Utah Distributed Systems Meetup and Reading Group - Raft

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Outline

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Introduction

Nearly all content and images from Diego Ongaro and John Ousterhout's 2014 paper, In Search of an Understandable Consensus Algorithm (Extended Version).

Introduction

- Raft is a consensus algorithm for managing a replicated log.
- Equivalent to Paxos in operation, except more understandable.
- Separates leader election, log replication, safety, and reduces possible states.
- Easier to learn.
- Supports cluster membership changes.

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Notable raft features

- Strong leader
- Randomized timeouts for leader election
- Membership changes

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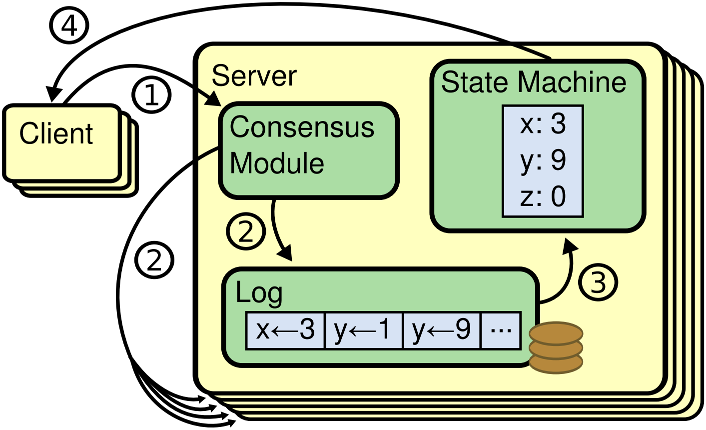
④
Server
State Machine
x: 3
y: 9
z: 0
Client
①
Consensus Module
②
②
Log
x←3
y←1
y←9
...
③

- State machines must be completely deterministic.
- State machines operate on events popped from a log.
- Logs are managed by the consensus algorithm.

Consensus algorithms

- should provide safety - never return an incorrect result.
- should provide availability - must work when a majority of servers are up.
- should not depend on timing.
- can mitigate poor performance. A slow minority shouldn't be waited for.

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- super opaque and subtle - probably due to weird decomposition.
- multi-Paxos only has possible approach sketches! Attempts to flesh out missing details differ from Lamport's sketch and each other, and some have not been published.
- Paxos is symmetric peer-to-peer at its core (no leaders) which is inefficient when a bunch of decisions need to be made.
- Paxos is good for proving theorems about Paxos, but said proofs matter little when real implementations can differ so drastically.

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- Abstract
- 1. Introduction
- 2. Replicated state machines
- 3. What's wrong with Paxos?
- 4. Designing for understandability

Goals

- Reduce developer design work (no unproven protocols)
- Safe under all conditions
- Available under typical conditions
- Efficient for common operations
- Understandable

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Understandability

- When faced with a choice, choose the easiest to explain.
- Subdivide problems
- Shrink state space

Nondeterminism

- Nondeterminism usually eliminated
- except where it makes the system simpler! (randomized approaches)

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- 5.1. Raft basics
- 5.2. Leader election
- 5.3. Log replication
- 5.4. Safety
- 5.5. Follower and candidate crashes
- 5.6. Timing and availability

Simulation

`raftconsensus.github.io`

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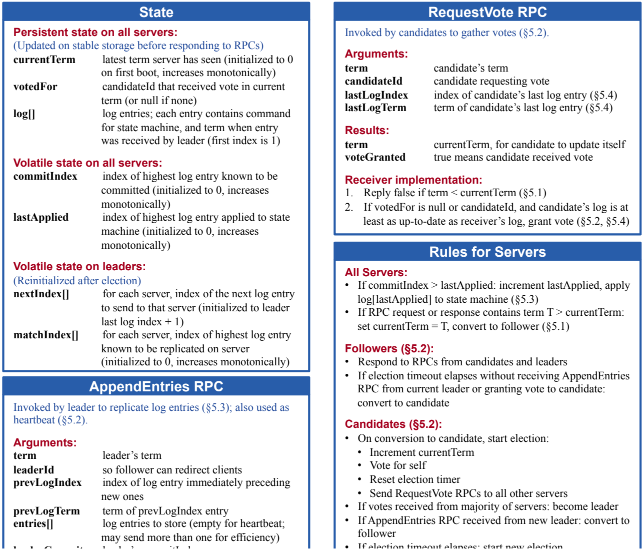


State

Persistent state on all servers:

(Updated on stable storage before responding to RPCs)

currentTerm	latest term server has seen (initialized to 0 on first boot, increases monotonically)
votedFor	candidateId that received vote in current term (or null if none)
log[]	log entries; each entry contains command for state machine, and term when entry was received by leader (first index is 1)

Volatile state on all servers:

commitIndex	index of highest log entry known to be committed (initialized to 0, increases monotonically)
lastApplied	index of highest log entry applied to state machine (initialized to 0, increases monotonically)

Volatile state on leaders:

(Reinitialized after election)

nextIndex[]	for each server, index of the next log entry to send to that server (initialized to leader last log index + 1)
matchIndex[]	for each server, index of highest log entry known to be replicated on server (initialized to 0, increases monotonically)

AppendEntries RPC

Invoked by leader to replicate log entries (§5.3); also used as heartbeat (§5.2).

Arguments:

term	leader's term
leaderId	so follower can redirect clients
prevLogIndex	index of log entry immediately preceding new ones
prevLogTerm	term of prevLogIndex entry
entries[]	log entries to store (empty for heartbeat; may send more than one for efficiency)

RequestVote RPC

Invoked by candidates to gather votes (§5.2).

Arguments:

term	candidate's term
candidateId	candidate requesting vote
lastLogIndex	index of candidate's last log entry (§5.4)
lastLogTerm	term of candidate's last log entry (§5.4)

Results:

term	currentTerm, for candidate to update itself
voteGranted	true means candidate received vote

Receiver implementation:

1. Reply false if term < currentTerm (§5.1)
2. If votedFor is null or candidateId, and candidate's log is at least as up-to-date as receiver's log, grant vote (§5.2, §5.4)

Rules for Servers

All Servers:

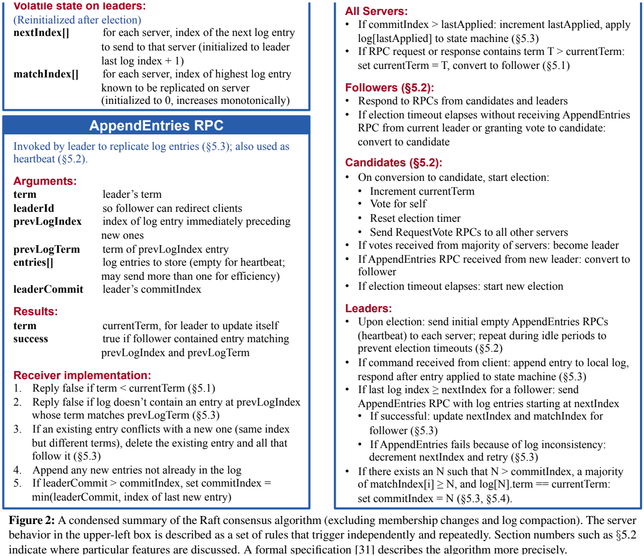
- If commitIndex > lastApplied: increment lastApplied, apply log[lastApplied] to state machine (§5.3)
- If RPC request or response contains term T > currentTerm: set currentTerm = T, convert to follower (§5.1)

Followers (§5.2):

- Respond to RPCs from candidates and leaders
- If election timeout elapses without receiving AppendEntries RPC from current leader or granting vote to candidate: convert to candidate

Candidates (§5.2):

- On conversion to candidate, start election:
  - Increment currentTerm
  - Vote for self
  - Reset election timer
  - Send RequestVote RPCs to all other servers
- If votes received from majority of servers: become leader
- If AppendEntries RPC received from new leader: convert to follower
- If election timeout elapses: start new election



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leaderCommit	leader's commitIndex

Results:

term	currentTerm, for leader to update itself
success	true if follower contained entry matching prevLogIndex and prevLogTerm

Receiver implementation:

1. Reply false if term < currentTerm (§5.1)
2. Reply false if log doesn't contain an entry at prevLogIndex whose term matches prevLogTerm (§5.3)
3. If an existing entry conflicts with a new one (same index but different terms), delete the existing entry and all that follow it (§5.3)
4. Append any new entries not already in the log
5. If leaderCommit > commitIndex, set commitIndex = min(leaderCommit, index of last new entry)

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Leaders:

- Upon election: send initial empty AppendEntries RPCs (heartbeat) to each server; repeat during idle periods to prevent election timeouts (§5.2)
- If command received from client: append entry to local log, respond after entry applied to state machine (§5.3)
- If last log index ≥ nextIndex for a follower: send AppendEntries RPC with log entries starting at nextIndex
  - If successful: update nextIndex and matchIndex for follower (§5.3)
  - If AppendEntries fails because of log inconsistency: decrement nextIndex and retry (§5.3)
- If there exists an N such that N > commitIndex, a majority of matchIndex[i] ≥ N, and log[N].term == currentTerm: set commitIndex = N (§5.3, §5.4).

Figure 2: A condensed summary of the Raft consensus algorithm (excluding membership changes and log compaction). The server behavior in the upper-left box is described as a set of rules that trigger independently and repeatedly. Section numbers such as §5.2 indicate where particular features are discussed. A formal specification [31] describes the algorithm more precisely.

Leaders

- Leaders get complete responsibility for managing the replicated log.
- All changes flow from the leader to others.

Subproblems

- Leader election (5.2)
- Log replication (5.3)
- Safety (5.4)

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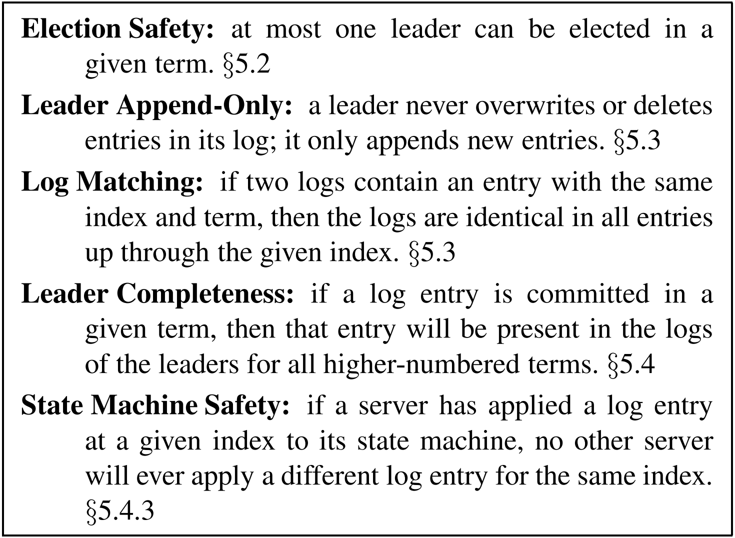

Election Safety: at most one leader can be elected in a given term. §5.2

Leader Append-Only: a leader never overwrites or deletes entries in its log; it only appends new entries. §5.3

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. §5.3

Leader Completeness: if a log entry is committed in a given term, then that entry will be present in the logs of the leaders for all higher-numbered terms. §5.4

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. §5.4.3

Algorithm

- Raft cluster contains several servers - e.g. five allows for two failures.
- Servers are in one of only three states - leader, follower, or candidate.
- There should only be one leader. Leader handles all client requests.
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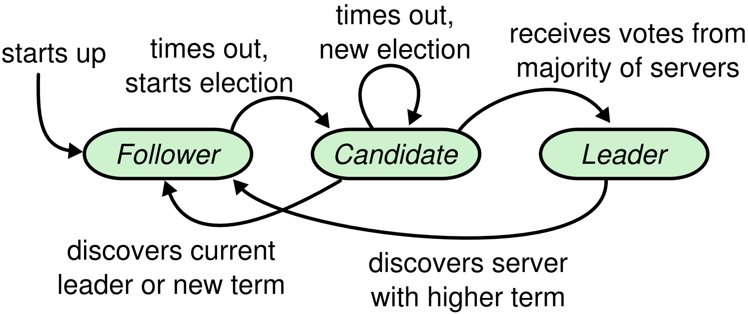
starts up
times out,
starts election
times out,
new election
receives votes from
majority of servers
Follower
Candidate
Leader
discovers current
leader or new term
discovers server
with higher term

Terms

- A term is arbitrary length.
- Terms are numbered with consecutive integers.
- Terms begin with an election.
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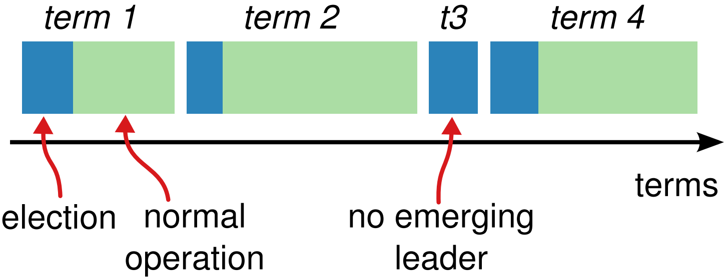
term 1
term 2
t3
term 4
terms
election
normal operation
no emerging leader

Only two main RPCs, three if you count log compaction

- RequestVote - initiated by candidates, used during elections.
- AppendEntries - initiated by leaders for heartbeats and log replication.
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RPC properties

- RPCs are retried until responses are received.
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- If a server hears no AppendEntries call before an election timeout, it begins an election.

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- Votes for itself and requests votes from the other servers.

Election termination

One of three things:

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- Winning is assumed if you receive a majority of votes.
- Each follower will vote for at most one candidate per term, first-come-first-served.
- At any time if any server hears a heartbeat message with a leader in the current term or newer, it assumes the source is the leader.

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Randomized election timeouts!

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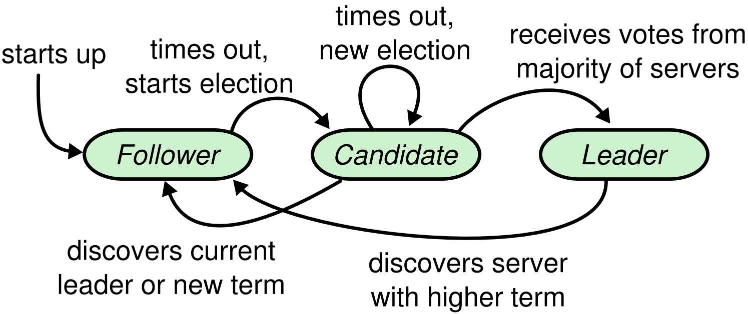


starts up

times out, starts election

times out, new election

receives votes from majority of servers

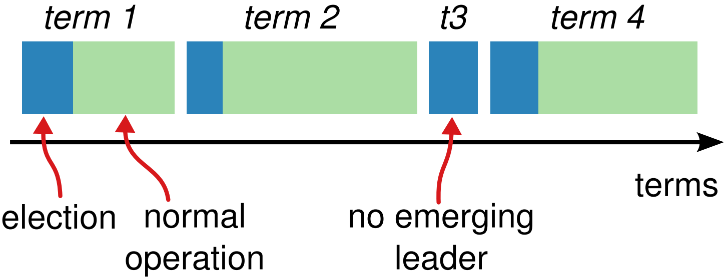
Follower

Candidate

Leader

discovers current leader or new term

discovers server with higher term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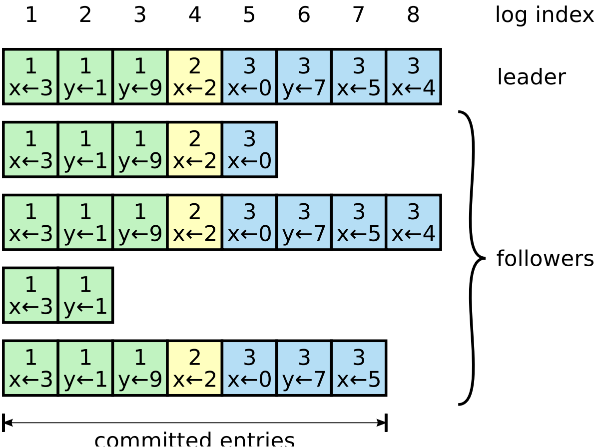

log index	1	2	3	4	5	6	7	8
leader	1 x←3	1 y←1	1 y←9	2 x←2	3 x←0	3 y←7	3 x←5	3 x←4
followers	1 x←3	1 y←1	1 y←9	2 x←2	3 x←0			
	1 x←3	1 y←1	1 y←9	2 x←2	3 x←0	3 y←7	3 x←5	3 x←4
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- Leaders service client requests.
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- Every log entry is given a term id.
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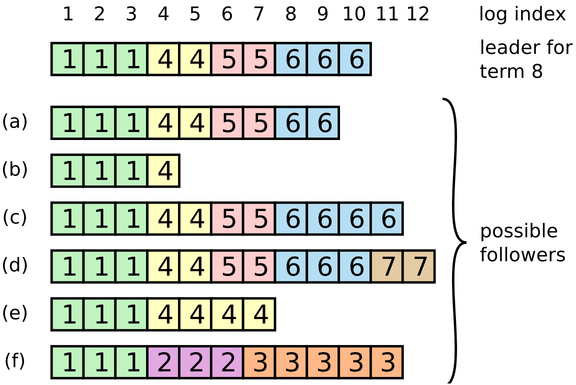

log index	1	2	3	4	5	6	7	8	9	10	11	12
leader for term 8	1	1	1	4	4	5	5	6	6	6		
(a)	1	1	1	4	4	5	5	6	6			
(b)	1	1	1	4								
(c)	1	1	1	4	4	5	5	6	6	6	6	
(d)	1	1	1	4	4	5	5	6	6	6	7	7
(e)	1	1	1	4	4	4	4					
(f)	1	1	1	2	2	2	3	3	3	3	3	

possible followers

Conflict handling

- Leaders force followers logs to duplicate their own.
- Conflicting entries will get overwritten.
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5.4.1 Election restriction

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5.4.2 Committing entries from previous terms

A leader cannot assume an entry that exists on a majority of servers from a previous term is committed.

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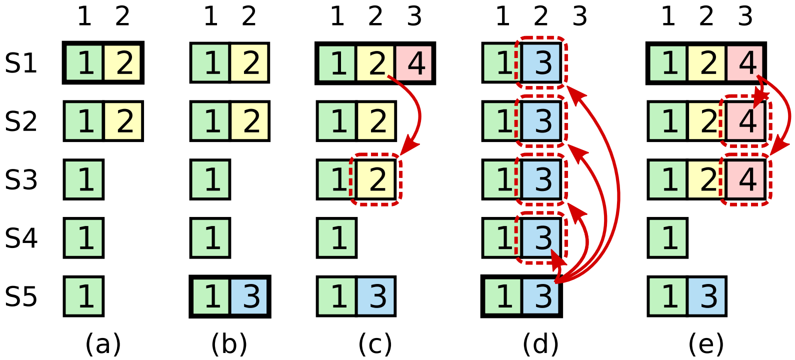

5.4.3 Safety argument

Proof

Algorithm

2 Algorithm

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- 5.4. Safety
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Timing requirement

- $broadcastTime << electionTimeout << MTBF$
- *broadcastTime* and *MTBF* are usually fixed.
- *broadcastTime* is usually dominated by disk write time, since logs are persisted to stable storage.
- So, *electionTimeout* is typically between 10ms and 500ms.

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Simulation

`raftconsensus.github.io`

Outline

Other practical concerns

Other practical concerns

3 Other practical concerns
- 6. Cluster membership changes
- 7. Log compaction
- 8. Client interaction

Overall idea

- Must adhere to one-leader-per-term rule during switch.
- Rules out any direct or atomic configuration switches.
- Two-phase approach uses joint-consensus: for a term the system uses the union of the two configurations.

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- Current leader might not be part of new configuration - leaders step down after committing configuration and possibly shouldn't count themselves as part of the majority.
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Linearizability

Clients must make all operations idempotent, or attach unique serial numbers to all commands, in case the request is received but the response is lost.

Read-only ops

- Leaders should know the latest information on what entries are committed, so at least one heartbeat or operation needs to have happened when the leader starts.
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Paper Conclusion

4 Paper Conclusion
- 9. Implementation and evaluation
- 10. Related work
- 11, 12. Conclusion & Acknowledgements

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9.1. Understandability

- How do you measure understandability?
- You teach two otherwise-identical classes on Paxos and Raft, and make kids take tests!
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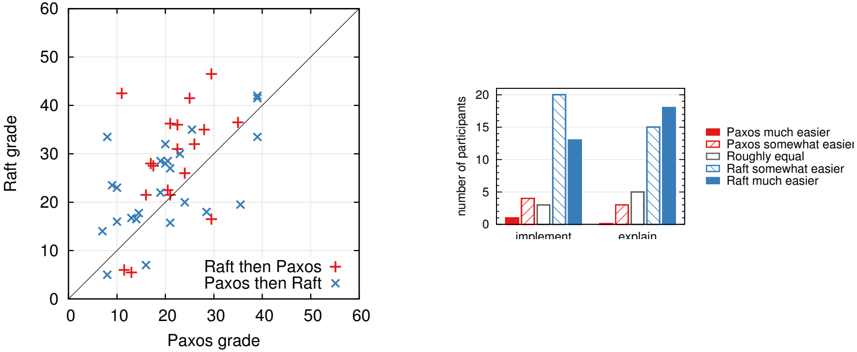
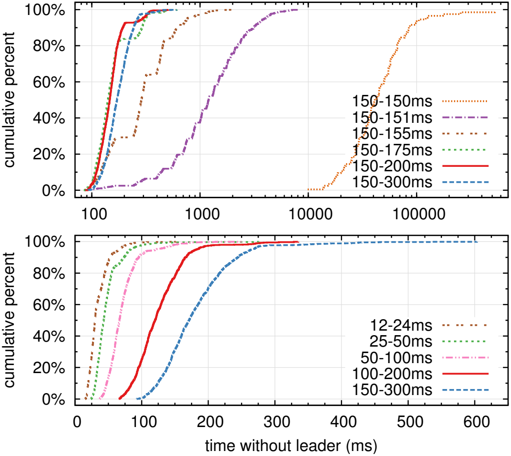
How’d they do?


Raft grade
60
50
40
30
20
10
0
0
10
20
30
40
50
60
Paxos grade
Raft then Paxos +
Paxos then Raft ×
number of participants
20
15
10
5
0
implement
explain
Paxos much easier
Paxos somewhat easier
Roughly equal
Raft somewhat easier
Raft much easier

9.2. Correctness

They wrote proofs! See citations.

9.3. Performance



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- Paxos
- Implementations of Paxos
- Implementations of consensus systems (Chubby, ZooKeeper, Spanner, etc)
- Performance improvements for Paxos
- Viewstamped Replication - similar to Raft, about as old as Paxos.

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- VR and ZooKeeper are also leaderbased, but are more complicated (you can add log entries during elections, etc)
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- Every request must go through the leader.
- Doesn't horizontally scale well.

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- You trust all your servers, but one gets hacked.
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- You don't trust some of your servers.
- You don't trust all of your servers.
- Bitcoin comparison?

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Space
MONKEY

Space Monkey!

- Distributed Hash Tables
- Consensus algorithms
- Reed Solomon
- Monitoring and sooo much data
- Security and cryptography engineering

Space Monkey!

Come work with us!