Paxos

15-712 Fall 2007

Some slides in this lecture borrowed from Mike Reiter, Robert Morris

(Several slides in this section borrowed from): Introduction to Agreement Algorithms

Mike Reiter

Distributed Systems

- A collection of computing devices that can communicate with each other
- How are distributed systems different from sequential ones?
  - May be impossible to observe the global state
  - Can incur *partial* failures (devices or communication)
  - Measures are different
    - Time is still important, but messages are, too
  - Much more difficult to reason about and get right

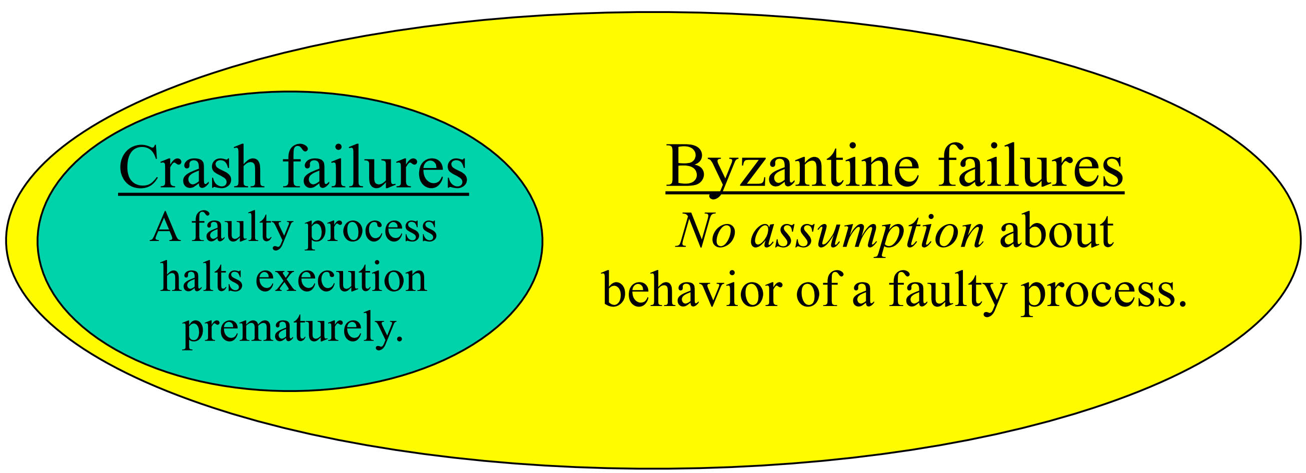
Agreement Problems

- High-level goal: Processes in a distributed system reach *agreement* on a value
- Numerous problems can be cast this way
  - Transactional commit, atomic broadcast, …

- The system model is critical to how to solve the agreement problem—or whether it can be solved at all
  - Failure assumptions
  - Timing assumptions

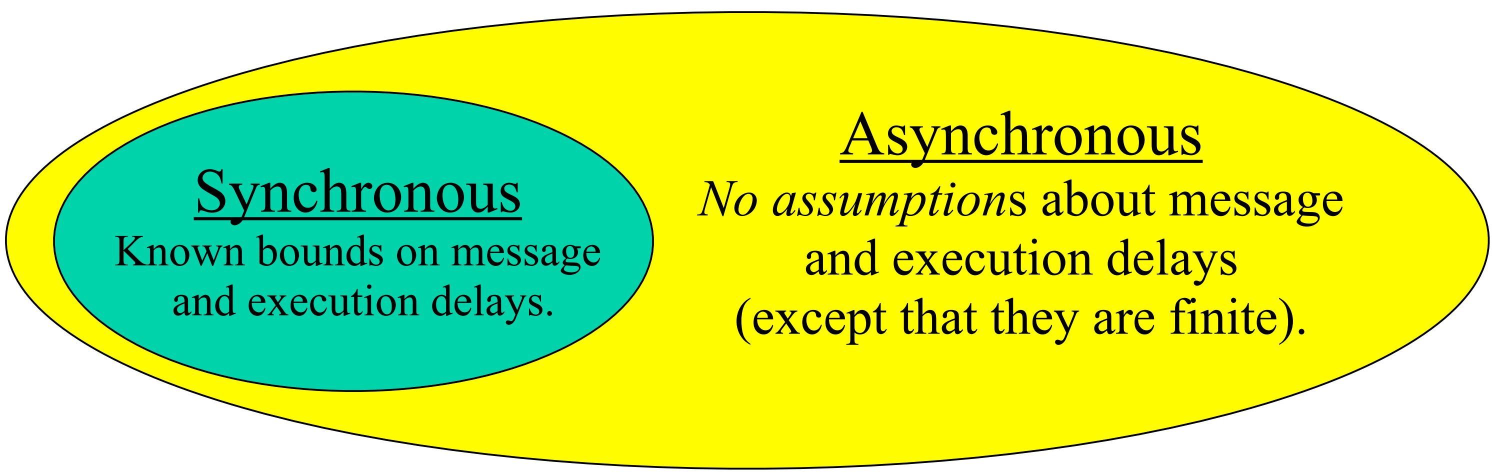
Failure Model

- A process that behaves according to its I/O specification throughout its execution is called <u>correct</u>
- A process that deviates from its specification is <u>faulty</u>
- There are many gradations of faulty. Two of interest are:



Timing Model

- Specifies assumptions regarding delays between
  - execution steps of a correct process
  - send and receipt of a message sent between correct processes
- Again, many gradations. Two of interest are:



Today

- Crash-failure
- Asynchronous

- Next week:
  - Byzantine failure
  - Sync & Async

Consensus

- Each process begins with a value
- Each process can irrevocably *decide* on a value
- Up to $t < n$ processes may be faulty

- Problem specification
  - Termination: Each correct process decides some value.
  - Agreement: Correct processes do not decide different values.
  - Validity: If all processes begin with the same input, then any value decided by a correct process must be that input.

Consensus: Synchronous Crash Model

Algorithm for 

:

$S_i \leftarrow$ {initial value}

for $k = 1 \ldots t+1$

send S_i to all processes

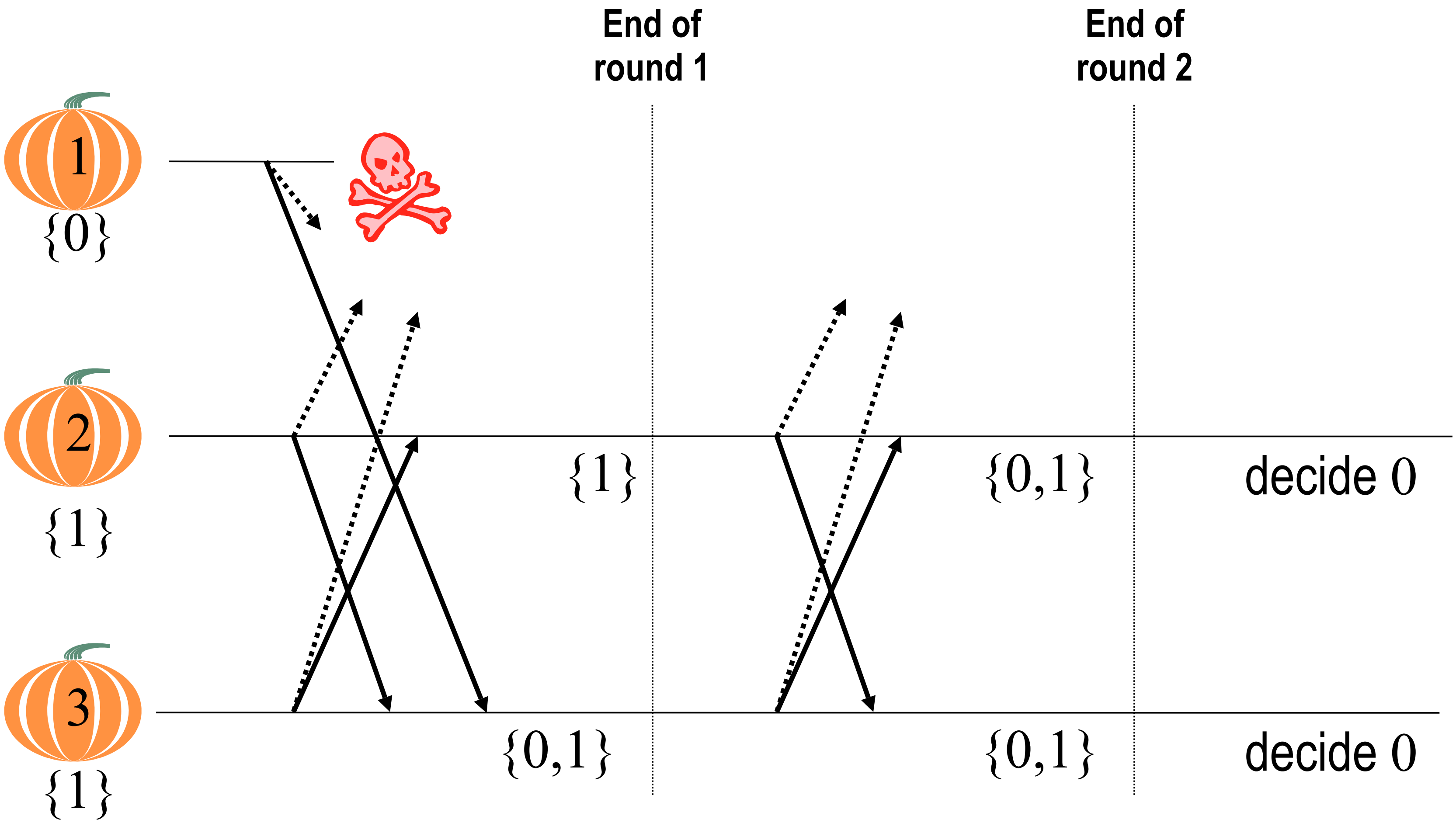
receive S_j from 

for all j

$$S_i \leftarrow S_i \cup \left(\bigcup_j S_j \right)$$

decide $\min(S_i)$

Example with $t = 1$



Consensus: Asynchronous Crash Model

<u>Theorem</u> [Fischer, Lynch, Paterson]: There is *no* algorithm to solve consensus in an asynchronous system for any $t \geq 1$.

At least, if you want termination.

But that's okay - we'll scrap that requirement...

Refresher

Refresher

- 2-phase commit
  - Have to wait for all nodes + coord to be up
  - Have to know how each node voted
  - coord must be up to decide
  - Works, but system is down while any one component is down: long repair times

Back to State Machine Replication

- Works for any replicated service
  - storage, lock server (Google's chubby), etc.
  - Every replica must see same operations in same order
    - If deterministic ops, all replicas will be in same state

Strawman: Primary/Backup

- Primary assigns order of ops, sends them to all replicas
  - What if primary fails?
    - What about operation in flight when primary failed?
    - Need to pick a new primary
    - But can't have two, or order is wrong!
  - Simple approaches don't work
    - Lowest #'d server? Partition / lost pings => 2 primaries

Basic system structure

- Ordinary (non-failure) operation:
  - Pick a primary
  - Let it sequence things
  - Works efficiently and happily
- But make sure that on failure
  - The system is *always* correct
  - How can we do this?

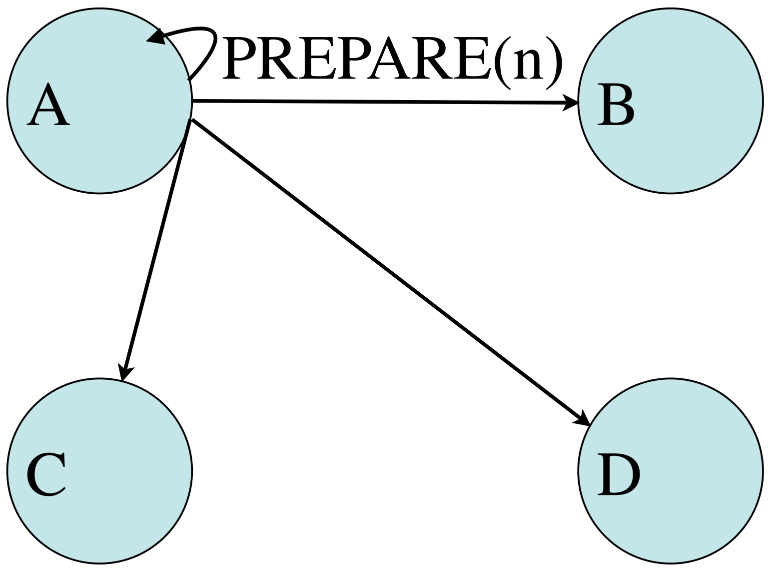
Agreement

- Leader chooses proposed value to agree on
  - Broadcasts to all participants, tries to assemble majority
  - If majority respond, life is good
- What if leader crashes after contacting only some nodes?
- What if got majority, then failed?
- What if two leaders simultaneously?

Paxos

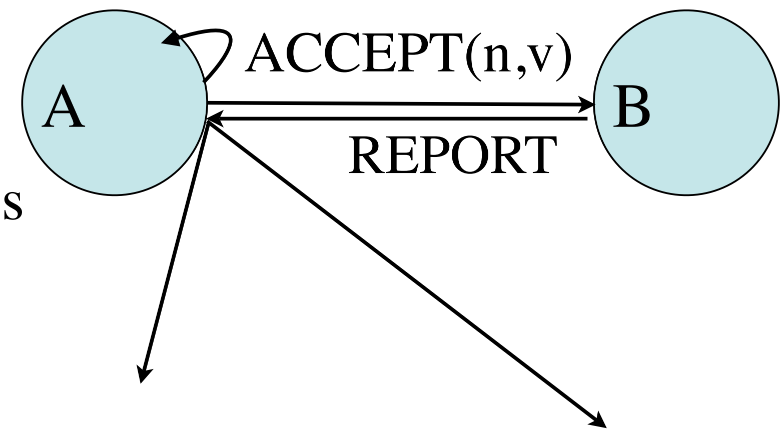
- Three phases
  - Each node maintains state:
    - Na, Va: Highest N that node has accepted and value V
    - Np: highest N seen in any PREPARE
- Phase 1:
  - Some node decides it's a leader
  - Picks *unique* proposal # n > higher known #s
  - Sends PREPARE(n) to every node
  - recv(PREPARE(n)):
  - if n > Np
    - return RESPONSE(Na, Va)
    - Np = n

Phase 1



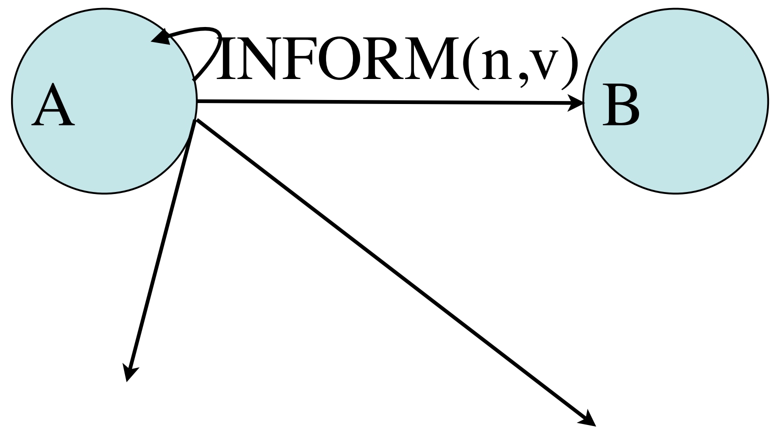
Phase 2

- If response from majority of nodes
  - If RESPONSE(n, v) has a value
    - v = value of highest n
    - else v = pick anything
  - send ACCEPT(n, v) to all nodes
- on recv(ACCEPT(n,v))
  - if n >= Np
    - Na = n
    - Va = v
- If majority accept, we have a value!
  - But we might not know! Leader crash b4 report...



Phase 3

- Tell everyone the agreed-upon answer



Failures: Multiple Leaders

- Two leaders must use different *n*
  - Augment n with node ID, etc.
- A: PREPARE(5)
- A,B,C: RESPONSE(5, v)
- D: PREPARE(6)
- B,C,D: RESPONSE(6,v)
- A: ACCEPT(5, v)
- B,C: No! We want to hear >= 6
- A: PREPARE(7)
- D: ACCEPT(6, v)
- B,C: No! We want to hear >= 7
- ...

Multiple Leaders

- Can continue forever
  - But won't in most failures
  - Broadcast leader election, random backoff, etc.
  - Could even use more robust leader election (may be useful in wide-area): gossip, etc.

Leader failure

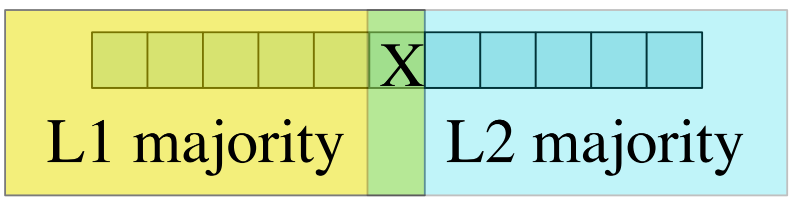
- Before sending ACCEPTs
  - Some other node will decide to become leader
  - Old leader never reached agreement, so just ignore
  - Our new N > old N will ensure that their old requests are flushed out even if they're delayed

Failure after sending ACCEPT?

- Key idea:
  - Once a majority agrees, it can never un-agree
  - Why? They send back the value they agreed upon
    - Two majorities *must* overlap, so new leader will always hear old agreed-upon value
    - If leader hears a v, it must pick that v as its own
- (Same as ensuring correctness with two leaders (but not progress))

Requires persistence

- e.g., node reboot after RESPONSE
  - L1 PREPARE(10). node X Np = 10
  - L2: PREPARE(11); majority intersecting *only* at node X response. node X Np = 11
    - L2 picks a value v=200
  - X crashes & reboots, *resets Np* (ERROR!)
  - L1 sends ACCEPT(n=10, v=100)
    - It's accepted! Node X forgot...



Optimizations

- Doing this every time is *expensive*
  - Can amortize across multiple requests using a *view*
  - Use Paxos to agree on a {leader, view, participant set}
  - First req from new leader: Normal paxos
  - Subsequent reqs: Directly send “accept”, respond back “accepted”.

Paxos in Practice

- Example: Google's "Chubby" lock server
  - Uses paxos to manage locks & leases & leader election
  - But then most services use cheaper mechanisms (e.g., using the leader)
  - Much like the optimizations to using Paxos itself
    - Pick a leader, let it do the work in the absence of failures