Paxos Consensus, Abstracted and Deconstructed

Álvaro García Pérez, Alexey Gotsman, Yuri Meshamn, and Ilya Sergey

April 19th 2008
Consensus

• Several nodes, which can crash
Consensus

- Several nodes, which can crash
- Each node proposes a value
Consensus

- Several nodes, which can crash
- Each node proposes a value
- All non-crashed nodes agree on a single value
Deterministic state machine

C_1 \rightarrow \text{Clients submit commands} \rightarrow \text{Database} \rightarrow C_2 \rightarrow C_3
Machine totally orders commands and computes the sequence of results
Deterministic state machine

Machine totally orders commands and computes the sequence of results
State machine replication

Clients send commands to all replicas
Replicas may receive commands in different orders
State machine replication

Totally order commands via a sequence of consensus instances
State machine replication

Replicas compute the same sequence of results
State machine replication

Replicas compute the same sequence of results
State machine replication

Replicas compute the same sequence of results

Correctness: replicated implementation is linearizable wrt single-server one: replication transparent to clients
The zoo of consensus protocols

- Viewstamped replication (1988)
- Paxos (1998)
- Disk Paxos (2003)
- Paxos Commit (2004)
- Fast Paxos (2006)
- Stoppable Paxos (2008)
- Mencius (2008)
- Vertical Paxos (2009)
- ZAB (2009)
- Ring Paxos (2010)
- Egalitarian Paxos (2013)
- Raft (2014)
- M2Paxos (2016)
- Flexible Paxos (2016)
- Caesar (2017)
The zoo of consensus protocols:

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Complex protocols: constant fight for better performance.
The zoo of consensus protocols:

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Complex protocols: constant fight for better performance
The Part-Time Parliament

LESLIE LAMPORT
Digital Equipment Corporation

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.

Categories and Subject Descriptors: C2.4 [Computer-Communications Networks]: Distributed Systems—Network operating systems; D4.5 [Operating Systems]: Reliability—Fault-tolerance; J.1 [Administrative Data Processing]: Government

General Terms: Design, Reliability

Additional Key Words and Phrases: State machines, three-phase commit, voting

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.

The author appears to be an archeologist with only a passing interest in computer science. This is unfortunate; even though the obscure ancient Paxon civilization he describes is of little interest to most computer scientists, its legislative system is an excellent model for how to implement a distributed computer system in an asynchronous environment. Indeed, some of the refinements the Paxons made to their protocol appear to be unknown in the systems literature.
The Part-Time Parliament

LESLIE LAMPORT
Digital Equipment Corporation

Paxos Made Simple

Leslie Lamport

Abstract

The Paxos algorithm, when presented in plain English, is very simple.
Paxos Made Simple

Paxos Made Moderately Complex

ROBBERT VAN RENESSE and DENIZ ALTINBUKEN, Cornell University

This article explains the full reconfigurable multidegree Paxos (or multi-Paxos) protocol. Paxos is by no means a simple protocol, even though it is based on relatively simple invariants. We provide pseudocode and explain it guided by invariants. We initially avoid optimizations that complicate comprehension. Next we discuss liveness, list various optimizations that make the protocol practical, and present variants of the protocol.

Categories and Subject Descriptors: C.2.4 [Computer-Communication Networks]: Distributed Systems—Network operating systems; D.4.5 [Operating Systems]: Reliability—Fault-tolerance

General Terms: Design, Reliability

Additional Key Words and Phrases: Replicated state machines, consensus, voting

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Abstract

Raft is a consensus algorithm for managing a replicated log. It produces a result equivalent to (multi-)Paxos, and it is as efficient as Paxos, but its structure is different from Paxos; this makes Raft more understandable than Paxos and also provides a better foundation for building practical systems. In order to enhance understandability, Raft separates the key elements of consensus, such as leader election, log replication, and safety, and it enforces a stronger degree of coherency to reduce the number of states that must be considered. Results from a user study demonstrate that Raft is easier for students to learn than Paxos. Raft also includes a new mechanism for changing the cluster membership, which uses overlapping majorities to understand than Paxos: after learning both algorithms, 33 of these students were able to answer questions about Raft better than questions about Paxos.

Raft is similar in many ways to existing consensus algorithms (most notably, Oki and Liskov’s Viewstamped Replication [27, 20]), but it has several novel features:

- **Strong leader:** Raft uses a stronger form of leadership than other consensus algorithms. For example, log entries only flow from the leader to other servers. This simplifies the management of the replicated log and makes Raft easier to understand.

- **Leader election:** Raft uses randomized timers to elect leaders. This adds only a small amount of mechanism to the heartbeats already required for any consensus algorithm.
In Search of an Understandable Consensus Algorithm

Abstract

Raft is a consensus algorithm for multi-log. It produces a result equivalent to Paxos, but it is as efficient as Paxos, but its source code was written from Paxos; this makes Raft more independent of Paxos and also provides a better foundation for practical systems. In order to enhance usability, Raft separates the key elements of leader election, log replication, and safety, and it also provides a stronger degree of coherency to members of the cluster membership, which uses

Unfortunately, Paxos has two significant drawbacks. The first drawback is that Paxos is exceptionally difficult to understand. The full explanation [15] is notoriously opaque; few people succeed in understanding it, and only with great effort. As a result, there have been several attempts to explain Paxos in simpler terms [16, 20, 21]. These explanations focus on the single-decade subset, yet they are still challenging. In an informal survey of attendees at NSDI 2012, we found few people who were comfortable with Paxos, even among seasoned researchers. We struggled with Paxos ourselves; we were not able to understand the complete protocol until after reading several simplified explanations and designing our own alternative protocol.
Paxos Made Live - An Engineering Perspective
(2006 Invited Talk)

Tushar Chandra, Robert Griesemer, and Joshua Redstone

Google Inc.

ABSTRACT
We describe our experience in building a fault-tolerant database using the Paxos consensus algorithm. Despite the existing literature in the field, building such a database proved to be non-trivial. We describe selected algorithmic and engineering problems encountered, and the solutions we found for them. Our measurements indicate that we have built a competitive system.

Categories and Subject Descriptors
D.4.5 [Operating systems]: Reliability—Fault-tolerance; B.4.5 [Input/output and data communications]: Reliability, Testing, and Fault-Tolerance—Redundant design

General Terms
Experimentation, Performance, Reliability

Keywords
Experiences, Fault-tolerance, Implementation, Paxos database is just an example. As a result, the consensus problem has been studied extensively over the past two decades. There are several well-known consensus algorithms that operate within a multitude of settings and which tolerate a variety of failures. The Paxos consensus algorithm [8] has been discussed in the theoretical [16] and applied community [10, 11, 12] for over a decade.

We used the Paxos algorithm (“Paxos”) as the base for a framework that implements a fault-tolerant log. We then relied on that framework to build a fault-tolerant database. Despite the existing literature on the subject, building a production system turned out to be a non-trivial task for a variety of reasons:

- While Paxos can be described with a page of pseudocode, our complete implementation contains several thousand lines of C++ code. The blow-up is not due simply to the fact that we used C++ instead of pseudo notation, nor because our code style may have been verbose. Converting the algorithm into a practical, production-ready system involved implementing many features and optimizations – some published in the lit-
Paxos Made Live - An Engineering Perspective
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ABSTRACT
We describe our experience in building a fault-tolerant database using the Paxos consensus algorithm. Existing literature in the field, building such a database, is non-trivial. We describe the algorithmic engineering problems encountered, and the solutions to them. Our measurements indicate that we have a competitive system.

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D.4.5 [Operating systems]: Reliability—Fault-tolerance;
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General Terms
Experimentation, Performance, Reliability

Keywords
Experiences, Fault-tolerance, Implementation, Paxos

- There are significant gaps between the description of the Paxos algorithm and the needs of a real-world system. In order to build a real-world system, an expert needs to use numerous ideas scattered in the literature and make several relatively small protocol extensions. The cumulative effort will be substantial and the final system will be based on an unproven protocol.

- While Paxos can be described with a page of pseudocode, our complete implementation contains several thousand lines of C++ code. The blow-up is not due simply to the fact that we used C++ instead of pseudocode notation, nor because our code style may have been verbose. Converting the algorithm into a practical, production-ready system involved implementing many features and optimizations – some published in the lit-
Paxos Made Live

(200)

Tushar Chandra, Rob Hukin

ABSTRACT

We describe our experience in building a fault-tolerant database using the Paxos consensus algorithm. Despite the existing literature in the field, building such a database turned out to be non-trivial. We describe selected algorithmic engineering problems encountered, and the solutions we devised for them. Our measurements indicate that we have built a competitive system.

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Experimentation, Performance, Reliability

Keywords

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5.1 Handling disk corruption

Replicas witness disk corruption from time to time. A disk may be corrupted due to a media failure or due to an operator error (an operator may accidentally erase critical data). When a replica’s disk is corrupted and it loses its persistent state, it may renege on promises it has made to other replicas in the past. This violates a key assumption in the Paxos algorithm. We use the following mechanism to address this problem [14].

Disk corruptions manifest themselves in two ways. Either file(s) contents may change or file(s) may become inaccessible. To detect the former, we store the checksum of the contents of each file in the file. The latter may be indistinguishable from a new replica with an empty disk – we detect this case by having a new replica leave a marker in GFS after start-up. If this replica ever starts again with an empty disk, it will discover the GFS marker and indicate that it has a corrupted disk.

A replica with a corrupted disk rebuilds its state as follows. It participates in Paxos as a non-voting member; meaning that it uses the catch-up mechanism to catch up but does not respond with promise or acknowledgment messages. It remains in this state until it observes one complete instance of Paxos that was started after the replica started rebuilding its state. By waiting for the extra instance of Paxos, we ensure that this replica could not have reneged on an earlier promise.
5.1 Handling disk corruption

Replicas witness disk corruption from time to time. A disk may be corrupted due to a media failure or due to an operator error (an operator may accidentally erase critical data). When a replica’s disk is corrupted and it loses its persistent state, it may renege on promises it has made to other replicas in the past. This violates a key assumption in the Paxos algorithm. We use the following mechanism to address this problem [14].

Disk corruptions manifest themselves in two ways. Either file(s) contents may change or file(s) may become inaccessible. To detect the former, we store the checksum of the contents of each file in the file\(^2\). The latter may be indistinguishable from a new replica with an empty disk – we detect this case by having a new replica leave a marker in GFS after an empty disk operation that it has a corrupted disk.

A replica with a corrupted disk rebuilds its state as follows. It participates in Paxos as a non-voting member; meaning that it uses the catch-up mechanism to catch up but does not respond with promise or acknowledgment messages. It remains in this state until it observes one complete instance of Paxos that was started after the replica started rebuilding its state. By waiting for the extra instance of Paxos, we ensure that this replica could not have reneged on an earlier promise.
Goals

• Develop methods for proving protocols correct, including realistic deployments
• Get insights into their structure
Goals

- Develop methods for proving protocols correct, including realistic deployments
- Get insights into their structure
- Focus on single-decree Paxos and Multi-Paxos
Approach

- Modular reasoning: verify parts of the protocol separately instead of the whole thing
Approach

- Modular reasoning: verify parts of the protocol separately instead of the whole thing
- Linearizability implies refinement
  [Filipovic et al. 2009]
Approach

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Approach

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• Linearizability implies refinement [Filipovic+ 2009]

\[
P_1 \sqsubseteq S_1 \\
P_2(S_1) \sqsubseteq S_2
\]
Approach

• Modular reasoning: verify parts of the protocol separately instead of the whole thing
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Approach

- Modular reasoning: verify parts of the protocol separately instead of the whole thing
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\[ P_1 \sqsubseteq S_1 \]
\[ P_2(S_1) \sqsubseteq S_2 \]
\[ P_3(S_2) \sqsubseteq S_3 \]
Approach

• Modular reasoning: verify parts of the protocol separately instead of the whole thing
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Approach

• Modular reasoning: verify parts of the protocol separately instead of the whole thing
  • Linearizability implies refinement [Filipovic+ 2009]
  • Transformations of the network semantics, à la *Verified System Transformers* of the Verdi framework [Wilcox+ 2015]
Approach

- Modular reasoning: verify parts of the protocol separately instead of the whole thing
- Linearizability implies refinement [Filipovic+ 2009]
- Transformations of the network semantics, à la *Verified System Transformers* of the Verdi framework [Wilcox+ 2015]

Prove one variant of the protocol without unpacking the proof of a simpler variant
• **Acceptors** = members of parliament: can vote to accept a value, majority wins
• **Proposer** = parliament speaker: proposes its value to vote on
• **Phase 1**: a proposer chooses a round $r$ and convinces a majority of acceptors to switch to $r$

• Acceptor switches only if it’s current round is less
• **Phase 1**: a proposer chooses a round $r$ and convinces a majority of acceptors to switch to $r$

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• **Phase 1**: a proposer choses a round $r$ and convinces a majority of acceptors to switch to $r$

• Acceptor switches only if it’s current round is less
- **Phase 2**: the proposer sends its value tagged with the round number
- Acceptor only accepts a value tagged with the round it is in
• Phase 2: the proposer sends its value tagged with the round number

• Acceptor only accepts a value tagged with the round it is in
• Phase 1: a proposer chooses a round $r'$ and convinces a majority of acceptors to switch to $r'$
• Phase 1: a proposer chooses a round $r'$ and convinces a majority of acceptors to switch to $r'$. 
• Acceptor sends to the proposer its round number and value.
• **Phase 1:** a proposer chooses a round $r'$ and convinces a majority of acceptors to switch to $r'$

• Acceptor sends to the proposer its round number and value

• If some acceptor has accepted a value, the proposer proposes the value with the highest round number
Phase 1: a proposer chooses a round $r'$ and convinces a majority of acceptors to switch to $r'$.

Acceptors send to the proposer their round number and value.

If some acceptor has accepted a value, the proposer proposes the value with the highest round number.

Ensures that the chosen value $v_2$ will not be changed.
Modular structure in single-decree Paxos

• Steal abstractions from an existing analysis of Paxos [Boichat+ 2003]

• Show their linearizability → modular proof of Paxos
Round Based Register
[Boichat+ 2003]

- Data type encapsulating the state of acceptors

- `read(int k)`
  Phase 1 of Paxos

- `write(int k, val v)`
  Phase 2 of Paxos
read(int k) {
    query acceptors and switch them to round k;
    if (majority of acceptors acknowledge) {
        if (no acceptor has accepted a value) {
            return (false, undef);
        }
        else {
            v ::= value at acceptor with highest round;
            return (true, v);
        }
    }
    else { return (false, undef); } 
}
read(int k) {
    query acceptors and switch them to round k;
    if (majority of acceptors acknowledge) {
        if (no acceptor has accepted a value) {
            return (false, undef);
        }
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        }
        else {
            v ::= value at acceptor with highest round;
            return (true, v);
        }
    }
    else {
        return (false, undef);
    }
}
write(int k, val v) {
    update acceptors at round k with value v;
    if (majority of acceptors acknowledges) {
        return true;
    } else {
        return false;
    }
}
write(int k, val v) {
    update acceptors at round k with value v;
    if (majority of acceptors acknowledges) {
        return true;
    }
    else {
        return false;
    }
}

write(int k, val v) {
    update acceptors at round k with value v;
    if (majority of acceptors acknowledges) {
        return true;
    }
    else {
        return false;
    }
}
Round Based Consensus
[Boichat+ 2003]

- Routine leading Phase 1 and Phase 2 in the Paxos algorithm
- `proposeRC(int k, val v)`
proposeRC(int k, val v0) {
    (res, v) := read(k);
    if (res) {
        if (v = undef) {
            v := v0;
        }
        res := write(k, v);
        if (res) { return (true, v); }
    }
    return (false, undef);
}
proposeRC(int k, val v0) {
    (res, v) := read(k);
    if (res) {
        if (v = undef) {
            v := v0;
        }
        res := write(k, v);
        if (res) { return (true, v); }
    }
    return (false, undef);
}
Paxos

- Entry module, encapsulates rounds
- `proposeP(val v)`
proposeP(val v0) {
    pick a round k;
    do {
        (res, v) := proposeRC(k, v0);
        increase round k;
    } while (!res);
    return v;
}
proposeP(val v0) {
    pick a round k;
    do {
        (res, v) := proposeRC(k, v0);
        increase round k;
    } while (!res);
    return v;
}
Contribution

Round-based register is linearizable wrt an atomic, single-server specification strong enough to prove single-decree Paxos correct.
abs_v := undef;
abs_round := 0;
vals := {undef};
read(int k) {
  atomic {
    pick random vR from vals;
    pick random boolean b;
    if (b) {
      if (k >= abs_round) {
        abs_round := k;
        if (!(abs_v = undef)) {
          v := abs_v;
        }
      } else { v := vR; }
    } else { v := vR; }
    return (true, v);
  }
}

write(int k, val vW) {
  atomic {
    pick random boolean b;
    vals := vals U {vW};
    if (b && (k >= abs_round)) {
      abs_round := k;
      abs_v := vW;
      return true;
    } else {
      return false;
    }
  }
}
read(int k) {
    atomic {
        pick random vR from vals;
        pick random boolean b;
        if (b) {
            if (k >= abs_round) {
                abs_round := k;
                if (!(abs_v = undef)) {
                    v := abs_v;
                }
            }
            else { v := vR; }
        }
        else { v := vR; }
        return (true, v);
    }
    else {
        return (false, undef);
    }
}

write(int k, val vW) {
    atomic {
        pick random boolean b;
        vals := vals U {vW};
        if (b && (k >= abs_round)) {
            abs_round := k;
            abs_v := vW;
            return true;
        }
        else {
            return false;
        }
    }
}
abs_v := undef;
abs_round := 0;
vals := {undef};

read(int k) {
    atomic {
        pick random vR from vals;
        pick random boolean b;
        if (b) {
            if (k >= abs_round) {
                abs_round := k;
                if (!(abs_v = undef)) {
                    v := abs_v;
                }
            } else { 
                v := vR;
            }
        } else { v := vR; }
        return (true, v);
    }
    else {
        return (false, undef);
    }
}

write(int k, val vW) {
    atomic {
        pick random boolean b;
        vals := vals U {vW};
        if (b && (k >= abs_round)) {
            abs_round := k;
            abs_v := vW;
            return true;
        } else {
            return false;
        }
    }
}
Read may succeed even if \( k \) is lower than the current round
→ a failing write “contaminates” some acceptor, modeled by value \( v_R \) and boolean \( b \)
abs_v := undef;
abs_round := 0;
vals := {undef};

read(int k) {
    atomic {
        pick random vR from vals;
Pick random boolean b;
        if (b) {
            if (k >= abs_round) {
                abs_round := k;
                if (!(abs_v = undef)) {
                    v := abs_v;
                }
            else { v := vR; }
        }
        else { v := vR; }
        return (true, v);
    }
    else { return (false, undef); 
    }
}

write(int k, val vW) {
    atomic {
        pick random boolean b;
        vals := vals U {vW};
        if (b && (k >= abs_round)) {
            abs_round := k;
            abs_v := vW;
            return true;
        }
        else { return false; }
    }
}
If a write succeeds, a succeeding read will pick the written value.

A decision taken in consensus cannot be changed.

```cpp
abs_v := undef;
abs_round := 0;
vals := {undef};

read(int k) {
    atomic {
        pick random vR from vals;
        pick random boolean b;
        if (b) {
            if (k >= abs_round) {
                abs_round := k;
                if (!abs_v) {
                    v := abs_v;
                } else {
                    v := vR;
                }
            } else {
                v := vR;
            }
        return (true, v);
    }
else {
    return (false, undef);
    }
}

write(int k, val vW) {
    atomic {
        pick random boolean b;
        vals := vals U {vW};
        if (b && (k >= abs_round)) {
            abs_round := k;
            abs_v := vW;
            return true;
        } else {
            return false;
        }
    }
}

proposeRC(int k, val v0) {
    (res, v) := read(k);
    if (res) {
        if (v = undef) {
            v := v0;
        }
        res := write(k, v);
        if (res) {
            return (true, v);
        }
    } else {
        return (false, undef);
    }
```
State machine replication requires solving a sequence of consensus instances
Multi-Paxos

State machine replication requires solving a sequence of consensus instances

- Naive solution: execute a separate Paxos instance for each sequence element
Multi-Paxos

State machine replication requires solving a sequence of consensus instances

- **Naive solution**: execute a separate Paxos instance for each sequence element
- **Multi-Paxos**: execute Phase 1 once for multiple sequence elements
Contribution

Multi-Paxos refines the naive solution, shown by transformations of the network semantics à la Verdi [Wilcox+ 2015]
Simple Semantics

snd(2, P1(r))

rcv(1, P1(r))
Out-of-Thin-Air Semantics

rcv(1, P1(r))
Out-of-Thin-Air Semantics

Pred(δ₁, P1(r))

rcv(1, P1(r))
Slot-Replicating Semantics

snd(2, P1(r), 1)
rcv(1, P1(r), 1)
Slot-Replicating Semantics

snd(2, P1(r), 1) → rcv(1, P1(r), 1)

1

2

3
Widening Semantics

\[ \text{snd}(2, P1(r), 1) \]

\[ \text{rcv}(1, P1(r), 1) \]

\[ \text{rcv}(1, P1(r), i) \]

\[ \text{rcv}(1, P1(r), i) \]
Widening Semantics

\[ \text{snd}(2, P1(r), 1) \]

\[ \text{rcv}(1, P1(r), 1) \]

\[ P1(r) \in T \]
Widening Semantics

Out-of-thin-air compliant:
if slot $i$ receives $m \in T$ from $\rho$, then $\text{Pred}(\delta_\rho, m)$
Optimised Widening Semantics

snd(2, P1(r), 1)
rcv(1, P1(r))
Optimised Widening Semantics

Phase 1 of single-decree Paxos → results in Multi-Paxos
Summary

• Modular reasoning to verify each component separately

• Linearisability as a correctness criterium for refinement

• Deconstruction of single-decree Paxos by [Boichat+ 2003] linearises wrt non-deterministic specifications

• Behaviour-preserving transformations of the network semantics à la Verdi [Wilcox+ 2015]

• Multi-Paxos can be verified without unpacking the correctness proof of single-decree Paxos
Summary

- Modular reasoning to verify each component separately
- Linearisability as a correctness criterion for refinement
- Deconstruction of single-decree Paxos by [Boichat+ 2003] linearises wrt non-deterministic specifications
- Behaviour-preserving transformations of the network semantics à la Verdi [Wilcox+ 2015]
- Multi-Paxos can be verified without unpacking the correctness proof of single-decree Paxos

Thanks!