Implementing Distributed Consensus

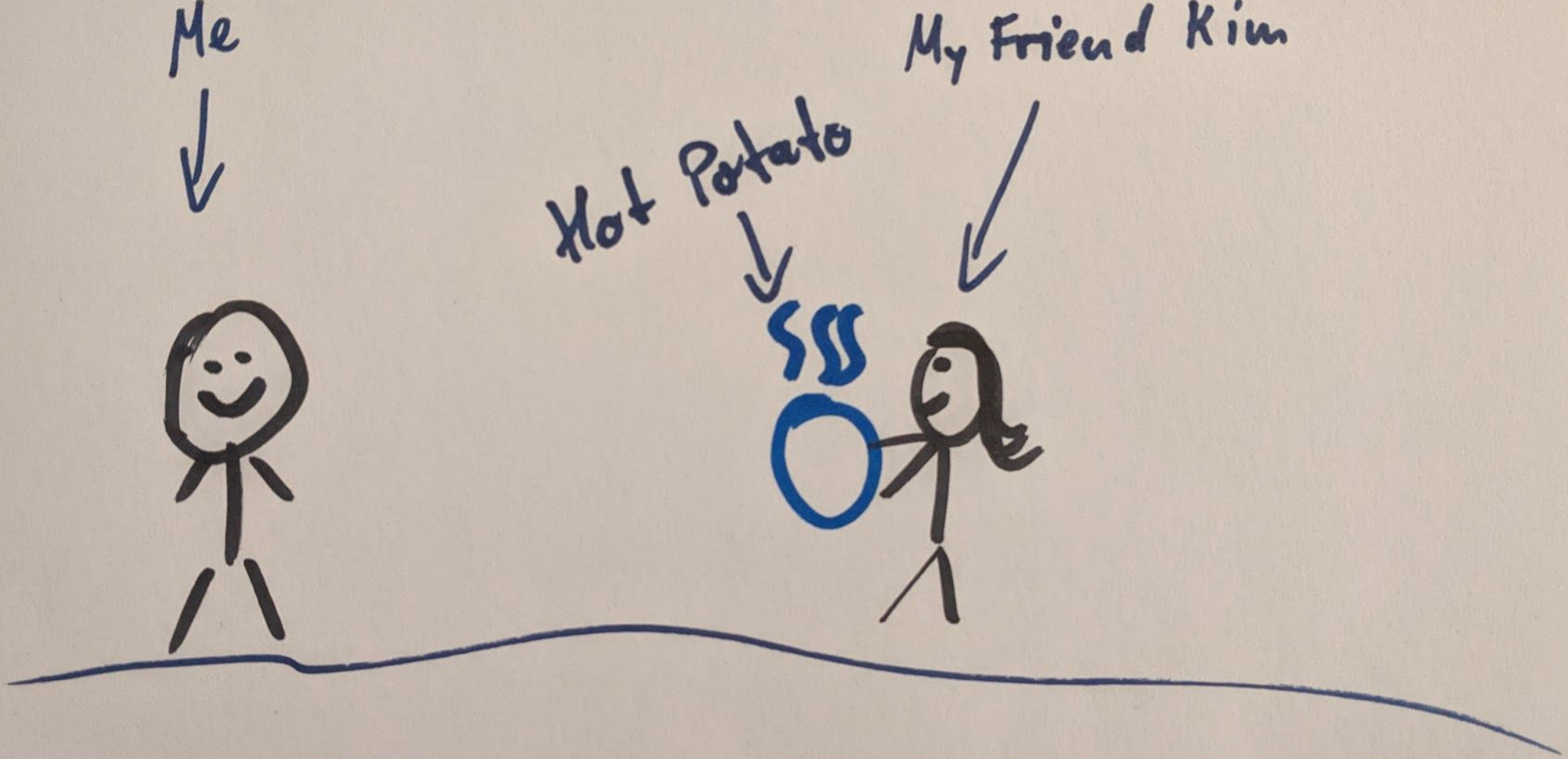
Dan Lüdtke
danrl@google.com

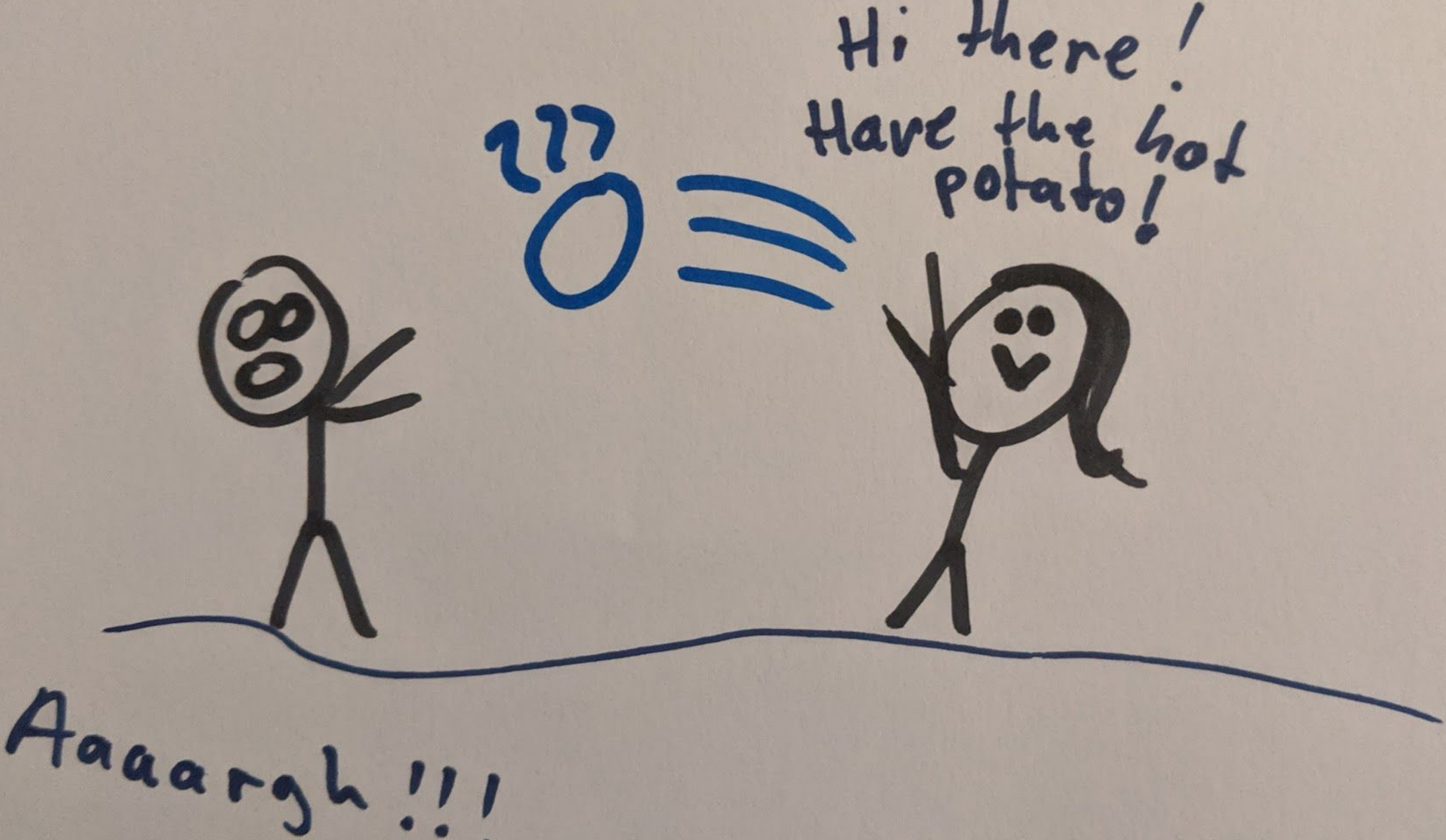
Disclaimer This work is not affiliated with any company (including Google). This talk is the result of a personal education project!

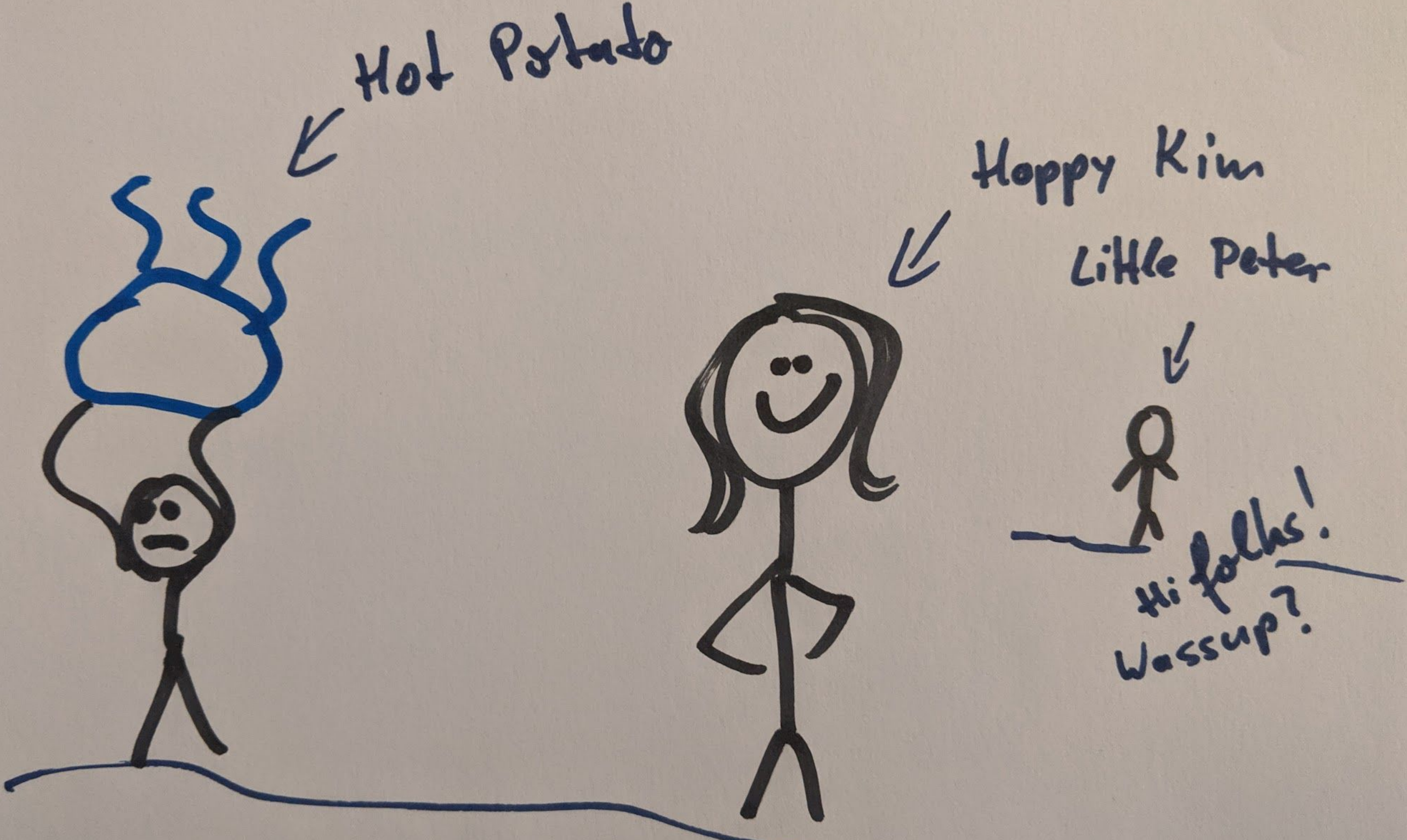
What?

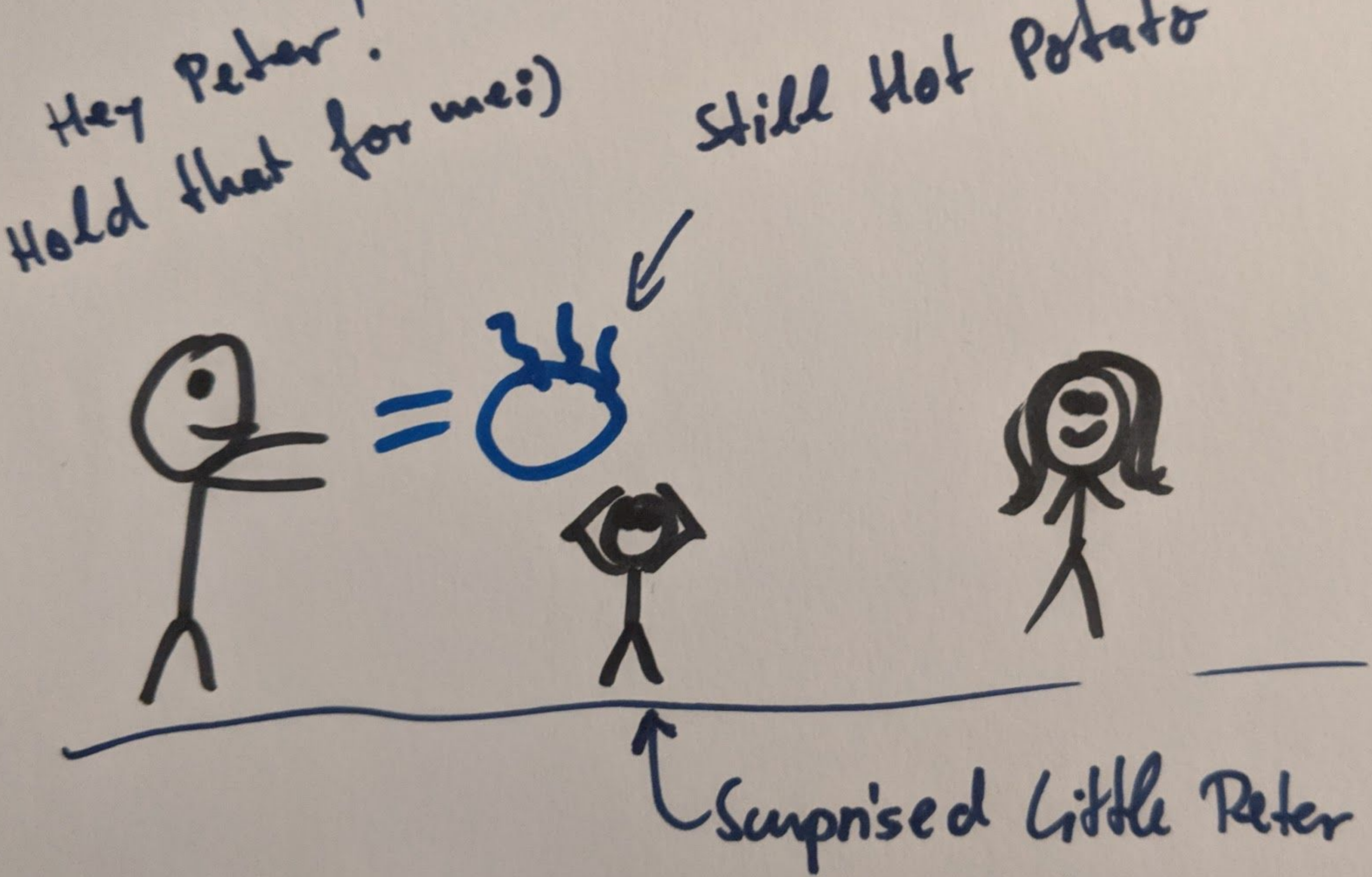
- My hobby project of learning about Distributed Consensus
  - I implemented a Paxos variant in Go
  - I learned a lot about how computers reach consensus
  - This talk: A fine selection of some of the mistakes I made
- Language used: Go
  - Code is likely readable for enthusiasts of other languages as well
  - I relied on some Go features, similar features exist in other languages

Distributed Consensus

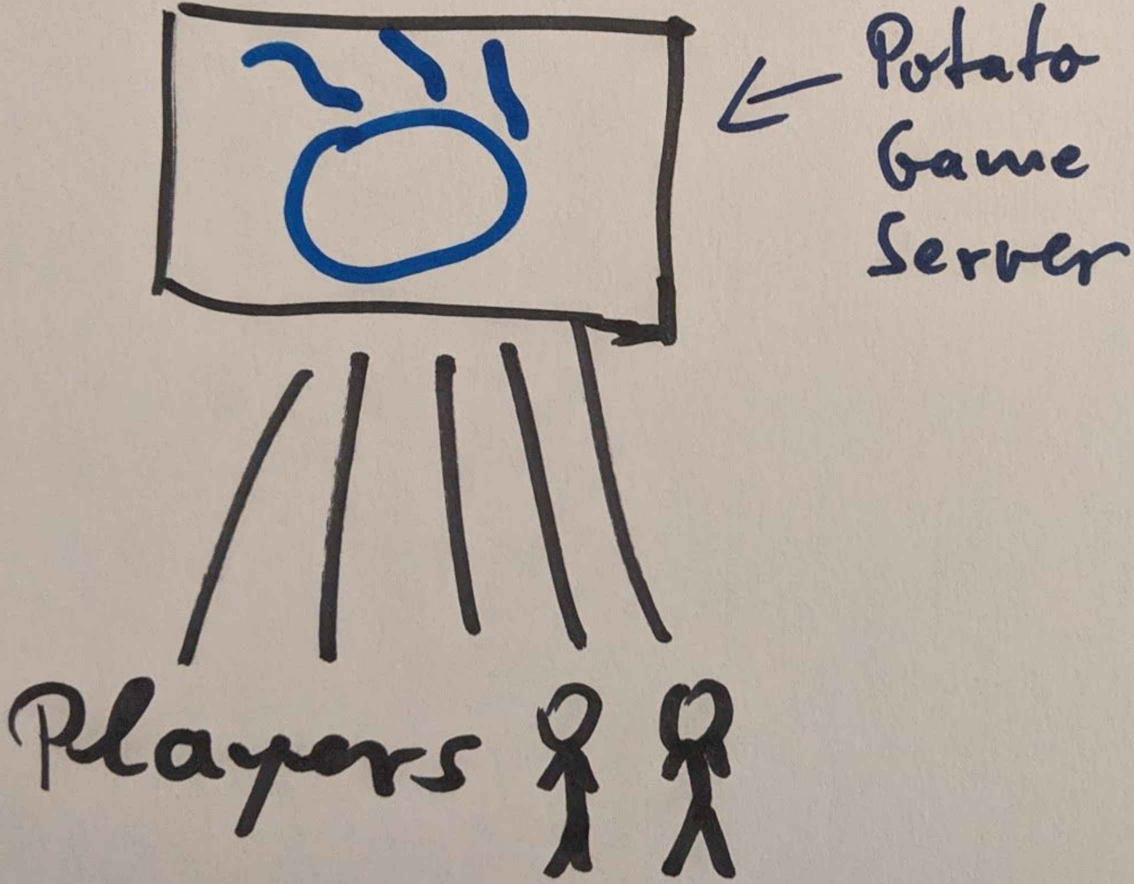

Me
Hot Potato
My Friend Kim

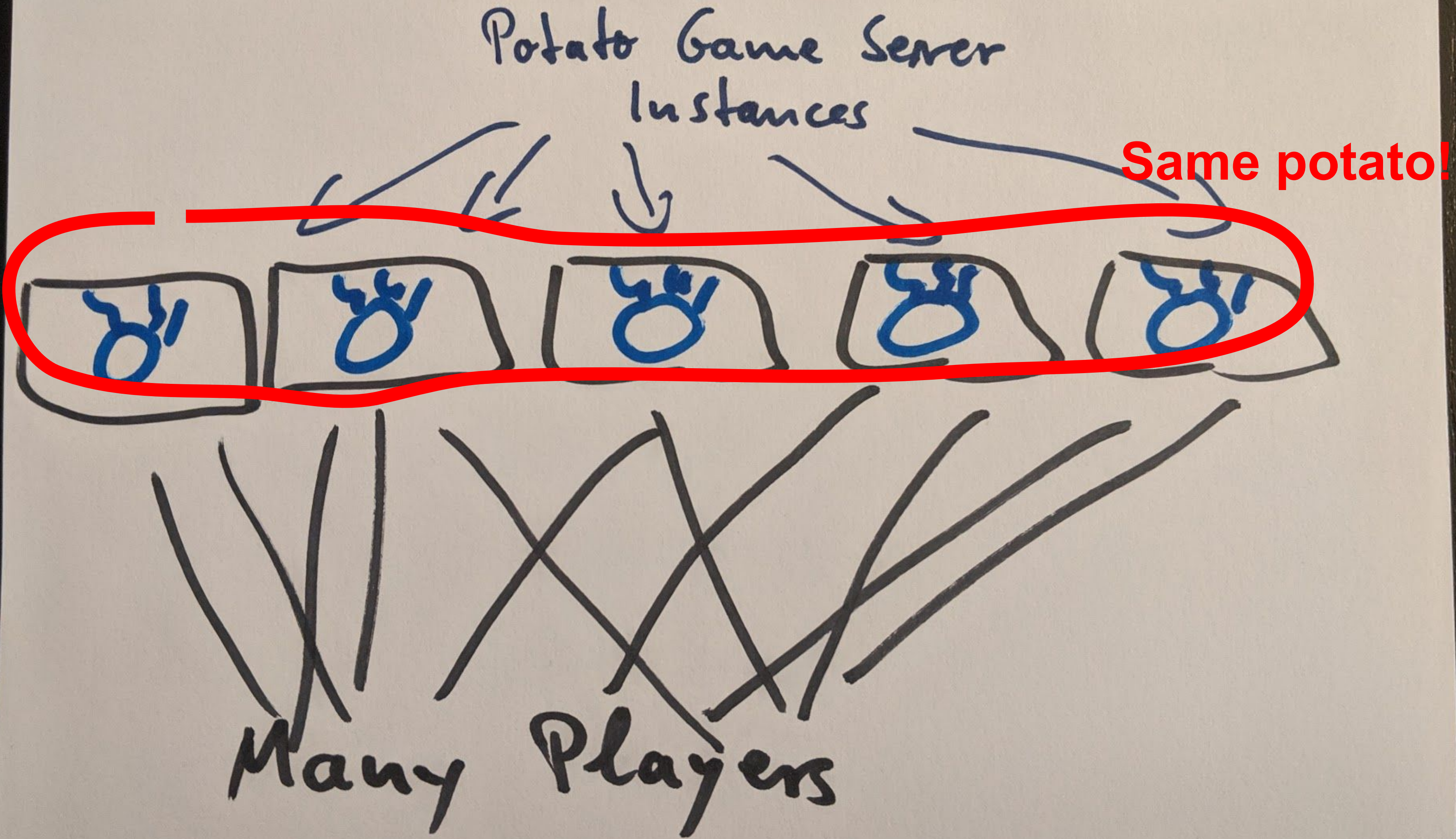

???
Hi there!
Have the hot potato!
Aaaargh!!!

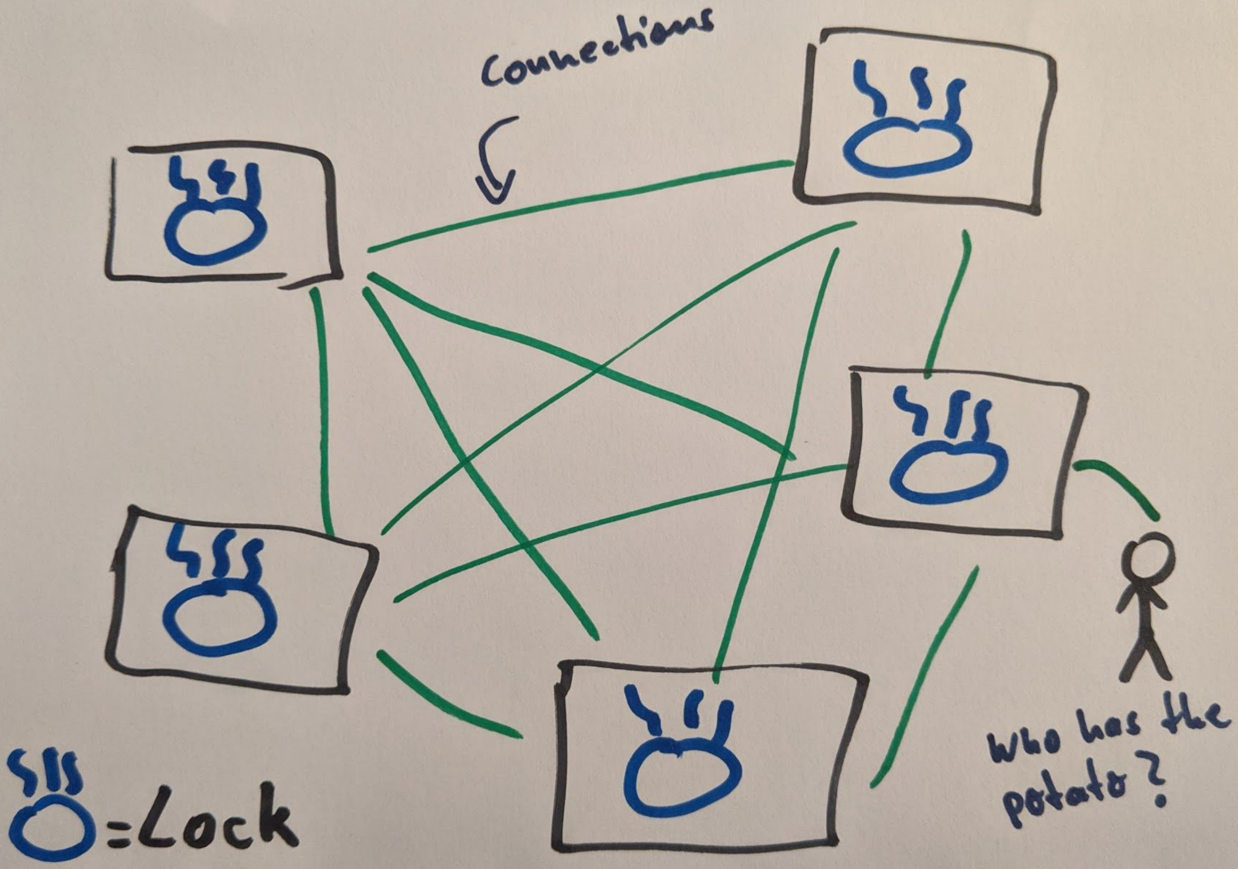

Hot Potato
Happy Kim
Little Peter
Hi folks!
Wassup?


Hey Peter!
Hold that for me:)
Still Hot Potato
Surprised Little Peter

More Friends


Potato Game Server
Players


Potato Game Server
Instances
Same potato!
Many Players


Connections
Who has the potato?
=Lock

Protocols

- Paxos
  - Multi-Paxos
  - Cheap Paxos
- Raft
- ZooKeeper Atomic Broadcast
- Proof-of-Work Systems
  - Bitcoin
- Lockstep Anti-Cheating
  - Age of Empires

Implementations

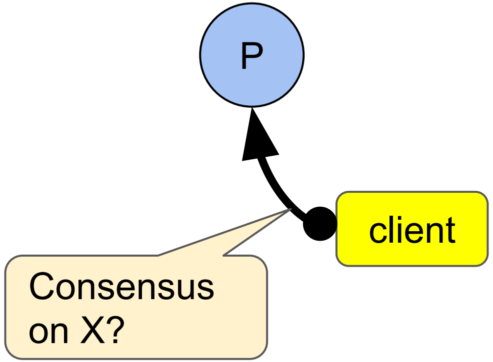
- Chubby
  - coarse grained lock service
- etcd
  - a distributed key value store
- Apache ZooKeeper
  - a centralized service for maintaining configuration information, naming, providing distributed synchronization

Raft Logo: Attribution 3.0 Unported (CC BY 3.0) Source: https://raft.github.io/#implementations
Etcd Logo: Apache 2 Source: https://github.com/etcd-io/etcd/blob/master/LICENSE
Zookeeper Logo: Apache 2 Source: https://zookeeper.apache.org/

Paxos

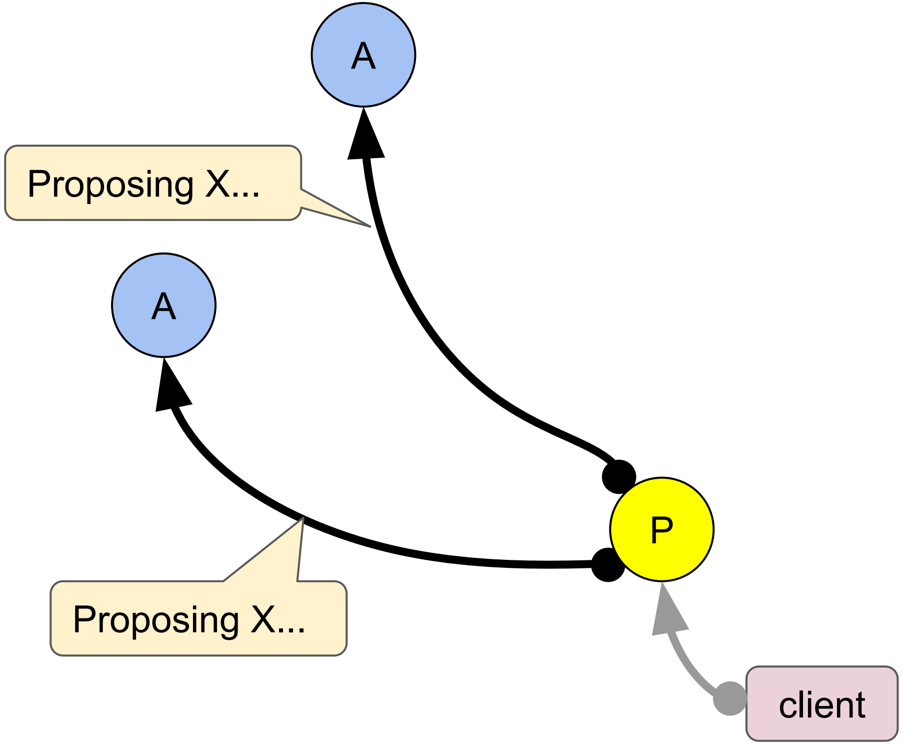
Paxos Roles

- Client
    - Issues request to a *proposer*
    - Waits for response from a *learner*
        - Consensus on value X
        - No consensus on value X
- Proposer
- Acceptor
- Learner
- Leader



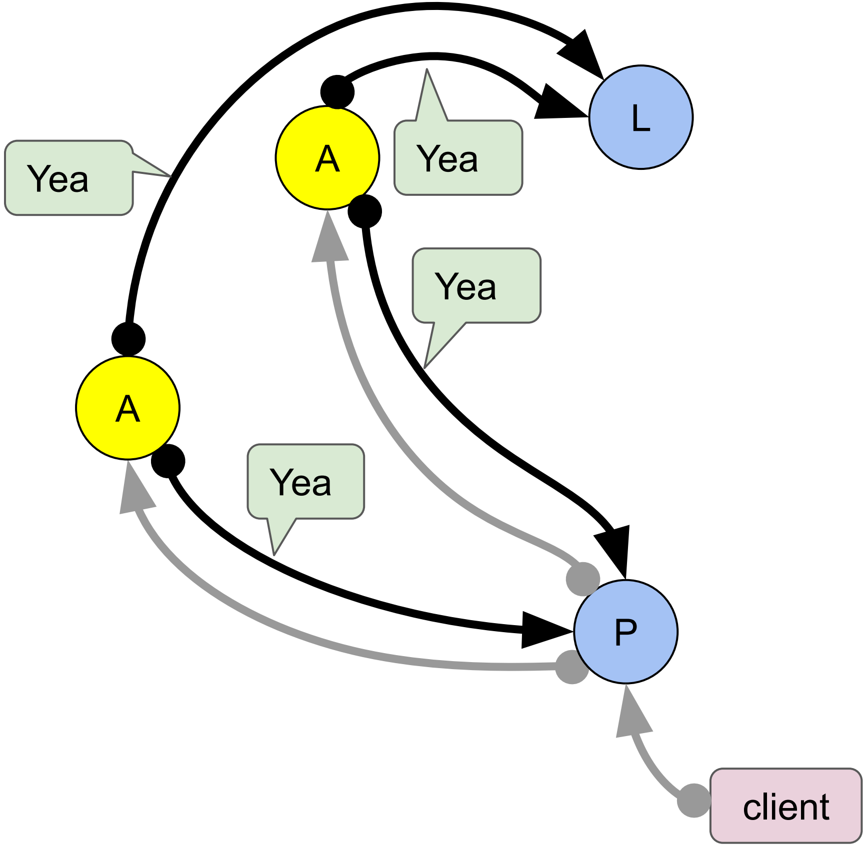
Paxos Roles

- Client
- Proposer (P)
  - Advocates a *client* request
  - Asks acceptors to agree on the proposed value
  - Move the protocol forward when there is conflict
- Acceptor
- Learner
- Leader



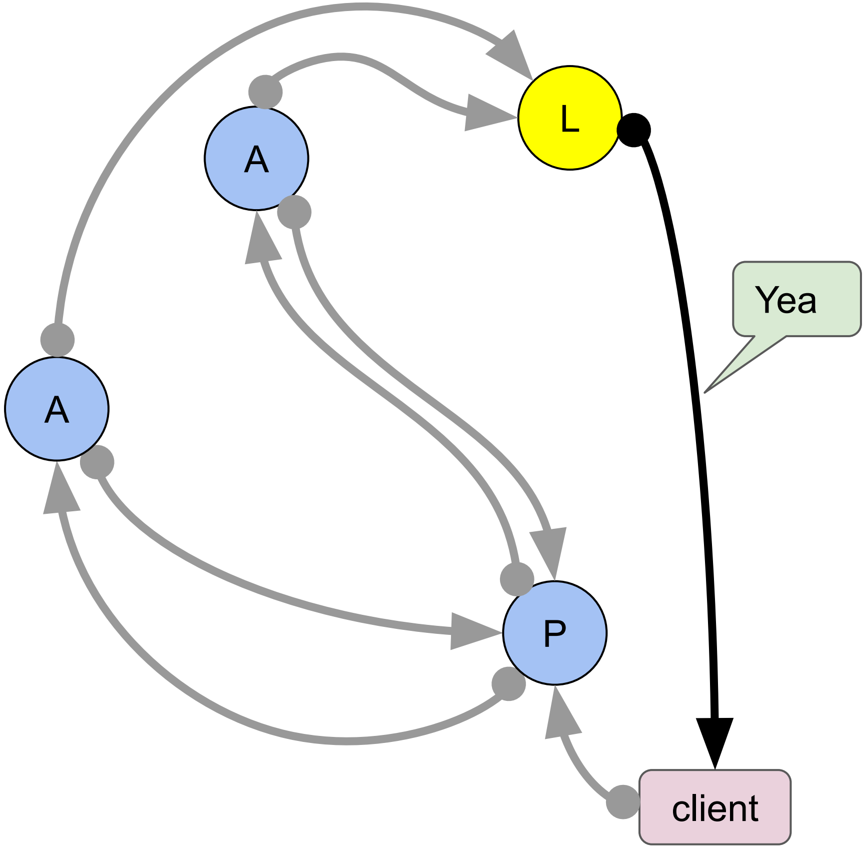
Paxos Roles

- Client
- Proposer (P)
- Acceptor (A)
    - Also called "voter"
    - The fault-tolerant "memory" of the system
    - Groups of acceptors form a *quorum*
- Learner
- Leader



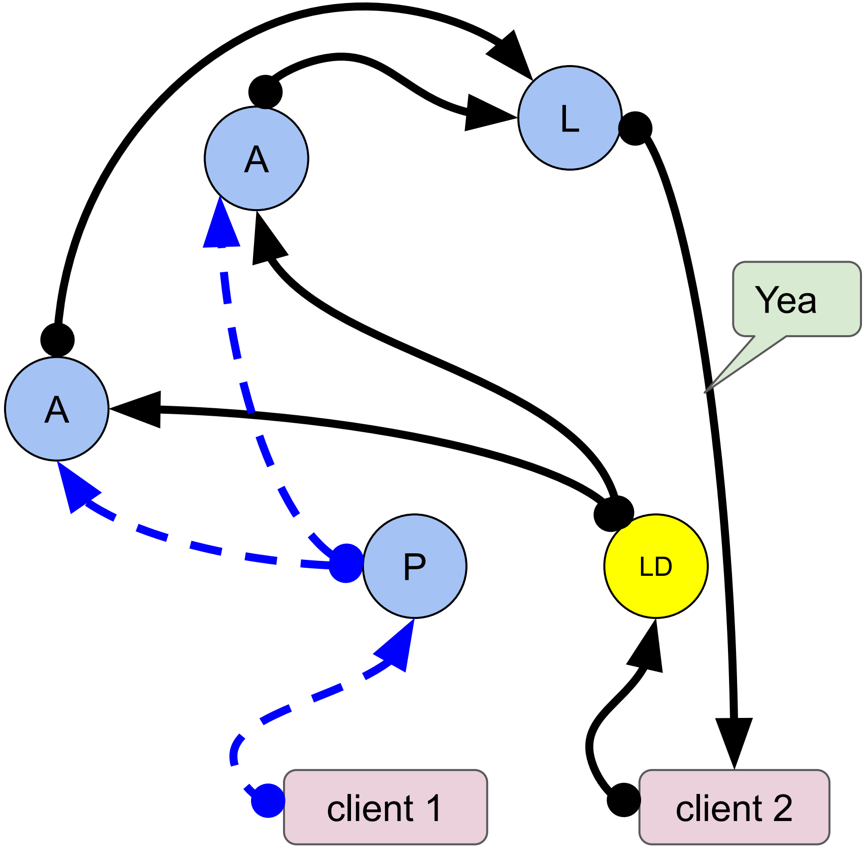
Paxos Roles

- Client
- Proposer (P)
- Acceptor (A)
- Learner (L)
    - Adds replication to the protocol
    - Takes action on learned (agreed on) values
    - E.g. respond to *client*
- Leader



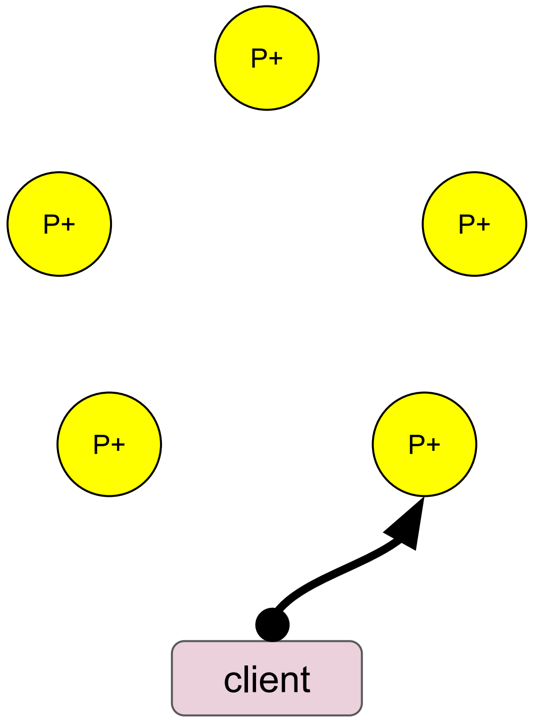
Paxos Roles

- Client
- Proposer (P)
- Acceptor (A)
- Learner (L)
- Leader (LD)
    - Distinguished *proposer*
    - The only *proposer* that can make progress
    - Multiple *proposers* may believe to be leader
    - *Acceptors* decide which one gets a majority



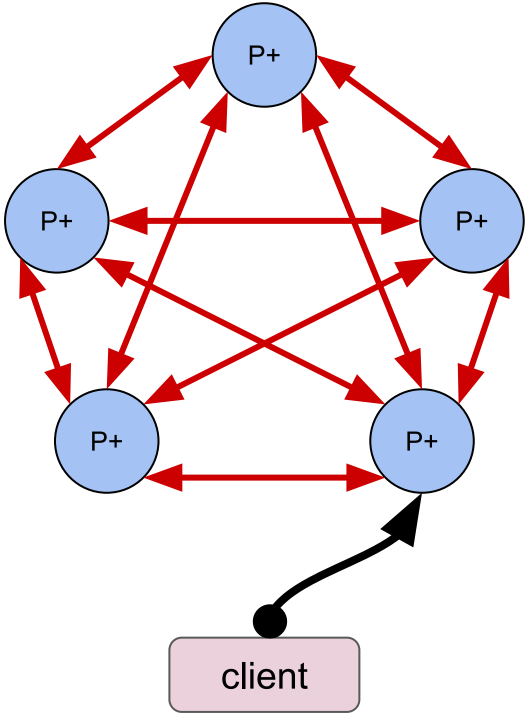
Coalesced Roles

- A single processors can have multiple roles
- P+
    - Proposer
    - Acceptor
    - Learner
- Client talks to any processor
    - Nearest one?
    - Leader?



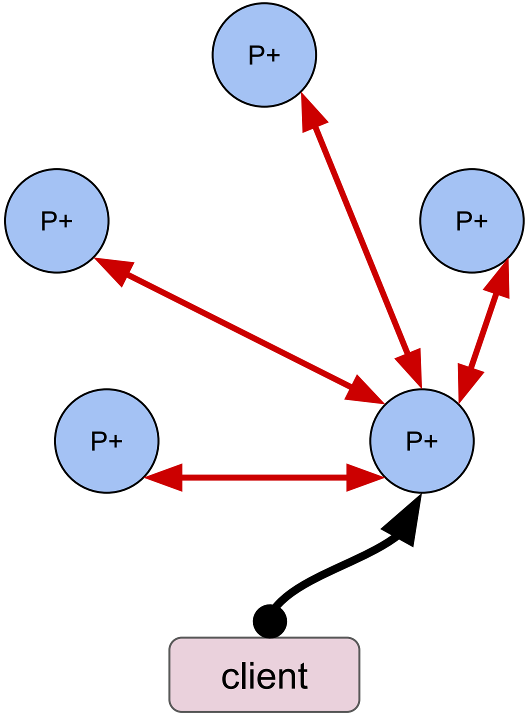
Coalesced Roles at Scale

- P+ system is a complete digraph
  - a directed graph in which every pair of distinct vertices is connected by a pair of unique edges
  - *Everyone talks to everyone*
- Let **n** be the number of processors
  - a.k.a. Quorum Size
- **Connections** = **n** * (**n** - 1)
  - Potential network (TCP) connections

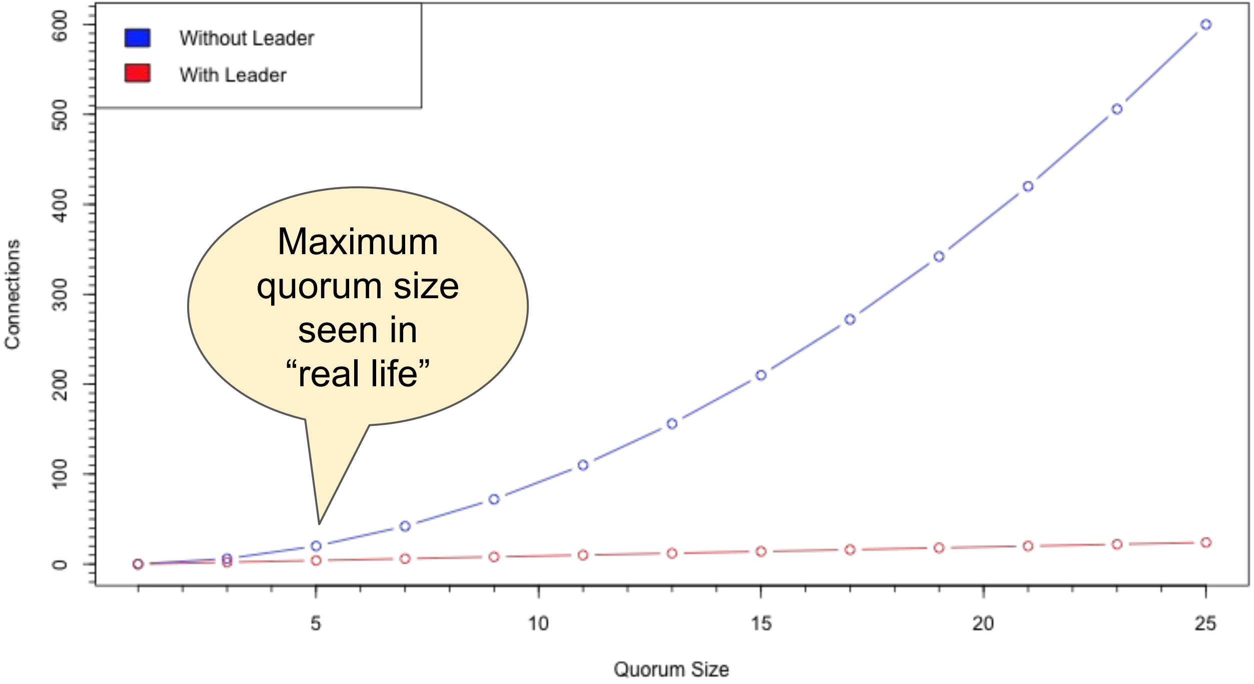


Coalesced Roles with Leader

- P+ system with a leader is a directed graph
  - *Leader talks to everyone else*
- Let **n** be the number of processors
  - a.k.a. Quorum Size
- **Connections** = **n** - 1
  - Network (TCP) connections



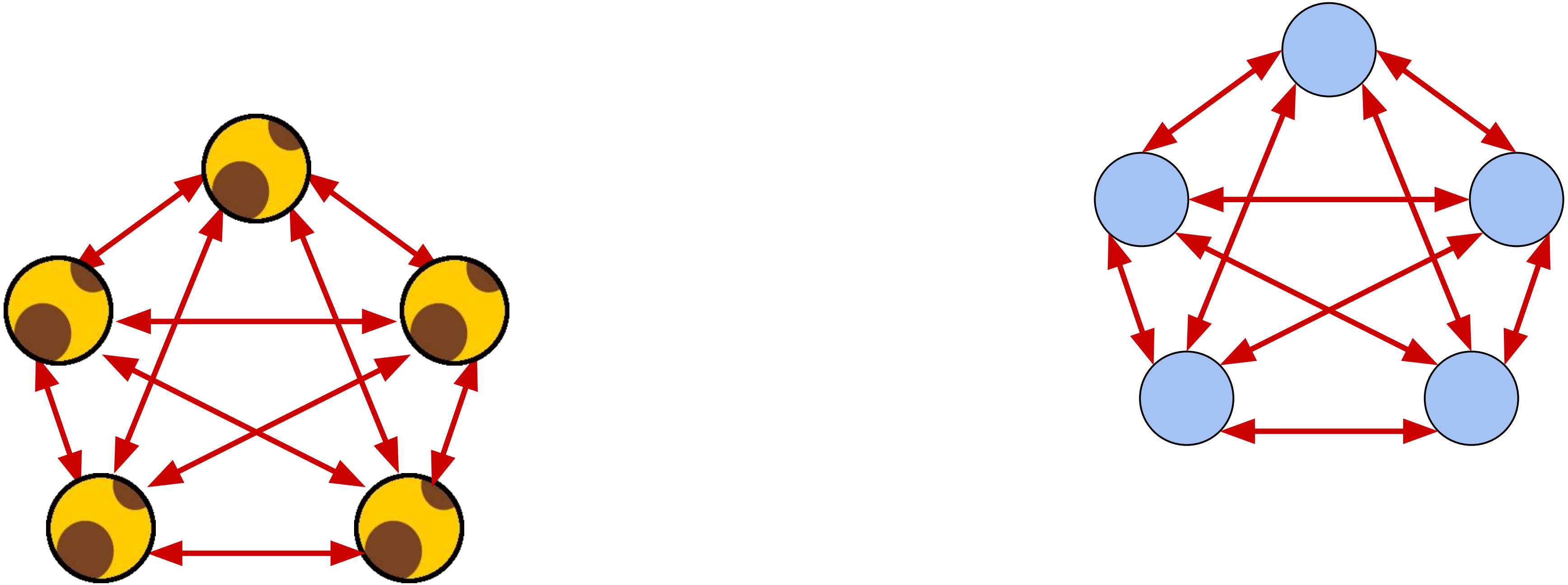
Coalesced Roles at Scale



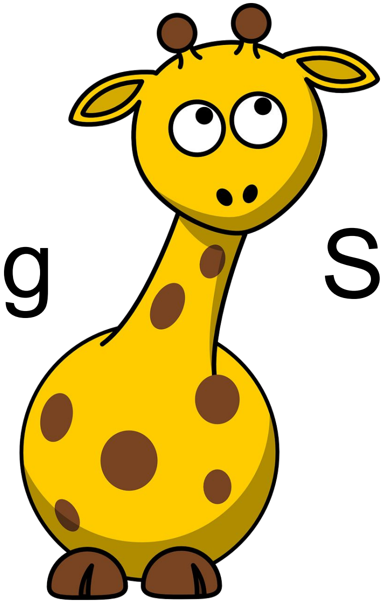
Maximum quorum size seen in "real life"

Limitations

- Single consensus
    - Once consensus has been reached no more progress can be made
    - But: Applications can start new Paxos runs
- Multiple proposers may believe to be the leader
    - dueling proposers
    - theoretically infinite duel
    - practically retry-limits and jitter helps
- Standard Paxos not resilient against Byzantine failures
    - Byzantine: Lying or compromised processors
    - Solution: Byzantine Paxos Protocol



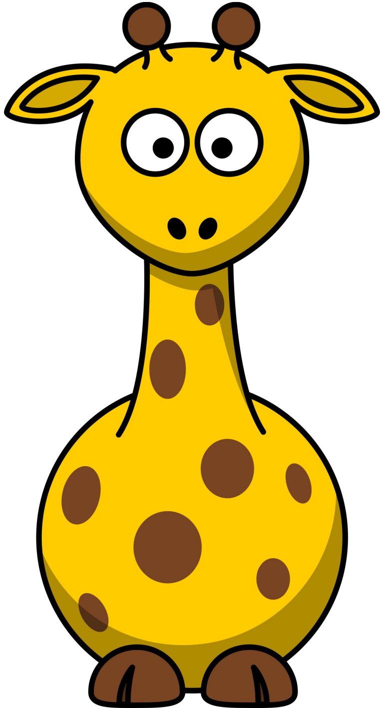
Introducing Skinny

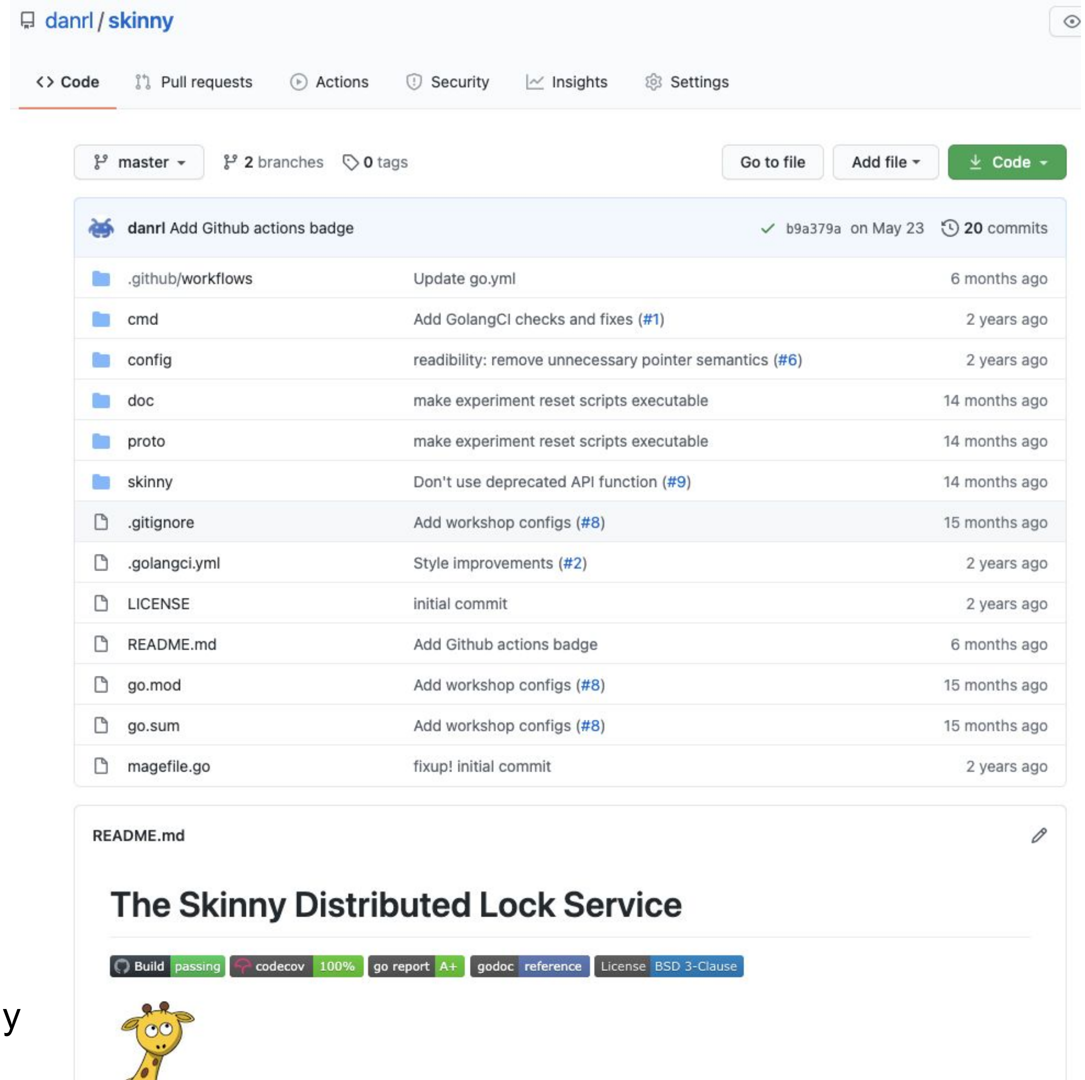


- Paxos-based
- Minimalistic
- Educational
- Lock Service

Skinny "Features"

- Designed to be *easy to understand*
- Relatively easy to observe
- Coalesced Roles
- Single Lock
  - Locks are always advisory!
  - A lock service does not enforce obedience to locks.
- Go
- Protocol Buffers
- gRPC
- Do not use in production!





danrl Add Github actions badge ✓ b9a379a on May 23 20 commits

.github/workflows	Update go.yml	6 months ago
cmd	Add GolangCI checks and fixes (#1)	2 years ago
config	readibility: remove unnecessary pointer semantics (#6)	2 years ago
doc	make experiment reset scripts executable	14 months ago
proto	make experiment reset scripts executable	14 months ago
skinny	Don't use deprecated API function (#9)	14 months ago
.gitignore	Add workshop configs (#8)	15 months ago
.golangci.yml	Style improvements (#2)	2 years ago
LICENSE	initial commit	2 years ago
README.md	Add Github actions badge	6 months ago
go.mod	Add workshop configs (#8)	15 months ago
go.sum	Add workshop configs (#8)	15 months ago
magefile.go	fixup! initial commit	2 years ago

README.md

The Skinny Distributed Lock Service

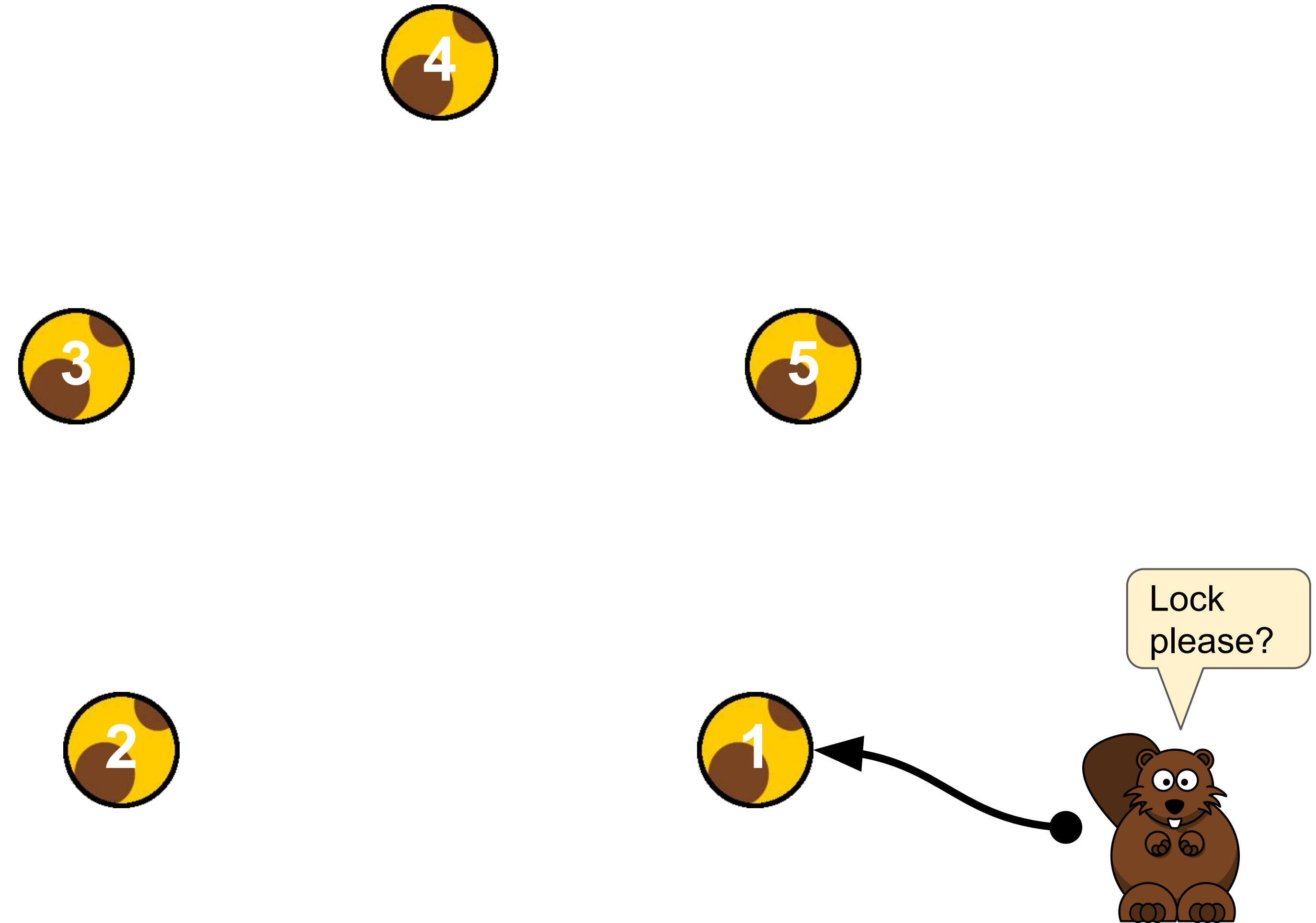
github.com/danrl/skinny

Assuming a wide quorum

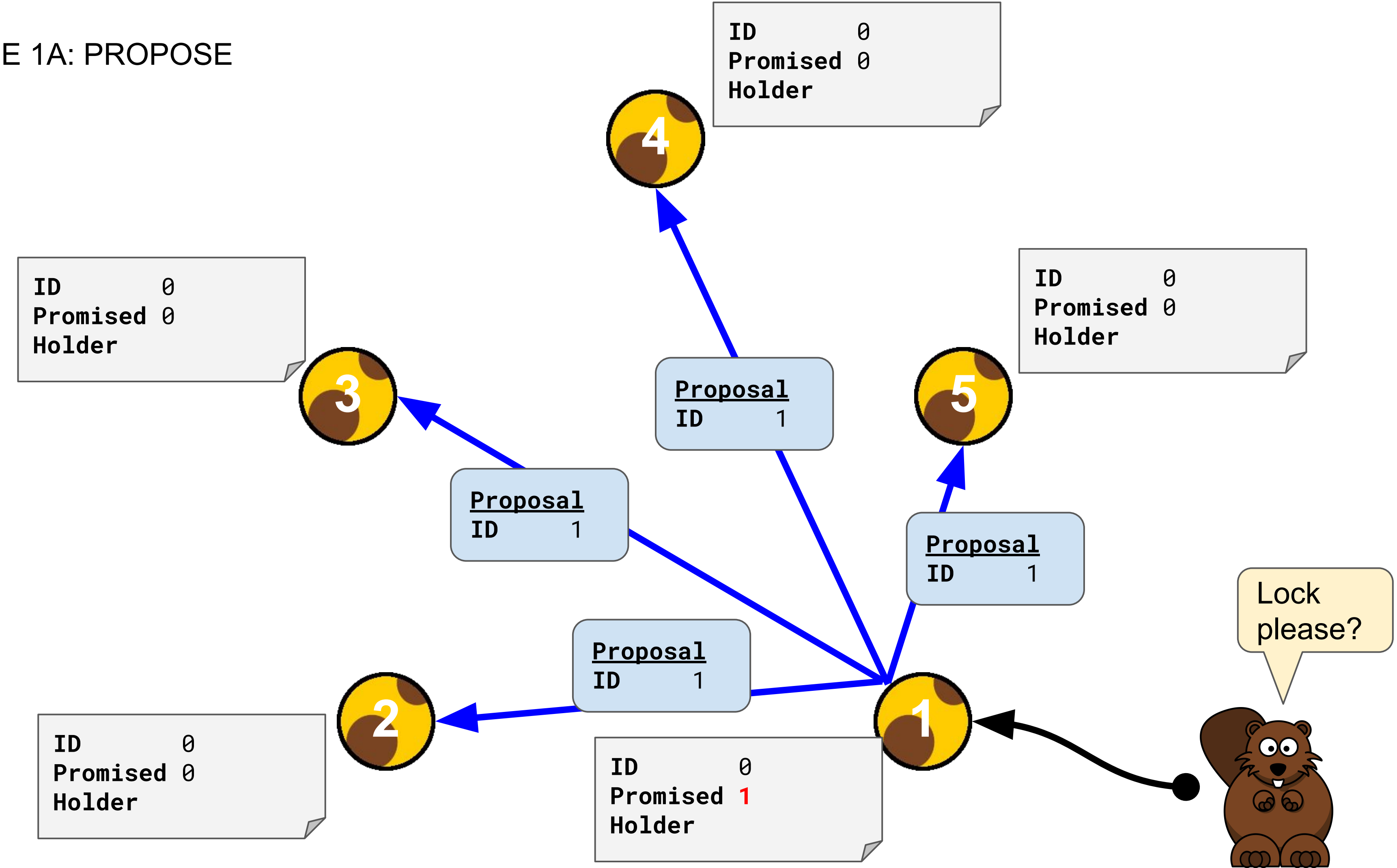
- Instances
  - Oregon (North America)
  - São Paulo (South America)
  - London (Europe)
  - Taiwan (Asia)
  - Sydney (Australia)
- Unusual in practice
  - "Terrible latency"
- Perfect for observation and learning
  - Timeouts, Deadlines, Latency

How Skinny reaches consensus

SKINNY QUORUM



PHASE 1A: PROPOSE



ID 0
Promised 0
Holder

ID 0
Promised 0
Holder

ID 0
Promised 0
Holder

Proposal
ID 1

Proposal
ID 1

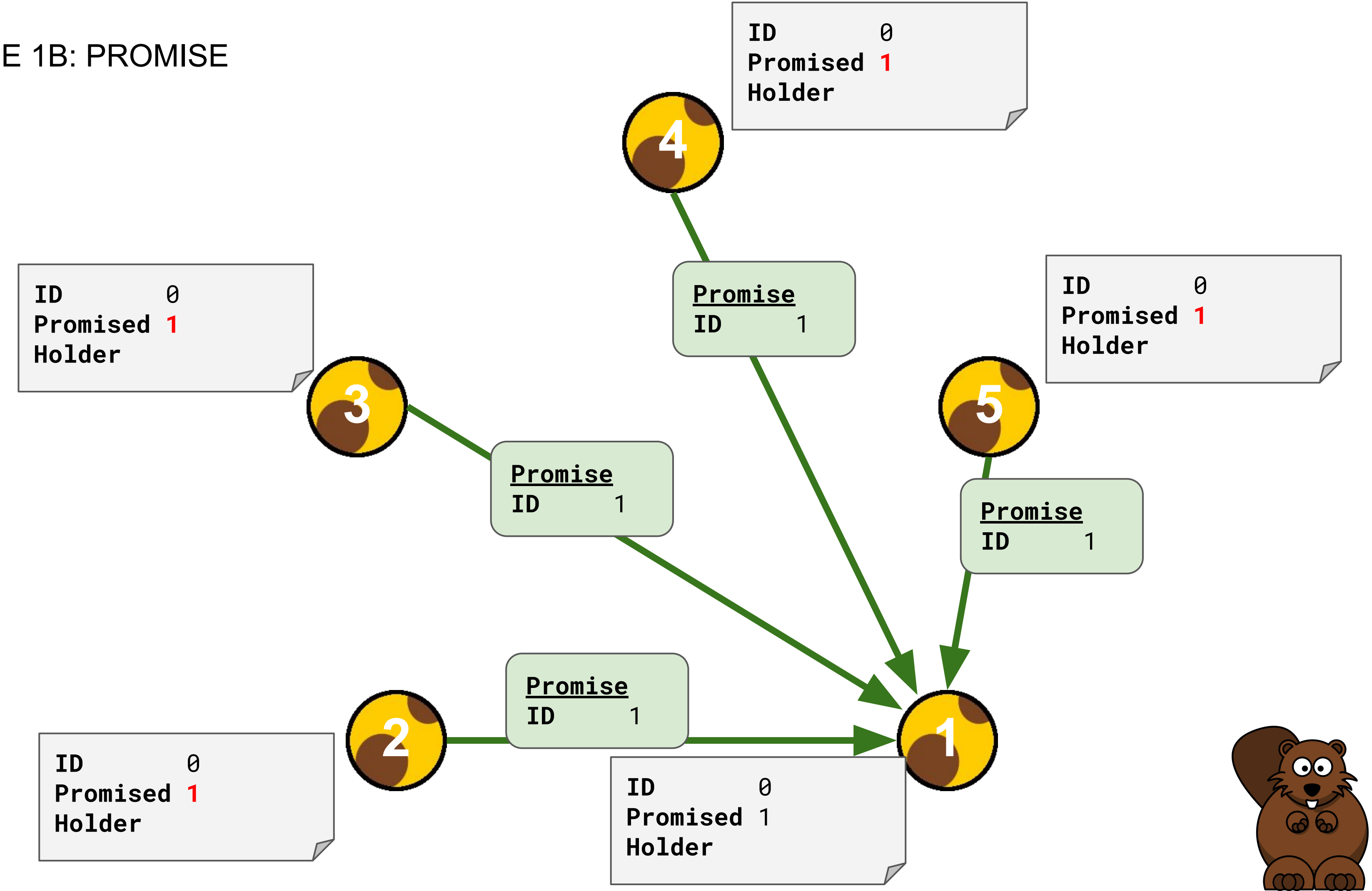
Proposal
ID 1

Proposal
ID 1

ID 0
Promised 0
Holder

ID 0
Promised 1
Holder

PHASE 1B: PROMISE



ID 0
Promised 1
Holder

Promise
ID 1

ID 0
Promised 1
Holder

Promise
ID 1

ID 0
Promised 1
Holder

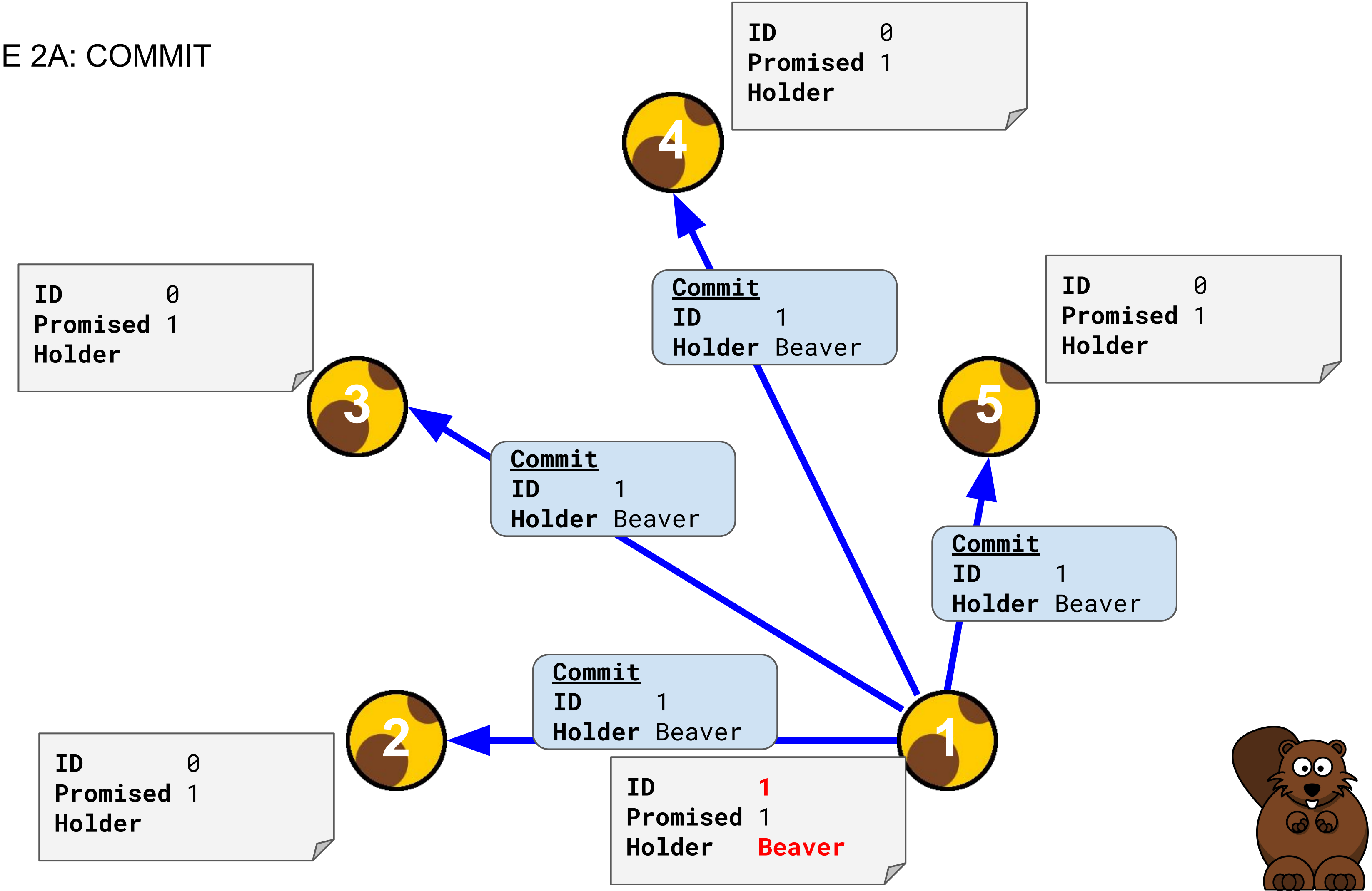
Promise
ID 1

ID 0
Promised 1
Holder

Promise
ID 1

ID 0
Promised 1
Holder

PHASE 2A: COMMIT



ID 0
Promised 1
Holder

ID 0
Promised 1
Holder

Commit
ID 1
Holder Beaver

ID 0
Promised 1
Holder

Commit
ID 1
Holder Beaver

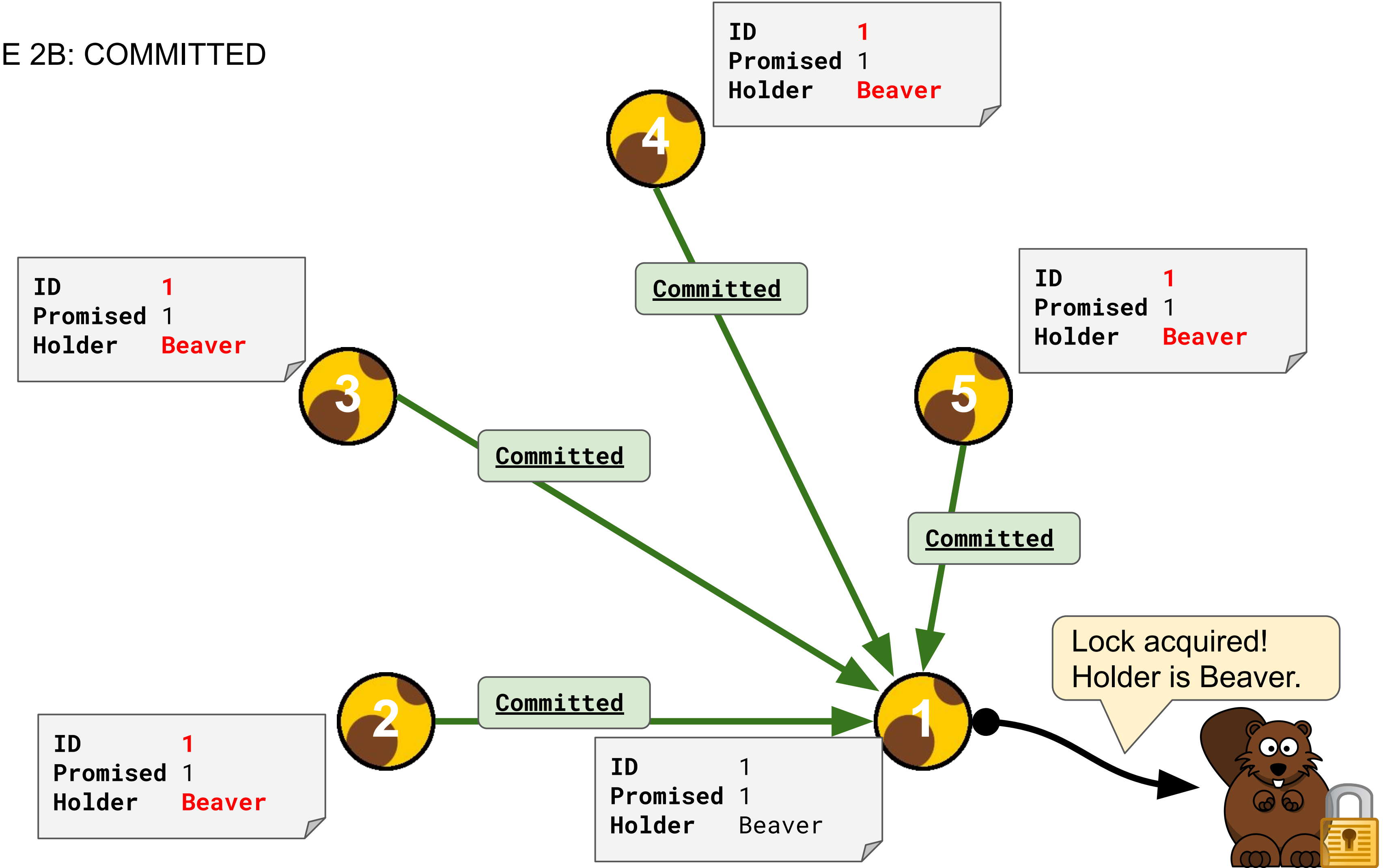
Commit
ID 1
Holder Beaver

Commit
ID 1
Holder Beaver

ID 0
Promised 1
Holder

ID **1**
Promised 1
Holder **Beaver**

PHASE 2B: COMMITTED



ID 1
Promised 1
Holder Beaver

ID 1
Promised 1
Holder Beaver

ID 1
Promised 1
Holder Beaver

ID 1
Promised 1
Holder Beaver

ID 1
Promised 1
Holder Beaver

Lock acquired!
Holder is Beaver.

How Skinny deals with Instance Failure

SCENARIO

4

ID	9
Promised	9
Holder	Beaver

3

ID	9
Promised	9
Holder	Beaver

5

ID	9
Promised	9
Holder	Beaver

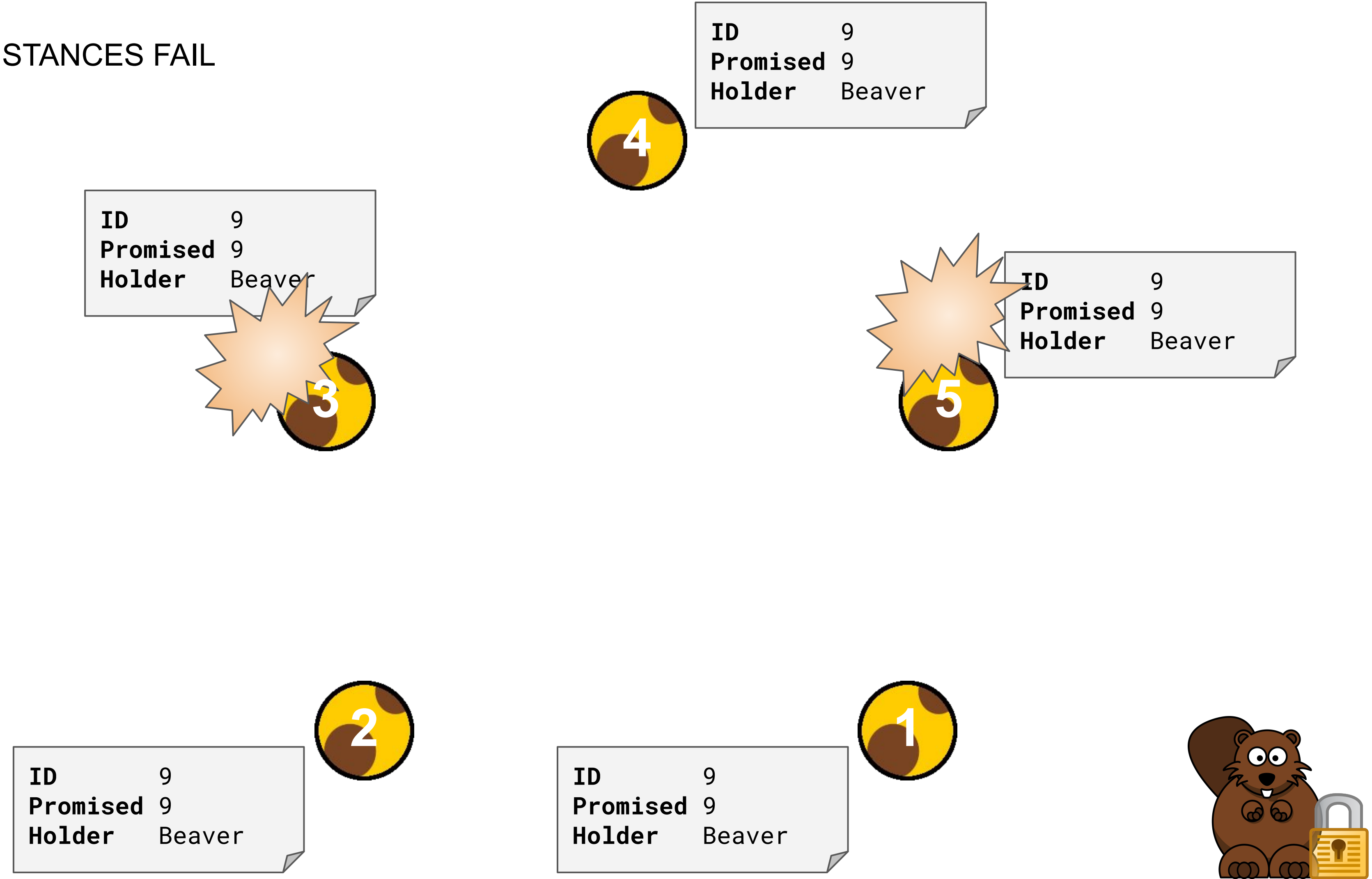
2

ID	9
Promised	9
Holder	Beaver

1

ID	9
Promised	9
Holder	Beaver

TWO INSTANCES FAIL



ID	9
Promised	9
Holder	Beaver

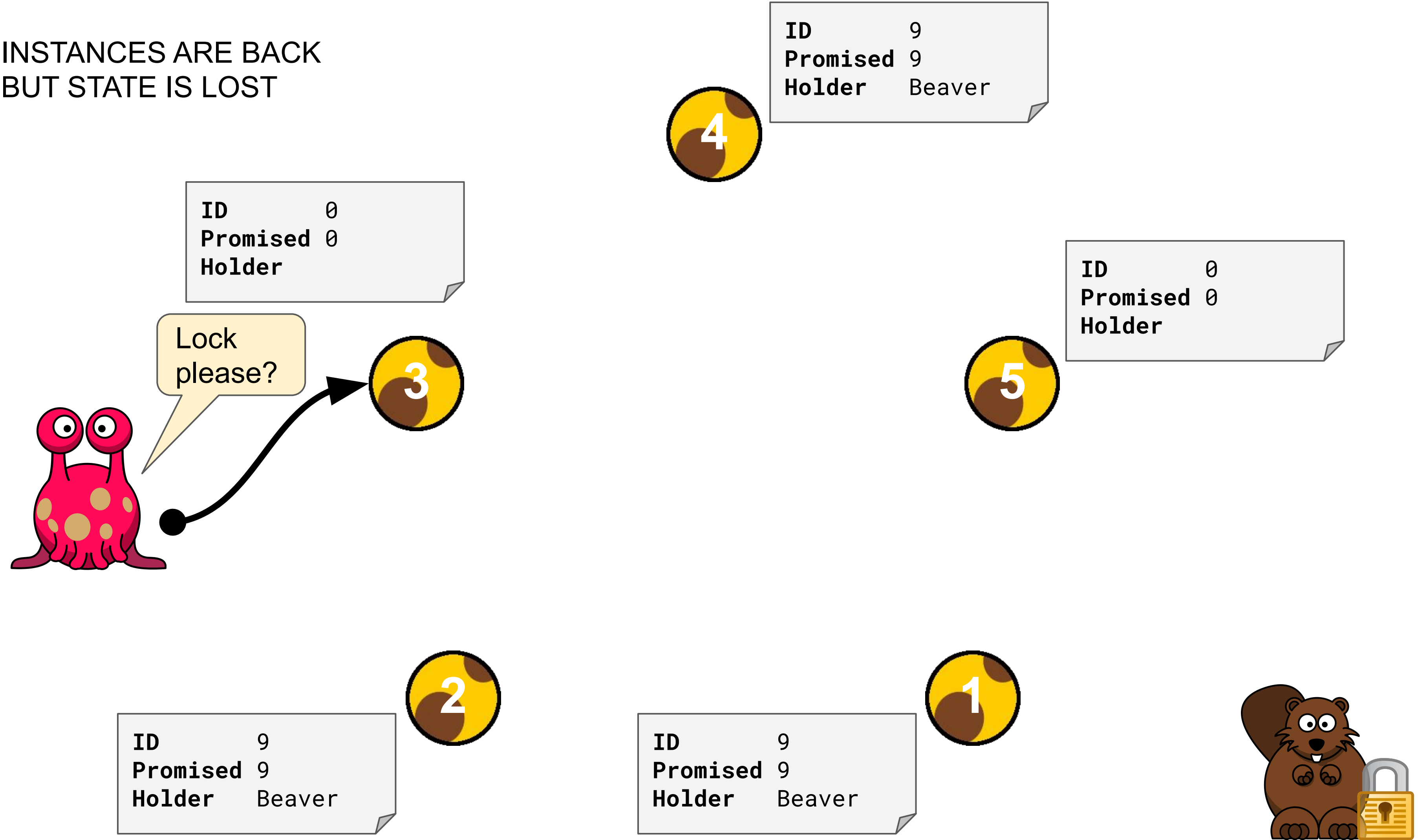
ID	9
Promised	9
Holder	Beaver

ID	9
Promised	9
Holder	Beaver

ID	9
Promised	9
Holder	Beaver

ID	9
Promised	9
Holder	Beaver

INSTANCES ARE BACK
BUT STATE IS LOST



ID 9
Promised 9
Holder Beaver

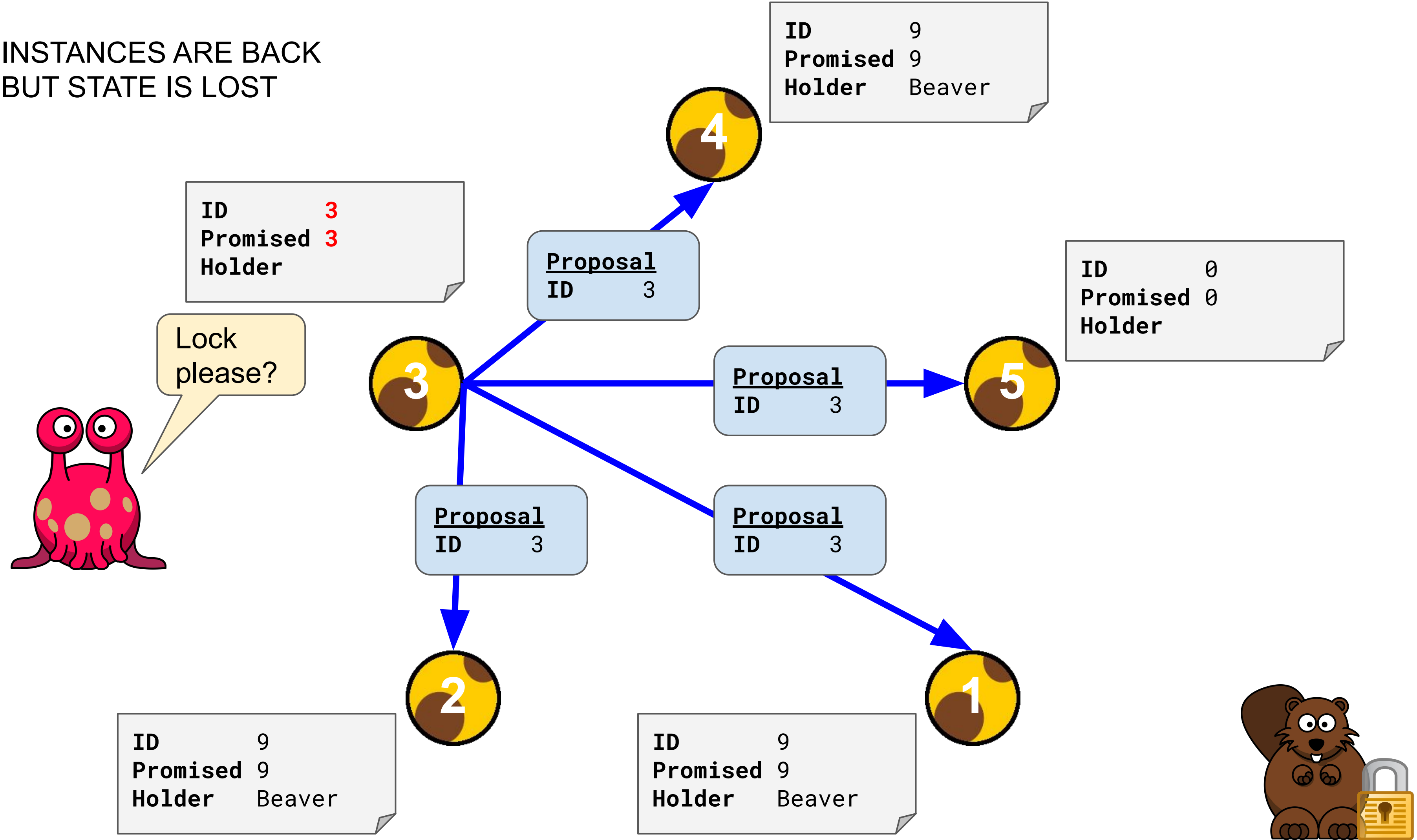
ID 0
Promised 0
Holder

ID 0
Promised 0
Holder

ID 9
Promised 9
Holder Beaver

ID 9
Promised 9
Holder Beaver

INSTANCES ARE BACK
BUT STATE IS LOST



Lock please?

ID	3
Promised	3
Holder	

ID	9
Promised	9
Holder	Beaver

ID	0
Promised	0
Holder	

ID	9
Promised	9
Holder	Beaver

ID	9
Promised	9
Holder	Beaver

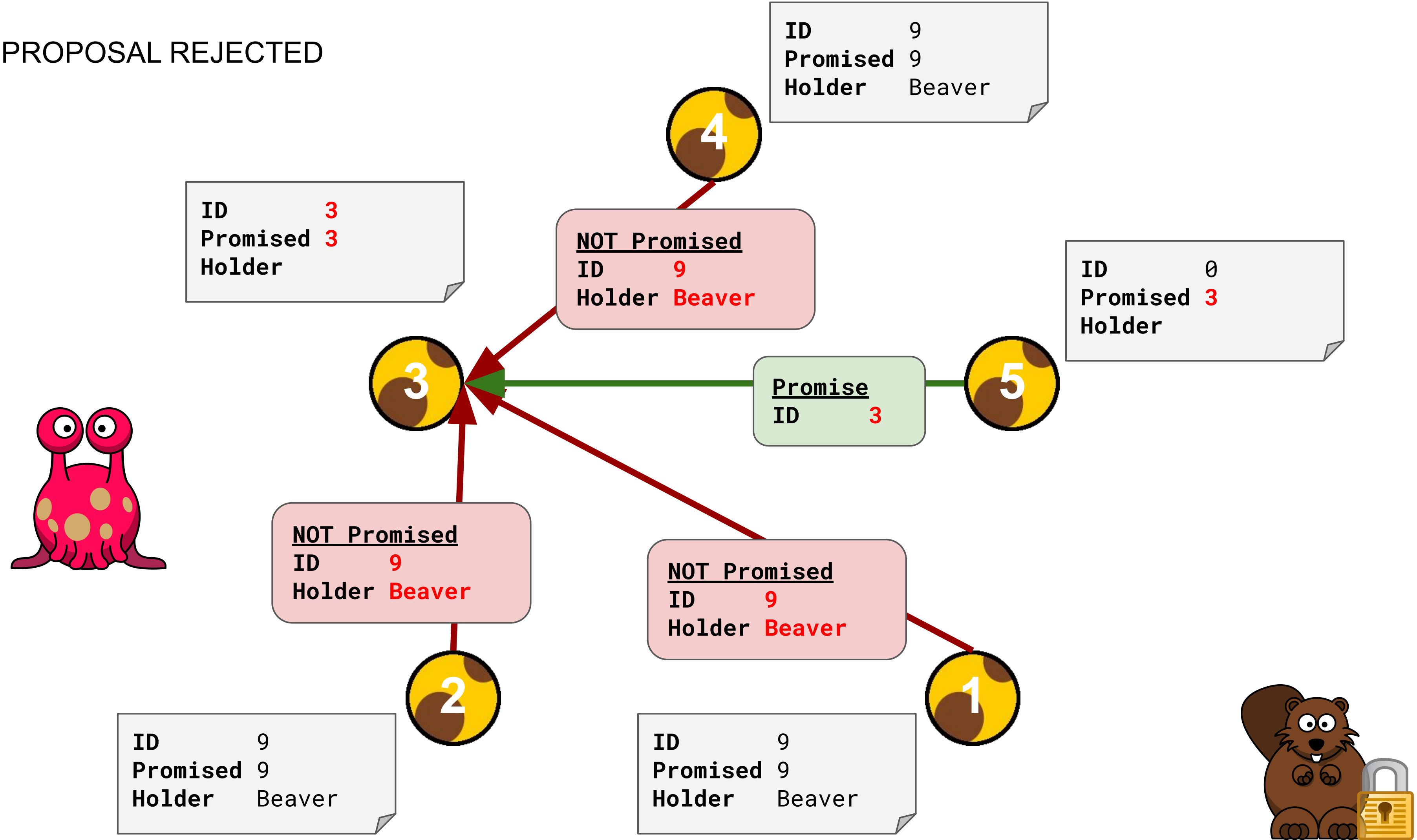
Proposal
ID 3

Proposal
ID 3

Proposal
ID 3

Proposal
ID 3

PROPOSAL REJECTED



ID 9
Promised 9
Holder Beaver

ID 3
Promised 3
Holder

NOT Promised
ID 9
Holder Beaver

ID 0
Promised 3
Holder

Promise
ID 3

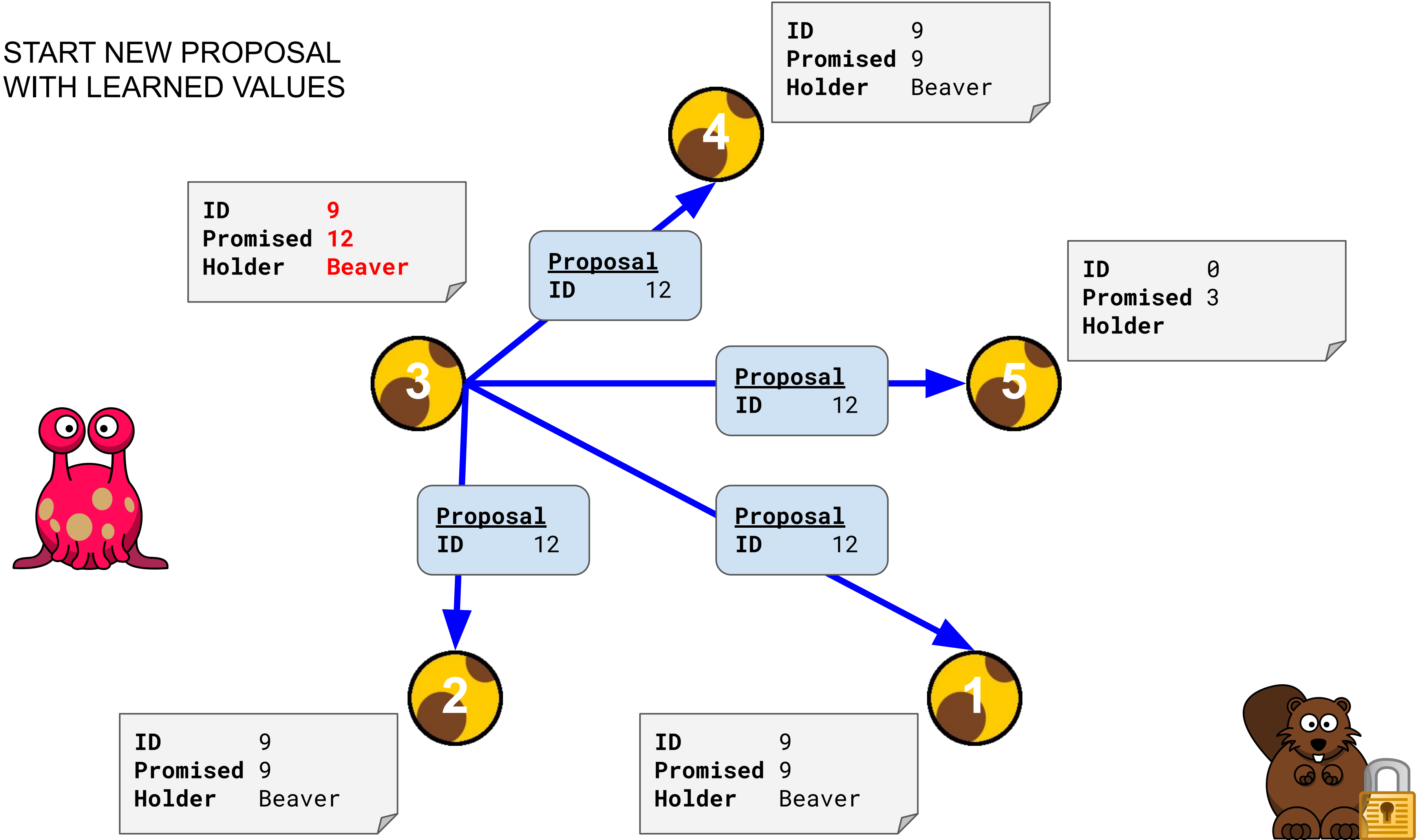
NOT Promised
ID 9
Holder Beaver

NOT Promised
ID 9
Holder Beaver

ID 9
Promised 9
Holder Beaver

ID 9
Promised 9
Holder Beaver

START NEW PROPOSAL WITH LEARNED VALUES



ID	9
Promised	9
Holder	Beaver

ID	9
Promised	12
Holder	Beaver

Proposal
ID 12

Proposal
ID 12

ID	0
Promised	3
Holder	

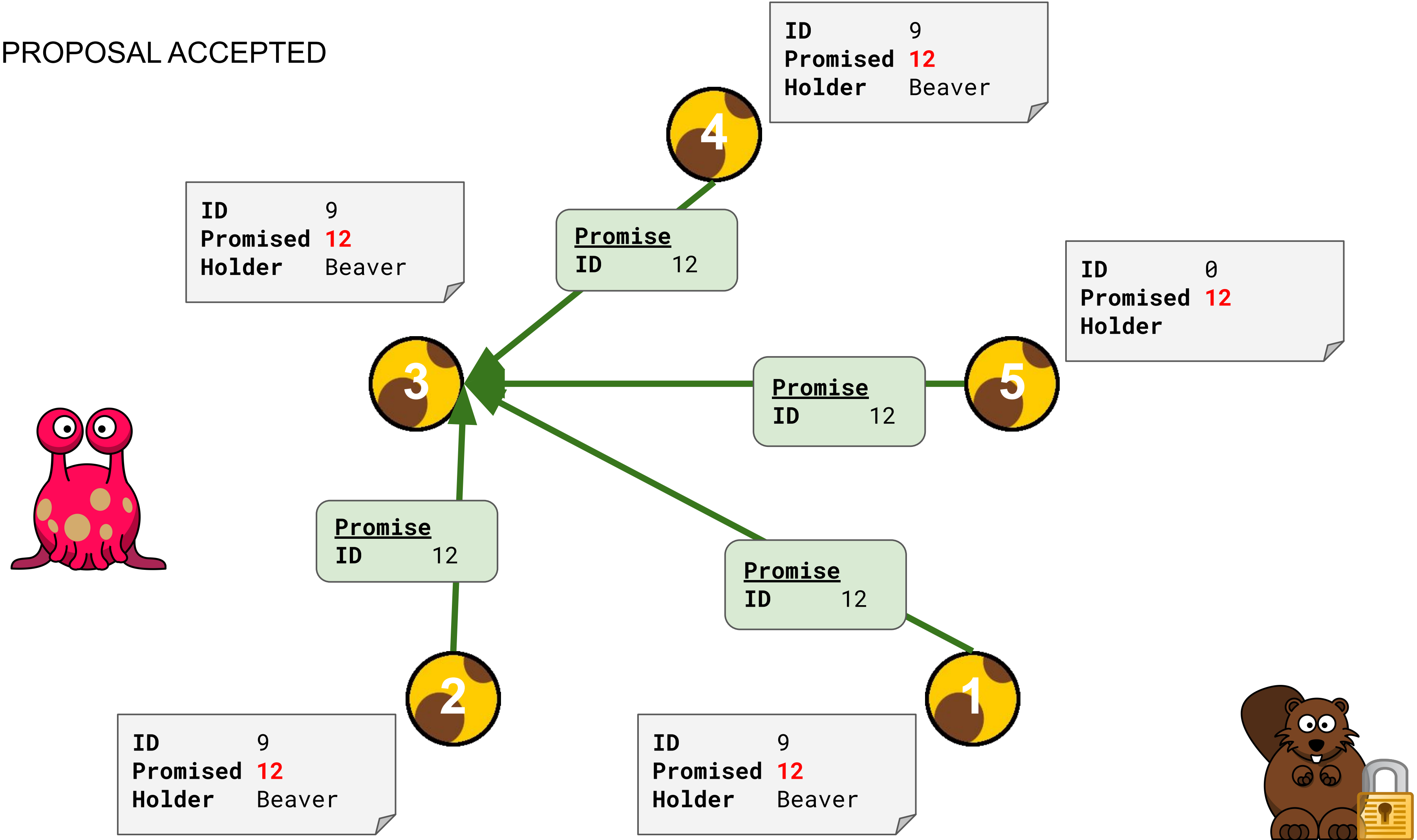
Proposal
ID 12

Proposal
ID 12

ID	9
Promised	9
Holder	Beaver

ID	9
Promised	9
Holder	Beaver

PROPOSAL ACCEPTED



ID 9
Promised 12
Holder Beaver

ID 9
Promised 12
Holder Beaver

Promise
ID 12

ID 0
Promised 12
Holder

Promise
ID 12

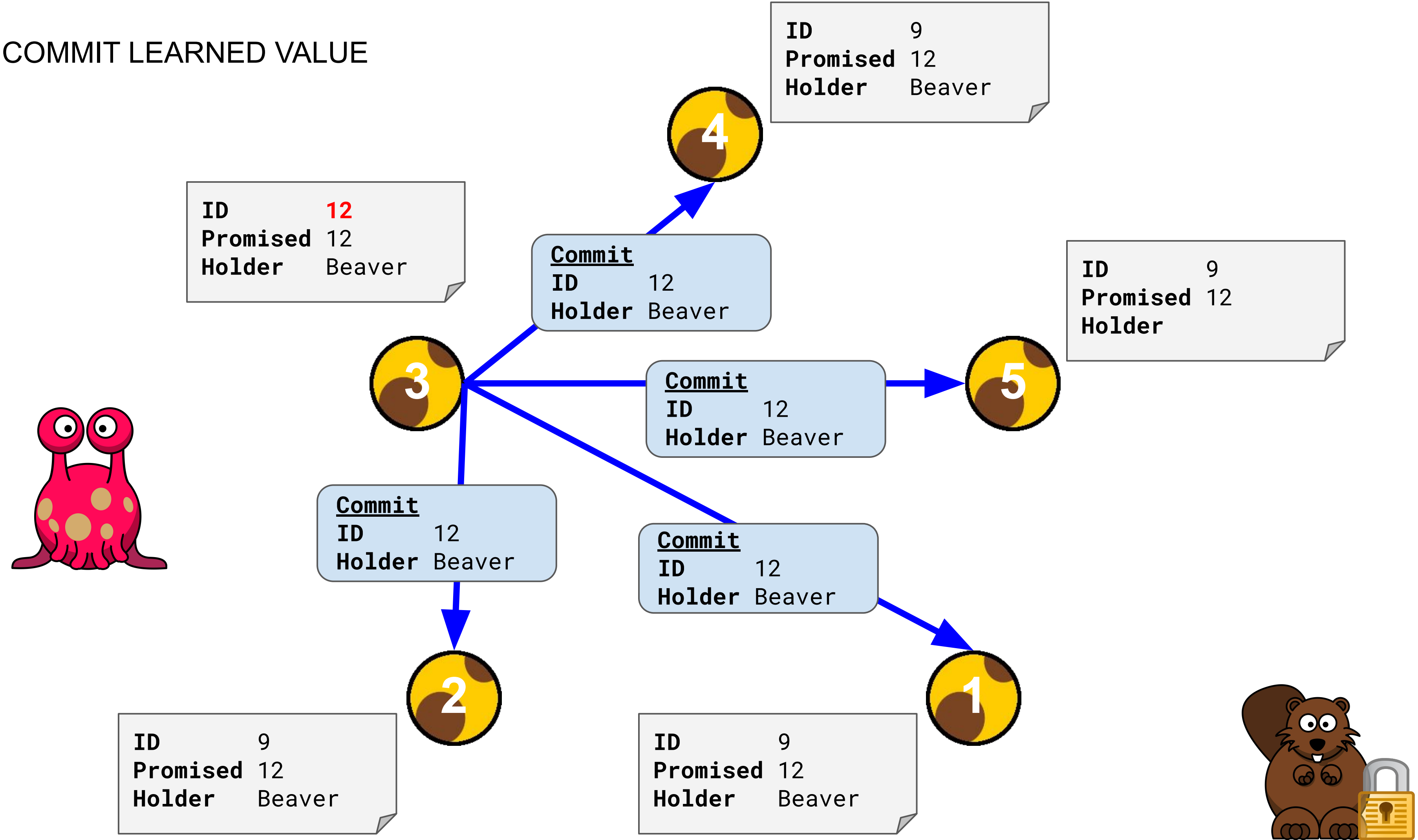
Promise
ID 12

Promise
ID 12

ID 9
Promised 12
Holder Beaver

ID 9
Promised 12
Holder Beaver

COMMIT LEARNED VALUE



ID 9
Promised 12
Holder Beaver

ID 12
Promised 12
Holder Beaver

Commit
ID 12
Holder Beaver

ID 9
Promised 12
Holder

Commit
ID 12
Holder Beaver

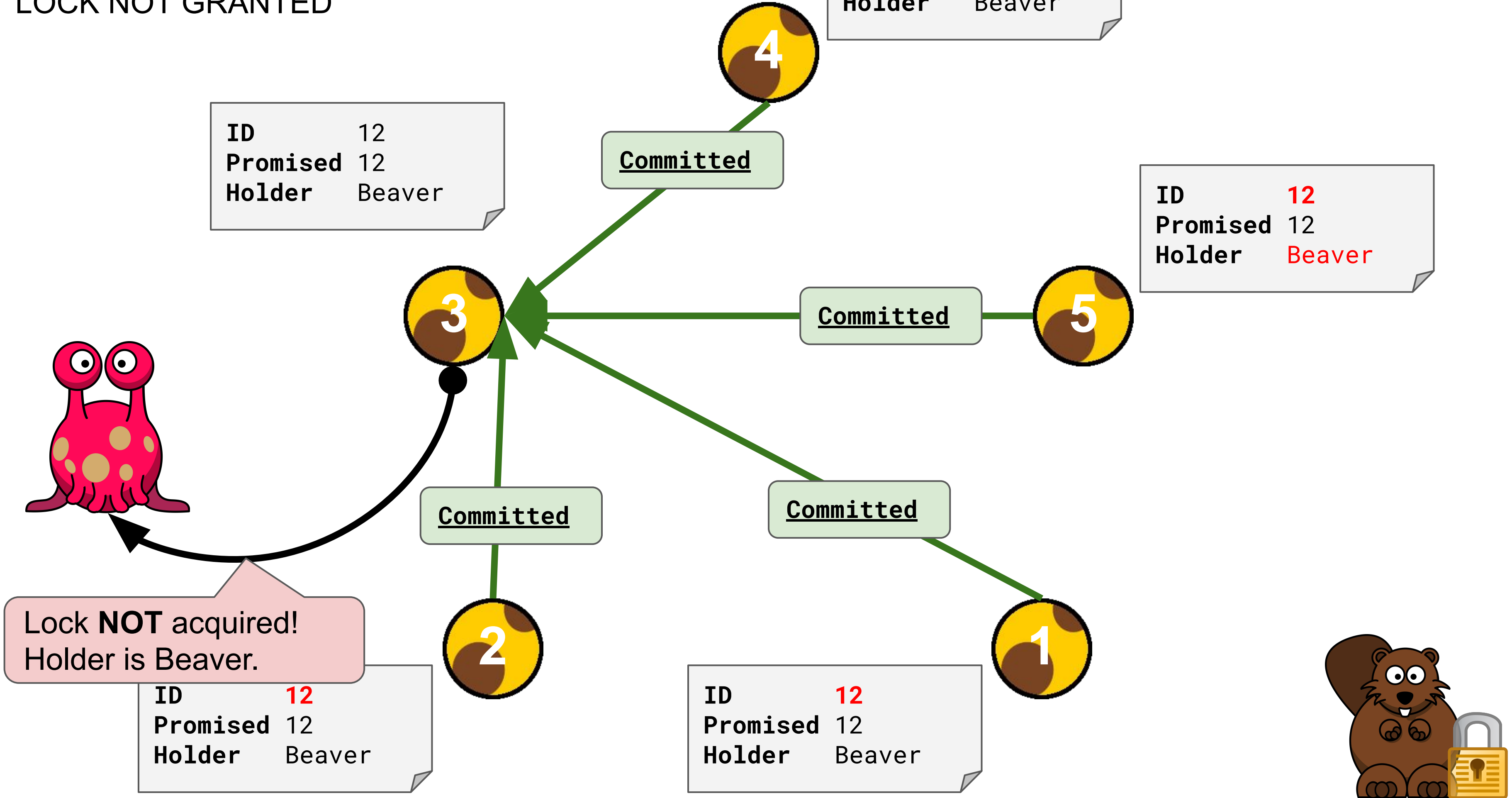
Commit
ID 12
Holder Beaver

Commit
ID 12
Holder Beaver

ID 9
Promised 12
Holder Beaver

ID 9
Promised 12
Holder Beaver

COMMIT ACCEPTED
LOCK NOT GRANTED



ID 12
Promised 12
Holder Beaver

ID 12
Promised 12
Holder Beaver

ID 12
Promised 12
Holder Beaver

Lock **NOT** acquired!
Holder is Beaver.

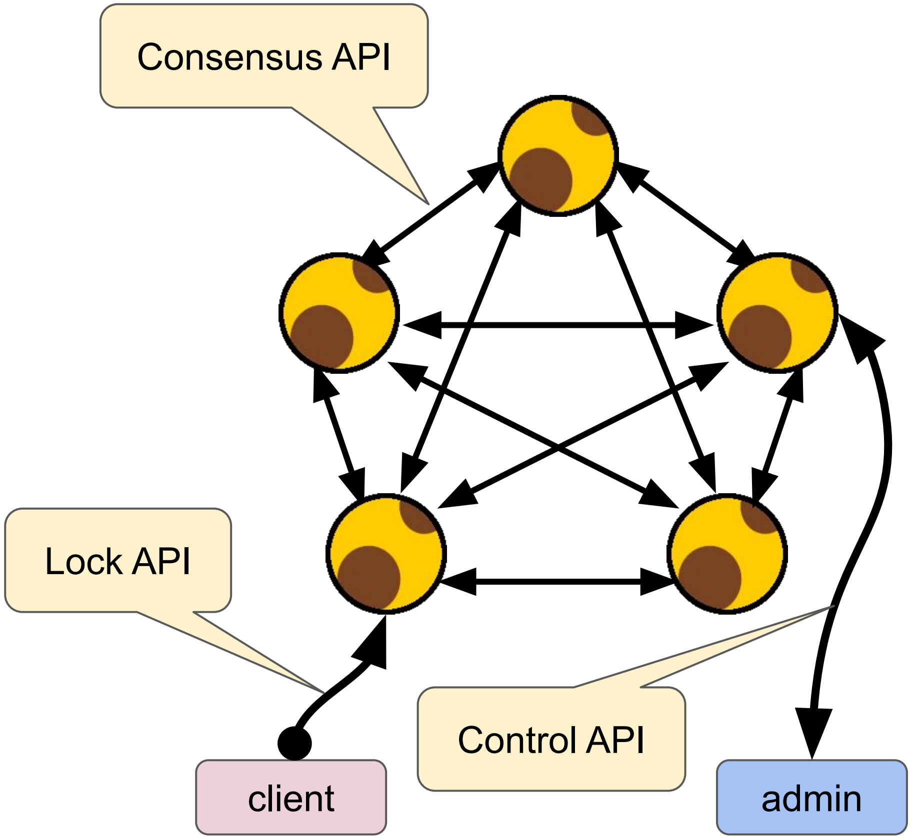
ID 12
Promised 12
Holder Beaver

ID 12
Promised 12
Holder Beaver

Skinny APIs

Skinny APIs

- Lock API
  - Used by clients to acquire or release a lock
- Consensus API
  - Used by Skinny instances to reach consensus
- Control API
  - Used by us to observe what's happening

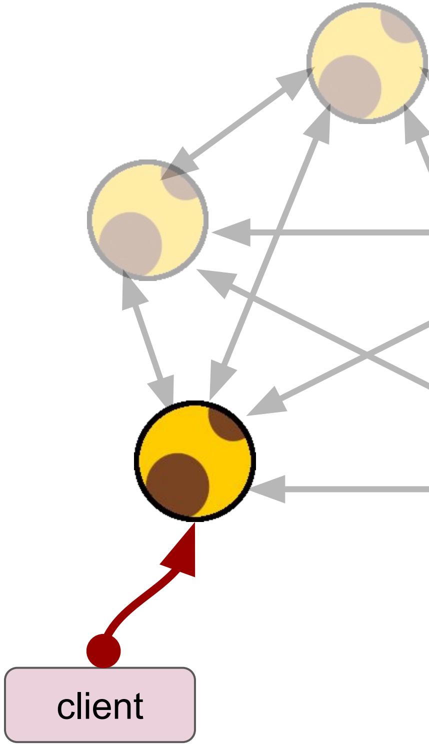


Lock API

```
message AcquireRequest {
   string Holder = 1;
}
message AcquireResponse {
   bool Acquired = 1;
   string Holder = 2;
}
```

```
message ReleaseRequest {}
message ReleaseResponse {
   bool Released = 1;
}
```

```
service Lock {
 rpc Acquire(AcquireRequest) returns (AcquireResponse);
 rpc Release(ReleaseRequest) returns (ReleaseResponse);
}
```

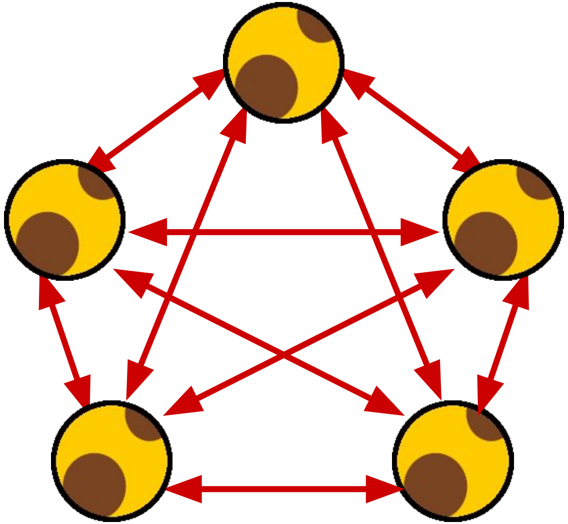


Consensus API

```
// Phase 1: Promise
message PromiseRequest {
   uint64 ID = 1;
}
message PromiseResponse {
   bool Promised = 1;
   uint64 ID = 2;
   string Holder = 3;
}
```

```
// Phase 2: Commit
message CommitRequest {
   uint64 ID = 1;
   string Holder = 2;
}
message CommitResponse {
   bool Committed = 1;
}
```

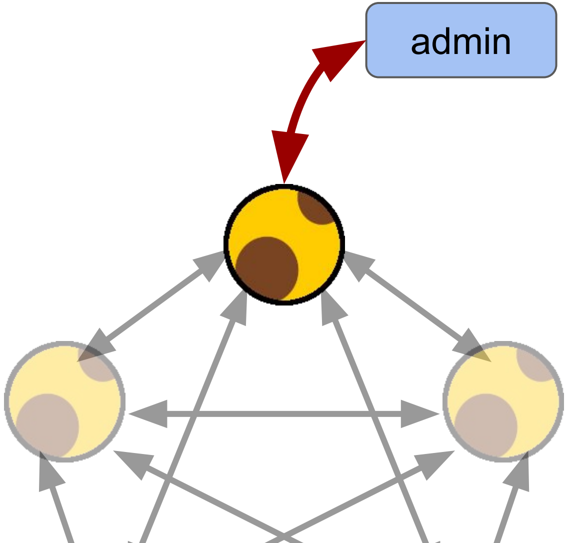
```
service Consensus {
   rpc Promise (PromiseRequest) returns (PromiseResponse);
   rpc Commit (CommitRequest) returns (CommitResponse);
}
```



Control API

```
message StatusRequest {}
message StatusResponse {
   string Name = 1;
   uint64 Increment = 2;
   string Timeout = 3;
   uint64 Promised = 4;
   uint64 ID = 5;
   string Holder = 6;
   message Peer {
       string Name = 1;
       string Address = 2;
   }
   repeated Peer Peers = 7;
}
```

```
service Control {
   rpc Status(StatusRequest) returns (StatusResponse);
}
```



~~My Stupid Mistakes~~
My Awesome Learning Opportunities

Reaching Out...

Skinny Instance

- List of peers
    - All other instances in the quorum
- Peer
    - gRPC Client Connection
    - Consensus API Client

```
// Instance represents a skinny instance
type Instance struct {
    mu sync.RWMutex
    // begin protected fields
    ...
    peers     []*peer
    // end protected fields
}

type peer struct {
    name    string
    address string
    conn    *grpc.ClientConn
    client  pb.ConsensusClient
}
```

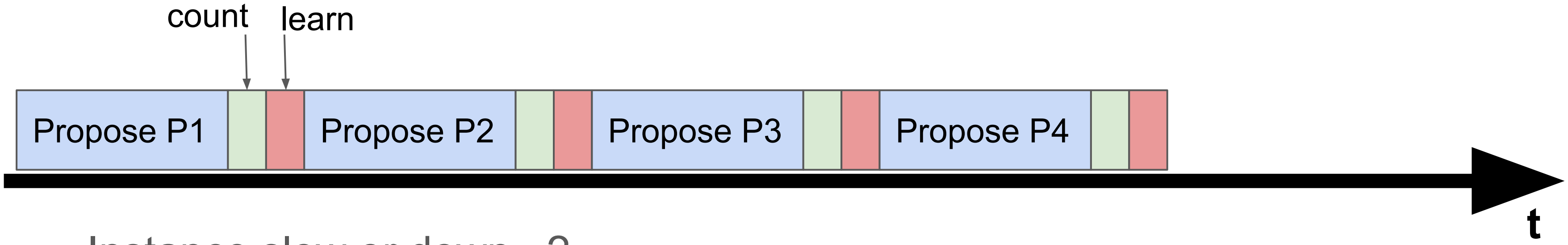
Propose Function

1. Send proposal to all peers
2. Count responses
   - Promises
3. Learn previous consensus (if any)

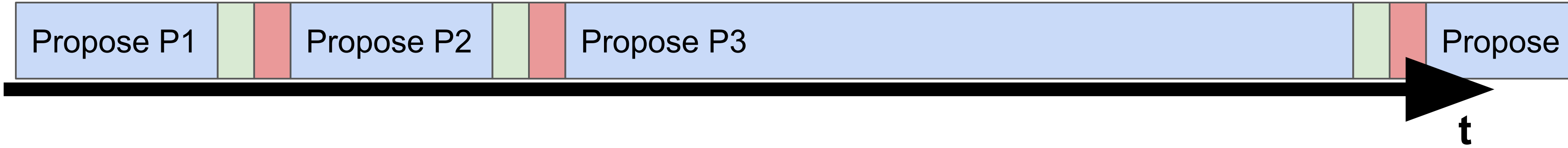
```
for _, p := range in.peers {
    // send proposal
    resp, err := p.client.Promise(
        context.Background(),
        &pb.PromiseRequest{ID: proposal})
    if err != nil {
        continue
    }
    if resp.Promised {
        yea++
    }
    learn(resp)
}
```

Resulting Behavior

- Sequential Requests
- Waiting for IO

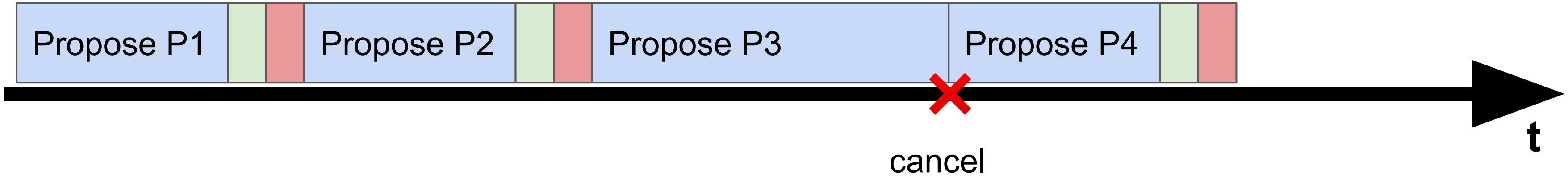


- Instance slow or down...?



Improvement #1

- Limit the Waiting for IO



Timeouts

- WithTimeout()
    - Here: 3 seconds
    - Skinny: Configurable
- Cancel() to prevent context leak

```
for _, p := range in.peers {
    // send proposal
    ctx, cancel := context.WithTimeout(
        context.Background(),
        time.Second*3)
    resp, err := p.client.Promise(ctx,
        &pb.PromiseRequest{ID: proposal})
    cancel()
    if err != nil {
        continue
    }
    if resp.Promised {
        yea++
    }
    learn(resp)
}
```

Improvement #2 (Idea)

- Parallel Requests

- What's wrong?

Improvement #2

- Concurrent Requests
- Synchronized Counting
- Synchronized Learning

Concurrency

- Goroutine!
- Context with timeout
- But how to handle success?

```
for _, p := range in.peers {
    // send proposal
    go func(p *peer) {
        ctx, cancel := context.WithTimeout(
            context.Background(),
            time.Second*3)
        defer cancel()

        resp, err := p.client.Promise(ctx,
            &pb.PromiseRequest{ID: proposal})
        if err != nil { return }

        // now what?
    }(p)
}
```

Synchronizing

- Define response data structure
- Channels to the rescue!
- Write responses to channel as they come in

```
type response struct {
    from     string
    promised bool
    id       uint64
    holder   string
}
responses := make(chan *response)
for _, p := range in.peers {
    go func(p *peer) {
        ...
        responses <- &response{
            from:     p.name,
            promised: resp.Promised,
            id:       resp.ID,
            holder:   resp.Holder,
        }
    }(p)
}
```

Synchronizing

- Counting
- yea := 1
  - Because we always vote for ourselves
- Learning

```
// count the votes
yea, nay := 1, 0
for r := range responses {
    // count the promises
    if r.promised {
        yea++
    } else {
        nay++
    }
    in.learn(r)
}
```

What's wrong?

- We did not close the channel
- **`range`** is blocking forever

```
responses := make(chan *response)
for _, p := range in.peers {
    go func(p *peer) {
        ...
        responses <- &response{...}
    }(p)
}

// count the votes
yea, nay := 1, 0
for r := range responses {
    // count the promises
    ...
    in.learn(r)
}
```

Solution: More synchronizing!

- Use **`WaitGroup`**
- Close channel when all requests are done

```
responses := make(chan *response)
wg := sync.WaitGroup{}
for _, p := range in.peers {
    wg.Add(1)
    go func(p *peer) {
        defer wg.Done()
        ...
        responses <- &response{...}
    }(p)
}
// close responses channel
go func() {
    wg.Wait()
    close(responses)
}()
// count the promises
for r := range responses {...}
```

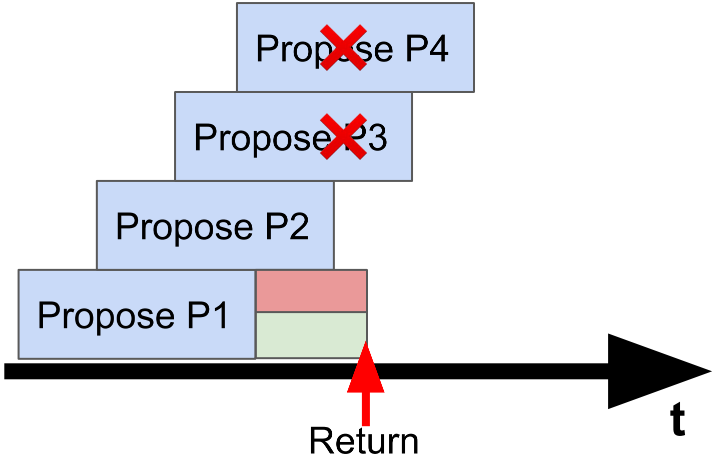
Result

Ignorance Is Bliss?

Early Stopping

Yea: ✅ ✅ ✅

Majority



Propose P4

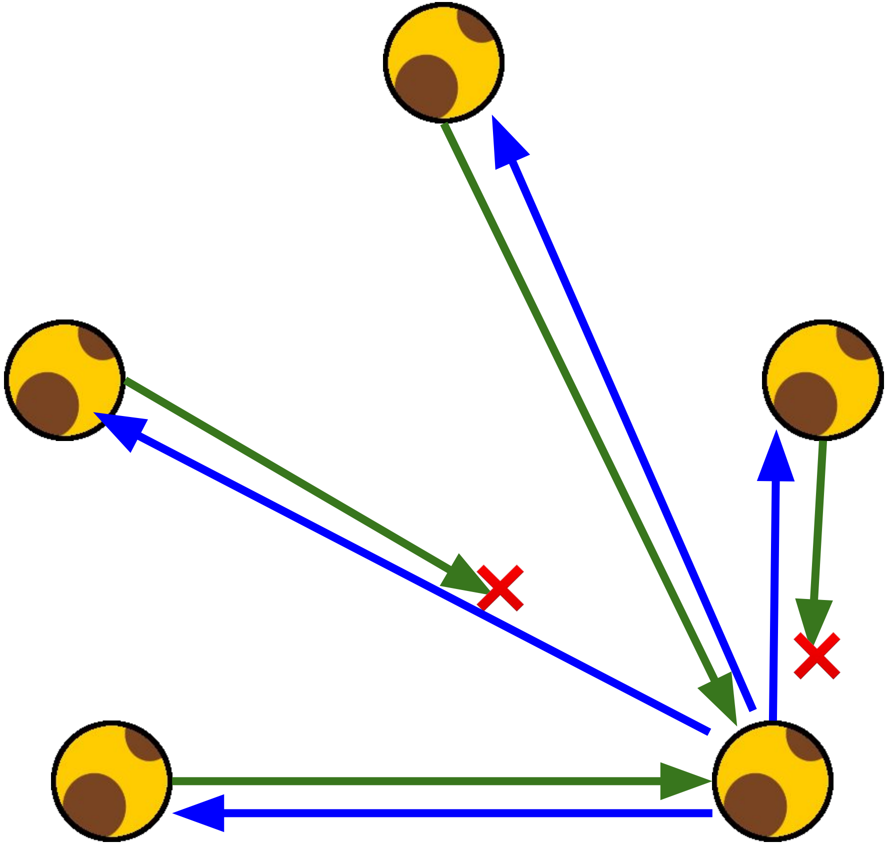
Propose P3

Propose P2

Propose P1

Return

t



Early Stopping (1)

- One context for all outgoing promises
- We cancel as soon as we have a majority
- We always cancel before leaving the function to prevent a context leak

```go
type response struct {
    from     string
    promised bool
    id       uint64
    holder   string
}
responses := make(chan *response)


ctx, cancel := context.WithTimeout(
    context.Background(),
    time.Second*3)


defer cancel()
```

Early Stopping (2)

- Nothing new here

```
wg := sync.WaitGroup{}
for _, p := range in.peers {
    wg.Add(1)
    go func(p *peer) {
        defer wg.Done()

        resp, err := p.client.Promise(ctx,
            &pb.PromiseRequest{ID: proposal})
        ... // ERROR HANDLING. SEE NEXT SLIDE!

        responses <- &response{
            from:     p.name,
            promised: resp.Promised,
            id:       resp.ID,
            holder:   resp.Holder,
        }
    }(p)
}
```

Early Stopping (3)

- We don't care about cancelled requests
- We want errors which are **not** the result of a canceled proposal to be counted as a **negative answer** (nay) later.
- For that we emit an **empty response** into the channel in those cases.

```
resp, err := p.client.Promise(ctx,
    &pb.PromiseRequest{ID: proposal})


if err != nil {
    if ctx.Err() == context.Canceled {
        return
    }

    responses <- &response{from: p.name}
    return
}


responses <- &response{...}
...
```

Early Stopping (4)

- Close responses channel once all responses have been received, failed, or canceled

```
go func() {
    wg.Wait()
    close(responses)
}()
```

Early Stopping (5)

- Count the votes
- Learn previous consensus (if any)
- Cancel all in-flight proposal if we have reached a majority

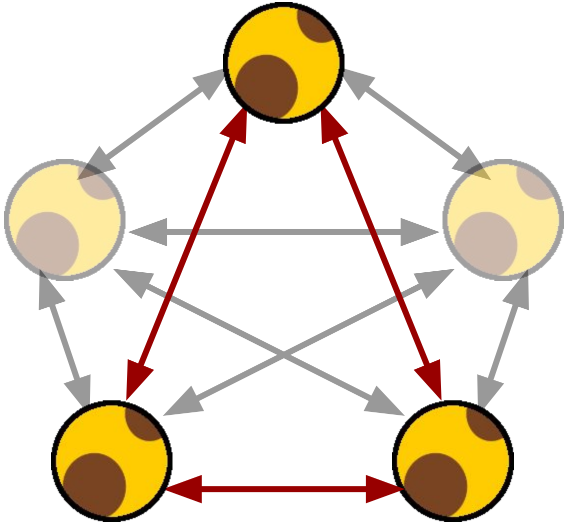
```
yea, nay := 1, 0
canceled := false
for r := range responses {
    if r.promised { yea++ } else { nay++ }

    in.learn(r)

    if !canceled {
        if in.isMajority(yea) || in.isMajority(nay) {
            cancel()
            canceled = true
        }
    }
}
```

Is this fine?

- Timeouts are now even more critical!
- "Ghost Quorum" Effect

Ghost Quorum

- Reason: Too tight timeout
- Some instances always time out
    - Effectively: Quorum of remaining instances
- Hidden reliability risk!
    - If one of the remaining instances fails, the distributed lock service is down!
    - No majority
    - No consensus



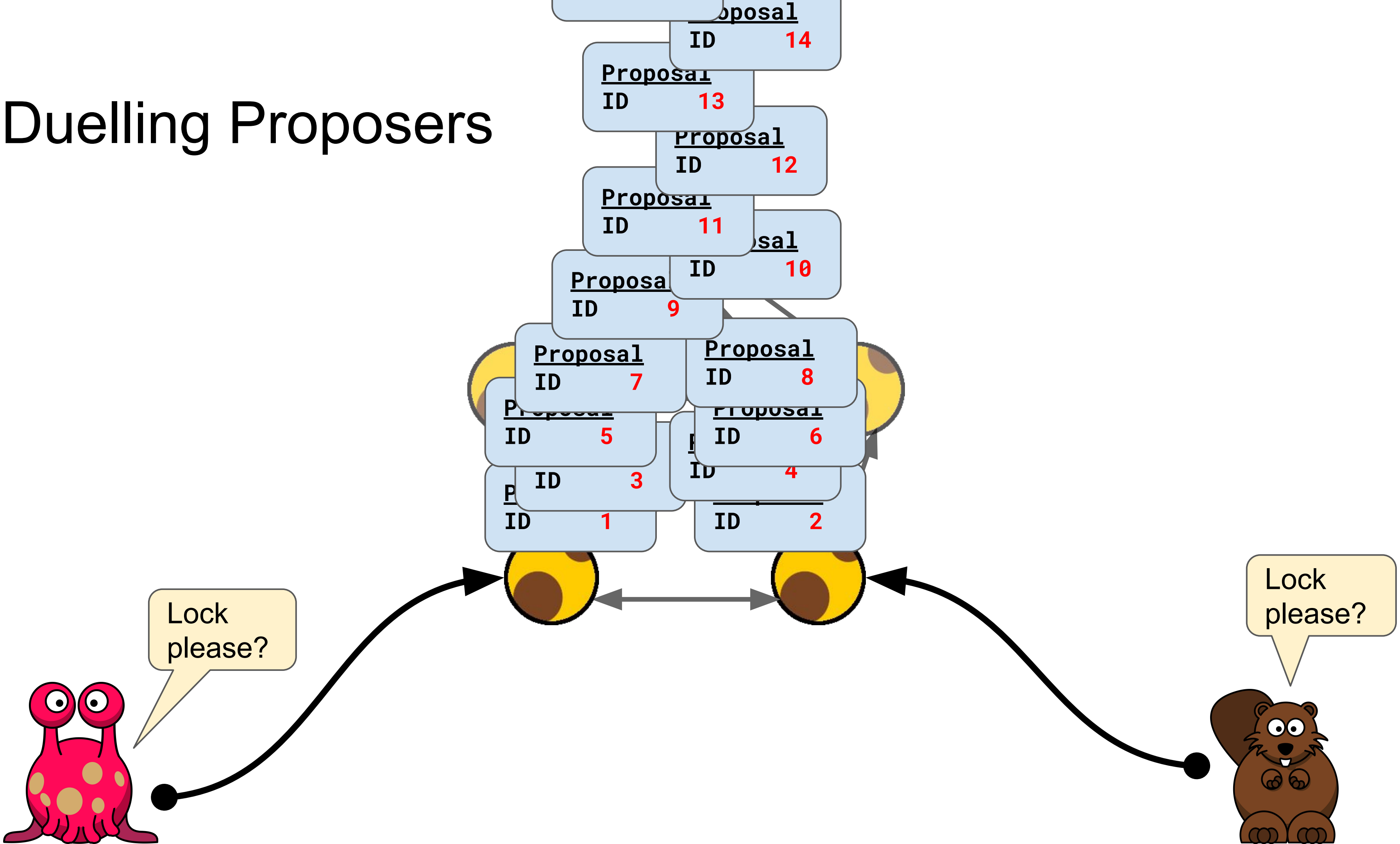
The Duel

What's wrong?

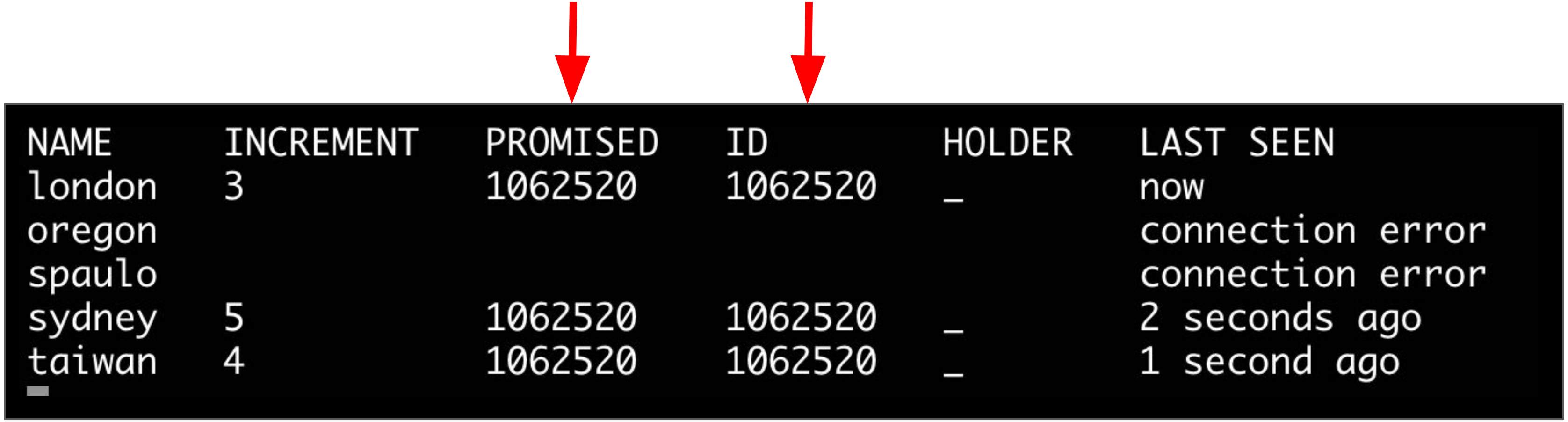
- Retry Logic
    - Unlimited retries!
- Coding Style
    - I should care about the return value.

```
...
retry:
id := id + in.increment
promised := in.propose(id)
if !promised {
    in.log.Printf("retry (%v)", id)
    goto retry
}
...
_ = in.commit(id, holder)
...
```

Duelling Proposers



Soon...



```
NAME      INCREMENT    PROMISED   ID        HOLDER   LAST SEEN
london    3            1062520    1062520   _        now
oregon                                               connection error
spaulo                                               connection error
sydney    5            1062520    1062520   _        2 seconds ago
taiwan    4            1062520    1062520   _        1 second ago
```

Instances **`oregon`** and **`spaulo`** were intentionally offline for a different experiment

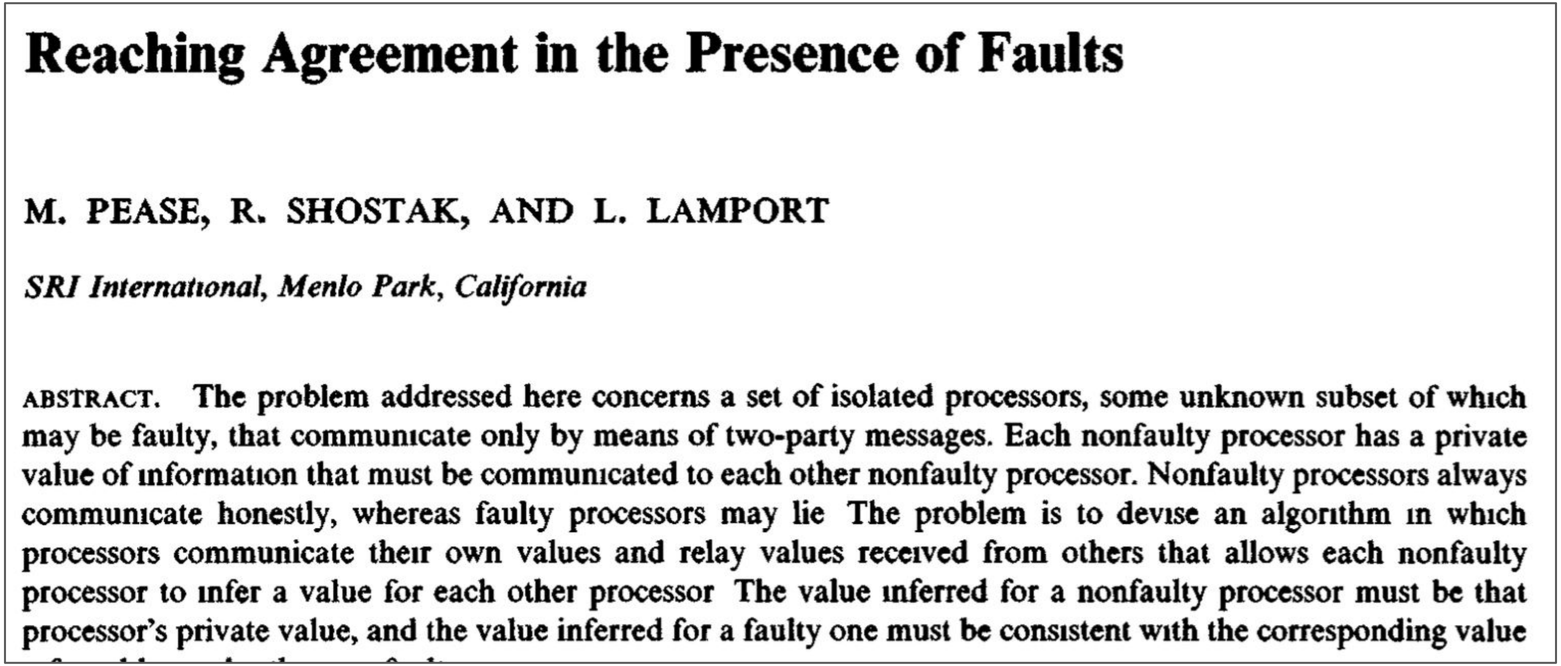
The Fix

- Retry Counter
- Backoff
- Jitter

```
...

retries := 0
retry:
promised := in.propose()
if !promised && retries < 3 {
    retries++
    backoff := time.Duration(retries) *
               2 * time.Millisecond
    jitter := time.Duration(rand.Int63n(1000)) *
              time.Microsecond
    time.Sleep(backoff + jitter)
    goto retry
}

...
```

Sources

Further Reading



Reaching Agreement in the Presence of Faults

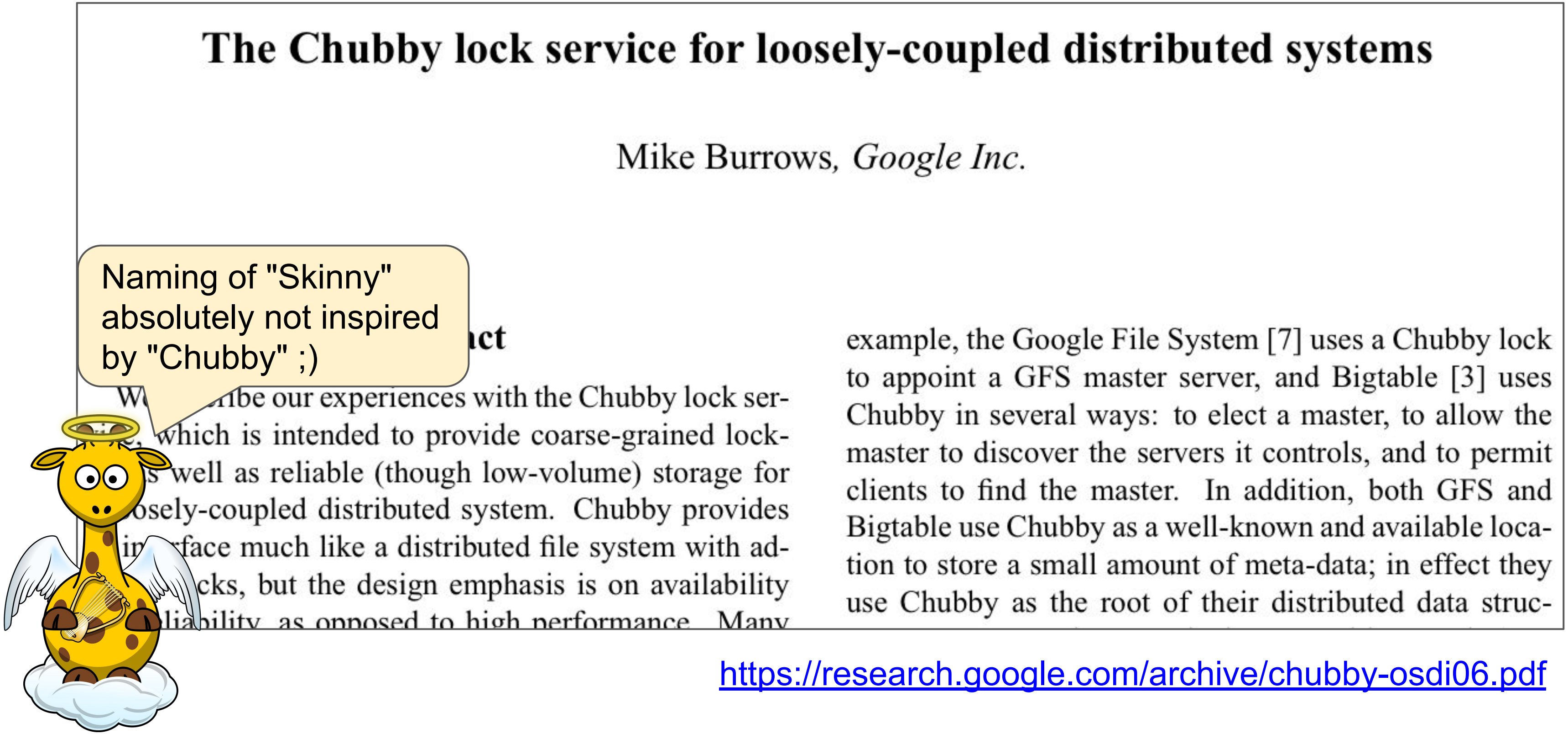
M. PEASE, R. SHOSTAK, AND L. LAMPORT

SRI International, Menlo Park, California

ABSTRACT. The problem addressed here concerns a set of isolated processors, some unknown subset of which may be faulty, that communicate only by means of two-party messages. Each nonfaulty processor has a private value of information that must be communicated to each other nonfaulty processor. Nonfaulty processors always communicate honestly, whereas faulty processors may lie The problem is to devise an algorithm in which processors communicate their own values and relay values received from others that allows each nonfaulty processor to infer a value for each other processor The value inferred for a nonfaulty processor must be that processor's private value, and the value inferred for a faulty one must be consistent with the corresponding value

https://lamport.azurewebsites.net/pubs/reaching.pdf

Further Reading



The Chubby lock service for loosely-coupled distributed systems

Mike Burrows, *Google Inc.*

…act

W… ribe our experiences with the Chubby lock ser- …e, which is intended to provide coarse-grained lock- …s well as reliable (though low-volume) storage for …osely-coupled distributed system. Chubby provides in…rface much like a distributed file system with ad- …cks, but the design emphasis is on availability …liability as opposed to high performance. Many

example, the Google File System [7] uses a Chubby lock to appoint a GFS master server, and Bigtable [3] uses Chubby in several ways: to elect a master, to allow the master to discover the servers it controls, and to permit clients to find the master. In addition, both GFS and Bigtable use Chubby as a well-known and available location to store a small amount of meta-data; in effect they use Chubby as the root of their distributed data struc-

https://research.google.com/archive/chubby-osdi06.pdf

Further Watching

Paxos Agreement - Computerphile
Dr. Heidi Howard
University of Cambridge Computer Laboratory
https://youtu.be/s8JqcZtvnsM

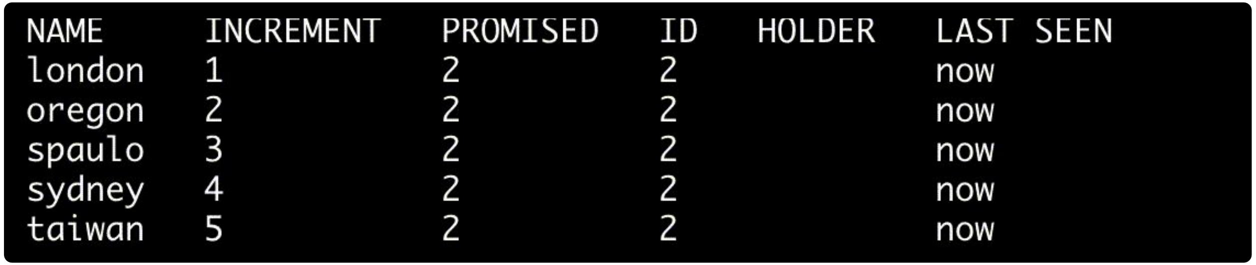
The Paxos Algorithm
Luis Quesada Torres
Senior Software Engineer
Site Reliability Engineering

The Paxos Algorithm
Luis Quesada Torres
Google Site Reliability Engineering
https://youtu.be/d7nAGI_NZPk

Try, Play, Learn!

- The Skinny Lock Server is open source software!
    - `skinnyd` lock server
    - `skinnyctl` control utility
- Terraform modules
- Ansible playbooks

github.com/danrl/skinny



```
NAME      INCREMENT    PROMISED    ID    HOLDER    LAST SEEN
london    1            2           2               now
oregon    2            2           2               now
spaulo    3            2           2               now
sydney    4            2           2               now
taiwan    5            2           2               now
```

Find me on Twitter **@danrl_com**
I blog about SRE and technology: https://**danrl.com**