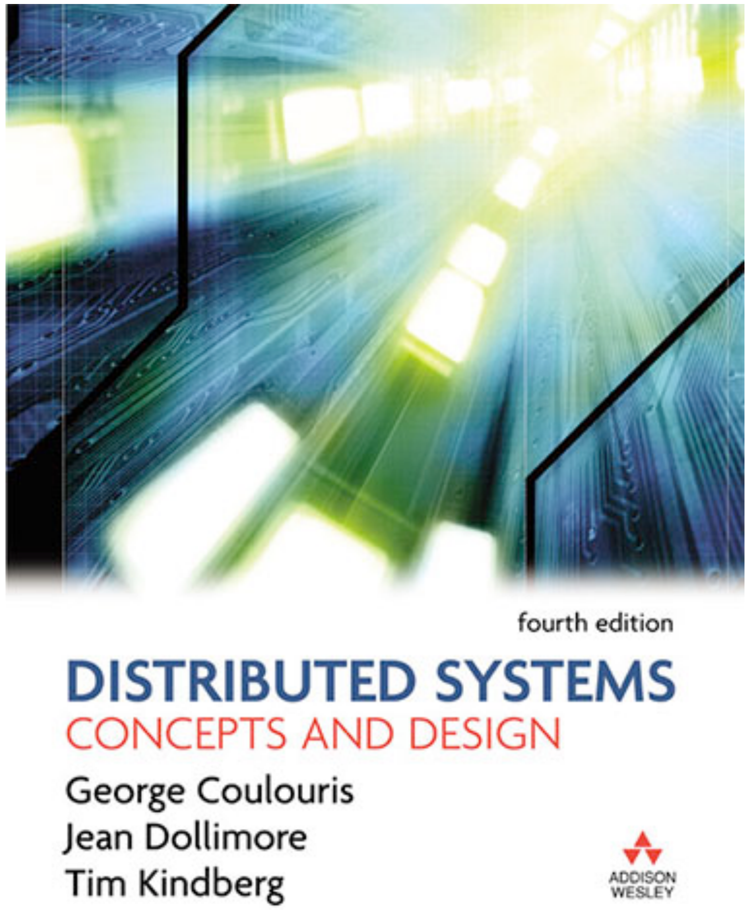
Coordination and Agreement



AIM: Coordination and/or Agreement

- Collection of algorithms whose goals vary

  but which share an aim that is fundamental in distributed systems

  for a set of distributed processes to coordinate their actions or to agree on one or more values.

Multicast Communication

Group (or Multicast) Communication

- Some lectures ago... Java API to IP multicast: example of implementation of group communication.
- Group communication requires coordination and agreement.
- AIM: for each of a group of processes to receive copies of the messages sent to the group, often with delivery guarantees.
- Delivery guarantees:
  - agreement on the set of messages that every process in the group should receive
  - agreement on the delivery ordering across the group members.

Essential Feature

- A process issues only one *multicast* operation to send a message to each of a group of processes instead of issuing multiple *send* operations to individual processes.
    - Example: in Java this operation is *aSocket.send(aMessage)*.
- Communication to all processes in the system, as opposed to a sub-group of them, is known as broadcast.

System Model

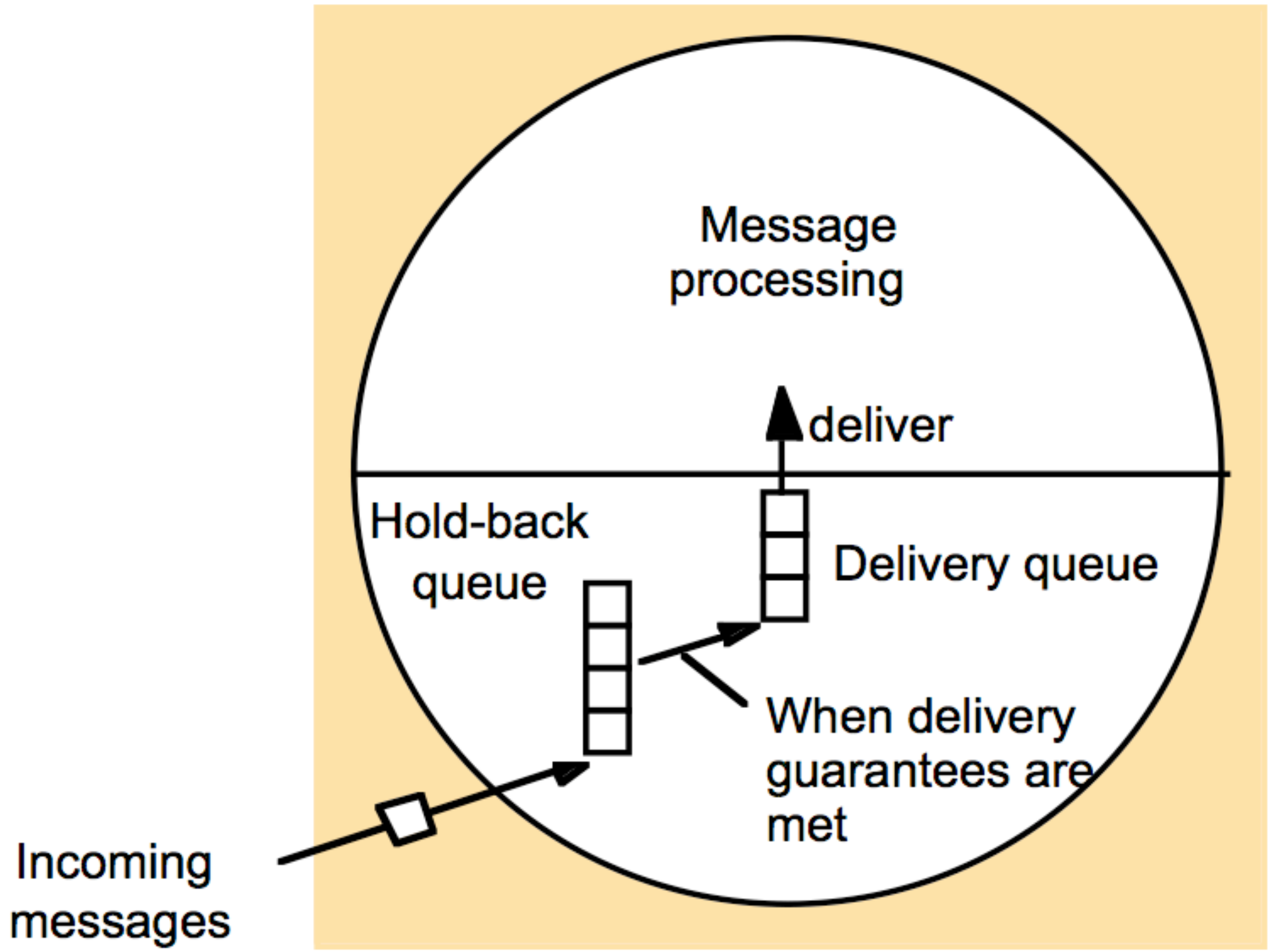
- Collection of processes, which communicate RELIABLY over 1-to-1 channels.
- Reliable communication defined in terms of
  - validity: if a correct process *p* sends a message *m* to a correct process *q*, then *q* eventually delivers *m*
  - no duplication: no message is delivered by a process more than once
  - no creation: if some process *q* delivers a message *m* with sender *p*, then *m* was previously sent to *q* by process *p*.
- No Duplication + No Creation = Integrity property

System Model (cont.)

- Processes may fail only by crashing.
- Processes are members of groups, which are the destinations of messages sent with the *multicast* operation.
- Communication primitives:
  - *multicast(g, m)*: sends a message *m* to all members of the group *g*.
  - *deliver(m)*: delivers a message sent by multicast to the calling process.
- Why *deliver* and not *receive*?

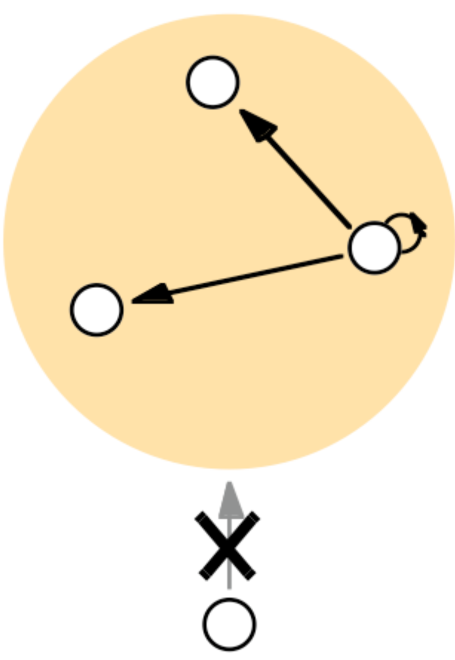
Message Deliver VS Message Receive

- *A multicast message is not always handed to the application layer inside the process as soon as it is received at the process's node* (this will be more clear when we will discuss multicast delivery semantics...).



System Model (cont.)

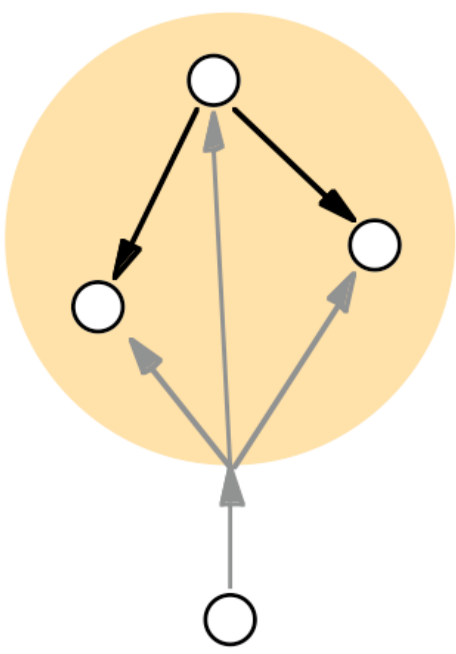
- Every message *m* carries
  - the unique identifier of the process *sender(m)* that sent it
  - the unique destination group identifier *group(m)*.
- We assume that processes do not lie about the origin or destinations of msgs.



Closed Group:

Only members of the group can multicast to it.

A process delivers to itself any message that it multicasts to the group.



Open Group:

Processes outside the group may send to it.

Basic Multicast - Specification

- A basic multicast is one that satisfies the following properties:
  - Validity: if a correct process multicasts message *m*, then every correct process eventually delivers *m*.
  - No Duplication: a correct process *p* delivers a message *m* at most once.
  - No Creation: if a correct process *p* delivers a message *m* with sender *s*, then *m* was previously multicast by process *s*.

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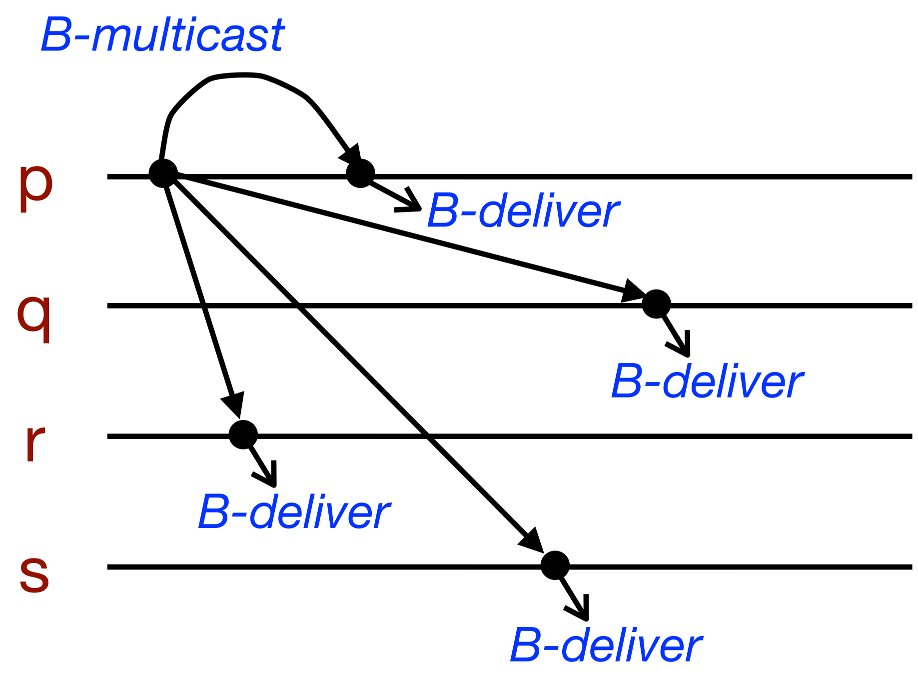
- No Duplication + No Creation = Integrity property
- Validity is a liveness property (*something good <u>eventually</u> happens*)
- No Duplication and No Creation are safety properties (*nothing bad happens*)

Basic Multicast - Algorithm

- Communication primitives:
  - *B-multicast*: basic multicast primitive
  - *B-deliver*: basic delivery primitive
- Implementation based on reliable 1-to-1 *send* operation:

To *B-multicast(g, m)*:
for each process p ∈ g, *send(p, m)*

On *receive(m)* at p:
B-deliver(m) at p



[Basic Multicast] Ack-Implosion Problem

- The implementation may use threads to perform the *send* operations concurrently, in an attempt to reduce the total time taken to deliver the msg.

- Liable to suffer from ack-implosion if the number of processes is large.

  - The acknowledgements sent as part of the reliable *send* operation are liable to arrive from many processes at about the same time.

  - The multicasting process's buffers will rapidly fill and it is liable to drop acknowledgments.

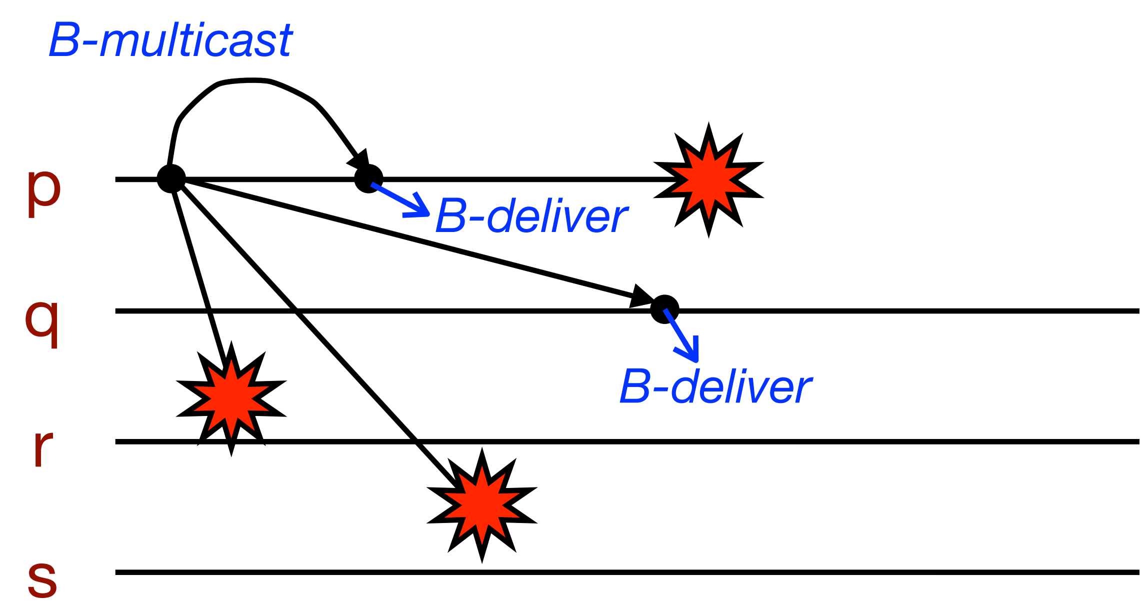
    ➡ It will therefore retransmit the msg, leading to yet more acks and further waste of network bandwidth.

Correctness of Basic Multicast Algorithm

- Properties derived from the properties of the underlying RELIABLE channels.
- No creation: follows directly from the corresponding property of reliable channels.
- No duplication: the same.
- Validity: derived from
  - the *reliable delivery property* of the communication channels
  - the sender sends the msg to every other process in the group

Scenario: Faulty Sender

- If the sender fails, some processes might deliver the message and other might not deliver it.



THE PROCESSES DO NOT *AGREE* ON THE DELIVERY OF THE MESSAGE!

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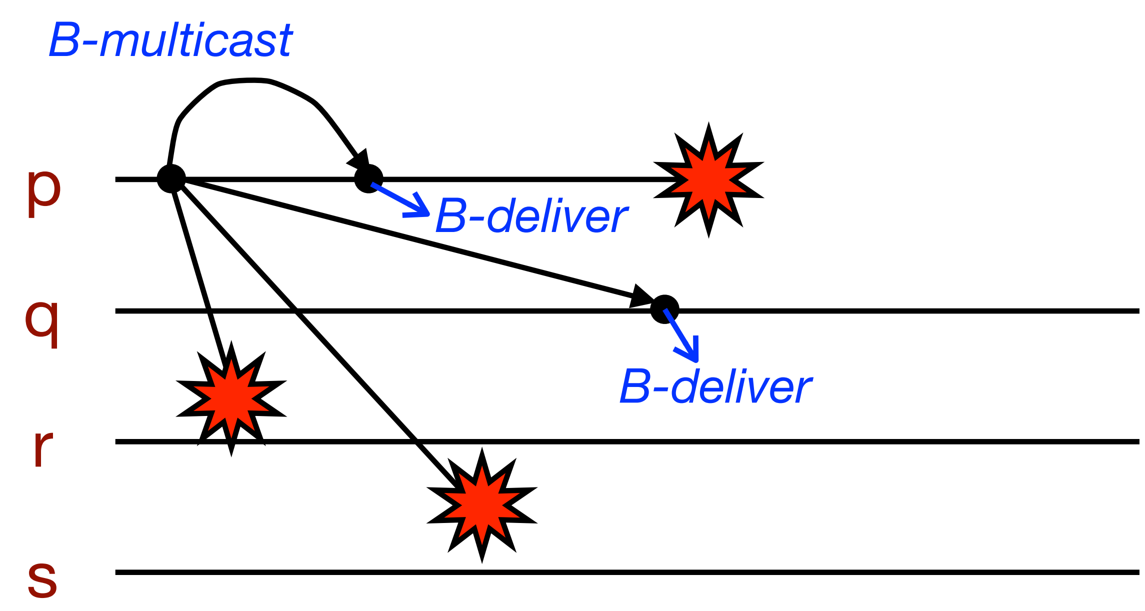

- Actually, even if the process sends the msg to all processes BEFORE crashing, the delivery is NOT ensured because reliable channels do not enforce the delivery when the sender fails!!

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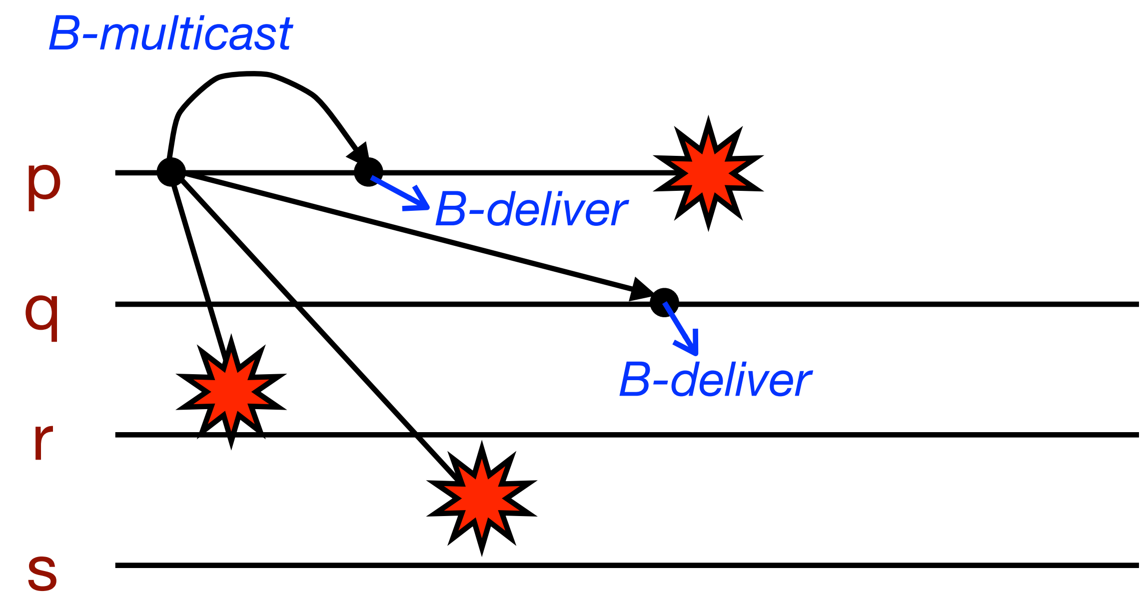

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We want to ensure AGREEMENT even when the sender fails.

Reliable Multicast - Properties

- Based on 2 primitives: *R-multicast* and *R-deliver*.

- A reliable multicast is one that satisfies the following properties:
  - No Duplication: a correct process *p* delivers a message *m* at most once.
  - No Creation: if a correct process *p* delivers a message *m* with sender *s*, then *m* was previously multicast by process *s*.
  - Validity: if a correct process multicasts message *m* then it will eventually deliver *m*.
  - Agreement: if a correct process delivers message *m*, then all the other correct processes in *group(m)* will eventually deliver *m*.

Validity + Agreement --> Liveness

- Validity: if a correct process multicasts message *m* then it will eventually deliver *m*.
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- Validity + Agreement --> Liveness property
  - if a correct process multicasts message *m* then it will eventually deliver *m*
  - if one process eventually delivers a message *m*, then since the correct processes agree on the set of messages they deliver

➡*m* will eventually be delivered to all the group's correct members.

Reliable Multicast Algorithm

- Implemented over B-multicast.

```
On initialization
    Received := {};

For process p to R-multicast message m to group g
    B-multicast(g, m);          // p ∈ g is included as a destination

On B-deliver(m) at process q with g = group(m)
    if (m ∉ Received)
    then
                Received := Received ∪ {m};
                if (q ≠ p) then B-multicast(g, m); end if
                R-deliver m;
    end if
```

Reliable Multicast Algorithm

- Implemented over B-multicast.

On initialization
    Received := {};

For process p to R-multicast message m to group g
    B-multicast(*g*, *m*); // $p \in g$ is included as a destination

On B-deliver(*m*) *at process q with g* = *group*(*m*)
    if ($m \notin$ *Received*)
    then
        Received := *Received* $\cup$ {*m*};
        if ($q \neq p$) *then B-multicast*(*g*, *m*); *end if*
        R-deliver m;
    end if

To *R-multicast* a message, a process *B-multicasts* the message to the processes in the destination group (including itself).

Reliable Multicast Algorithm

- Implemented over B-multicast.

When the message is *B-delivered*:
- the recipient in turn *B-multicasts* the message to the group (if it is not the original sender)
- then it *R-delivers* the message.

On initialization
  $Received := \{\};$

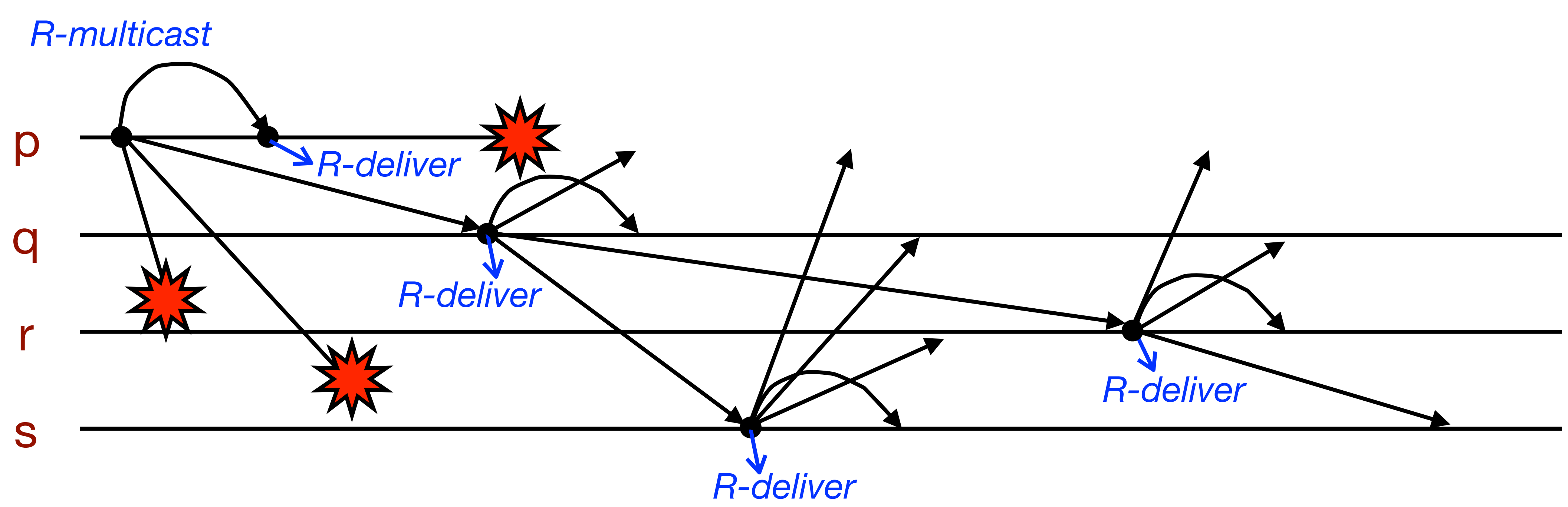
For process p to R-multicast message m to group g
  B-multicast(g, m); // $p \in g$ is included as a destination

On B-deliver(m) at process q with g = group(m)
  if $(m \notin Received)$
  then
    $Received := Received \cup \{m\};$
    if $(q \neq p)$ *then B-multicast(g, m); end if*
    R-deliver m;
  end if

since a message may arrive more than once, duplicates of the message are detected and not delivered.

Scenario: Faulty Sender

- process *p* crashes and its message is not *B-delivered* by processes *r* and *s*
- however, process *q* retransmits the message (i.e., *B-multicast* it)
- consequently, the remaining *correct* processes also *B-deliver* it and subsequently *R-deliver* it



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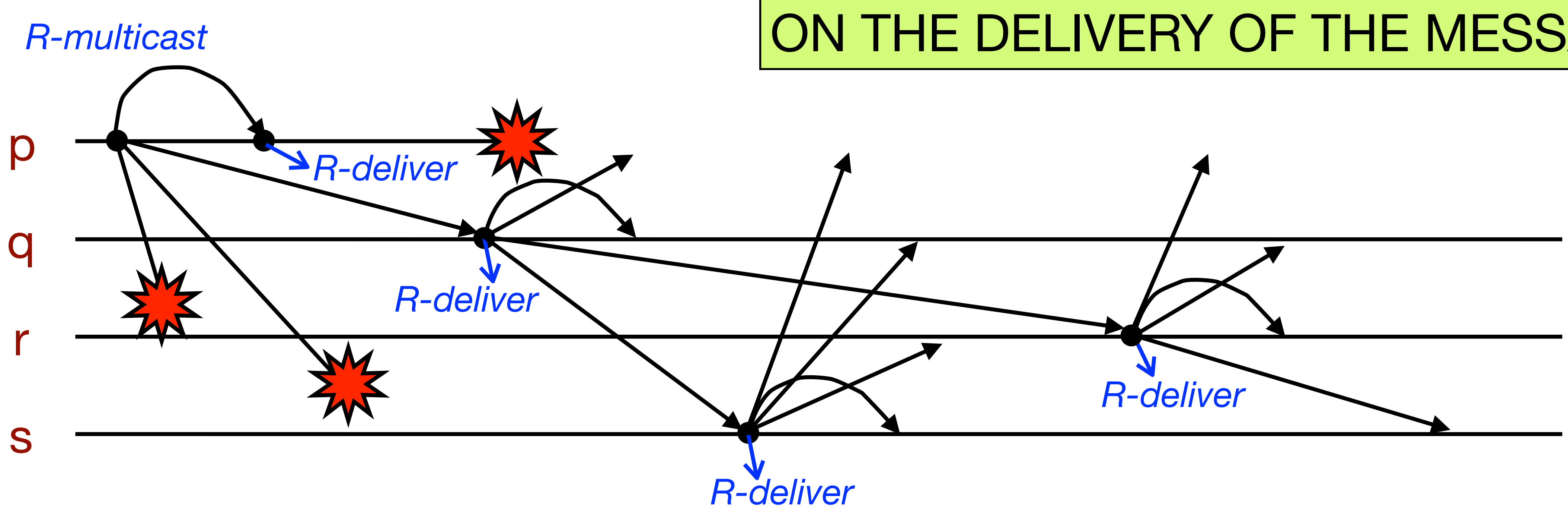
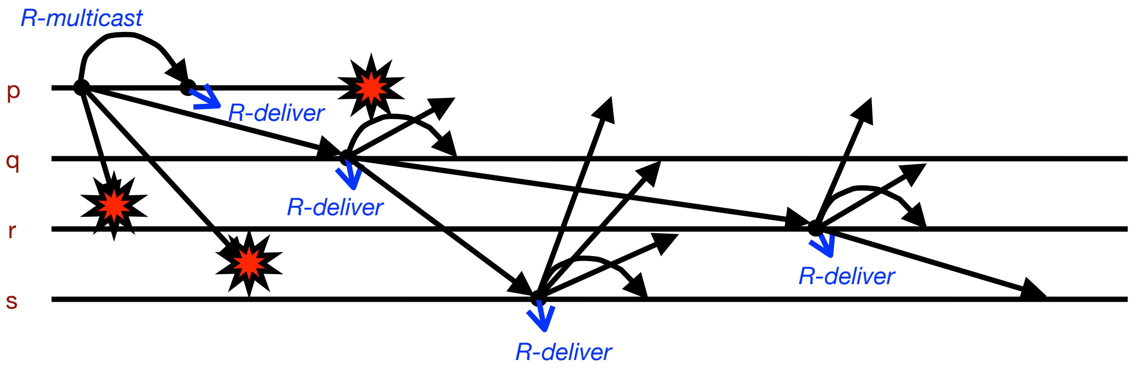
THE CORRECT PROCESSES *AGREE* ON THE DELIVERY OF THE MESSAGE!



On the Agreement Property

Property of "atomicity": all or nothing.

- *If a process that multicasts a message crashes before is has delivered it, than it it is possible that the message will not be delivered to any process in the group.*
- *But if it is delivered to some correct process, then all the other correct processes will deliver it.*



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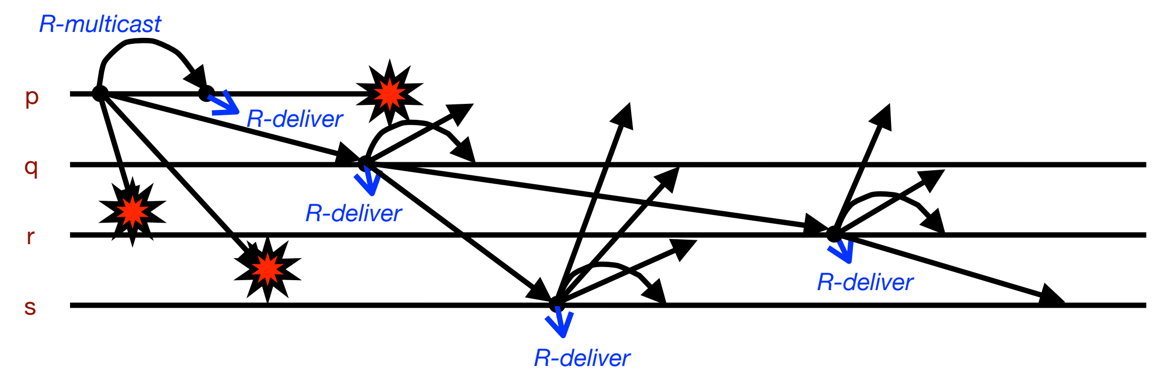
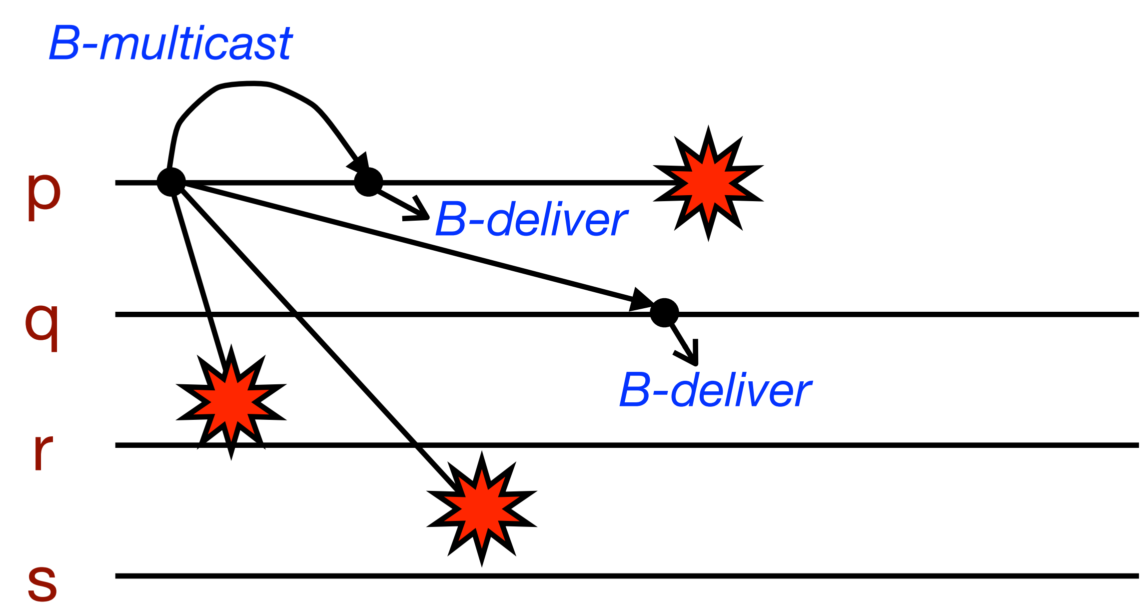
- *But if it is delivered to some correct process, then all the other correct processes will deliver it*.

Note: **NOT** a property of the B-multicast algorithm!

The sender may fail at any point while *B-multicast* proceeds, so some processes may deliver a msg while others do not.





Algorithm Analysis + HOMEWORK

- The algorithm satisfies validity, since a correct process will eventually *B-deliver* the message to itself.

- The algorithm satisfies integrity, because of

  (1) the integrity property of the underlying communication channels

  (2) the fact that duplicates are not delivered.

What about agreement? It follows because... HOMEWORK! :-)

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  (2) the fact that duplicates are not delivered.

  What about agreement? It follows because... HOMEWORK! :-)

- The algorithm is correct in an asynchronous system (no timing assumptions)

  BUT inefficient for practical purpose: each message sent |g| times to each process ($O(|G|^2)$ messages).

Ordered Multicast

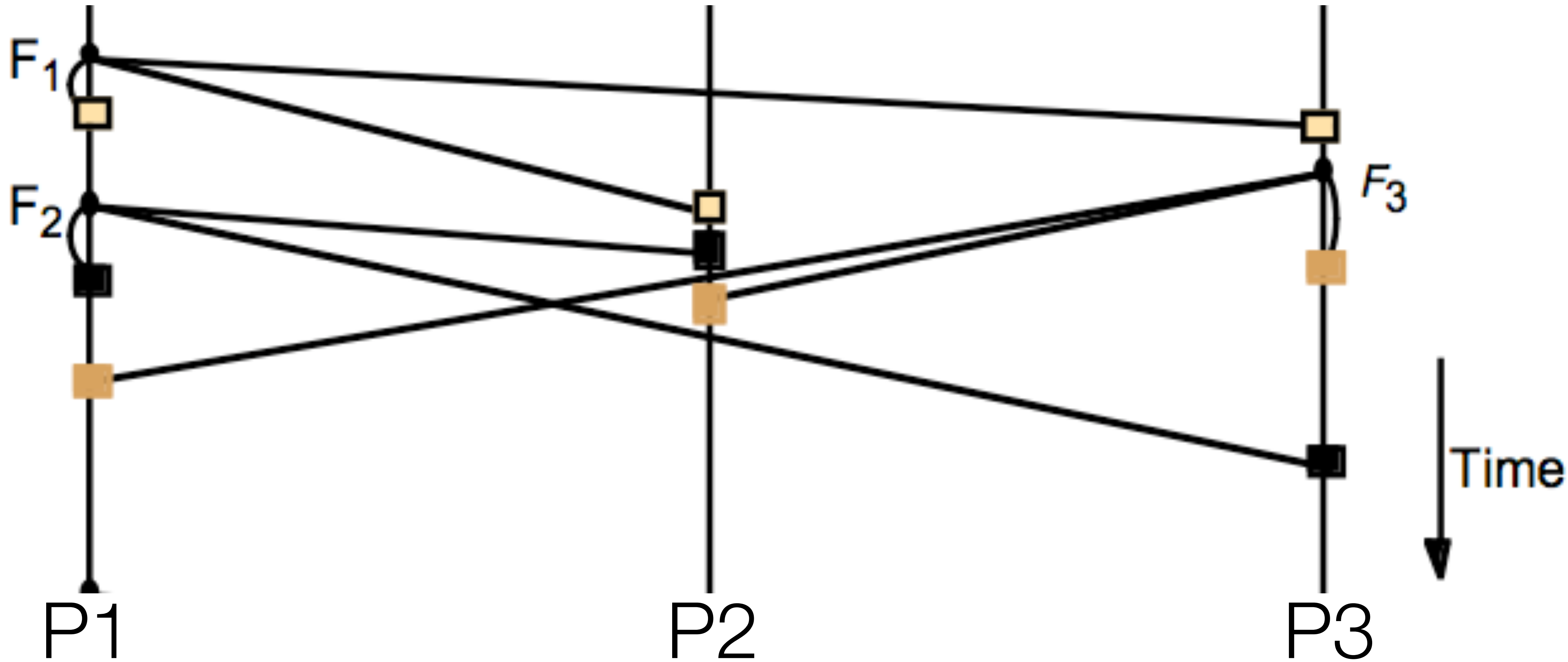
- The basic multicast algorithm delivers messages to processes in an arbitrary order, due to arbitrary delays in the underlying 1-to-1 send operations.

- Common ordering requirements:
  - FIFO ordering: if a correct process issues *multicast(g, m)* and then *multicast(g, m')* (*multicast(g, m)* $\rightarrow_i$ *multicast(g, m')*), then every correct process that delivers *m'* will deliver *m* before *m'*. Partial relation.
  - Causal ordering: *multicast(g, m)* $\rightarrow$ *multicast(g, m')*, then any correct process that delivers *m'* will deliver *m* before *m'*. Partial relation.
  - Total ordering: if a correct process delivers message *m* before it delivers *m'*, then any other correct process that delivers *m'* will deliver *m* before *m'*.

- N.B.: causal ordering implies FIFO ordering.

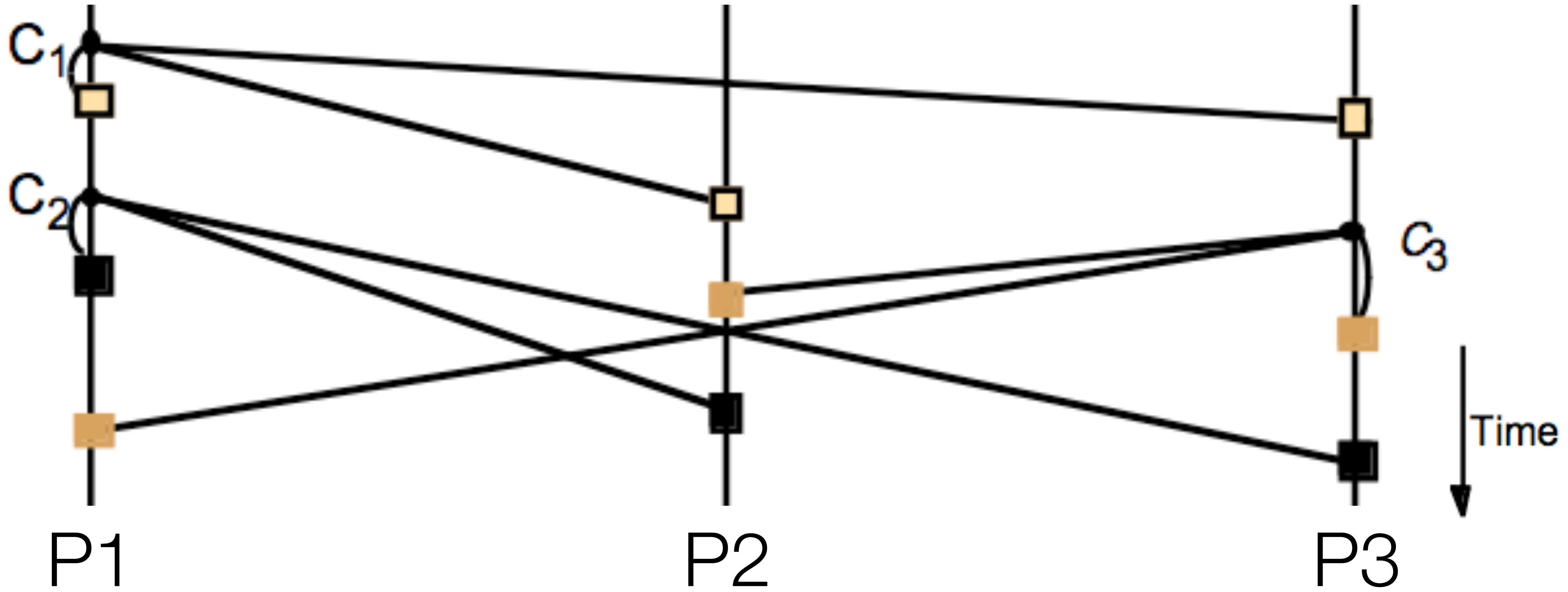
Example: FIFO Ordering

- FIFO ordering: if a correct process p_i issues *multicast(g, m)* and then *multicast (g, m')* (*multicast(g, m)* $\rightarrow_i$ *multicast(g, m')*), then every correct process that delivers *m'* will deliver *m* before *m'*. Partial relation.



Example: Casual Ordering

- Casual ordering: *multicast(g, m)* → *multicast(g, m')*, then any correct process that delivers *m'* will deliver *m* before *m'*. Partial relation.



Example: Total Ordering

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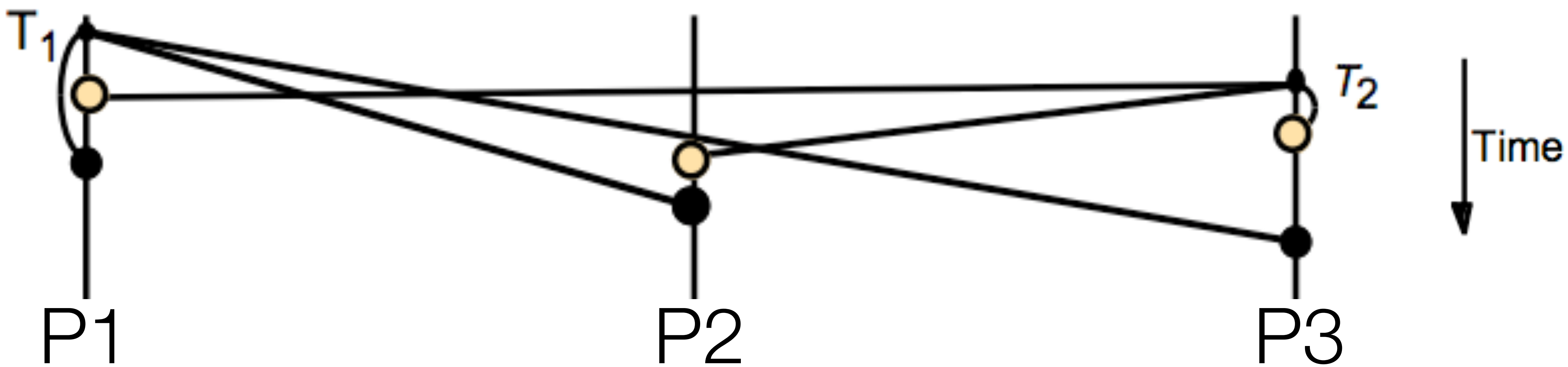

Example: Bulletin Board

- Consider an application in which users post messages to bulletin boards.
- Each user runs a bulleting-board application process.
- Every topic of discussion has its own process group.
- When a user posts a message to a bulletin board, the application multicasts the user's posting to the corresponding group.
- Each user's process is a member of the group for the topic he/she is interested ==> the user will receive just the postings concerning that topic.

[Bulletin Board Example] Ordering Requirements

- Reliable multicast required if every user is to receive every posting eventually.

Bulletin board: *os.interesting*		
Item	From	Subject
23	A.Hanlon	Mach
24	G.Joseph	Microkernels
25	A.Hanlon	Re: Microkernels
26	T.L'Heureux	RPC performance
27	M.Walker	Re: Mach
end		

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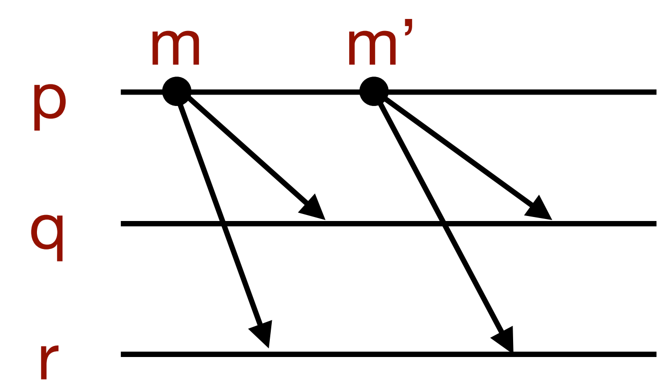
Causal ordering needed to guarantee this relationship.

If multicast delivery was totally ordered, then the items would be consistent between the users (users could refer unambiguously, for example, to “message 24”).

Implementing FIFO Ordering

FIFO ordering: if a correct process p_i issues *multicast(g, m)* and then *multicast (g, m')* (*multicast(g, m)* $\rightarrow_i$ *multicast(g, m')*), then every correct process that delivers *m'* will deliver *m* before *m'*.

- Two primitives: *FO-multicast* and *FO-deliver*
- Achieved with sequence numbers (remember? CSP...).
- We assume non-overlapping groups.
- A process p has variables:
  - S^p_g : how many messages p has sent to g
  - R^q_g : sequence number of the latest message p has delivered from process q that was sent to g



Basic FIFO Multicast: FO-Multicast and FO-Deliver

- For p to *FO-multicast* a message to group g:

  it piggy backs the value S^p_g onto the message;

  it *B-multicasts* the message to g;

  $S^p_g = S^p_g + 1$.

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- Upon a receipt of a message from q bearing the seq. number S, p checks:

  IF $(S = R^q_g + 1)$ **THEN** it *FO-delivers* the message, setting $R^q_g := S$.

  ELSIF $(S > R^q_g + 1)$ **THEN**

  it places the message in its *hold-back queue* until

  the intervening messages have been delivered and

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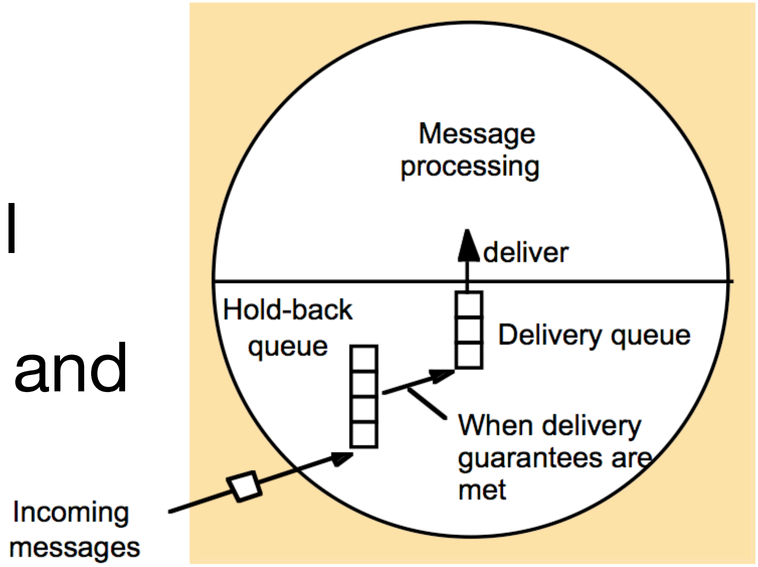

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  $S^p_g = S^p_g + 1$.

If we use *R-multicast* instead of *B-multicast*, then we obtain a reliable FIFO multicast.

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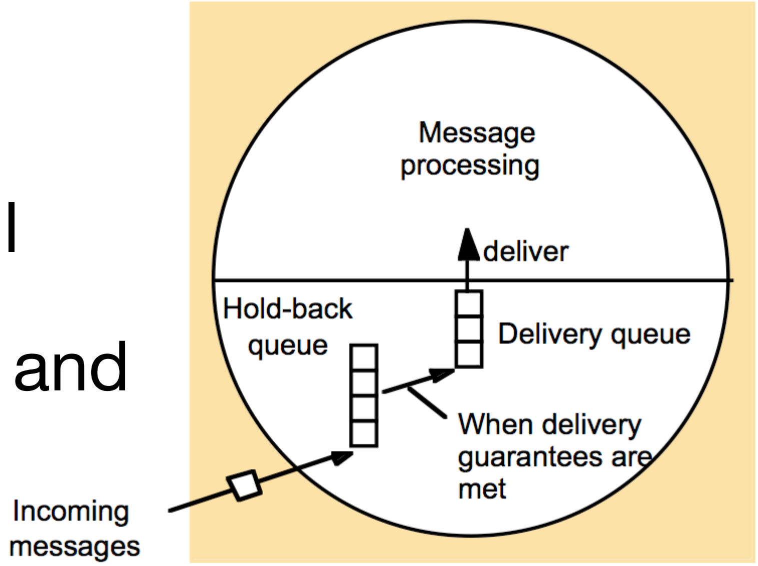
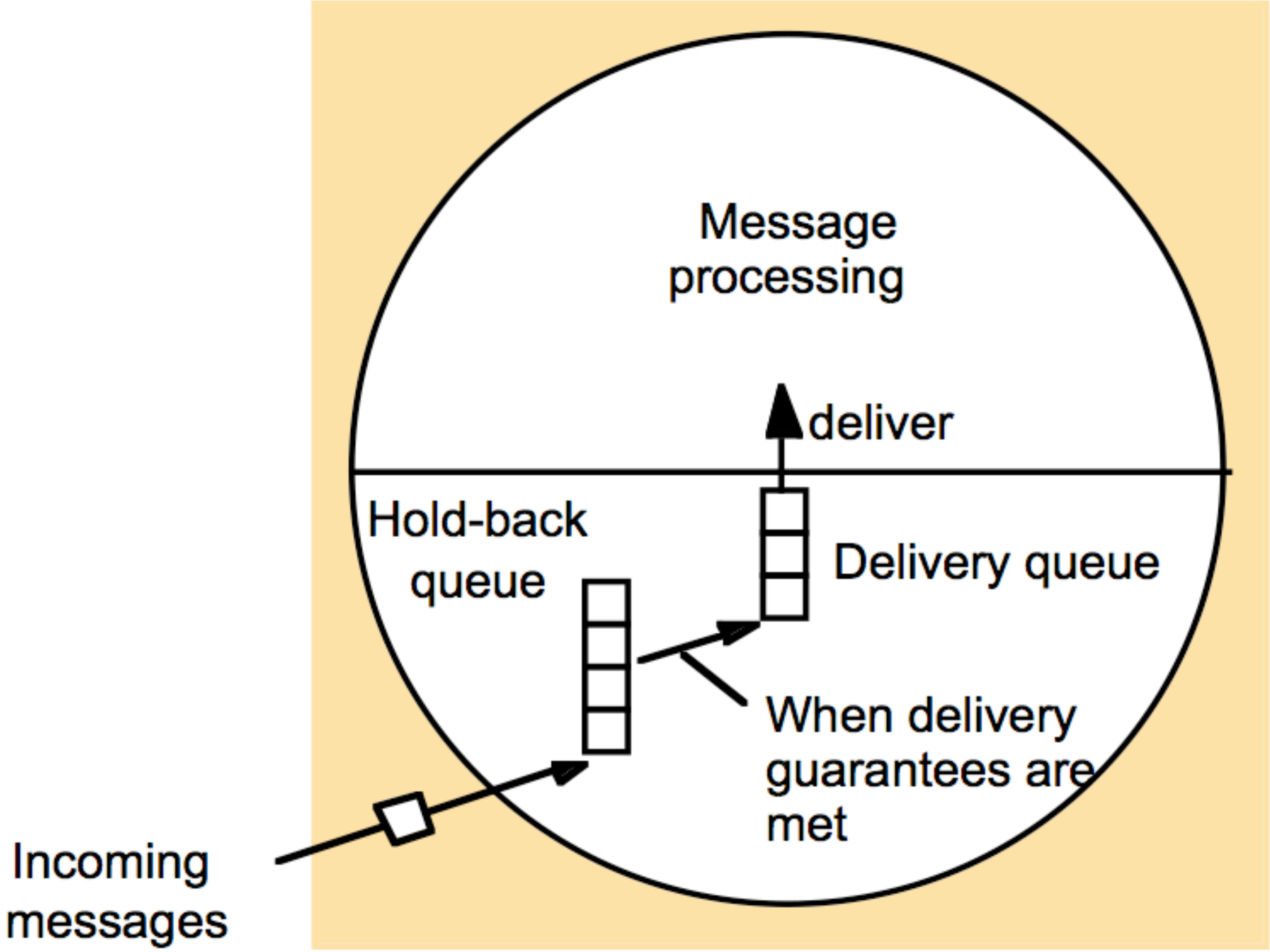


Hold-Back Queue for Arriving Multicast Messages



Condition for FIFO Ordering Satisfied Because...

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  ELSIF ($S > R^q_g + 1$) **THEN** it places the message in its *hold-back queue* until the intervening messages have been delivered and $S = R^q_g + 1$.

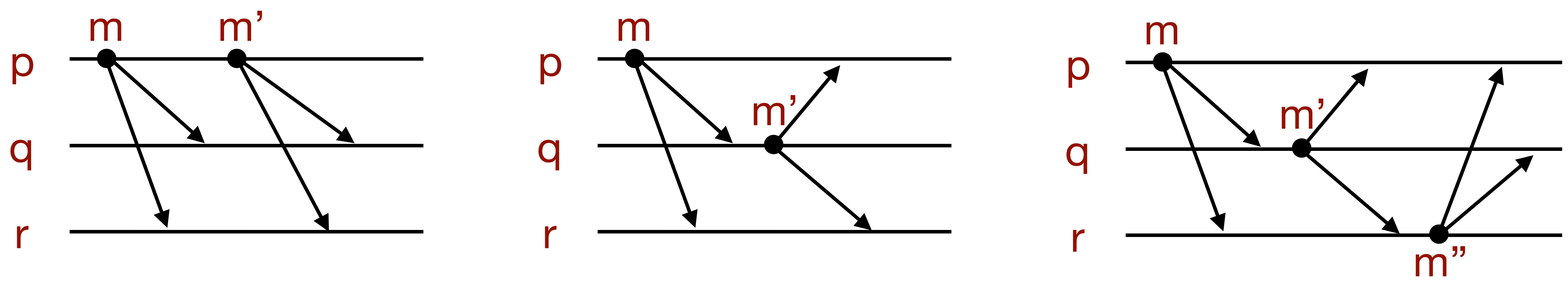
1. All messages from a given sender are delivered in the same sequence.

2. Delivery of a message is delayed until its sequence number has been reached.

- N.B.: this is so only under the assumption that groups are NON-overlapping.

Implementing Causal Ordering

Casual ordering: *multicast(g, m)* → *multicast(g, m')*, then any correct process that delivers *m'* will deliver *m* before *m'*.



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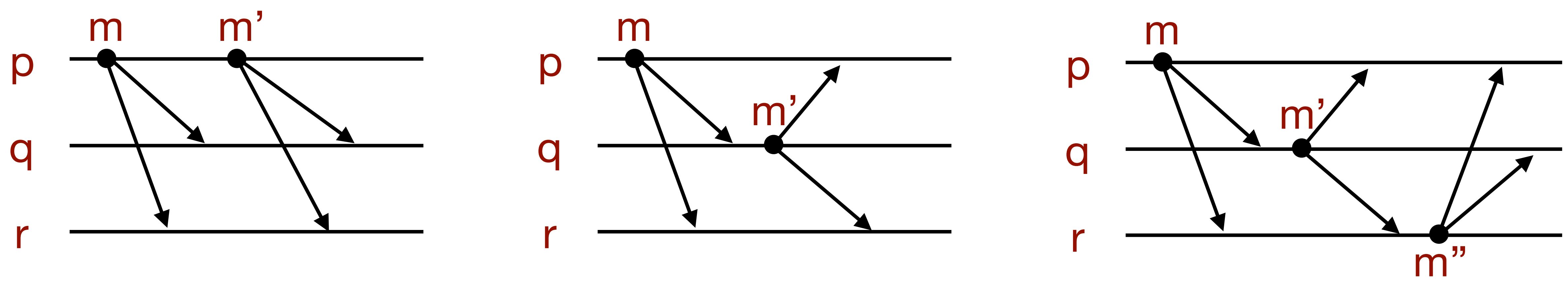

- Algorithm for non-overlapping closed groups (Birman et al., 1991).
- It takes into account of the happened-before relationship only as it is established by multicast messages.
- Each process maintain its own vector timestamp: the entries count the number of multicast messages from each process that happened-before the next message to be multicast.

Causal Ordering Using Vector Timestamps

Algorithm for group member p_i ($i = 1, 2..., N$)

On initialization

$V_i^g[j] := 0$ ($j = 1, 2..., N$);

To CO-multicast message m to group g

$V_i^g[i] := V_i^g[i] + 1;$

B-multicast(g, <V_i^g, m>);

the process add 1 to its entry in the timestamp and *B-multicasts* the msg along with its timestamp to g

On B-deliver(<V_j^g, m>) *from* p_j, *with* $g = group(m)$

place <V_j^g, m> in hold-back queue;

wait until $V_j^g[j] = V_i^g[j] + 1$ and $V_j^g[k] \le V_i^g[k]$ ($k \ne j$);

CO-deliver m; // after removing it from the hold-back queue

$V_i^g[j] := V_i^g[j] + 1$;

Causal Ordering Using Vector Timestamps

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B-multicast$(g, <V_i^g, m>)$;

On B-deliver$(<V_j^g, m>)$ *from* p_j, *with* $g = group(m)$
place $<V_j^g, m>$ in hold-back queue;
wait until $V_j^g[j] = V_i^g[j] + 1$ and $V_j^g[k] \le V_i^g[k]$ $(k \ne j)$;
CO-deliver m; // after removing it from the hold-back queue
$V_i^g[j] := V_i^g[j] + 1$;

Causal Ordering Using Vector Timestamps

Algorithm for group member p_i $(i = 1, 2 \ldots, N)$

On initialization

$V_i^g[j] := 0 \; (j = 1, 2 \ldots, N)$;

To CO-multicast message m to group g

$V_i^g[i] := V_i^g[i] + 1$;

B-multicast$(g, < V_i^g, m >)$;

On B-deliver$(< V_j^g, m >)$ *from* p_j, *with* $g = group(m)$

place $< V_j^g, m >$ in hold-back queue;

wait until $V_j^g[j] = V_i^g[j] + 1$ and $V_j^g[k] \le V_i^g[k] \; (k \ne j)$;

CO-deliver m; // after removing it from the hold-back queue

$V_i^g[j] := V_i^g[j] + 1$;

it has delivered any message that p_j had delivered

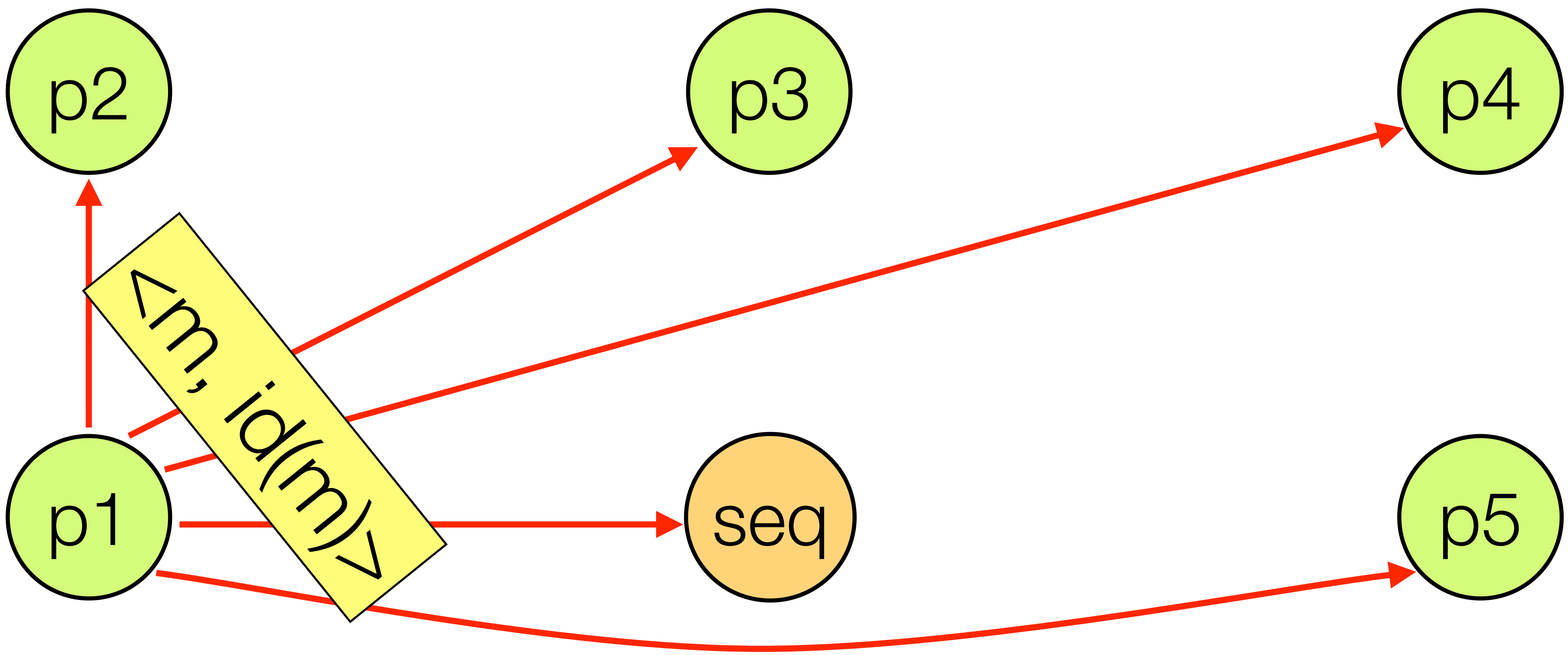
it has delivered any earlier message sent by p_j

Implementing Total Ordering

Total ordering: if a correct process delivers message *m* before it delivers *m'*, then any other correct process that delivers *m'* will deliver *m* before *m'*.

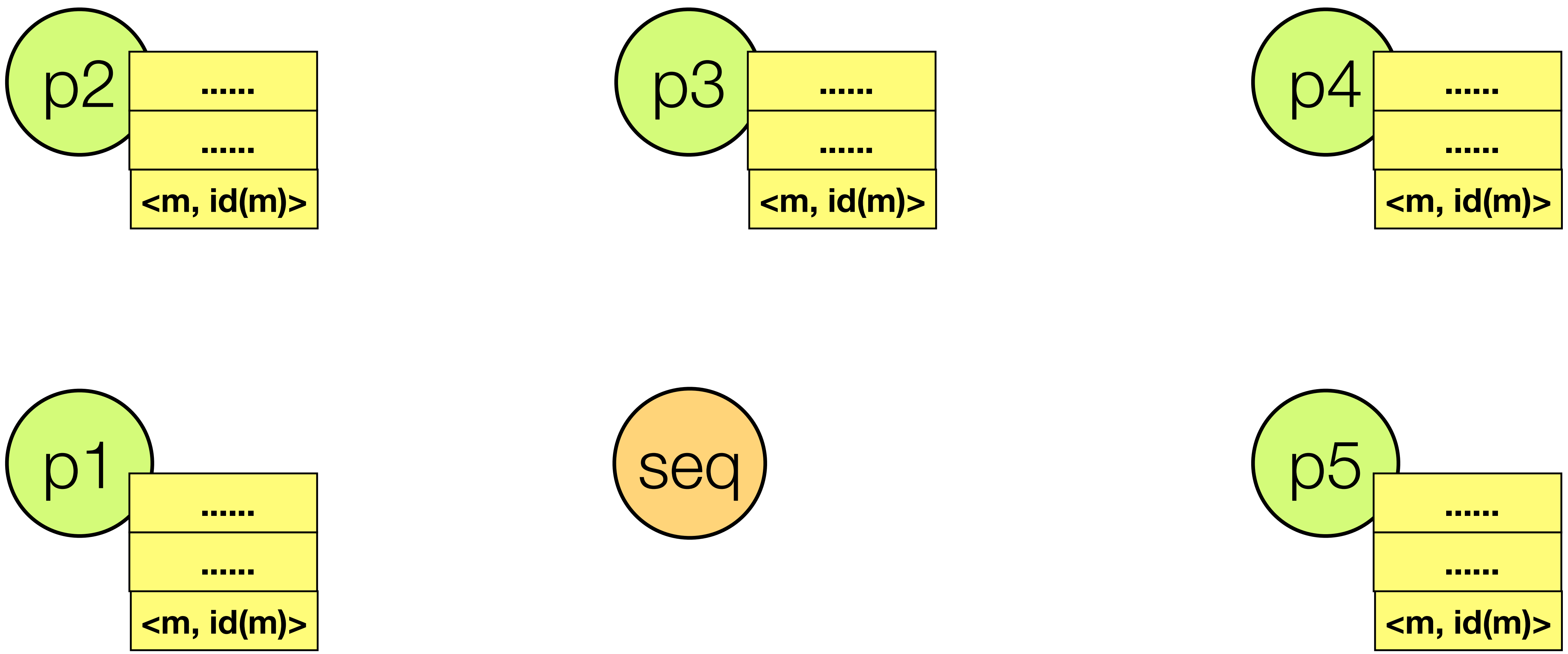
- We assume non-overlapping groups.
- Key idea: to assign totally ordered identifiers to multicast messages so that each process makes the same ordering decision based upon these identifiers.
- How: processes keep **group-specific sequence numbers** (rather than *process-specific sequence numbers* as for FIFO ordering).
- Key question: how to assign sequence numbers to messages?
- Two possible approaches: (central) sequencer or distributed agreement.

Total Ordering Using a Sequencer



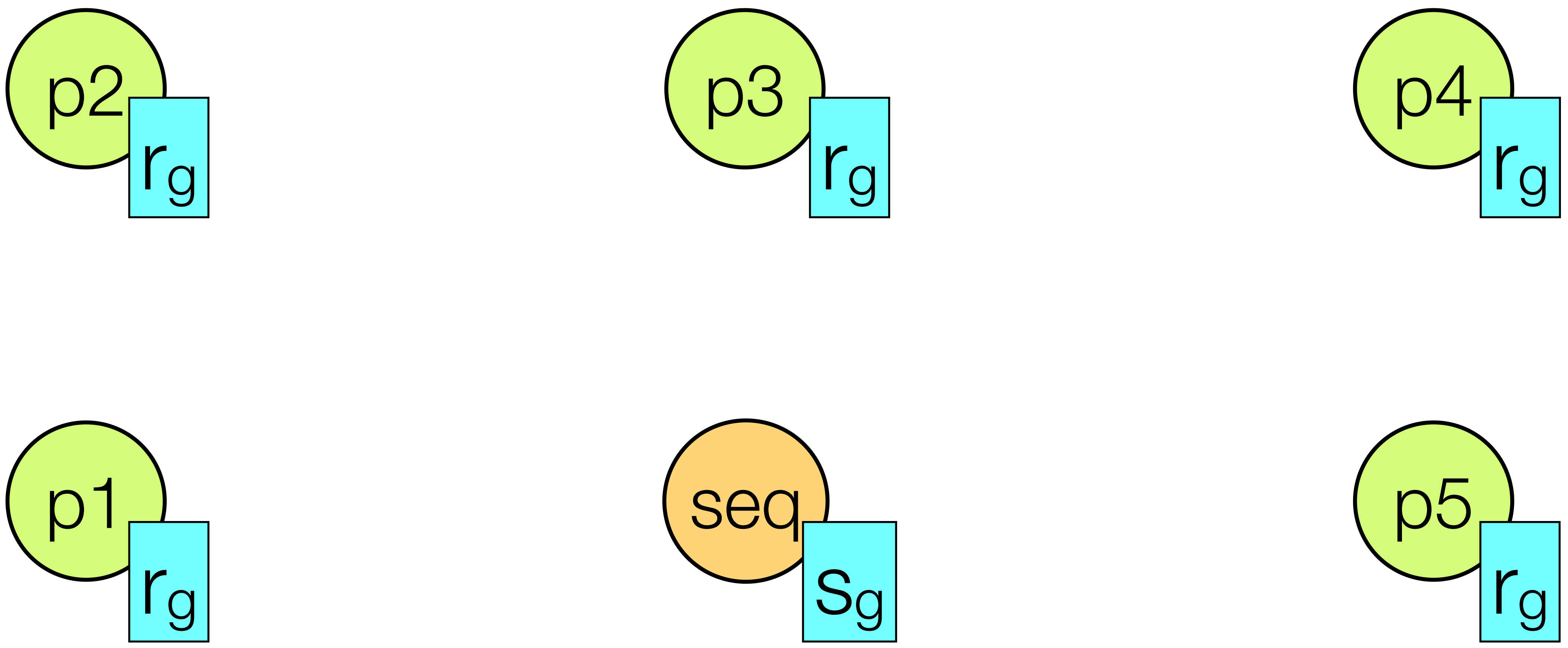
- To *TO-multicast* a message m to a group g, p1 attaches a unique identifier id (m) to it.
- The messages for g are sent to the sequencer for g as well as to the members of g (the sequencer may be chosen to be a member of g).

Total Ordering Using a Sequencer



- On *B-deliver(<m, id(m)>)* a process (but NOT THE SEQUENCER) places the message <m, id(m)> in its hold-back queue.

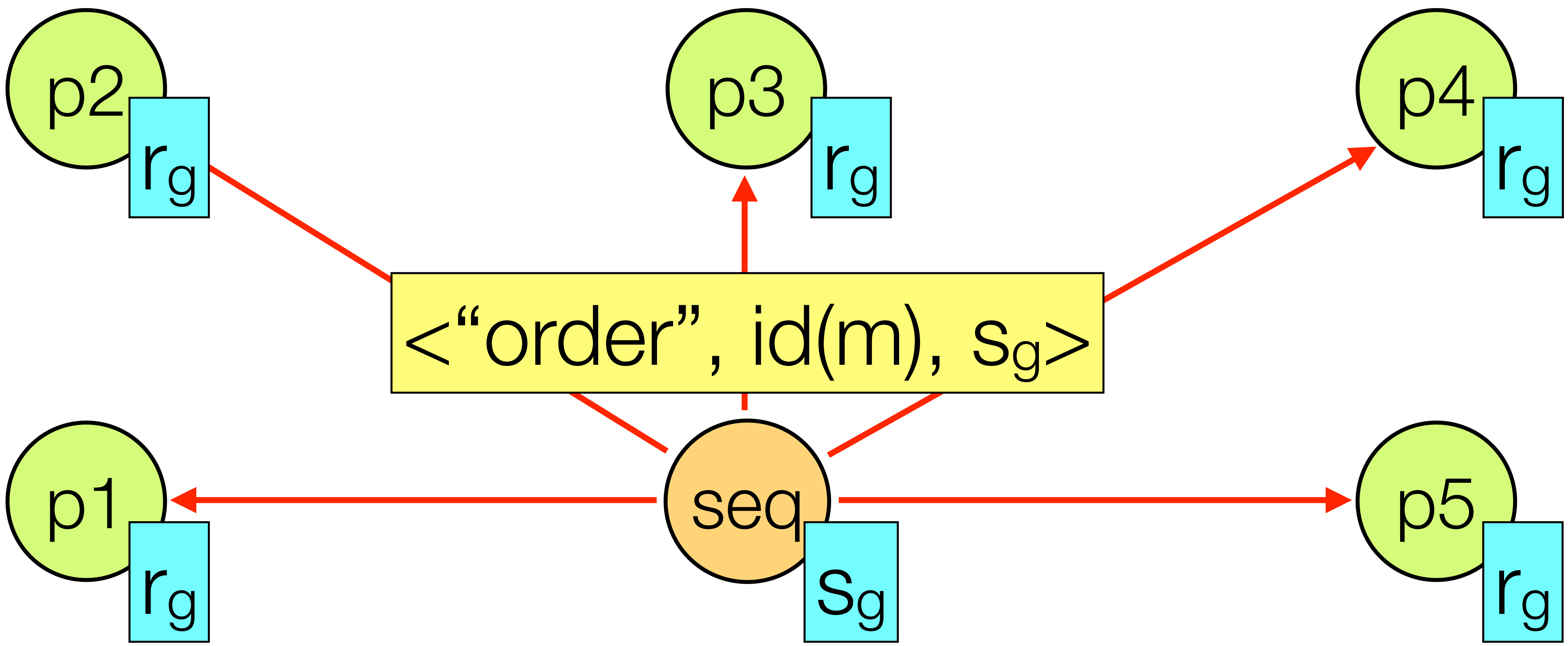
Total Ordering Using a Sequencer



- The sequencer maintains a group-specific sequence number s_g, which it uses to assign increasing and consecutive sequence numbers to the messages that it *B-delivers*.

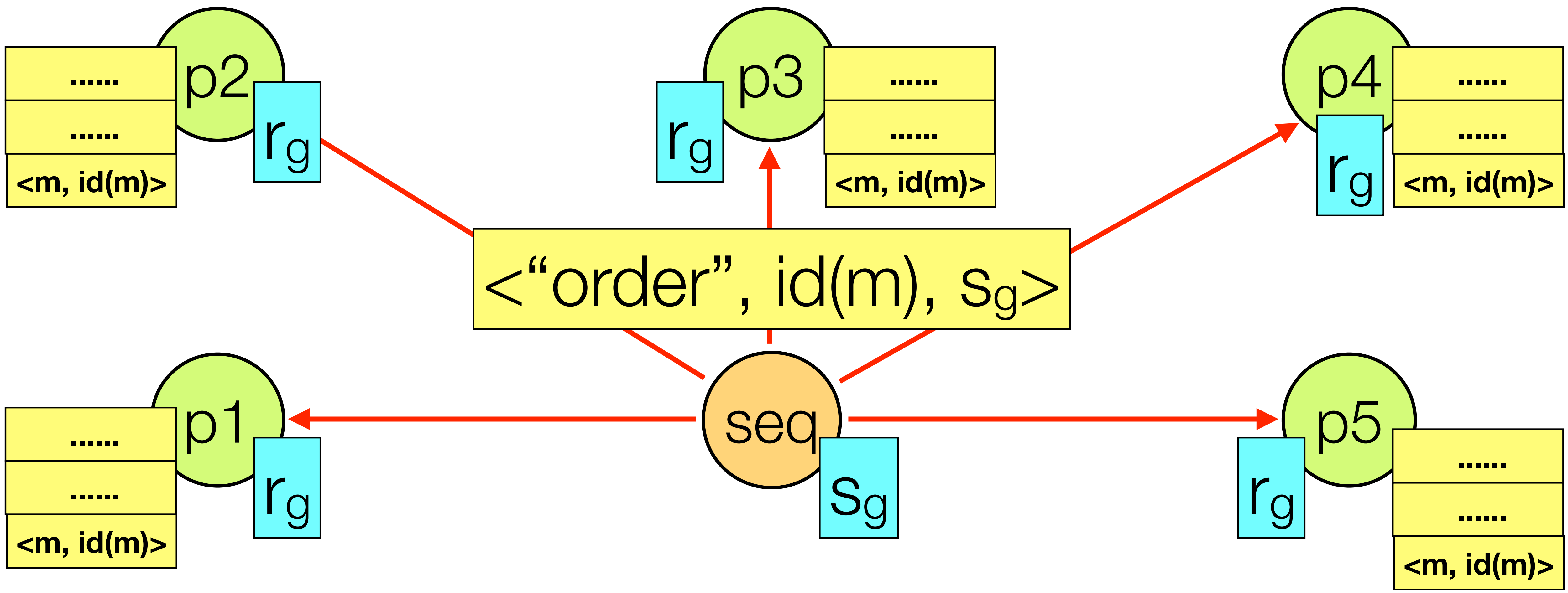
- Processes have their local group-specific sequence number r_g.

Total Ordering Using a Sequencer



- On *B-deliver(<m, id(m)>)* the sequencer announces the sequence numbers by *B-multicasting* "order" messages to g.

Total Ordering Using a Sequencer



- A message will remain in a hold-back queue indefinitely until it can be *TO-delivered* according to the corresponding sequence number ($s_g = r_g$).

Total Ordering Using a Sequencer: Algorithm

- Algorithm for sequencer of g

On initialization: s_g := 0;

On B-deliver(<*m*, *i*>) *with g = group*(*m*)
    B-multicast(*g*, <"order", *i*, s_g>);
    $s_g := s_g + 1$;

- Algorithm for group member p

On initialization: $r_g := 0$;

To TO-multicast message m to group g
    B-multicast($g \cup \{sequencer(g)\}$, <*m*, *i*>);

On B-deliver(<*m*, *i*>) *with g = group*(*m*)
    Place <*m*, *i*> in hold-back queue;

On B-deliver(m_{order} = <"order", *i*, *S*>) *with g = group*(m_{order})
    wait until <*m*, *i*> in hold-back queue and $S = r_g$;
    TO-deliver m;   // (after deleting it from the hold-back queue)
    $r_g = S + 1$;

Total Ordering Using a Sequencer: Algorithm

- Algorithm for sequencer of g

```
On initialization: s_g := 0;

On B-deliver(<m, i>) with g = group(m)
    B-multicast(g, <"order", i, s_g>);
    s_g := s_g + 1;
```

N.B.: since the sequence numbers are well defined by the sequencer, the criterion of total ordering is met.

- Algorithm for group member p

```
On initialization: r_g := 0;

To TO-multicast message m to group g
    B-multicast(g ∪ {sequencer(g)}, <m, i>);

On B-deliver(<m, i>) with g = group(m)
    Place <m, i> in hold-back queue;

On B-deliver(m_order = <"order", i, S>) with g = group(m_order)
    wait until <m, i> in hold-back queue and S = r_g;
    TO-deliver m;        // (after deleting it from the hold-back queue)
    r_g = S + 1;
```

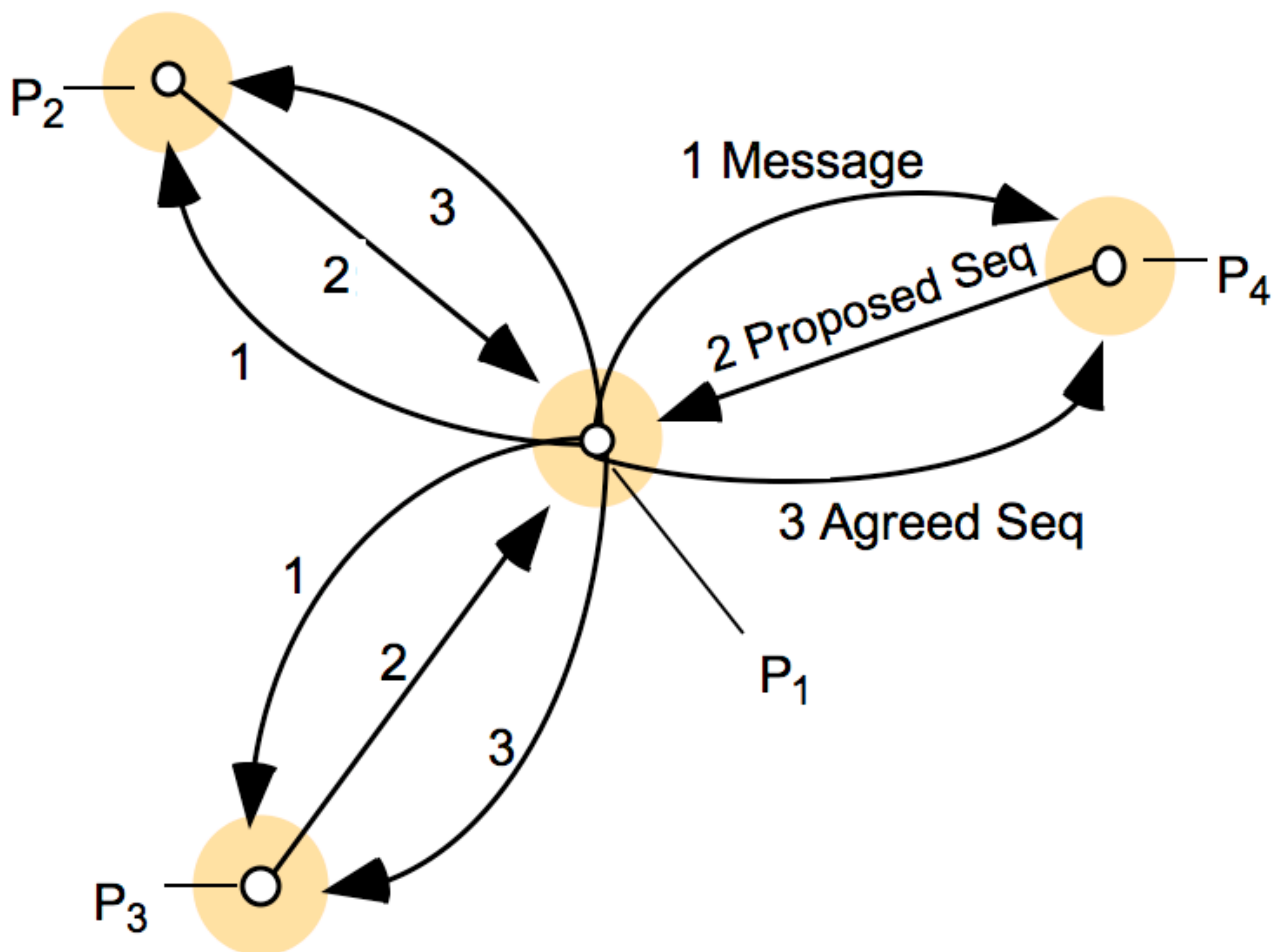
Homework

- Show (by informal discussion) that if two processes use a FIFO-ordered variant of B-multicast, then the totally ordered multicast is also causally ordered.

Total Ordering Using Distributed Agreement

- The obvious problem with a sequencer-based approach is that the sequencer may become a bottleneck and is a critical point of failure.
- Practical algorithms exist that address this problem (ask me if interested).
- Approach NOT based on a sequencer:
  - Key Idea: the processes collectively agree on the assignment of sequence numbers to messages in a distributed fashion.

Total Ordering Using Distributed Agreement



Homework

- Essential reading:

  X. Défago, A. Schiper, and P. Urbán.
  Total order broadcast and multicast algorithms: Taxonomy and survey.
  ACM Computing Surveys 36(4), 372-421, 2004.