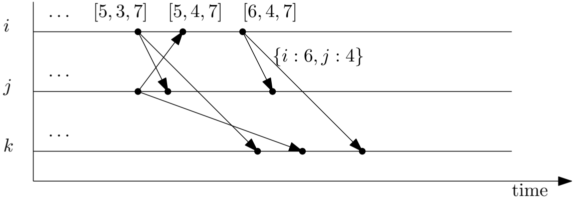
- On $\text{receive}_i(j, (m, V_m))$, i.e., m tagged with V_m, buffer m until:

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

  upon which:
  - increment j's entry: $V[j] := V[j] + 1$
  - trigger $\text{deliver}_i(m)$
  - (and retest other messages in buffer)

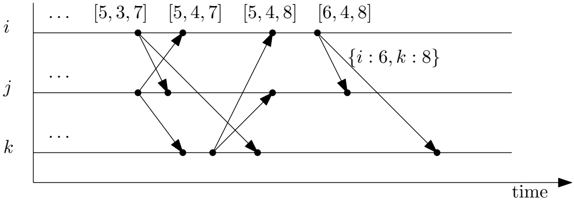
Causal broadcast – improvements (1)

- Sending the full vector is not really needed
- For each sender, message $n+1$ 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 respect FIFO
  - cost of getting FIFO pales in comparison
  - would violate basic guarantees, such as monotonic writes
- Also, preferably want to respect causality (causal arbitration)
  - happens when FIFO + broadcasting to all (including self)
  - so, preferably/normally in actual mechanisms

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

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