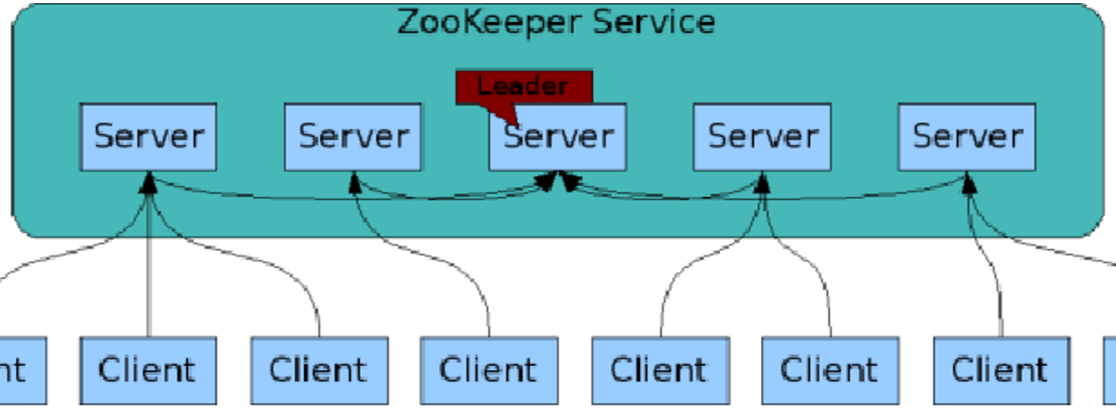
# Log-Centric Distributed Systems

Motivations and an overview of the Raft protocol

# Some Highly Recommended References

- “The Log: What every software engineer should know about real-time data's unifying abstraction”
  - Jay Kreps
  - https://engineering.linkedin.com/distributed-systems/log-what-every-software-engineer-should-know-about-real-time-datas-unifying
- “In search of an understandable consensus algorithm”
  - Diego Ongaro, John K Ousterhout
  - https://www.usenix.org/system/files/conference/atc14/atc14-paper-ongaro.pdf
- “The RAFT Consensus Algorithm”
  - http://www.andrew.cmu.edu/course/14-736/applications/ln/riconwest2013.pdf
  - Diego Ongaro and John Ousterhout

# The ZooKeeper Service




Zookeeper is itself an interesting distributed system

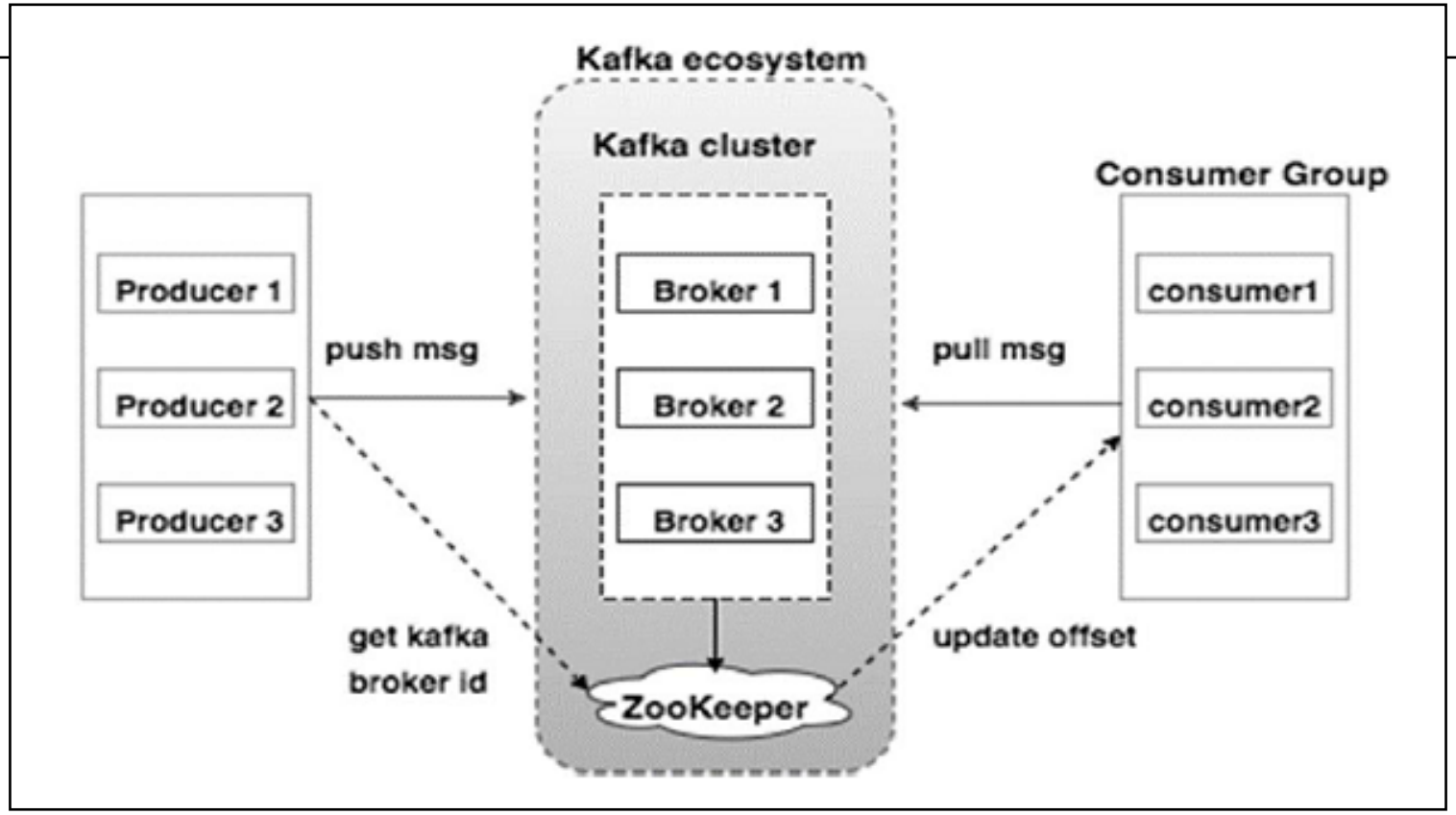
These are your microservices

- ZooKeeper Service is replicated over a set of machines
- All machines store a copy of the data in memory (!)
- A leader is elected on service startup
- Clients only connect to a single ZooKeeper server & maintains a TCP connection.
- Client can read from any Zookeeper server.
- Writes go through the leader & need majority consensus.

https://cwiki.apache.org/confluence/display/ZOOKEEPER/ProjectDescription

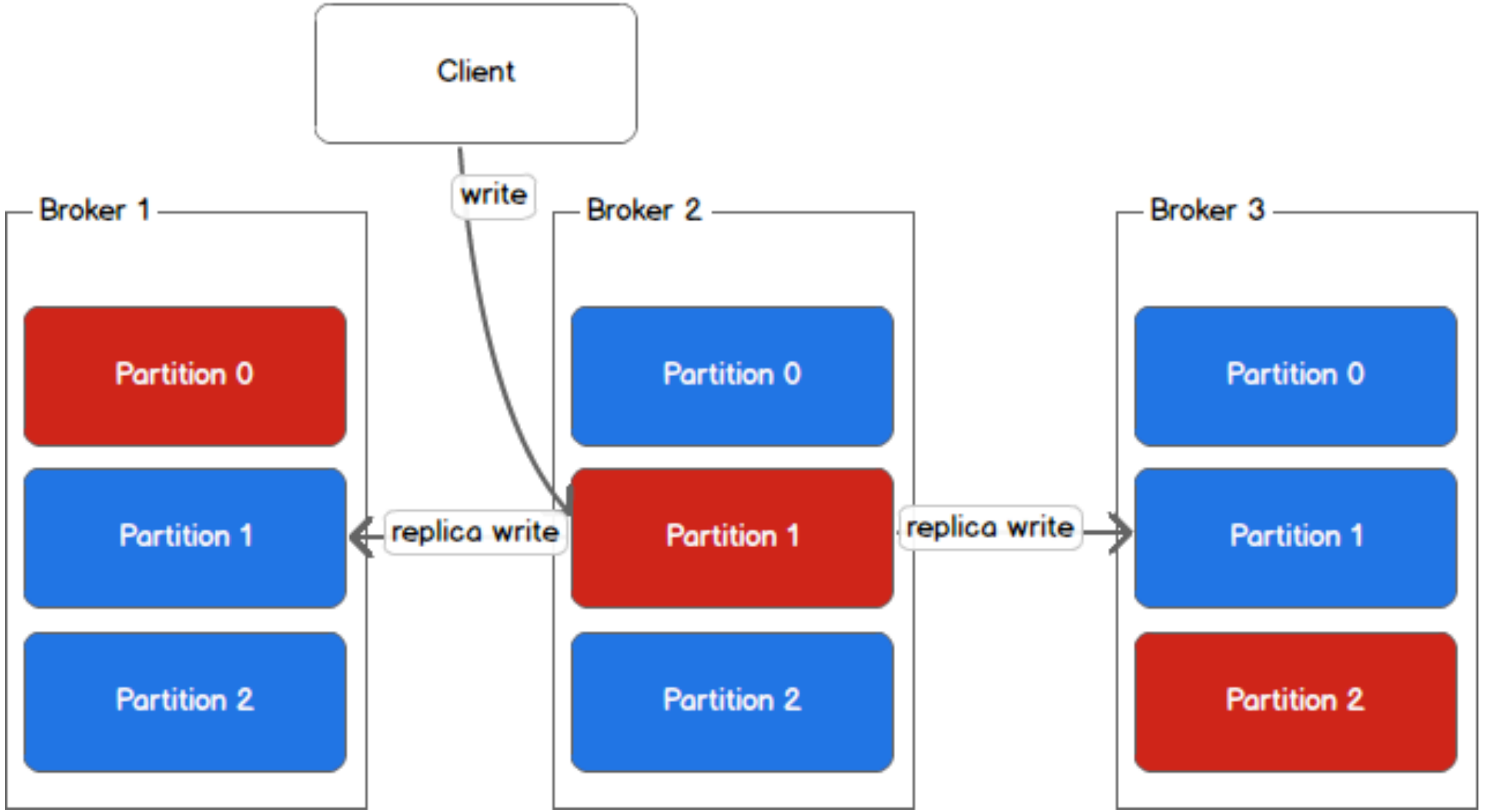
# Kafka Uses Clusters of Brokers

- Kafka is run as a cluster of brokers on one or more servers.




Kafka uses Zookeeper to manage state of clients and leadership of brokers.

# Leader (red) and replicas (blue)




A producer writes to Partition 1 of a topic. Broker 2 is the leader. It writes replicas to Brokers 1 and 3

# Logs and Service Mesh Control Planes

Consul and ETCD resemble Zookeeper

You can use them to implement a control plane for your service mesh

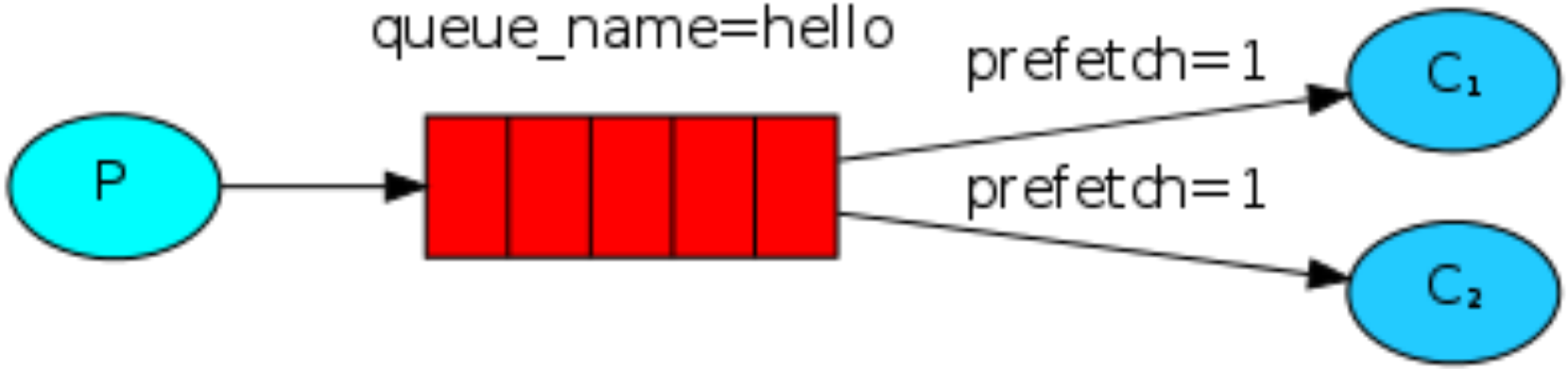
Ex: see https://www.consul.io/intro/vs/proxies.html for Consul + Envoy

They use a protocol called RAFT

Simpler than Zookeeper's Zab protocol

# But First, a Queue-Centric Design

- RabbitMQ's Work Queue Tutorial Example
- A publisher puts work in a queue
- The broker distributes it to consumers in round-robin fashion
- The consumers send ACKs after they have processed the message
- Consumers can limit the number of messages they receive.



# Some Features and Considerations for Queue-Centric Systems

- If a consumer crashes before sending an ACK, the broker will resend the message to another consumer, if one is available
- But detecting a failed consumer is a fundamentally hard problem
  - See next slide
  - These are corner cases until you have a major network disruption, then these cascade all at once
  - A resent $1B transaction is a catastrophe
- It is possible that the broker can acquire a backlog of un-ACK'd messages, hindering performance
- What if the broker crashes?
  - RabbitMQ provides some persistency mechanisms, but are these first class design considerations?

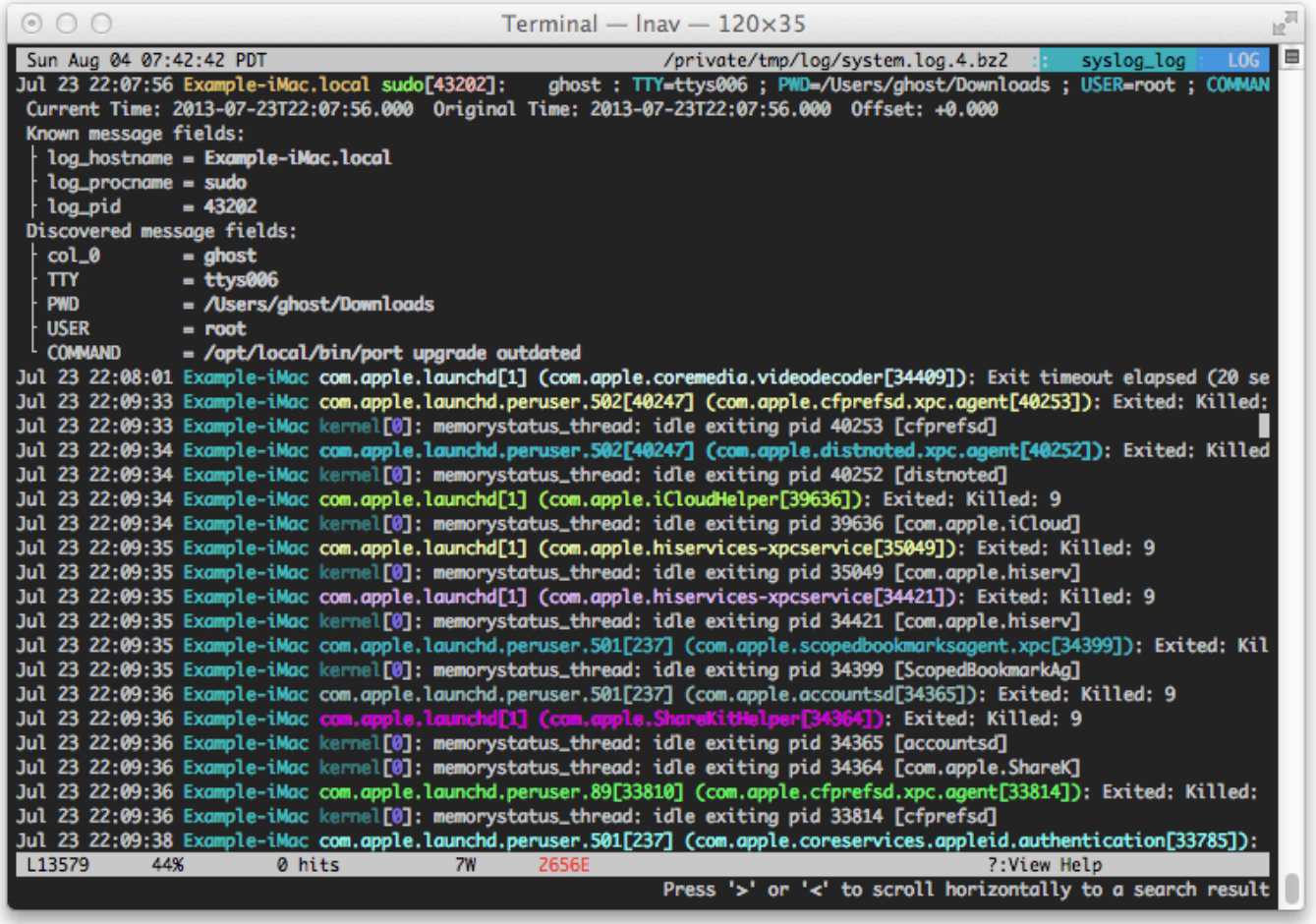
| Issue | Solution |
| --- | --- |
| Consumer crashes | Broker detects the crash using a **heartbeat.** This works well for small systems (Zookeeper) but doesn't scale. See **Gossip Protocol** |
| Consumer is very slow | Heartbeat detects that the consumer is alive but taking a very long time to send an ACK. Solution: use a **time out**. The broker needs to tell the consumer to stop processing the message, complicating the implementation. Time outs need to be selected correctly. |
| Consumer is temporarily inaccessible | Consumer A doesn’t crash but the heartbeat fails. The broker resends the message to Consumer B. Then network returns and Consumer A sends the ACK. The message got processed twice. |
| Broker is temporarily inaccessible | The broker’s host server is temporarily off the network. The broker thinks all un-ACK’d messages are lost and so re-queues them. It will want to redeliver them when it detects consumers are available again, but then a cascade of ACKs will arrive. How do you handle this? |

Some issues with detecting failed message delivery

# Towards a Log-Centric Architecture: Application Logs, Queues, and State Logs

# Application Logs

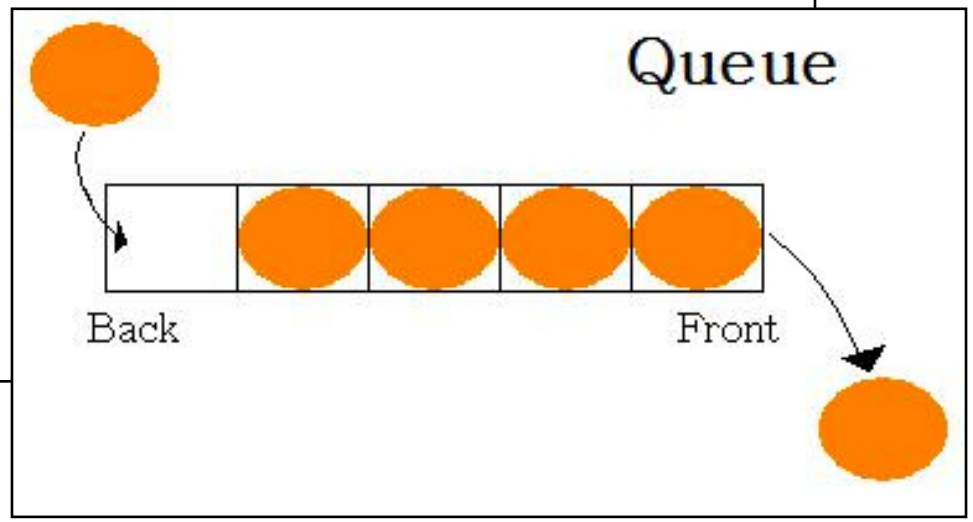
- The info, warning, error, and other debugging messages you put into your code.
  - Very useful for detecting errors, debugging, etc.
  - Consolidation is critical in distributed systems: ELK stack → Service Mesh
- **Human readable, unstructured format**



# Message Queues

- Message Queue: a data structure containing a **consumable** list of entries.
  - Publishers create entries
  - Brokers receive and deliver entries
  - Consumers consume entries
  - Entries are machine readable.
  - Entries are removed when they are consumed.

We discussed these limits in the Kafka lectures: queues are not good for replays --> state management

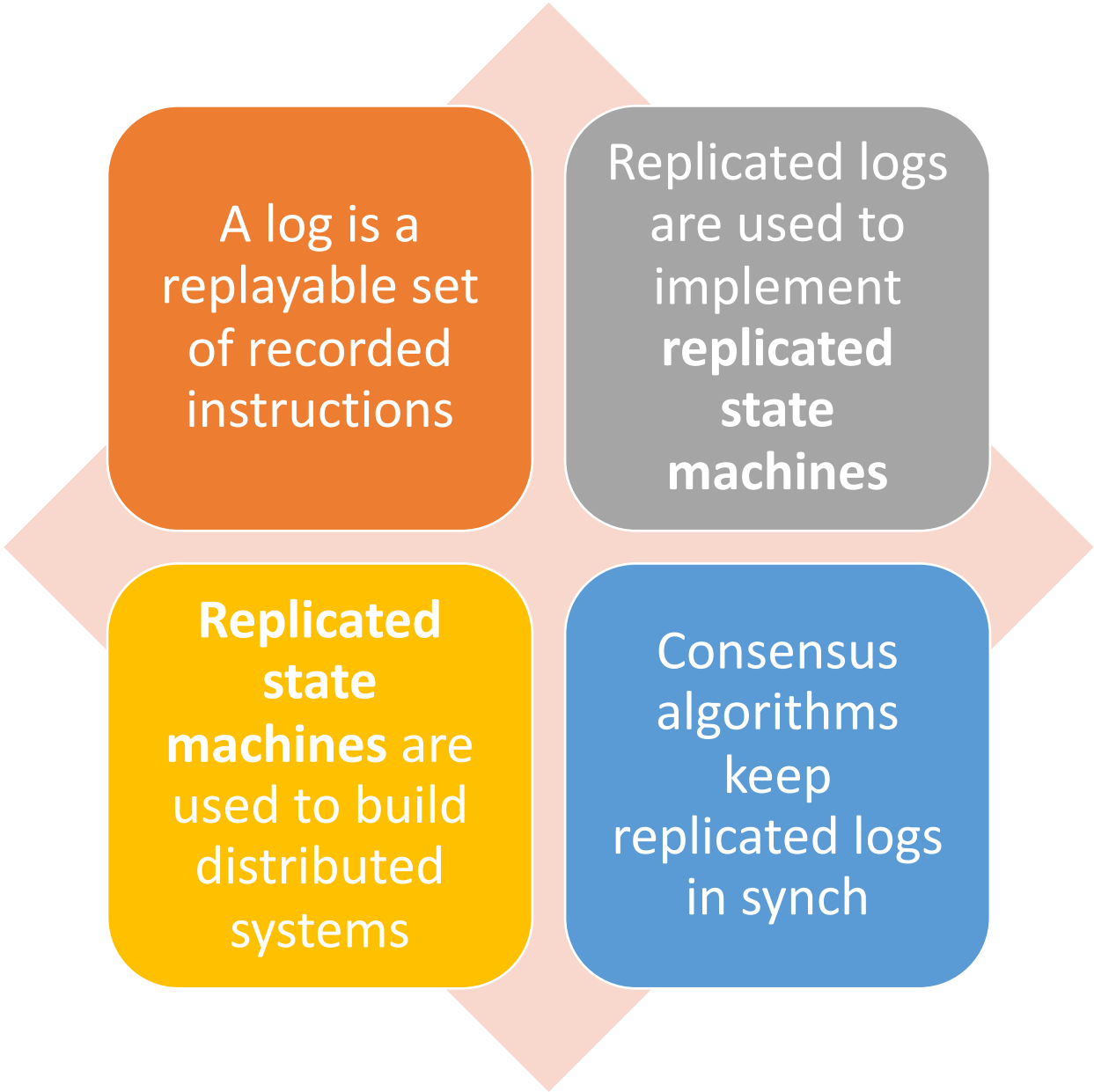


# The Other Type of Log: System State Records

- Logs: records of state changes in a system
  - **Machine readable**
  - Distributed logs -> distributed state machines
- Logs can be for internal consumption
  - Enables a system to recover state on restart or failover
  - Ex: Zookeeper and Kafka internals
- Logs can be for external consumption
  - Different types of processes share a state machine: same logs are processed differently
  - Ex: Clients to Zookeeper, Kafka

Kirk records a message in case Spock needs to take over.

# Logs and State Machines



# Example: MySQL Dump

- You can use MySQL's dump command to create a restorable version of your DB.
  - These are logs
- What if you needed to restore lots of replicated databases from the same dump?

```
CREATE TABLE IF NOT EXISTS `mg_oro_analytics_data` (
  `id` int(10) unsigned NOT NULL AUTO_INCREMENT COMMENT 'Id',
  `period` datetime NOT NULL DEFAULT '0000-00-00 00:00:00' COMMENT 'Period',
  `store_id` int(11) DEFAULT NULL COMMENT 'Store_id',
  `customer_id` int(11) DEFAULT NULL COMMENT 'Customer_id',
  PRIMARY KEY (`id`,`period`),
  KEY `IDX_MG_ORO_ANALYTICS_DATA_ID` (`id`),
  KEY `IDX_MG_ORO_ANALYTICS_DATA_CUSTOMER_ID_PERIOD` (`customer_id`,`period`)
) ENGINE=MyISAM  DEFAULT CHARSET=utf8 COMMENT='mg_oro_analytics_data'
/*!50100 PARTITION BY RANGE (TO_DAYS(period))
(PARTITION p_2014_01_04 VALUES LESS THAN (735602) ENGINE = MyISAM,
 PARTITION p_2014_02_04 VALUES LESS THAN (735633) ENGINE = MyISAM,
 PARTITION p_2014_03_04 VALUES LESS THAN (735661) ENGINE = MyISAM,
 PARTITION p_2014_04_04 VALUES LESS THAN (735692) ENGINE = MyISAM,
 PARTITION p_2014_05_04 VALUES LESS THAN (735722) ENGINE = MyISAM,
 PARTITION p_2014_06_04 VALUES LESS THAN (735753) ENGINE = MyISAM) */ AUTO_INCREMENT=358 ;
```

# Logs and Queues

- These are similar data structures
  - Basics: First in, first out
- Important difference is that logs are persistent while queue entries are transient
  - Persistence can have limits: Kafka quality of service
- Message queue: the broker often needs to know if the message was delivered and processed correctly
  - Is it safe to delete an entry?
  - ACK or NACK
  - Stateful
- Log system: client is responsible for knowing the last entry it consumed
  - The broker just keeps track of the log records
  - Stateless, or REST-like, interactions with clients (idempotent)

| Property | Description |
| --- | --- |
| Ordered | Logs record state changes, so they must be in sequence (indexed) |
| Correct | We are confident that a log entry was recorded correctly |
| Complete | There are no missing records between the first and last entry |
| Machine Readable | Log entries are serialized data structures, operations |
| Persistently Stored | The logs are stored on highly stable media |
| Available | Applications that depend upon the logs can get them |

Some Desirable Properties of State Logs

# High Availability Requires Log Replication

There must be a failover source of logs if the primary source is lost.

Weak consistency may be OK: a replica may be behind the primary copy, but otherwise, they match exactly

**Consensus algorithms** address this problem

**Paxos** is the most famous consensus algorithm

Lamport, L., 1998. The part-time parliament. *ACM Transactions on Computer Systems (TOCS)*, *16*(2), pp.133-169.

But it is hard to understand and implement

Zookeeper and Chubby, for instance, don’t use it

# Raft Consensus Protocol

- Raft has been developed to provide a more comprehensible consensus protocol for log-oriented systems
- Several implementations
  - https://raft.github.io/
  - See also http://thesecretlivesofdata.com/raft/
- It resembles but is simpler than Zookeeper's Zab protocol
- Ongaro, D. and Ousterhout, J.K., 2014, June. In search of an understandable consensus algorithm. In *USENIX Annual Technical Conference* (pp. 305-319)

I'll use some slides from https://raft.github.io/

# Remember: Raft is a protocol, not a piece of software

Software like Consul and ETCD use the protocol.

Zab, Viewstamped Replication, and Paxos are alternative protocols

# Properties of Consensus Systems

| Property | Description |
| --- | --- |
| Safety | Never return incorrect results to queries |
| Availability | The system functions as long as a majority of servers are operational |
| Ordered Messages | Message order does not depend on system clocks; slow networks are not a problem |
| Majority Commits | Logs are recorded if a majority of members accepts the write. Don’t need to wait on complete consensus. |

# Raft Protocol Guarantees: Always True (1/5)

**Election Safety:** at most one leader can be elected in a given term.

# Raft Protocol Guarantees: Always True (2/5)

**Leader Append-Only:** a leader never overwrites or deletes entries in its log; it only appends new entries.

# Raft Protocol Guarantees: Always True (3/5)

**Log Matching:** if two logs contain an entry with the same index and term, then the logs are identical in all entries up through the given index.

# Raft Protocol Guarantees: Always True (4/5)

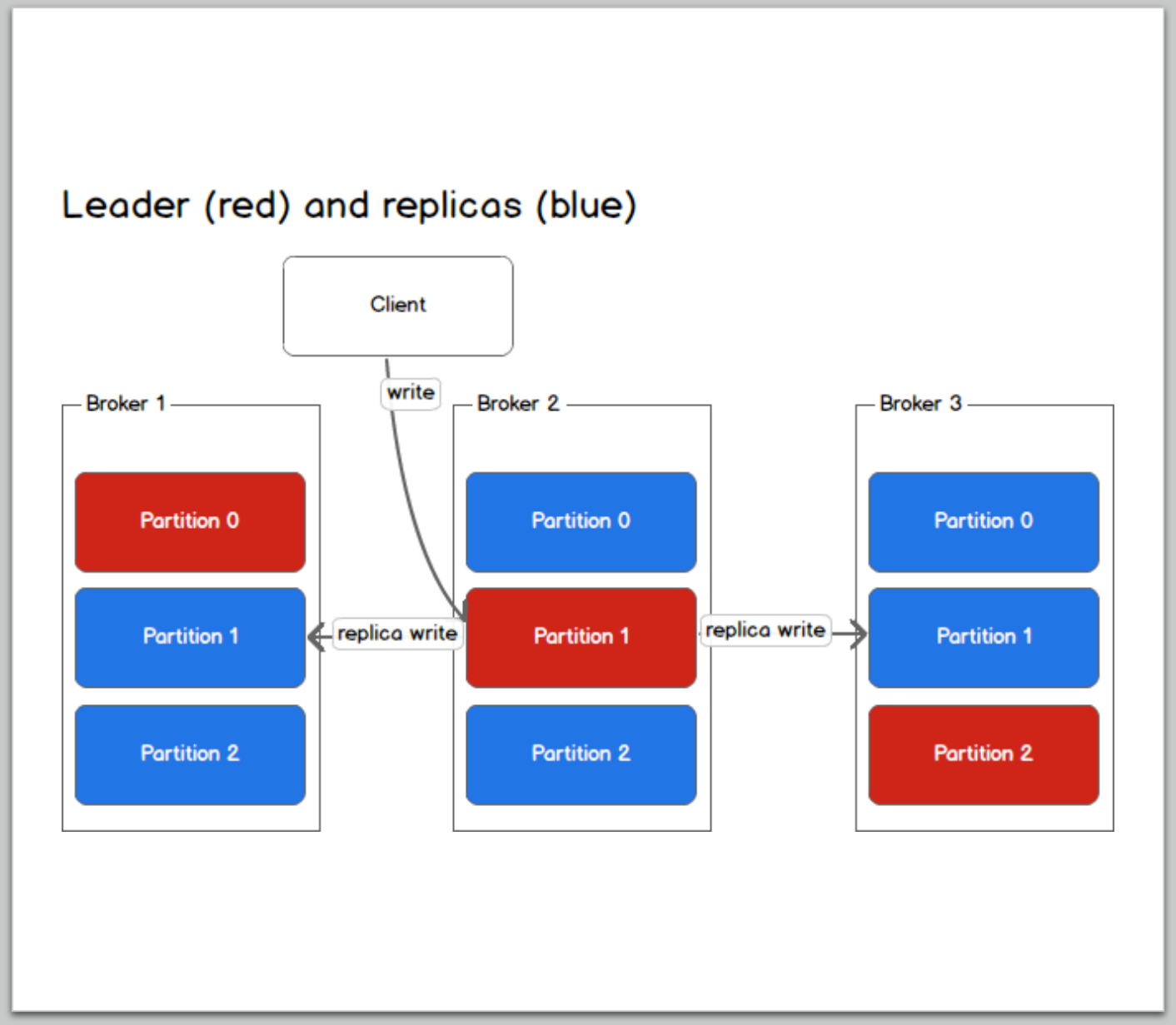
**Leader Completeness:** If a log entry is committed in a given term, then the entry will appear in the logs of leaders of future

# Raft Protocol Guarantees: Always True (5/5)

**State Machine Safety:** if a server has applied a log entry at a given index to its state machine, no other server will ever apply a different log entry for the same index.

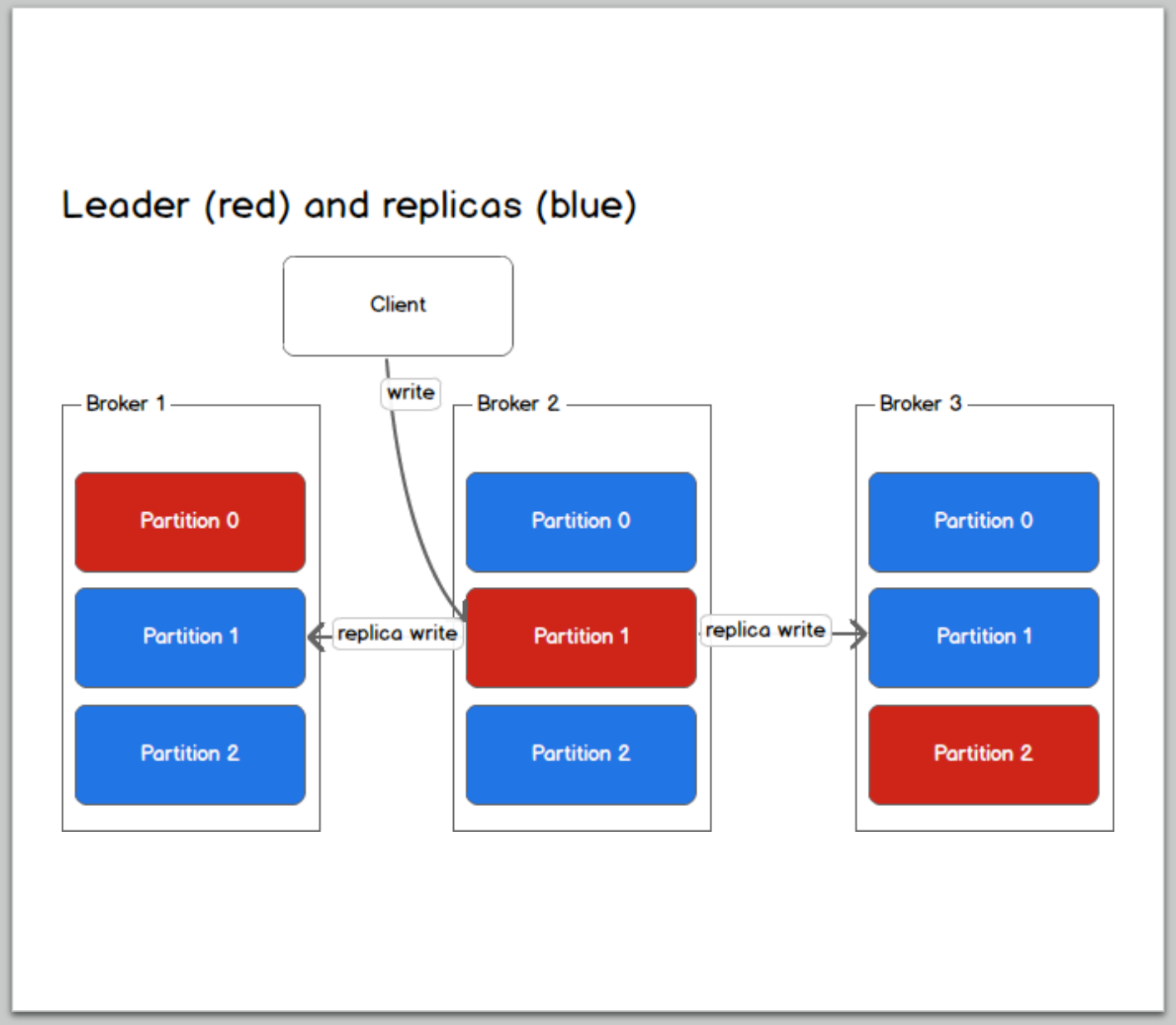
# Raft Basics: Strong Leader and Passive Followers

- In Raft, the leader supervises all write operations
- The leader service/broker accept write requests from clients
  - Follower-brokers redirect write requests from clients to the leader broker
- We saw this with Kafka and ZK



# Raft Basics: Strong Leader and Passive Followers

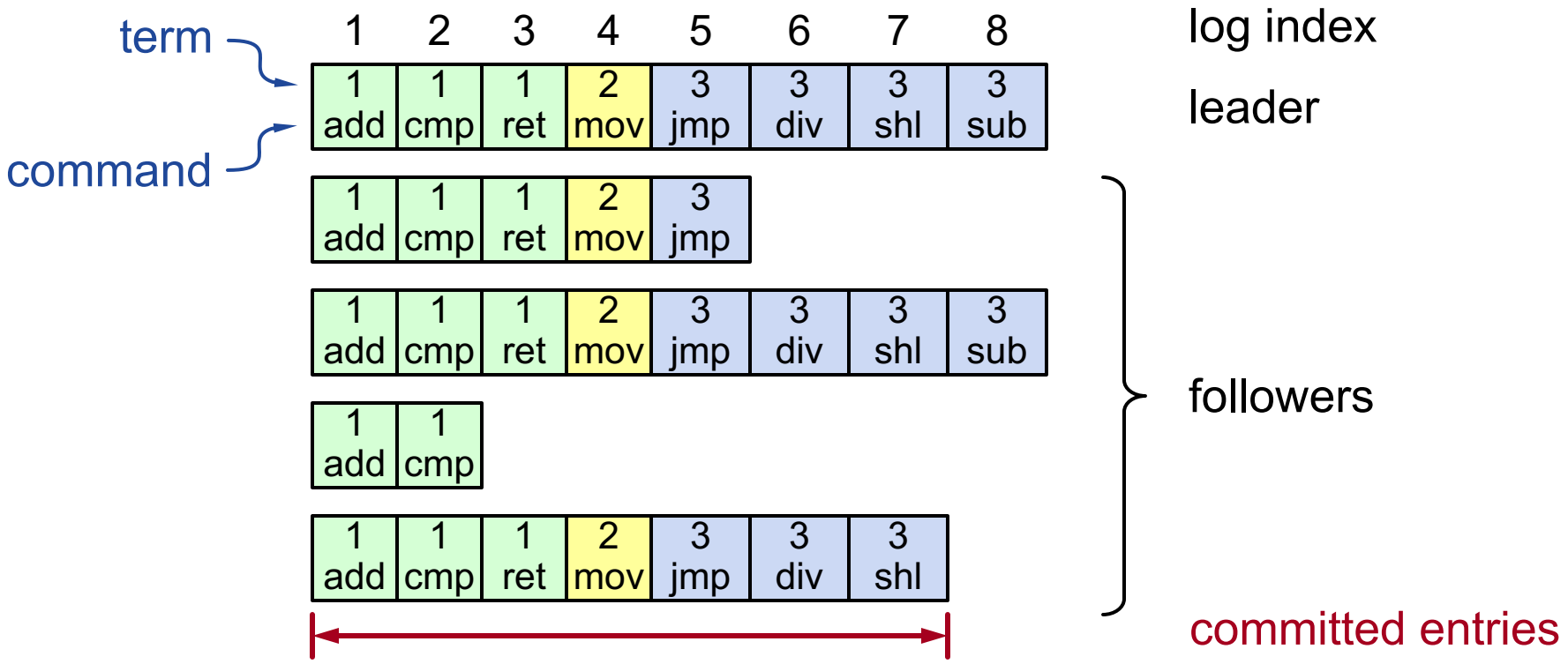
- The leader sends log updates to all followers
- If a majority of followers accept the update, the leader instructs everyone to commit the message.



# Raft Achieves Eventual Consistency

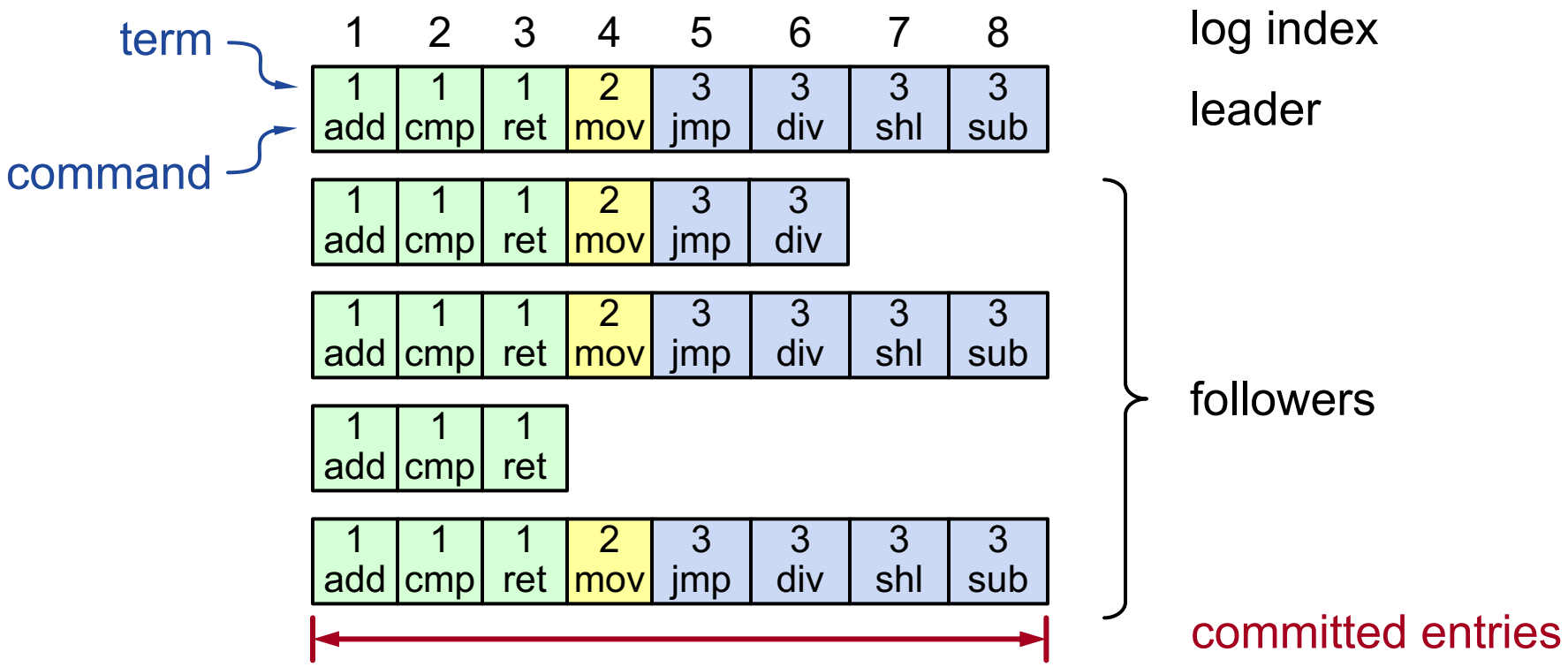
- A minority of followers can have fewer committed messages than the majority at any given time
- But lagging members will have a subset of committed messages

# Log Structure Snapshot




- **Log entry = index, term, command**
- **Log stored on stable storage (disk); survives crashes**
- **Entry committed if known to be stored on majority of servers**
  - Durable, will eventually be executed by state machines

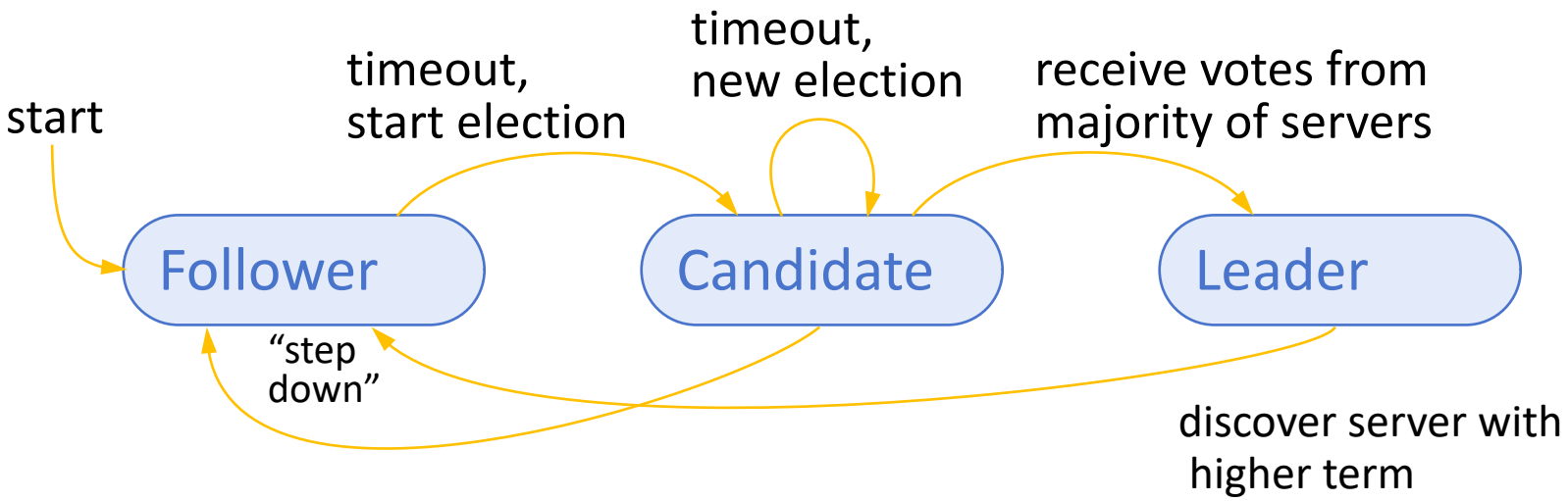
# Log Structure Snapshot+1



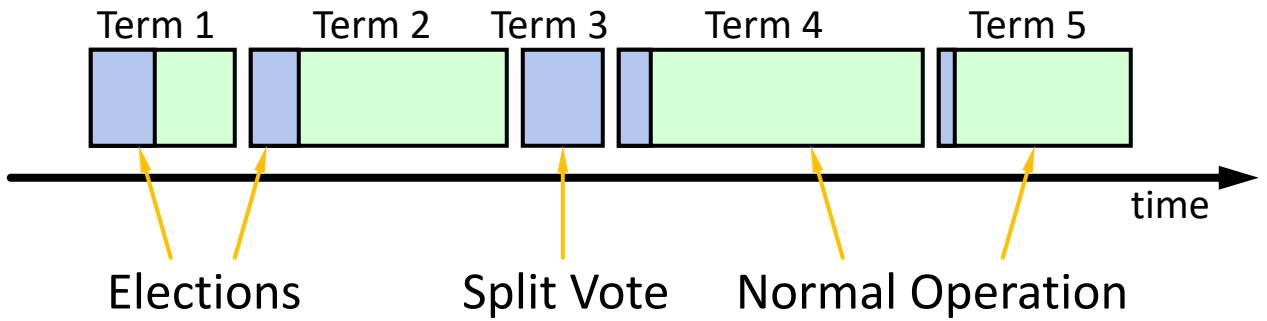
# Leaders and Leadership Changes

- There is at most one leader at any time
- A system needs a new leader if the leader fails or becomes disconnected from a majority of followers
  - Heartbeat failures
- New leaders are chosen by election from among the followers
  - Followers become candidates if they detect that a leader has failed
  - Only one candidate can win
- A **term** is the time period that a particular leader is in charge

Raft Server States:




Raft Time Evolution:



# Key Raft Properties

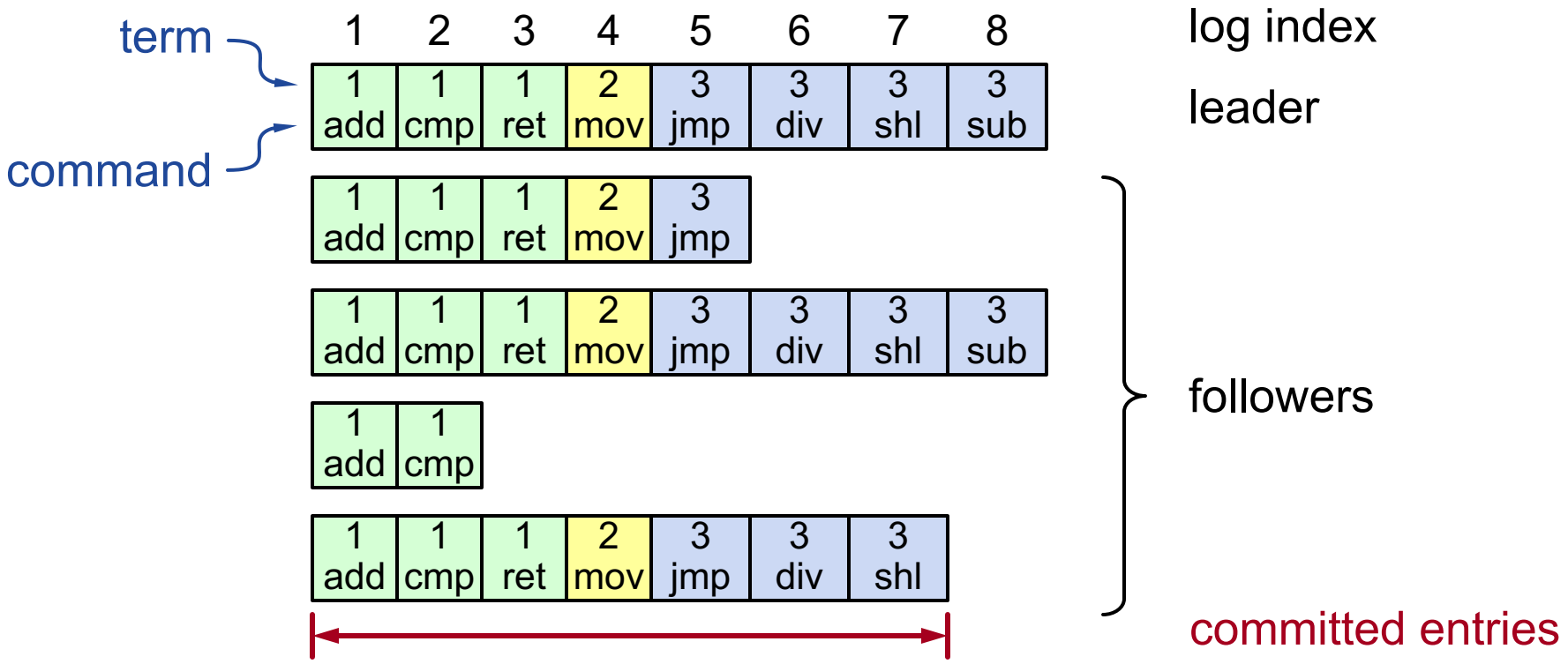
- **Election Safety:** At most, only one leader can be elected
- **Leader Append-Only:** Leaders can only append entries to their logs. They never overwrite old entries.
- **Log Matching**: if two logs have the same index and same term, then the logs are identical in all entries up to that index
- **Leader Completeness:** If a log entry is committed in a given term, then the entry will appear in the logs of leaders of future terms
- **State Machine Safety:** if a server has applied an entry, no server will ever overwrite this entry

Desirable qualities, but how do we implement it?

# Logs and Committed Logs

- Servers can have log entries that are volatile
- Log entries are only **committed** after a majority of servers have accepted the log message.
- **Committed logs are guaranteed**
- Clients only get acknowledgements about committed log entries

# Log Structure Snapshot



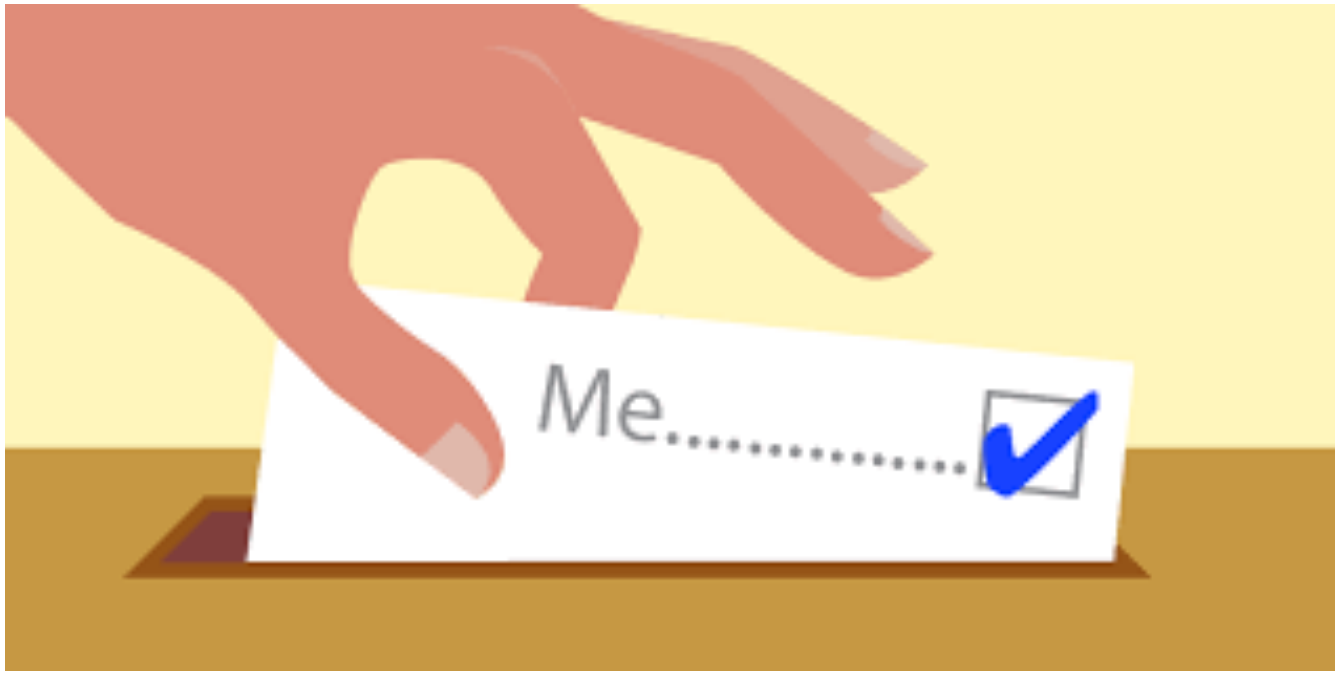

- **Log entry = index, term, command**
- **Log stored on stable storage (disk); survives crashes**
- **Entry committed if known to be stored on majority of servers**
  - Durable, will eventually be executed by state machines

# Raft Election Process (1/4)

- Leaders send heartbeat messages periodically
- If a **follower** doesn't receive a heartbeat during an "election timeout" period, it changes to a **candidate.**

# Raft Election Process (2/4)

The candidate votes for itself

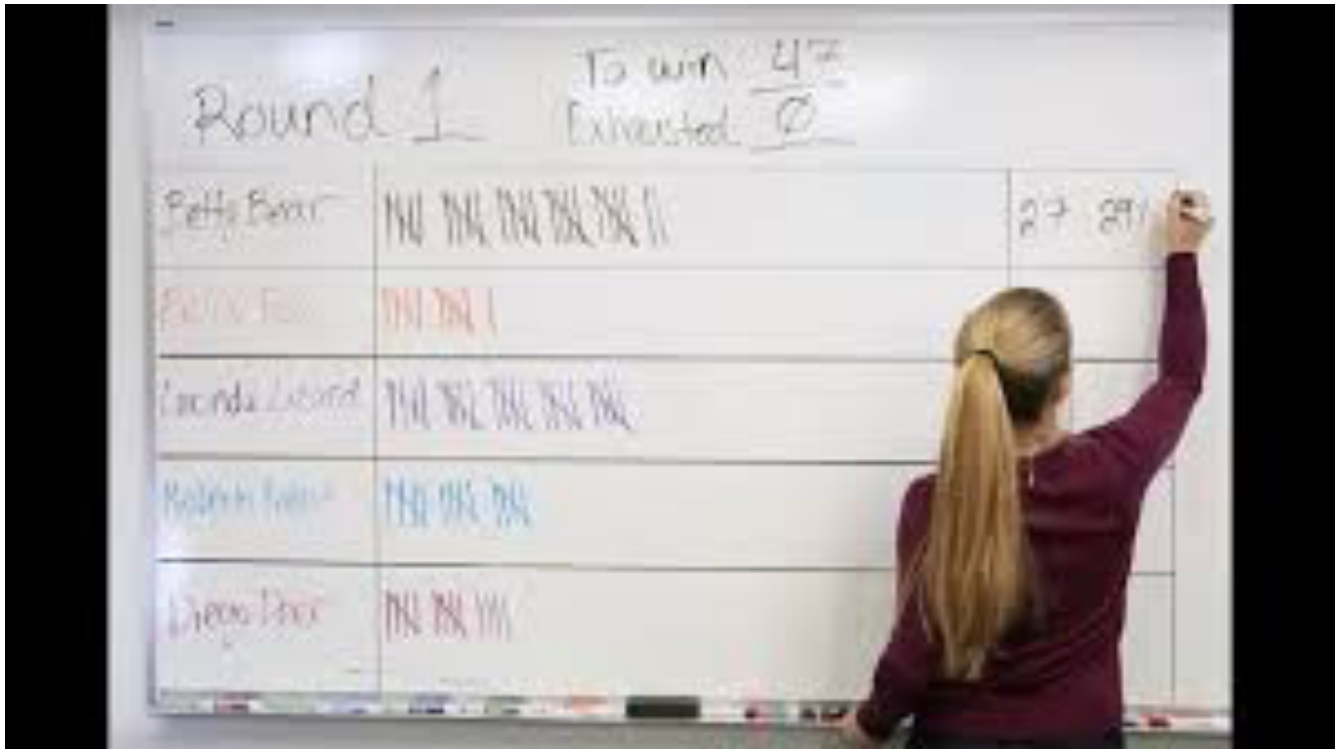


# Raft Election Process (3/4)

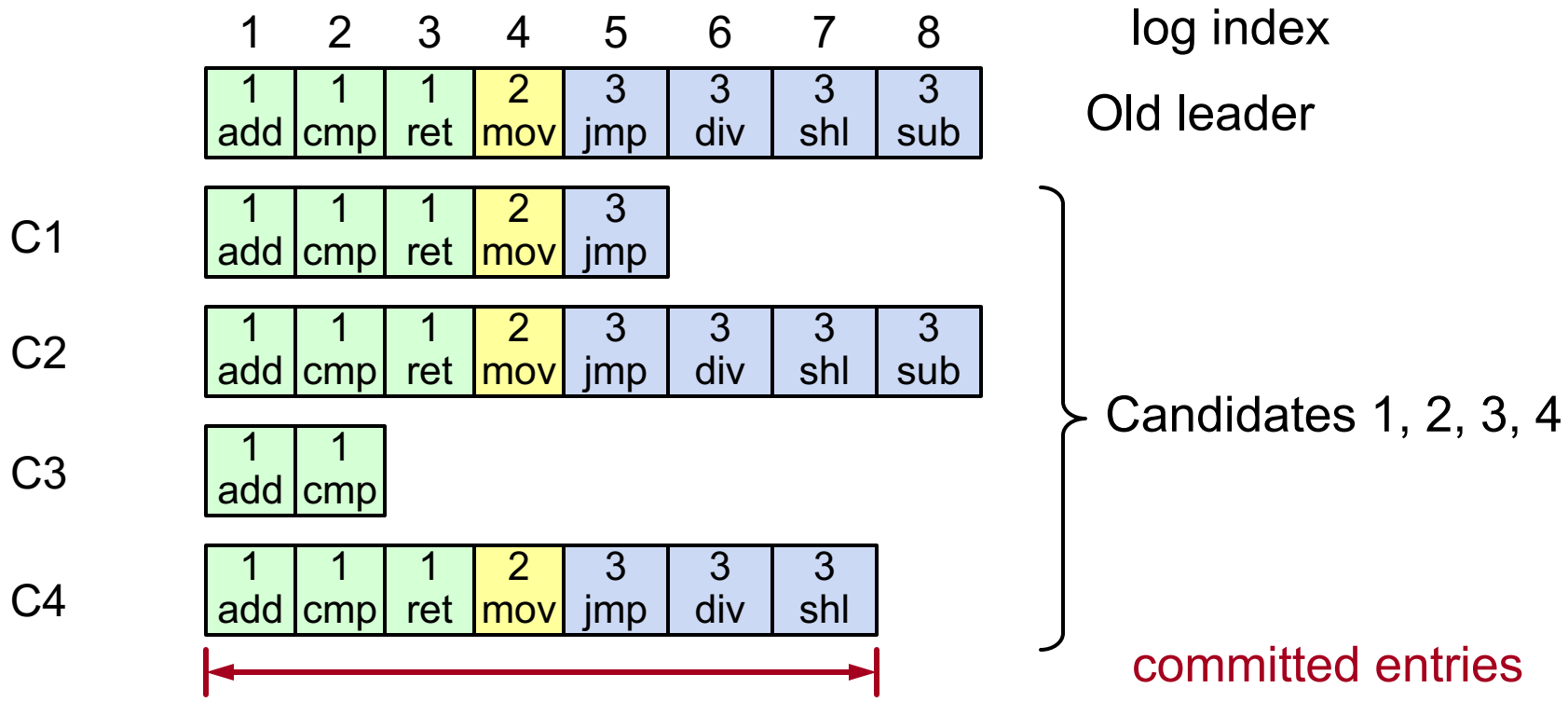

- The candidate sends RequestVote messages to all other servers
  - Candidate sends its **term** and **index** to all the other servers
  - If a server is in follower state and receives a RequestVote, it votes for the candidate if the candidate's last term and index are >= its own committed messages
  - If the server is in candidate state and has a term and index < the other candidate's, it reverts to follower state and votes for the candidate

# Raft Election Process (4/4)

- When a candidate receives votes from a majority of servers, it wins the election and becomes the new leader



# Election



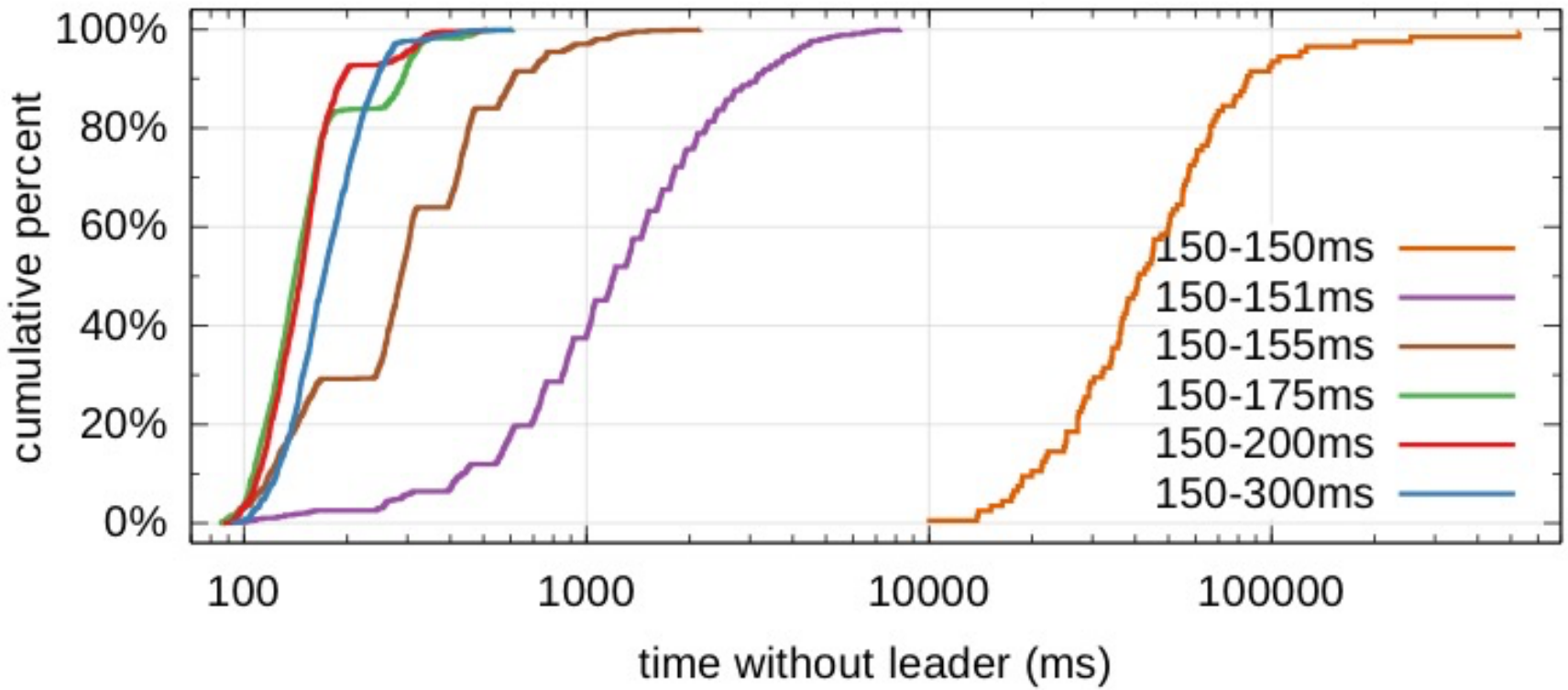

- **Candidates C2 and C4 can win the election with 3 votes**
  - Candidates C1 and C3 will vote for either
  - Candidate C4 can win if gets votes from C1 and C3 before contacting Candidate 2
- **Note a split election is possible: Candidate 1 votes for Candidate 2, and Candidate 3 votes for Candidate 4, for example**
- **Log entry 8 was not committed, but that's ok: the client hasn't received an acknowledgement**

# Split Elections

- If no candidate receives a majority of votes, the election fails and must be held again.
- Raft uses random election timeouts.
- If a leader hasn’t been elected within the election time out, a candidate increments its term and starts a new election.
- Each server has a different time out, chosen at random.
  - Typically, only one server at a time will be in candidate state
- This randomness is key for the system to find a new leader quickly

# Randomized Timeouts

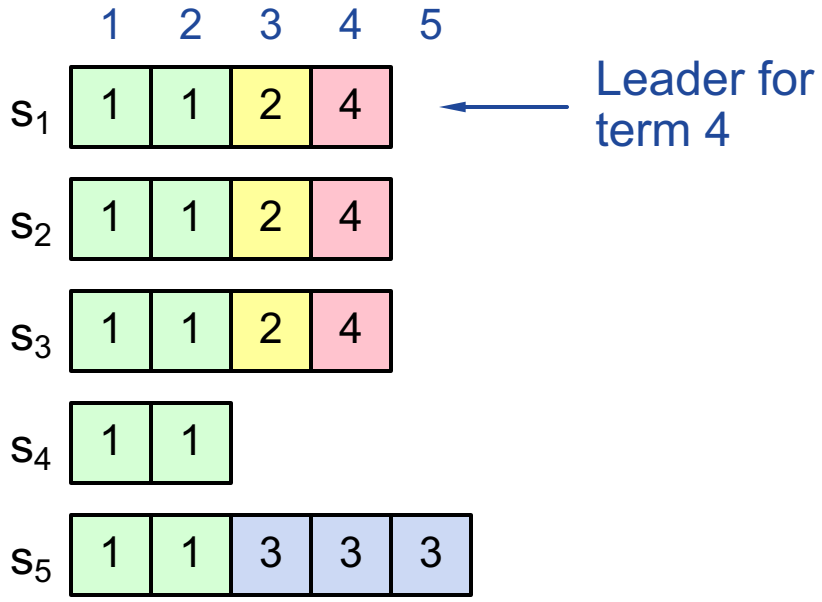
- How much randomization is needed to avoid split votes?




- Conservatively, use random range ~10x network latency

# New Commitment Rules

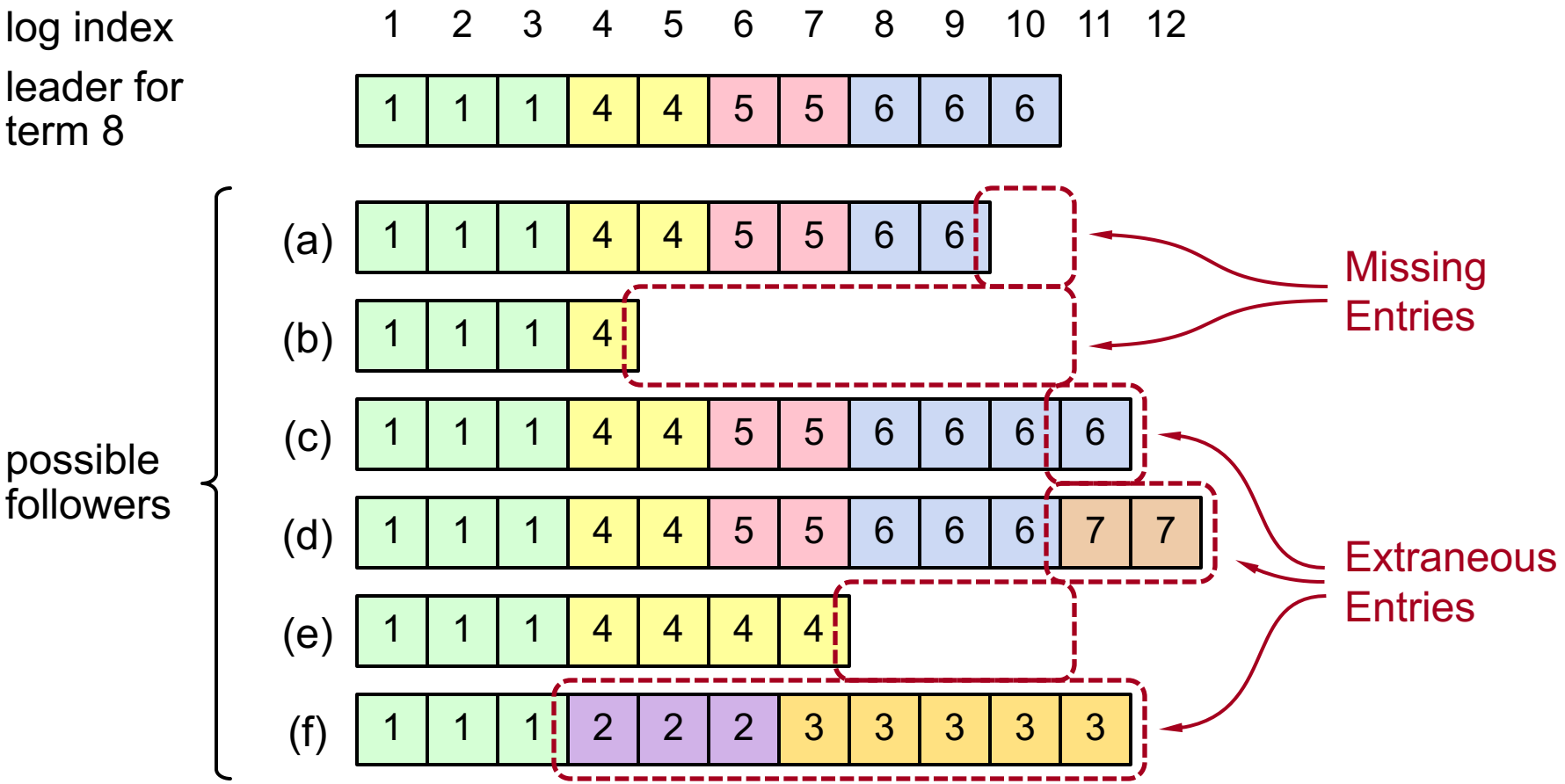
- **For a leader to decide an entry is committed:**
  - Must be stored on a majority of servers
  - **At least one new entry from leader's term must also be stored on majority of servers**
- **Once entry 4 committed:**
  - $s_5$ cannot be elected leader for term 5
  - Entries 3 and 4 both safe




**Combination of election rules and commitment rules makes Raft safe**

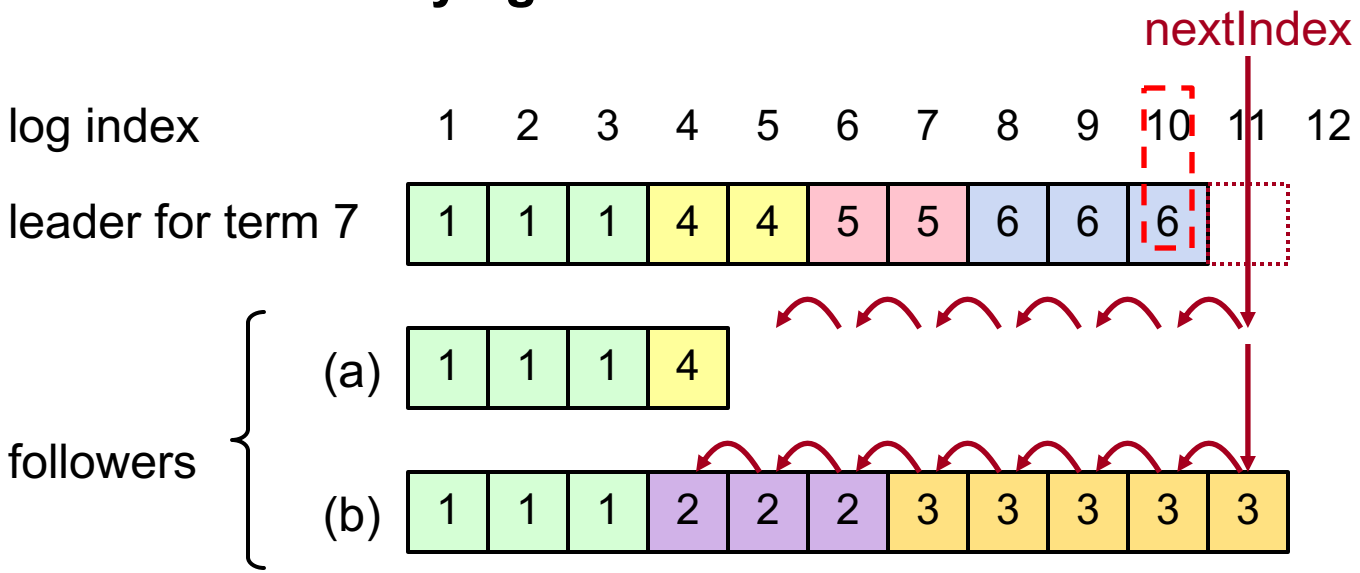
# Log Inconsistencies

## Leader changes can result in log inconsistencies:



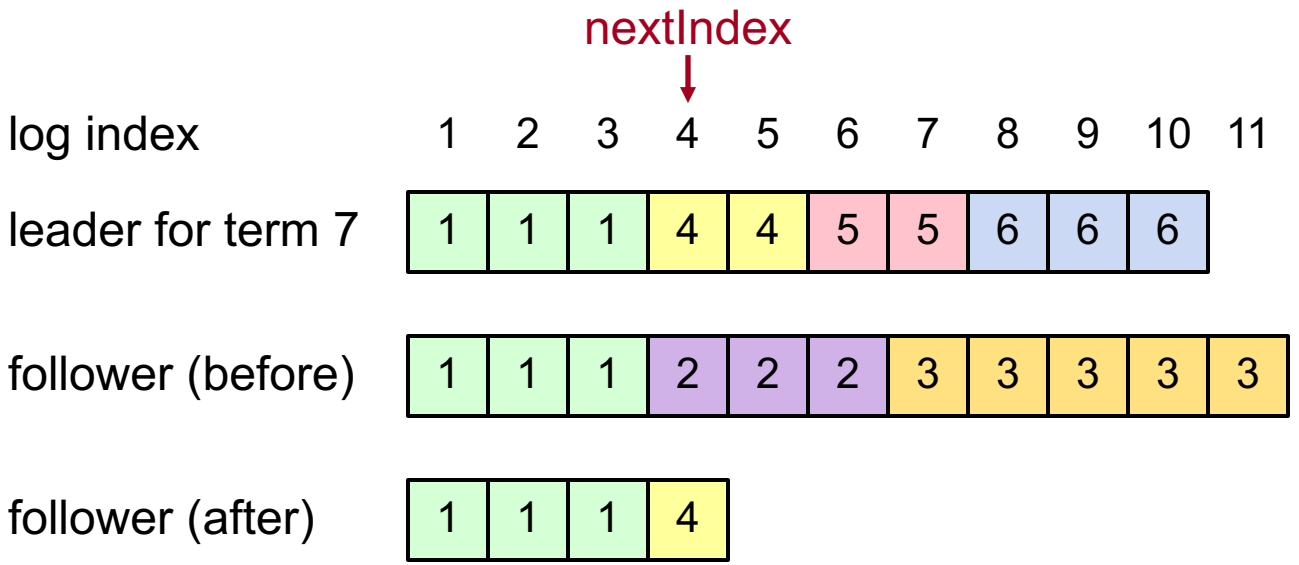
# Repairing Follower Logs

- **New leader must make follower logs consistent with its own**
  - Delete extraneous entries
  - Fill in missing entries
- **Leader keeps nextIndex for each follower:**
  - Index of next log entry to send to that follower
  - Initialized to (1 + leader's last index)
- **When AppendEntries consistency check fails, decrement nextIndex and try again:**



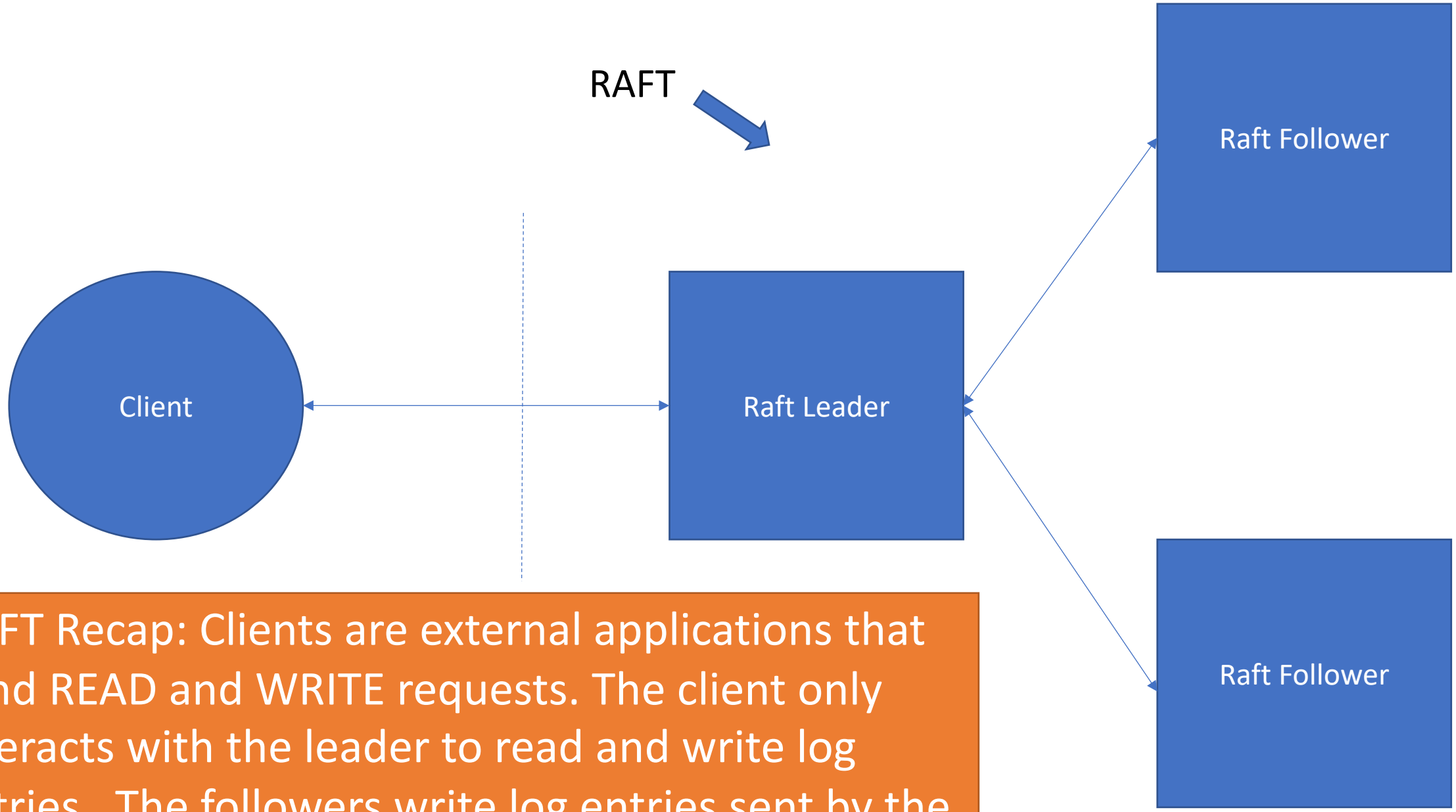
# Repairing Logs, cont'd

- **When follower overwrites inconsistent entry, it deletes all subsequent entries:**



# Neutralizing Old Leaders

- **Deposed leader may not be dead:**
  - Temporarily disconnected from network
  - Other servers elect a new leader
  - Old leader becomes reconnected, attempts to commit log entries
- **Terms used to detect stale leaders (and candidates)**
  - Every RPC contains term of sender
  - If sender's term is older, RPC is rejected, sender reverts to follower and updates its term
  - If receiver's term is older, it reverts to follower, updates its term, then processes RPC normally
- **Election updates terms of majority of servers**
  - Deposed server cannot commit new log entries




RAFT Recap: Clients are external applications that send READ and WRITE requests. The client only interacts with the leader to read and write log entries. The followers write log entries sent by the leader. A follower can become a new leader.

# Client Protocol

- **Send commands to leader**
  - If leader unknown, contact any server
  - If contacted server not leader, it will redirect to leader
    - Even for READS
    - Compare with Zookeeper
    - Client guaranteed to get latest committed log state, but Raft doesn't scale as well
- **Leader does not send the response to the client until the command has been logged, committed, and executed by leader's state machine**
- **If request times out (e.g., leader crash):**
  - Client reissues command to some other server
  - Eventually redirected to new leader
  - Retry request with new leader

# Raft and Configuration Changes (Brief)

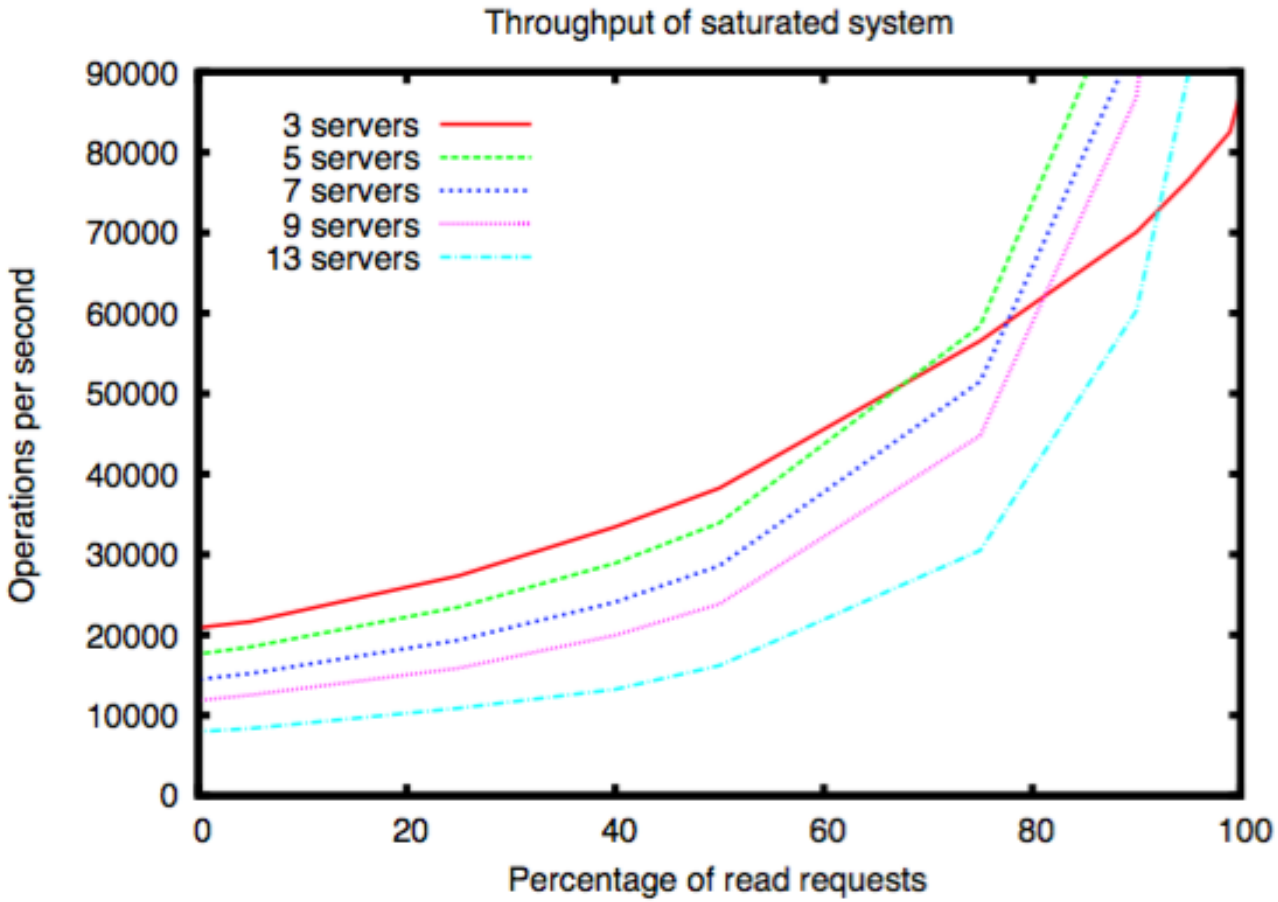
- Raft's consensus approach requires that a leader never gives up on unreachable servers.
  - Quasi-static collections of servers
- Raft can also handle situations in which new servers are added to the system and old servers are cleanly removed.
- It does this by requiring **joint consensus** between the old and new collections.
- New servers are non-voting members until they have come up to speed.
- This is an interesting approach for handling **Continuous Deployment** scenarios.
  - More in a future lecture

# Some Limits of Raft (1/4)

- All READ requests also go to the leader
  - Guarantee: all clients get the same response to READ operations
  - The followers are just there as backups
- When the Raft leader is stable, Raft provides strong consistency to its clients
  - Every client request gets the same answer
- But this can limit throughput compared to systems like Zookeeper
  - Zookeeper has weaker consistency but is more scalable for READs

# Some Limits of Raft (2/4)

- All the log protocols are designed for clients that primarily READ.
- Any strong leader system will not scale well if there are a lot of WRITEs.
  - Can you see why?



# Some Limits of Raft (3/4)

- Raft may not scale across geographically distant data centers or cloud regions
  - Consul supplements Raft with another protocol called SWIM
- The problem: network communication speed and network unreliability will make the system unwieldy
  - You wouldn’t build DNS with Raft
  - Can you see why?
- Blockchain (from Bitcoin) is a (maybe) similar logging protocol that works at large scale but (maybe) doesn’t work well as small scale

# Some Limits of Raft (4/4)

- Raft members communicate with each other using RPC calls.
- What if a malicious or faulty server is in the cluster?
  - It could tamper with logs
  - It could inappropriately share logs
  - It could disrupt the system by calling elections
- These are called Byzantine failures

# Replicating databases