Christopher Jones

DRAFT

Achieving distributed consensus with Paxos

Part II Project

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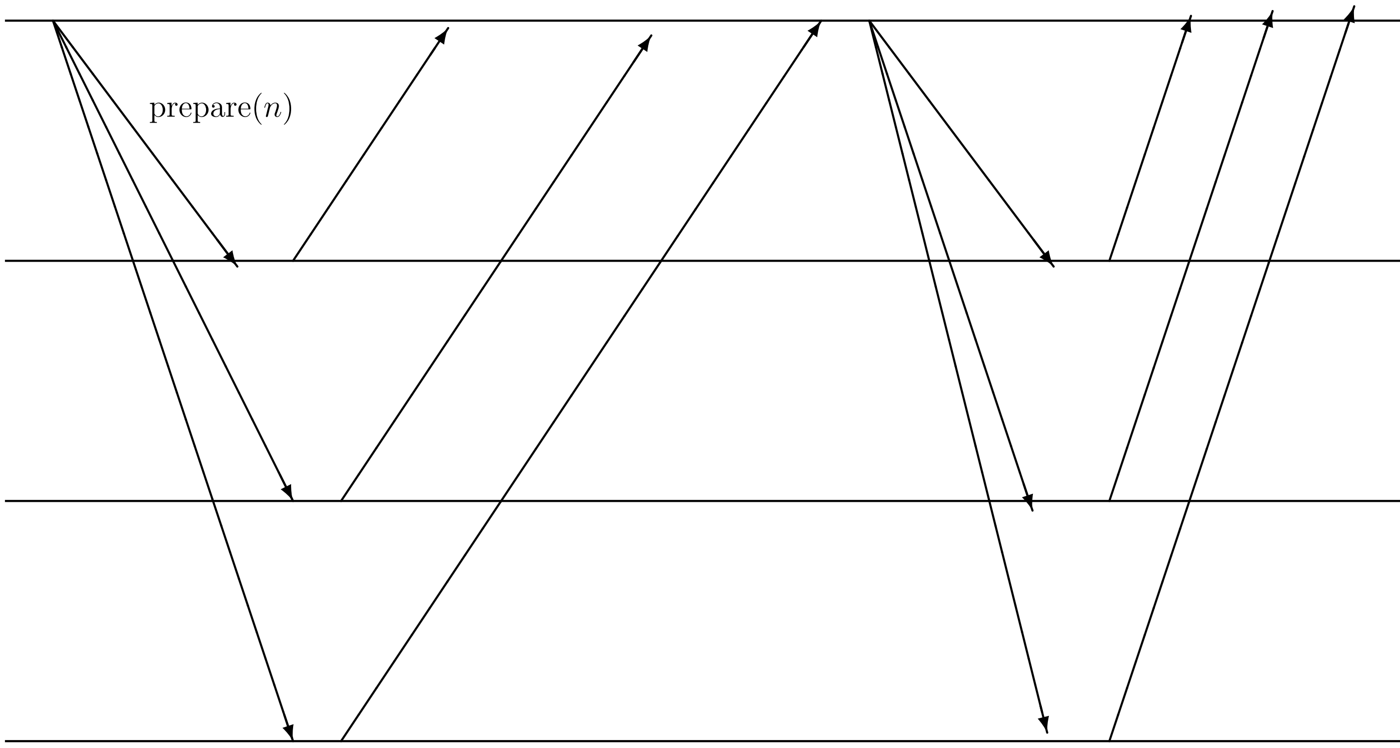
prepare(n)

Contents

Chapter 1

Introduction

1.1 Background

Distributed systems suffer from a number of possible errors and failure modes. Unreliability is present in the network where messages can be delayed, re-ordered and dropped and processes can exhibit faulty behaviour such as stalling and crashing. The result of this is that distributed systems can end up inconsistent states and even unable to make progress.

Consensus is the reaching of agreement in the face of such unreliable conditions. Transaction systems, distributed databases and leadership elections are all applications that require consensus in order to remain consistent. Consensus algorithms provide a means by which to reach agreement across in a distributed system in the face of such unreliability; this is crucial in the design of distributed systems.

Paxos is a consensus algorithm first described by Lamport [4] that allows for consensus to be reached under the typical unreliable conditions present in a distributed system. It is a three-phase commit system that relies on processes participating in the *Synod* voting protocol in order to tolerate the failure of a minority of processes.

Paxos is used internally in large-scale production systems such as Google's Chubby [1] distributed lock service, where it is used to maintain consistency between replicas. Microsoft's Autopilot [3] system for data centre management also uses Paxos, again to replicate data across machines. The extreme generality of Paxos allows it to be used as an underlying primitive for various distributed systems techniques. State Machine Replication [10] is a technique whereby any application that behaves like a state machine can be replicated across a number of machines participating in the Paxos protocol. Likewise, atomic broadcast [9] can be implemented with Paxos as an underlying primitive.

Over time Paxos has been extended and modified to emphasise different performance trade-offs. Multi-Paxos is the most typically deployed variant which allows for explicit agreement over a sequence of values. Another example, Fast Paxos [6], is a variant that reduces the number of message delays between proposing a value and it being chosen. More recently, Flexible Paxos [2] is a variant that relaxes the requirement on same-phase quorums intersecting in order to improve performance.

There are a number of alternative means of reaching consensus. Viewstamped replication [7] is primarily a replication protocol but can be used as a consensus algorithm. Raft [8] is a modern alternative to Paxos that attempts to reduce the complexity of implementing Paxos. Why didn't we use these though?

1.2 Aims

The aim of this project was to produce an implementation of the Multi-Paxos variant of the Paxos algorithm to replicate a toy distributed application. This is the variant that is used most widely in production systems and provides a foundation upon which to use state machine replication to replicate an application.

OCaml will be used as the primary development language. Why OCaml?

Evaluation and simulator explanation.

Chapter 2

Preparation

2.1 Theotrical background

2.1.1 Assumptions of the environment

When considering developing a system with distributed consensus, it is necessary to consider the assumptions made in the environment in which such a system will operate. This is to ensure there is enough functionality embedded in the conesnsus system to ensure that consensus is reached under a given set of assumptions.

A *process* (or networked process) is an instance of the program running on a networked machine in a distributed system. Assumptions of these processes that participate in the system:

- Processes can undergo *crash failures*. A crash failure is defined as a process terminating but not entering an invalid state.
- Processes may recover from crash failures. They can rejoin the system in some valid state.
- Processes operate at arbitrary speeds. This cannot be distinguished by other processes from arbitrarily long delays in the network.

Assumptions of the network in which these processes communicate:

- All processes can communicate with one another.
- The network environment is *asynchronous*. That is, messages may take an arbitrarily long time to be delivered.
- Messages may be re-ordered upon delivery.
- Messages may be duplicated in the network.
- Messages may be dropped from the network.

- Messages are not corrupted or modified in the network.
- A message that is received by one process was, at some point in the past, sent by another process.

The last two assumptions assume a system that does not tolerate what are known generally as *Byzantine failures*.

2.1.2 Aim of consensus

With distributed consensus, we wish for a network of processes to agree on some value. In consensus algorithms it is assumed that processes can somehow propose values to one participating processes. The goal of distributed consensus is, given a number of processes that can each propose some value v, that one of the proposed values is chosen. This is the *single-decree* case, that is only one value is proposed by each process and only one is chosen.

In the *multi-decree* case, agreement is reached over a sequence of values. That is, each process will propose a sequence of valus $v_1, v_2, \ldots, v_n$ and the role of the consensus protocol is to have the system choose one such sequence from all those proposed. This multi-decree case allows for the state machine replication technique to be employed to replicate an application across a number of machines in a distributed system.

2.1.3 State machine replication

A desirable goal of distributed computing is to replicate an application across a number of machines so that each *replica* has the same strongly-consistent view of the application's state. This technique is referred to as State machine replication (SMR); it leads to both for increased fault tolerance and higher availability. Multi-decree consensus protocols provide a primitive by which an application (that behaves like a state machine) can be replicated.

Each process participating in the consensus protocol runs the replicated state machine application, with each process starting in the same state. Then by treating the values proposed in the consensus protocol as *commands* to perform a state transition, then by running a consensus protocol each process will receive the same serialized sequence of commands $c_1, c_2, \ldots, c_n$. These commands are treated as commands to perform a state transition and as such each process perform the same sequence of transitions from the same starting state and thus

Role	Purpose	Number required
Proposer	Propose values to acceptors. Send prepare requests with proposal numbers.	$f + 1$
Acceptor	Decide whether to *adopt* a proposal based on its proposal number Decide whether to *accept* a proposal based on a higher numbered proposal having arriving.	$2f + 1$
Learner	Learn value chosen by majority of acceptors	$f + 1$

Table 2.1: Summary of the roles in single-decree Paxos. In this description the system can tolerate the failure of up to f of each given role.

be a replica of the the state machine application.

Before considering how to implement SMR in the multi-decree case, it is useful to examine how Paxos operates in the simpler single-decree case.

2.1.4 Single-decree Paxos

Single-decree Paxos is the variant of the algorithm that allows for a single value to be chosen from a set of proposals and provides a foundation for the multi-decree case that will be considered next. The terminology used here follows Lamport's paper [5] describing the single-decree protocol in simple terms. Processes take the roles of *proposers*, *acceptors* and *learners*, each of which has a designated task in the Paxos algorithm. In reality these roles are often co-located within a single process but it is simply to consider each separately. The prupose of each role and the number of each role required to tolerate f failures is summarised in Table 2.1.

Proposers that wish to propose a value v submit proposals of the form (n, v), where $n \in \mathbb{N}$ is called a proposal number. Each proposer may propose one proposal at a time and may only use strictly increasing proposal numbers for each proposal. Furthermore, each proposer must use a disjoint set of proposal numbers. The Paxos algorithm is divided into a number of stages described below.

Phase 1a (Prepare phase) A proposer wishing to propose a value first sends a `prepare`(n) message to a majority of the set of acceptors, where n is the highest proposal number it has used so far.

Phase 1b (Promise phase) In this phase an acceptor receiving a `prepare(`n`)` message must decide whether or not to *adopt* this proposal number. Adopting a proposal number is the act of promising not to accept a future proposal number n' such that $n' < n$. The acceptor will adopt n if it is the highest proposal number it has received thus far, in which case it will reply to the proposer with a `promise(`n''`,`v`)` message, where n'' is the highest proposal number it has previously accepted and v is the corresponding proposal's value. Otherwise, it can simply ignore the proposer or send a `NACK` message so the proposer can abandon the proposal.

Phase 2a (Accept phase) Upon receipt of a `promise(`n`,`v`)` message from a majority of the set of acceptors, the proposer replies to each with an `accept(`n'`,`v'`)`, where n' is the highest proposal number returned by the acceptors in the promise phase and v' is its corresponding value.

Phase 2b (Commit phase) An acceptor receiving a `accept(`n`,`v`)` message from a proposer will decide whether to commit the proposal for v. If the acceptor hasn't made a promise to adopt a proposal number higher than n, then it will commit v, otherwise it will ignore this message or send a `NACK` to the proposer.

Once this process is completed, a majority of the acceptors will have chosen the same proposed value. Learners are required to learn what value was chosen by the majority. A number of different methods can be employed to deliver this information. Acceptors can, on choosing a value to accept, broadcast their decision to the set of learners. An alternative method is to have a distringuished learner (or small subset of) that are sent all decisions which then forward onto the set of learners when they have learned the majority.

Talk about some simple examples with corresponding timing diagrams.

2.1.5 Multi-decree Paxos

Single-decree Paxos can be naively extended by allowing proposers to propose values one at a time. However, this is wasteful as it requires that proposers send `prepare` messages for each proposal they wish to make. A number of optimisations and extensions can be put in place to increase the efficiency of the system. The system here primarily follows PAXOS MADE MODERATELY COMPLEX and introduces different types of nodes. Also discussed here is how to extend the system to use state machine replication. The new roles and their

Role	Purpose	Number required
Client	Send commands to replicas and receive responses	N/A
Replica	Receive requests from clients. Serialize proposals and send to leaders. Receive decisions and apply to the replicated application state. Handle reconfiguration of set of leaders	$f + 1$
Leader	Request acceptors adopt ballots.	$f + 1$
Acceptor	Fault tolerant distributed memory. Voting protocol.	$2f + 1$

Table 2.2: Summary of the roles in Multi Paxos. In this description the system can tolerate the failure of up to f of each given role. Note that clients do not explicitly participate in the protocol and so there is no requirement on any number being live at any given time.

correspondence to the single-decree roles are summarised in Table 2.2.

Diagram showing the communication pattern of nodes in Mutli-Paxos. Contrast with the single-decree case.

Clients and replicas are introduced to provide a means of implementing the replicated state machine.

Clients

The purpose of clients is to allow for commands to be sent externally to the system which can then be formed into proposals internally. This allows the system to behave in a manner more like that of a typically deployed distributed system (with a client / server architecture) and provides a degree of failure transparency.

A command c takes the form (κ, cid, op), where κ is a unique identifier for the client, cid is a unique identifier for the client's sent commands and op is the operation the command should perform. Clients broadcast a `request(`c`)` message to the replicas and each is issued a `response(`cid`,`$result$`)` when consensus is reached and it has been applied to each replica's application state.

Replicas

Replicas receive commands and attempt to serialize them by converting each command c into a proposal (s, c), where $s \in \mathbb{N}$ is a slot number. The slot number describes ordering of the sequence in which the commands should be committed; this is not to be confused with the proposal number n in the single-decree protocol.

Different replicas may form different sequences of proposals and so broadcasts a `propose(`s`,`c`)` message to the set of leaders and awaits a `decision(`s'`,`c'`)` message. The resulting decision may differ in its slot number and so the replica may have to re-propose a command it has proposed for the decided slot. Upon receipt of decisions the replica will applying the associated operation to the application state, maintaining the replicated application.

(Also reconfigurations)

Diagram showing message flow between clients and replicas to clarify the last points.

Ballots and pvalues

Explain ballots.

- A ballot may map a command to multiple slots.
- A slot may be mapped to multiple ballots.
- Leaders can attempt to secure adoption of multiple ballots concurrently.

Ballot numbers are either pairs (r, λ) (where $r \in \mathbb{N}$ is called a round number and λ is a leader's unique identifier) or $\bot$, a specially designated least ballot number.

A *pvalue* is a triple (b, s, c) consisting of a ballot number, a slot number and a command. These are analogous to to the (n, v) pairs used in the single-decree case. In the single-decree case, we required that each proposer used a disjoint subset of $\mathbb{N}$ for their proposal numbers. We can avoid this requirement as each ballot number encodes the identifier of the leader directly in its ballot number (i.e. no two leaders can generate equal ballot numbers).

We require ballot numbers to be totally ordered so that acceptors can compare which ballot number is less than another when choosing whether to adopt or accept. Letting $\mathcal{B}$ denote the set of all ballot numbers, we define the relation $\leq \in \mathcal{B} \times \mathcal{B}$ which satisfies the following two conditions:

$$\forall (n, \lambda), (n', \lambda') \in \mathcal{B}.\ (n, \lambda) \leq (n', \lambda') \iff (n \leq n') \vee (n = n' \wedge \lambda \leq \lambda') \tag{2.1}$$
$$\forall\, b \in \mathcal{B}\ .\ \bot \leq b \tag{2.2}$$

Note this implies that we require leader identifiers be equipped with a total order relation as well.

Quorums

Explanation of quorum systems.

Let $\mathcal{Q}$ be the set of all quorums of acceptors, that is $\mathcal{Q} = \mathcal{P}(\mathcal{A})$. Quorums are *valid* if they share at least one common member, that is

$$\forall Q_1, Q_2 \in \mathcal{Q}\ .\ Q_1 \cap Q_2 \neq \emptyset$$

Hence we can use a majority quorum by requiring that $|Q_1| = |\mathcal{A}|\ /\ 2$.
Need to really think about these quorum systems.

The Synod Protocol

The synod protocol is the protocol undertaken by the set of leaders and acceptors in order to decide which command is committed to which slot. The protocol proceeds in two phases similarly to the single-decree case except now leaders and acceptors operate over pvalues.

In the absence of receiving any `propose(`s`,`c`)` messages from replicas, leaders attempt to secure an initial ballot with ballot number $(0, \lambda_i)$, where λ_i is the identifier of the ith leader. They do this by broadcasting a `phase1a(`b`)` message in the same format as that below.

Phase 1a Leaders attempt to secure an initial ballot by broadcasting `phase1a(`(n, λ)`)` message.

Phase 1b Acceptors receiving a `phase1a`$((n, \lambda))$ compare (n, λ) to the highest ballot number they have adopted thus far. This is initially $\perp$ so acceptors will adopt the first ballot number they receive automatically. If $b \leq (n, \lambda)$, then the acceptor will adopt this new ballot number. In either case, the acceptor will reply with a

Chapter 3

Implementation

3.1 High level structure of program

In this section the high level structure of the program is discussed. See figure blah blah for an overview of the structure of a typical process.

Each of the processes takes the *role* of either a client, replica, leader or acceptor. These roles each have a different function in the system within their *role module*, which contains all the functionality associated specifically with a given role.

Each of the roles shares a number of common middlewares in the program, the main being the messaging subsystem. The purpose of this subsystem is to provide indirection between the way that messages are treated by the role modules and the method by which they are actually sent over the network. The desire is to have messages behave as an atomic primitive with semantics as described in Assumptions section, obscuring all of the protocol-level functionality in sending the messages over an IP network.

The role module is divided up into two separate `Lwt` threads. The response server handles the receipt of messages from other processes and performs any required processing accordingly (this is still role specific), which can result in sending further messages. Any concurrent processing required of the role is performed concurrently in the role specific systems.

Each of the processes requires additional information at start-up, such as

1. The role it should take.
2. The address at which it should start a server to receive messages.
3. The set of addresses of all the participating processes of all roles.

Items (1) and (2) are consumed via comand line arguments when the program is run. (3) requires the use of a configuration file, the relative path to which is

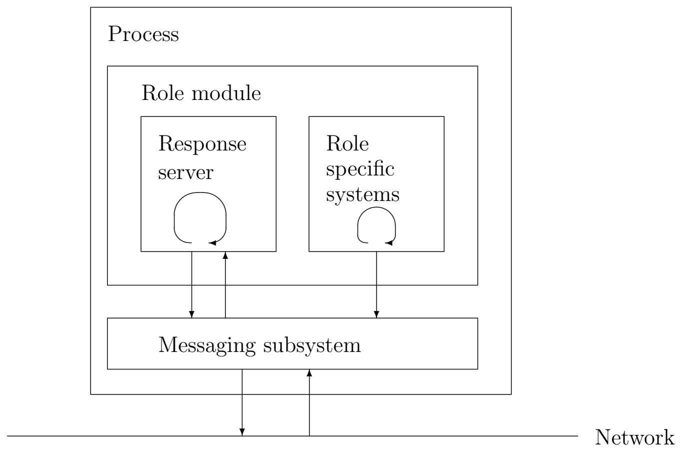

Figure 3.1: High level subsystems of a process

provided as a command line argument. The configuration file is formatted in JSON and provides, for each role, a list of all of the addresses of each process. An example configuration file is included in Reference the appendix. Figure blah blah shows a flow diagram describing how initialisation proceeds

(Addresses are provided as an IP address (V4 or V6) and a port number)

Flow diagram of init.

3.2 Data structures

Before proceeding the implementation of the systems described above, it is necessary to examine the data structures that will be used.

3.2.1 Identifiers

Unique identifiers are required to identify each process in the system. To avoid having a central authority distribute these identifiers at start-up a method where any process can generate their own unique identifer is used. Universally Unique Identifers[1] (UUIDs) are used in this case as they are a well established standard and have support in the OCaml Core library. UUIDs are also totally ordered and so satisy the condition that we have such an ordering on the identifers of leaders.

[1]https://tools.ietf.org/html/rfc4122

```
module type APPLICATION = sig
  type state = (int, string) List.Assoc.t
  type operation = Nop
                 | Create of int * string
                   ...
  type result = Success
              | Failure
                ...
  val initial_state : state
  val apply : state -> operation -> state * result
   ...
end
```

Figure 3.2: Signature of the key value store module

Command	Arguments	Semantics
Nop		No operation, No change to state
Create	`(K,V)`	Add new `(K,V)` pair to the state If key already present, then return Failure

Table 3.1: Set of operations that can be applied to the application state, along with their corresponding arguments and their semantics. Note that Create and Update commands are separate, each with their own success and failure semantics in order to reduce ambiguity of how the application operates.

Hence replicas, leaders and acceptor identifiers have the type `Core.Uuid.t`. As we wish to expose clients to a request / response protocol it is necessary to store a map of client identifiers to addresses by each replica. Rather, by modifying client identifiers to be of the form `Core.Uuid.t * Uri.t`, the address actually forms part of the identifier.

3.2.2 Key value store

The key value store is the application that is to be replicated. Hence each replica process will maintain its own independent copy of the application state. The application itself needs not maintain any synchronisation logic, it need only behave as a state machine. The state is represented by an association list (commonly called a dictionary) that maps integer keys to string values. Operations each have

```
type t = Bottom
       | Number of int * leader_id
```

Figure 3.3: Types of ballot numbers.

their own semantics described in Table 3.1. The application follows a state machine pattern given that if each replica starts in the initial state and each applies the same sequence of operations in the same order, the resulting state is the same.

When a command has been committed to a slot by the consensus algorithm, the command's operation is applied to the state. This returns a new state and a result, which represents the updated state held by the replica and the resulting information returned to the replica (the client does not receive a whole copy of the new state in its reply). The signature of this key value store is shown in figure blah blah.

3.2.3 Ballots

The definition of ballot numbers from the Preparation chapter lends itself to the types of ballot numbers being represented by an algebraic datatype. Ballots are hence the tagged union of Bottom (representing the least ballot $\perp$) or a pair consiting of an integer and a leader identifer (representing pairs (n, λ)). The type definition is included in Figure blah blah.

Figure blah blah shows the interface exposed by the Ballot module. Note that the concrete type of ballot numbers isn't exposed, only the abstract type `t`. Therefore outside of this module the representation of ballot numbers is hidden. This prevents a large number of errors, such as decrementing a round number when they should strictly increase, from arising by rejecting them at compile-time. However, this requires a number of functions be supplied so that ballot numbers can be manipulated outside this module.

Hence a given leader can generate an initial ballot number with their identifer. Subsequent ballot numbers can be generated by calling a successor function, which increments the round number each time. By exposing such an interface we prevent errors such as using negative round numbers from being able to compile.

The module provides functions to test equality and the ordering of ballots. These

```
type t
val bottom : unit -> t
val init : leader_id -> t
val succ_exn : t -> t
```

Figure 3.4: The interface exposed by the Ballot module. These are the types of functions that can be used to generate ballot numbers. Note the naming of the function `succ_exn` implies it can throw an exception, which occurs when calling the function on `bottom`.

work over the structure of ballots, comparing them first for correct types and then checking round number and leader id equality. Also in the Ballot module are functions for serialisation and deserialisation to and from JSON, required by the messaging system for sending ballots.

3.3 Messages

- Talk about the Cap'n Proto schema format. Include snippets of the schema file and how it relates to messages we are required to send (could easily fit the schema into a two page appendix as well).
- Include mention of serialization of certain parts of the application as JSON. Design decisions of how to divide up serialization code between data structures, etc. Where to do draw the line between JSON serialization and Cap'n Proto schema etc.
- Now talk about implementation of the Cap'n Proto server. How functions-as-values were used to allow callbacks to be performed by the server.
- Recall / reference the message semantics required from the preparation chapter. Explain how we carefully handle exceptions to ensure we get the desired semantics of messaging from Cap'n Proto.

3.4 Clients and replicas - better title?

3.4.1 Clients

- Talk about how clients operate outside the system
- How they send messages to replicas.

- Include .mli interface for replicas, the record (with mutable fields) for storing replicas.

3.4.2 Replicas

- Leading on from clients, explain how messages can be re-ordered / lost / delayed from clients and how broadcasts from replicas allow progress in the event of replica failure.
- Describe the two-fold operation of replicas. They receive and perform deduplication of broadcast client messages. They then go on to propose to commit commands to given slots. They also handle when leaders reject their proposals so they can be re-proposed later. They also maintain the application state (in this case the replicated key-value store.)
- Interesting points to discuss include looking at a snippet of the deduplication function and discussing it. Also looking at how mutexes are used to hold locks on the sets of commands, proposals, decisions etc.
- Include a diagram of the three different sets of commands, proposals and decisions and how each moves from one set to another in different sets of circumstances.

3.5 Synod protocol

3.5.1 Quorums

- Describe how the quorum system was implemented. Show the .mli interface as a snippet and describe how this can be used to achieve majority quorums.
- Show briefly how the majority checking function was implemented.

3.5.2 Acceptors

- Discuss the operation of acceptors - how they form the fault tolerant memory of Paxos.
- Discuss the functions (along with snippets) by which acceptors adopt and accept ballots.

3.5.3 Leaders

- Describe how the operation of leaders is split into two sub-processes - scouts and commanders.
- Operational description of how scouts and commanders communicate concurrently. Diagram displaying how there is a message queue that these sub-processes use to send "virtual" messages.
- Snippets of the signatures and structs used to construct these sub-processes.

Scouts

- Describe how scouts secure ballots with acceptors. Relate this to operation of acceptors above.
- State how scouts enqueue virtual adopted messages after securing adoption from quorum of acceptors.
- Describe how pre-emption can occur when a commander is waiting for adoption.

Commanders

- Explain how commanders attempt to commit their set of proposals.
- Give detail on the pmax and "arrow" function as used in the paper.
- Describe how pre-emption can occur when a commander is waiting for acceptance.

3.6 Summary

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Appendix A

Cap'n Proto schema file

```
@0x9207445e65eea38d;

interface Message {
  # Interface for RPC messaging system

  struct Command {
    clientId @0 :Data;
    # Id of the client that issued command

    commandId @1 :UInt16;
    # Id of the command being issued

    operation @2 :Text;
    # Encodes the operation that will be applied to state of application
    # The type of this is temporary for now

    clientUri @3 :Text;
  }
  # Structure represents the command sent in RPC

  clientRequest @0 (command :Command) -> ();
  # Method clientRequest is a message sent from the client to a replica
  # The client issues a command and response is returned in another messa

  decision @1 (slot_number :UInt16, command :Command) -> ();
  # Replicas receive decision messages sent by a leader
  # Consists of a command and a slot number
  # Slot number is the place slot in which the command has been decided
  # to occupy by the synod protocol

  sendProposal @2 (slot_number :UInt16, command :Command) -> ();
  # Method sendProposal is a message sent from a replica to a leader.
  # Proposals consists of a command and a slot for which that command
  # is proposed.

  clientResponse @3 (commandId :UInt16, result :Text) -> ();
  # Method clientResponse is a message sent from replica to a client
  # Returns the id of the command and result of issuing it

  # ———— CHANGE TYPES OF THOSE BELOW ————————————————————————————

  phase1 @4 (ballotNumber :Text) -> (result :Text);
  # Method phase1 is a message sent from leader to an acceptor
  # As an acceptor responds to each phase1 message with a reply
  # based deterministically on the request we implement in a simple
  # request / response format as above.
  #

  phase2 @5 (pvalue :Text) -> (result :Text);
  # ...
  # ...
  # ...

  # Wrt arguments of the last two messages we have a more experimental appr
  #   - Instead of providing each argument as a Capnp type, instead
  #     each argument will be provided as JSON text. This is because
  #     the format of these messages will be optimised later (state
  #     reduction can be performed on the pvalues we are required to
  #     send) so no point in writing lots of serialization code when
  #     it will change in the future anyway
}
```

Appendix B

Projct Proposal