State-Machine Replication

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

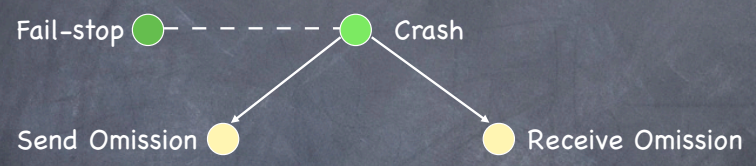
A hierarchy of failure models

Crash

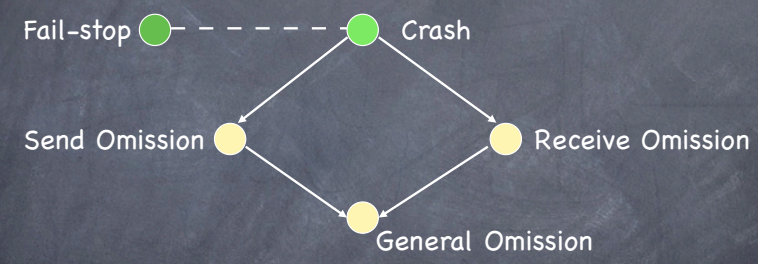
A hierarchy of failure models

Fail-stop - - - - - - - Crash

A hierarchy of failure models



A hierarchy of failure models



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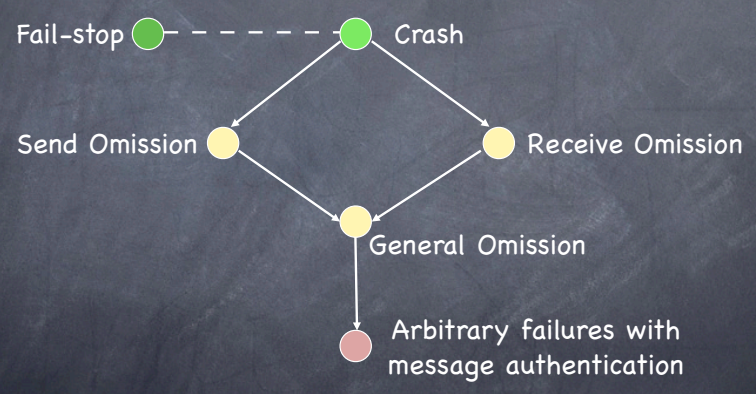

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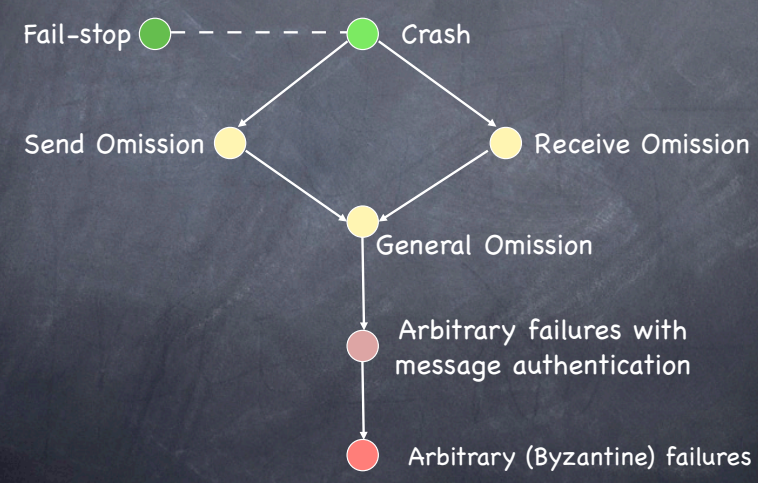

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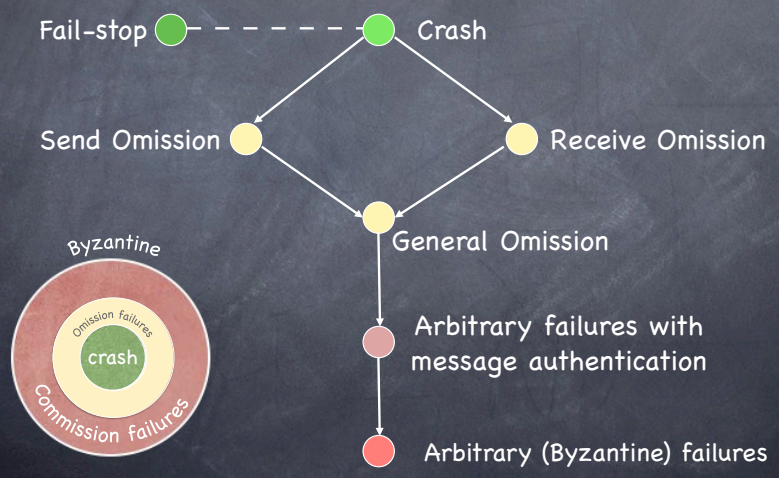
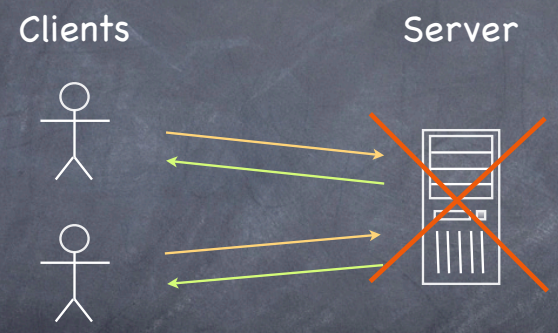


The Problem



Solution: replicate server!

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

Non-determinism

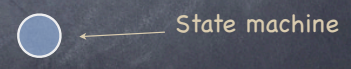
An event is non-deterministic if the state that it produces is not uniquely determined by the state in which it is executed

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

The Solution

1. Make server deterministic (state machine)



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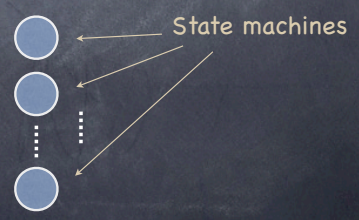

The Solution

1. Make server deterministic (state machine)
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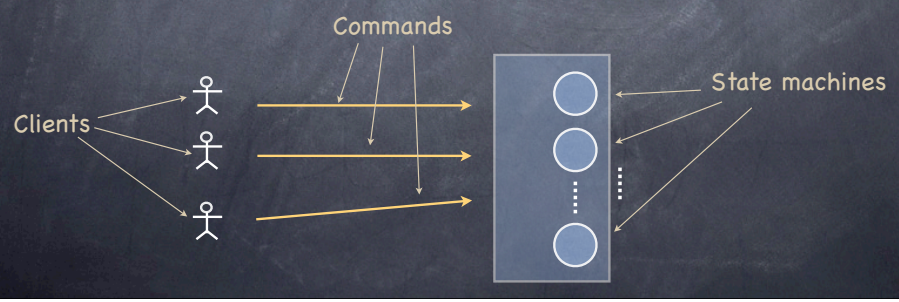
3. Ensure correct replicas step through the same sequence of state transitions



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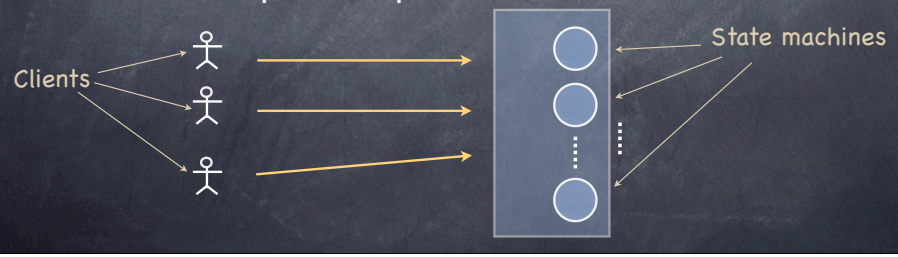

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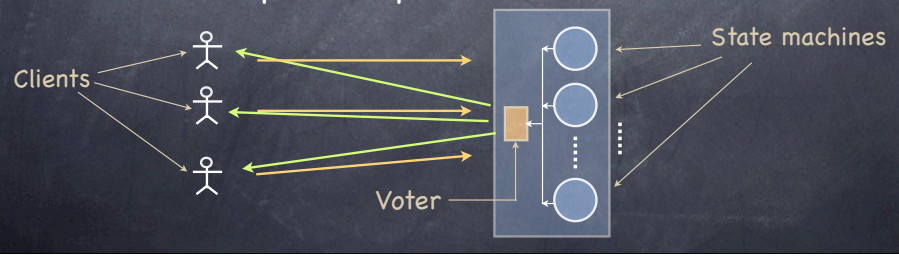
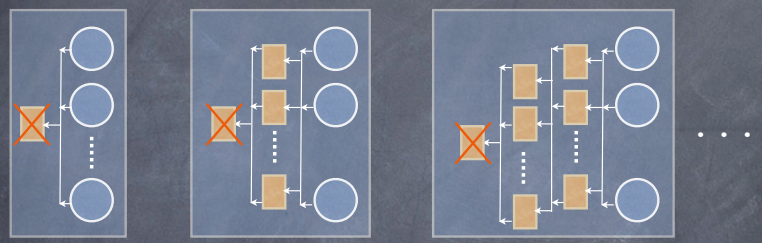


A conundrum



A: voter and client share fate!

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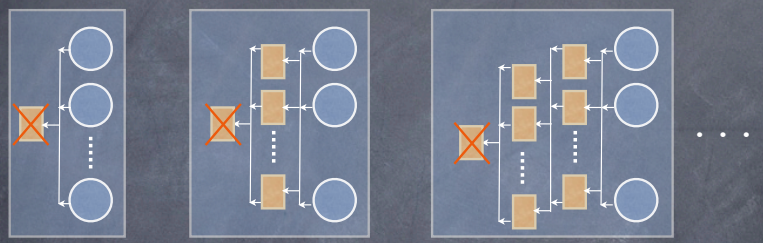

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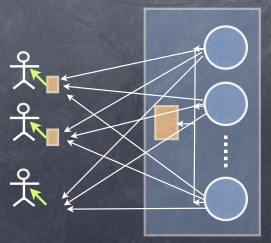


State Machines

- Set of state variables + Sequence of commands
- A command
  - Reads its read set values (opt. environment)
  - Writes to its write set values (opt. environment)
- A deterministic command
  - Produces deterministic wsvs and outputs on given rsv
- A deterministic state machine
  - Reads a fixed sequence of deterministic commands

Replica Coordination

All non-faulty state machines receive all commands in the same order

- Agreement: Every non-faulty state machine receives every command
- Order: Every non-faulty state machine processes the commands it receives in the same order

Primary-Backup

The Idea

- Clients communicate with a single replica (primary)
- Primary:
  - sequences clients' requests
  - updates as needed other replicas (backups) with sequence of client requests or state updates
  - waits for acks from all non-faulty clients
- Backups use timeouts to detect failure of primary
- On primary failure, a backup is elected as new primary

Primary-backup and non-determinism

- Non-deterministic commands executed only at the primary
- Backups receive either
  - state updates (non-determinism?)
  - command sequence (non-determinism?)

Where should RC be implemented?

- In hardware
  - sensitive to architecture changes
- At the OS level
  - state transitions hard to track and coordinate
- At the application level
  - requires sophisticated application programmers

Hypervisor-based Fault-tolerance

- Implement RC at a virtual machine running on the same instruction-set as underlying hardware
- Undetectable by higher layers of software
- One of the great come-backs in systems research!
  - CP-67 for IBM 369 [1970]
  - Xen [SOSP 2003], VMware

The Hypervisor as a State Machine

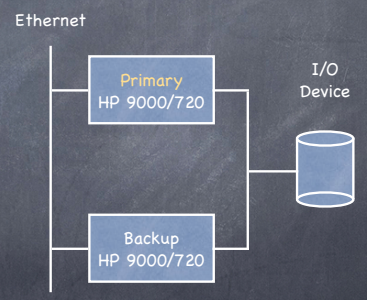
- Two types of commands
  - virtual-machine instructions
  - virtual-machine interrupts (with DMA input)
- State transition must be deterministic
  - ...but some VM instructions are not (e.g. time-of-day)
  - interrupts must be delivered at the same point in command sequence

The Architecture

- Good-ol' Primary-Backup
- Primary makes all non-deterministic choices

I/O Accessibility Assumption

Primary and backup have access to same I/O operations



Ensuring identical command sequences

- Ordinary (deterministic) instructions
- Environment (nondeterministic) instructions

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- Environment Instruction Assumption

  Hypervisor captures all environment instructions, simulates them, and ensures they have the same effect at all state machines

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- Instruction Stream Interrupt Assumption

  Hypervisor can be invoked at specific point in the instruction stream

Ensuring identical command sequences

- Ordinary (deterministic) instructions
- Environment (nondeterministic) instructions
- Environment Instruction Assumption
- VM interrupts must be delivered at same point in instruction sequence at all replicas
- Instruction Stream Interrupt Assumption
  - implemented via recovery register
  - interrupts at backup are ignored

The failure-free protocol

P0: On processing environment instruction i at pc, HV of primary p :

sends $[e_p, pc, Val_i]$ to backup b
waits for ack

P1: If p'HV receives Int from its VM:

p buffers Int until epoch ends

P2: If epoch ends at p:

p sends to b all buffered Int in e_p
p waits for ack
p delivers all VM Int in e_p
$e_p := e_p + 1$
p starts e_p

P3: If b'HV processes environment instruction i at pc :

b waits for $[e_b, pc, Val_i]$ from p
returns Val_i

If b receives $[E, pc, Val]$ from p :

b sends ack to p
b buffers Val for delivery at E, pc

P4: If b'HV receives Int from its VM

b ignores Int

P5: If epoch ends at b:

b waits from p for interrupts for e_b
b sends ack to p
b delivers all VM Int buffered in e_b
$e_b := e_b + 1$
b starts e_b

If the primary fails...

P6: If b receives a failure notification instead of $[e_b, pc, Val_i]$, b executes i

If in P5 b receives failure notification instead of Int:

$e_b := e_b + 1$
b starts e_b <--- failover epoch
b is promoted primary for epoch $e_b + 1$

If p crashes before sending Int to b, Int is lost!

Failures and the environment

- No exactly-once guarantee on outputs
- On primary failure, avoid input inconsistencies
  - time must increase monotonically
    - at epoch boundaries, primary informs backup of value of its clock
  - interrupts must be delivered as a fault-free processor would
    - but interrupts can be lost...
    - weaken constraints on I/O interrupts

On I/O device drivers

IO1: If an I/O instruction is executed and the I/O operation performed, the issuing processor delivers a completion interrupt, unless it fails. If the processor fails, the I/O device continues as if the interrupt had been delivered.

IO2: An I/O device may cause an uncertain interrupt (indicating the operation has been terminated) to be delivered by the processor issuing the I/O instruction. The instruction could have been in progress, completed, or not even started.

On an uncertain interrupt, the device driver reissues the corresponding I/O instruction–not all devices though are idempotent or testable

Backup promotion and uncertain interrupts

P7: The backup's VM generates an uncertain interrupt for each I/O operation that is outstanding right before the backup is promoted primary (at the end of the failover epoch)

The Hypervisor prototype

- Supports only one VM to eliminate issues of address translation
- Exploits unused privileged levels in HP's PA-RISC architecture (HV runs at level 1)
- To prevent software to detect HV, hacks one assembly HP-UX boot instruction

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- Nondeterministic ordinary instructions (Surprise!)

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  - TLB misses handled by software
  - Primary and backup may execute a different number of instructions!

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RC in the Hypervisor

- Nondeterministic ordinary instructions (Surprise!)
  - TLB replacement policy non-deterministic
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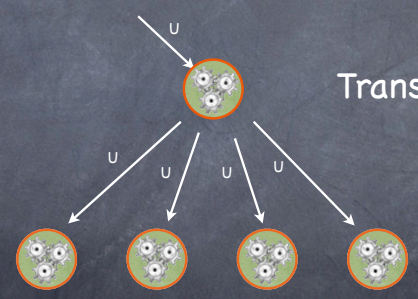
HV takes over TLB replacement

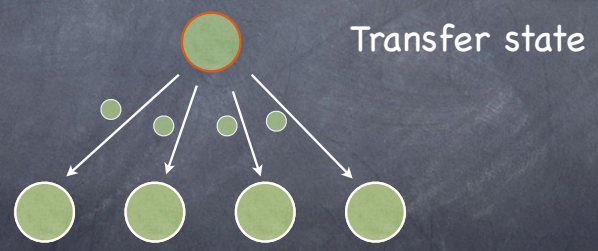
- Optimizations
  - p sends Int immediately
  - p blocks for acks only before output commit

Primary-backup: Updates



Transfer update

Primary-backup: Updates



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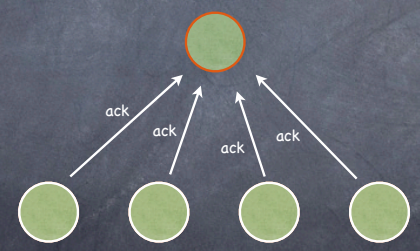

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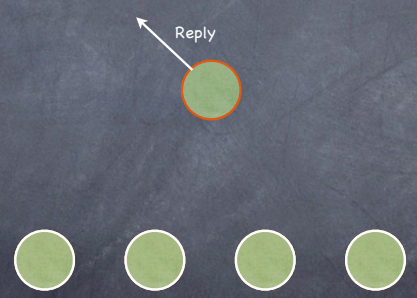
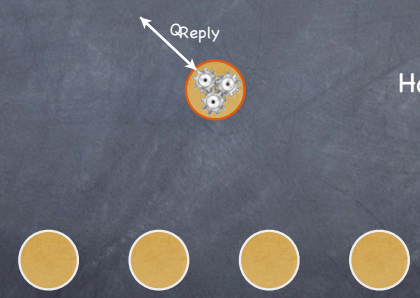


Primary-backup: Queries



However...

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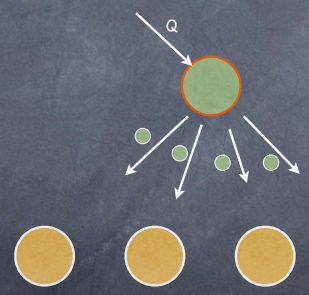
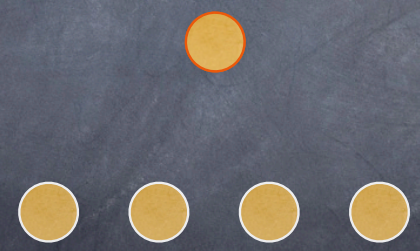


Primary cannot respond until it has received ack for prior updates!

Chain replication

Van Renesse, Schneider, OSDI '04



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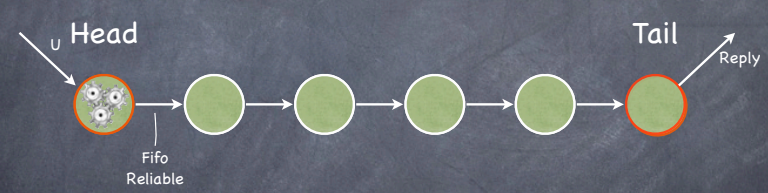

Chain replication: Queries

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Furthermore...

Chain replication: Queries

Van Renesse, Schneider, OSDI '04

Tail can respond immediately,
without waiting for the new update

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"