Why Election?

- Example 1: Your Bank maintains multiple servers in their cloud, but for each customer, one of the servers is responsible, i.e., is the leader
  - What if there are two leaders per customer?
    - Inconsistency
  - What if servers disagree about who the leader is?
    - Inconsistency
  - What if the leader crashes?
    - Unavailability

Why Election?

- Example 2: In the sequencer-based algorithm for total ordering of multicasts, the "sequencer" = leader
- Example 3: Group of cloud servers replicating a file need to elect one among them as the primary replica that will communicate with the client machines
- Example 4: Group of NTP servers: who is the root server?

What is Election?

- In a group of processes, elect a *Leader* to undertake special tasks.
- What happens when a leader fails (crashes)
  - Some (at least one) process detects this (how?)
  - Then what?
- Focus of this lecture: Election algorithm
  1. Elect one leader only among the non-faulty processes
  2. All non-faulty processes agree on who is the leader

System Model/Assumptions

- **Any process can call for an election.**
- **A process can call for at most one election at a time.**
- **Multiple processes can call an election simultaneously.**
  - **All of them together must yield a single leader only**
- **The result of an election should not depend on which process calls for it.**
- **Messages are eventually delivered.**

Problem Specification

- **At the end of the election protocol, the non-faulty process with the best (highest) election *attribute value* is elected.**
  - **Attribute examples: leader has highest id or address. Fastest cpu. Most disk space. Most number of files, etc.**
- **Protocol may be initiated anytime or after leader failure**
- **A *run* (execution) of the election algorithm must always guarantee at the end:**
  - **Safety:** $\forall$ **non-faulty p: (p's `elected` = (q: a particular non-faulty process with the best attribute value) or $\perp$)**
  - **Liveness:** $\forall$ **election: (election terminates)**

    & $\forall$ p: non-faulty process, p's `elected` is not $\perp$

Algorithm 1: Ring Election

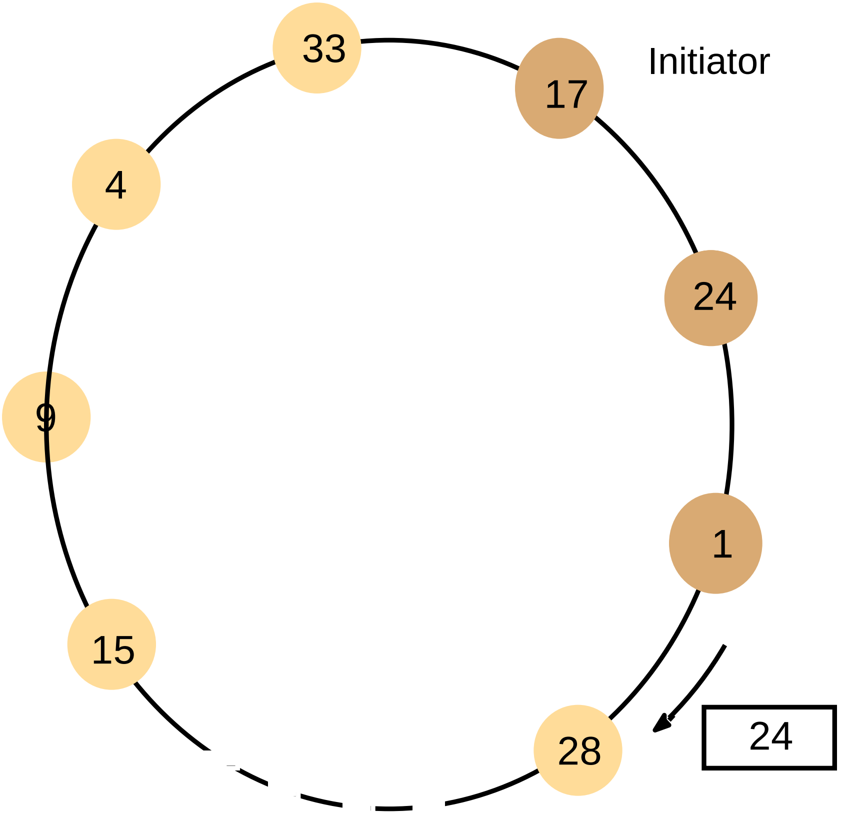
- **N Processes are organized in a logical ring**
  - **p_i has a communication channel to $p_{(i+1) \bmod N}$**
  - **All messages are sent clockwise around the ring.**
- **Any process p_i that discovers the old coordinator has failed initiates an "election" message that contains p_i's own id:attr. This is the *initiator* of the election.**
- **When a process p_i receives an *election* message, it compares the attr in the message with its own attr.**
  - **If the arrived attr is greater, p_i forwards the message.**
  - **If the arrived attr is smaller and p_i has not yet forwarded an election message, it overwrites the message with its own id:attr, and forwards it.**
  - **If the arrived id:attr matches that of p_i, then p_i's attr must be the greatest (why?), and it becomes the new coordinator. This process then sends an "elected" message to its neighbor with its id, announcing the election result.**
- **When a process p_i receives an elected message, it**
  - **sets its variable *elected*$_i$ ← id of the message.**
  - **forwards the message, unless it is the new coordinator.**

Ring-Based Election: Example

(In this example, attr:=id)

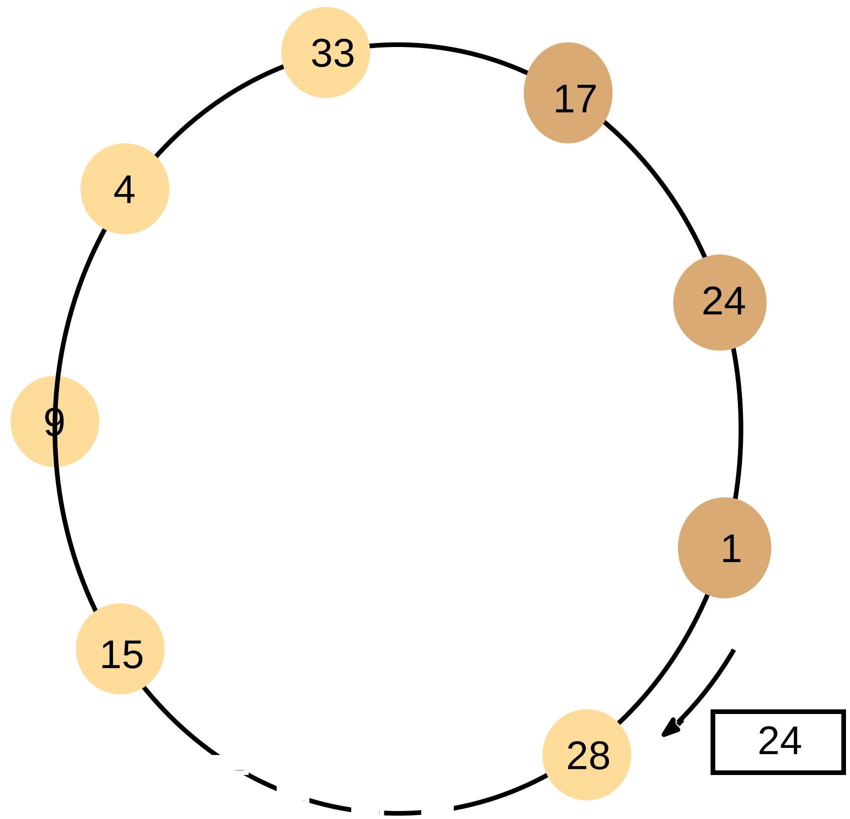
- In the example: The election was started by process 17.
  The highest process identifier encountered so far is 24.
  (final leader will be 33)

- The worst-case scenario occurs when the counter-clockwise neighbor (@ the initiator) has the highest attr.



Ring-Based Election: Analysis

- The worst-case scenario occurs when the counter-clockwise neighbor has the highest attr.



In a ring of N processes, in the worst case:

- A total of N-1 messages are required to reach the new coordinator-to-be (election messages).
- Another N messages are required until the new coordinator-to-be ensures it is the new coordinator (election messages – no changes).
- Another N messages are required to circulate the elected messages.
- Total Message Complexity = 3N-1
- Turnaround time = 3N-1

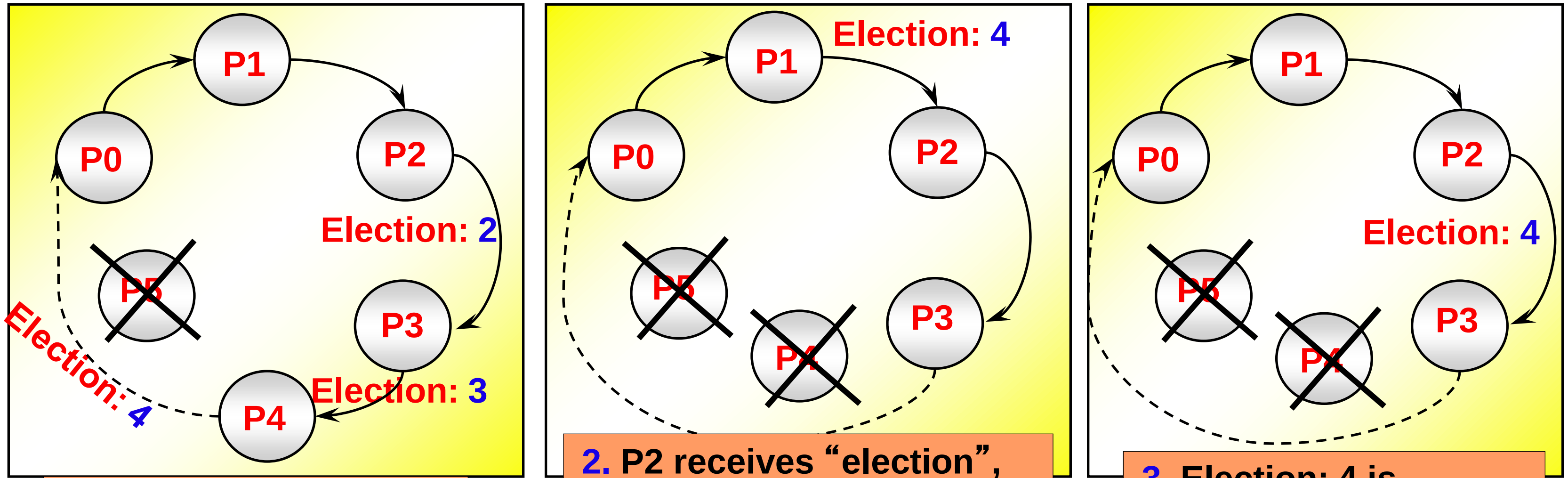
Correctness?

Assume – no failures happen during the run of the election algorithm

- Safety and Liveness are satisfied.

What happens if there are failures during the election run?

Example: Ring Election



1. P2 initiates election after old leader P5 failed

2. P2 receives "election", P4 dies

3. Election: 4 is forwarded for ever?

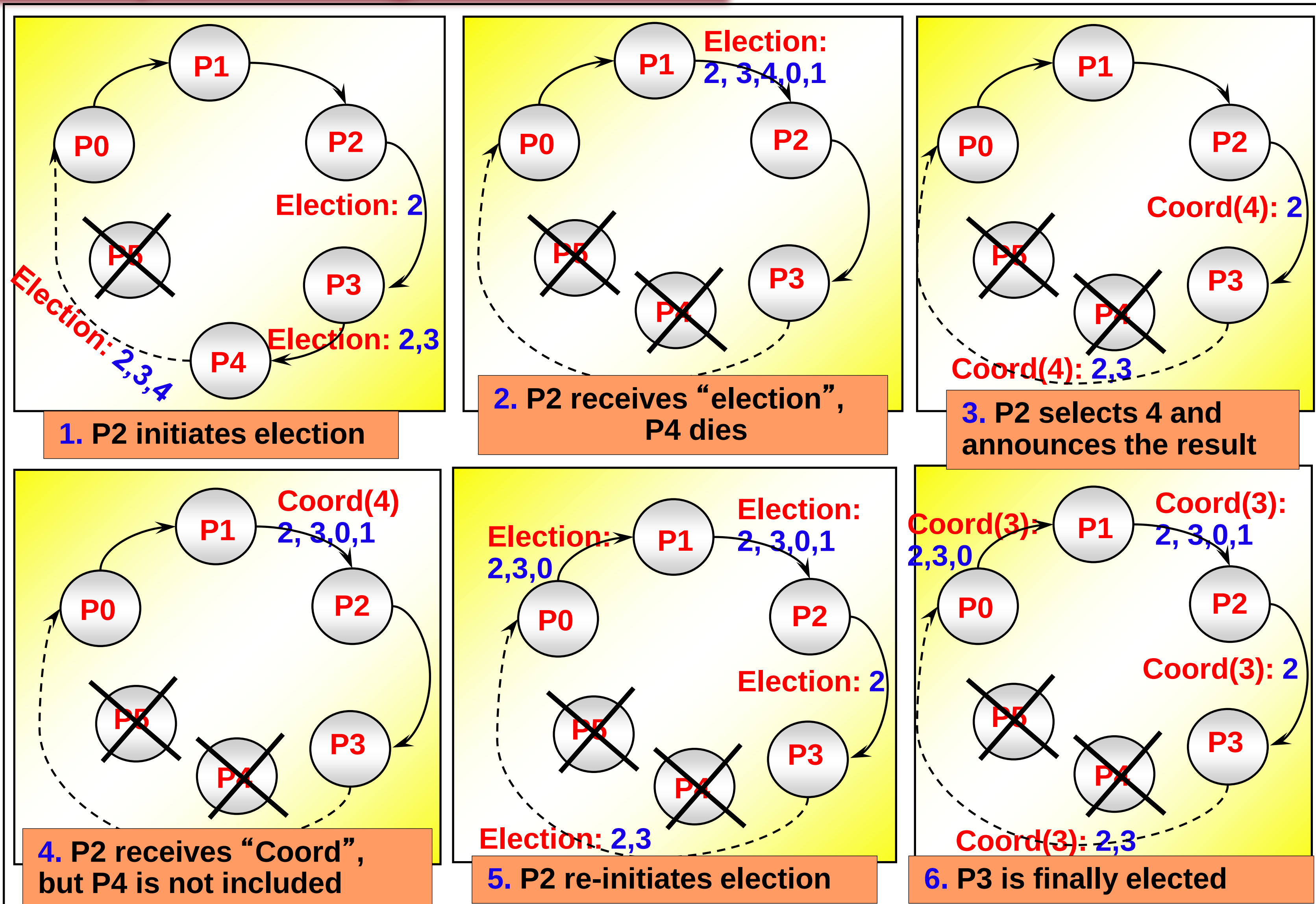
May not terminate when process failure occurs during the election!
Consider above example where attr == id

Does not satisfy liveness

Algorithm 2: Modified Ring Election

- Processes are organized in a logical ring.
- Any process that discovers the coordinator (leader) has failed initiates an "election" message.
- The message is circulated around the ring, bypassing failed processes.
- Each process appends (adds) its id:attr to the message as it passes it to the next process (without overwriting what is already in the message)
- Once the message gets back to the initiator, it elects the process with the best election attribute value.
- It then sends a "coordinator" message with the id of the newly-elected coordinator. Again, each process adds its id to the end of the message, and records the coordinator id locally.
- Once "coordinator" message gets back to initiator,
  - election is over if would-be-coordinator's id is in id-list.
  - else the algorithm is repeated (handles election failure).

Example: Ring Election



Modified Ring Election

- **Supports concurrent elections – an initiator with a lower id blocks other initiators' election messages**
- **Reconfiguration of ring upon failures**
  - **Can be done if all processes "know" about all other processes in the system (Membership list! – MP2)**
- **If initiator non-faulty …**
  - **How many messages? 2N**
  - **What is the turnaround time? 2N**
  - **Size of messages? O(N)**
- **How would you redesign the algorithm to be fault-tolerant to an initiator's failure?**
  - **One idea: Have the initiator's successor wait a while, timeout, then re-initiate a new election. Do the same for this successor's successor, and so on…**
  - **What if timeouts are too short… starts to get messy**

Leader Election Is Hard

- **The Election problem is related to the *consensus problem***
- **Consensus is impossible to solve with 100% guarantee in an asynchronous system with no bounds on message delays and arbitrarily slow processes**
- **So is leader election in fully asynchronous system model**
- **Where does the modified Ring election start to give problems with the above asynchronous system assumptions?**
  - ***pi* may just be very slow, but not faulty (yet it is not elected as leader!)**
  - **Also slow initiator, ring reorganization**

Algorithm 3: Bully Algorithm

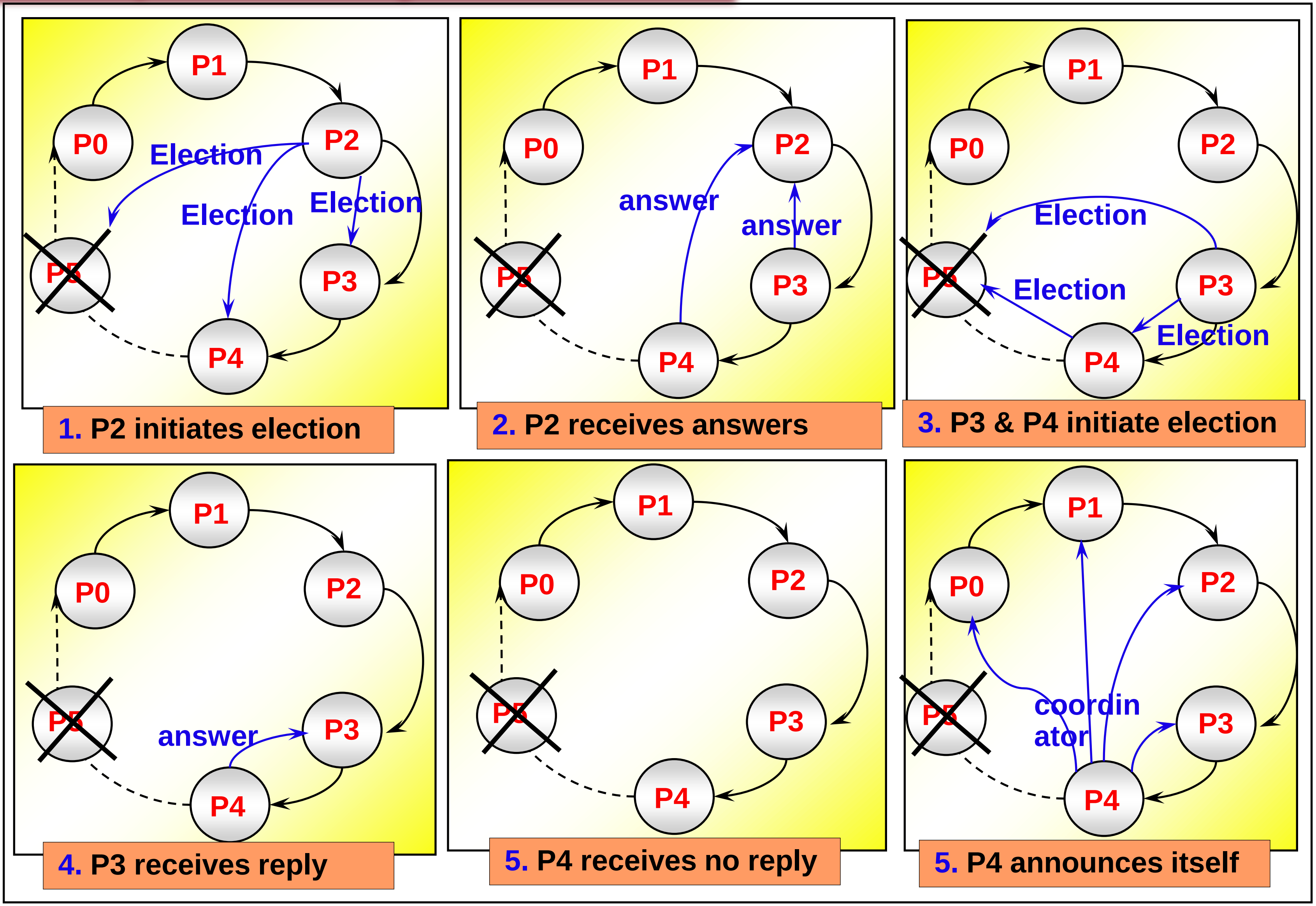
- **Assumptions:**
  - **Synchronous system**
    - **All messages arrive within T_{trans} units of time.**
    - **A reply is dispatched within $T_{process}$ units of time after the receipt of a message.**
    - **if no response is received in $2T_{trans} + T_{process}$, the process is assumed to be faulty (crashed).**
  - **attr==id**
  - **Each process knows all the other processes in the system (and thus their id's)**

Algorithm 3: Bully Algorithm

- When a process finds the coordinator has failed, if it knows its id is the highest, it elects itself as coordinator, then sends a *coordinator* message to all processes with lower identifiers than itself
- A process initiates election by sending an *election* message to only processes that have a higher id than itself.
  - If no answer within timeout, send coordinator message to lower id processes → Done.
  - if any answer received, then there is some non-faulty higher process → so, wait for coordinator message. If none received after another timeout, start a new election.
- A process that receives an "election" message replies with *answer* message, & starts its own election protocol (unless it has already done so)

Example: Bully Election

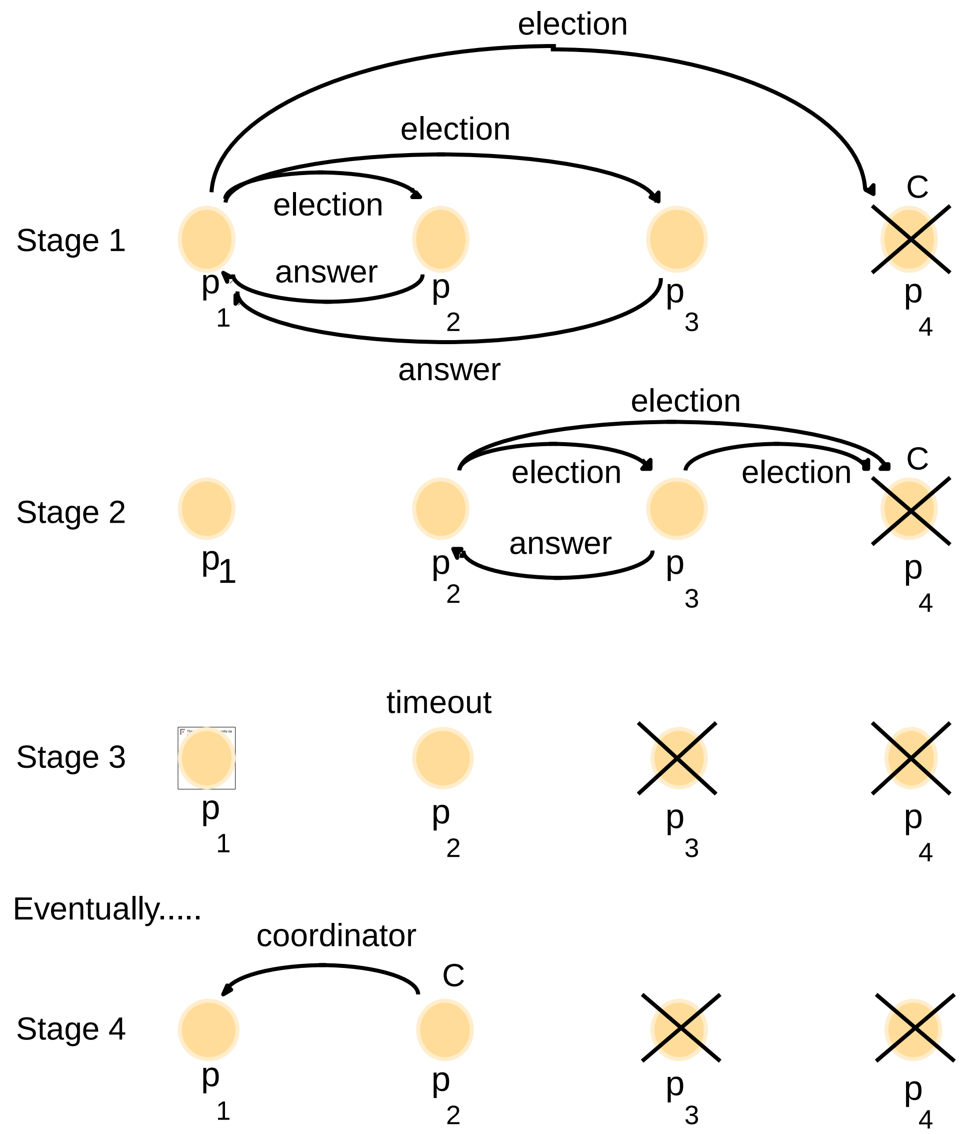
answer=OK



The Bully Algorithm with Failures

The coordinator p_4 fails and p_1 detects this

p_3 fails



Analysis of The Bully Algorithm

- **Best case scenario: The process with the second highest id notices the failure of the coordinator and elects itself.**
  - *N-2* **coordinator messages are sent.**
  - **Turnaround time is one message transmission time.**

Analysis of The Bully Algorithm

- **Worst case scenario: When the process with the lowest id in the system detects the failure.**
  - **N-1 processes altogether begin elections, each sending messages to processes with higher ids.**
    - » **i-th highest id process sends i-1 election messages**
  - **The message overhead is** *$O(N^2)$.*
  - **Turnaround time is approximately 5 message transmission times if there are no failures during the run:**
    1. **Election message from lowest id process**
    2. **Answer to lowest id process from 2nd highest id process**
    3. **Election from 2nd highest id process**
    4. **Timeout for answers @ 2nd highest id process**
    5. **Coordinator message from 2nd highest id process**

Summary

- Coordination in distributed systems requires a leader process
- Leader process might fail
- Need to (re-) elect leader process
- Three Algorithms
  - Ring algorithm
  - Modified Ring algorithm
  - Bully Algorithm