Byzantine Fault Tolerance and Consensus

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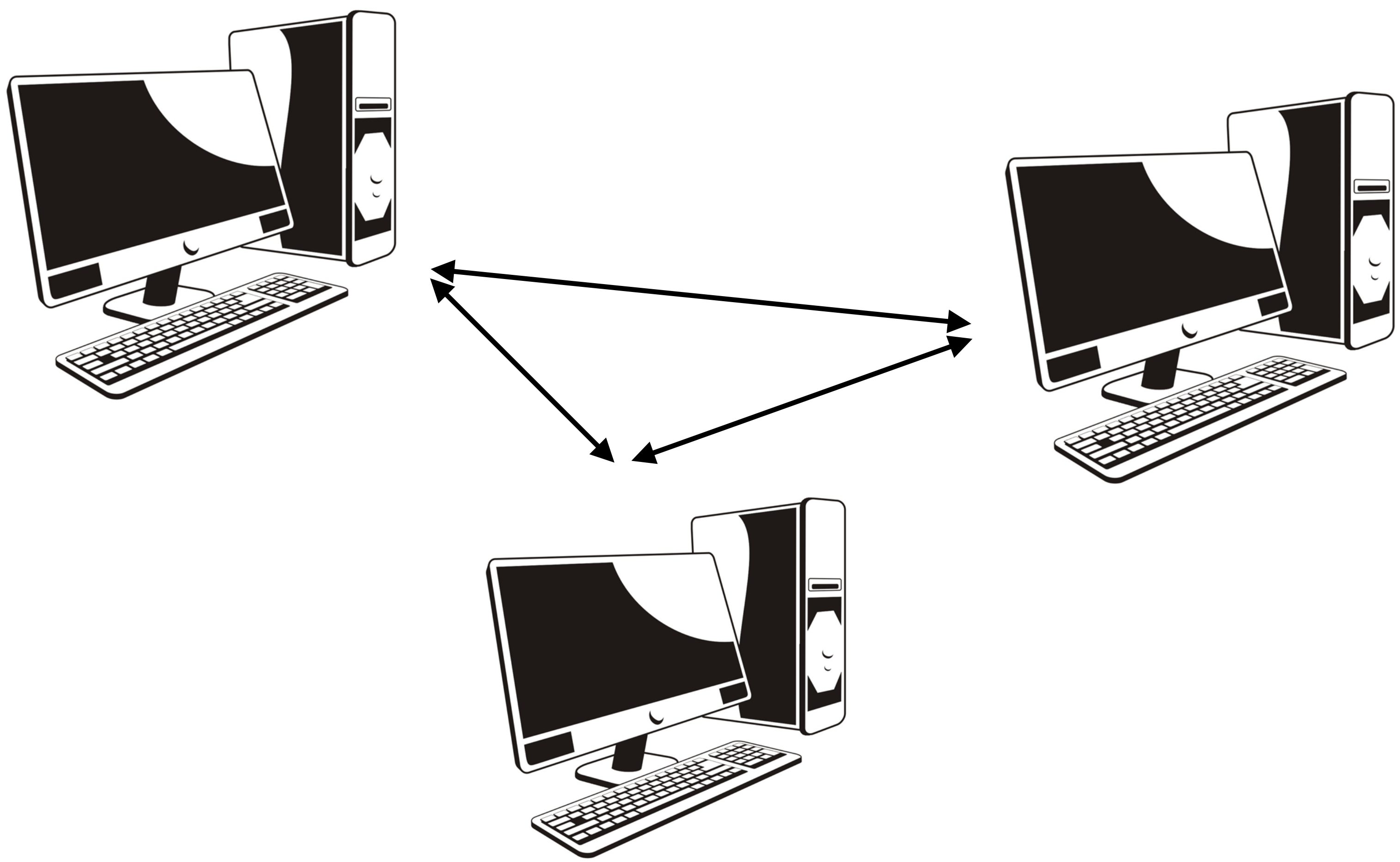
(Original) Problem

Correct
process



General goal:
Run a distributed algorithm

(Original) Problem

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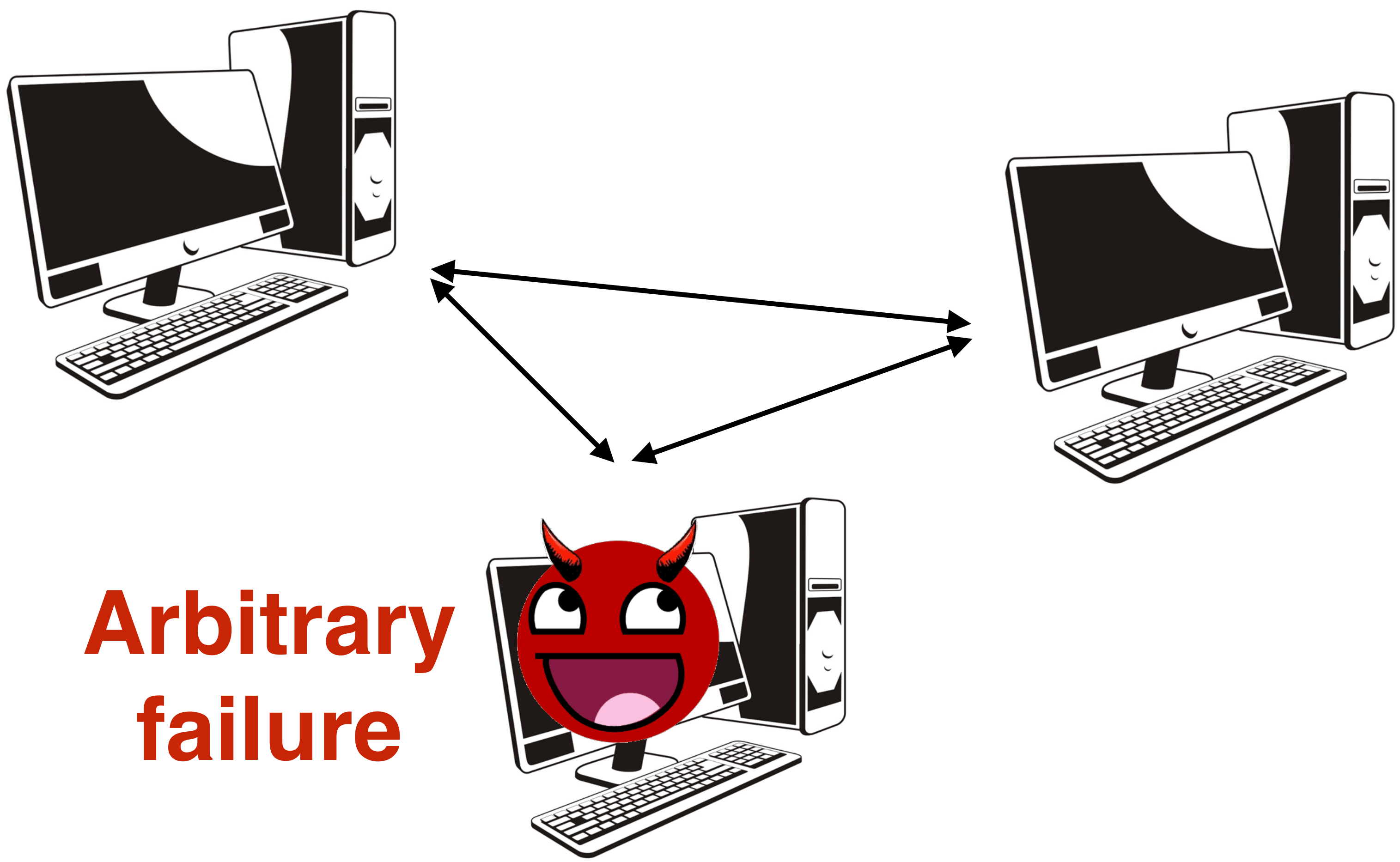
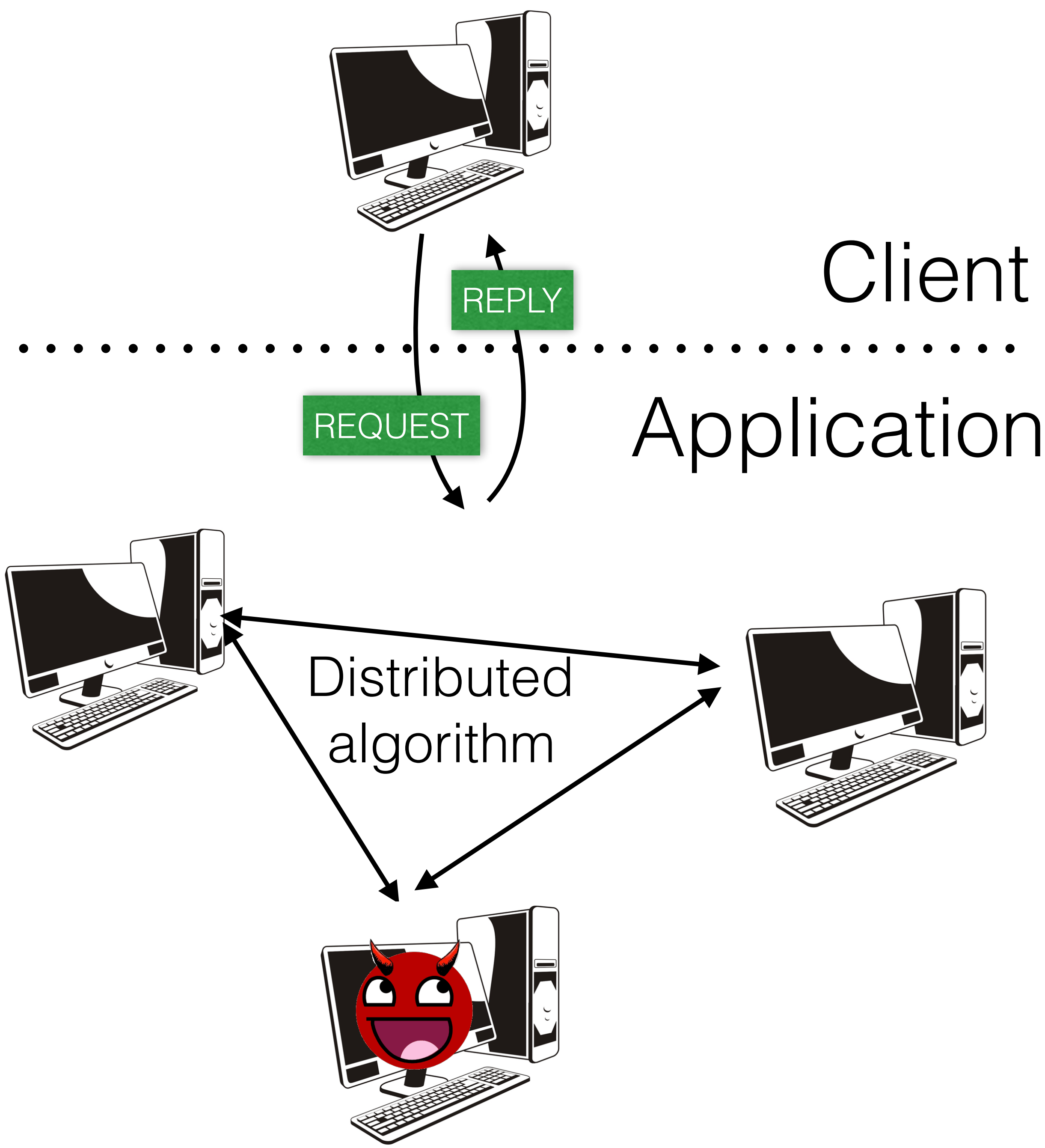


Arbitrary failure

General goal:
Run a distributed algorithm

(Recasting the) Problem

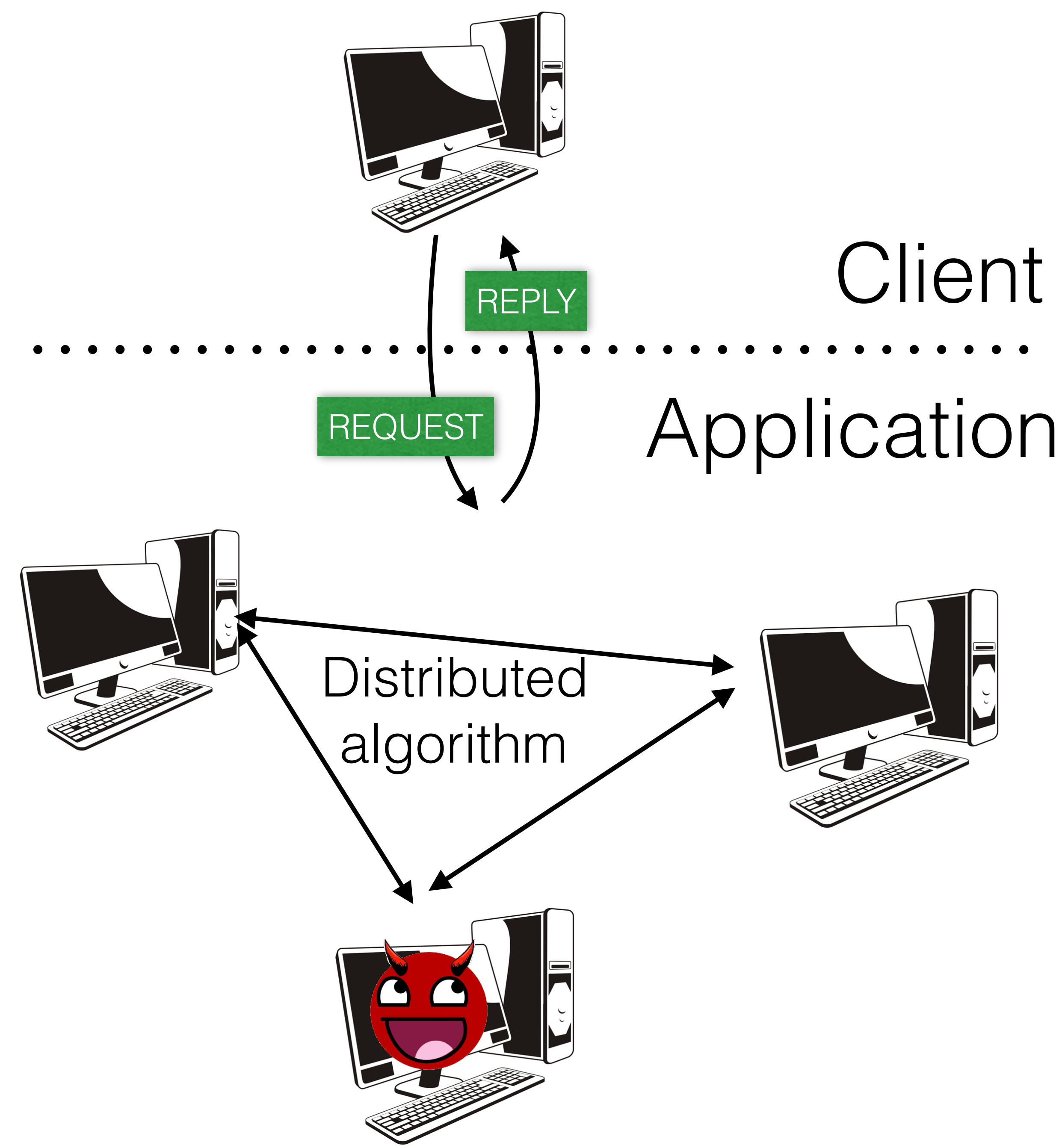


Recasting the problem

Application requirements:

- High-Availability
  (give a reply to a request)
- Reliability
  (give correct replies)

Boils down to fault-tolerance



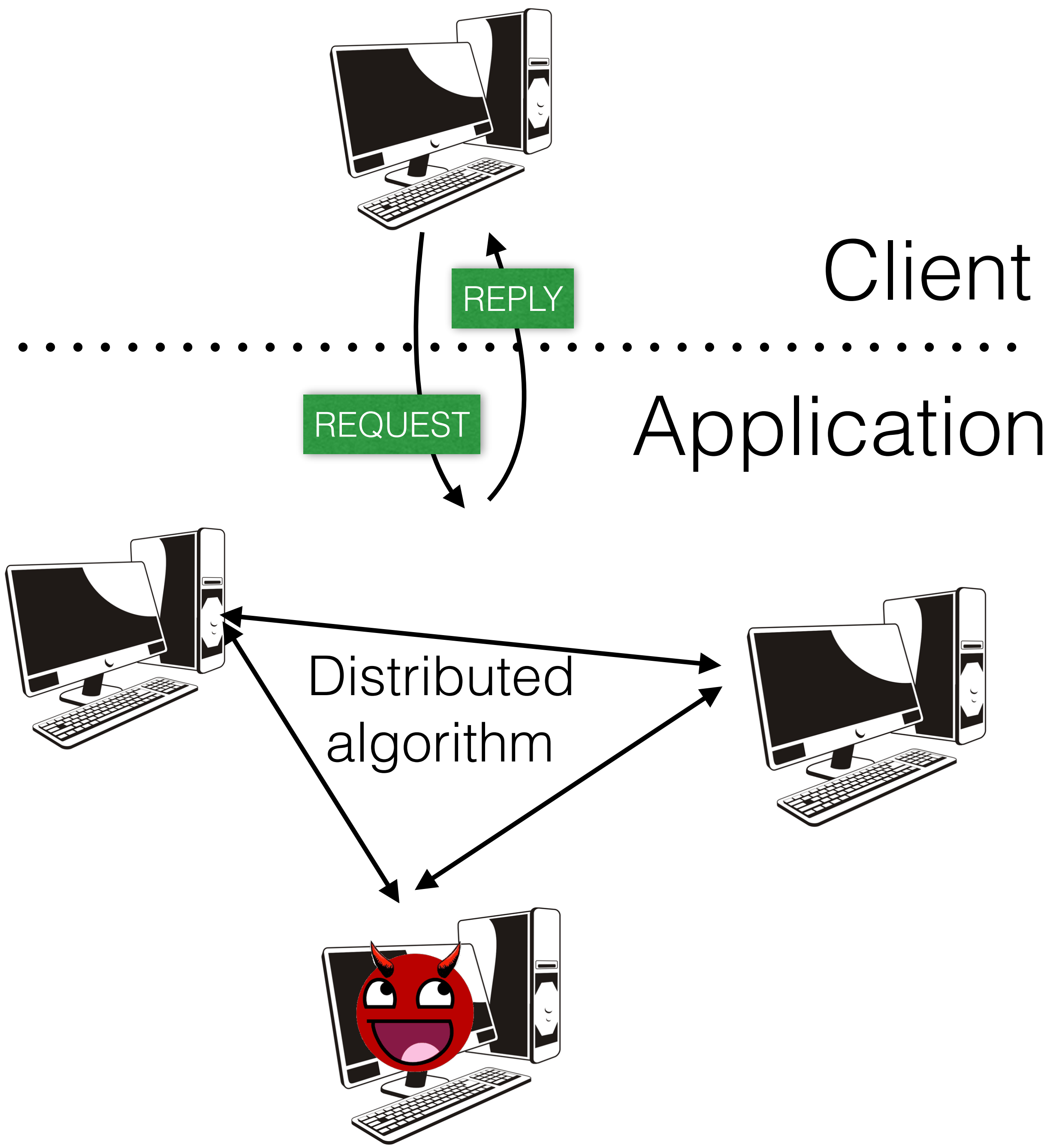
Solution

Fault-tolerance basic techniques:

- Agreement = Consensus
- Replication = State Machine Replication

In the following we will see…

- PBFT
- Seminal algorithm for Byzantine Fault Tolerance



PBFT

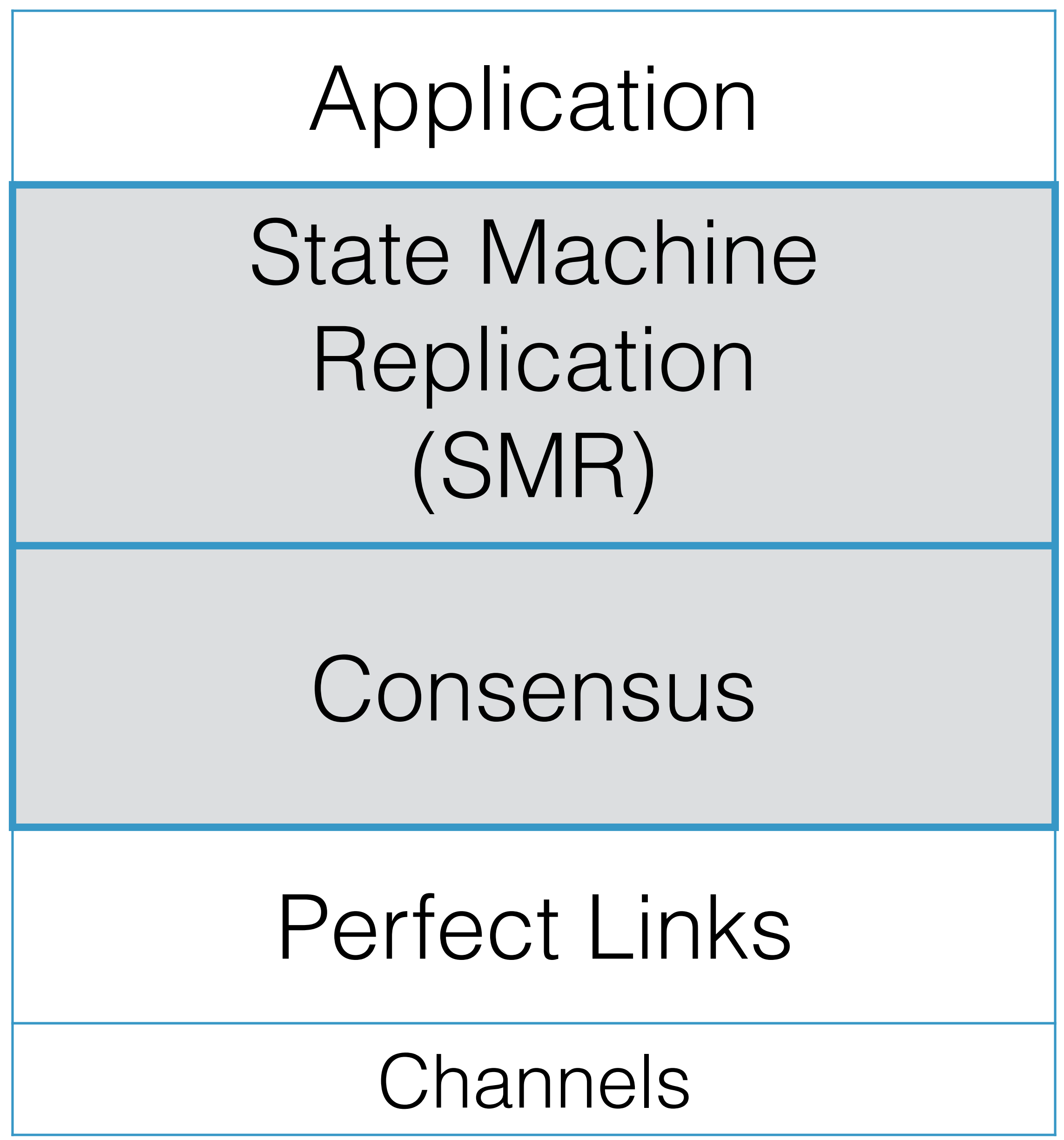
Practical Byzantine Fault Tolerance

OSDI'99

Miguel Castro

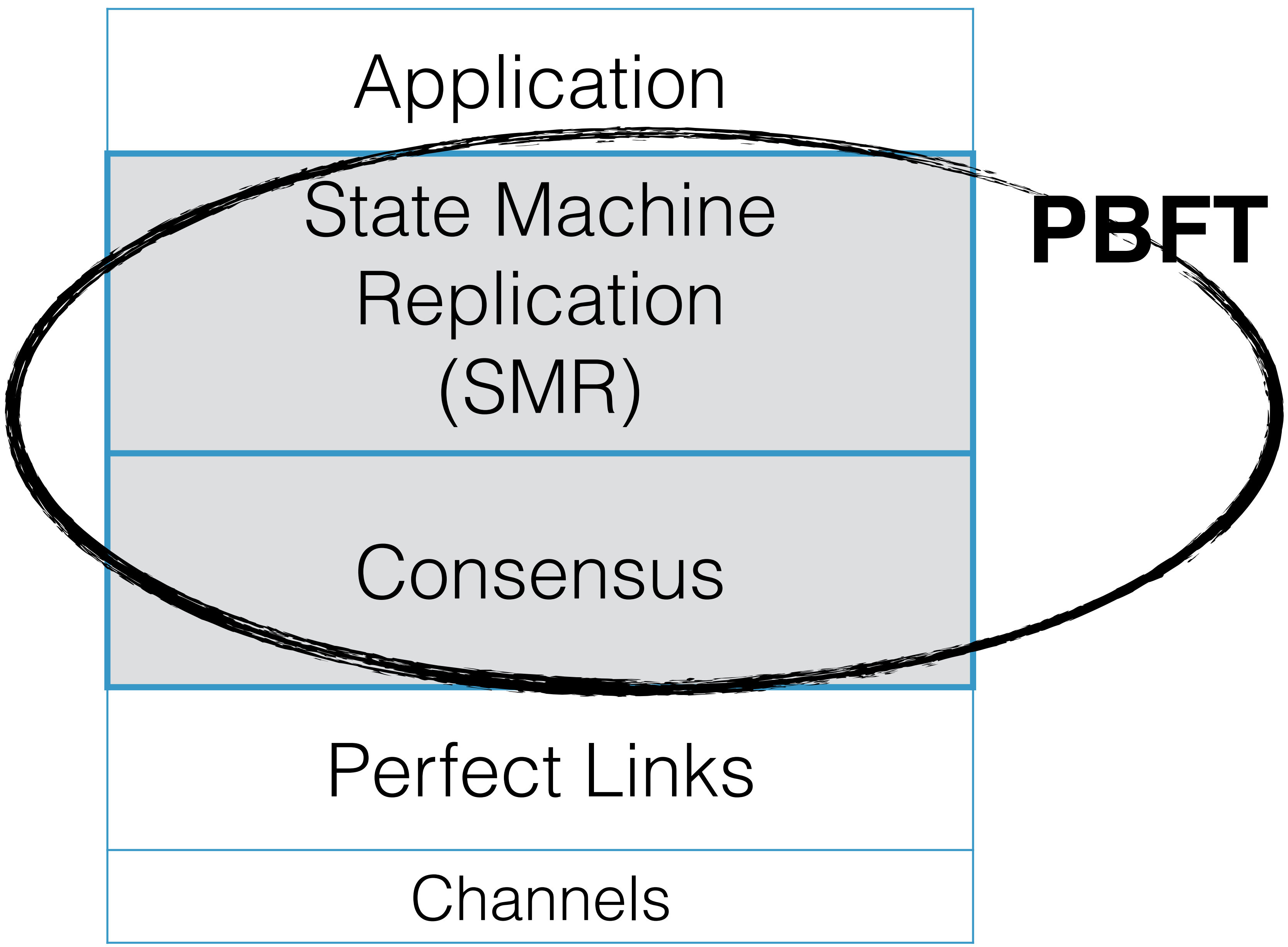
Barbara Liskov

Modules



Application
State Machine
Replication
(SMR)
Consensus
Perfect Links
Channels

Modules



Application
State Machine Replication (SMR)
PBFT
Consensus
Perfect Links
Channels

Overview

PBFT:

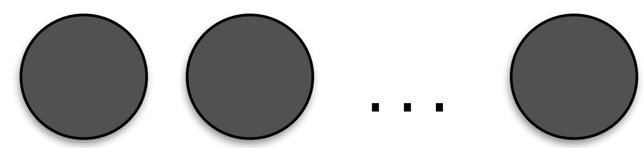
- **System model**
  — slightly different from what we've seen so far
- SMR
- Consensus

System model

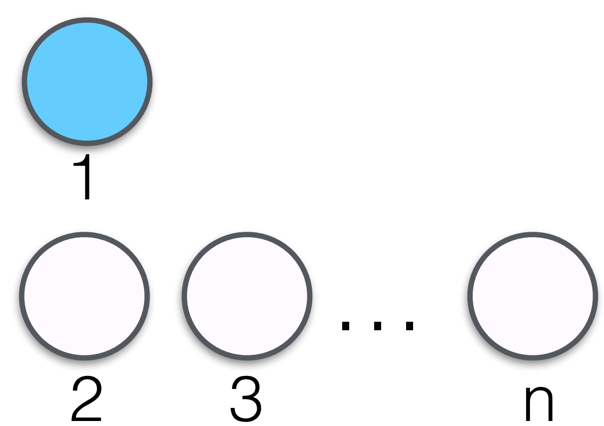
Processes

Three types of processes in this algorithm:

- Clients



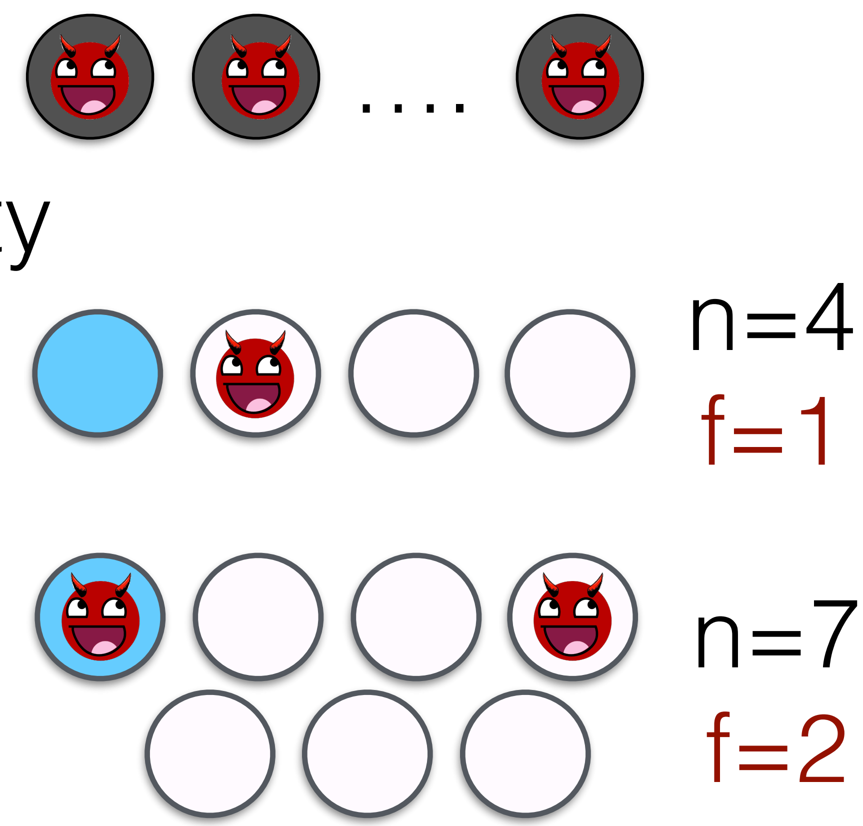
- n replicas
    - one of them is <u>primary</u>
    - others are <u>backup</u>



System model

Failure model

- Arbitrary (Byzantine) faults
- Clients:
  - Any client can be faulty
- Replicas:
  - $n = 3f + 1$
  - *f* faulty (upper bound)



System model

Network & crypto

- Assume perfect links
- Direct links between any two processes
- For messages:
  - Public-key signatures, message authentication codes
  - <u>Avoid spoofing, replays, corruption</u>
- Clients are authenticated
  - Can revoke access to faulty clients

Overview

PBFT:

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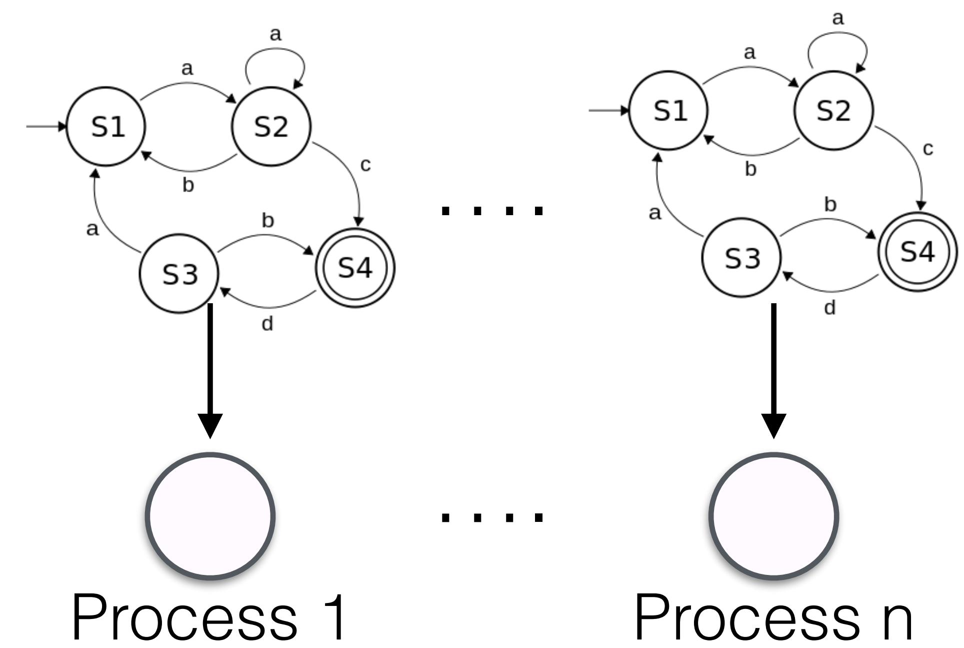
- Consensus

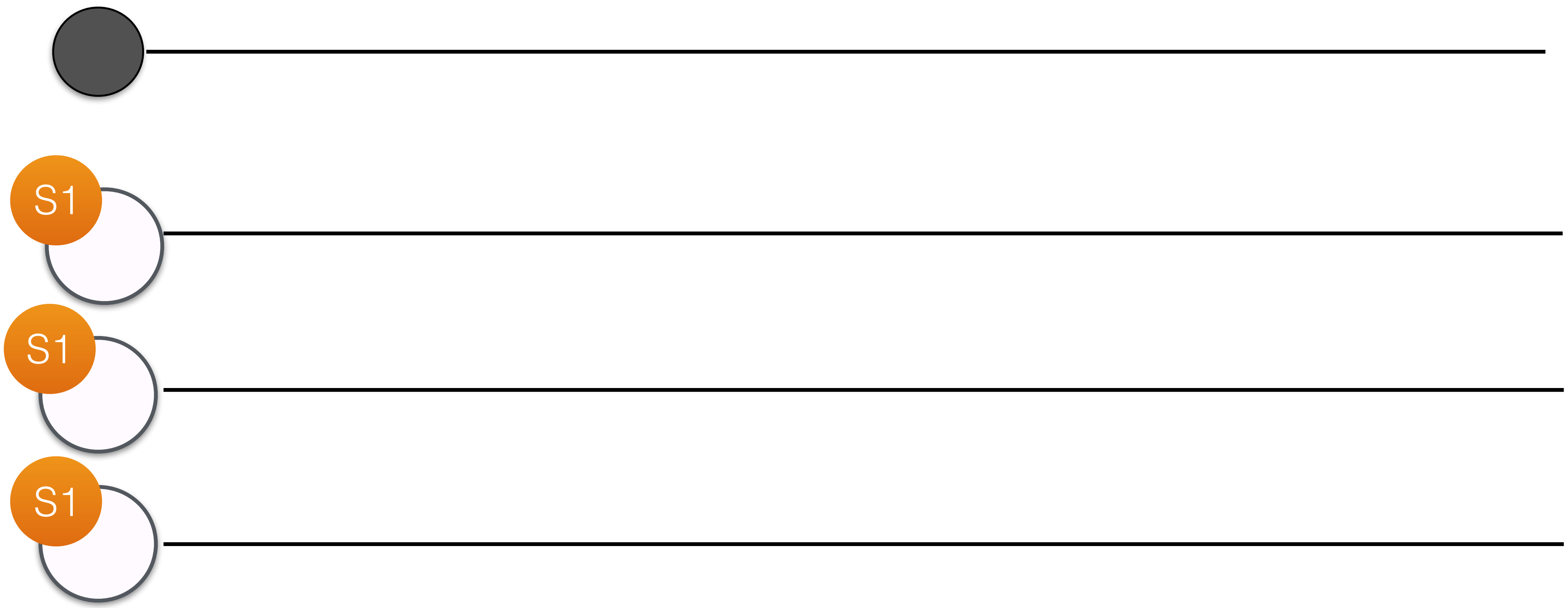
State Machine Replication
(SMR)



- A fault-tolerance technique
- Basic ideas:
  - Application = state machine
  - Run the application on multiple processes
  - Each processes is a faithful replica of the application
- Note: We can ignore the primary/backup distinction in this example

SMR

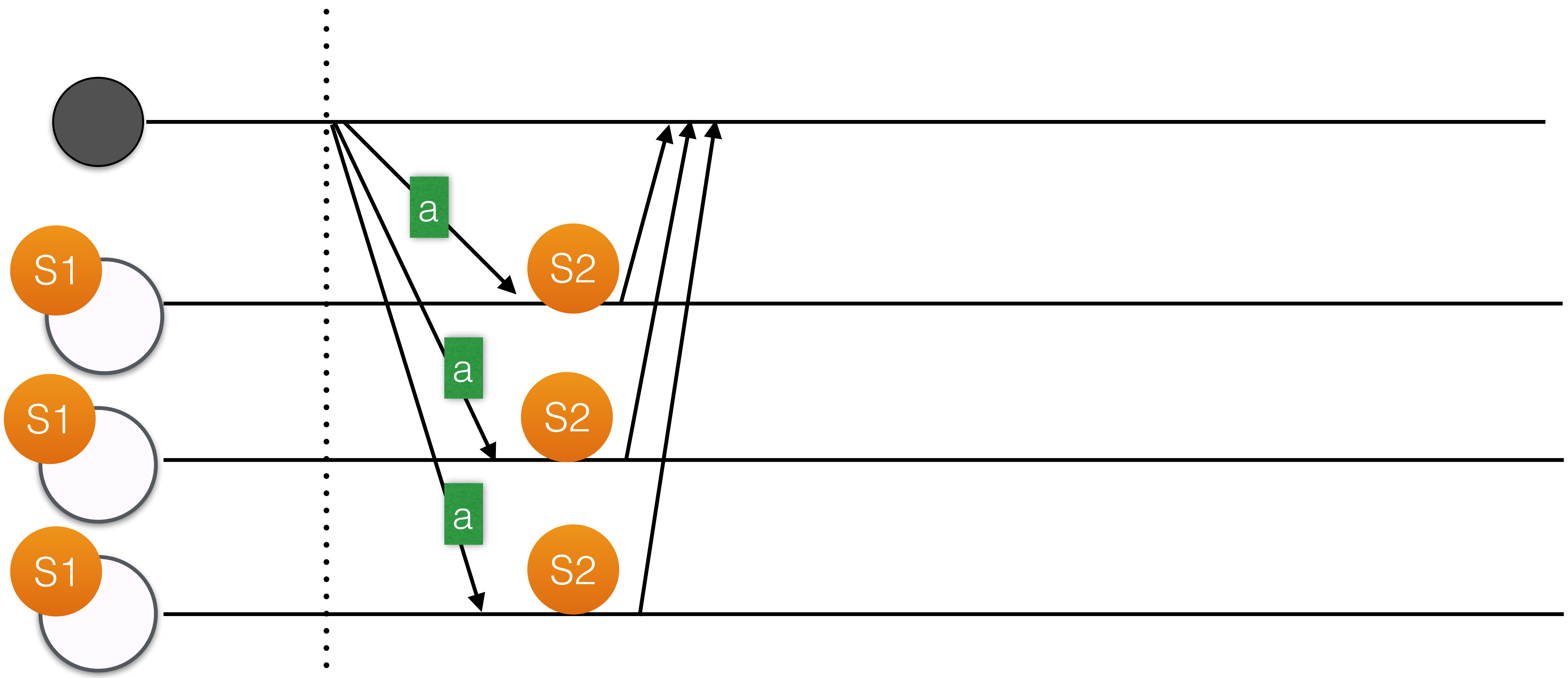
in a nutshell



All SMR replicas start from the same state (S1)

SMR

in a nutshell



All SMR replicas start from the same state (S1)

Transition to state (S2) due to operation ‘a’

SMR

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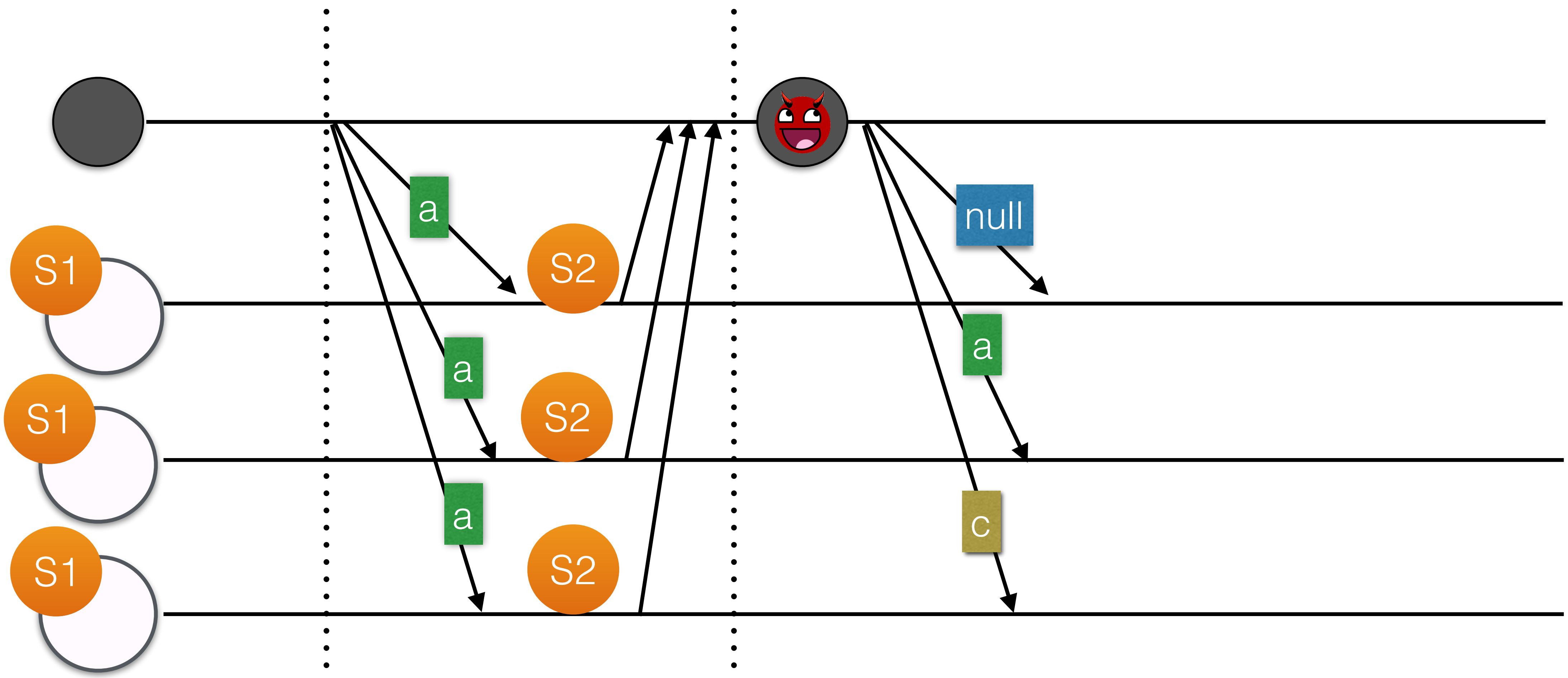

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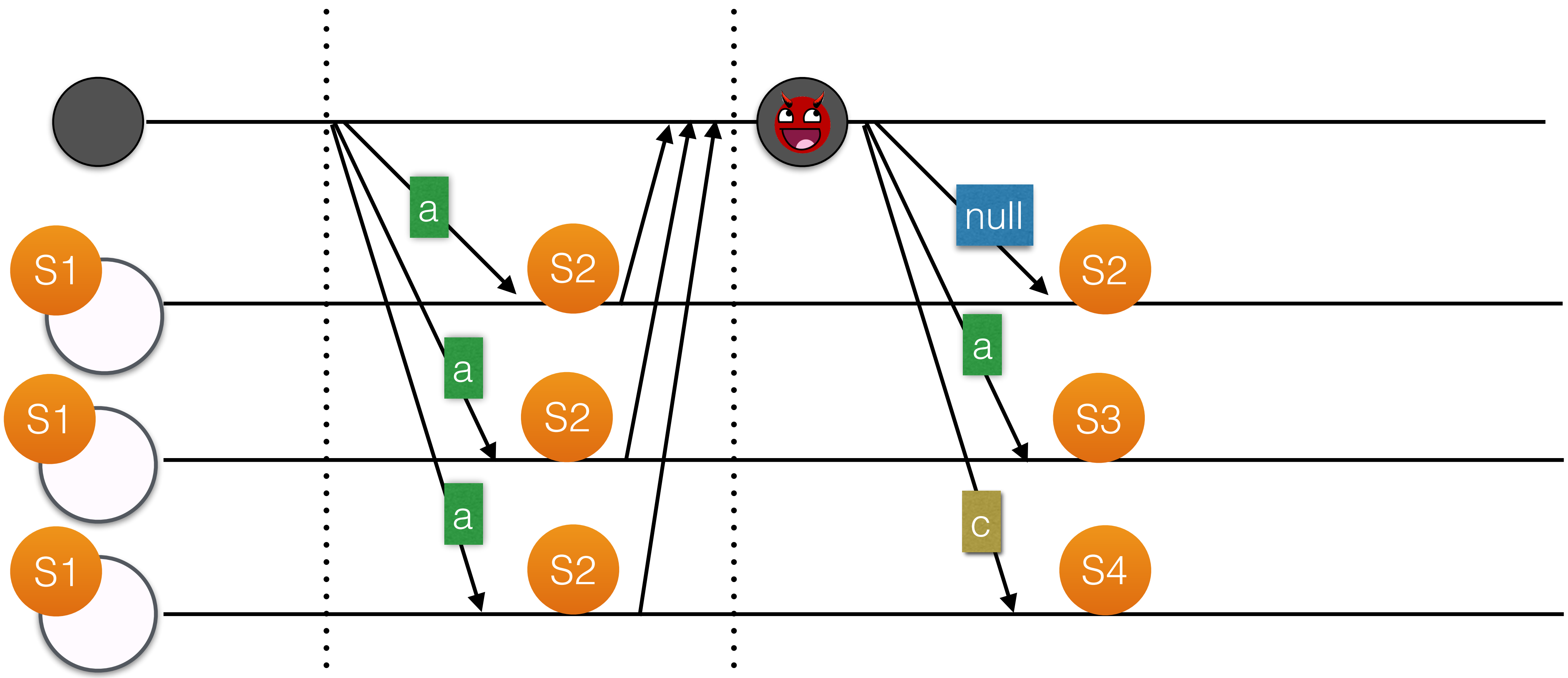

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A faulty client can wreak havoc

SMR

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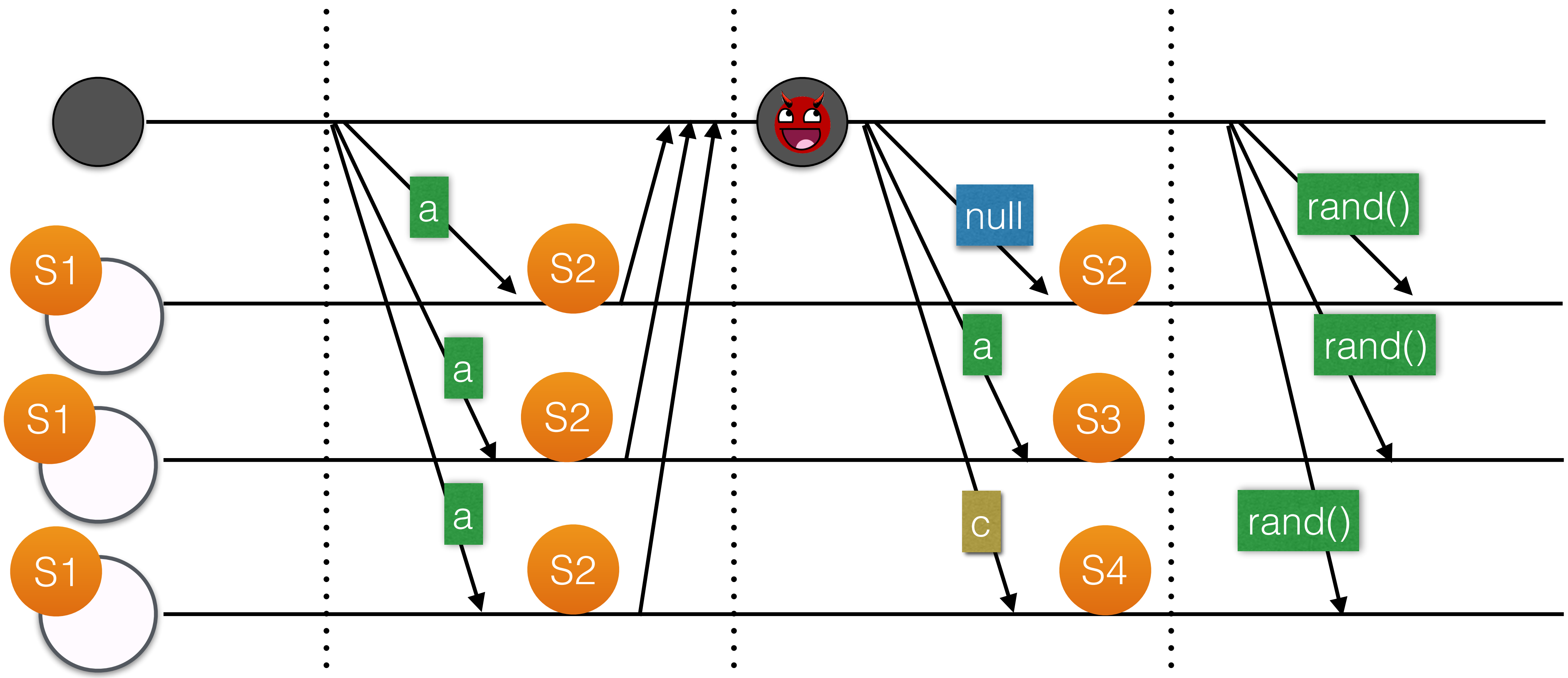

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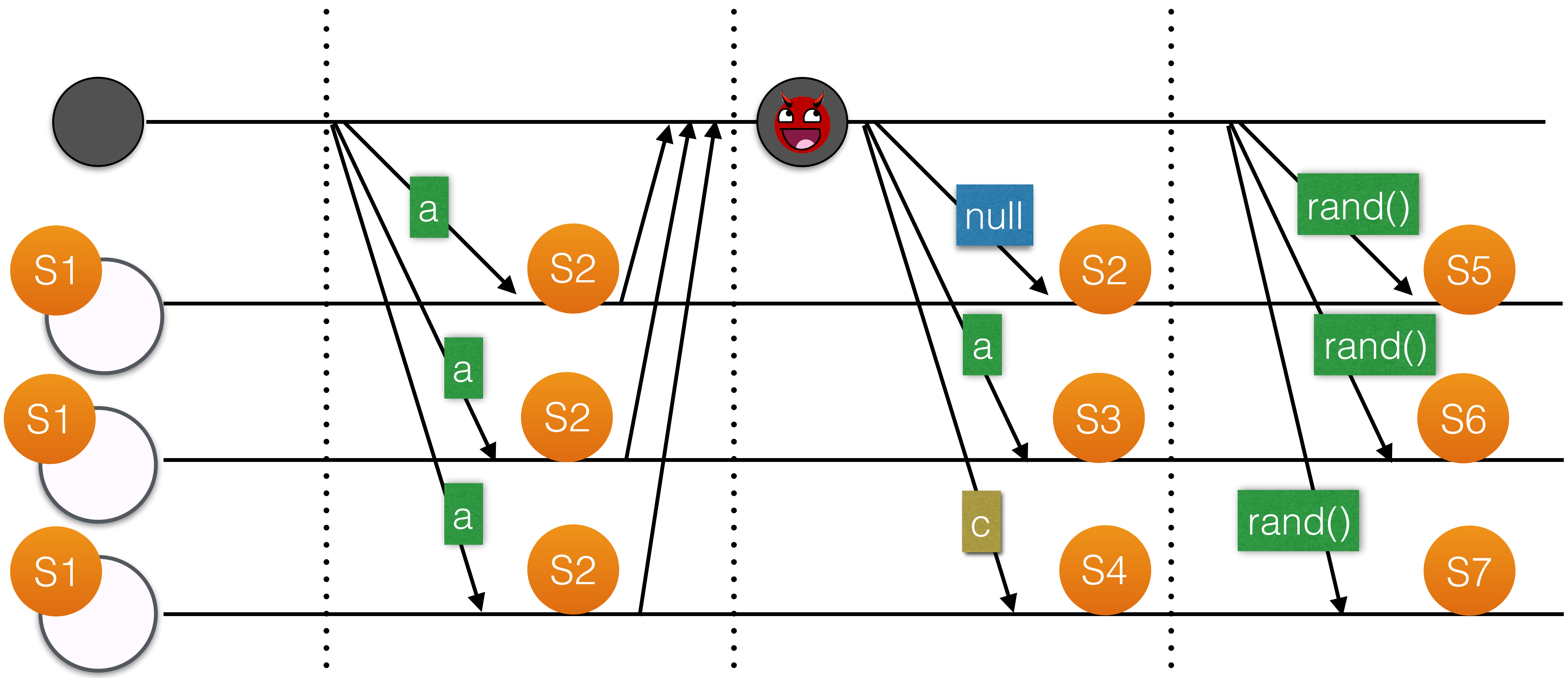

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Non-determinism is also harmful

SMR

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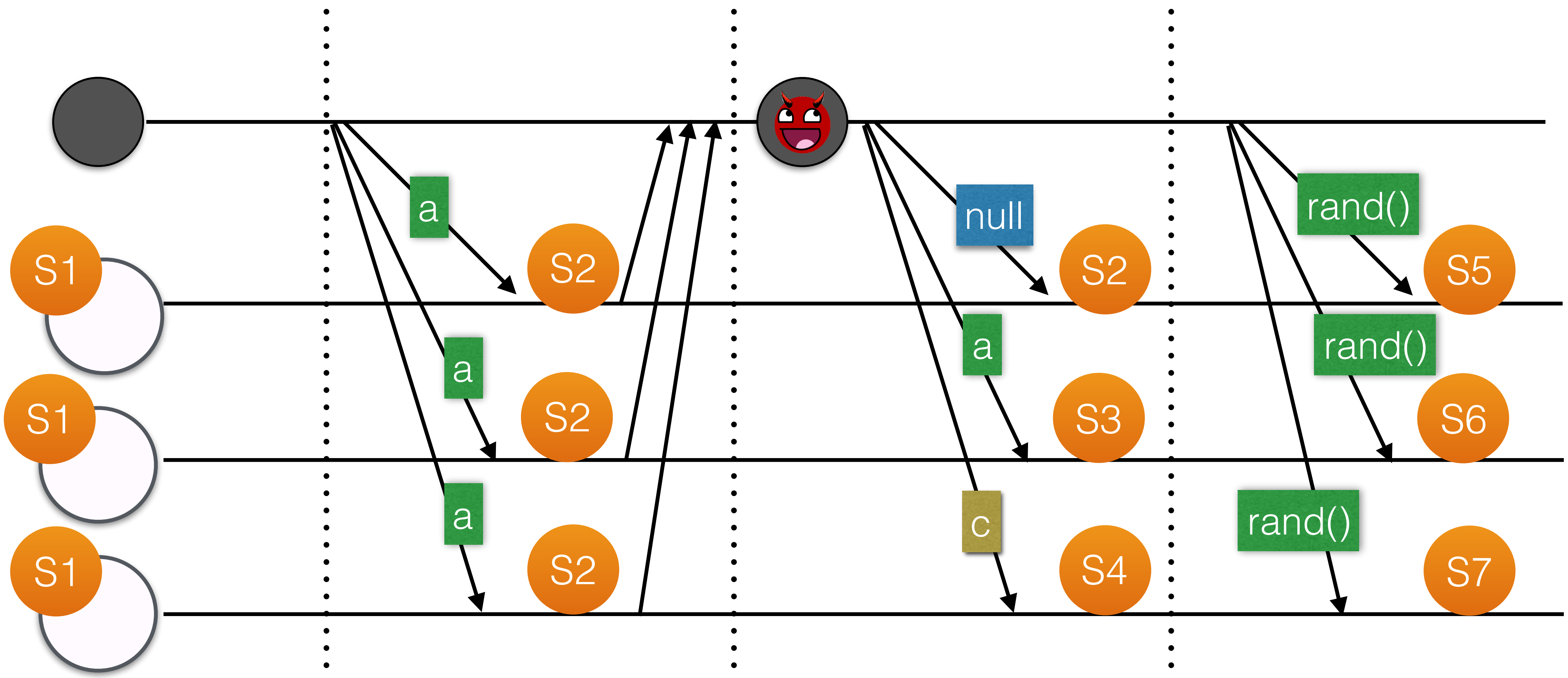

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Diverging states!

SMR

Requirements

- Avoid diverging states
- All replicas must:

  1. Start in the same state
  2. Execute the same sequence of operations
  3. Use only provided operation (+parameters), thus avoid non-determinism

SMR
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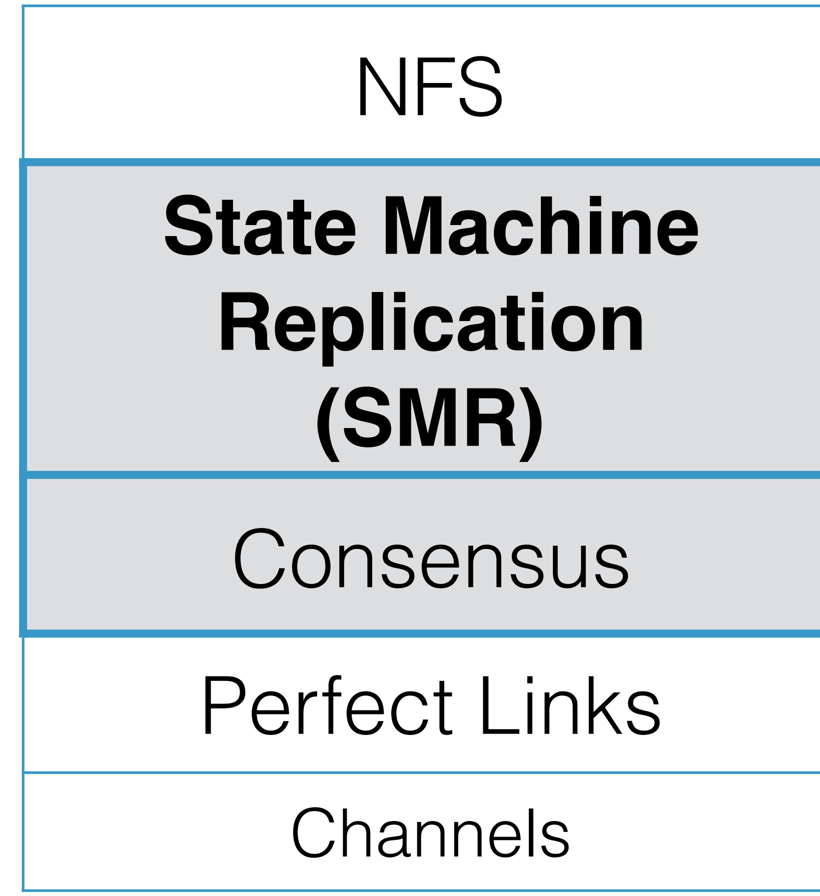
Simple

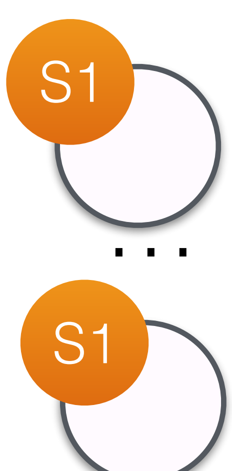
Consensus

Depends on application

SMR
in PBFT



- Application = a distributed file system — Network File System (NFS)
- Operations = write to a file, delete, etc.
- Primary/backup distinction is relevant



SMR
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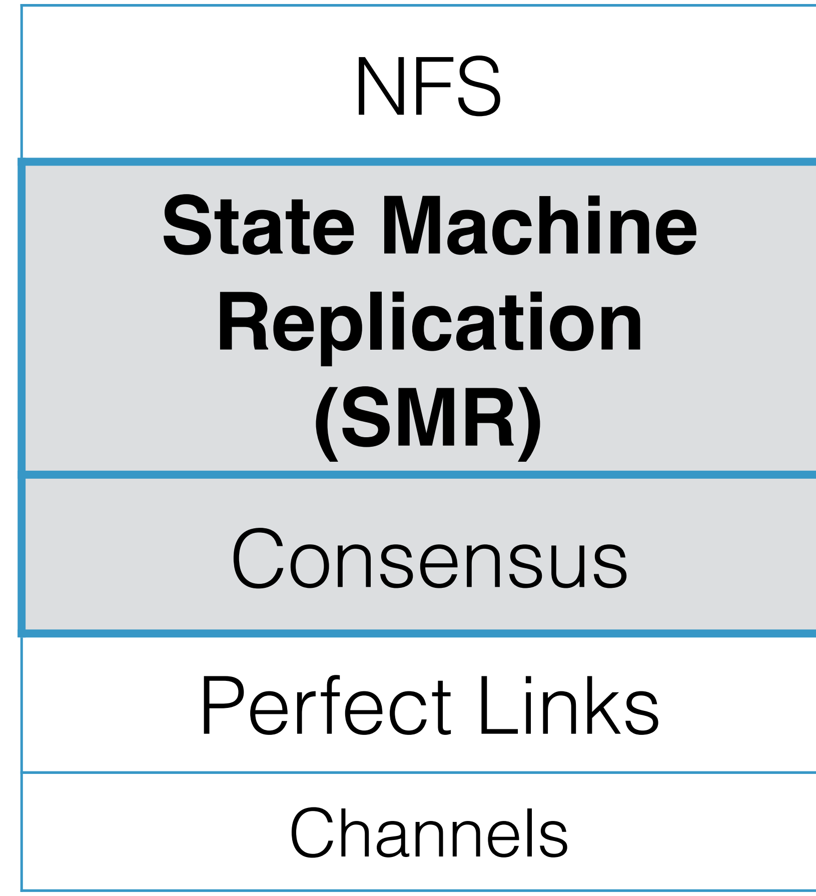

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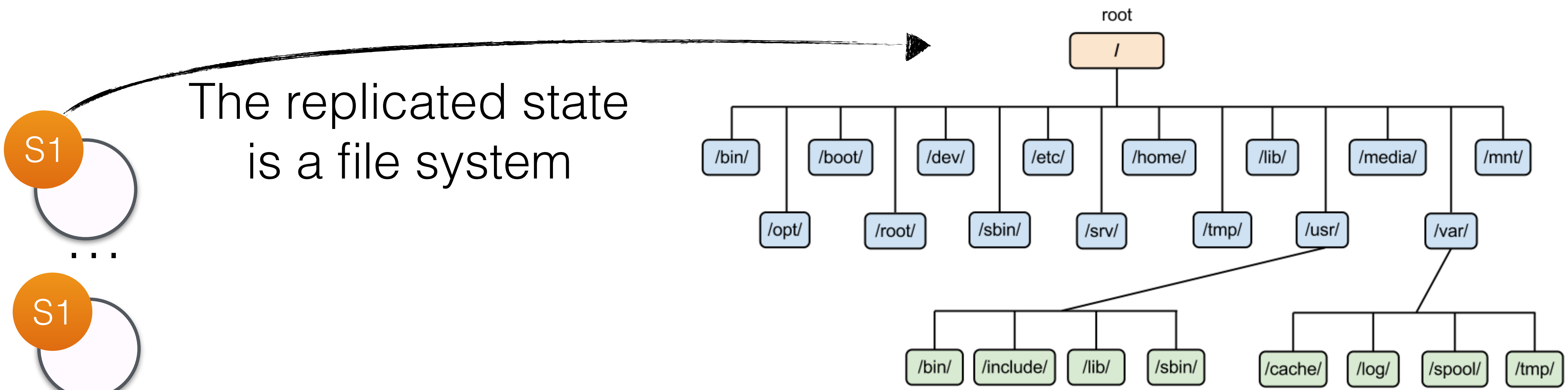

SMR
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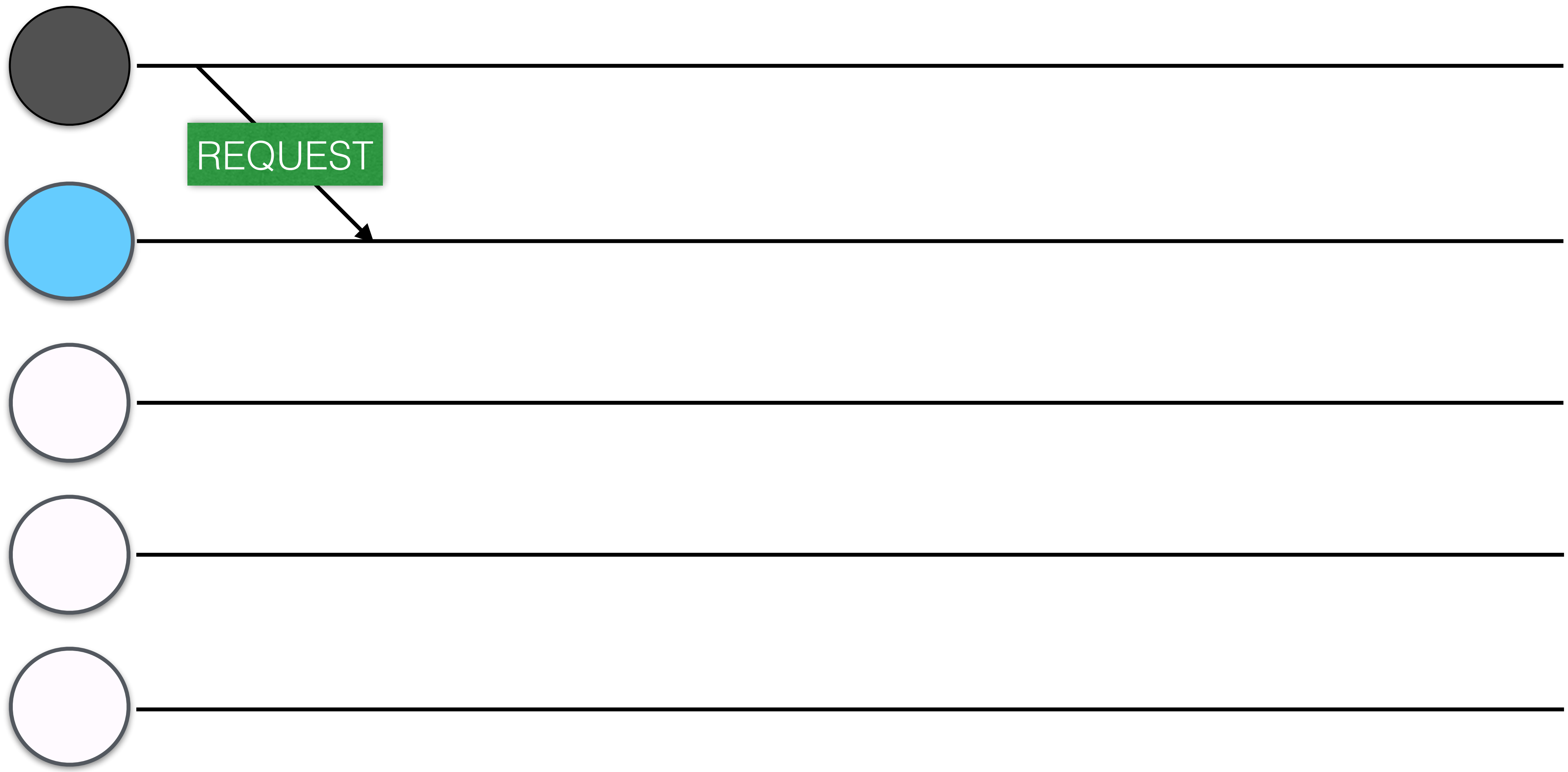

Client contacts
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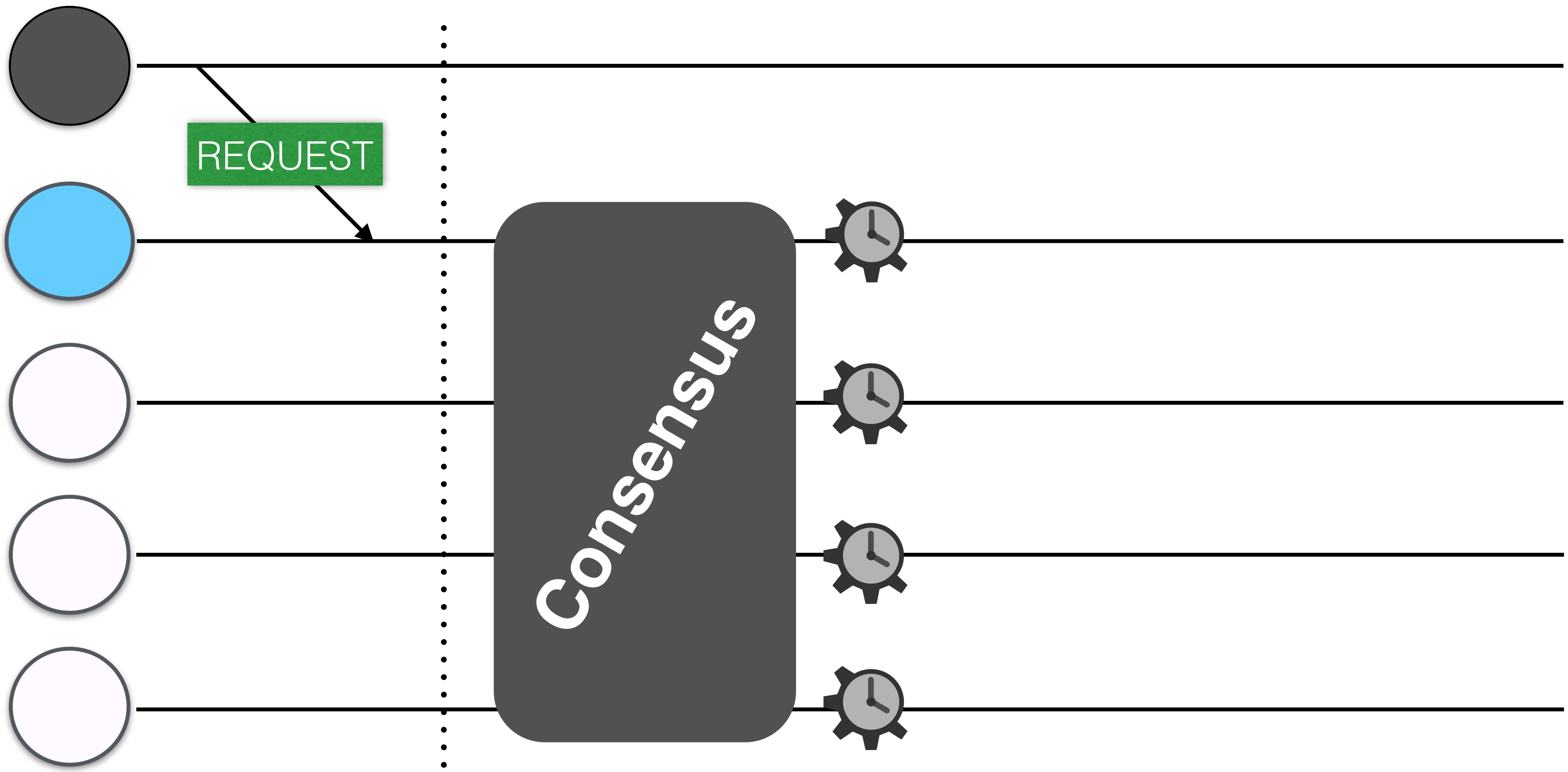
with a request

SMR

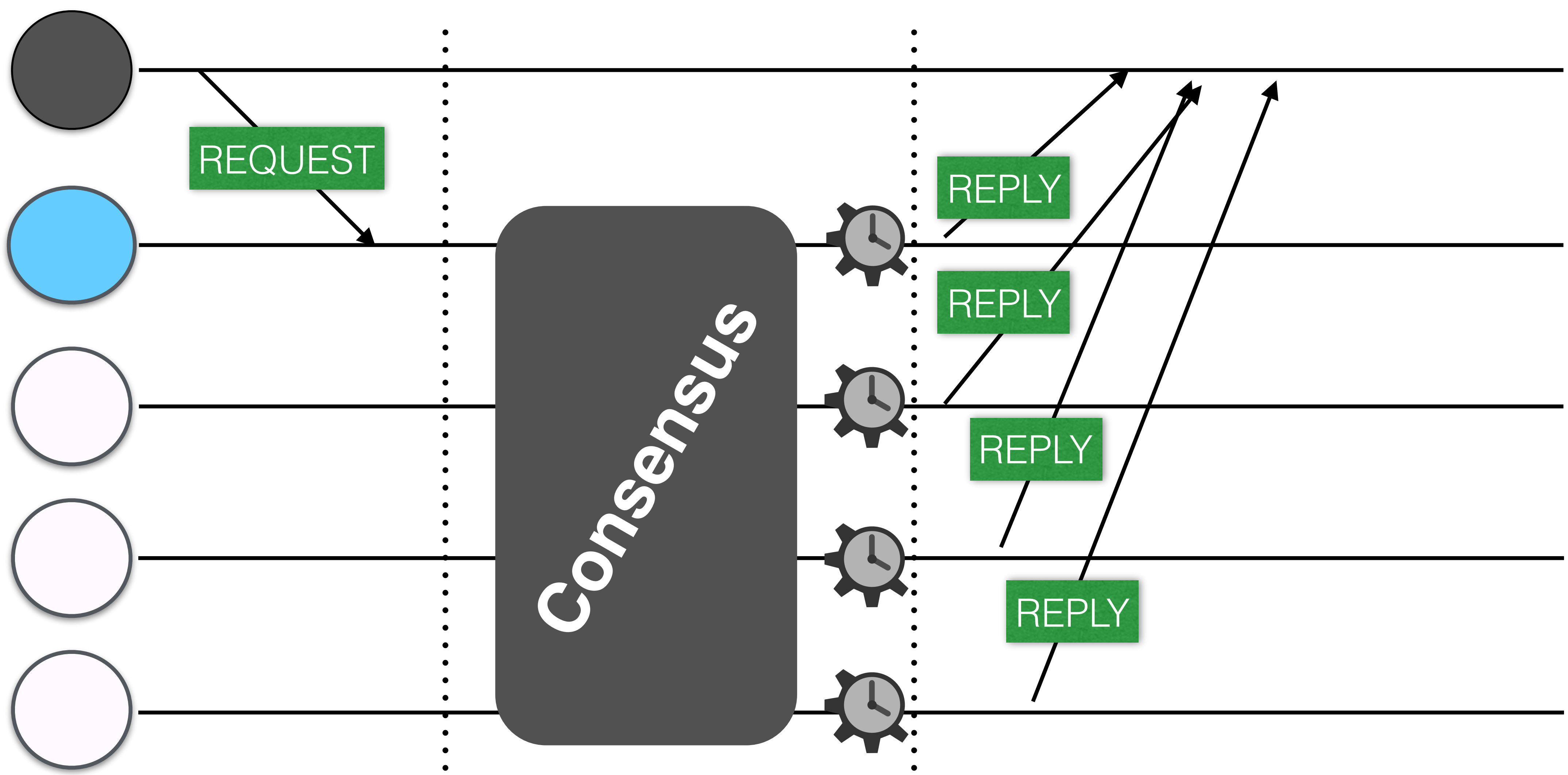
in PBFT



Client contacts the primary with a request

All replicas agree on the request & execute it

SMR
in PBFT

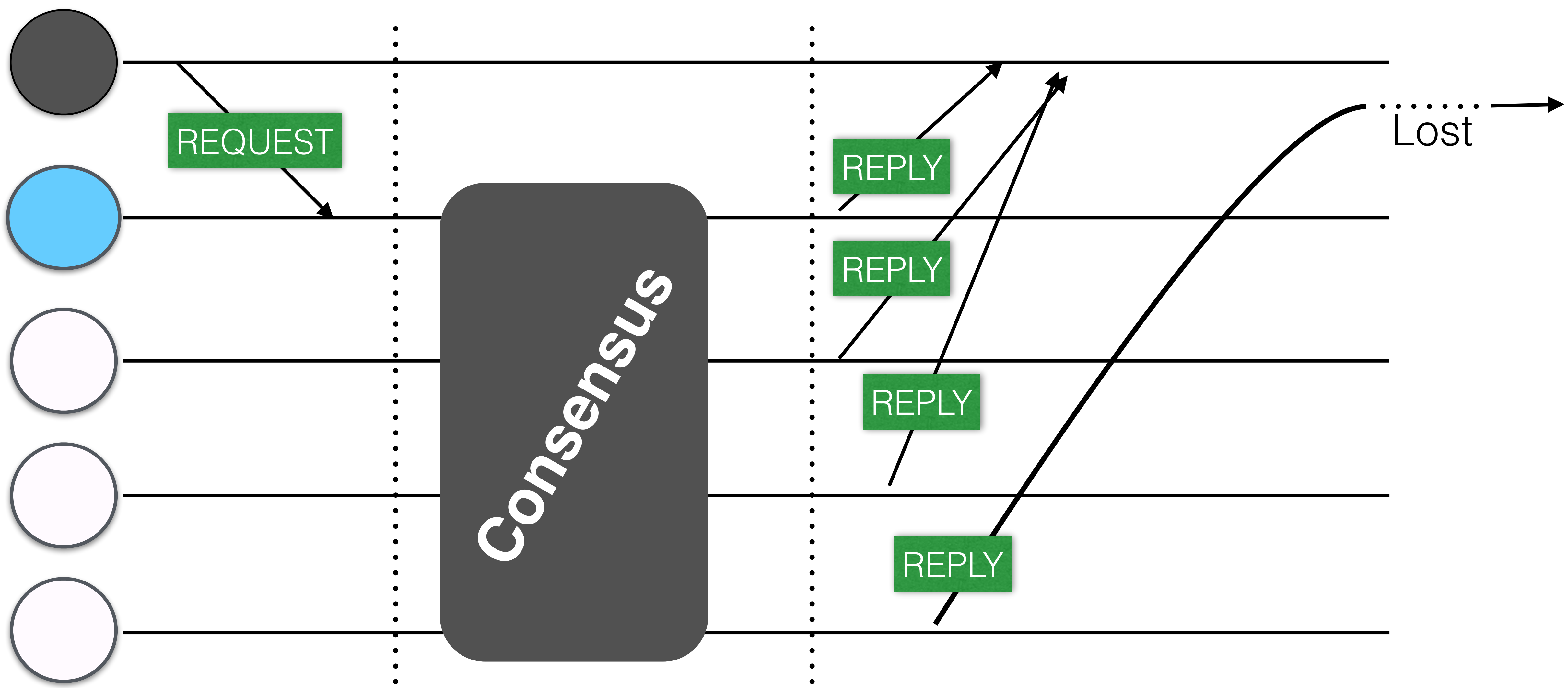


Client contacts the primary with a request

All replicas agree on the request & execute it

Client gets the same reply from all correct replicas

SMR
in PBFT



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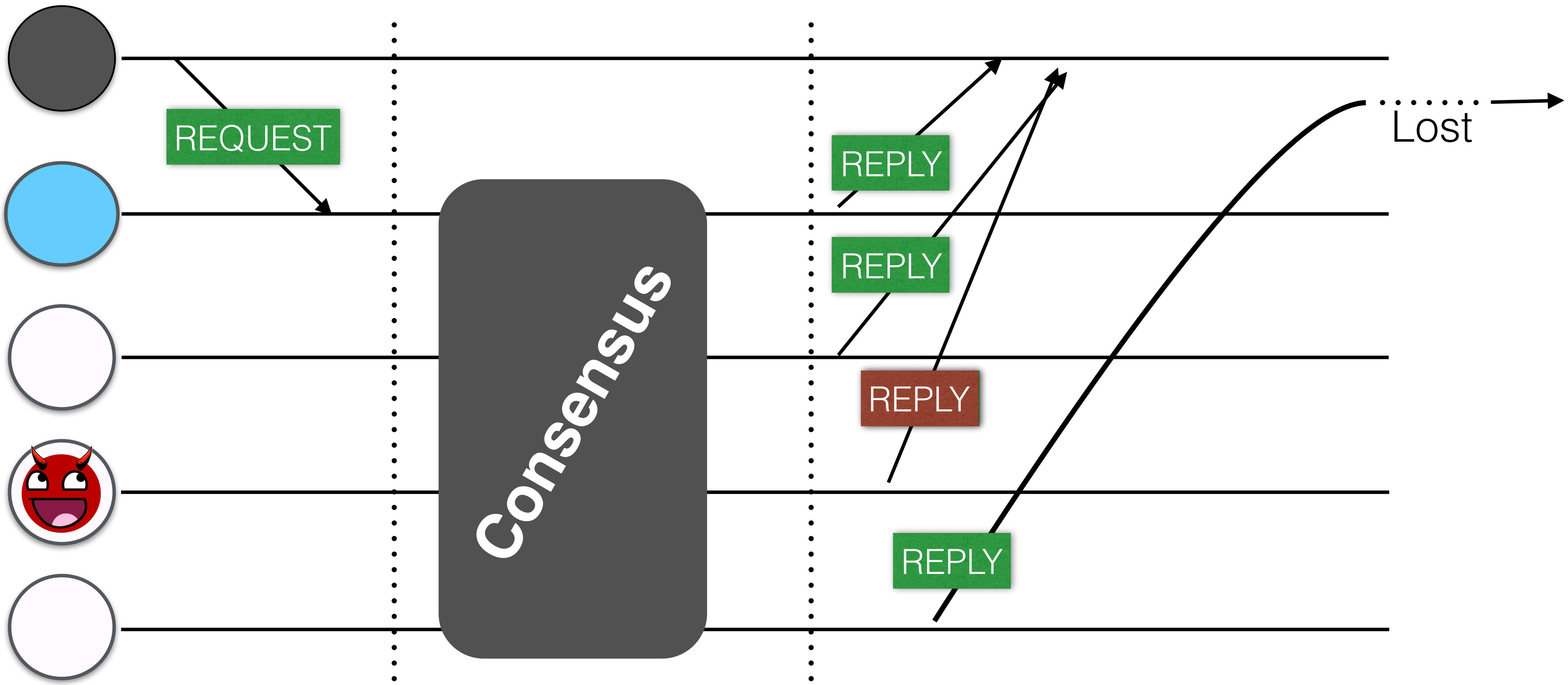
Redundancy in Replies = Cope with failures

SMR

in PBFT



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All replicas agree
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Redundancy in Replies
=
Cope with failures

Overview

PBFT:

- System model
  — slightly different from what we've seen so far

- SMR

- **Consensus**

Consensus

- The core for many algorithms, including:
- TRB, Group membership, View synchronous b-cast, State machine replication

Traditionally

Instance

- Processes propose <u>values</u>
- Agree on a proposed value

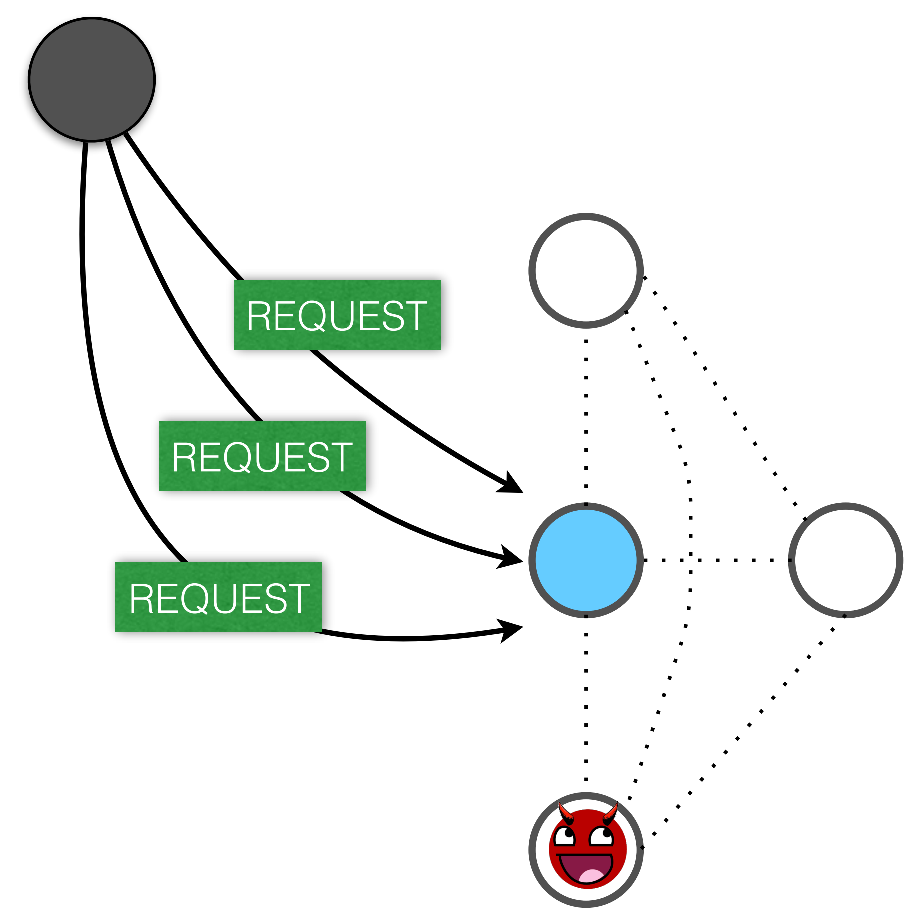
In PBFT:

Instance

- Clients propose <u>requests</u>
- Primary multicasts the requests to backup replicas
- Primary & replicas agree on the sequence of request

Consensus
in PBFT

- We'll assume one client
  - Proposals = requests for application operations
- Assume:
  - n = 4, f = 1
  - The faulty replica does not cooperate
- Concurrent requests:
  - Consensus to agree on a sequential execution of requests



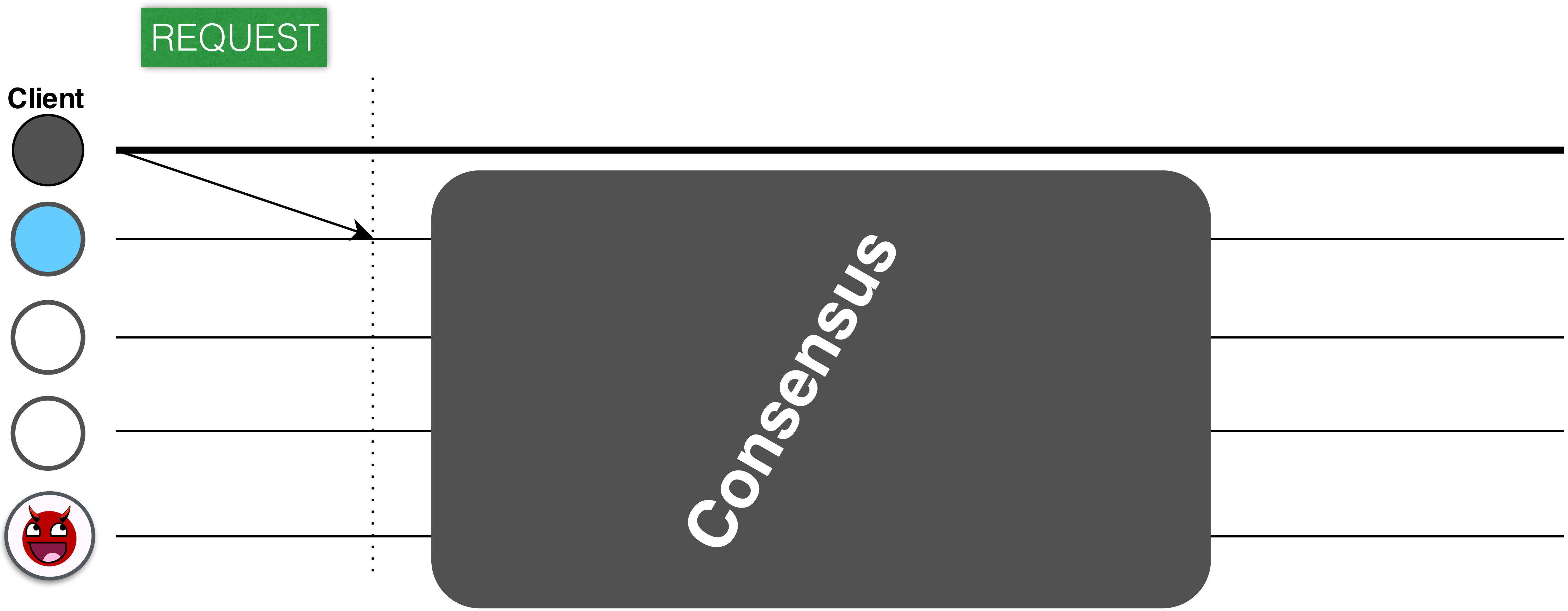
Consensus
in PBFT

Algorithm ideas:

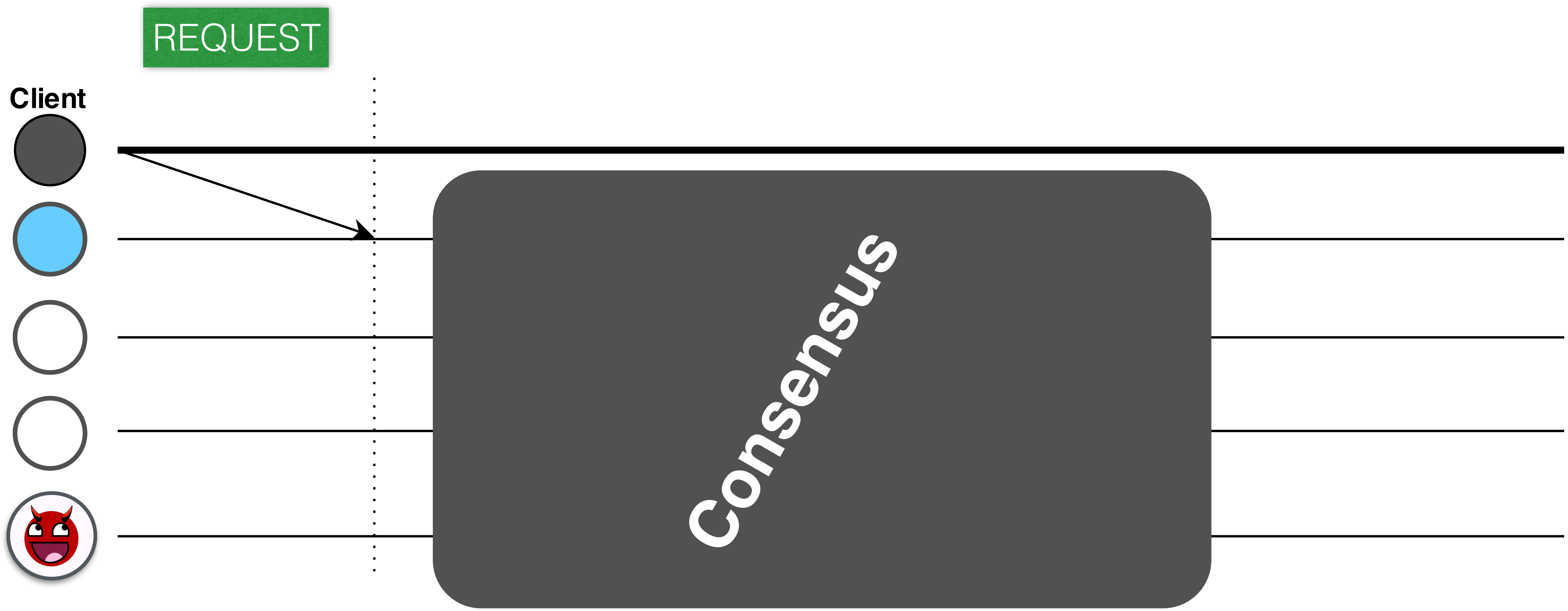
- Client sends requests to the primary replica
- Execute a sequence of consensus instances:
  - Each instance is dedicated to a request
  - Instances (and therefore requests) are sequentially ordered by the primary
  - Backup replicas adopt requests from the primary in the imposed order

Properties: **Validity, Agreement, Termination, Integrity**

Consensus
in PBFT



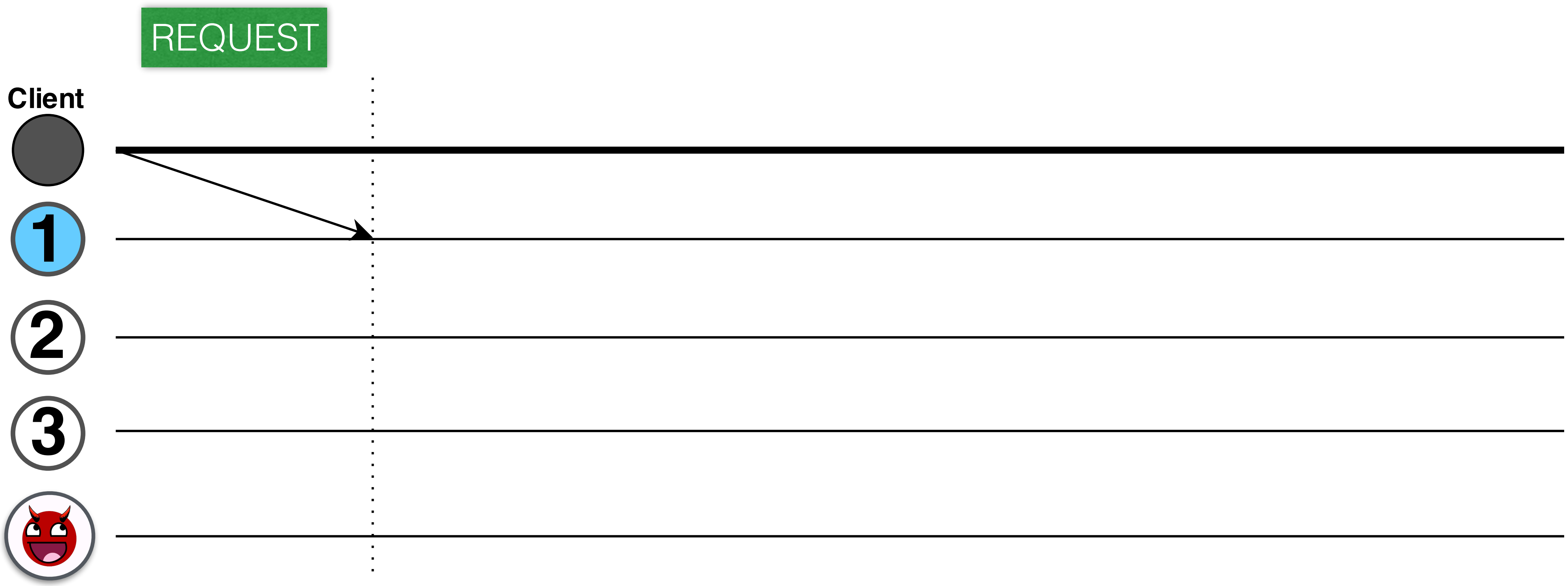
Consensus
in PBFT



A three-phase protocol

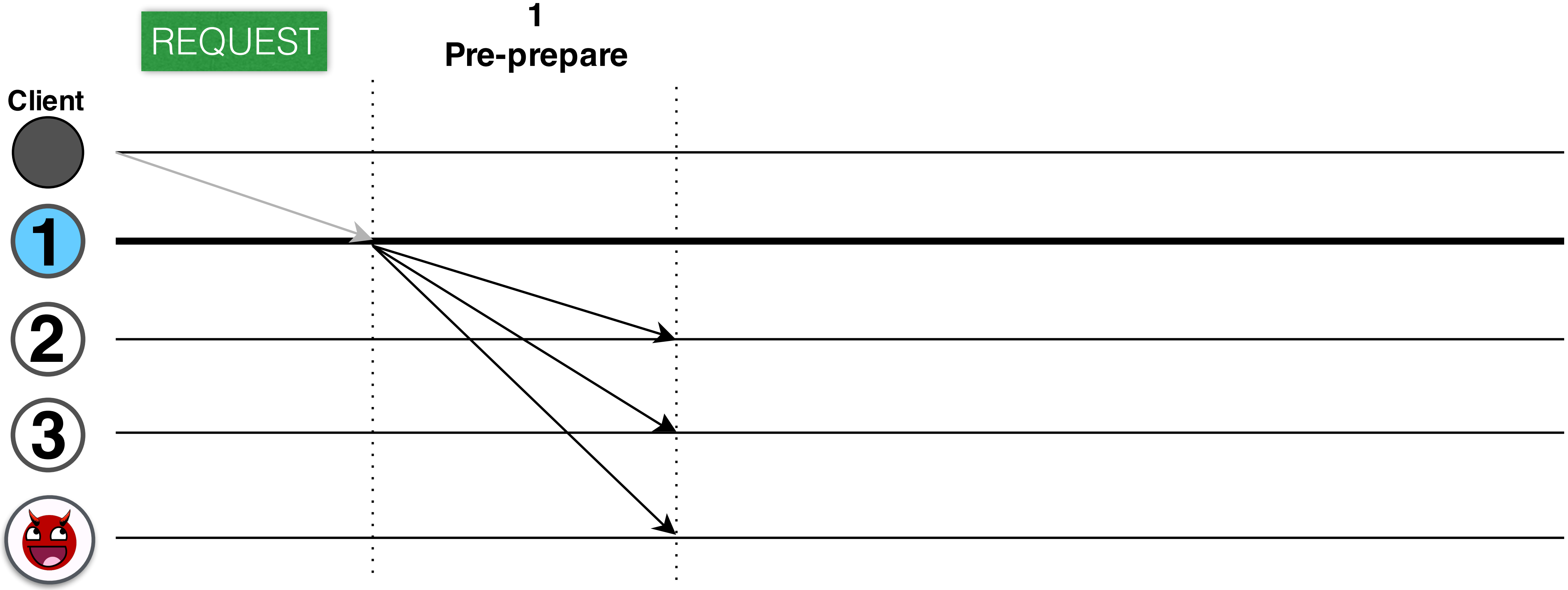
Consensus instance

= three-phase protocol



Consensus instance

= three-phase protocol



Consensus instance

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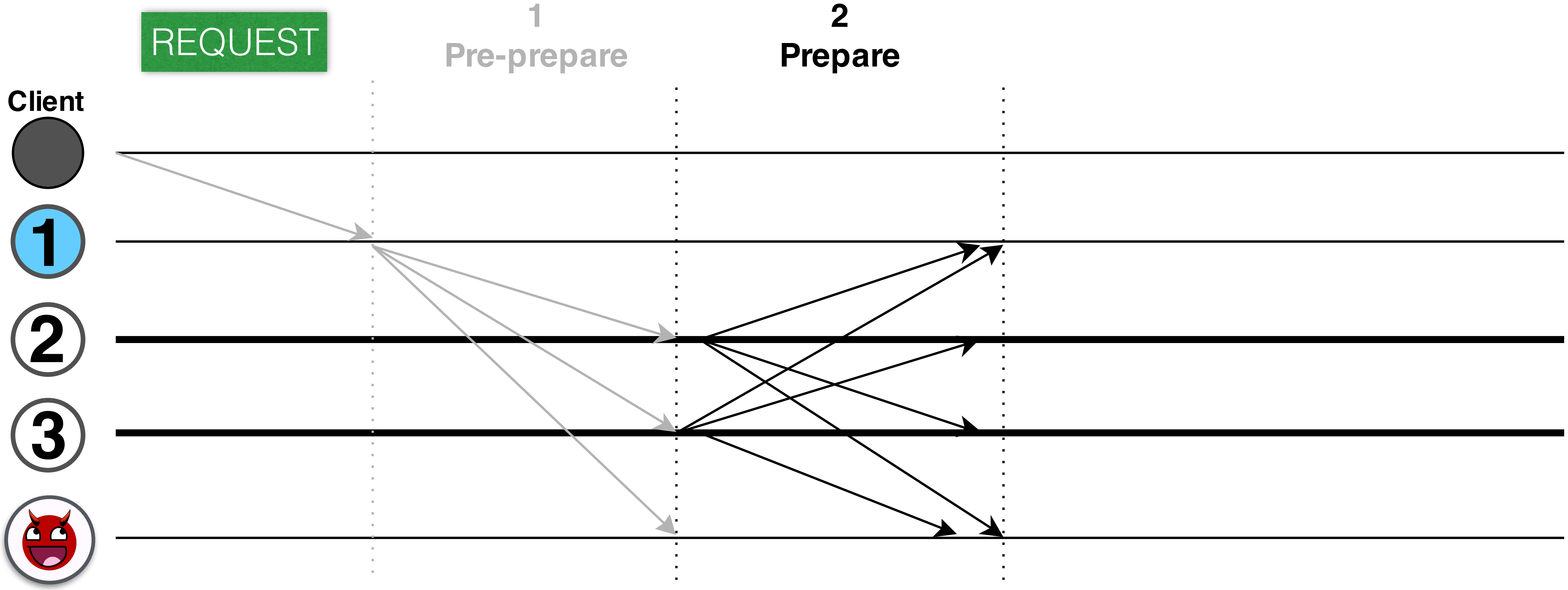

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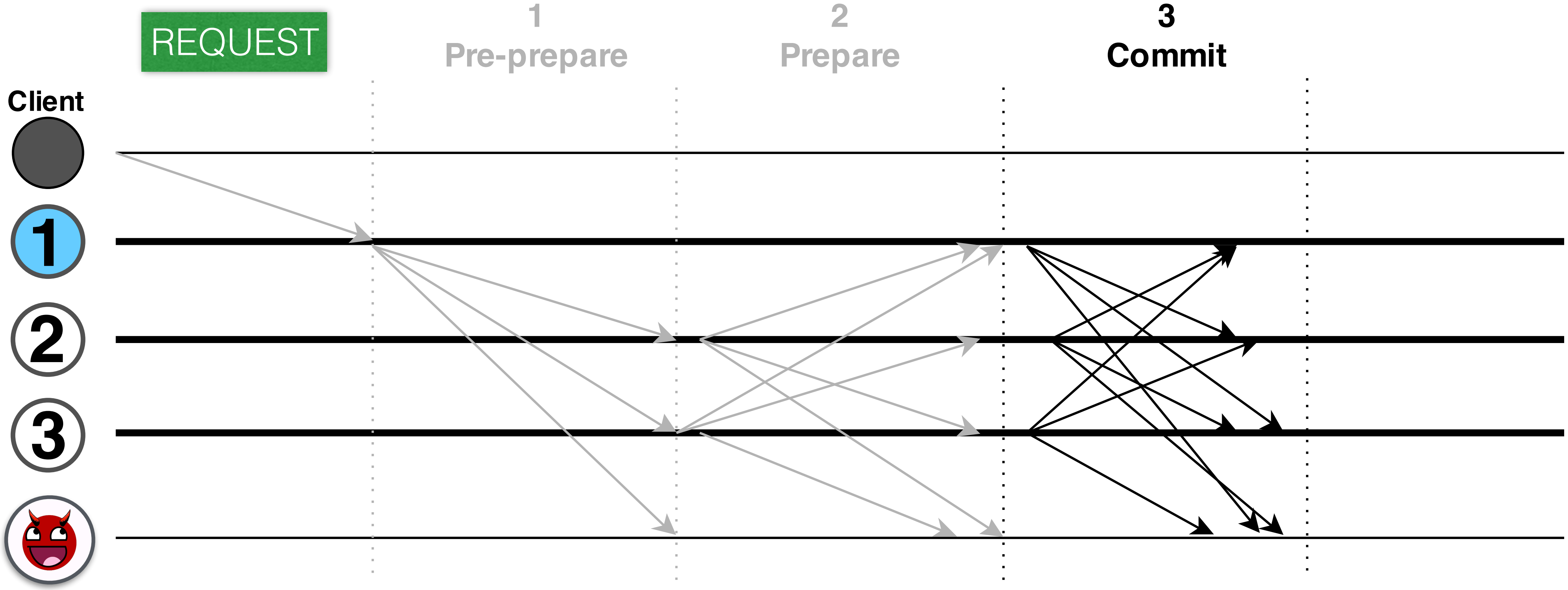

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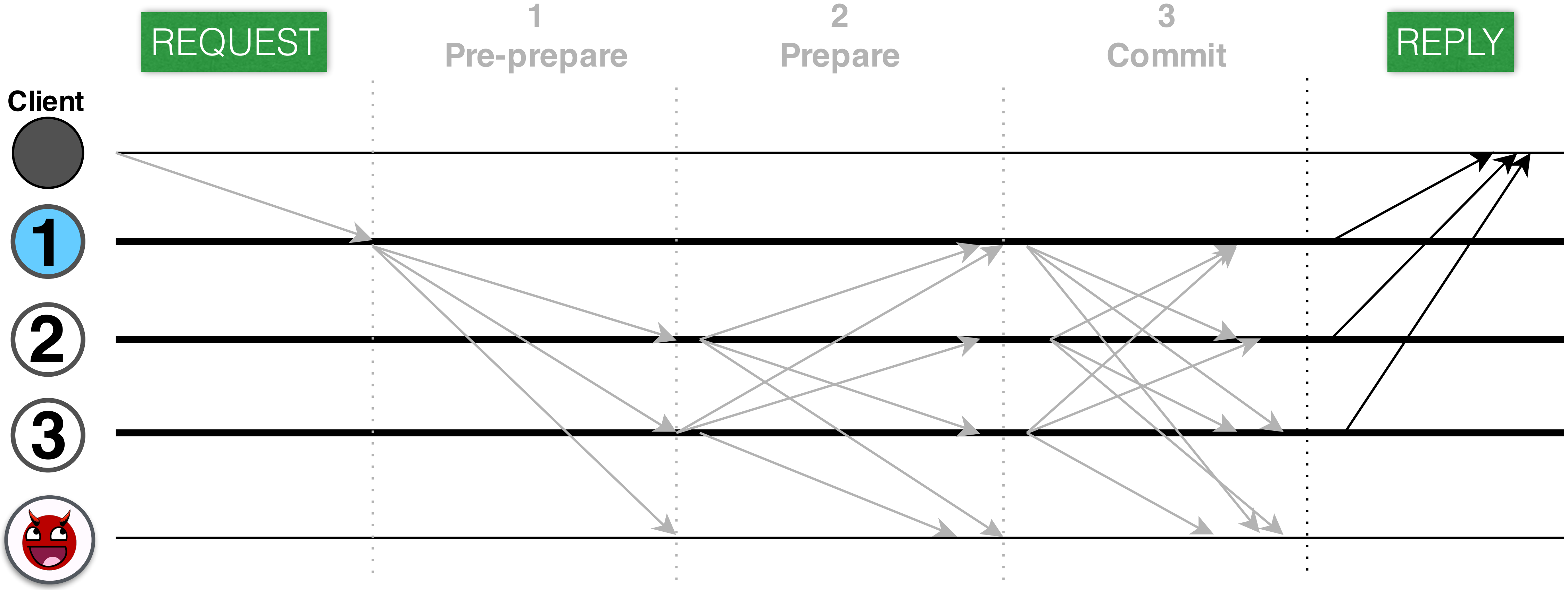

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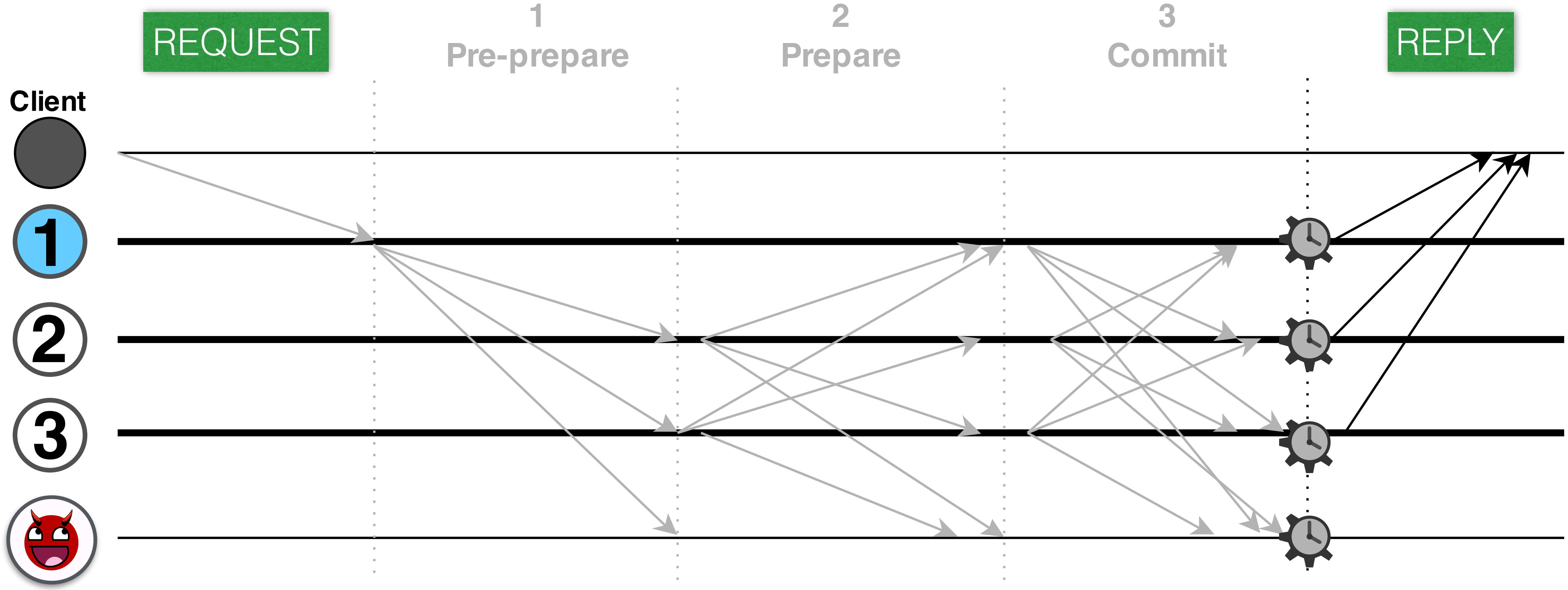

Consensus
Corner case

What if the primary is faulty, e.g.
does not multicast the request to the backups?

- View change protocol: primary replaced by one of the backups
- Idea:
  - Replicas are numbered 1 … n
  - In view *v*, the replica *p* is the primary, where
    $p = v \bmod n$

Consensus

Why 3 phases?

1. PRE-PREPARE
2. PREPARE
3. COMMIT

Consensus

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Agree on (the order of) requests
within the same view

Consensus

Why 3 phases?

1. PRE-PREPARE
2. PREPARE
3. COMMIT

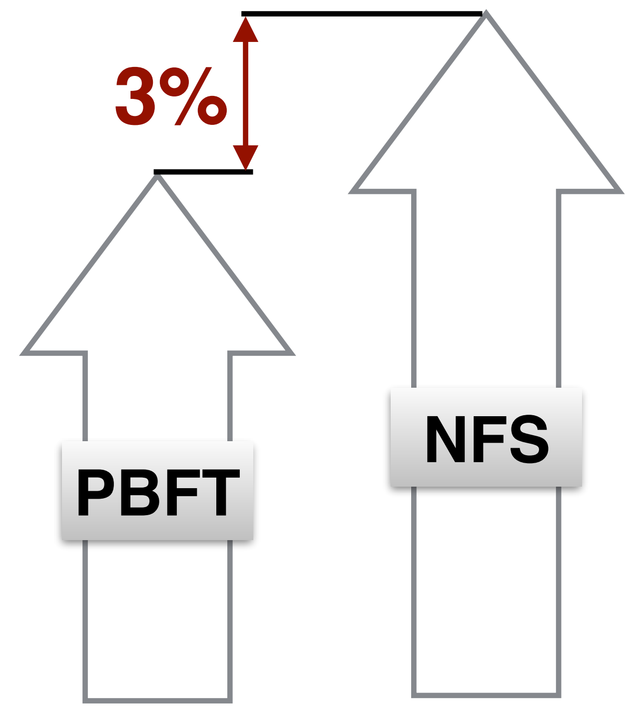
Agree on (the order of) requests <u>within the same view</u>

Ensure that requests which execute are totally ordered <u>across different views</u>

+

Garbage collection

Practical BFT



"Reasonable overhead"

- Does not assume synchrony
- Some clever optimizations:
  - MD5 replaces digital signatures
  - Message digests
  - Read-only requests, tentative execution

Further reading

- Castro, M., & Liskov, B. (1999). Practical Byzantine fault tolerance. OSDI, (February), 1–14. Available at: http://dl.acm.org/citation.cfm?id=296806.296824

- Castro, M. (2011). Practical Consensus. Microsoft Research Cambridge. Available at: http://msrvideo.vo.msecnd.net/rmcvideos/167097/dl/167097.pdf