Impossibility of Distributed Consensus with One Faulty Process

The Weakest Failure Detector for Solving Consensus

October 22, 2015
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- Agreement: Every correct process decides the same value
System Model

- Asynchronous processing: A process can take arbitrarily long to execute its next step.
- Crash failures: A process cannot detect the failure of another process.
- Every message is eventually delivered, but can take arbitrarily long to reach or delivered out of order.
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- **Configuration**: Consists of the internal state of each process along with the state of the message buffer.
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Deciding Run: A run is a deciding run if some process reaches a decision in that run
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- **0(1)-valent configuration**: A configuration from which runs deciding only 0(1) exist
Theorem

There is no consensus protocol that can tolerate the failure of one process.
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What does impossibility mean? Any consensus protocol that respects validity and agreement conditions, must have a possible run, in which no correct process terminates.
Intuition : 2 process case

Scenario 1:
▶ \( p_1 \) starts with input 0
▶ \( p_2 \) fails without executing any step
▶ \( p_1 \) decides 0 and terminates

Scenario 2:
▶ \( p_1 \) fails without executing any step
▶ \( p_2 \) starts with input 1
▶ \( p_2 \) decides 1 and terminates

Scenario 3:
▶ \( p_1 \) starts with 0 and \( p_2 \) starts with 1
▶ Messages take a long time to reach, so \( p_1 \)'s and \( p_2 \)'s view of the system is same as Scenario 1 and 2, resp.
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Proof of the Impossibility Result

The proof proceeds by contradiction. Suppose an algorithm $P$ exists that solves consensus despite one failure.

We show that $P$ has a bivalent initial configuration.

Then we show that from every bivalent configuration, a possible sequence of events can again result in a bivalent configuration.
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$(0, 0, 0, \ldots, 0), (1, 0, 0, \ldots, 0), (1, 1, 0, \ldots, 0), \ldots, (1, 1, 1, \ldots, 1)$
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There exists two adjacent configurations in the path that are of
different valency. And they differ in the input value of only one
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There exists two adjacent configurations in the path that are of different valency. And they differ in the input value of only one process $i$

Now construct a run where $i$ crashes without taking any steps. Then, processes $< i$ decide on $0$ and process $> i$ decide on $1$. 
Lemma

Let $C$ be a bivalent configuration and $e = (p, m)$ be an event applicable to $C$. Then, there exists a bivalent configuration reachable from $C$ in which $e$ has been applied.
What to do now?

Even if there is no "perfect" protocol, cases when processes do not terminate may be rare.

One approach: Every process has access to a local failure detector module. The module need not be perfect. It can suspect a correct process to have failed or not suspect a failed process.
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- **Weak Completeness**: There is a time after which every process that crashes is suspected by some correct processes.
- **Perpetual Strong Accuracy**: Any correct process is never suspected by any process.
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And both of these are useless!
Eventually weak failure detector, $\diamond W$
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These are examples of eventually forever properties: Properties that forever hold true after some finite amount of time.
Theorem

*It is possible to solve consensus using* $\diamond W$ *if* $n > 2f$
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What do we mean by the “weakest” failure detector?
Any failure detector that solves consensus with $n > 2f$ can emulate $\Diamond W$
A practical implementation of $\diamond W$

Every process sends "I am alive" messages periodically.

If a process $p$ does not hear from another process $q$ for some time, it adds $q$ to the list of processes suspected to have failed.

If $p$ later receives the "I am alive" message from $q$, it removes $q$ from its list and increases the timeout for $q$.

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Outline of the Algorithm
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- Otherwise, the algorithm enters the next round
Weakest failure detector

Instead of emulating $\Diamond W$, we show that any failure detector can emulate $\Omega$ (defined below) which can in turn emulate $\Diamond W$.
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Definition
A failure detector $\Omega$ satisfies the following properties :

- Its output at a process $p$ is a single process $q$ that $p$ trusts to be correct at that time
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- Easy to see that $\Omega$ is at least as strong as $\diamondsuit W$
- An emulator for $\diamondsuit W$ using $\Omega$ outputs the set of processes that are not trusted in $\Omega$
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- Processes exchange and update their graphs.
- A finite subgraph of this graph contains the node that every process should trust.
Conclusion

A consensus algorithm satisfying all the three properties in an asynchronous environment tolerating a single node failure is impossible.

Since a purely asynchronous system does not exist, it tells us any practical algorithm can get into infinite executions, however rare they are.

We need to relax constraints that make extra assumptions about the system to solve consensus.

⋄ W solves consensus algorithm by assuming weak properties about the failure detection module.

It is the weakest failure detection module using which we can solve consensus.
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- It is the weakest failure detection module using which we can solve consensus.