Paxos: Agreement for Replicated State Machines

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Review: Types of Distributedness

- NFS: distributed to share data across clients through filesystem interface
- Ivy: distributed to provide illusion of seamless shared memory across clients
- 2PC: distributed because different nodes have different functions (e.g., Bank A, Bank B)
- What about distributedness to make system more available?
Centralization: Single Points of Failure

• Consider what happens when nodes fail:
  – NFS server?
  – Bank A?
  – CPU that owns a page in Ivy?

• In all these systems, there is single node with “authoritative” copy of some data

• Single point of failure: kill one node, clients may grind to halt

• How can we do better?
Replication

• **Replicate** data on several servers
• If server(s) fail, hopefully others still running; data still available, clients can still make progress
• **Consistency?**
  – Informally speaking, all replicas should hold identical copies of data
  – So as users’ requests modify data, must somehow *keep* all data identical on all replicas
2PC vs. Replication

• 2PC works well if **different nodes play different roles** (e.g., Bank A, Bank B)

• 2PC isn’t perfect
  – Must wait for all sites and TC to be up
  – Must know if each site voted yes or no
  – TC must be up to decide
  – Doesn’t tolerate faults well; must wait for repair

• Can clients make progress when some nodes unreachable?
  – Yes! When data replicated.
State Machine Replication

• Any server essentially a **state machine**
  – Disk, RAM, CPU registers are state
  – Instructions transition among states
  – User requests cause instructions to be executed, so cause transitions among states

• Replicate state machine on multiple hosts
  – Every replica must see same operations in same order
  – If deterministic, replicas end in same state
Ensuring All Replicas See Operations in Same Order

- Nominate one “special” server: primary
- Call all other servers backups
- Clients send all operations to current primary
- Primary’s role:
  - Chooses order for clients’ operations
  - Sends clients’ operations to backups
  - Replies to clients
Ensuring All Replicas See Operations in Same Order

Didn’t we say the whole point was availability, and fault-tolerance?

**What if primary fails?**

- Primary
  - Primary’s role:
    - Chooses order for clients’ operations
    - Sends clients’ operations to backups
    - Replies to clients
Primary Failure

- Last operation received by primary may not be complete
- Need to pick new primary
- Can’t allow two simultaneous primaries! *(Why?)*
- Define: lowest-numbered live server is primary
  - After failure, everyone pings everyone
  - Does everyone now know who new primary is?
- Maybe not:
  - Pings may be lost: two primaries
  - Pings may be delayed: two primaries
  - Network partition: two primaries
Idea: Majority Consensus

• Require a majority of nodes to agree on primary
• At most one network partition can contain majority
• If pings lost, and thus two potential primaries, **majorities must overlap**
  – Node(s) in overlap can see both potential primaries, raise alarm about non-agreement!
Technique: View Change Algorithm

- Entire system goes through sequence of views
- **View**: \{view \#, set of participant nodes\}
- View change algorithm must ensure agreement on *unique successor for each view*
- Participant set within view allows all nodes to agree on primary
  - Same rule: lowest-numbered ID in set is primary
Technique: View Change Algorithm

If two nodes agree on view, they will agree on primary

• View: \{view #, set of participant nodes\}
• View change algorithm must ensure agreement on unique successor for each view
• Participant set within view allows all nodes to agree on primary
  – Same rule: lowest-numbered ID in set is primary
View Change Requires Fault-Tolerant Agreement

- Envision view as \textit{opaque value}
- Want all nodes to agree on same value (i.e., same view)
- At most one value may be chosen
- Want to agree \textit{despite lost messages and crashed nodes}
- Can’t guarantee to agree!
  - Can guarantee \textit{not to agree} on different values!
  - i.e., guarantee \textit{safety, but not liveness}
Paxos: Fault-Tolerant Agreement Protocol

- Protocol eventually succeeds provided
  - Majority of participants reachable
  - Participants know how to generate value to agree on
    - i.e., Paxos doesn’t determine the value nodes try to agree on—value is an opaque input to Paxos

- Only widely used algorithm for fault-tolerant agreement in state machine replication
Review: State Machine Replication, Primary-Backup, Paxos

• **How did we get here?**
  • Want to replicate a system for availability
  • View system as state machine; replicate the state machine
  • Ensure all replicas see same ops in same order
  • Primary orders requests, forwards to replicas
  • All nodes must agree on primary
  • All nodes must agree on view
    – Participant with lowest address in view is primary
  • **Paxos** guaranteed to complete only when all nodes agree on input (in this case, input is view)
Overview of Paxos

- One (or more) nodes decide to be leader
- Leader chooses proposed value to agree on
  - (In our case, value is view: \{view #, participant set\})
- Leader contacts Paxos participants, tries to assemble majority
  - Participants can be fixed set of nodes (configured)
  - Or can be all nodes in old view (including unreachable nodes)
- If a majority respond, successful agreement
Agreement is Hard!

- What if two nodes decide to be leader?
- What if network partition leads to two leaders?
- What if leader crashes after persuading only some nodes?
- What if leader got majority, then failed, without announcing result?
  - Or announced result to only a few nodes?
  - New leader might choose different value, despite previous agreement
Paxos: Structure

• Three phases in algorithm
• May need to restart if nodes fail or timeouts waiting for replies
• State in each node running Paxos, per-value (view):
  – $n_a$: greatest $n$ accepted by node (init: -1)
  – $v_a$: value received together with $n_a$ (init: nil)
  – $n_h$: greatest $n$ seen in Q1 message (init: -1)
  – done: leader says agreement reached; can use new value (i.e., start new view) (init: 0)
Paxos: Phase 1

A node (maybe more than one) decides to be leader, then it
picks proposal number, \( n \)
must be unique, good if higher than any known proposal number
use last known proposal number + 1, append node’s own ID
sends Q1(n) message to all nodes (including self)
if node receives Q1(n) and \( n > n_h \)
\( n_h = n \)
send reply R1(\( n_a, v_a \)) message
if leader receives R1 messages from majority of nodes (including self)
  if any R1(n, v) contained a value (v)
    v = value sent with highest n
  else leader gets to choose a value (v)
    v = {old view# + 1, set of pingable nodes}
  send Q2(n, v) message to all responders
if node receives Q2(n, v) and n >= n_h
  n_h = n_a = n
  v_a = v
  send reply R2() message
Paxos: Phase 3

if leader receives R2() messages from majority of protocol participants
   send Q3() message to all participants
if node receives Q3()  
   done = true
   agreement reached; agreed-on value is \( v_a \)
   (primary is lowest-numbered node in participant list within \( v_a \))
Paxos: Timeouts

• All nodes wait a maximum period *(timeout)* for messages they expect
• Upon timeout, a node *declares itself a leader* and initiates a new Phase 1 of algorithm
Paxos with One Leader, No Failures: Phase 1

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### Paxos with One Leader, No Failures: Phase 1

$n = 11$

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### Paxos with One Leader, No Failures: Phase 1

"Q1(11)"

$$n = 11$$

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</table>
Paxos with One Leader, No Failures:
Phase 1

\[ n = 11 \]

\[ \text{"Q1(11)"} \]

\[
\begin{array}{cccccc}
0 & 1 & 2 & 3 & 4 \\
\text{n}_a & -1 & -1 & -1 & -1 & -1 \\
\text{v}_a & \text{nil} & \text{nil} & \text{nil} & \text{nil} & \text{nil} \\
\text{n}_h & -1 & -1 & -1 & -1 & -1 \\
\text{done} & F & F & F & F & F \\
\end{array}
\]
### Paxos with One Leader, No Failures: Phase 1

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<tr>
<td>$v_a$</td>
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<tr>
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<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>done</td>
<td>F</td>
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Paxos with One Leader, No Failures: Phase 1

```
<table>
<thead>
<tr>
<th>Node</th>
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<th>va</th>
<th>nh</th>
<th>done</th>
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<td>F</td>
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<tr>
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<tr>
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</tr>
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<td>4</td>
<td>-1</td>
<td>nil</td>
<td>11</td>
<td>F</td>
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</tbody>
</table>
```

```
"R1(-1, nil)"
```
### Paxos with One Leader, No Failures: Phase 2

<table>
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<tr>
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<th>1</th>
<th>2</th>
<th>3</th>
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<tr>
<td>$n_a$</td>
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<tr>
<td>$v_a$</td>
<td>nil</td>
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<tr>
<td>$n_h$</td>
<td>11</td>
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<td>11</td>
<td>11</td>
</tr>
<tr>
<td>done</td>
<td>F</td>
<td>F</td>
<td>F</td>
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</tbody>
</table>

R1 from majority! all v’s nil
### Paxos with One Leader, No Failures: Phase 2

<table>
<thead>
<tr>
<th>n_a</th>
<th>v_a</th>
<th>n_h</th>
<th>done</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>nil</td>
<td>11</td>
<td>F</td>
</tr>
<tr>
<td>-1</td>
<td>{1, {0, ..., 4}}</td>
<td>11</td>
<td>F</td>
</tr>
<tr>
<td>-1</td>
<td>nil</td>
<td>11</td>
<td>F</td>
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<tr>
<td>-1</td>
<td>nil</td>
<td>11</td>
<td>F</td>
</tr>
</tbody>
</table>

- **n_a** represents the number of votes received by the leader.
- **v_a** represents the proposed value.
- **n_h** represents the number of heartbeats.
- **done** indicates whether the process is finished.
Paxos with One Leader, No Failures: Phase 2

\[ \text{“Q2}(11, \{1, \{0, \ldots, 4\}\}) \]
Paxos with One Leader, No Failures:
Phase 2

```
\text{\texttt{Q2(11, \{1, \{0, ..., 4}\})}}
```

```
\begin{array}{cccccc}
\text{n}_a & -1 & -1 & -1 & -1 & -1 \\
\text{v}_a & \text{nil} & \{1, \{0, ..., 4\}\} & \text{nil} & \text{nil} & \text{nil} \\
\text{n}_h & 11 & 11 & 11 & 11 & 11 \\
\text{done} & F & F & F & F & F \\
\end{array}
```
Paxos with One Leader, No Failures: Phase 2

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<td>11</td>
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<tr>
<td>$v_a$</td>
<td>${1, {0, \ldots, 4}}$</td>
<td>${1, {0, \ldots, 4}}$</td>
<td>${1, {0, \ldots, 4}}$</td>
<td>${1, {0, \ldots, 4}}$</td>
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<td>$n_h$</td>
<td>11</td>
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<tr>
<td>done</td>
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Paxos with One Leader, No Failures: Phase 2

\[
\begin{array}{cccccc}
0 & 1 & 2 & 3 & 4 \\
n_a & 11 & 11 & 11 & 11 & 11 \\
v_a & \{1, \{0, \ldots, 4\}\} & \{1, \{0, \ldots, 4\}\} & \{1, \{0, \ldots, 4\}\} & \{1, \{0, \ldots, 4\}\} & \{1, \{0, \ldots, 4\}\} \\
n_h & 11 & 11 & 11 & 11 & 11 \\
done & F & F & F & F & F \\
\end{array}
\]
### Paxos with One Leader, No Failures: Phase 3

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<tbody>
<tr>
<td><strong>R2 from majority!</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>( n_a )</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>( v_a )</td>
<td>{1, {0, ..., 4}}</td>
<td>{1, {0, ..., 4}}</td>
<td>{1, {0, ..., 4}}</td>
<td>{1, {0, ..., 4}}</td>
<td>{1, {0, ..., 4}}</td>
</tr>
<tr>
<td>( n_h )</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td><strong>done</strong></td>
<td>F</td>
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</table>

- \( n_a \) represents the number of processes that have received the proposal.
- \( v_a \) is the value of the proposal.
- \( n_h \) indicates if the proposal has been accepted.
- F indicates that the proposal has not been accepted.

The R2 from majority! ensures that the proposal is accepted if a quorum of processes agrees on the proposal value.
Paxos with One Leader, No Failures: Phase 3

\[ n_a \quad 11 \quad 11 \quad 11 \quad 11 \quad 11 \]

\[ v_a \quad \{1, \{0, \ldots, 4\}\} \quad \{1, \{0, \ldots, 4\}\} \quad \{1, \{0, \ldots, 4\}\} \quad \{1, \{0, \ldots, 4\}\} \quad \{1, \{0, \ldots, 4\}\} \]

\[ n_h \quad 11 \quad 11 \quad 11 \quad 11 \quad 11 \]

\[ \text{done} \quad F \quad F \quad F \quad F \quad F \]
### Paxos with One Leader, No Failures: Phase 3

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<td>$n_h$</td>
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### Paxos with One Leader, No Failures: Phase 3

All nodes agree on view \( \{1, \{0, \ldots, 4\}\} \)

New primary: lowest ID, so node 0

<table>
<thead>
<tr>
<th>( n_a )</th>
<th>11</th>
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<tr>
<td>( v_a )</td>
<td>( {1, {0, \ldots, 4}} )</td>
<td>( {1, {0, \ldots, 4}} )</td>
<td>( {1, {0, \ldots, 4}} )</td>
<td>( {1, {0, \ldots, 4}} )</td>
<td>( {1, {0, \ldots, 4}} )</td>
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<tr>
<td>( n_h )</td>
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Paxos: Number of Leaders

• Clearly, when no failures, no message losses, and one leader, **Paxos reaches agreement**

• How can one ensure that with high probability, only one leader?
  – Every node must be willing to become leader in case of failures
  – Every node should delay random period after realizing pingable nodes have changed, or delay own ID x some constant
Paxos: Ensuring Agreement

• When would non-agreement occur?
  – When nodes with different $v_a$ receive Q3

• Safety goal:
  – If Q3 could have been sent, future Q3s guaranteed to reach nodes with same $v_a$
Risk: More Than One Leader

- Can occur after timeout during Paxos algorithm, partition, lost packets
- Two leaders must use different n in their Q1()s, by construction of n
- Suppose two leaders proposed n = 10 and n = 11
More Than One Leader (2)

• Case 1: proposer of 10 didn’t receive R2()s from majority of participants
  – Proposer never will receive R2()s from majority, as no node will send R2() in reply to Q2(10,...) after seeing Q1(11)
  – Or proposer of 10 may be in network partition with minority of nodes
More than One Leader (3)

• Case 2: proposer of 10 (10) did receive R2()s from majority of participants
  – Thus, 10’s originator may have sent Q3()!
  – But 10’s majority must have seen 10’s Q2() before 11’s Q1()
    • Otherwise, would have ignored 10’s Q2, and no majority could have resulted
  – Thus, 11 must receive R1 from at least one node that saw 10’s Q2
  – Thus, 11 must be aware of 10’s value
  – Thus, 11 would have used 10’s value, rather than creating one!
More than One Leader (3)

Result: agreement on 10’s proposed value!

from majority of participants

- Thus, 10’s originator may have sent Q3()!
- But 10’s majority must have seen 10’s Q2() before 11’s Q1()
  - Otherwise, would have ignored 10’s Q2, and no majority could have resulted
- Thus, 11 must receive R1 from at least one node that saw 10’s Q2
- Thus, 11 must be aware of 10’s value
- Thus, 11 would have used 10’s value, rather than creating one!
Risk: Leader Fails Before Sending Q2()s

- Some node will time out and become a leader
- Old leader didn’t send any Q3()s, so no risk of non-agreement caused by old leader
- Good, but not required, that new leader chooses higher n for proposal
  - Otherwise, timeout, some other leader will try
  - Eventually, will find leader who knew old n and will use higher n
Risks: Leader Failures

• Suppose leader fails after sending minority of Q2()s
  – Same as two leaders!

• Suppose leader fails after sending majority of Q2()s
  – i.e., potentially after reaching agreement!
  – Also same as two leaders!
Risk: Node Fails After Receiving Q2(), and After Sending R2()

• If node doesn’t restart, possible timeout in Phase 3, new leader
• If node does restart, it must remember $v_a$ and $n_a$ on disk!
  – Leader might have failed after sending a few Q3()s
  – New leader must choose same value
  – This failed node may be only node in intersection of two majorities!
Paxos: Summary

- Original goal: replicated state machines!
  - Want to continue, even if some nodes not reachable
- After each failure, perform view change using Paxos agreement
- i.e., agree on exactly which nodes in new view
- Thus, everyone can agree on new primary
- No discussion here of how to render data consistent across replicas!