6.852 Lecture 24, part 1

- Paxos (continued
- Reading:
  - Lamport: The Part-Time Parliament
- Part 2: Self-stabilization

Paxos consensus algorithm

- Consensus in asynchronous network
  - impossible if a single process may fail
  - need to solve for real applications
    - weaken requirements
- Strategy: “safe” protocol, contingent termination
  - guarantee validity and agreement always
  - guarantee termination if system “stabilizes”
    - no more failures, recoveries, message losses
    - time for message delivery/process steps within “normal” bounds
  - termination should be fast when system is stable
    - only need system to be stable long enough to terminate

Paxos consensus protocol

- Paxos algorithm implements replicated state machine
  - tolerates stopping failures/recoveries, message loss/duplication
- Heart of Paxos algorithm is “synod” consensus protocol
  - use consensus to agree on sequence of steps
    - as in Herlihy's wait-free universal construction from consensus

Paxos consensus protocol

- Ballot: $(b,d) \in BId \times V \cup \{ \perp \}$
  - an attempt to reach consensus
  - V is consensus domain, d is "decree" (a value or nothing yet)
  - ballot created by any process at any time (restrict later)
    - new ballot must have new id, initially no associated value (i.e., $\perp$)
    - value assigned later, satisfying certain conditions
  - ballot ids totally ordered
  - process may vote for or abstain from a ballot (but not both)
    - can abstain from sets of ballots, including ones not yet initiated
  - ballot **succeeds** if a write quorum votes for it
  - ballot is **dead** if a read quorum abstains from it
    - read quorum has nonempty intersection with every write quorum

Paxos consensus protocol

- Each ballot processed in three phases of messages
  - initiate new ballot, choose decree for ballot (need read quorum)
  - try to get ballot to succeed (need write quorum to **vote**)
  - let everyone know if successful
- Initiator "drives" processing of ballot
  - other processes only respond to messages from initiator
- Anyone can ignore/neglect any ballot at any time
  - only affects progress
- Many ballots can be processed concurrently
  - ballots can be initiated at any time
  - ballots with larger ids are "later"

Paxos consensus protocol

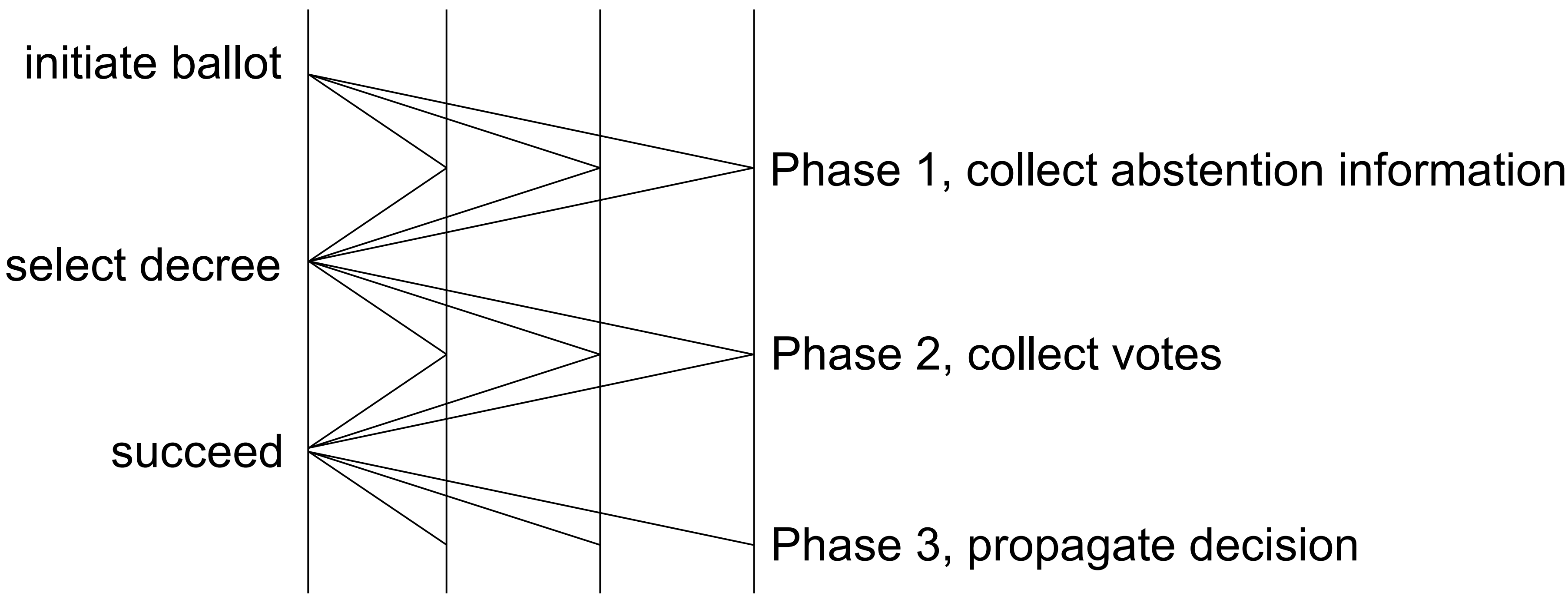
- Phase 1:
  - NextBallot(b), where b not previously used ballot id
    - sent by some process p to some read quorum (or more)
  - LastVote(b,v), sent by q to p in reply to NextBallot(b) from p
    - v is vote by q with largest ballot id smaller than b (null if none)
    - q promises not to vote for (i.e., abstains from) ballots with ids between v's and b's (must keep track of abstentions).
  - p selects value when it gets a read quorum of responses
    - decree of latest ballot that had a vote (among LastVote responses)
    - if all LastVote responses are null, choose own decree

Paxos consensus protocol

- Phase 2:
  - BeginBallot(b,d), where d is determined in Phase 1
    - sent by p to a write quorum (or more)
  - Voted(b,q), sent by q to p in reply to BeginBallot(b,d) from p
    - q must not have abstained from b (by LastVote for some other ballot)
  - p decides on d if it gets a write quorum of votes (i.e., responses)
- Phase 3
  - Success(d), sent by p to everyone
    - p can terminate after sending if channels are reliable
  - any process decides on d upon receiving Success(d) from anyone
    - can it terminate if channels are reliable?

Paxos consensus protocol

- Communication pattern for a ballot
  - like 3-phase commit



Paxos consensus protocol

- Recall:
  - ballot **succeeds** if a write quorum votes for it
  - ballot is **dead** if a read quorum abstains from it
  - read quorum has nonempty intersection with every write quorum
    - no ballot can be both dead and successful
- Lemma: For initiated ballots (b,d) and (b',d'), if b > b', then either d = d' or b' is dead.

Modifying the ** condition for assigning ballot values

- Instead of checking:

  ** For every b' < b, either val(b') = v or b' is dead.

- Check the apparently-weaker condition:

  *** Either:

  Every b' < b is dead, or

  there exists b' < b with val(b') = val(b), and such that every b'' with b' < b'' < b is dead.

- *** is easier to check in a distributed algorithm (will show how).
- And *** implies **, by easy induction on the number of steps in an execution.

Ensuring ***

*** Either every b' < b is dead, or there exists b' < b with val(b') = val(b), such that every b'' with b' < b'' < b is dead.

- Phase 1:
  - Originator process i tells other processes the new ballot number b.
  - Each recipient j abstains from all smaller-numbered ballots it hasn't yet voted for.
  - Each j sends back to i:
    - The largest ballot number < b that it has ever voted for, if any, together with its value v.
    - Else a message saying there is no such ballot.
  - When originator i collects this information from a read-quorum R, it assigns a value v to ballot b:
    - If anyone in R says it voted for a ballot < b, then v = the value associated with the largest-numbered of these ballots.
    - If not, v = any initial value.
- Claim this choice satisfies ***:

Ensuring ***

- *** Either every b' < b is dead, or there exists b' < b with val(b') = val(b), such that every b'' with b' < b'' < b is dead.
- Why does this choice satisfy ***?
- Case 1: Someone in R says it voted for a ballot < b.
  - Say b' is the largest such ballot number.
  - Then everyone in R has abstained from all ballots between b' and b.
  - So, choosing val(b) = val(b') ensures the second clause of ***.
- Case 2: Everyone in R says it did not vote for a ballot < b.
  - Then everyone in R has abstained from all ballots < b, ensuring they are all dead.
  - Satisfies the first clause of ***.

Paxos consensus protocol

- Protocol requires:
  - ballot id for new ballot has never been used
  - not voting for ballots previously abstained from
  - remembering previous votes (for LastVote)
- Simplify by restricting processes further:
  - ballot id is sequence number plus process id (to break ties)
  - remember largest b sent in LastVote(b,v)
    - never vote for ballots with ids less than b
    - also ignore NextBallot(b') when $b' \leq b$
  - remember only latest ballot voted for (ballot id and decree)
    - send in response to NextBallot (if not ignored)

Liveness

- To guarantee termination when the system stabilizes, we must restrict its nondeterminism.
  - say that process initiates ballot in response to BallotTrigger
- Most importantly, must restrict when BallotTrigger so that, after stabilization:
  - It asks only one process to start ballots (leader).
  - It doesn't tell the leader to start new ballots too often---allows enough time for ballot to complete.
- E.g., BallotTrigger might:
  - Use knowledge of "normal case" time bounds to try to detect who is failed.
  - Choose smallest-index non-failed process as leader (refresh periodically).
  - Tell the leader to try a new ballot every so often---allowing enough "normal case" message delays to finish the protocol.
- Note the BallotTrigger uses time---not purely asynchronous.
- But we know we can't solve the problem otherwise.
- Algorithm tolerates inaccuracies in BallotTrigger: If it "guesses wrong" about failures or delays, termination may be delayed, but safety properties are still guaranteed.

Replicated state machines

- Paper also deals with repeated consensus, in particular, on a sequence of operations for a replicated state machine.
- Use infinitely many instances of Paxos to agree on first operation, second, third,…
- Strategy similar to Herlihy's universal construction, which uses repeated consensus to decide on successive operations for an atomic object.
- Lamport's paper also includes various optimizations, LTTR.
- Considerable follow-on work, engineering Paxos to work for maintaining real data.
  - Disk Paxos
  - HP, Microsoft, Google,…