Paxos: Agreement for Replicated State Machines

Brad Karp
UCL Computer Science

CS GZ03 / M030
20th October 2014
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?**

- **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
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 opaque value
• Want all nodes to agree on same value (i.e., same view)
• At most one value may be chosen
• Want to agree despite lost messages and crashed nodes
• Can’t guarantee to agree!
  – Can guarantee not to agree on different values!
  – i.e., guarantee 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
Paxos: Phase 2

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

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_a$</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>$v_a$</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
</tr>
<tr>
<td>$n_h$</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>done</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>
Paxos with One Leader, No Failures: Phase 1

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_a$</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>$v_a$</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
</tr>
<tr>
<td>$n_h$</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>done</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>

$n = 11$
Paxos with One Leader, No Failures: Phase 1

“Q1(11)”

\[ n = 11 \]

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n_a )</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>( v_a )</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
</tr>
<tr>
<td>( n_h )</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>done</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>
Paxos with One Leader, No Failures: Phase 1

```
<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>n_a</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>v_a</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
</tr>
<tr>
<td>n_h</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>done</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>
```

“Q1(11)”

n = 11
Paxos with One Leader, No Failures: Phase 1

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_a$</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>$v_a$</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
<td>nil</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>done</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>
Paxos with One Leader, No Failures:
Phase 1

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>na</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>va</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
</tr>
<tr>
<td>nh</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>done</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_a$</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>$v_a$</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
<td>nil</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>done</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_a$</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>$v_a$</td>
<td>nil</td>
<td>{1, {0, …, 4}}</td>
<td>nil</td>
<td>nil</td>
<td>nil</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>done</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>
Paxos with One Leader, No Failures: Phase 2

```
<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>na</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>va</td>
<td>nil</td>
<td>{1, {0, ..., 4}}</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
</tr>
<tr>
<td>nh</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>done</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>
```

"Q2(11, {1, {0, ..., 4}})"
## Paxos with One Leader, No Failures: Phase 2

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_a$</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>$v_a$</td>
<td>nil</td>
<td>${1, {0, \ldots, 4}}$</td>
<td>nil</td>
<td>nil</td>
<td>nil</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>done</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>

"Q2(11, \{1, \{0, \ldots, 4\}\})"
# Paxos with One Leader, No Failures: Phase 2

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<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>${1, {0, \ldots, 4}}$</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>
</tr>
<tr>
<td>$n_h$</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>done</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>
Paxos with One Leader, No Failures: Phase 2

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

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

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

done F F F F F
## Paxos with One Leader, No Failures: Phase 3

<table>
<thead>
<tr>
<th>R2 from majority!</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>n_a</th>
<th>11</th>
<th>11</th>
<th>11</th>
<th>11</th>
<th>11</th>
</tr>
</thead>
<tbody>
<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>
</tbody>
</table>

<table>
<thead>
<tr>
<th>n_h</th>
<th>11</th>
<th>11</th>
<th>11</th>
<th>11</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>done</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>


Paxos with One Leader, No Failures: Phase 3

\[ \begin{array}{cccccc}
0 & 1 & 2 & 3 & 4 \\
\text{n}_a & 11 & 11 & 11 & 11 & 11 \\
\text{v}_a & \{1, \{0, \ldots, 4\}\} & \{1, \{0, \ldots, 4\}\} & \{1, \{0, \ldots, 4\}\} & \{1, \{0, \ldots, 4\}\} & \{1, \{0, \ldots, 4\}\} \\
\text{n}_h & 11 & 11 & 11 & 11 & 11 \\
\text{done} & F & F & F & F & F \\
\end{array} \]
**Paxos with One Leader, No Failures:**  
*Phase 3*

<table>
<thead>
<tr>
<th></th>
<th>n_a</th>
<th>v_a</th>
<th>n_h</th>
<th>done</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>11</td>
<td>{1, {0, ..., 4}}</td>
<td>11</td>
<td>T</td>
</tr>
<tr>
<td>1</td>
<td>11</td>
<td>{1, {0, ..., 4}}</td>
<td>11</td>
<td>T</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>{1, {0, ..., 4}}</td>
<td>11</td>
<td>T</td>
</tr>
<tr>
<td>3</td>
<td>11</td>
<td>{1, {0, ..., 4}}</td>
<td>11</td>
<td>T</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>{1, {0, ..., 4}}</td>
<td>11</td>
<td>T</td>
</tr>
</tbody>
</table>
**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>Node</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<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, \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>
</tr>
<tr>
<td>(n_h)</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>done</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>T</td>
</tr>
</tbody>
</table>
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!