CS6213: Special Topics in Distributed Computing

Distributed Consensus

Consensus

- *Common meaning*:

  a way for a **set of parties** to come to a **shared** agreement.

- *In distributed computing*: ensuring that among the values proposed by a collection of processes, a ***single one*** is chosen.

  - Uniformity: Only a *single* value is chosen
  - Non-triviality: *Only* a value that has been proposed may be chosen
  - Irrevocability: Once *agreed* on a value, the processes do not change their decision.

Why Consensus?

Why Distributed Consensus is difficult?

- Arbitrary message delays (asynchronous network)
- Independent parties (nodes) can go offline (and also back online)
- Network partitions
- Message reorderings
- Malicious (Byzantine) parties

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Reaching a Consensus

(and constructing a protocol for this)

Waa Cow!
Sapore
Hwang's
Cendana College
College of Alice & Peter Tan (CAPT)
Café Agora
CAPT Multipurpose Hall
USP Office
University Scholars Programme, National...
Cinnamon College
Yale-NUS College
Tembusu College
Education Resource Centre
University Town, NUS
Starbucks
The Shiok Shack
bluPort - NUS UTown
UTown Residence
South Tower
Town Green
FairPrice Xpress NUS
Stephen Riady Centre
National University of Singapore...
CREATE Tower NUS
National Research Foundation Singapore
Campus for Research Excellence and Technological Enterprise
Berlin Wall Fragments
Church of The Holy Cross
NUS High Boarding School
NUS High School of Math and Science
PCF Sparkletots Preschool. Clementi...
Clementi Rd
Clementi Ave 1
College Ave West
College Ave E
AYE (Toll road)
Folkestone Rd
Dover Rd
St Margaret's Rd
Maidstone Rd
Sandwich Rd
Deal Rd

Reaching a Consensus on where to have a dinner

Waa Cow!

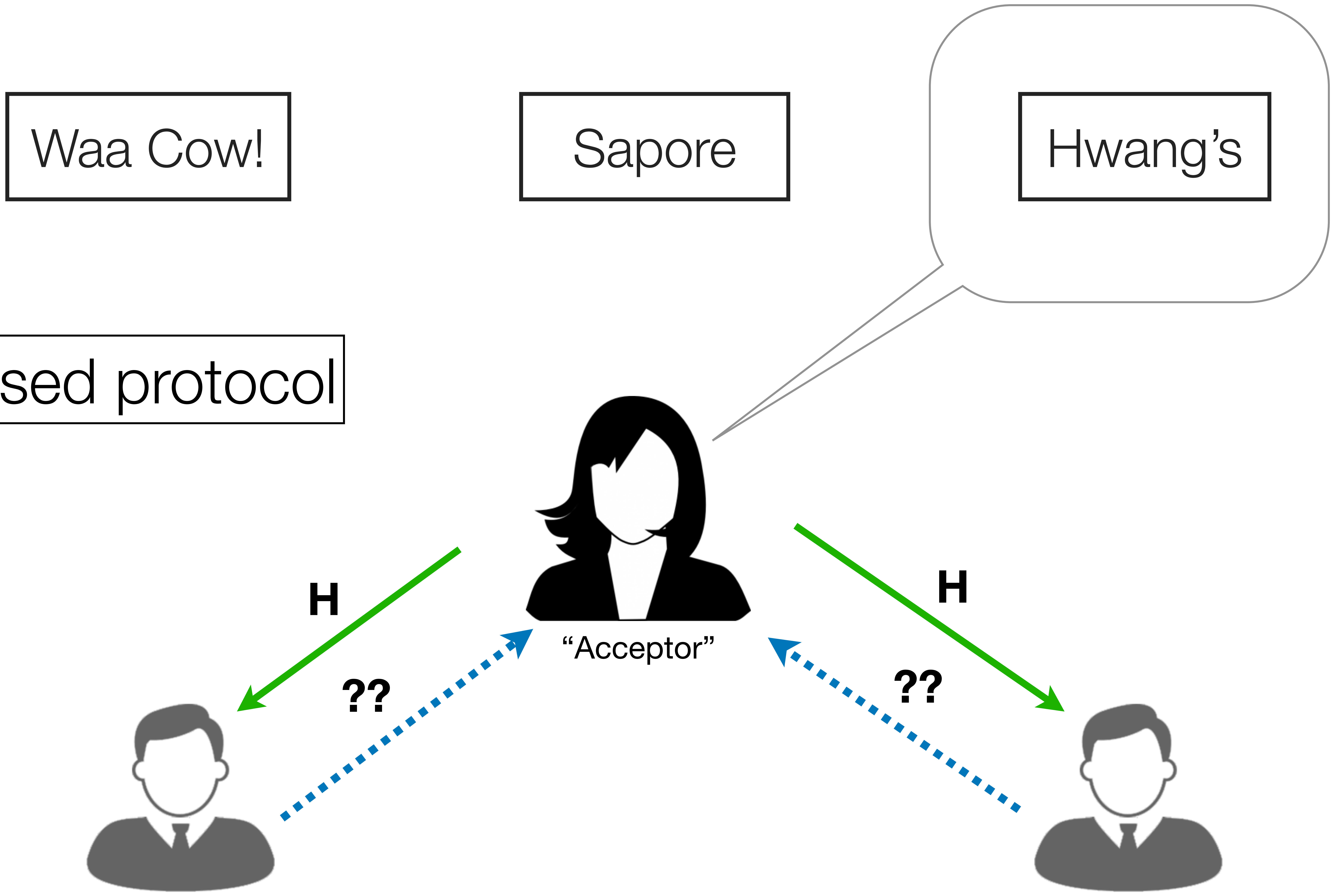
Sapore

Hwang’s

Waa Cow! Sapore Hwang’s

?? ??

Centralised protocol



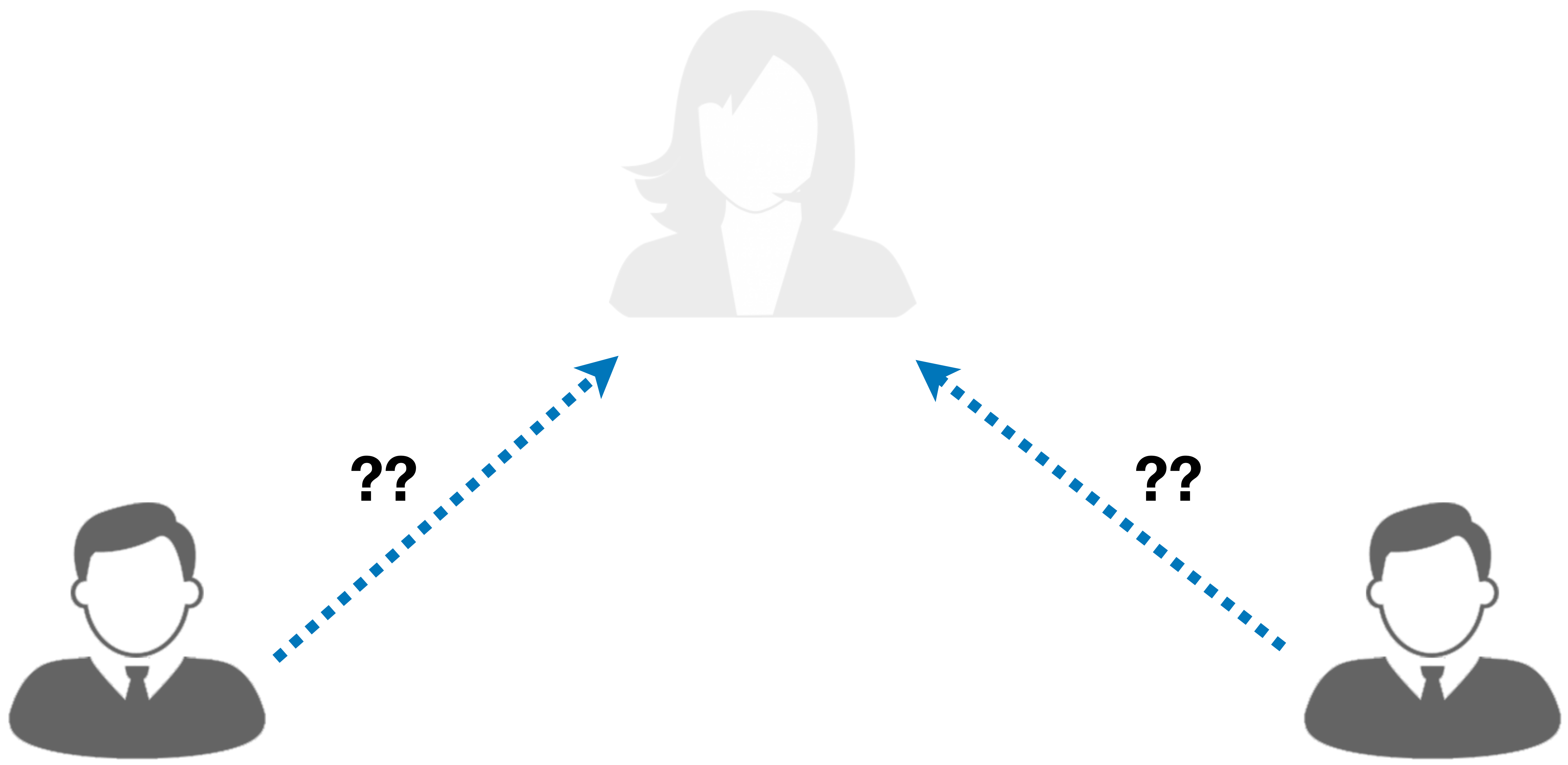
Problem 1

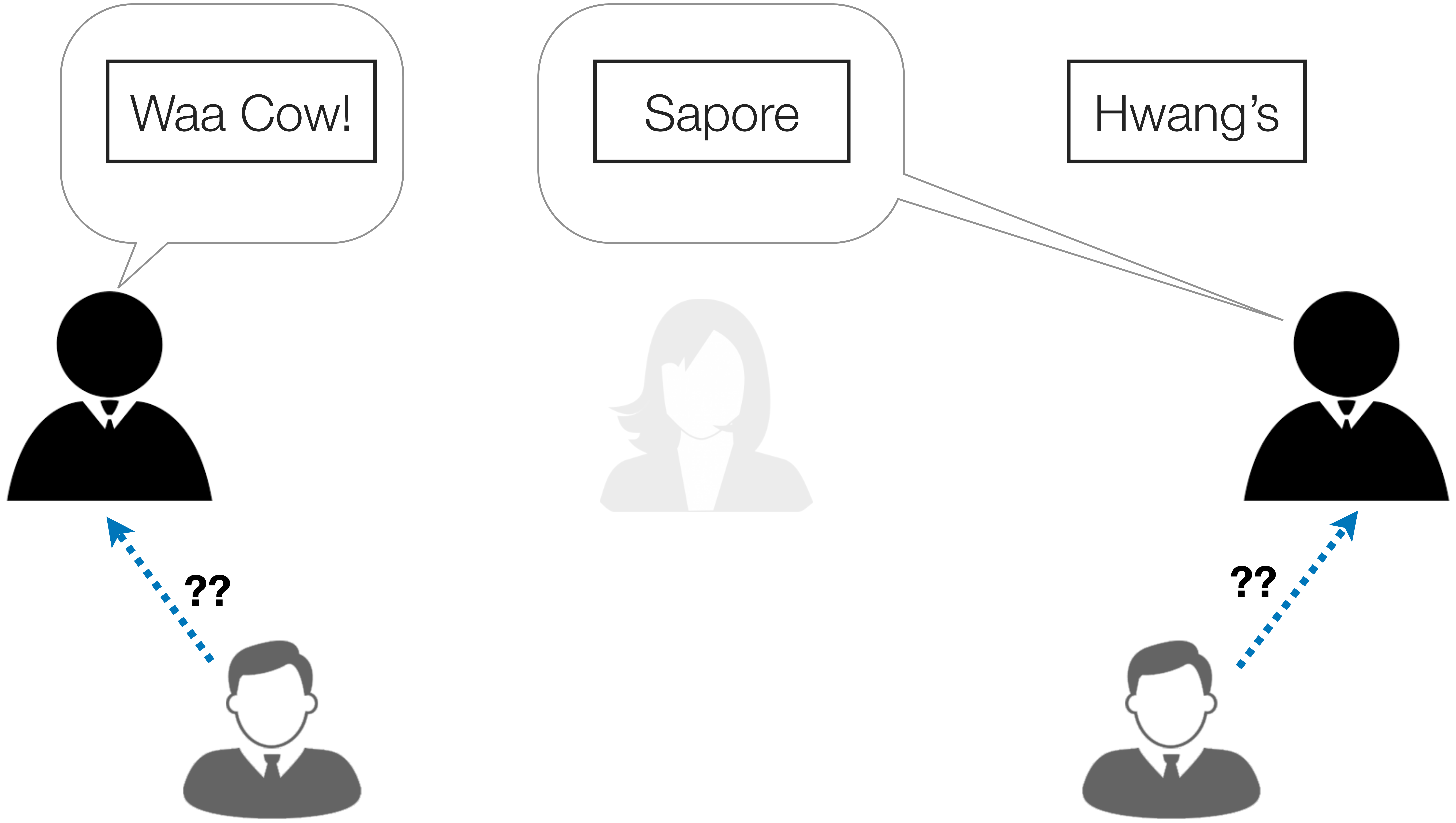
A single acceptor can *go offline* or *take forever* to answer.

Waa Cow!

Sapore

Hwang’s




Waa Cow!
Sapore
Hwang's
??
??

Problem 2

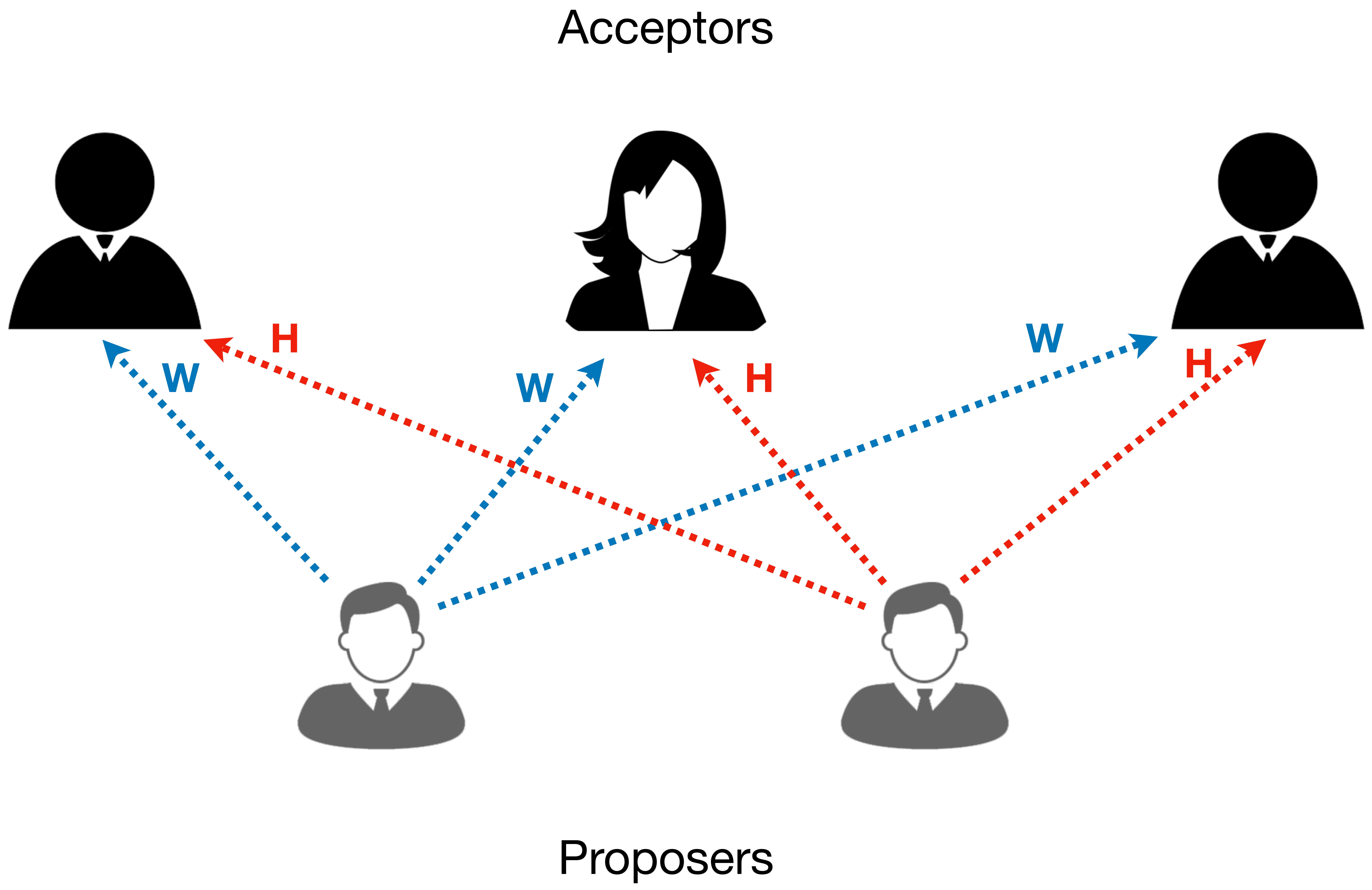
Multiple *acceptors* might disagree on the outcomes:

now they need to *reach a consensus* themselves.

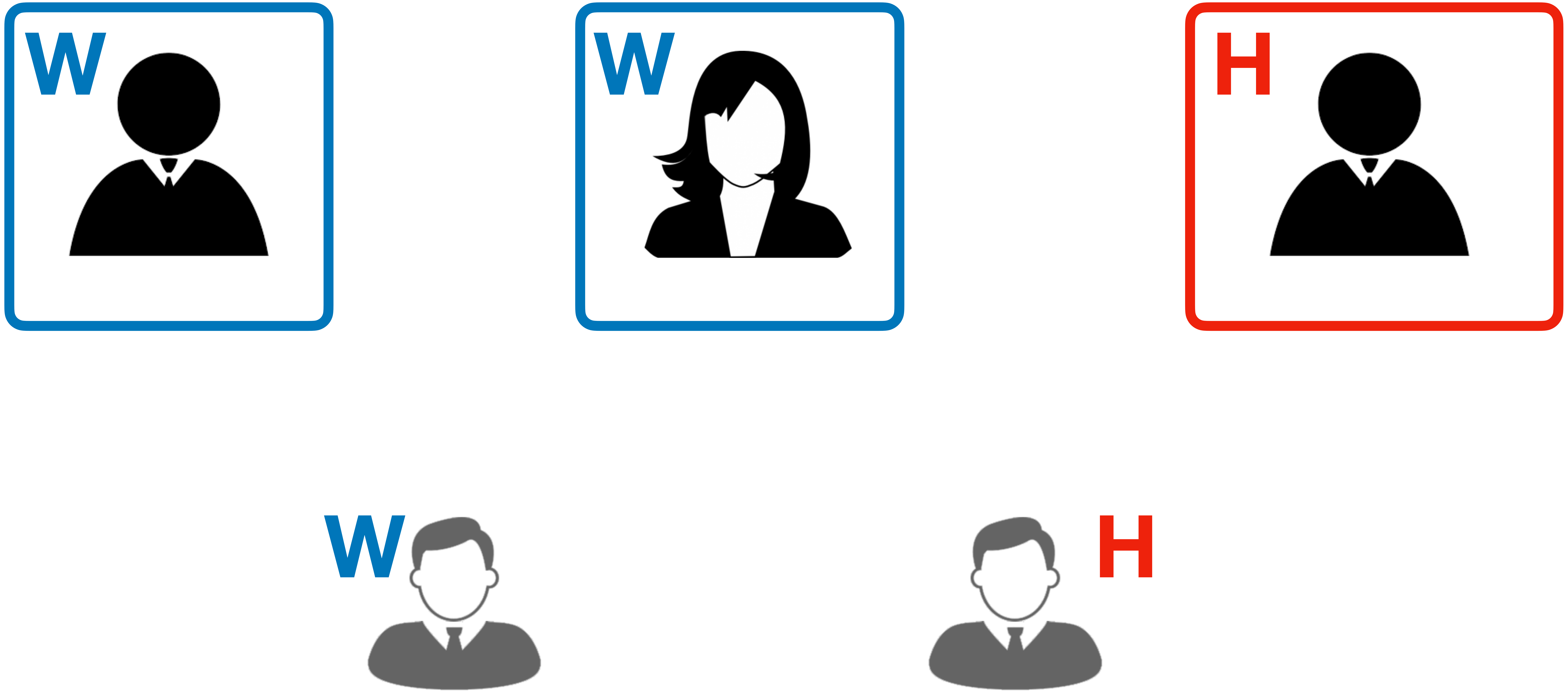
Separation of Concerns

- Proposers: suggest a value (a restaurant to go);
- Acceptors: support some proposal;
- The **proposer** with a *majority of acceptors* supporting its proposal wins.

  Others learn the outcome by querying all the acceptors.


Acceptors
H
W
W
H
W
H
Proposers

Acceptors



Proposers

Key Idea 1

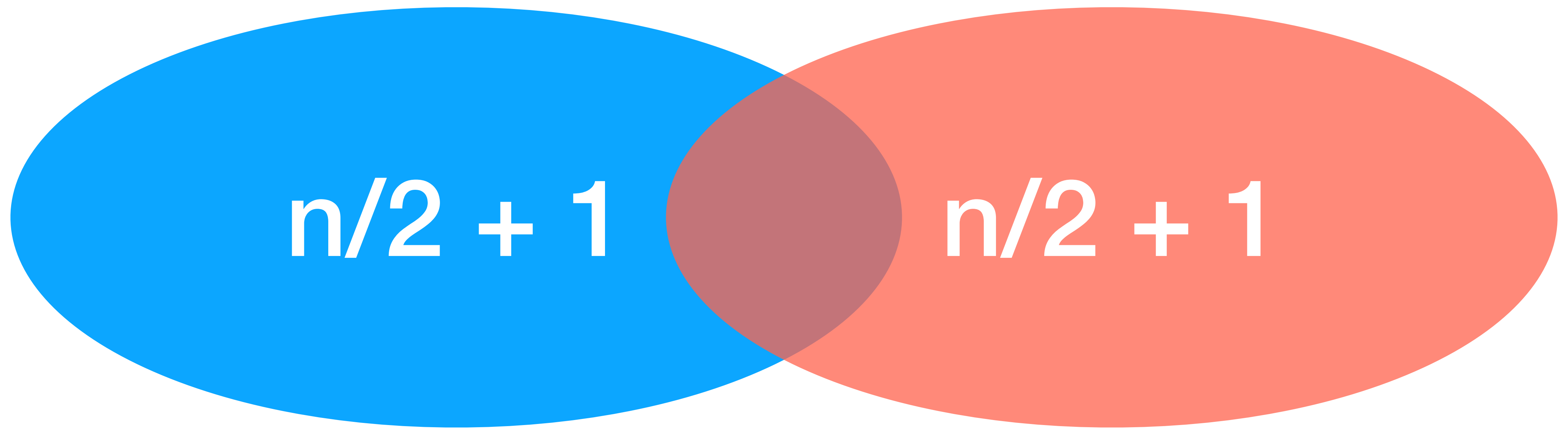
Rely on majority quorums for agreement

to prevent the “split brain” problem.

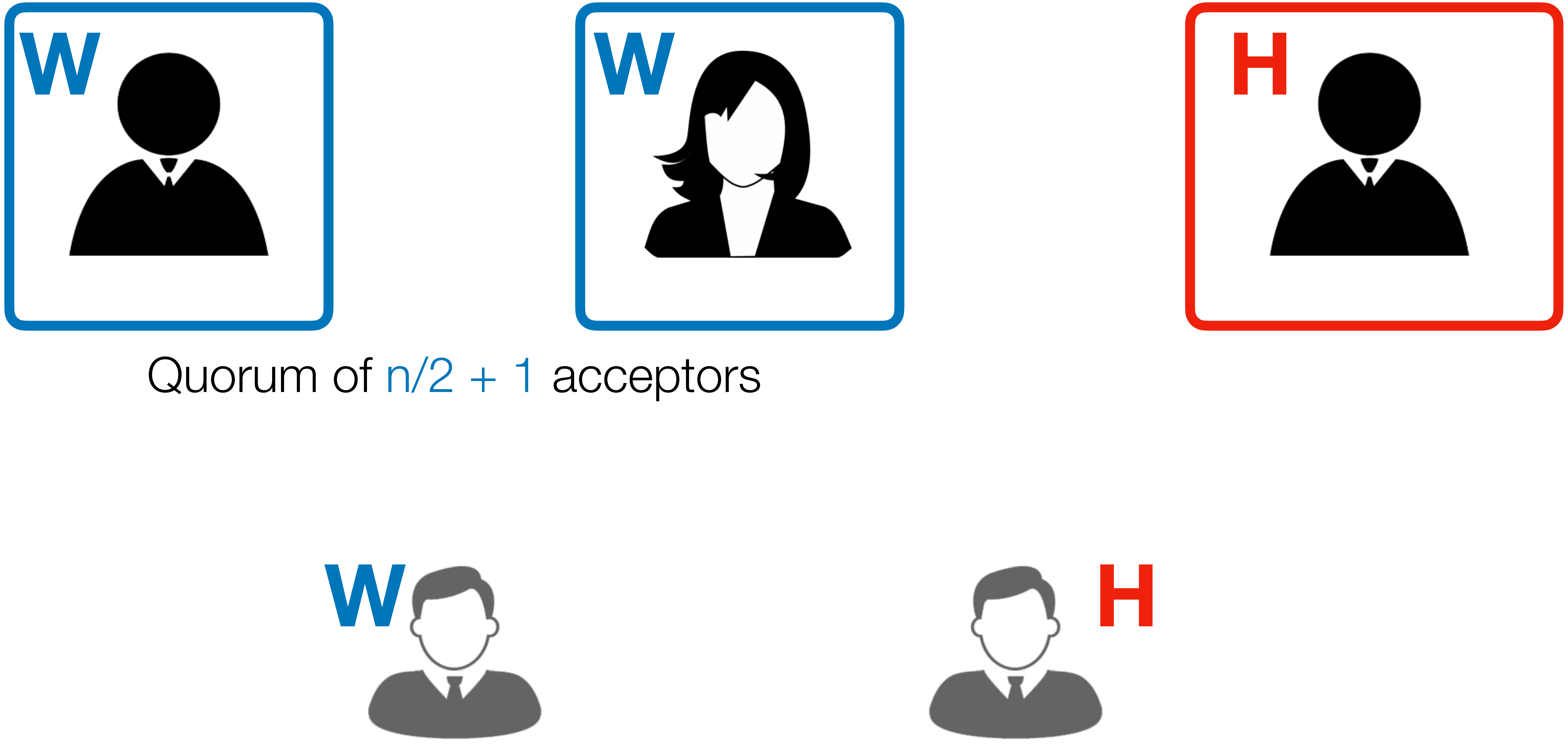
- *Common meaning*: **Quorum** is the minimum number of members to conduct the business on behalf of the entire group they represent;
- *In computing*: quorum is *a **necessary** number of processes* to agree on the decision in the presence of potentially faulty ones.

Key Properties of Quorums

- *Property 1:* any two quorums must have non-empty intersection



- *Property 2:* no need for the *global* agreement: can tolerate some faults n = 3



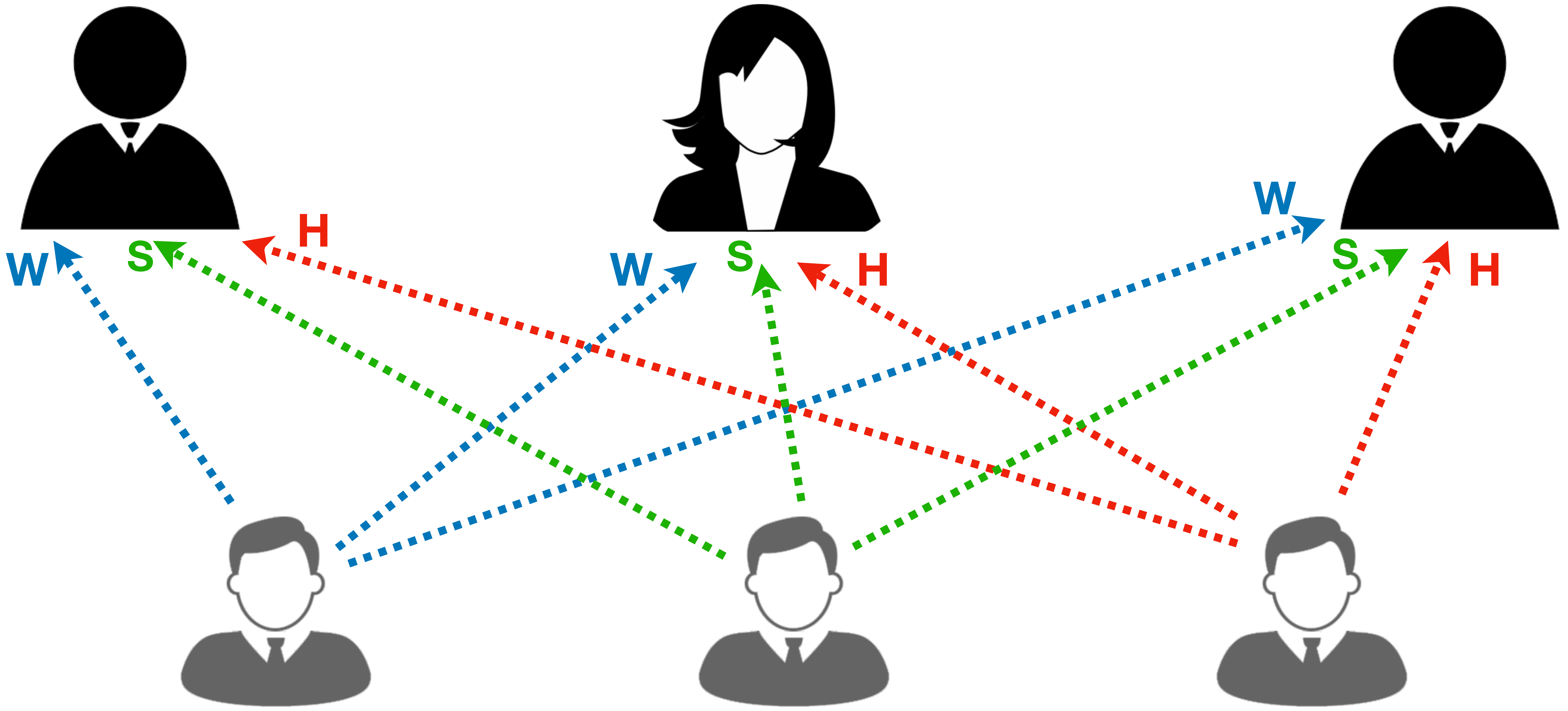
Quorum of n/2 + 1 acceptors

Problem

A quorum is difficult to obtain in a *single* interaction.

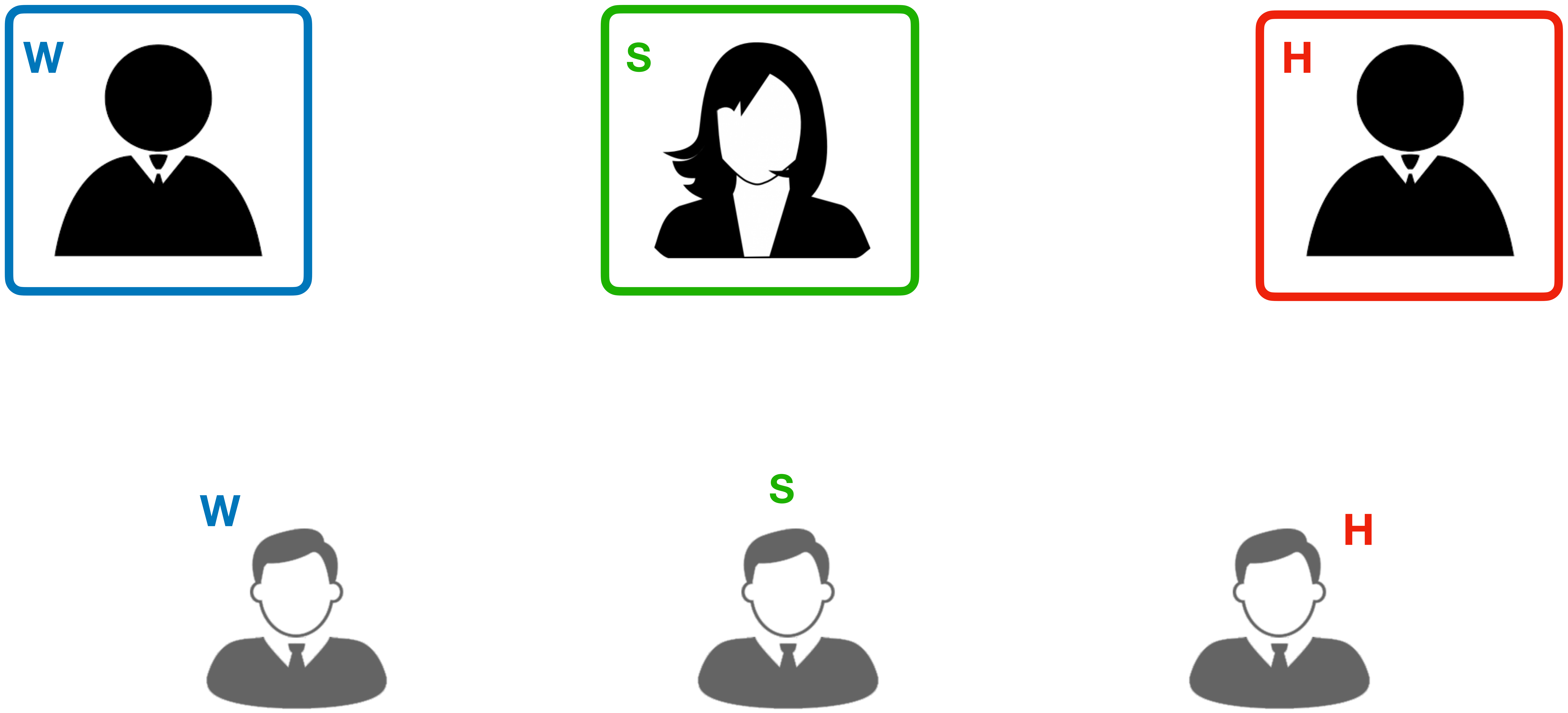
As the result, such a system will often *get stuck*.

Acceptors



Proposers

Acceptors



Proposers

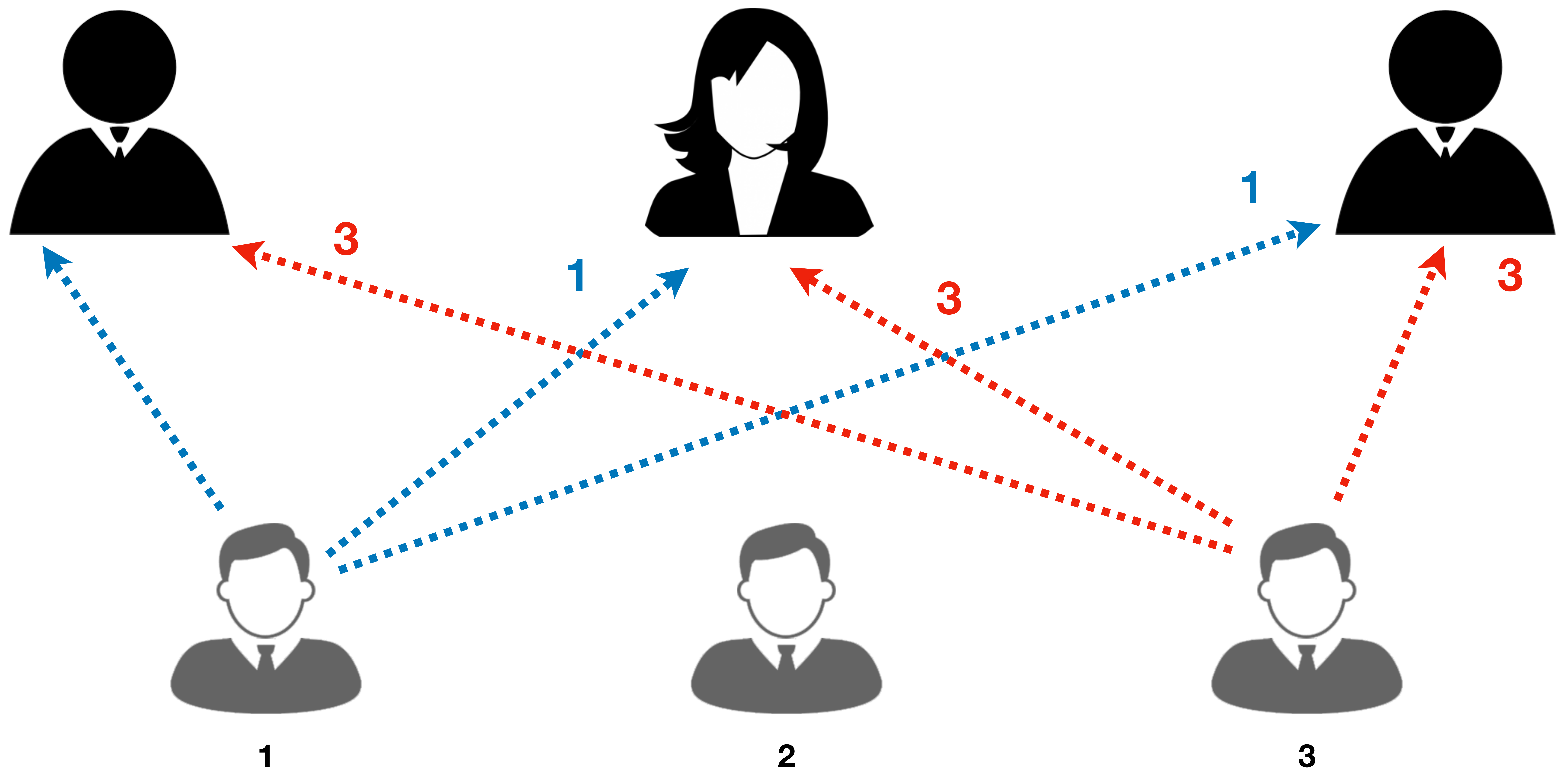
Key Ideas 2 and 3

- Proceed in rounds:
  - A proposer first “secures” itself a quorum, willing to support its proposal (i.e., becomes a “leader”);
  - *Only if a quorum is secured*, it goes on to “propose” a value.
- Introduce fixed globally known *priorities* between proposers to “break ties” when securing quorums.
  - Acceptors only “choose to support” proposers with *higher* priorities than they have already seen.

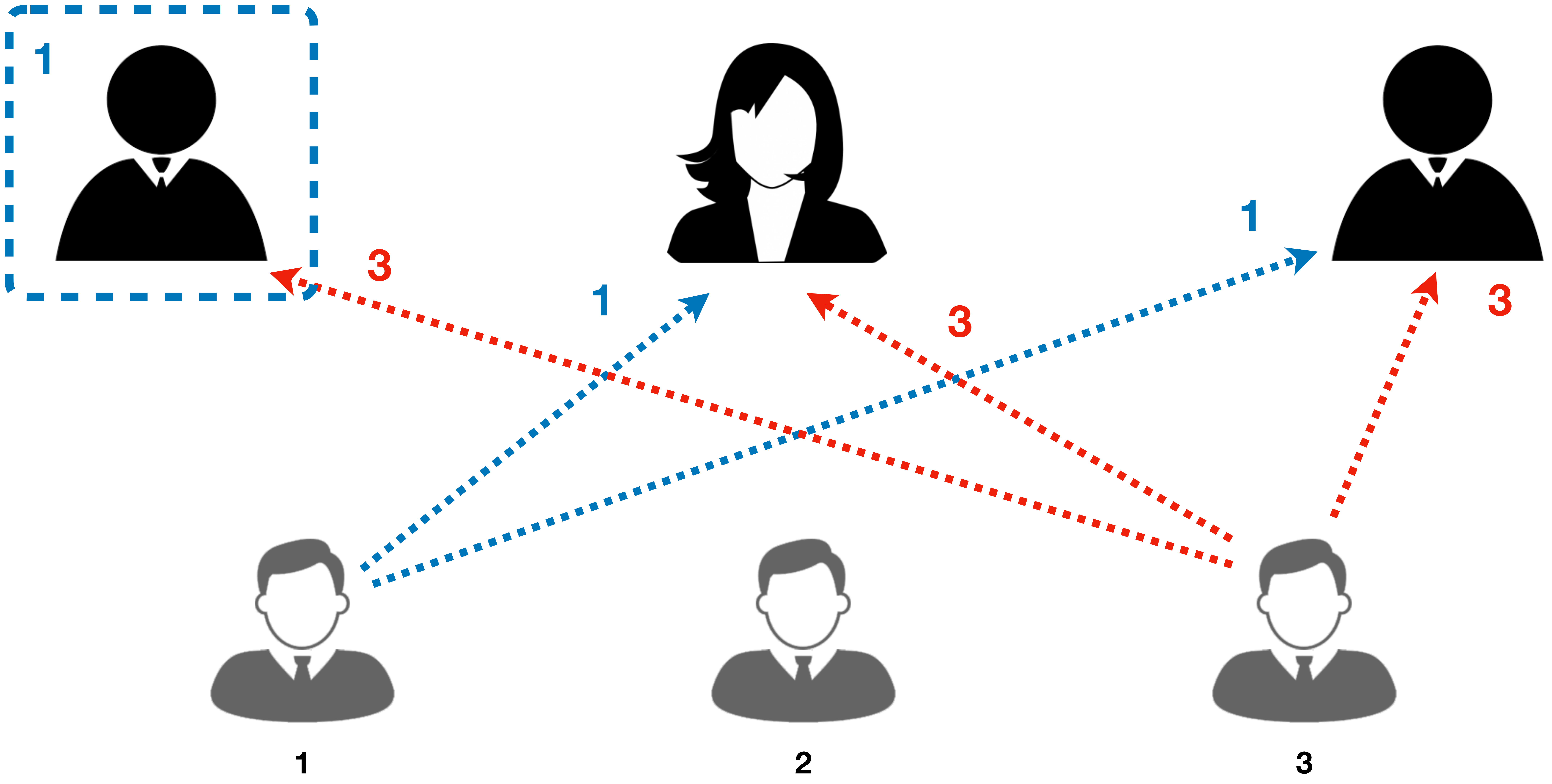
Some Terminology

- Rounds — **Phases**
  - Phase 1 — “prepare”, securing quorums to propose
  - Phase 2 — “accept”, sending values to accept
- Fixed priorities — **Ballots**

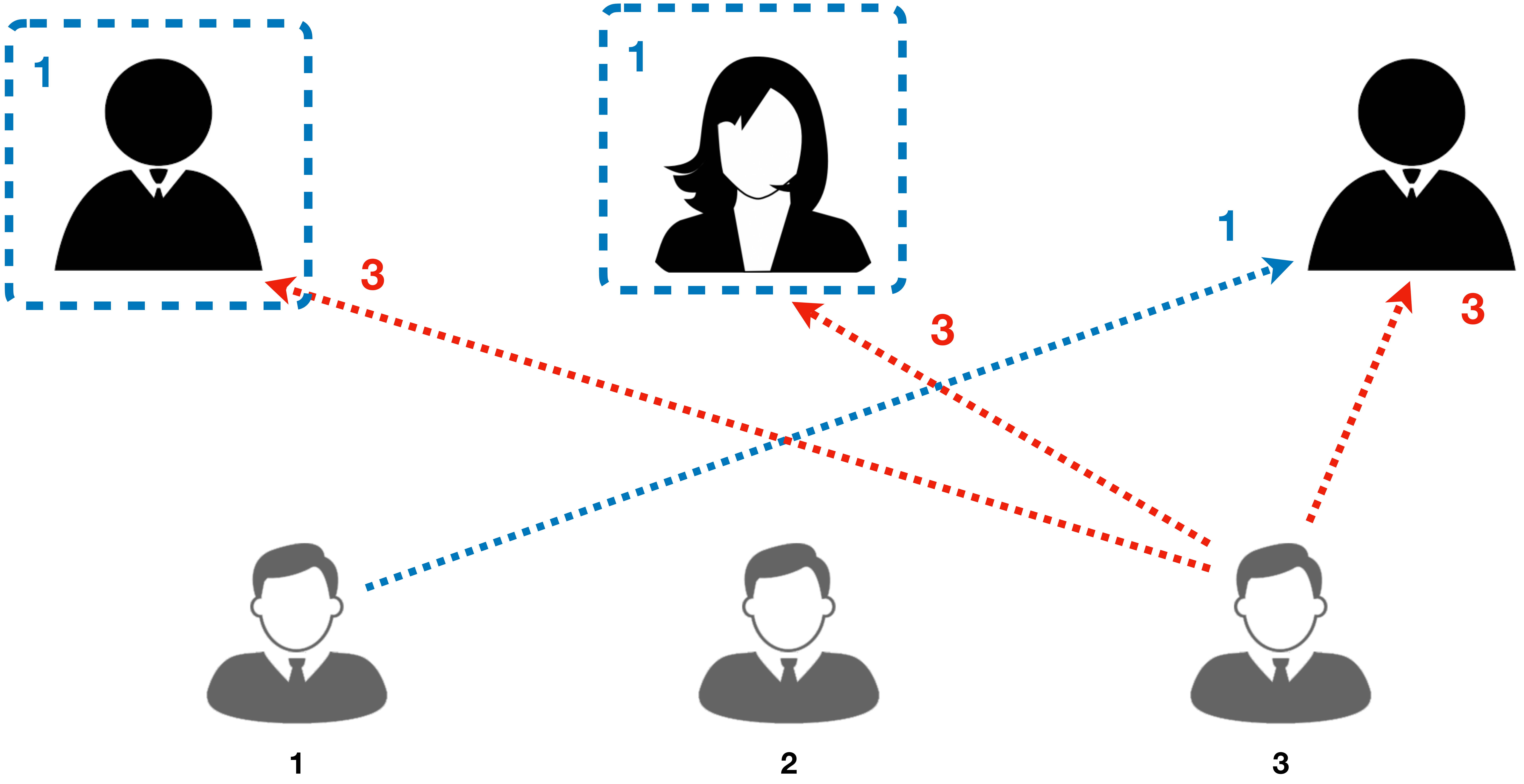
Phase 1



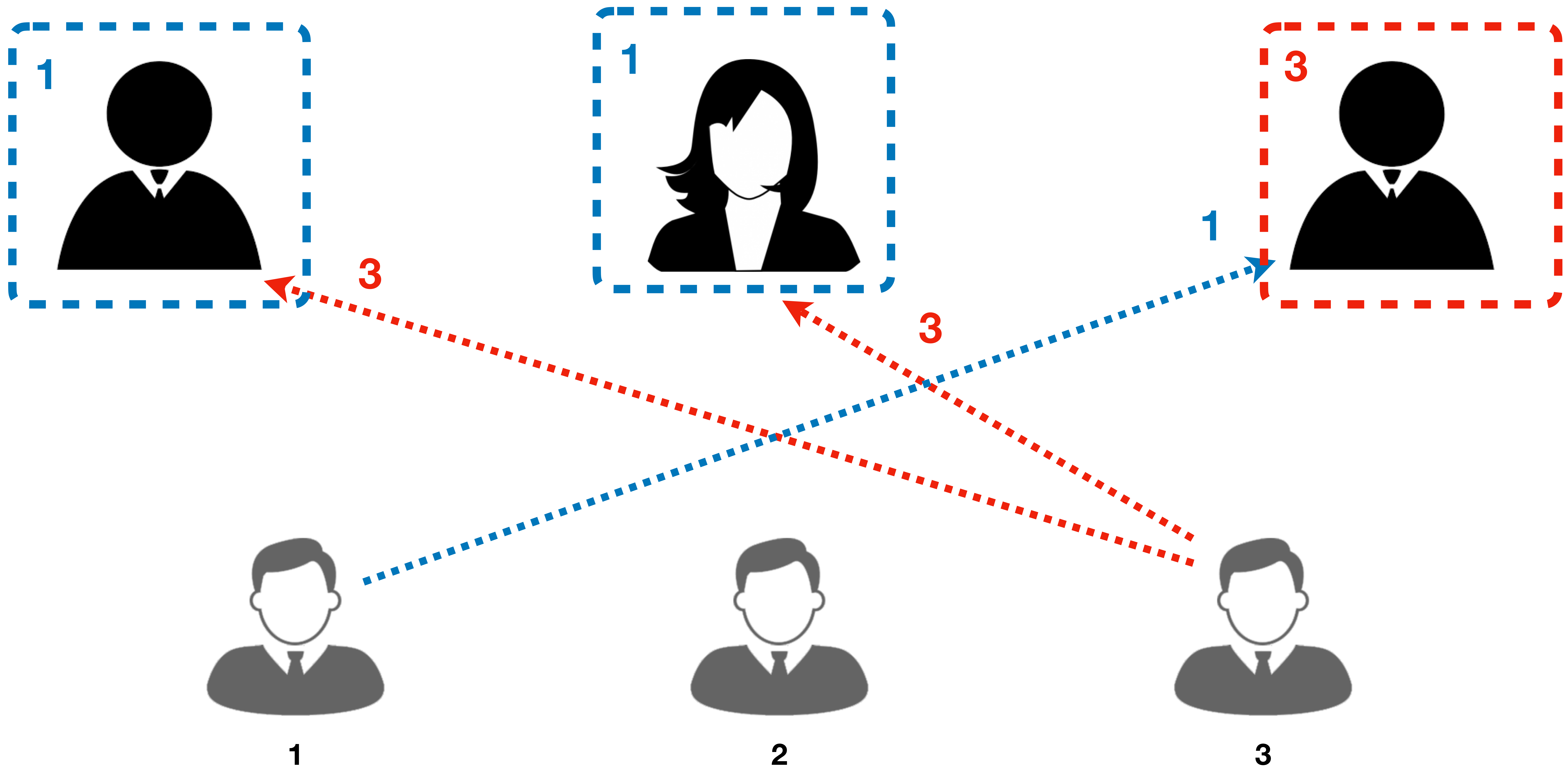
Phase 1



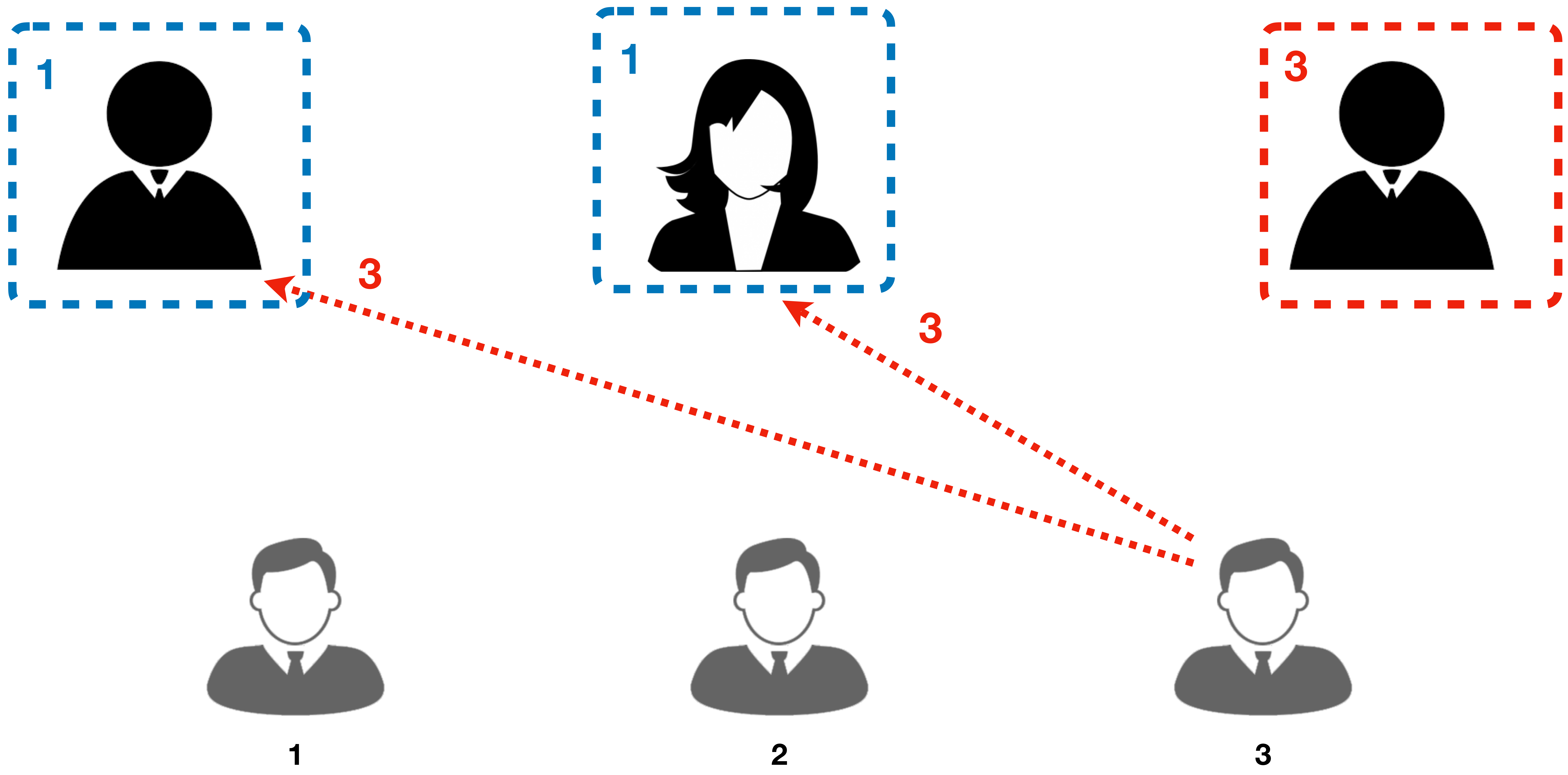
Phase 1



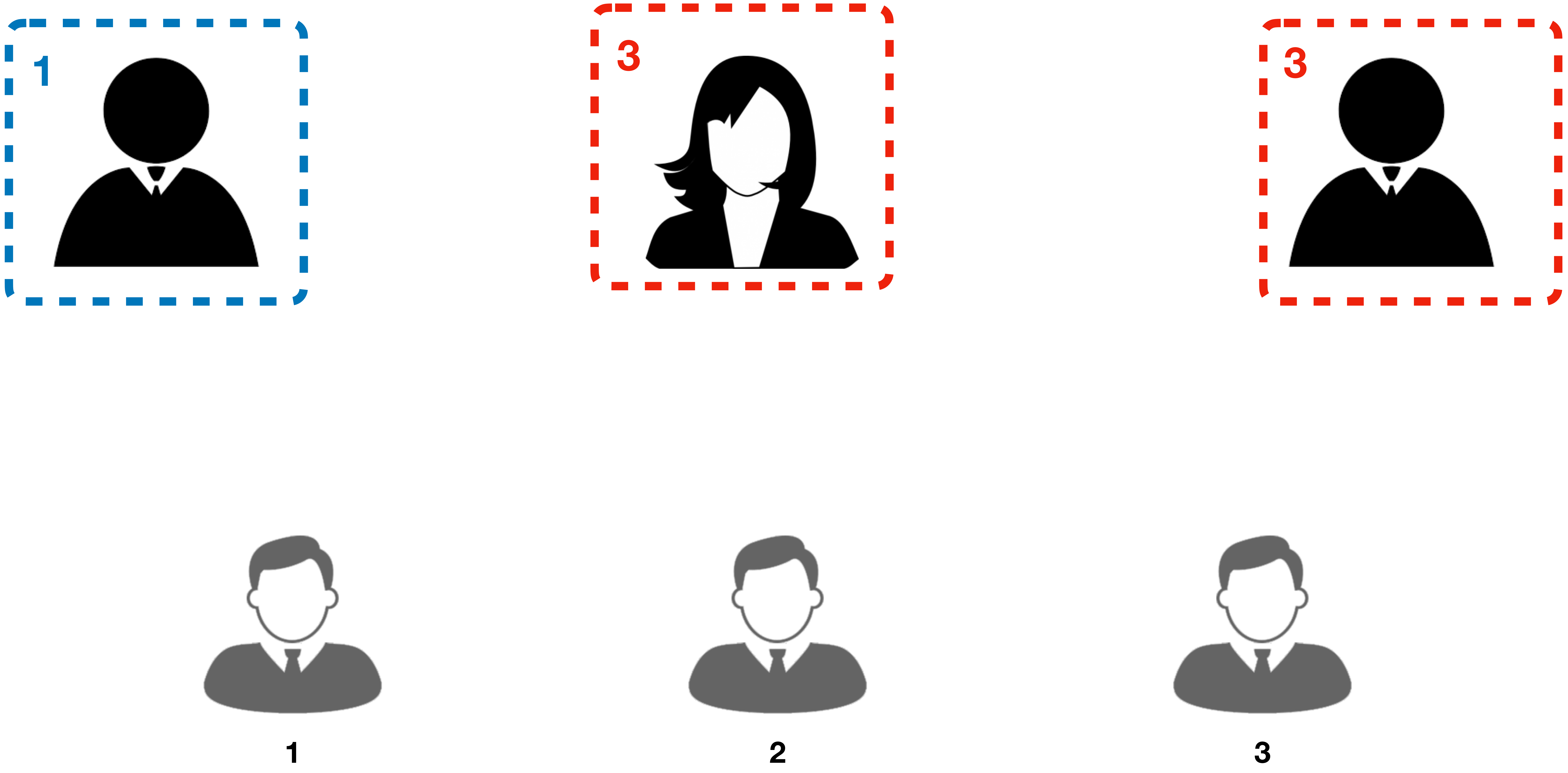
Phase 1



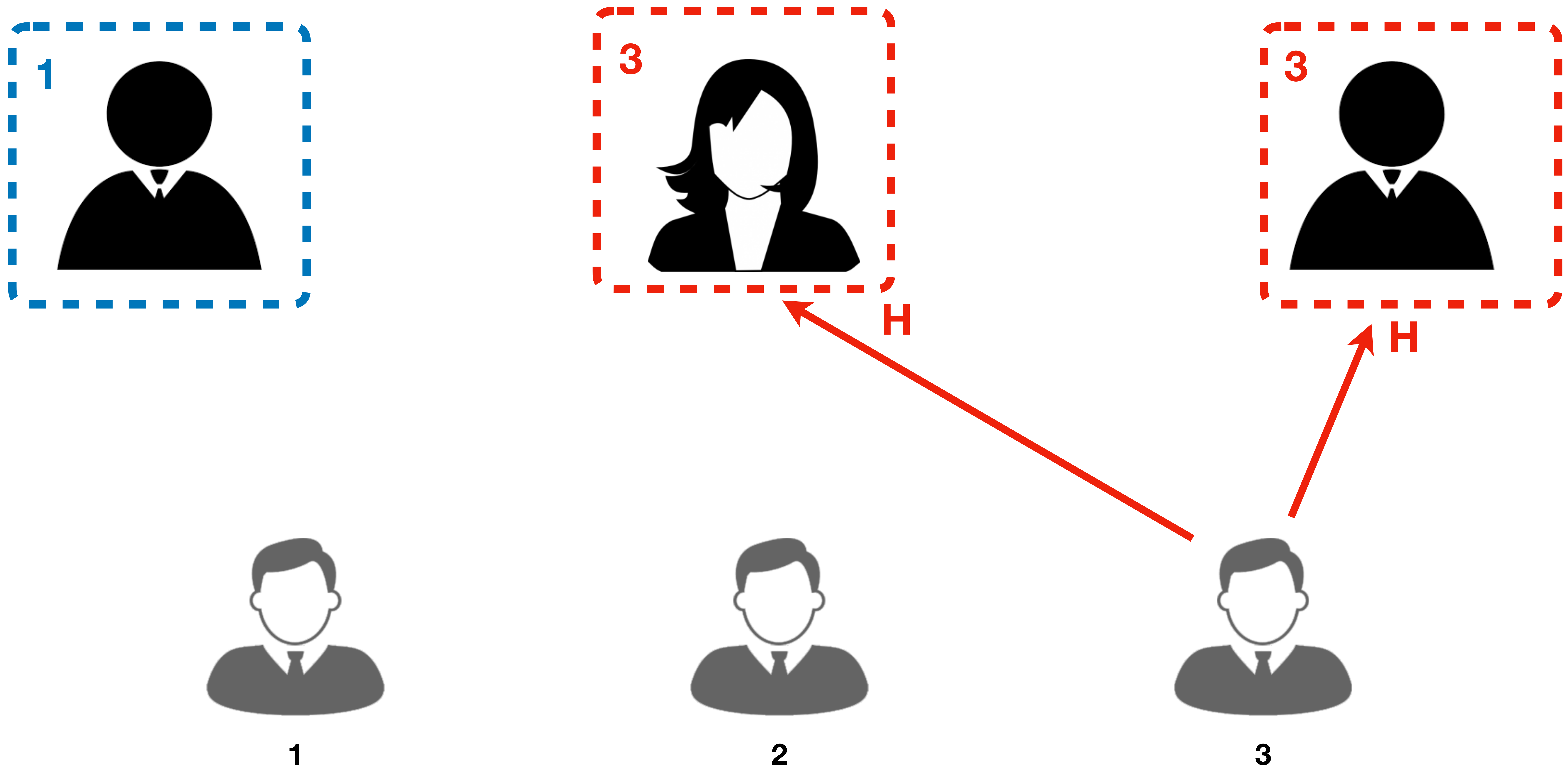
Phase 1



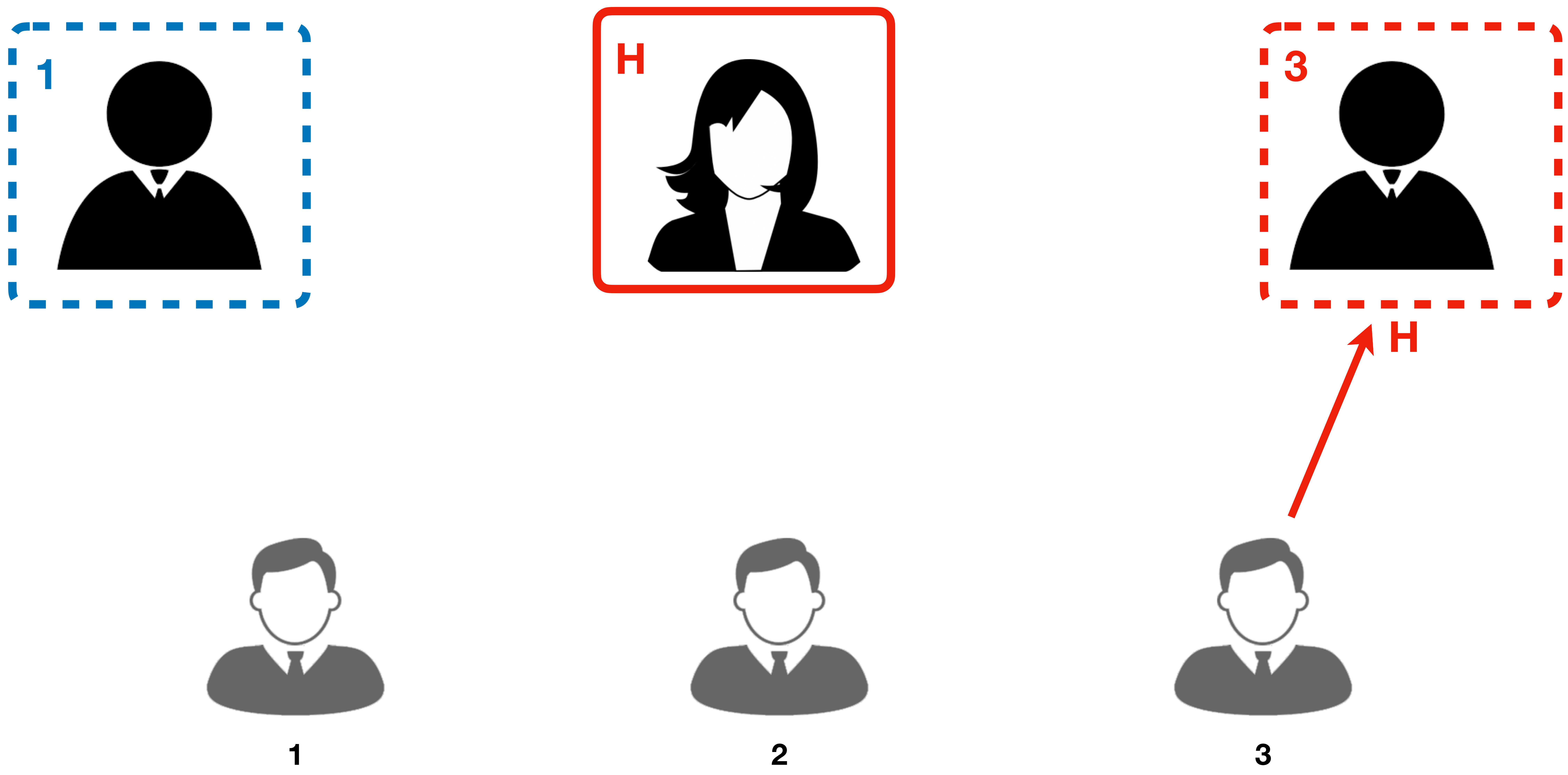
Phase 1



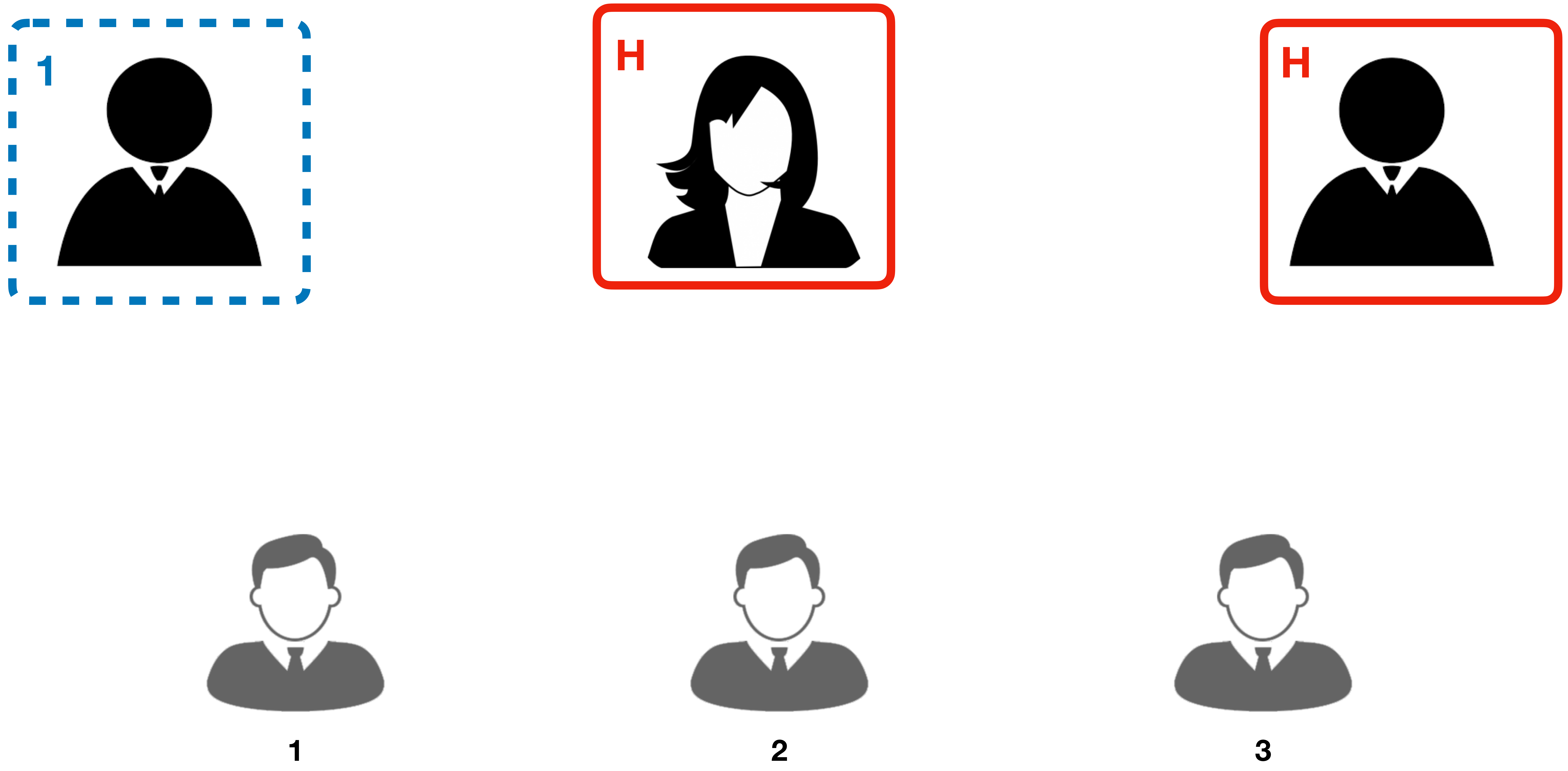
Phase 2



Phase 2

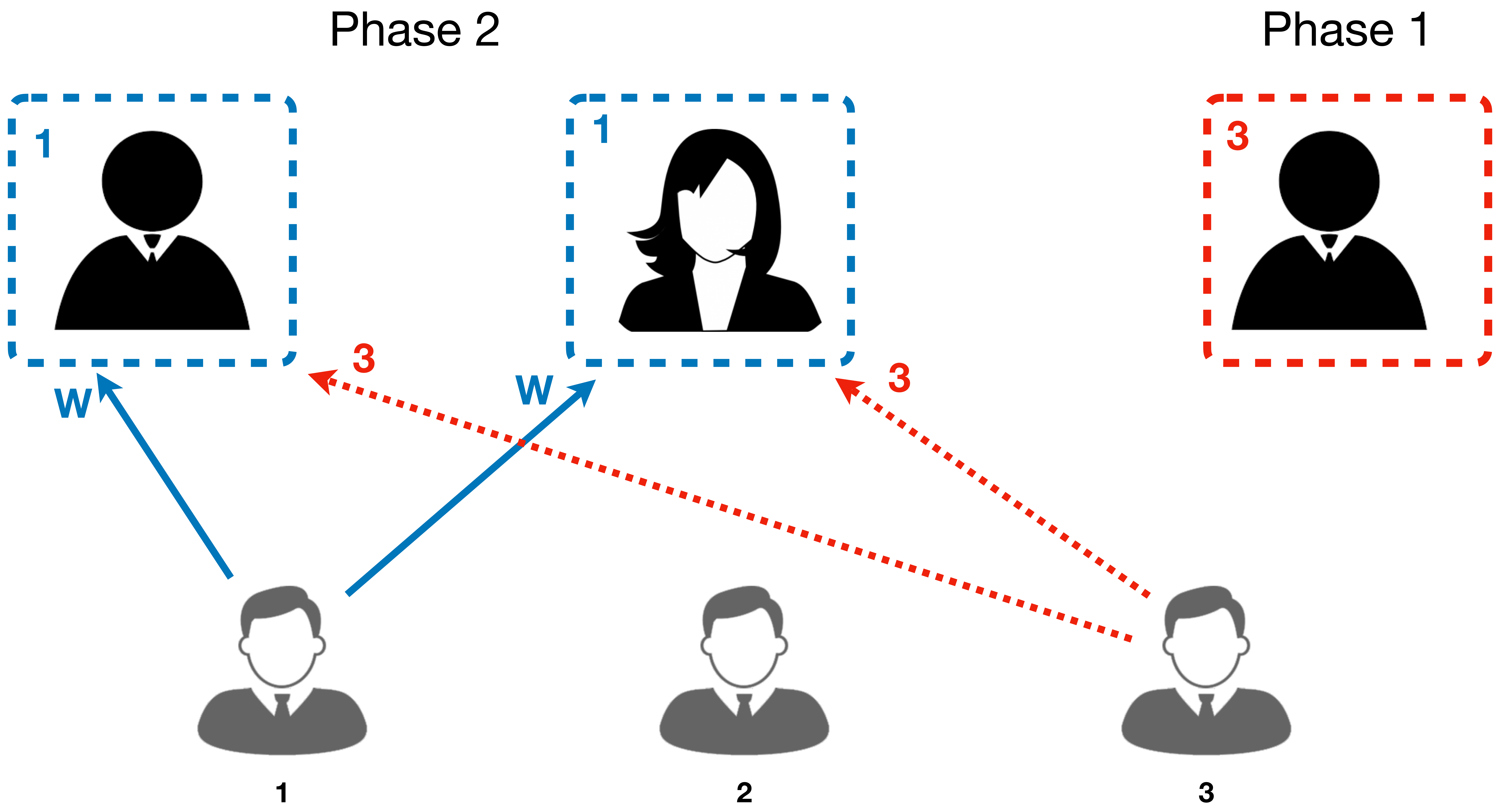


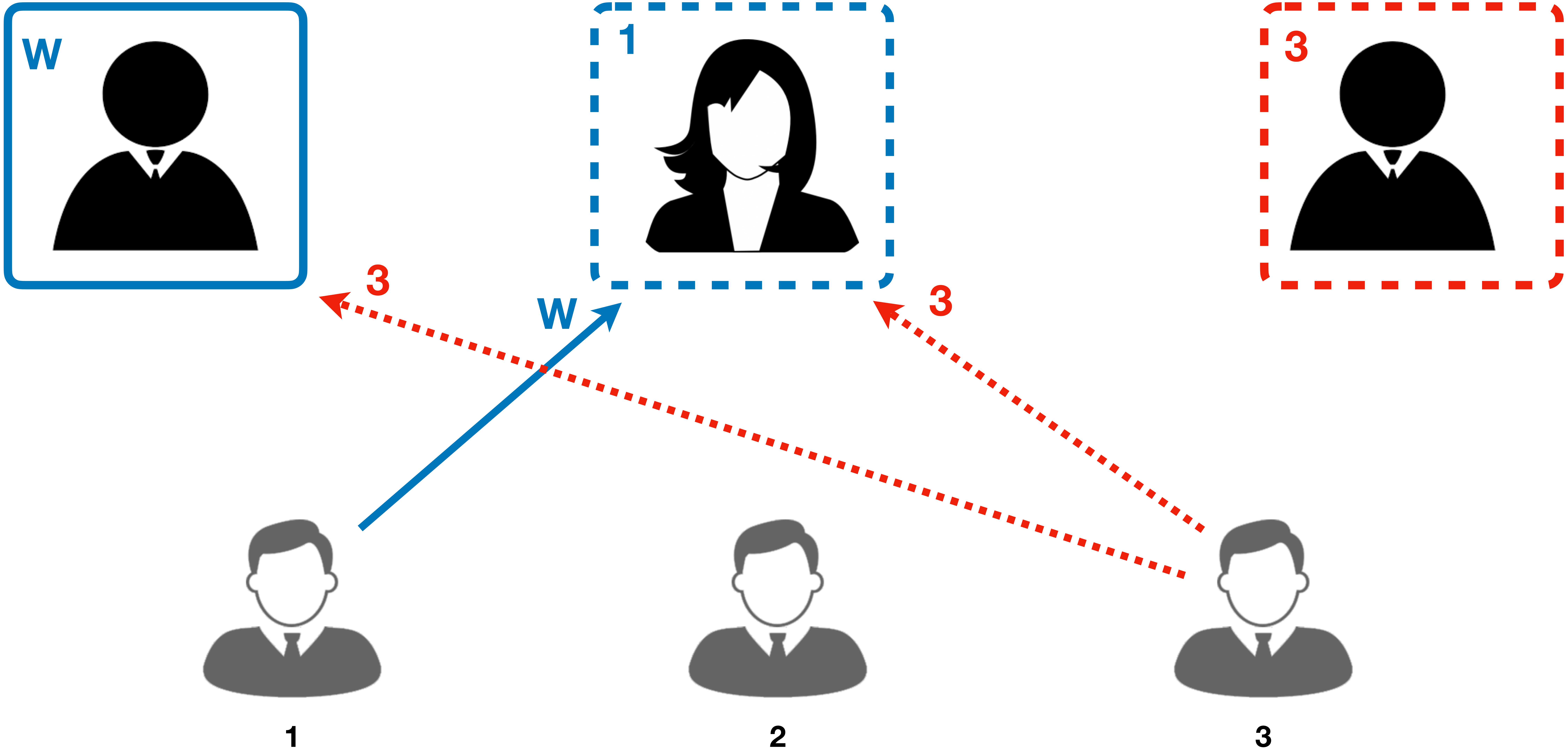
Phase 2

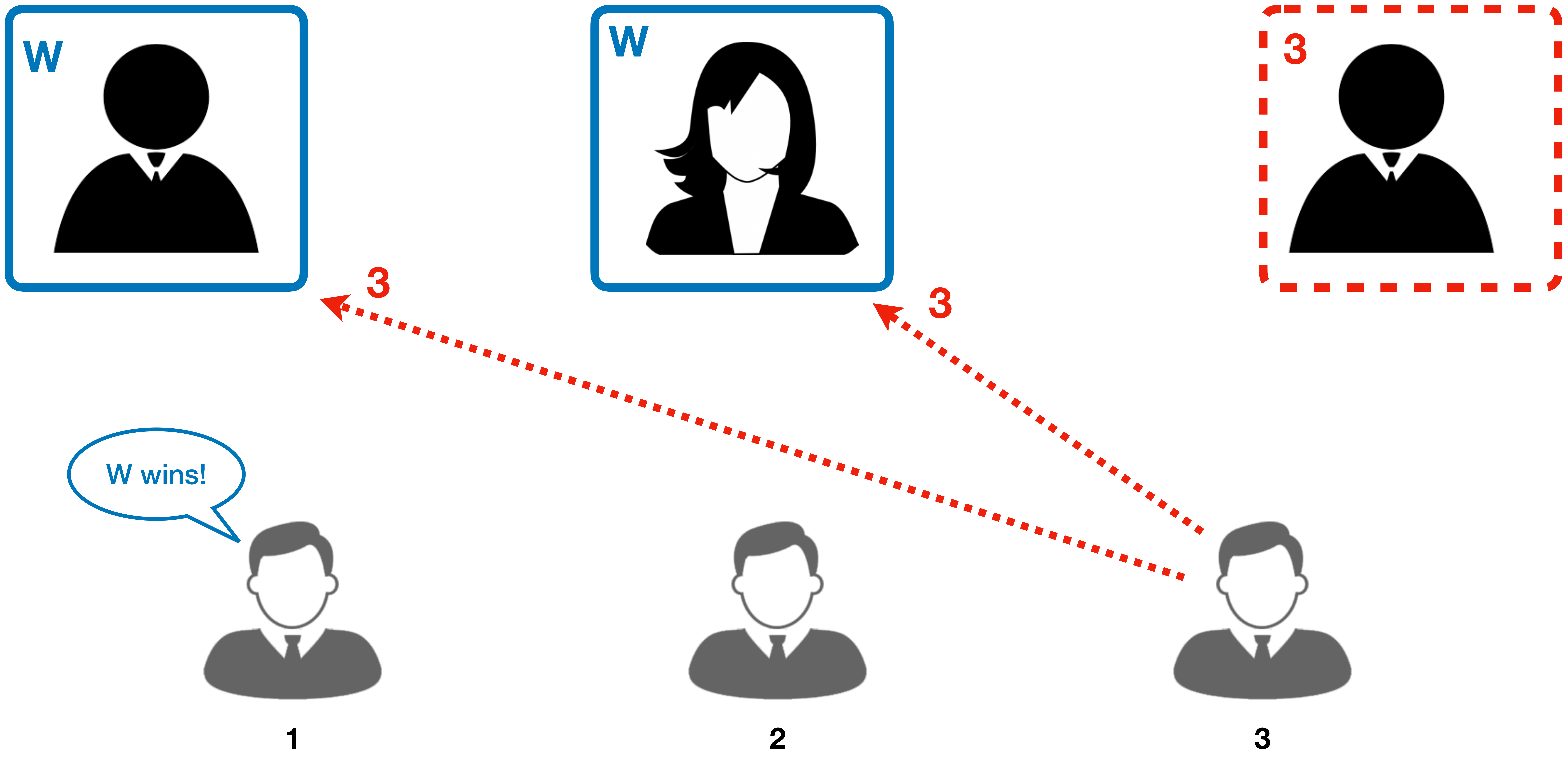


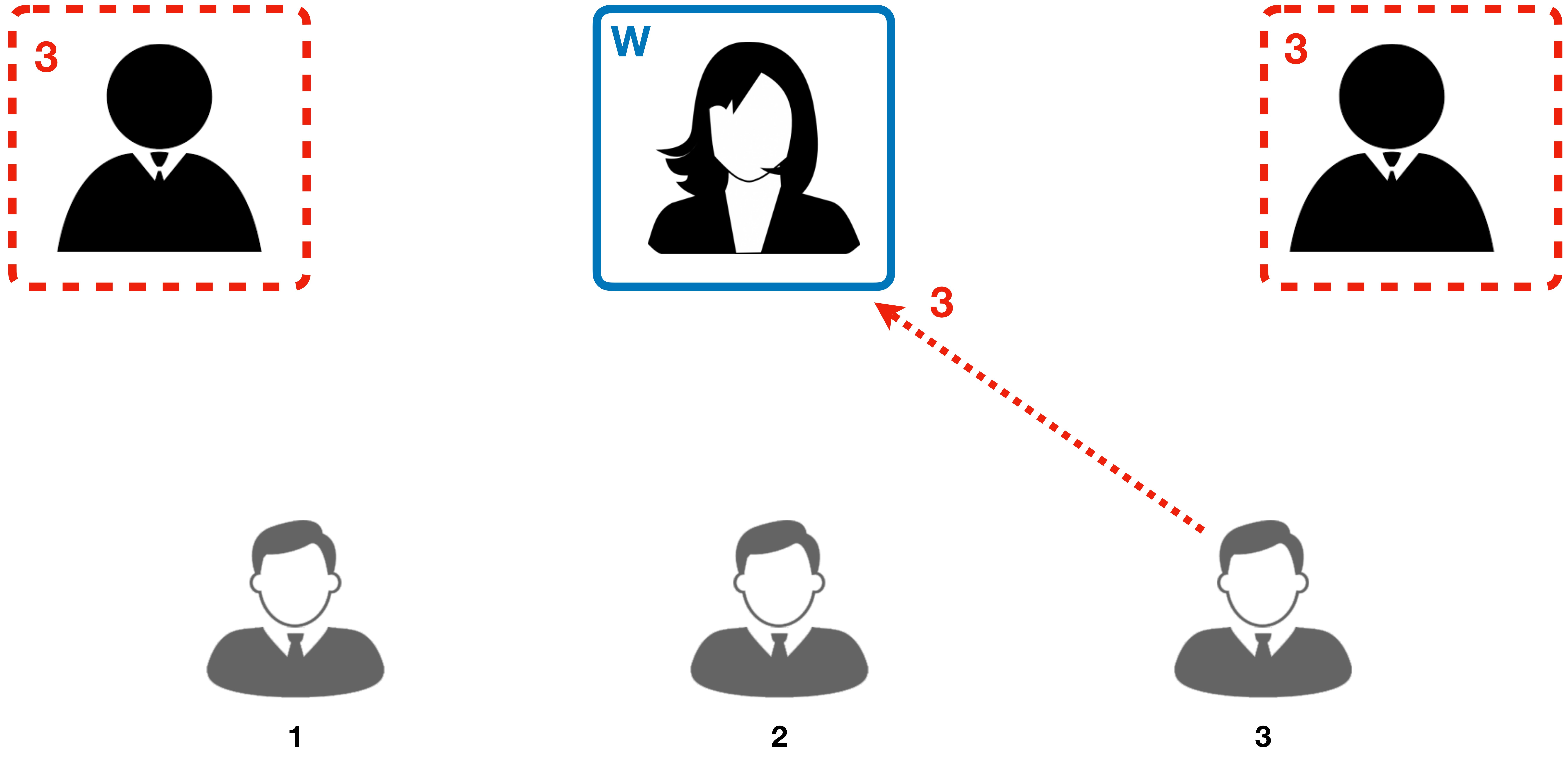
Problem 3

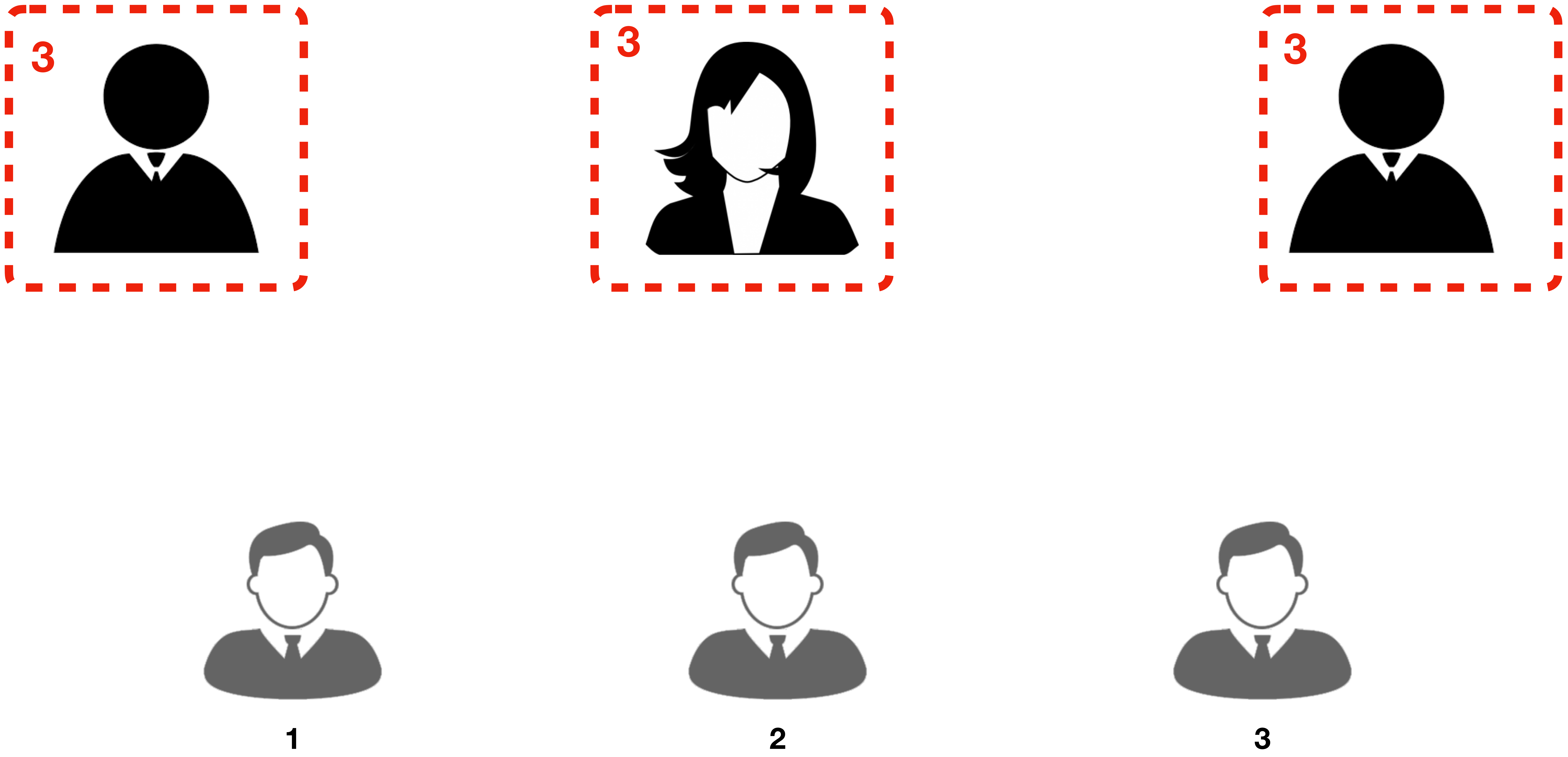
Because of asynchrony, low-priority Phase 2 can be *interrupted* by a high-priority Phase 1

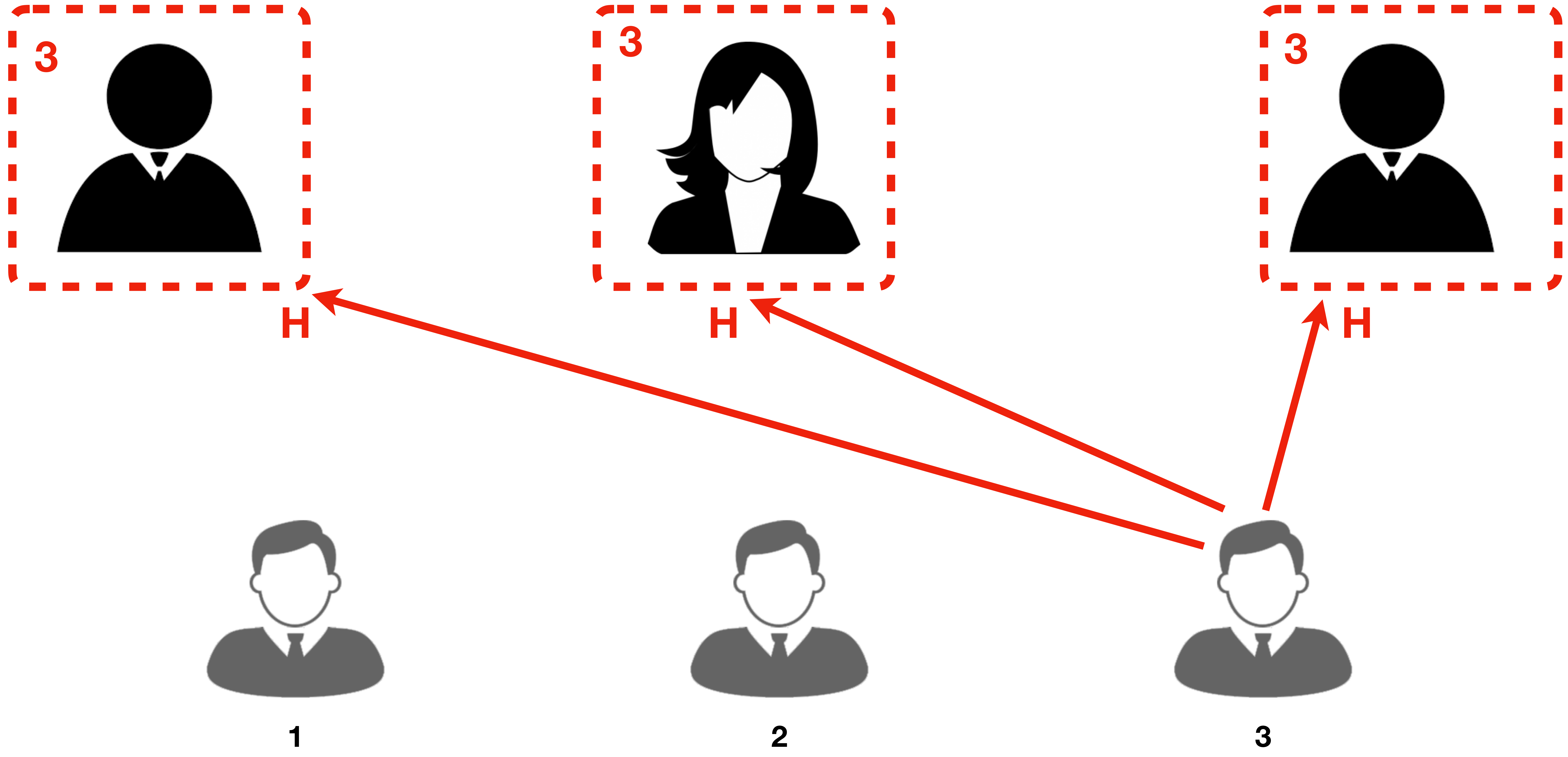

Phase 2
Phase 1
1
1
3
W
W
3
3
1
2
3

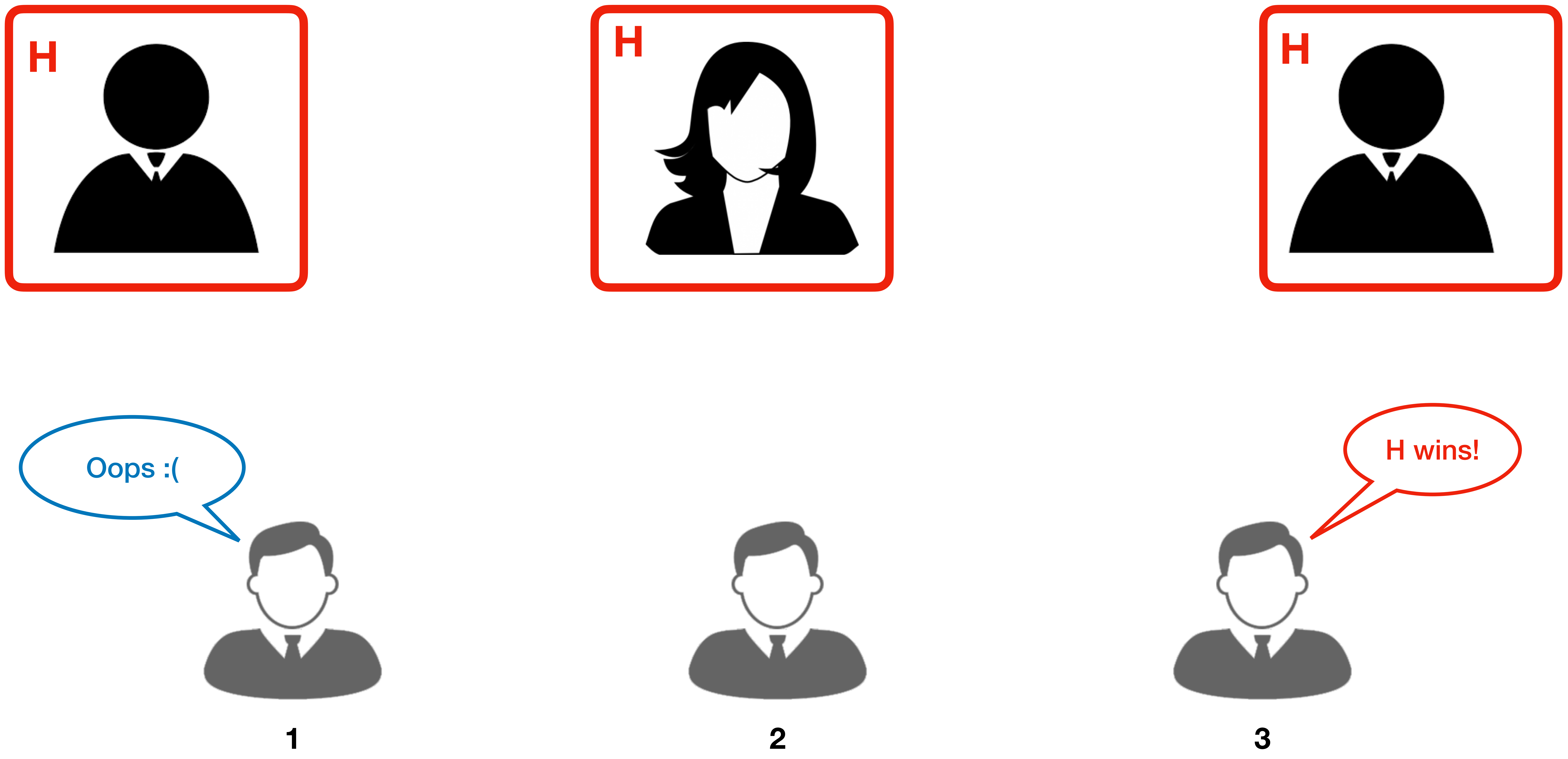

W
1
3
3
W
3
1
2
3


W
W
3
3
3
W wins!
1
2
3


3
W
3
3
1
2
3


3
3
3
1
2
3


3
3
3
H
H
H
1
2
3


H
H
H
Oops :(
H wins!
1
2
3

Problem 3

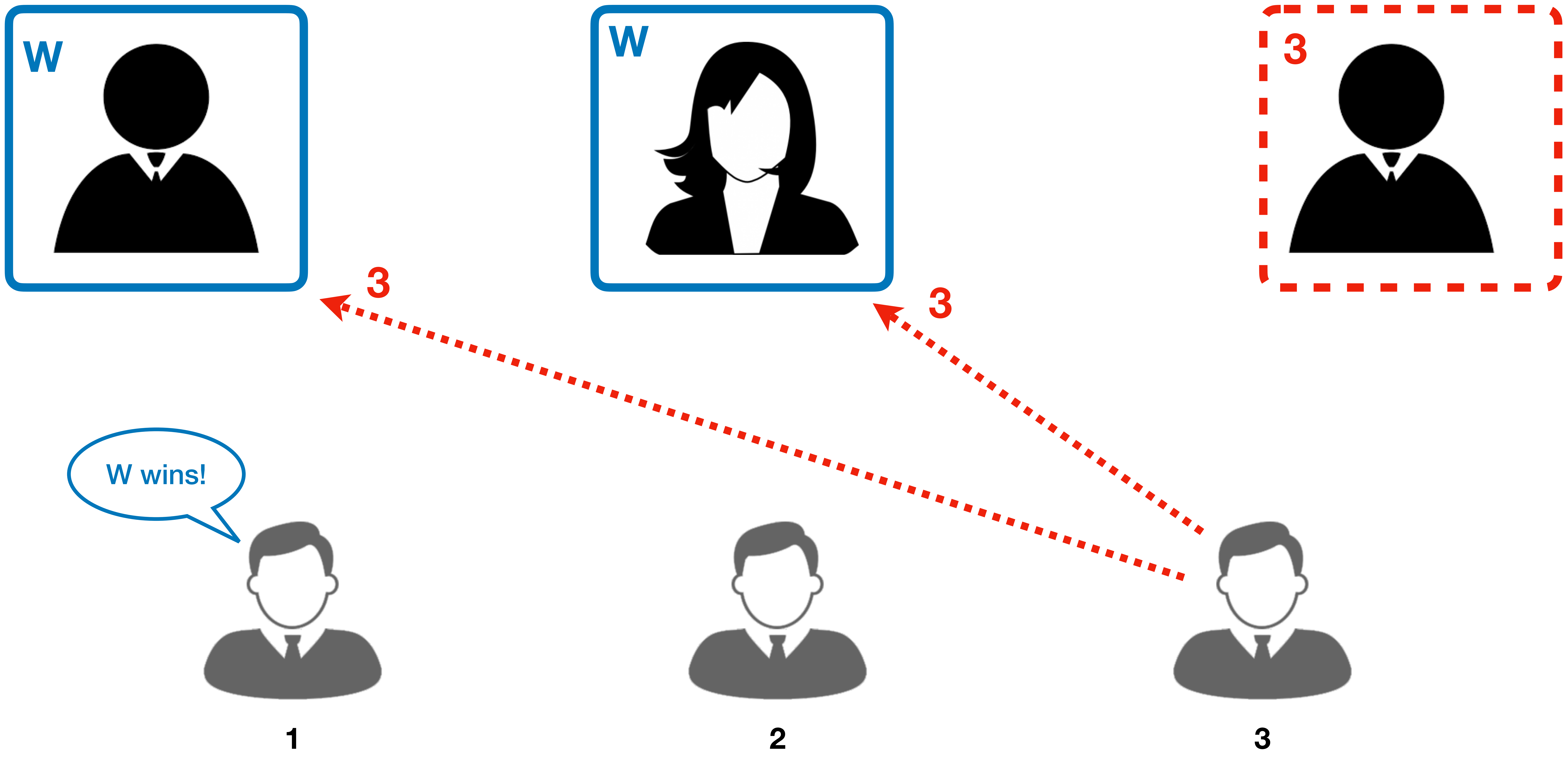
How to ensure irrevocability of consensus

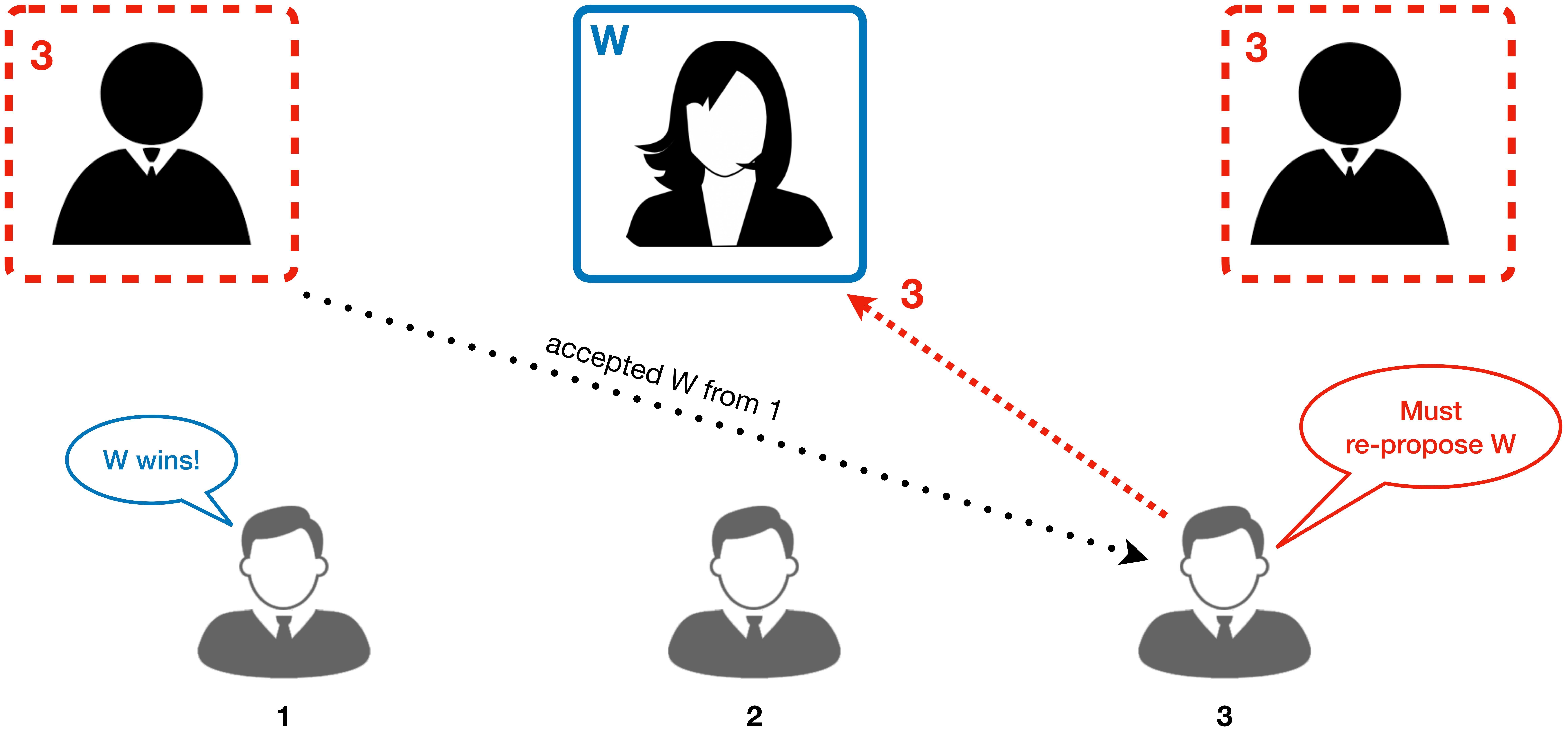
in the presence of *priorities* and *asynchrony*?

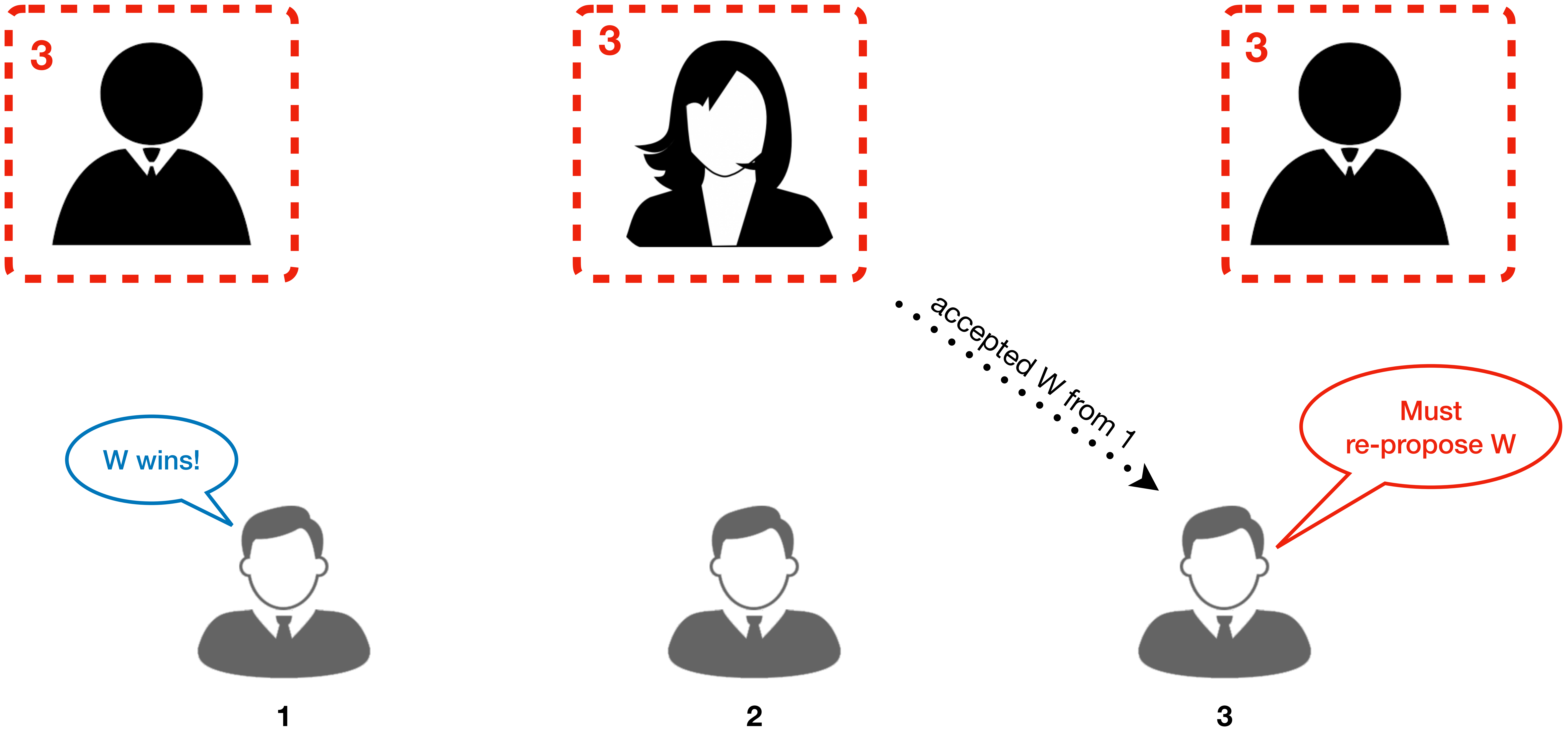
Key Idea 4

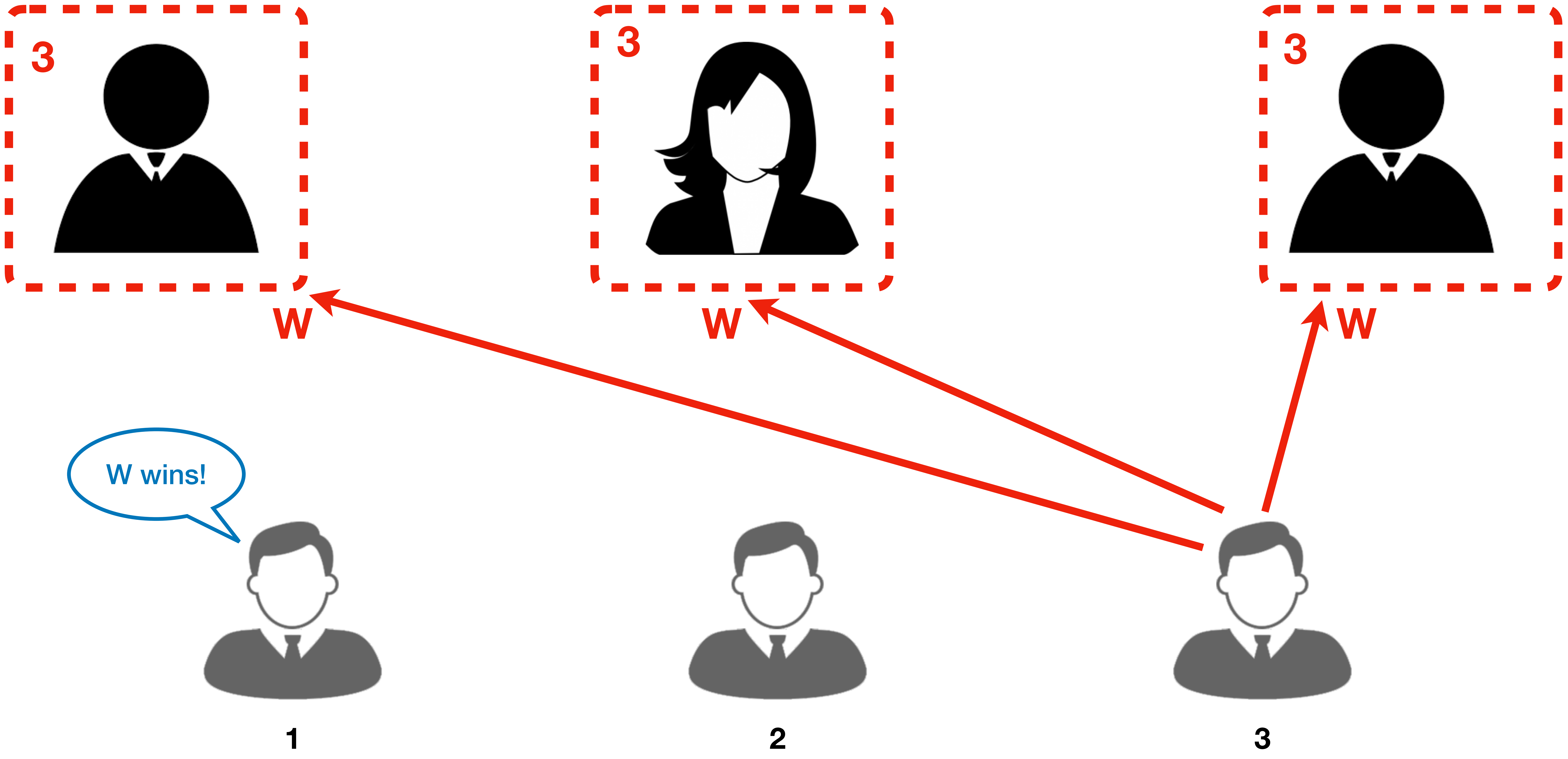
- Cooperation between Proposers and Acceptors:
  - **Acceptors**, when agreeing to support a proposer, *must* “tell” what was the *highest-ballot value* they have accepted;
  - *Higher-ballot* **proposers** *re-propose* already (partially) accepted values from the *lower-ballot* proposers, who secured the quorum before.

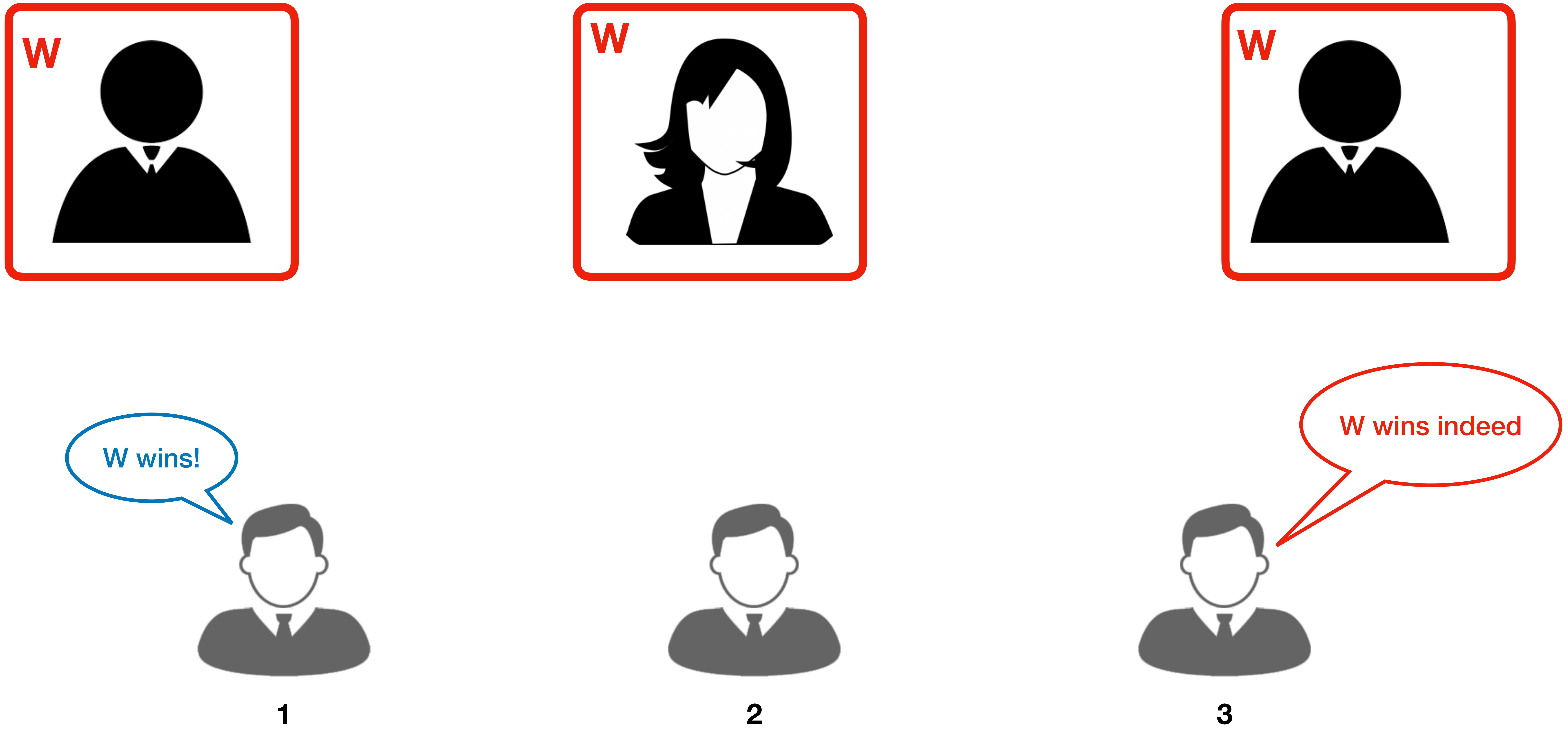
- This way, a proposer “knows" that, once it secured its quorum, either
  - **its own proposal**, or some higher-ballot one will be accepted
  - **if its proposal got accepted, it will not be revoked** (thanks to quorum intersection)


W
W
3
3
3
W wins!
1
2
3


3
W
3
3
accepted W from 1
W wins!
Must re-propose W
1
2
3


3
3
3
accepted W from 1
W wins!
Must re-propose W
1
2
3


3
3
3
W
W
W
W wins!
1
2
3


W
W
W
W wins!
W wins indeed
1
2
3

Two-Phase Ballot-based Consensus

- Proposers suggest values, acceptors decide upon acceptance;
- Each proposal goes in two rounds:
  - **Phase 1**: securing a quorum of acceptors for a proposal
  - **Phase 2:** sending out the proposal
- Acceptors agree only to support ballots *higher* than what they've seen;
- They inform proposers of *previously accepted values*,
  which those then re-propose.

The Algorithm in a Nutshell

Phase 1

Proposer

- Send my ballot **b** to all acceptors
- Wait for response of *at least* n/2 + 1 acceptors

Acceptor

- Upon receiving a **ballot b**
  - if it's the first one, remember it and send "ok" back.
  - if it's higher than **b′** we supported before, send back a previously accepted **(b′, v′)**, and remember **b** as what's currently supported.

Phase 2

Proposer

- When heard back from n/2 + 1 acceptors, send them back (**b**, **w**), where
  - **b** is my ballot
  - **w** is the value from the acceptors with the highest ballot, or *my own* value.

Acceptor

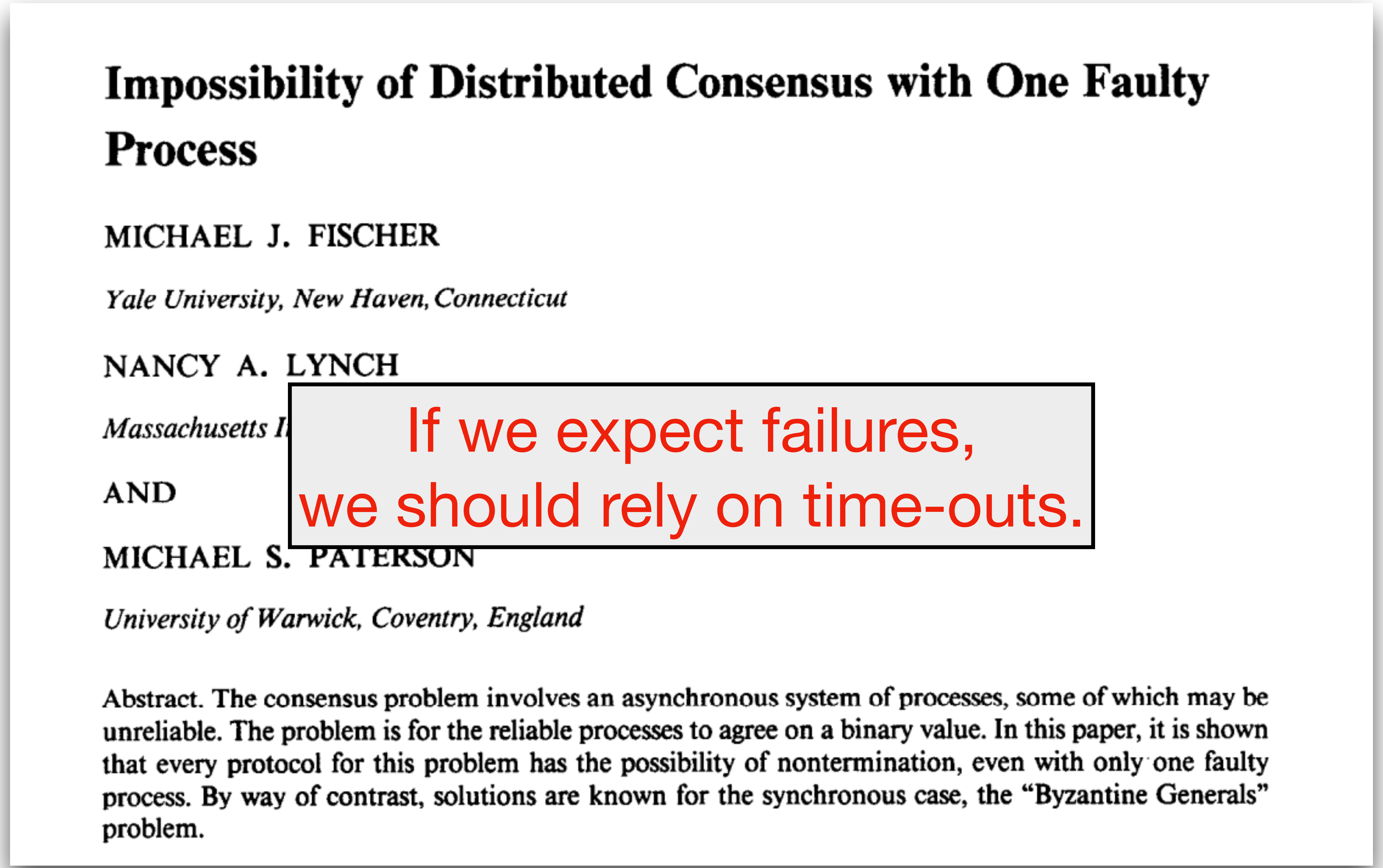
- Accept incoming value **w** if it comes with a ballot **b**, which we currently support; ignore otherwise.

Learning an Accepted Value

- A dedicated *learner* sends request to all acceptors;
- If at least n/2 + 1 acceptors respond back with *the same* value **v**, this is an accepted value.
- Correctness of this reasoning follows from *irrevocability*.

Learning an Accepted Value

- A dedicated *learner* sends request to all acceptors;
- If at least $n/2 + 1$ acceptors respond back with *the same* value **v**, this is an accepted value.
- Correctness of this reasoning follows from *irrevocability*.
- And what if $n/2 + 1$ have the value, but one of them *does not respond*?
- In this case we need to introduce a *time out* (synchrony).



Impossibility of Distributed Consensus with One Faulty Process

MICHAEL J. FISCHER

Yale University, New Haven, Connecticut

NANCY A. LYNCH

Massachusetts I

AND

MICHAEL S. PATERSON

University of Warwick, Coventry, England

Abstract. The consensus problem involves an asynchronous system of processes, some of which may be unreliable. The problem is for the reliable processes to agree on a binary value. In this paper, it is shown that every protocol for this problem has the possibility of nontermination, even with only one faulty process. By way of contrast, solutions are known for the synchronous case, the "Byzantine Generals" problem.

If we expect failures,
we should rely on time-outs.

Paxos

- A practical fault-tolerant distributed consensus algorithm;
- Invented in 1990, published in 1998;
- Nowadays used everywhere: Google (Bigtable, Chubby), IBM, Microsoft;
- You have just seen it explained.

History of Paxos

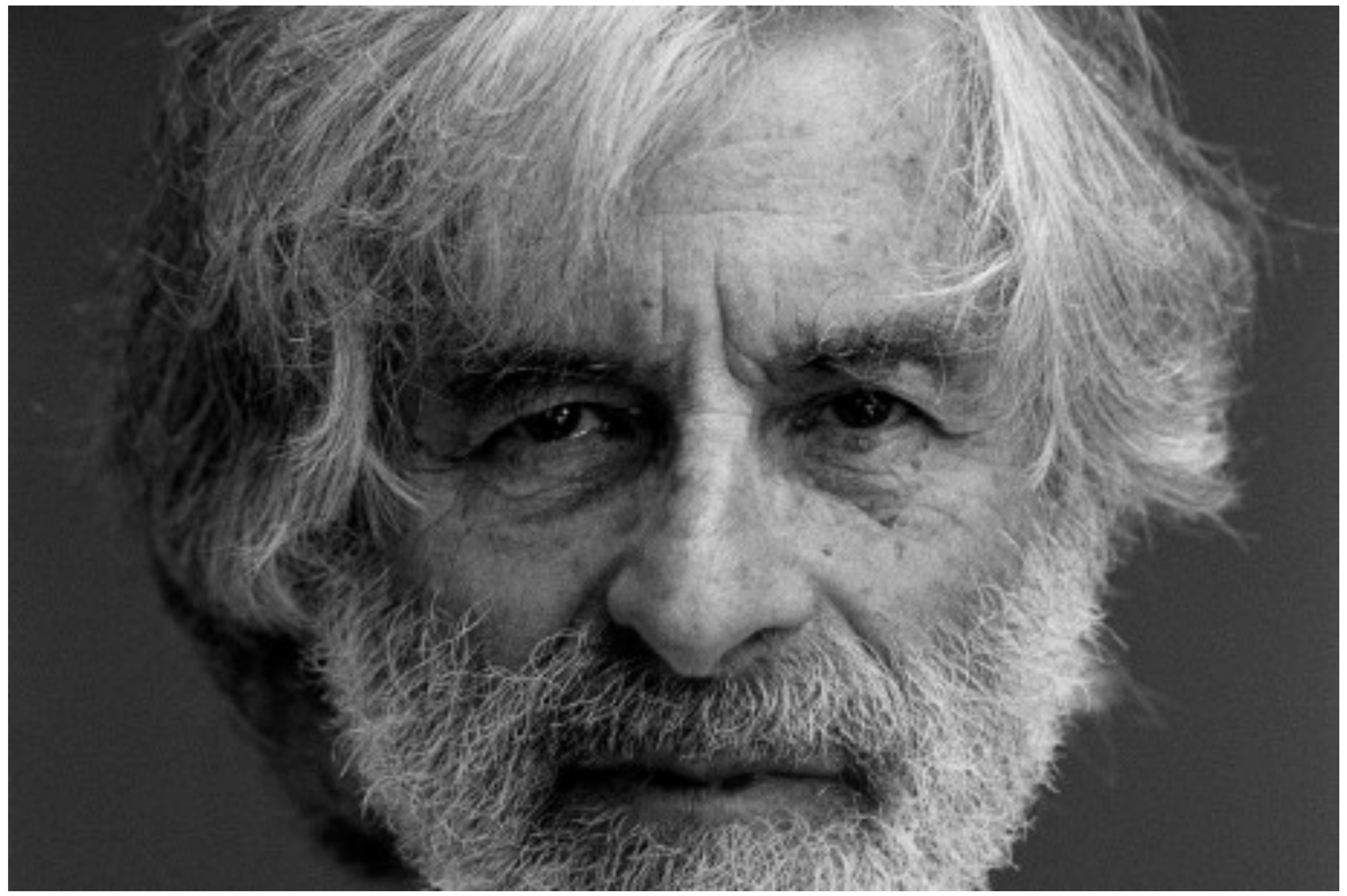
1990: Paxos first described

1998: Paxos paper published

2005: First practical deployments

2010: Widespread use!

2014: Lamport gets Turing Award


Leslie Lamport
(also known for LaTeX, Vector clocks, TLA)
Turing Award winner 2014

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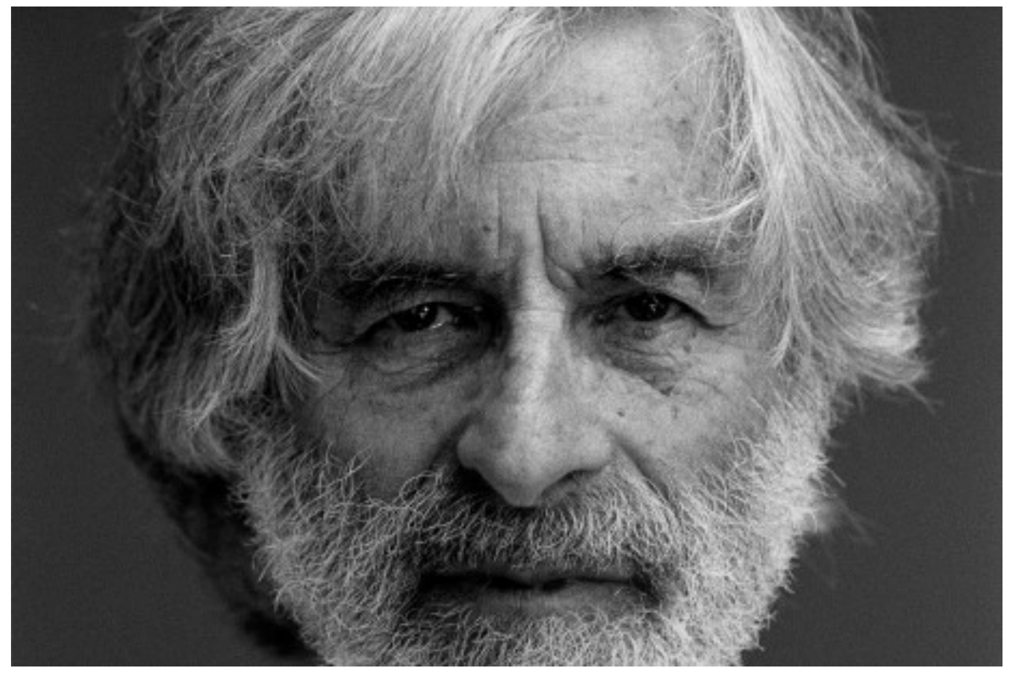
Recent archaeological discoveries on the island of Paxos reveal that the parliament functioned despite the peripatetic propensity of its part-time legislators.

The legislators maintained consistent copies of the parliamentary record, despite their frequent forays from the chamber and the forgetfulness of their messengers.



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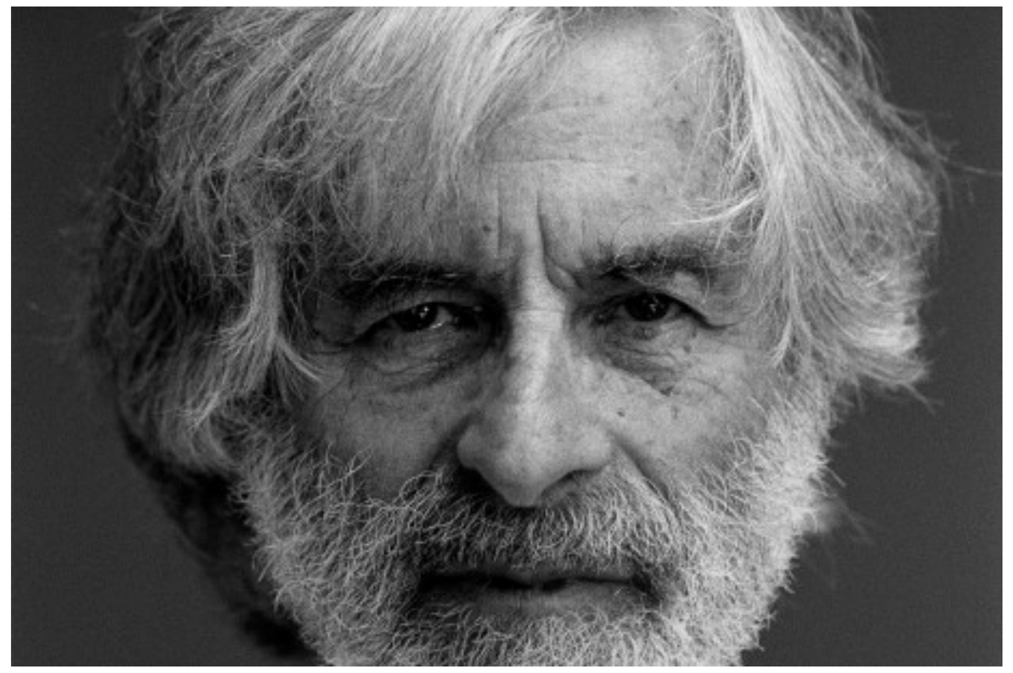
2005: Fi

2010: W

2014: La

- The ABCDs of Paxos [2001]
- Paxos Made Simple [2001]
- Paxos Made Practical [2007]
- Paxos Made Live [2007]
- Paxos Made Moderately Complex [2011]
- Paxos Consensus, Deconstructed and Abstracted [2018]



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Multi-Paxos

- Presented in the original Lamport's 1998 paper.
- Uses the described idea for a *sequence* of "slots" (think *transactions*).
- Includes *reconfiguration* (changing set of acceptors on the fly).
- Naive implementation: run Simple Paxos for *each slot*.
    - Better approach — secure a quorum for *several slots*.

Running Paxos with Scala Actors

```
class PaxosConfiguration(val proposers: Seq[ActorRef],
                         val learners:  Seq[ActorRef],
                         val acceptors: Seq[ActorRef]) { ... }
```

```
def createPaxosInstance(system: ActorSystem, numProposers: Int,
                        numAcceptors: Int, numLearners: Int): PaxosConfiguration = {

  val acceptors = createAcceptors(system, numAcceptors)
  val proposers = createProposers(system, numProposers, acceptors)
  val learners = createLearners(system, numLearners, acceptors)
    new PaxosConfiguration(proposers, learners, acceptors)
}
```

```
  def createProposers(system: ActorSystem, numProposers: Int, acceptors: Seq[ActorRef]) = {
    for (i <- 0 until numProposers) yield {
      system.actorOf(Props(ProposerClass, this, acceptors, i), name = s"Proposer-P$i")
    }
  }
```

Live Demo

Alternative Consensus Protocols

- View-Stamped Replication
  by Brian M. Oki and Barbara Liskov, 1989

- Raft
  by Diego Ongaro and John K. Ousterhout, 2014

To Take Away

- Fault-Tolerant Consensus Protocols are a *critical component* of modern *distributed systems* and *applications*

- Consensus properties are *uniformity*, *non-triviality*, and *irrevocability*

- The key ideas of Lamport's Paxos protocol are:
  - Majority *quorums* (avoiding split brain and enabling fault-tolerance);
  - *Two-phase* structure (secure-then-commit);
  - Dichotomy and cooperation between *proposers and acceptors*.