Introduction to fault-tolerance

Availability

The availability of a system is the probability that the system will perform its required action

Availability

The availability of a system is the probability that the system will perform its required action

Example:

- one workstation
- crashes once a week
- takes 2 minutes to recover

Availability

The availability of a system is the probability that the system will perform its required action

Example:

- one workstation
- crashes once a week
- takes 2 minutes to recover

Availability:

$$1 - p_{crash} = 1 - 2 \cdot 10^{-4} = 0.9998$$

Availability

The availability of a system is the probability that the system will perform its required action

Example:

- ~~one~~ 30 workstations
- crash once a week
- take 2 minutes to recover

Availability:

Availability

The availability of a system is the probability that the system will perform its required action

Example:

- ~~one~~ 30 workstations
- crash once a week
- take 2 minutes to recover

Availability:

$$(1 - p_{crash})^{30} \approx 1 - n \cdot p_{crash} = 0.994$$

Increasing availability

- Avoid a single point of failure
  - use replication (in time, or space)
  - replicas communicate through narrow interface (e.g. send/receive)

Increasing availability

- Avoid a single point of failure
  - use replication (in time, or space)
  - replicas communicate through narrow interface (e.g. send/receive)
- Example
  - Replicate the workstation 30 times

Availability:

Increasing availability

- Avoid a single point of failure
  - use replication (in time, or space)
  - replicas communicate through narrow interface (e.g. send/receive)
- Example
  - Replicate the workstation 30 times

Availability:

$$1 - p^n_{crash} = 1 - (2 \cdot 10^{-4})^{30} = 1 - 10^{111}$$

Modeling faults

- Mean Time To Failure/ Mean Time To Recover
  - close to hardware
- Threshold: f out of n
  - makes condition for correct operation explicit
  - measures fault-tolerance of architecture, not single components
- Set of explicit failure scenarios

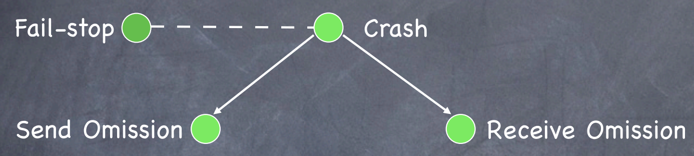
A hierarchy of failure models

Crash

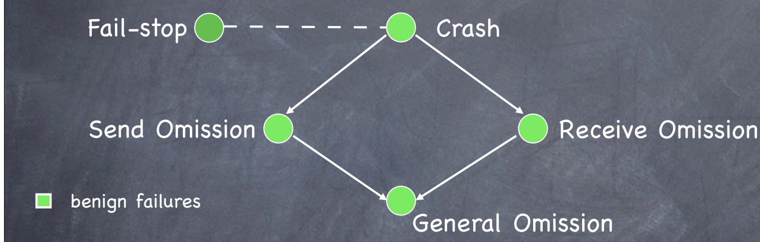
A hierarchy of failure models

Fail-stop - - - - - - - Crash

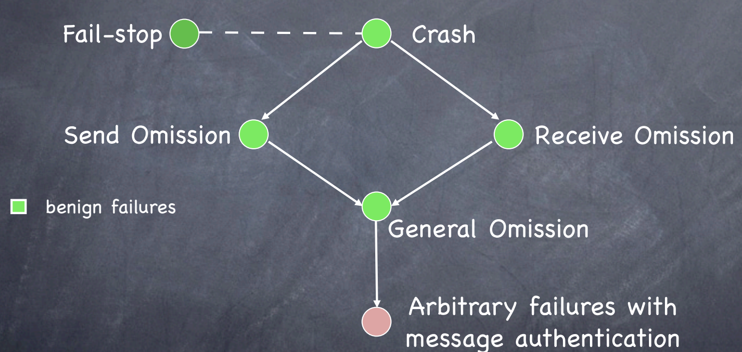
A hierarchy of failure models



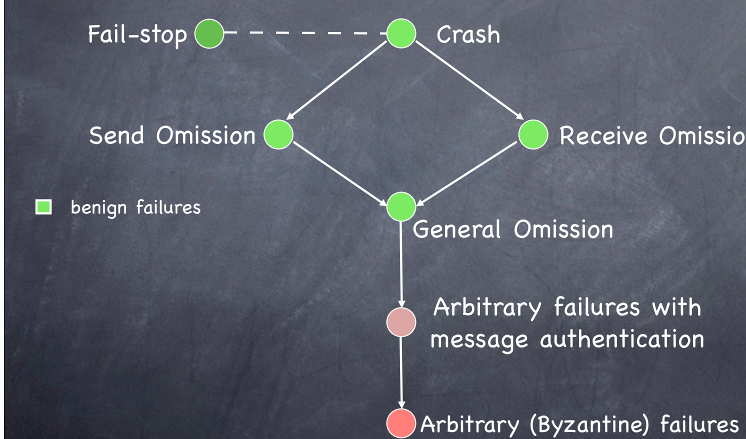
A hierarchy of failure models



A hierarchy of failure models



A hierarchy of failure models



Replication in space

- Run parallel copies of a unit
- Vote on replica output
- Failures are masked
- High availability, but at high cost

Replication in time

- When a replica fails, restart it (or replace it)
- Failures are detected, not masked
- Lower maintenance, lower availability
- Tolerates only benign failures
- Better than you think...

Non-determinism

An event is non-deterministic if the state that it produces is not uniquely determined by the state in which it is executed

Handling non-deterministic events at different replicas is challenging

- Replication in time requires to reproduce during recovery the original outcome of all non-deterministic events
- Replication in space requires each replica to handle non-deterministic events identically

Primary-Backup

The Idea

- Clients communicate with a single replica (the primary)
- The primary updates the other replicas (backups)
- Backups detect the failure of the primary using a timeout mechanism,
- Clients fail over to a backup

Note: Non-deterministic events are executed only at the primary

Terminology

- The failover time of a primary-backup service is the longest time the service can be without a primary
- The service has a server outage at t if some correct client sends a request at time t to the service, but does not receive a response
- A (k,Δ)-bofo service is one in which all server outages can be grouped into at most k intervals of time, each of at most length Δ

PB: A specification

(Budhiraja, Marzullo, Schneider, Toueg)

PB1: There exists a local predicate $Prmy_s$ on the state of each server s. At any time, there is at most one server s whose state satisfies $Prmy_s$

PB2: Each client i maintains a server identity $Dest_i$ such that to make a request, client i sends a message to $Dest_i$

PB3: If a client request arrives at a server that is not the current primary, then that request is not enqueued (and therefore is not processed)

PB4: There exist fixed values k and Δ such that the service behaves like a single (k,Δ)-bofo server

A simple example: system model

- point-to-point communication
- non-faulty channels
- upper bound δ on message delivery time
- at most one server crashes

A simple example: system model

- point-to-point communication
- non-faulty channels
- upper bound δ on message delivery time
- at most one server crashes
- Two processes:
  - the primary p_1
  - the backup p_2

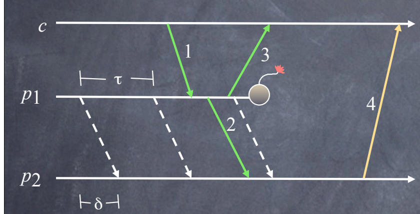
A simple example: p_1's protocol

- On receipt of a client request, process p_1
  - consumes request and updates its state
  - send state update message to p_2
  - sends response to client without waiting for ack from p_2
- p_1 sends heartbeat message to p_2 every τ seconds

A simple example: p_2's protocol

- Upon receiving a state update from p_1, p_2 updates its state
- If p_2 does not receive a heartbeat for $\tau + \delta$ seconds,
  - p_2 declares itself primary
  - it informs the clients
  - it begins consuming subsequent requests from clients

It meets the spec



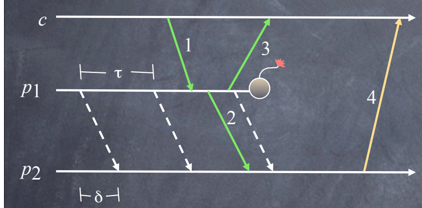
PB1: $Prmy_{p_1} \wedge Prmy_{p_2} = false$

Failover: Time during which $\neg Prmy_{p_1} \wedge \neg Prmy_{p_2}$

$Prmy_{p_1} \equiv p_1$ has not crashed

$Prmy_{p_2} \equiv p_2$ has not received a message from p_1 for $\tau + \delta$ seconds

It meets the spec



PB1: $Prmy_{p_1} \wedge Prmy_{p_2} = false$

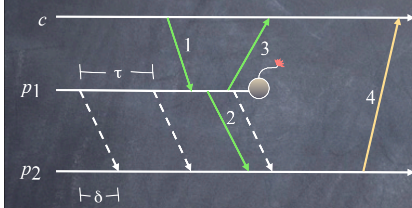
Failover: Time during which

$\neg Prmy_{p_1} \wedge \neg Prmy_{p_2}$

$Prmy_{p_1} \equiv p_1$ has not crashed

$Prmy_{p_2} \equiv p_2$ has not received a message from p_1 for $\tau + \delta$ seconds

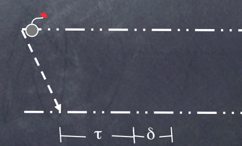
It meets the spec



PB1: $Prmy_{p_1} \wedge Prmy_{p_2} = false$

Failover: Time during which

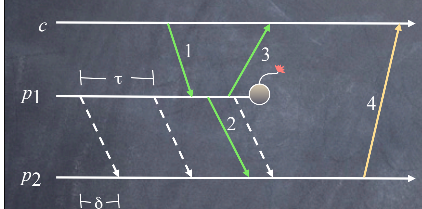
$\neg Prmy_{p_1} \wedge \neg Prmy_{p_2}$



$Prmy_{p_1} \equiv p_1$ has not crashed

$Prmy_{p_2} \equiv p_2$ has not received a message from p_1 for $\tau + \delta$ seconds

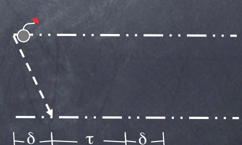
It meets the spec...



PB1: $Prmy_{p_1} \wedge Prmy_{p_2} = false$

Failover: Time during which

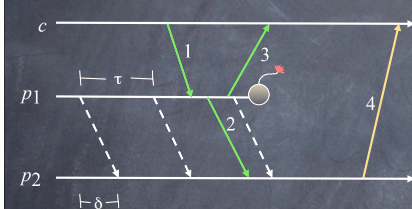
$\neg Prmy_{p_1} \wedge \neg Prmy_{p_2}$



$Prmy_{p_1} \equiv p_1$ has not crashed

$Prmy_{p_2} \equiv p_2$ has not received a message from p_1 for $\tau + \delta$ seconds

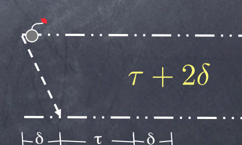
It meets the spec



PB1: $Prmy_{p_1} \wedge Prmy_{p_2} = false$

Failover: Time during which

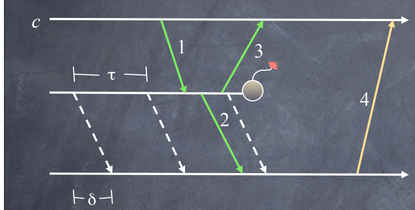
$\neg Prmy_{p_1} \wedge \neg Prmy_{p_2}$



$Prmy_{p_1} \equiv p_1$ has not crashed

$Prmy_{p_2} \equiv p_2$ has not received a message from p_1 for $\tau + \delta$ seconds

...indeed, it does!



PB2, PB3: Follow immediately from protocol

PB4: Find k, Δ to implement (k,Δ)-bofo server

- k = 1 (since at most one crash)
- Δ = longest interval during which a request elicits no response

– assume p_1 crashes at t_c

– any client request sent to p_1 at time $t_c - \delta$ or later may be lost

– p_2 may not become the new primary until $t_c + \tau + 2\delta$

– client may not learn that p_2 is new primary for another δ

$$\Delta = \tau + 4\delta$$

Some like it hot

- Hot Backups process information from the primary as soon as they receive it
- Cold Backups log information received from primary, and process it only if primary fails
- Rollback Recovery implements cold backups cheaply:
  - the primary logs directly to stable storage the information needed by backups
  - if the primary crashes, a newly initialized process is given content of logs—backups are generated “on demand”