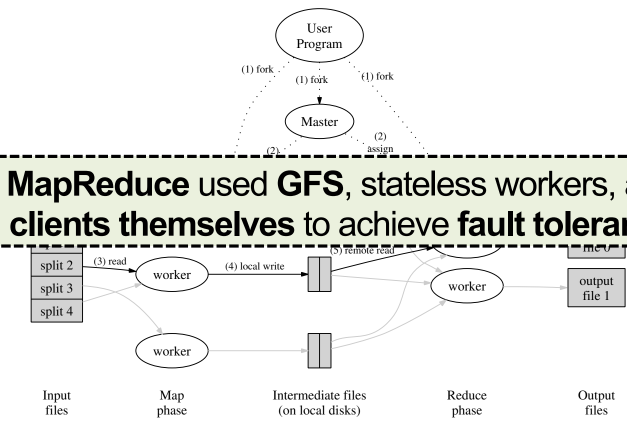
Primary-Backup Replication

COS 418: *Distributed Systems*
Lecture 5

Kyle Jamieson

Simplified Fault Tolerance in MapReduce



MapReduce used **GFS**, stateless workers, and **clients themselves** to achieve **fault tolerance**

Limited Fault Tolerance in Totally-Ordered Multicast

- Stateful server replication for **fault tolerance…**
- But **no story** for **server replacement** upon a **server failure → no replication**

Today: Make **stateful** servers **fault-tolerant?**

Plan

1. **Introduction to Primary-Backup replication**
2. Case study: VMWare's fault-tolerant virtual machine

- Upcoming – **Two-phase commit** and **Distributed Consensus** protocols

Primary-Backup: Goals

- **Mechanism:** Replicate and separate servers
- **Goal #1:** Provide a highly reliable service
  - Despite some server and network failures
    - **Continue operation** after failure
- **Goal #2:** Servers should behave just like a single, more reliable server

State machine replication

- **Any server** is essentially a ***state machine***
  - Set of (key, value) pairs is **state**
  - Operations **transition** between states
- Need an op to be executed on all replicas, or none at all
  - *i.e.*, we need **distributed all-or-nothing atomicity**
  - If op is deterministic, replicas will end in same state
- **Key assumption:** Operations are deterministic
  - We will relax this assumption later today

Primary-Backup (P-B) approach

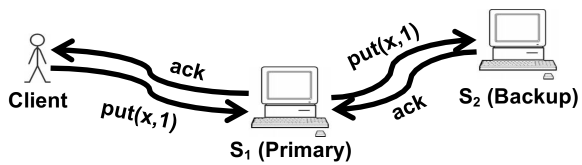
- Nominate one server the ***primary,*** call the other the ***backup***
  - Clients send all operations (get, put) to current primary
  - The primary **orders** clients' operations
- Should be only **one primary at a time**

Need to keep clients, primary, and backup in sync: **who is primary** and **who is backup**

Challenges

- Network and server **failures**
- Network **partitions**
  - Within each network partition, near-perfect communication between servers
  - Between network partitions, **no communication between servers**

Primary-Backup (P-B) approach



1. Primary logs the operation locally
2. Primary sends operation to backup and waits for ack
   - Backup performs or just adds it to its ***log***
3. Primary performs op and **acks** to the client
   - After backup has applied the operation and ack'ed

View server

- A ***view server*** decides who is primary, who is backup
  - Clients and servers depend on view server
    - Don't decide on their own (might not agree)
- Challenge in designing the view service:
  - Only want one primary at a time
  - Careful protocol design needed
- For now, **assume** view server **never fails**

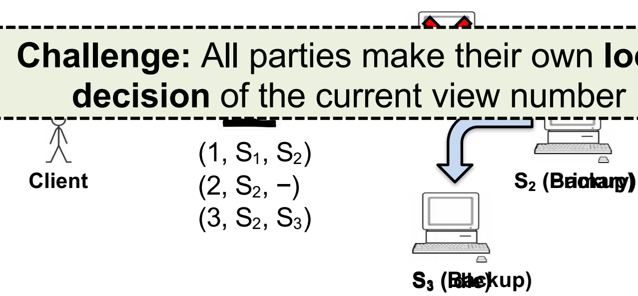
Monitoring server liveness

- Each replica periodically ***pings*** the view server
  - View server declares replica ***dead*** if it missed N pings in a row
  - Considers the replica ***alive*** after a single ping
- *Can a replica **be alive but declared "dead"** by view server?*
  - Yes, in the case of network failure or partition

The view server decides the current view

- ***View*** = (view #, primary server, backup server)

Challenge: All parties make their own **local decision** of the current view number



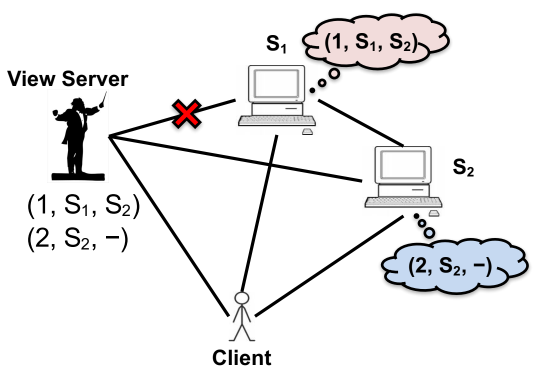
Agreeing on the current view

- In general, any number of servers can ping view server
- Okay to have a view with a primary and **no backup**
- Want everyone to **agree** on the **view number**
  - **Include** the view # in RPCs between all parties

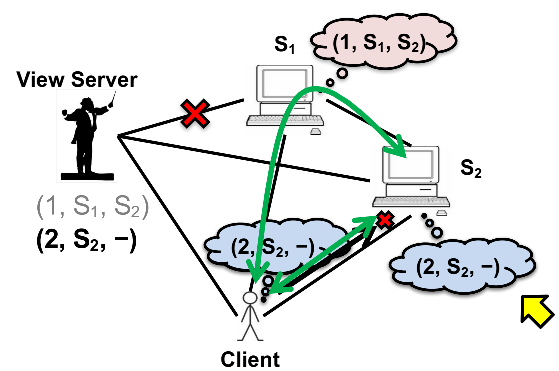
Transitioning between views

- *How to ensure new primary has up-to-date state?*
  - Only promote a previous backup
    - *i.e.,* don't make a previously-idle server primary
  - Set liveness detection timeout > state transfer time
- *How does view server know whether backup is up to date?*
  - View server sends ***view-change*** message to all
  - Primary **must ack new view** once backup is up-to-date
  - View server stays with current view until ack
    - Even if primary has or <u>appears</u> to have failed

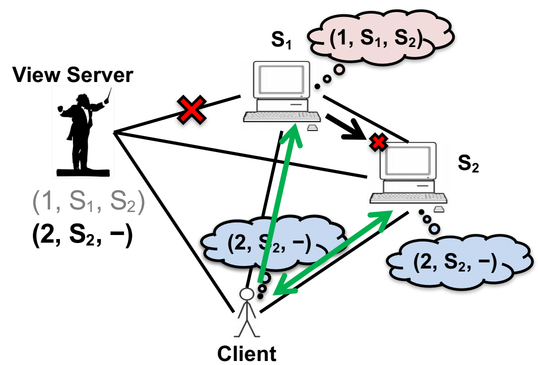
Split Brain



Server S_2 in the old view



Server S_2 in the new view



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State transfer via operation log

- *How does a new backup get the current state?*
  - If S_2 is backup in view *i* but was not in view *i*−1
  - S_2 asks primary to transfer the state

- One alternative: transfer the **entire operation log**

Simple, but **inefficient** (operation log is long)

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State transfer via snapshot

- Every op must be either **before** or **after** state transfer
  - If op **before** transfer, transfer must **reflect** op
  - If op **after** transfer, primary **forwards the op** to the backup after the state transfer finishes

- If each client has only one RPC outstanding at a time, state = map + result of the last RPC from each client
  - (Had to save this anyway for "at most once" RPC)

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Summary of rules

1. View *i*'s **primary** must have been primary/backup in view *i*−1
2. A **non-backup** must reject forwarded requests
   - Backup accepts forwarded requests only if they are in its idea of the current view
3. A **non-primary** must reject direct client requests
4. Every operation must be **before or after** state transfer

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Primary-Backup: Summary

- First step in our goal of making **stateful** replicas **fault-tolerant**
- Allows replicas to provide **continuous service** despite **persistent net and machine failures**
- Finds repeated application in **practical systems (next)**

Plan

1. Introduction to Primary-Backup replication

2. **Case study: VMWare's fault-tolerant virtual machine**
   Scales *et al.*, SIGOPS Operating Systems Review 44(4), Dec. 2010 (PDF)

- Upcoming – **Two-phase commit** and **Distributed Consensus** protocols

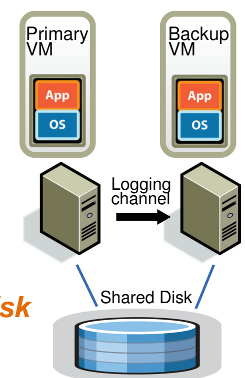
VMware vSphere Fault Tolerance (VM-FT)

- **Goals:**

1. Replication of the **whole virtual machine**
2. **Completely transparent** to applications and clients
3. **High availability** for any existing software

Overview

- Two virtual machines (***primary***, ***backup***) on different bare metal
- ***Logging channel*** runs over network
- Fiber channel-attached ***shared disk***

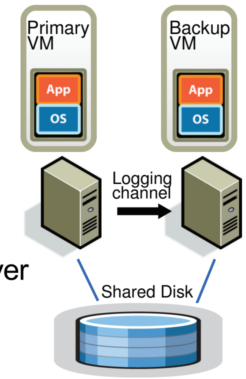


Virtual Machine I/O

- **VM inputs**
  - Incoming network packets
  - Disk reads
  - Keyboard and mouse events
  - Clock timer interrupt events
- **VM outputs**
  - Outgoing network packets
  - Disk writes

Overview

- **Primary** sends **inputs** to backup
- **Backup outputs** dropped
- Primary-backup **heartbeats**
  - If primary fails, backup takes over



VM-FT: Challenges

1. **Making the backup an exact replica of primary**
2. Making the system behave like a single server
3. Avoiding two primaries (Split Brain)

Log-based VM replication

- **Step 1:** Hypervisor at the primary **logs the causes of non-determinism:**

1. Log results of **input events**
   - Including current program counter value for each
2. Log results of **non-deterministic instructions**
   - *e.g.* log **result** of timestamp counter read (RDTSC)

Log-based VM replication

- **Step 2:** Primary hypervisor **sends log entries to backup hypervisor** over the logging channel

- Backup hypervisor **replays** the log entries
  - **Stops backup VM** at next input event or non-deterministic instruction
    - Delivers **same input** as primary

    - Delivers **same non-deterministic instruction result** as primary

VM-FT Challenges

1. Making the backup an exact replica of primary

2. **Making the system behave like a single server**
   - **FT Protocol**

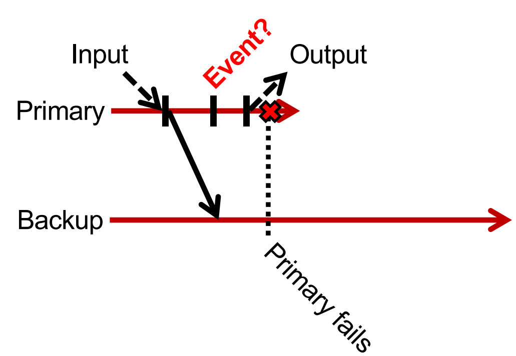
3. Avoiding two primaries (Split Brain)

Primary to backup failover

- When backup takes over, non-determinism will make it **execute differently** than primary would have done
  - **This is okay!**

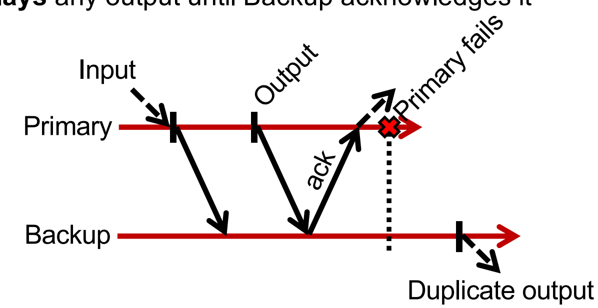
- **Output requirement:** When backup VM takes over, its execution is **consistent** with **outputs** the primary VM has already sent

The problem of inconsistency



FT protocol

- Primary **logs each output** operation
  - **Delays** any output until Backup acknowledges it



Can restart execution at an output event

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VM-FT: Challenges

1. Making the backup an exact replica of primary
2. Making the system behave like a single server
3. **Avoiding two primaries (Split Brain)**
   - Logging channel may **break**

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Detecting and responding to failures

- Primary and backup each run UDP heartbeats, monitor logging traffic from their peer
- Before "going live" (backup) or finding new backup (primary), execute an **atomic test-and-set** on a variable in shared storage
- If the replica finds variable already set, it **aborts**

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VM-FT: Conclusion

- Challenging application of primary-backup replication
- Design for correctness and consistency of replicated VM outputs despite failures
- Performance results show generally **high performance, low logging bandwidth overhead**

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11:59 PM tonight:
Assignment 1 Deadline

Friday Precept:
Go concurrency & RPC
Cristian's algorithm

Monday topic:
Two-Phase Commit

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