Distributed Systems

The second half of *Concurrent and Distributed Systems*

https://www.cl.cam.ac.uk/teaching/current/ConcDisSys

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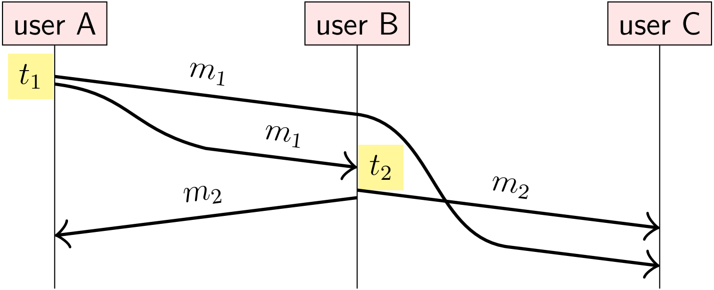
Computer Science Tripos, Part IB

Lecture 4

Broadcast protocols and logical time

Physical timestamps inconsistent with causality



$m_1 = (t_1,$ "A says: The moon is made of cheese!"$)$
$m_2 = (t_2,$ "B says: Oh no it isn't!"$)$

Problem: even with synced clocks, $t_2 < t_1$ is possible.
Timestamp order is inconsistent with expected order!

Logical vs. physical clocks

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We will look at two types of logical clocks:

- Lamport clocks
- Vector clocks

Lamport clocks algorithm

on initialisation **do**
    $t := 0$ ▷ each node has its own local variable t
end on

on any event occurring at the local node **do**
    $t := t + 1$
end on

on request to send message m **do**
    $t := t + 1$; send (t, m) via the underlying network link
end on

on receiving (t', m) via the underlying network link **do**
    $t := \max(t, t') + 1$
    deliver m to the application
end on

Lamport clocks in words

- Each node maintains a counter t,
  incremented on every local event e
- Let $L(e)$ be the value of t after that increment
- Attach current t to messages sent over network
- Recipient moves its clock forward to timestamp in the message (if greater than local counter), then increments

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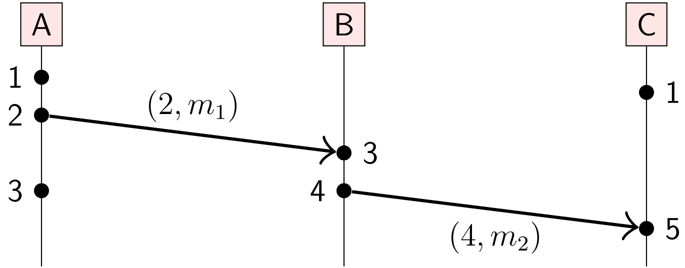
Properties of this scheme:

- If $a \to b$ then $L(a) < L(b)$
- However, $L(a) < L(b)$ does not imply $a \to b$
- Possible that $L(a) = L(b)$ for $a \neq b$

Lamport clocks example



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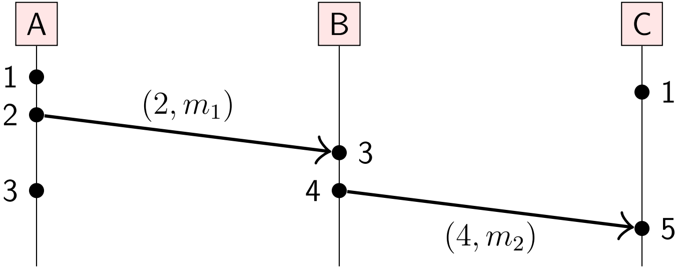

Let $N(e)$ be the node at which event e occurred.
Then the pair $(L(e), N(e))$ **uniquely identifies** event e.

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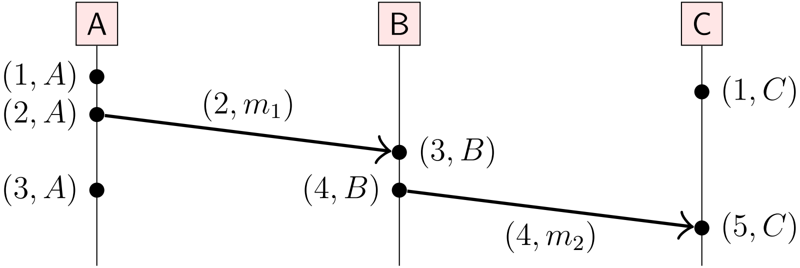

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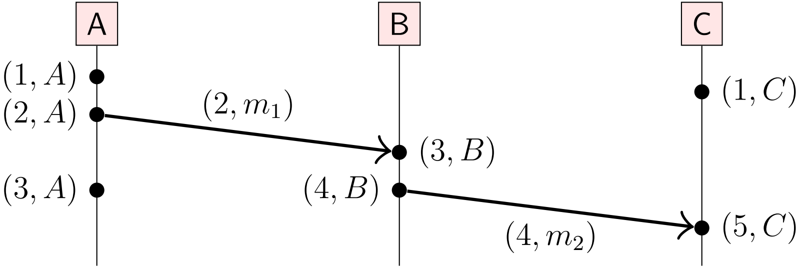

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Define a **total order** $\prec$ using Lamport timestamps:

$$(a \prec b) \iff (L(a) < L(b) \lor (L(a) = L(b) \land N(a) < N(b)))$$

This order is **causal**: $(a \rightarrow b) \Longrightarrow (a \prec b)$

Vector clocks

Given Lamport timestamps $L(a)$ and $L(b)$ with $L(a) < L(b)$ we can't tell whether $a \rightarrow b$ or $a \parallel b$.

If we want to detect which events are concurrent, we need **vector clocks**:

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If we want to detect which events are concurrent, we need **vector clocks**:

- Assume n nodes in the system, $N = \langle N_1, N_2, \ldots, N_n \rangle$
- Vector timestamp of event a is $V(a) = \langle t_1, t_2, \ldots, t_n \rangle$
- t_i is number of events observed by node N_i

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- t_i is number of events observed by node N_i
- Each node has a current vector timestamp T
- On event at node N_i, increment vector element $T[i]$
- Attach current vector timestamp to each message
- Recipient merges message vector into its local vector

Vector clocks algorithm

on initialisation at node N_i **do**
  $T := \langle 0, 0, \dots, 0 \rangle$ ▷ local variable at node N_i
end on

on any event occurring at node N_i **do**
  $T[i] := T[i] + 1$
end on

on request to send message m at node N_i **do**
  $T[i] := T[i] + 1$; send (T, m) via network
end on

on receiving (T', m) at node N_i via the network **do**
  $T[j] := \max(T[j], T'[j])$ for every $j \in \{1, \dots, n\}$
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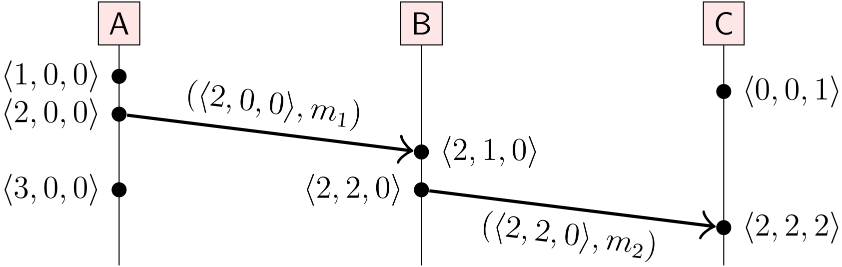
Assuming the vector of nodes is $N = \langle A, B, C \rangle$:



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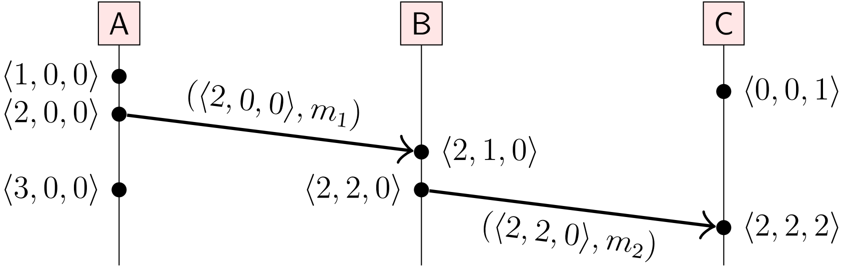

The vector timestamp of an event e represents a set of events, e and its causal dependencies: $\{e\} \cup \{a \mid a \rightarrow e\}$

For example, $\langle 2, 2, 0 \rangle$ represents the first two events from A, the first two events from B, and no events from C.

Vector clocks ordering

Define the following order on vector timestamps (in a system with n nodes):

- $T = T'$ iff $T[i] = T'[i]$ for all $i \in \{1, \dots, n\}$
- $T \leq T'$ iff $T[i] \leq T'[i]$ for all $i \in \{1, \dots, n\}$
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$V(a) \leq V(b)$ iff $(\{a\} \cup \{e \mid e \rightarrow a\}) \subseteq (\{b\} \cup \{e \mid e \rightarrow b\})$

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$V(a) \leq V(b)$ iff $(\{a\} \cup \{e \mid e \to a\}) \subseteq (\{b\} \cup \{e \mid e \to b\})$

Properties of this order:

- $(V(a) < V(b)) \iff (a \to b)$
- $(V(a) = V(b)) \iff (a = b)$
- $(V(a) \parallel V(b)) \iff (a \parallel b)$

Broadcast protocols

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Build upon system models from lecture 2:

- Can be **best-effort** (may drop messages) or
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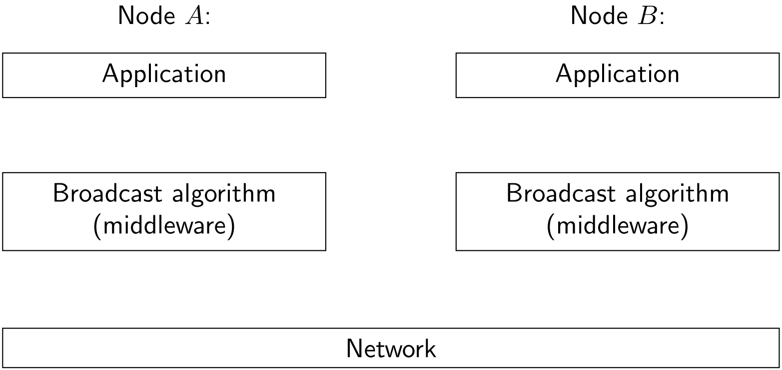
Build upon system models from lecture 2:

- Can be **best-effort** (may drop messages) or **reliable** (non-faulty nodes deliver every message, by retransmitting dropped messages)
- Asynchronous/partially synchronous timing model $\Longrightarrow$ **no upper bound** on message latency

Receiving versus delivering



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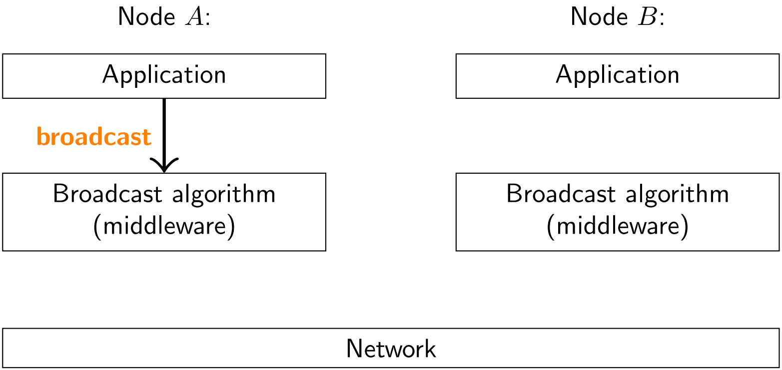

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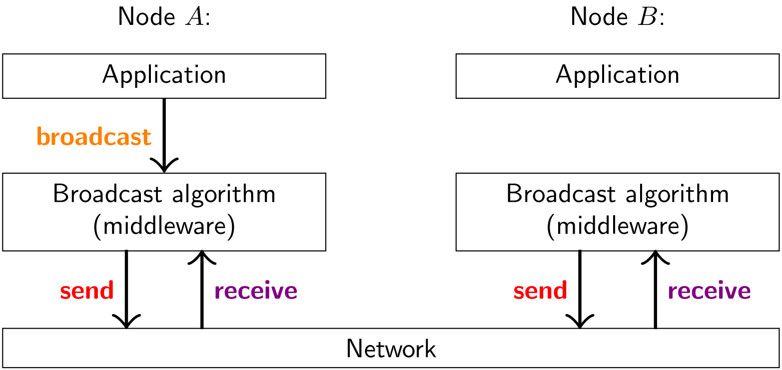

Assume network provides point-to-point **send**/**receive**

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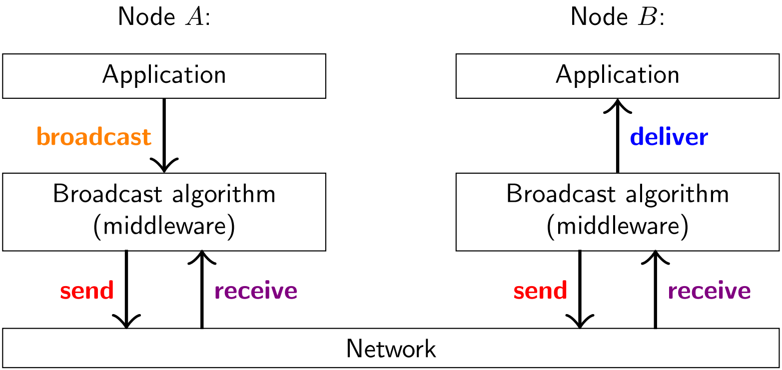

Assume network provides point-to-point **send**/**receive**

After broadcast algorithm **receives** message from network, it may buffer/queue it before **delivering** to the application

Forms of reliable broadcast

FIFO broadcast:
If m_1 and m_2 are broadcast by the same node, and broadcast$(m_1) \rightarrow$ broadcast(m_2), then m_1 must be delivered before m_2

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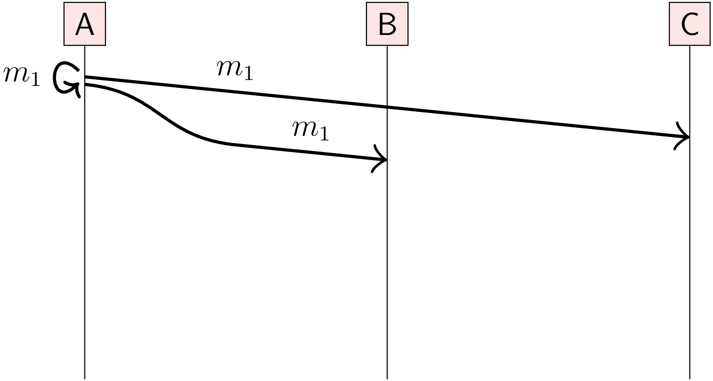
FIFO-total order broadcast:
Combination of FIFO broadcast and total order broadcast

FIFO broadcast



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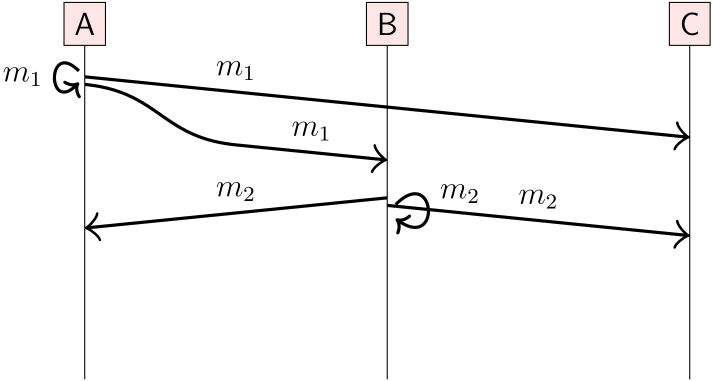

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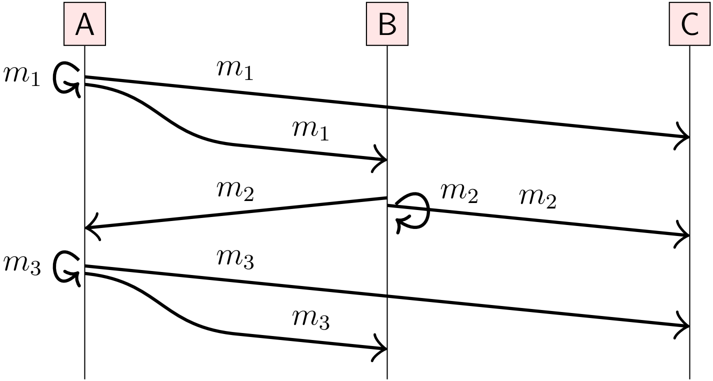

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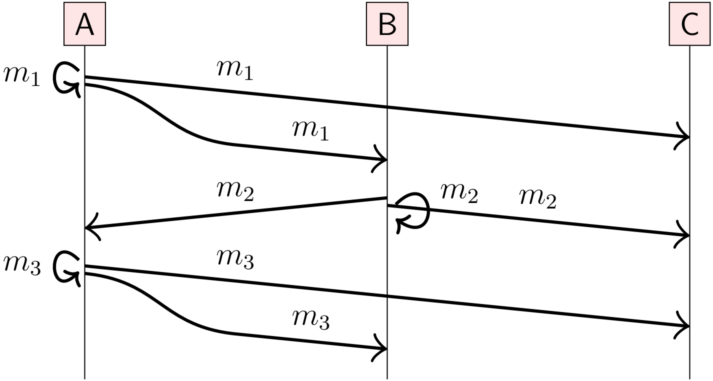

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Messages sent by different nodes can be delivered in any order.

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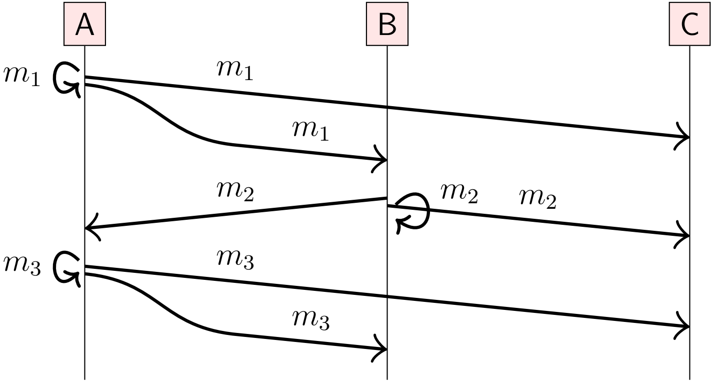

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Valid orders: (m_2, m_1, m_3) or (m_1, m_2, m_3) or (m_1, m_3, m_2)

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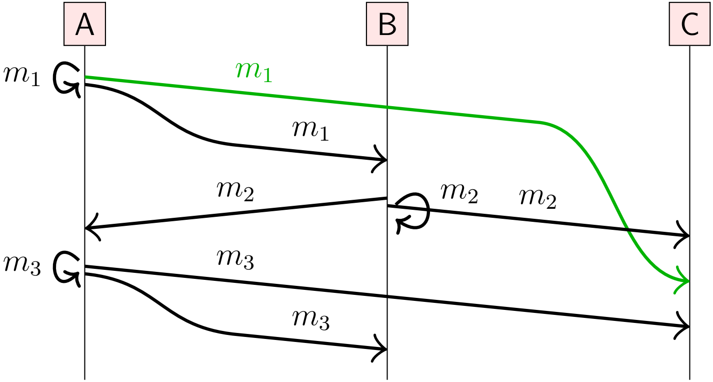

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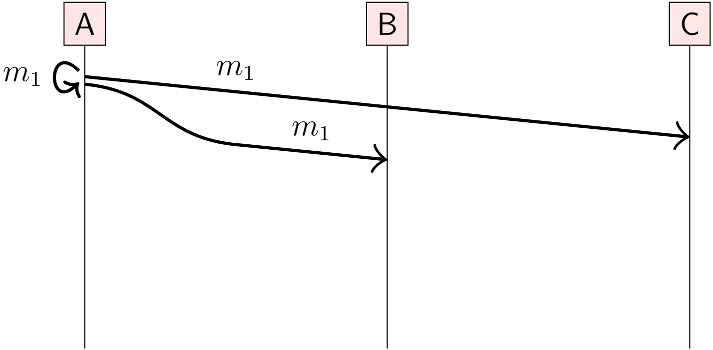

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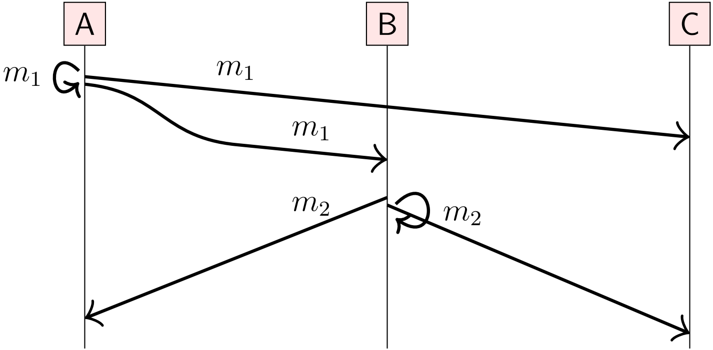

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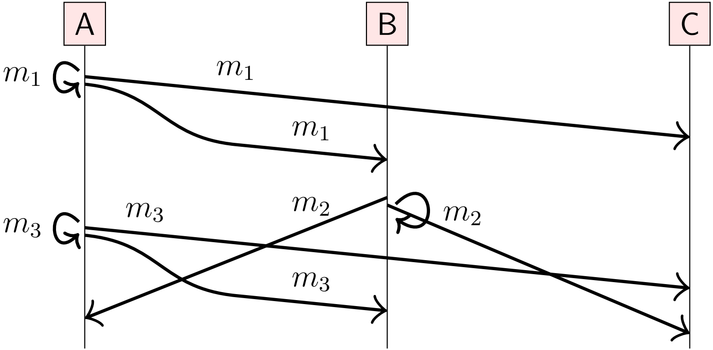

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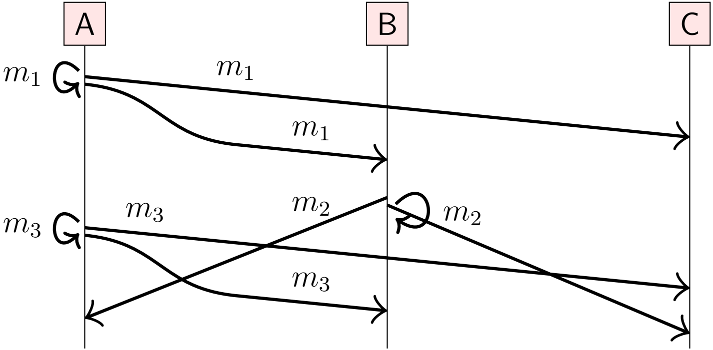

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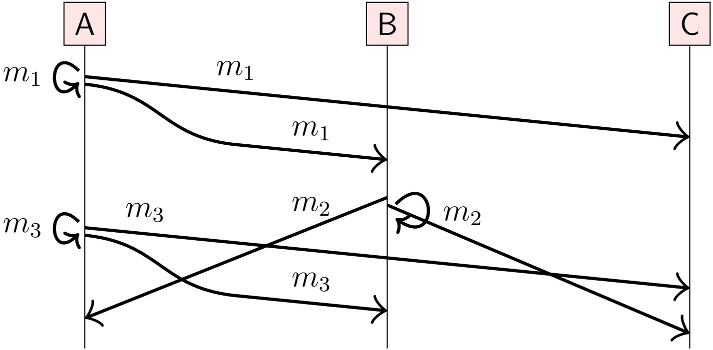

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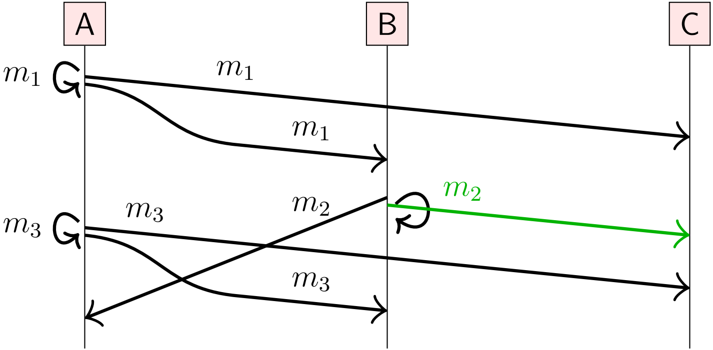

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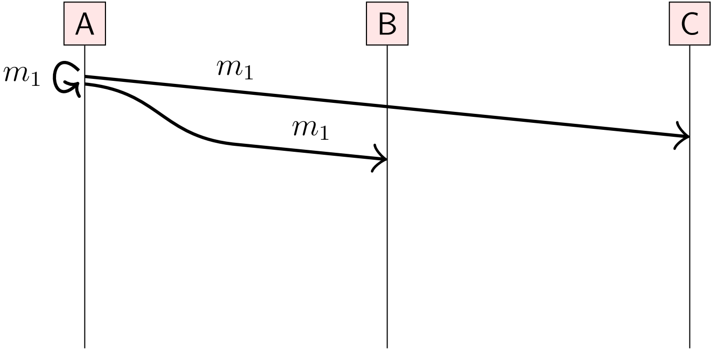

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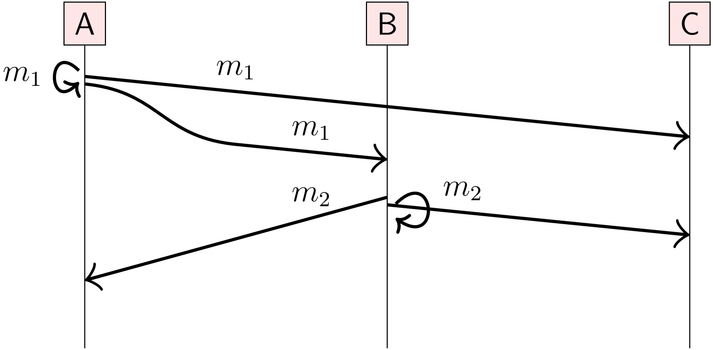

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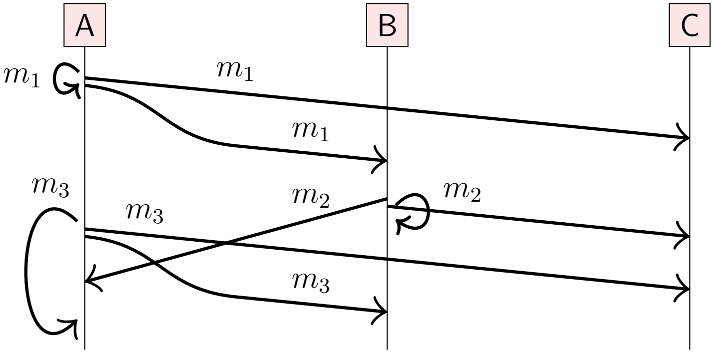

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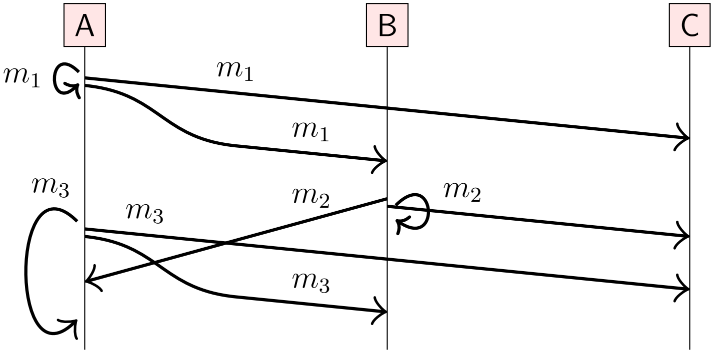

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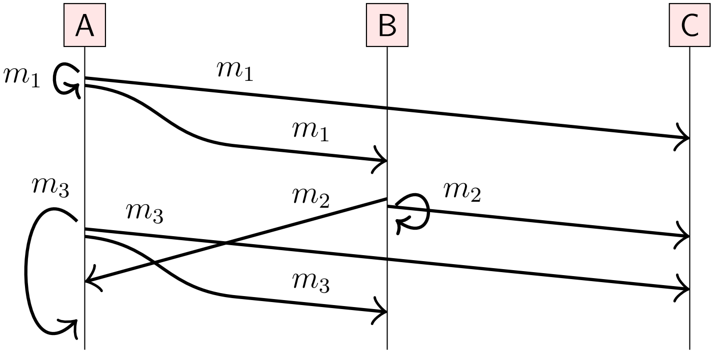

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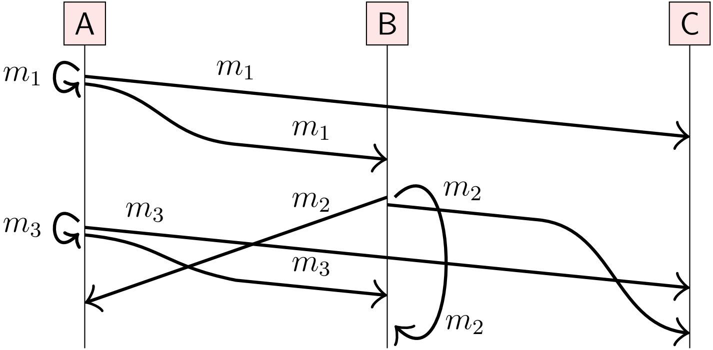
This includes a node's deliveries to itself!

Total order broadcast (2)



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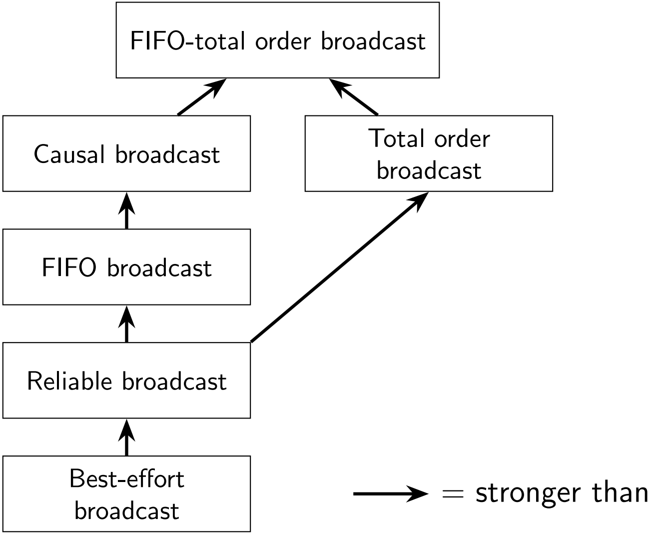
Relationships between broadcast models



Broadcast algorithms

Break down into two layers:

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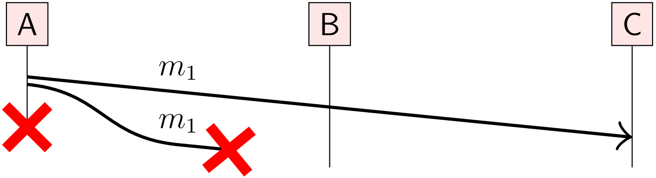
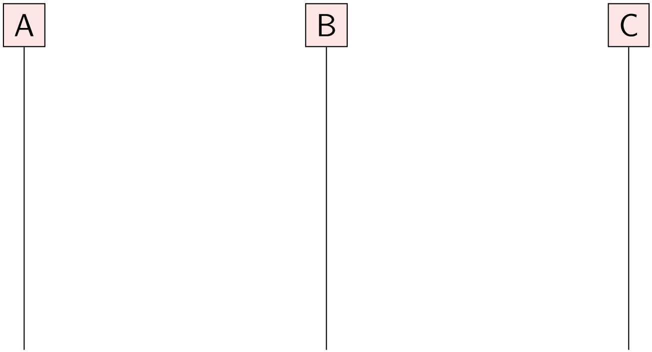
- Use reliable links (retry + deduplicate)
- Problem: node may crash before all messages delivered



Eager reliable broadcast

Idea: the **first time** a node receives a particular message, it **re-broadcasts** to each other node (via reliable links).



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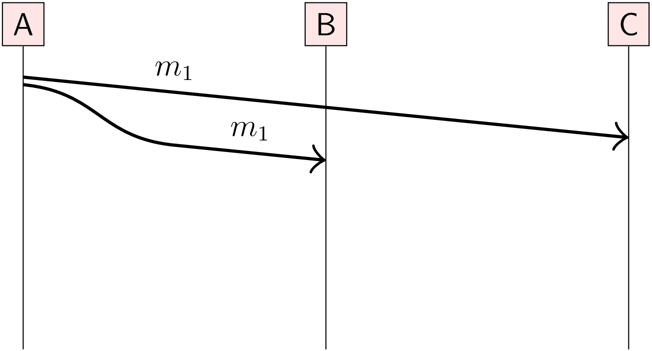

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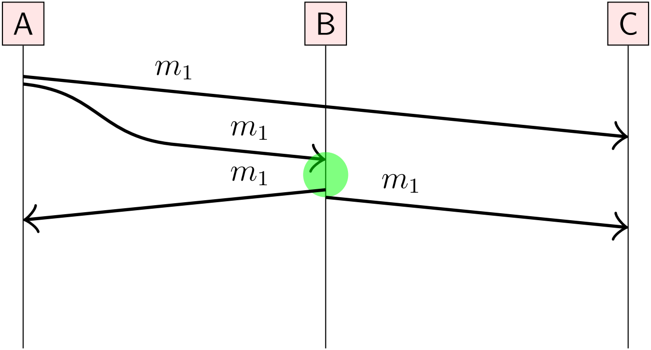

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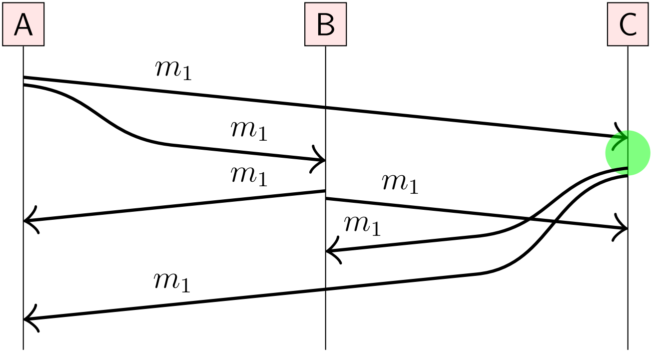

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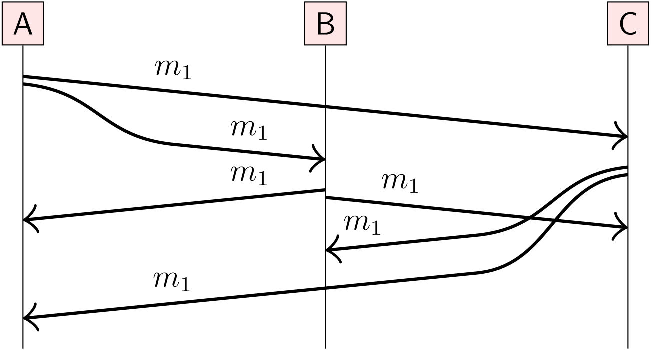
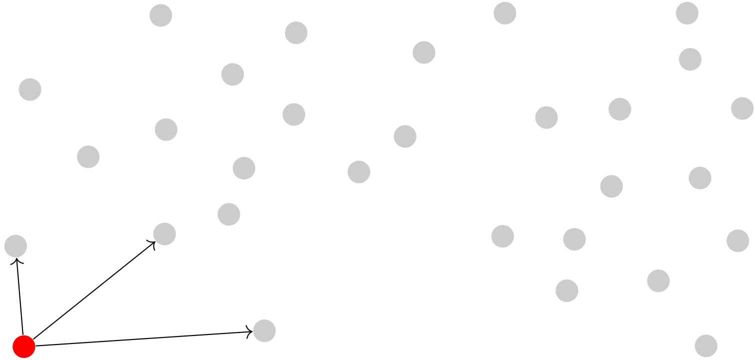


Reliable, but... up to $O(n^2)$ messages for n nodes!

Gossip protocols

Useful when broadcasting to a large number of nodes.
Idea: when a node receives a message for the first time, **forward it to 3 other nodes**, chosen randomly.



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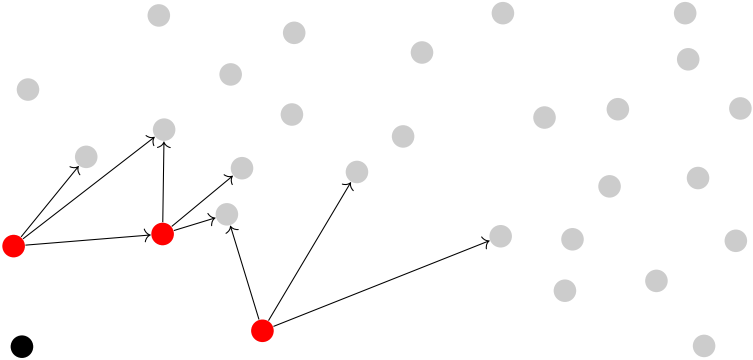

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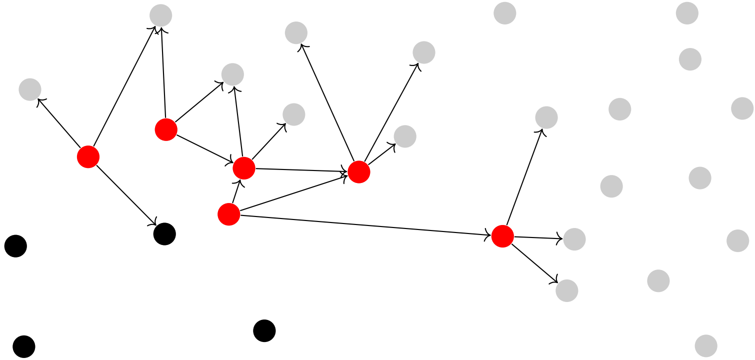

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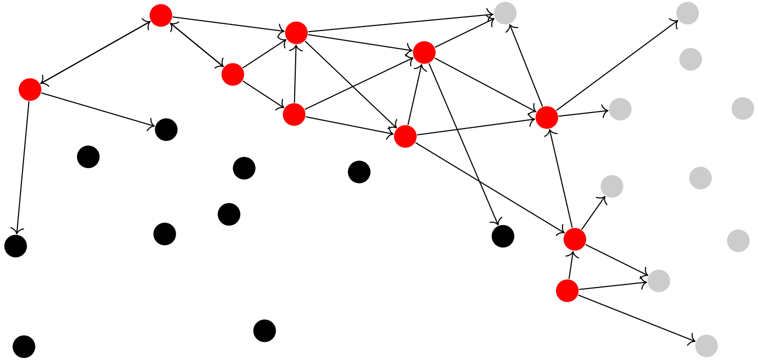

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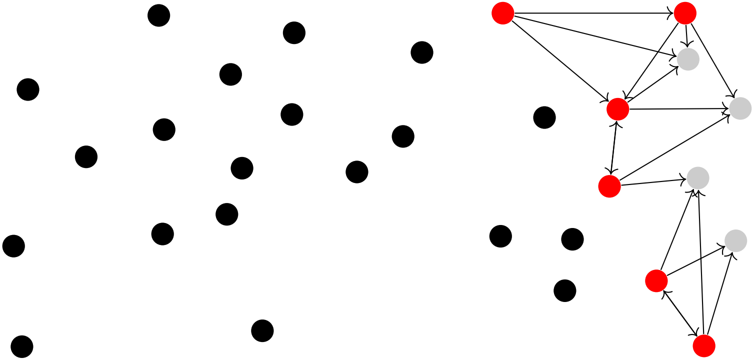

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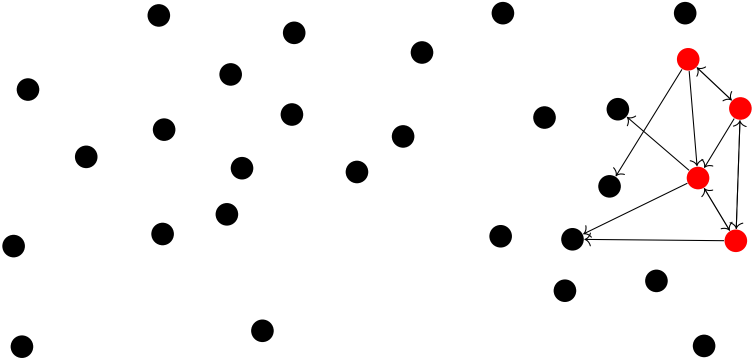

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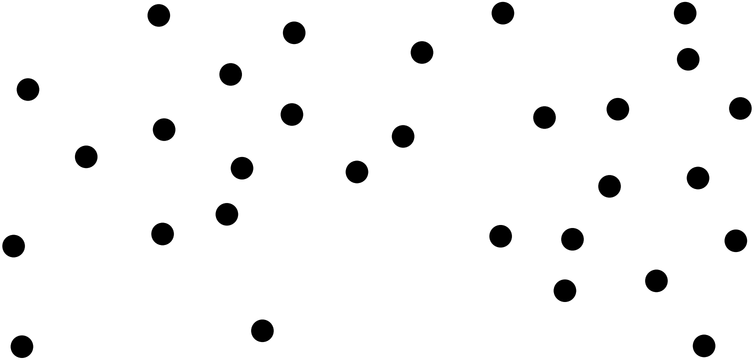

Eventually reaches all nodes (with high probability).

FIFO broadcast algorithm

on initialisation **do**
 $sendSeq := 0;\ delivered := \langle 0, 0, \dots, 0 \rangle;\ buffer := \{\}$
end on

on request to broadcast m at node N_i **do**
 send $(i, sendSeq, m)$ via reliable broadcast
 $sendSeq := sendSeq + 1$
end on

on receiving msg from reliable broadcast at node N_i **do**
 $buffer := buffer \cup \{msg\}$
 while $\exists sender, m.\ (sender, delivered[sender], m) \in buffer$ **do**
  deliver m to the application
  $delivered[sender] := delivered[sender] + 1$
 end while
end on

Causal broadcast algorithm

on initialisation **do**
  $sendSeq := 0;\ delivered := \langle 0, 0, \ldots, 0 \rangle;\ buffer := \{\}$
end on

on request to broadcast m at node N_i **do**
  $deps := delivered; deps[i] := sendSeq$
  send $(i, deps, m)$ via reliable broadcast
  $sendSeq := sendSeq + 1$
end on

on receiving msg from reliable broadcast at node N_i **do**
  $buffer := buffer \cup \{msg\}$
  while $\exists (sender, deps, m) \in buffer.\ deps \leq delivered$ **do**
    deliver m to the application
    $buffer := buffer \setminus \{(sender, deps, m)\}$
    $delivered[sender] := delivered[sender] + 1$
  end while
end on

Vector clocks ordering

Define the following order on vector timestamps (in a system with n nodes):

- $T = T'$ iff $T[i] = T'[i]$ for all $i \in \{1, \dots, n\}$
- $T \leq T'$ iff $T[i] \leq T'[i]$ for all $i \in \{1, \dots, n\}$
- $T < T'$ iff $T \leq T'$ and $T \neq T'$
- $T \parallel T'$ iff $T \not\leq T'$ and $T' \not\leq T$

Total order broadcast algorithms

Single leader approach:

- One node is designated as leader (sequencer)
- To broadcast message, send it to the leader; leader broadcasts it via FIFO broadcast.

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- Attach Lamport timestamp to every message
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Lamport clocks approach:

- Attach Lamport timestamp to every message
- Deliver messages in total order of timestamps
- Problem: how do you know if you have seen all messages with timestamp $< T$? Need to use FIFO links and wait for message with timestamp $\geq T$ from *every* node