Today’s Question

- How do we handle failures?
  - Cannot answer this fully (yet!)
  - You’ll learn new terminologies, definitions, etc.
  - Let’s start with some new definitions.
  - One of the two fundamental challenges in distributed systems
    - Failure
    - Ordering (with concurrency)

Two Different System Models

- Synchronous Distributed System
  - Each message is received within bounded time
  - Each step in a process takes $lb < time < ub$
  - (Each local clock’s drift has a known bound)
  - Examples: Multiprocessor systems

- Asynchronous Distributed System
  - No bounds on message transmission delays
  - No bounds on process execution
  - (The drift of a clock is arbitrary)
  - Examples: Internet, wireless networks, datacenters, most real systems
  - These are used to reason about how protocols would behave, e.g., in formal proofs.

Failure Model

- What is a failure?
  - We’ll consider: process omission failure
    - A process disappears.
    - Permanently: crash-stop (fail-stop) – a process halts and does not execute any further operations
    - Temporarily: crash-recovery – a process halts, but then recovers (reboots) after a while

- We will focus on crash-stop failures
  - They are easy to detect in synchronous systems
  - Not so easy in asynchronous systems

Why, What, and How

- Why design a failure detector?
  - First step to failure handling
- What do we want from a failure detector?
  - No miss (completeness)
  - No mistake (accuracy)
- How do we design one?
What is a Failure Detector?

needs to know about \( p_i \)'s failure

\( (p_i \) is a non-faulty process or alive process)  

There are two styles of failure detectors:

I. Ping-Ack Protocol

- \( p_i \) queries \( p_j \) once every \( T \) time units  
- If \( p_j \) does not respond within another \( T \) time units of being sent the ping, \( p_i \) detects/declares \( p_j \) as failed

\[ \text{Worst case Detection time} = 2T \]

The waiting time \( T \) can be parameterized.

II. Heartbeating Protocol

- \( p_j \) maintains a sequence number  
- \( p_j \) sends \( p_i \) a heartbeat with incremented seq. number after every \( T \) time units

\[ \text{If } T \gg \text{round trip time of messages, then worst case detection time} \approx 3T \] (why?)  

The "3" can be changed to any positive number since it is a parameter

In a Synchronous System

- The Ping-Ack and Heartbeat failure detectors are always correct. For example (there could be other ways),  
  - Ping-Ack: set waiting time \( T \) to be \( > \) round-trip time upper bound  
  - Heartbeat: set waiting time \( 3T \) to be \( > \) round-trip time upper bound

- The following property is guaranteed:  
  - If a process \( p_j \) fails, then \( p_i \) will detect its failure as long as \( p_i \) itself is alive  
  - Its next ack/heartbeat will not be received (within the timeout), and thus \( p_i \) will detect \( p_j \) as having failed
Failure Detector Properties
• What do you mean a failure detector is “correct”?
• Completeness = every process failure is eventually detected (no misses)
• Accuracy = every detected failure corresponds to a crashed process (no mistakes)
• What is a protocol that is 100% complete?
• What is a protocol that is 100% accurate?
• Completeness and Accuracy
  – Can both be guaranteed 100% in a synchronous distributed system (with reliable message delivery in bounded time)
  – Can never be guaranteed simultaneously in an asynchronous distributed system
  – Why?

Completeness and Accuracy in Asynchronous Systems
• Impossible because of arbitrary message delays
  – If a heartbeat/ack is dropped (or several are dropped) from pj, then pj will be mistakenly detected as failed (inaccurate detection)
  – How large would the T waiting period in ping-ack or 3*T waiting period in heartbeating, need to be to obtain 100% accuracy?
  – In asynchronous systems, delays on a network link are impossible to distinguish from a faulty process
• Heartbeating – satisfies completeness but not accuracy (why?)
• Ping-Ack – satisfies completeness but not accuracy (why?)
• Point: You can’t design a perfect failure detector!
  – You need to think about what metrics are important.

Completeness or Accuracy? (in Asynchronous System)
• Most failure detector implementations are willing to tolerate some inaccuracy, but require 100% completeness.
• Plenty of distributed apps designed assuming 100% completeness, e.g., p2p systems
  – “Err on the side of caution”.
  – Processes not “stuck” waiting for other processes
• But it’s ok to mistakenly detect once in a while since
  – the victim process need only rejoin as a new process
• Both Heartbeating and Ping-Ack provide
  – Probabilistic accuracy (for a process detected as failed, with some probability close to 1.0 (but not equal), it is true that it has actually crashed).

Failure Detection in a Distributed System
• That was for one process pj being detected and one process pi detecting failures
• Let’s extend it to an entire distributed system
• Difference from original failure detection is
  – We want failure detection of not merely one process (pj), but all processes in system

CSE 486/586 Administrivia
• PA2A due in two weeks (Fri, 2/19)
• Please use Piazza; all announcements will go there.
  – If you want an invite, let me know.
• Please come to my office during the office hours!
  – Give feedback about the class, ask questions, etc.
Efficiency of Failure Detector: Metrics

- **Bandwidth**: the number of messages sent in the system during steady state (no failures)
  - Small is good
- **Detection Time**
  - Time between a process crash and its detection
  - Small is good
- **Scalability**: Given the bandwidth and the detection properties, can you scale to a 1000 or million nodes?
  - Large is good
- **Accuracy**
  - Large is good (lower inaccuracy is good)

Accuracy Metrics

- **False Detection Rate**: Average number of failures detected per second, when there are in fact no failures
- Fraction of failure detections that are false
- Tradeoffs: If you increase the T waiting period in ping-ack or 3*T waiting period in heartbeating what happens to: Detection Time?
  - False positive rate?
  - Where would you set these waiting periods?

Centralized Heartbeat

```
pj, Heartbeat Seq. j++
```

Ring Heartbeat

```
pj, Heartbeat Seq. n++
```

All-to-All Heartbeat

```
pj, Heartbeat Seq. k++
```

Other Types of Failures

- Let's discuss the other types of failures
- Failure detectors exist for them too (but we won't discuss those)
Other Failure Types

- Communication omission failures
  - Send-omission: loss of messages between the sending process and the outgoing message buffer (both inclusive)
  - What might cause this?
  - Channel omission: loss of message in the communication channel
  - What might cause this?
  - Receive-omission: loss of messages between the incoming message buffer and the receiving process (both inclusive)
  - What might cause this?

- Communication channel failures
  - Loss of messages in the communication channel

- Other Failure Types
  - Arbitrary failures
    - Arbitrary process failure: arbitrarily omits intended processing steps or takes unintended processing steps.
    - Arbitrary channel failures: messages may be corrupted, duplicated, delivered out of order, incur extremely large delays, or non-existent messages may be delivered.
    - Above two are Byzantine failures, e.g., due to hackers, man-in-the-middle attacks, viruses, worms, etc.
    - A variety of Byzantine fault-tolerant protocols have been designed in literature!

Omission and Arbitrary Failures

<table>
<thead>
<tr>
<th>Class of failure</th>
<th>Affects</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fail-stop</td>
<td>Process</td>
<td>Process halts and remains halted. Other processes may detect this state.</td>
</tr>
<tr>
<td>Omission</td>
<td>Channel</td>
<td>A message inserted in an outgoing message buffer never arrives at the other end’s incoming message buffer.</td>
</tr>
<tr>
<td>Send-omission</td>
<td>Process</td>
<td>A process completes send, but the message is not put in its outgoing message buffer.</td>
</tr>
<tr>
<td>Receive-omission</td>
<td>Process</td>
<td>A message is put in a process’s incoming message buffer, but that process does not receive it.</td>
</tr>
<tr>
<td>Arbitrary (Byzantine) channel</td>
<td>Process/channel</td>
<td>Process/channel exhibits arbitrary behaviour: it may send/transmit arbitrary messages at arbitrary times, commit omissions; a process may stop or take an incorrect step.</td>
</tr>
</tbody>
</table>

Summary

- Failure detectors are required in distributed systems to keep system running in spite of process crashes
- Properties – completeness & accuracy, together unachievable in asynchronous systems but achievable in synchronous systems
  - Most apps require 100% completeness, but can tolerate inaccuracy
- 2 failure detector algorithms - heartbeating and ping
- Distributed FD through heartbeating: centralized, ring, all-to-all
- Metrics: bandwidth, detection time, scale, accuracy
- Other types of failures
- Next: the notion of time in distributed systems

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