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
  - $failed(i) \wedge \neg failed(j) \Rightarrow \exists s \in P_j : permsusp(s, i)$
- 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.

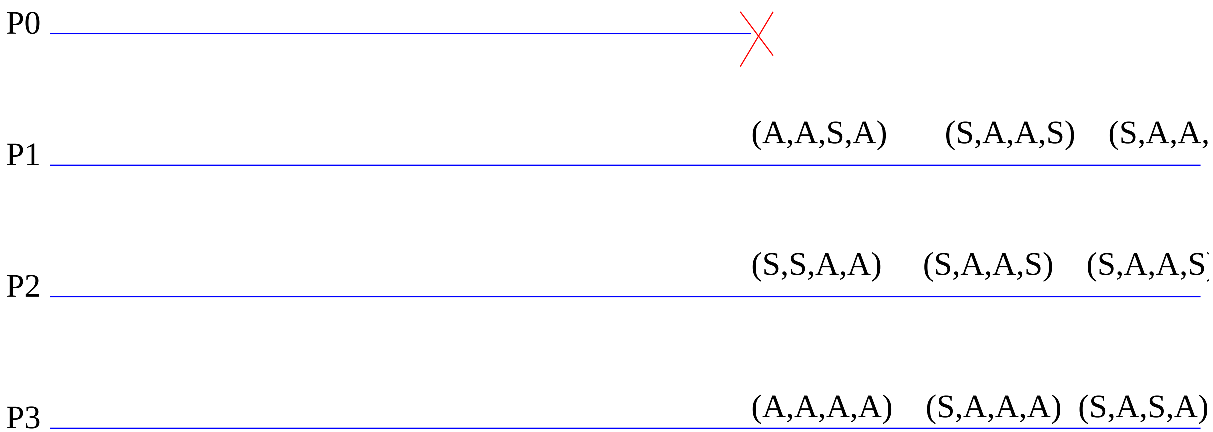
Implementable Accuracy Property

Infinitely Often Accuracy: No correct process is permanently suspected.

- $\neg failed(i) \Rightarrow \forall s : \neg permsusp(s, i)$
- 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 = Strong Completeness + Infinitely Often Accuracy

Example



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 δ such that all messages sent by P_i after s take at most δ units of time.
  - P_i, s, δ 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
$IO.suspects := IO.suspects - \{i\}$;
$timeout$[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 aboue the entire system infinitely often
- Algorithm at P_i: main idea
  $timestamp$: 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 $timeout$;

GIO detector

(A1) send "alive" to all processes after every t units;

(A2) On receiving "alive" from P_i;

$timestamp[i]$:= time; // any increasing counter will do

if $i \in IOG.suspects$ then

$timeout[i]$++;

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

if $k \in IOG.suspects \wedge timestamp[i] \leq timestamp[k]$

$IOG.suspects := IOG.suspects - \{k\}$;

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

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

$IOG.suspects := IOG.suspects \cup \{i\}$;

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
  - IO-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.

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

- 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 */

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

(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.