CLOCK / SYNCHRONIZATION

Ex 1: Considering the problem of physical clock synchronization, provide the definitions of internal and external clock synchronization. In addition,

1. provide the description of an algorithm that can be used to synchronize clocks,
2. specify which type of synchronization it ensures and
3. details the necessary assumptions to let it work correctly.

4. explain the differences between internal and external clock synchronisation

External clock synchronization:

- Processes synchronize their clock C_i with an authoritative external source S
- Let D>0 be the synchronization bound and S be the source of UTS (Universal Time Coordinated)
- Clocks C_i (for i=1,2,…,N) are externally synchronized with a time source S (UTC) if for each time interval I:

  $|S(t) - C_i(t)| < D$ for i=1,2,…,N and for real time t in I
- We say that clocks C_i are accurate within the bound of D

Internal clock synchronization:

- All the processes synchronize their clocks C_i between them
- Let D>0 be the synchronization bound an let C_i and C_j the clocks at processes p_i and p_j respectively
- Clocks are internally synchronized in a time interval I:

  $|C_i(t) - C_j(t)| < D$ for i,j=1,2,…,N and for all time t in I
- We say that clocks C_i, C_j agree within the bound of D

Algorithm to synchronize clocks:

- Christan's algorithm (external, request-driven):
  - Uses a time server S that receives a signal from an UTS source
  - Works (probabilistically) also in an asynchronous system
  - Based on message round trip (RTT)
  - Synchronization is reached only if RTT is small wrt. required accuracy
  - Process p asks the current time through a message m_r and receives t in m_t from S
  - Process p sets its clock to t + (RTT/2), RTT is round trip time (RTT) experienced by p
  - Accuracy is ±(RTT/2 - min), min is minimum transmission delay:
    - Case 1: delay Δ = estimate of response – real time
      = (RTT/2) – (RTT – min) = -(RTT/2 - min)
    - Case 2: delay Δ = estimate of response – real time
      = (RTT/2) – (min) = +(RTT/2 - min)
  - Time server is single point of failure (→ periods in which synchronization not possible)
  - Time server not crashing or getting attacked (→ use cluster of synchronized servers, redundancy, authentication)
- Berkeley's algorithm (internal, broadcast-based):
  - Master-slave structure, based on gathering the clocks from other processes and computing the differences and respective correction
  - Master process p_m sends a message with a timestamp t_1 (local clock value) to each process of the system (p_m included)
  - When p_i receives message from master, it sends back reply with its timestamp t_2 (local clock value)

- When master receives reply message, it reads local clock t_3 and computes difference between the clocks: difference $\Delta = (t_1 + t_3)/2 - t_2$
- Master behaviour:
  - Computes difference Δp_i between the master clock and clock of every other process p_i (including master)
  - Computes average avg of all Δp_i without considering faulty processes (clock differs more than certain threshold)
  - Computes correction of each process (including faulty processes):
    $Adg_{pi} = avg - \Delta p_i$
- Slaves behaviour:
  - When process receives correction, it applies it to local clock
  - If correction is negative, don't adjust the value but slow down the clock by hiding interrupts
- Accuracy depends on maximum RTT (round trip time), master does not consider clock values associated to RTT greater than the maximum
- Fault tolerance:
  - If master crashes, new master is elected
  - Tolerant to arbitrary behaviour (eg. wrong values from slaves)

Ex 1: Discuss why passing from a synchronous system to an eventually synchronous one, it is no longer possible for failure detectors to ensure the property of strong accuracy while it is possible to ensure the property of eventual strong accuracy.

- Synchronous: upper bounded delays wrt. processing, communication and physical clocks or existence of common global clock
- Partial (eventually) synchronous: synchronous most of time with bounded asynchronous periods (there is a unknown time t after which the system becomes synchronous)
- Strong accuracy: If a process p is detected by any process, then p has crashed.
- Eventually strong accuracy: Eventually, no correct process is suspected by any correct process.
- It is no longer possible to ensure strong accuracy, because the system can have an unknown period of time in which the system behaves asynchronous. In this period a correct process might not send its heartbeat reply although it is correct. In this case the perfect failure detector (strong accuracy) detects a crash and will not revise it although the process might be correct.
- It is possible to ensure eventual strong accuracy. In asynchronous period of time a not replying correct process will be flagged as suspect. After the asynchronous period the correct process will deliver its heartbeat reply in bounded time, so that the eventually perfect failure detector (eventually strong accuracy) revises its false judgement and restore the correct process.

LINKS

Ex 4: Describe properties of *fair-loss*, *stubborn* and *perfect* point-to-point channels. In addition, discuss the relationship between point-to-point channels abstraction and TCP/UDP protocols.

Fair-loss:

- Basic idea that messages might be lost but with probability >0
- Properties:
  - Fair-loss: If correct process p infinitely often sends a message m to a correct process q, then q delivers m an infinite number of times.

- Finite duplication: If a correct process p sends a message m a finite number of times to process q, then m cannot be delivered an infinite number of times by q.
- No creation: If some process q delivers a message m with sender p, then m was previously sent to q by process p.

Stubborn:

- After timeout resend each sent message again
- Properties:
  - Stubborn delivery: If a correct process p sends a message m once to a correct process q, then q delivers m an infinite number of times.
  - No creation: If some process q delivers a message m with sender p, then m was previously sent to q by process p.

Perfect:

- Deliver each message not more than once
- Properties:
  - Reliable delivery: 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.

TCP/UDP protocols:

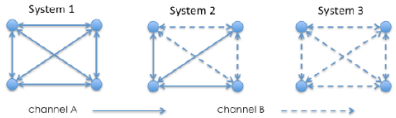
- Communication channels providing data exchange between server and client
- Port-to-port instead of point-to-point
- TCP (perfect):
  - Sends data correctly (reliable, ordered and error checked)
  - Higher transmission time
- UDP (fair-loss):
  - Sends data without considering failures
  - Data might be lost
  - Provides checksum function for receiver

IMPL. PERFECT FAILURE DETECTOR / COMPOSED / FP2P + PP2P

Ex 1: Let channel A and channel B be two different types of point-to-point channels satisfying the following properties:

- channel A: if a correct process p_i sends a message m to a correct process p_j at time t, then m is delivered by p_j by time $t+\delta$
- channel B: if a correct process p_i sends a message m to a correct process p_j at time t, then m is delivered by p_j with probability p_{cons} (p_{cons} <1).

Let us consider the following systems composed by 4 processes p_1, p_2, p_3 and p_4 connected trough channels A and channels B.



Assuming that each process p_i is aware of the type of channel connecting it to any other process, answer to the following questions:

1. is it possible to design an algorithm implementing a perfect failure detector in system 2 if only processes having an outgoing channel of type B can fail by crash?
2. is it possible to design an algorithm implementing a perfect failure detector in system 2 if any process can fail by crash?
3. is it possible to design an algorithm implementing a perfect failure detector in system 3?

For each point, if an algorithm exists write its pseudo-code, otherwise show the impossibility.

1. Yes, because crash can be detected by p_2 through messages in the type A channels:
   pp2p: Perfect Point-to-Point link (channel A)
   fp2p: Fair-loss Point-to-Point link (channel B)

   Upon event <Init> do
   Correct := {P_1, P_2, P_3, P_4}
   Alive := {};
   $\Delta := 2*\delta$; !!!

```
        // Δ := 4*δ;
        Starttimer(Δ);

Upon event <Timeout> do
        Forall p ϵ correct do
                Trigger xp2pSend(HBRQ);
        Alive = {};
        Starttimer(Δ);
        If myID = P1 do
                Update Correct; Correct = Alive;          !!!
                Trigger xp2pSend('Alive', Alive);

Upon even <xp2pDeliver('Alive', List) do
        Forall p ϵ (Correct\List) do
                Trigger Crash(p);
        // Correct := List;

Upon event <xp2pDeliver(HBRQ)> from pi do
        Alive = Alive U {pi}
        Trigger xp2pDeliver(HBRL);                !!!
        // Trigger xp2pSend(HBRL);

Upon event <xp2pDeliver(HBRL)> from pi do
        Alive = Alive U {pi}
```

2. No, counterexample: If process p_1 crashes, the perfect failure detector will detect it due to the type A channels. Then, further messages of p_3 might get lost due to the delivering probability $p_{cons} < 1$ of all remaining type B channels. In this case, a crash of p_3 will be detected, although p_3 might be alive.

3. No, counterexample: All messages of p_3 might get lost due to the delivering probability $p_{cons} < 1$ of all remaining type B channels. In this case, a crash of p_3 will be detected, although p_3 might be alive.

IMPL. LEADER ELECTION / LINE / PP2P

Ex 2: Consider a distributed system composed by n processes $\{p_1,p_2,\ldots,p_n\}$ that communicate by exchanging messages on top of a line topology, where p_1 and p_n are respectively the first and the last process of the network.
Initially, each process knows only its left neighbour and its right neighbour (if they exist) and stores the respective identifiers in two local variables LEFT and RIGHT.
Processes may fail by crashing, but they are equipped with a perfect oracle that notifies at each process the new neighbour (when one of the two fails) through the following primitives:

- **Left_neighbour(p_x)**: process p_x is the new left neighbour of p_i
- **Right_neighbour(p_x)**: process p_x is the new right neighbour of p_i

Both the events may return a NULL value in case p_i becomes the first or the last process of the line.
Each process can communicate only with its neighbours.

Write the pseudo-code of an algorithm implementing a Leader Election primitive assuming that channels connecting two neighbour processes are perfect.

```
Upon event <Init> do
        RIGHT := myID + 1;
        LEFT := myID - 1;
        leader := P1;

Upon event <Right_neighbour(px)> do
        RIGHT := px;
```

Upon event <Left_neighbour(p_x)> do
    LEFT := p_x;
    If LEFT = ⊥ do
        leader = MyID;
        Trigger Leader(leader);
        Trigger pp2pSend('New Leader', leader);

Upon event <pp2pSend('New Leader', p) do
    leader = p;
    Trigger Leader(p);
    Trigger pp2pSend('New Leader', leader);

IMPL. Same as Ex 2 but implement PERFECT FAILURE DETECTOR / LINE / PP2P primitive.

Upon event <Init> do
    RIGHT := myID + 1;
    LEFT := myID - 1;
    Alive := π;

Upon event <Right_neighbour(p_x)> do
    Alive := Alive \ RIGHT;
    Trigger Crash(RIGHT);
    Trigger pp2pSend('Failed', RIGHT);
    RIGHT := p_x;

Upon event <Left_neighbour(p_x)> do
    Alive := Alive \ LEFT;
    Trigger Crash(LEFT);
    Trigger pp2pSend('Failed', LEFT);
    LEFT := p_x;

Upon event <pp2pDeliver('Failed', p)> do
    If p ϵ Alive do
        Alive := Alive \ p;
        Trigger Crash(p);
        Trigger pp2pSend('Failed', p);

Module 1.1 Interface of a printing module

Module:

Name: Print.

Events:

Request: ⟨ *PrintRequest* | rqid, str ⟩: Requests a string to be printed. The token rqid is an identifier of the request.

Confirmation: ⟨ *PrintConfirm* | rqid ⟩: Used to confirm that the printing request with identifier rqid succeeded.

Module 1.2 Interface of a bounded printing module

Module:

Name: BoundedPrint.

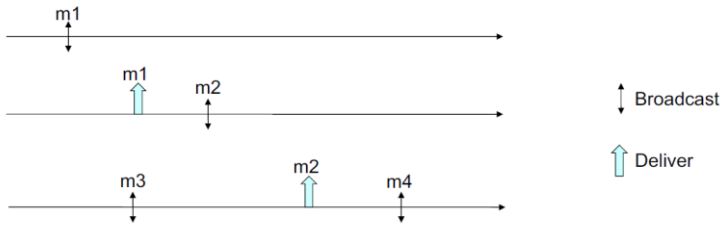
Events:

Request: ⟨ *BoundedPrintRequest* | rqid, str ⟩: Request a string to be printed. The token rqid is an identifier of the request.

Confirmation: ⟨ *PrintStatus* | rqid, status ⟩: Used to return the outcome of the printing request: Ok or Nok.

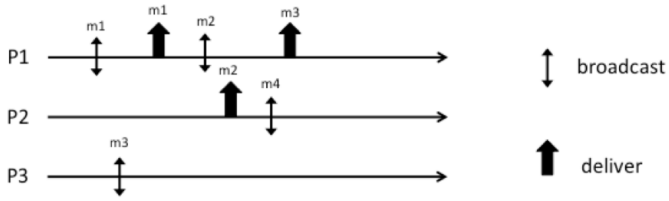
Indication: ⟨ *PrintAlarm* ⟩: Used to indicate that the threshold was reached.

Provide all the delivery sequences such that both total order and causal order are satisfied.



m_3, m_1, m_2, m_4
m_1, m_3, m_2, m_4
m_1, m_2, m_3, m_4

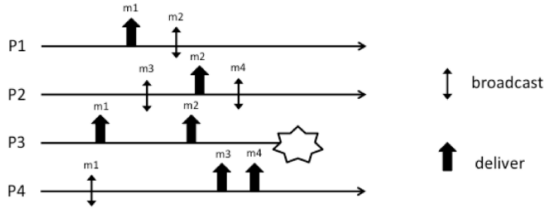
1. Provide all the possible sequences satisfying Causal Order
2. Complete the execution in order to have a run satisfying FIFO order but not causal order



1. m_3, m_1, m_2, m_4
   m_1, m_3, m_2, m_4
   m_1, m_2, m_3, m_4
   m_1, m_2, m_4, m_3

2. p1: m1→, →m1, m2→, →m3, →m4, →m2
   p2: →m1, →m2, m4→, →m4, →m3
   p3: m3→, →m1, →m3, →m4, →m2

1. Provide the list al all the possible delivery sequences that satisfy both Total Order and Causal Order
2. Complete the history (by adding the missing delivery events) in order to satisfy Total Order but not Causal Order
3. Complete the history (by adding the missing delivery events) in order to satisfy FIFO Order but not Causal Order nor Total Order

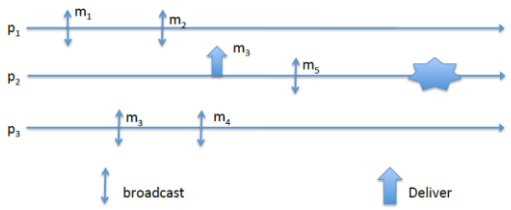


1. m1, m2, m3, m4
   m1, m3, m2, m4
   m3, m1, m2, m4

2. p1: →m1, m2→, →m3, →m4, →m2
   p2: →m1, m3→, →m3, →m2, m4→, →m4
   p3: →m1, →m3, →m2, →m4, crash
   p4: m1→, →m1, →m3, →m4, →m2

3. p1: →m1, m2→, →m3, →m4, →m2
   p2: →m1, m3→, →m3, →m2, m4→, →m4
   p3: →m1, →m3, →m2, →m4, crash
   p4: m1→, →m3, →m4, →m2, →m1

Ex 1: Consider the partial execution depicted in the following figure:



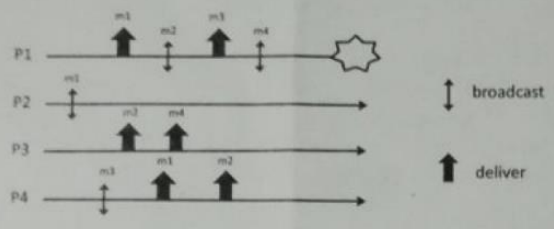
1. Complete the execution (by adding delivery of messages) in order to obtain a run satisfying *Non Uniform Reliable Broadcast.*
2. Complete the execution (by adding delivery of messages) in order to obtain a run satisfying *Uniform Reliable Broadcast.*
3. Considering the two runs provided in point 1 and 2, do they satisfy some ordering property? If so, which type of ordering?

1. p1: m1→, m2→, →m1, →m2, →m3, →m4
   p2: →m3, m5→, crash
   p3: m3→, m4→, →m1, →m2, →m3, →m4

2. p1: m1→, m2→, →m1, →m2, →m3, →m4, →m5
   p2: →m3, m5→, →m5, crash
   p3: m3→, m4→, →m1, →m2, →m3, →m4, →m5

3. Reliable Broadcast does not have any property on ordering deliveries on messages, but only on the set of delivering messages. Only ordering property has to be considered: Deliver after Sending.

Ex 1: Consider the execution depicted in the Figure



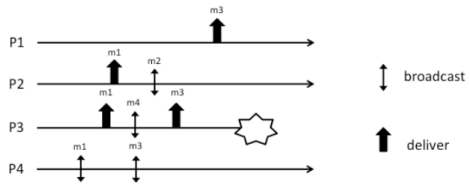
Answer to the following questions:

1. Provide all the delivery sequences that satisfy both causal order and total order
2. Complete the execution in order to have a run satisfying TO(NUA, WNUTO), FIFO order but not causal order

1. m1, m2, m3, m4
   m1, m3, m2, m4

2. p1: →m1, m2→, →m3, m4→, →m4, m5→, →m5, crash
   p2: m1→, →m1, →m2, →m4, →m3
   p3: →m1, →m2, →m4, →m3
   p4: m3→, →m1, →m2, →m4, →m3

Ex 2: Consider the partial execution depicted in the Figure



Answer to the following questions:

1. Provide all the possible sequences that satisfy causal order and total order.
2. Provide all the possible sequences that satisfy TO (UA, WNUTO) and do not satisfy causal order.

1. m1, m2, m3, m4
   m1, m2, m4, m3
   m1, m3, m2, m4
   m1, m3, m4, m2
   m1, m4, m2, m3
   m1, m4, m3, m2

   Since m4 does not need to be delivered:
   m1, m3, m2
   m1, m2, m3

2. m4, m3, m1, m2
   m3, m4, m1, m2
   m3, m1, m4, m2
   m3, m1, m2, m4
   m4, m1, m3, m2
   m4, m1, m2, m3

   Since m4 does not need to be delivered:
   m3, m1, m2

Ex 3:
Describe the hierarchy of total order primitives discussing order and agreement properties. Show an original run (i.e., a run not shown during the classes):

- . satisfying TO(NUA,SUTO) and not satisfying TO(UA,SUTO)
- satisfying TO(UA,WUTO) and not satisfying TO(UA,SUTO)

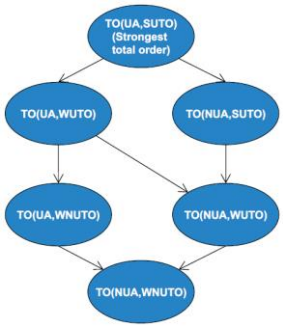
Agreement property:

1. Uniform (UA): If a process (correct or not) TODelivers a message m, then all correct processes will eventually TODeliver m
2. Non-Uniform (NUA): If a correct process TODelivers a message m, then all correct processes will eventually TODeliver m

Order Property:

1. Strong Uniform TO (SUTO): If some process TODelivers some message m1 before message m2, then a process TODelivers m2 only after it has TODelivered m1
2. Weak Uniform TO (WUTO): If process p and q both TODeliver messages m1 and m2, then p TODelivers m1 before m2 if and only if q TODelivers m1 before m2

3. Strong Non-Uniform TO (SNUTO): If some correct process TODelivers some message m1 before message m2, then a correct process TODelivers m2 only after it has TODelivered m1
4. Weak Non-Uniform TO (WNUTO): If correct processes p and q both TODeliver messages m1 and m2, then p TODelivers m1 before m2 if and only if q TODelivers m1 before m2



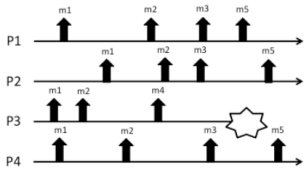
TO(NUA, SUTO), NOT TO(UA, SUTO):

P1: m1, m2
P2: m1, m2
P3: m1, m2, m3, crash

TO(UA, WUTO), NOT TO(UA, SUTO):

P1: m1, m2, m3
P2: m1, m2, m3
P3: m1, m3, crash

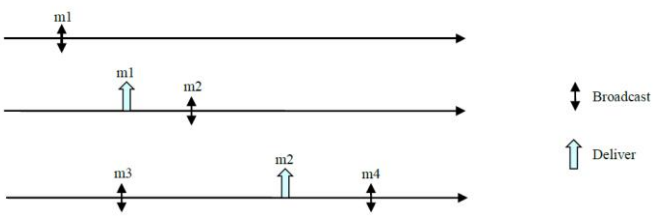
Ex 3: Consider the run depicted in the figure:



1. Which type of total ordering is satisfied by the run? Specify both the agreement and the ordering properties.
2. Modify the run in order to satisfy TO(UA, WUTO) but not TO (UA SUTO)
3. Modify the run in order to satisfy TO(NUA, WNUTO) but not TO(NUA, WUTO)

1. TO(NUA, SUTO)
2. P1 & P2 & P4: m1, m2, m3, m4, m5
3. P3: m1, m2, m4, m5, m3

Ex 2:
Consider the following partial history



Find the number of all delivery sequences that respect total order of deliveries and do not respect causal order of sendings. (provide an explanation of the answer)

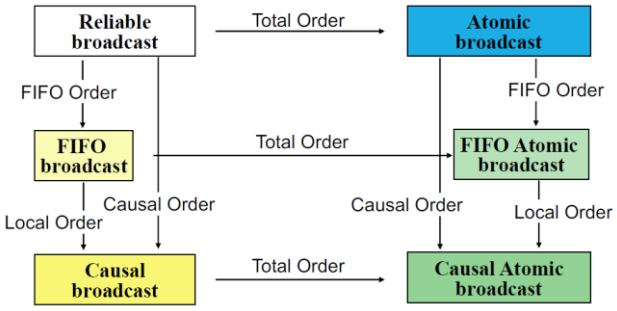
FIFO: m3→m4 (change to m4→m3 to violate causal order)
LO: m1→m2 (not changeable because it would change given history of p2, keep TO)
m2→m4 (not changeable because it would change given history of p3, keep TO)

m1, m2, m4, m3 (one possible delivery sequence)
OR:

FIFO: m3→m4 (change to m4→m3 to violate FIFO order)
LO: m1→m2 (change to m2→m1)
m2→m4 (change to m4→m2)

m4, m2, m1, m3
m4, m2, m3, m1
m4, m3, m2, m1 (3 possible delivery sequences)

Ex 2: Consider the FIFO, Causal and Total Order broadcast primitives. Describe the relations (equivalence, orthogonality, inclusion) that exist among them, providing examples (runs) as a motivation to your answer



FIFO: If some process broadcasts message m1 before it broadcasts message m2, then no correct process delivers m2 unless it has already delivered m1.
Causal: For any message m1 that potentially caused a message m2, no process delivers m2 unless it has already delivered m1 (see potentially causes).
Total: Total order orders all messages, even those from different senders and those that are not causally related. The message is delivered to all or none of the processes and, if the message is delivered, every other message is ordered either before or after this message.
Causal Order → FIFO Order
FIFO Order !→ Causal Order
Causal Order ←→ (=) FIFO Order + Local Order (if process delivers m before sending m', then no correct process deliver m' if it not already delivered m)
Total order is orthogonal to FIFO and Causal order.
TO: p1: m1→, m2→, →m2, →m1
p2: →m2, →m1

FIFO: p1: m1→, m2→, →m3, →m1, →m2
p2: →m1, m3→, →m2, →m3

Causal: p1: m1→, →m3, →m1, →m2, →m4
p2: →m1, m2→, →m3, →m2, m4→, →m4
p3: m3→, →m1, →m2, →m3, →m4

IMPL. UNIFORM RELIABLE BROADCAST / COMPOSED / FP2P

Ex 2: Consider a distributed system composed by n processes $\{p_1,p_2,\ldots,p_n\}$. Each process is connected to all the others trough fair-loss point-to-point links and has access to a perfect failure detector.

Write the pseudo-code of an algorithm implementing a Uniform Reliable Broadcast primitive.

Additionally, answer to the following questions:

1. Is it possible to provide a quiescent implementation of the Uniform Reliable Broadcast primitive?
2. Given the system model described here, is it possible to provide an implementation that uses only data structure with finite size?

```
Upon event <Init> do
        Sent = {};
        Delivered = {};
        Pending = {};                       !!!
        Correct = π;
        DEL[] = [{}];
        ACK[] = [{}];
        Starttimer(Δ);

Upon event <Crash(p)> do
        Correct = Correct \ {p};

// Broadcast to all correct processes and save msg in Sent
Upon event <URB_Broadcast(m)> do
        Forall p ϵ Correct do
                Trigger fp2pSend(m) to p;
        Sent = Sent U {<'MSG', m>};

// Save arrival of msg and retransmit an ACK
Upon event <fp2pDeliver('MSG', m) from p do
        Pending = Pending U {<'MSG', m, p>};                    !!!
        Trigger fp2pSend('ACK', m, myID) to p;

// Save the arrival of the msg at target process
Upon event <fp2pDeliver('ACK', m, pi)> from p do
        ACK[m] = ACK[m] U {p};

// If msg is arrived in all correct target processes, send delivering order to all correct processes
Upon exists m | Correct ⊆ ACK[m] do
        Forall p ϵ Correct do
                Trigger fp2pSend('DEL', m);
        Sent = Sent U {<'DEL', m>};

// Resend all msg after every timeout
Upon event <timeout> do
        Forall <*, m> ϵ Sent do                 // Don't care if 'MSG' or 'DEL'
                Trigger fp2pSend(*, m);
        // Starttimer(Δ);
```

```
Upon event <fp2pDeliver('DEL', m)> from p do
        Forall p ϵ Correct do
                Trigger fp2pSend('DEL', m);
        Sent = Sent U {<'DEL', m>};
        DEL[m] = DEL[m] U {<m, p>}

Upon exists m | Correct ⊆ DEL[m] do
        If m ∉ delivered
                Delivered = delivered U {m}
                Trigger URB_Deliver(m);
```

1. Not in the case of fair-loss point-to-point links, since messages have to be transmitted infinitely often to be sure that it will be delivered due to the finite duplication property.

2. No, since every message gets an entry in the DEL[] and ACK[] arrays and an infinite number of messages are possible.

IMPL. CONSENSUS / RING / PP2P

Ex 4: Consider a distributed system formed by n processes p_1, p_2, …, p_n connected along a ring i.e., a process p_i is initially connected to a process $p_{(i+1) \bmod n}$ through a unidirectional perfect point-to-point link.
Write the pseudo-code of a distributed algorithm implementing a consensus primitive.

```
Upon event <Init> do
        U = I;
        Decision = ⊥;
        Decided = False;                !!!
        If (myID = P1) do
                T = generate_token();
                Trigger pp2pSend('Token', T) to next process P(myID+1)mod n;
                T = {};
        Else do
                T = ⊥;                  !!!
                // T  = {};

Upon event <Propose(v)> do
        U = val;
        If T ≠ {} do                    !!! Only takes proposals if token here
                T = T U {<R, U>};       !!!
                T = T U {<U>};

Upon event <Deliver('Token', Ti)> do
        T = Ti;
        Starttimer(1);
        Trigger pp2pSend('Token', T) to next process P(myID+1)mod n;
        T = {};
```

Upon T ≠ {} AND |T| = n *(// AND Decision = ⊥)* do !!! What if token n+1 comes?
    Decision = min(T);
    Trigger Decide(Decision);
    Decided = T; !!!

IMPL. TOTAL ORDER BROADCAST / COMPOSED / WITH LEADER AND RELIABLE BROADCAST

Ex 4:
Consider an asynchronous distributed system composed by n processes $p_1, p_2 \ldots p_n$. Each process is equipped with an oracle that provides the name of a leader and processes communicate through a reliable broadcast primitive. Answer the following questions:
1) Write the pseudo code of an algorithm that implements a "Total Order Broadcast" primitive without considering process crashes
2) discuss if the protocol implements also causal order of broadcast messages (motivate the answer)
3) modify the pseudo code of the protocol to handle the crash of the leader

1.
Upon event <Init> do
    Leader = p1;
    Delivered = {};
    Pending = {};

Upon event <leader(p)> do
    Leader = p;

Upon event <TO_B(m)> do
    Trigger RB_B(m);

// Save locally all incoming messages if you are leader
Upon event <RB_D(m)> do
    If m ∉ delivered AND myID = Leader do
        Pending = Pending U {m};

Upon Pending ≠ {} AND myID = Leader do
    List = sort(Pending);
    Pending = Pending \ List;
    Trigger RB_B('DEL', List);

Upon event <RB_D('DEL', List)> do
    For all (m) ϵ List do
        Delivered = Delivered U {m};
        Trigger TO_D(m);

2.
No, since only the delivery sequence of the leader is considered, which is not depending on causal ordering but the delivery delays.

3.
Upon event <Init> do
    …
    Correct = PI;

```
Upon event <crash(p)> do
        Correct = Correct \ p;
        If Leader = p do
                Trigger leader(maxrank(Correct));
```

IMPL. TOTAL ORDER BROADCAST / RING / FP2P & PERFECT FAILURE DETECTOR

Ex 5: Consider a distributed system composed by n processes $\{p_1,p_2,\ldots,p_n\}$ that communicate by exchanging messages on top of a ring topology.
Initially, each process knows only its left neighbour and its right neighbour and stores the respective identifiers in two local variables LEFT and RIGHT.
Processes may fail by crashing, but they are equipped with a perfect failure detection system that notifies at each process the new neighbour (when one of the two fails) through the following primitives:

- **Left_neighbour(p_x)**: process p_x is the new left neighbour of p_i
- **Right_neighbour(p_x)**: process p_x is the new right neighbour of p_i

Each process can communicate only with its neighbours.

The student answer to the following points:

- Write the pseudo-code of an algorithm implementing a Total Order Broadcast primitive assuming that channels connecting two neighbour processes are fair-loss links.
- Discuss which is the strongest Total order specification satisfied by the proposed algorithm.

```
Upon event <Init> do
        If myID = 1 do
                LEFT = N;
        Else do
                LEFT = myID – 1;
        If myID = N do
                RIGHT = 1;
        Else do
                RIGHT = myID + 1;
        Sent = {};
        Starttimer(Δ);

Upon event <timeout> do
        For all (m) ϵ Sent do
                Trigger fp2pSend(m) to right neighbour;
        Starttimer(Δ);

Upon event <TO_B(m)> do
        Trigger fp2pSend(m) to right neighbour;
        Sent = Sent U {m};

Upon event <fp2pDeliver(m)> do
        Trigger fp2pSend(m) to right neighbour;
        Sent = Sent U {m};

Upon event <right_neighbour(px)> do
        RIGHT = px;

Upon event <left_neighbour(px)> do
        LEFT = px;
```

CONSENSUS & TO MISSING

IMPL. FIFO RELIABLE BROADCAST / COMPOSED / FP2P

Ex 4: Consider a distributed system constituted by n processes $\prod=\{p_1, p_2 \ldots p_n\}$ with unique identifiers that exchange messages through fair-loss point-to-point links and are structured through a line (i.e., each process p_i can exchange messages only with processes p_{i-1} and p_{i+1} when they exists). Processes are not going to fail.
Write the pseudo-code of an algorithm implementing FIFO Reliable Broadcast.

```
Upon event <Init> do
        Sn = 0;
        Send = {};
        Pending = {};
        Next = [1]^N;                    // Save current round for each process
        Starttimer(Δ);

Upon event <FIFO_Broadcast(m)> do
        Sn = Sn + 1;
        // Trigger fp2pSend(m, self, Sn) to P_myID-1 & P_myID+1;
        Send = Send U {(m, self, Sn)};

Upon event <timeout> do
        Forall (m, p, Sn) ϵ Send do
                Trigger fp2pSend(m, p, Sn) to P_myID-1 & P_myID+1;
        Starttimer(Δ);

Upon event <fp2pDeliver(m, p, Sn)> do
        // Trigger fp2pSend(m, p, Sn) to P_myID-1 & P_myID+1;        // Resending to next process
        Send = Send U {(m, p, Sn)};
        Pending = Pending U {(m, p, Sn)};
        While exists (m', p, Sn') ϵ Pending, s.t. Sn' = next[p] do
                next[p] = next[p] + 1;
                // pending = pending \ {(m', p, Sn')};
                trigger FIFO_Deliver(m);
```

IMPL. FIFO RELIABLE BROADCAST / LINE / FP2P

Ex 5: Consider a distributed system composed by n processes $\{p_1,p_2,\ldots,p_n\}$ that communicate by exchanging messages on top of a line topology, where p_1 and p_n are respectively the first and the last process of the network.
Initially, each process knows only its left neighbour and its right neighbour (if they exist) and stores the respective identifiers in two local variables LEFT and RIGHT.

Processes may fail by crashing, but they are equipped with a perfect failure detection system that notifies at each process the new neighbour (when one of the two fails) through the following primitives:

- **Left_neighbour(p_x)**: process p_x is the new left neighbour of p_i
- **Right_neighbour(p_x)**: process p_x is the new right neighbour of p_i

Both the events may return a NULL value in case p_i becomes the first or the last process of the line. Each process can communicate only with its neighbours.

Write the pseudo-code of an algorithm implementing a FIFO Reliable Broadcast primitive assuming that channels connecting two neighbour processes are fair-loss links.

```
Upon event <Init> do
        If myID = 1 do
                LEFT = NULL;
        Else do
                LEFT = myID – 1;
```

```
If myID = N do
        RIGHT = NULL;
Else do
        RIGHT = myID + 1;
Sent = {};
Sn = 0;
Pending = {};
Next = [1]^N;                  // Save current round for each process
Starttimer(Δ);

Upon event <timeout> do
        Forall (m, p, Sn) ϵ Send do
                Trigger fp2pSend(m, p, Sn) to PmyID-1 & PmyID+1;
        Starttimer(Δ);

Upon event <FIFO_Broadcast(m)> do
        Sn = Sn + 1;
        // Trigger fp2pSend(m, self, Sn) to PmyID-1 & PmyID+1;
        Send = Send U {(m, self, Sn)};

Upon event <right_neighbour(px)> do
        RIGHT = px;

Upon event <left_neighbour(px)> do
        LEFT = px;

Upon event <fp2pDeliver(m, p, Sn)> do
        // Trigger fp2pSend(m, p, Sn) to PmyID-1 & PmyID+1;    // Resending to next process
        Send = Send U {(m, p, Sn)};
        Pending = Pending U {(m, p, Sn)};
        While exists (m', p, Sn') ϵ Pending, s.t. Sn' = next[p] do
                next[p] = next[p] + 1;
                // pending = pending \ {(m', p, Sn')};
                trigger FIFO_Deliver(m);
```

IMPL. SERVER / COMPOSED / CONSENSUS & PERFECT FAILURE DETECTOR & UNIFORM RELIABLE BC

Ex 3: Consider a distributed system composed by N servers $\{s_1, s_2, \dots s_n\}$ and M clients $\{c_1, c_2, \dots c_m\}$.
Each client c_i runs its algorithm and it can request to the servers the execution of a particular task T_i. The servers system will execute the task T_i and, after that, a notification will be sent to c_i that T_i has been completed.
The Figure shows the code executed by a generic client c_i.

Operation executeTask (T_i)	Upon pp2pdeliver (TASK_COMPLETED, T_i) from s_j
1. For each $s_i \in \{s_1, s_2, \dots s_n\}$ 2. pp2psend (TASK_REQ, T_i, c_i) to s_i;	1. **trigger** completedTask (T_i);

Write the pseudo-code of an algorithm, executed by servers, able to allocate tasks assuming that:

- Once clients ask for a task execution, they remain blocked until the task is not terminated.
- Any two clients c_i and c_j can concurrently require the execution of two different tasks T_i and T_j;
- Each task is univocally identified by the pair (T_i, c_i);
- Each server can manage at most one task at every time;
- At most N-1 servers can crash;
- Servers can use a uniform consensus primitive;
- Servers can use a failure detector P;
- Servers communicate through a uniform reliable broadcast primitive.

Note that, if a server crashes while executing a task, such task needs to be re-allocated and re-processed by a different server.

```
Upon event <Init> do
        Busy = False;
        Pending = {};
        Correct = S;
        Cons_Run = False;                  // Consensus running
        Assignment = {};                   // Store (server, task)

Upon event <pp2pDeliver(TASK_REQ, Ti, sni, ci)> do          // sni = sequence number
        Pending = Pending U {(Ti, sni, ci)}

When (Pending ≠ {}) AND (NOT Cons_Run) AND (NOT Busy) do
        Task = select_Task(Pending);
        Cons_Run = True;
        Trigger Propose(pi, Task);                  // propose itself for task

Upon event <decide(pi, Task)> do
        Cons_Run = False;
        Assignment = Assignment U {(pi, Task)};
        Pending = Pending \ Task;
        If myID = pi do
                Busy = True;
                EXECUTE_TASK();
                Trigger pp2pSend(TASK_COMPLETED, Task) to client;
                Busy = False;
                Trigger URB_Broadcast(COMPLETE, Task, myID);

Upon event <URB_Deliver(COMPLETE, Task, p)> do
        Assignment = Assignment \ {(pi, Task)};

Upon event <crash(p)> do
        Correct = Correct \ {p};
        When exists (p, Task) ϵ Assignment do          // Reassign task to other server
                Assignment = Assignment \ {(p, Task)};
                Pending = Pending U {(p, Task)};
```

UNIFORM CONSENSUS

Ex 3: Provide the specification of the uniform consensus problem, describe the behavior of a uniform consensus algorithm and discuss its performance in terms of message complexity (i.e., number of messages needed to reach consensus).

Specification:

Module: UniformConsensus, instance uc

Events: Request <uc, Propose | v>: Proposes value v for consensus
Indication <uc, Decide | v>: Outputs a decided v of consensus

Properties: Termination: Every correct process eventually decides some value.
Validity: If a process decides v, then v was proposed by some process.
Integrity: No process decides twice.
Uniform agreement: No two processes decide differently.

If a process wants to propose a value, it broadcasts the value to all other processes and saves it locally. Each delivering process saves the proposed value and the broadcasting process number locally. In each round each process broadcasts the current list of proposed values. When all correct processes proposed and no value is decided yet a new round starts. After N (number of processes) rounds each process decides a value from the list by choosing the minimum. A perfect failure detector gets crashing processes.
The algorithm takes N rounds, so N communication steps. Moreover, in each round each process sends it proposal set to all other processes, that is $O(N^3)$ number of messages.

FLOODING CONSENSUS

Ex 3: Describe the flooding consensus algorithm and discuss its correctness. Furthermore, discuss why this algorithm does not satisfy the uniform consensus specification (use examples whenever appropriate).

If a process wants to propose a value, it broadcasts the value to all other processes and saves it locally. Each delivering process saves the proposed value and the broadcasting process number locally and its current round. When all correct processes proposed in a round and no value is decided yet a new round starts. In each round each process broadcasts the current list of proposed values. A decision is made if in the first round all correct processes proposed or in two rounds in a row the same correct processes proposed. Then, each process decides a value from the current round list by choosing the minimum and broadcasts it to all other processes. Each process delivering a decision from a correct process decides and rebroadcasts its value if no decision is made yet. A perfect failure detector gets crashing processes.

Properties: Termination: Every correct process eventually decides some value.
Validity: If a process decides v, then v as proposed by some process.
Integrity: No process decides twice.
Agreement: No two correct processes decides differently.

Validity and Integrity: Follow from the properties on the communication channels.
Termination: At most after N rounds processes decide.
Agreement: The same deterministic function is applied to the same values by correct processes.
No, the flooding consensus algorithm does not satisfy the uniform consensus specification (Uniform Agreement: No two processes decide differently). In case a process decides a value and then crashes. The decision will not be broadcasted to all the other processes. All other processes get notified by the PFD and start the next round. Another proposed value might be decided by the remaining correct processes.

REGULAR CONSENSUS & SYNCHRONIZATION

Ex 1: Detail how the structure of a regular consensus algorithm changes moving from a synchronous system to an eventually synchronous one.

Regular Consensus algorithm:

Basic Idea: Processes exchange their values. When all proposals from correct processes are available a one value can be chosen.
Problem: Due to failures, some values can be lost
Solution: A value can be selected only when no failures happen during the communication
Algorithm: Each process saves locally in each round the delivered proposals of the other processes. When no decision is made yet and all correct processes proposed, a decision is triggered. Otherwise a new round is started.

In asynchronous system, no reliable prediction for faulty processes can be made (no perfect failure detector). The Paxos algorithms make some progress (liveness) only when network behaves in a 'good way' for long enough periods of time.

Paxos Consensus algorithm:

Basic Idea: Use actors (Proposer proposing values, multiple Acceptors committing on a final decided value, Learners passively assisting to decision and obtaining final decided value).
Majority is needed to guarantee only one value is accepted
If proposal with value v and number n is issued, then there is a set S consisting of majority of acceptors such that either (a) no acceptor in S has accepted any proposal numbered less than n, or (b) v is the value highest-number proposal among all proposals numbered less than n accepted by the acceptors in S.
Algorithm: Phase 1 (Prepare request), Phase 2 (Accept request)

Phase 1: - proposer sends prepare request (PREPARE, n) to majority of acceptors
- acceptors reply with highest number accepted less than n, else $\perp$ (or denial if n too old)

Phase 2: - proposer receives from majority and sends accept request with n from prepare request and v of highest-numbered proposal of responses
- acceptor accepts request, if not already responded having number greater than n
- learners receive from majority of acceptors, decide and resend to other learners

Properties: Liveness is not guaranteed (due to FLP), Omissions delay protocol but don't block it, Proposers are elected using leader election protocol

Ex 2: Consider a distributed system composed of N processes $p_1, p_2, \dots p_N$, each having a unique identifier myID. Initially, all processes are correct (i.e. correct={ $p_1, p_2, \dots p_N$ }). Consider the following algorithm:

```
upon event Xbroadcast(m)
        sn = sn+1;
        ∀ p ∈ correct
                pp2pSend ("MSG", m, sn, myId);

upon event pp2pReceive ("MSG", m, sn, i)
        if ((m ∉ delivered) ∧ (<sn, i> > lastDelivered))
                trigger XDeliver (m);
                delivered = delivered ∪ {m};
                lastDelivered = <sn, i>;

upon event crash (pi)
        correct = correct / {pi}
```

Let us assume that: (i) links are perfect, (ii) the failure detector is perfect and (iii) initially local variables are initialized as follows sn=0, delivered =∅, e lastDelivered=<0, ->.
Answer to the following questions:

1. Does the `Xbroadcast()` primitive implement a Reliable Broadcast, a Best Effort Broadcast or none of the two?
2. Considering the ordered broadcast communication primitives discussed during the lectures (FIFO, Causal, Total), explain which ones can be satisfied by the `Xbroadcast()` implementation.

1. None, due to Validity property: If correct process p broadcasts a message m, then every correct process (process p) eventually delivers m. Counterexample: process p broadcasts message m with sn=1, then broadcasts message m' with sn=2. If m' is delivered before m, m cant be delivered anymore since <sn=1, p> < lastDelivered=2.

2. FIFO is not satisfied, due to FIFO delivery property: If some process broadcasts message m1 before it broadcasts message m2, then no correct process delivers m2 unless it has already delivered m1. Counterexample: process p broadcasts message m with sn=1, then broadcasts message m' with sn=2. m' can be delivered before m, since <sn=2, p> > lastDelivered=0.
If FIFO is violated, Causal is not ensured, since: Causal = FIFO + Local Order.
Total order is not satisfied. Counterexample: process p1 broadcasts m1 with sn=1 then broadcasts m2 with sn=2. Process p2 receives m1 before m2, so it delivers m1 before m2. Process p1 receives m2 before m1, so only delivers m2, since <sn=1, p> < lastDelivered=2.

Ex 3: Consider a distributed system composed of N processes $p_1, p_2, \ldots p_N$, each having a unique identifier myID. Initially, all processes are correct (i.e. correct={ $p_1, p_2, \ldots p_N$ }). Consider the following algorithm:

```
upon event Xbroadcast(m)
        mysn = mysn+1;
        ∀ p ∈ correct
                pp2pSend ("MSG", m, mysn, myId);

upon event pp2pReceive ("MSG", m, sn, i)
        mysn= mysn+1;
        if (m ∉ delivered)
          trigger XDeliver (m);
          delivered = delivered ∪ {m};

upon event crash (pi)
        correct = correct / {pi}
```

Let us assume that: (i) links are perfect, (ii) the failure detector is perfect and (iii) initially local variables are initialized as follows mysn=0 e delivered =∅.
Answer to the following questions:

1. Does the `Xbroadcast()` primitive implement a Reliable Broadcast, a Best Effort Broadcast or none of the two?
2. Considering only the ordering property of broadcast communication primitives discussed during the lectures (FIFO, Causal, Total), explain which ones can be satisfied by the `Xbroadcast()` implementation.

Provide examples to justify your answers.

1. Xbroadcast implements a Best Effort Broadcast, but no Reliable Broadcast.
   Best Effort: All properties are satisfied:
   a. Validity is ensured due to the reliable delivery property of the perfect p2p links and the fact that the sender sends the message to every correct process in the system.
   b. No Duplication is ensured due the No Duplication property of perfect p2p links and the assumption of uniqueness of messages (different IDs of messages).
   c. No Creation is ensured due to the No creation property of perfect p2p links.

   Not Reliable, since a message sent by a faulty process and delivered by only one correct process will not be retransmitted to the remaining correct processes. Therefore, the RB4 Agreement property is not satisfied.

2. FIFO is not satisfied. Counterexample: Correct process p broadcasts m1, then broadcasts m2. The algorithm does not make any ordering specifications. So delivering m2 before m1 is allowed, since both are delivered for the first time.
   If FIFO is violated, Causal is not ensured, since: Causal = FIFO + Local Order.
   Total order is not satisfied. Counterexample: Correct process p1 broadcasts m1, then broadcasts m2. The algorithm does not make any ordering specifications. So delivering m2 before m1 is allowed, while correct process p2 is delivering m1 before m2. This is possible, since each message is delivered for the first time.

RELIABLE BROADCAST & SYNCHRONIZATION

Ex 1: Consider the two implementations of reliable broadcast for synchronous and asynchronous system models that have been described during the lectures. Describe how the two algorithms work, discuss the impact asynchrony has on the design of their structure and detail their message complexity (best and worst case).

The Reliable Broadcast satisfy the following properties:

1. Validity: If a correct process p broadcasts m, then p eventually delivers m.
2. No duplication: No message is delivered more than once.
3. No creation: If a process delivers a message m with sender s, then m was previously broadcast by process s.

4. Agreement: If a message m is delivered by some correct process, then m is eventually delivered by every correct process.

In synchronous and in asynchronous mode the Best-Effort Broadcast is used. The synchronous model uses the perfect failure detector in addition, since in asynchronous mode no reliable prediction of faulty processes are possible. Therefore, in asynchronous mode, each message will be broadcasted to all other processes. Each delivering message triggers a retransmitting to all other processes. The algorithm is called eager, in sense that it retransmit every message. Due to that fact the complexity is in best case equal to the complexity in worst case. N (number of processes) BEB messages are created for each RB message. For each BEB delivery N retransmitting broadcast messages are created.
In comparison the synchronous RB saves locally each receiving message and its sending process. In case of a crash or receiving a message from a faulty process, each message from the respective crashing process is rebroadcast (at least) to all correct processes. In the best case, 1 BEB message is created per 1 RB message. In the worst case of N-1 failures, N-1 BEB messages are created per 1 RB message.

RELIABLE BROADCAST & SYNCHRONIZATION

Ex 1: Discuss the assumption on the weaker system model (synchrony assumption and failures) upon which a regular reliable broadcast is able to work correctly. Consider now a uniform reliable broadcast algorithm, how the weaker system model changes in order the algorithm works correctly.

The weaker model gives a PFD to detect crashes. Moreover, synchrony implies upper boundes delays wrt. processing, communication and physical clocks or existence of common global clock. Therefore, the RB implementation in synchronous systems are lazy in the sense that it retransmits only when necessary. Each delivered message and its sending process is saved locally. In case of crashing process or receiving a message from a already crashes process, the messages of the respective process is re broadcasted. In the best case, 1 BEB message per 1 RB message. In the worst case, n-1 BEB messages per 1 TB message (when n-1 failures).

The uniform RB in synchronous systems saves receiving messages and its sending process until a process receives the message m from all correct processes. Then m is delivered, if message m is not yet delivered. There exists an algorithm for asynchronous system when assuming a ‘majority of correct processes’. Without the assumption of majority but partially synchrony, a probabilistic broadcast can be used.

PROBABILISTIC BROADCAST

Ex 1:
Discuss which is the system model where the use of a primitive of probabilistic broadcast is better than the use of a reliable broadcast primitive. In addition discuss the parameters that can tuned in an implementation of probabilistic broadcast based on gossiping in order to improve the probability to delivery at each process.

Probabilistic broadcast is better when a uniform reliable broadcast for partially synchronous system (using an eventually perfect failure detector) but without the assumption of a majority of correct processes is needed.

A process sends a message to a set of randomly chosen k processes. With higher k, more processes can be reached in one round to achieve higher reliability (higher probability of delivering each process). The algorithm performs a maximum number of r rounds. With higher r (more rounds), the probability of not reaching a process is reduced, so a higher reliability of the broadcast (higher probability of delivering each process) is achieved.

Ex 4: Consider a distributed system composed by n processes $p_1, p_2 \ldots p_n$ with unique and totally ordered identifiers. Every process p_i can access a local physical clock CK_i. Clocks are synchronized with accuracy D and their drift rates can be considered negligible. Processes can fail by crashing.

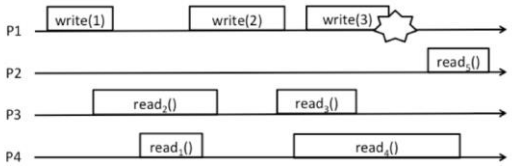
1. Write the pseudo-code of an algorithm implementing a Total Order Broadcast specification satisfying the SUTO property and using the following primitives:

   Timely Best-Effort-Broadcast:
   - No message is delivered more than once;
   - If a message m is delivered by some process p_j, then m has been previously broadcasted by some process p_i
   - If a correct process p_i broadcast a message m at time t, every correct process p_j will deliver m within time $t+\delta$ (con δ>0). (Non-correct processes can either deliver within time $t+\delta$ o will not deliver)

   Timely Perfect Failure Detector:
   - If a process p_i crashes at time t, every correct process p_j will suspect p_i within time $t+\delta'$ (con δ'>0).
   - If a process p_i is suspected by a process p_j, then p_i has crashed.

2. Discuss which kind of *agreement* (UA, NUA or none) is satisfied by your solution, providing execution examples as a motivation.

Consider the execution depicted in the following figure and answer the questions



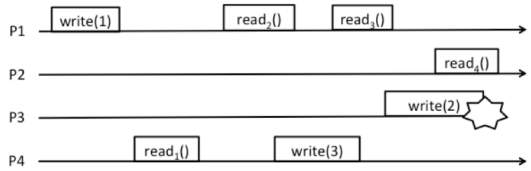
1. Define ALL the values that can be returned by read operations (Rx) assuming the run refers to a regular register.

2. Define ALL the values that can be returned by read operations (Rx) assuming the run refers to an atomic register.

1. R1: 1, 2
   R2: {}, 1, 2
   R3: 1, 2, 3
   R4: 2, 3
   R5: 2, 3

2. R1: 1, 2
   R2: {}, 1, 2
   R3: If R1 = 2 OR R2 = 2 → R3 = 2, 3
   Else R3 = 1, 2, 3
   R4: 2, 3
   R5: If R3 = 3 → R5 = 3
   Else R5 = 2, 3

Consider the execution depicted in the following figure and answer the questions

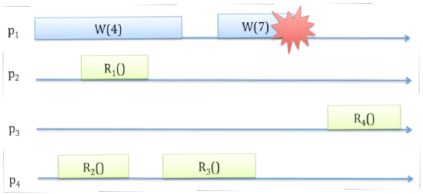


1. Define ALL the values that can be returned by read operations (Rx) assuming the run refers to a regular register.
2. Define ALL the values that can be returned by read operations (Rx) assuming the run refers to an atomic register.

1. R1: 1,
   R2: 1, 3
   R3: 1, 3, 2
   R4: 3, 2

2. R1: 1
   R2: 1, 3
   R3: If R2 = 3 → R3 = 3, 2
   Else R3 = 1, 3, 2
   R4: If R3 = 2 → R4 = 2
   Else R4 = 3, 2

Ex 3: Consider the operations executed on a (1,N) register shown in the run below.



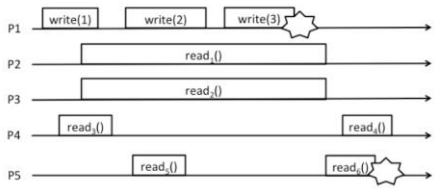
Assuming that the initial value of the register is 0, answer the following questions:

1. List the value returned by each read operation considering the register be regular. Explain why.
2. List the value returned by each read operation considering the register be atomic. Explain why.

1. R1 = 0, 4
   R2 = 0, 4
   R3 = 0, 4, 7
   R4 = 4, 7

2. R1 = 0, 4
   R2 = 0, 4
   R3: If R1 = 4 OR R2 = 4 → R3 = 4, 7
   Else R3 = 0, 4, 7
   R4: If R3 = 7 → R4 = 7
   Else R4 = 4, 7

Ex 3: Consider the execution depicted in the following figure and answer the questions

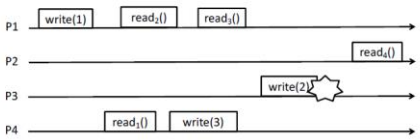


1. Define ALL the values that can be returned by read operations (Rx) assuming the run refers to a regular register.
2. Define ALL the values that can be returned by read operations (Rx) assuming the run refers to an atomic register.

1. R1 = 0, 1, 2, 3
   R2 = 0, 1, 2, 3
   R3 = 0, 1
   R4 = 2, 3
   R5 = 1, 2
   R6 = {}, 2, 3

2. R1 = 0, 1, 2, 3
   R2 = 0, 1, 2, 3
   R3 = 0, 1
   R4: If R1 = 3 OR R2 = 3 → R4 = 4
   Else → R4 = 2, 3
   R5 = 1, 2
   R6: If R1 = 3 OR R2= 3 → R6 = {}, 3
   Else R6 = {}, 2, 3

Ex 2: Consider the execution depicted in the following figure and answer the questions



1. Define ALL the values that can be returned by read operations (Rx) assuming the run refers to a regular register.
2. Define ALL the values that can be returned by read operations (Rx) assuming the run refers to an atomic register.

1. R1 = 1
   R2 = 1, 3
   R3 = 1, 3
   R4 = 3, 2

2. R1 = 1
   R2 = 1, 3
   R3: If R2 = 3 → R3 = 3
   Else R3 = 1, 3
   R4 = 3, 2

Ex 1: Describe the functioning of the "Majority Voting" algorithm used to implement distributed regular registers. Detail the corresponding system model. Explain how this algorithm satisfies the Validity and Termination properties of the specification.

Also called Fail-silent algorithm: "process crashes can never be reliably detected." (No perfect failure detector).

Assumptions: - N processes whose 1 writer and N readers
- A majority of correct processes

Communication: - PP2P
- Best Effort Broadcast

Idea: - Each process locally stores copy of current value of register
- Each written value is univocally associated to a timestamp
- Writer and reader processes use a set of witness processes, to track last value written
- Quorum: intersection of any two sets of witness processes is not empty
- Majority Voting: each set is constituted by majority of processes

Write: - Broadcast value to be written with new timestamp to all processes
- Each delivering process writes new value if it is latest and resends ACK
- Return / confirm if majority (>N/2) of processes responded with respective timestamp

Read: - Broadcast reading request with reading id
- Each delivering process resends local register value with reading id
- Save all incoming values in list
- If majority (>N/2) of processes responded, take value of latest timestamp and confirm / return

Correctness: - Termination: from properties of communication primitives and assumption of majority of correct processes
- Validity: from intersection property of quorums

IMPL. REGULAR REGISTER / LINE / PP2P

Ex 4: Consider a distributed system constituted by n processes $\prod=\{p_1, p_2 \dots p_n\}$ with unique identifiers that exchange messages through perfect point-to-point links and are structured through a line (i.e., each process p_i can exchange messages only with processes p_{i-1} and p_{i+1} when they exists and stores their identifiers in two local variables `right` and `left`).
Each process p_i knows the initial number of processes in the system (i.e., every process p_i knows the value of n).

1. Assuming that processes are not going to fail, write the pseudo-code of an algorithm that implements a regular register
2. Discuss what happen to the proposed algorithm if processes may fail and discuss if it implements a CA, CP or AP system.

```
Upon event <Init> do
    R = GET_RIGHT();
    L = GET_LEFT();
    Correct = π;
    ACK = {};
    Val = ⊥;
    Writing = False;

Upon event <Write(v)> do
    Val = v;                          // Set own local register value
    Trigger pp2pSend('WRITE', v) to L;
    Trigger pp2pSend('WRITE', v) to R;
    ACK = {};                         // Collect ACKs of updated registers
    Writing = True;
```

```
Upon event <pp2pDeliver('WRITE', v)> from pi do
        Val = v;
        If pi = R do                    // If WRITE comes from the right
                Trigger pp2pSend('ACK', myID) to R;
                Trigger pp2pSend('WRITE', v) to L;
        Else do                         // If WRITE comes from the left
                Trigger pp2pSend('ACK', myID) to L;
                Trigger pp2pSend('WRITE', v) to R;

Upon event <pp2pDeliver('ACK', id)> from pi do
        If Writing do                   // If you are the process that sent the write order
                ACK = ACK U {id};
        Else if pi = R do
                Trigger pp2pSend('ACK', id) to L;
        Else
                Trigger pp2pSend('ACK', id) to R;

When correct = ACK do
        // Writing = False;
        Trigger WriteReturn();
```

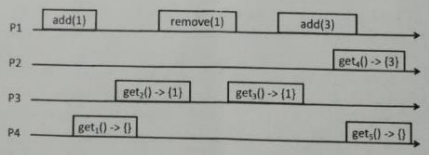
No crashes: CA system, since all processes connected and available & consistent
A crash disconnects system: AP system

Ex 2: Consider a set object that can be accessed by a set of processes. Processes may invoke the following operations on the object:

- add(v): it adds the value v in to the set
- remove(v) it removes the value v from the set
- get(): it returns the content of the set.

Informally, every get() operation returns all the values that have been added before its invocation and that have not been removed by any remove().
For the sake of simplicity, assume that a value can be added/removed just once in the execution.

Consider the distributed execution depicted in the Figure



Answer to the following questions:

1. Is the proposed execution linearizable? Motivate your answer with examples.
2. Consider now the following property: "every get() operation returns all the values that have been added before its invocation and that have not been removed by any remove(). If an add(v)/remove(v) operation is concurrent with the get, the value v may or may be not returned by the get()".
   Provide an execution that satisfy get validity and that is not linerizable.

1. S = {$get_2()$, add(1), $get_2()$, $get_3()$, rm(1), $get_5()$, add(3), get_4}

2. P1: <----------ADD(1)----------->
   P2: <--get(1)--> <--get({})--->

Ex 1: Describe primary-backup and active replication schemes. In particular, discuss for both schemes the possible failure scenarios and how they can be managed.

Primary-backup:

Primary: Receives invocations from clients and sends back the answers.

Backup: Interacts with primary. Is used to guarantee fault tolerance by replacing a primary when crashes

1. When update messages are received by backups, they update their state and send back the ack to primary
2. Primary waits for ack message from each correct backup and then sends back the answer, res, to the client

Guarantee of linearizability due to the order in which primary receive clients' invocations define the order of operation on the object.

Failure scenarios (in all cases new leader need to be elected):

1. Primary fails after client receives answer.
   a. Client does not receive response due to pp2p. If response is lost, client retransmits request after timeout. New primary will recognize the request re-issued by client and sends back the result without updating the replicas.
   b. Client receives answer and everything is all right, but a new leader is elected.
2. Primary fails before sending update messages.
   a. Client does not get answer and resends requests after timeout. New Primary will handle request as new.
3. Primary fails after sending update messages and before receiving all ack messages.
   a. When primary fails, elect new leader among all correct replicas (guarantee atomicity due to update received either by all or by no one.

Active replication:

There is no coordinator. All replicas have same role. Each replica is deterministic, i.e. if any replica starts from same state and receives same input, they produce same output. As matter of fact clients will receive same response one from each replica. Active replication does not need recovery action upon failure of a replica.

Guarantee linearizability by:

1. Atomicity: If a replica executes an invocation, all correct replicas execute same invocation.
2. Ordering: (At least) no two correct replicas have to execute two invocations in different order.

➔ TOTAL ORDER Broadcast is needed (including the clients)

Ex 3: Provide the statement of the CAP theorem and the sketch/intuition of its proof.

and present an example of a system which is CA, CP and AP.

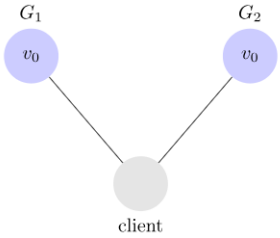
The CAP theorem states that a distributed system cannot simultaneously be consistent, available, and partition tolerant.

Consistency: Any read operation that begins after a write operation completes must return that value, or the result of a later write operation.

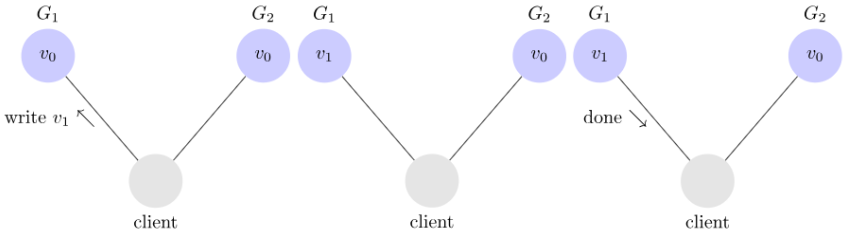
Availability: Every request received by a non-failing node in the system must result in a response.

Partition Tolerance: The network will be allowed to lose arbitrarily many messages sent from one node to another.

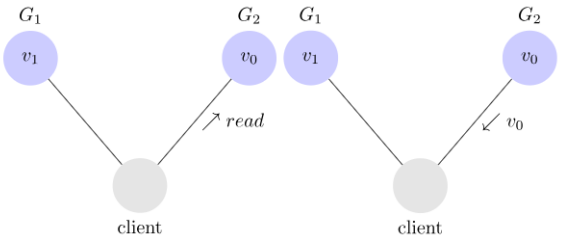
Proof: Assume for contradiction that there does exist a system that is consistent, available, and partition tolerant. A sketch of simple partitioned system:



Next, we have our client request that v1 be written to G1. Since our system is available, G1 must respond. Since the network is partitioned, however, G1 cannot replicate its data to G2.



Next, we have our client issue a read request to G2. Again, since our system is available, G2 must respond. And since the network is partitioned, G2 cannot update its value from G1. It returns v0.



G2 returns v0 to our client after the client had already written v1 to G1. This is inconsistent.

CA: Examples: Single-site databases, Cluster databases, Fiefdoms
Traits: 2-phase commit, Cache validation protocols

CP: Examples: Distributed databases, Distributed locking, Majority protocols
Traits: Pessimistic locking, Make minority partitions unavailable

AP: Examples: Coda, Web caching, DNS
Traits: expirations/leases, Conflict resolution

Ex 4: Consider a distributed system composed of N processes $p_1, p_2, \ldots p_N$, each having a unique identifier myID. Processes are arranged in a k-ary tree and each process just knows[1] its father (if any) and its children (if any).
Each process maintains locally a value $v \in \{0,1\}$.

1. Assuming that processes are not going to fail, write the pseudo-code of an algorithm that is able to compute and report to the issuing process the sum of all the values stored by processes.
2. Assuming that the system is synchronous with message delivery times bounded by δ and negligible computation time, discuss what happen to the algorithm (both in terms of termination and validity of the computed average) when one Byzantine process is in the network.

Ex 2: Describe the *active replication* scheme, and discuss the following points:

1. Assume that processes are provided with a *best effort broadcast* primitive. How does the algorithm functioning change and how should the algorithm be modified to be correct?
2. How does the algorithm functioning change if *f* replicas may be Byzantine faulty? How should the algorithm be modified to be correct?

Active replication:

There is no coordinator. All replicas have same role. Each replica is deterministic, i.e. if any replica starts from same state and receives same input, they produce same output. As matter of fact clients will receive same response one from each replica. Active replication does not need recovery action upon failure of a replica.

Guarantee linearizability by:

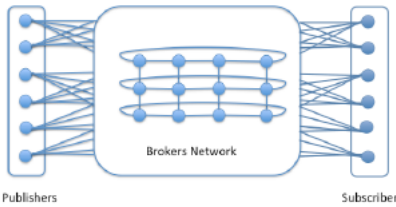
1. Atomicity: If a replica executes an invocation, all correct replicas execute same invocation.
2. Ordering: (At least) no two correct replicas have to execute two invocations in different order.

➔ TOTAL ORDER Broadcast is needed (including the clients)

A BEB can be used to broadcast the invocations to all replicas. The delivering event of each replica has to be extended with the execution of the operation sent by the process. After successful execution the replicas send back an ACK to the process to signalize their response.

Consider N = #replicas. Process can return its response when (N+f)>2 ACKs are received. So a majority over f Byzantines are achieved.

Ex 5: Let us consider a distributed system composed by publishers, subscribers and brokers. Processes are arranged in a network made as follows and depicted below:



1. Each publisher is connected to k brokers trough perfect point-to-point links;
2. Each subscriber is connected to k brokers trough perfect point-to-point links;
3. Each broker is connected to k brokers trough perfect point-to-point links and the resulting broker network is k-connected [1](4-connected in the example);

Answer to the following questions:

1. Write the pseudo-code of an algorithm implementing the event-flooding dissemination scheme assuming that processes are not going to fail.
2. Discuss how many crash failures the proposed algorithm can tolerate.
3. Modify the proposed algorithm in order to tolerate f Byzantine processes in the broker network and discuss the relation between f and k.

Ex 1: Consider the following algorithm

```
init:
        sn=0; last[]=[0]*; pending=∅; neighbors=%set of neighbors for the current process.

upon event xCast(m):
        sn=sn+1;
        for each p_i ∈ neighbors do
                send MSG (m, sn, myId) to p_i
        trigger XDeliver(m)

upon event rcv(m, sn_m, src, id):
        if src=id and src ∈ neighbors and sn_m > last[src]
                then trigger XDeliver(m)
                        last[src]=sn_m
                        for each p_i ∈ neighbors do
                                send MSG (m, sn_m, src, myId) to p_i
                else
                        pending = pending ∪ {<m, sn_m, src, id>}

when exists <m, sn_m, src> occurring at least f+1 times in pending and such that sn_m > last[src]:
        trigger XDeliver(m)
        last[src]=sn_m
        for each p_i ∈ neighbors do
                send MSG (m, sn_m, src, myId) to p_i
```

Consider the network depicted above

Let us assume that (i) each channel depicted in the figure is an authenticated perfect point-to-point link, (ii) up to f processes may by Byzantine in each neighborhood and (iii) each correct process executes the algorithm in Figure.

Discuss the truthfulness of the following sentences when f=1.

1. If a correct process p delivers a message m, them m has been previously broadcasted by a correct process q.
2. If a correct process p broadcast m then every correct process will eventually deliver m.
3. Let us consider two messages m and m' broadcasted by the same source q. If a process p delivers m before than m', then m has been sent before than m' from q.

Ex 4: Let us consider a reliable broadcast primitive. Explain how the algorithm implementing the primitive must be changed while moving from the assumption of crash failures to the assumption of Byzantine failures. Discuss, in particular, the relation between the number of processes in the system *n* and the number of failures *f*.

The Reliable Broadcast algorithm saves locally each message and the respective sending process. In case of a crash of or of incoming message from a crashing process, each message is rebroadcasted to all processes to achieve the Agreement property. The algorithm in synchronous is lazy in the sense that it retransmits only when necessary.
The Byzantine Reliable Broadcast uses Authenticated PP2P Links to ensure the authenticity and correctness of a sending process. Each delivering process sends an echo to all processes to signalize the delivering of a message. Each delivering echo is also saved locally. As soon as the number of processes which sent message m to a process (majority over Byzantines) or a process delivered more than f READY messages, the process rebroadcasts a READY message to all other processes. As soon as a process delivers more than 2f READY deliveries the message can be finally delivered.
In total each message broadcasting is followed by an SEND, ECHO and READY phase. In comparison to the RB without Byzantines the messages are double checked and messages have to be delivered by a threshold of number of processes to guarantee the Totality property.
The goal is to achieve majority voting over f Byzantine processes. The number of correct processes is given by N – f (N: #processes in system):

N – f > 2f Threshold to achieve majority over Byzantine processes
N > 3f #Number of processes in system more than 3 times number of Byzantines

→ Number of votes must be greater than (N+f)/2: If N > 3f is guaranteed, threshold (N+f)/2 > (3f+f)/2 = 2f (more than twice the number of number of Byzantines)

Ex 4: Provide the specification of the Byzantine Consistent Broadcast communication primitive, describe an algorithm implementing it and discuss the relation between the number of processes n and the number of Byzantine failures f.

Byzantine Consistent Broadcast Specification:

- Uses Authenticated Perfect Links
- Events:
  1. Request: Broadcast message m to all processes. Executed only by process s.
  2. Indication: Deliver message m broadcast by process p.
- Properties:
  1. Validity: If a process p broadcasts a message m, then every correct process eventually delivers m.
  2. No duplication: Every correct process delivers at most one message.
  3. Integrity: If some correct process delivers a message m with sender p and process p is correct, then m was previously broadcast by p.
  4. Consistency: If some correct process delivers a message m and another correct process delivers a message m', then m = m'.

A message is broadcast to each process in the system. Each delivered message triggers an rebroadcast of an ECHO signal. As soon as more than (N+f)/2 ECHOs of the same message from different processes are delivered, the actually message m is delivered.
The goal is to achieve majority voting over f Byzantine processes. The number of correct processes is given by N – f (N: #processes in system):

N – f > 2f Threshold to achieve majority over Byzantine processes
N > 3f #Number of processes in system more than 3 times number of Byzantines

→ Number of votes must be greater than (N+f)/2: If N > 3f is guaranteed, threshold (N+f)/2 > (3f+f)/2 = 2f (more than twice the number of number of Byzantines)

IMPL. COUNTER / RING / PP2P

Ex 4: Consider a distributed system where processes are arranged in a ring topology. Every link of the ring is implemented trough a perfect point-to-point channel. Each process in the system has a unique identifier and it stores, in a local variable called `next`, the identifier of the next process in the ring.

Answer to the following questions:

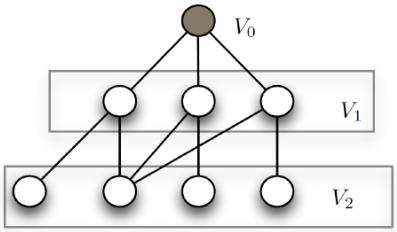
1. Write the pseudo-code of an algorithm implementing a counting abstraction that eventually reports the number of processes in the ring, assuming that processes are not going to fail. **Note**: The student is free to define the interface of the abstraction.
2. Discuss what happen to the counting oracle if processes are anonymous.

```
Upon event <Init> do
        Next = P(i+1) mod n
        Count = 0;

Upon event <Start()> do
        If Count = 0 do
                Count = 1;
                Trigger pp2pSend('COUNT', myID, Count) to Next;
        Else do                                  // If already counted
                Trigger Count(Count);

Upon event <pp2pDeliver('COUNT', id, c)> do
        If id = myID do
                Count = c;
                Trigger Count(Count);
        Else do
                c = c +1;
                Trigger pp2pSend('COUNT', id, c);
```

→ Infinite loop

!!! Synchronous → time-bounded

Ex 4: Consider a synchronous distributed system formed by a leader v_0 and a set of processes sharing the same ID (i.e., processes are anonymous). Processes and leader are connected through the topology depicted in figure



Processes are partitioned in n sets V1, V2,…. Vn corresponding to their distance from the leader. Each process knows its distance from the leader stored in the local variable denoted *distance*. Each process at distance i communicates with processes at distance i+1 through perfect point to point bidirectional link. Each process stores into a local variable *max_distance* the maximum distance of a process from the leader.

Write a round-based distributed algorithm (pseudo-code of the leader and of a process) that allows the leader to count the number of processes in V2. (provide before the pseudo code a short high-level description on how the algorithm works)

Ex 5

Consider a consensus protocol based on rotating coordinator paradigm. Discuss the structure of the algorithm and the under which condition processes converges to a consensus value.

Ex 2: Describe the basic approaches presented in the course for information dissemination inside *publish/subscribe systems* discussing characteristics and limitations (e.g. "*the approach X is the best option when ……. because……., while it is the worst option when ……because……*").