Distributed Systems

10. Quorum-Based Consensus: Paxos

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Consensus Goal

Allow a group of processes to agree on a result

– All processes must agree on the same value
– The value must be one that was submitted by at least one process (the consensus algorithm cannot just make up a value)
We saw versions of this

- Mutual exclusion
  - Agree on who gets a resource or who becomes a coordinator

- Election algorithms
  - Agree on who is in charge

- Other uses of consensus:
  - Synchronize state to manage replicas: make sure every group member agrees on the message ordering of events
  - Manage group membership
  - Agree on distributed transaction commit

- General consensus problem:
  - How do we get unanimous agreement on a given value?
  
  value = sequence number of a message, key=value, operation, whatever…
Achieving consensus seems easy!

- One request at a time
- Server that never dies
Servers might die – let's add replicas

- One request at a time
We rely on a quorum (majority) to read successfully

No quorum = failed read!
What about concurrent updates?

- Coordinator processes requests one at a time
- But now we have a single point of failure!
- We need something safer
Consensus algorithm goal

Goal: agree on one result among a group of participants

Create a fault-tolerant consensus algorithm that does not block if a majority of processes are working

- Processors may fail (some may need stable storage)
- Messages may be lost, out of order, or duplicated
- If delivered, messages are not corrupted

Quorum: majority (>50%) agreement is the key part: If a majority of coins show heads, there is no way that a majority will show tails at the same time.

If members die and others come up, there will be one member in common with the old group that still holds the information.
Consensus requirements

• Validity
  – Only proposed values may be selected

• Uniform agreement
  – No two nodes may select different values

• Integrity
  – A node can select only a single value

• Termination (Progress)
  – Every node will eventually decide on a value
Paxos (Παξος) Consensus algorithm
Paxos

Goal: agree on a single value even if multiple systems propose different values concurrently

Common use: provide a consistent ordering of events from multiple clients
- All machines running the algorithm agree on a proposed value from a client
- The value will be associated with an event or action
- Paxos ensures that no other machine associates the value with another event

Fault-tolerant distributed consensus algorithm
- Does not block if a majority of processes are working
- The algorithm needs a majority \((2P+1)\) of processors survive the simultaneous failure of \(P\) processors

Paxos provides abortable consensus
- A client’s request may be rejected
- It then has to re-issue the request
If your request is not accepted, you can submit it again later:

```c
while (submit_request(R) != ACCEPTED) ;
```

Think of R as a `key:value` pair in a database where multiple clients might want to modify the same key.
Paxos players

**Client**: makes a request

**Proposers**:
- Get a request from a client and run the protocol to get everyone in the cluster to agree
- **Leader**: elected coordinator among the proposers (not necessary but simplifies message numbering and ensures no contention) – we don’t need to rely on the presence of a single leader

**Acceptors**:
- Multiple processes that remember the state of the protocol
- **Quorum** = any majority of acceptors

**Learners**:
- When agreement has been reached by acceptors, a Learner executes the request and/or sends a response back to the client

These different roles are usually part of the same system
Proposal numbers

• **Paxos ensures a consistent ordering in a cluster of machines**
  – Events are ordered by sequential event IDs \( N \)
• Client wants to log an event: sends request to a Proposer
  – E.g., *value, v = “add $100 to my checking account”*

• **Proposer**
  – Increments the latest proposal number (event ID) it knows about
    • ID = sequence number
  – Asks all the acceptors to reserve that proposal #

• **Acceptors**
  – A majority of acceptors have to accept the requested proposal #
Proposal Numbers

• Each proposal has a **unique** number (created by proposer)
  – Must be unique (e.g., `<sequence #>.<process_id>`)

• Newer proposals take precedence over older ones

• Each acceptor
  – Keeps track of the largest number it has seen so far
  – Lower proposal numbers get rejected
    • Acceptor sends back the `{number, value}` of the currently accepted proposal
    • Proposer has to “play fair”:
      – It will ask the acceptors to accept the `{number, value}`
      – Either its own or the one it got from the acceptor
Paxos in action

Goal: have all acceptors agree to a value $v$ associated with a proposal

Paxos nodes: one machine may serve several roles
Paxos in action: Phase 0

Client sends a request to a proposer

Client sends a request to a proposer $\text{request}(v)$
Paxos in action: Phase 1a – \textit{PREPARE}

**Proposer**: creates a proposal \#N (\textit{N acts like a Lamport time stamp}), where \textit{N} is greater than any previous proposal number used by this proposer

\textbf{Send to Quorum of Acceptors} (however many you can reach – but a majority)

\begin{itemize}
  \item \textbf{Prepare}(N)
  \item \(N = \langle \text{seq# . process\_ID} \rangle\)
\end{itemize}
Paxos in action: Phase 1b – PROMISE

**Acceptor:**
if proposer’s ID > any previous proposal
promise to ignore all requests with IDs < N
reply with info about highest accepted proposal if there was one: \{ N’, value \}

Need to get Promise messages from a majority of acceptors

Promise to ignore all proposals < N
Promise contains the previous N
Paxos in action: Phase 2a – *PROPOSE*

**Proposer**: if proposer receives promises from the quorum (majority):
- Attach a value $v$ to the proposal (the event).
- Send *Propose* to quorum with the *chosen* value
If promise was for another \(\{N', v\}\), proposer MUST accept $v$ for the *highest* accepted proposal
Paxos in action: Phase 2b – ACCEPT

**Acceptor**: if the promise still holds, then announce the value $v$

Send **Accepted** message to Proposer and every Learner

BUT: if a higher proposal # may have been received during this time then send NACK to proposer so it can try again

Most often, there are no learners and the "accept" phase is just the messages being sent to the service
Paxos in action: Phase 2c – ACCEPT

**Learner**: Respond to client and/or take action on the request

Client \rightarrow Proposer

Proposer

Acceptor

Accept\((N, v)\)

Quorum

Acceptor

Acceptor

Acceptor

Learners

Do \((N, v)\)

Server

Server

Server

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Paxos: A Simple Example – All Good
Paxos in action: Phase 0

Client sends a request to a proposer

Client → Proposer

Request("e")

Learner

Quorum

Acceptors

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Paxos in action: Phase 1a – PREPARE

**Proposer**: picks a sequence number: 5

**Send to Quorum of Acceptors**

- Client
- Proposer
- Learner
- Quorum

1. Proposer: picks a sequence number: 5
2. Send to Quorum of Acceptors: `Proposer` prepares and sends `Prepare(5)`
Paxos in action: Phase 1b – PROMISE

**Acceptor**: Suppose 5 is the highest sequence # any acceptor has seen. Each acceptor PROMISES not to accept any lower numbers.

- **Proposer**
- **Quorum**: Promise to ignore all proposals < 5
- **Learner**
Paxos in action: Phase 2a – ACCEPT

**Proposer**: Proposer receives the promise from a majority of acceptors
Proposer must accept that `<seq, value>`

```
Propose(5, “e”)
```
Acceptor: Acceptors state that they accepted the request
Paxos: A Simple Example – Higher Proposal
Client sends a request to a proposer

Client

Request(“e”)

Proposer

Learner

Quorum

Acceptor

Acceptor

Acceptor
Paxos in action: Phase 1a – \textit{PREPARE}

\textbf{Proposer}: picks a sequence number: 5

\textbf{Send to Quorum of Acceptors}

One acceptor receives a higher offer BEFORE it gets this PREPARE message

- \textit{Prepare(5)}
- \textit{Prepare(7)}

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Paxos in action: Phase 1b – PROMISE

**Acceptor**: If an acceptor previously received a higher ID, it will not respond

The diagram illustrates the Paxos protocol in action during Phase 1b. The client initiates a proposal (Proposer), which is then propagated to acceptors. Acceptors with the highest ID respond, while others do not participate due to their lower IDs. The diagram shows three acceptors: one with max_id=5, another with max_id=7, and a learner. The acceptors with max_id=5 respond to the proposal (Promise(5)), while the one with max_id=7 does not respond (No response).
Paxos in action: Phase 1a – PREPARE

**Proposer**: The other proposer’s messages now reach the other acceptors

*Send to Quorum of Acceptors*
**Acceptor**: Higher proposal numbers will get promises fulfilled
Proposer 2 gets a quorum of responses
**Proposer**: Now the first proposer sends ACCEPT messages. They get rejected because the acceptors made other promises.

- Propose(5, “e”)

**Diagram**:
- Client
- Proposer
- Acceptor
- Acceptor
- Acceptor
- Proposer 2
- Learner
Paxos in action: Phase 2a – ACCEPT

**Proposer**: The second proposer’s messages are accepted – it’s the highest ID
Acceptor: Acceptors state that they accepted the request

Announce(7, “f”)

Accepted(7, “f”)

Learners

Client

Proposer

Proposer 2

Acceptors
Paxos: Keep trying if you need to

• A proposal $N$ may fail because
  – The acceptor may have made a new promise to ignore all proposals less than some value $M > N$
  – A proposer does not receive a quorum of responses: either *promise* (phase 1b) or *accept* (phase 2b)

• Algorithm then has to be restarted with a higher proposal #
Paxos summary

• Paxos allows us to ensure consistent (total) ordering over a set of events in a group of machines
  – Events = commands, actions, state updates

• Each machine will have the latest state or a previous version of the state

• Paxos used in:
  – Google Chubby lock manager / name server
  – Apache Zookeeper (clone of Google Chubby)
  – Cassandra lightweight transactions
  – Google Spanner, Megastore
  – Microsoft Autopilot cluster management service from Bing
  – VMware NSX Controller
  – Amazon Web Services, DynamoDB
Paxos summary

To make a change to the system:

– Tell the proposer (leader) the event/command you want to add
  • Note: these requests may occur concurrently
  • Leader = one elected proposer. Not necessary for Paxos algorithm but an optimization to ensure a single, increasing stream of proposal numbers. Cuts down on rejections and retries.

– The proposer picks its next highest event ID and asks all the acceptors to reserve that event ID
  • If any acceptor sees has seen a higher event ID, it rejects the proposal & returns that higher event ID
  • The proposer will have to try again with another event ID

– When the majority of acceptors accept the proposal, accepted events are sent to learners, which can act on them (e.g., update system state)
  • Fault tolerant: need 2k+1 servers for k fault tolerance
Implementation

• Use only one proposer at a time – the leader
  – Other nodes can be active backups just in case the leader dies
  – No need to worry about sync of proposal # – those are local per proposer
  – Acts like a fault-tolerant coordinator
    • Avoids failed proposals due to higher numbers from other proposers

• Alternatively, embed proposer logic into client library
  – Too many clients issuing concurrent requests can cause a large # of retries

• Learners rarely needed
  – Acceptors are often running on the system that processes the request
    (e.g., data store, log, …)
  – Just send an acknowledgement directly to the client.
The End