Implementable Failure Detectors in Asynchronous Systems

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Outline of the talk

- Motivation
- Properties of Failure Detectors
  - Completeness (Strong and Weak)
  - Accuracy (Eventual weak)
- Properties introduced in this paper
  - Infinitely Often Accuracy
  - Conditional Accuracy
  - Global Accuracy
- Implementation of IO detectors
- Application: Server Maintenance Problem
Failure Detection: Motivation

- The most basic module for many fault-tolerant systems
- Function: Which entities have failed?
  - Processes, channels, messages
  - Focus on process failures
- Converting blocking program to a non-blocking one
  - wait for a message from \( P_j \) becomes
  - wait for (a message from \( P_j \)) or (\( P_j \) suspected)
- Desirable Properties of Failure Detectors
  - Completeness: failed entity is suspected
  - Accuracy: unfailed entity is not suspected
Model of a Distributed Computation

• messages:
  • asynchronous (no upper bound on message delays)
  • reliable, no FIFO assumption
• no shared clock or memory
• Model of a process failure
  • crash: ceases all its activities
  • does not announce its crash
  • no malicious behavior
Model of a run

- One distributed program has multiple runs possible depending on
  - external inputs
  - message ordering
  - failure patterns of processes
  - time taken by messages
- Each run results in a sequence of states at each process
  - finite if the process fails
  - infinite otherwise
- Notation
  - $P_i, P_j$: processes
  - $s, t$: local states (totally ordered for a single process)
Failure Detection: Completeness

- Predicates
  - $suspects(s,i) \equiv P_i$ is suspected in state $s$
  - $permsusp(s,i) \equiv \forall t : s \leq t : suspects(t,i)$
  - $failed(i) \equiv P_i$ has failed
- **Strong Completeness:** a failed process is permanently suspected by all correct processes
  - $failed(i) \land \neg failed(j) \Rightarrow \exists s \in P_j : permsusp(s,i)$
- **Weak Completeness:** a failed process is permanently suspected by some correct process
  - $failed(i) \Rightarrow \exists s : permsusp(s,i)$
- Note: all properties implicitly universally quantified for runs.
Failure Detection: Accuracy

- Eventual Weak Accuracy
  - Eventually some correct process is never suspected by any correct process
- EW Detector: weak completeness + eventual weak accuracy
- Consensus problem can be solved in an asynchronous system given EW detector [CT 96].
- Consensus problem is impossible to solve in an asynchronous system [FLP 85] (even when at most one process fails).
- Therefore, there is no failure detector which provides weak completeness and eventual weak accuracy.
Implementable Accuracy Property

Infinitely Often Accuracy: No correct process is permanently suspected.

- $\neg \text{failed}(i) \Rightarrow \forall s : \neg \text{permsusp}(s, i)$

- Alternatively, any wrong suspicion is discovered in finite time (eventually).
  
  You will make mistakes in an asynchronous system. Just ensure that you discover your mistakes (eventually).

- IO Detector $= \text{Strong Completeness} + \text{Infinitely Often Accuracy}$
Example

P0  

P1  (A,A,S,A) (S,A,A,S) (S,A,A)

P2  (S,S,A,A) (S,A,A,S) (S,A,A)

P3  (A,A,A,A) (S,A,A,A) (S,A,S,A)

A = Alive  S = Suspected
Implementation of failure detectors

- Algorithm that does not satisfy IO accuracy (similar to watchd on Unix[HuaKin 96]).
  - Every $k$: units broadcast “are you alive”
    - wait for timeout period $t < k$.
    - suspect = processes that did not respond
  - Another example [Beck91]
    - multicast polling messages periodically
    - processes are expected to reply with “I am alive” messages immediately
    - If the answer is missing for three times consecutively, it assumes that this process has crashed.
Correct Implementation of IO failure detectors

- An algorithm that satisfies IO accuracy
  - Broadcast “alive” message every $k$ units
  - On receiving “alive” from $P_i$
    - unsuspect $P_i$
    - reset the timer for $P_i$
  - On expiry of the timer for $P_i$
    - suspect $P_i$
- **Key idea:** there should not be any interval of time in which messages are ignored
Conditional Properties

- Motivation: better properties when the computation is well-behaved

- Partial Synchrony:
  - A run is partially synchronous if there exists a state $s$ in a correct process $P_i$ and a bound $\delta$ such that all messages sent by $P_i$ after $s$ take at most $\delta$ units of time.
  - $P_i$, $s$, $\delta$ may not be known in advance

- Conditional Eventual Weak Accuracy
  - A failure detector satisfies conditional eventual weak accuracy if for all partially synchronous runs it satisfies eventual weak accuracy.
IO detector at $P_j$ with the conditional accuracy

$IO.suspects$ : set of processes initially $\emptyset$;
$timeout$: array[1..N] of integer initially $t$;
$watch$: timer initially set to $timeout$;

(A1) send “alive” to all processes after every $t$ units;

(A2) On receiving “alive” from $P_i$;

if $i \in IO.suspects$ then

$IO.suspects := IO.suspects \setminus \{i\}$;
$timeout[i]++$;

Set $watch[i]$ timer for $timeout[i]$;

(A3) on expiry of $watch[i]$

$IO.suspects := IO.suspects \cup \{i\}$;
Infinitely Often Global Accuracy

- Stronger property than IO accuracy
  Example: Whenever P1 is accurate about P2, it is mistaken about P3 and vice versa
- GIO accuracy Every process is accurate above the entire system infinitely often
- Algorithm at $P_i$: main idea

```c
timestamp: array[1..N] of integer initially 0;
/* when was the last time $P_i$ received a message from $P_j$ */
IOG.suspects : set of processes initially $\emptyset$;
timeout: array[1..N] of integer initially $t$;
watch: array[1..N] of timer initially set to timeout;
```
GI0 detector

(A1) send “alive” to all processes after every $t$ units;

(A2) On receiving “alive” from $P_i$;

\[
timestamp[i] := time; \quad // \text{any increasing counter will do}
\]

if $i \in IOG.\text{suspects}$ then

\[
timeout[i]++;
\]

for $k \in \{1, \ldots, n\}$ do

if $k \in IOG.\text{suspects} \land timestamp[i] \leq timestamp[k]$

\[
IOG.\text{suspects} := IOG.\text{suspects} - \{k\};
\]

Set $watch[k]$ timer for $timeout[k]$;

(A3) on expiry of $watch[i]$

\[
IOG.\text{suspects} := IOG.\text{suspects} \cup \{i\};
\]
Summary of IO detectors

- **Strong Completeness**
  - Every failed process is permanently suspected (eventually).

- **Infinitely Often Accuracy**
  - No unfailed process is permanently suspected.
  - (global) every process has accurate view of the system infinitely often.

- **Conditional Accuracy**
  - In a partially synchronous run, there exists a correct process which is eventually never suspected by anybody.
Synchronous vs Asynchronous Systems

- **Argument**: Just use a large value of timeout
  - Latency in failure detection high
  - trade-off between response time and accuracy of failure detection

- **Algorithms must work correctly in spite of inaccurate suspicions**
  - 10-accuracy implies any inaccurate suspicion will be detected in finite time
Fault-Tolerant Servers

- Need a continuously running service
- For simplicity assume that the service is stateless
  - e.g. web server for documents
- Use $N$ servers for $N - 1$ fault-tolerance
- Requirement:
  - (At least) one server responds to the request
  - Preferably only one server responds
Fault-Tolerant Server: Requirements

- **Token**: Whoever has the token is the current leader
- **Availability**:
  - There is always at least one token (modulo timeout period).
- **Efficiency**:
  - There are never two or more tokens (modulo message arrival period).
- **Under partial synchrony**:
  - Exactly one token under partial synchrony.
Algorithm for Availability and Efficiency

- process $P_i$ is assumed to have a token if
  - all processes with smaller indices than $i$ are suspected
  - $P_i$ is not suspected.

$s.token(i) \equiv \forall j : j < i : s.suspects[j] \land \neg s.suspects[i].$

- Note
  - Efficiency requires Infinitely often accuracy
  - Large timeouts not desirable
  - Algorithm does not satisfy “exactly one token” under partial synchrony.
Solution: Main ideas

- Process $P_i$ has a token
  - if all processes that are currently not suspected by $P_i$ have ticket times that are greater than that of $P_i$.

- Ticket time of $P_k$: logical time when
  - it was suspected by some process $P_i$ such that (according to $P_i$)
  - $P_k$ had a token before the suspicion and
  - $P_i$ has a token after the suspicion.

- If a process with a token is suspected its ticket time will become greater than all other ticket times.
  - Movement of a token from a slow process
Algorithm for $P_i$

ticket: array[1..N] of (int,int) initially $\forall i : ticket[i] = (0, i)$
suspected: array[1..N] of boolean; /* set by IO detector */

token(k) $\equiv (\forall j \neq k : suspected[j] \lor (ticket[j] > ticket[k]))$
$\land \neg suspected[k]$

(R1) Upon suspicion of $P_k$ with token(k)
    if token(i) then
        ticket[k] := Lamport's logical clock;
        send "slow", k, ticket[k] to all processes

(R2) Upon receiving "slow",k,t
    ticket[k] := max(ticket[k], t);
Properties of the Algorithm

• Availability
  • Under false suspicion
  • Under failures

• Efficiency
  • Any inaccurate suspicion is detected due to IO accuracy

• Exactly one token under partial synchrony
  • All slow processes lose tokens
Conclusions

- Fault Tolerance crucial in distributed systems
- Be careful about the properties of your failure detector
- IO detectors give best of both the worlds
  - asynchronous behavior: mistakes will be discovered.
  - (partially) synchronous behavior: agreement, exactly one token etc.