CSE 552
Paxos

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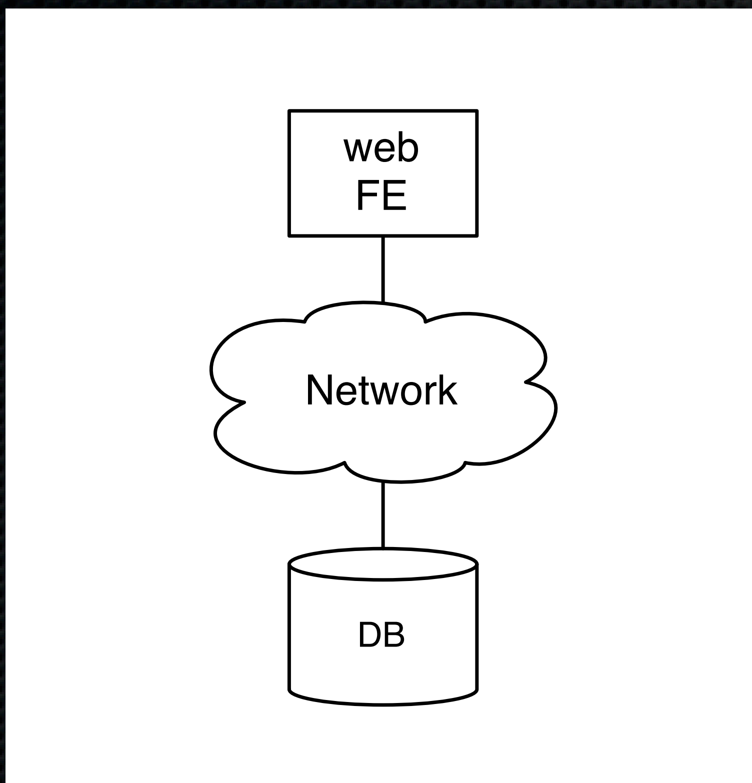
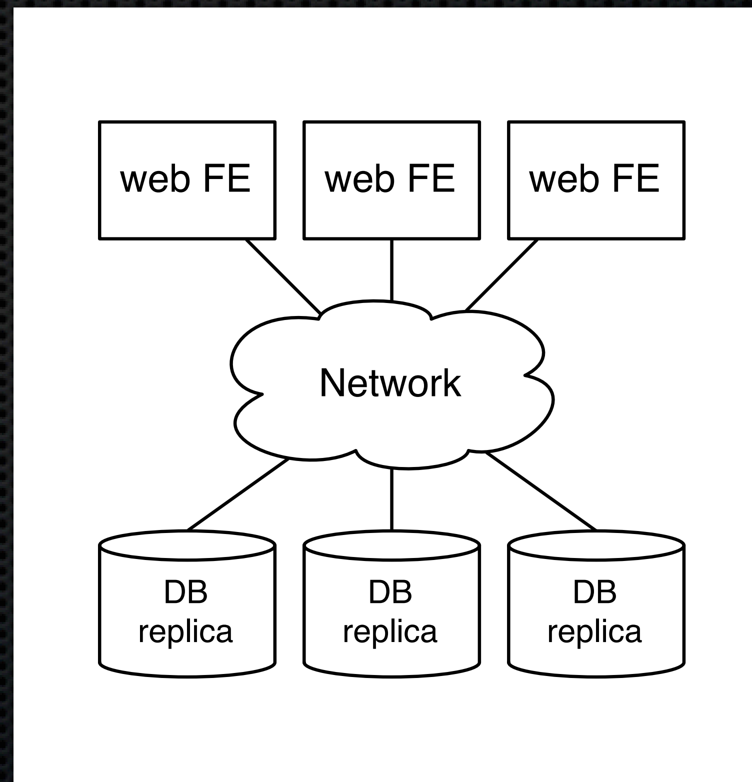
Remember from last time...



VS



Replication for availability

Execute multiple replicas of a server

- keep the replicas "in sync" somehow
- if a replica fails, there is enough redundancy in the system for clients to receive service from the surviving replicas

Strawman #1

Simple idea:

- each client sends all writes to all available replicas

Issues?

Issue: ordering

Have to make sure each replica processes requests in the same order as other replicas

- somehow, the replicas need to agree on the order of inputs

Issue: determinism

Replicas need to be deterministic, otherwise they can diverge

- determinism: the next state is a function only of the input and the current state
- non-determinism
  - many potential sources: checking the system time, multithreaded timing, etc.

Issue: recovery

Failed replicas will miss requests from clients

- need to have some mechanism for them to play catch-up after they recover

Strawman #2

Primary-backup

- clients communicate with a single replica (the primary)
  - primary chooses order of requests
  - primary updates the backups
  - primary “resolves” non-determinism
- backups detect failure of the primary using timeout
  - clients failover to a backup in case of primary failure

Issues?

Issue: failure detection

The usual problem: how long of a timeout to set for our failure detector?

- too short and primary will be falsely accused of failure
- too long and availability/performance is affected

Issue: lag

When is it safe for the primary to ACK a client's request?

- option #1: wait until all backups are updated
  - slow but safe
- option #2: once primary is updated, but before backups
  - fast but unsafe

Issue: primary election

If primary fails, which backup should become the new primary?

- issue becomes complicated in the case of multiple simultaneous perceived failures -- laggy networks or partitions, for example
- need to come to agreement on who the primary is, otherwise have dueling primaries

Issue: recovery

Same problem as with initial strawman

- once primary has failed, need to bring it back online and play catch-up with the new primary

Paxos

A set of protocols for dealing with replicated state machines

- attempts to solve several problems
  - agreeing on the order and value of inputs
  - dealing with asynchrony (both of network and of processors)
    - hence, dealing with failure (both of network and of processors)

The "synod" protocol

The basic building block of Paxos

- goal: get the system to agree on a single value
- three roles: proposers, acceptors, learners
    - proposers issue a series of rounds of proposals, suitably constrained
    - a value is "chosen" when a majority of acceptors accept it
    - sometime later, learners learn that the value is chosen

Outline

Synod

- how it works
- why it works

Replicated state machine protocol

- how it works
- optimizations

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Synod

Two phase protocol

- **phase 1:** proposer decides it wants to propose a value, and to do that, has to learn constraints on what can be proposed
- **phase 2:** proposer proposes a value, acceptors accept or reject it

Phase 1, step a

Proposer:

- selects an unused proposal number N
  - each proposer owns some subset of proposal number space
  - e.g., proposal number = localcount.proposerID
- sends "prepare" request with N to a majority of acceptors

Implications

- proposer must stably store previously used local proposer #s and proposer ID

Phase 1, step b

Acceptor:

- if acceptor receives a "prepare" request with number N, and N is greater than any prepare request to which it has responded:
    - it makes a promise not to accept any more proposals < N
    - it responds with the highest numbered proposal, if any, it has already accepted
- otherwise, do nothing

Implications: must stably store...

- highest numbered prepare request to which it has responded
- highest numbered proposal/value that it has ever accepted

Phase 2, step a

Proposer:

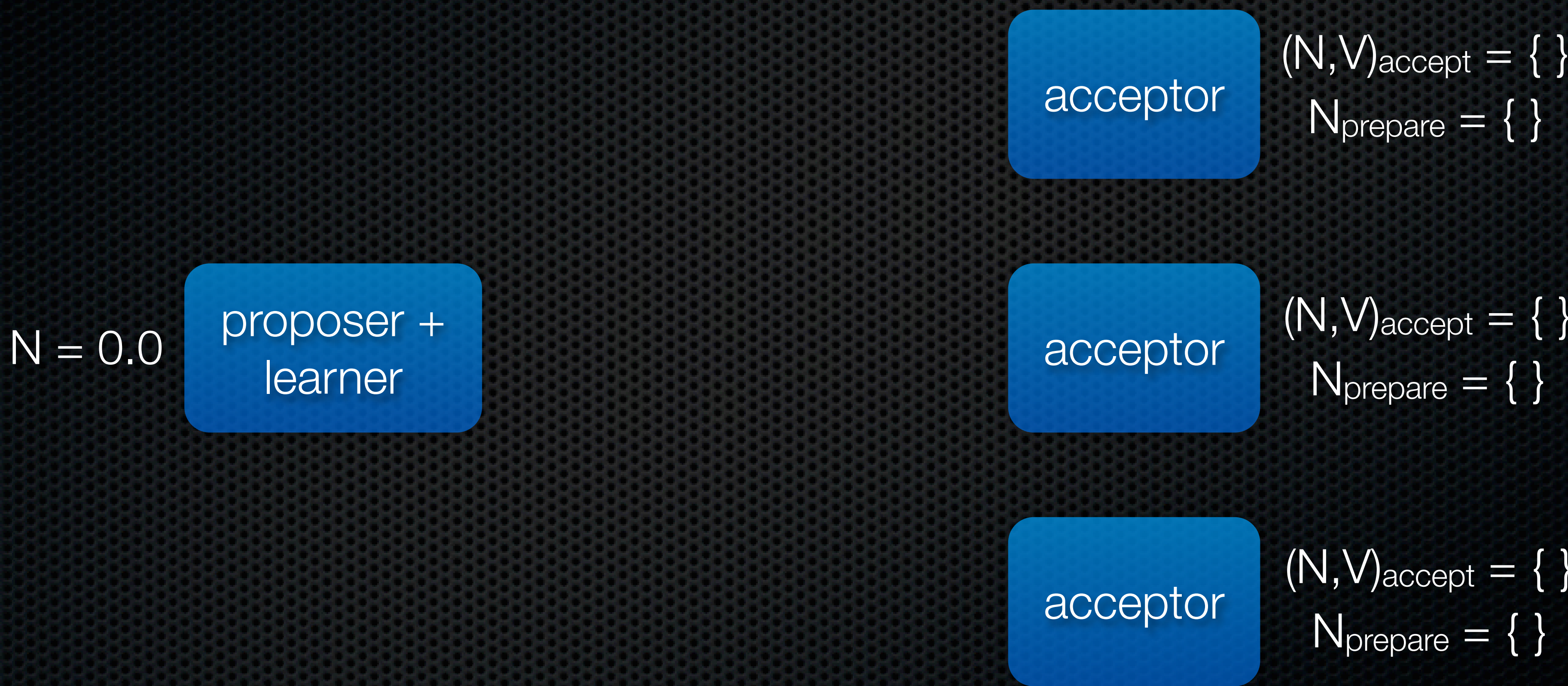
- if receives a response to step 1b from a majority of acceptors:
  - send to a majority of acceptors an “accept” request for proposal numbered N with value V
  - V is the value of the highest-numbered propoal among responses, or any value if responses reported no proposals
- else, do nothing

Phase 2, step b

Acceptor:

- if receive an “accept” request for proposal N value V:
  - accept the proposal, unless it has already responded to a prepare request having number greater than N
  - optional: inform a distinguished learner of the outcome
- else do nothing

Common case is simple



Common case is simple

N = 1.0

proposer + learner

acceptor

$(N,V)_{accept} = \{ \}$

$N_{prepare} = \{ \}$

acceptor

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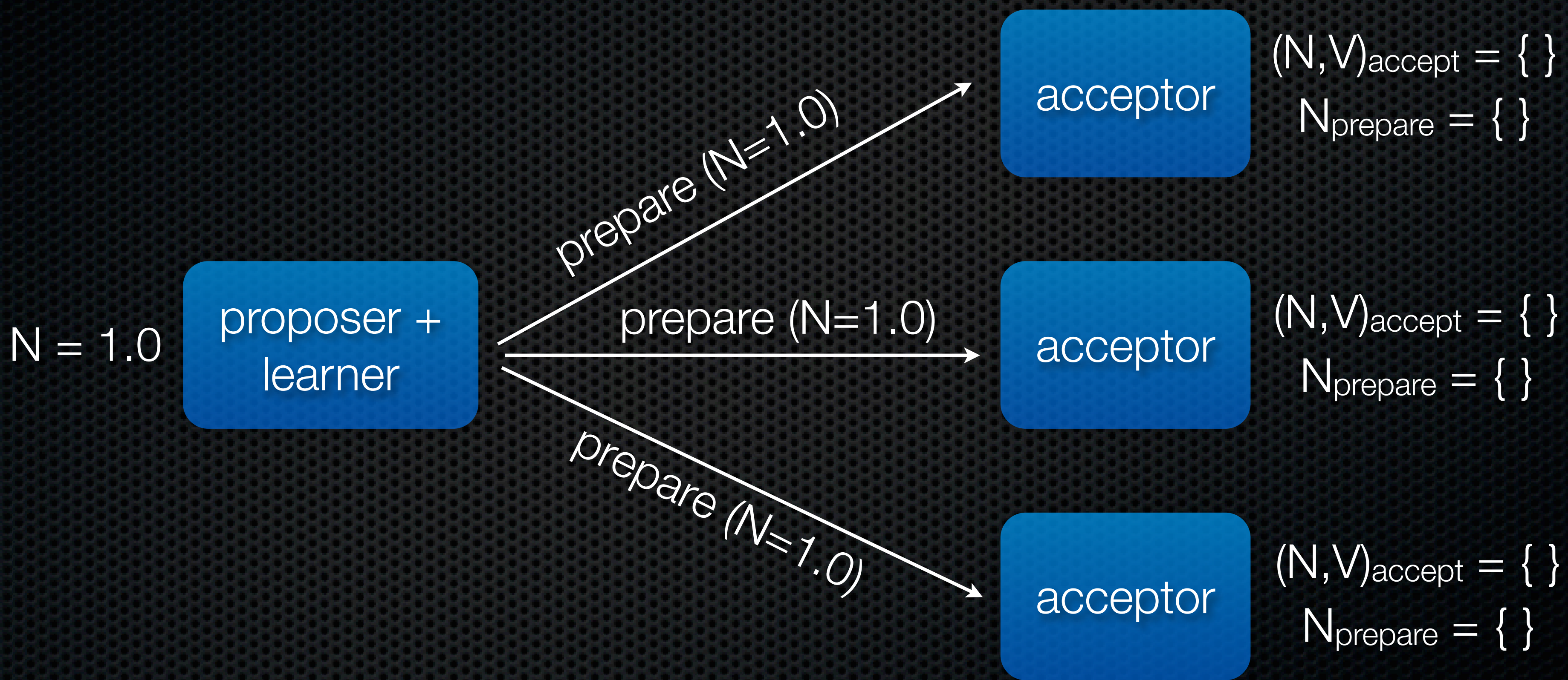

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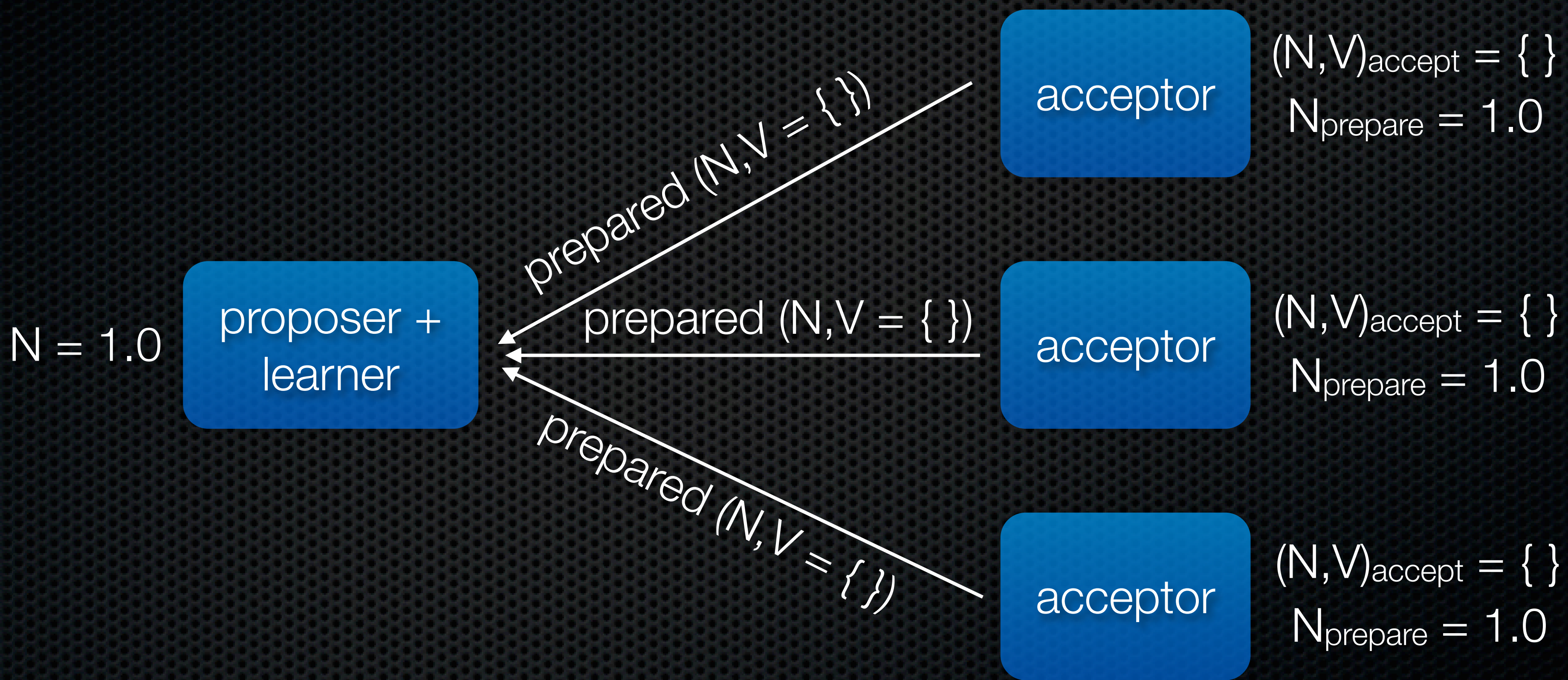

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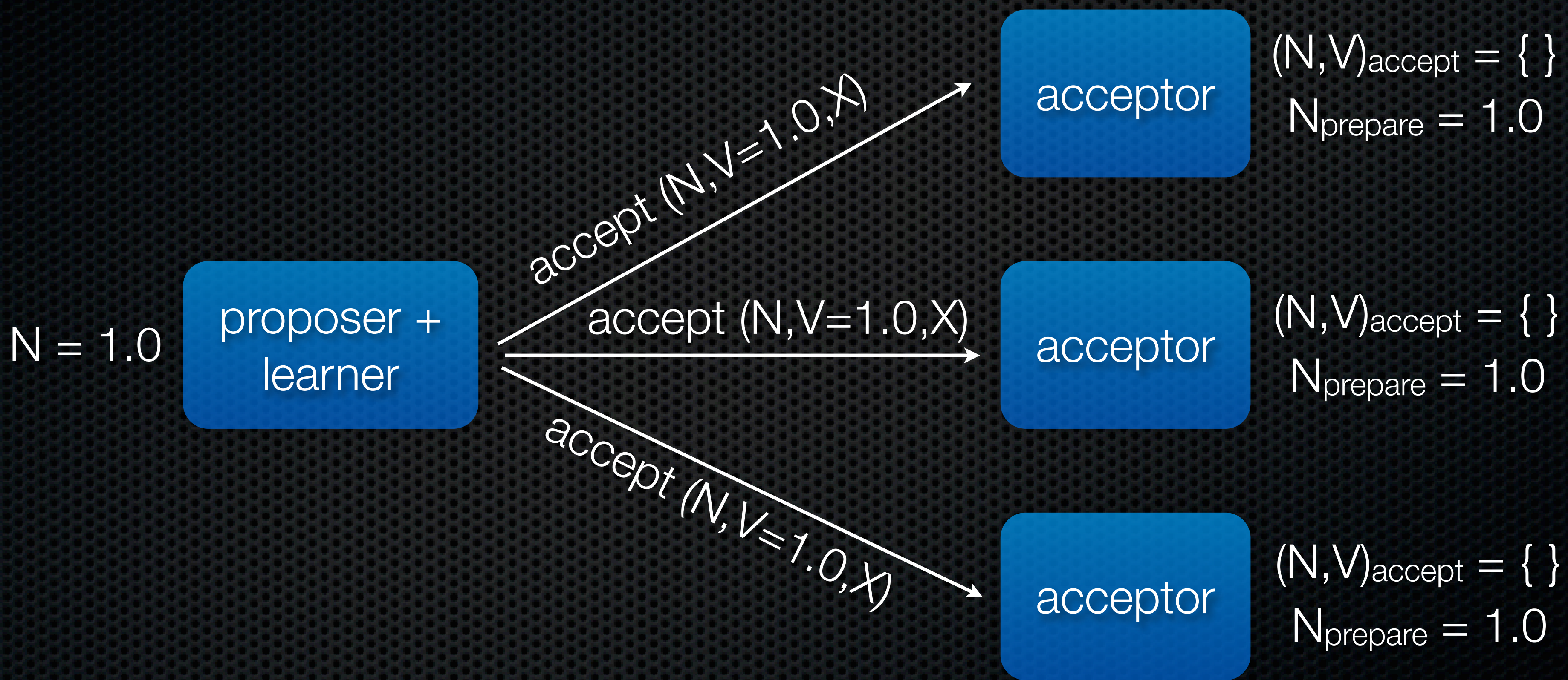

Common case is simple

N = 1.0

proposer + learner

acceptor

$(N,V)_{accept} = 1.0, X$

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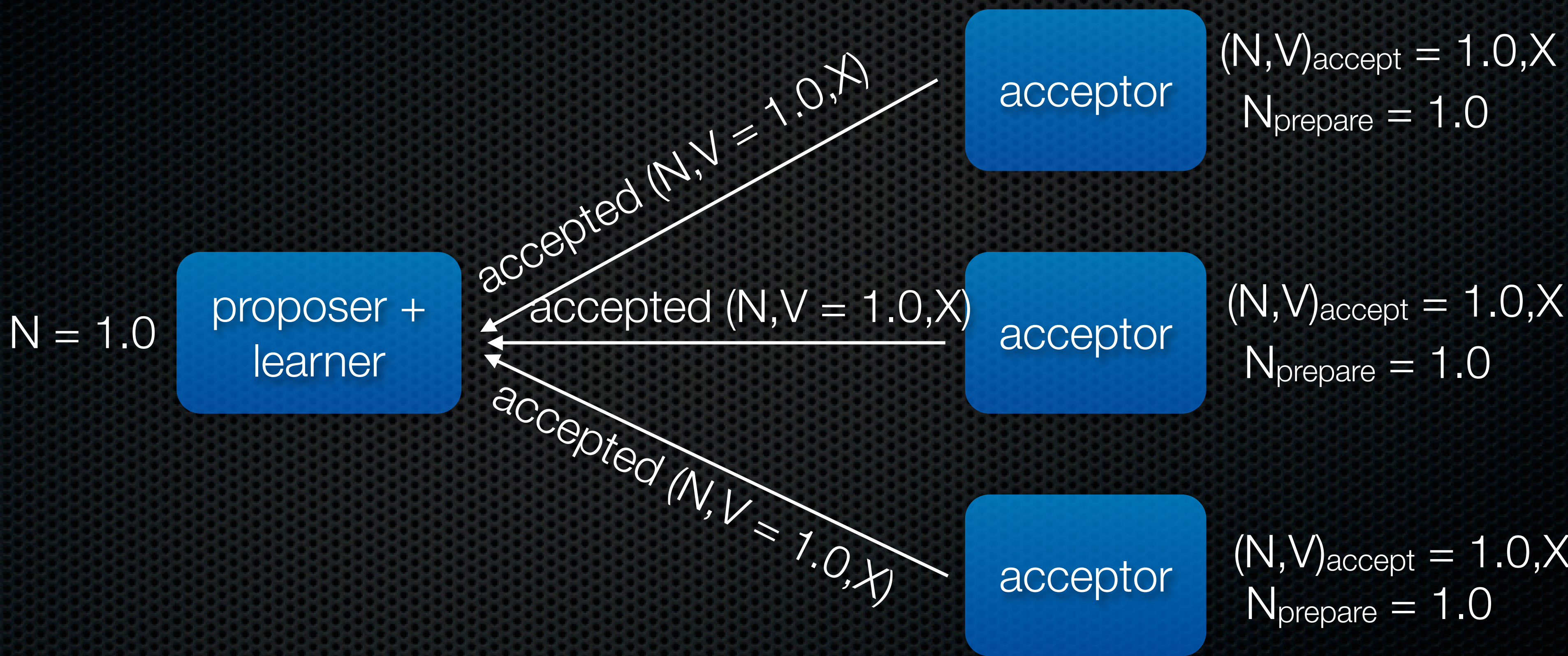

Worst case is unlikely

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N = 0.1 proposer + learner

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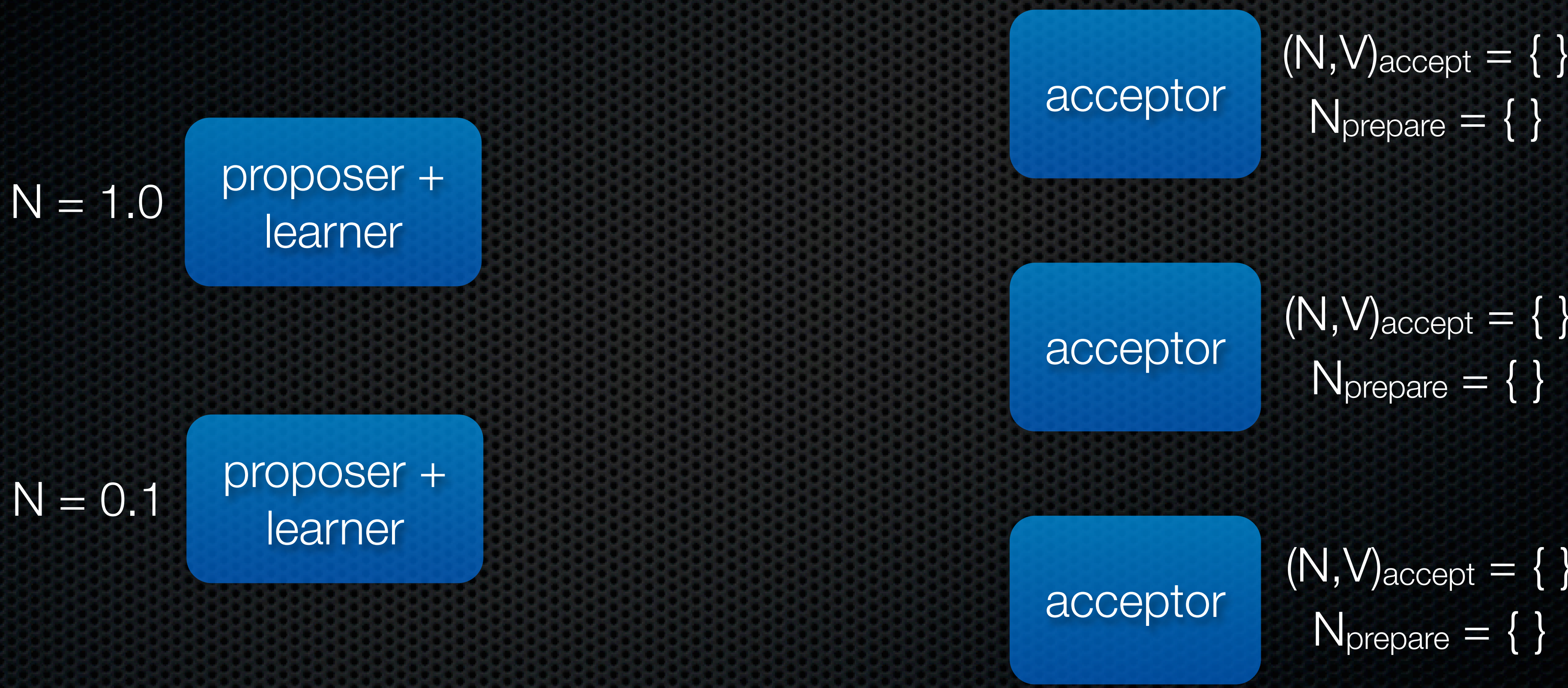

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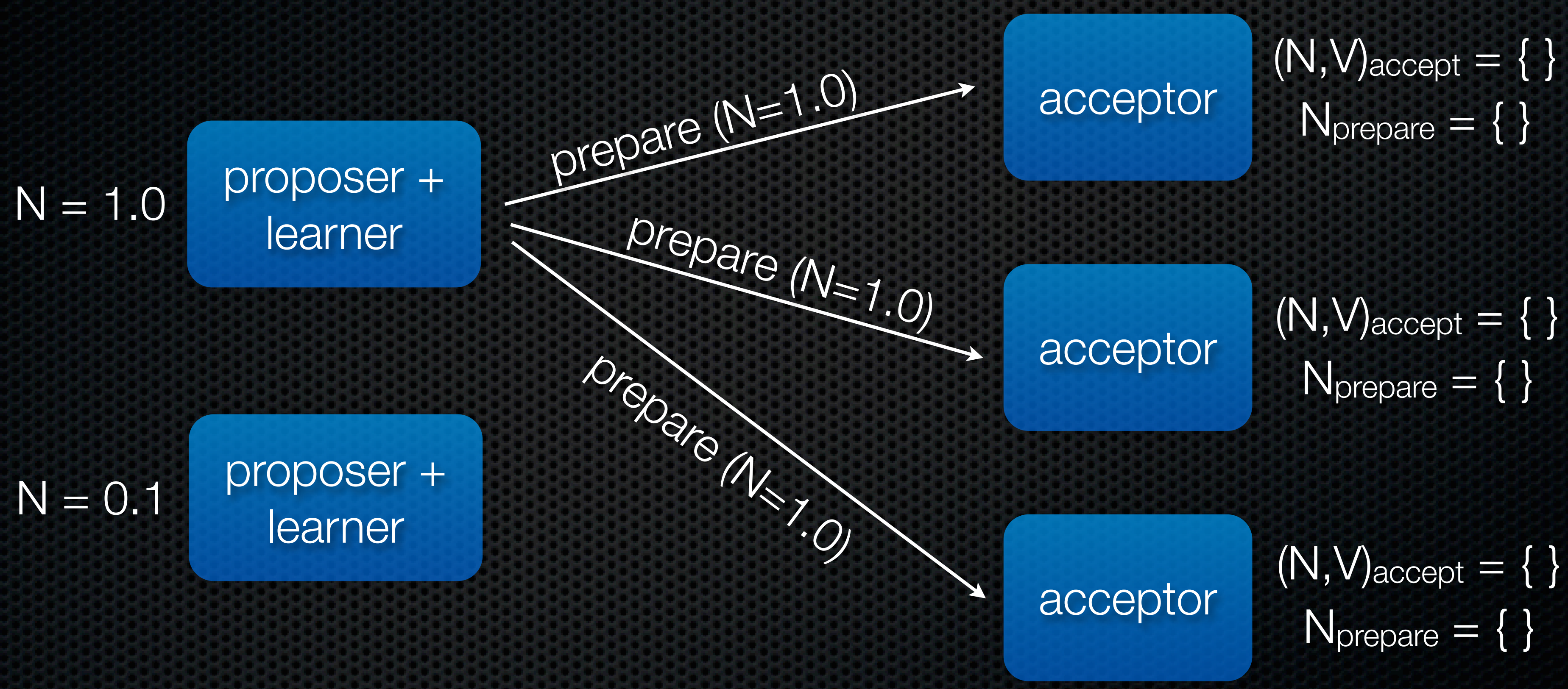

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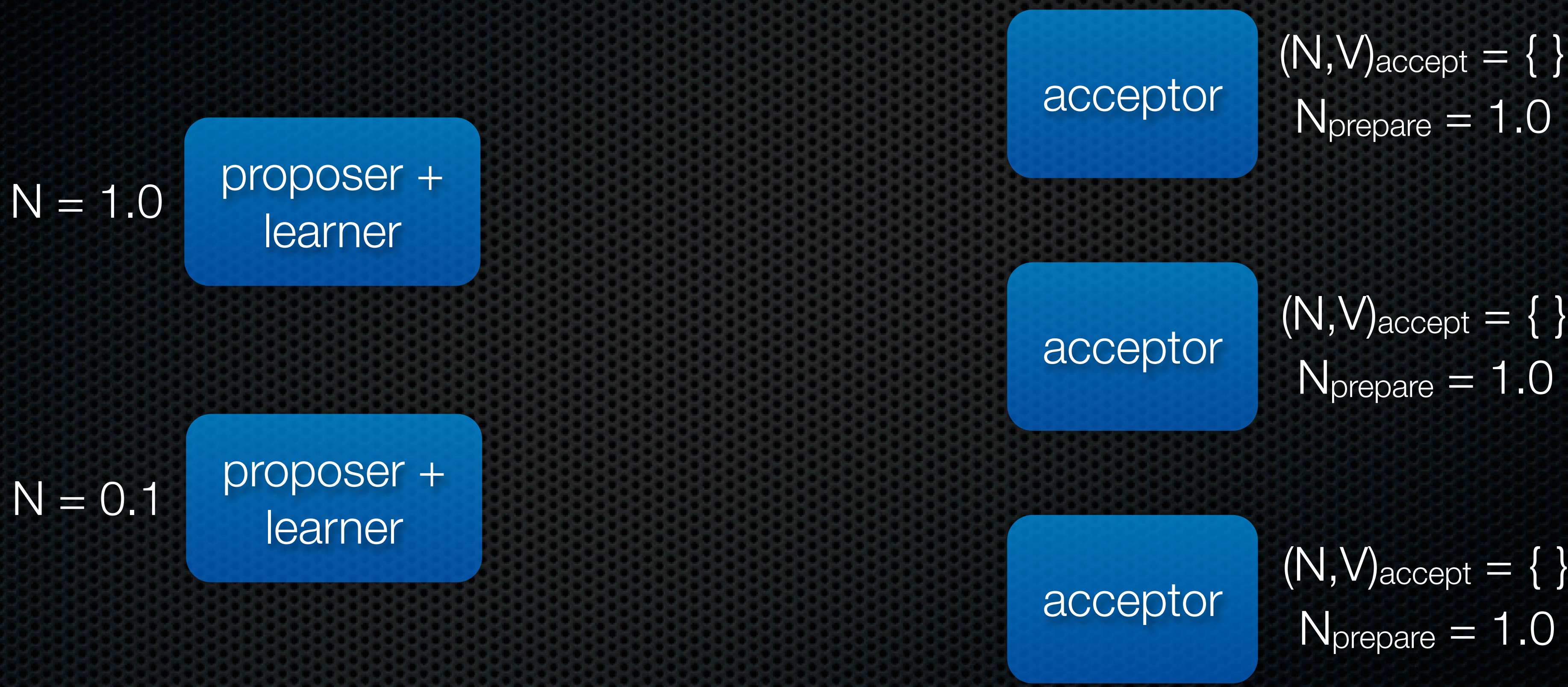

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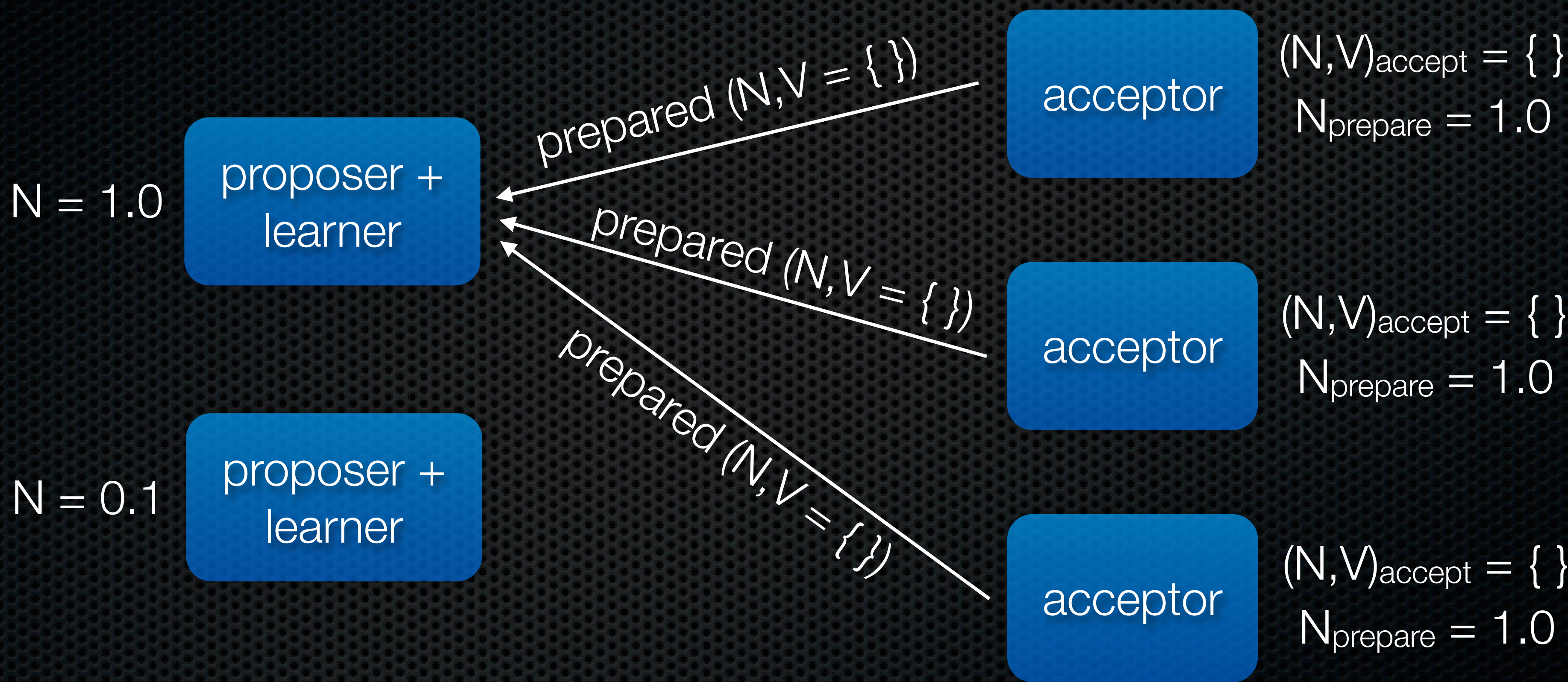

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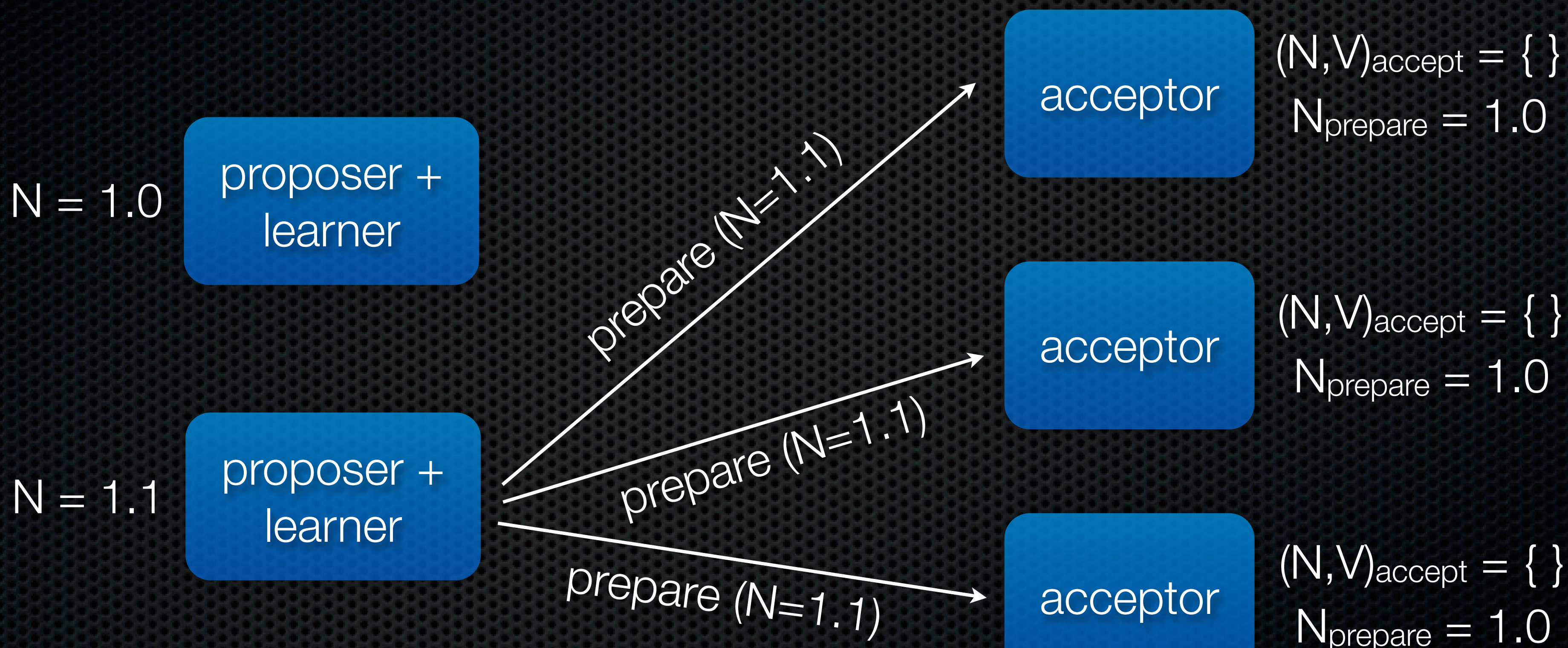

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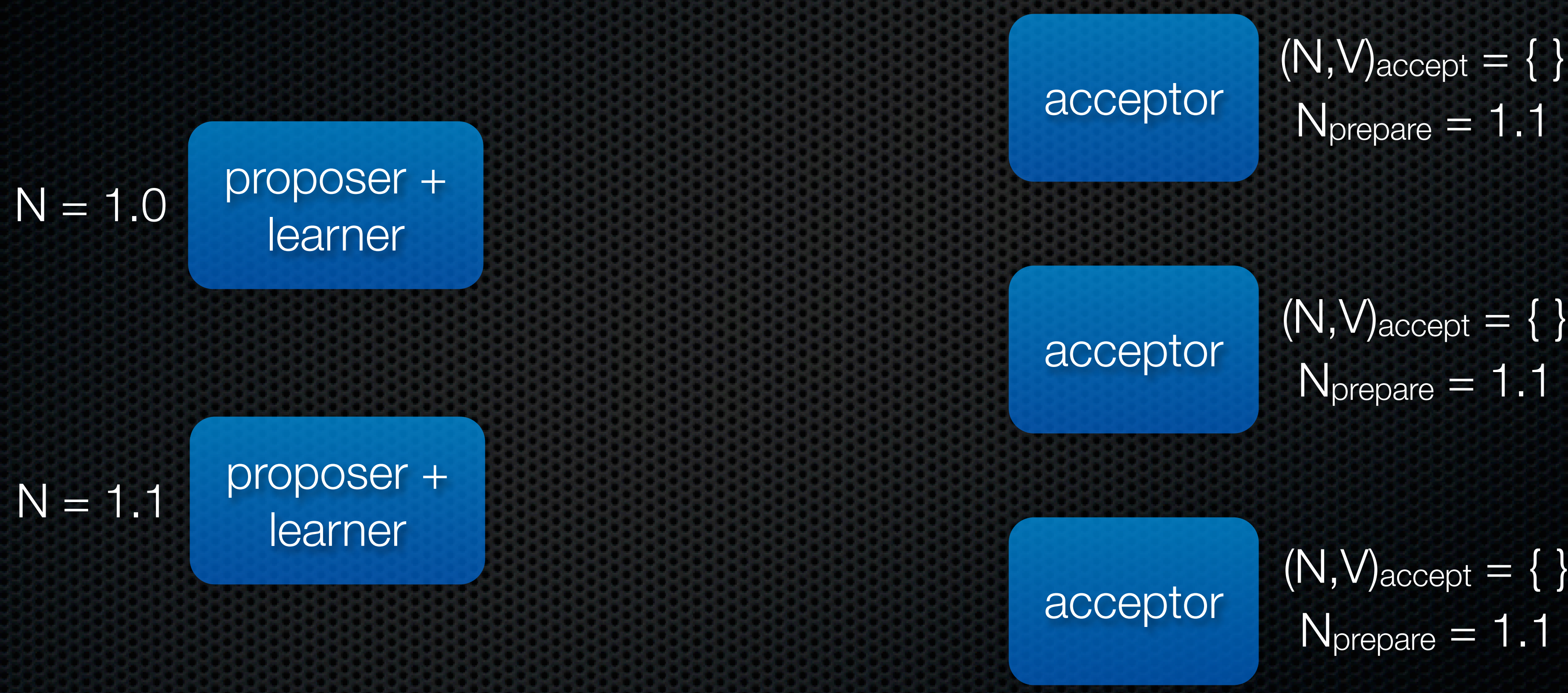

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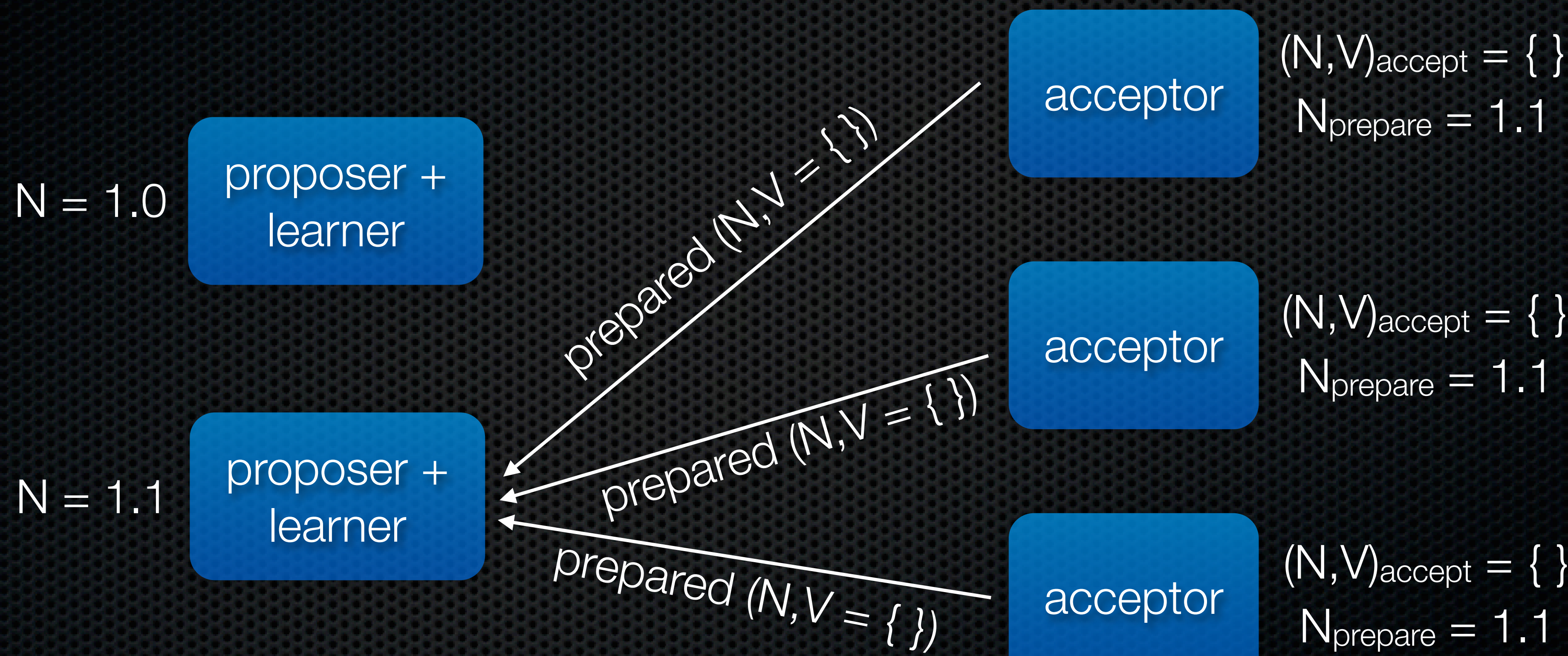

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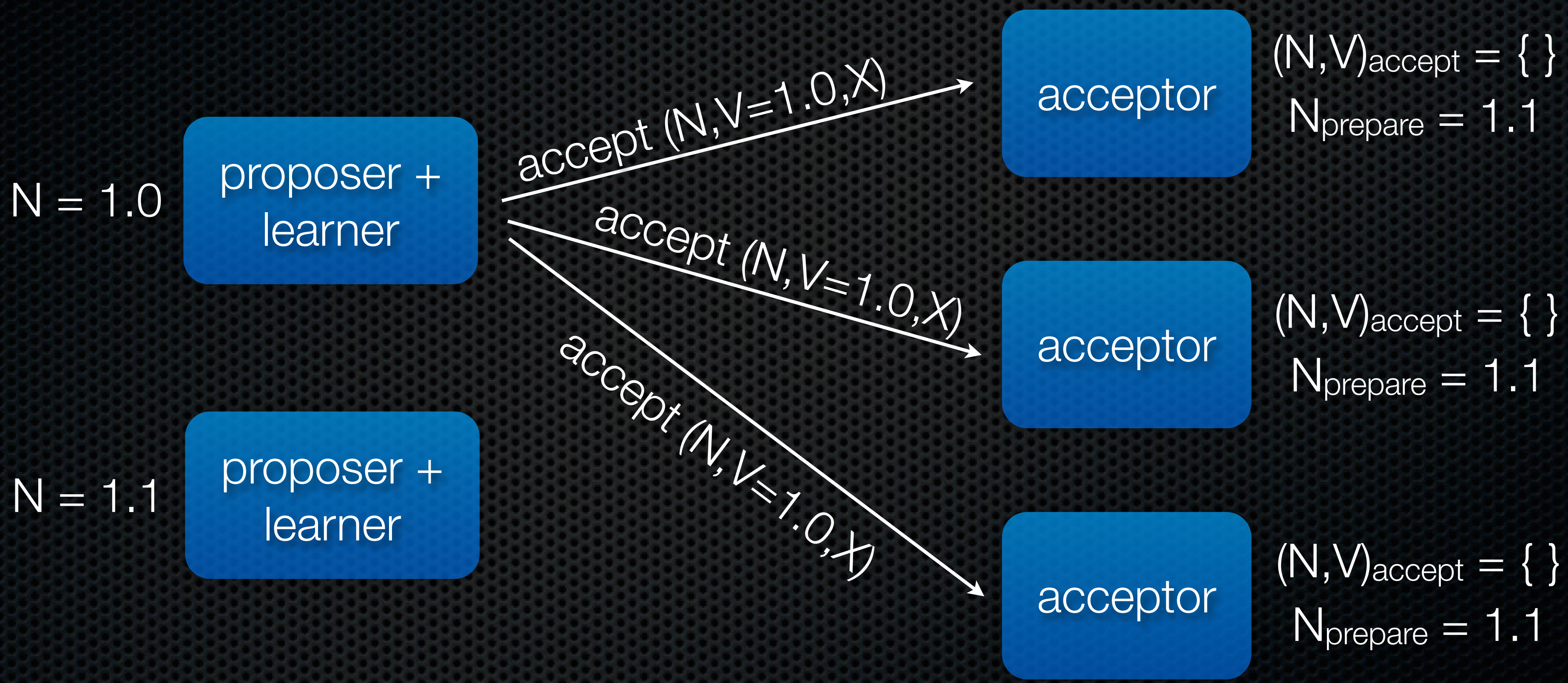

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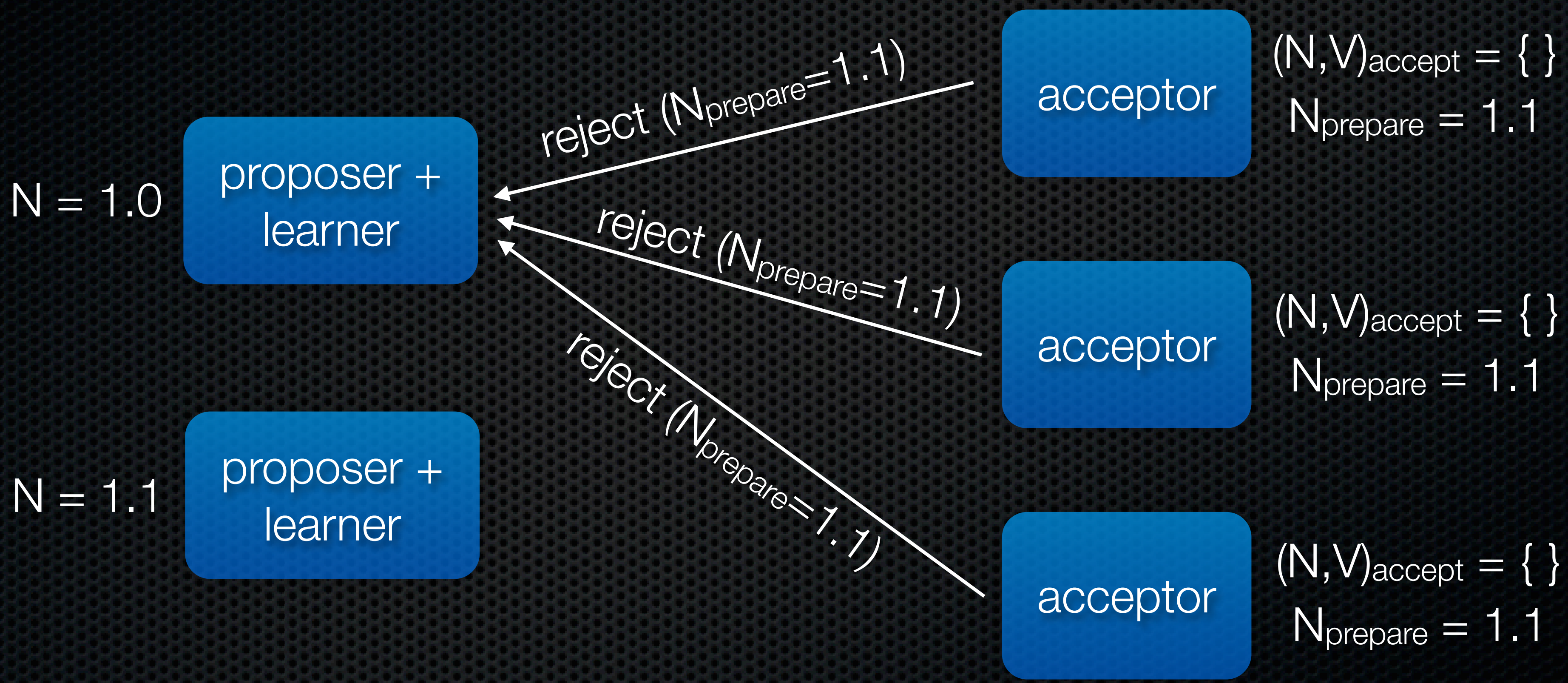

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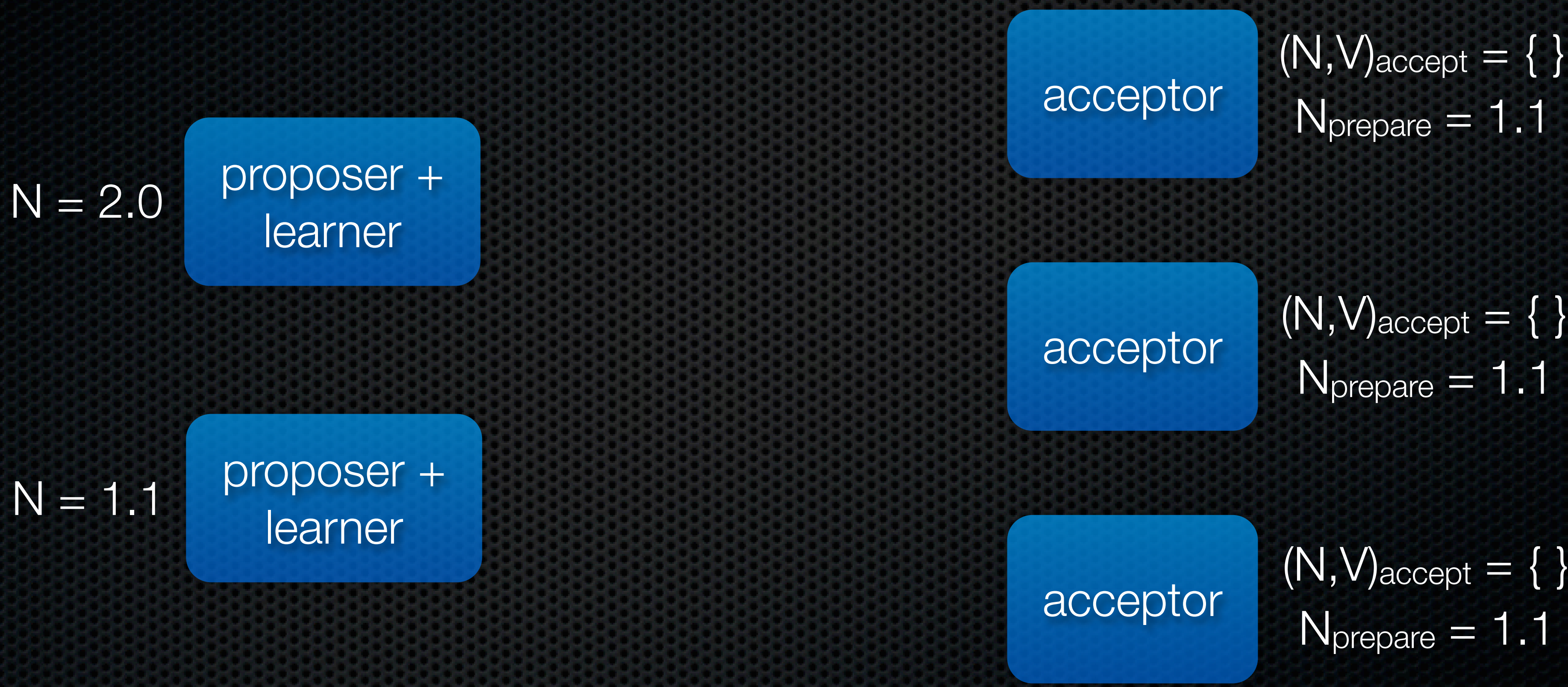

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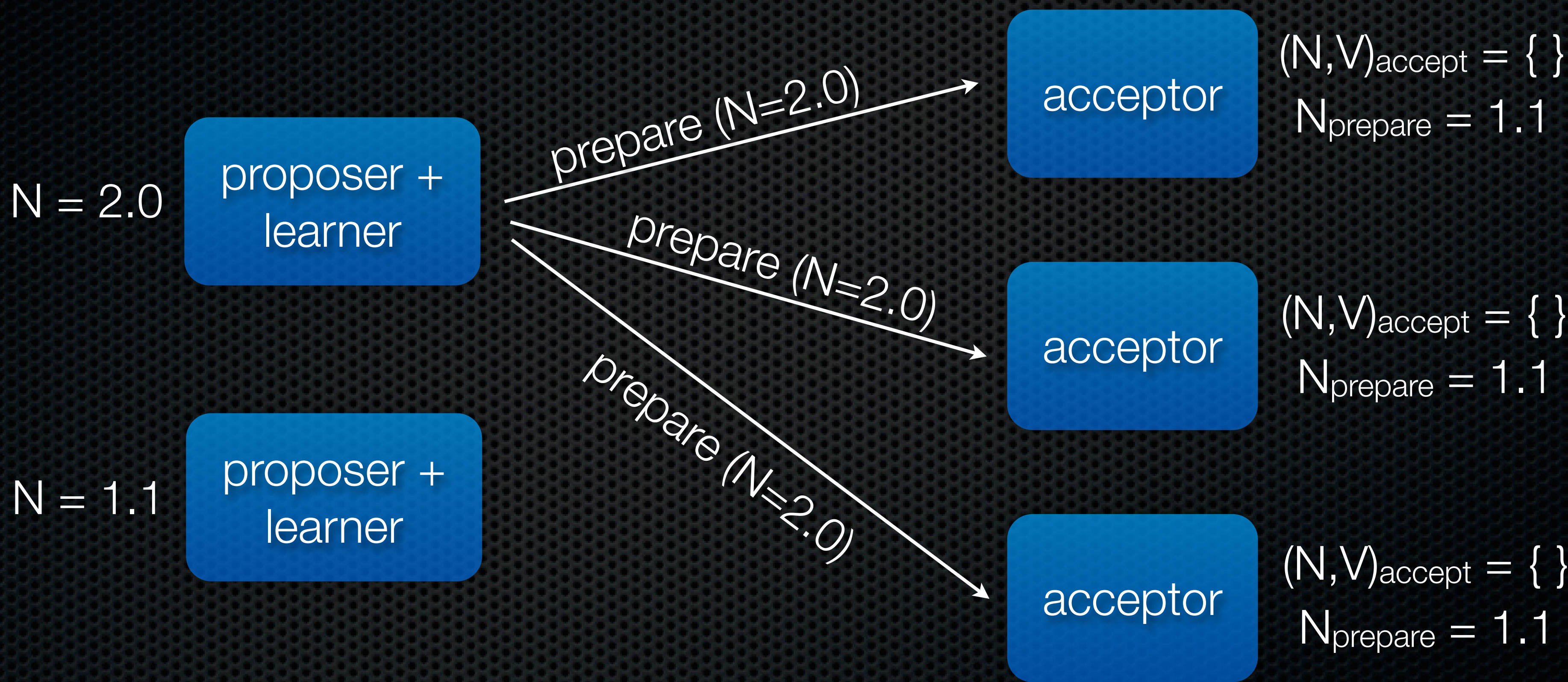

Worst case is unlikely

$N = 2.0$ proposer + learner

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acceptor $(N,V)_{accept} = \{\ \}$ $N_{prepare} = 2.0$

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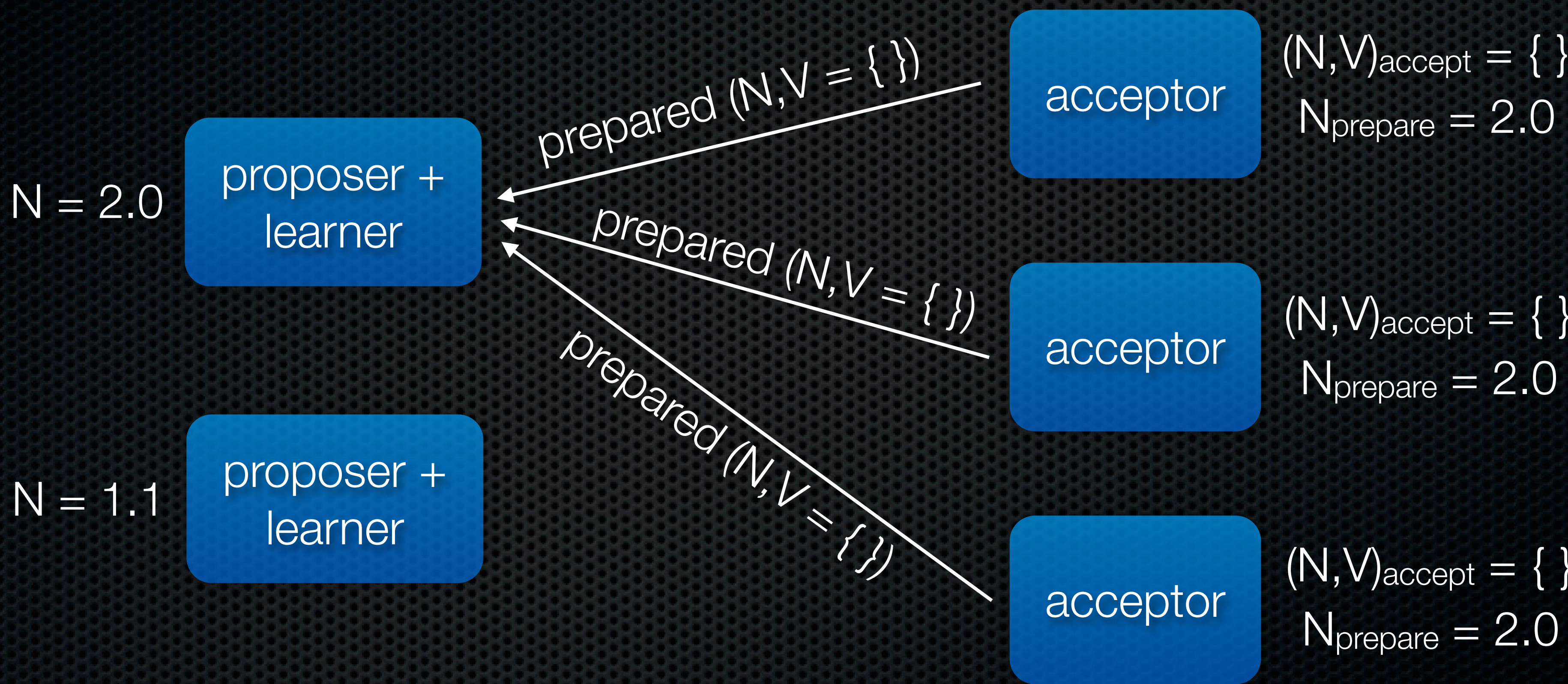

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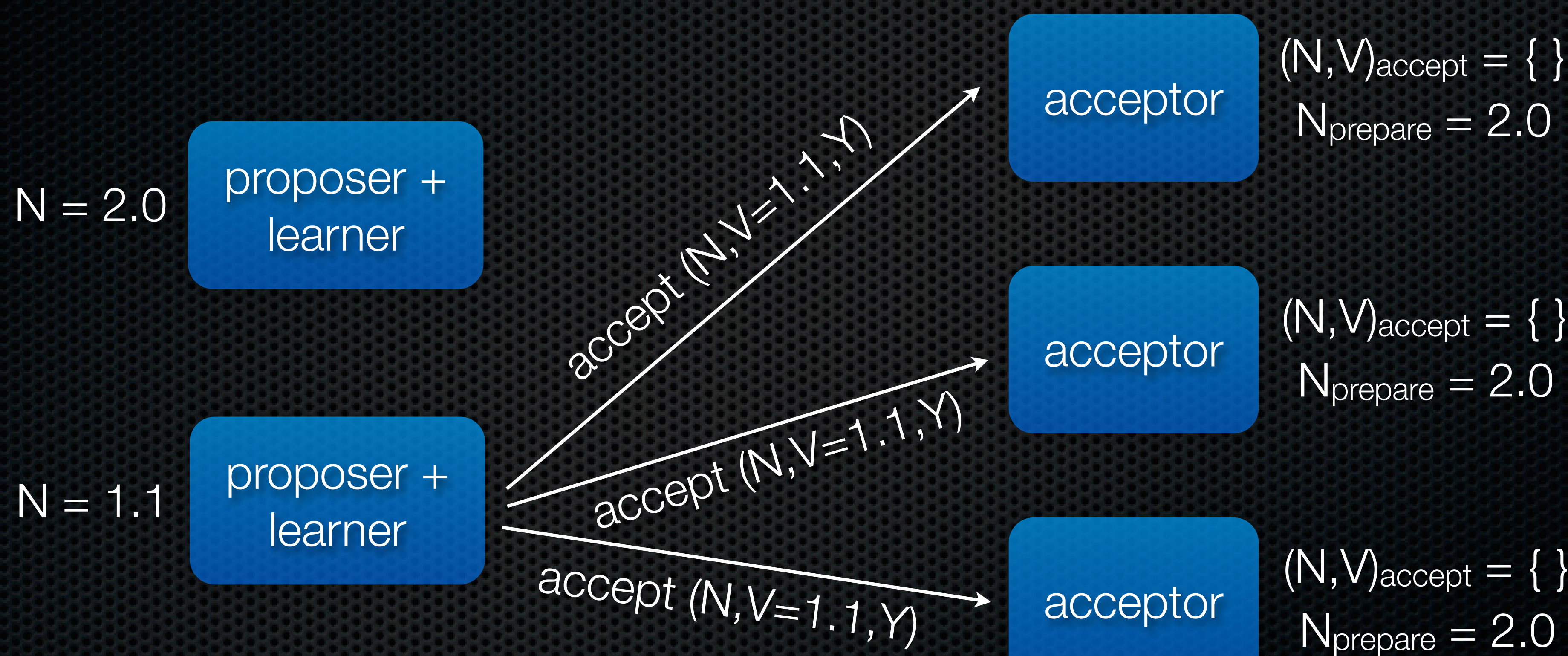

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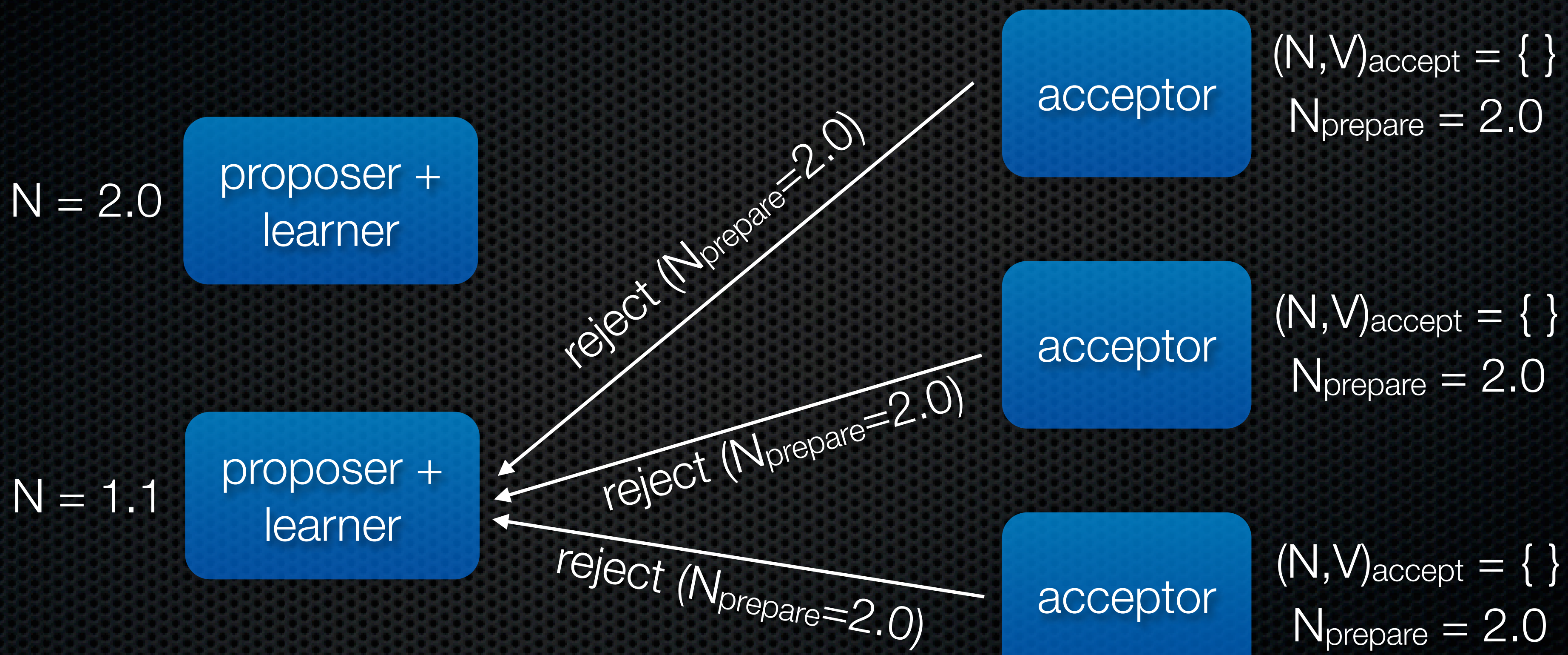

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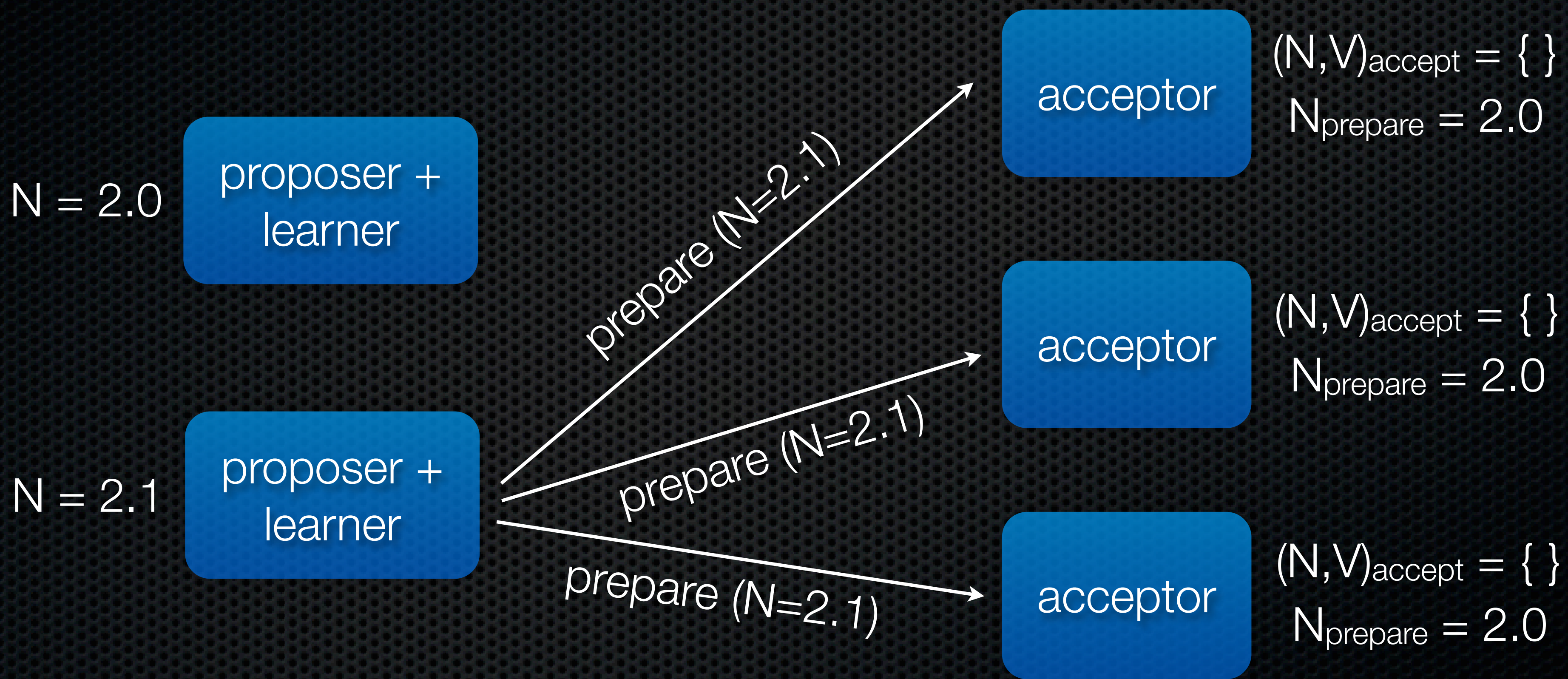

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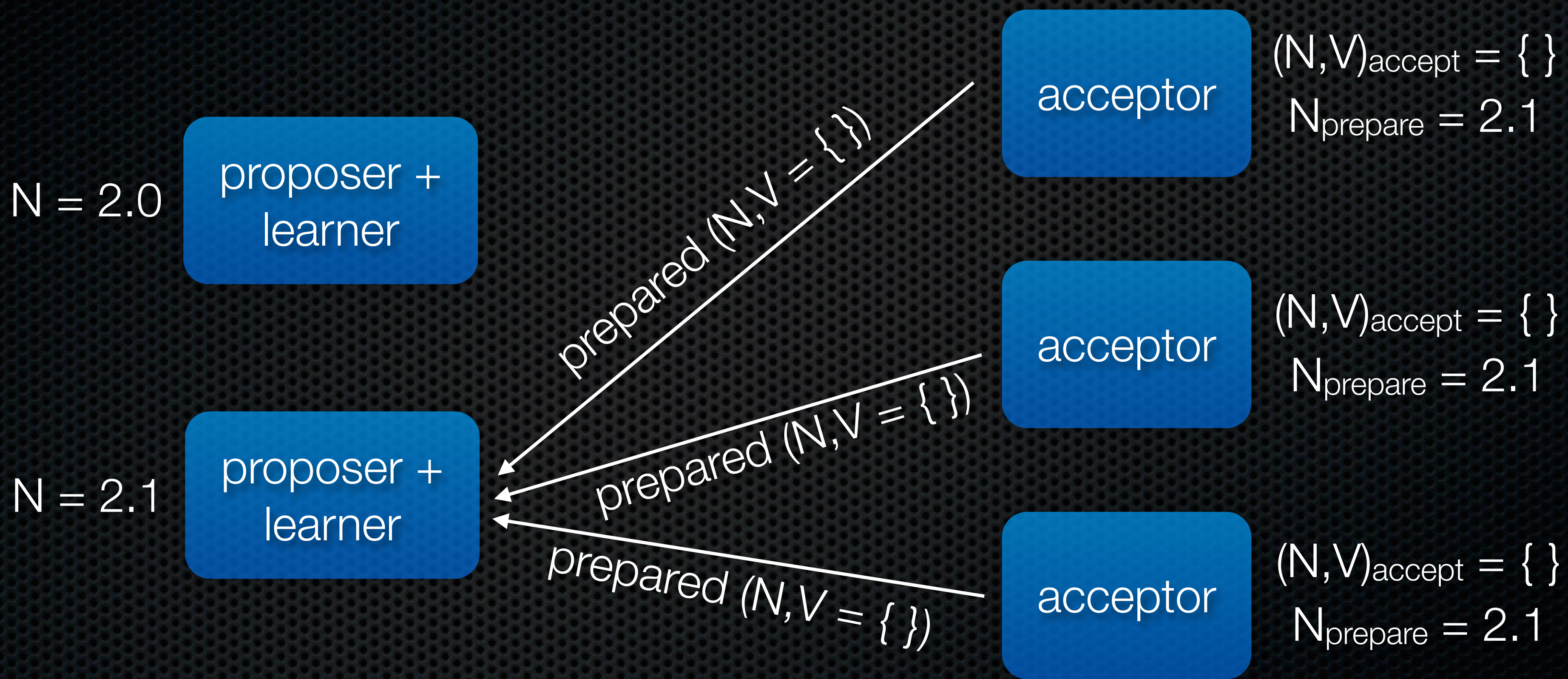

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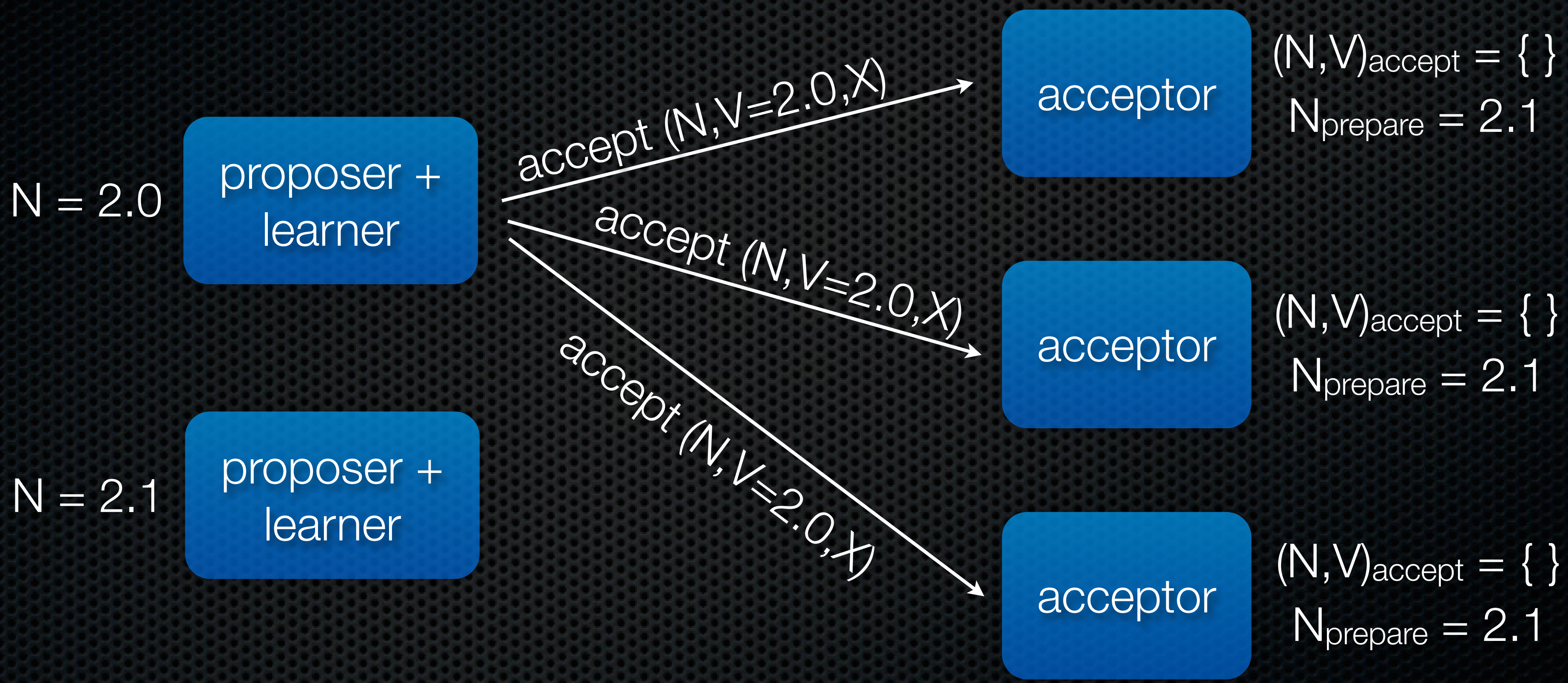

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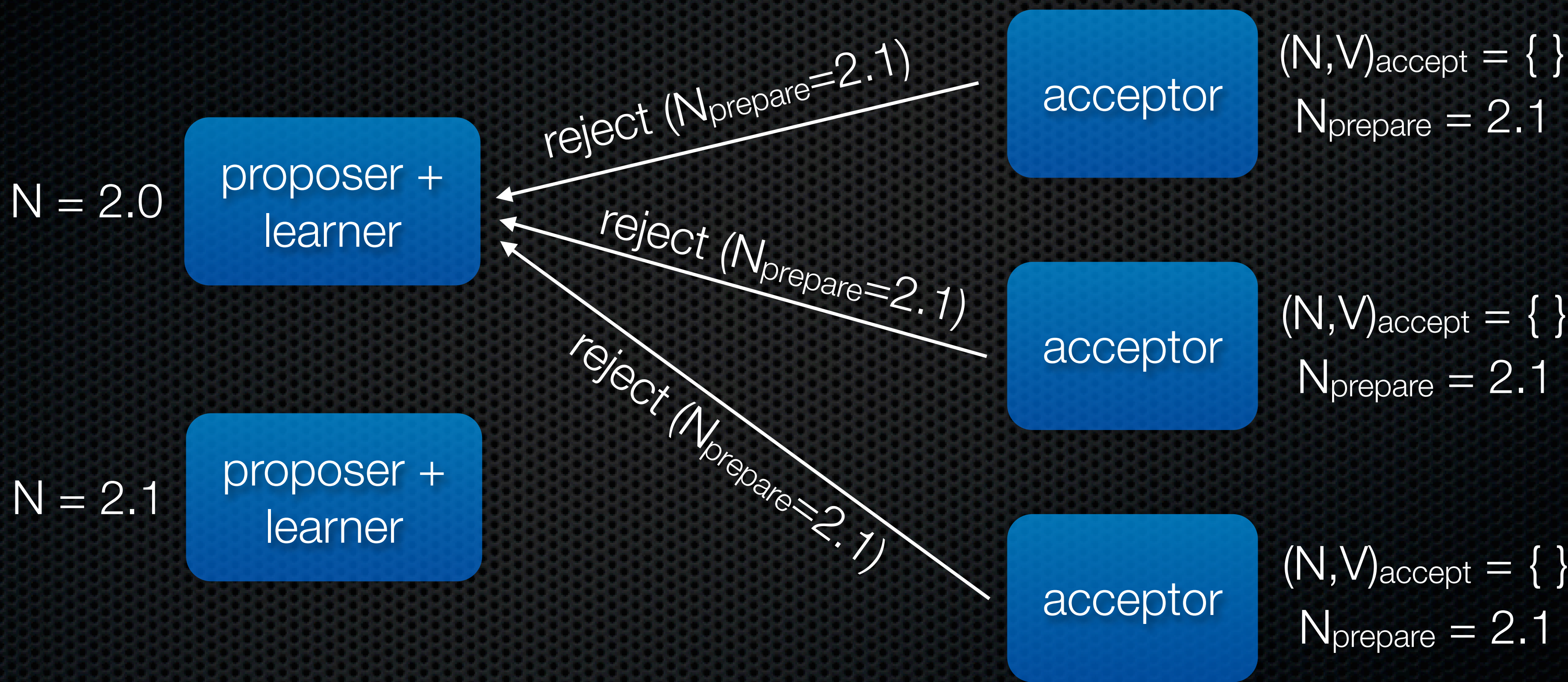

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AND SO ON...

Fun paxos games

Assume there are 5 agents, and three leaders L1/L2/L3

- leaders don’t know if a value is yet chosen

Leader L1 issues prepare in round 3.L1, and gets back:

- (2.L2, X), -, -, (2.L2, X), (2.L2, X)
    - what is the correct next step?

Fun paxos games

Leader L1 issues prepare in round 3.L1, and gets back:

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Fun paxos games

Leader L1 issues prepare in round 3.L1, and gets back:

- (2.L2, X), -, (2.L3, Y), -, (2.L2, X)
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Fun paxos games

Leader L1 issues prepare in round 3.L1, and gets back:

- { }, { }, (2.L3, Y), { }, { }
  - what is the correct next step?

Outline

Synod

- how it works
- why it works

Replicated state machine protocol

- how it works
- optimizations

Deriving paxos

Context

- assume an asynchronous system
  - messages can be dropped, reordered, delayed, but not corrupted
  - agents can take arbitrarily long to respond to messages
- assume fail-stop failures only
  - agents function correctly, or not at all

What Paxos promises

Paxos will:

- guarantee “safety” under all circumstances
  - including many simultaneous leaders, high rate of failure/recovery
- terminate under some circumstances
  - if a single leader runs by itself in a round for a long enough time period that it can talk to a majority of agents twice

Safety

"Safety" = consistency + validity

- only a single value is chosen
  - an agent never learns that a value is chosen unless it has been
- only a value that has been proposed may be chosen

Let's start deriving

Imagine a single leader exists, does phase 1a, sends out accepts in 2a, then dies.

- if a majority of agents hear 1a and 2a, the proposal must be chosen according to our termination criteria

- **HENCE**, an agent must accept the first proposal it hears

Only a single value is chosen

Assume in round M that value V is chosen

- then, every higher-numbered proposal that is chosen must have value V
  - but, a proposer can't predict if its proposal will be chosen

- **HENCE**, if a proposal M with value V has been chosen, every higher-numbered proposal must have value V

Implications

During phase 1, a proposer must find out what proposals might have been chosen already

- and if it is conceivable that a proposal has been chosen, it must select the same value for its future proposals

During phase 1, a proposer must prevent “temporally concurrent” proposals from previous rounds from being chosen

- otherwise it might not learn about them

So...

During phase 1

- acceptors must:
  - (a) report back on values they have accepted
  - (b) promise not to accept values from lower-numbered proposals
- proposer must:
  - assume the highest-numbered, accepted proposal might have been chosen, and adopt it for its next proposal in phase 2

Together, can use induction to prove safety

Why majority?

If a proposal is chosen, a majority of agents accepted the value

- any two majority sets share at least one agent
- during interrogation in phase 1, if you hear back from a majority of agents, at least one will be in that “chosen” set

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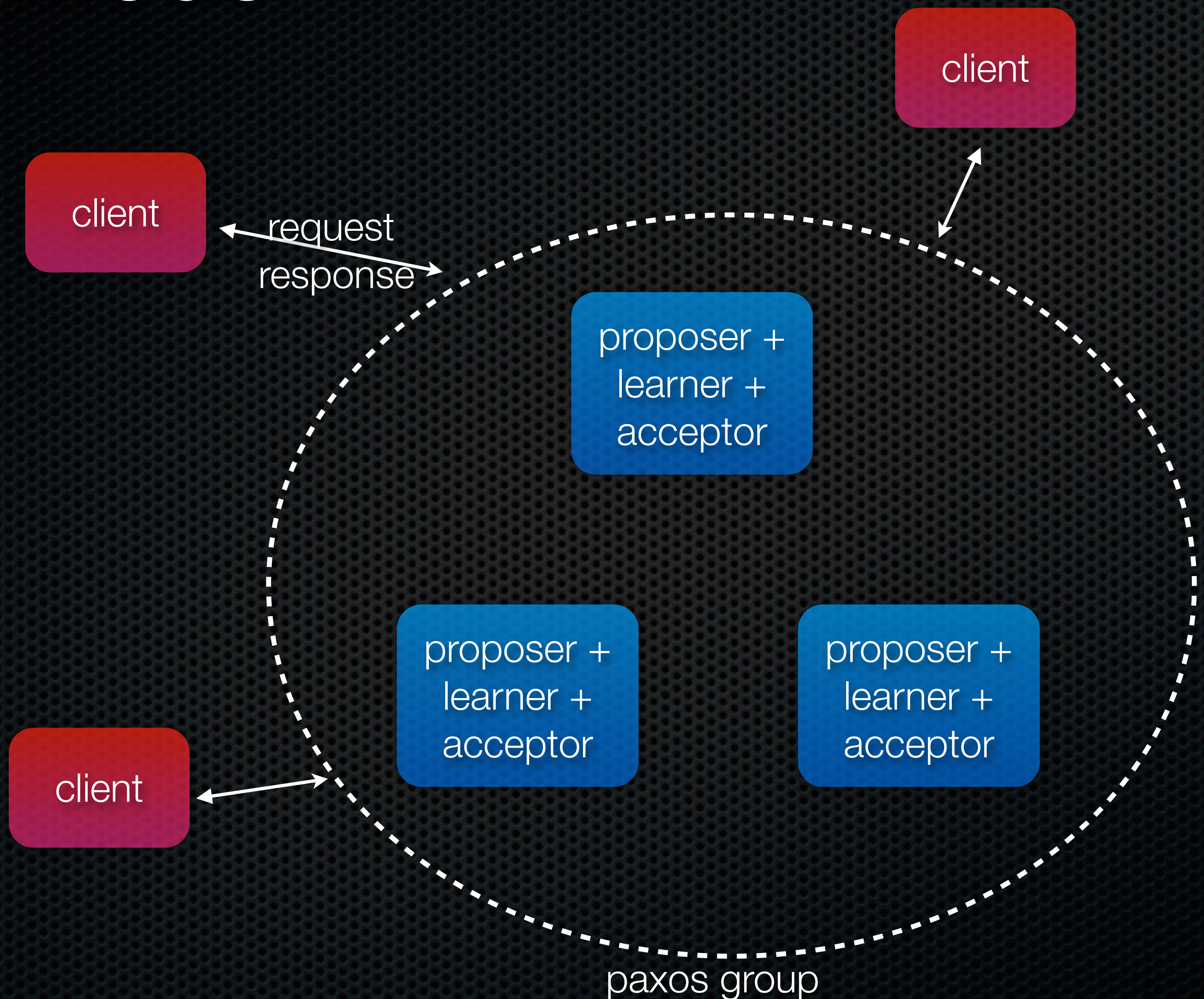
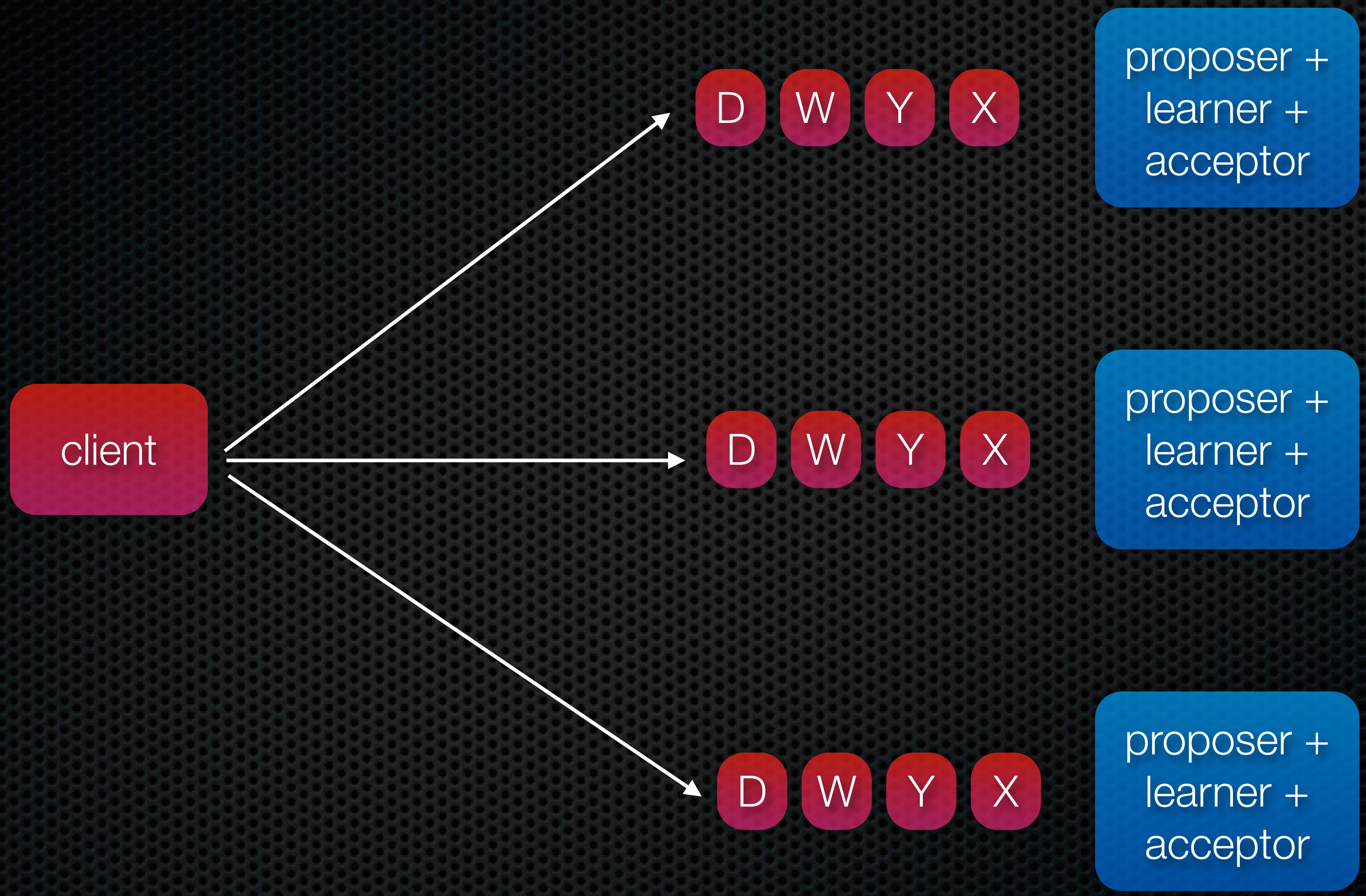
Model


client
client
request
response
proposer + learner + acceptor
proposer + learner + acceptor
proposer + learner + acceptor
client
paxos group

Model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proposer + learner + acceptor
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Implementation

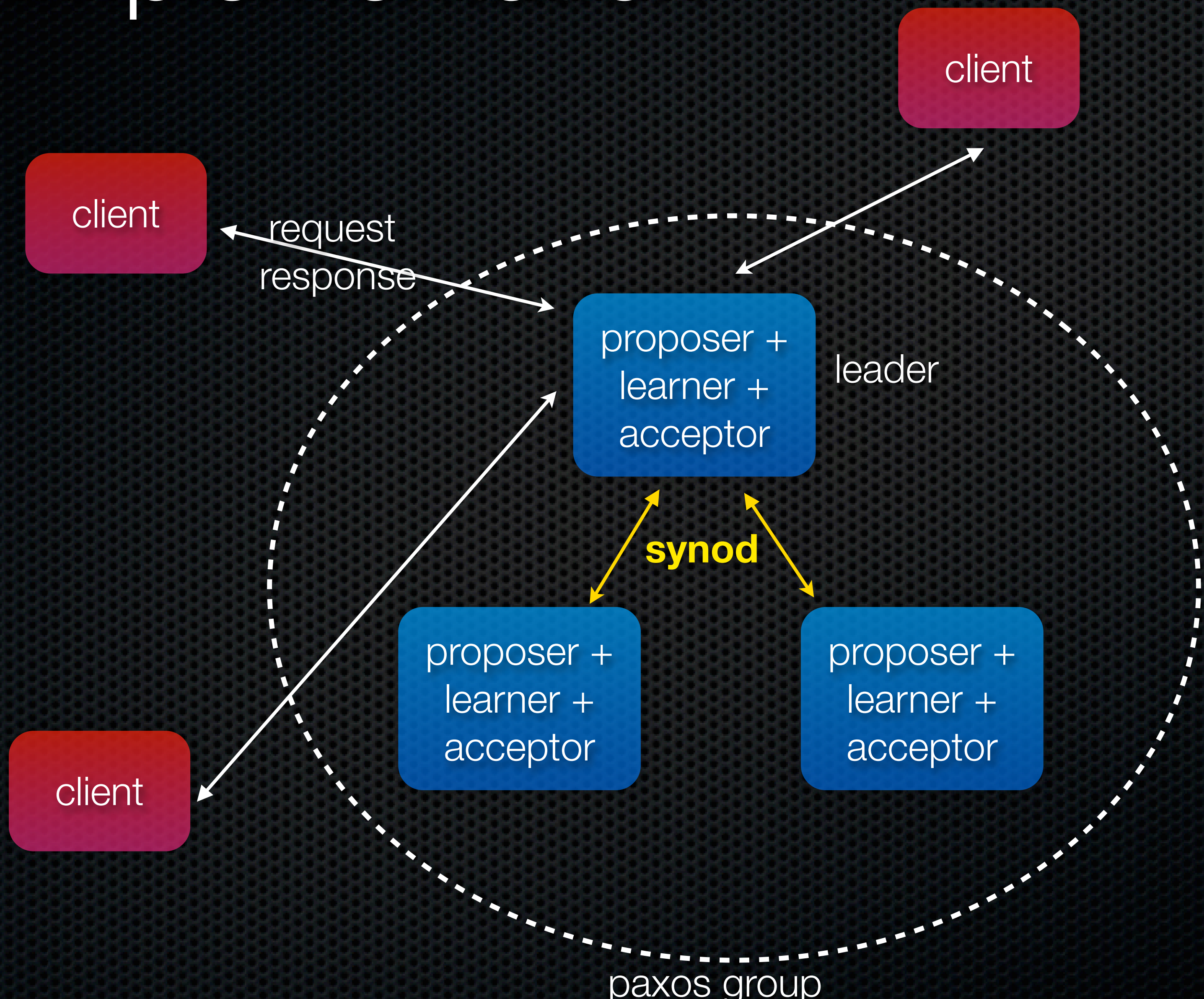
One paxos agent is elected to be the “leader”

- we’ll talk about how in a bit

All clients funnel their requests through the leader

- the leader orders the requests
- for each request, the leader runs a paxos synod instance
  - the Jth instance of paxos synod determines the Jth command in the sequence passed to the replicas

Implementation



Newly elected leader

Since L is a learner in all instances of consensus, it should already know most of the commands that have been chosen. For example, it might know commands 1-10, 13, and 15.

- it executes phase 1 of 11, 12, and 14, and of all instances 16 and larger
  - maybe it learns 14 and 16 are constrained, and 11, 12, and all commands after 16 are unconstrained
  - L executes phase 2 of 14 and 16, choosing commands for them

Stop-gap

Now, all replicas can execute 1-10, but not 13-16, because 11 and 12 haven't yet been chosen

- L can either:
    - (a) take the next two commands issued to be 11 and 12
    - (b) immediately propose a special "no-op" command for 11 and 12
- L then runs phase 2 of consensus for 11 and 12
    - once consensus achieved, all replicas execute all commands through 16

Multipaxos

Now, the leader has executed phase 1 for all open slots

- it can just proceed to phase 2 for those slots
- “short-circuit” the two-phase protocol in the common case

On leader failure...

Any of the surviving agents can self-promote to leader

- do so by running phase 1
- paxos synod takes care of multiple concurrent self-promotions
- if you get your value chosen, you're the new leader, otherwise, step back

Membership changes

We need to distinguish between:

- temporary failure plus eventual recovery
- permanent failure leading to membership change

Membership change requires consensus

- use Paxos to agree on membership change proposals