Distributed Consensus: Making Impossible Possible

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defined to be the largest vote v in $Votes(\mathcal{B})$ cast by p with $v_{bal} < b$, or to be $null_p$ if there was no such vote. Since $null_p$ is smaller than any real vote cast by p, this means that $MaxVote(b, p, \mathcal{B})$ is the largest vote in the set

$$\{v \in Votes(\mathcal{B}) : (v_{pst} = p) \wedge (v_{bal} < b)\} \cup \{null_p\}$$

For any nonempty set Q of priests, $MaxVote(b, Q, \mathcal{B})$ was defined to equal the maximum of all votes $MaxVote(b, p, \mathcal{B})$ with p in Q.

Conditions $B1(\mathcal{B})$–$B3(\mathcal{B})$ are stated formally as follows.[8]

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$B1(\mathcal{B})$–$B3$
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Lemma

for any B

Proof of
For any b
decree dif

To prove t
The Paxo
$B_{qrm} \subseteq B$

1. Choose
PROOF
2. $C_{bal} >$
PROOF
3. $B_{vot} \cap$
PROOF

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[9] Paxon mat
were not a
paragraph-s

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

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

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

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

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

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

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

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

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

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

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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MIT, Cambridge, MA 02139
lynch@tds.lcs.mit.edu

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

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What is Consensus?

“The process by which we reach agreement over system state between unreliable machines connected by asynchronous networks”

Why?

- Distributed locking
- Banking
- Safety critical systems
- Distributed scheduling and coordination

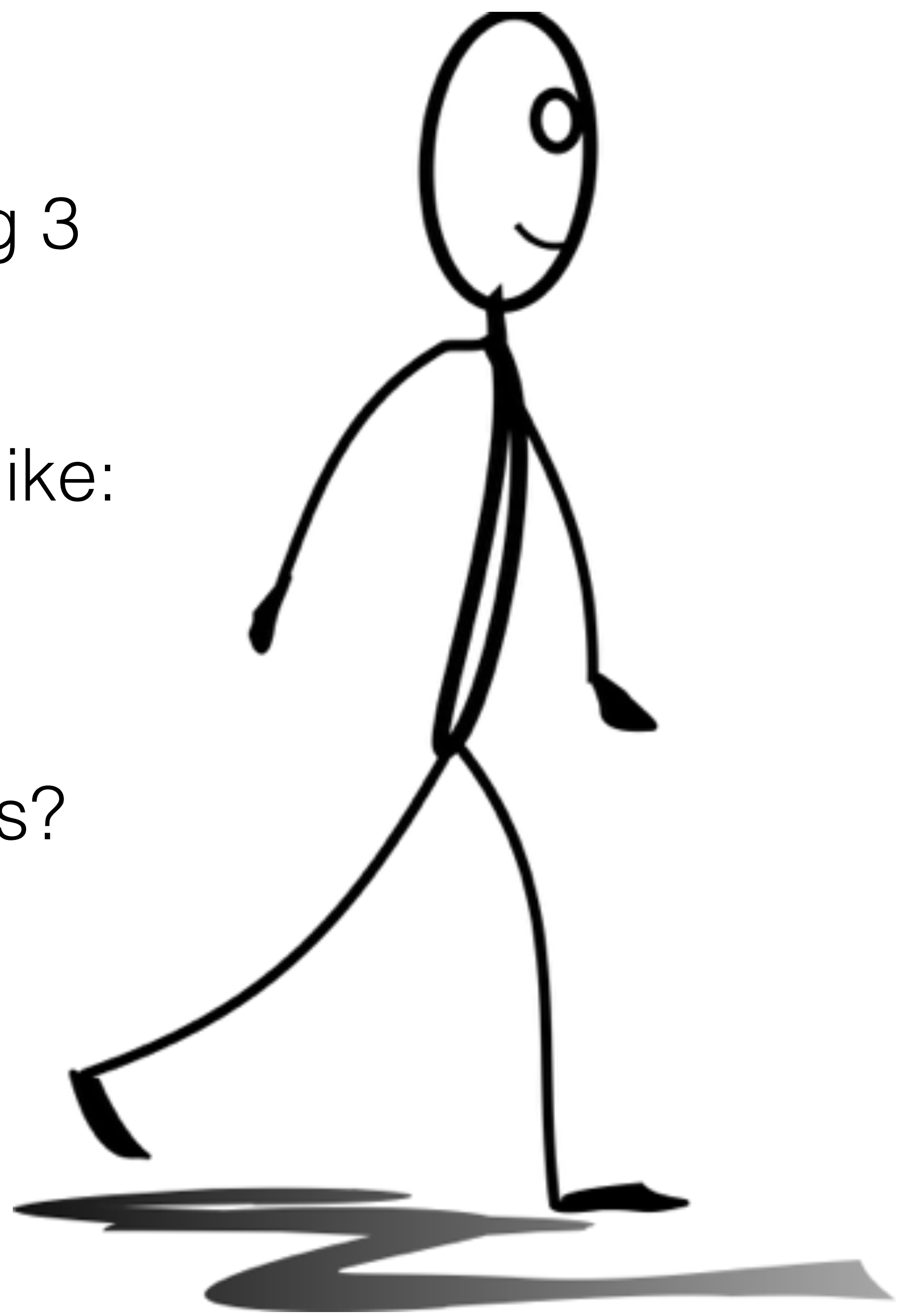
Anything which ***requires*** guaranteed agreement

A walk through history

We are going to take a journey through the developments in distributed consensus, spanning 3 decades.

We are going to search for answers to questions like:

- how do we reach consensus?
- what is the best method for reaching consensus?
- can we even reach consensus?
- what's next in the field?



FLP Result

off to 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

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

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

Solution to FLP

In practice:

We accept that sometimes the system will not be available. We mitigate this using timers and backoffs.

In theory:

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

Paxos

Lamport's original consensus algorithm

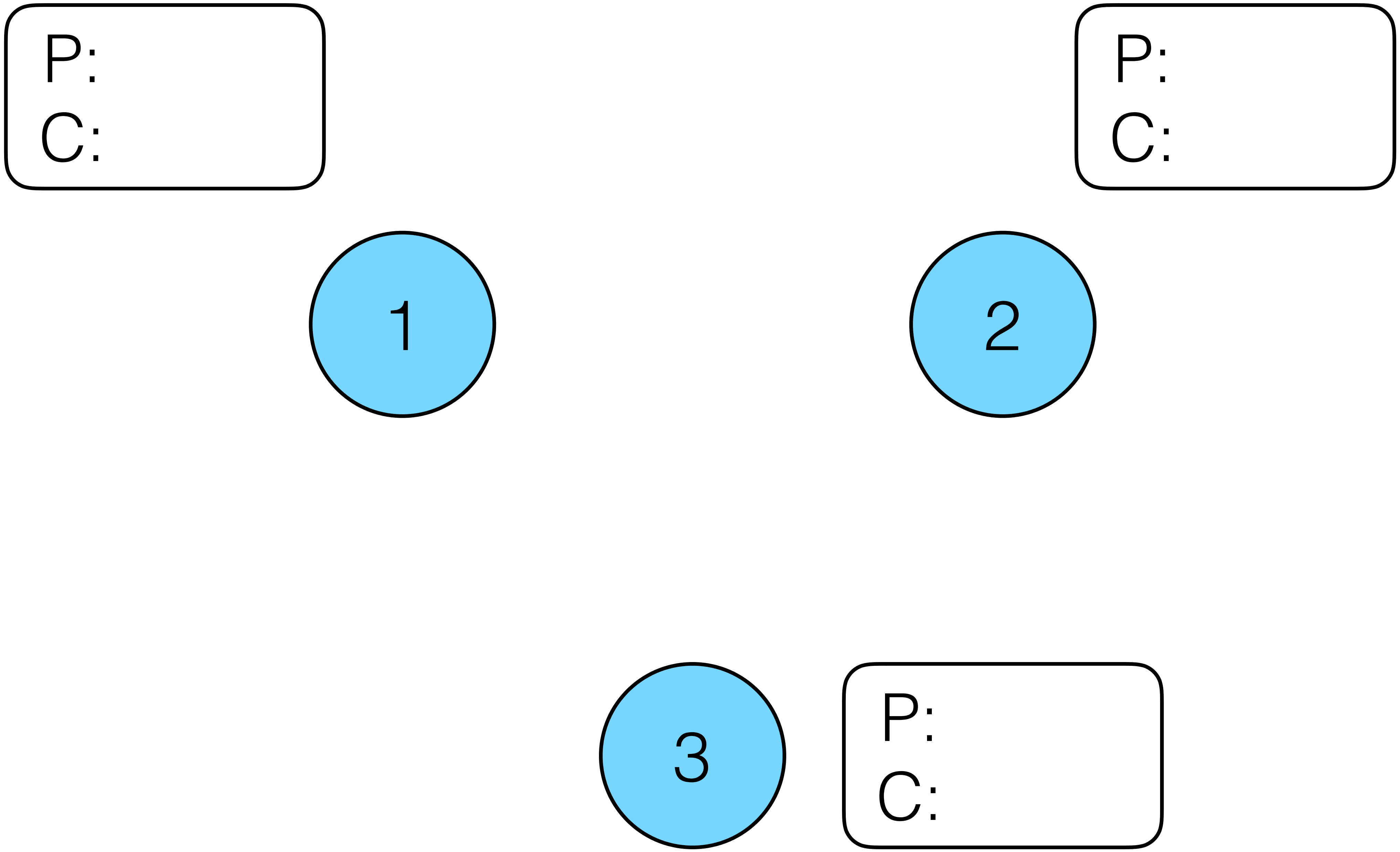
The Part-Time Parliament
Leslie Lamport
ACM Transactions on Computer Systems
May 1998

Paxos

The original consensus algorithm for reaching agreement on a single value.

- two phase process: promise and commit
- majority agreement
- monotonically increasing numbers

Paxos Example - Failure Free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P:
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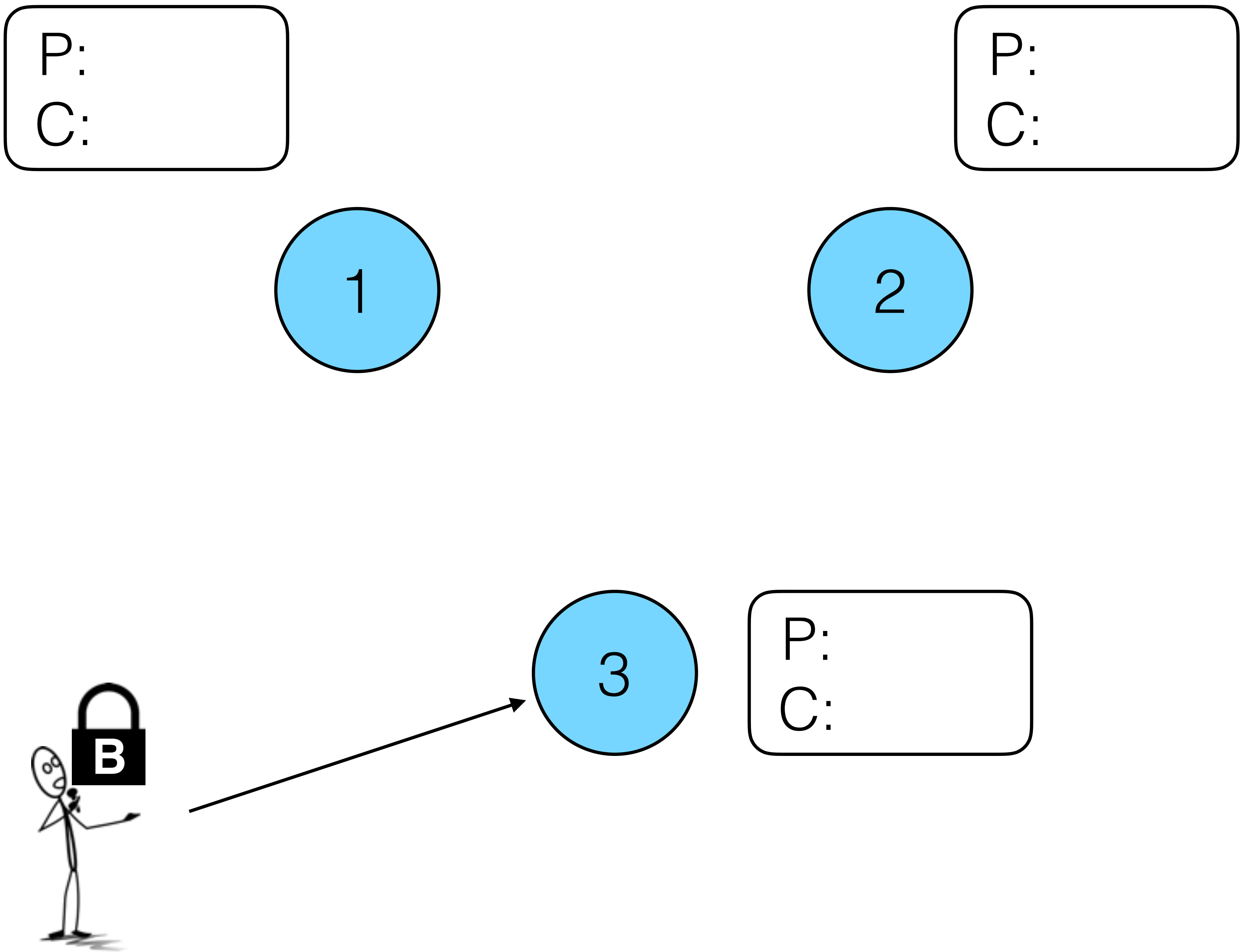
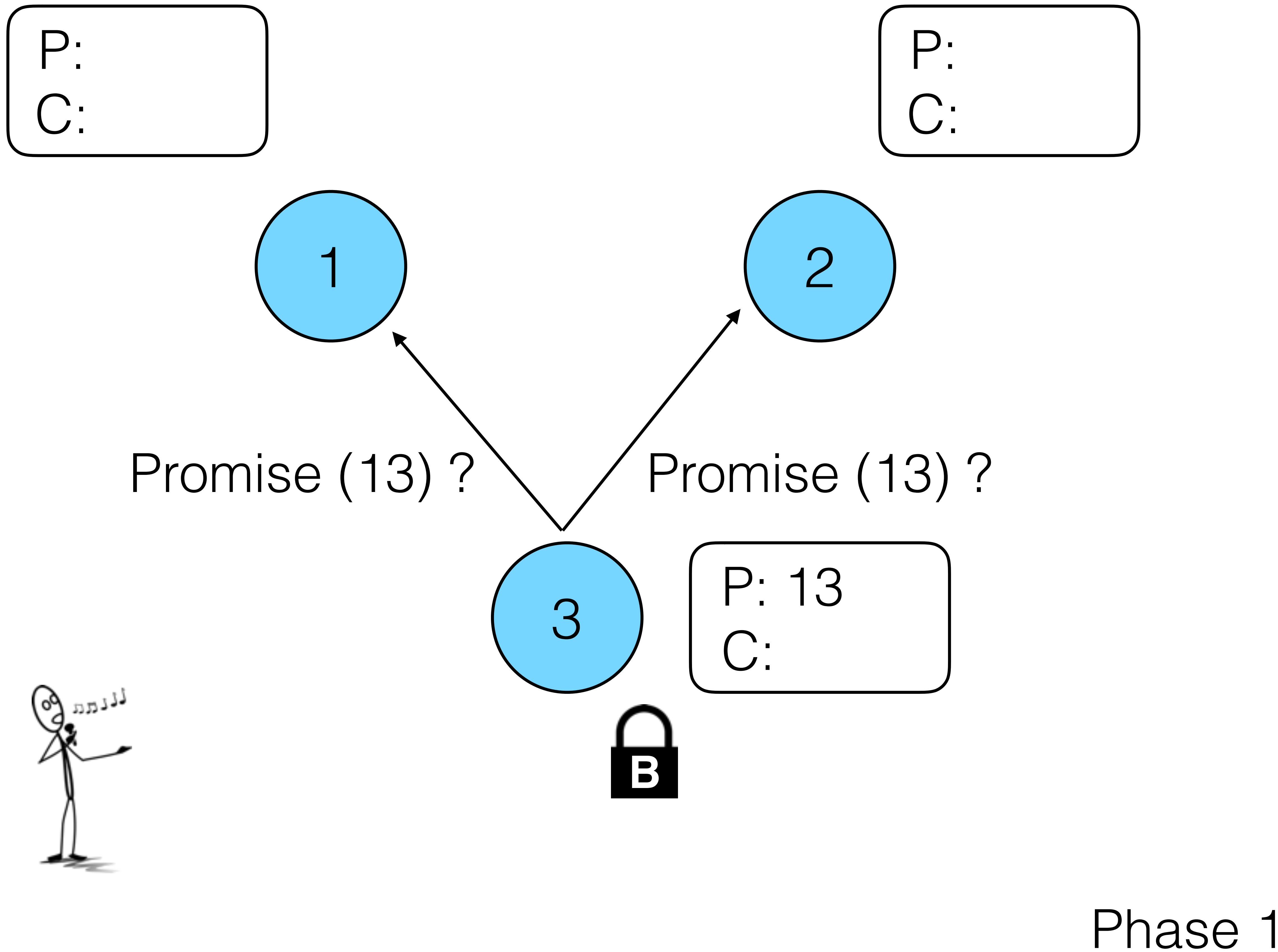


Incoming request from Bob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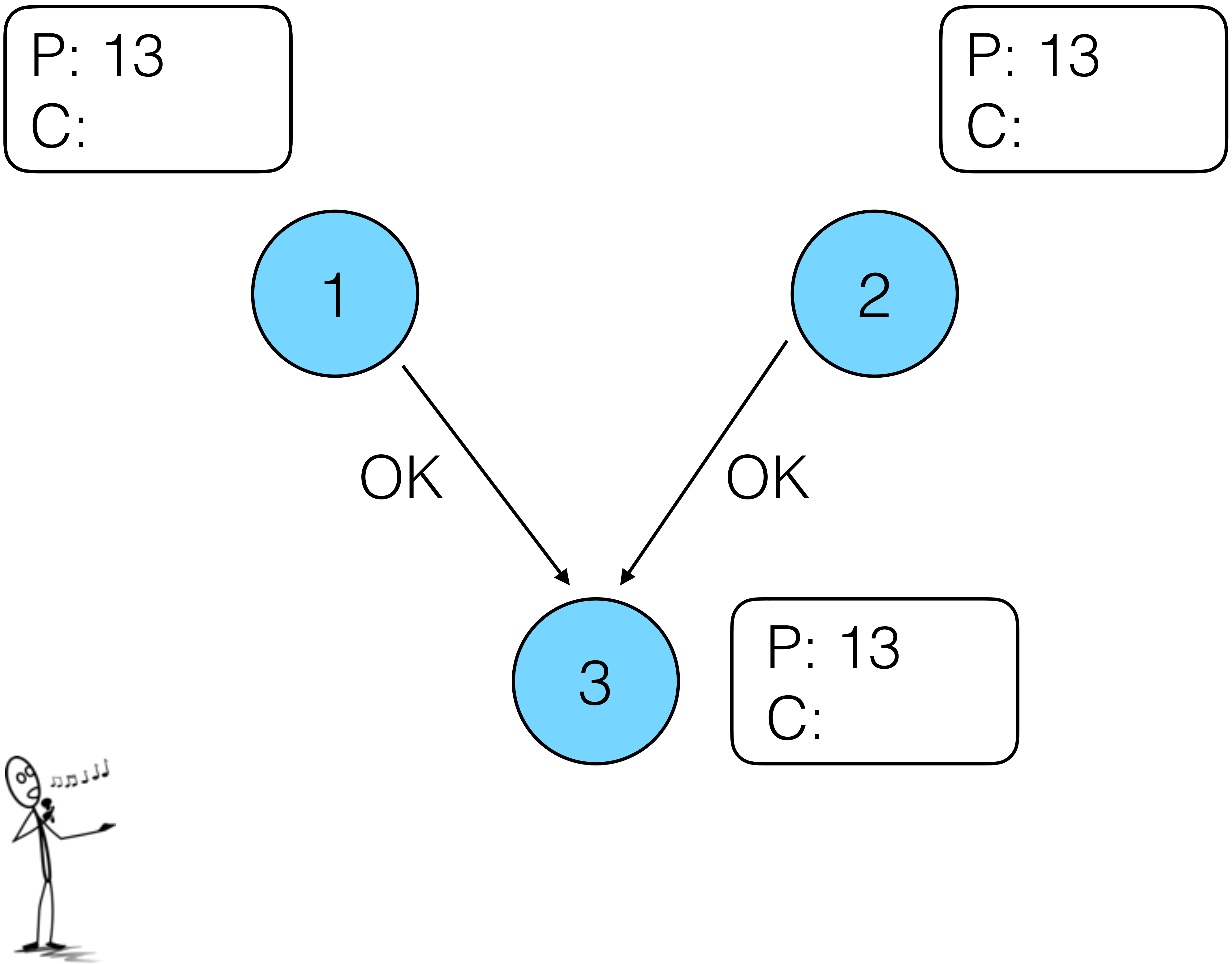
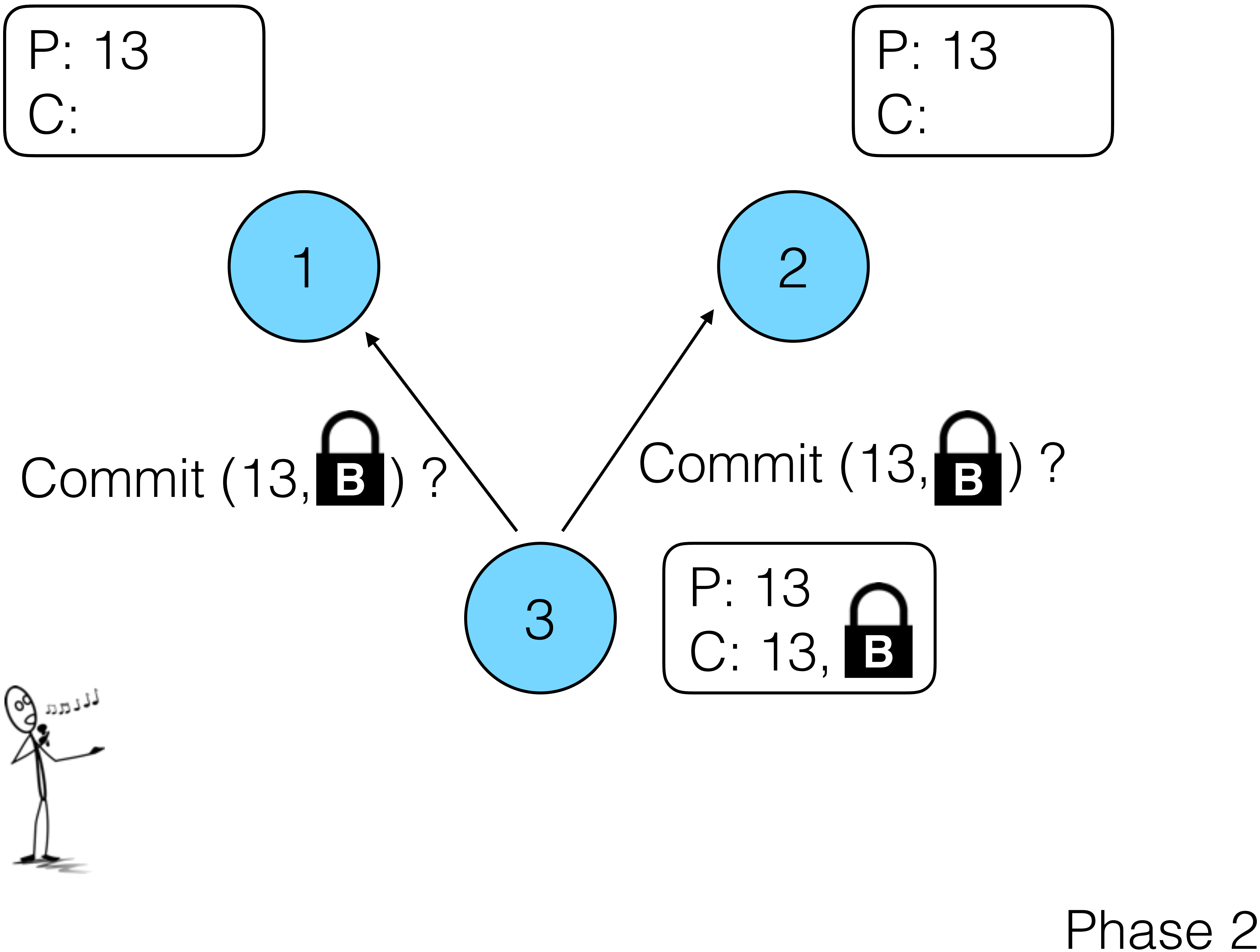
P:
C:
1
2
Promise (13) ?
Promise (13) ?
3
P: 13
C:
B
Phase 1



Phase 1


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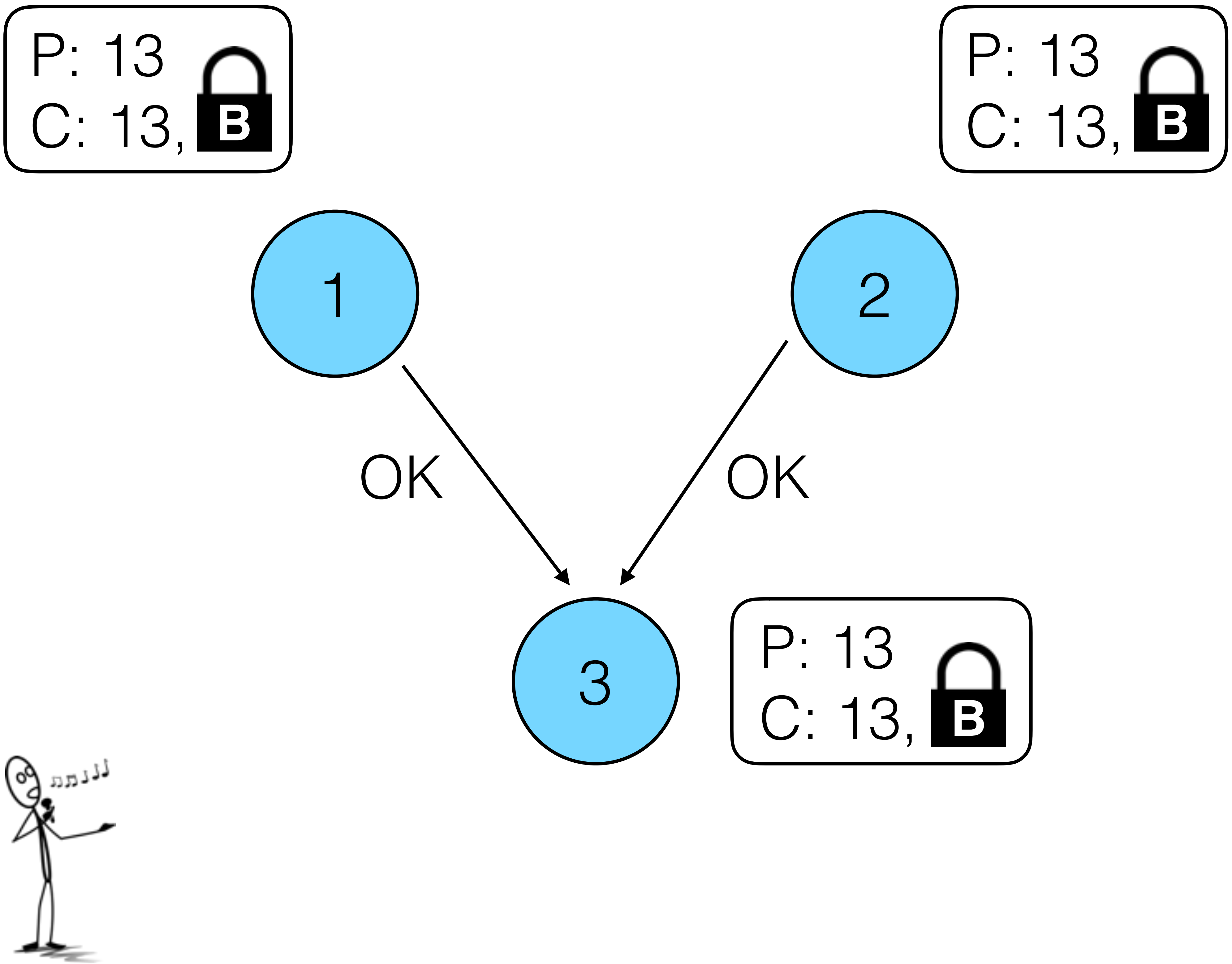
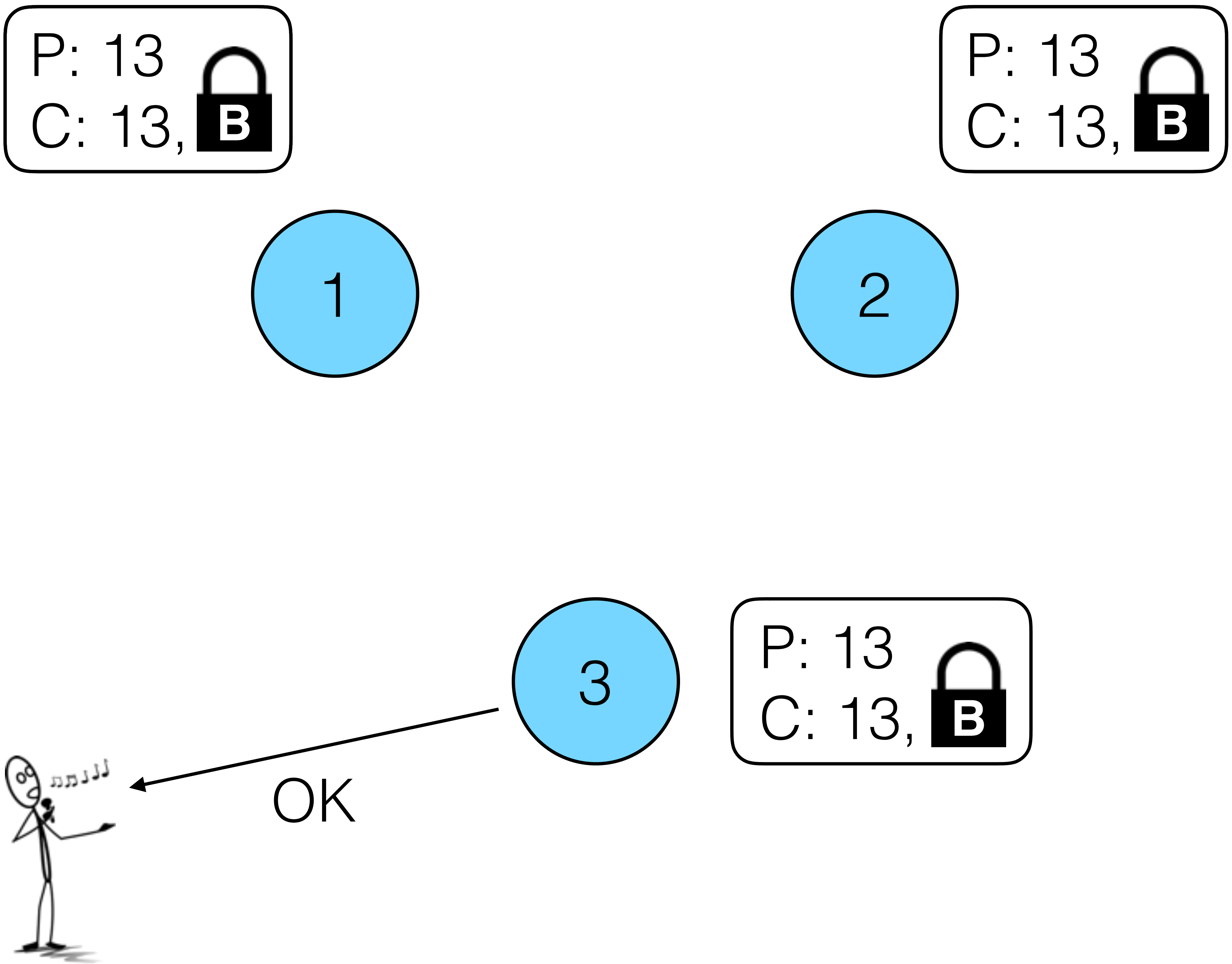
1
2
Commit (13, B) ?
Commit (13, B) ?
3
P: 13
C: 13, B
Phase 2

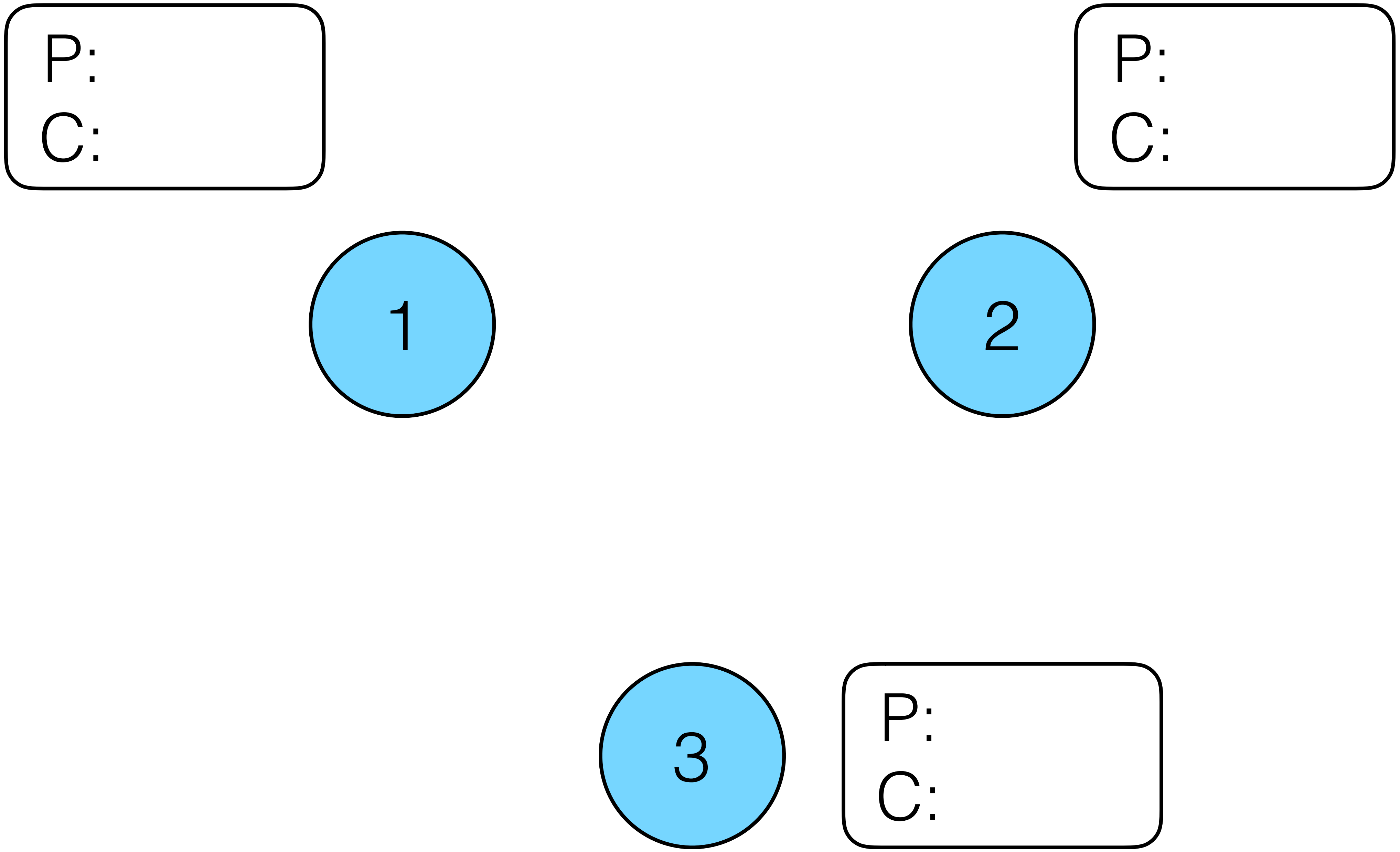


Phase 2



Bob is granted the lock

Paxos Example - Node Failure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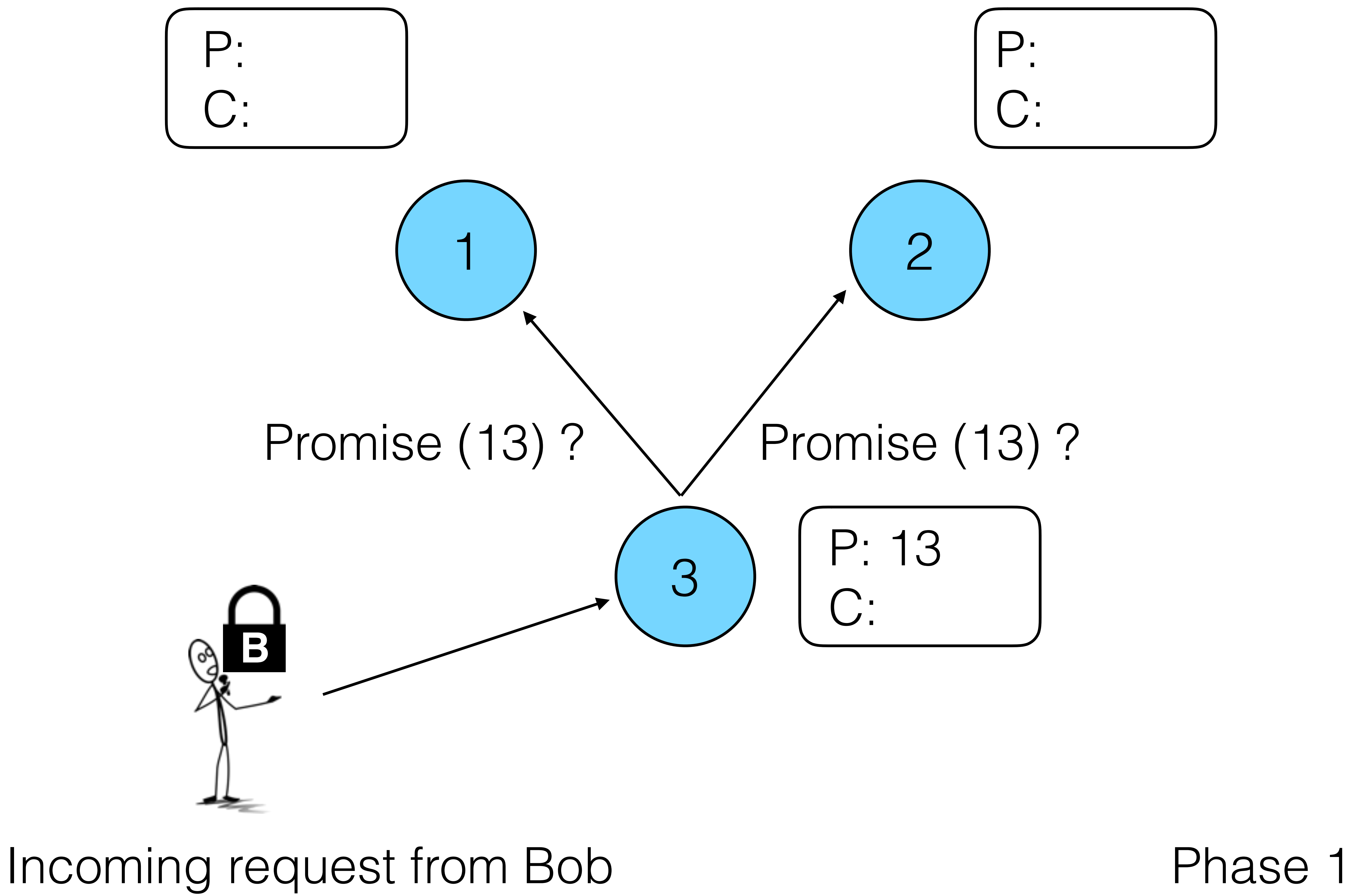
C:


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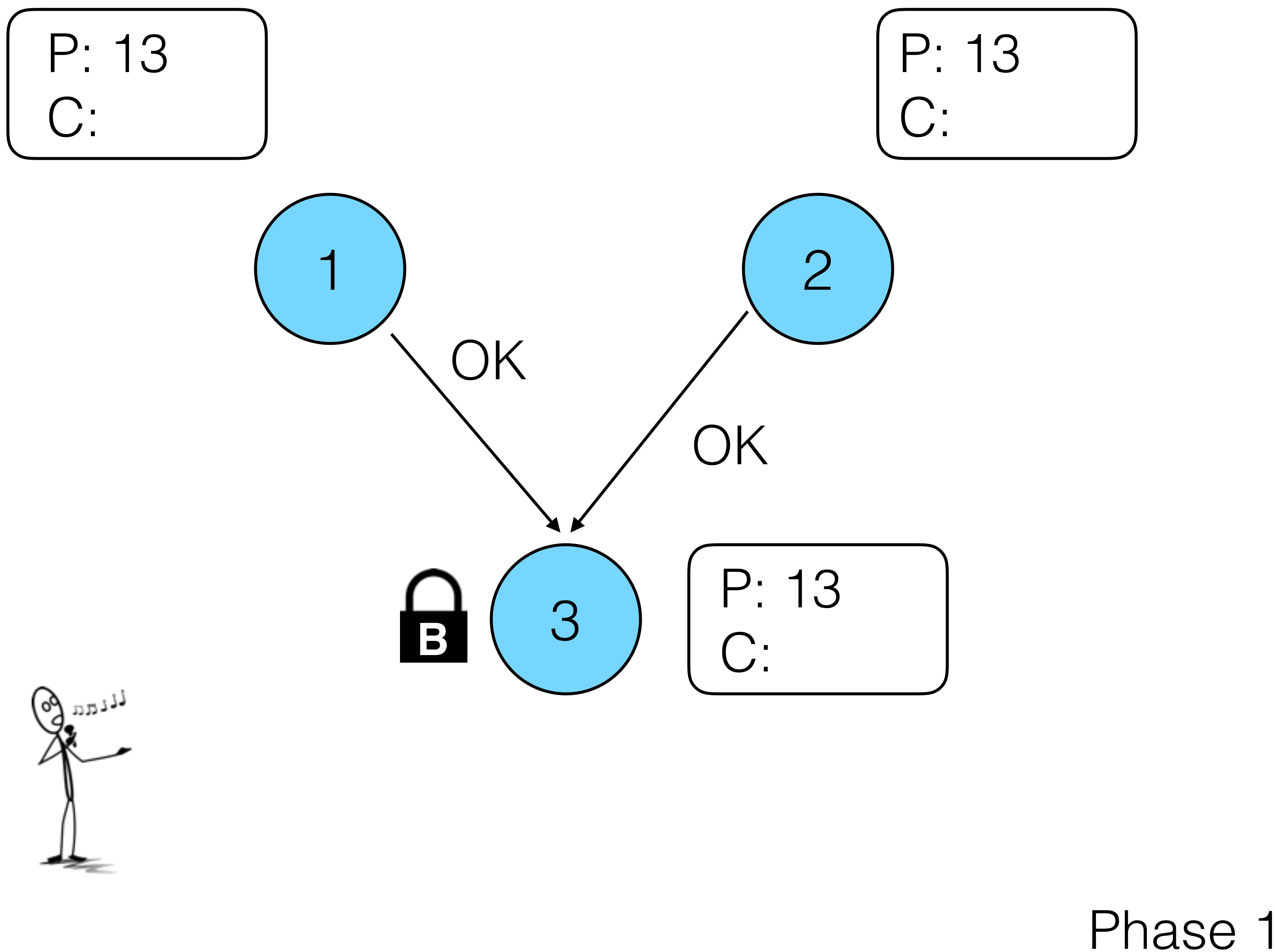
2
Promise (13) ?
Promise (13) ?
3
P: 13
C:
B
Incoming request from Bob
Phase 1


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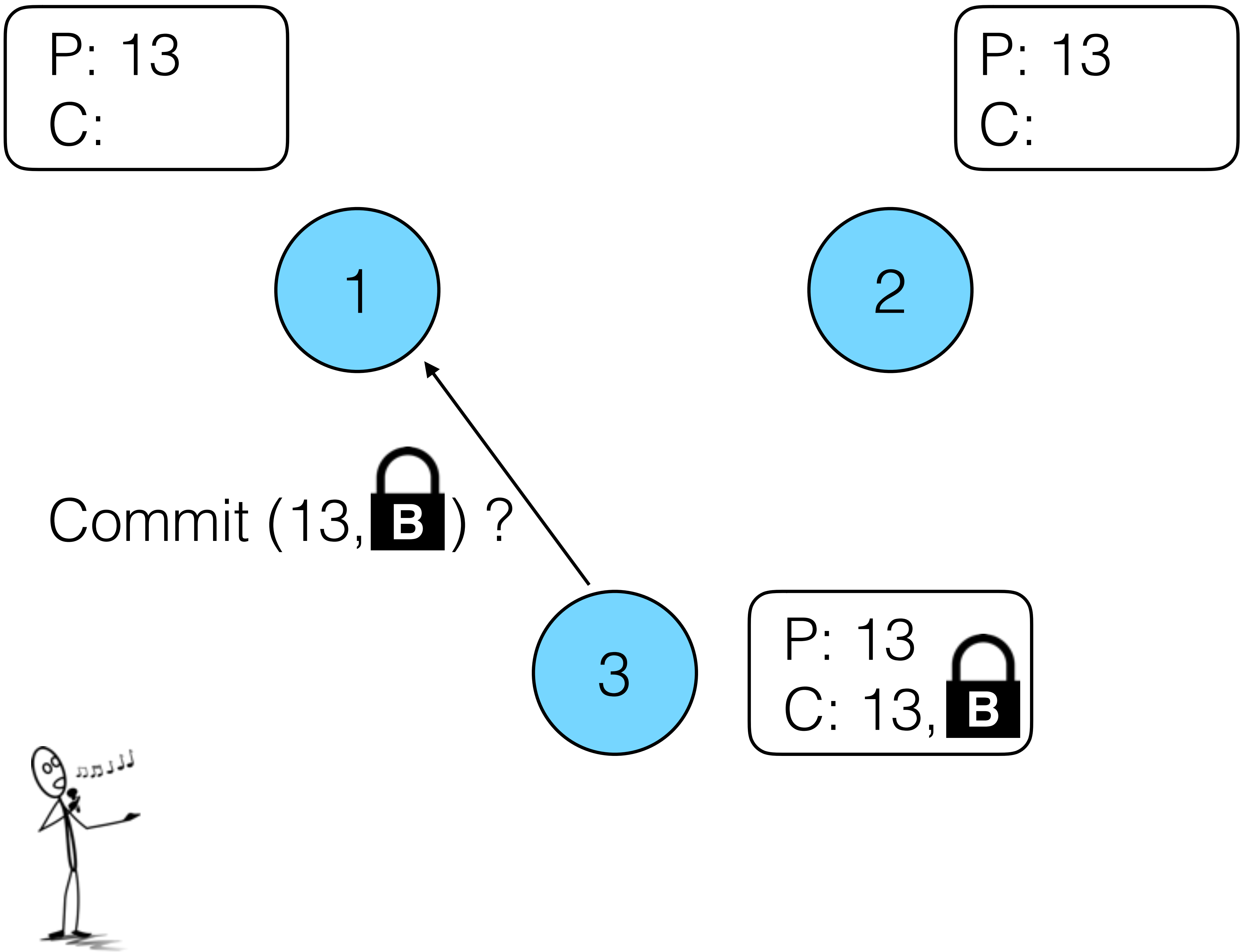
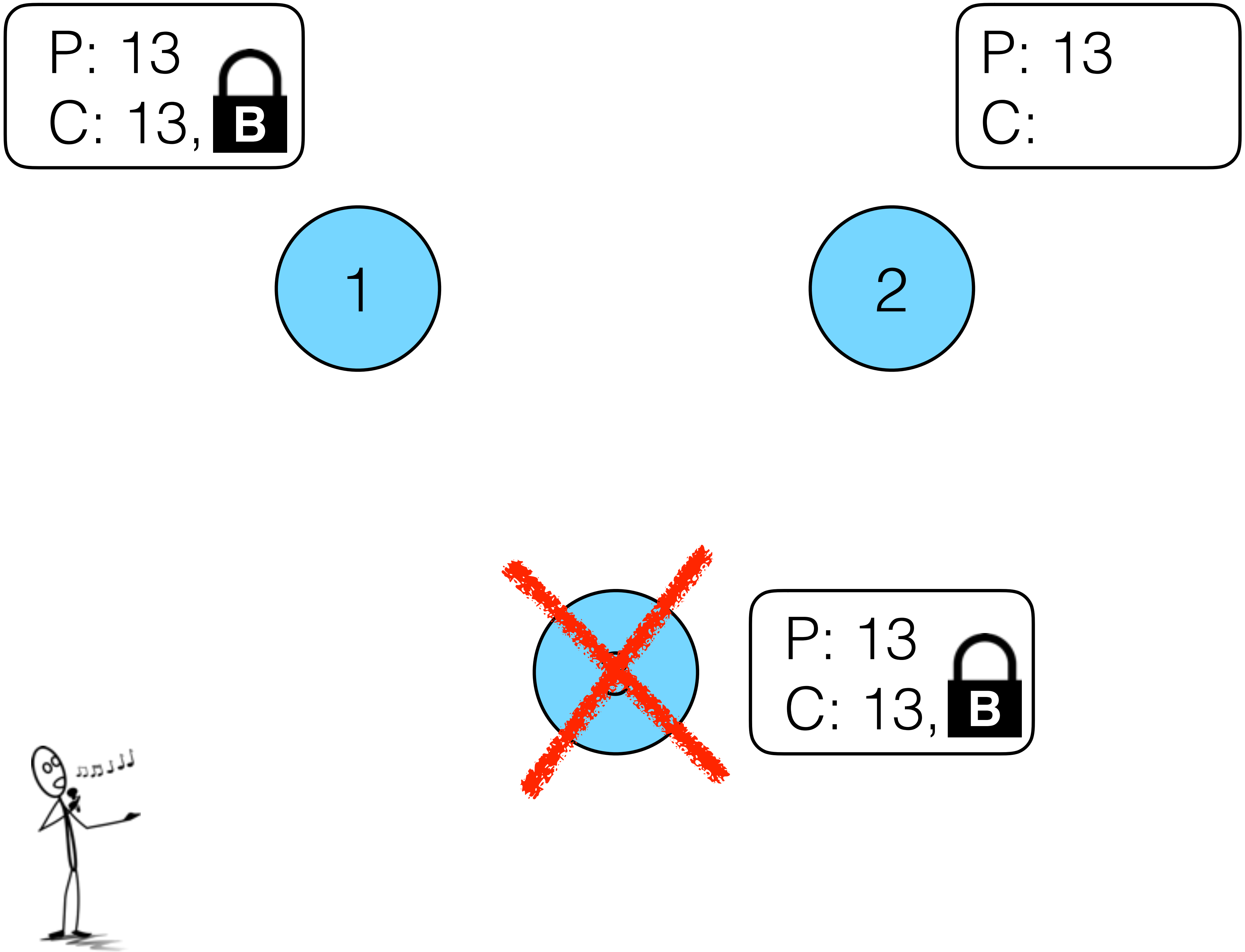
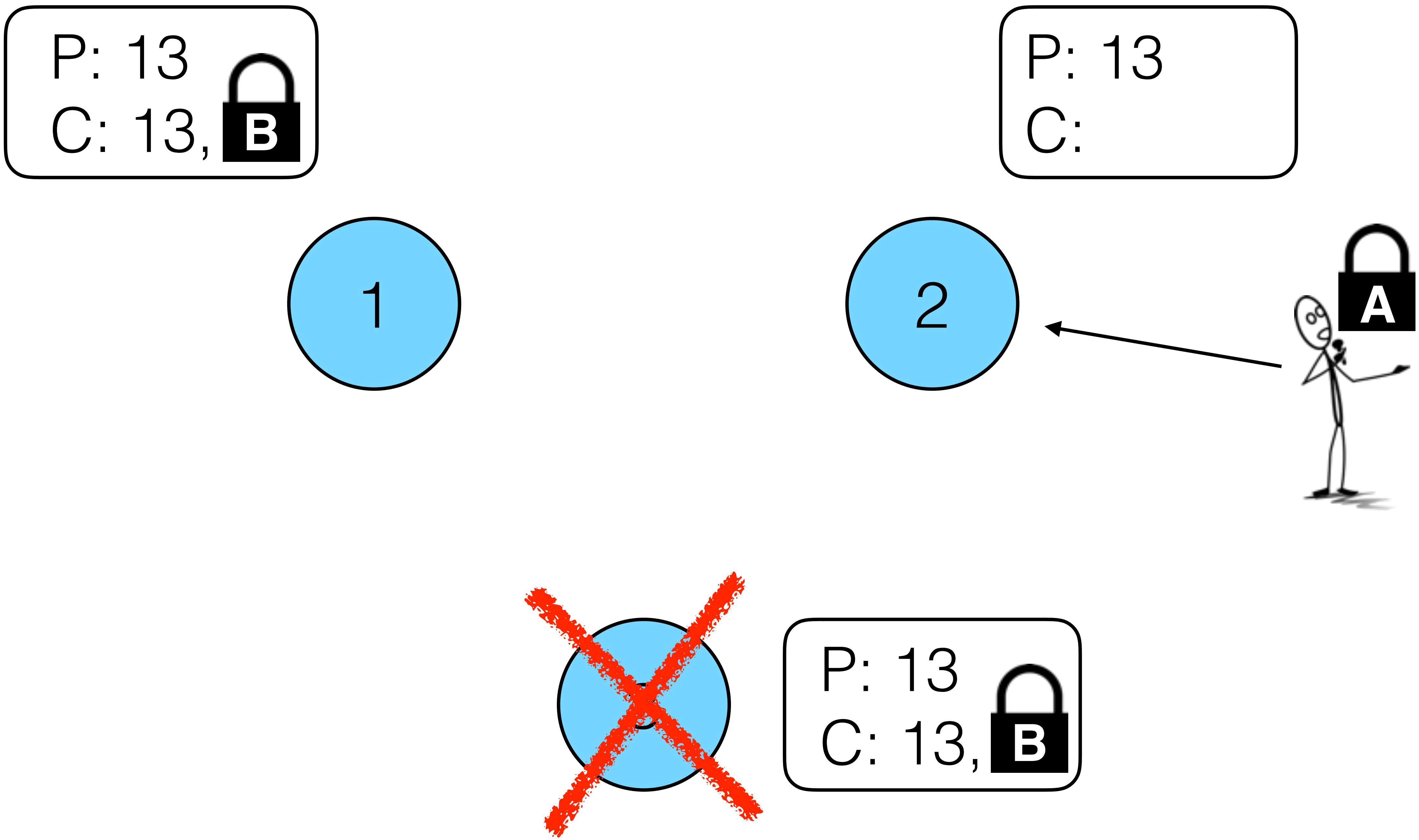
P: 13
C:
Phase 1



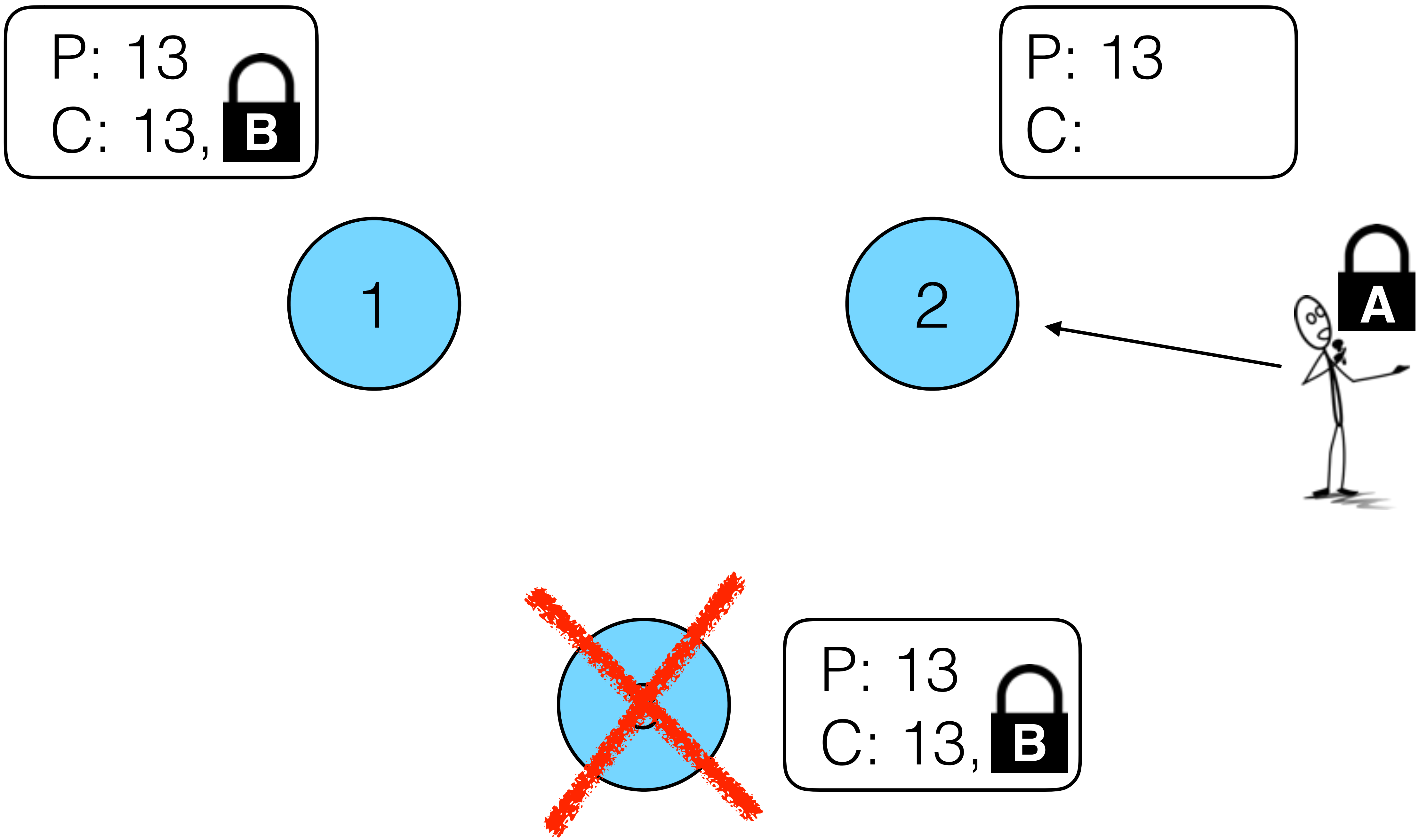
Phase 2



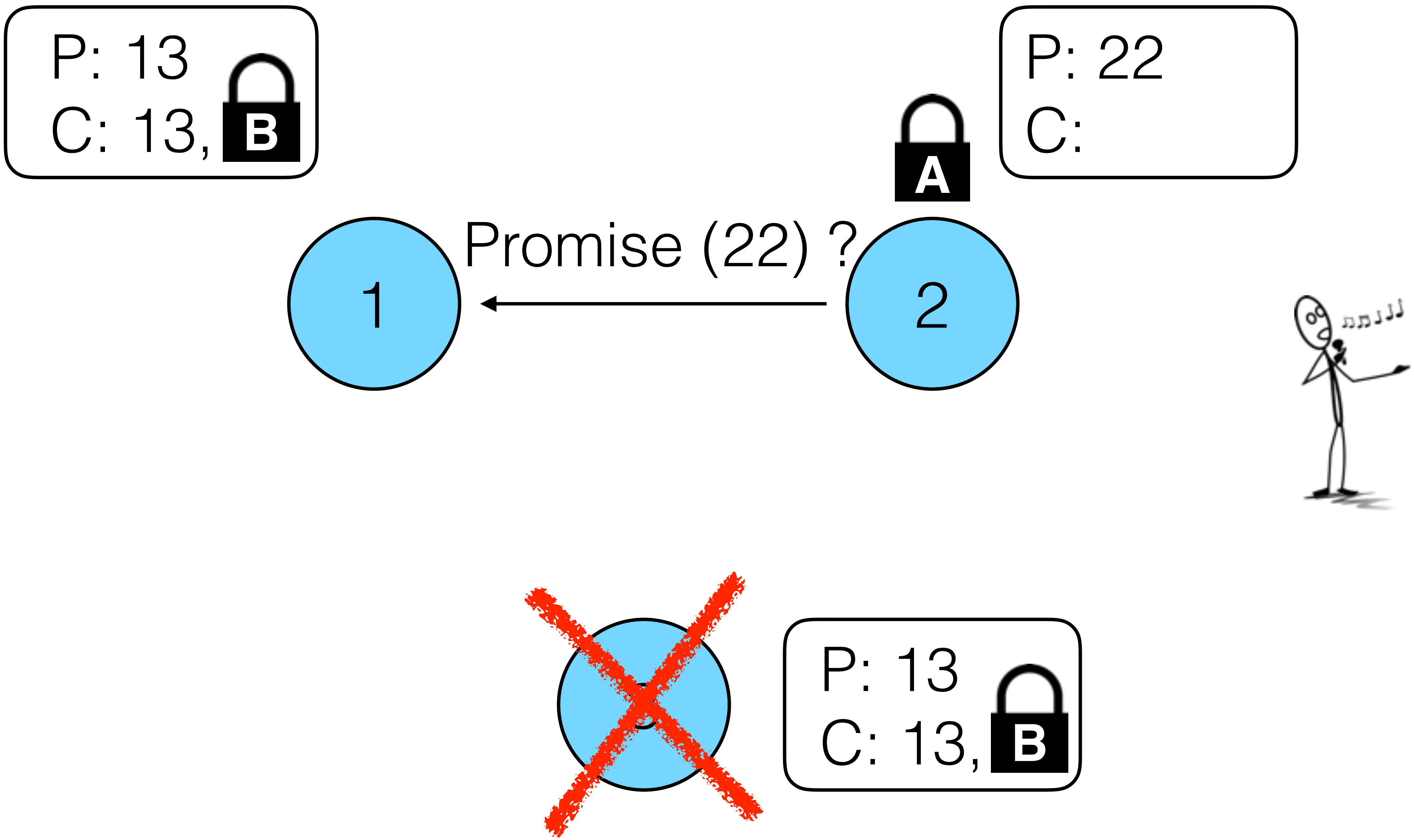
Phase 2



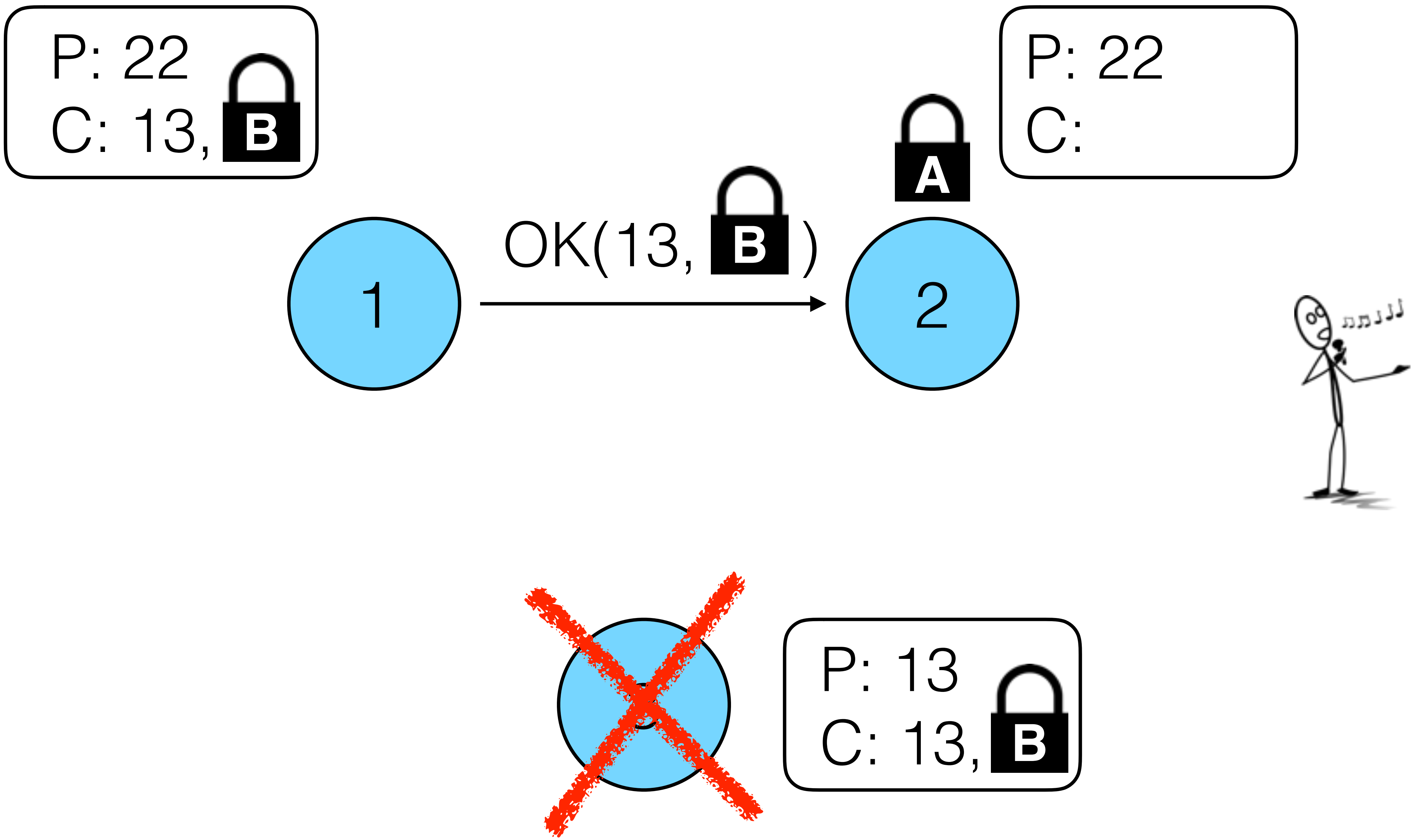
Alice would also like the lock



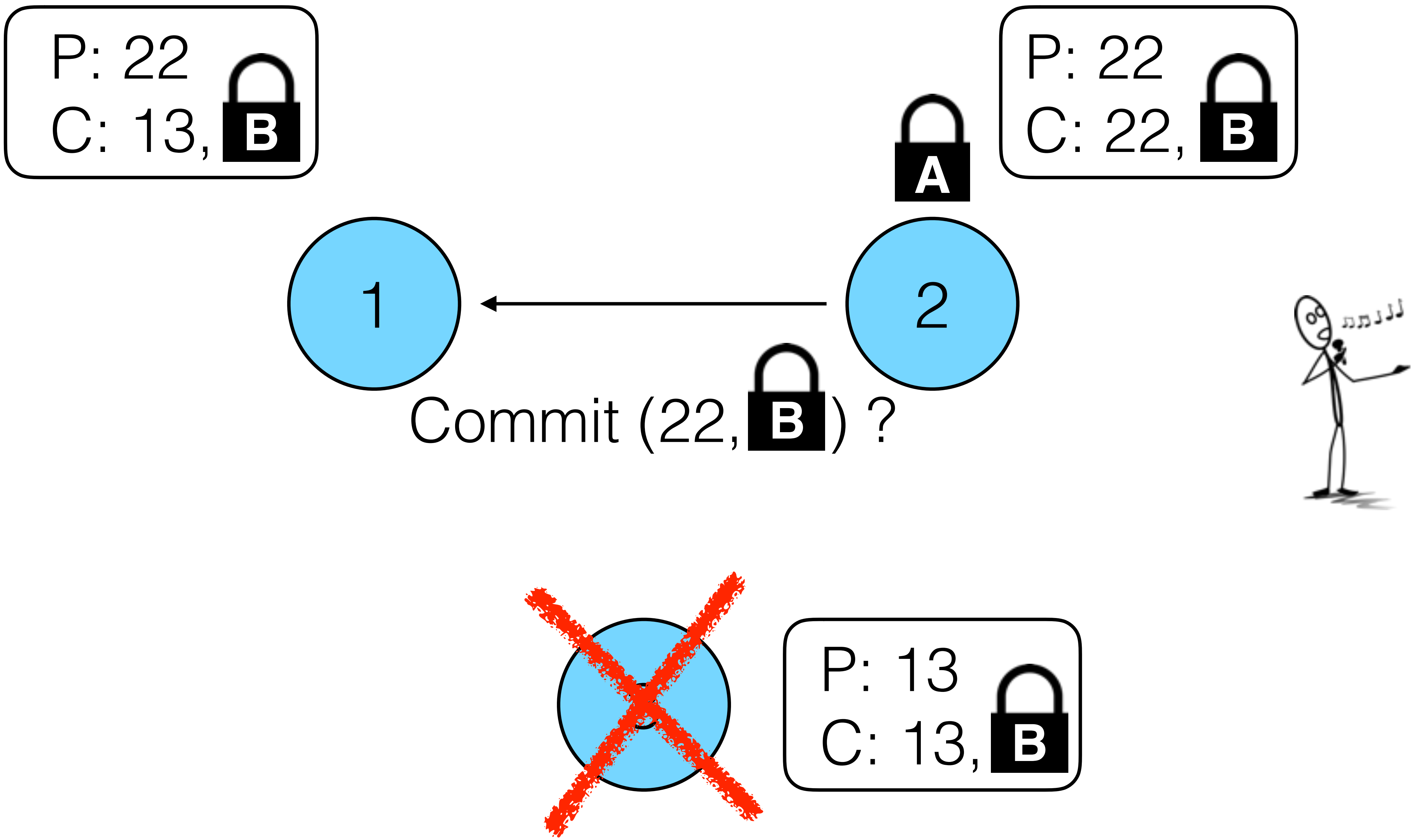
Alice would also like the lock



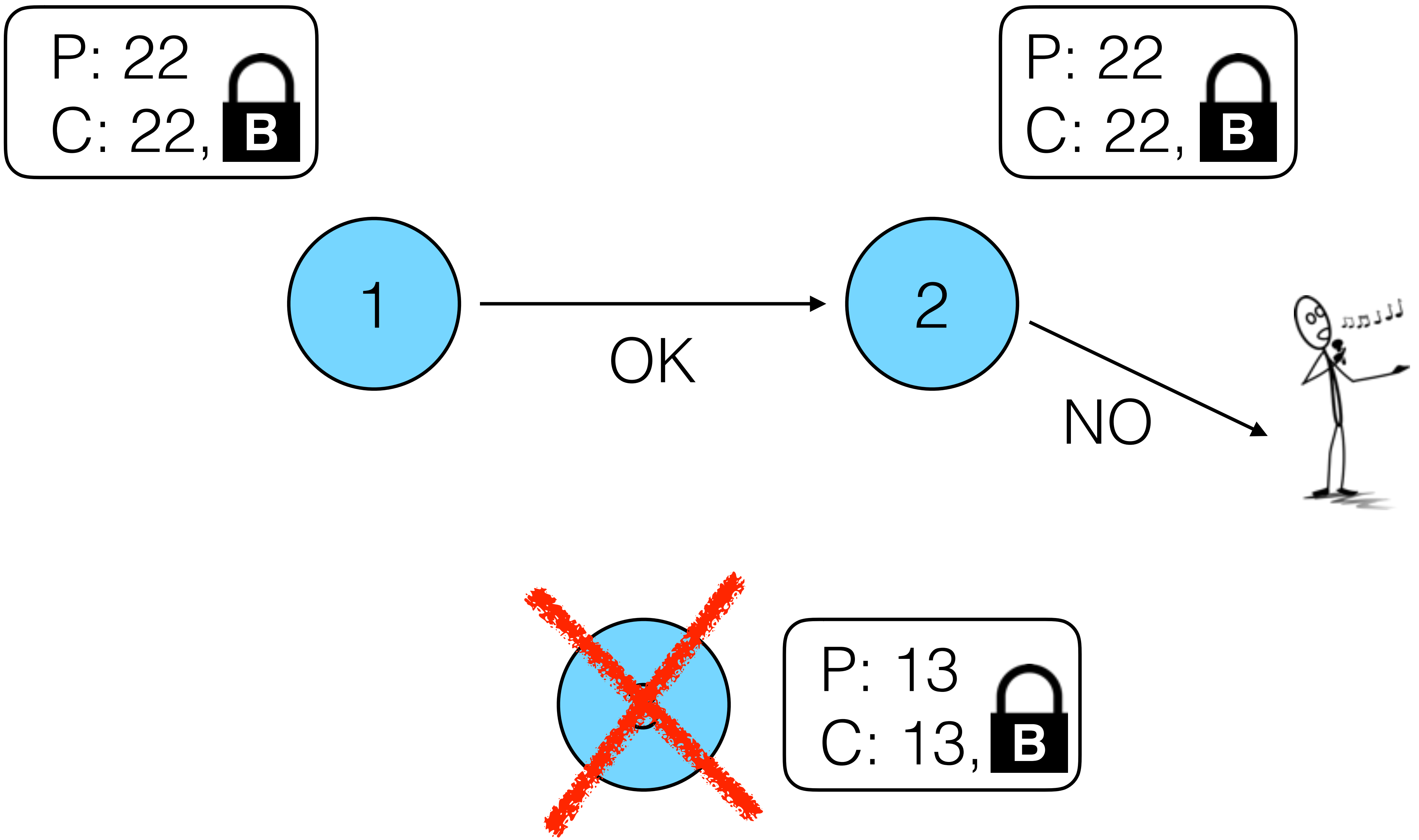
Phase 1



Phase 1



Phase 2



Phase 2

Paxos Summary

Clients must wait two round trips (2 RTT) to the majority of nodes. Sometimes longer.

The system will continue as long as a majority of nodes are up

Multi-Paxos

Lamport's leader-driven consensus algorithm

Paxos Made Moderately Complex
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.

Implication:

Bob now only has to wait one RTT

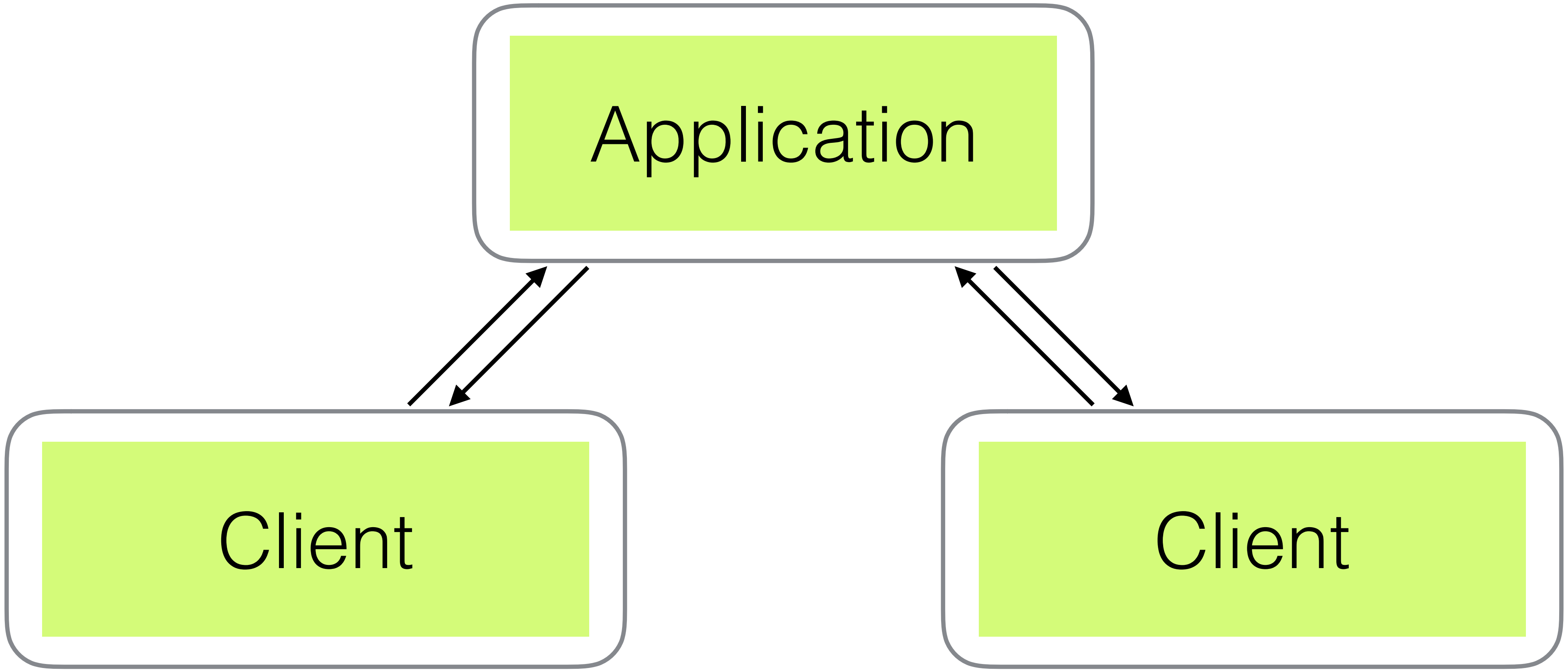
State Machine Replication

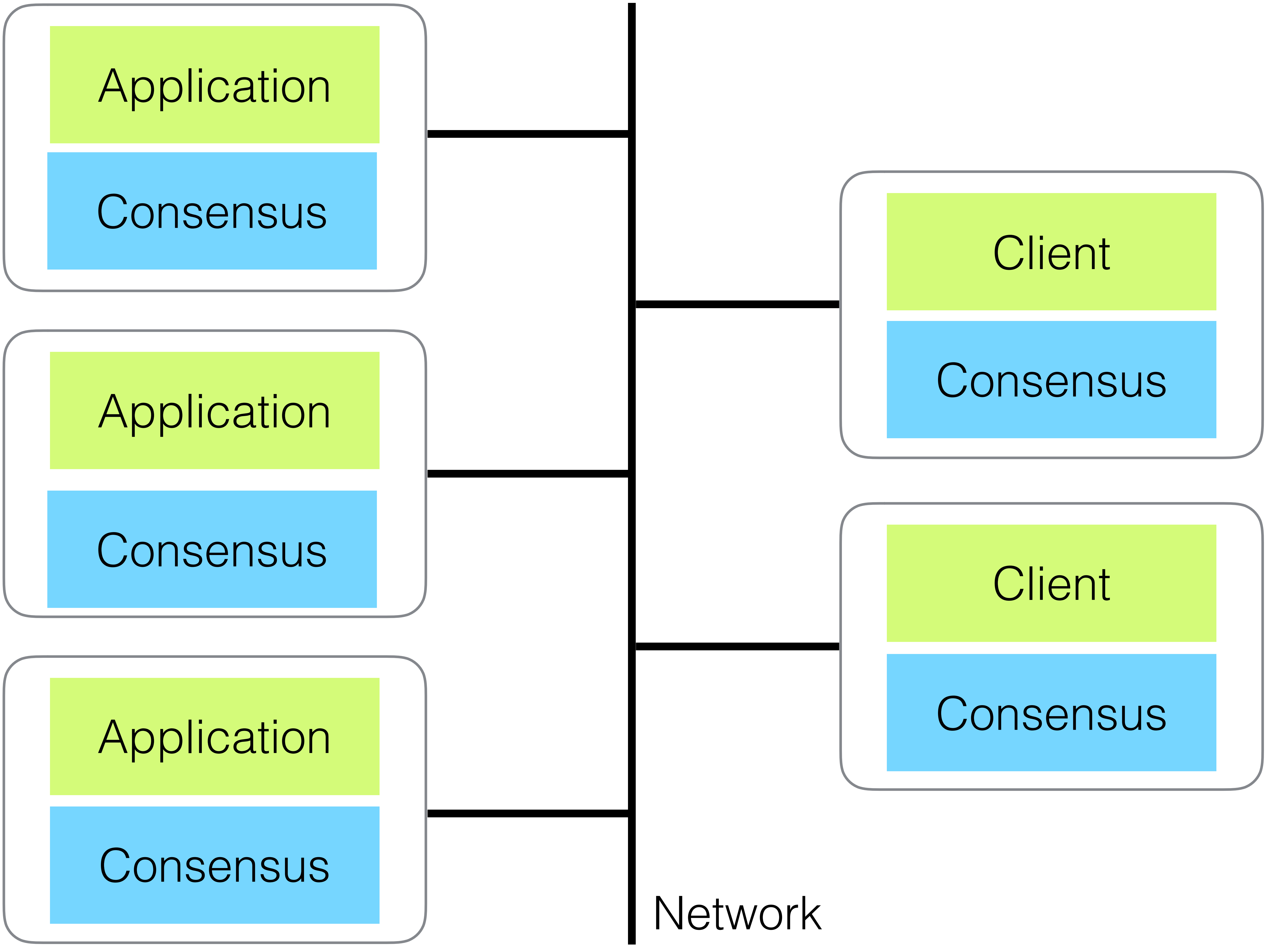
fault-tolerant services using consensus

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

State Machine Replication

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




Application
Consensus
Application
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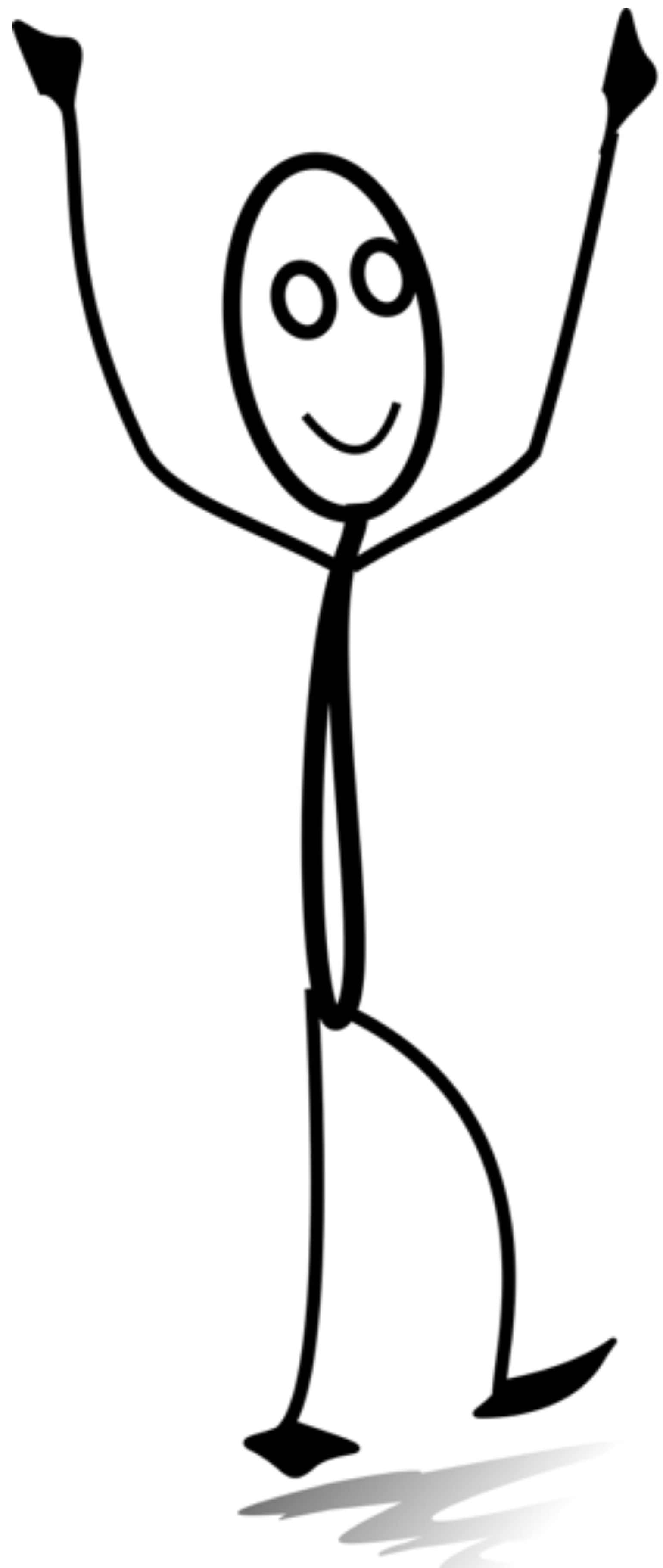
Client
Consensus
Network

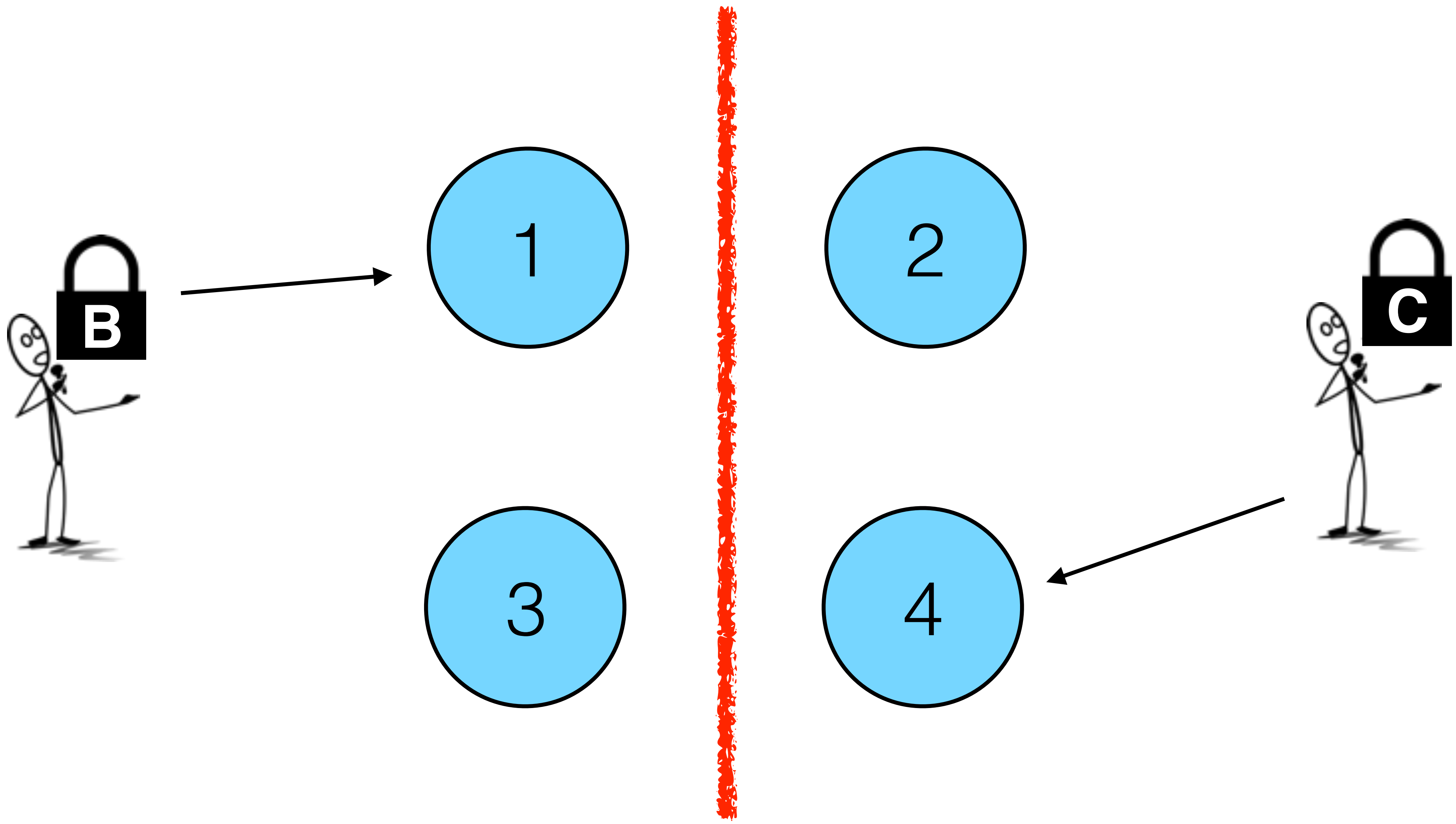


CAP Theorem

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

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

Paxos Made Live

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

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."

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

Fast Paxos
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 either:

- reduce the number of failures we guarantee to tolerance, or
- increase the size of the quorum, or
- a combination of both

Egalitarian Paxos

Don’t restrict yourself unnecessarily

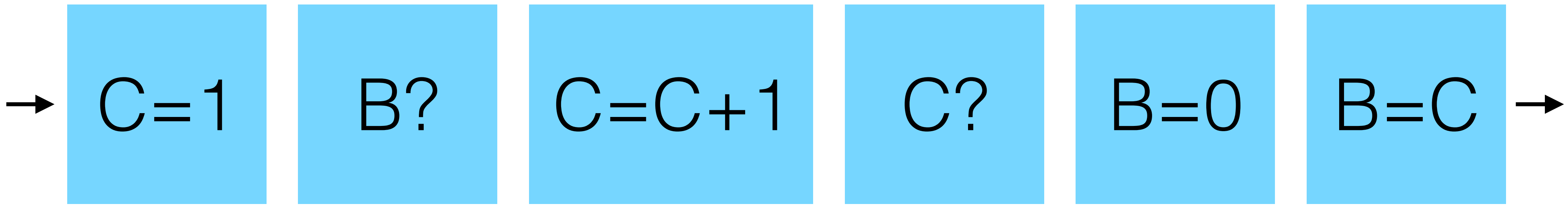
There Is More Consensus in Egalitarian Parliaments
Iulian Moraru, David G. Andersen, Michael Kaminsky
SOSP 2013

also see Generalized Consensus and Paxos

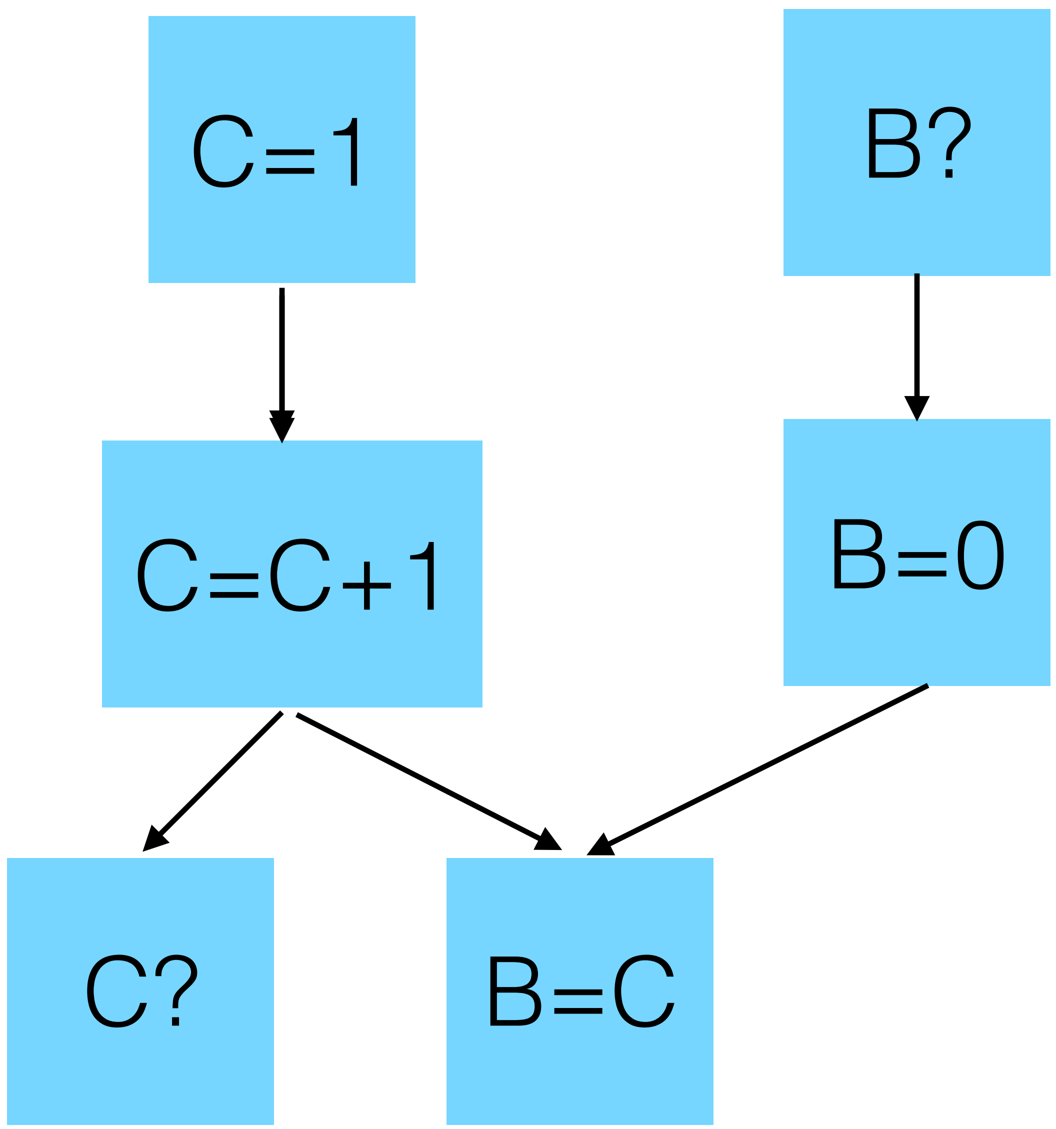
Egalitarian Paxos

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

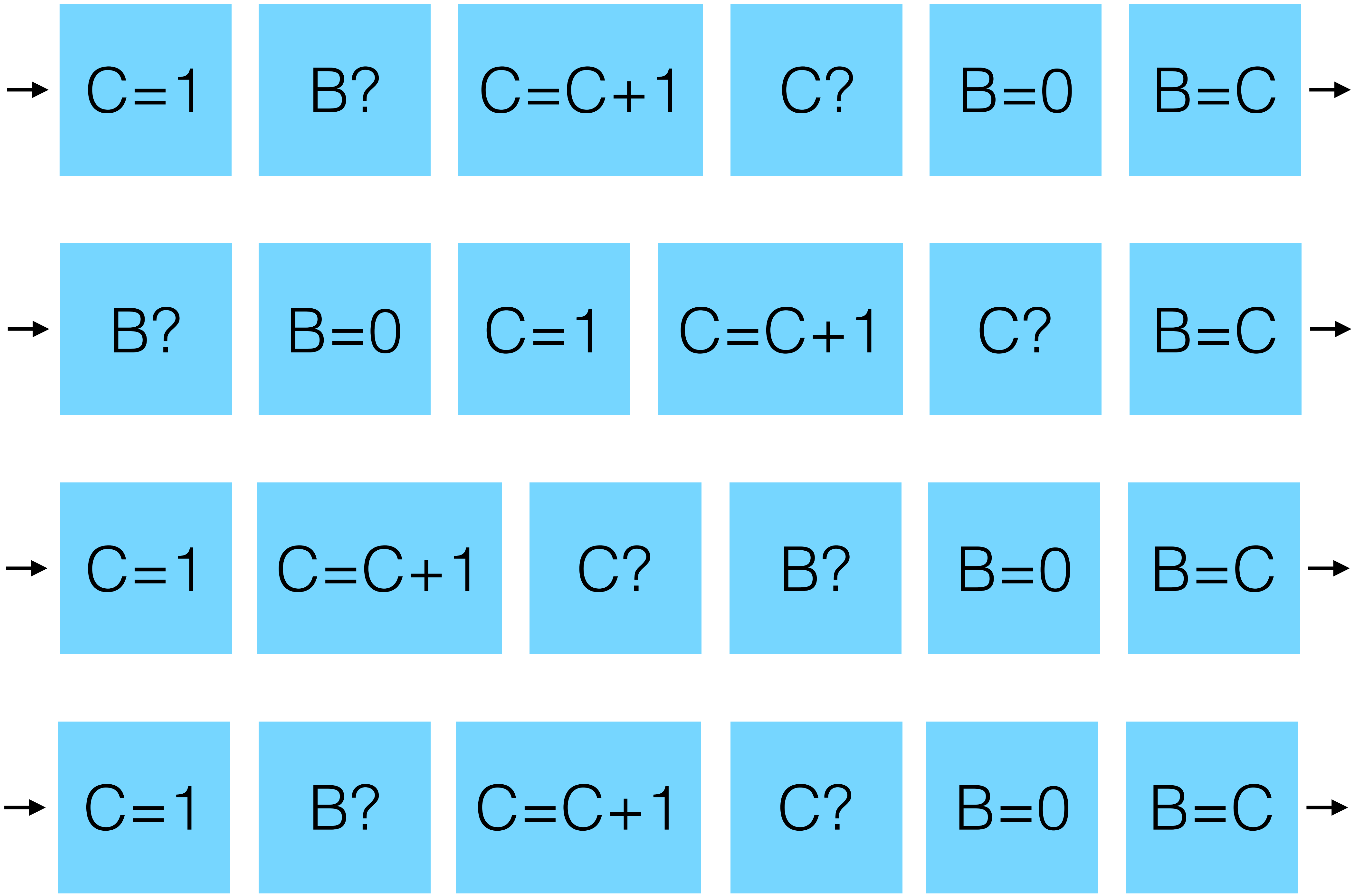
However, sometimes the ordering can be relaxed…



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.

Viewstamped Replication Revisited

the forgotten algorithm

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

Viewstamped Replication Revisited (VRR)

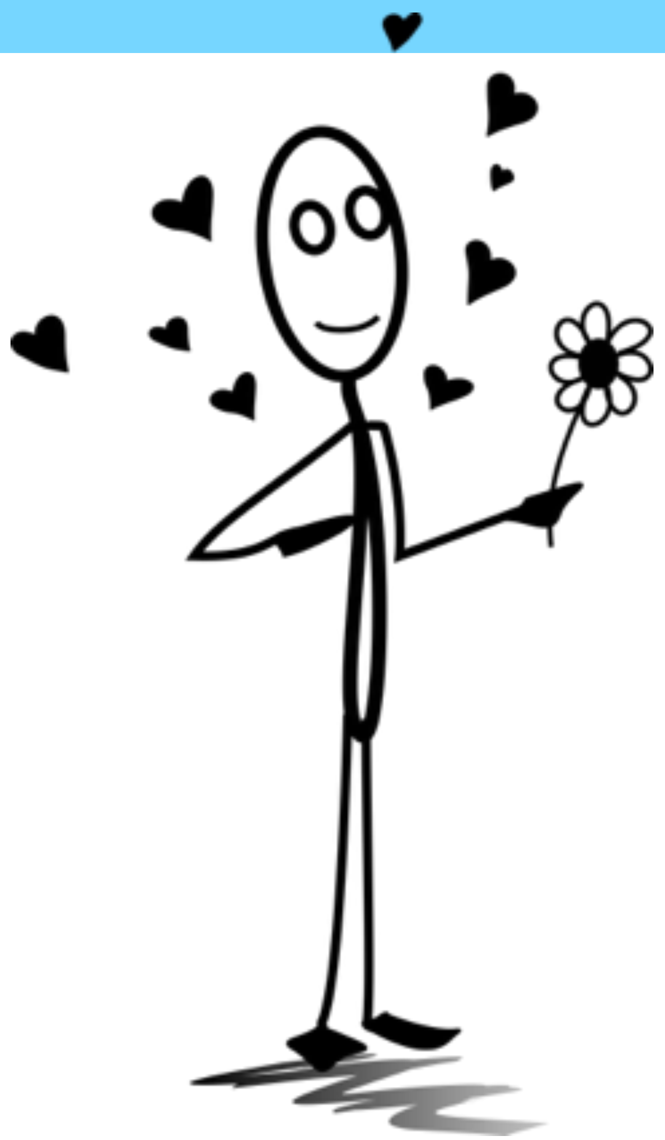
Interesting and well explained variant of SMR + Multi-Paxos.

Key features:

- Round robin leader election
- Dynamic Membership

Raft Consensus

Paxos made understandable



<u>In Search of an Understandable Consensus Algorithm</u>
Diego Ongaro and John Ousterhout
USENIX Annual Technical Conference
2014

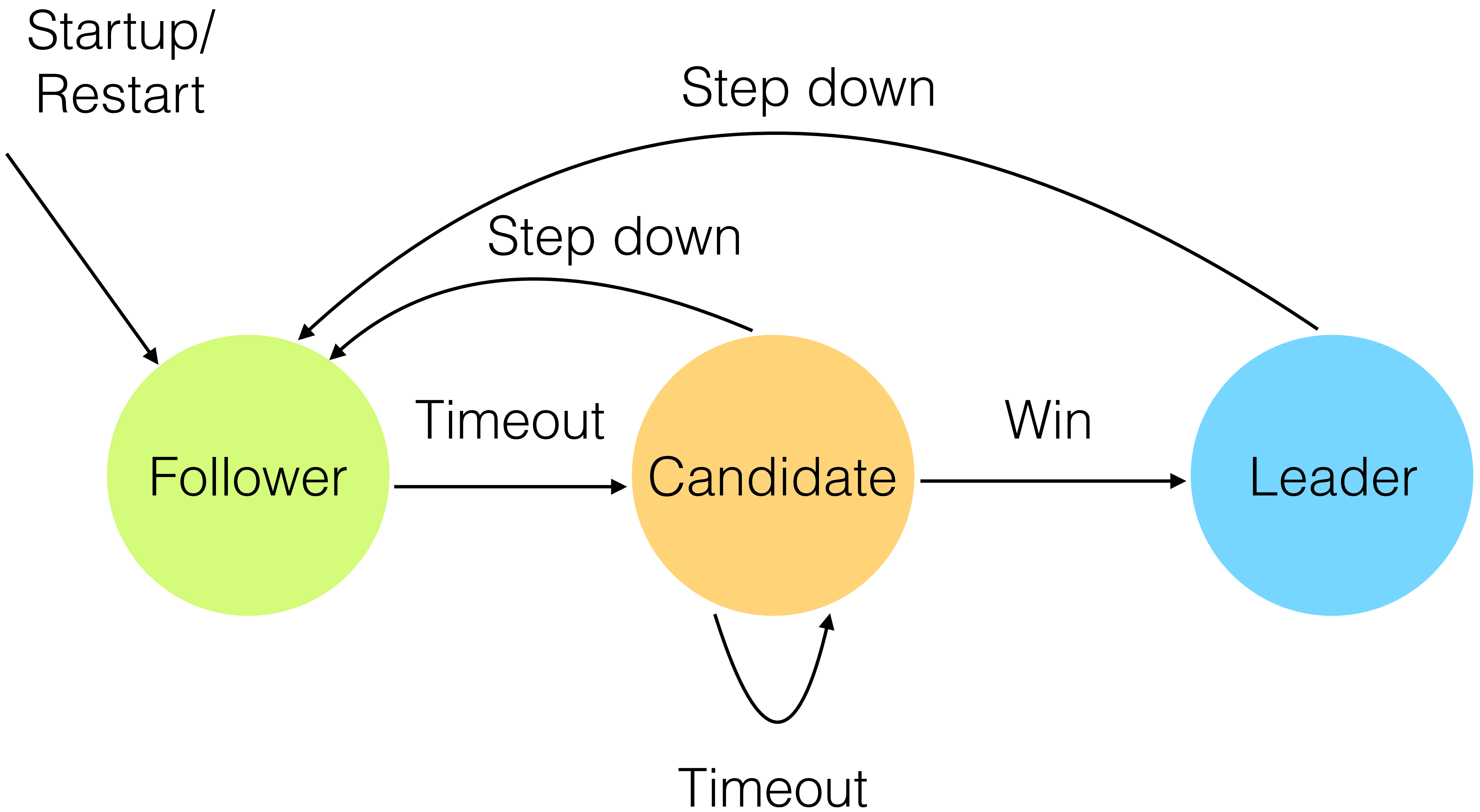
Raft

Raft has taken the wider community by storm. Due to its understandable description.

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

Key features:

- Really strong leadership - all other nodes are passive
- Dynamic membership and log compaction


Startup/
Restart
Step down
Step down
Timeout
Win
Follower
Candidate
Leader
Timeout

Ios

Why do things yourself, when you can delegate it?

to appear

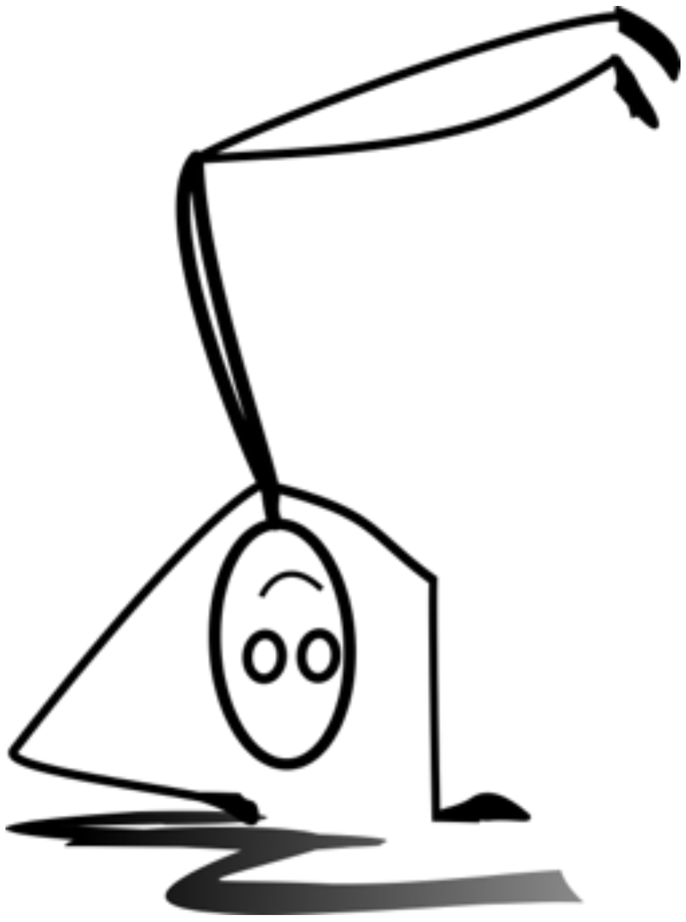
Ios

The issue with leader-driven algorithms like Multi-Paxos, Raft and VRR is that throughput is limited to one node.

Ios allows a leader to safely and dynamically delegate their responsibilities to other nodes in the system.

Hydra

consensus for geo-replication



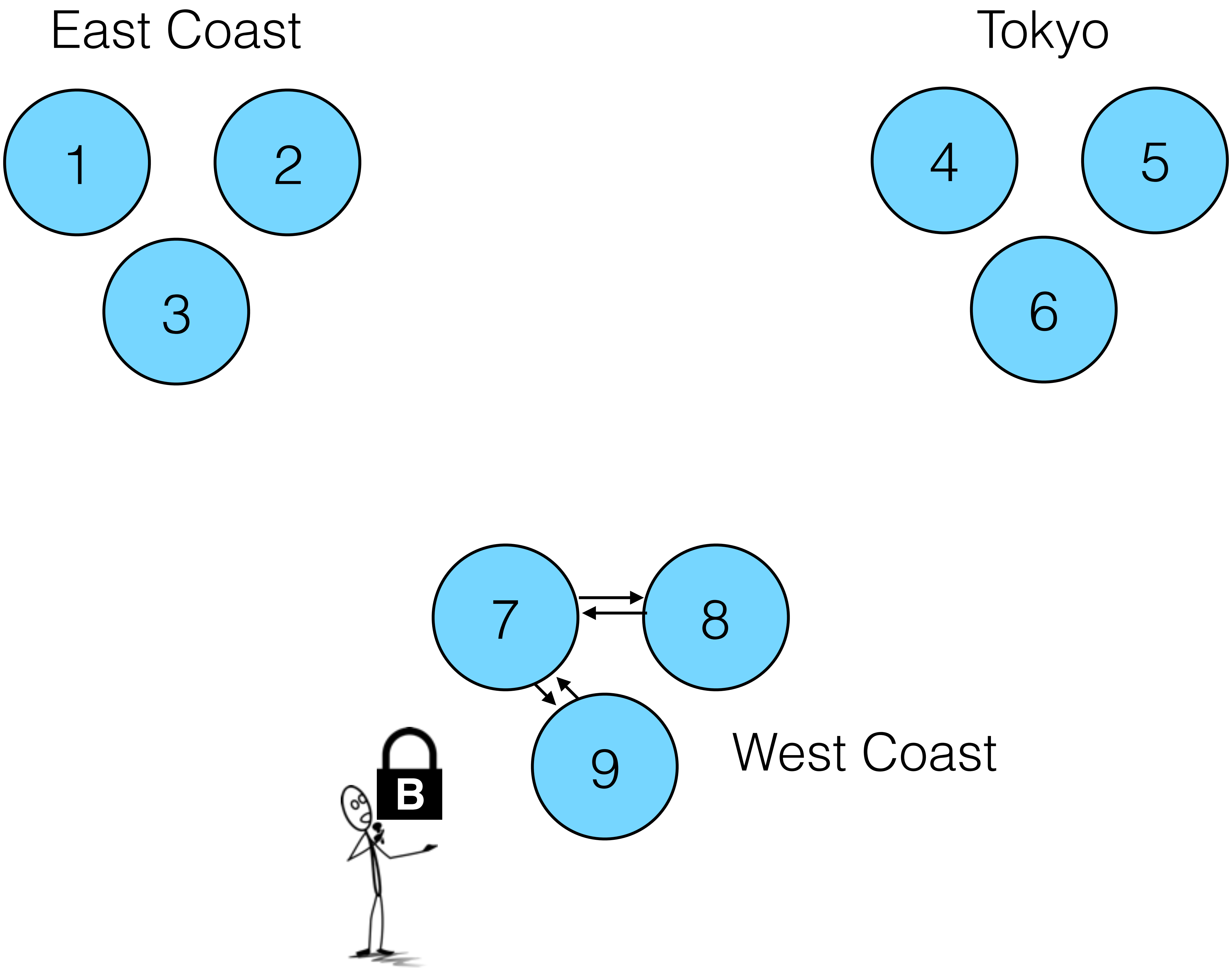
to appear

Hydra

Distributed consensus for systems which span multiple datacenters.

We use Ios for replication within the datacenter and a Egalitarian Paxos like protocol for across datacenters.

The system has a clear leader but most requests simply bypass the leader.


East Coast
Tokyo
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2
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5
6
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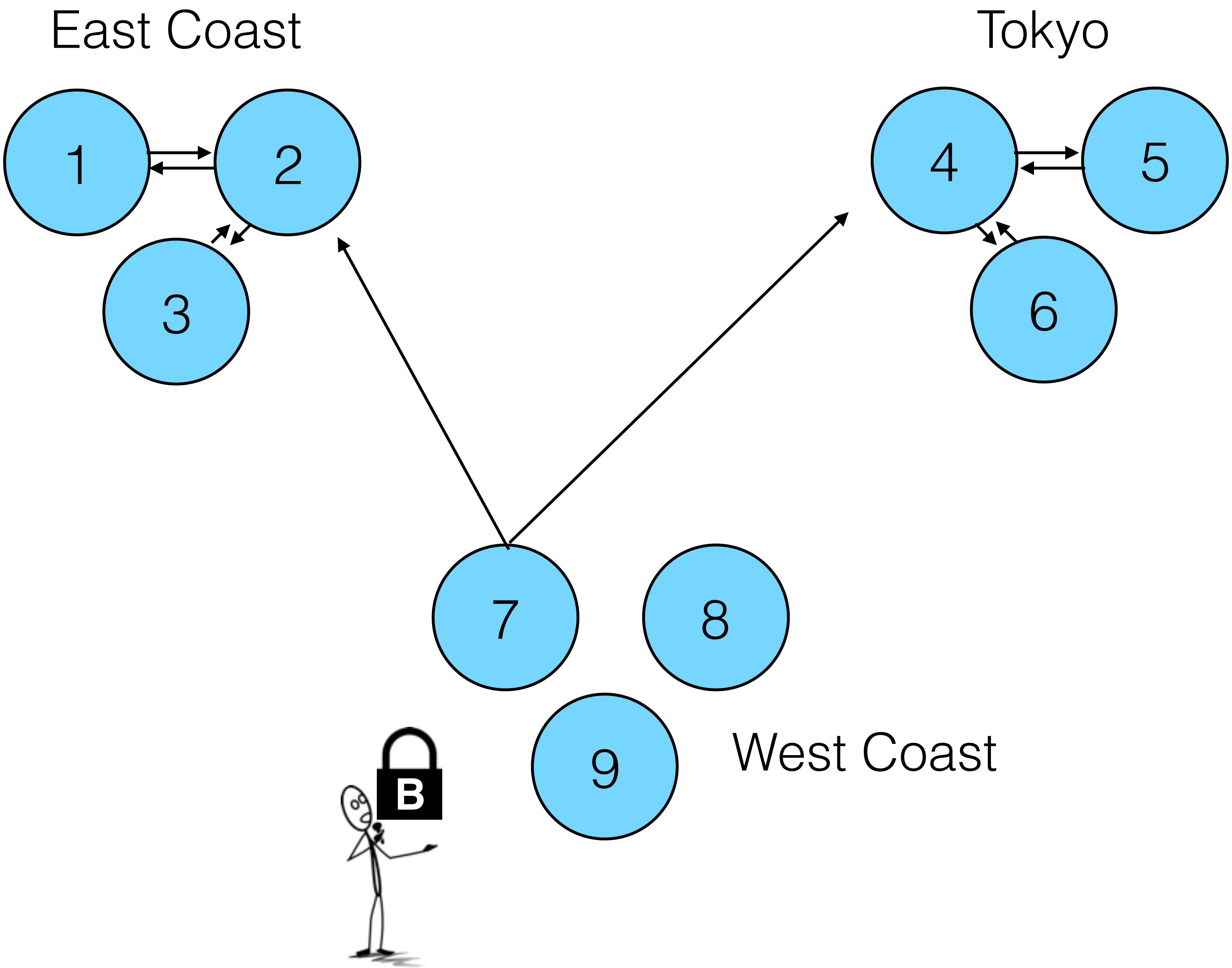
8
9
West Coast
B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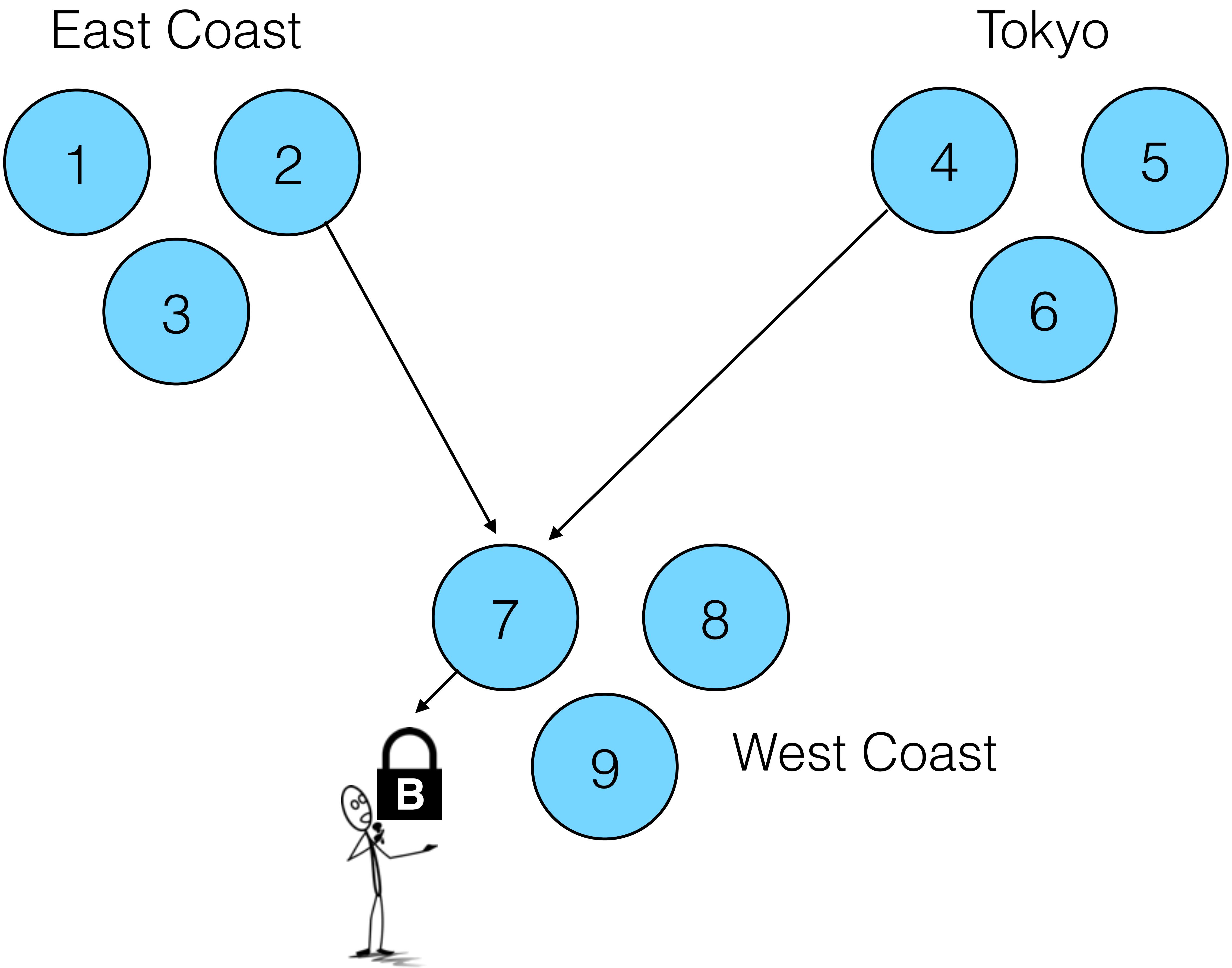
East Coast
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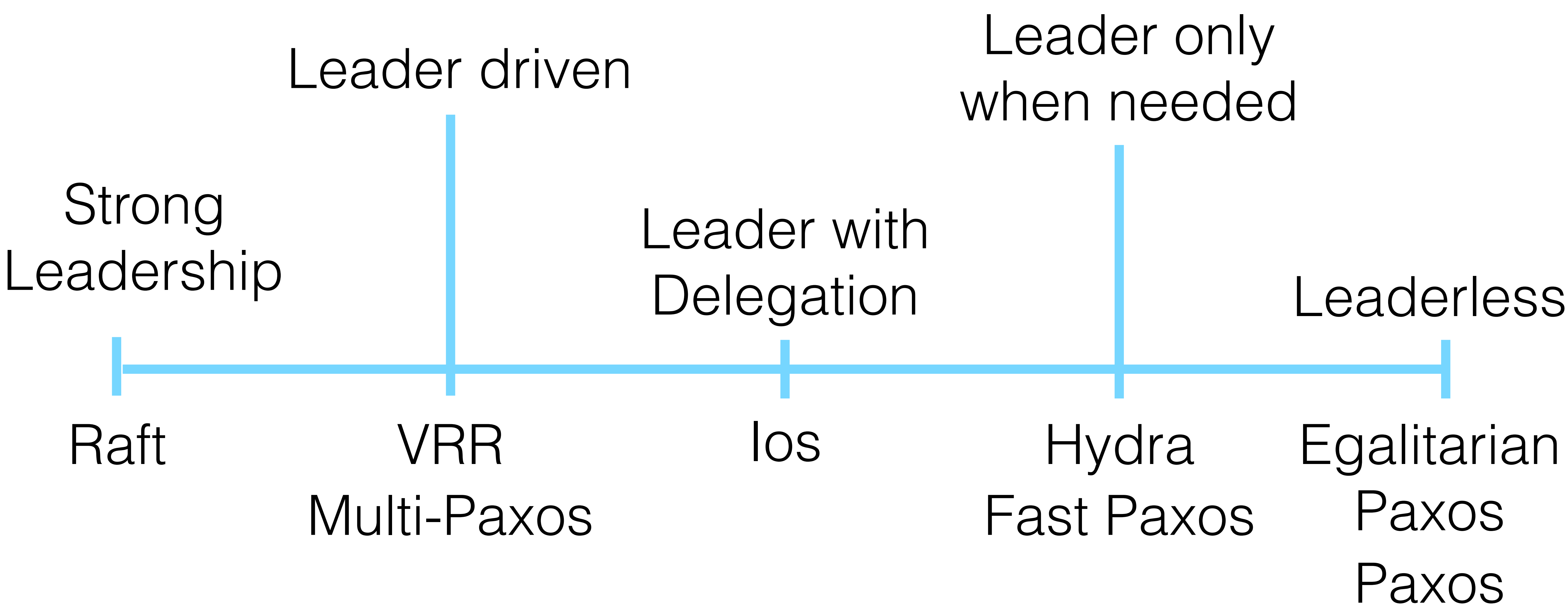
West Coast

The road we travelled

- **2 impossibility results:** CAP & FLP
- **1 replication method:** State machine Replication
- **6 consensus algorithms:** Paxos, Multi-Paxos, Fast Paxos, Egalitarian Paxos, Viewstamped Replication Revisited & Raft
- **2 future algorithms:** Ios & Hydra

How strong is the leadership?



Who is the winner?

Depends on the award:

- Best for minimum latency: VRR
- Easier to understand: Raft
- Best for WANs (conflicts rare): Egalitarian Paxos
- Best for WANs (conflicts common): Fast Paxos

Future

1. More algorithms offering a compromise between strong leadership and leaderless

2. More understandable consensus algorithms

3. Achieving consensus is getting cheaper, even in challenging settings

4. Deployment with micro-services and unikernels

5. Self-scaling replication - adapting resources to maintain resilience level.

Stops we drove passed

We have seen one path through history, but many more exist.

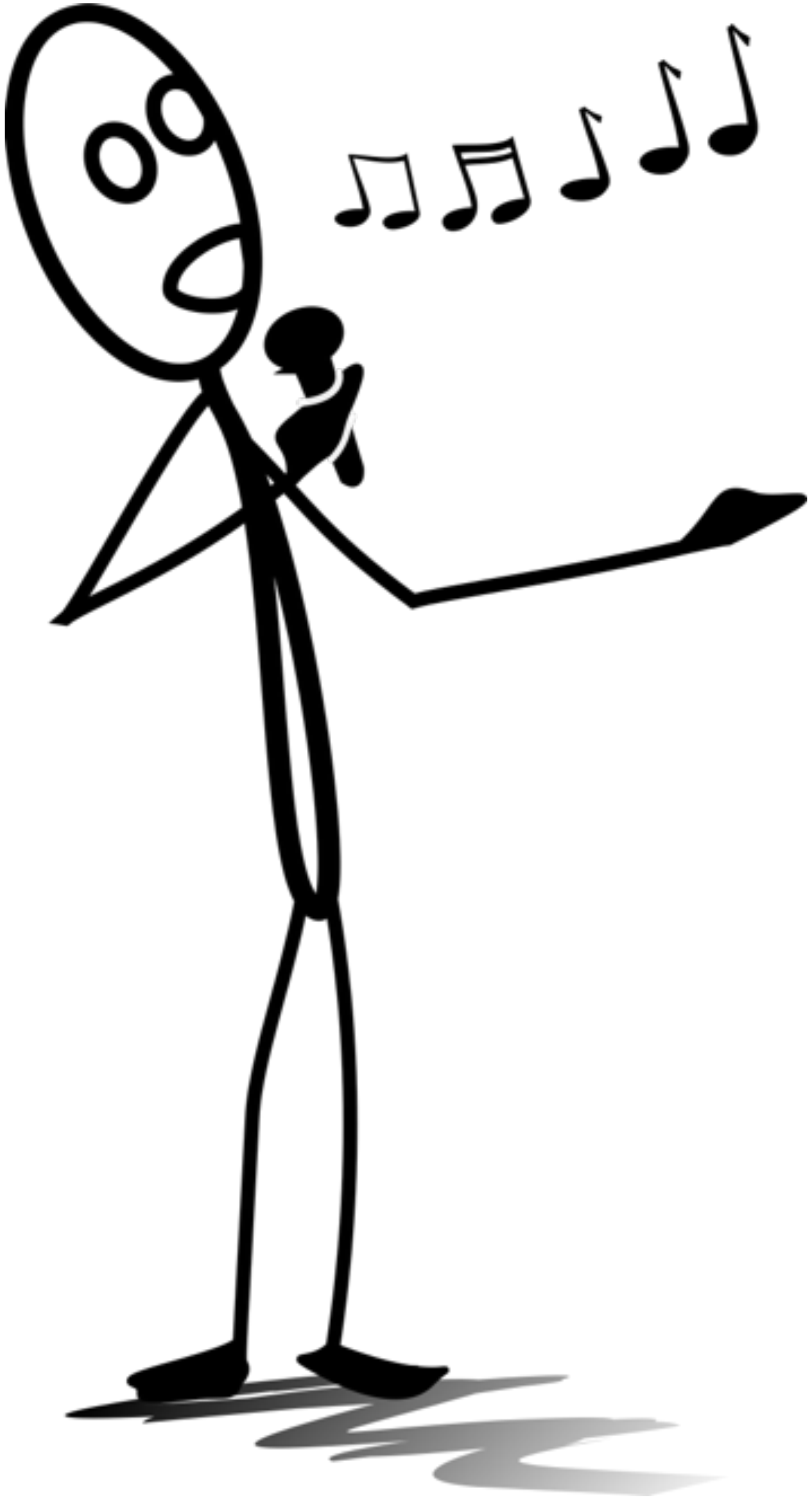
- Alternative replication techniques e.g. chain replication and primary backup replication
- Alternative failure models e.g. nodes acting maliciously
- Alternative domains e.g. sensor networks, mobile networks, between cores

Summary

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

Consensus is useful and achievable.

Find the right algorithm for your specific domain.



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