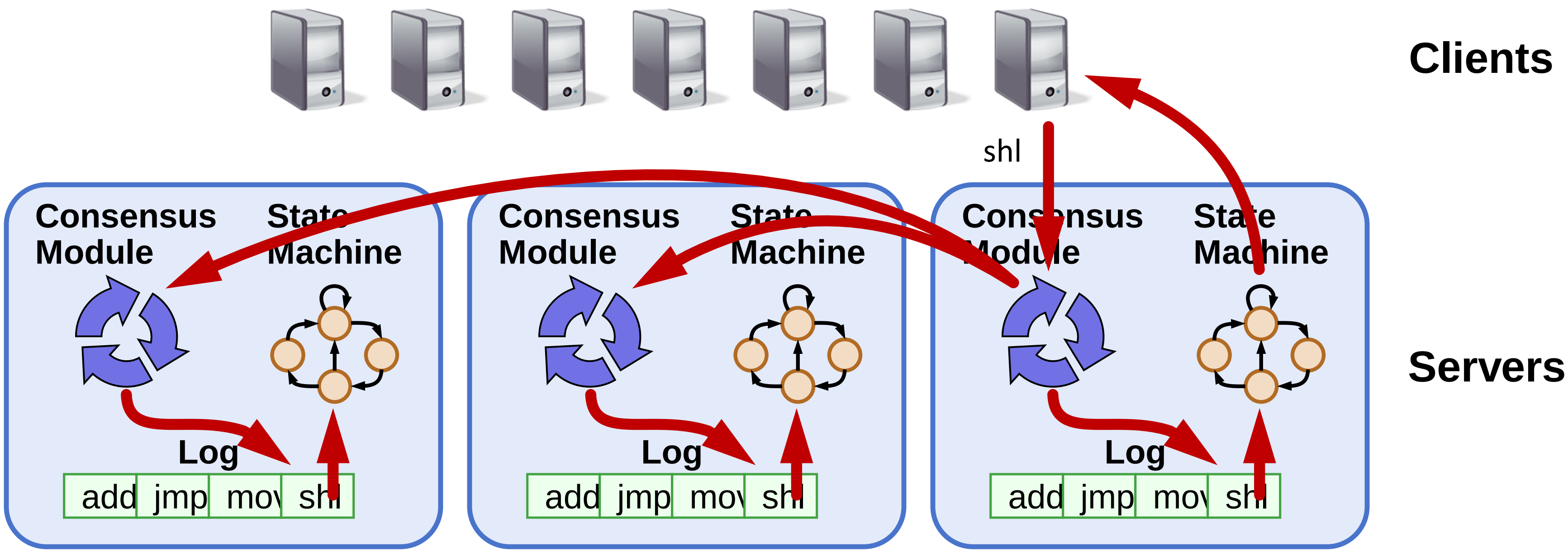
Consensus on Replicated Logs

Assignment 2 & Assignment 3

Based on the Raft paper and Michael Freedman's slides

Goal: Log Replication

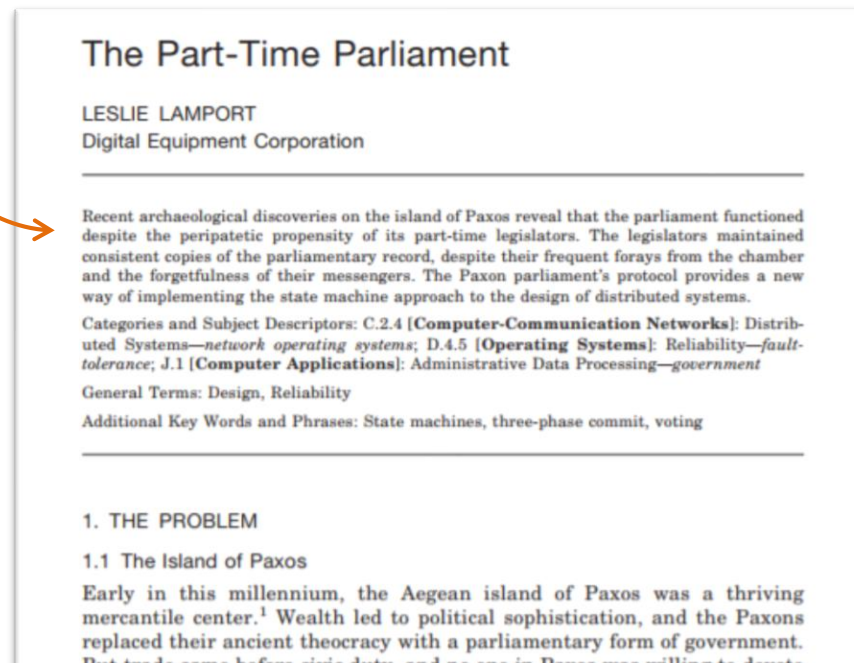


- Log Replication => replicated state machine
  - All servers execute same commands in same order
- Consensus module ensures proper log replication

Distributed Log Consensus Tool: Raft

- The Raft paper
  - Diego Ongaro, John K. Ousterhout. In search of an understandable consensus algorithm. ***USENIX ATC 2014***. [Best Paper Award]

Compared with Paxos



The Part-Time Parliament

LESLIE LAMPORT
Digital Equipment Corporation

Recent archaeological discoveries on the island of Paxos reveal that the parliament functioned despite the peripatetic propensity of its part-time legislators. The legislators maintained consistent copies of the parliamentary record, despite their frequent forays from the chamber and the forgetfulness of their messengers. The Paxon parliament's protocol provides a new way of implementing the state machine approach to the design of distributed systems.

Categories and Subject Descriptors: C.2.4 [**Computer-Communication Networks**]: Distributed Systems—*network operating systems*; D.4.5 [**Operating Systems**]: Reliability—*fault-tolerance*; J.1 [**Computer Applications**]: Administrative Data Processing—*government*

General Terms: Design, Reliability

Additional Key Words and Phrases: State machines, three-phase commit, voting

1. THE PROBLEM

1.1 The Island of Paxos

Early in this millennium, the Aegean island of Paxos was a thriving mercantile center.[1] Wealth led to political sophistication, and the Paxons replaced their ancient theocracy with a parliamentary form of government.

Raft Overview

(http://thesecretlivesofdata.com/raft/)

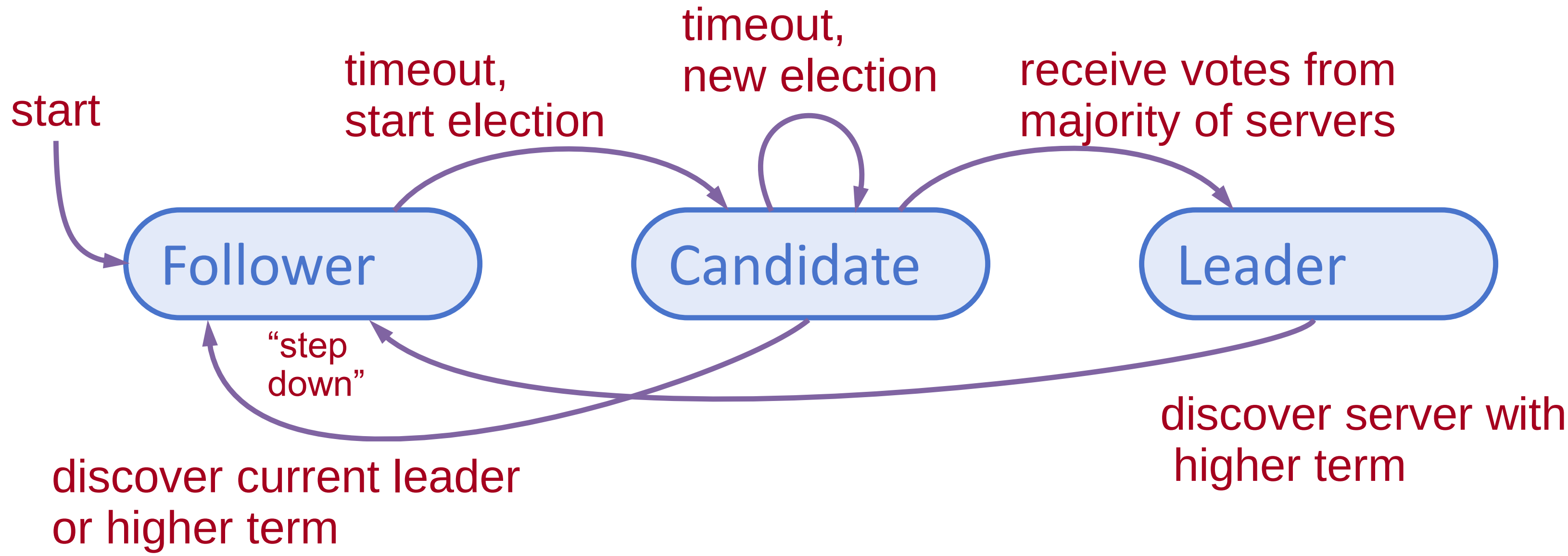
1. **Leader election**
2. **Normal operation (basic log replication)**
3. **Safety and consistency after leader changes**
4. **Neutralizing old leaders**
5. **Client interactions**

Server States

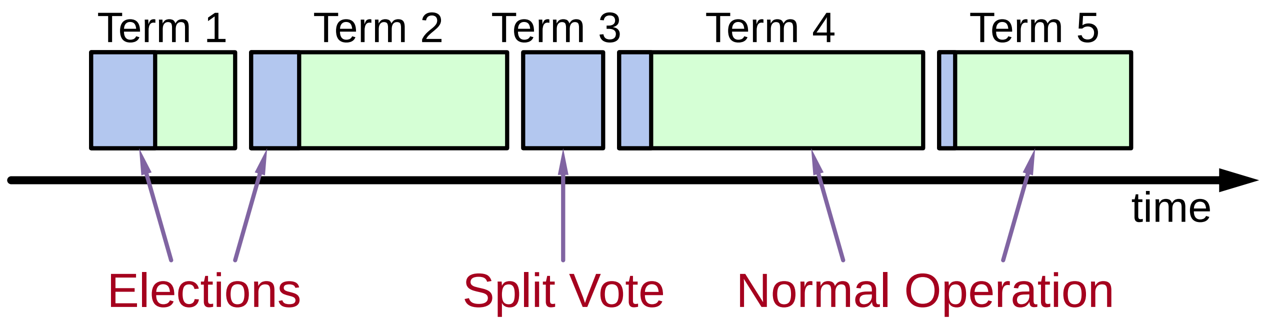
- At any given time, each server is either:
  - **Leader**: handles all client interactions, log replication
  - **Follower**: completely passive
  - **Candidate**: used to elect a new leader
- Normal operation: 1 leader, N-1 followers

Liveness Validation

- Servers start as followers
- Leaders send **heartbeats** (empty *AppendEntries* RPCs) to maintain authority
- If **electionTimeout** elapses with no RPCs (100-500ms), follower assumes leader has crashed and starts new election



Terms (aka epochs)



- Time divided into terms
  - Election (either failed or resulted in 1 leader)
  - Normal operation under a single leader
- Each server maintains **current term** value
- **Key role of terms: identify obsolete information**

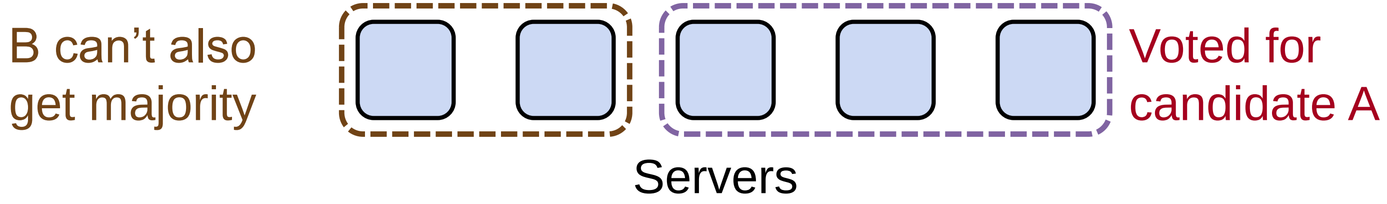
Elections

- **Start election:**
  - Increment current term, change to candidate state, vote for self

- **Send *RequestVote* to all other servers, retry until either:**
  1. Receive votes from majority of servers:
     - Become leader
     - Send *AppendEntries* heartbeats to all other servers
  2. Receive RPC from valid leader:
     - Return to follower state
  3. No-one wins election (election timeout elapses):
     - Increment term, start new election

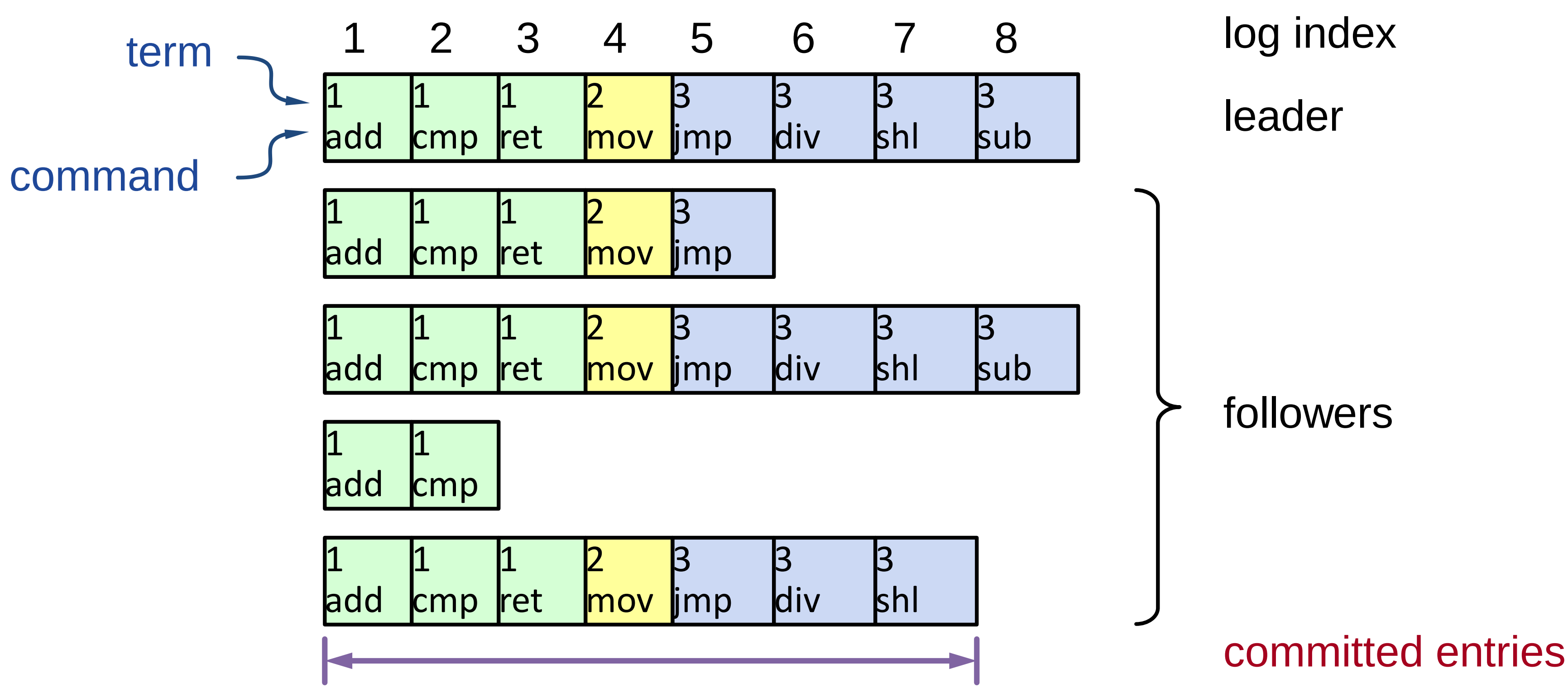
Elections

- **Safety**: allow at most one winner per term
  - Each server votes only once per term (persists on disk)
  - Two different candidates can't get majorities in same term



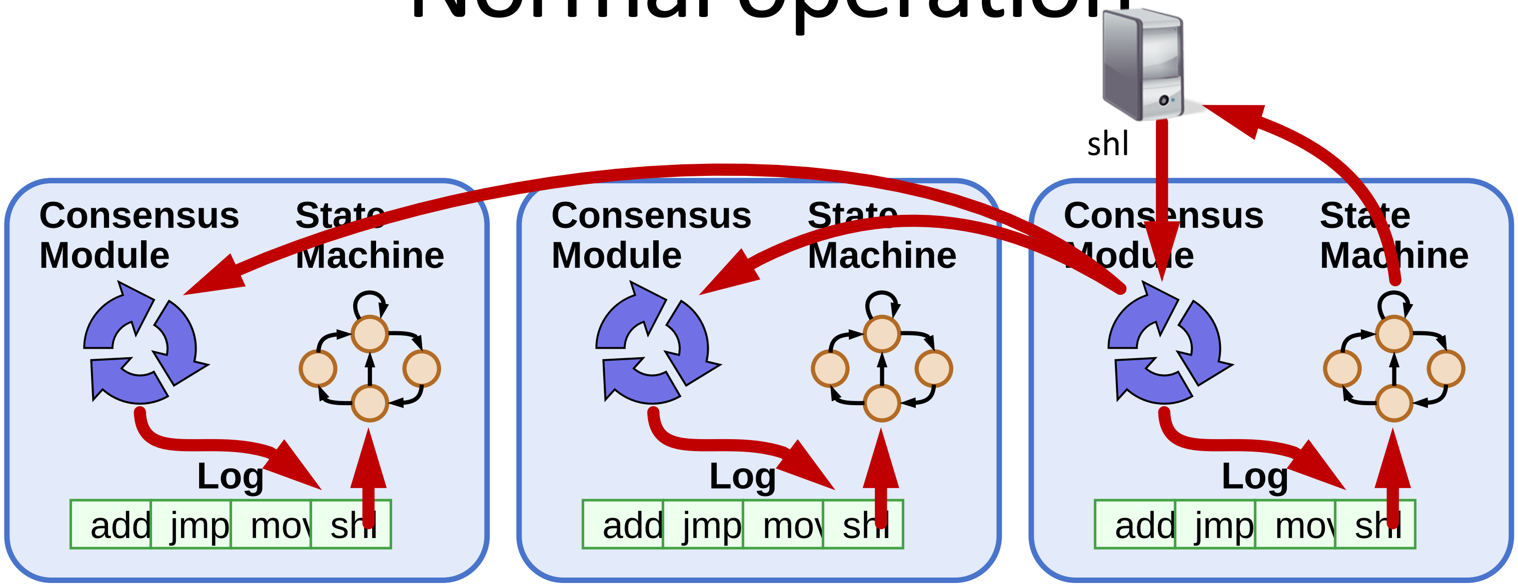
- **Liveness**: some candidate must eventually win
  - Each choose election timeouts ***randomly*** in [T, 2T]
  - One usually initiates and wins election before others start
  - Works well if T >> network RTT

Log Structure



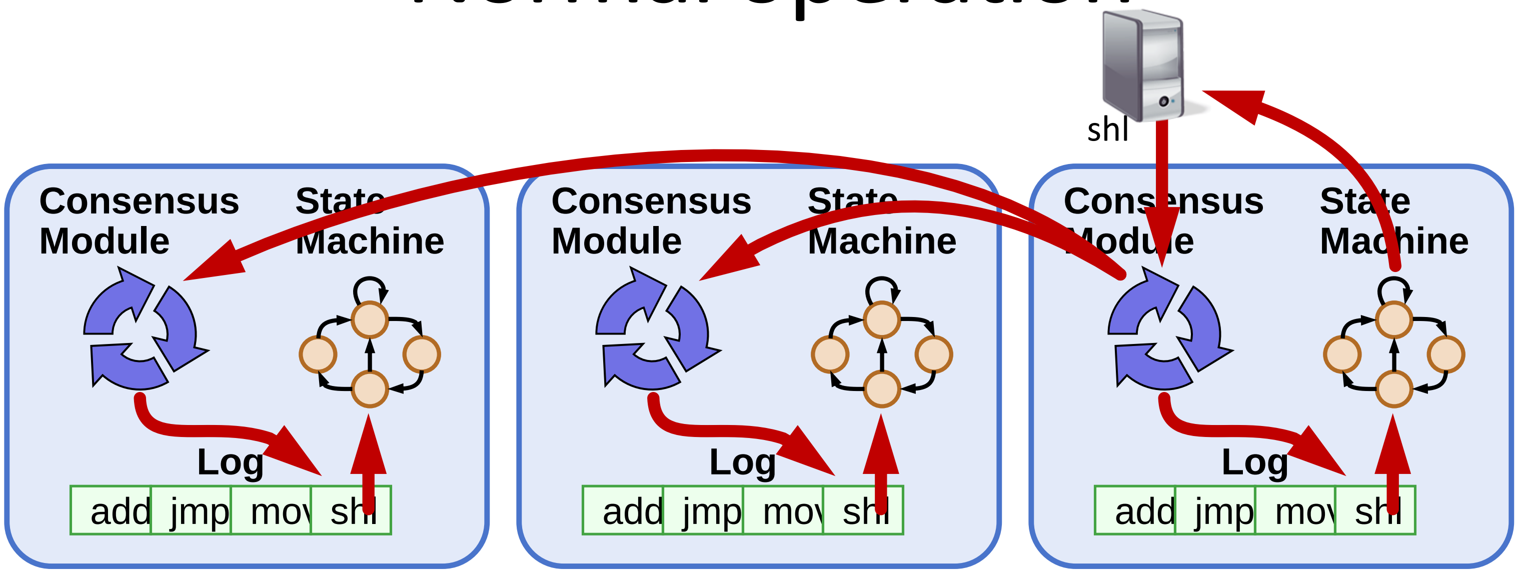
- Log entry = < index, term, command >
- Log stored on stable storage (disk); survives crashes
- Entry **committed** if known to be stored on majority of servers
  - Durable / stable, will eventually be executed by state machines

Normal operation



- Client sends command to leader
- Leader appends command to its log
- Leader sends *AppendEntries* RPCs to followers
- Once new entry committed:
  - Leader passes command to its state machine, sends result to client
  - Leader piggybacks commitment to followers in later *AppendEntries*
  - Followers pass committed commands to their state machines

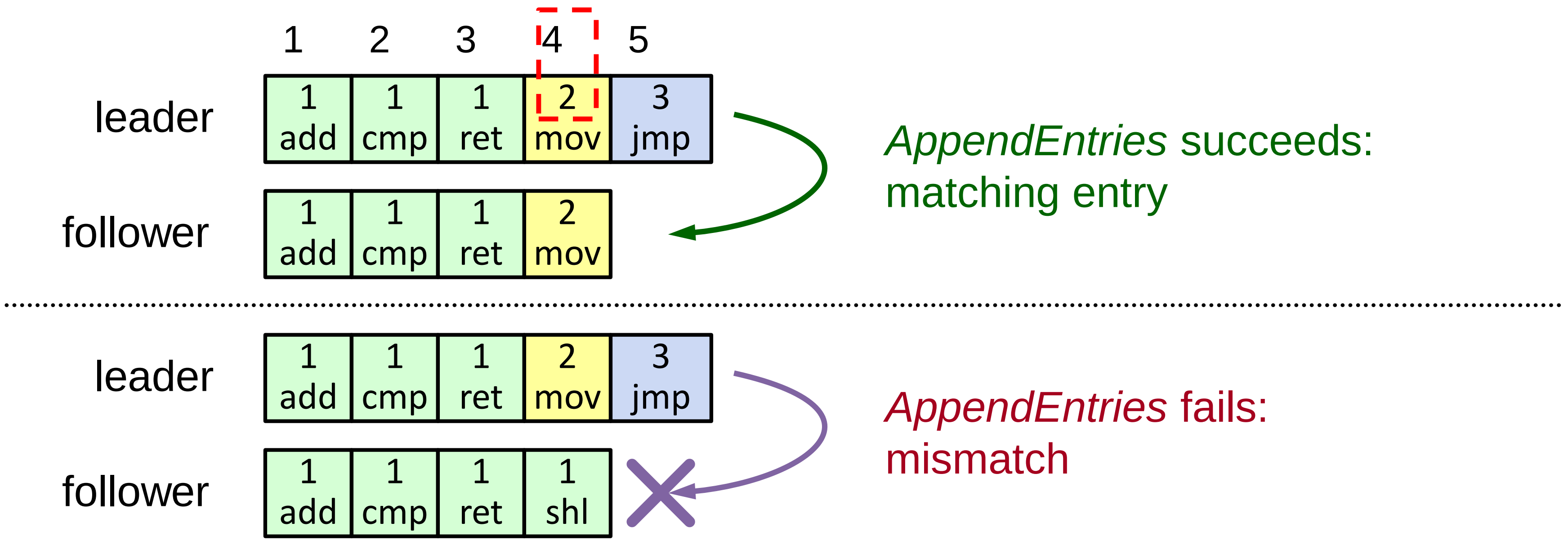
Normal operation



- Crashed / slow followers?
  - Leader retries RPCs until they succeed

- Performance is optimal in common case:
  - One successful RPC to any majority of servers

Log Operation: Consistency Check



- *AppendEntries* has <index, term> of entry preceding new ones
- Follower must contain matching entry; otherwise it rejects
- Implements an **induction step**, ensures coherency

Safety Requirement

Once log entry applied to a state machine, no other state machine must apply a different value for that log entry

- Raft safety property: If leader has decided log entry is committed, entry will be present in logs of all future leaders

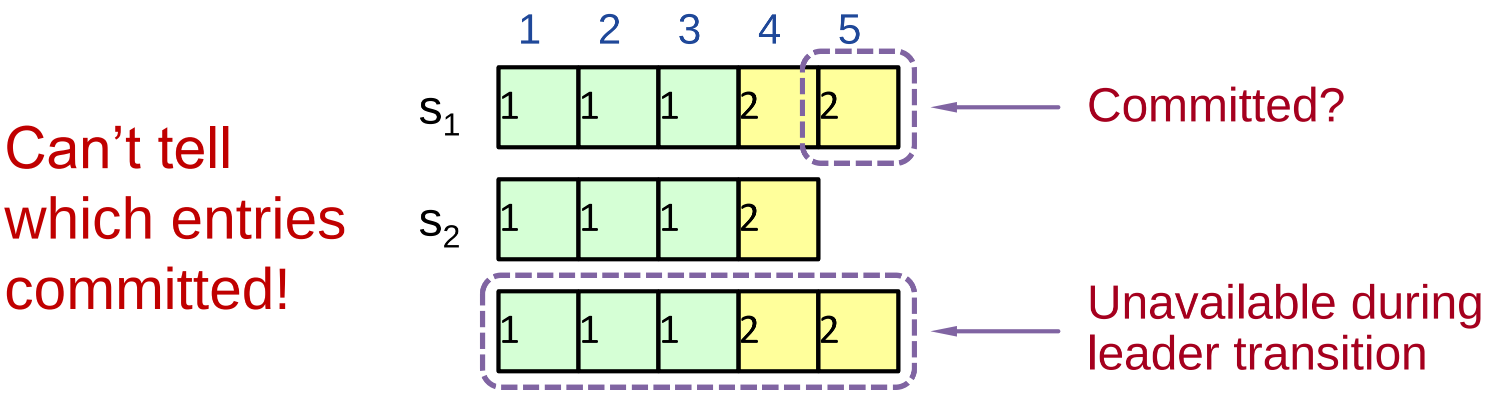
- Why does this guarantee higher-level goal?
  1. Leaders never overwrite entries in their logs
  2. Only entries in leader's log can be committed
  3. Entries must be committed before applying to state machine

Committed → Present in future leaders' logs

Restrictions on commitment

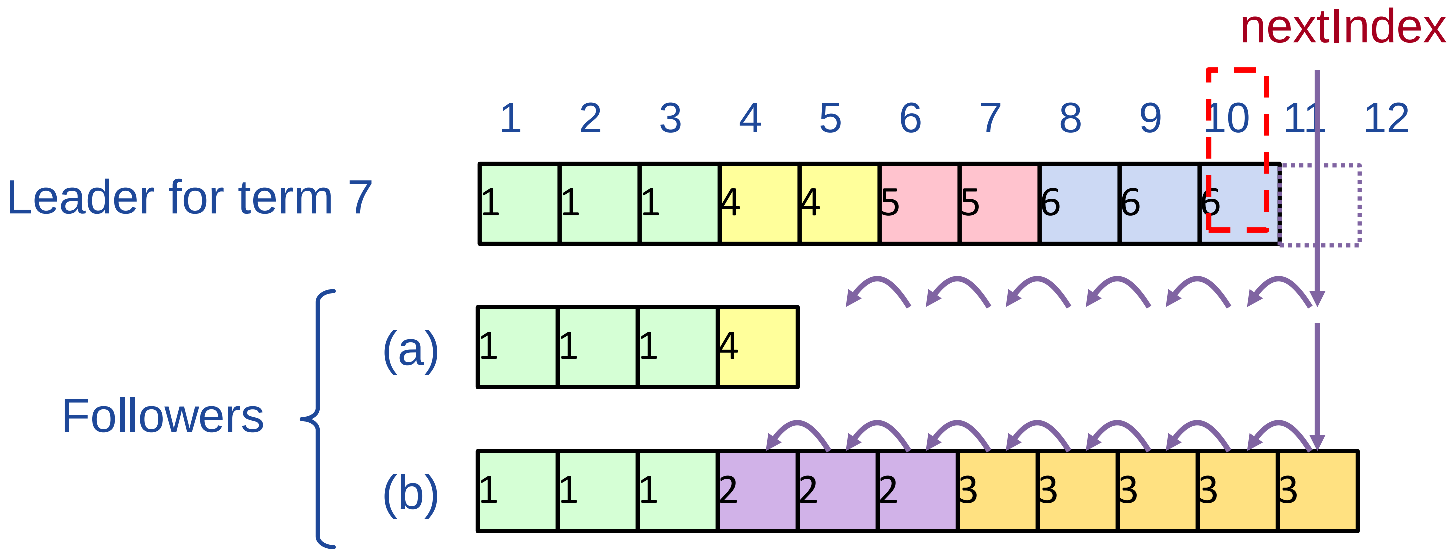
Restrictions on leader election

Picking the Best Leader



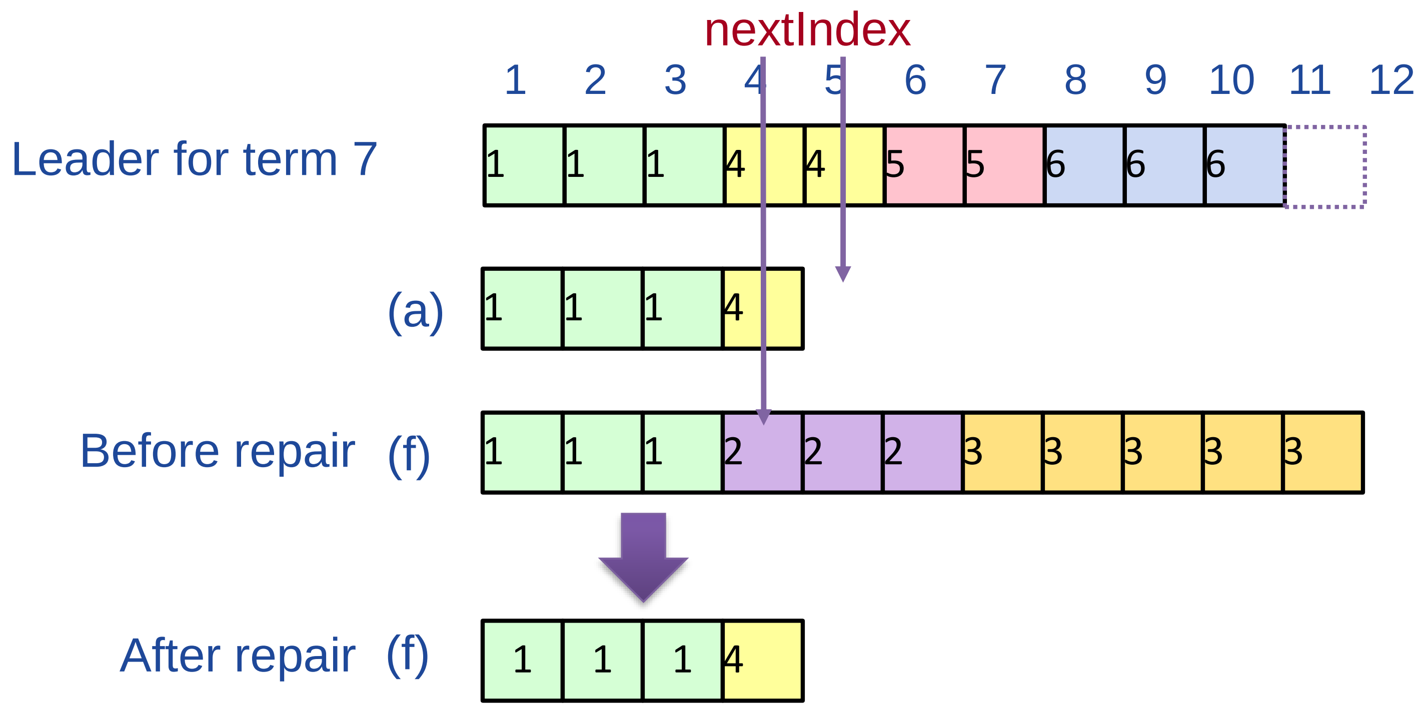
- Elect candidate most likely to contain all committed entries
  - In *RequestVote*, candidates incl. index + term of last log entry
  - Voter V denies vote if its log is “more complete”: (newer term) or (entry in higher index of same term)
  - Leader will have “most complete” log among electing majority

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)
- If *AppendEntries* consistency check fails, decrement nextIndex, try again

Repairing Follower Logs



Neutralizing Old Leaders

Leader temporarily disconnected

→ other servers elect new leader

→ old leader reconnected

→ old leader attempts to commit log entries

- Terms used to detect stale leaders (and candidates)
  - Every RPC contains term of sender
  - Sender's term < receiver:
    - Receiver: Rejects RPC (via ACK which sender processes…)
  - Receiver's term < sender:
    - Receiver reverts to follower, updates term, processes RPC
- Election updates terms of majority of servers
  - Deposed server cannot commit new log entries

Client-to-Server Protocol

- **Send commands to leader**
  - If leader unknown, contact any server, which redirects client to leader
- **Leader only responds after command logged, committed, and executed by leader**
- **If request times out (e.g., leader crashes):**
  - Client reissues command to new leader (after possible redirect)
- **Ensure exactly-once semantics even with leader failures**
  - E.g., Leader can execute command then crash before responding
  - Client should embed unique ID in each command
  - This client ID included in log entry
  - Before accepting request, leader checks log for entry with same id

Assignment 2: Raft Leader Election

- Resources
  - Raft paper, illustrated Raft guide (http://thesecretlivesofdata.com/raft/)
- Software
  - https://github.com/Zhang-Xiaoda/NJU-DisSys-2017
  - Focus primary on the code and tests for the Raft implementation in src/raft and simple RPC-like system in src/labrpc, (read the code in these packages first)

Assignment 2: Raft Leader Election

- At the beginning:

```
zhang@ubuntu:~/gopath/NJU-DisSys-2017$ export GOPATH=$PWD
zhang@ubuntu:~/gopath/NJU-DisSys-2017$ cd src/raft/
zhang@ubuntu:~/gopath/NJU-DisSys-2017/src/raft$ ls
config.go  persister.go  raft.go  test_test.go  util.go
zhang@ubuntu:~/gopath/NJU-DisSys-2017/src/raft$ go test -run Election
Test: initial election ...
--- FAIL: TestInitialElection (5.01s)
        config.go:286: expected one leader, got none
Test: election after network failure ...
--- FAIL: TestReElection (5.01s)
        config.go:286: expected one leader, got none
FAIL
exit status 1
FAIL    raft    10.016s
```

- Implement Raft by adding code to raft/raft.go (***only***)
  - find some example code of how to send and receive RPC

- Your task: Leader election:
  - First task is to fill the *RequestVoteArgs* and *RequestVoteReply* structs

Assignment 2: Raft Leader Election

- Modify *Make()* to create a background goroutine that starts an election by sending out *RequestVote* RPC when it hasn't heard from another peer for a while
  - You need to implement *RequestVote* RPC handler so that servers will vote for one another
- To implement heartbeats, you will need to define *AppendEntries* struct (though you will not need any real payload yet), and have the leader send them out periodically
  - Also need to implement *AppendEntries* RPC handler
- make sure the election timeouts **don't** always fire at the same time

Assignment 2: Raft Leader Election

- At the end:

```
zhang@ubuntu:~/gopath/NJU-DisSys-2017$ export GOPATH=$PWD
zhang@ubuntu:~/gopath/NJU-DisSys-2017$ cd src/raft/
zhang@ubuntu:~/gopath/NJU-DisSys-2017/src/raft$ ls
config.go  persister.go  raft.go  test_test.go  util.go
zhang@ubuntu:~/gopath/NJU-DisSys-2017/src/raft$ go test -run Election
Test: initial election ...
  ... Passed
Test: election after network failure ...
  ... Passed
PASS
ok      raft    9.014s
```

- Advice:
  - Remember field names of any structures you will be sending over RPC must start with ***capital letters***
  - Read and understand the paper before you start. Figure 2 in the paper may provide a good guideline.
  - ***Start early!***

Assignment 3: Raft Log Consensus

- Software as the above
- Will not implement cluster membership changes (Section 6) or log compaction / snapshotting (Section 7)
- Part I
  - Implement the leader and follower code to append new log entries
    - implementing *Start(),* completing the *AppendEntries* RPC structs, sending them, and completing the *AppendEntry* RPC handler
    - pass the *TestBasicAgree*() test, try to pass all test before "Persist"

Assignment 3: Raft Log Consensus

```
zhang@ubuntu:~/gopath/NJU-DisSys-2017/src/raft$ go test -run FailNoAgree
Test: no agreement if too many followers fail ...
  ... Passed
PASS
ok      raft    3.809s
zhang@ubuntu:~/gopath/NJU-DisSys-2017/src/raft$ go test -run ConcurrentStarts
Test: concurrent Start()s ...
  ... Passed
PASS
ok      raft    1.160s
zhang@ubuntu:~/gopath/NJU-DisSys-2017/src/raft$ go test -run Rejoin
Test: rejoin of partitioned leader ...
  ... Passed
PASS
ok      raft    6.573s
zhang@ubuntu:~/gopath/NJU-DisSys-2017/src/raft$ go test -run Backup
Test: leader backs up quickly over incorrect follower logs ...
  ... Passed
PASS
ok      raft    17.090s
```

Assignment 3: Raft Log Consensus

- Part II
  - Handle the fault tolerant aspects of the Raft protocol
    - require that Raft keep persistent state that survives a reboot (see Figure 2 for which states should be persistent)
  - won't use the disk; instead, it will save and restore persistent state from a *Persister* (see *persister.go*)
    - initialize its state from that *Persister*, and should use it to save its persistent state each time the state changes.
  - You should determine at what points in the Raft protocol your servers are required to persist their state, and insert calls to *persist*() in those places

Assignment 3: Raft Log Consensus

- Pass the Persist test:

```
zhang@ubuntu:~/gopath/NJU-DisSys-2017/src/raft$ go test -run Persist1
Test: basic persistence ...
  ... Passed
PASS
ok      raft    4.618s
zhang@ubuntu:~/gopath/NJU-DisSys-2017/src/raft$ go test -run Persist2
Test: more persistence ...
  ... Passed
PASS
ok      raft    17.522s
zhang@ubuntu:~/gopath/NJU-DisSys-2017/src/raft$ go test -run Persist3
Test: partitioned leader and one follower crash, leader restarts ...
  ... Passed
PASS
ok      raft    2.151s
```

- Try to pass the further challenging tests towards the end
  – need to implement the optimization to allow a follower to back up the leader's *nextIndex* by more than one entry at a time

作业说明

1）邮件标题格式
  – 学号(字母大写)_姓名_作业2-3
2）附件格式
  – 报告为pdf，代码rar
  – 文件名：学号(字母大写)_姓名_作业2-3
3）报告内容与格式
  – 详细说明如何达到目标：简述分析与设计、实现演示、总结等；
4）杜绝任何形式的代码拷贝与报告抄袭，遵循学术规范。
5）提交邮箱：distrisys@126.com
6）截止日期：2019.6.2