View Change Protocols and Reconfiguration

COS 418: *Distributed Systems*
Lecture 11

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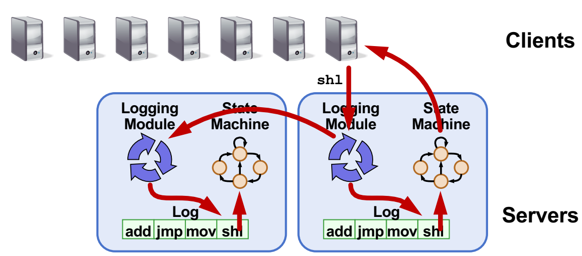
Today

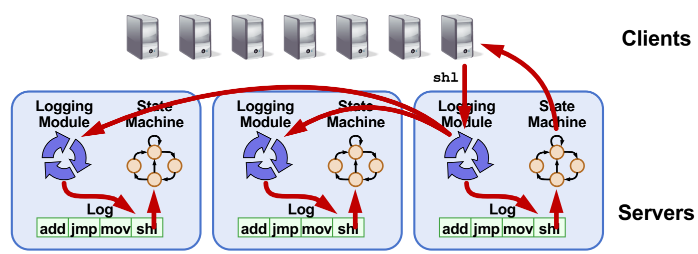
1. **More primary-backup replication**
2. View changes
3. Reconfiguration

Review: primary-backup replication

- Nominate one replica ***primary***
  – Clients send all requests to **primary**
  – Primary **orders** clients' requests



From two to many



- **Last time:** Primary-Backup case study
- **Today:** State Machine Replication with **many** replicas
  – **Survive more failures**

Introduction to *Viewstamped Replication*

- **State Machine Replication** for any number of replicas
- ***Replica group:*** Group of **2*f* + 1** replicas
  – Protocol can tolerate ***f*** **replica** crashes

Viewstamped Replication Assumptions:

1. Handles ***crash failures*** only
   – Replicas fail only by **completely stopping**
2. **Unreliable network:** Messages might be lost, duplicated, delayed, or delivered out-of-order

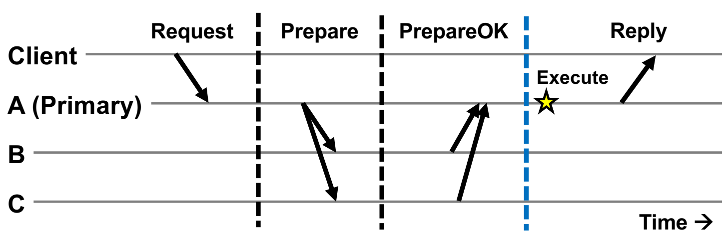
Replica state

1. ***configuration:*** identities of all 2*f* + 1 replicas
2. In-memory ***log*** with clients' requests in assigned order

⟨op1, args1⟩	⟨op2, args2⟩	⟨op3, args3⟩	⟨op4, args4⟩	...

Normal operation

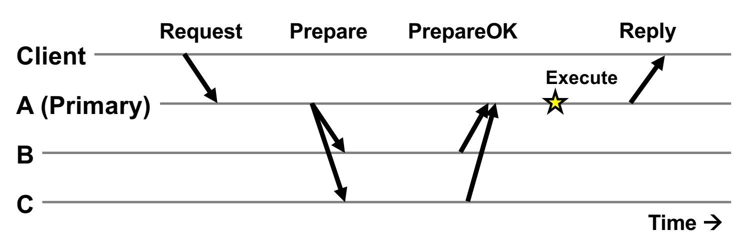
(*f* = 1)



1. Primary adds request to end of its log
2. Replicas add requests to their logs in primary's log order
3. Primary **waits for *f*** PrepareOKs → request is ***committed***

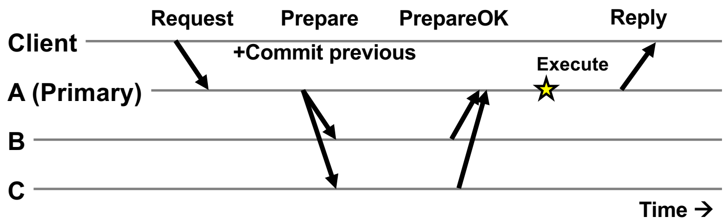
Normal operation: Key points

(*f* = 1)



- Protocol guarantees **state machine replication**
- On **execute,** primary knows request in *f* + 1 = 2 nodes' logs
  – Even if *f* = 1 then **crash,** **≥ 1 retains request in log**

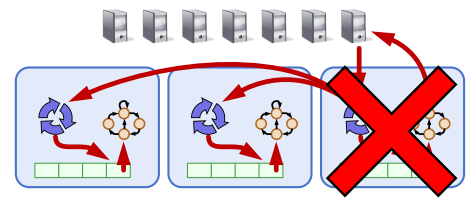
Where's the commit message? (*f* = 1)



- Previous Request's commit **piggybacked** on current **Prepare**
- No client Request after a timeout period?
  - Primary sends **Commit** message to all backups

The need for a view change

- So far: **Works** for *f* failed **backup** replicas
- But what if the *f* failures include a **failed primary?**
  - All clients' requests go to the **failed primary**
  - **System halts** despite **merely *f* failures**



Today

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2. **View changes**
   - **With Viewstamped Replication**
   - Using a View Server
   - Failure detection
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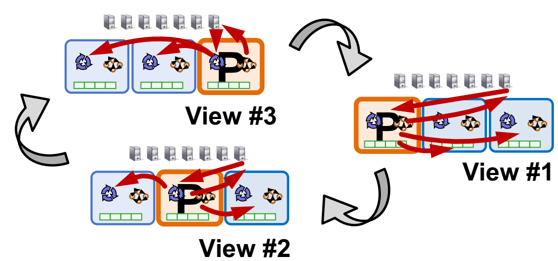
Views

- Let **different replicas** assume role of primary **over time**
- System moves through a sequence of **views**
  - ***View*** = (view number, primary id, backup id, ...)



View change protocol

- Backup replicas **monitor** primary
- If primary seems **faulty** (no Prepare/Commit):
  - Backups execute the ***view change protocol*** to select new primary
    - View changes execute **automatically**, **rapidly**
- Need to keep clients and replicas in sync: same **local** state of **the current view**
  - Same local state at **clients**
  - Same local state at **replicas**

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Making the view change correct

- View changes happen **locally** at each replica
- **Old primary** executes requests in the old view, **new primary** executes requests in the new view
- Want to **ensure state machine replication**
- **So correctness condition: Executed requests**
  1. **Survive** in the new view
  2. Retain the **same order** in the new view

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Replica state (for view change)

1. ***configuration:*** **sorted** identities of all $2f + 1$ replicas
2. In-memory ***log*** with clients' requests in assigned order
3. ***view-number:*** identifies primary in configuration list
4. ***status:*** **normal** or in a **view-change**

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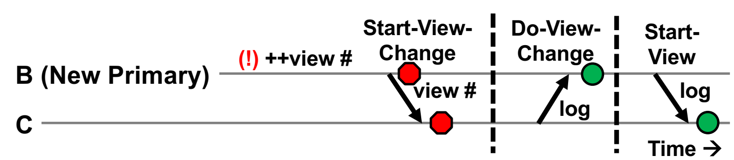
View change protocol

(f = 1)



1. B notices A has failed, sends **Start-View-Change**
2. C replies **Do-View-Change** to new primary, with its log
3. B waits for f replies, then sends **Start-View**
4. On receipt of Start-View, C replays log, accepts new ops

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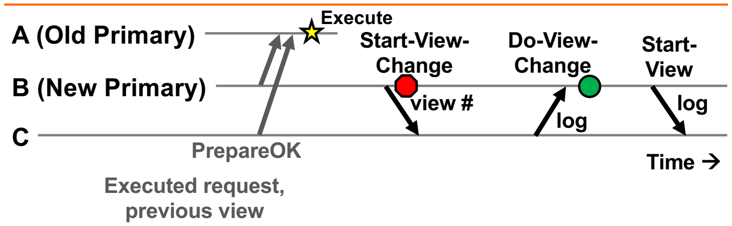
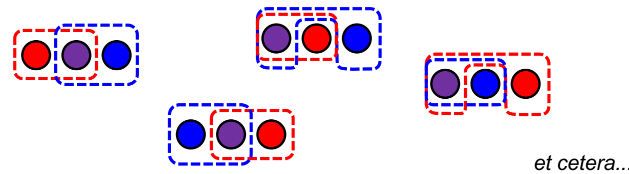
View change protocol: Correctness (*f* = 1)



- Old primary **A** must have received one or two **PrepareOK** replies for that request (*why?*)
- Request is in B's or C's **log (or both):** so it **will survive** into new view

Principle: Quorums (*f* = 1)



- Any **group of *f* + 1 replicas** is called a ***quorum***
- **Quorum intersection property:** Two quorums in 2*f* + 1 replicas must **intersect** at **at least one replica**

Applying the quorum principle

Normal Operation:

- Quorum that processes one request: **Q1**
  - ...and 2nd request: **Q2**
- **Q1** ∩ **Q2** has at least **one replica** →
  - Second request **reads first request's effects**

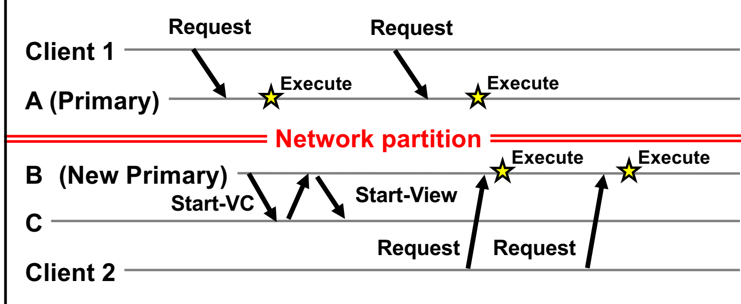
Applying the quorum principle

View Change:

- Quorum processes previous (committed) request: **Q1**
  - ...and that processes **Start-View-Change: Q2**
- **Q1** ∩ **Q2** has at least **one replica** →
  - View Change **contains committed request**

Split Brain

(not all protocol messages shown)



- What's **undesirable** about this sequence of events?
- Why won't this ever happen? What **happens instead?**

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   - **Using a View Server**
   - Failure detection
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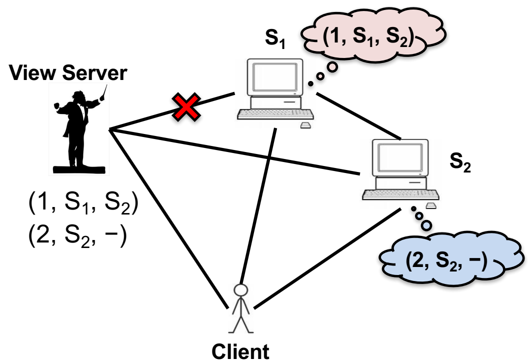
Would centralization simplify design?

- A single ***View Server*** could **decide who** is primary
  - Clients and servers depend on view server
    - Don't decide on their own (might not agree)
- Goal in designing the VS:
  - Only **want one primary** at a time for correct **state machine replication**

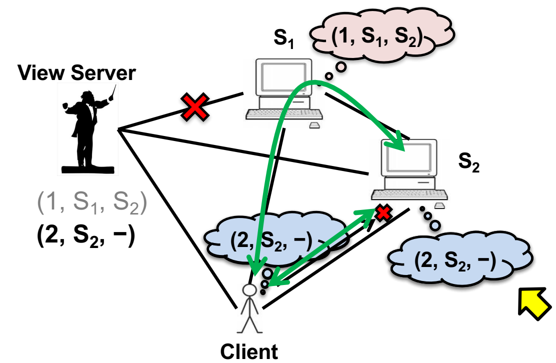
View Server protocol operation

- For now, **assume** VS **never fails**
- Each replica now periodically ***pings*** the VS
  - VS declares replica ***dead*** if missed *N* pings in a row
  - Considers replica ***alive*** after a single ping received
- **Problem:** Replica can **be alive but because of network connectivity, be declared "dead"**

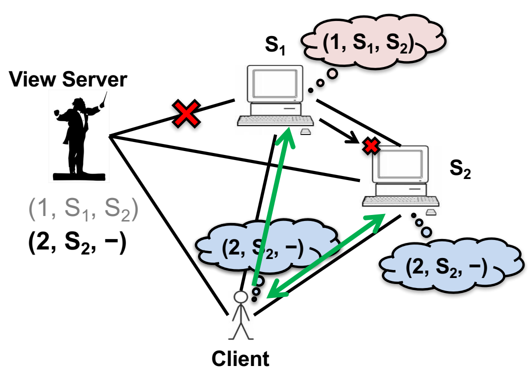
View Server: Split Brain



One possibility: S_2 in old view



Also possible: S_2 in new view



Split Brain and view changes

Take-away points:

- Split Brain problem **can be avoided** both:
  - In a **decentralized** design (VR)
  - With **centralized** control (VS)
- But protocol must be **designed carefully** so that replica state does not **diverge**

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   - With Viewstamped Replication
   - Using a View Server
   - **Failure detection**

3. Reconfiguration

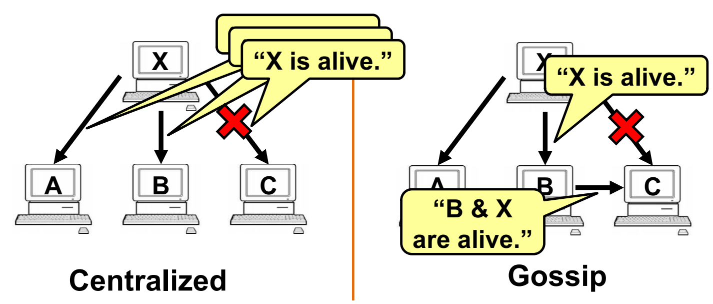
Failure detection

- Both **crashes** and **network failures** are frequent: the **"common case"**
- Q: How does one replica estimate **whether another has crashed,** or is still alive?
- A: ***Failure detection*** algorithm
  - **So far, we've seen** Viewstamped Replication *e.g.*:
    - Replicas listen for **Prepare** or **Commit** messages from the Primary
    - Declare primary **failed** when hear none for **some period of time**

Failure detection: Goals

- **Completeness:** Each failure is detected
- **Accuracy:** There is no mistaken detection
- **Speed:** Time to first detection of a failure
- **Scale (if significant in system context):**
  - Equal **processing load** on each node
  - Equal **network message load**

Centralized versus Gossip



- **C thinks X** is dead
- **Overcomes** failure

Today

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The need for reconfiguration

- What if we want to **replace a faulty replica** with a different machine?
  - For example, one of the **backups may fail**
- What if we want to **change the replica group size?**
  - **Decommission** a replica
  - **Add** another replica (increase ***f***, possibly)
- Protocol that handles these possibilities is called the ***reconfiguration protocol***

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Replica state (for reconfiguration)

1. ***configuration:* sorted** identities of all $2f + 1$ replicas
2. In-memory ***log*** with clients' requests in assigned order
3. ***view-number:*** identifies primary in configuration list
4. ***status:* normal** or in a **view-change**
5. ***epoch-number:*** indexes configurations

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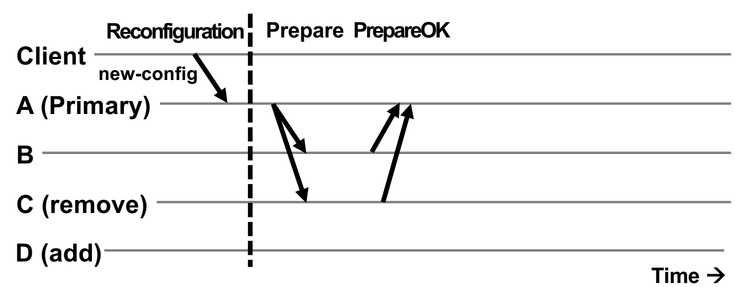
Reconfiguration (1)

(*f* = 1)



- Primary immediately **stops accepting new requests**

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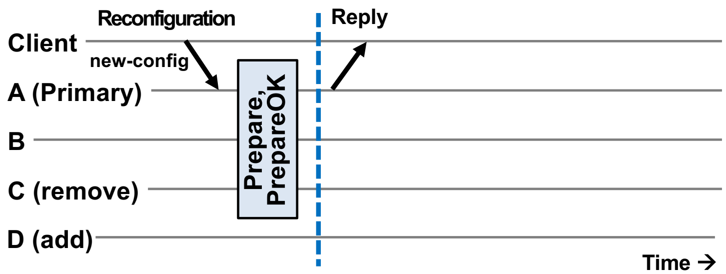
Reconfiguration (2)

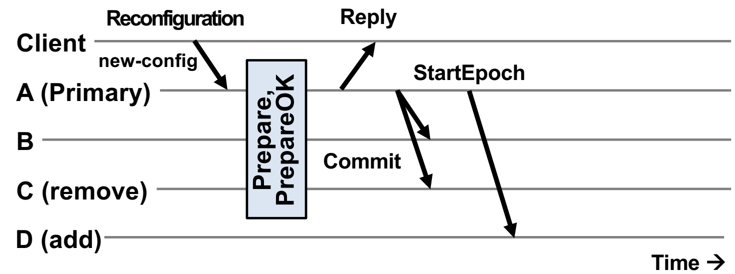
(*f* = 1)



- Primary immediately **stops accepting new requests**
- **No up-call** executing this request

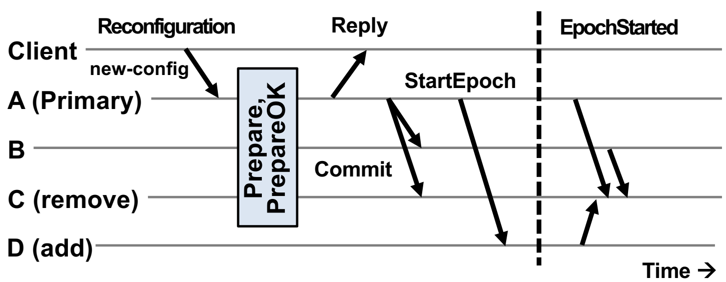
Reconfiguration (3)

(*f* = 1)



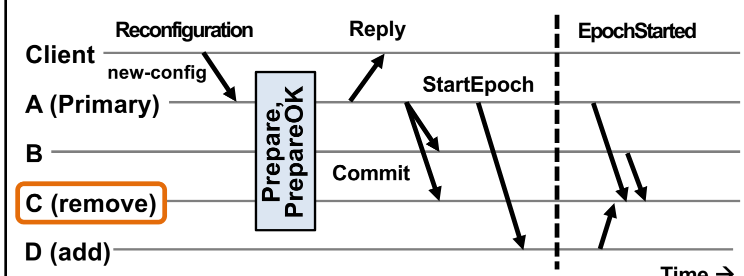
- Primary sends Commit messages to **old** replicas
- Primary sends ***StartEpoch*** message to **new** replica(s)

Reconfiguration in new group {A, B, D}



1. Update state with new **epoch-number**
2. Fetch state from old replicas, update log
3. Send ***EpochStarted*** msgs to replicas being removed

Reconfiguration at replaced replicas {C}



1. Respond to state transfer requests from others
2. Send **StartEpoch** messages to **new** replicas if they **don't hear EpochStarted** (not shown above)

Shutting down old replicas

- If admin **doesn't wait** for reconfiguration to complete, may cause **> f failures in old group**
- **Can't shut down replicas** on receiving Reply at client
- **Fix:** A new type of request ***CheckEpoch*** to report the current epoch, goes thru **normal request processing**

Conclusion: What's useful when

- **Primary fails** or has network connectivity problems?
- Majority partitioned from primary?

→ Rapidly execute view change

- Replica **permanently fails** or is **removed?**
- Replica **added?**

→ Administrator initiates reconfiguration protocol

Monday topic:
Consensus and Paxos