Distributed Consensus: Why Can't We All Just Agree?

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Sometimes inconsistency is not an option

- Distributed locking
- Safety critical systems
- Distributed scheduling
- Strongly consistent databases
- Blockchain

- Leader election
- Orchestration services
- Distributed file systems
- Coordination & configuration
- Strongly consistent databases

Anything which ***requires*** guaranteed agreement

What is Distributed Consensus?

*“The process of reaching agreement over state between **unreliable hosts** connected by **unreliable networks**, all operating **asynchronously**”*

defined to be the largest vote v in $Votes(\mathcal{B})$ cast by p with ...

if there was no s

means that Max

For any nonemp

maximum of all

Conditions $B1$

$B1(\mathcal{B})$

$B2(\mathcal{B})$

$B3(\mathcal{B})$

Although the de

implies that Ma

numbers were or

To show that

$B1(\mathcal{B})$–$B3(\mathcal{B})$ in

$\mathcal{B}$ is for the same

Lemma *If* $B1($

for any B, B' *in*

Proof of Lemm

For any ballot B

decree different f

To prove the lem

The Paxons gave

$B_{qrm} \subseteq B_{vot}$ and

1. Choose $C \in \Psi$
   PROOF: C exi
2. $C_{bal} > B_{bal}$
   PROOF: By 1
3. $B_{vot} \cap C_{qrm}$
   PROOF: By B

[8] I use the Paxon m

[9] Paxon mathematic were not as sophis paragraph-style pro

$I3(p) \triangleq$ [Associated variables: $prevBal[p]$, $prevDec[p]$, $nextBal[p]$]

$$\begin{aligned}&\wedge\ prevBal[p] = MaxVote(\infty, p, \mathcal{B})_{bal}\\ &\wedge\ prevDec[p] = MaxVote(\infty, p, \mathcal{B})_{dec}\\ &\wedge\ nextBal[p] \geq prevBal[p]\end{aligned}$$

$I4(p) \triangleq$ [Associated variable: $prevVotes[p]$]

$$\begin{aligned}&(status[p] \neq idle) \Rightarrow\\ &\qquad \forall v \in prevVotes[p] : \wedge\ v = MaxVote(lastTried[p], v_{pst}, \mathcal{B})\\ &\qquad\qquad\qquad\qquad\qquad \wedge\ nextBal[v_{pst}] \geq lastTried[p]\end{aligned}$$

$I5(p) \triangleq$ [Associated variables: $quorum[p]$, $voters[p]$, $decree[p]$]

$$\begin{aligned}&(status[p] = polling) \Rightarrow\\ &\qquad \wedge\ quorum[p] \subseteq \{v_{pst} : v \in prevVotes[p]\}\\ &\qquad \wedge\ \exists B \in \mathcal{B} : \wedge\ quorum[p] = B_{qrm}\\ &\qquad\qquad\qquad\qquad \wedge\ decree[p] = B_{dec}\\ &\qquad\qquad\qquad\qquad \wedge\ voters[p] \subseteq B_{vot}\\ &\qquad\qquad\qquad\qquad \wedge\ lastTried[p] = B_{bal}\end{aligned}$$

$I6 \triangleq$ [Associated variable: $\mathcal{B}$]

$$\begin{aligned}&\wedge\ B1(\mathcal{B}) \wedge B2(\mathcal{B}) \wedge B3(\mathcal{B})\\ &\wedge\ \forall B \in \mathcal{B} : B_{qrm} \text{ is a majority set}\end{aligned}$$

$I7 \triangleq$ [Associated variable: $\mathcal{M}$]

$$\begin{aligned}&\wedge\ \forall NextBallot(b) \in \mathcal{M} : (b \leq lastTried[owner(b)])\\ &\wedge\ \forall LastVote(b, v) \in \mathcal{M} : \wedge\ v = MaxVote(b, v_{pst}, \mathcal{B})\\ &\qquad\qquad\qquad\qquad\qquad\qquad \wedge\ nextBal[v_{pst}] \geq b\\ &\wedge\ \forall BeginBallot(b, d) \in \mathcal{M} : \exists B \in \mathcal{B} : (B_{bal} = b) \wedge (B_{dec} = d)\\ &\wedge\ \forall Voted(b, p) \in \mathcal{M} : \exists B \in \mathcal{B} : (B_{bal} = b) \wedge (p \in B_{vot})\\ &\wedge\ \forall Success(d) \in \mathcal{M} : \exists p : outcome[p] = d \neq \text{BLANK}\end{aligned}$$

The Paxons had to prove that I satisfies the three conditions given above. The first condition, that I holds initially, requires checking that each conjunct is true for the initial values of all the variables. While not stated explicitly, these initial values can be inferred from the variables' descriptions, and checking the first condition is straightforward. The second condition, that I implies consistency, follows from $I1$, the first conjunct of $I6$, and Theorem 1. The hard part was proving the third condition, the invariance of I, which meant proving that I is left true by every action. This condition is proved by showing that, for each conjunct of I, executing any action when I is true leaves that conjunct true. The proofs are sketched below.

$I1(p)$ $\mathcal{B}$ is changed only by adding a new ballot or adding a new priest to B_{vot} for some $B \in \mathcal{B}$, neither of which can falsify $I1(p)$. The value of $outcome[p]$ is changed only by the **Succeed** and **Receive** *Success* **Message** actions. The enabling condition and $I5(p)$ imply that $I1(p)$ is left true by the **Succeed** action. The enabling condition, $I1(p)$, and the last conjunct of $I7$ imply that $I1(p)$ is left true by the **Receive** *Success* **Message** action.

A Hundred Impossibility Proofs for Distributed Computing

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1 Introduction

This talk is about impossibility results in the area of distributed computing. In this category, I include not just results that say that a particular task cannot be accomplished, but also lower bound results, which say that a task cannot be accomplished within a certain bound on cost.

I started out with a simple plan for preparing this talk: I would spend a couple of weeks reading all the impossibility proofs in our field, and would categorize them according to the ideas used. Then I would make wise and general observations, and try to predict where the future of this area is headed. That turned out to be a bit too ambitious; there are many more such results than I thought. Although it is often hard to say what constitutes a "different result", I managed to count over 100 such impossibility proofs! And my search wasn't even very systematic or exhaustive.

It's not quite as hopeless to understand this area as it might seem from the number of papers. Although there are 100 different results, there aren't 100 different ideas. I thought I could contribute something by identifying some of the commonality among the different results.

So what I will do in this talk will be an incomplete version of what I originally intended. I will give you a tour of the impossibility results that I was able to collect. I apologize for not being comprehensive, and in particular for placing perhaps undue emphasis on results I have been involved in (but those are the ones I know best!). I will describe the techniques used, as well as giving some historical perspective. I'll intersperse this with my opinions and observations, and I'll try to collect what I consider to be the most important of these at the end. Then I'll make some suggestions for future work.

2 The Results

I classified the impossibility results I found into the following categories: shared memory resource allocation, distributed consensus, shared registers, computing in rings and other networks, communication protocols, and miscellaneous.

2.1 Shared Memory Resource Allocation

This was the area that introduced me not only to the possibility of doing impossibility proofs for distributed computing, but to the entire distributed computing research area.

In 1976, when I was at the University of Southern California, Armin Cremers and Tom Hibbard were playing with the problem of *mutual exclusion* (or allocation of one resource) in a shared memory environment. In the environment they were considering, a group of asynchronous processes communicate via shared memory, using operations such as read and write or test-and-set.

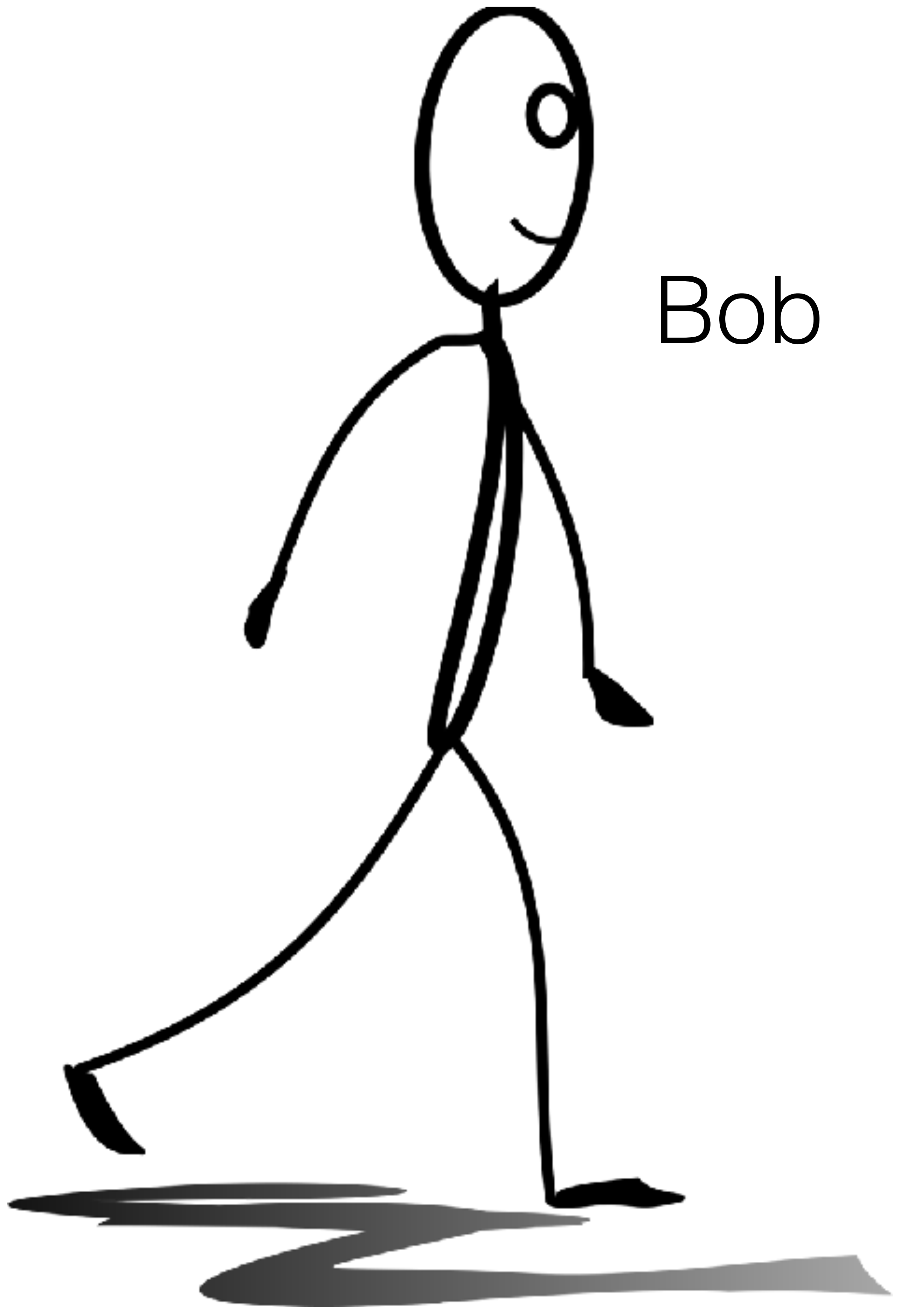
The previous work in this area had consisted of a series of papers by Dijkstra [38] and others, each presenting a new algorithm guaranteeing mutual exclusion, along with some other properties such as progress and fairness. The properties were specified somewhat loosely; there was no formal model used for

*This work was supported in part by the National Science Foundation (NSF) under Grant CCR-86-11442, by the Office of Naval Research (ONR) under Contract N00014-85-K-0168 and by the Defense Advanced Research Projects Agency (DARPA) under Contract N00014-83-K-0125.

A walk through time

We are going to take a journey through the developments in distributed consensus, spanning over three decades. Stops include:

- FLP Result & CAP Theorem
- Viewstamped Replication, Paxos & Multi-Paxos
- State Machine Replication
- Paxos Made Live, Zookeeper & Raft
- Flexible Paxos



Fischer, Lynch & Paterson Result

We begin with a slippery start

<u>Impossibility of distributed consensus with one faulty process</u>
Michael Fischer, Nancy Lynch and Michael Paterson
ACM SIGACT-SIGMOD Symposium on Principles of Database Systems
1983

FLP Result

We cannot guarantee agreement in an asynchronous system where even one host **might** fail.

Why?

We cannot reliably detect failures. We cannot know for sure the difference between a slow host/network and a failed host

Note: We can still guarantee safety, the issue limited to guaranteeing liveness.

Solution to FLP

In practice:

We approximate reliable failure detectors using heartbeats and timers. We accept that sometimes the service will not be available (when it could be).

In theory:

We make weak assumptions about the synchrony of the system e.g. messages arrive within a year.

Viewstamped Replication

the forgotten algorithm

Viewstamped Replication Revisited
Barbara Liskov and James Cowling
MIT Tech Report
MIT-CSAIL-TR-2012-021

Not the original from 1988, but recommended

Viewstamped Replication

In my view, the pioneering algorithm on the field of distributed consensus.

Approach: Select one node to be the 'master'. The master is responsible for replicating decisions. Once a decision has been replicated onto the majority of nodes then it is commit.

We rotate the master when the old master fails with agreement from the majority of nodes.

Paxos

Lamport's consensus algorithm

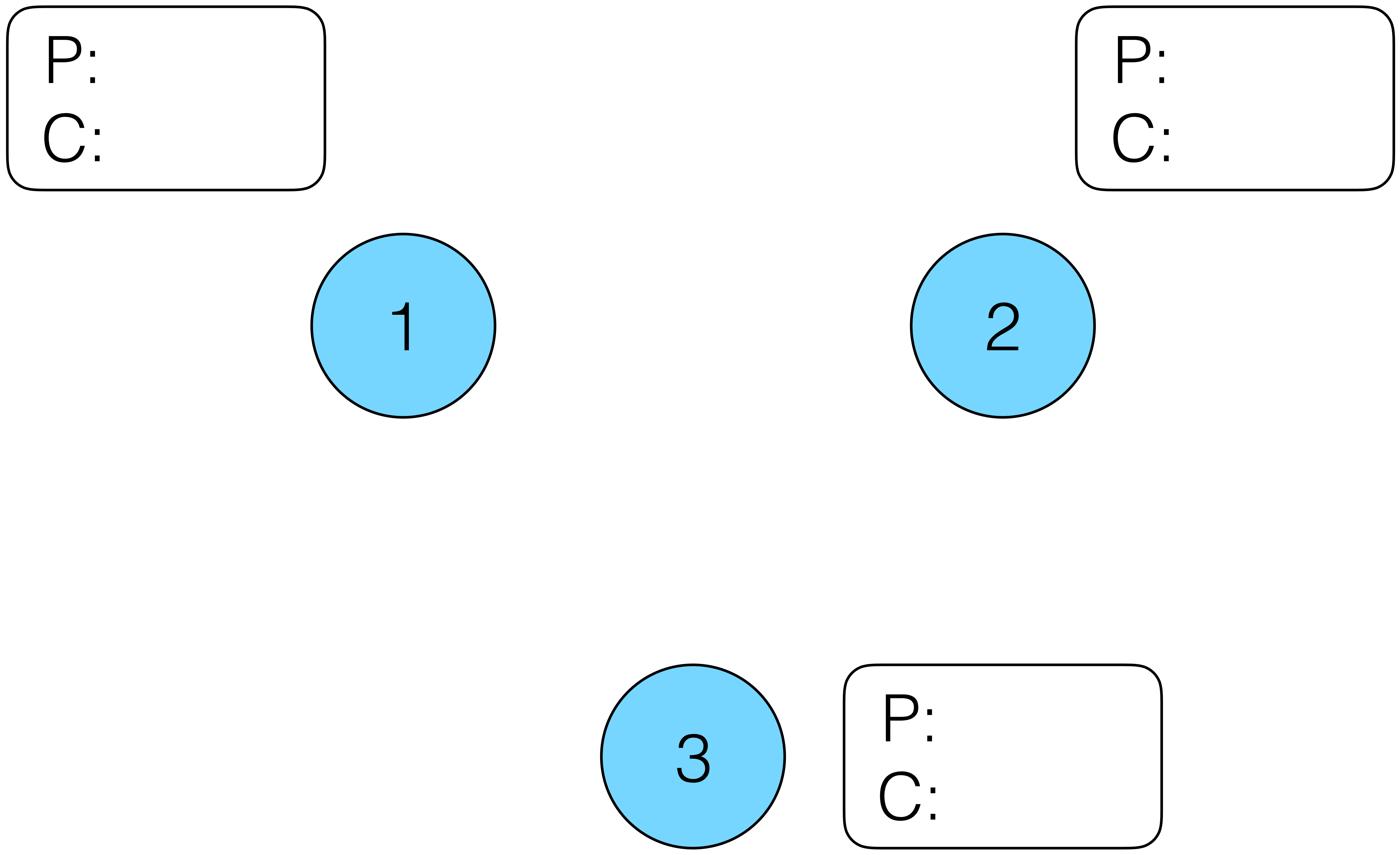
<u>The Part-Time Parliament</u>
Leslie Lamport
ACM Transactions on Computer Systems
May 1998

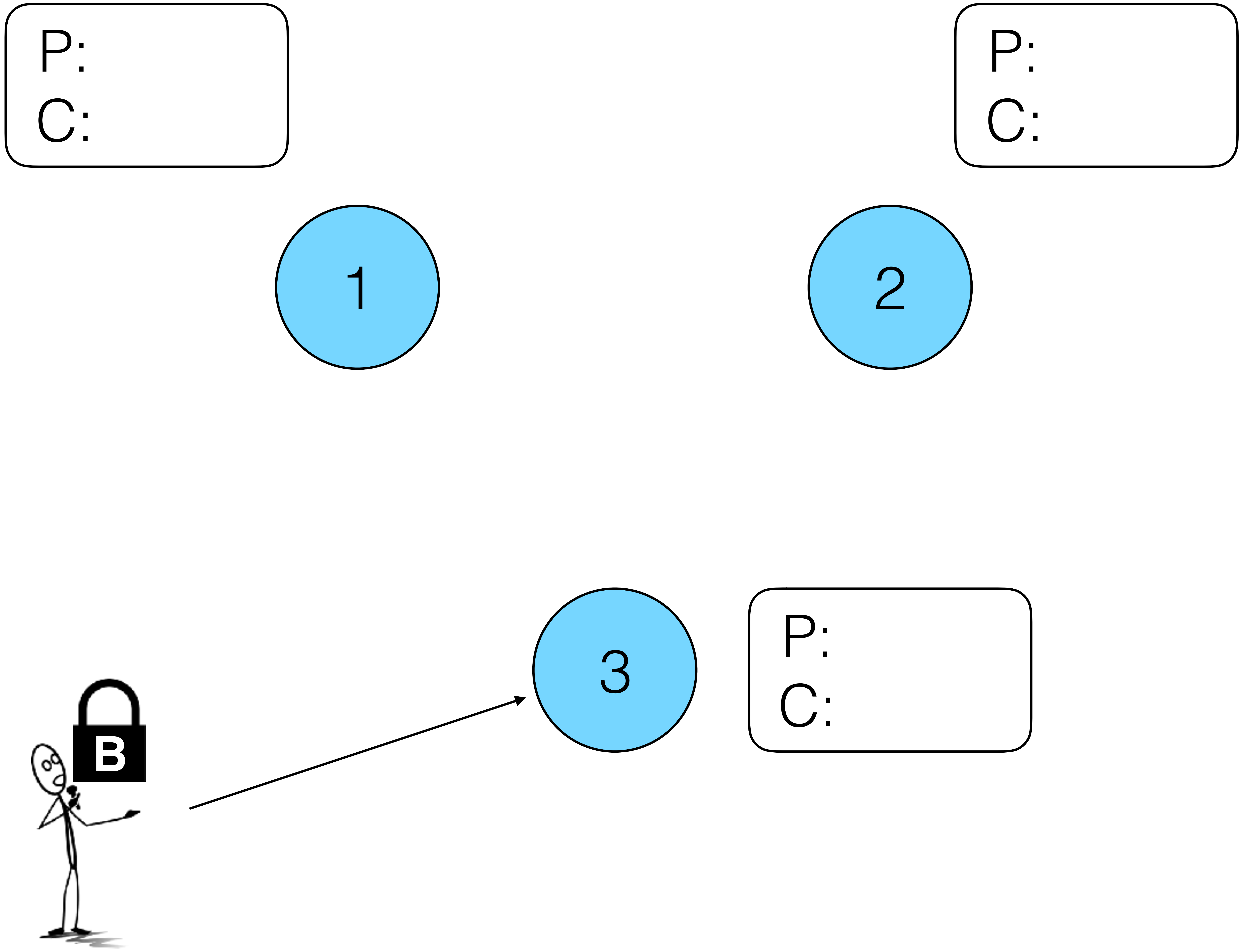
Paxos

The textbook algorithm for reaching consensus on a single value.

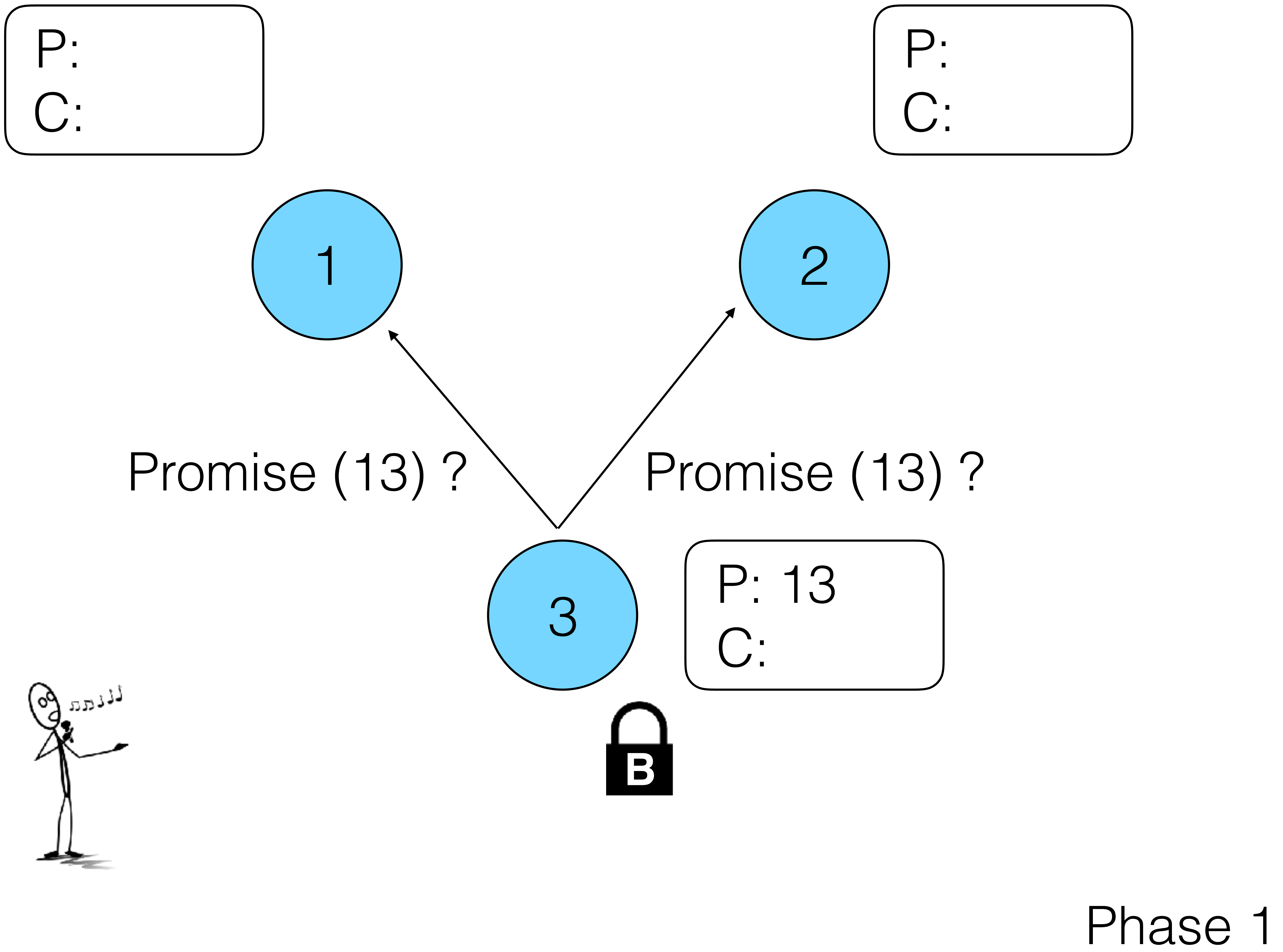
- two phase process: promise and commit
- each requiring majority agreement (aka quorums)

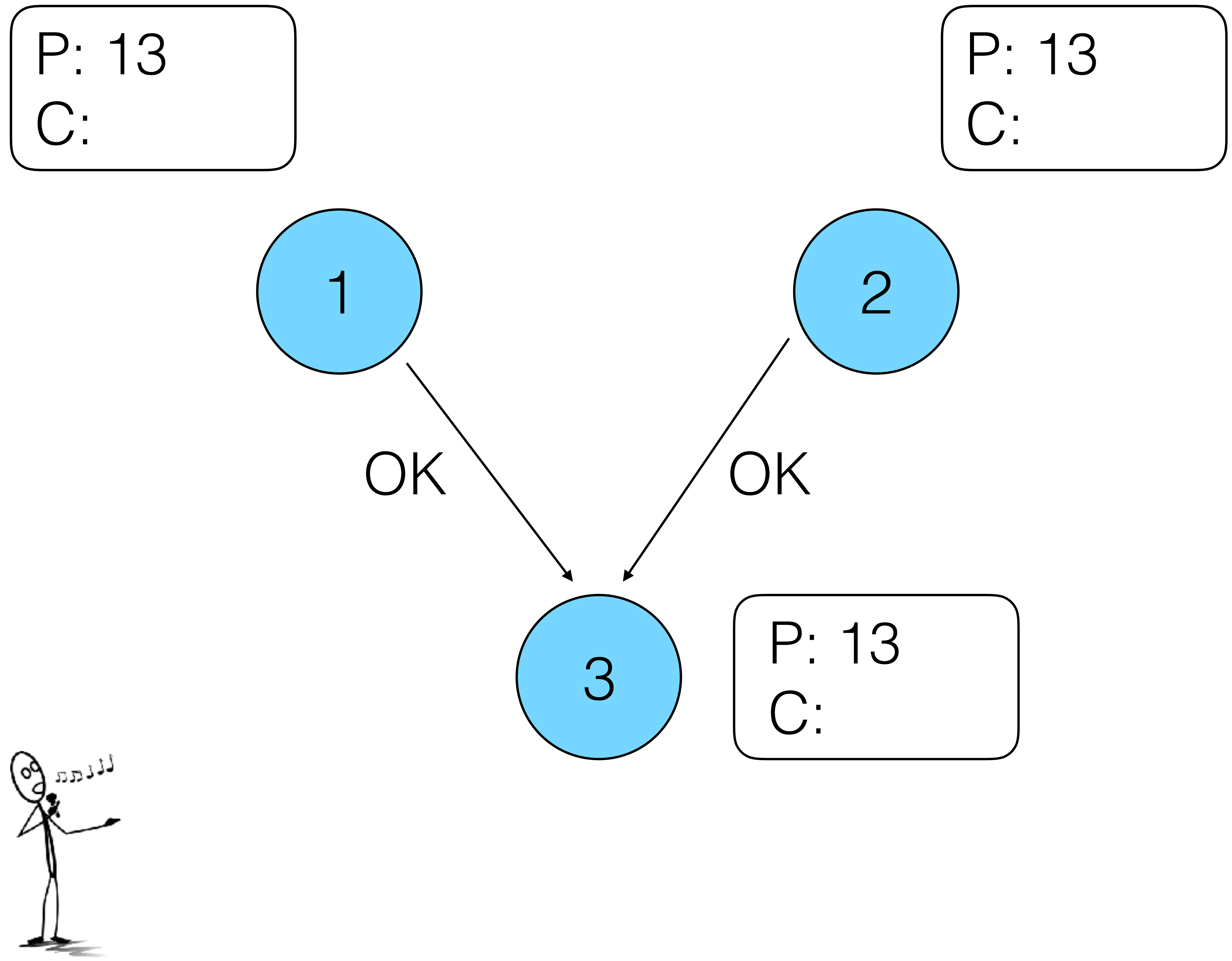
Paxos Example - Failure Free


P:
C:
P:
C:
1
2
3
P:
C:

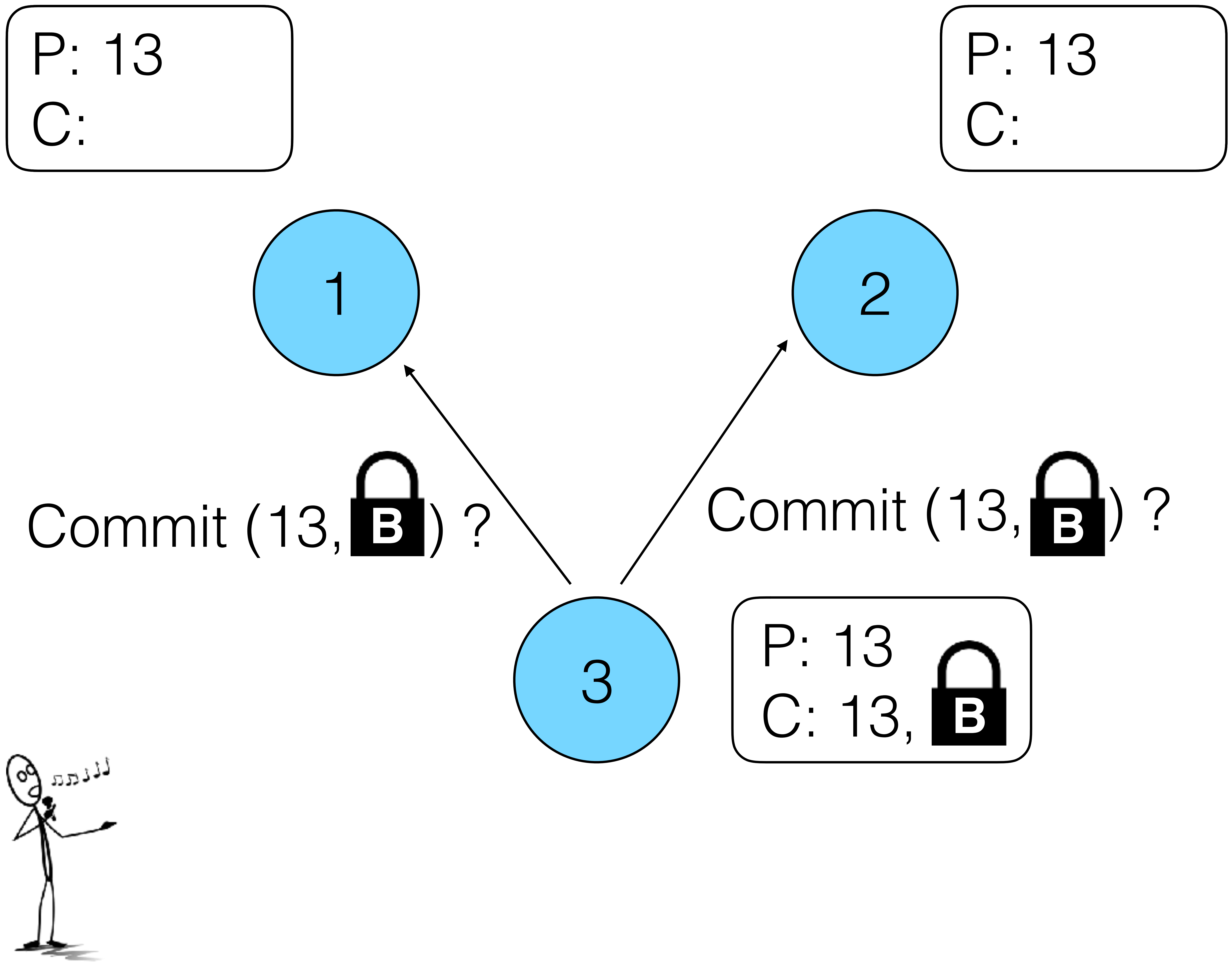


Incoming request from Bob

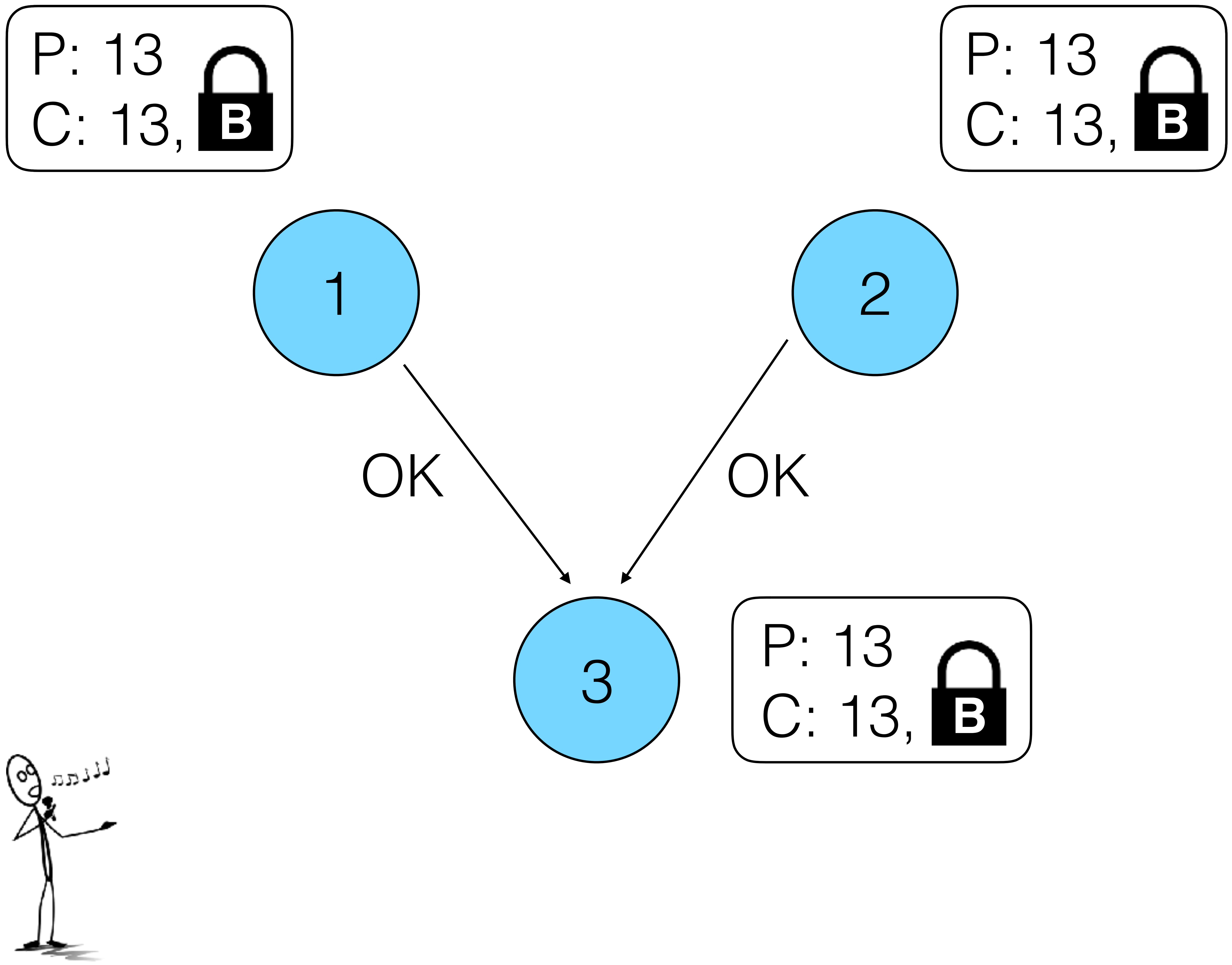

P:
C:
P:
C:
1
2
Promise (13) ?
Promise (13) ?
3
P: 13
C:
B
Phase 1



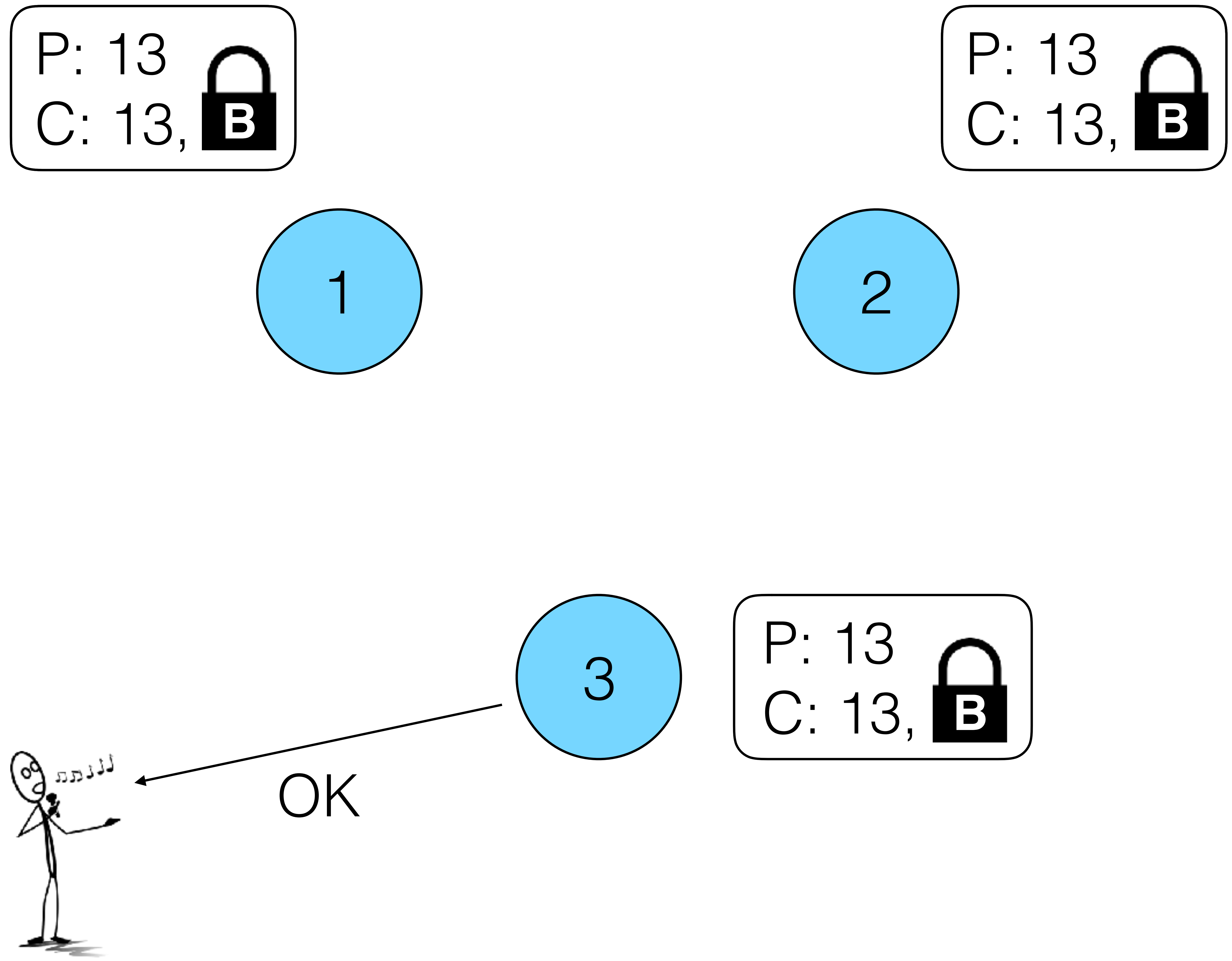
Phase 1



Phase 2

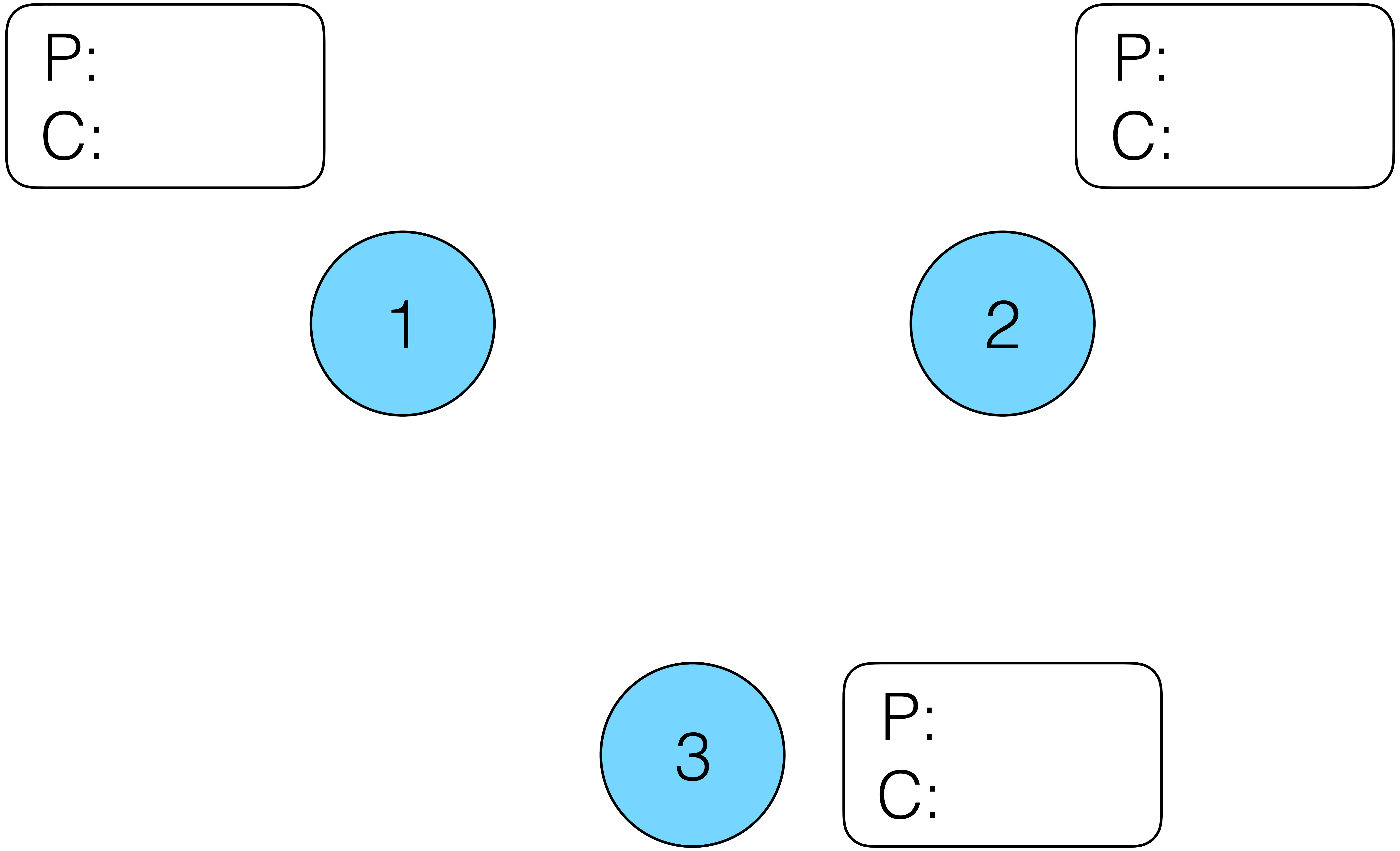


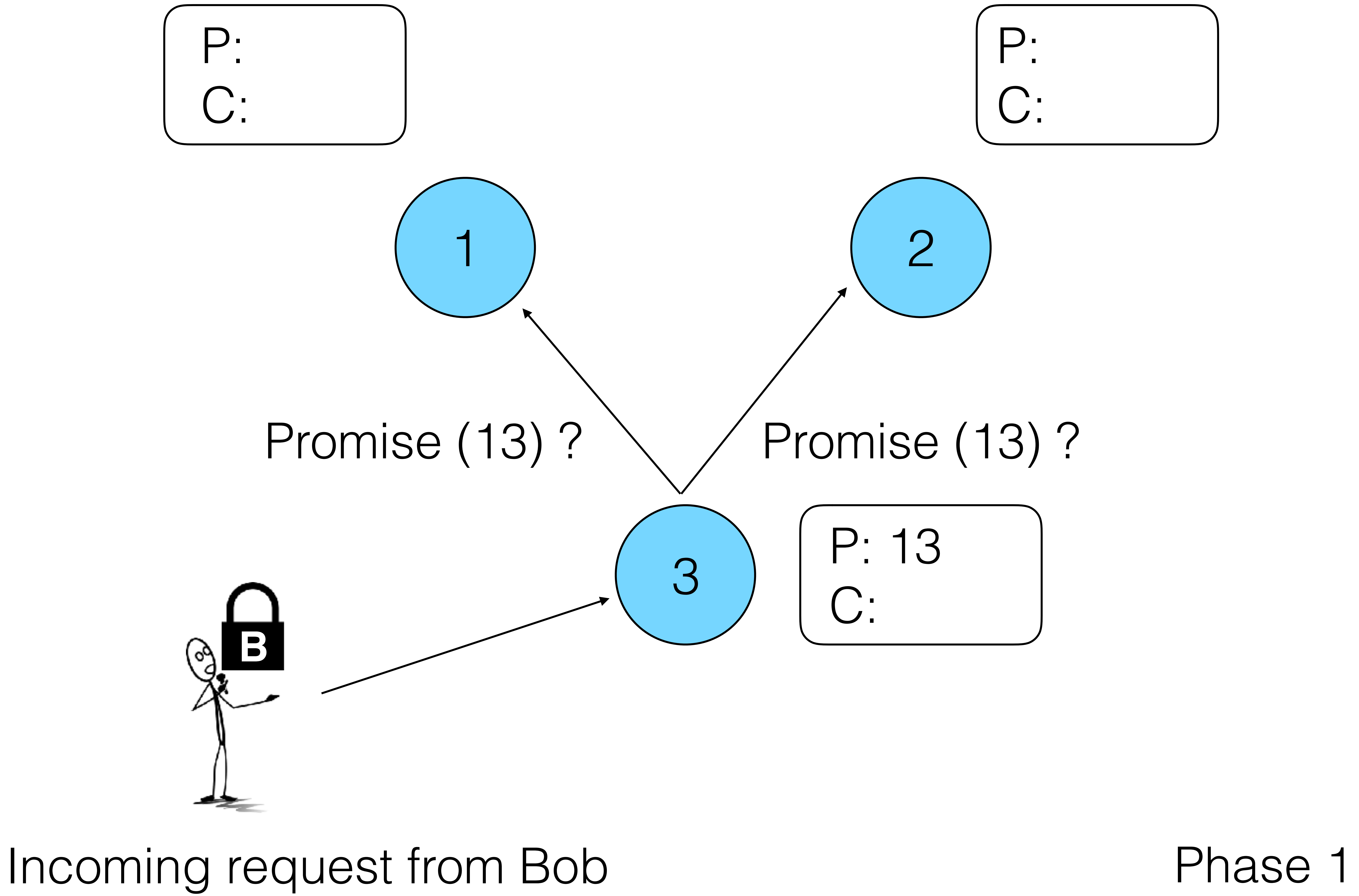
Phase 2

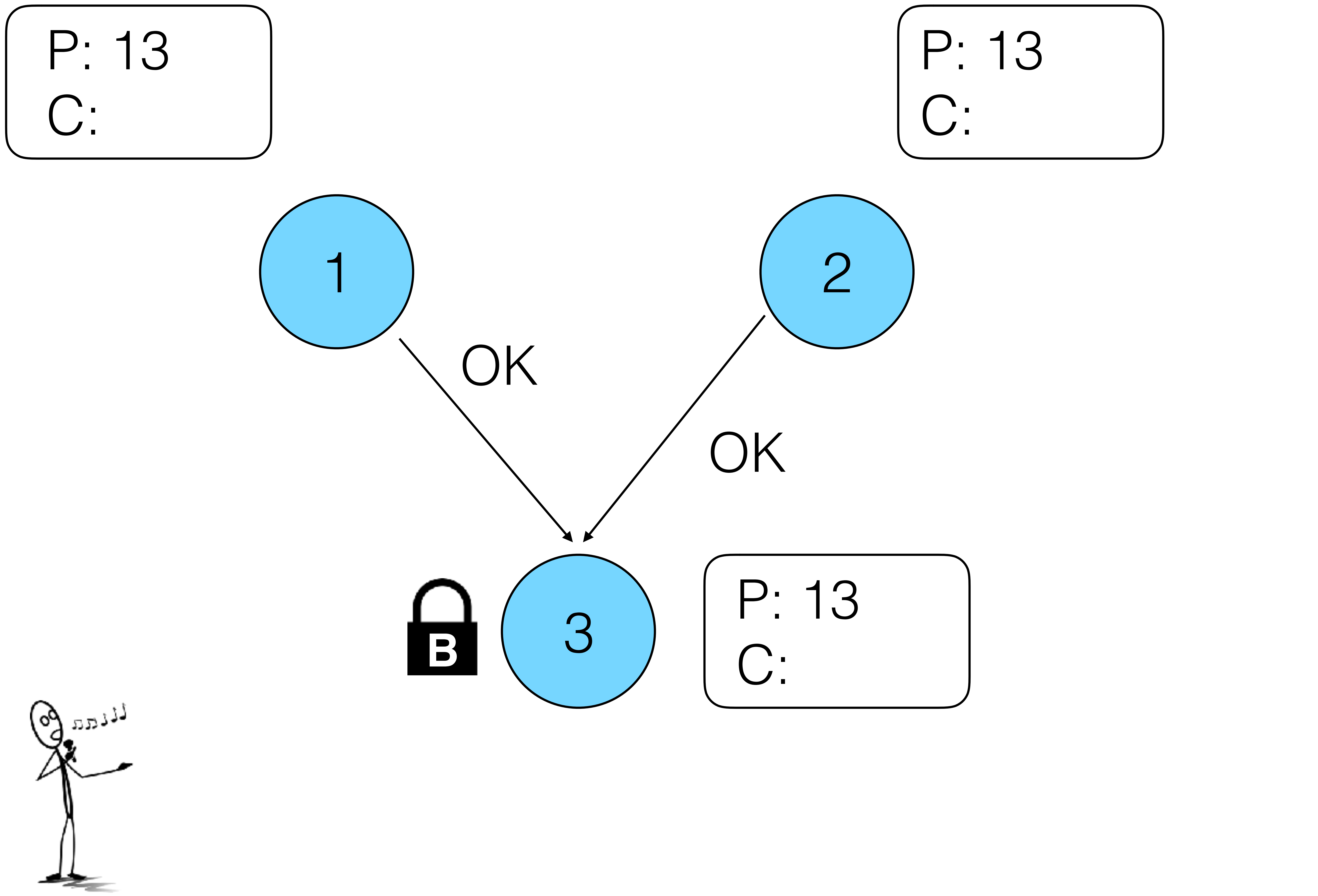


Bob is granted the lock

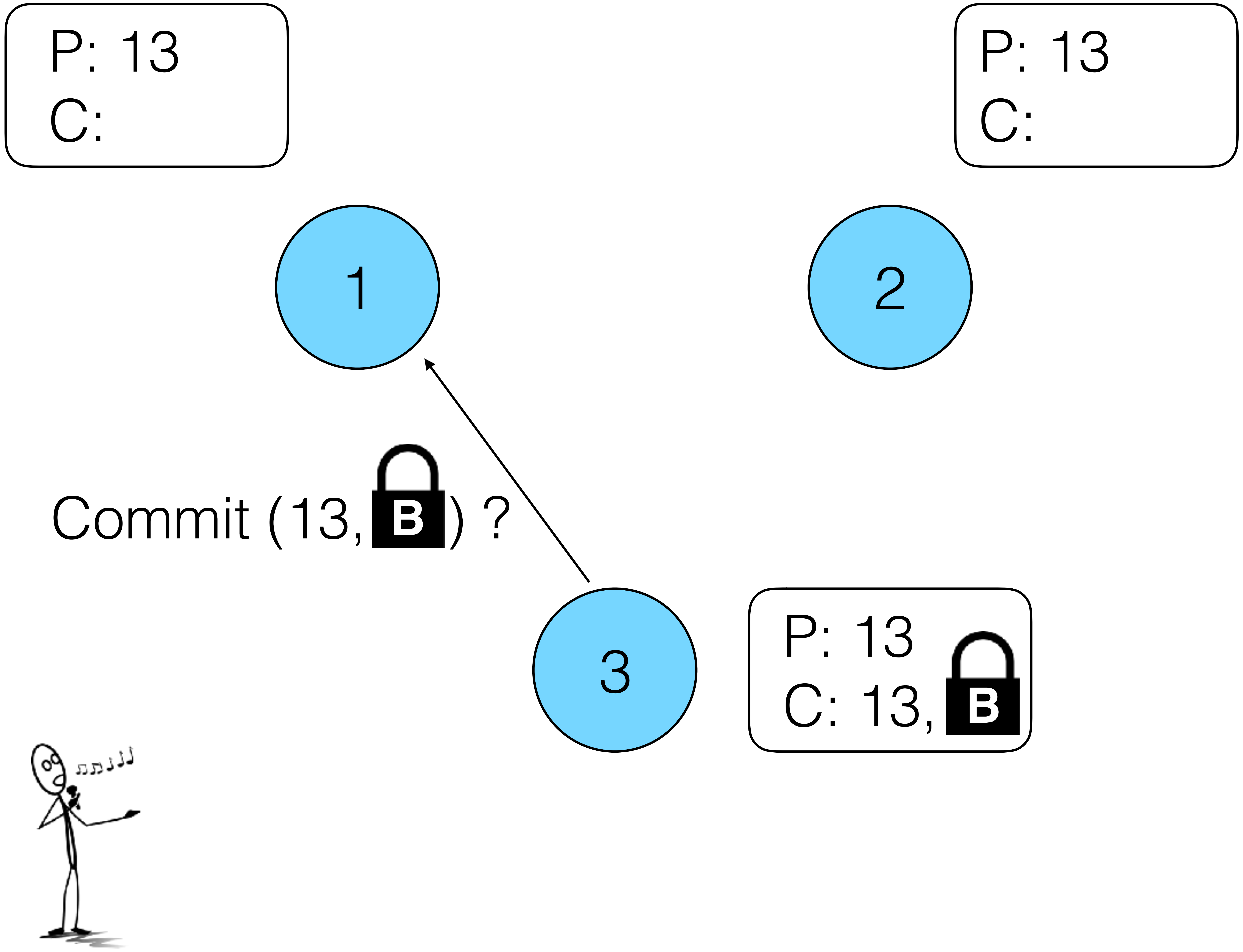
Paxos Example - Node Failure


P:
C:
P:
C:
1
2
3
P:
C:

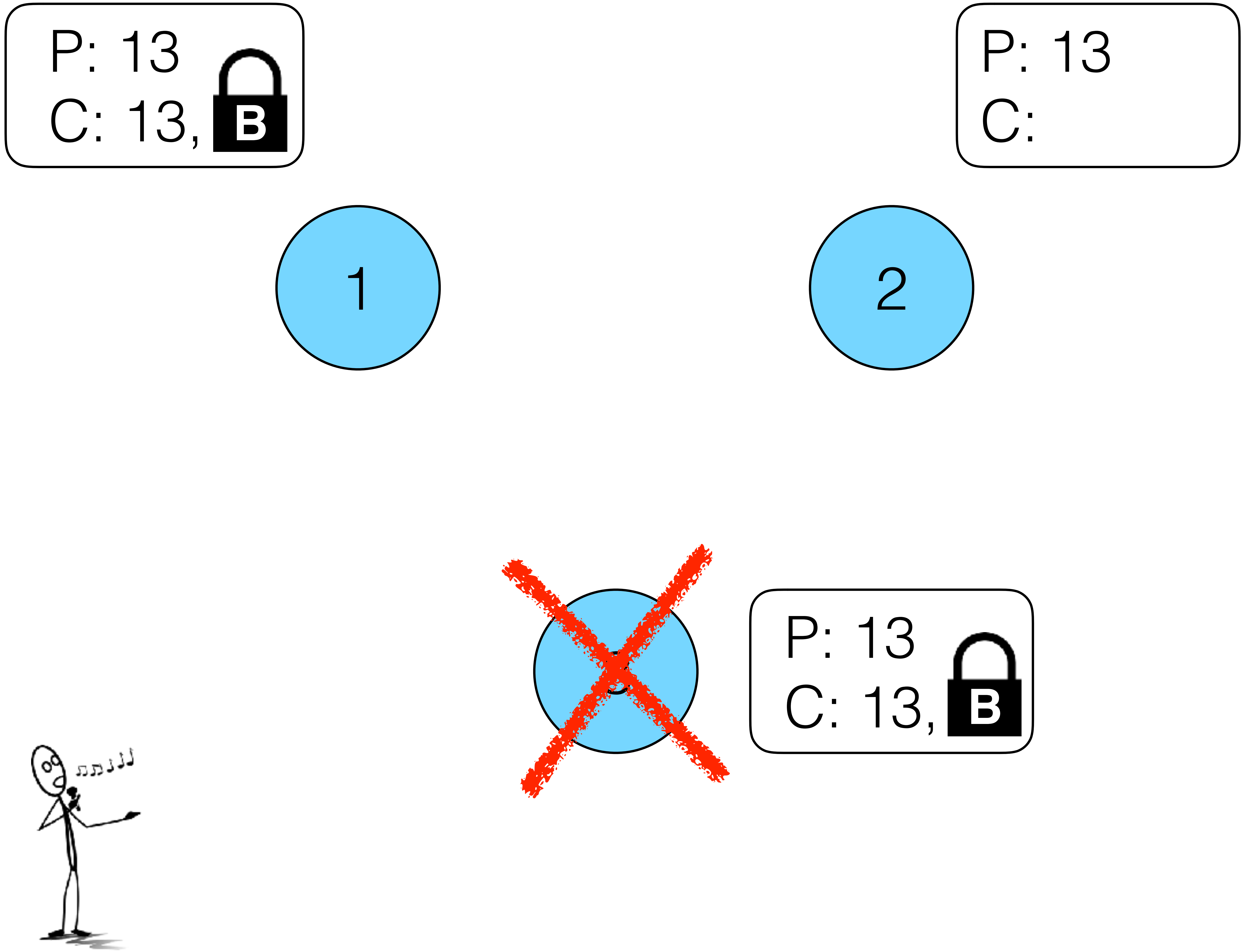

P:
C:
P:
C:
1
2
Promise (13) ?
Promise (13) ?
3
P: 13
C:
B
Incoming request from Bob
Phase 1



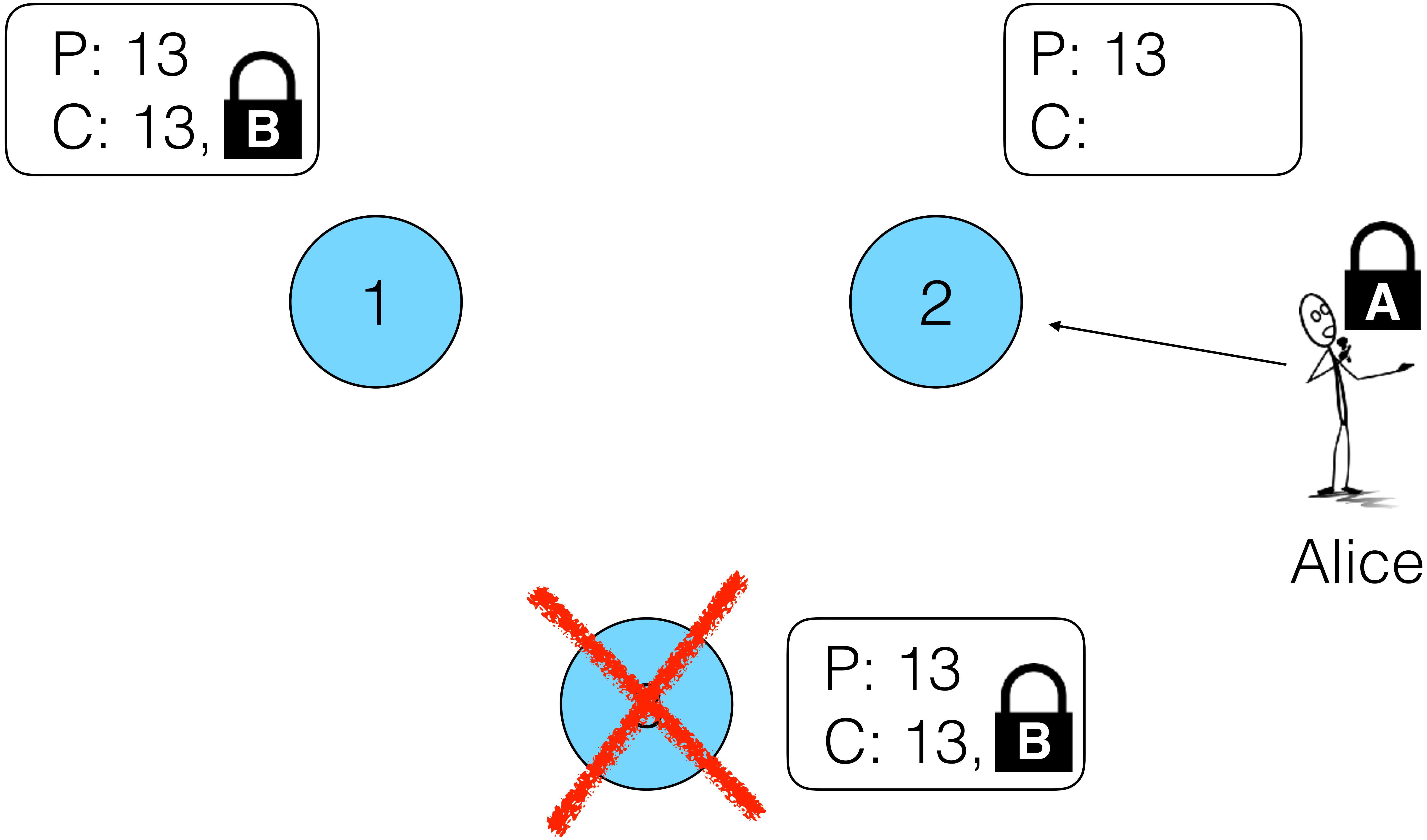
P: 13
C:
P: 13
C:
1
2
OK
OK
B
3
P: 13
C:
Phase 1

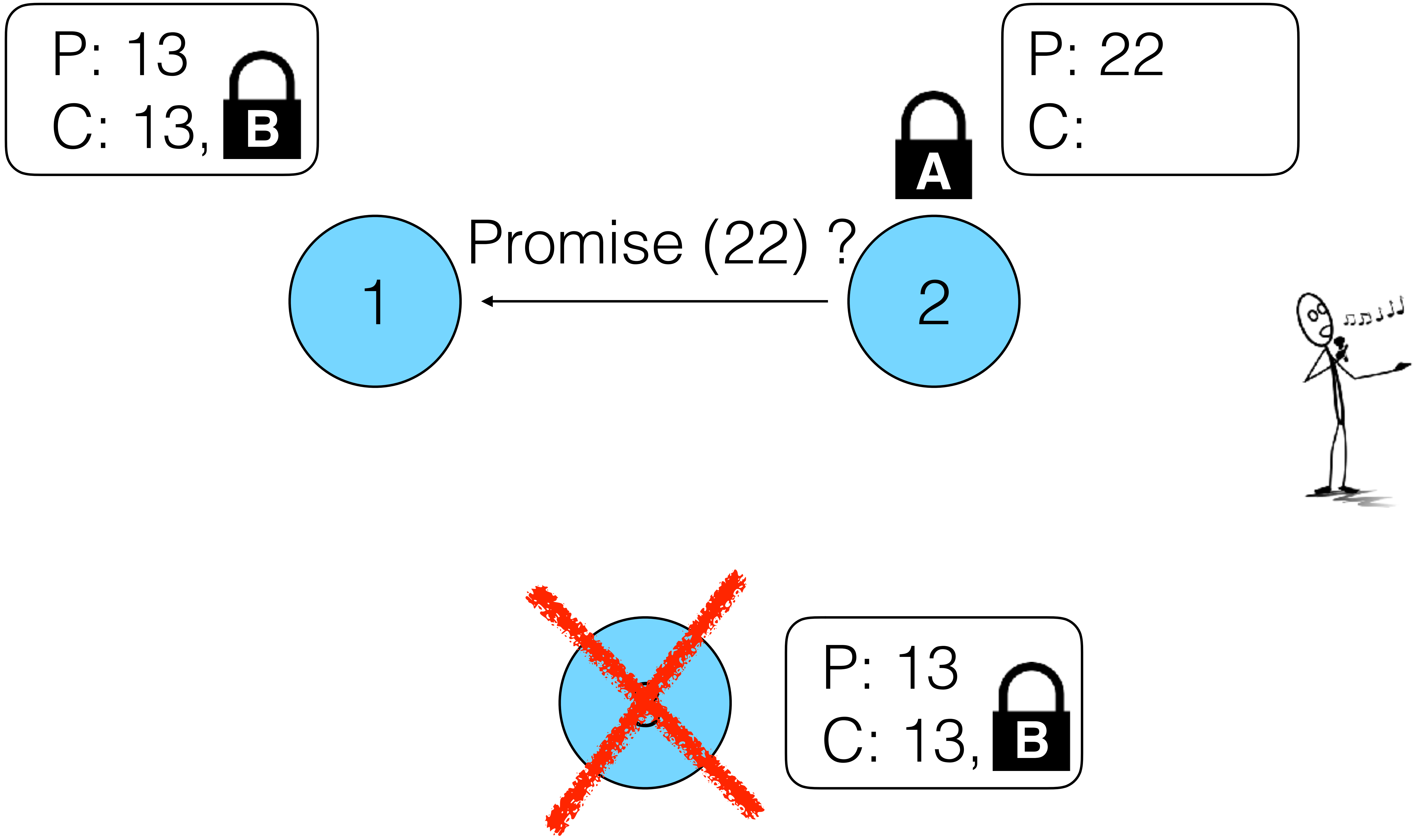


Phase 2

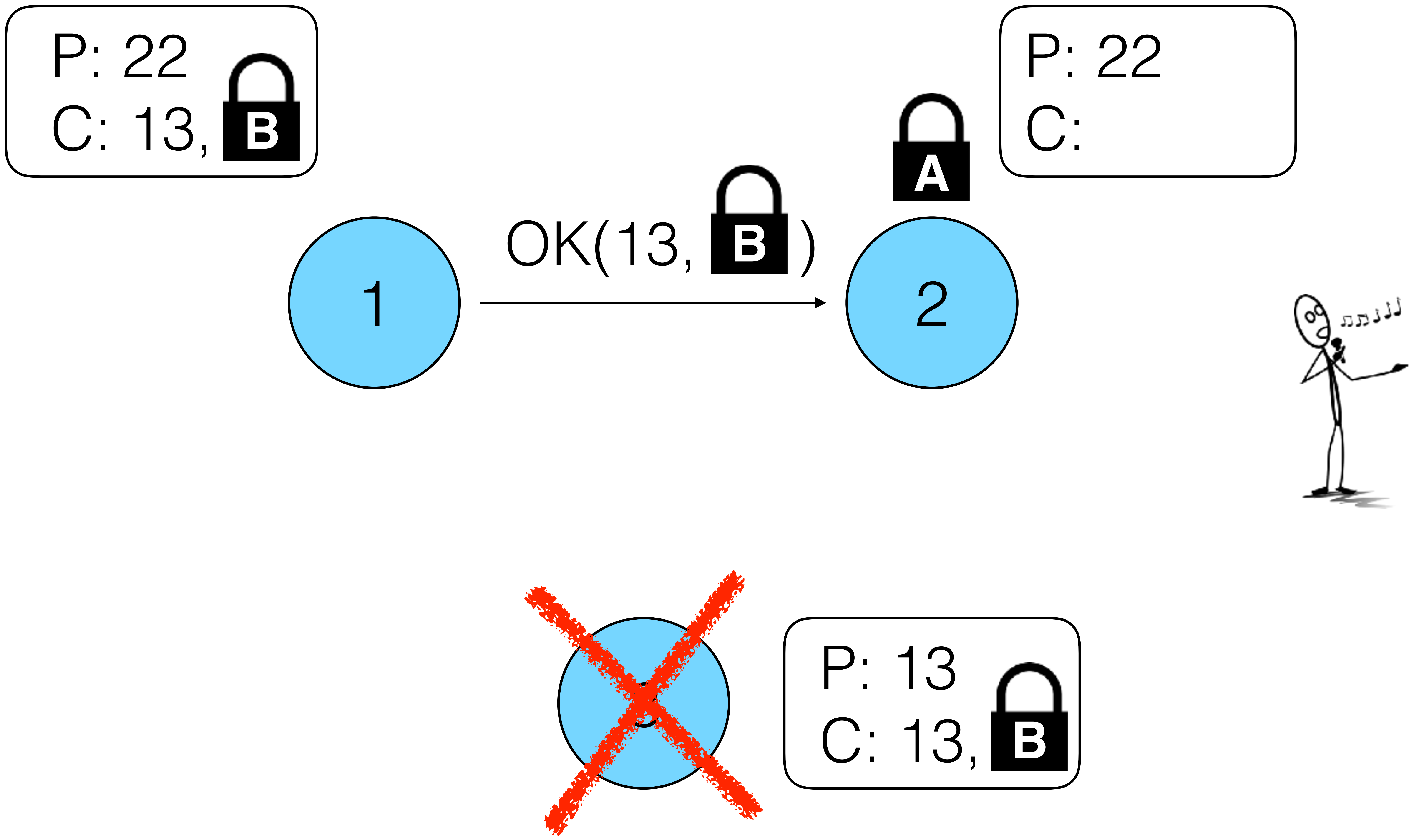


Phase 2

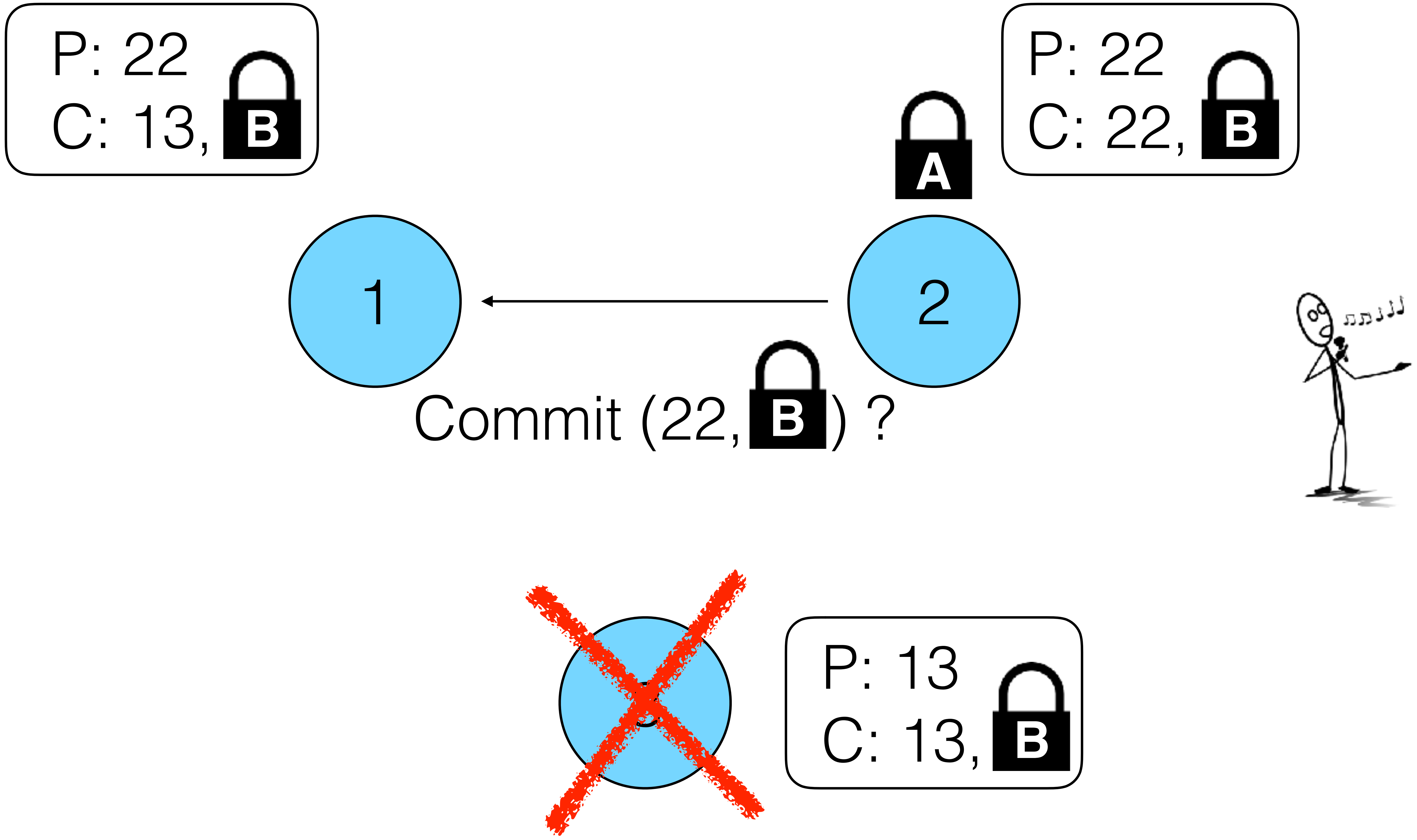

P: 13
C: 13, B
P: 13
C:
1
2
A
Alice
P: 13
C: 13, B



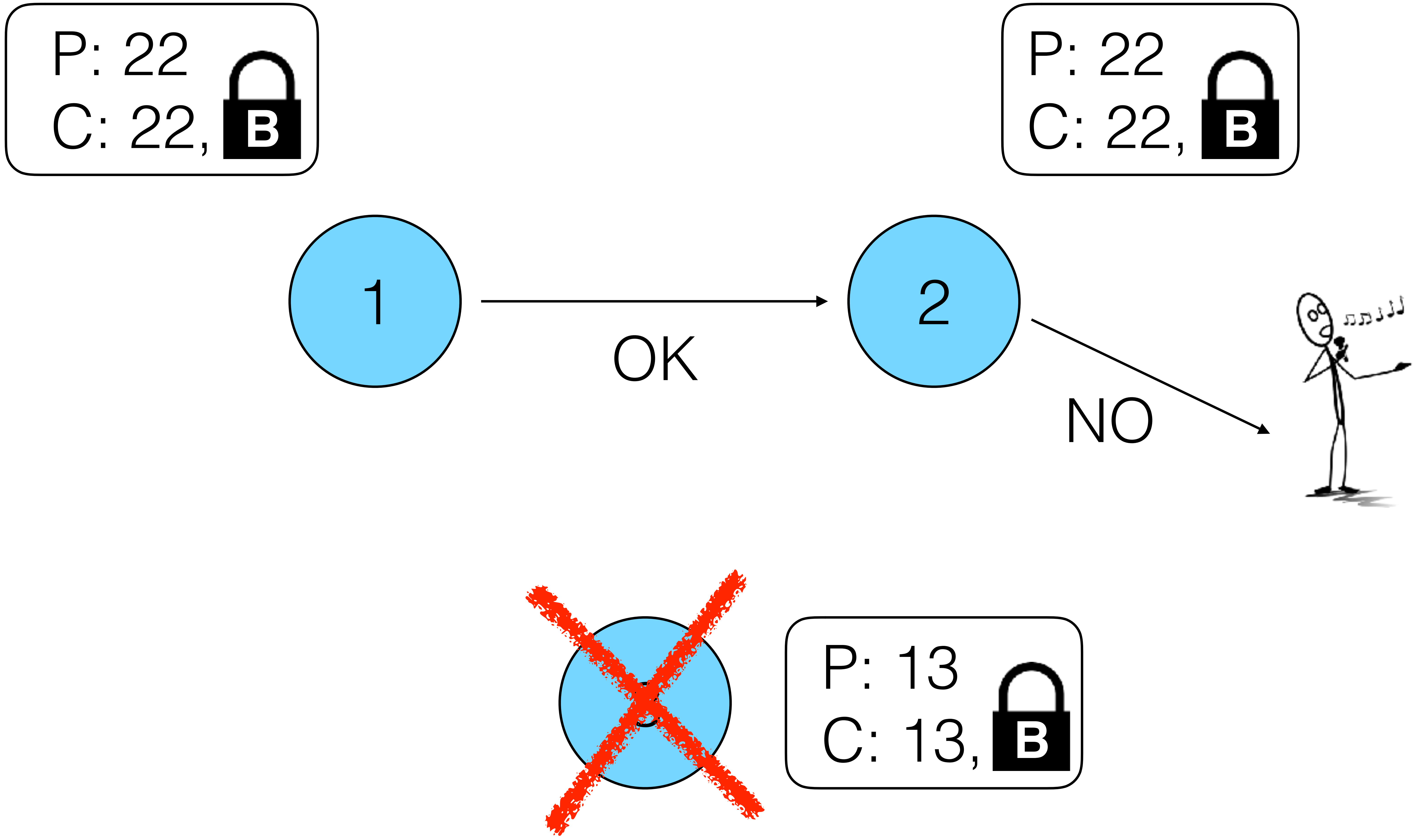
Phase 1



Phase 1

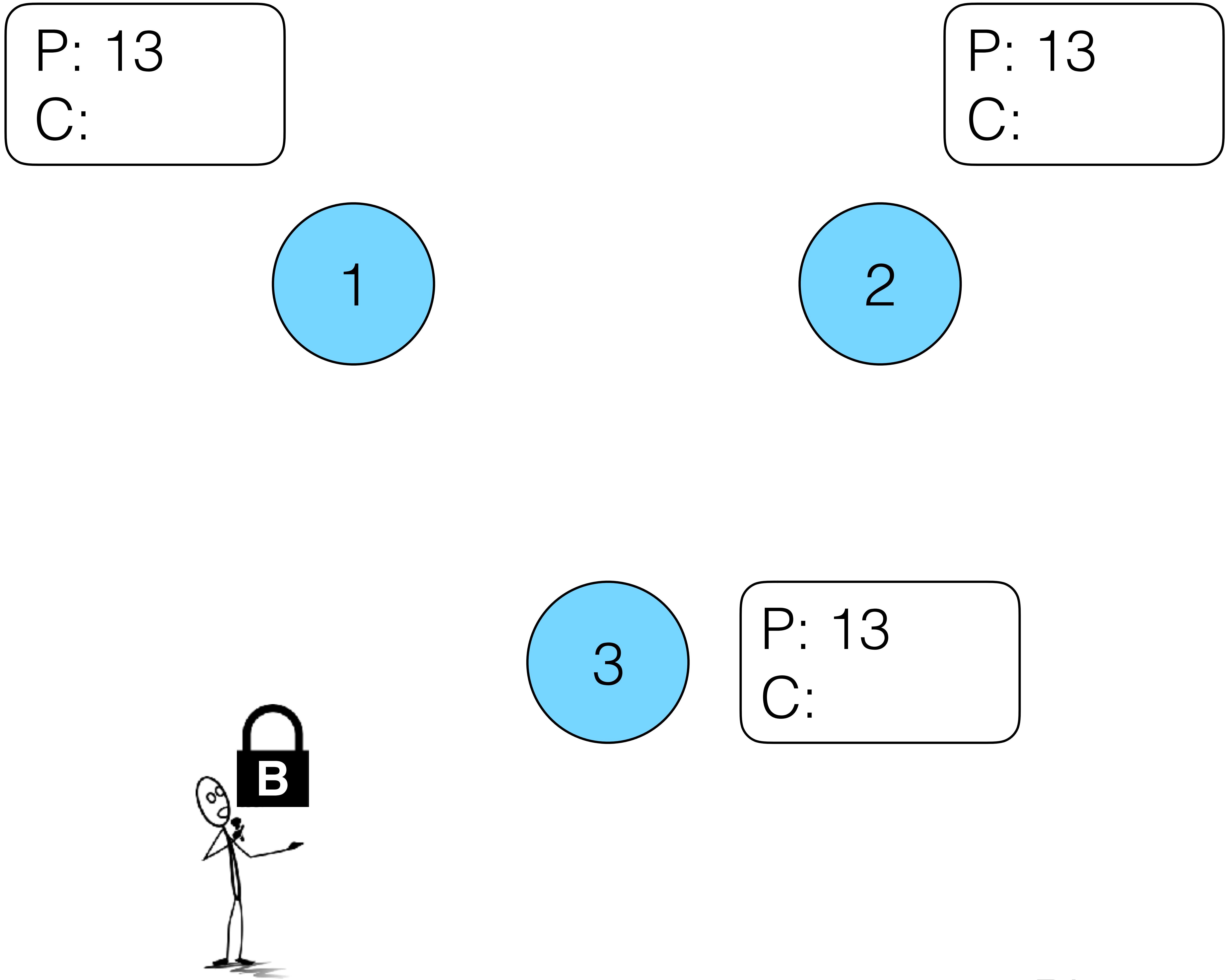


Phase 2

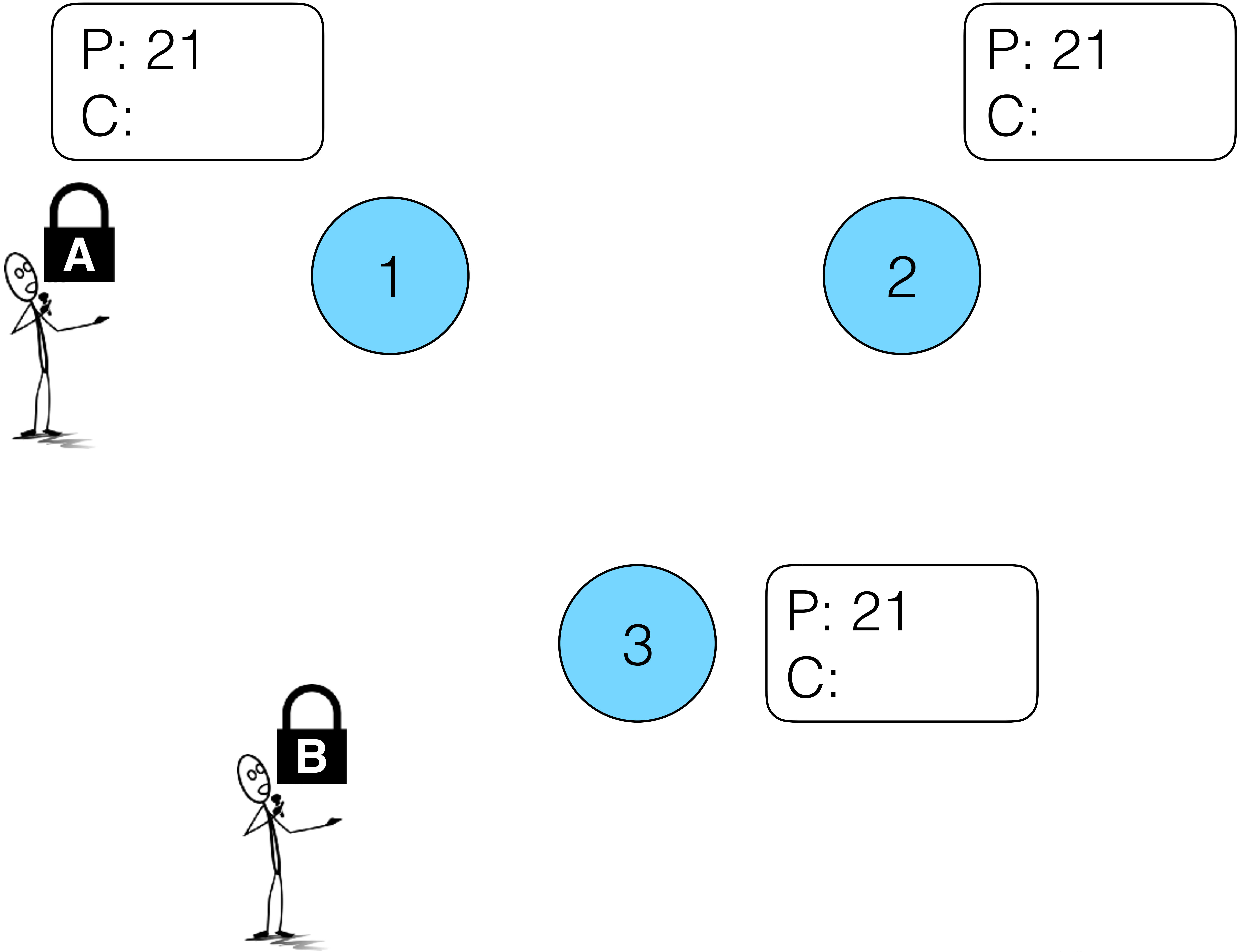


Phase 2

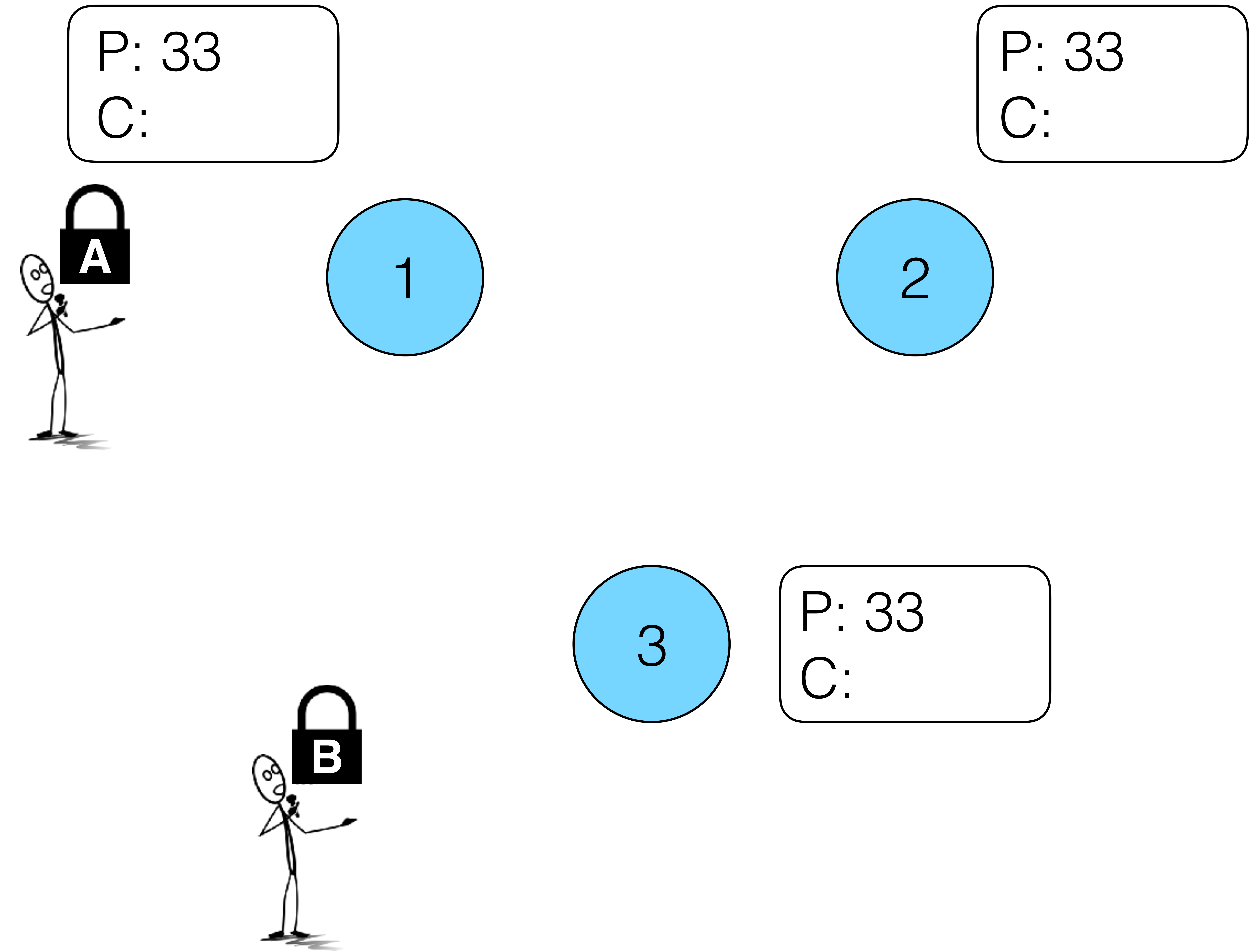
Paxos Example - Conflict



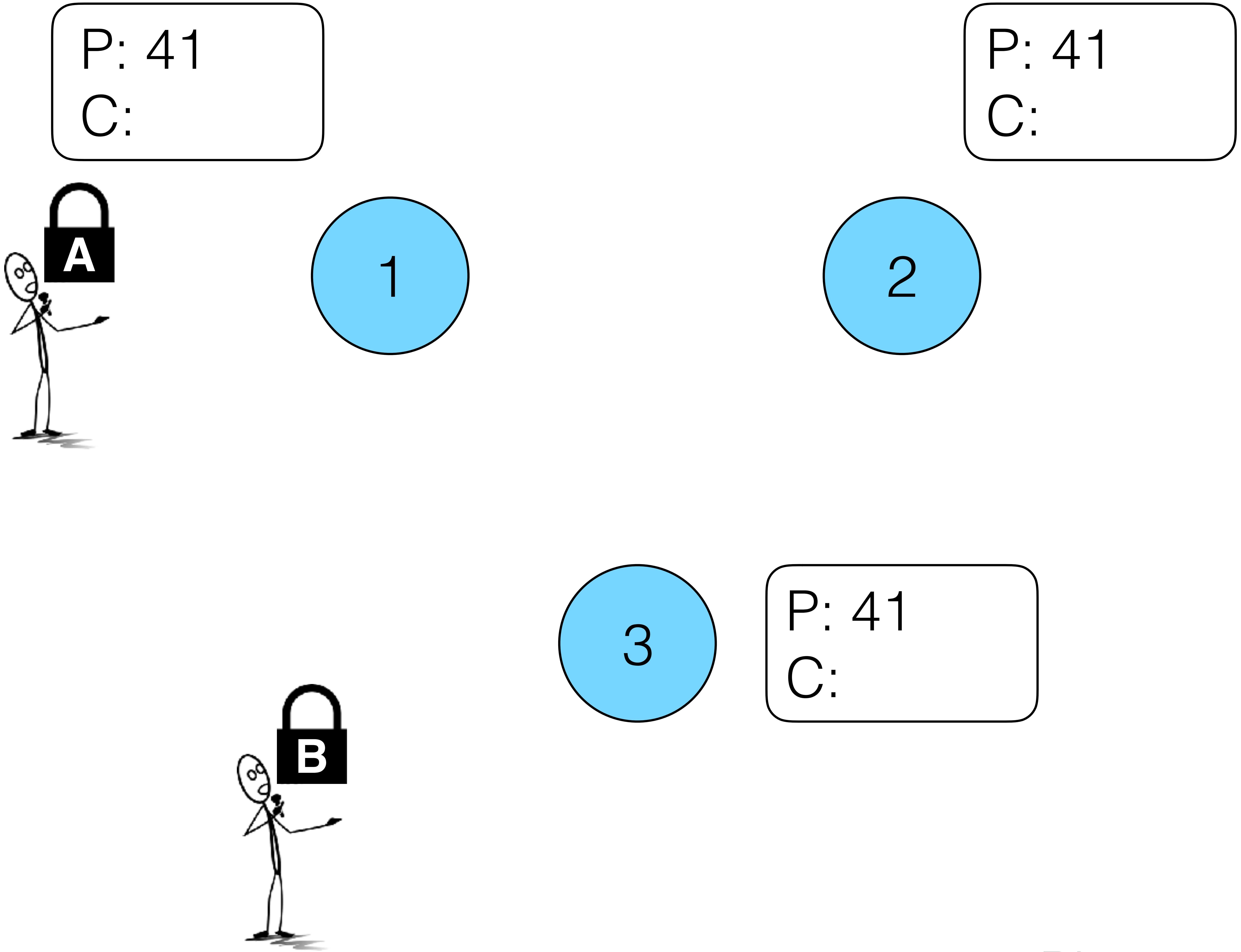
Phase 1 - Bob



Phase 1 - Alice



Phase 1 - Bob



Phase 1 - Alice

What does Paxos give us?

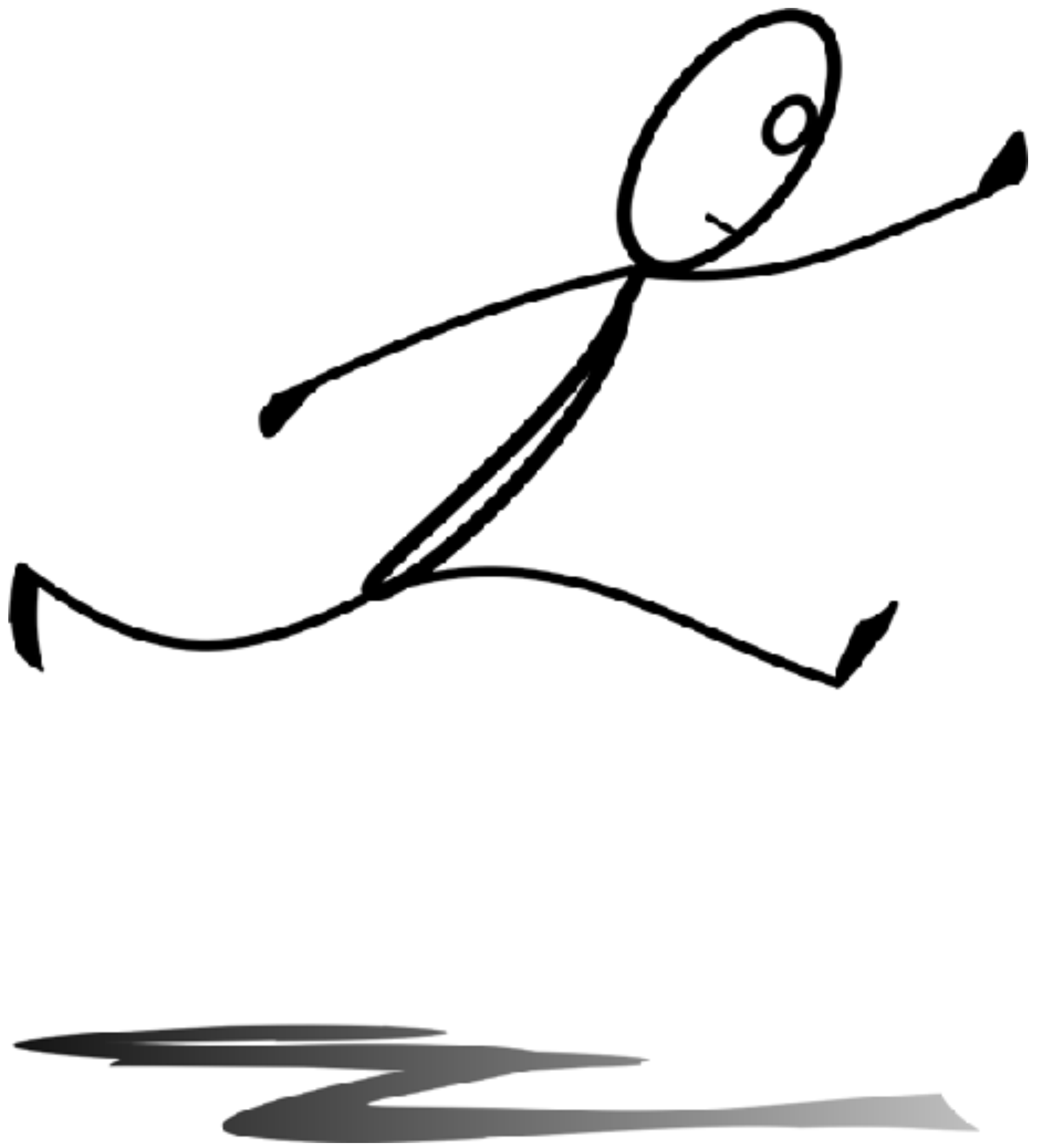
Safety - Decisions are always final

Liveness - Decision will be reached as long as a majority of nodes are up and able to communicate*. Clients must wait two round trips to the majority of nodes, sometimes longer.

*plus our weak synchrony assumptions for the FLP result

Multi-Paxos

Lamport's leader-driven consensus algorithm



<u>Paxos Made Moderately Complex</u>
Robbert van Renesse and Deniz Altinbuken
ACM Computing Surveys
April 2015

Not the original, but highly recommended

Multi-Paxos

Lamport's insight:

Phase 1 is not specific to the request so can be done before the request arrives and can be reused for multiple instances of Paxos.

Implication:

Bob now only has to wait one round trip

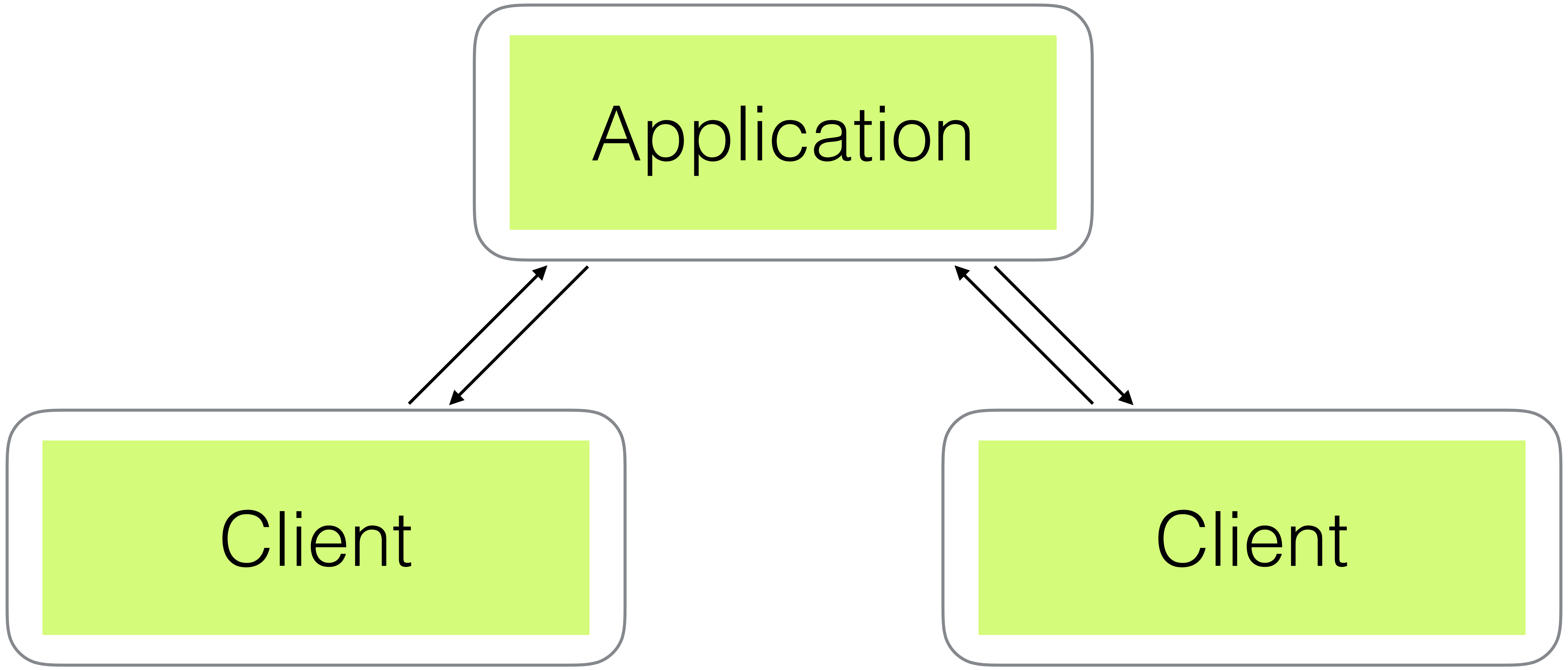
State Machine Replication

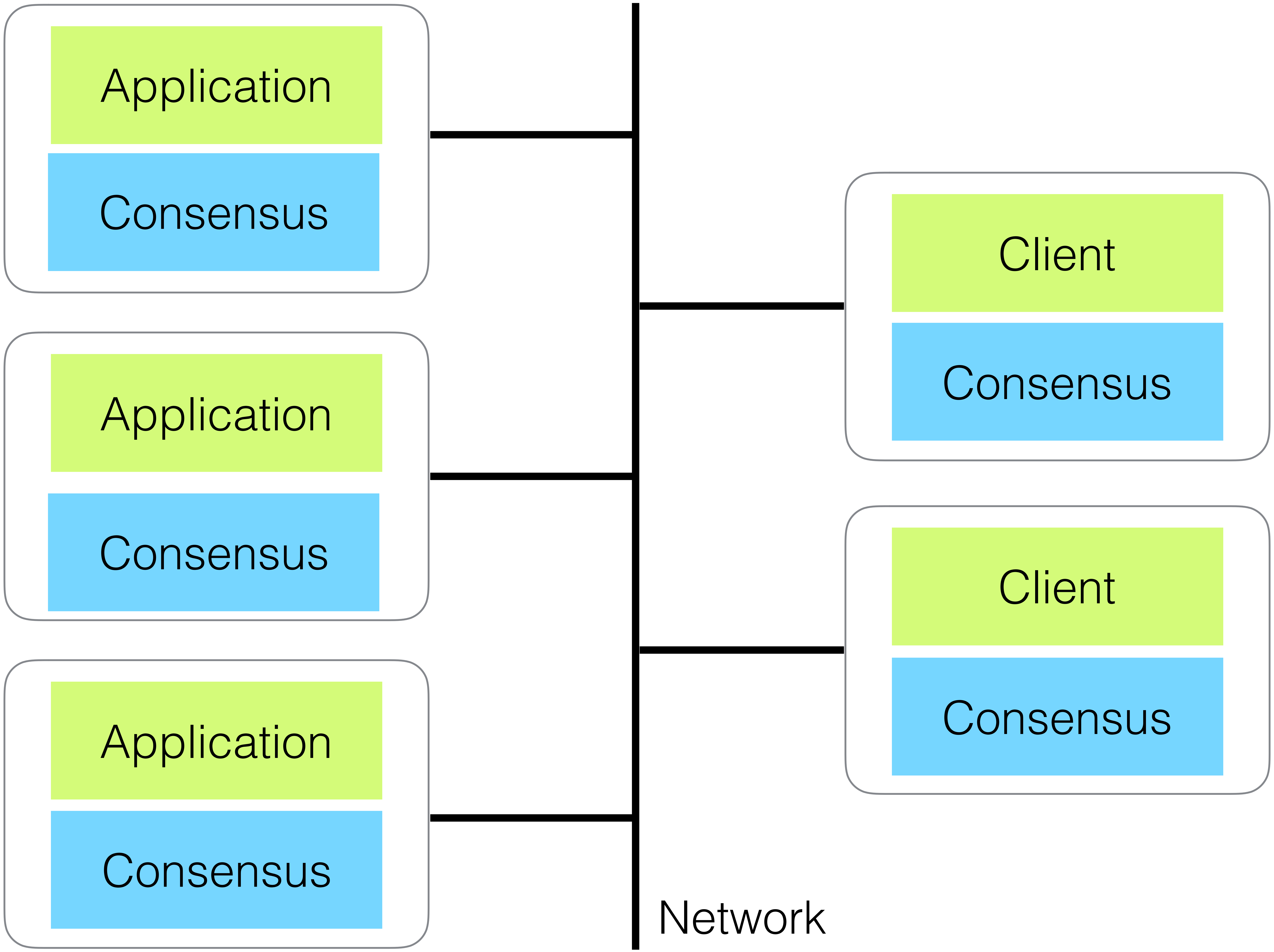
fault-tolerant services using consensus

Implementing Fault-Tolerant Services Using the State Machine Approach: A Tutorial
Fred Schneider
ACM Computing Surveys
1990

State Machine Replication (SMR)

A general technique for making a service, such as a database, fault-tolerant.




Application
Consensus
Application
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Client
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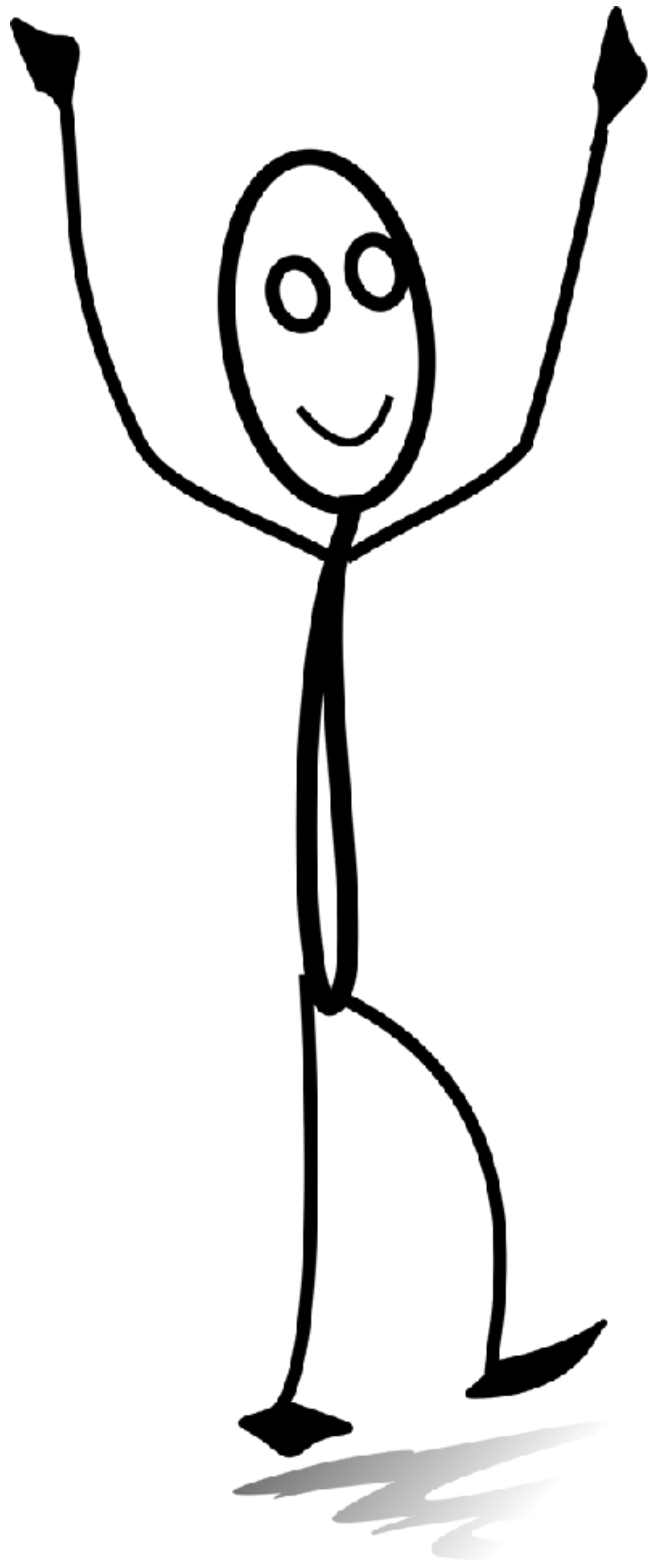
Client
Consensus
Network

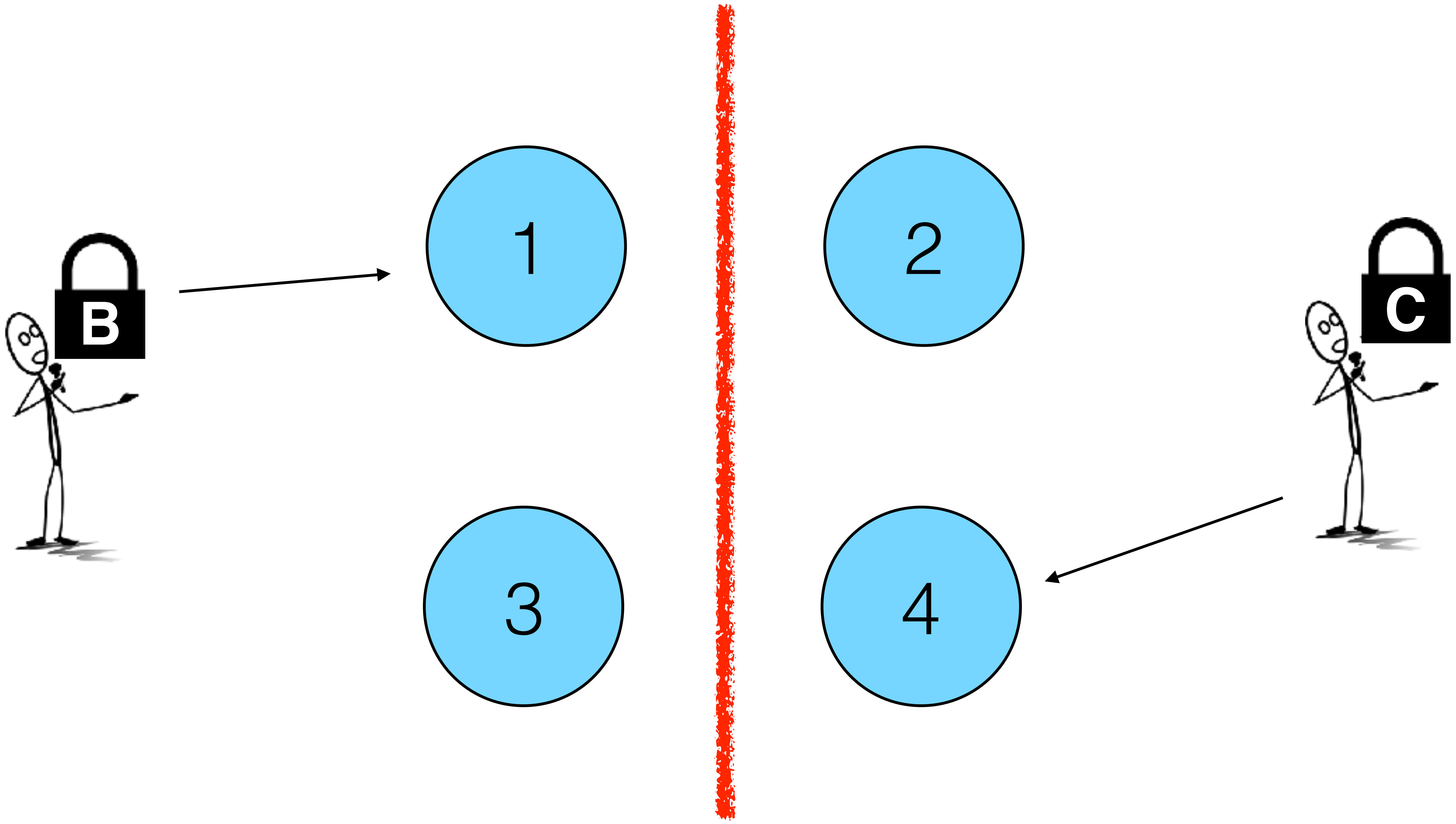


CAP Theorem

You cannot have your cake and eat it

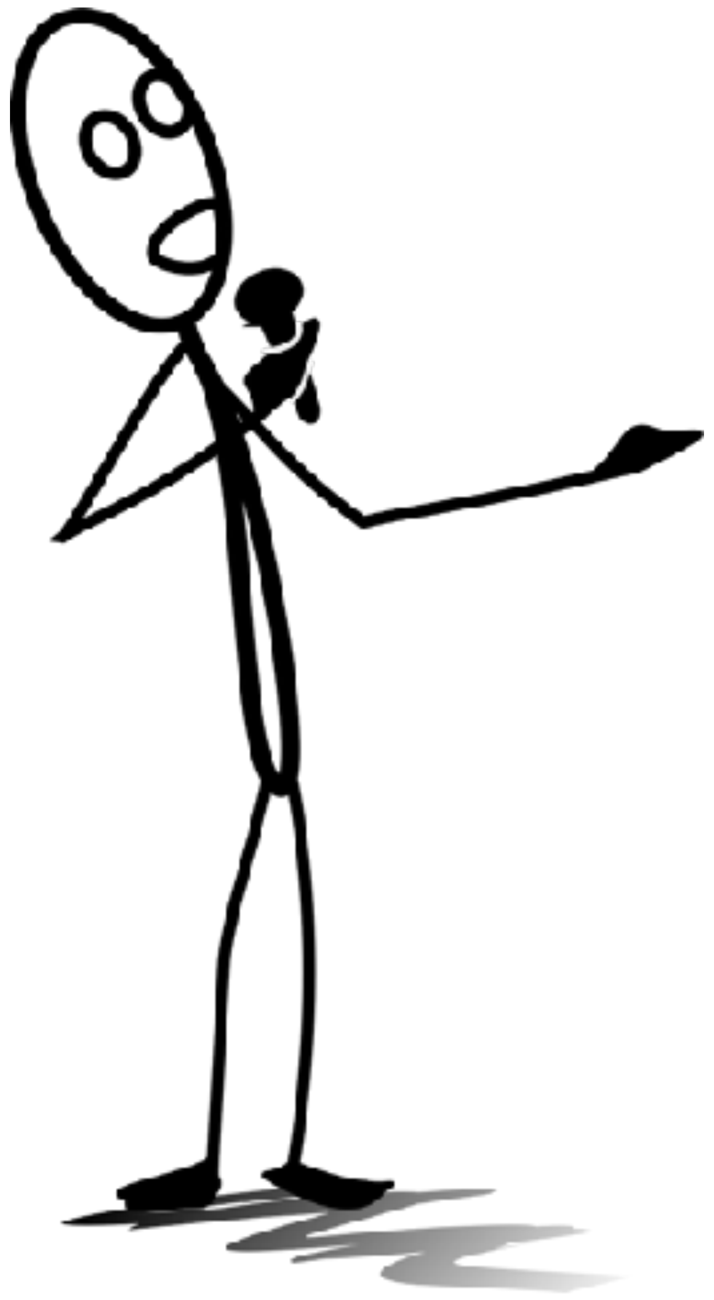
CAP Theorem
Eric Brewer
Presented at Symposium on Principles of Distributed Computing, 2000

Consistency, Availability & Partition Tolerance - Pick Two



Paxos Made Live & Chubby

How google uses Paxos



<u>Paxos Made Live - An Engineering Perspective</u>
Tushar Chandra, Robert Griesemer and Joshua Redstone
ACM Symposium on Principles of Distributed Computing
2007

Isn’t this a solved problem?

“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.”

Paxos Made Live

Paxos made live documents the challenges in constructing Chubby, a distributed coordination service, built using Multi-Paxos and State machine replication.

Challenges

- Handling disk failure and corruption
- Dealing with limited storage capacity
- Effectively handling read-only requests
- Dynamic membership & reconfiguration
- Supporting transactions
- Verifying safety of the implementation

Fast Paxos

Like Multi-Paxos, but faster

<u>Fast Paxos</u>
Leslie Lamport
Microsoft Research Tech Report
MSR-TR-2005-112

Fast Paxos

Paxos: Any node can commit a value in 2 RTTs

Multi-Paxos: The leader node can commit a value in 1 RTT

But, what about any node committing a value in 1 RTT?

Fast Paxos

We can bypass the leader node for many operations, so any node can commit a value in 1 RTT.

However, we must increase the size of the quorum.

Zookeeper

The open source solution

Zookeeper: wait-free coordination for internet-scale systems
Hunt et al
USENIX ATC 2010

Code: zookeeper.apache.org

Zookeeper

Consensus for the masses.

It utilizes and extends Multi-Paxos for strong consistency.

Unlike “Paxos made live”, this is clearly discussed and openly available.

Egalitarian Paxos

Don’t restrict yourself unnecessarily

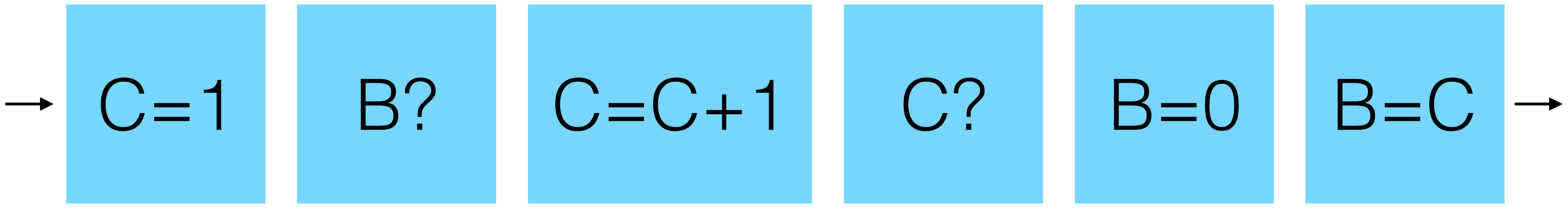
There Is More Consensus in Egalitarian Parliaments
Iulian Moraru, David G. Andersen, Michael Kaminsky
SOSP 2013

also see Generalized Consensus and Paxos

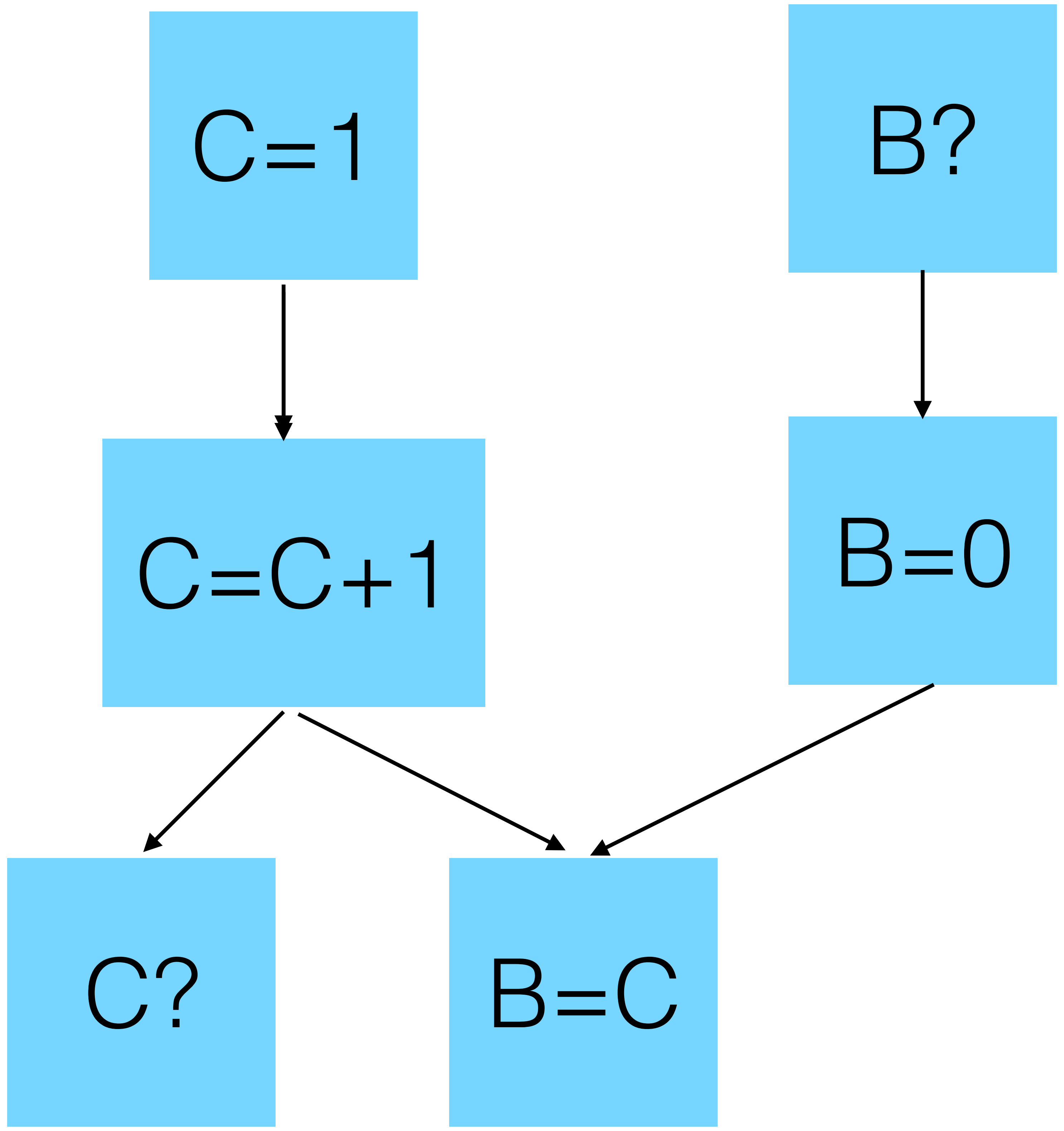
Egalitarian Paxos

The basis of SMR is that every replica of an application receives the same commands in the same order.

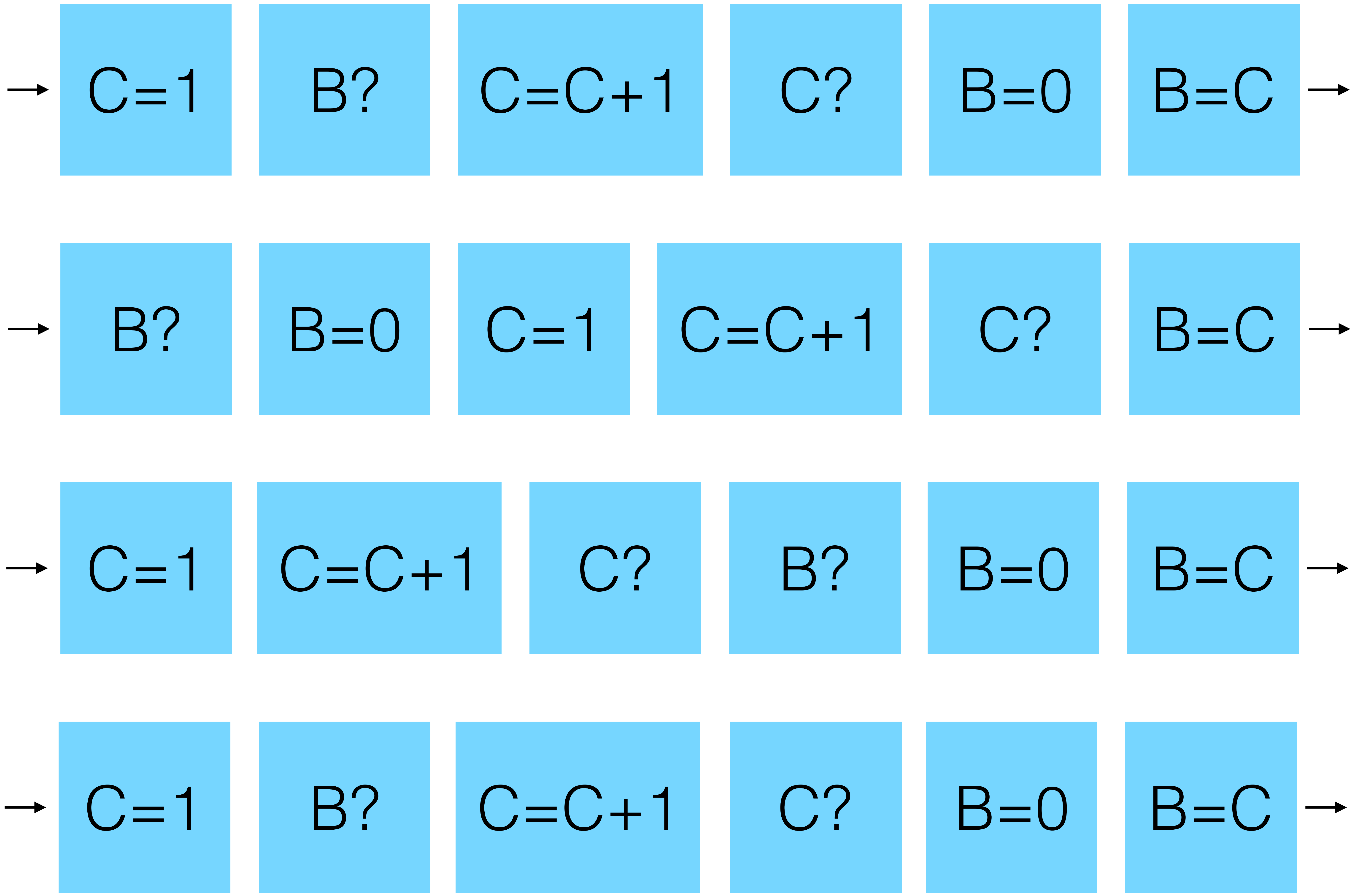
However, sometimes the ordering can be relaxed…



Total Ordering



Partial Ordering



Many possible orderings

Egalitarian Paxos

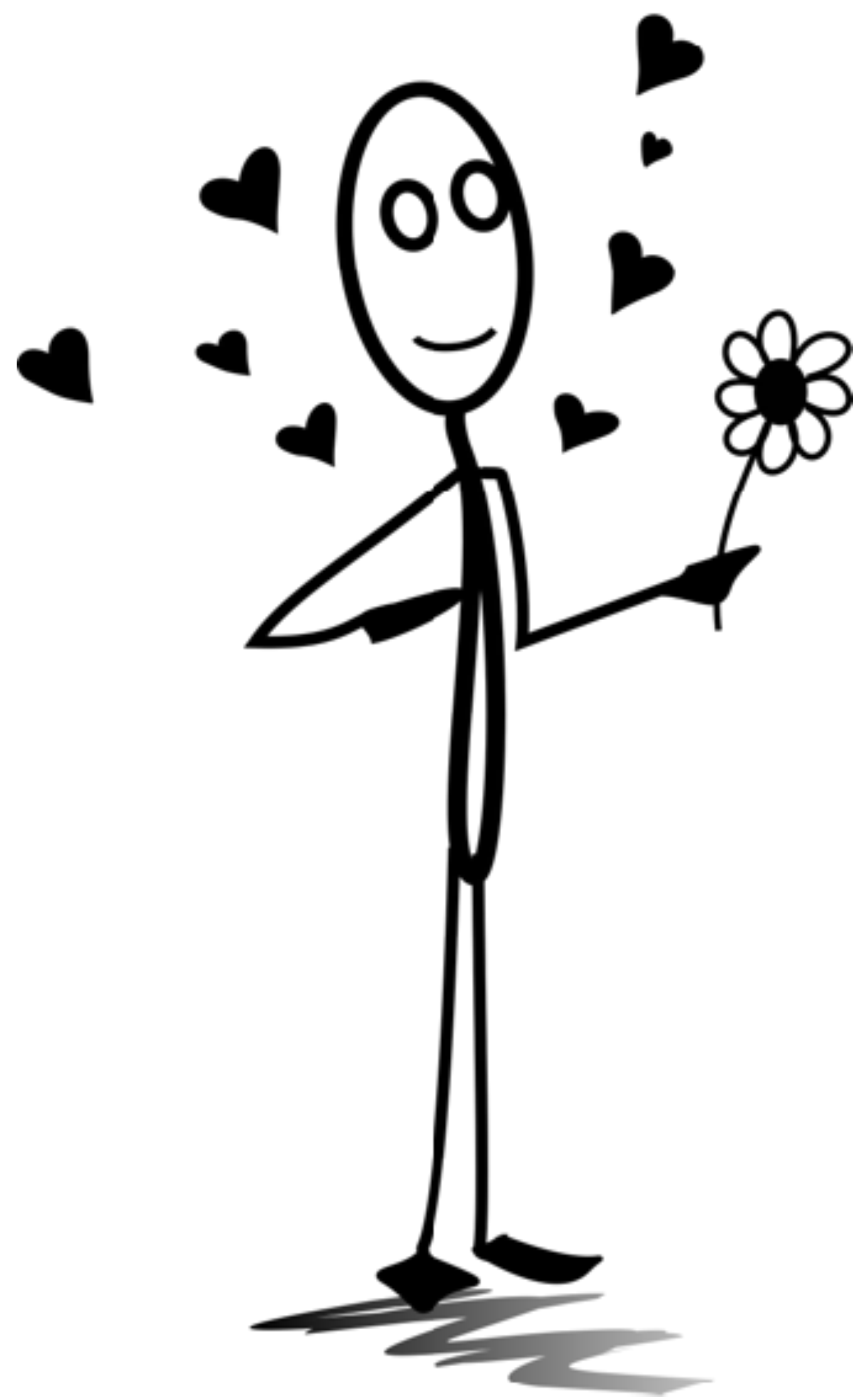
Allow requests to be out-of-order if they are commutative.

Conflict becomes much less common.

Works well in combination with Fast Paxos.

Raft Consensus

Paxos made understandable



In Search of an Understandable Consensus Algorithm
Diego Ongaro and John Ousterhout
USENIX ATC
2014

Raft

Raft has taken the wider community by storm. Largely, due to its understandable description.

It’s another variant of SMR with Multi-Paxos.

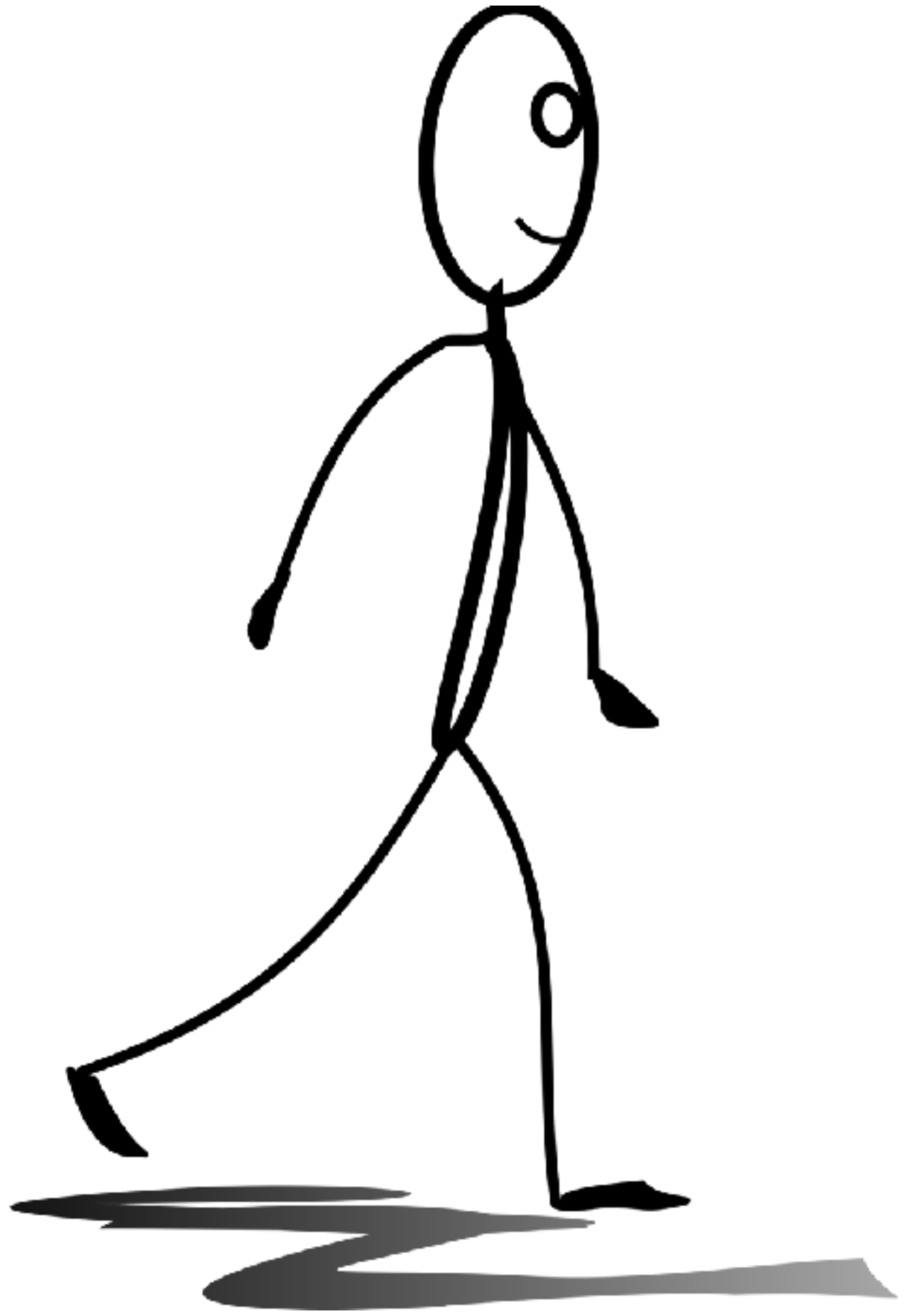
Key features:

- Really strong leadership - all other nodes are passive

- Various optimizations - e.g. dynamic membership and log compaction

Flexible Paxos

Paxos made scalable



Flexible Paxos: Quorum intersection revisited
Heidi Howard, Dahlia Malkhi, Alexander Spiegelman
ArXiv:1608.06696

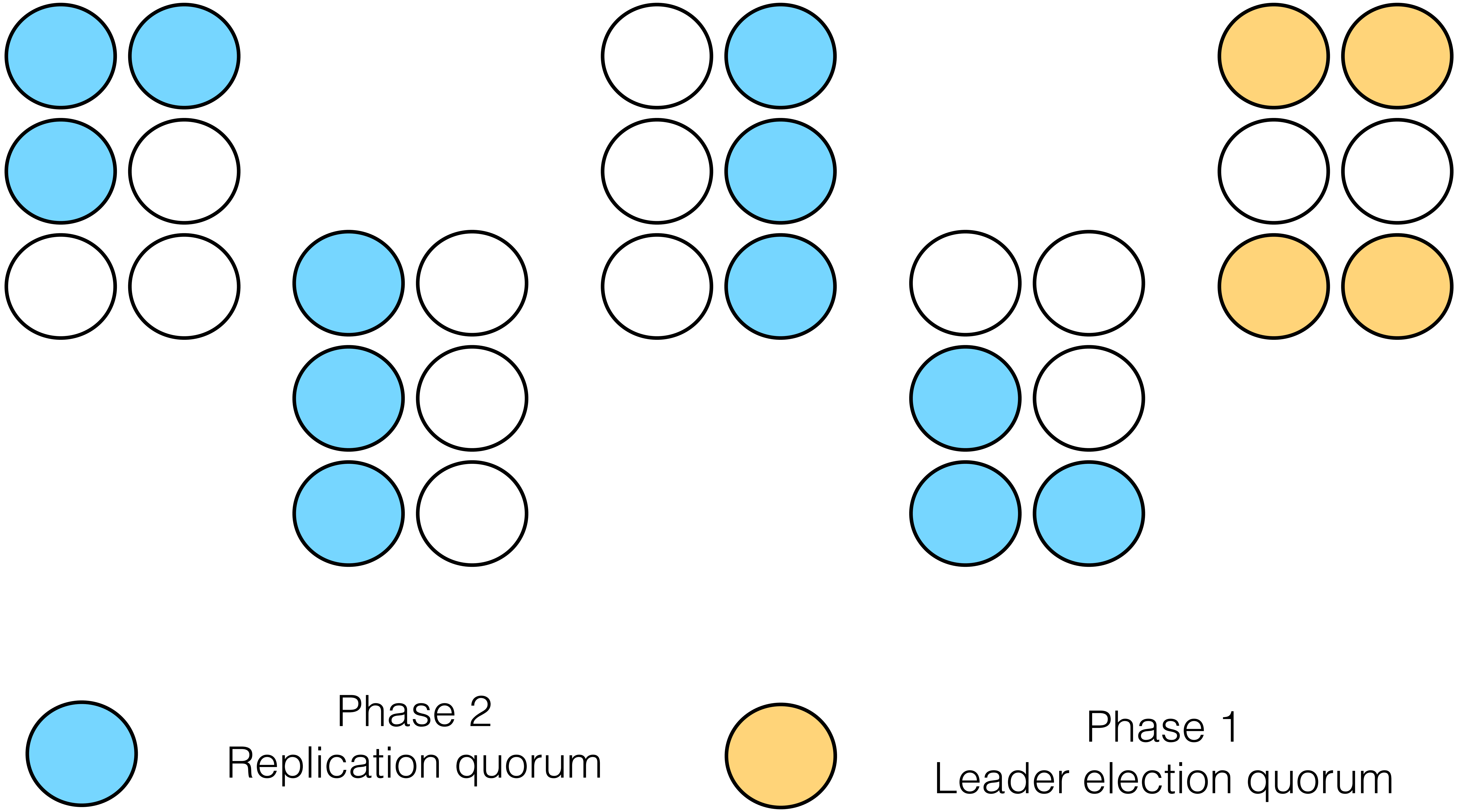
Majorities are not needed

Usually, we use require majorities to agree so we can guarantee that all quorums (groups) intersect.

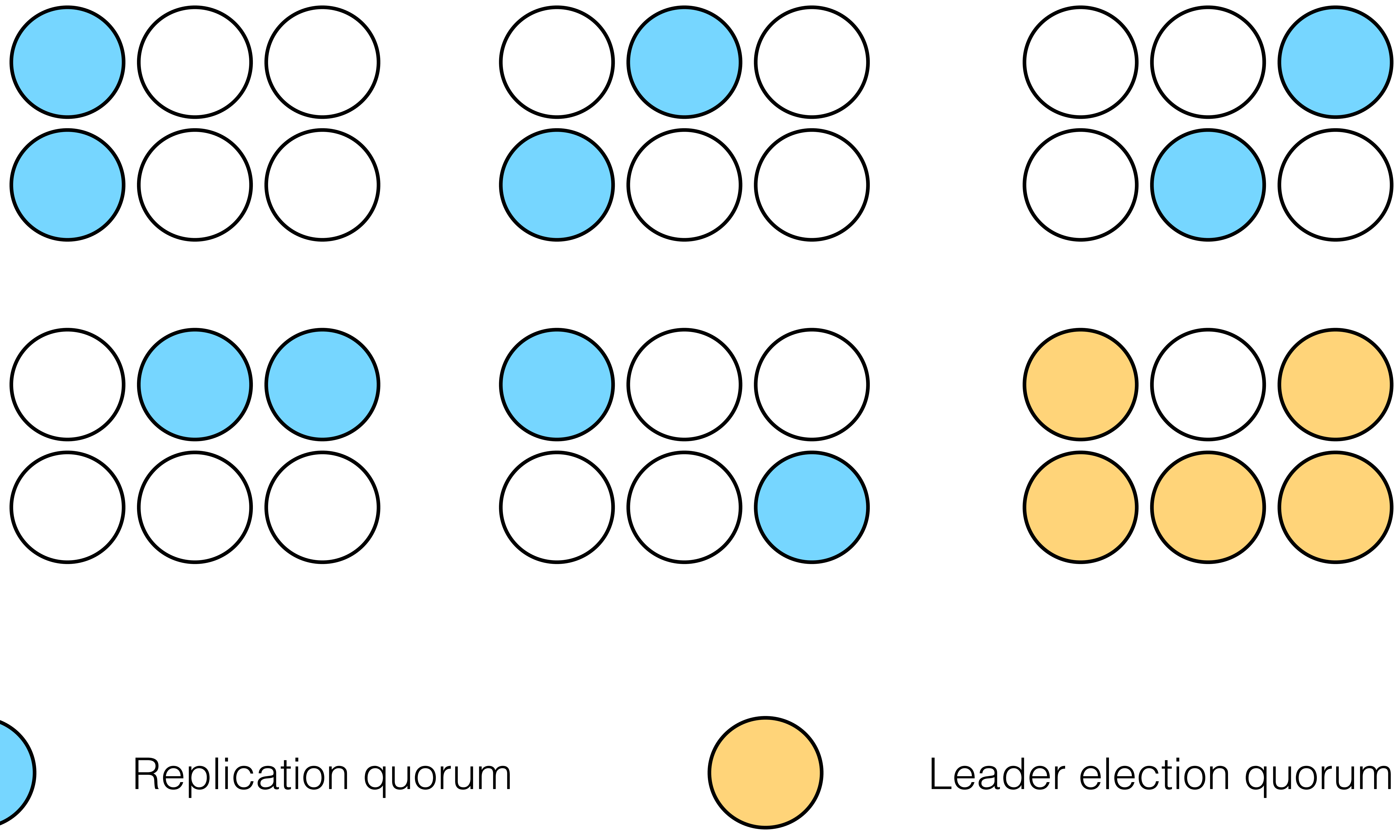
This work shows that not all quorums need to intersect. Only the ones used for phase 2 (replication) and phase 1 (leader election).

This applies to all algorithms in this class: Paxos, Viewstamped Replication, Zookeeper, Raft etc..

Example: Non-strict majorities



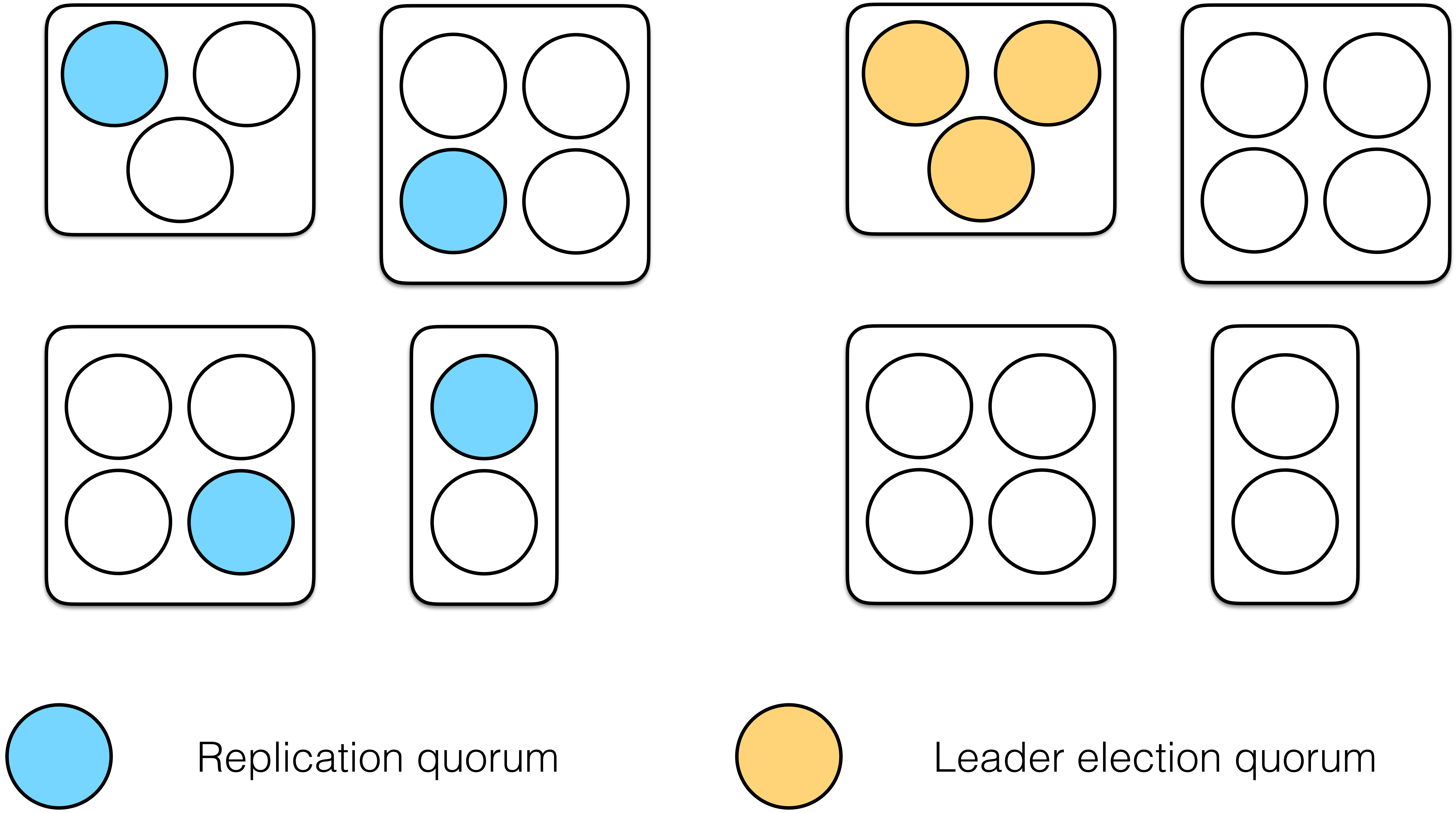
Example: Counting quorums



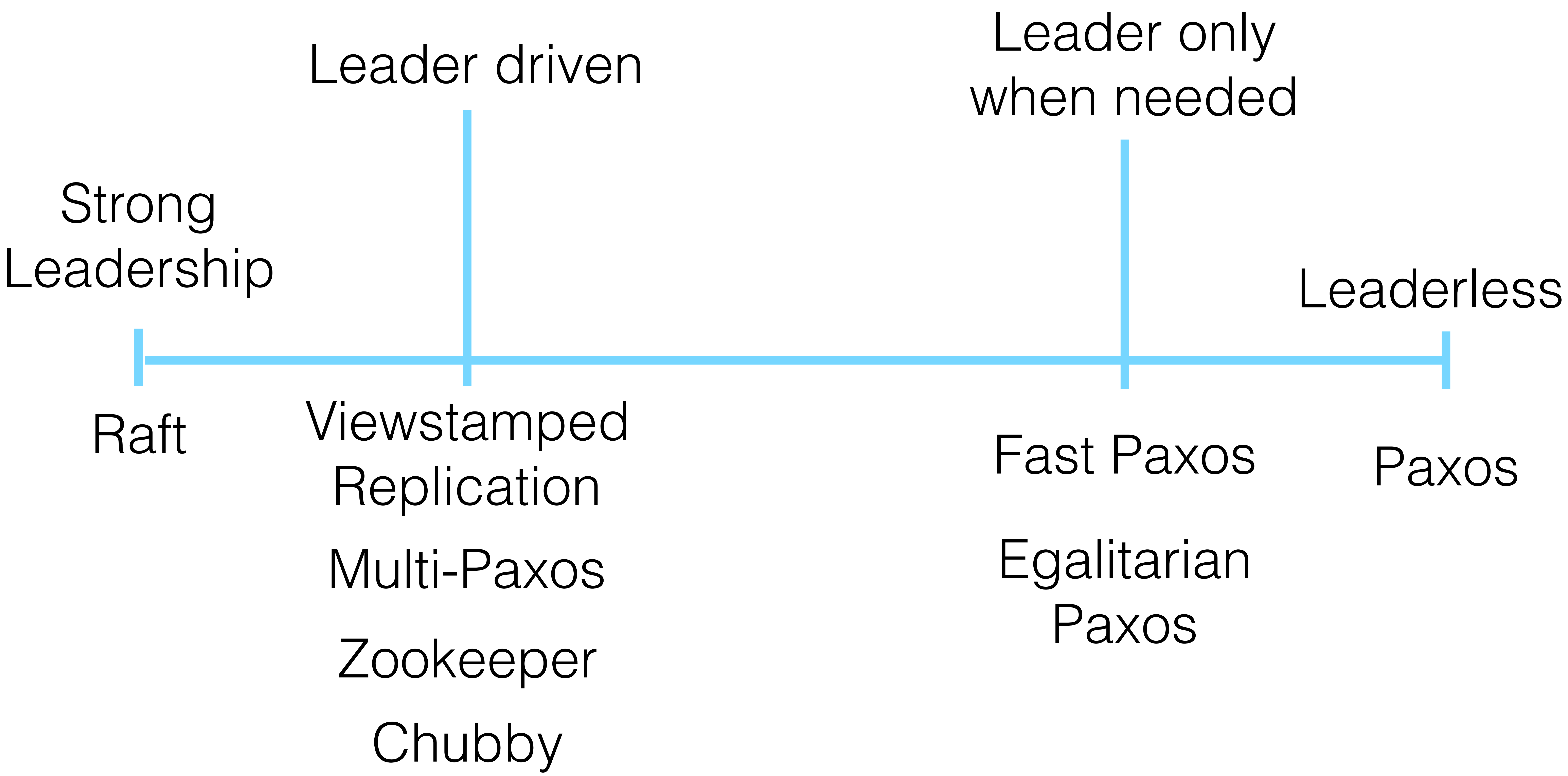
Replication quorum

Leader election quorum

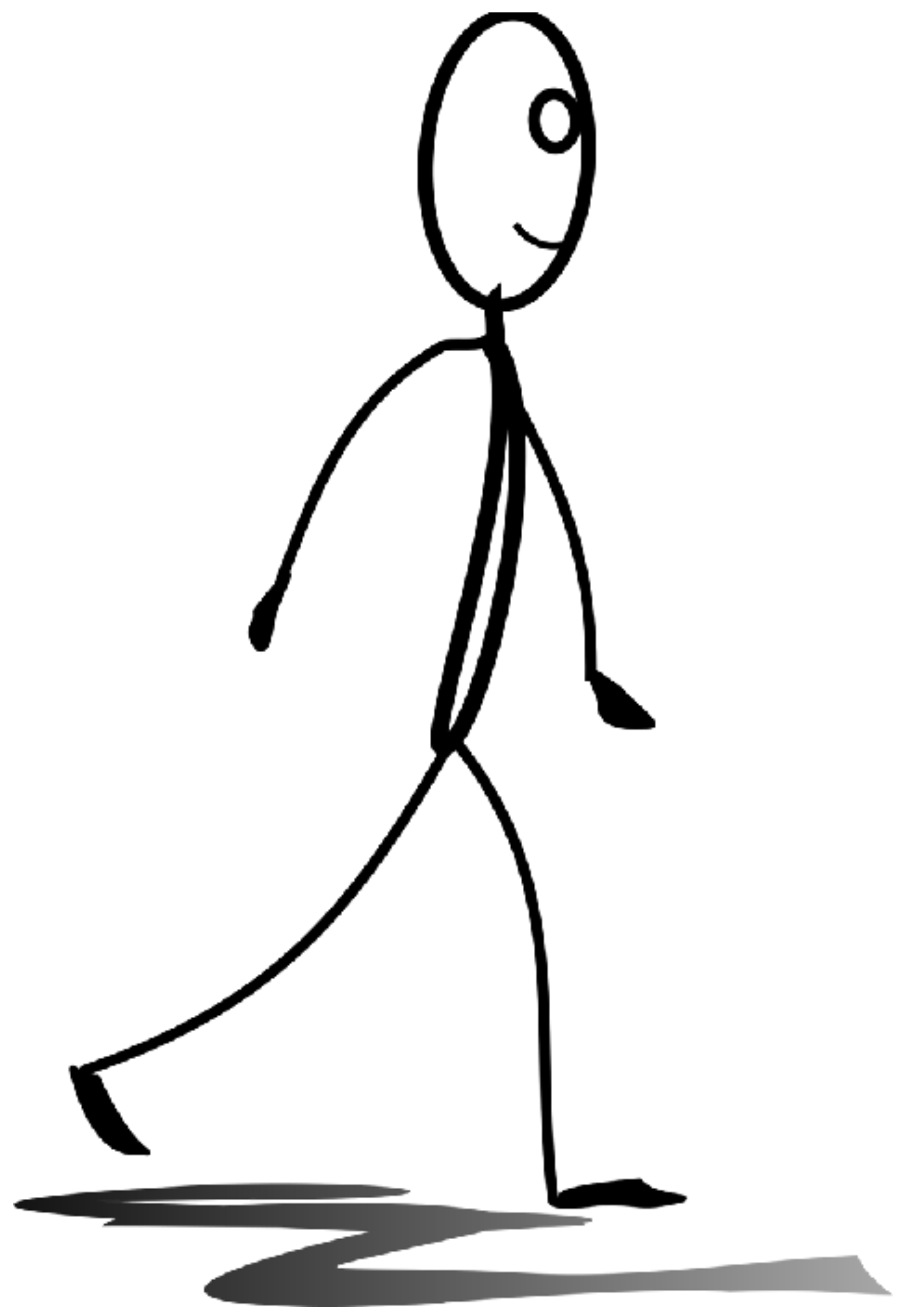
Example: Group quorums



How strong is the leadership?



Who is the winner?



Depends on the award:

- Best for minimum latency: Viewstamped Replication
- Most widely used open source project: Zookeeper
- Easiest to understand: Raft
- Best for WANs: Egalitarian Paxos

Future

1. More scalable consensus algorithms utilizing Flexible Paxos.

2. A clearer understanding of consensus and better explained algorithms.

3. Consensus in challenging settings such as geo-replicated systems.

Summary

Do not be discouraged by impossibility results and dense abstract academic papers.

Don’t give up on consistency. Consensus is achievable, even performant and scalable.

Find the right algorithm and quorum system for your specific domain. There is no single silver bullet.

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