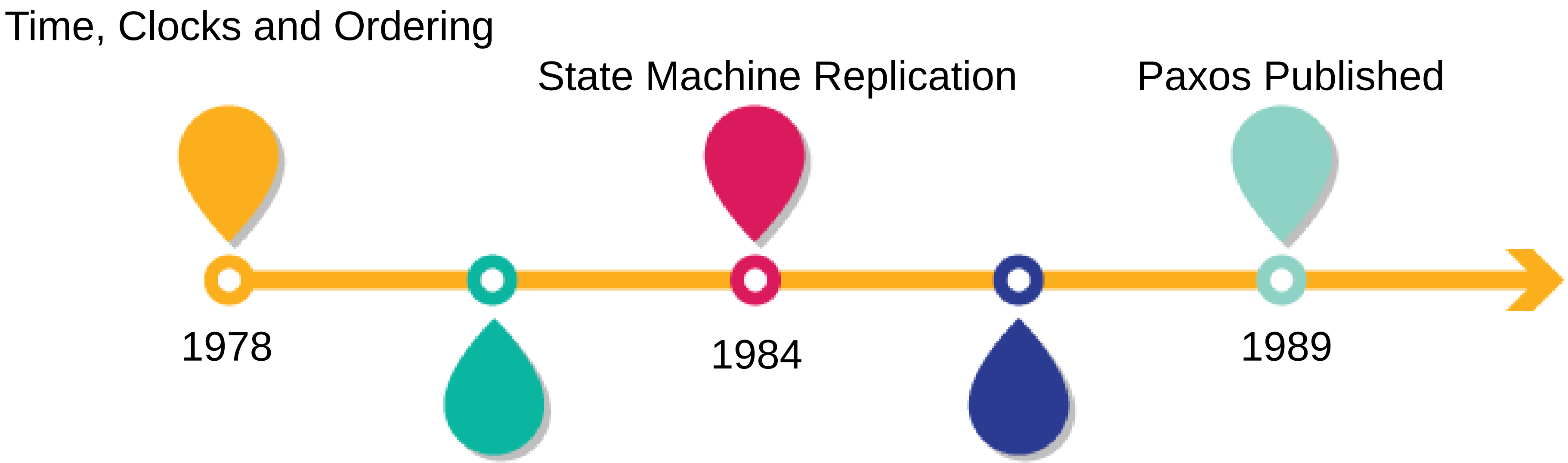
DISTRIBUTED SYSTEMS: PAXOS

CS6410

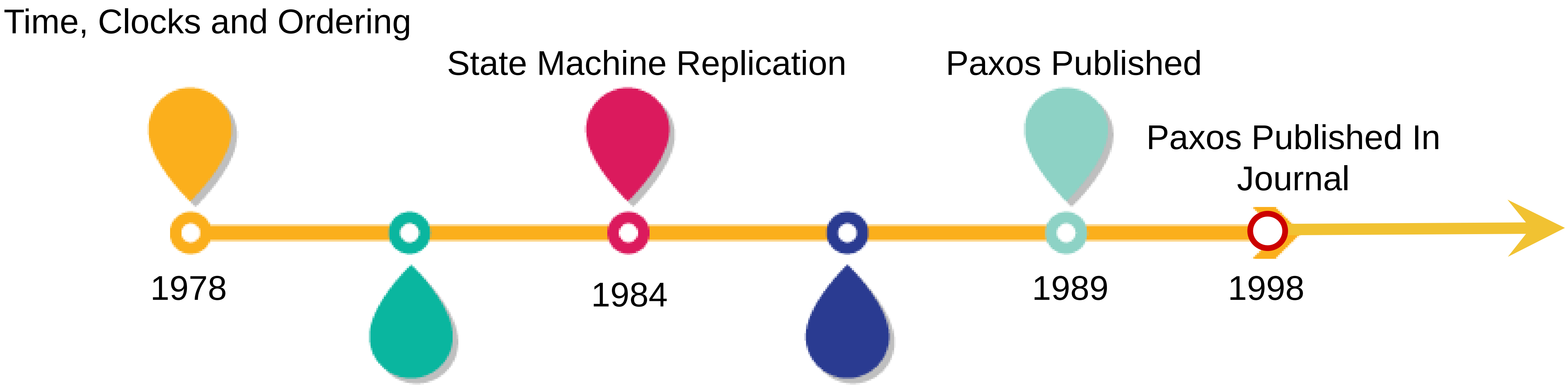
Hakim Weatherspoon

Slides borrowed liberally from past presentations from Robert Surton, Cecchetti, Burcu Canakci and Matt Burke

Timeline

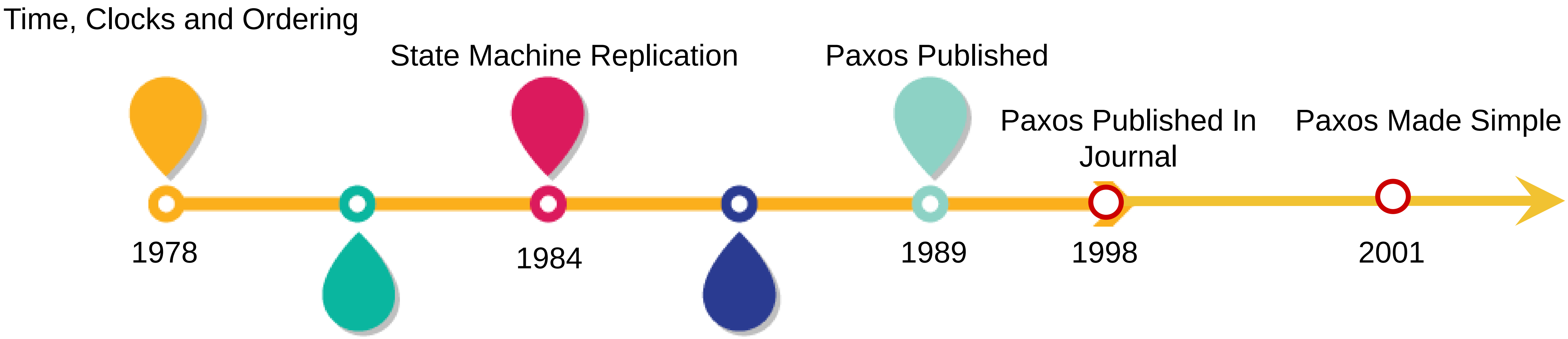

Time, Clocks and Ordering
State Machine Replication
Paxos Published
1978
1984
1989

Timeline

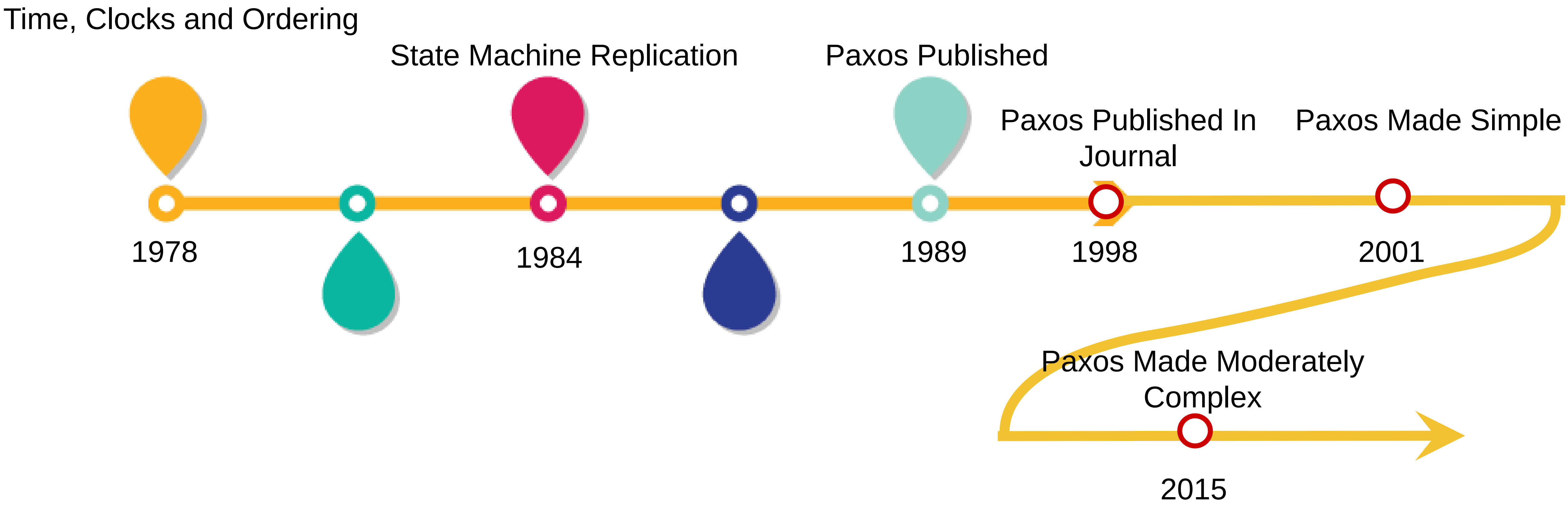


Time, Clocks and Ordering
State Machine Replication
Paxos Published
Paxos Published In Journal
1978
1984
1989
1998

Timeline


Time, Clocks and Ordering
State Machine Replication
Paxos Published
Paxos Published In Journal
Paxos Made Simple
1978
1984
1989
1998
2001

Timeline


Time, Clocks and Ordering
State Machine Replication
Paxos Published
Paxos Published In Journal
Paxos Made Simple
1978
1984
1989
1998
2001
Paxos Made Moderately Complex
2015

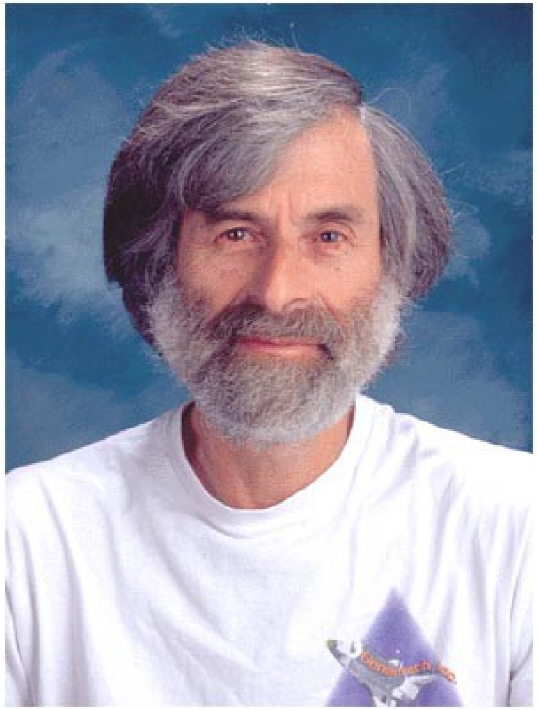
What is consensus?

- Assume a collection of processes that can propose values. A consensus algorithm ensures that a single one among the proposed values is chosen . . . We won’t try to specify precise liveness requirements.
- The consensus problem involves an asynchronous system of processes, some of which may be unreliable. The problem is for the reliable processes to agree on a binary value . . . every protocol for this problem has the possibility of nontermination . . .

What is consensus?

- Only a proposed value may be chosen.
- Only one, unique value may be chosen.
- All correct processes must eventually choose that value.

Paxos



Paxos

- The Part-Time Parliament (1998)
  - *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.*

The Part-Time Parliament

Paxos: The Lost Manuscript

- Finally published in 1998 after it was put into use
- Published as a "lost manuscript" with notes from Keith Marzullo
  - *"This submission was recently discovered behind a filing cabinet in the TOCS editorial office. Despite its age, the editor-in-chief felt that it was worth publishing. Because the author is currently doing field work in the Greek isles and cannot be reached, I was asked to prepare it for publication."*
- "Paxos Made Simple" simplified the explanation…a bit too much
  - Abstract: *The Paxos algorithm, when presented in plain English, is very simple.*

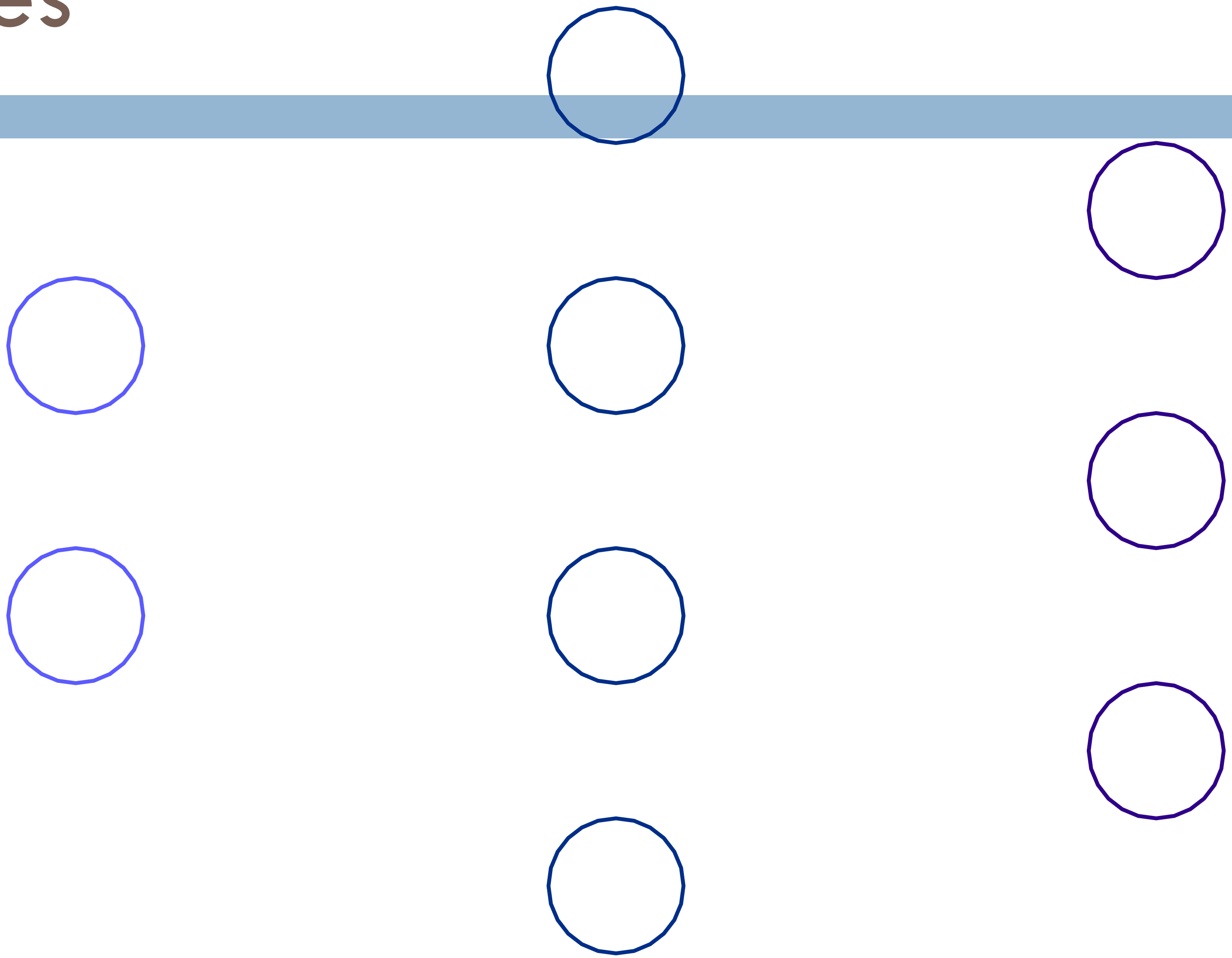
Assumptions about our model

- Processes can fail by **crashing**
  - No indication of failure; simply stops responding to messages
  - Failed processes cannot arbitrarily transition or send arbitrary messages

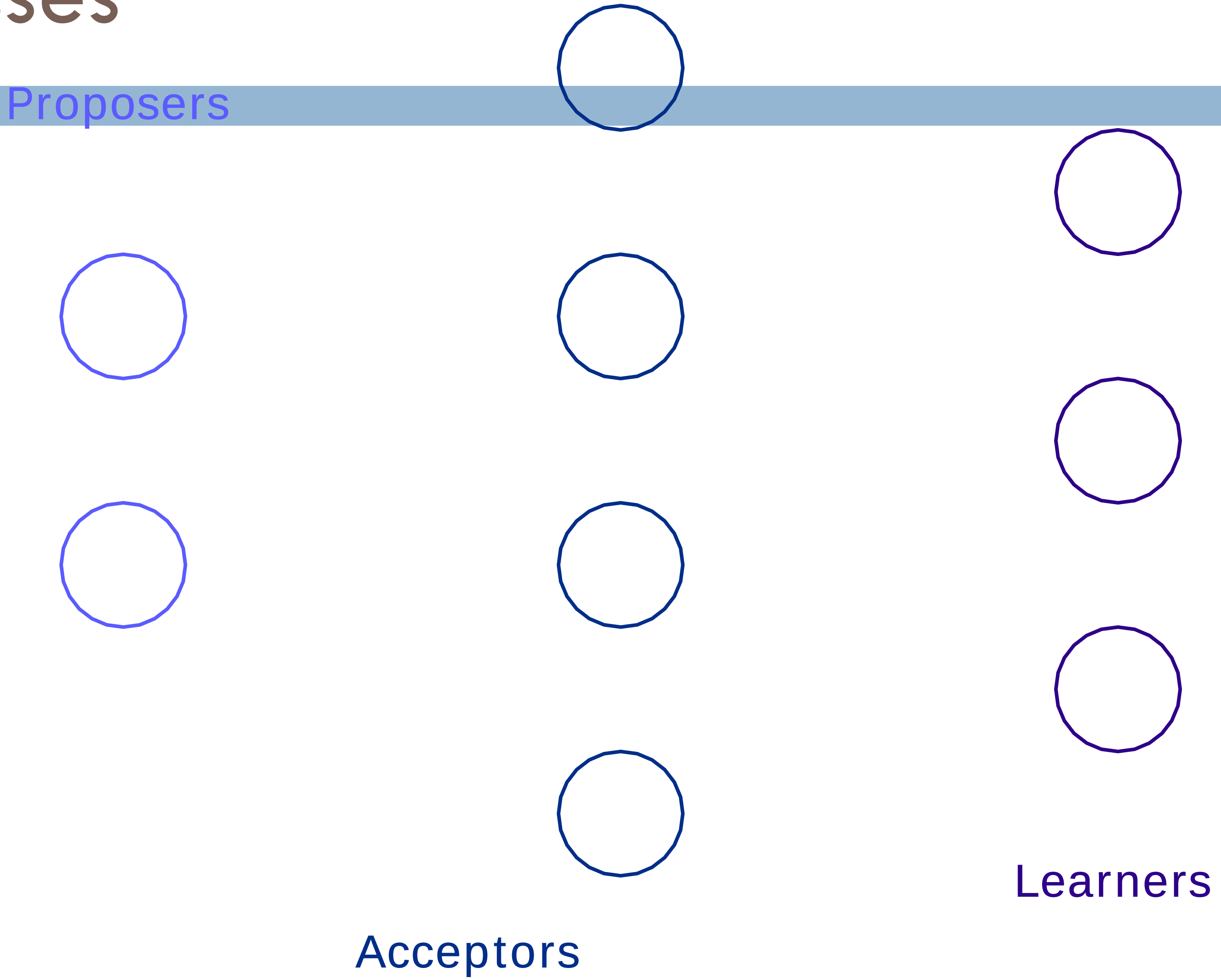
- **Asynchronous**, but **reliable**, network

  Messages can be
  - lost
  - duplicated
  - reordered
  - held arbitrarily long
  - If a msg is sent infinitely many time, it will be delivered infinitely many times.

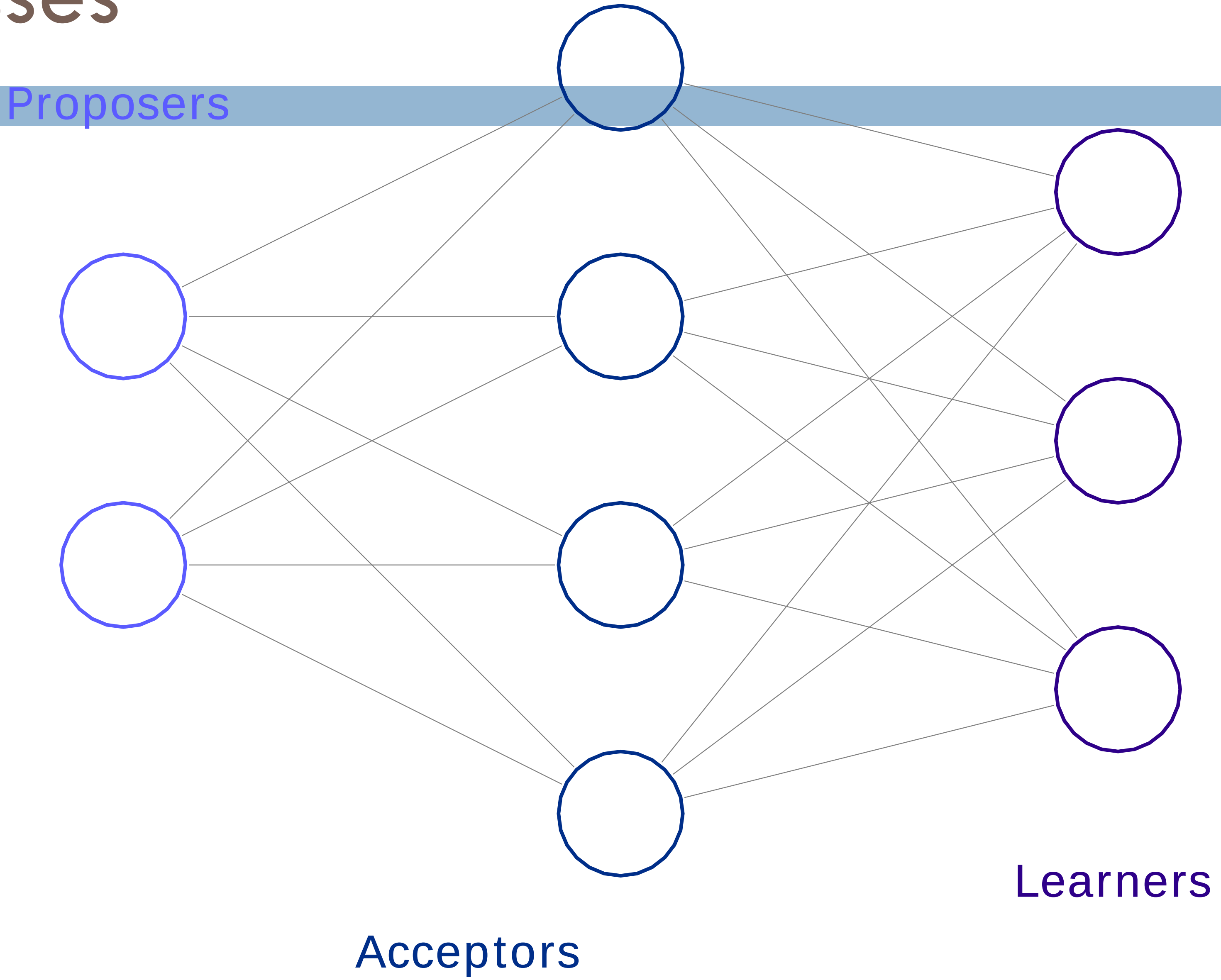
Processes



Processes



Processes



Any process might fail

- There must be multiple acceptors.

Only choose a single value

- A majority of acceptors must agree on the choice.

Property 1

- An acceptor must accept the first proposal it receives.

Wait—what?

- Majority-must-agree + Must-accept-first =

  Acceptors must be able to accept multiple proposals

Wait—what?

- Majority-must-agree + Must-accept-first =

  Acceptors must be able to accept multiple proposals
  - Number all proposals uniquely to distinguish them

Property 2

- If a proposal with value v is chosen, then every higher-numbered proposal *that is chosen*

  has value v.

Property 2a

- If a proposal with value v is chosen, then every higher-numbered proposal *accepted by any acceptor*

  has value v.

Property 2b

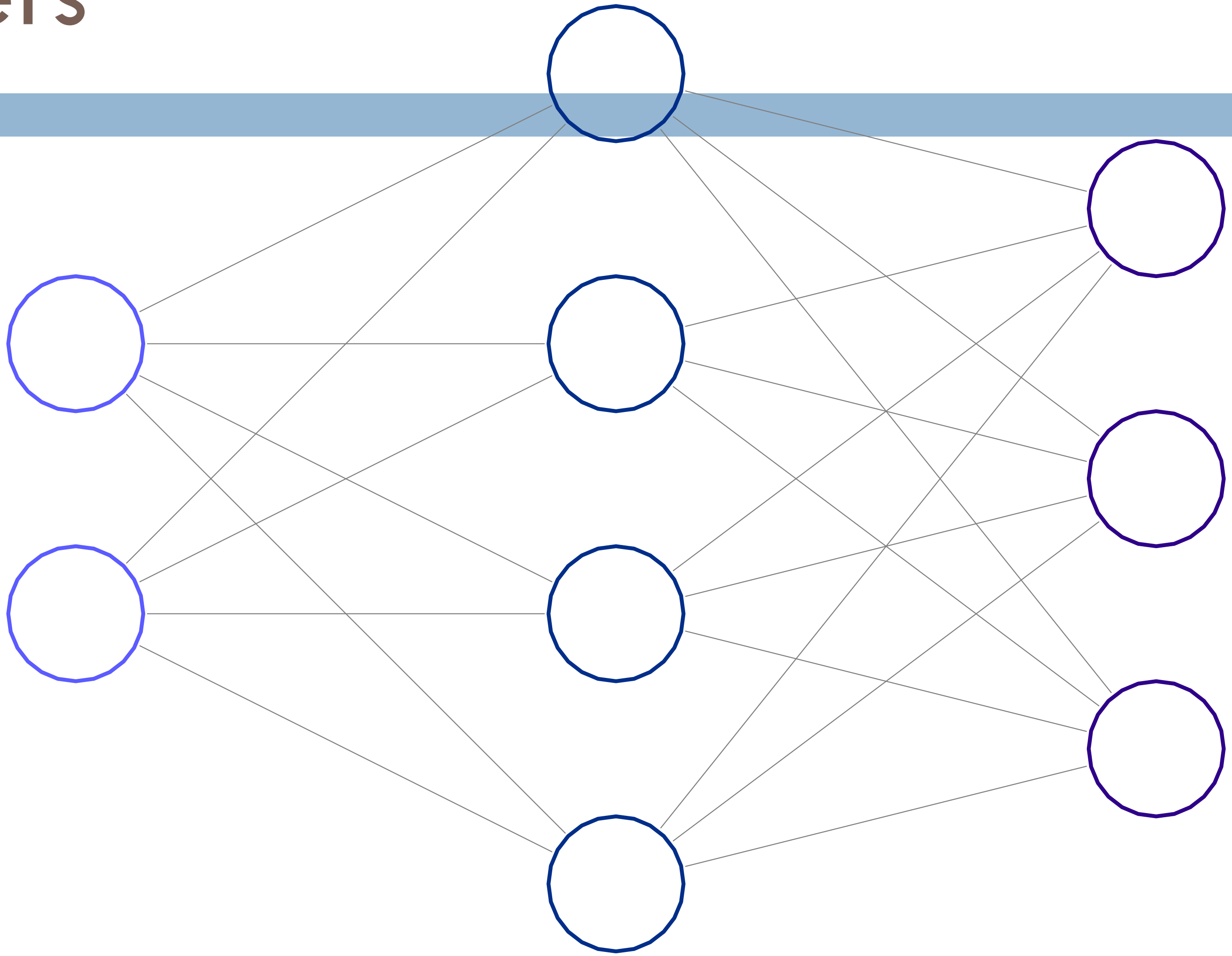
- If a proposal with value v is chosen, then every higher-numbered proposal *issued by any proposer*

  has value v.

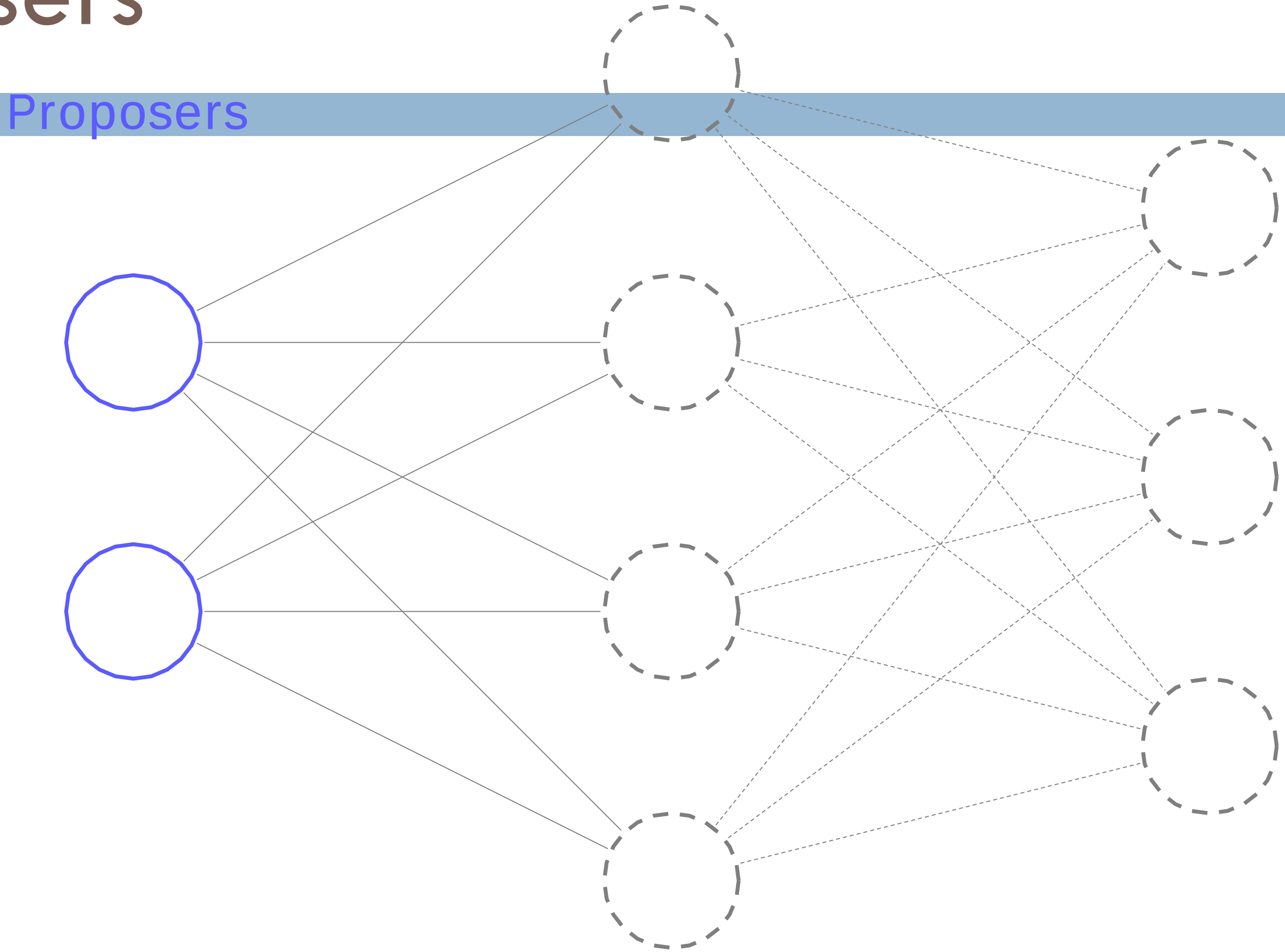
Property 2c

- For any *v* and *n*, if a proposal with value *v* and number *n* is issued, then there is a set *S* consisting of a majority of acceptors such that either
  - no acceptor in *S* has accepted any proposal numbered less than *n*, or
  - v is the value of the highest-numbered proposal among all proposals numbered less than *n* accepted by the acceptors in *S*.

Proposers



Proposers



Prepare requests

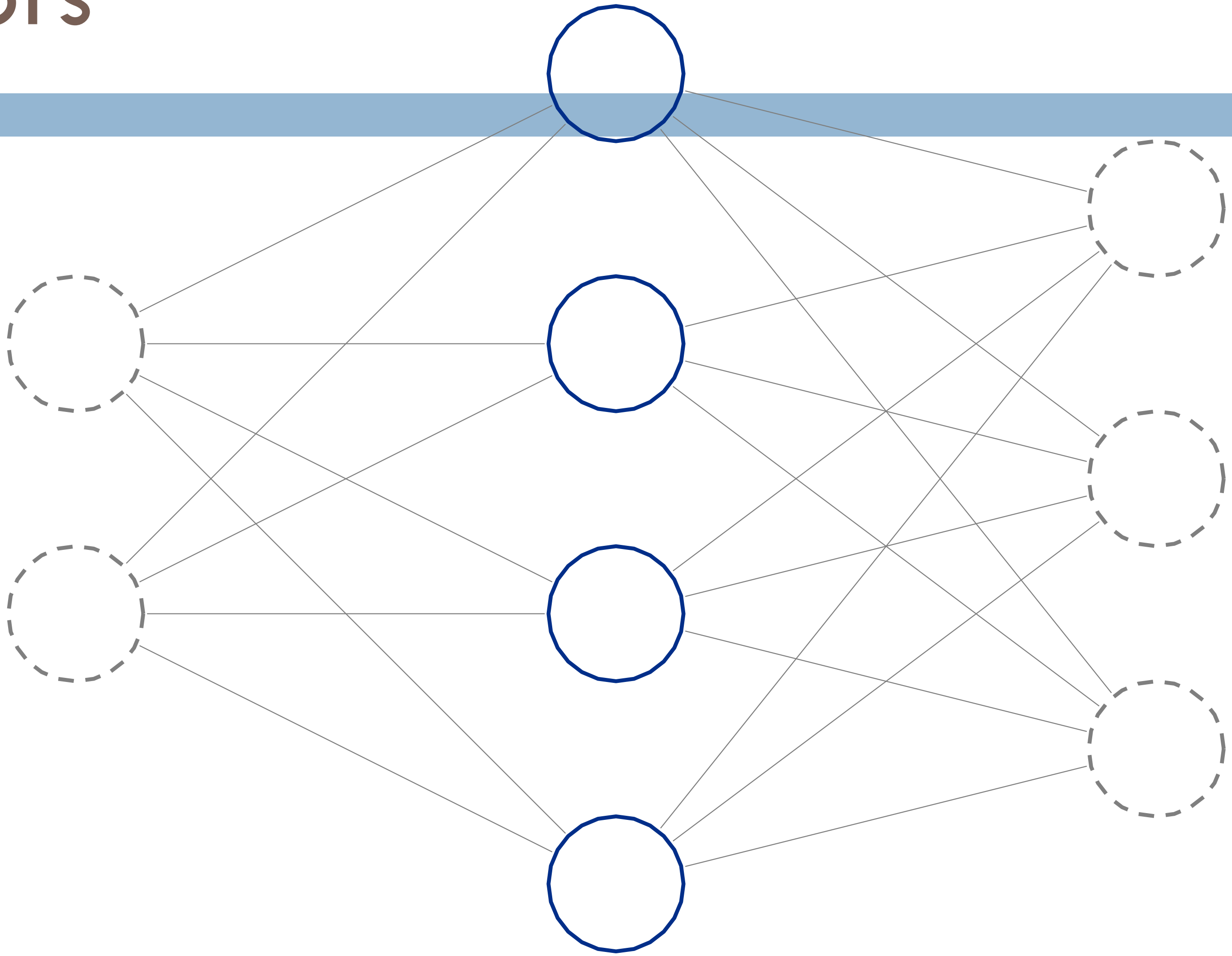
- Instead of predicting the future
  - Proposer sends **prepare** *n* to acceptors
  - Each acceptor replies with
    - A promise to reject lower proposals in future
    - If any, the highest accepted lower proposal

Accept request

- If a majority promise
  - Proposer sends **propose** *n*, *v*
- If there were accepted proposals
  - *v* must match the highest one

  (Otherwise, *v* can be arbitrary.)

Acceptors



Acceptors

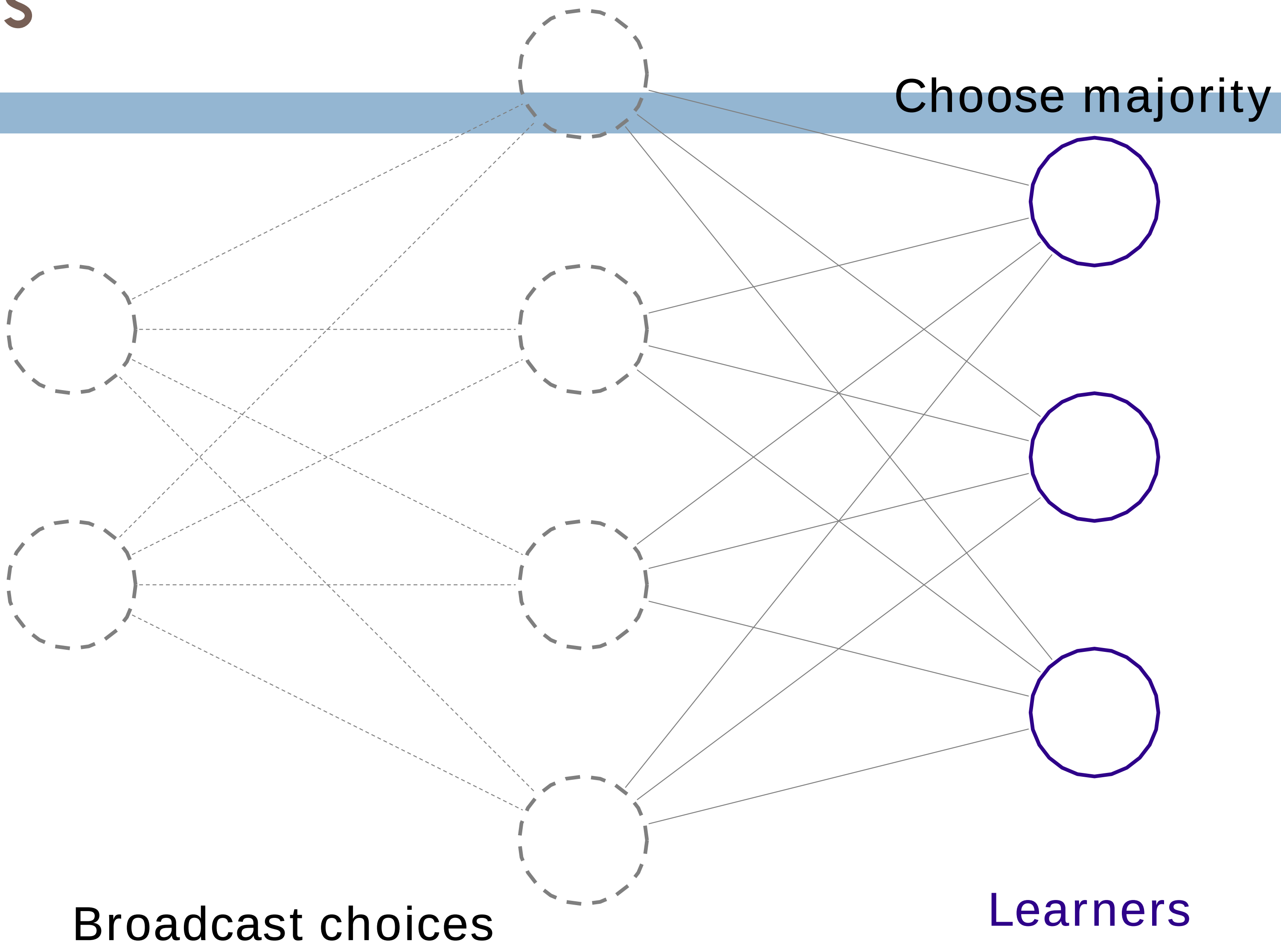
Property 1a

- An acceptor can accept a proposal numbered *n* iff it has not responded to a prepare request having a number greater than *n*.

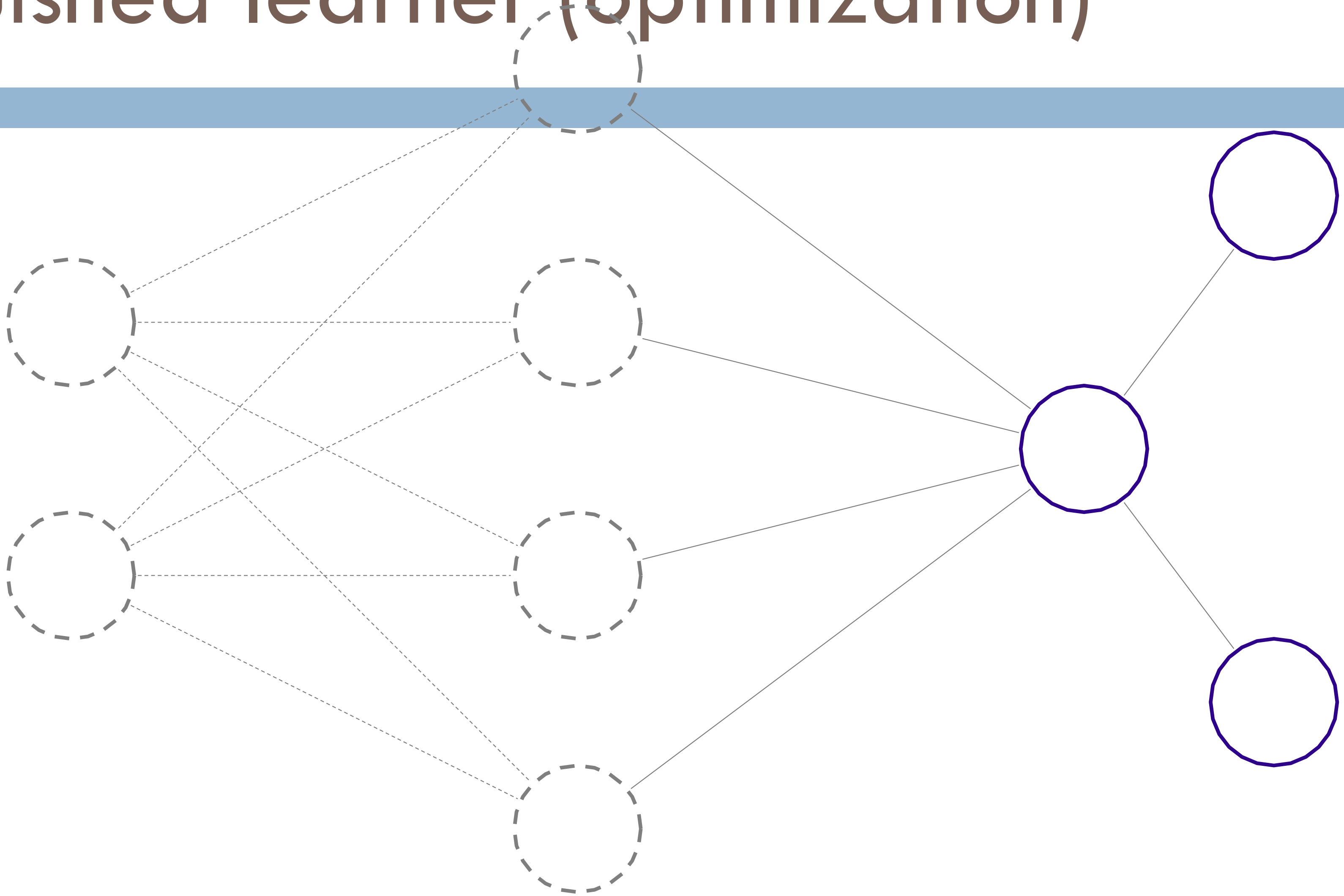
Responding to prepare requests

- An acceptors may respond to any prepare request
- To optimize, ignore requests lower than promised

Learners



Distinguished learner (optimization)



Progress

- P_1 receives promises for n_1
- P_2 receives promises for $n_2 > n_1$
- P_1 sends proposal numbered n_1, rejected
- P_1 receives promises for $n_1' > n_2$
- P_2 sends proposal numbered n_2, rejected
- P_1 receives promises for $n_2' > n_1'$
- P_1 sends proposal numbered n_1', rejected
- *ad infinitum*…

Paxos Made Moderately Complex

Robbert van Renesse and Deniz Altinbuken (Cornell University)
ACM Computing Surveys, 2015

"The Part-Time Parliament" was too confusing
"Paxos Made Simple" was overly simplified
Better to make it moderately complex!
Much easier to understand

Paxos Structure

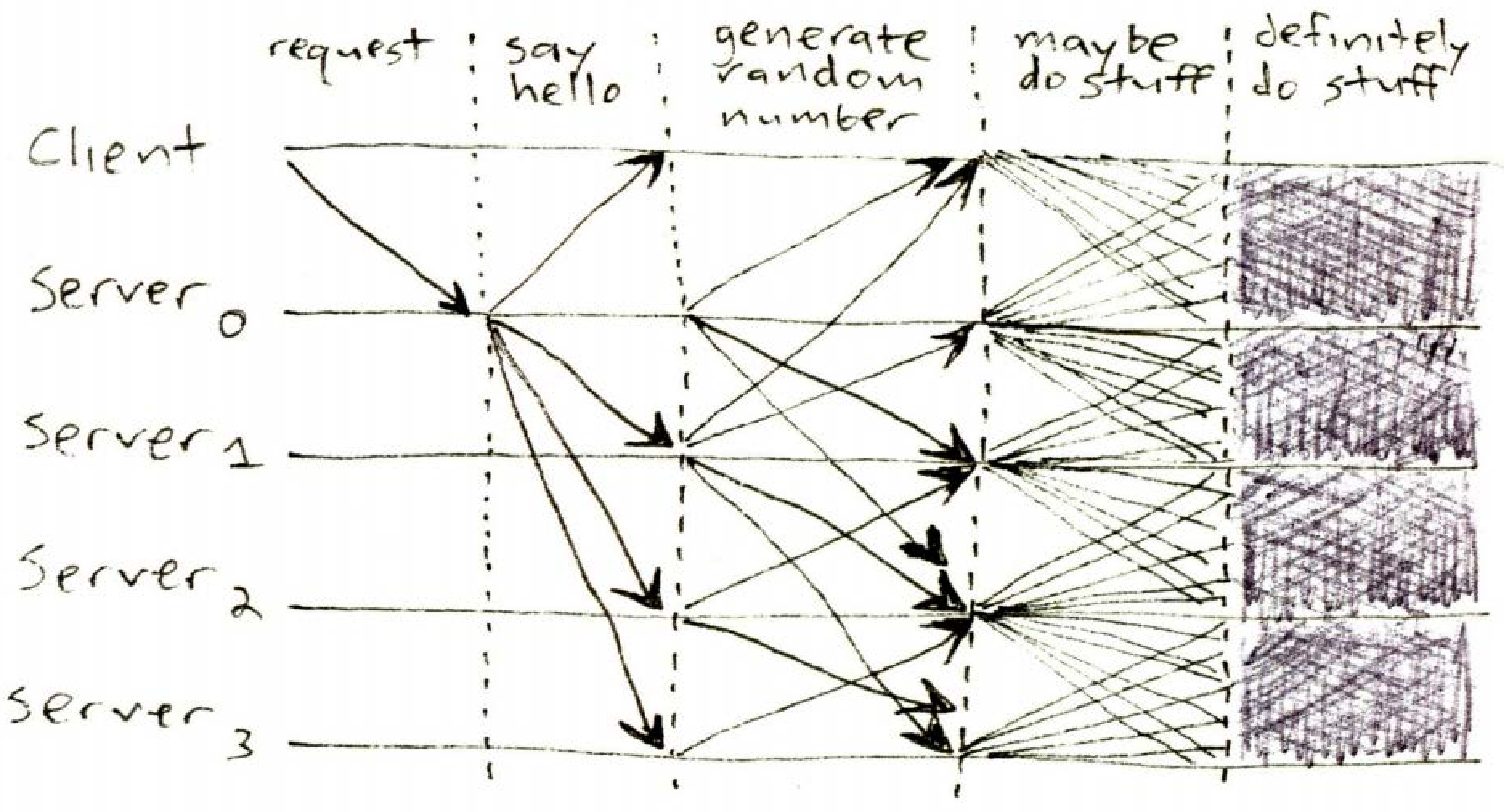
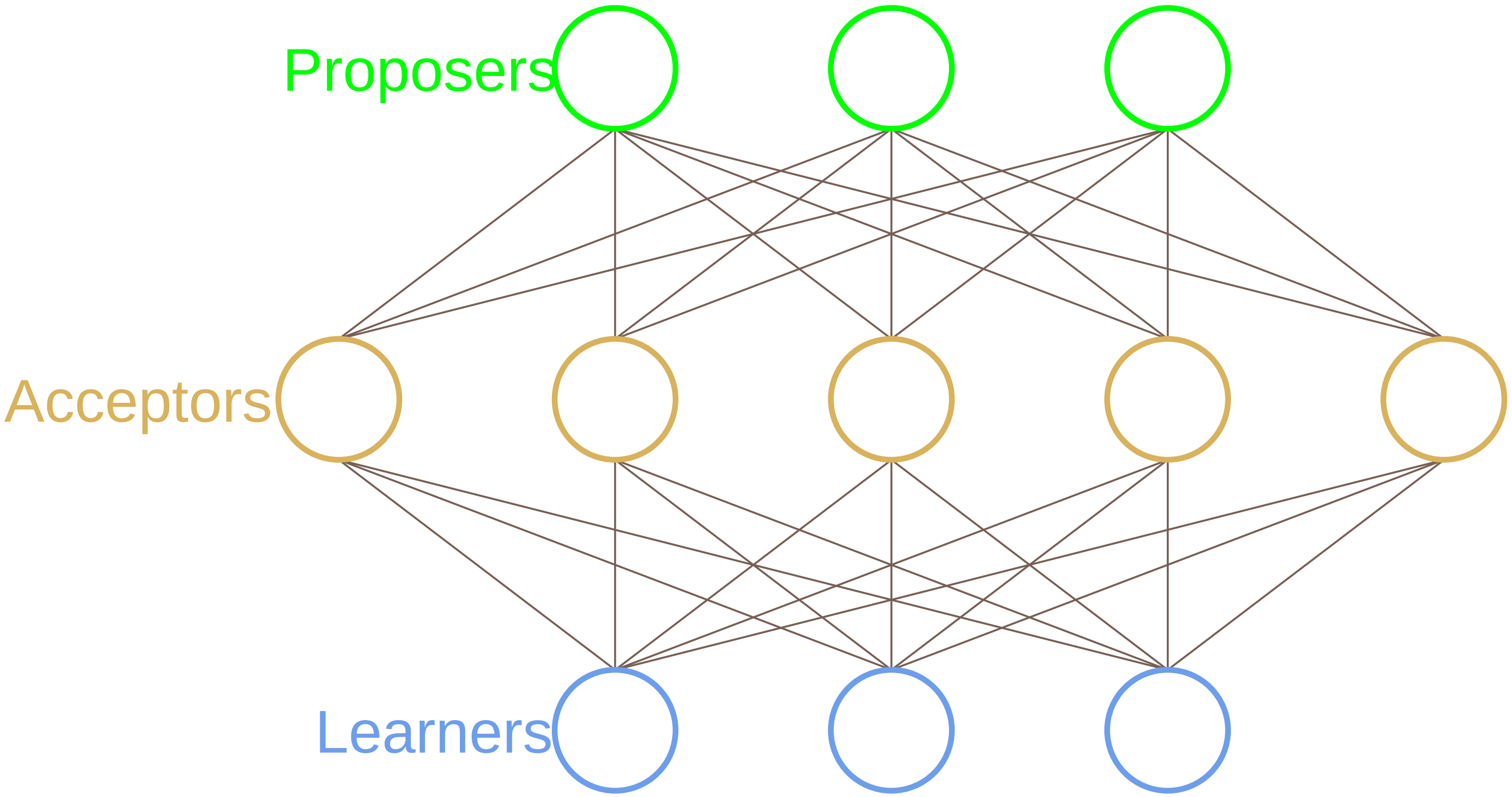


Figure from James Mickens. ;login: logout. *The Saddest Moment*. May 2013

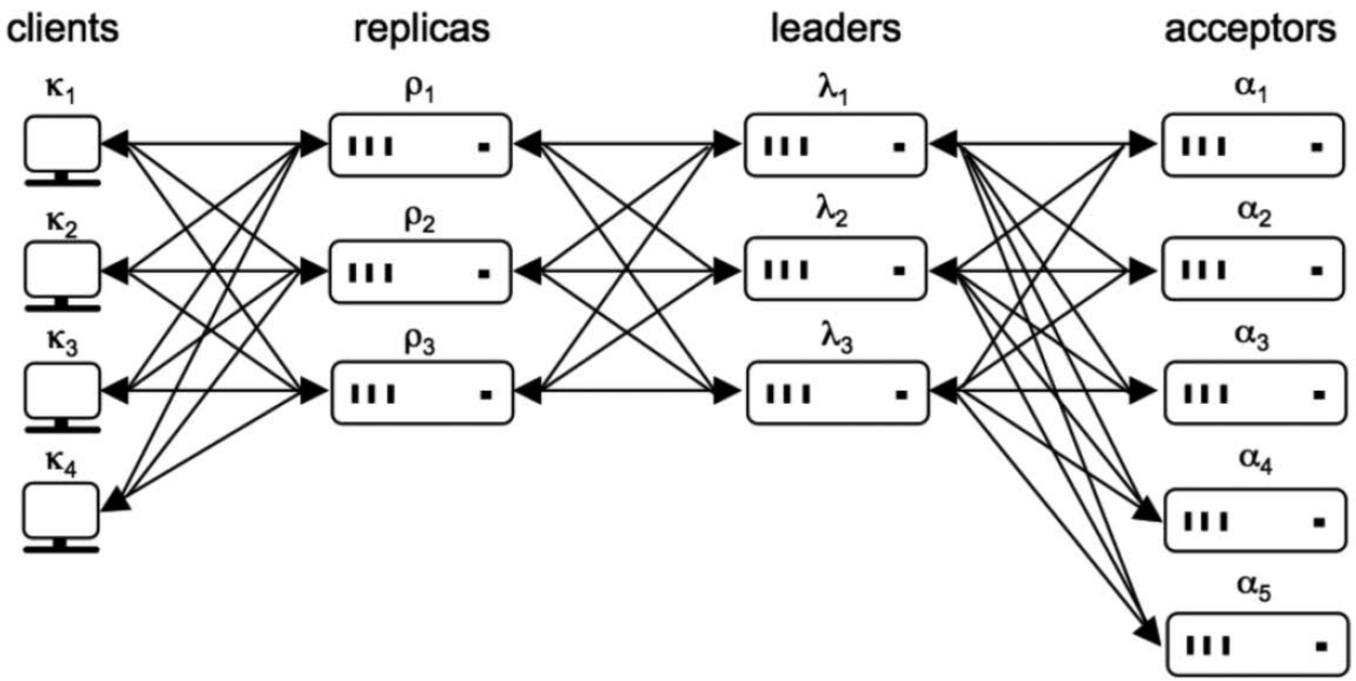
Paxos Structure



Moderate Complexity: Notation

Store data and propose to proposers

Function as proposers and learners without persistent storage



Communication pattern between types of processes in a setting where $f = 2$.

Figure from van Renesse and Altinbuken 2015

Single-Decree Synod

Decides on one command

System is divided into *proposers* and *acceptors*

The protocol executes in phases:

a. Proposer proposes a ballot b

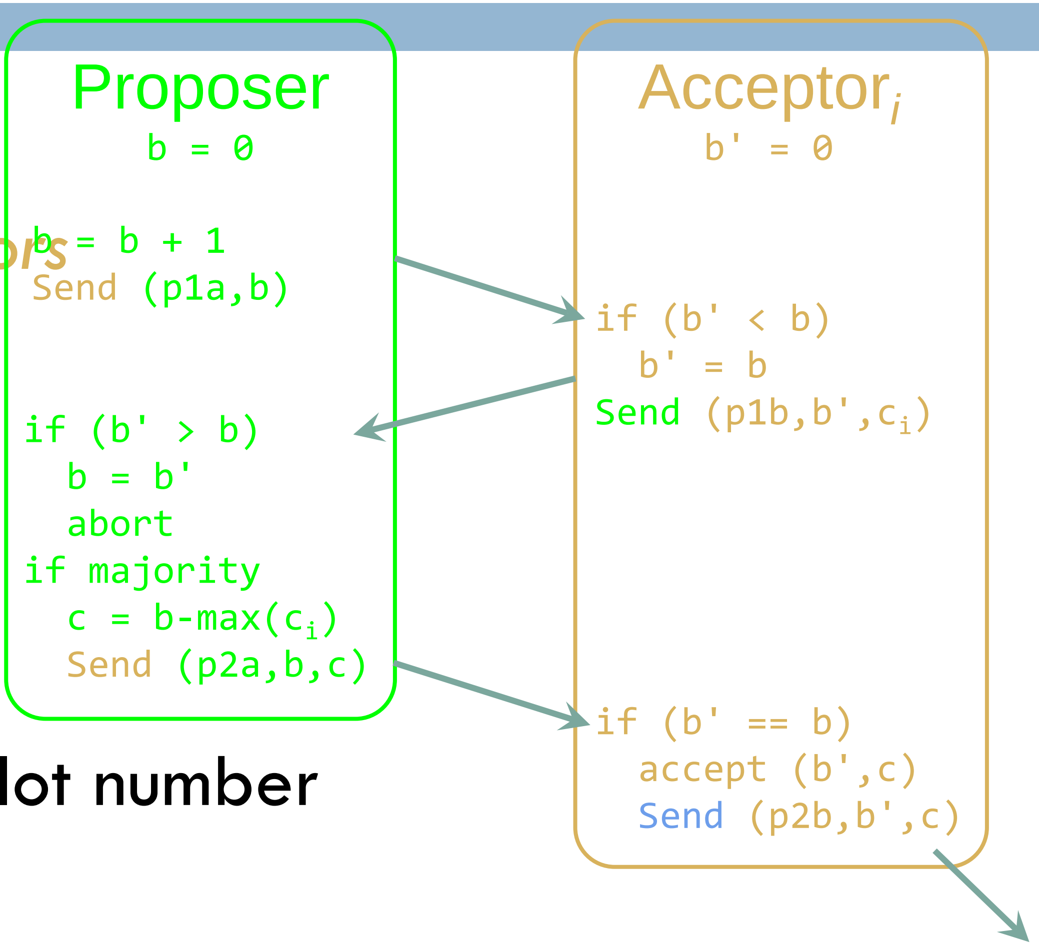
1. Acceptor$_i$ responds with (b', c_i)

a. If $b' > b$, update b and abort

   Else wait for majority of acceptors

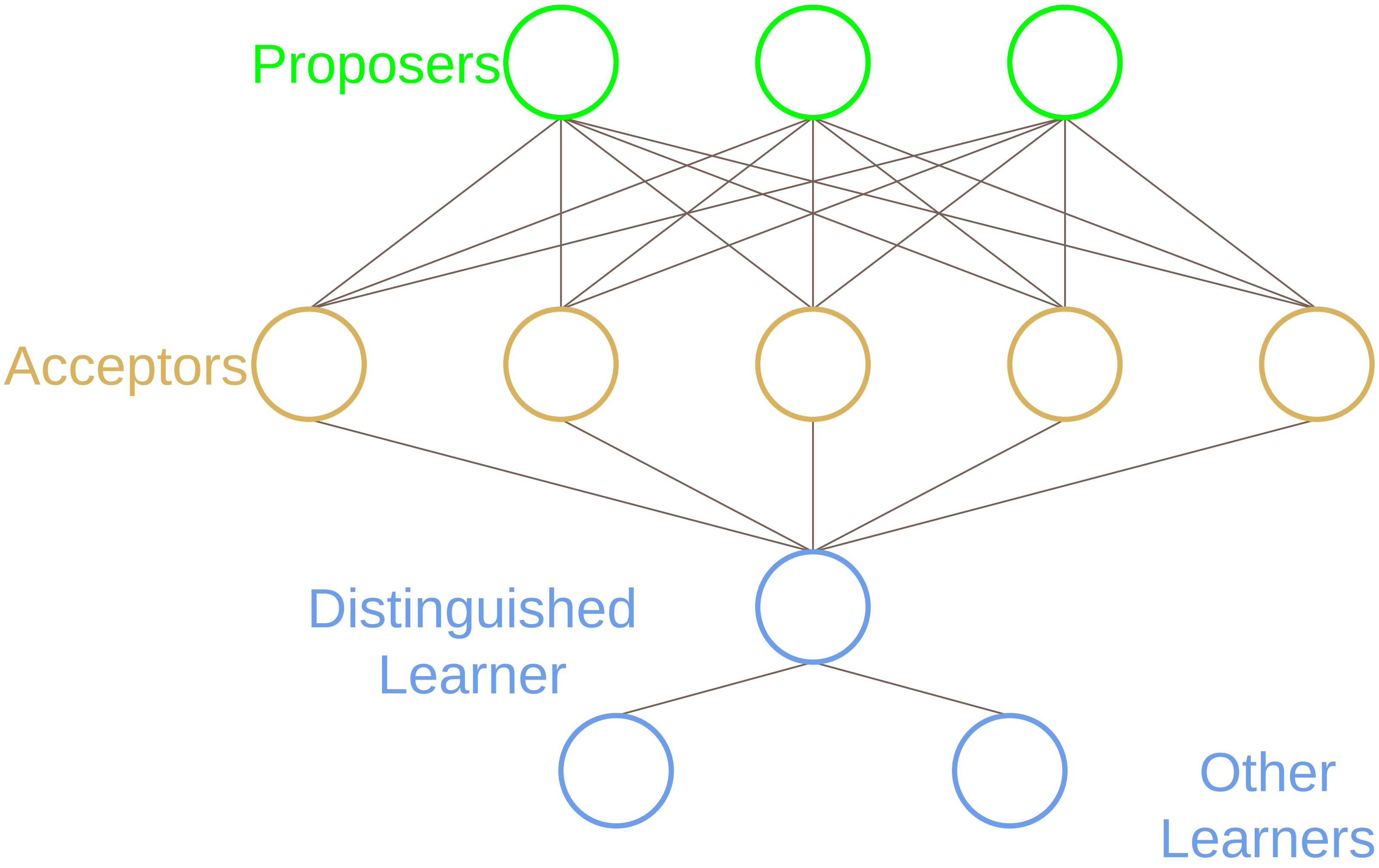
   Request received c_i with highest ballot number

b. If b' has not changed, accept

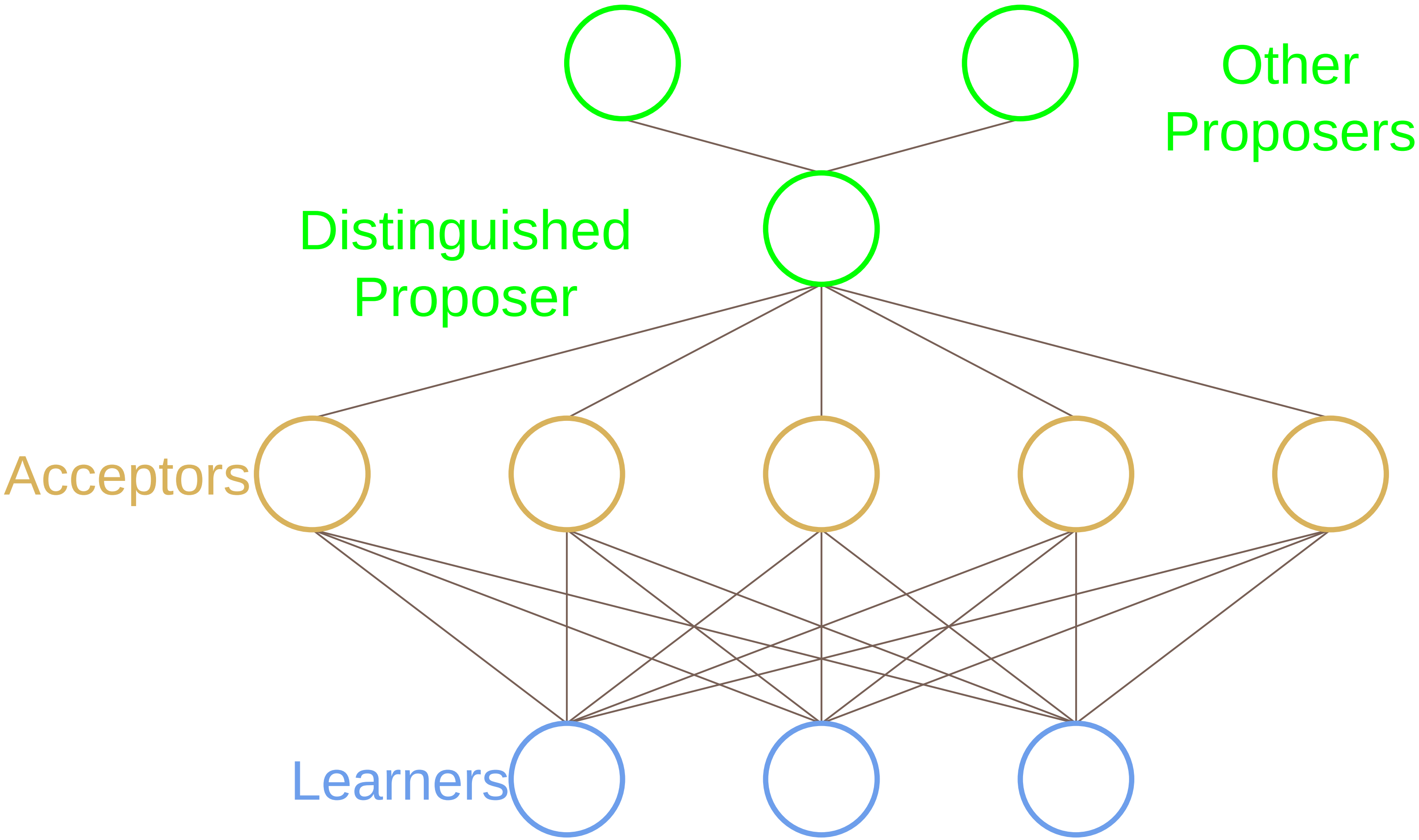


A *learner* learns c if it receives the same (p2b, b',c) from a majority of acceptors

Optimizations: Distinguished Learner



Optimizations: Distinguished Proposer



What can go wrong?

- A bunch of preemption
  - If two proposers keep preempting each other, no decision will be made
- Too many faults
  - Liveness requirements
    - majority of acceptors
    - one proposer
    - one learner
  - Correctness requires one learner

Deciding on Multiple Commands

Run Synod protocol for multiple slots

Sequential separate runs

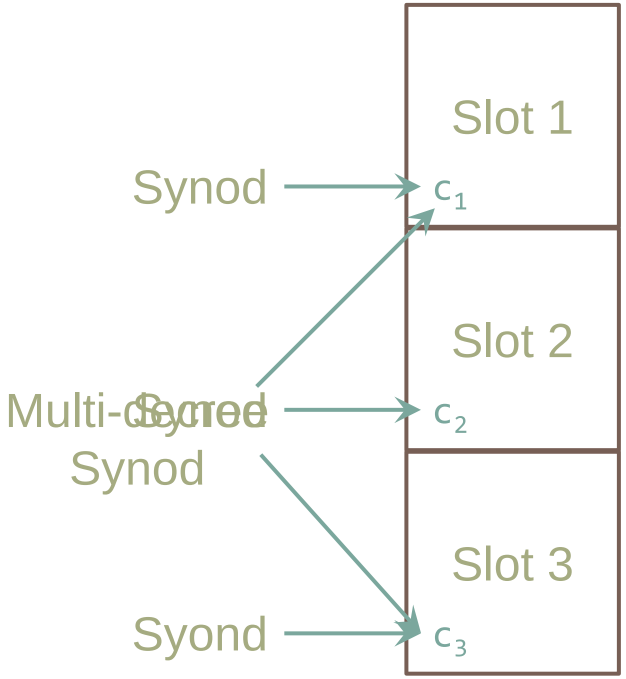
- Slow

Parallel separate runs

- Broken (no ordering)

One run with multiple slots

- Multi-decree Synod!



Paxos with Multi-Decree Synod

- Like single-decree Synod with one key difference:
  Every proposal contains a both a ballot and slot number
- Each slot is decided independently
  - On preemption (`if (b' > b) {b = b'; abort;}`),
    proposer aborts active proposals for all slots

Moderate Complexity: Leaders

Leader functionality is split into pieces

- Scouts – perform proposal function for a ballot number
  - While a scout is outstanding, do nothing
- Commanders – perform commit requests
  - If a majority of acceptors accept, the commander reports a decision
- Both can be preempted by a higher ballot number
  - Causes all commanders and scouts to shut down and spawn a new scout

Moderate Complexity: Optimizations

- Distinguished Leader
  - Provides both distinguished proposer and distinguished learner
- Garbage Collection
  - Each acceptor has to store every previous decision
  - Once $f + 1$ have all decisions up to slot s, no need to store s or earlier

Paxos Questions?

Backup

What is consensus?

Consensus is the problem of getting a set of processors to agree on some value.

What is consensus?

More formally, *consensus* is the problem of satisfying the following properties:

- Validity
- Agreement
- Integrity
- Termination

What is consensus?

More formally, *consensus* is the problem of satisfying the following properties:

- Validity
  - If all processes that propose a value propose v, then all correct deciding processes eventually decide v
- Agreement
- Integrity
- Termination

What is consensus?

More formally, *consensus* is the problem of satisfying the following properties:

- Validity
  - If all processes that propose a value propose v, then all correct deciding processes eventually decide v
- Agreement
  - If a correct deciding process decides v, then all correct deciding processes eventually decide v
- Integrity
- Termination

What is consensus?

More formally, *consensus* is the problem of satisfying the following properties:

- Validity
  - If all processes that propose a value propose v, then all correct deciding processes eventually decide v
- Agreement
  - If a correct deciding process decides v, then all correct deciding processes eventually decide v
- Integrity
  - Every correct deciding process decides at most one value, and if it decides v, then some process must have proposed v
- Termination

What is consensus?

More formally, *consensus* is the problem of satisfying the following properties:

- Validity
  - If all processes that propose a value propose v, then all correct deciding processes eventually decide v
- Agreement
  - If a correct deciding process decides v, then all correct deciding processes eventually decide v
- Integrity
  - Every correct deciding process decides at most one value, and if it decides v, then some process must have proposed v
- Termination