System Implementation Strategies + Raft Leader Election

March 2025

Lindsey Kuper (@lindsey@recurse.social)
@lindsey

"Oh, you wanted to *increment a counter*?! Good luck with that!" -- the distributed systems literature

2:55 PM · Mar 9, 2015

358 Reposts **15** Quotes **714** Likes **23** Bookmarks

23

Overview

- Successful System Implementation Strategies
  - Understand the Concepts and Code Structure
  - Iterative Design Process
  - Modular Programming
  - Tips on Debugging
- Raft Leader Election

Understanding Concepts and Code Structure

Understand the Concept and Code Structure

- What is the conceptual system you want to build? **Concept**
  - Understand the concept and verify your knowledge with some examples
  - Rewrite the algorithm to some pseudocode, which can serve as the guide during actual programming
- How is the system physically built? **Build**
  - Read the skeleton code
  - Map the algorithms/concepts to the given code structure
  - Draw flow charts to understand the code flow
- How to use the system? **Usage**
  - Read the testing script to see how an external user will talk to our system and invoke its APIs to accomplish desired tasks

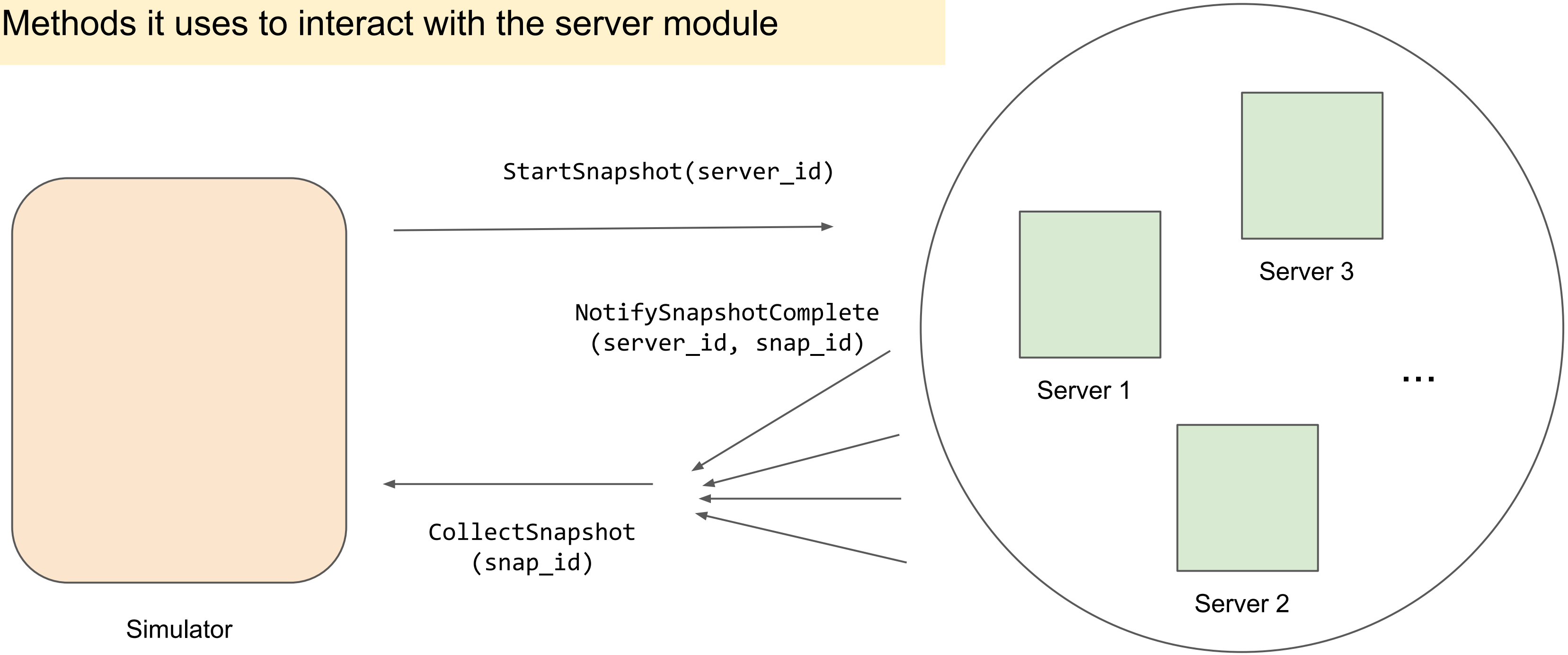
Understand Concept and Code Structure

- Fully comprehend the algorithm
- Spend time to map your understanding of the concept to the starter code
    - For both the system interface and individual modules, understand **what** data is transferred between and **how**
- Charts and pseudocode can help A LOT!

How is the System Physically Built?

Understand the simulator's implementation (see *simulator.go*)

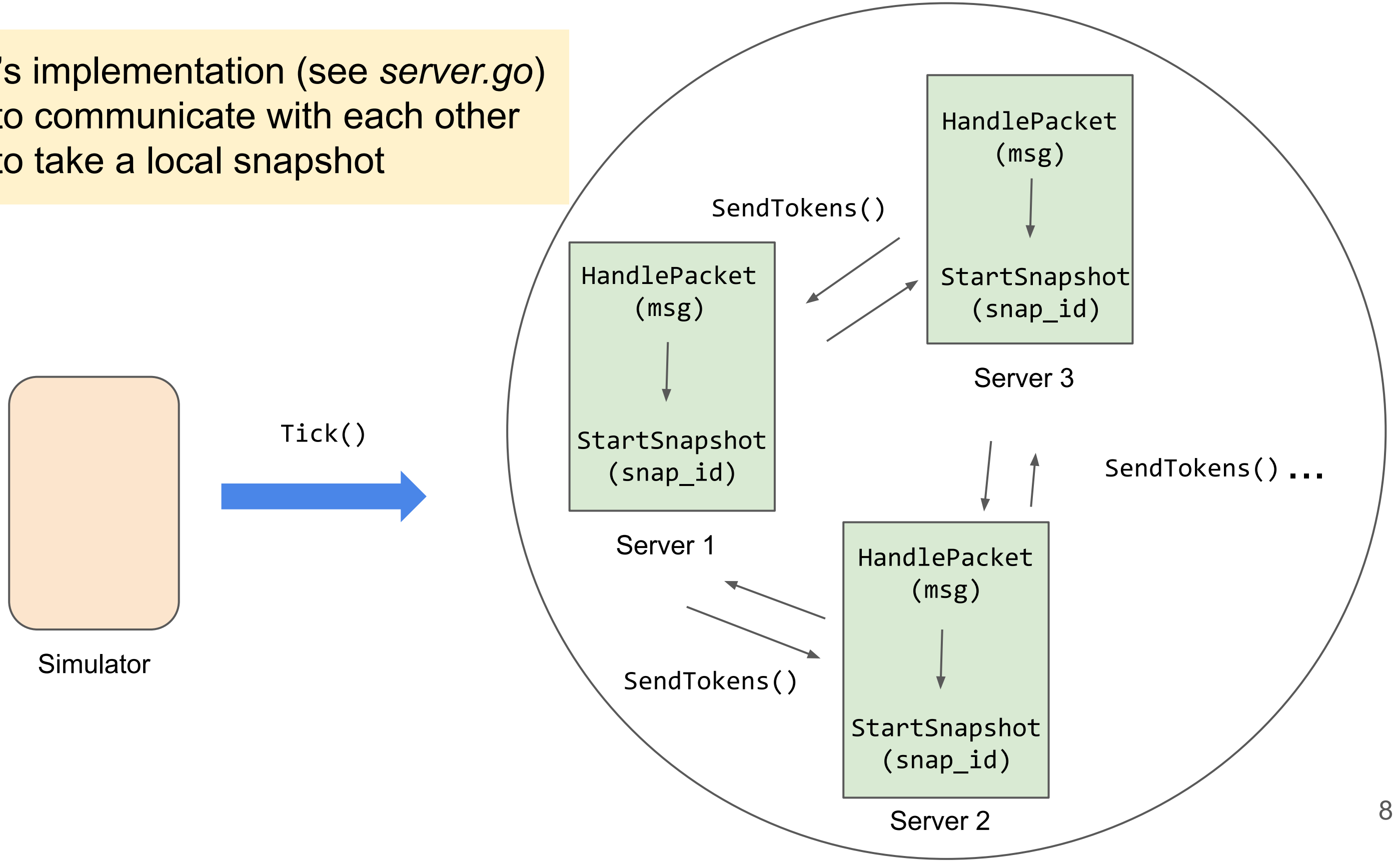
- The role of the simulator
- Methods it uses to interact with the server module



How is the System Physically Built?

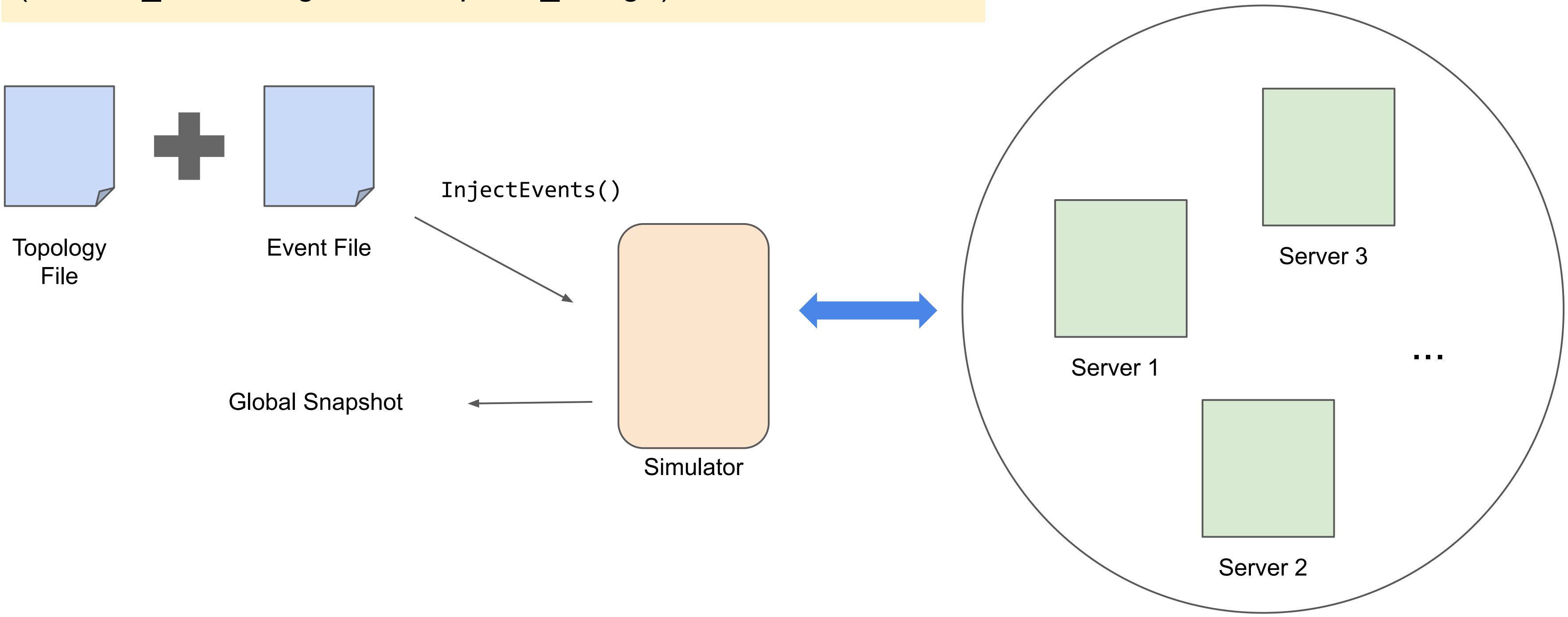
Understand the server's implementation (see *server.go*)

- Methods it uses to communicate with each other
- Methods it uses to take a local snapshot



How to Use the System?

Understand how the external environment talks to our system
(see *test_common.go* and *snapshot_test.go*)



Iterative Design Process

Iterative Design Process

Common design methodology in product design, including software design

You will understand a little more about your design when you start implementing it.

- Start with the base case (aka simplest case)
    - Example: one global snapshot at a time for Assignment 2, distributed MapReduce without any failure for Assignment 1.3
- Test regularly: should pass test case for 2 nodes, then 3 nodes and …
- Add one more complexity at a time

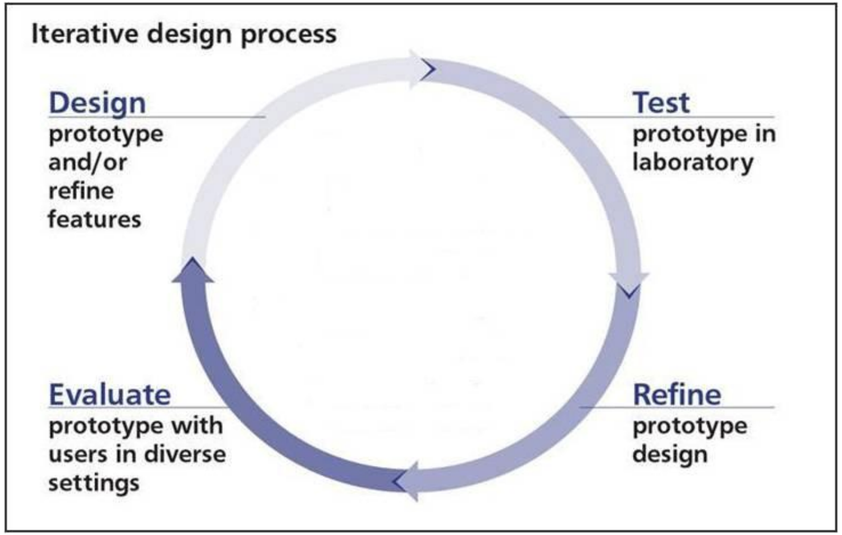
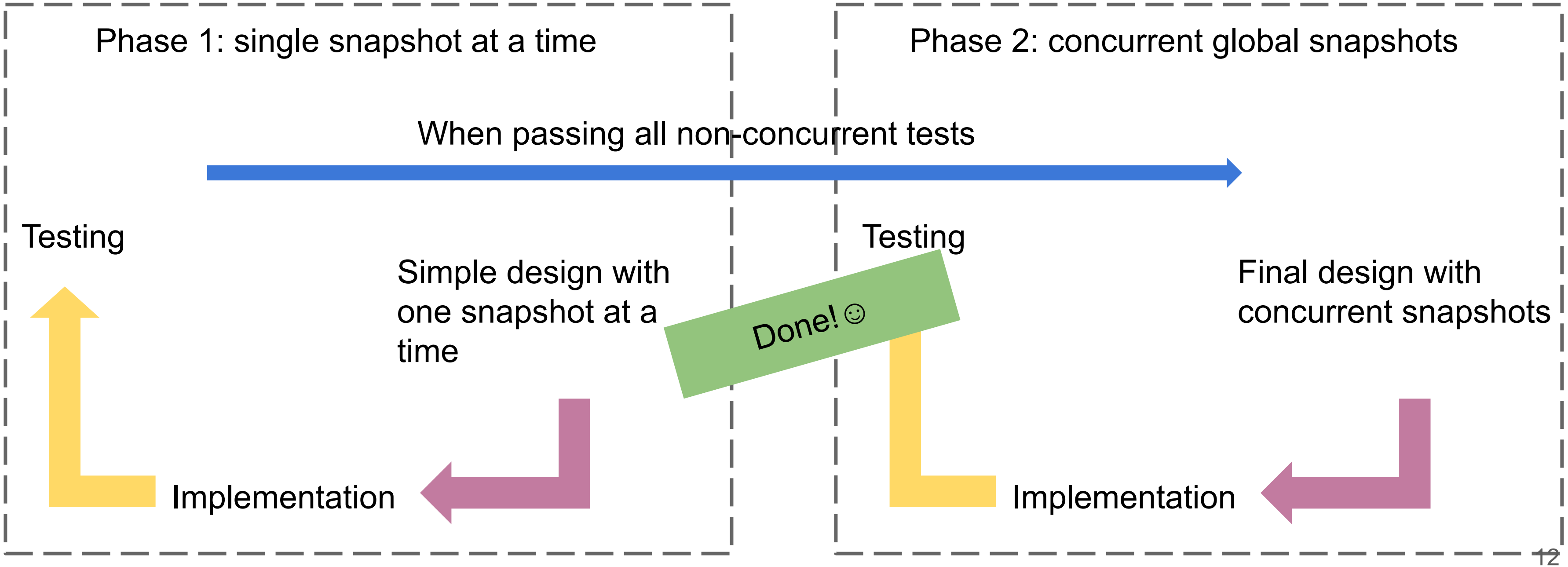


Image Source from the Internet

Iterative Design Process: Distributed Snapshot

Key Idea: Start Simple, then Build Up



Modular Programming

Modular Programming

Iterative design means code change every time when refining the design ☹️

Modular programming

- Decompose the system into several independent modules/pieces
- Use a set of simple yet flexible APIs for intra-module communication

Advantages of modular programming

- Makes it easier to reason about and debug each component of your system
- Requires minimal change in the code

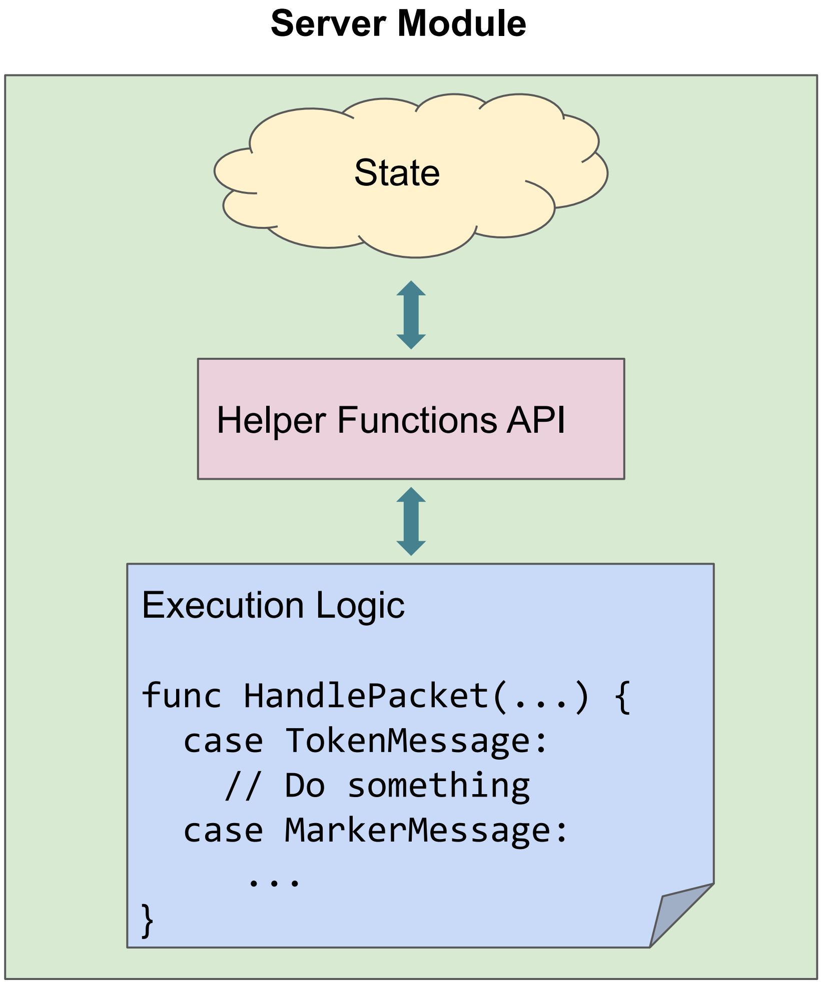
Modular Programming

Phase 1: single snapshot at a time

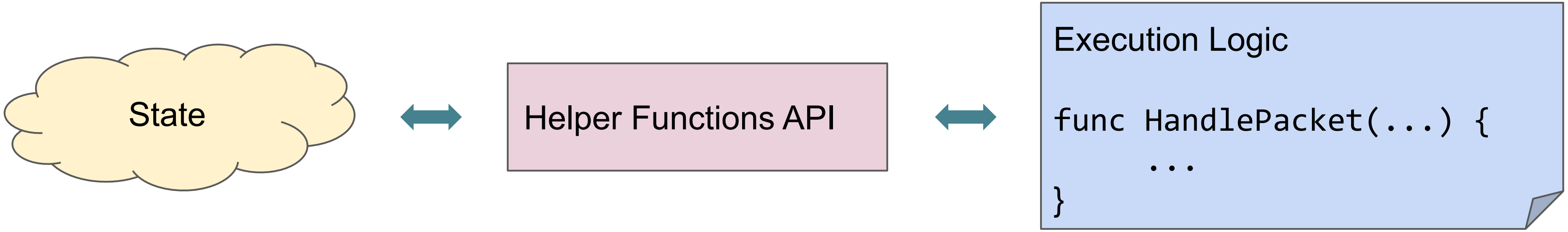
Divide our server module into 3 pieces:

- Server State
- Execution logic
- A layer of helper functions

Goal: write a flexible layer of helper functions



Modular Programming: Single Snapshot




```
// ID of the current snapshot
snapId: int (init to -1)

// State of the current snapshot
snapState: SnapshotState

// Track if each incoming channel has
seen a marker message (default to
false)
receivedMarker:
map(source channel, bool)
```

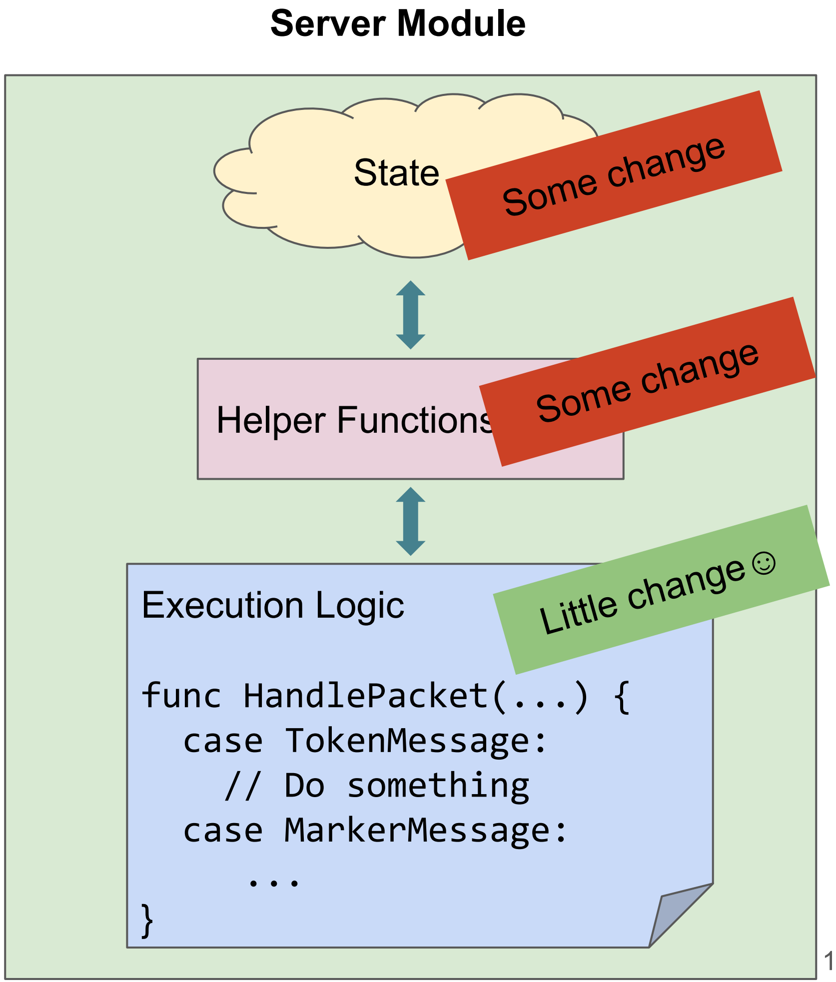
```
func updateSnapshot(src, msg) {
  snapMsg = SnapshotMessage(src, msg)
  snapState.messages.append(snapMsg)
}

func setReceivedMarker(src) {
  receivedMarker[src] = true
}

func firstMarkerMsg(snap_id) {
  return snapId != snap_id
}

Func receiveAllMarkers() {
  return receivedMarker.size == inboundLinks.size
}
```

```
func HandlePacket(src, msg) {
  ...
  case TokenMessage:
    updateSnapshot(src, msg)
    // Also, update server’s local state
  case MarkerMessage:
    snap_id = getSnapId(msg)
    if firstMarkerMsg(snap_id) {
      StartSnapshot(snap_id)
    } else {
      setReceivedMarker(src)
      if receiveAllMarkers() {
        // Notify simulator of the completion
      }
}
```

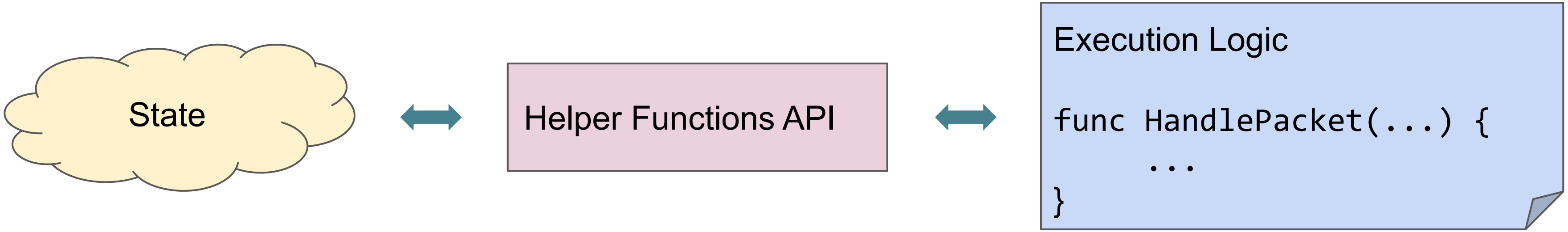
Modular Programming

Phase 2: concurrent snapshots

- Update the state variables and helper functions' implementation
- Keep the API and execution logic unmodified (almost)



Modular Programming: Concurrent Snapshots




```
// States of concurrent snapshots
// map snapshot ID to its state
snapStates: map(int, SnapshotState)

// For each snapshot, track if each
incoming channel has seen a marker
message (default to false)
receivedMarker:
map(int, map(source channel, bool))
```

1. Update state variables

```
func updateSnapshot(snap_id, src, msg) {
  snapMsg = SnapshotMessage(src, msg)
  snapStates[snap_id].messages.append(snapMsg)
}

func setReceivedMark(snap_id, src) {
  receivedMarker[snap_id][src] = true
}

func firstMarkerMsg(snap_id) {
  return (snap_id in snapStates.keys())
}

Func receiveAllMarkers(snap_id) {
  return receivedMarker[snap_id].size ==
inboundLinks.size
}
```

2. Update helper functions while keeping most of its API intact

```
func HandlePacket(src, msg) {
  ...
  case TokenMessage:
    for snap_id in snapStates.keys() {
      updateSnapshot(snap_id, src, msg)
    }
    // Also, update server's local state
  case MarkerMessage:
    snap_id = getSnapId(msg)
    if firstMarkerMsg(snap_id) {
      StartSnapshot(snap_id)
    } else {
      setReceivedMarker(snap_id, src)
      if receiveAllMarkers(snap_id) {
        // Notify simulator of the completion
      }
}
```

3. Minimal change on execution logic

Tips for Debugging

Tips on Debugging

- **Start Early! (This is imperative for Assignment #4)**
- Commit your code to Git often and early, and every time when you pass a new test (enable comparative debugging later if necessary)
- Have proper naming for variables and add comments in your code
  - Easier for both you and others to read and debug your code
- Take advantage of Go Playground if you are not familiar with any Go specifics
- Print statements are your friend!
- Read this ASAP

Prints Are Your Friend ☺

- Always verify the behavior of your program! Sometimes, it may not align with your expectation because of some hidden bugs.
- Track execution using printing statements to understand the code flow
  - Especially helpful in the early development of your design when the code complexity is not too high
- Help catch errors in the early stage
- Example
  - In Assignment 2, we can print out the server state before and after `HandlePacket()` and `StartSnapshot()` that you implement after each tick of the simulator

Raft Leader Election

Raft

- System for enforcing strong consistency (linearizability)
- Similar to Paxos and Viewstamped Replication, but much **simpler**
- Clear boundary between *leader election* and the *log consensus*
- Leader log is ground truth; log entries only flow in one direction (from leader to followers)

Leader election

Everyone sets a randomized timer that expires in [T, 2T] (e.g. T = 150ms)

When timer expires, increment term and send a `RequestVote` to everyone

Retry this until either:

1. You get majority of votes (including yourself): become leader
2. You receive an RPC from a valid leader: become follower again

Conditions for granting vote

1. (Assignment 3) We did not vote for anyone else in this term
2. (Assignment 3) Candidate term must be >= ours
3. (Assignment 4) Candidate log is at least as *up-to-date* as ours
    a. The log with higher term in the last entry is more up-to-date
    b. If the last entry terms are the same, then the longer log is more up-to-date

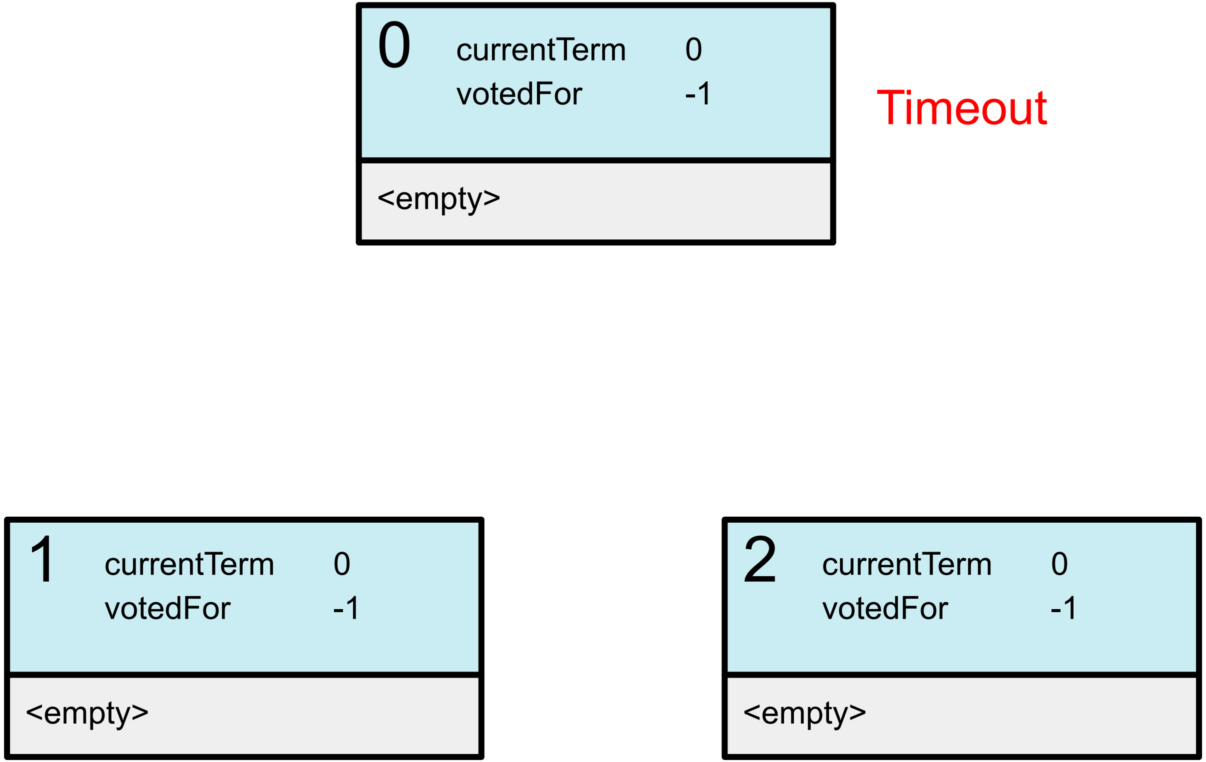
0		
	currentTerm	0
	votedFor	-1
	commitIndex	0
	lastApplied	0
	nextIndex	[ ]
	matchIndex	[ ]
(log entries here)		

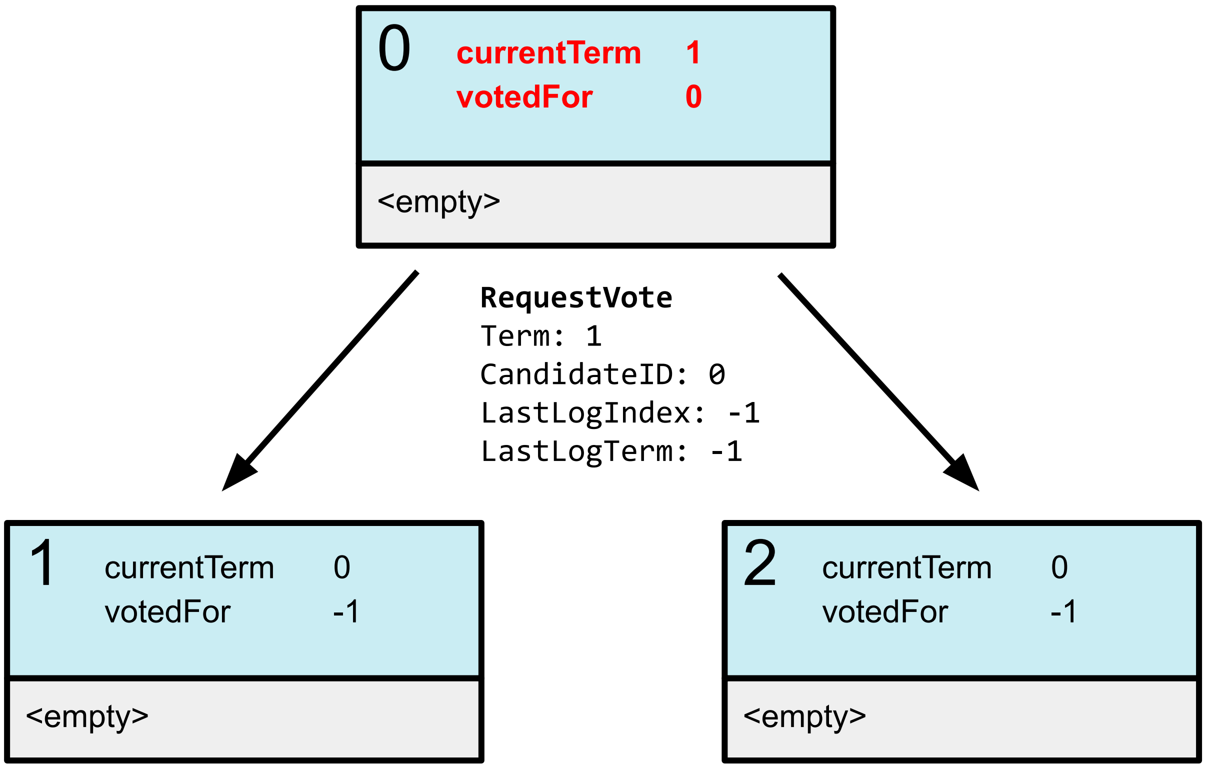
Logs are 1-indexed

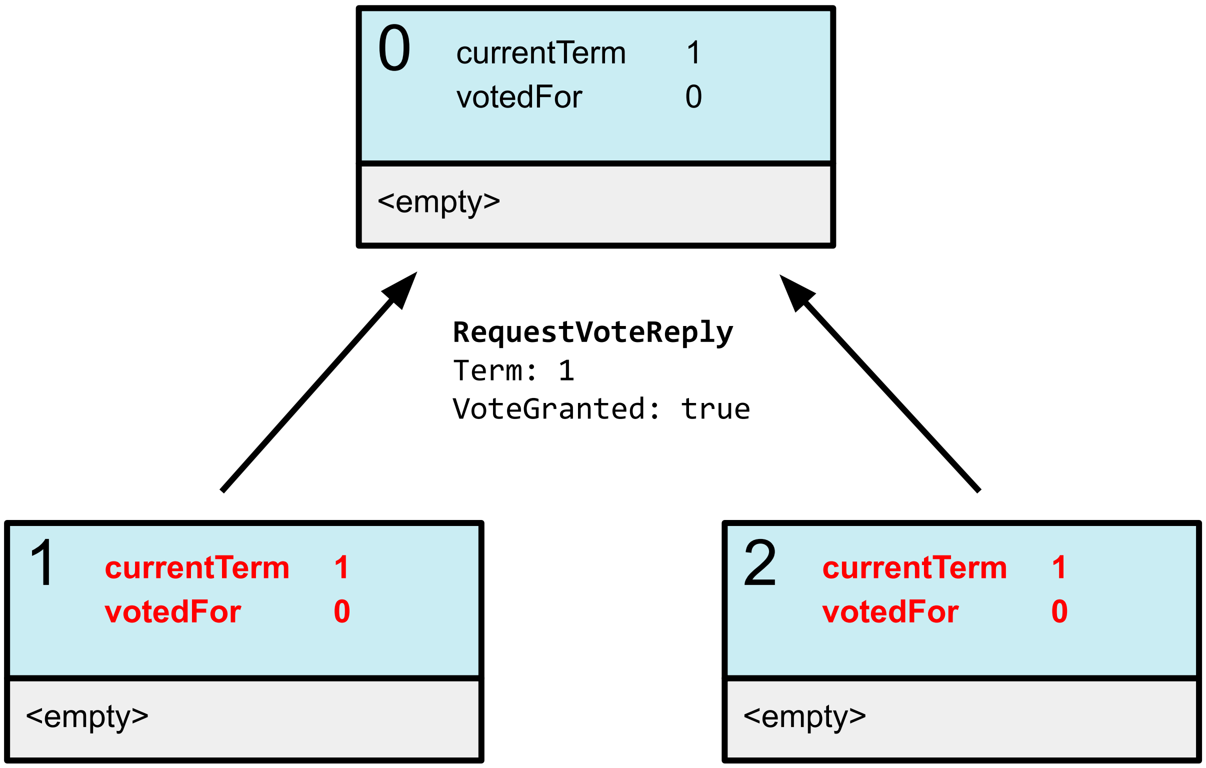
currentTerm	latest term server has seen
votedFor	candidate ID that received vote in current term, or -1 if none
commitIndex	index of highest log entry known to be committed
lastApplied	index of highest log entry applied to state machine

(Only on leader)

nextIndex	for each server, index of the next log entry to send to that server
matchIndex	for each server, index of highest log entry known to be replicated on the server


0
currentTerm 0
votedFor -1
<empty>
Timeout
1
currentTerm 0
votedFor -1
<empty>
2
currentTerm 0
votedFor -1
<empty>


0
currentTerm 1
votedFor 0
<empty>
RequestVote
Term: 1
CandidateID: 0
LastLogIndex: -1
LastLogTerm: -1
1
currentTerm 0
votedFor -1
<empty>
2
currentTerm 0
votedFor -1
<empty>


0
currentTerm 1
votedFor 0
<empty>
RequestVoteReply
Term: 1
VoteGranted: true
1
currentTerm 1
votedFor 0
<empty>
2
currentTerm 1
votedFor 0
<empty>

0 currentTerm 1
votedFor 0

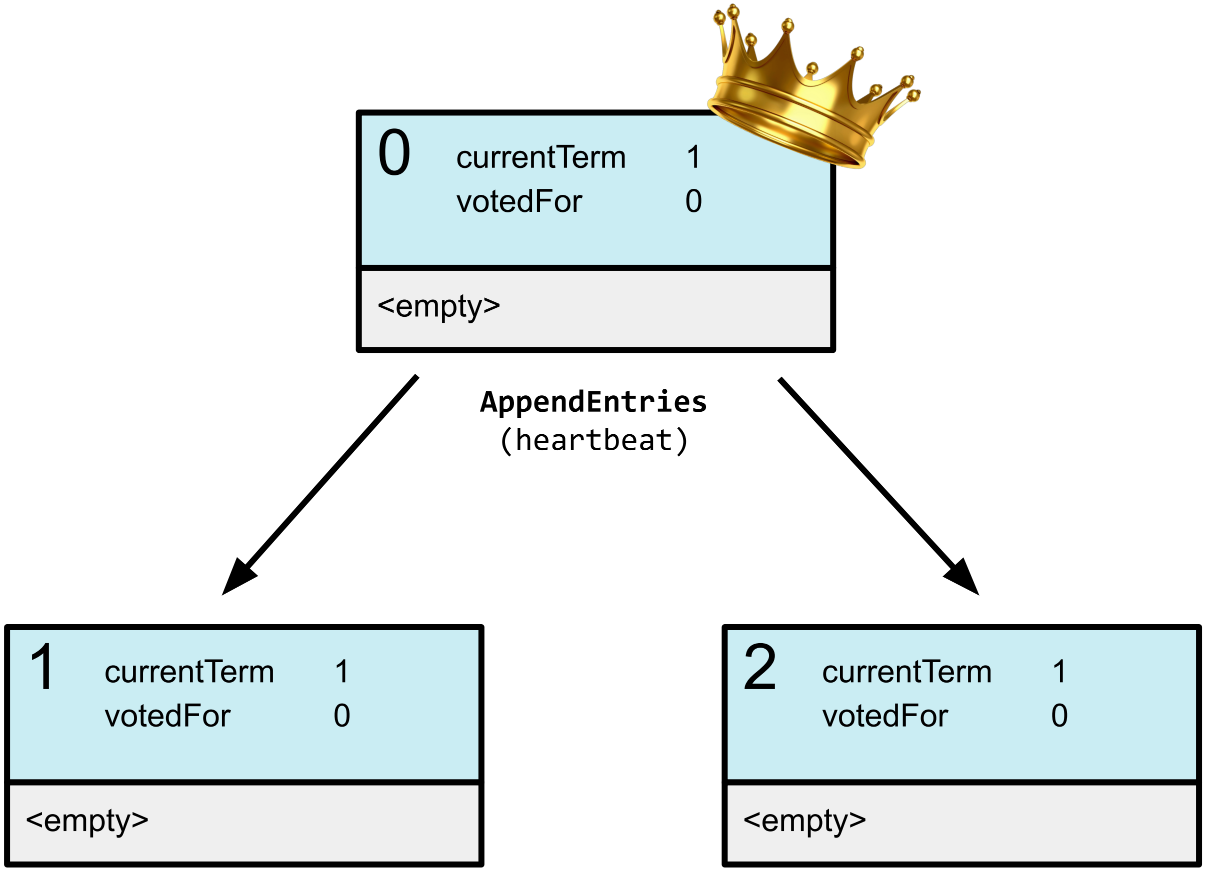
<empty>

1 currentTerm 1
votedFor 0

<empty>

2 currentTerm 1
votedFor 0

<empty>


0
currentTerm 1
votedFor 0
<empty>
AppendEntries
(heartbeat)
1
currentTerm 1
votedFor 0
<empty>
2
currentTerm 1
votedFor 0
<empty>

Assignments 3 and 4

You will implement the *leader election* portion of Raft in Assignment 3
You will implement the *log replication* portion of Raft in Assignment 4

Use `time.Timer` and `select` statements to implement timeout

- Need to time out on heartbeats (AppendEntries) → Start election
- Need to time out on waiting for majority of votes

When voting for yourself, you can skip the RPC

Importance of readability

A luxury for small projects, but a necessity for large and complex projects

A4 will build on top of your solution for A3
A3 only accounts for about 20% of the work

Some tips:

- Duplicate code is *really* bad; avoid at all costs
- If a function is more than 30 lines, it is too long → split!
- Avoid nested if-else's; use `return`s and `continue`s where possible