CS 455: INTRODUCTION TO DISTRIBUTED SYSTEMS

[ELECTION ALGORITHMS]

Failures, heartbeats, and detection
Heartbeats in a message
   Either pushed, or pulled, presage
A process’ failure
   And erratic systems behavior
Careful though
   In heartbeats you may drown
And tag a process down, when it’s slow
   And up when it’s down

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Topics covered in this lecture

- Election algorithms
  - Ring based algorithm
- Failure detectors
Election algorithms

- Algorithm for choosing a *unique* process to play a particular role
- When an elected process wants to *retire*, another election is needed
Calling an election

- When a process calls an election it initiates a particular run of the election algorithm.
- A given process does not call more than one election at a time.
  - With N processes there could be N concurrent elections.
- At any point a process \( p_i \) is either:
  - A participant: Engaged in the election algorithm.
  - Non-participant: Not engaged in the election algorithm.

The choice of the elected process must be unique

- Even in cases where several processes call the election simultaneously.
- E.g., 2 processes see a coordinator has failed and they both call elections.
The elected process is the one with the largest identifier

- The identifier is any value with the provision that the identifiers are unique and totally ordered
- E.g., electing process with the lowest computational load
  - Use \(<\text{load}, i\)> as the identifier
  - Process \(i\) is used to order identifiers with same load

Managing the identity of the elected process

- Each process \(p_i \ (i=1, 2, \ldots, N)\) has a variable \(\text{elected}_i\)
  - Contains identifier of the elected process
- When a process first becomes a participant in an election
  - Set this variable to \(\perp\) indicating that it is undefined
Requirements for the election algorithm

- **E1** (safety)
  - Participant process has $\text{elected}_i = \bot$ or $\text{elected}_i = P$
    - $P$ is a non-crashed process at the end of run with the largest identifier

- **E2** (liveness)
  - All processes $p_i$ participate and eventually either set $\text{elected}_i \neq \bot$ or crash

Measuring performance of election algorithms

- **Network bandwidth utilization**
  - How many messages are sent?

- **Turnaround time** for the algorithm
  - Number of message transmissions between the initiation and termination of a run
Ring-based elections

- Each process $p_i$ has a communication channel to the next process $(p_{(i+1)\mod N})$ in the next ring.
- All messages are sent clockwise around the ring.
Conducting elections

- Any process can begin an election

- Process marks itself as a participant and:
  1. Places its identifier in the election message
  2. Sends it to its clockwise neighbor

- On forwarding an election message
  - Process marks itself as a participant

When a process receives an election message it compares identifier with its own

- If the arrived identifier is greater
  - Forward message to its neighbor

- If the arrived identifier is smaller
  - If the process is not a participant
    - Substitute with own identifier and forward the message
  - If the process is already a participant
    - Do not forward the message
Selecting the coordinator

- If the received identifier is that of the receiver itself?
  - That process’ identifier must be the greatest
  - Becomes the coordinator

- Coordinator marks itself as a non-participant
  - Sends an elected message to its neighbor

When a process $p_i$ receives an elected message

- Marks itself as a non-participant
- Sets $elected_i$ to the identifier in the message
- Unless it is the coordinator, it forwards message to its neighbor
Ring based elections

Election was started by process 17

Participant processes are in green

Satisfying the requirements: Safety

- All identifiers are compared
  - A process must receive its own identifier back before sending an elected message

- For any two processes, the one with the larger identifier will not pass the other's identifier
  - Impossible that 2 processes will receive their own identifier back
Satisfying the requirements: Liveness

- Message traversals are guaranteed around the ring
  - The basic algorithm assumes no failures

- Duplicate messages arising when 2 processes start election at the same time?
  - Participant and non-participant states *extinguish* this ASAP and ...
  - *Always before* winning election result has been announced

Performance analysis

- If only a single process starts an election
  - *Worst case* is when *anti-clockwise neighbor* has the *highest* identifier
    - Total of N-1 messages to reach this neighbor
    - Will not announce election till its identifier completes another circuit ... N messages
    - Elected message is sent N times
    - Total of 3N-1 messages

  - Turnaround time also is 3N-1 in the worst case
    - Messages are sent *sequentially*
Failure detection

- In order to properly **mask** failures ...
  - We generally need to detect them well

- Failure detection is one of the cornerstones of fault tolerance in distributed systems
What it all boils down to …

- For a group of processes, non-faulty members must be able to decide:
  - Who is *still* a member and who is *not*

- We need to be able to detect when a member has failed

The two mechanisms for detecting failures

- Processes actively send "*are you alive?*" messages to each other
  - For which they obviously expect an answer

- Passively wait until heartbeats ("*I am alive!*") come in from different processes
  - In practice, active pinging occurs often as well
Huge body of theoretical work on failure detectors

- **Timeout** mechanisms are used to check whether a process has failed
- In real settings:
  - Due to unreliable networks, just because a process does not respond to a ping that does not mean it failed
  - So ... false positives can occur quite easily
    - A healthy process may be removed from the membership

Disambiguating network failures from node failures

- Multiple nodes participate in failure detection
- When a node notices a timeout on a ping message
  - The node contacts other nodes to see if they can reach the **presumed** failing node
Communication styles

- Asynchronous communications
  - No timing assumptions

- Synchronous communications have bounds on
  - Maximum message transmission delay
  - Time to execute each step of a process
  - Clock drift rates

Failure assumptions & failure detectors [1/2]

- Processes use reliable channels to communicate
  - Underlying protocol handles corruptions and retransmissions

- Failures of processes are independent
Failure assumptions & failure detectors [2/2]

- **Network partitions** are possible between the set of communicating processes.
- Over the internet with complex topologies and independent routing choices:
  - Connectivity may be **asymmetric**
    - Communication from $p$ to $q$ is possible, but not vice versa.
  - Connectivity may be **intransitive**
    - Communication is possible from $p$ to $q$ to $r$, but $p$ cannot communicate directly with $r$.

Failure detectors

- **Service** that processes queries about whether a process failed.
- Often implemented as an object **local to each process**:
  - Runs a failure detection algorithm in conjunction with counterparts at other processes.
- Not necessarily accurate:
  - Only as good as the information available at that process.
Unreliable failure detectors

- Produces one of two values when given the identity of a process
  - Suspected or Unsuspected
  - These values are just *hints* and may not accurately reflect if a process has failed
- **Unsuspected**
  - Detector recently received evidence suggesting process has not failed
- **Suspected**
  - Detector has some indication that process probably failed
    - Message not received for more than the nominal silence interval

Unreliable failure detectors

- Suspicions may be **misplaced**
  - Process may be functioning, but on the other side of a network partition
  - Process runs slower than expected
Reliable failure detectors

- Answers liveness queries with
  - Unsuspected
  - Failed

BUILDING FAILURE DETECTORS
Implementing an unreliable failure detector

- Each process \( p \), sends a **heartbeat** every \( T \) seconds
- Failure detector uses estimate of *maximum message transmission delay* of \( D \) seconds
- If failure detector at \( q \) does not receive heartbeat from \( p \) within \( T + D \) seconds of the last one?
  - Detector reports to \( q \) that \( p \) is Suspected
- If heartbeat is received within \( T + D \) then detector at \( q \) deems \( p \) to be OK

Choosing values for \( T \) and \( D \)

- If we choose **small values** for \( T \) and \( D \)?
  - Failure detector is likely to *suspect non-crashed* processes many times
  - Bandwidth will be consumed by heartbeat messages
- If we choose a large \( D \)?
  - **Crashed processes** will often be reported as Unsuspected
Practical solution to the problem

- Use timeout values that reflect *observed network delay* conditions
- If failure detector at $q$ receives heartbeats from $p$ every 20 seconds instead of 10 seconds?
  - Reset timeout for $p$ to 20 seconds
- Failure detector would still be unreliable
  - But *probability of accuracy* increases

Building reliable failure detectors

- Possible *only in synchronous systems*
- $D$ in this case is not an estimate, but an *absolute bound*
  - Absence of heartbeat from $p$ within $T+D$ seconds entitles detector at $q$ to *conclude* that $p$ has failed
Contrasting reliable and unreliable failure detectors

- Unreliable failure detectors can be
  - Inaccurate
    - Suspects process that has not failed
  - Incomplete
    - May not suspect a process that has failed

- Reliable failure detectors require a system that is synchronous
  - Few practical systems are

So why did we look at failure detectors?

- They help us think about failures in distributed systems
- Any practical system designed to cope with failures, must detect them
  - However imperfectly!
- Unreliable failure detectors with well-defined properties help us to provide practical solutions for coordinating processes
THE BULLY ALGORITHM

Bully algorithm (Garcia-Molina):
Key features

- Allows processes to crash during an election
- Assumptions:
  - Message delivery between processes is reliable
  - Synchronous system
    - Uses timeouts to detect a failure
  - Each process knows processes that have higher identifiers
    - Can communicate with them
Message types

- **Election**
  - Sent to announce an election

- **Answer**
  - Sent in response to an election message

- **Coordinator**
  - Sent to announce the identity of the elected process

Initiating elections

- A process begins this when it *notices* that the coordinator has failed
- Several processes may discover this concurrently
Reliable failure detectors are possible because the system is synchronous

- $T_{\text{trans}}$: Maximum transmission delay
- $T_{\text{process}}$: Maximum delay for processing a message
- Upper bound on elapsed time between sending a message to a process & receiving a response
  - $T = 2T_{\text{trans}} + T_{\text{process}}$
  - If no response arrives within $T$, local failure detector tags intended recipient as having failed

In the case of a failure

- Process that knows it has the highest identifier can elect itself as the coordinator
  - Simply send a coordinator message to processes with lower identifiers
When a process with a lower identifier detects coordinator failure it initiates an election

- Send an election message to processes with higher identifiers
  - Await answer messages in response
- If no response within time $T$, process considers itself the coordinator
- If an answer does arrive, wait for additional time $T'$ for coordinator message to arrive
  - If this does not arrive ... start another election

How a process responds to messages that it receives

- If a process $p_i$ receives a coordinator message, it sets its variable $elected_i$ to the coordinator ID
- If a process receives an election message
  1. Sends back an answer message and ...
  2. Begins another election
     - Unless it has started one already
But why is this called the bully algorithm?

- When a process is started to replace a crashed process ... it starts an election
- If this new process has the highest identifier?
  - It decides that it is the new coordinator and announces this
- The new process becomes the coordinator **even though** the current coordinator is functioning

**Election of a coordinator after the failure of p4**

- Stage 1
  - Election
  - Answer

- Stage 2
  - Election
  - Answer
Election of a coordinator after the failure of p4 and then p3

Eventually ...

Satisfying properties E1 and E2

- **E1** (safety)
  - Impossible for two processes to decide that they are the coordinator
    - Process with the lower identifier will discover that the other exists and defer to it

- **E2** (liveness)
  - Satisfied because of the assumption of reliable delivery
    - Processes either participate or crash
Safety ... not so soon

- Not guaranteed to meet safety condition if ...
  - Crashed processes are replaced by processes with the same identifier

- Process that replaces a crashed process (coordinator) may decide it has the highest ID
  - Just as another process (which detected the crash) is about to decide that it has highest ID

- Two processes may announce themselves as the coordinator concurrently

Safety ... not so soon

- No guarantees on message delivery order
  - Recipients reach different conclusions on which is the coordinator process

- E1 may also be broken if timeout values are inaccurate
  - If the process' failure detector is unreliable
A scenario where safety is violated due to inaccurate failure detection

- $p_3$ had not failed but was just *running slowly*
- $p_2$ sends its coordinator message, and $p_3$ does the same
  - $p_2$ receives this after it has sent its message
  - Sets $\text{elected}_2$ to $p_3$
- $p_1$ receives $p_2$'s message after $p_3$'s
  - Sets $\text{elected}_1$ to $p_2$

Performance of the algorithm

- **Best case**
  - $2^{nd}$ highest identifier notices coordinator failure
    - Elects itself immediately and sends $(N-2)$ coordinator messages
    - Turnaround time is 1 message
- **Worst case requires $O(N^2)$ messages**
  - Process with the lowest ID first detects failure
  - $(N-1)$ processes begin elections ... each sending messages to processes with higher identifiers
The contents of this slide set are based on the following references
