RDMA & Concurrent Algorithms

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MystenLabs

Based on joint work with, and slides from:

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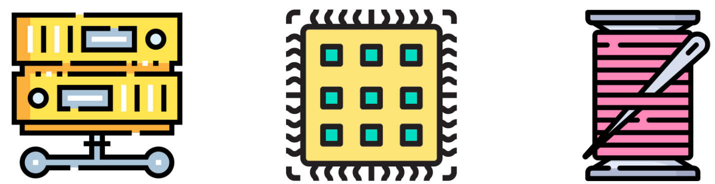
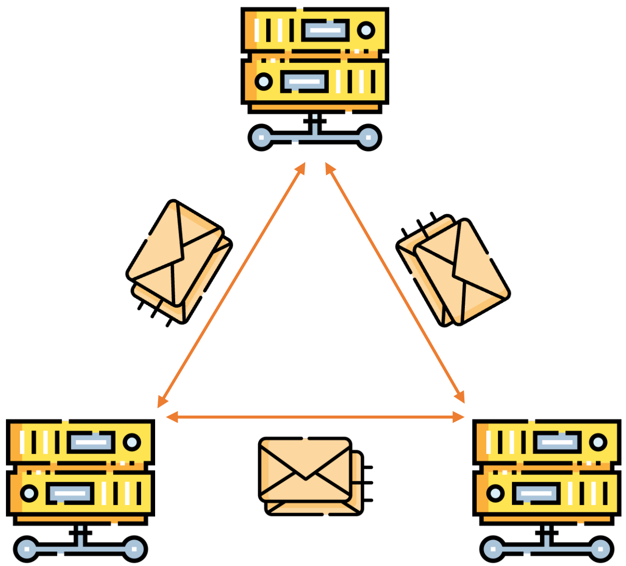
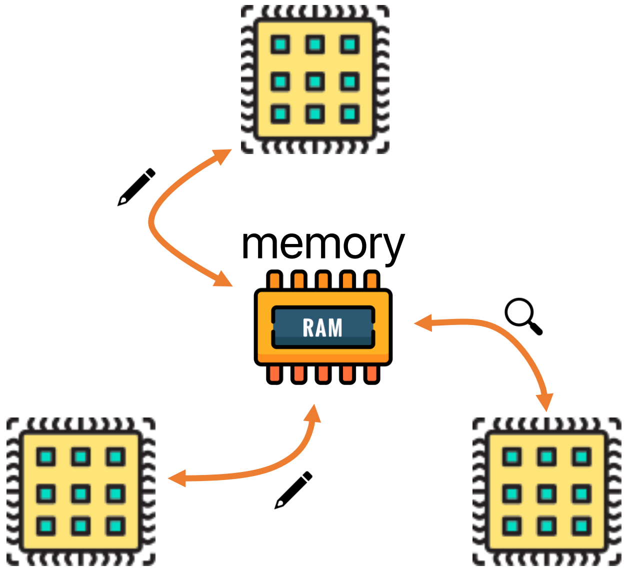
A Tale of Two Models

- processes
- collaborate on some common task
- improve performance or robustness





message-passing



shared-memory

Equal But Not Quite

The two models are equivalent [Attiya, Bar-Noy, Dolev 1995]
=
One can simulate the other

but, e.g., for solving consensus:

n = num processes f = num failures	Crash	
	Fault Tolerance	Common-case Complexity
Message Passing	$f < n/2$	**2** [Lamport'98]
Shared Memory	$\boldsymbol{f < n}$	4 [GL'02]

Models Reflect Technology

The two standard models reflect existing technology

BUT

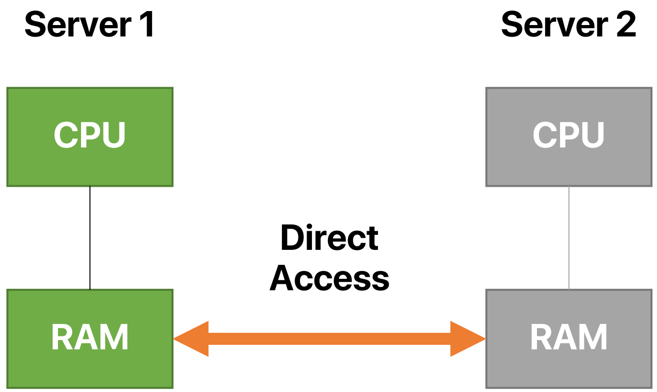
Technology evolves, new technologies emerge

SO

We need new models

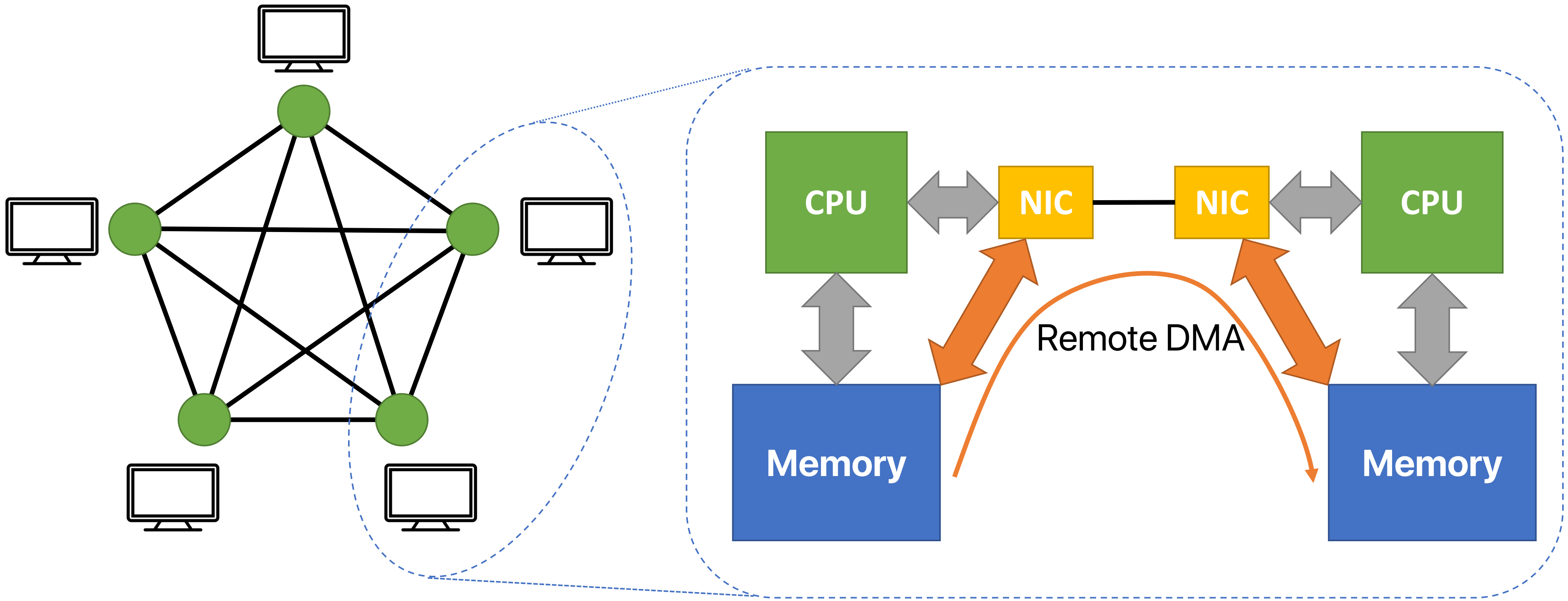
RDMA: Overview

- Networking hardware feature
- Direct access to remote memory
  - No CPU at remote side
  - No OS at either side
- Good performance
  - ~1 us latency
  - ~100-800 Gbps bandwidth
- Configurable access permissions

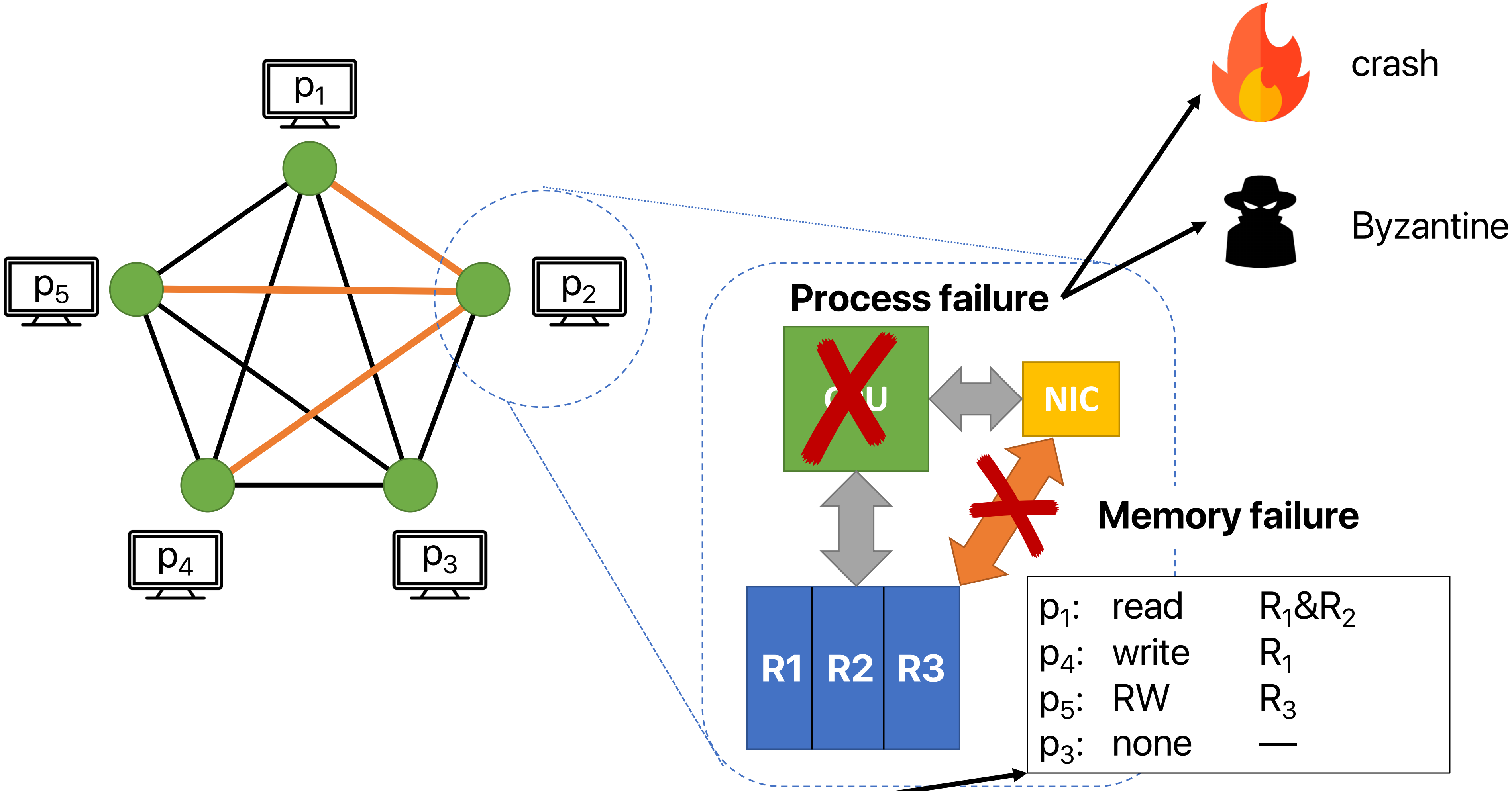


RDMA

Remote Direct Memory Access (RDMA)

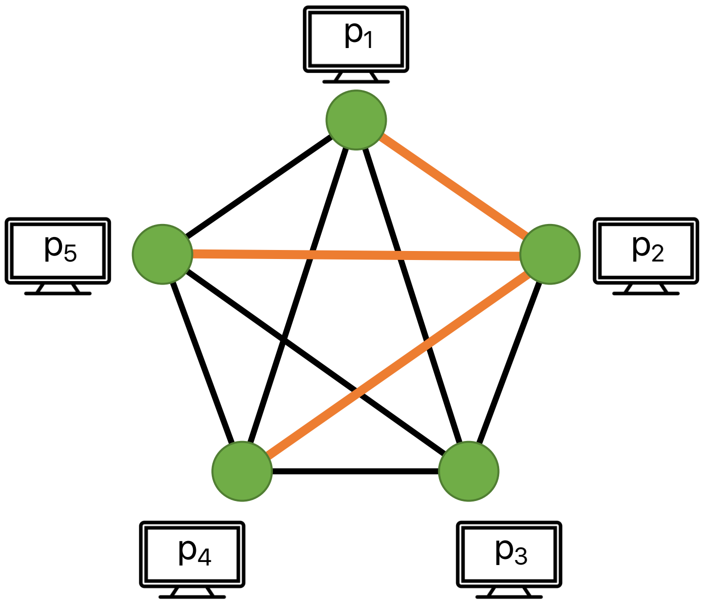


RDMA: Permissions and Failures

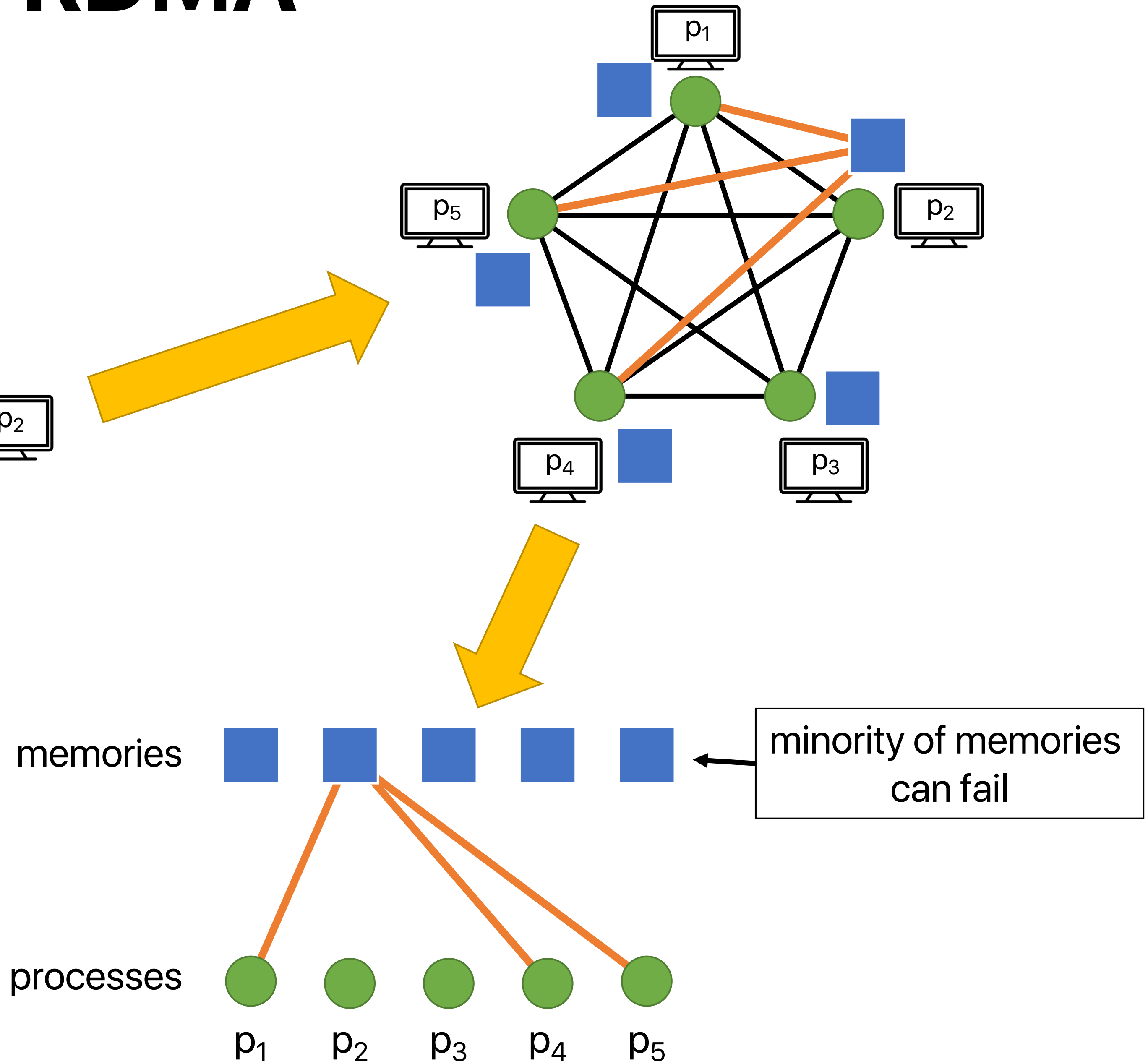


dynamic permissions: can be changed during execution

Modelling RDMA



Also called
"disaggregated memory"



Outline

- Introduction
- 3 remarkable results with RDMA:
  - Consensus with crash faults
  - Broadcast with Byzantine faults
  - Fast memory replication

Best of Both Worlds

n = num processes f = num failures	Crash	
	Fault Tolerance	Common-case Performance
Message Passing	$n > 2f$	**2** [Lamport'98]
Shared Memory	$\boldsymbol{n > f}$	4 [GL'02]
RDMA	$\boldsymbol{n > f}$	**2**

Refresher: O-Consensus

Paxos in Shared Memory

```
propose(v):
 while(true)
   Reg[i].T.write(ts);
   val := Reg[1,..,n].highestTspValue();
   if val = ⊥ then val := v;
   Reg[i].V.write(val,ts);
   if ts = Reg[1,..,n].highestTsp() then
      return(val)
   ts := ts + n
```

announce my timestamp

adopt value with highest ts (or mine if none)

announce my value, ts

if my timestamp is the highest, decide

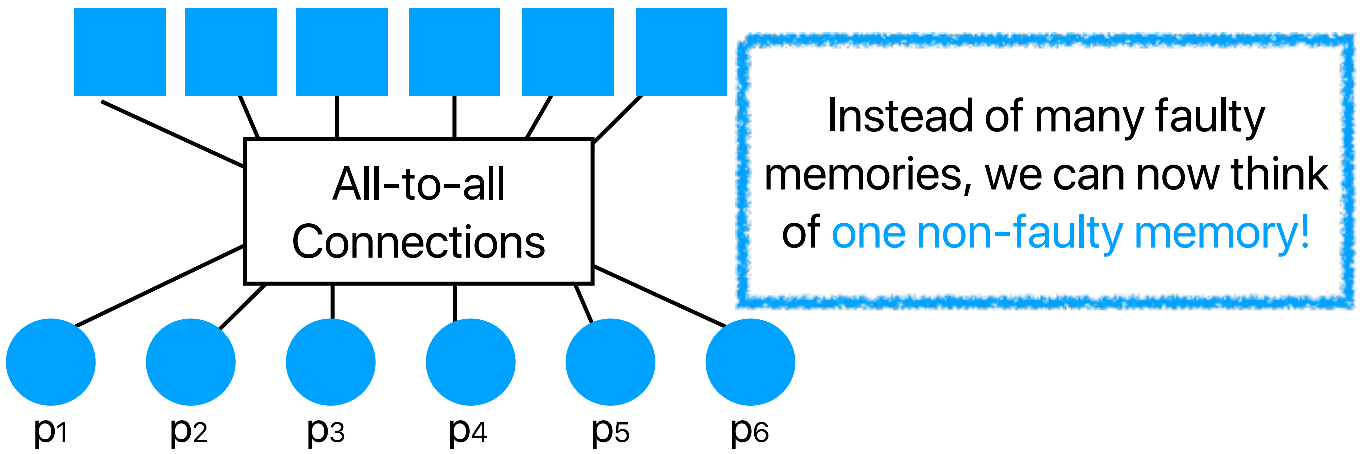
This assumes that shared memory never fails.

🤔 **What if memory can fail?** 🤔

Handling Memory Failures

Replication: Treat all memories the same

Send all write/read requests to all memories, wait to hear acknowledgement from majority



O-Consensus w Memory Failures

Disk Paxos [GafniLamport2002]

```
propose(v):
 while(true)
   for every memory m in parallel:
        Reg[m][i].T.write(ts);
        temp[m][1..n] = Reg[m][1..n].read();
    until completed for majority of memories
    val := temp[1..m][1..n].highestTspValue();
    if val = ⊥ then val := v;
    for every memory m in parallel:
        Reg[m][i].V.write(val,ts);
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    if ts = temp[1..m][1..n].highestTsp() then
        return(val)
    ts := ts + n
```
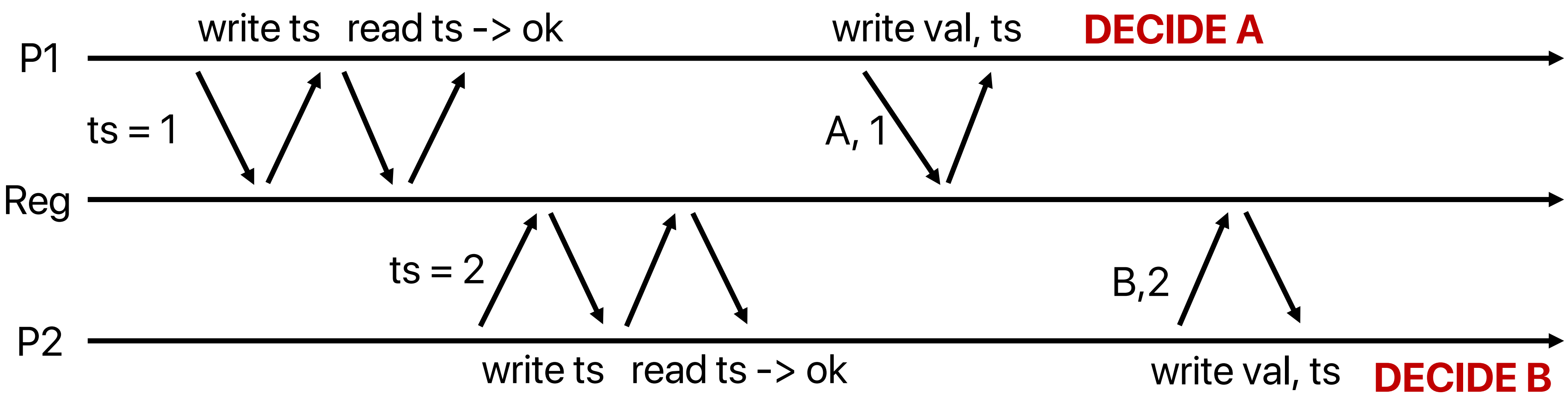

Why read again here?

☝️ **Need to check if I ran alone!**

What If We Didn't Read?



O-Consensus w Memory Failures

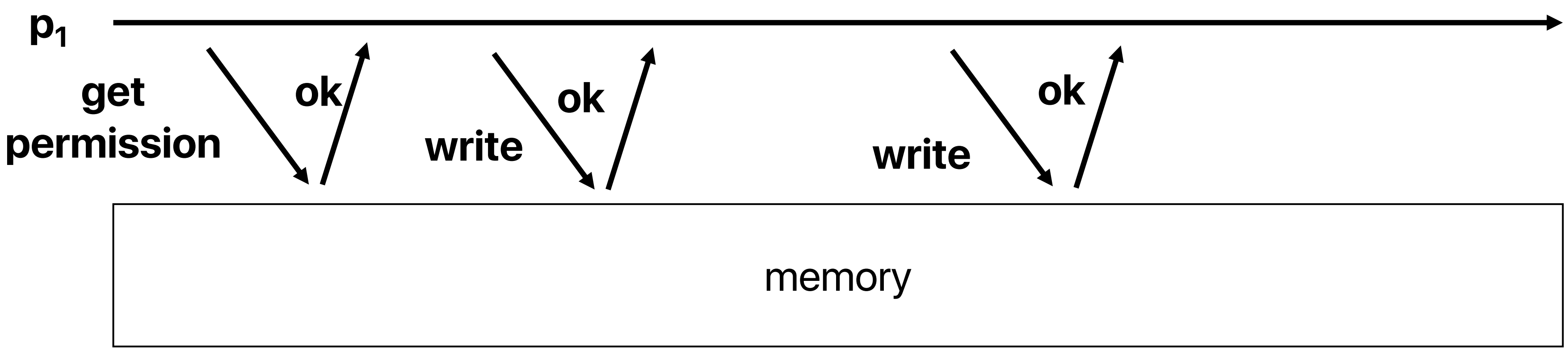
- If we don’t read again, we might miss a concurrent process’s timestamp
- This could lead to violation of agreement

- What if there was another way to determine if there was a concurrent process?
- We wouldn’t need the last read!

→ better complexity

Solo Detection w/ Permissions

Idea: Memory gives write permission to the last process that requested it.
→ Only one process has write permission on a memory at any time.



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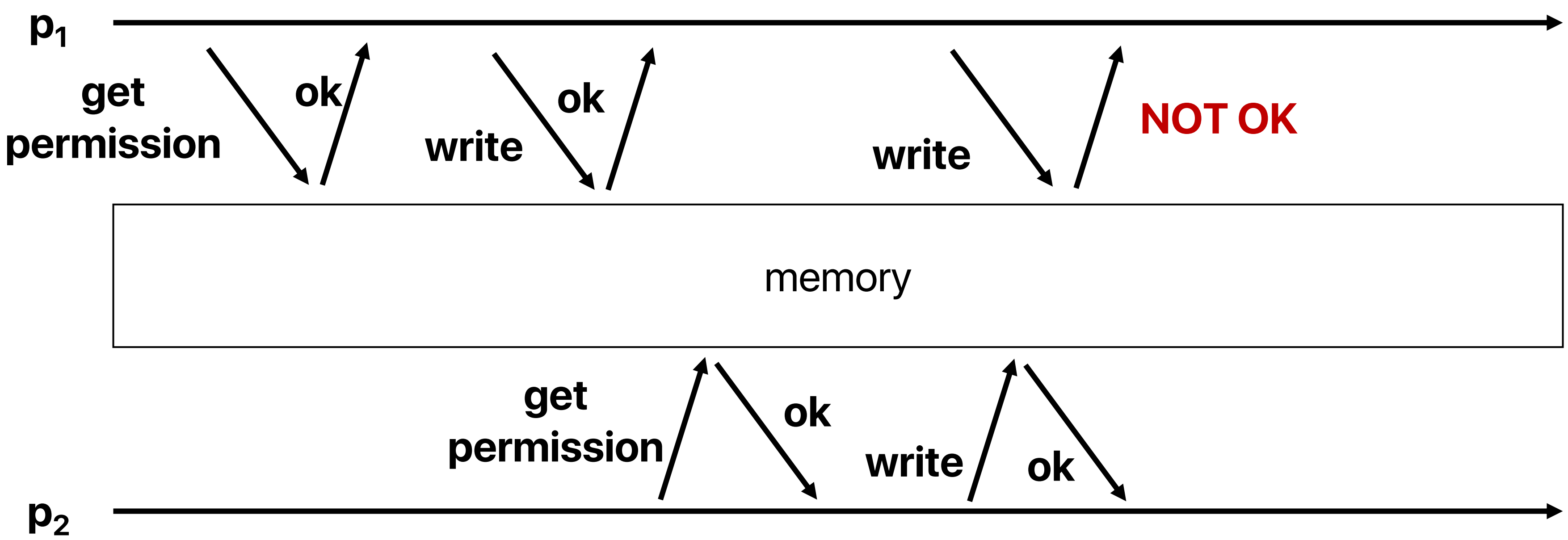

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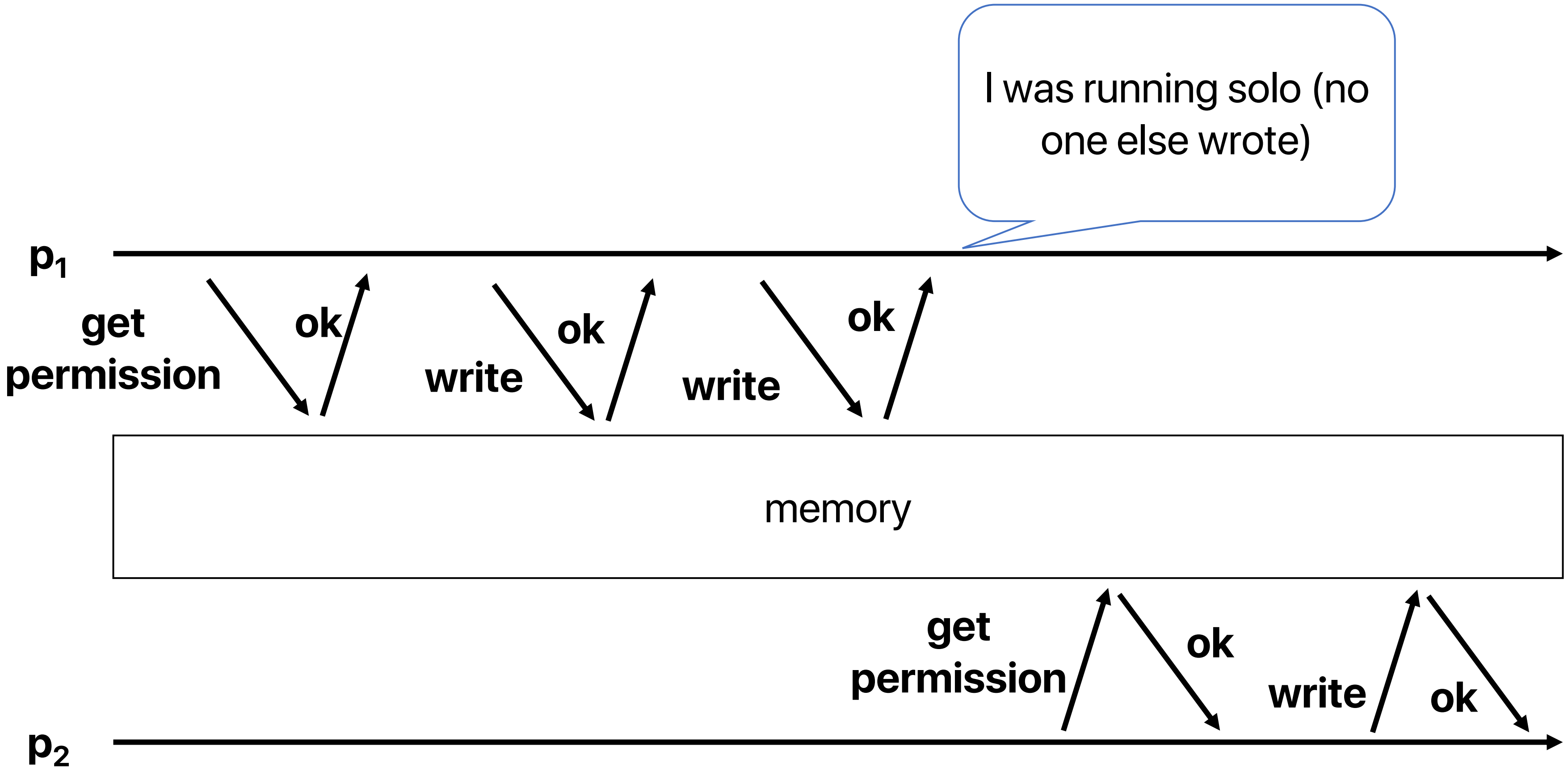


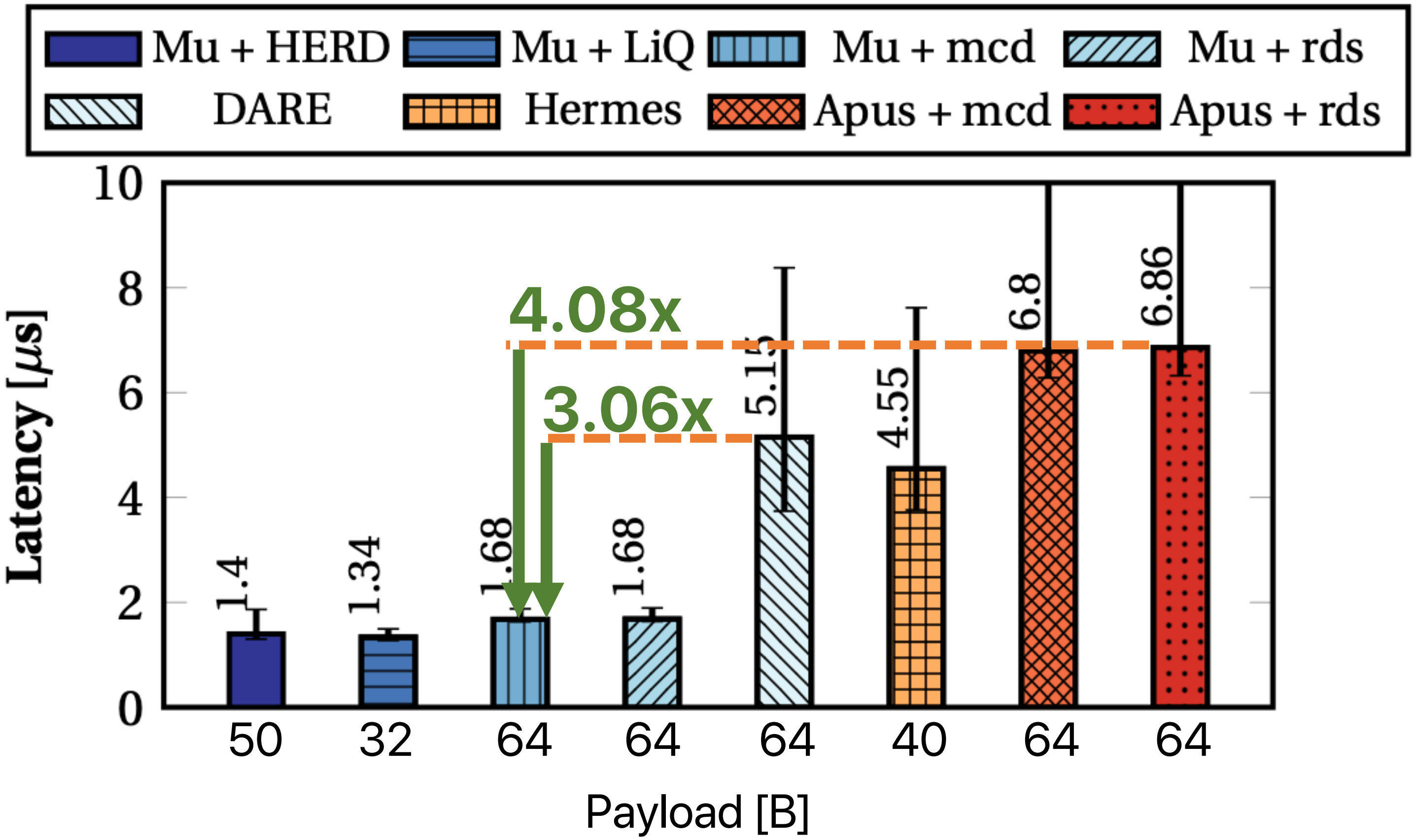
O-Consensus with Memory Failures and Permissions

```
propose(v):
 while(true)
    ts := ts + n
    for every memory m in parallel:
         m.getPermission();
         Reg[m][i].T.write(ts);
         temp[m][1..n] = Reg[m][1..n].read();
     until completed for majority of memories
     if ts < temp[1..m][1..n].highestTsp() then continue;
     val := temp[1..m][1..n].highestTspValue();
     if val = ⊥ then val := v;
     for every memory m in parallel:
          Reg[m][i].V.write(val,ts);
          temp[m][1..n] = Reg[m][1..n].read();
     until completed for majority of memories
     if writes succeeded at majority of memories then
          return(val)
```

No need to read again!

Quick Look: Replication Latency

[3x replication, 100Gbps Infiniband]



3-4x faster than state-of the art

Outline

- Introduction
- 3 remarkable results with RDMA:
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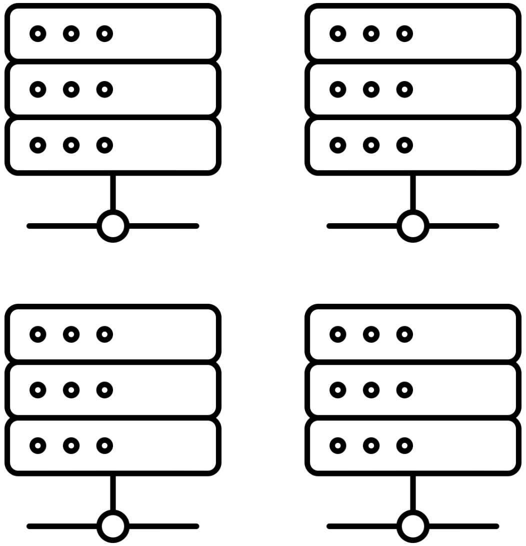
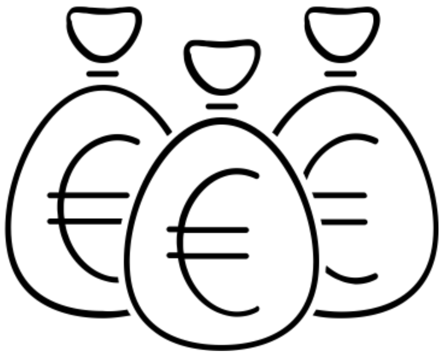
On Frugality

Number of replicas in the system

A system with $n = 3f + 1$ replicas has 33–50% more hardware than a system with $n = 2f + 1$, where f is the number of Byzantine replicas





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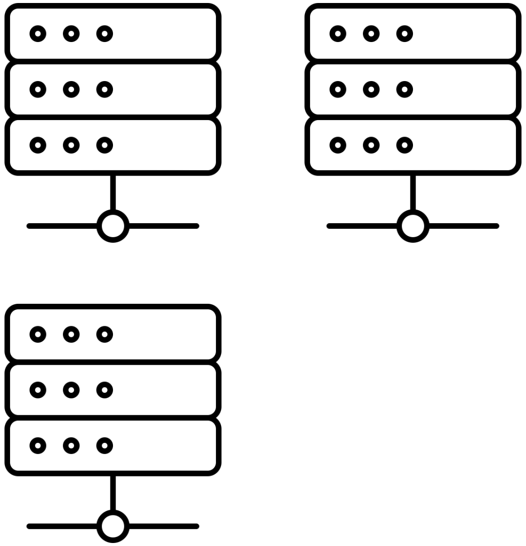
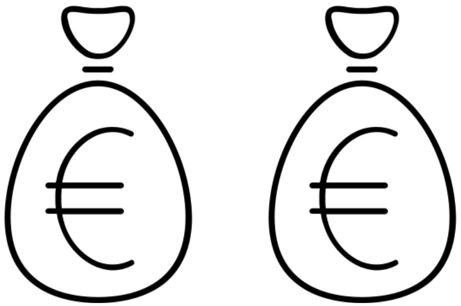
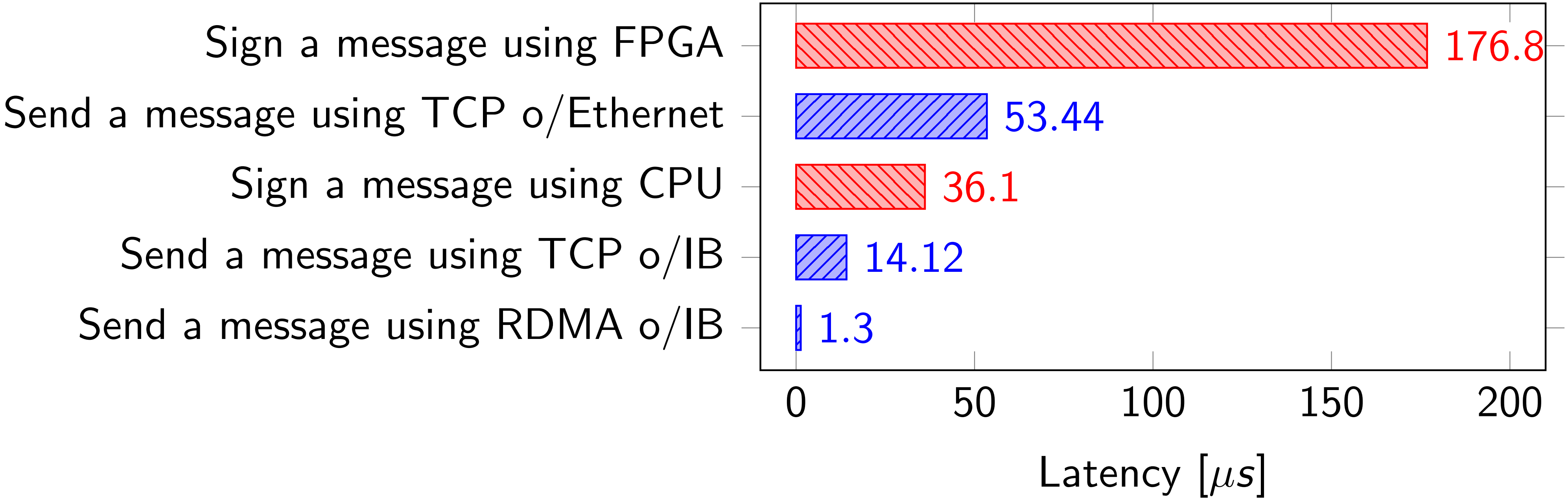




On Frugality

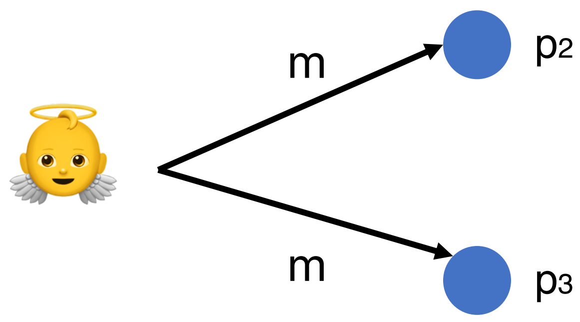
Number of digital signatures

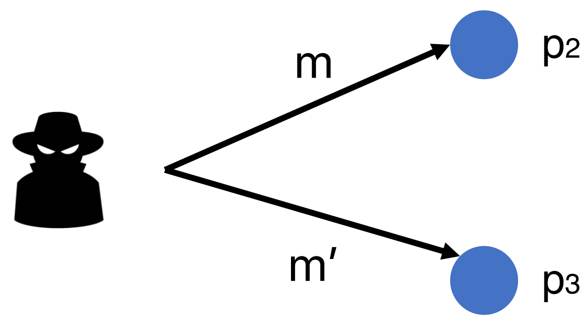


Goal

Address traditional distributed computing problems subject to Byzantine failures with few processes, $n = 2f + 1$, and few signatures

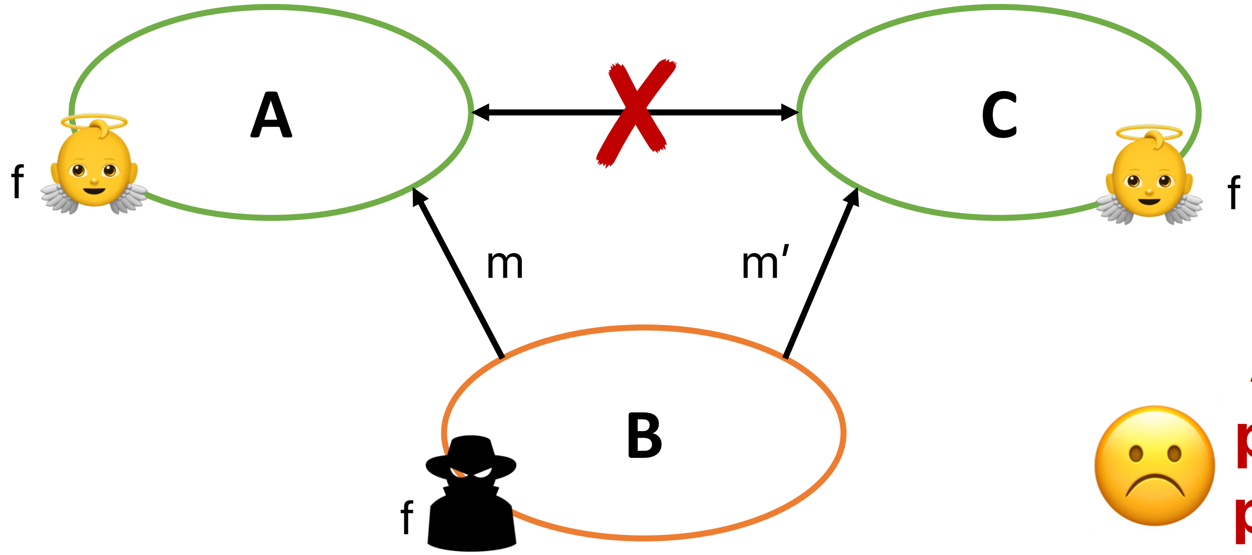
Equivocation





Preventing Equivocations in Message Passing

- Requires n=3f+1, where n is the total number of processes and up to f processes can be Byzantine
- Intuition:



Adversary can prevent correct processes from communicating

Byzantine fault-tolerance

Non-equivocation and digital signatures improve the fault-tolerance from $3f + 1$ to $2f + 1$ for reaching agreement

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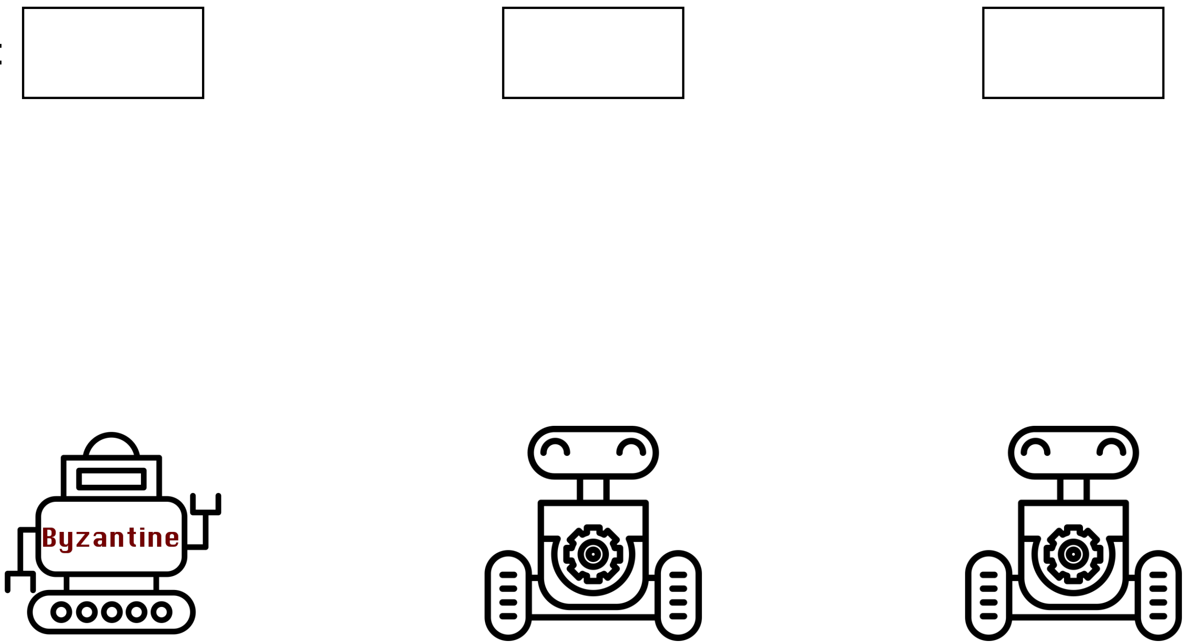
Shared memory M :



Process p_0 Process p_1 Process p_2

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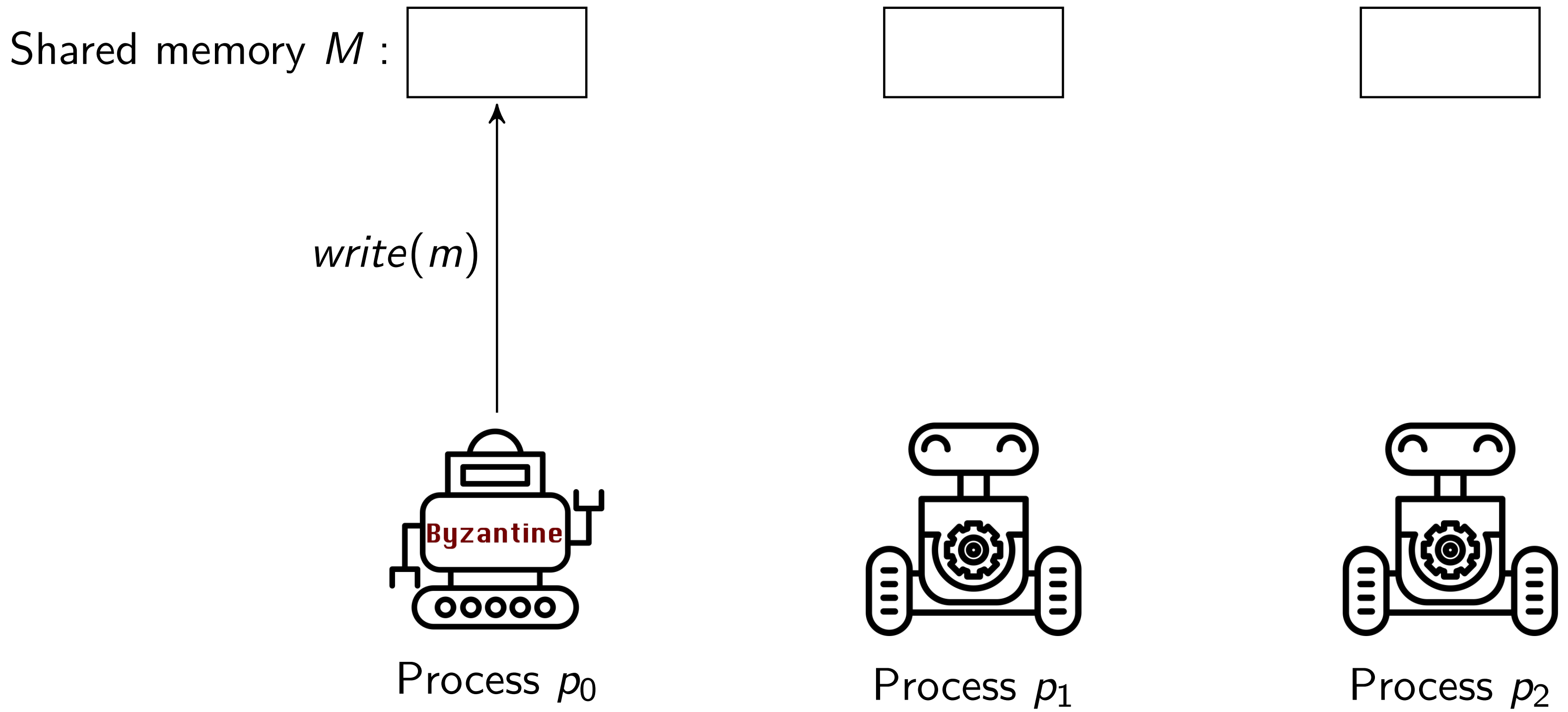

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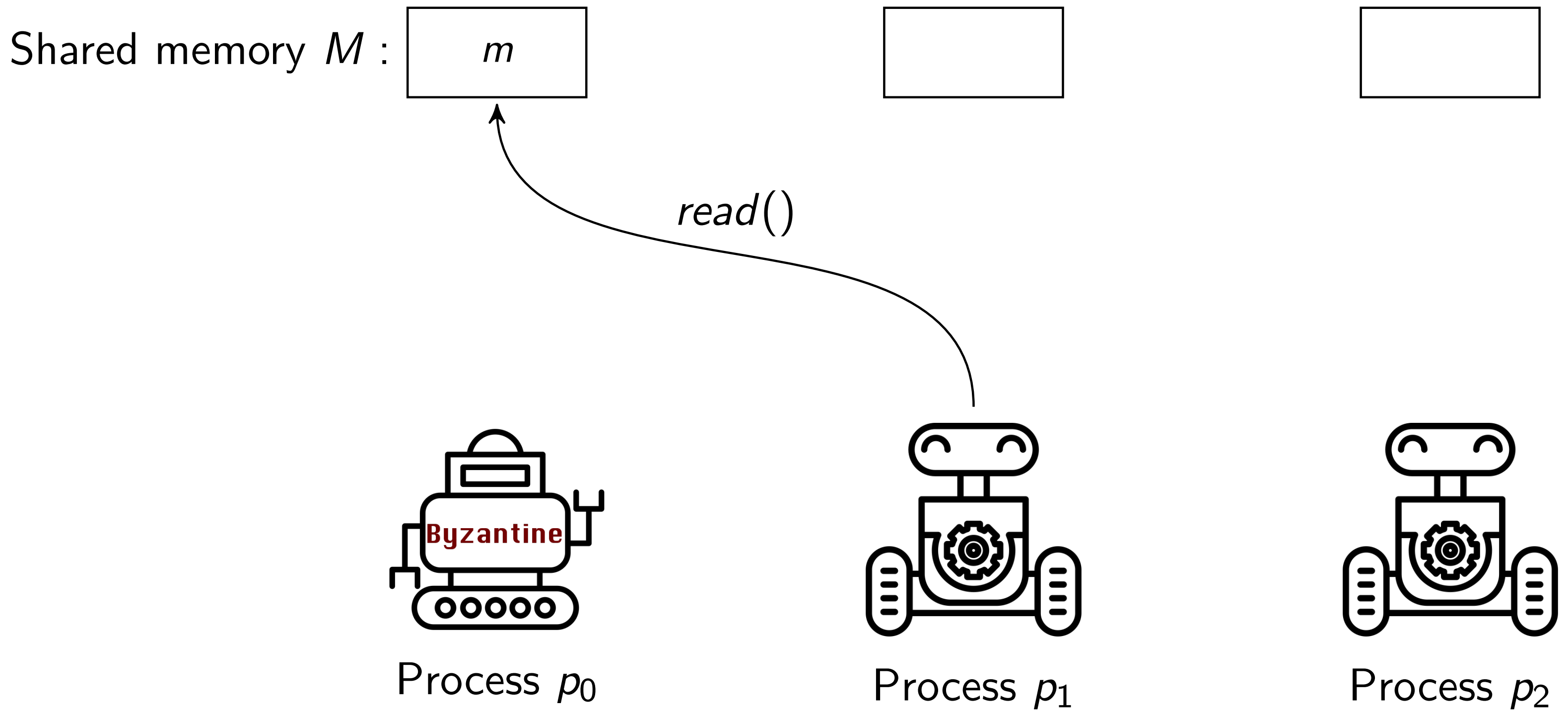

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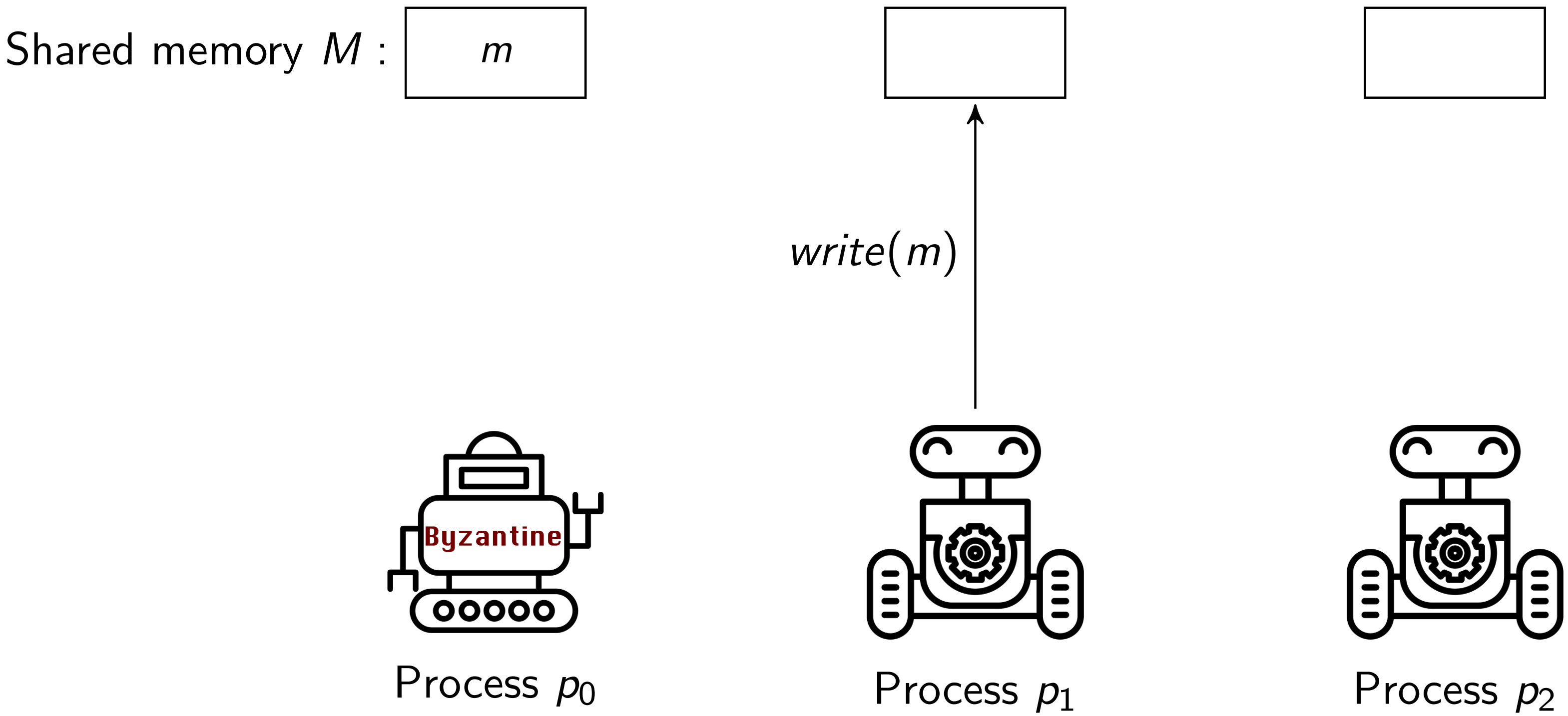

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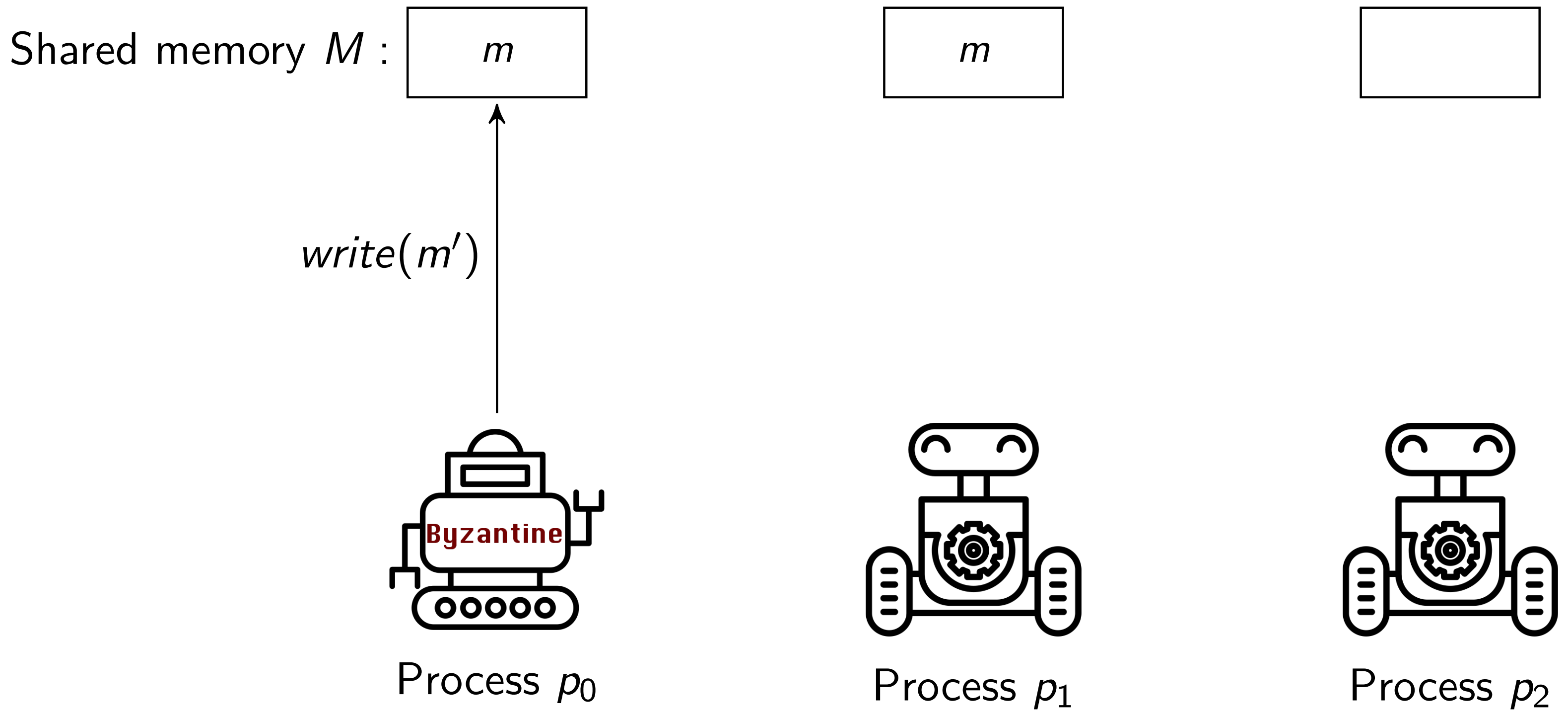

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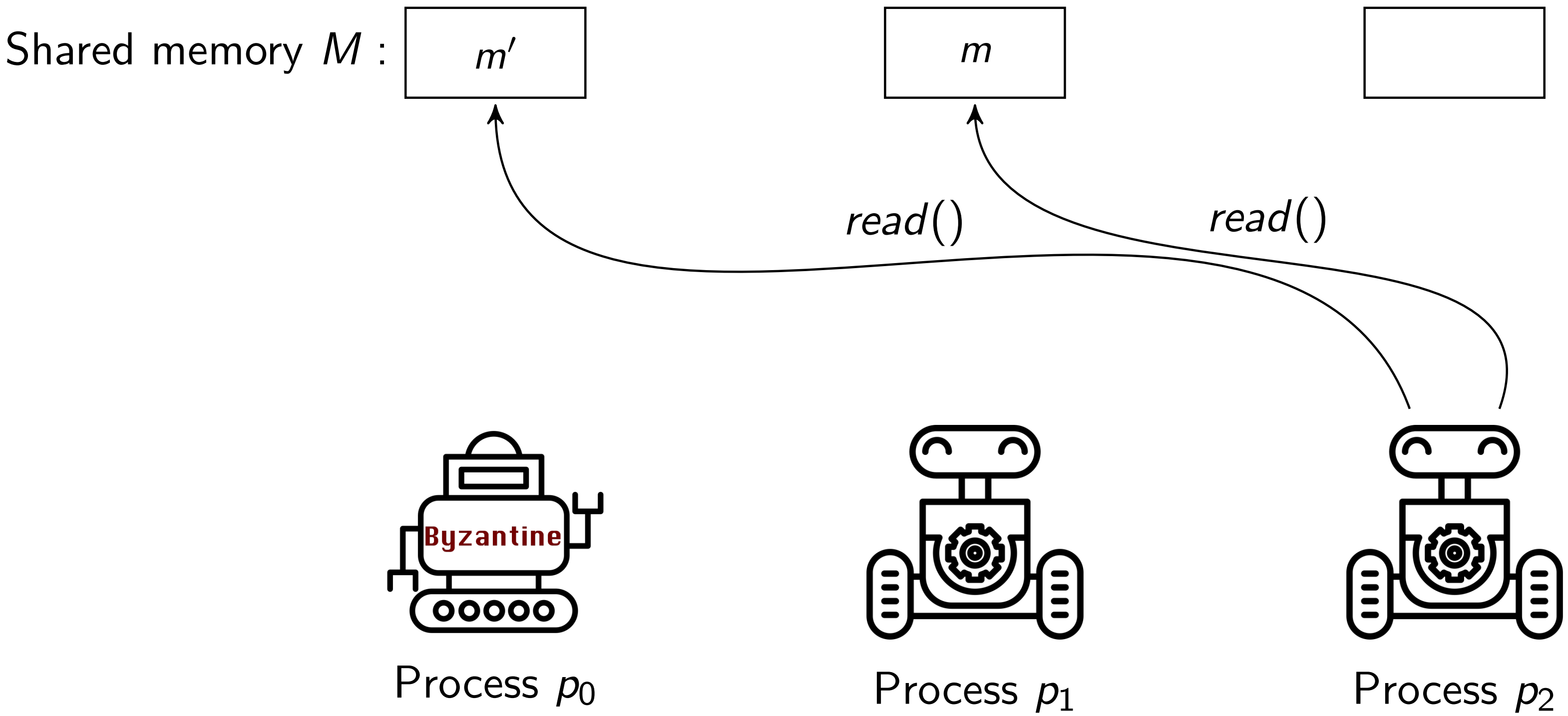

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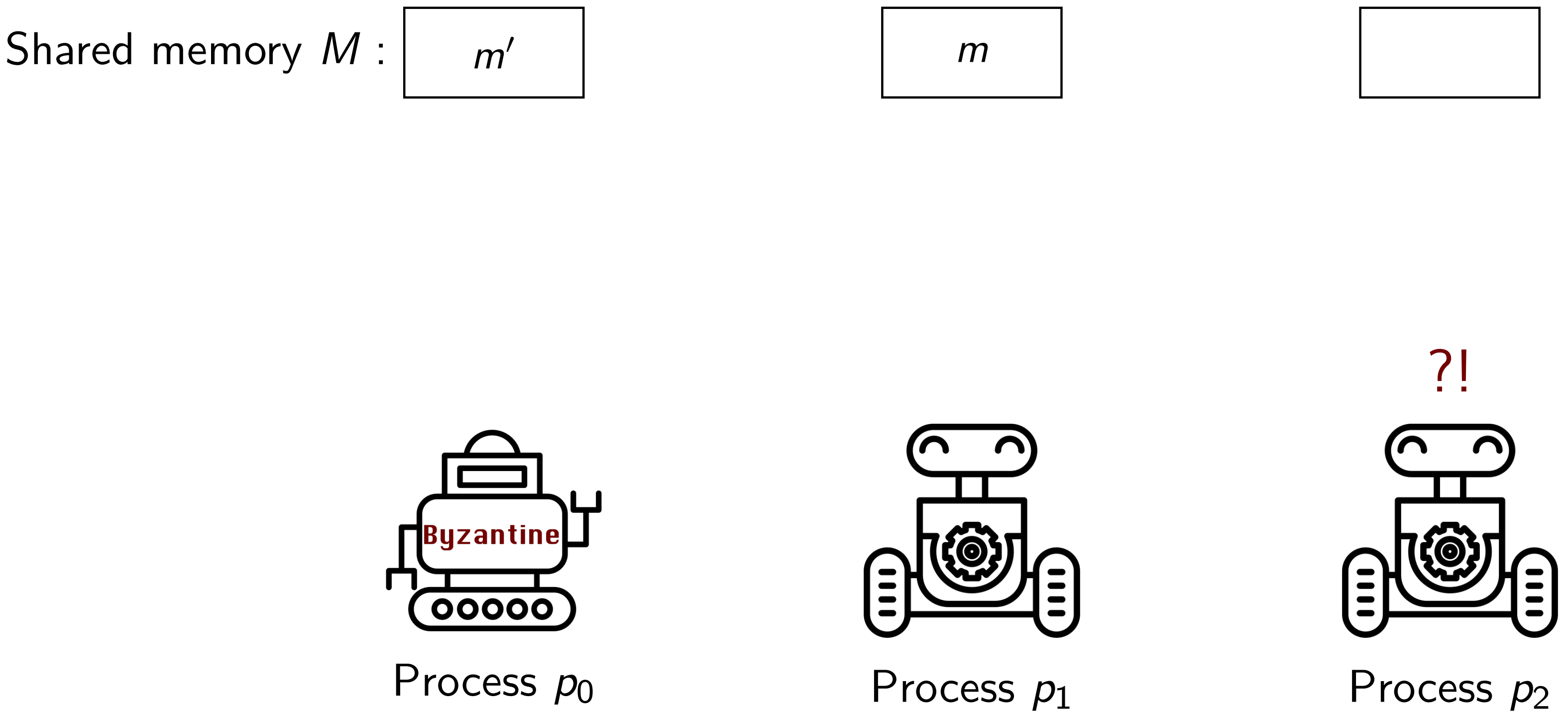

Model

Message-and-memory (M&M) [ABCGPT18] - allows processes to both pass messages and share memory M:

- Single-Writer Multi-Reader (SWMR) atomic registers
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Signatures - each process has access to the primitives *sign* and *verify*

Up to f Byzantine processes, where $n = 2f + 1$

- cannot write on a register that is not its own
- cannot forge the signature of a correct process

Outline

1. Algorithms for Consistent and Reliable Broadcast
   - Signature-free in well-behaved executions

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   - Signature-free in well-behaved executions

2. Lower bounds for Consistent and Reliable Broadcast

Consistent Broadcast	Reliable Broadcast
1	$O(n)$

Table: Total number of signatures created by correct processes

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   - Signature-free in well-behaved executions

2. Lower bounds for Consistent and Reliable Broadcast

Consistent Broadcast	Reliable Broadcast
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Table: Total number of signatures created by correct processes

3. Consensus protocol using Consistent Broadcast

Process roles

Primitives: *broadcast*(m) and *deliver*(m)

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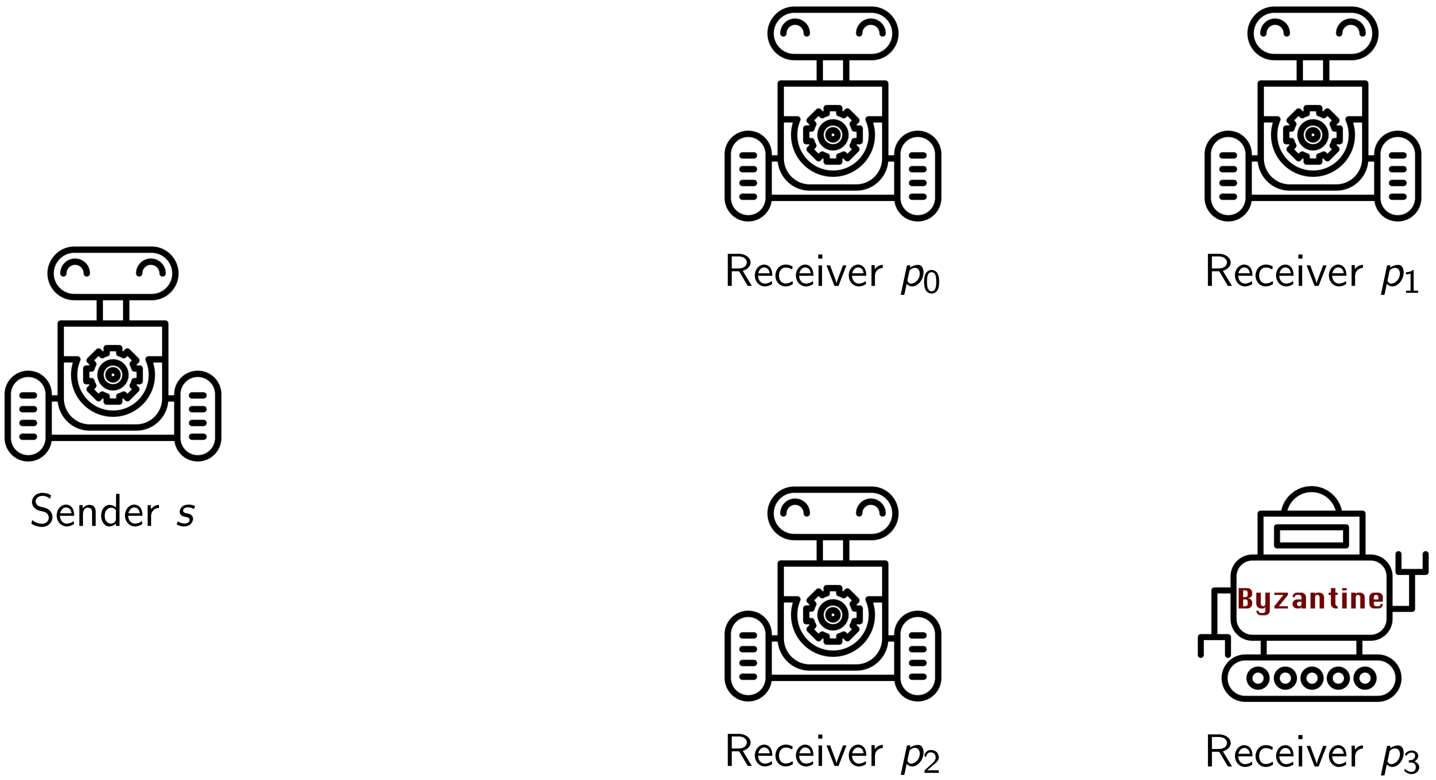
n and f refer to the replicators

Consistent Broadcast

Validity

If a correct process s broadcasts m, then every correct process eventually delivers m



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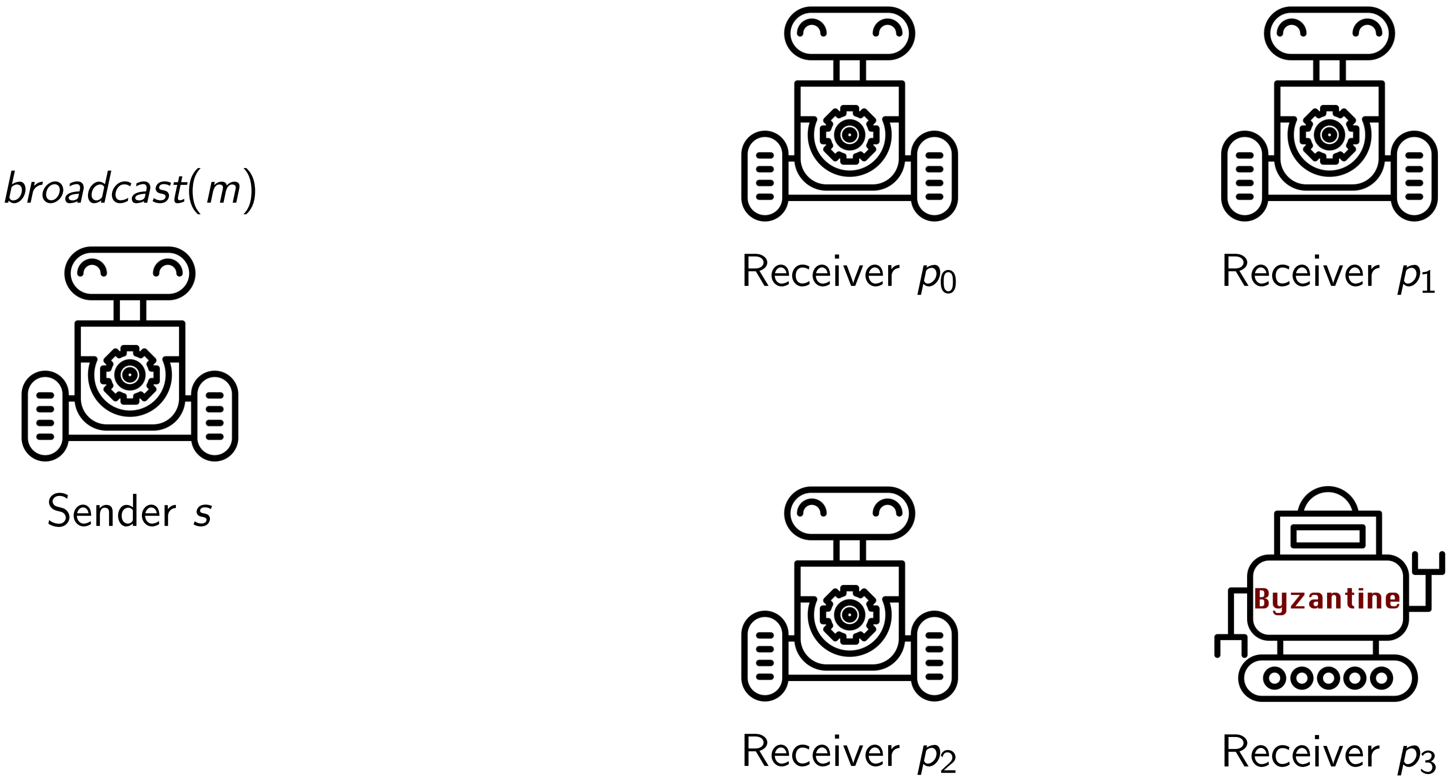

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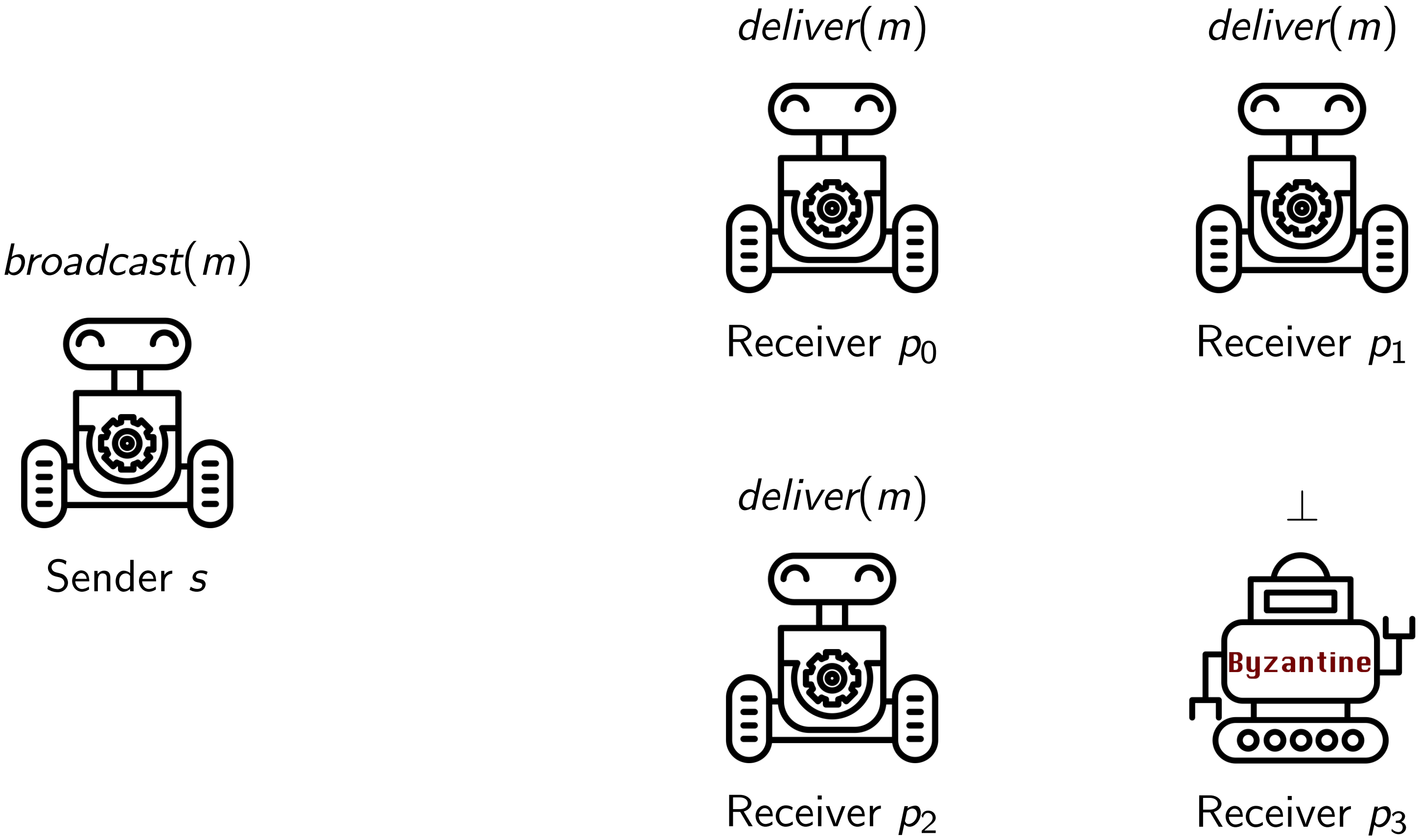
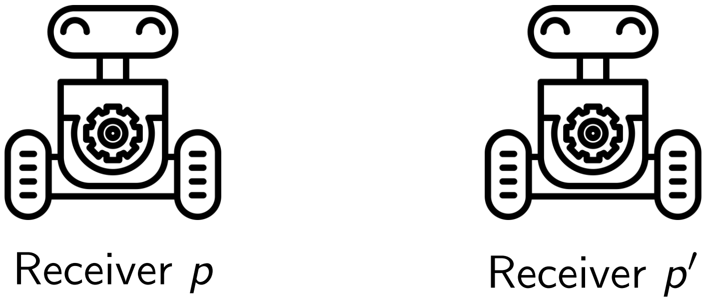


Consistent Broadcast
Consistency

If p and p' are correct processes, p delivers m, and p' delivers m', then $m = m'$



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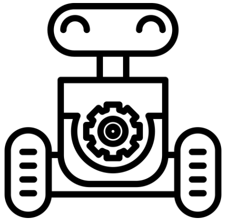
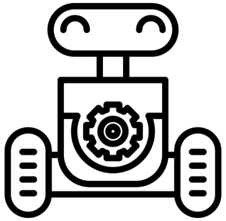
If p and p' are correct processes, p delivers m, and p' delivers m', then $m{=}m'$

deliver(m)



Receiver p

deliver(m')



Receiver p'

Consistent Broadcast

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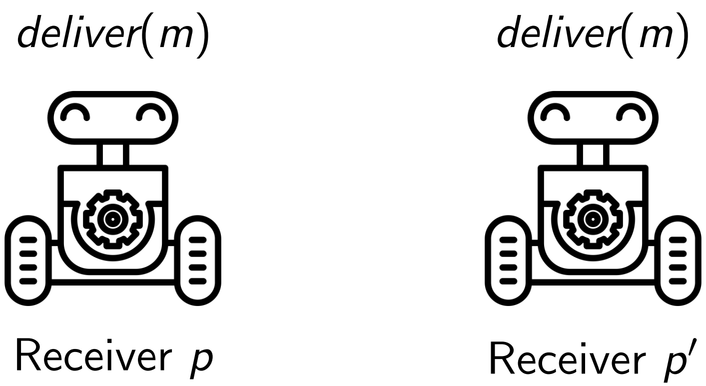

Consistent Broadcast
Integrity

If some correct process delivers m and s is correct, then s previously broadcast m

Sender s Receiver p

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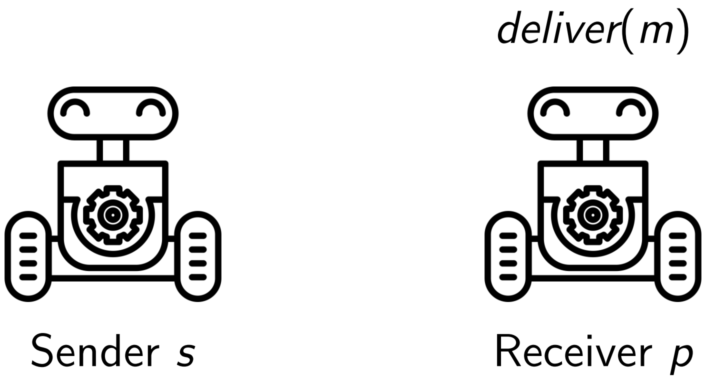

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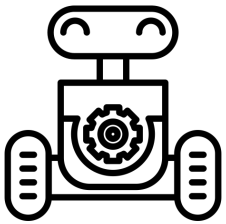
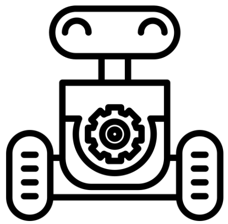
broadcast(m)



Sender s

deliver(m)



Receiver p

Consistent Broadcast

Validity - If a correct process s broadcasts m, then every correct process eventually delivers m

Consistency - If p and p' are correct processes, p delivers m, and p' delivers m', then $m{=}m'$

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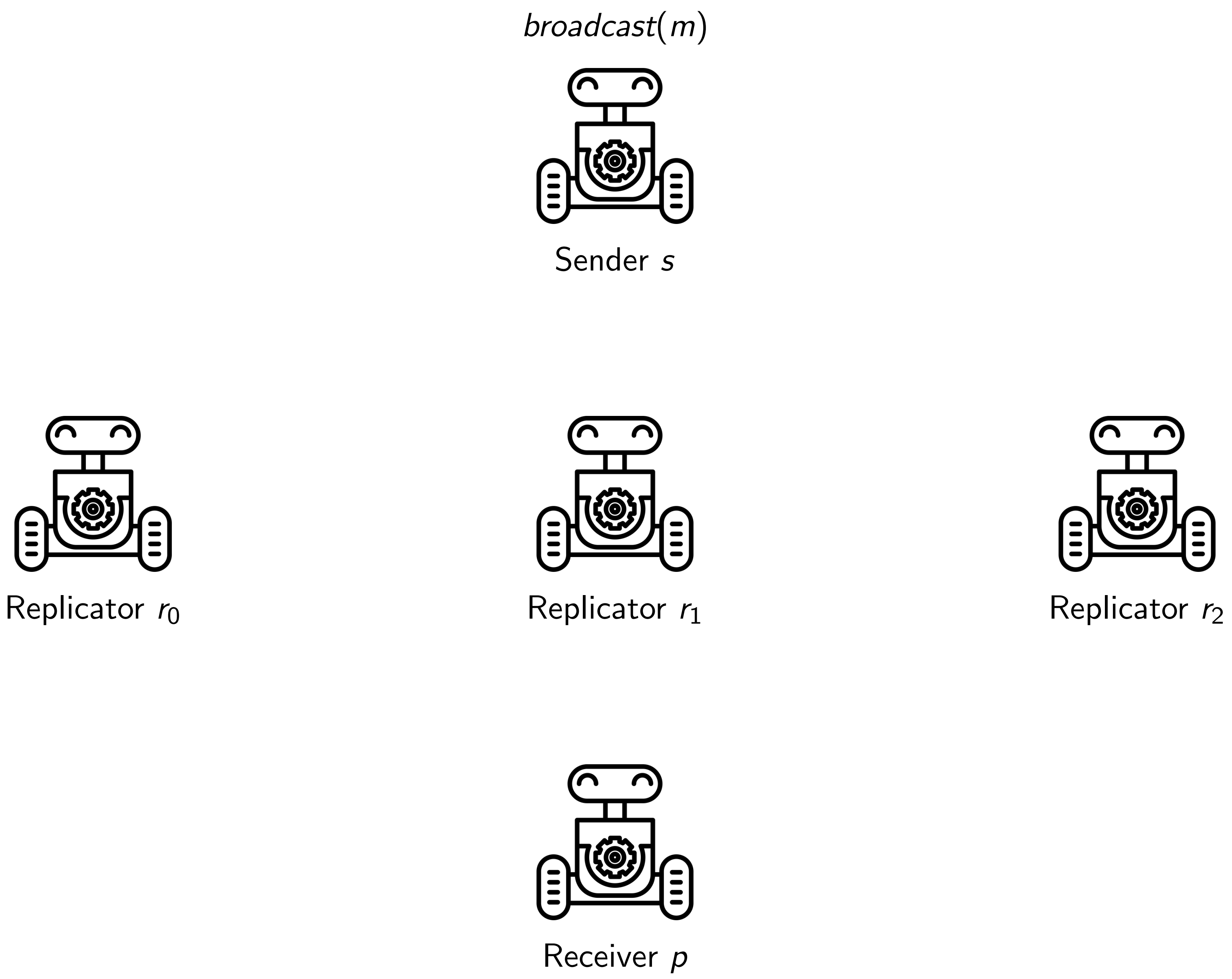
Consistent Broadcast

Algorithm sketch, $f = 1$. Fast path



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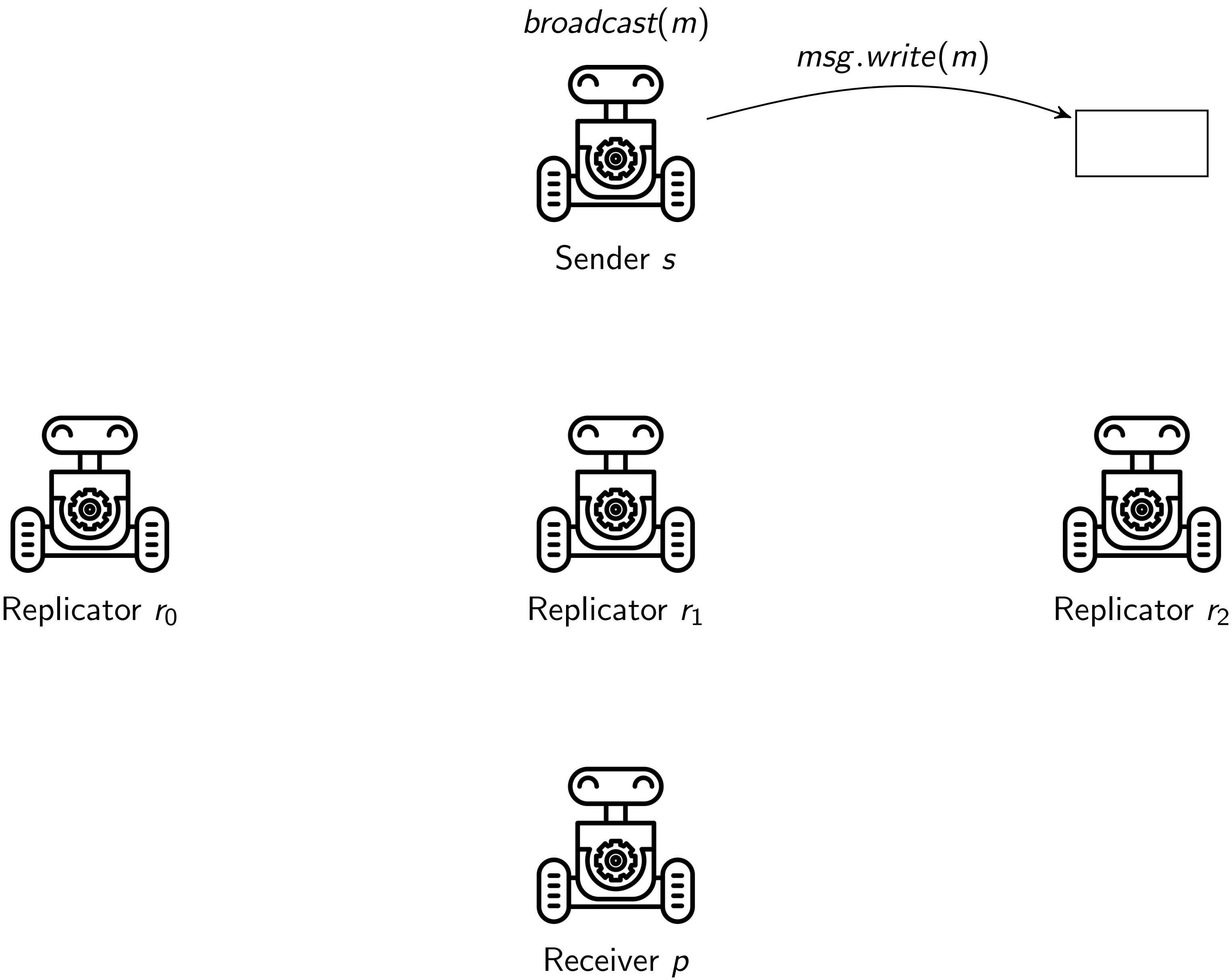

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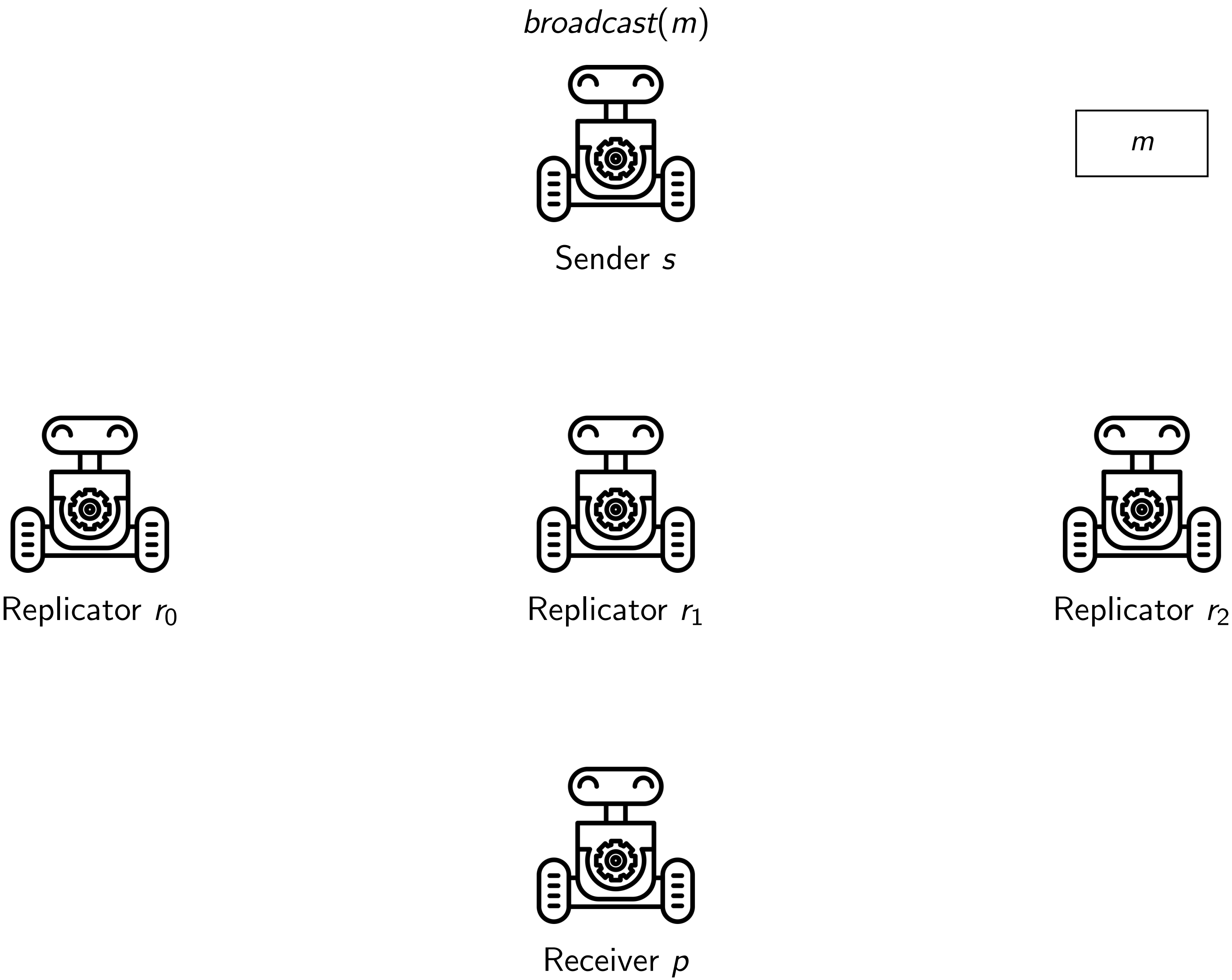

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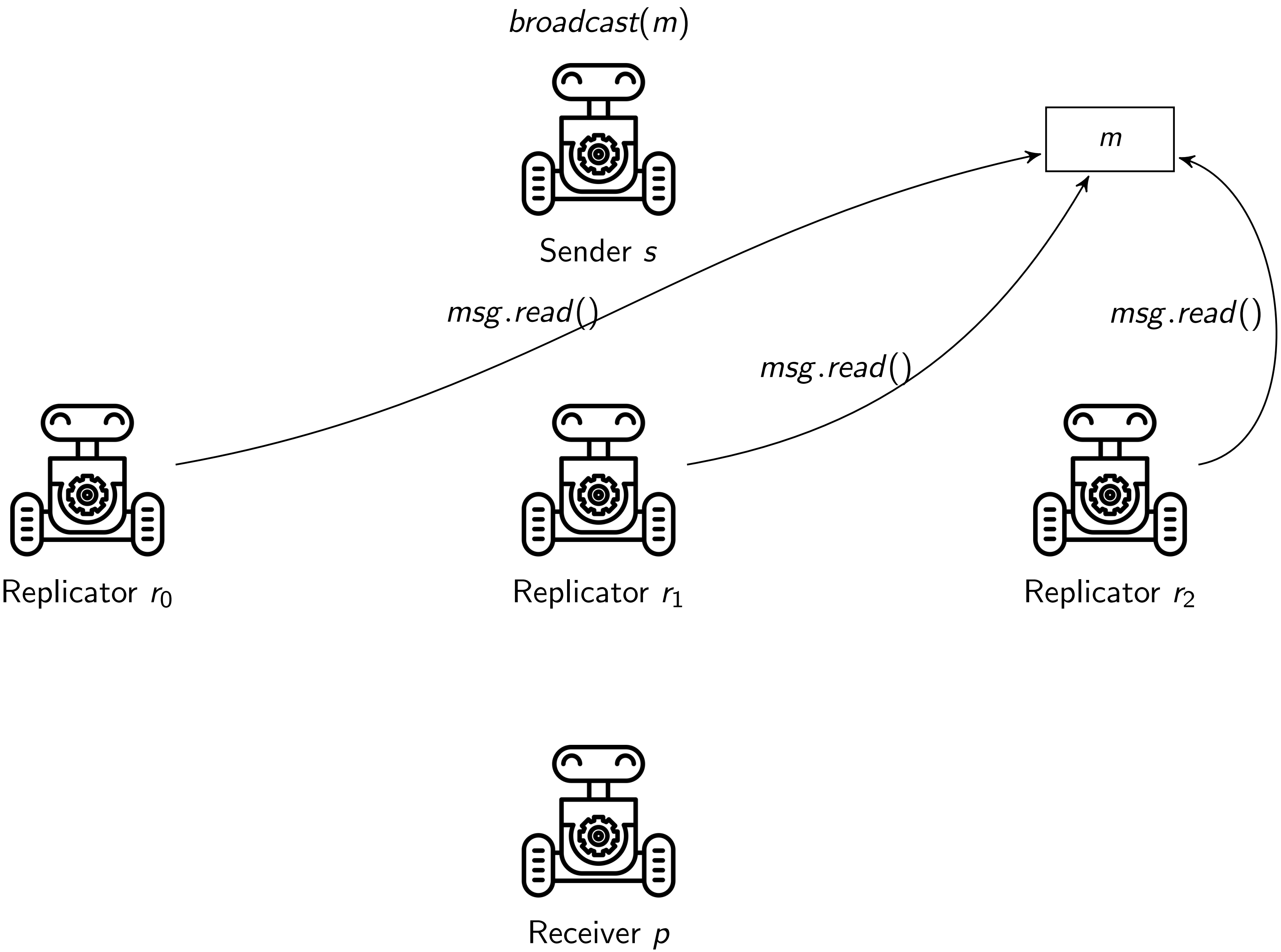

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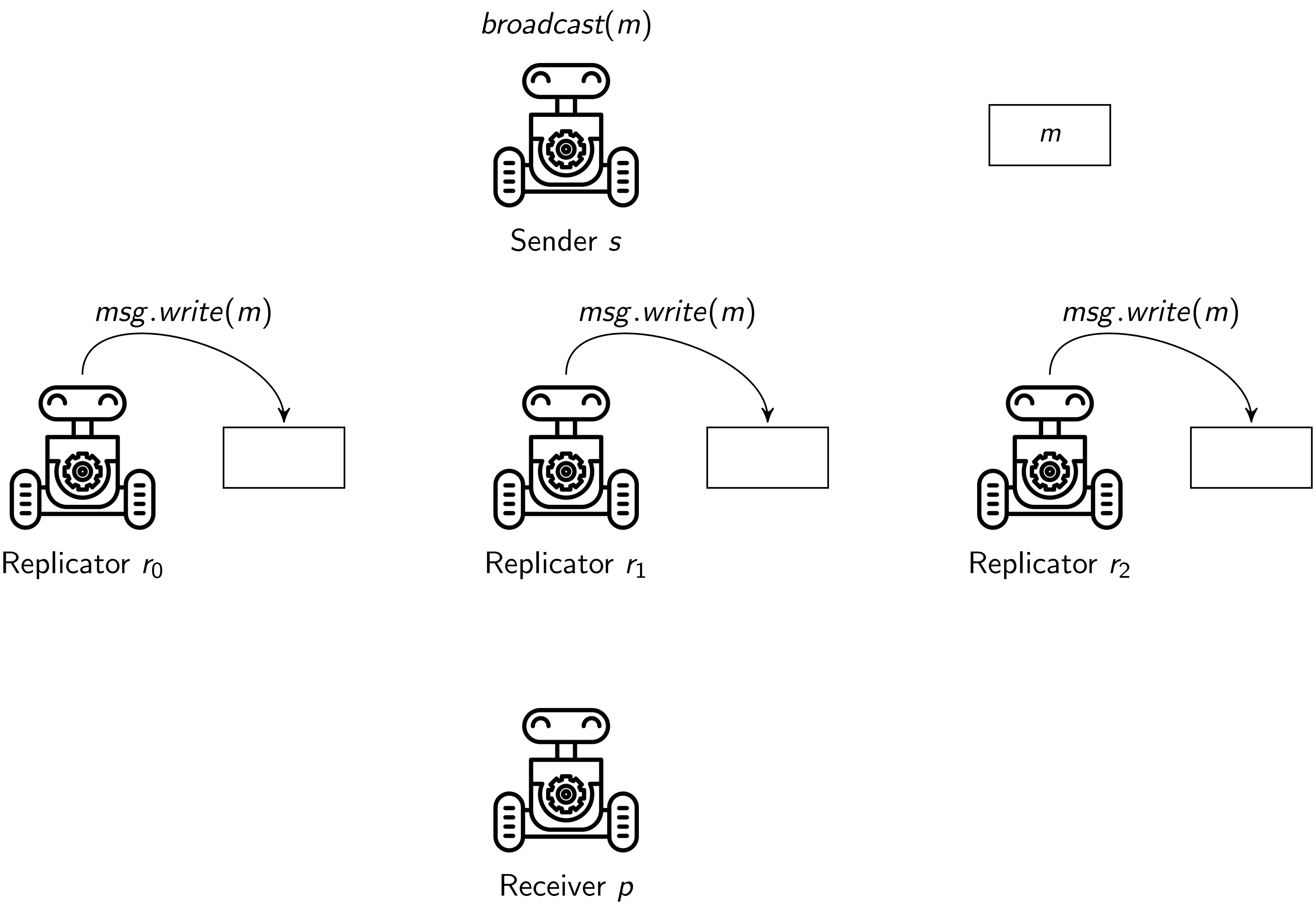

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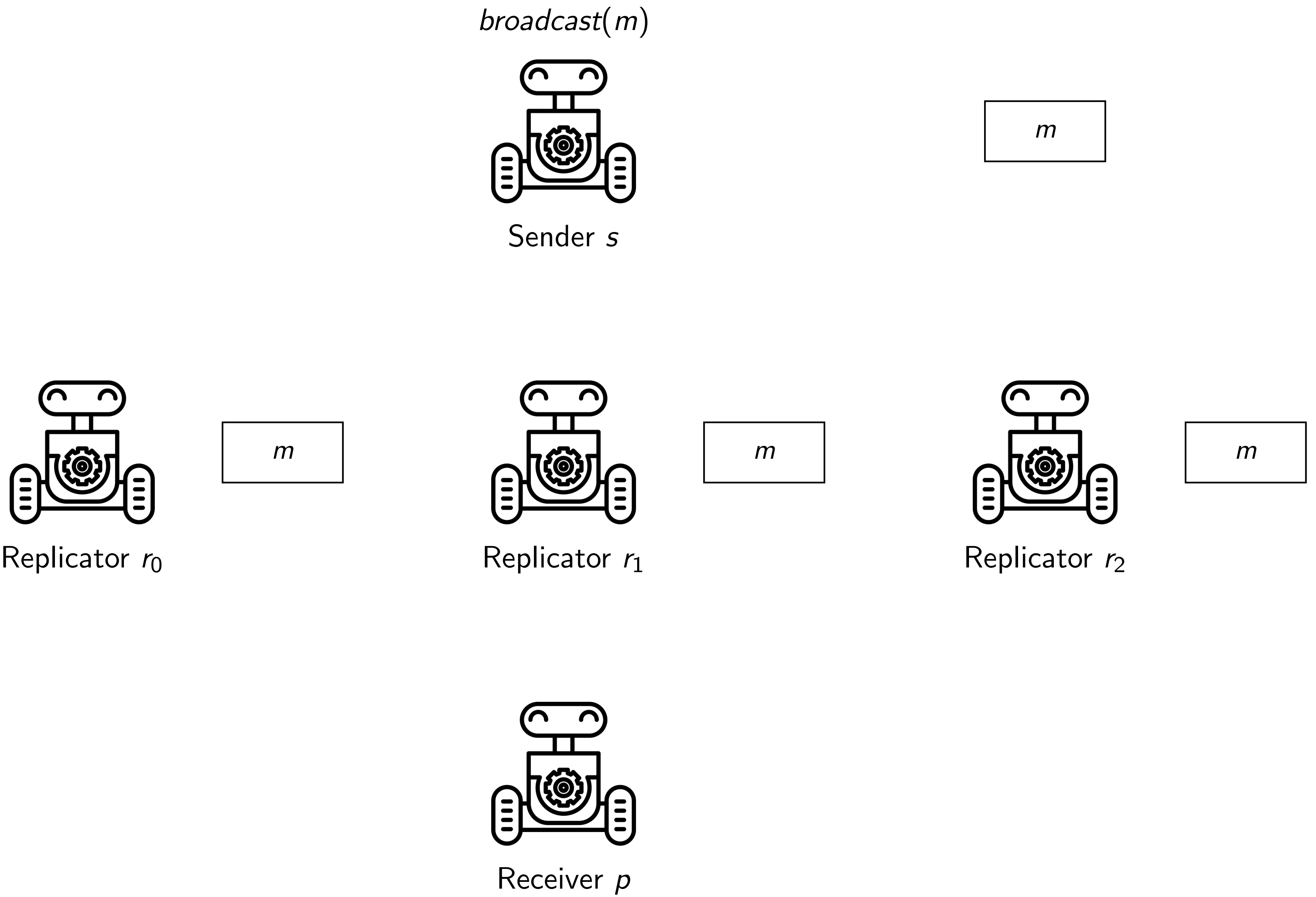

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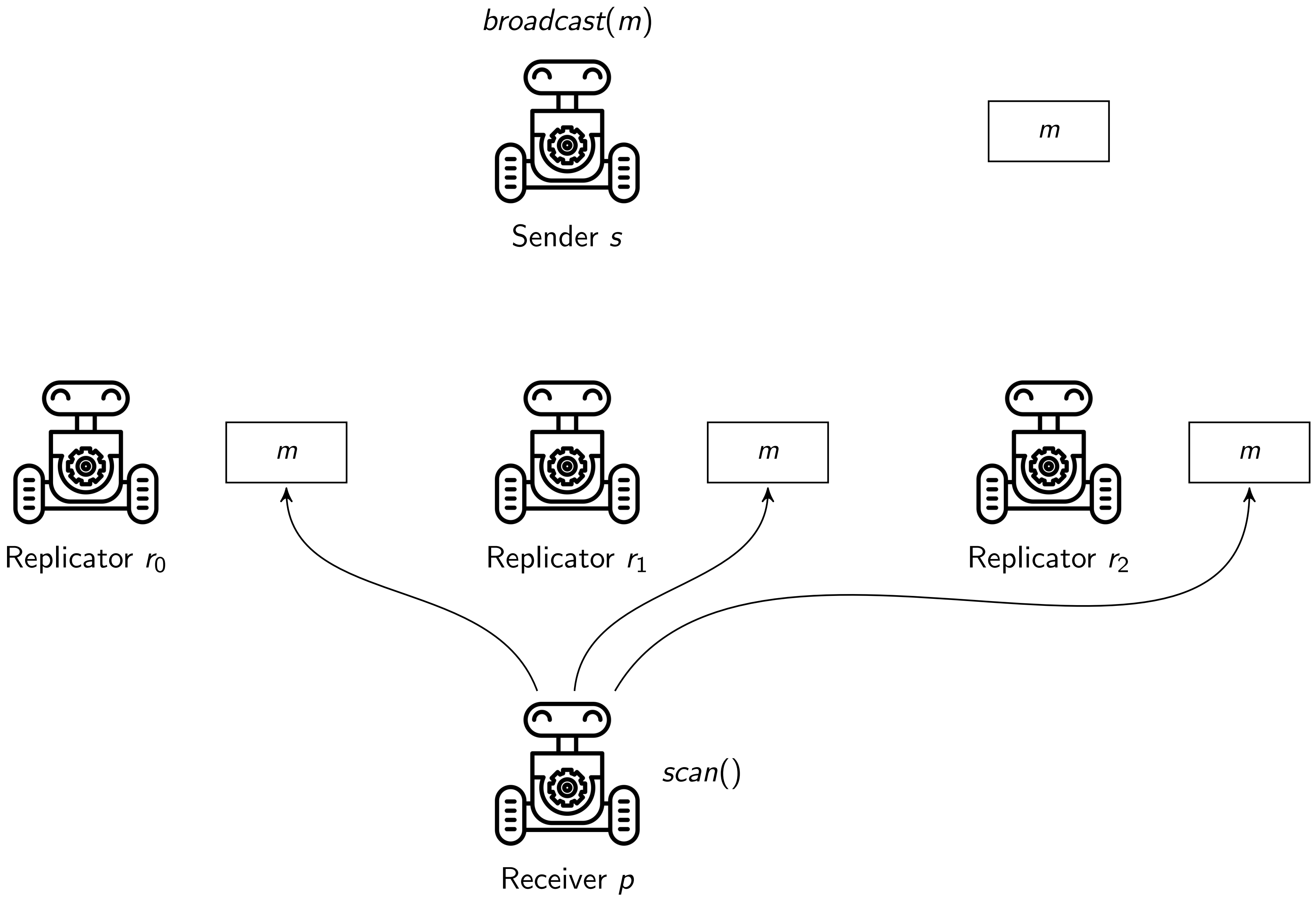

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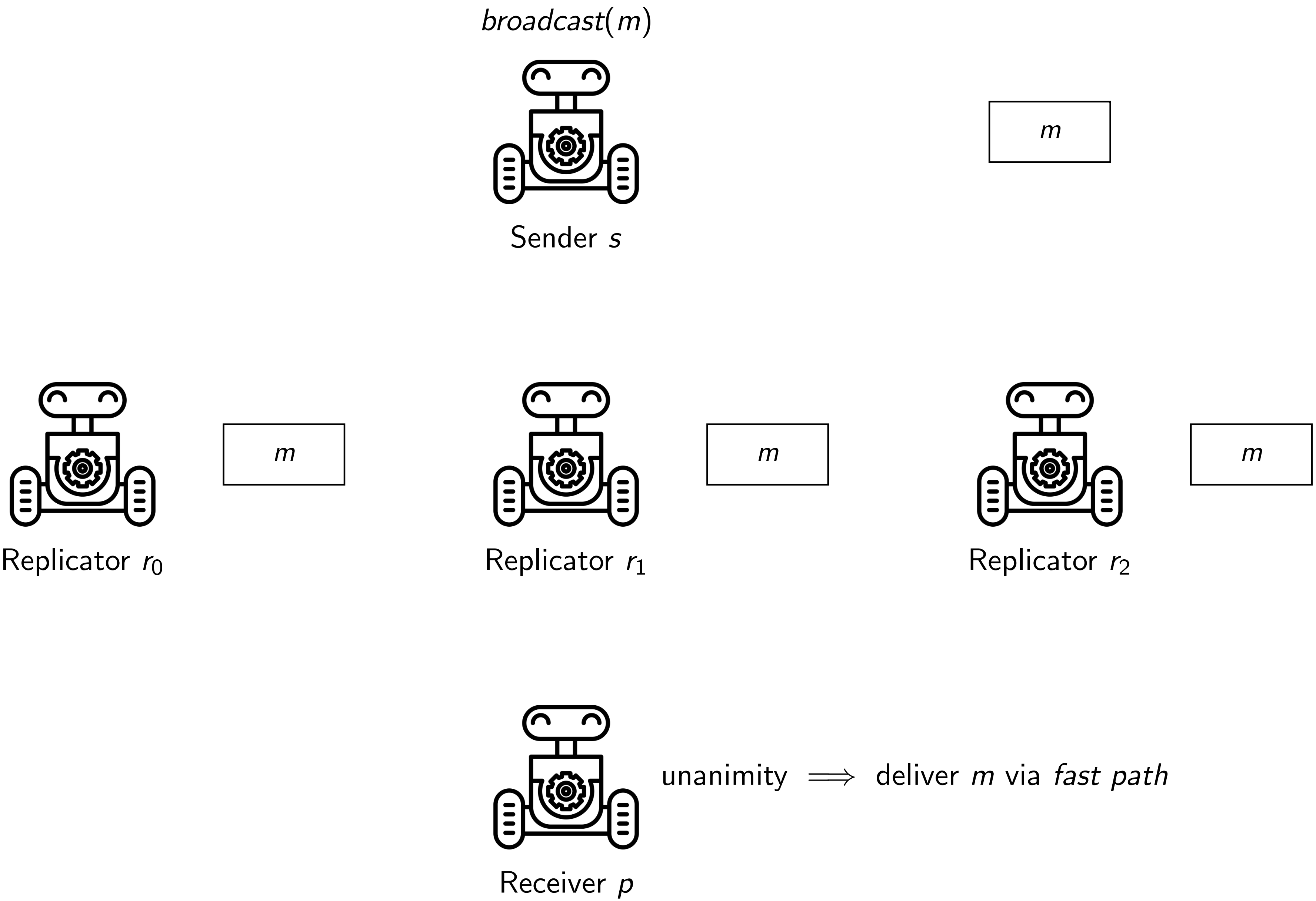

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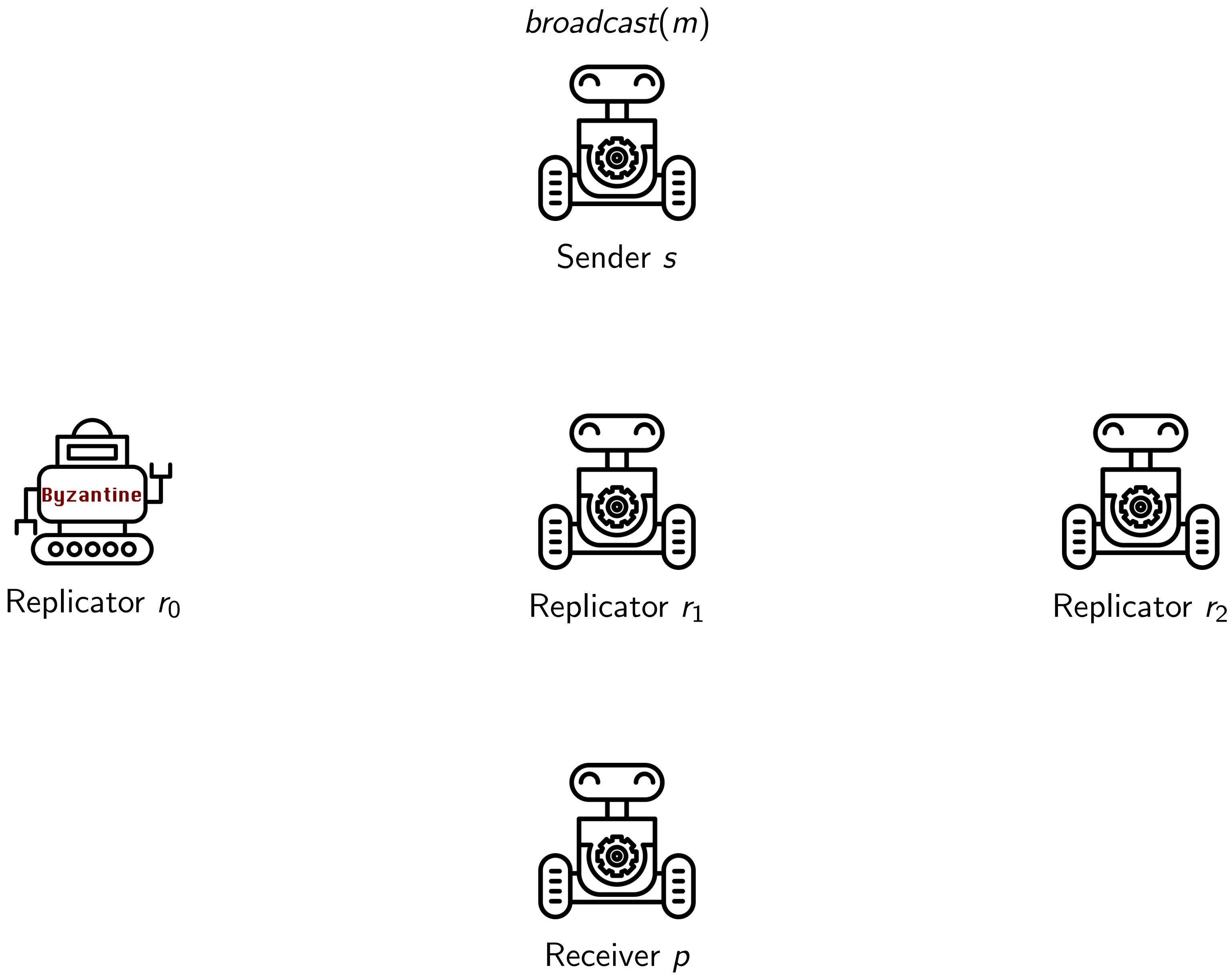

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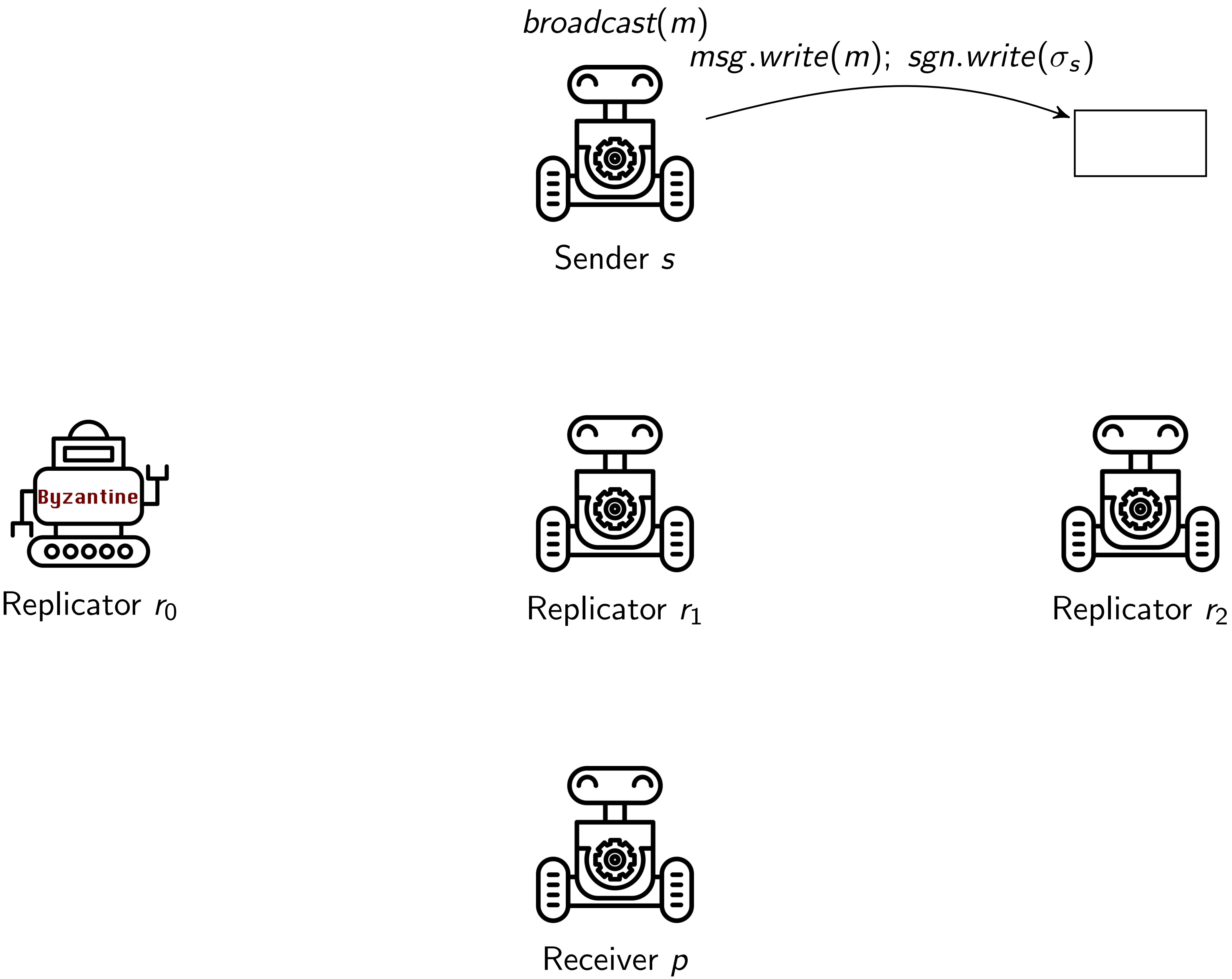

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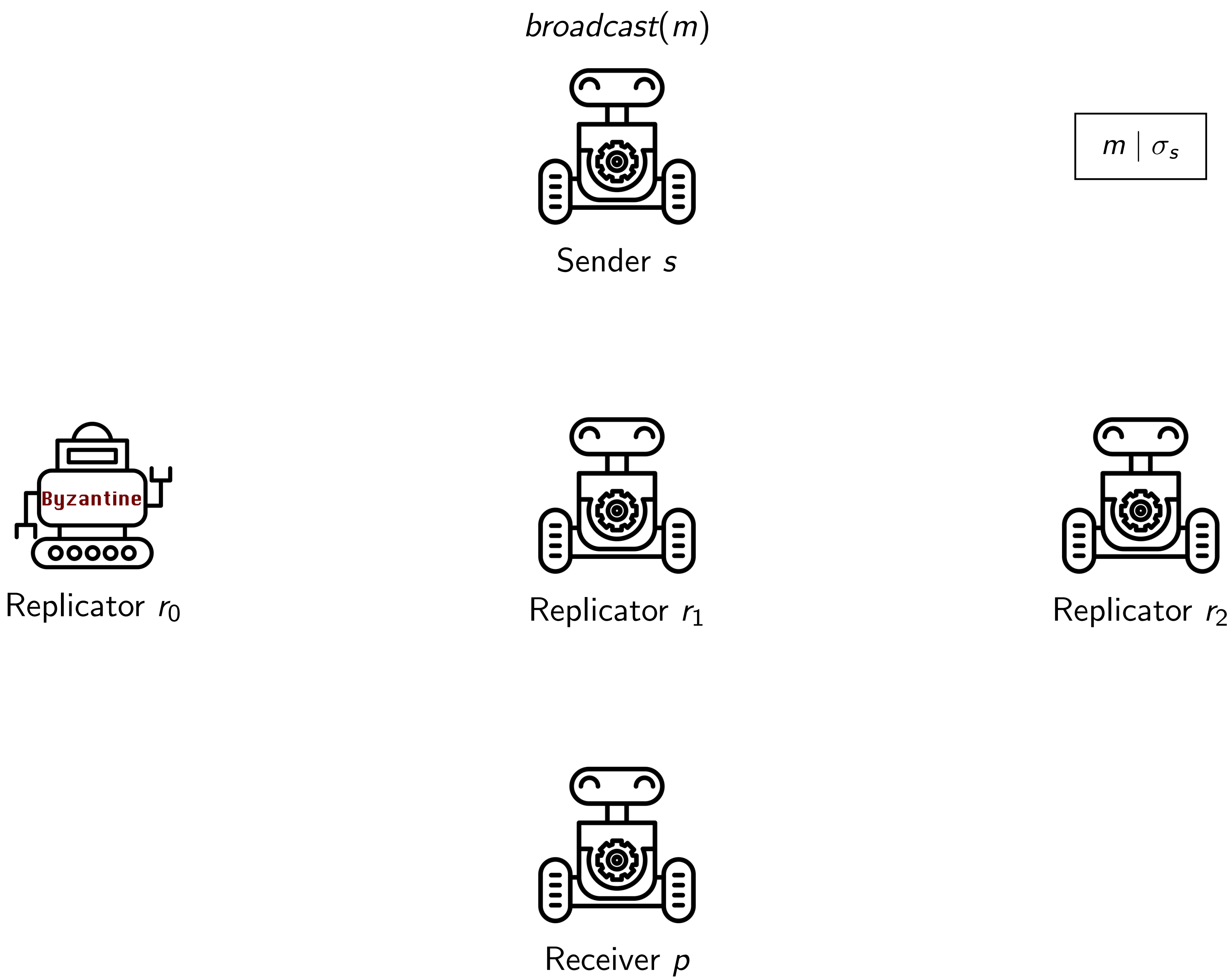

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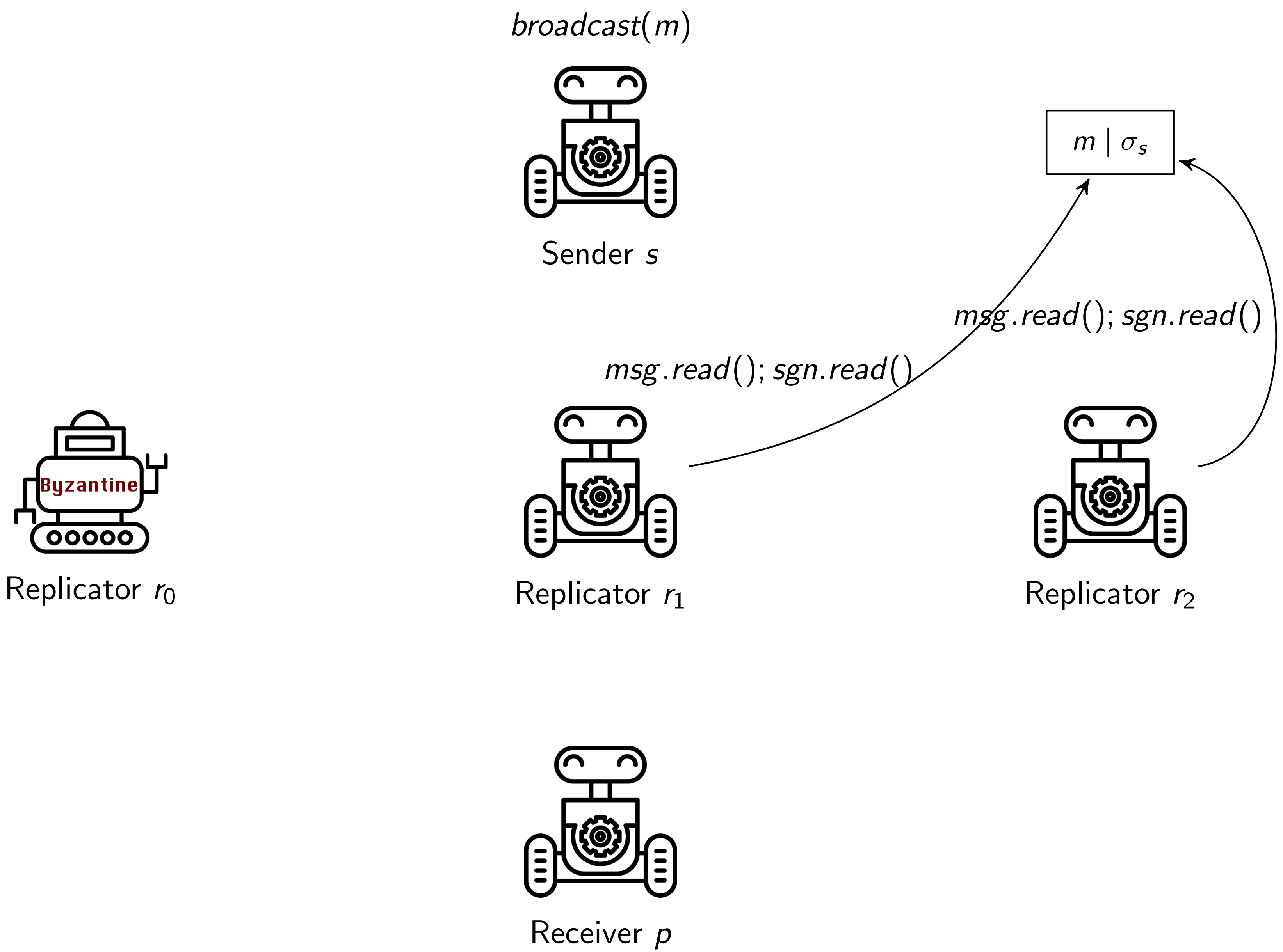

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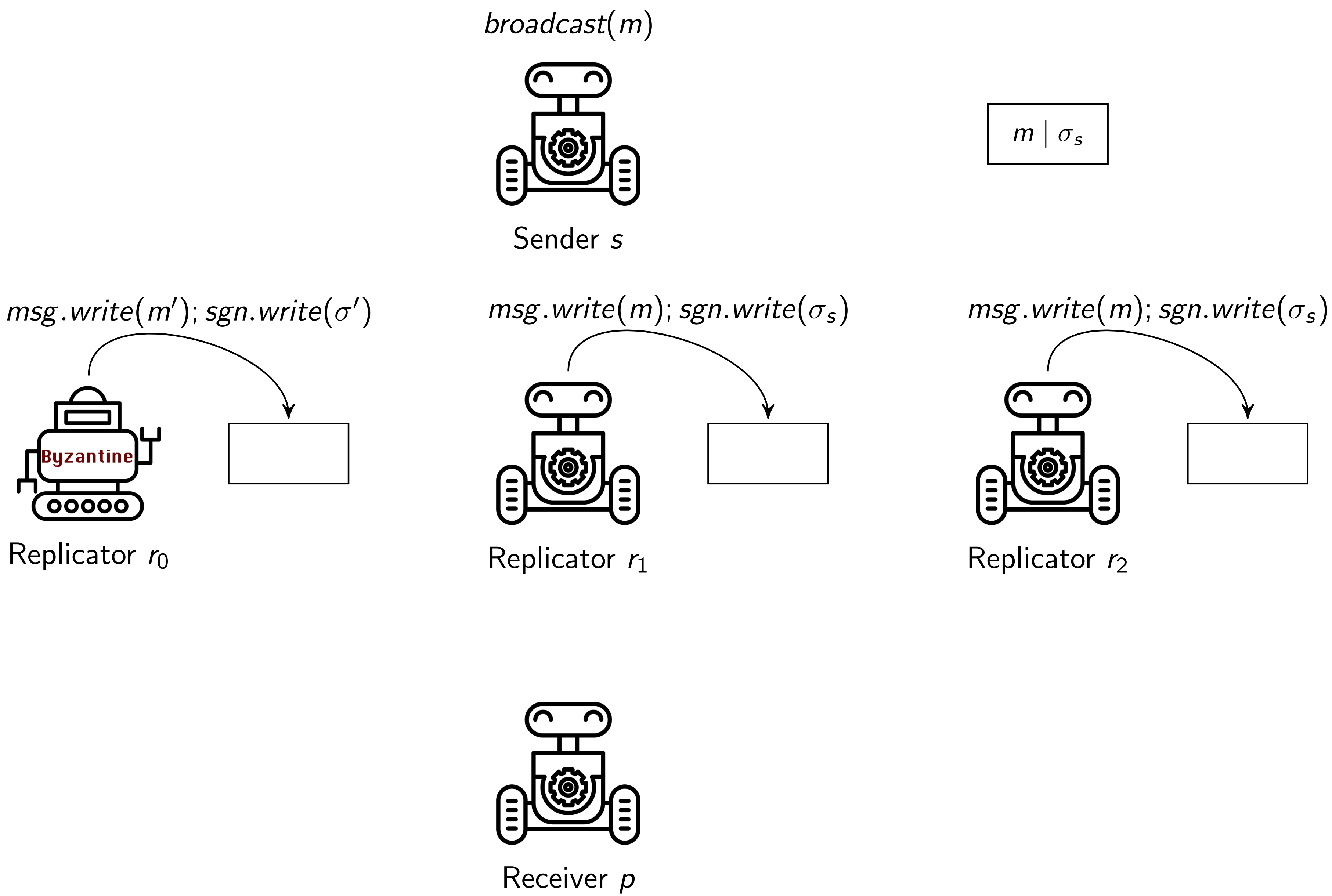

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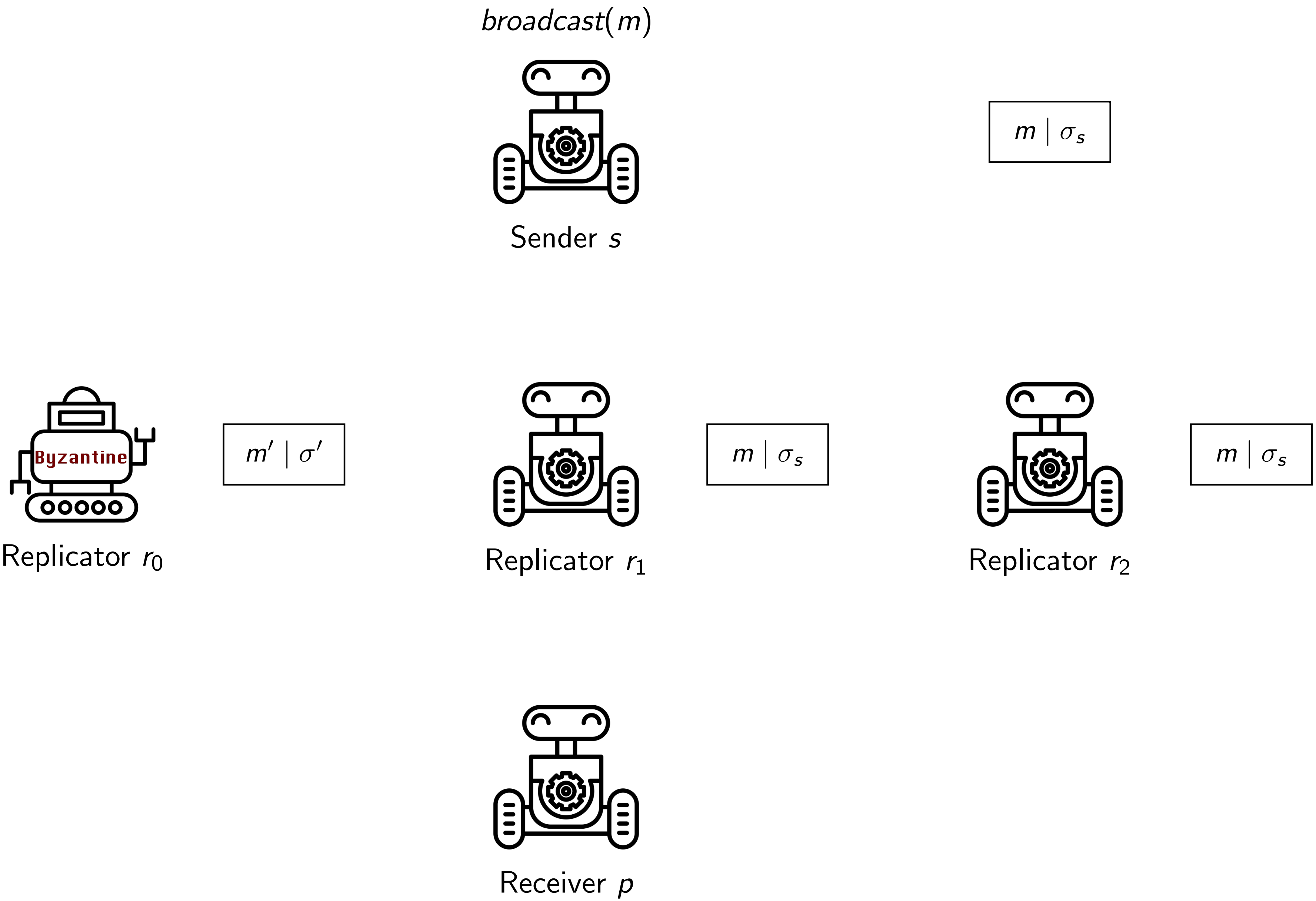

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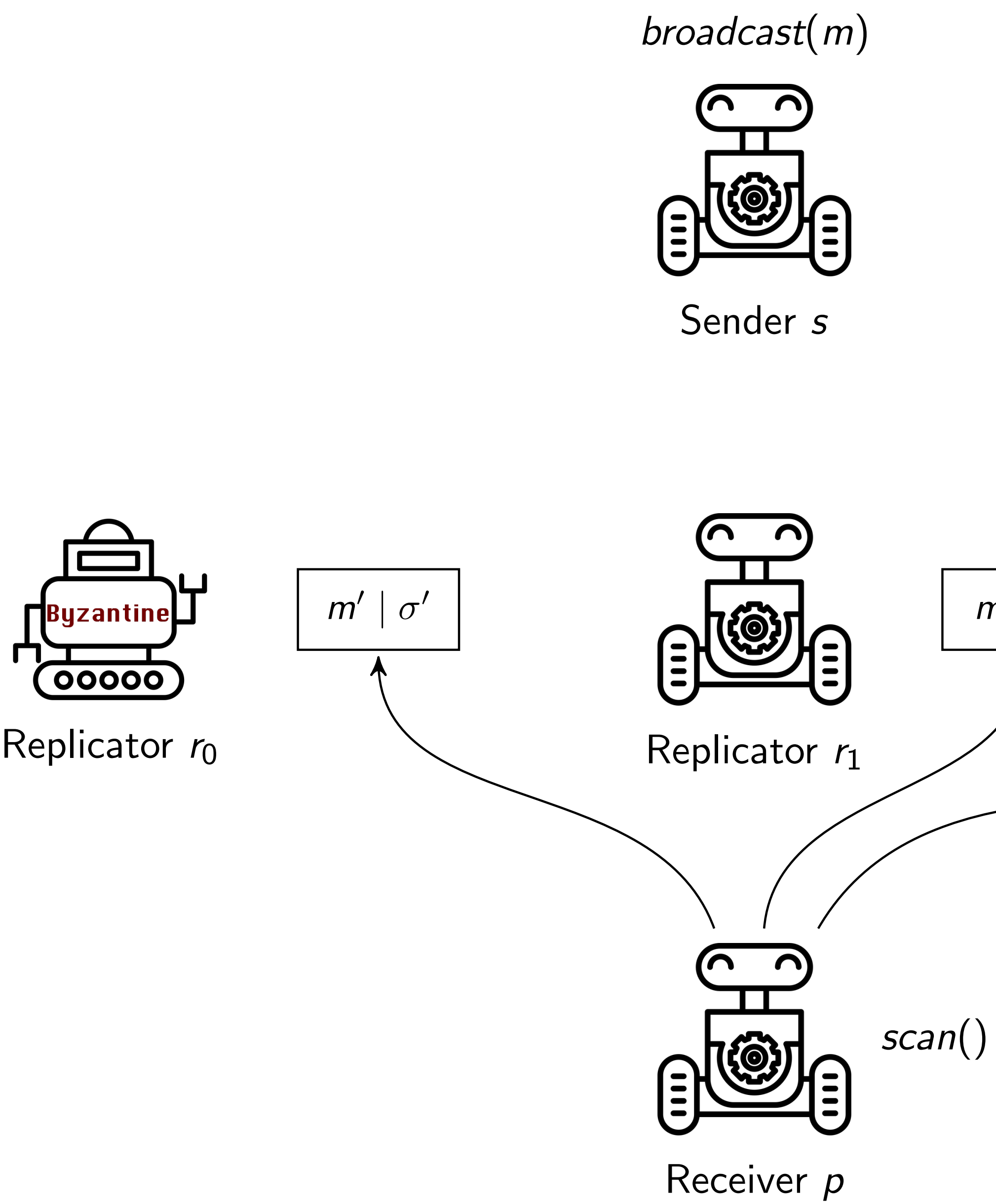

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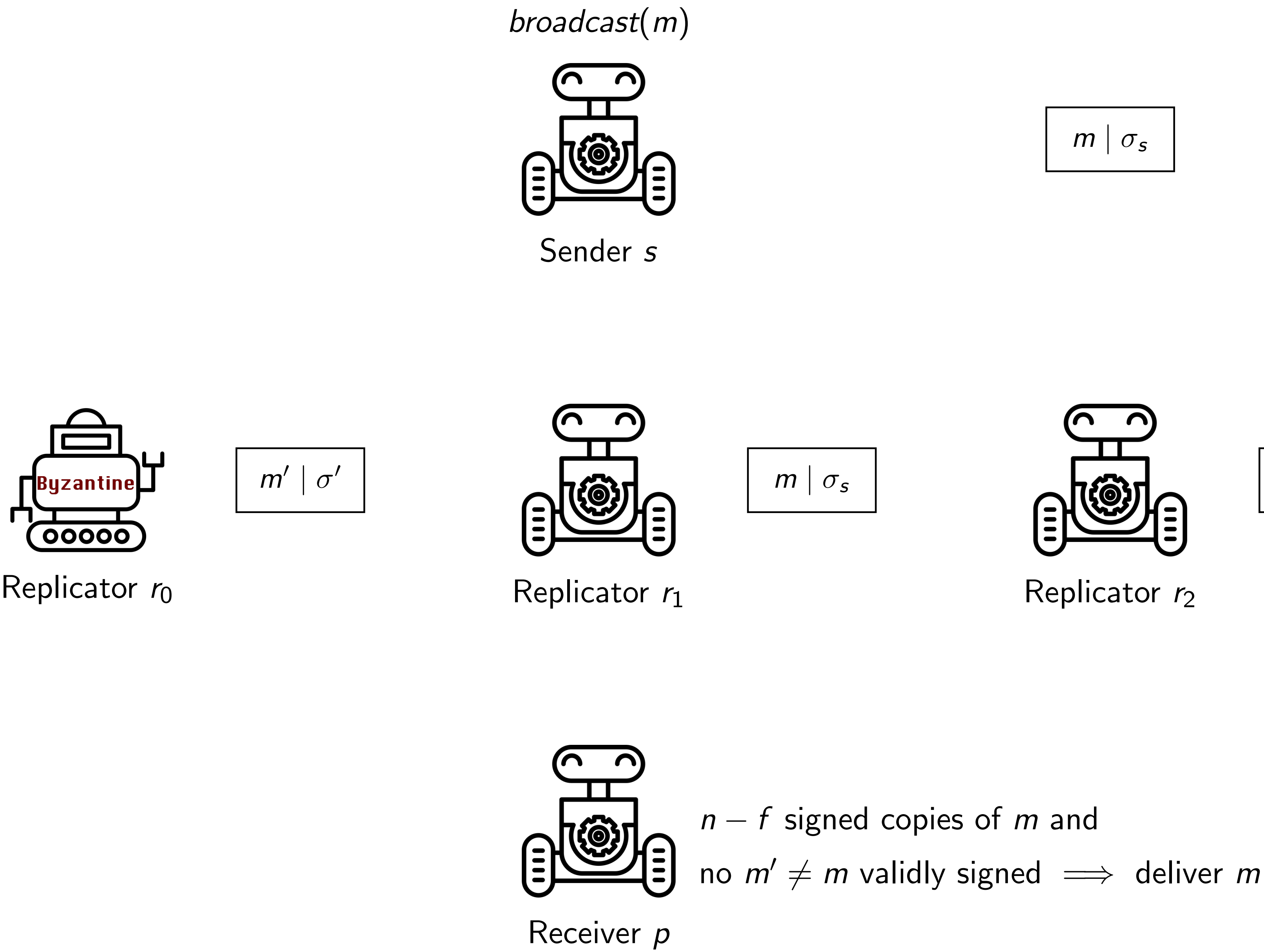
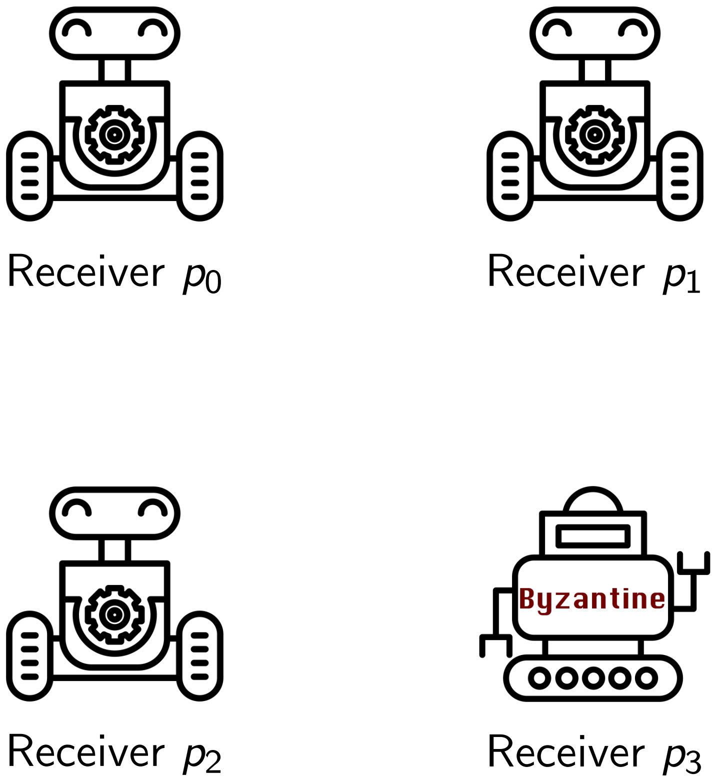


Reliable Broadcast

Same properties as Consistent Broadcast + Totality

If some correct process delivers m, then every correct process eventually delivers a message



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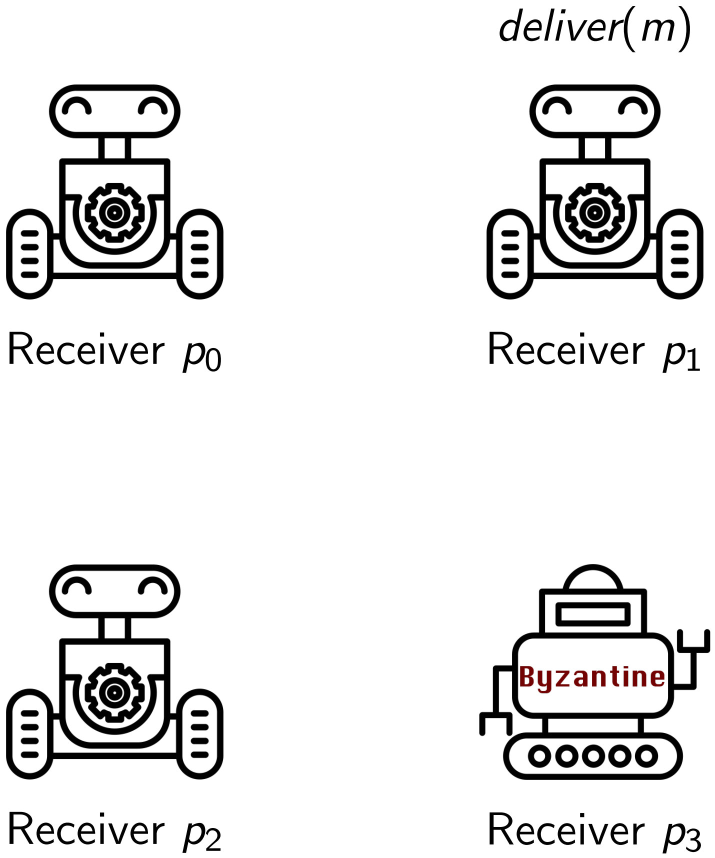

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Same properties as Consistent Broadcast + Totality

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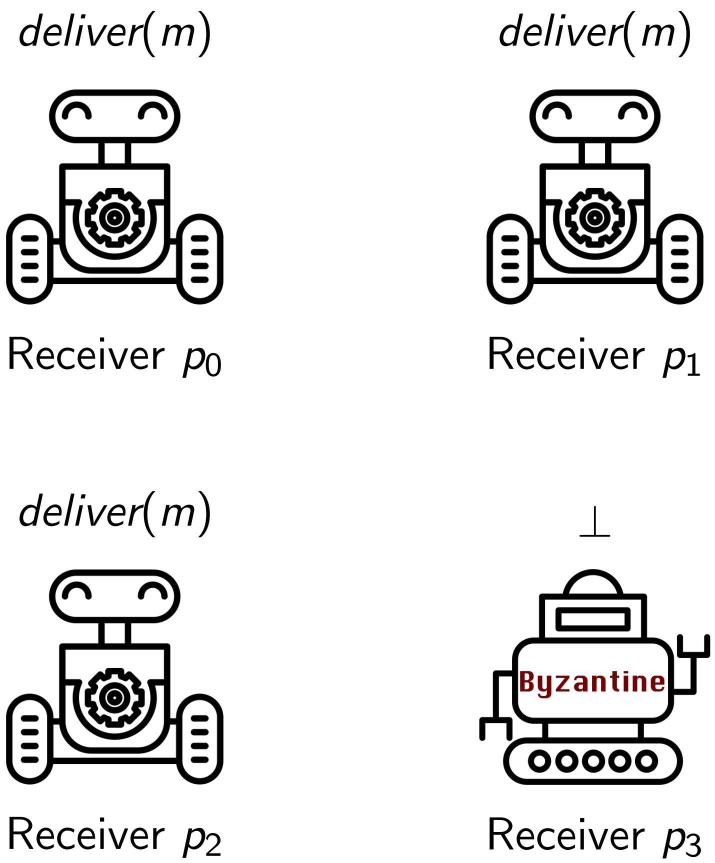

Reliable Broadcast

Validity - If a correct process s broadcasts m, then every correct process eventually delivers m

Consistency - If p and p' are correct processes, p delivers m, and p' delivers m', then $m{=}m'$

Integrity - If some correct process delivers m and s is correct, then s previously broadcast m

Totality - If some correct process delivers m, then every correct process eventually delivers a message

Consistent Broadcast vs Reliable Broadcast

Consistent and Reliable Broadcast behave the same way when the sender s is correct (recall the *Validity* property)

Consistent Broadcast vs Reliable Broadcast

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Yet when the sender is faulty ...

- Consistent Broadcast has no delivery guarantees: some correct processes may deliver a message, others may not

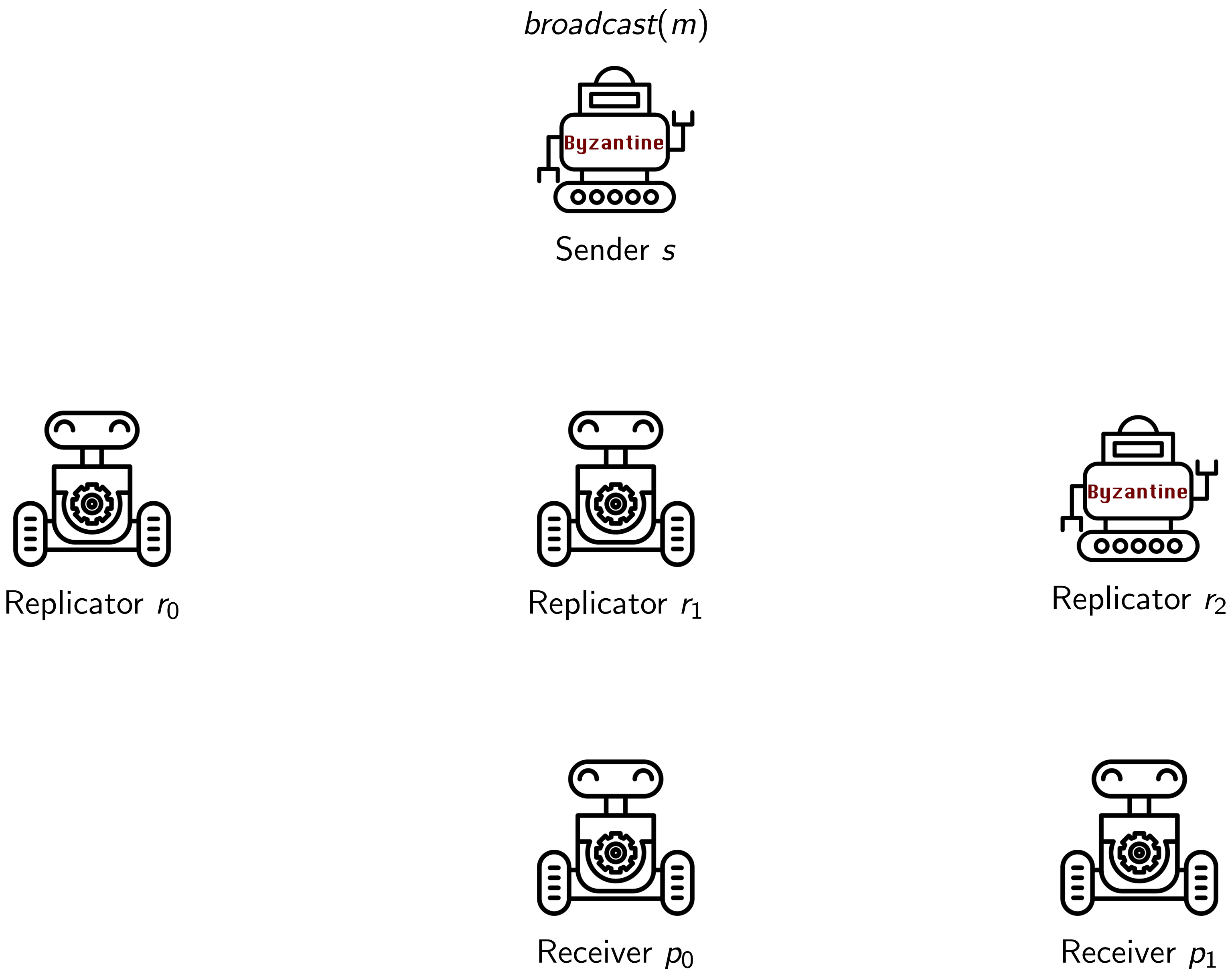
Consistent Broadcast vs Reliable Broadcast

Consistent and Reliable Broadcast behave the same way when the sender s is correct (recall the *Validity* property)

Yet when the sender is faulty ...

- Consistent Broadcast has no delivery guarantees: some correct processes may deliver a message, others may not
- while Reliable Broadcast guarantees every correct process eventually delivers a message as soon as one correct process delivered

Consistent Broadcast algorithm $= \neg$ sufficient



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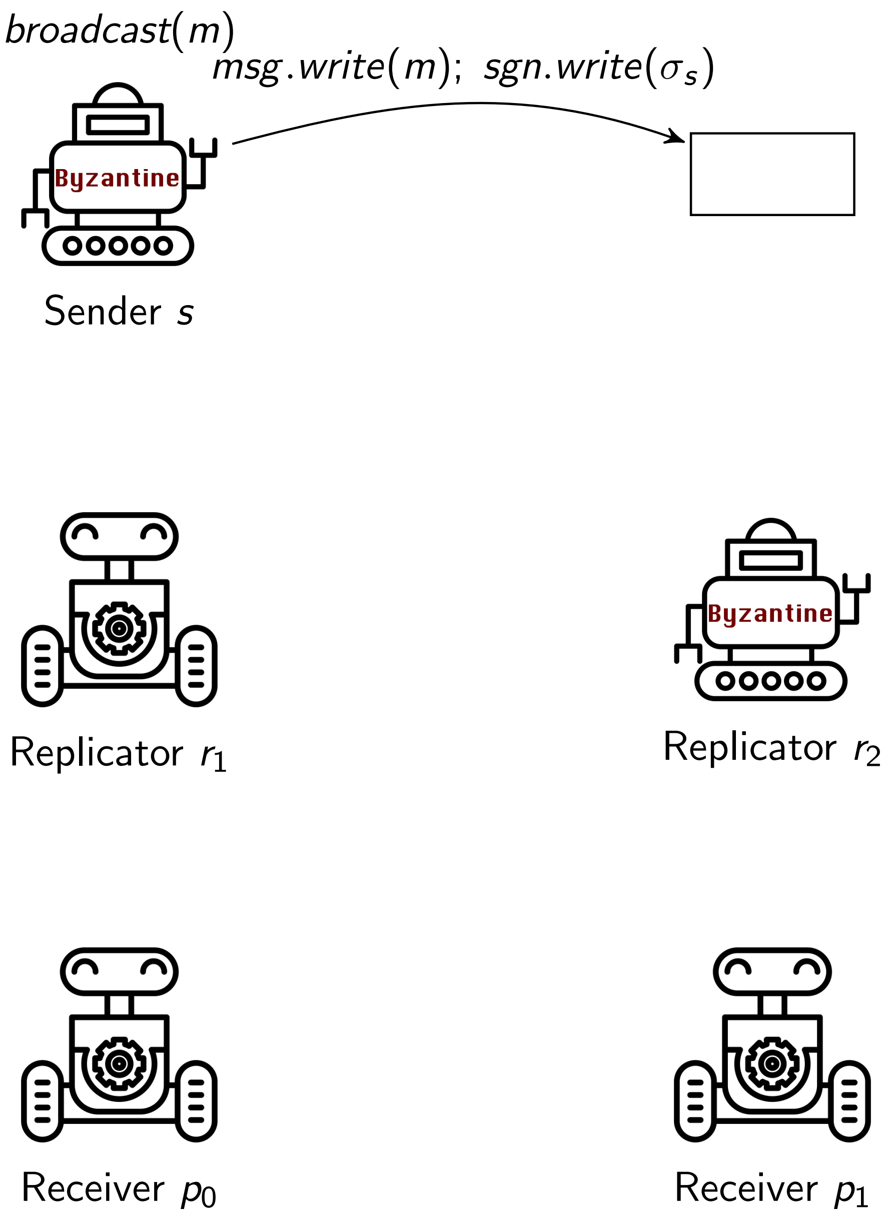

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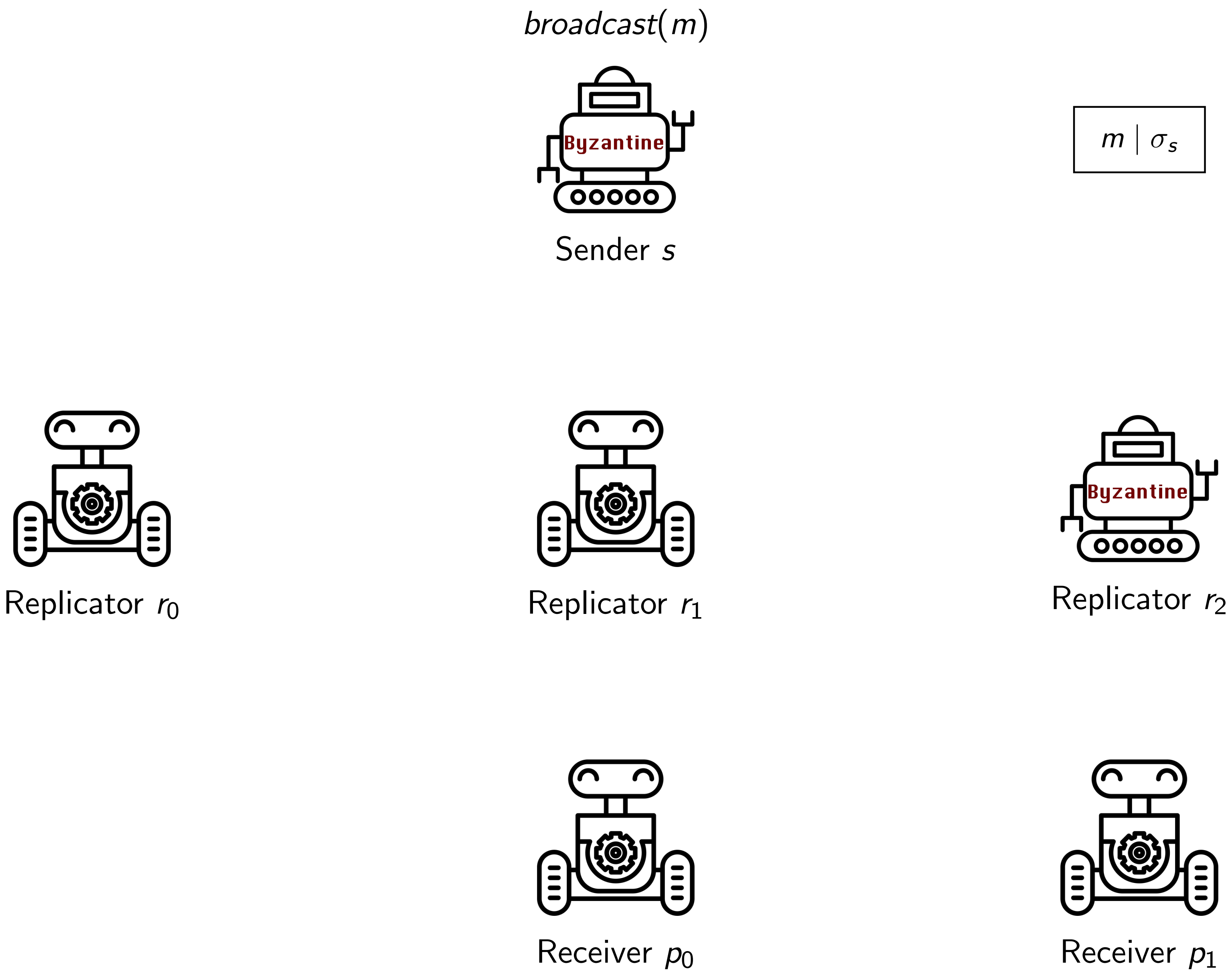

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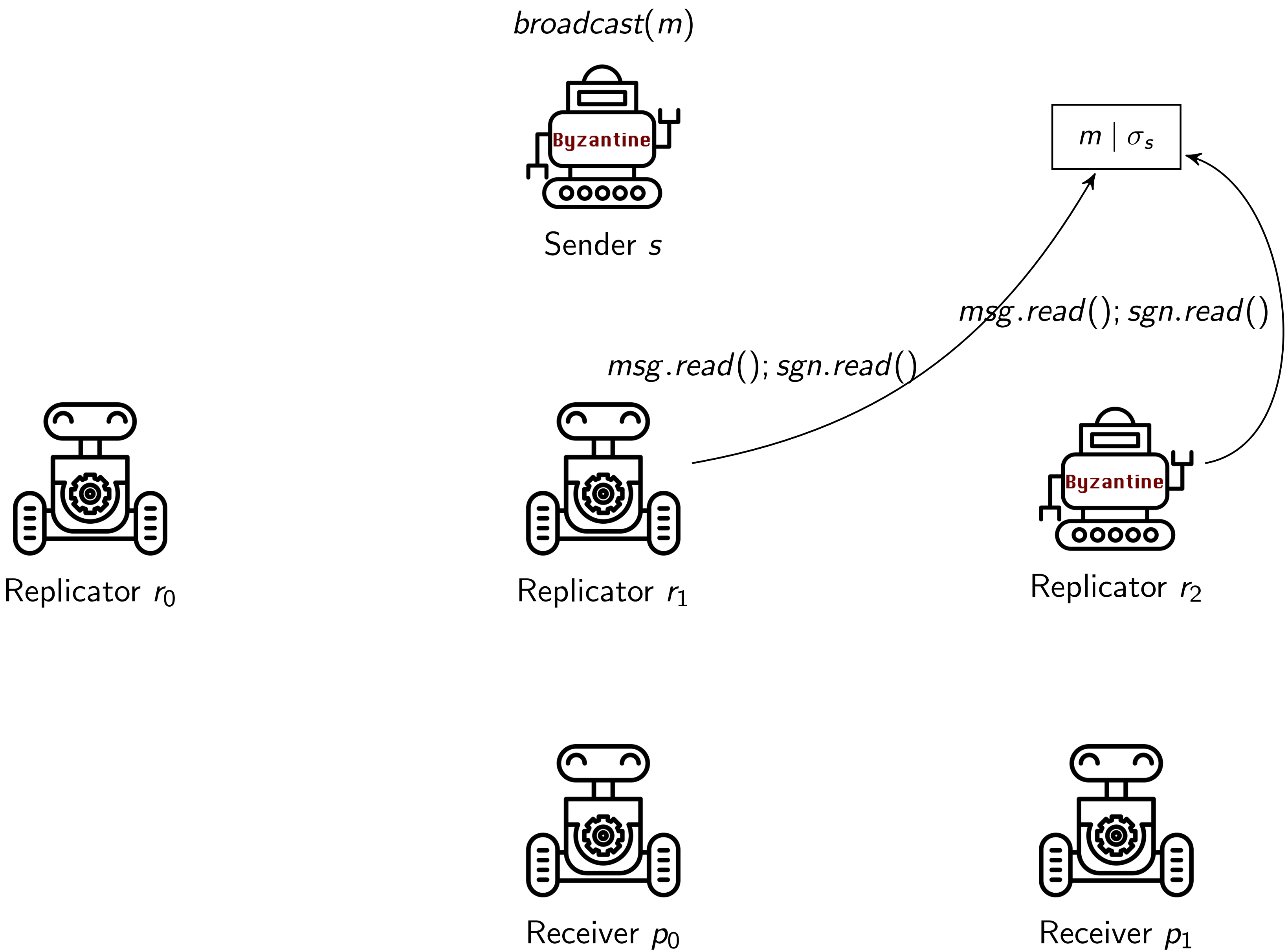

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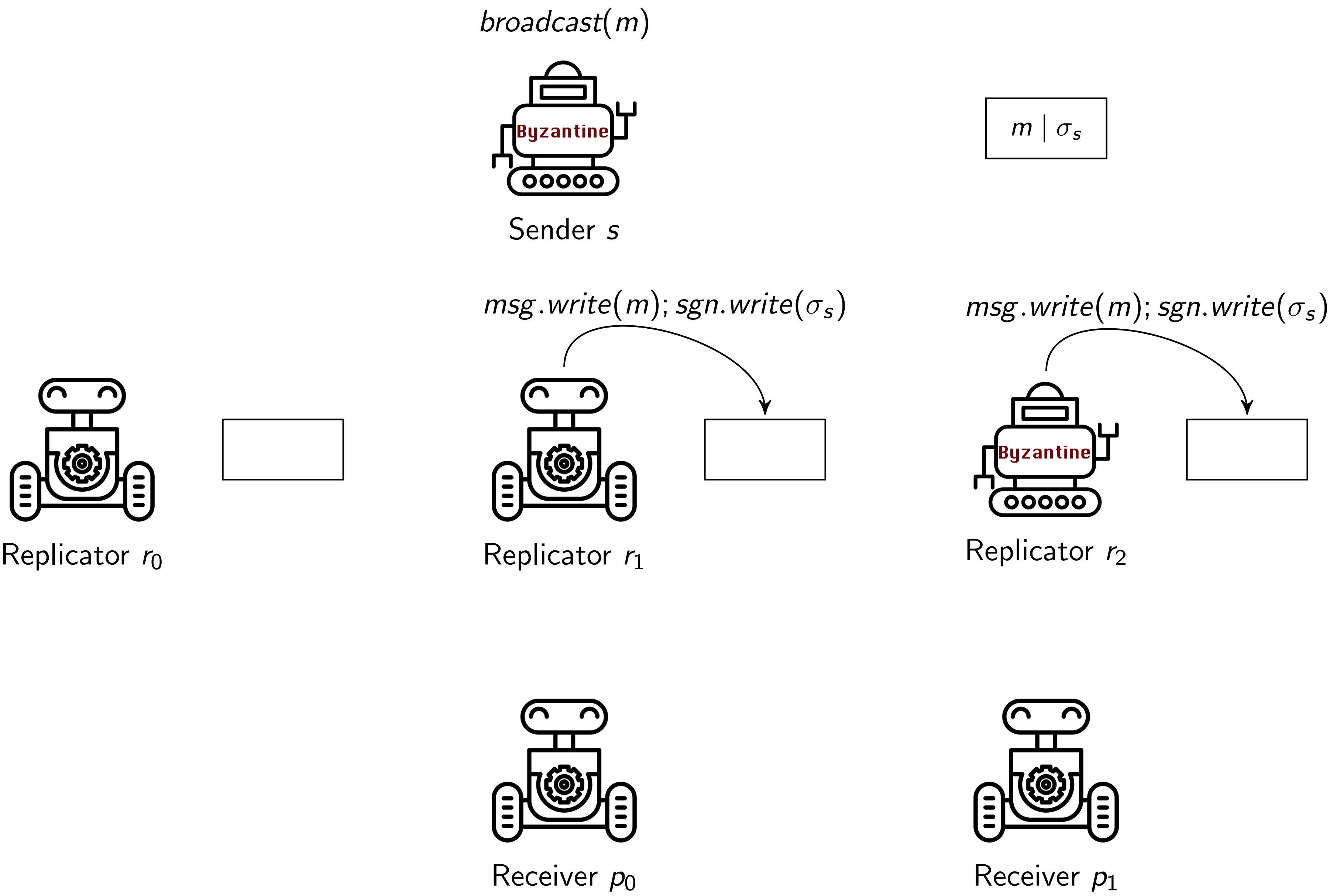

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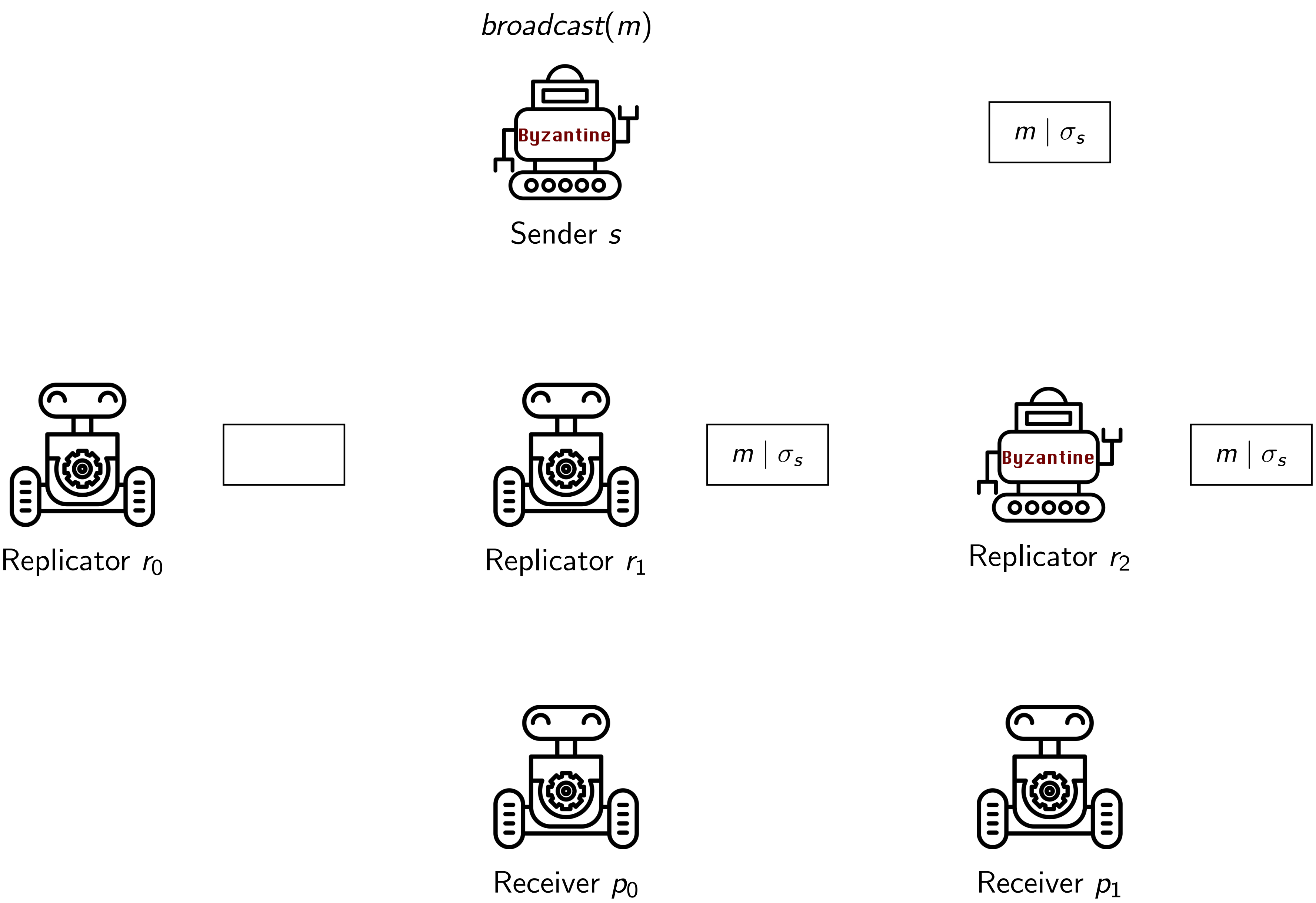

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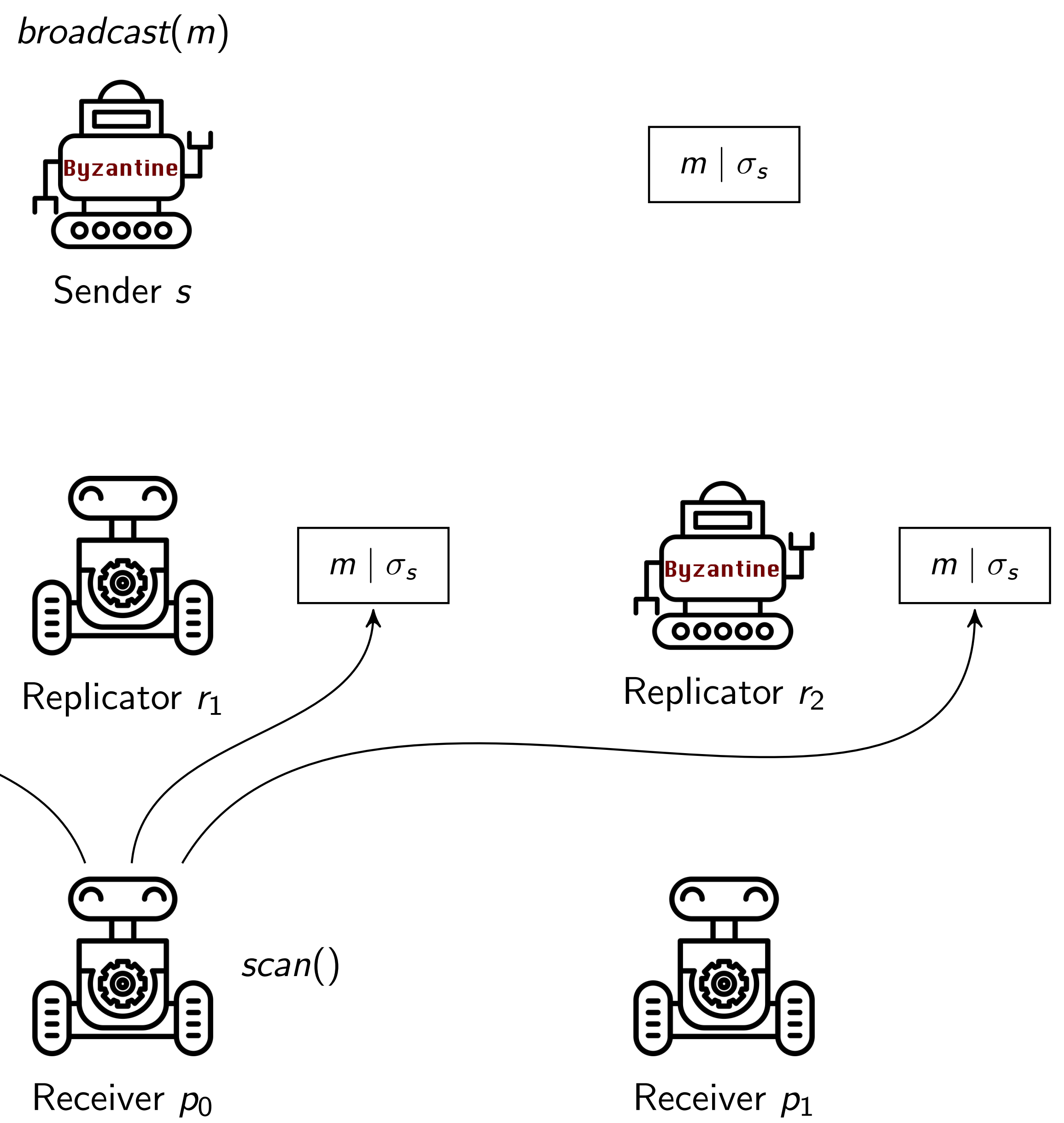

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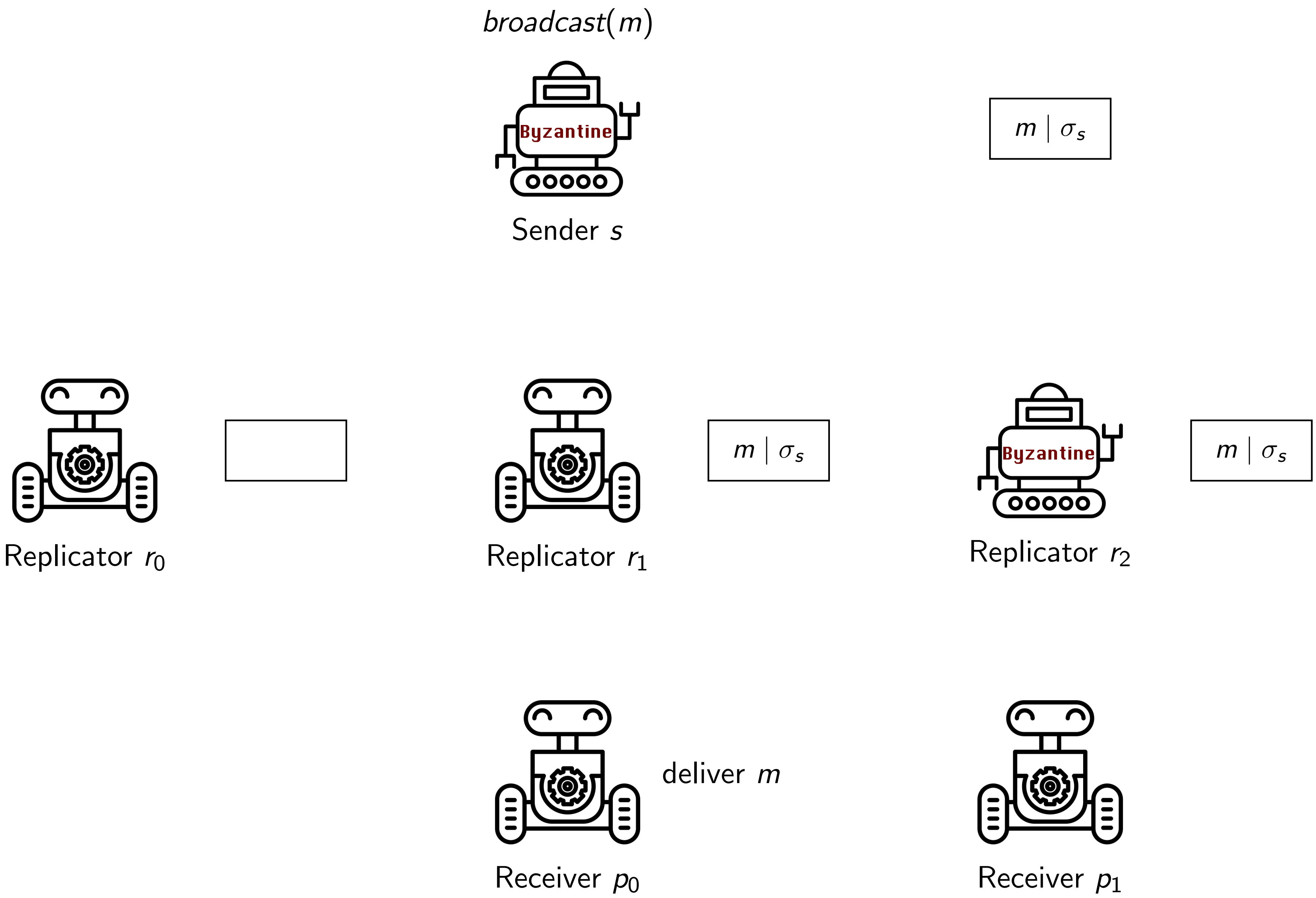

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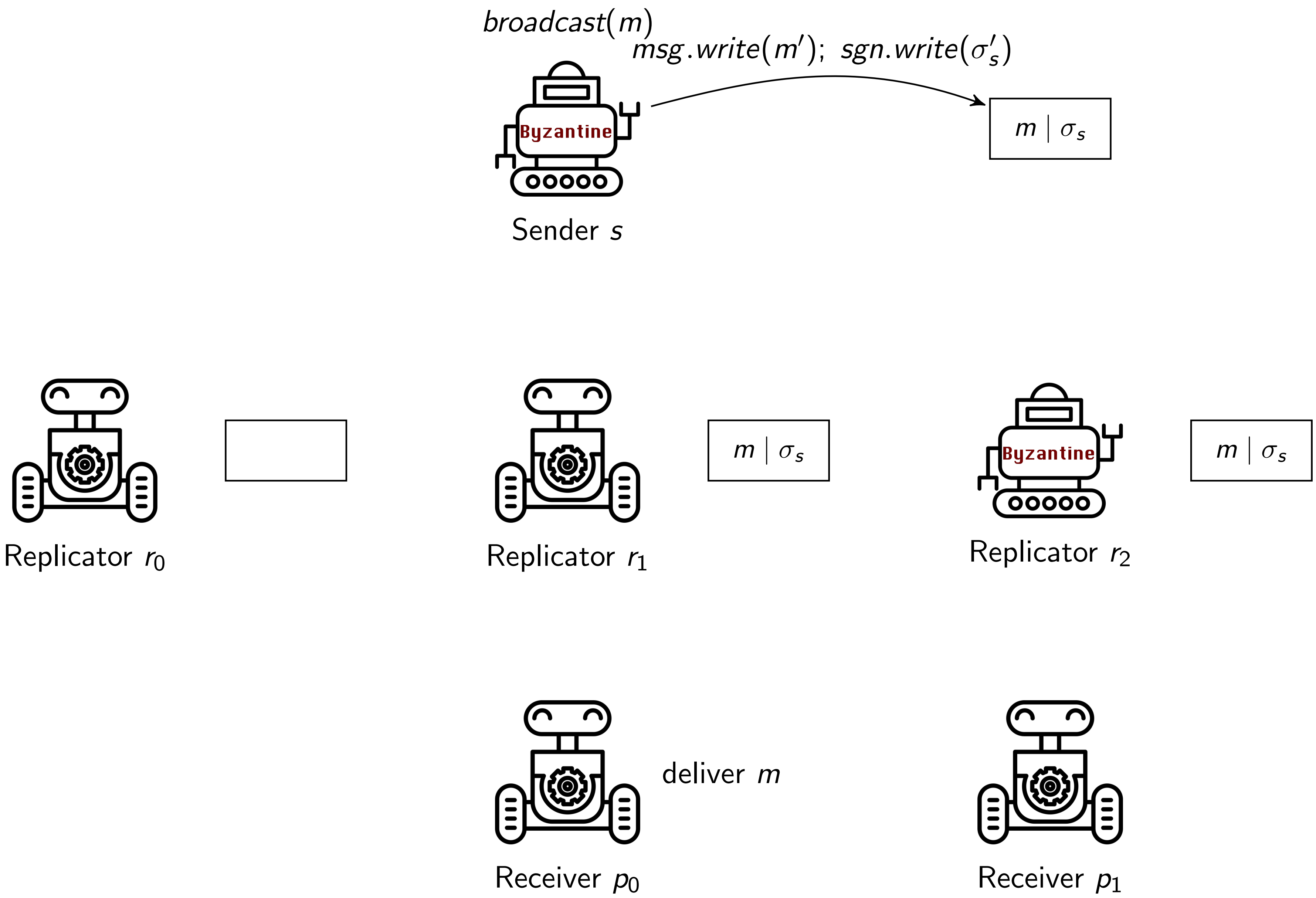

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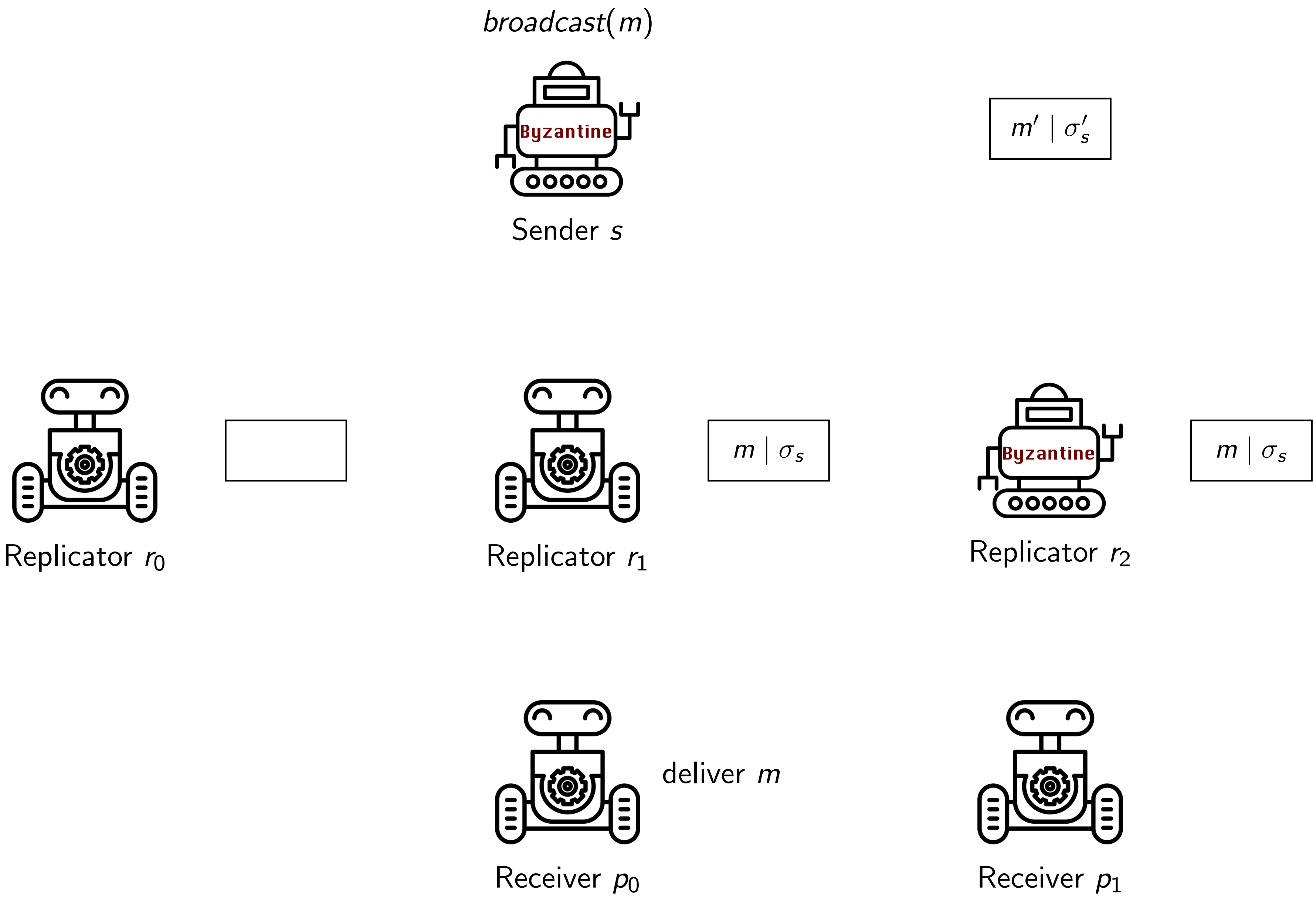

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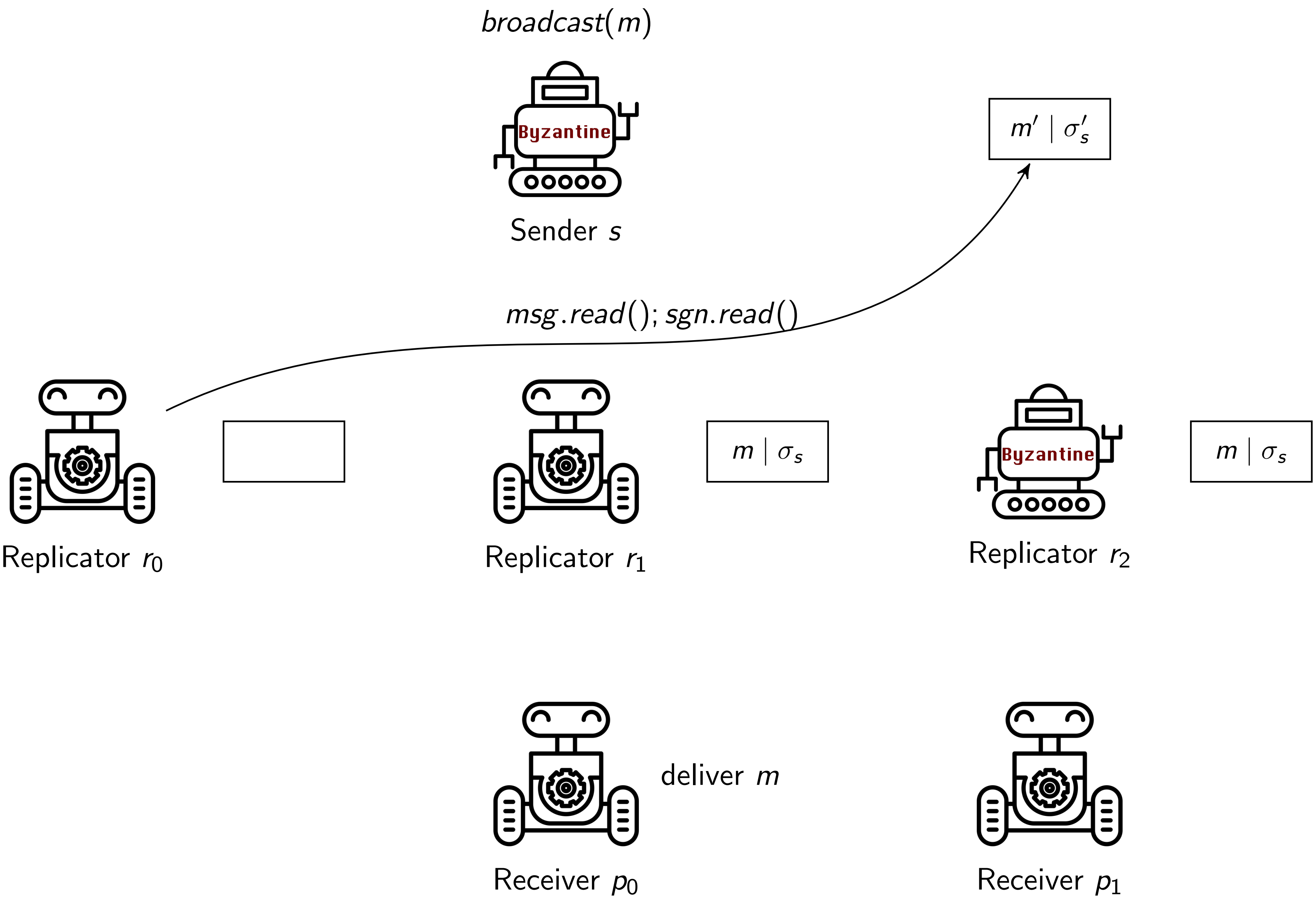

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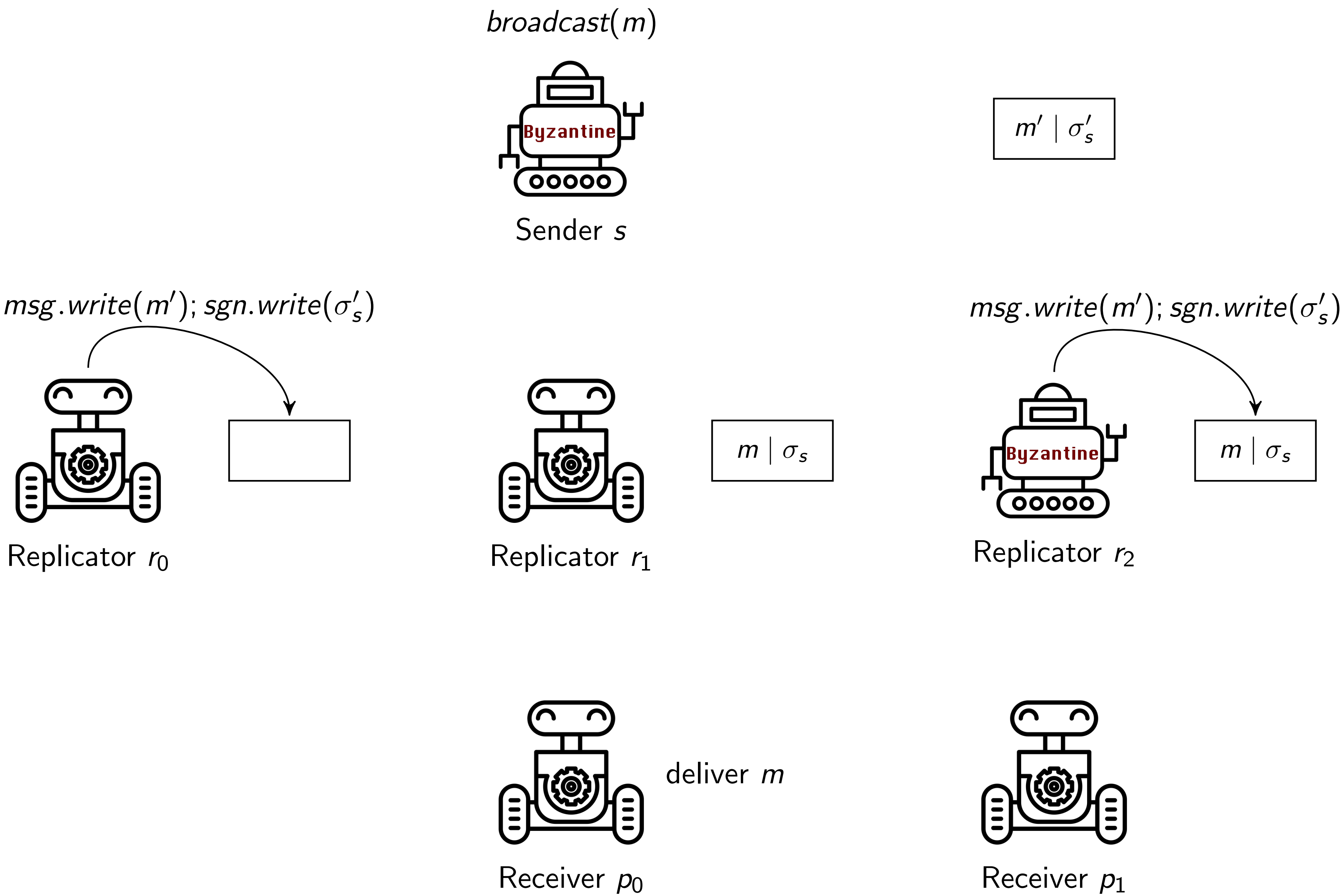

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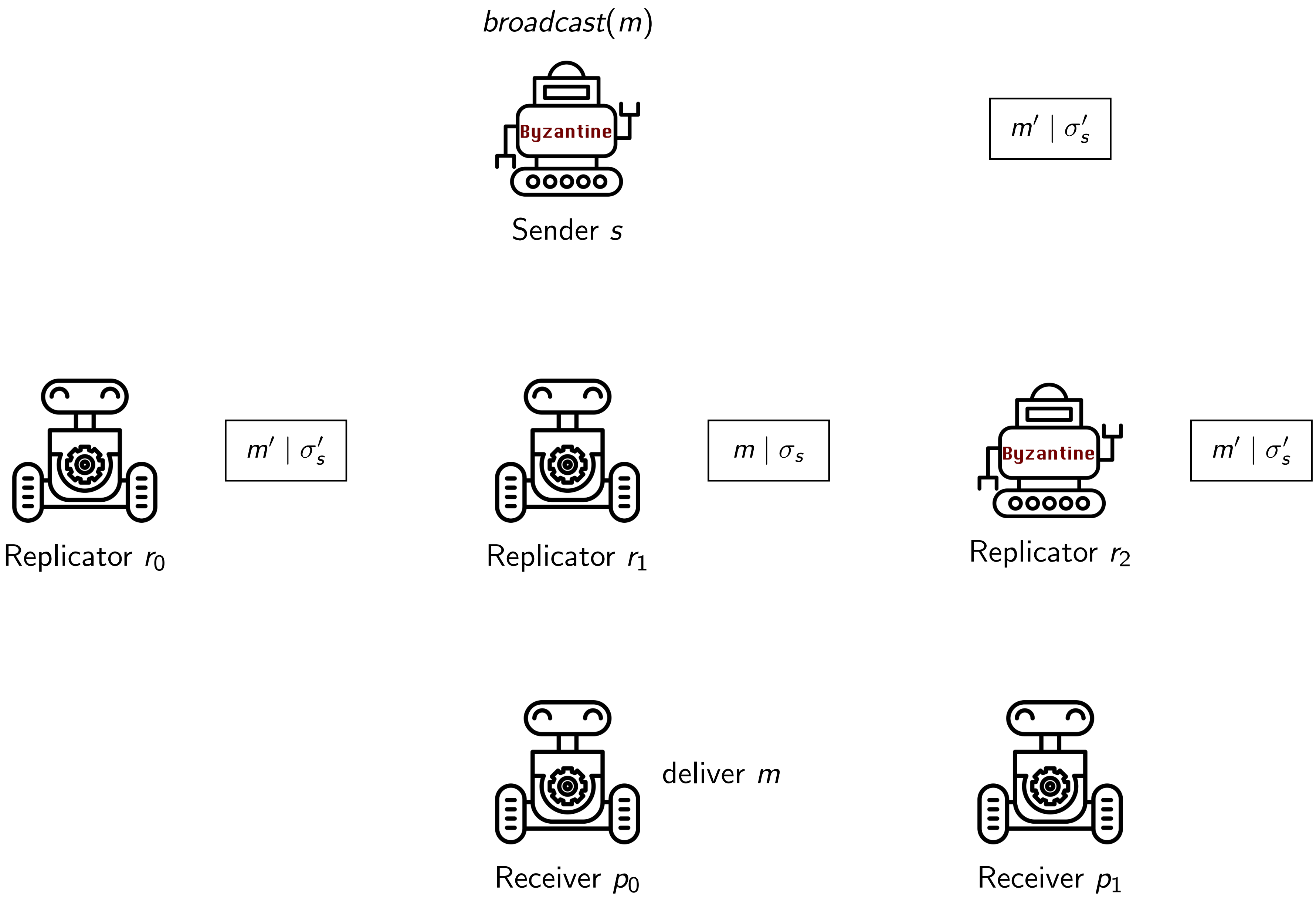

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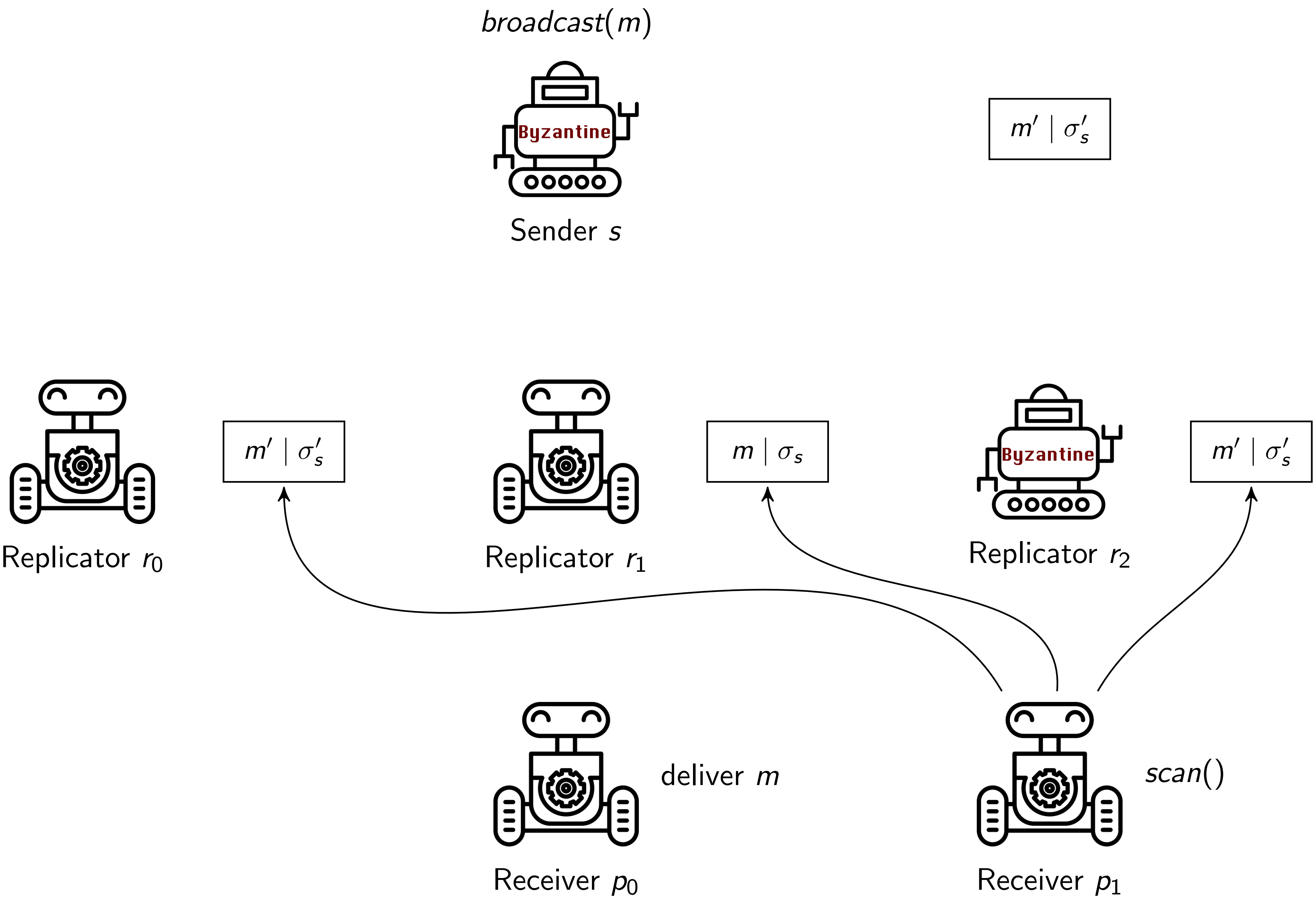

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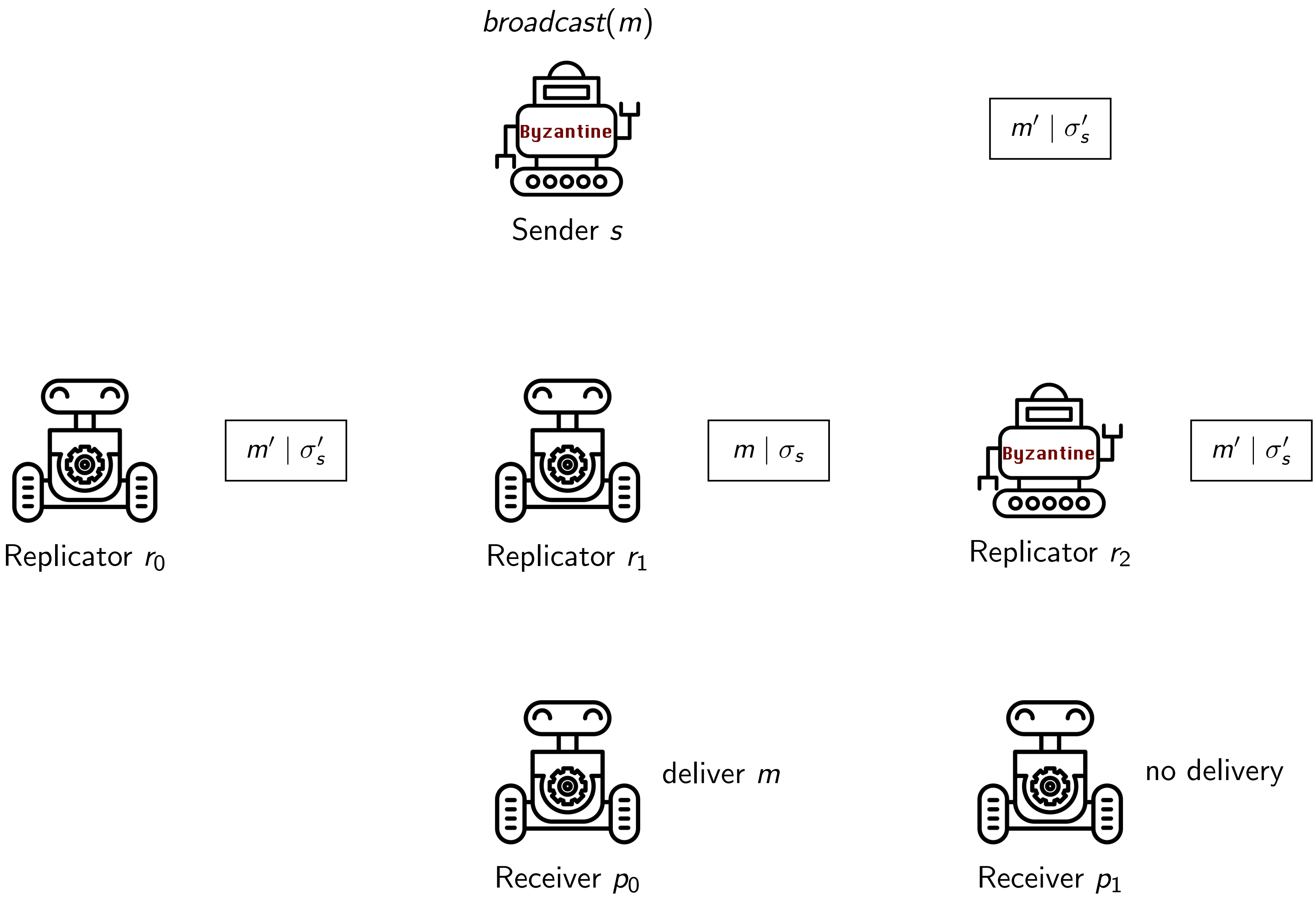


Reliable Broadcast

Algorithm details

Init - Echo - Ready mechanism

Reliable Broadcast

Algorithm details

Init - Echo - Ready mechanism

Uses Consistent Broadcast

Reliable Broadcast

Algorithm details

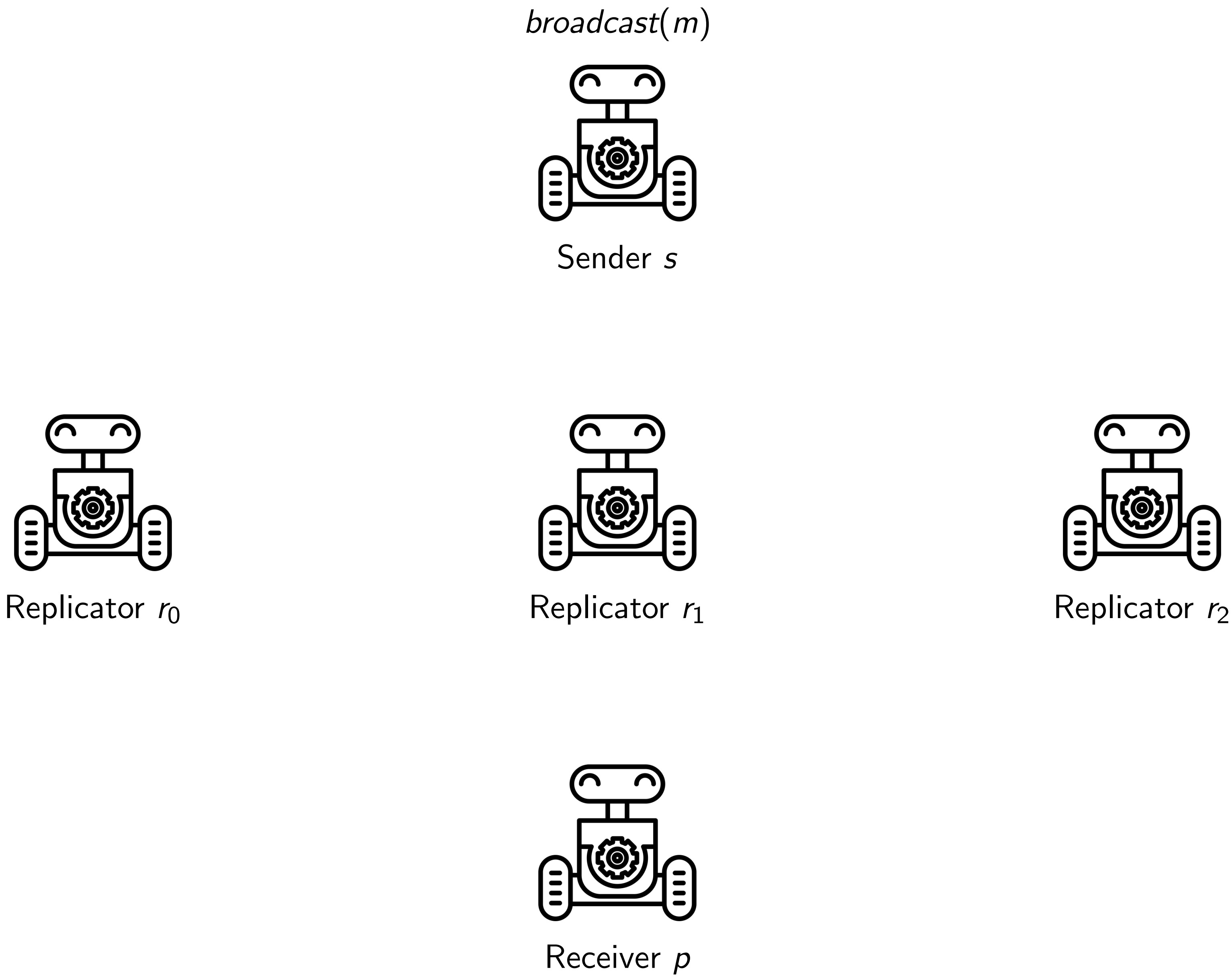
Init - Echo - Ready mechanism

Uses Consistent Broadcast

Similar delivery strategy to Consistent Broadcast: fast path, i.e., when there is unanimity and otherwise when $\exists\ n - f$ valid proof sets for m

Reliable Broadcast

Algorithm sketch, $f = 1$. Fast path



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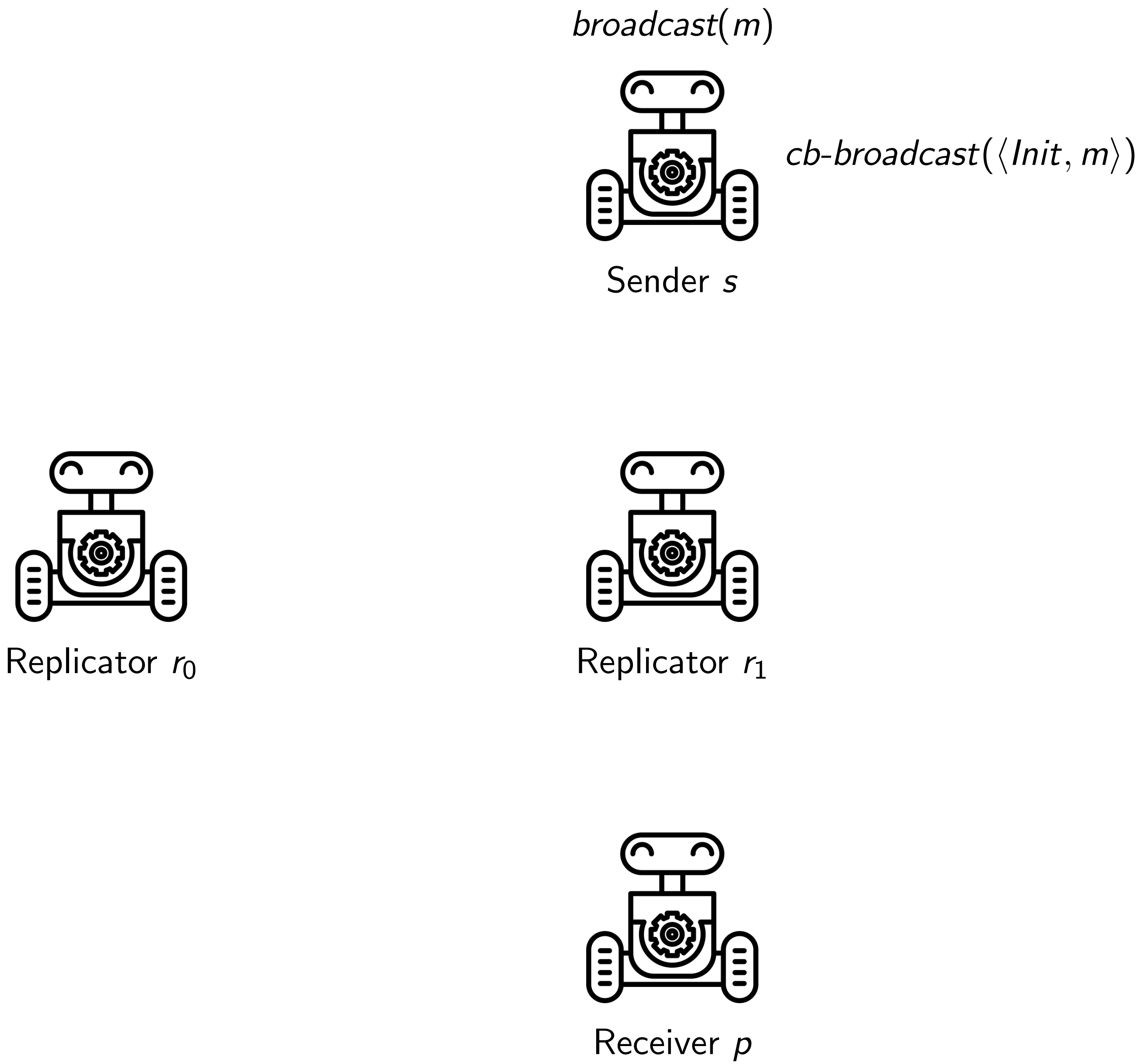

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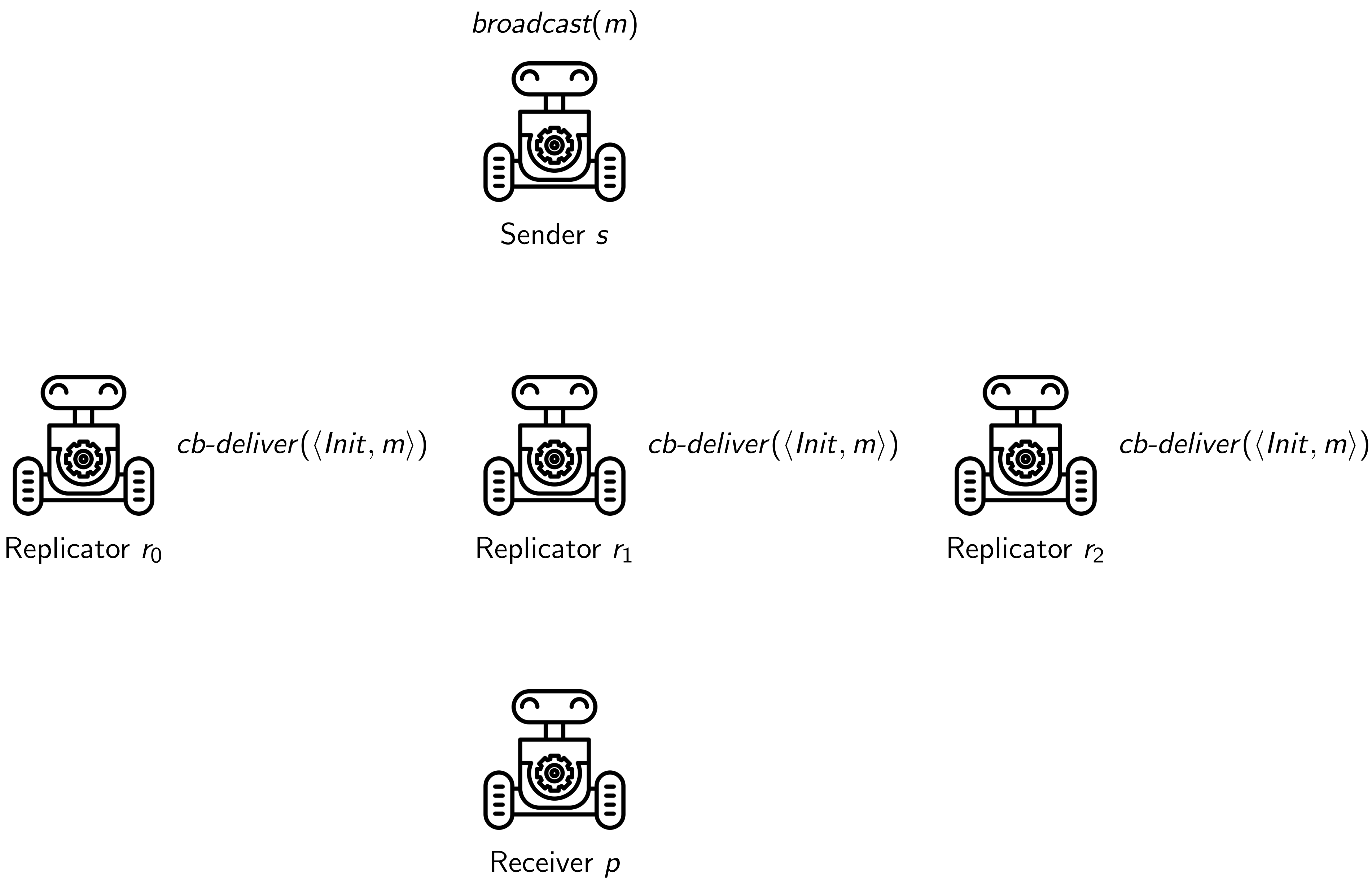

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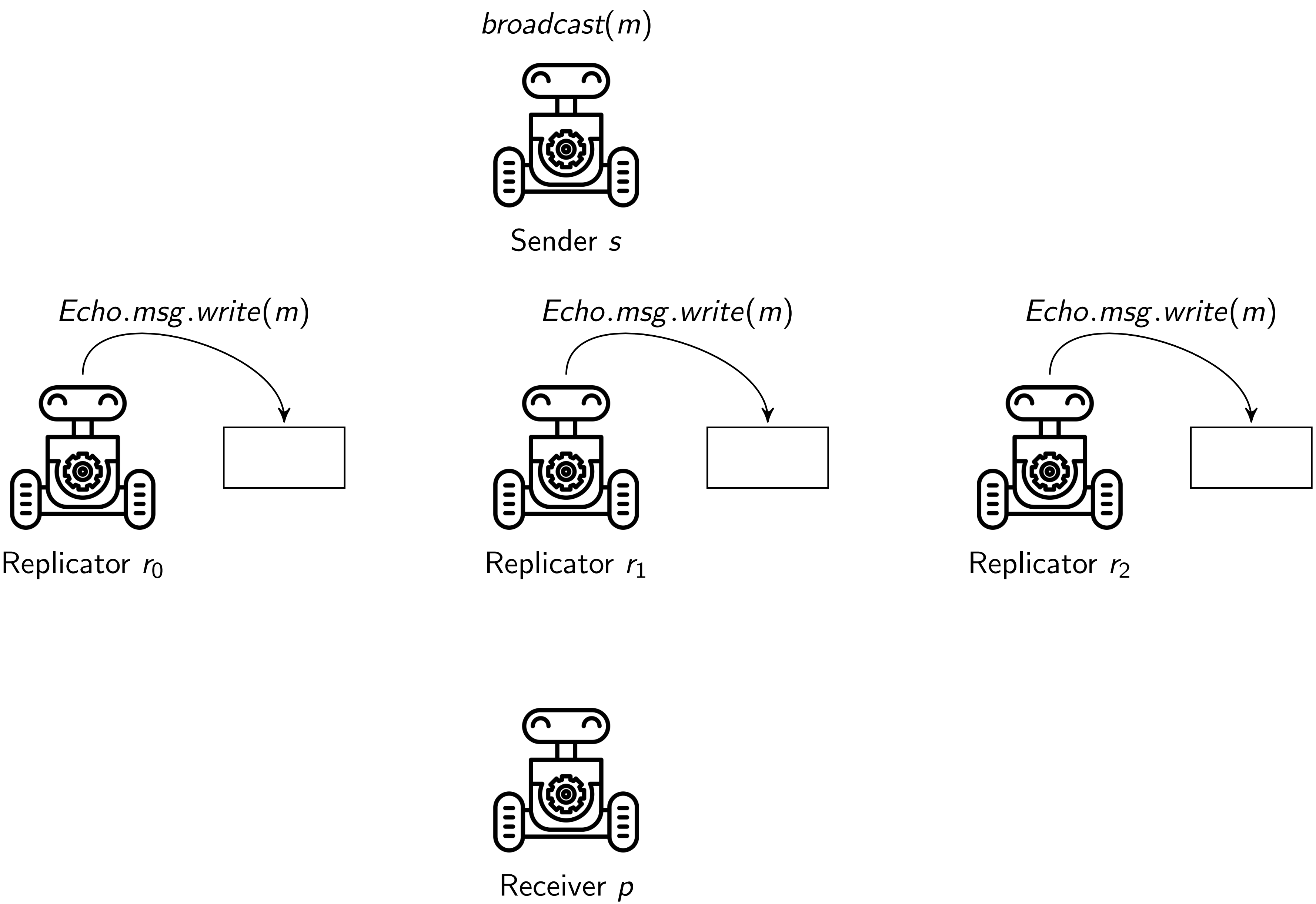

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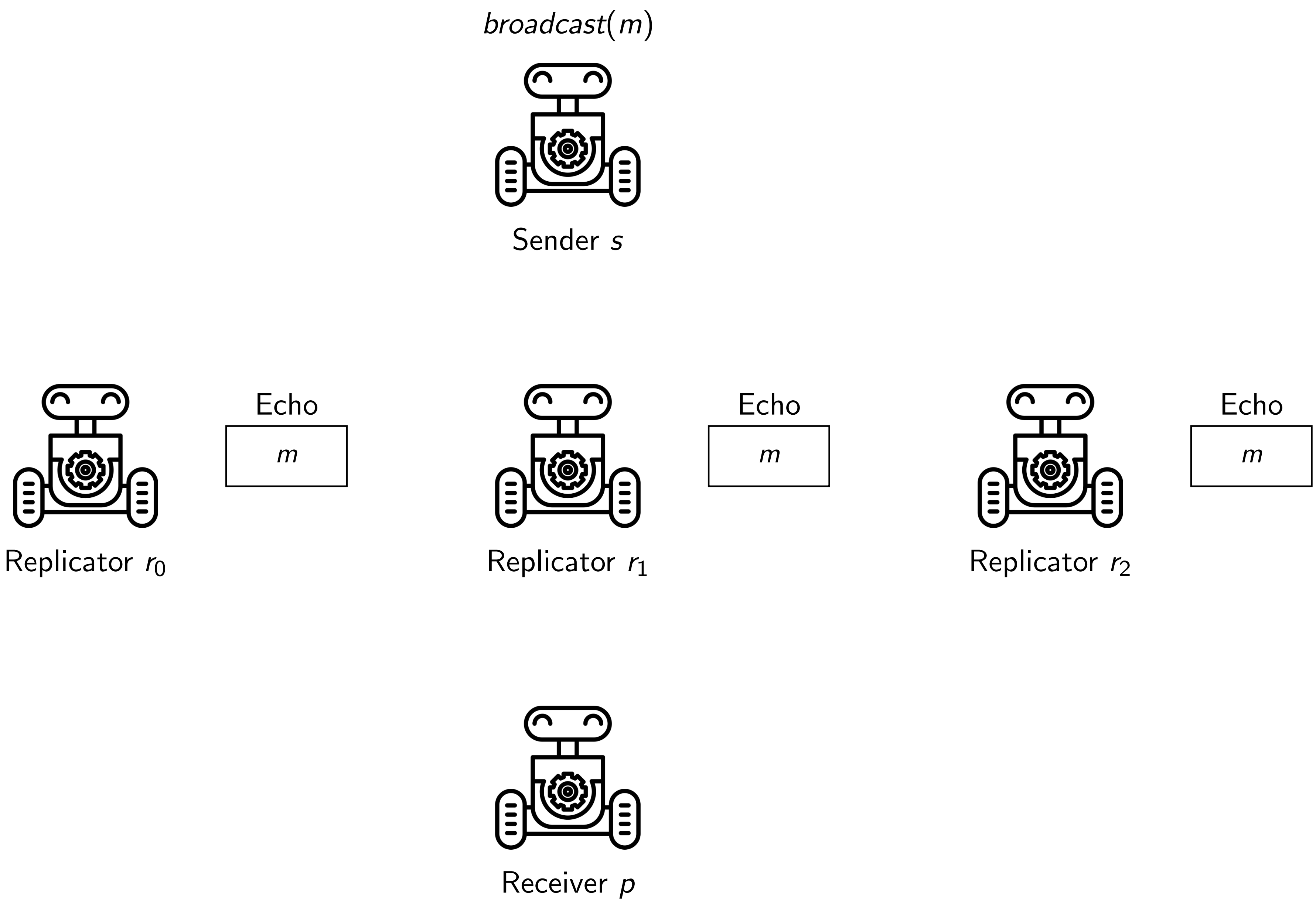

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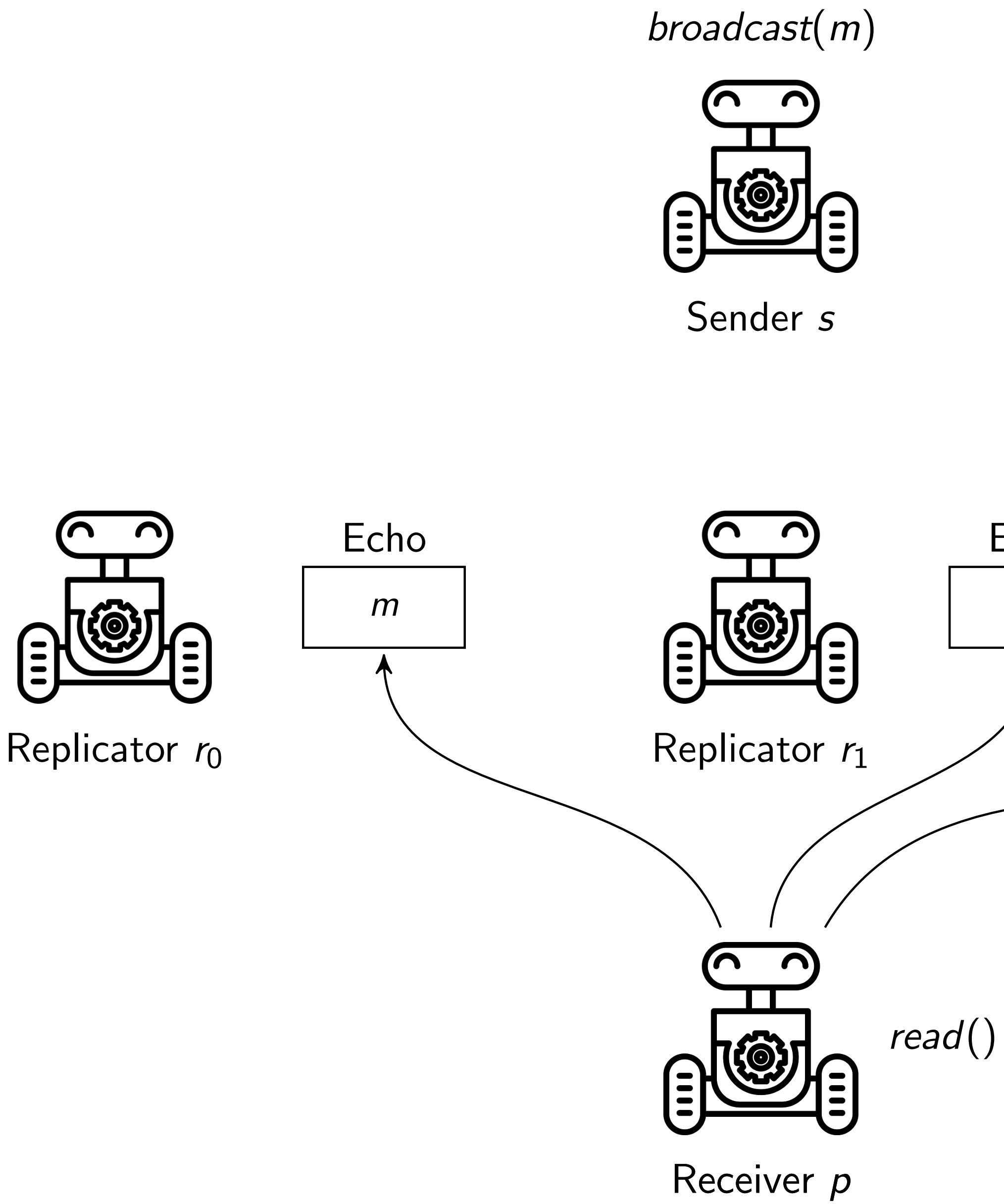

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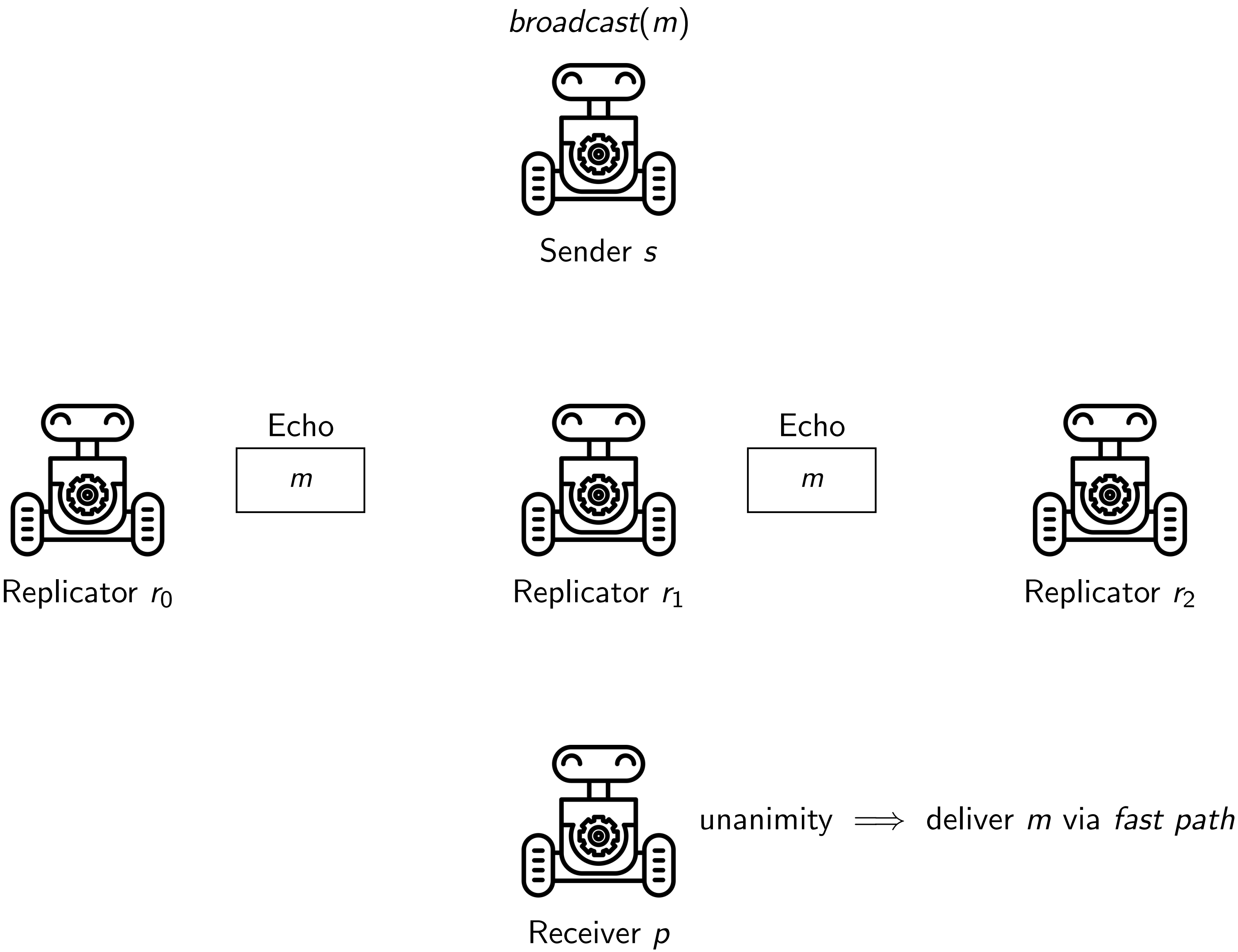
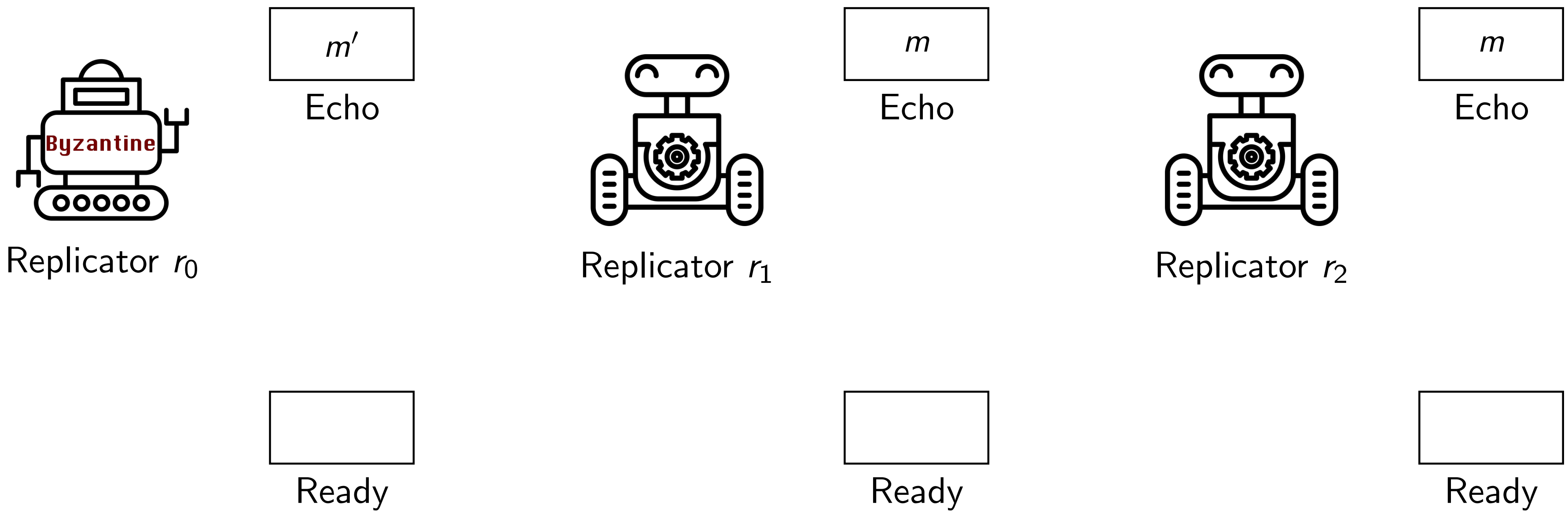


Reliable Broadcast

Algorithm sketch, $f = 1$. Construction of *ReadySet*



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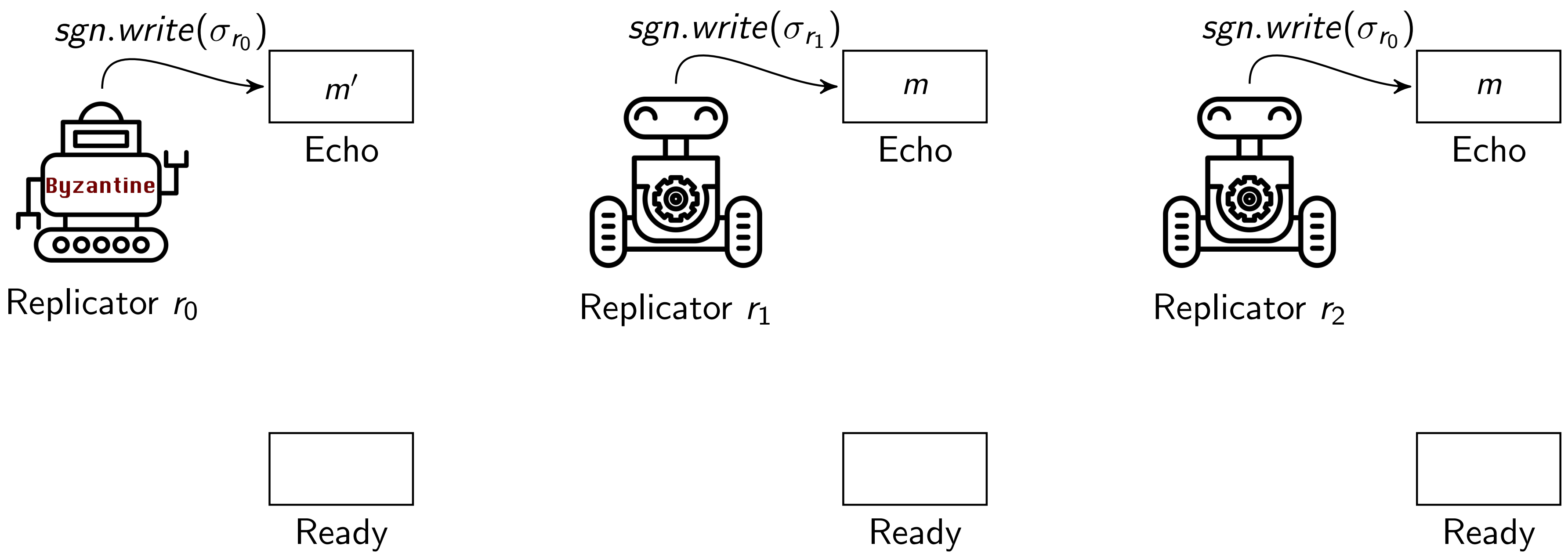

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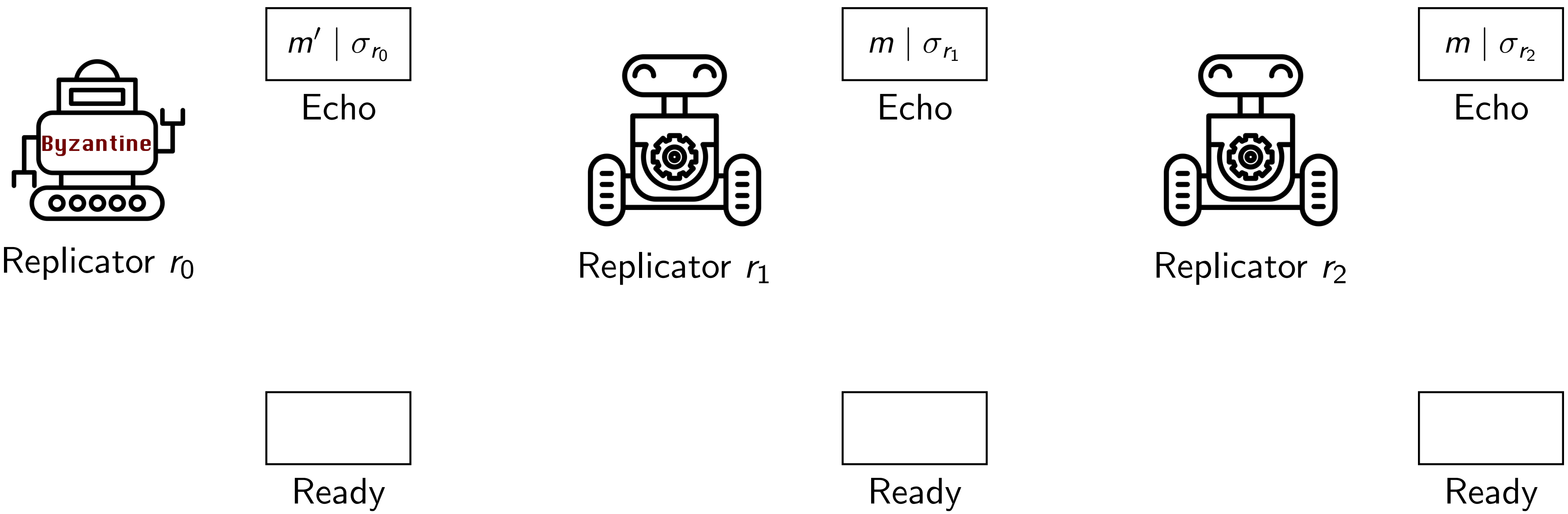

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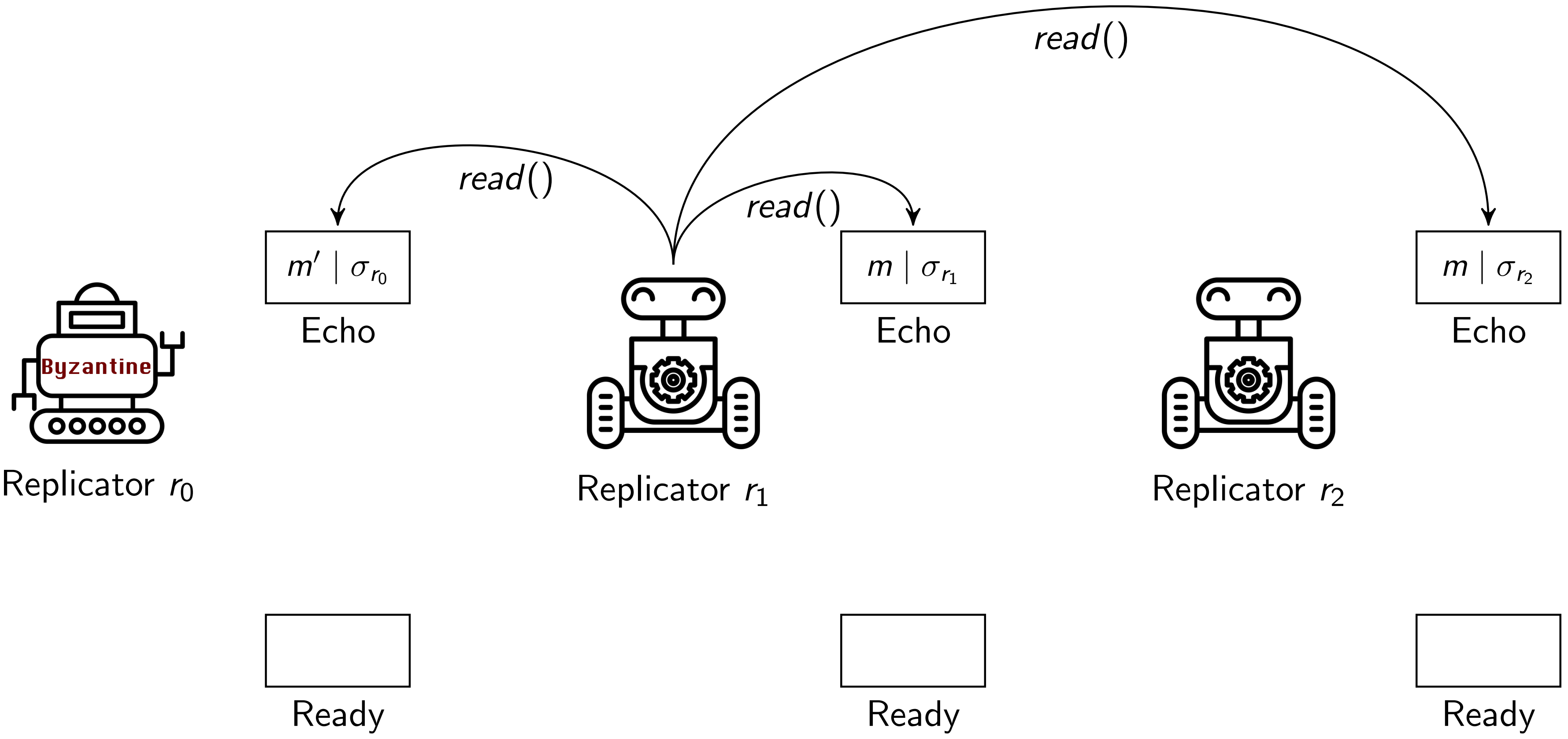

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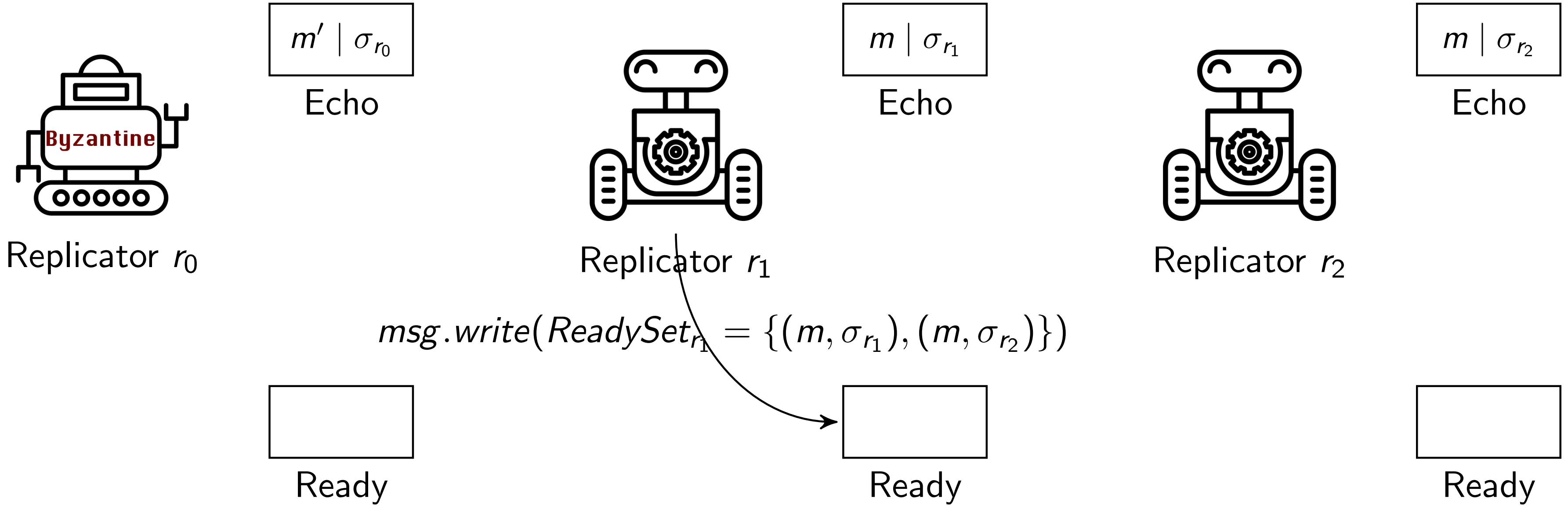

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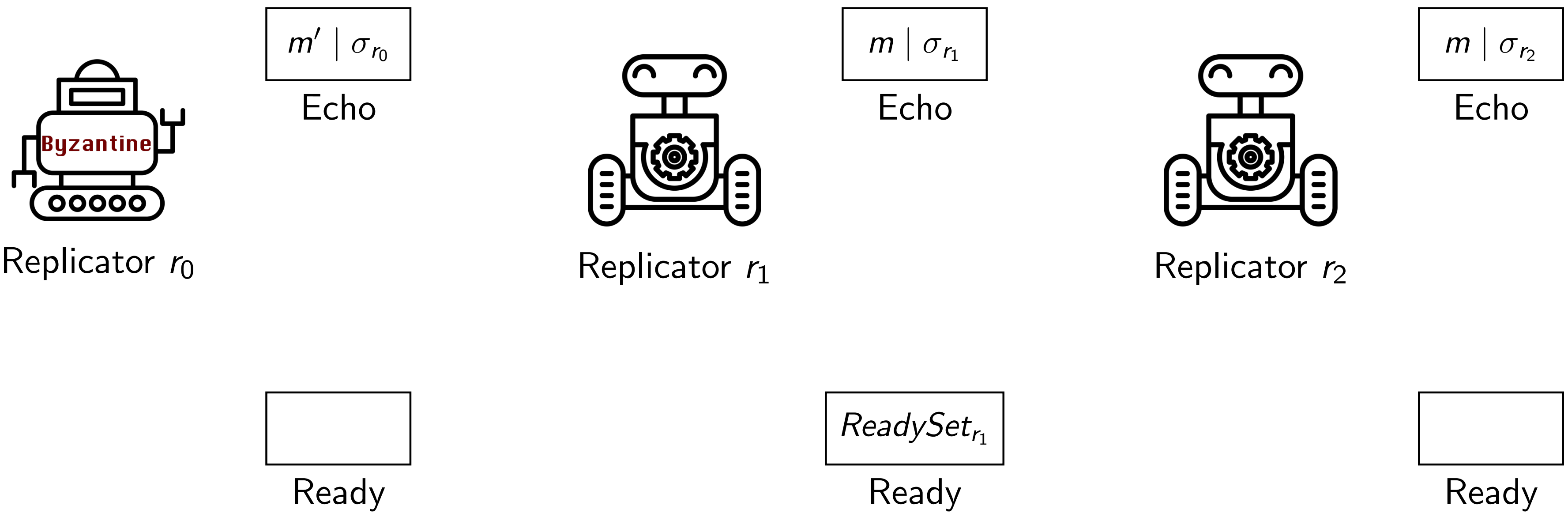
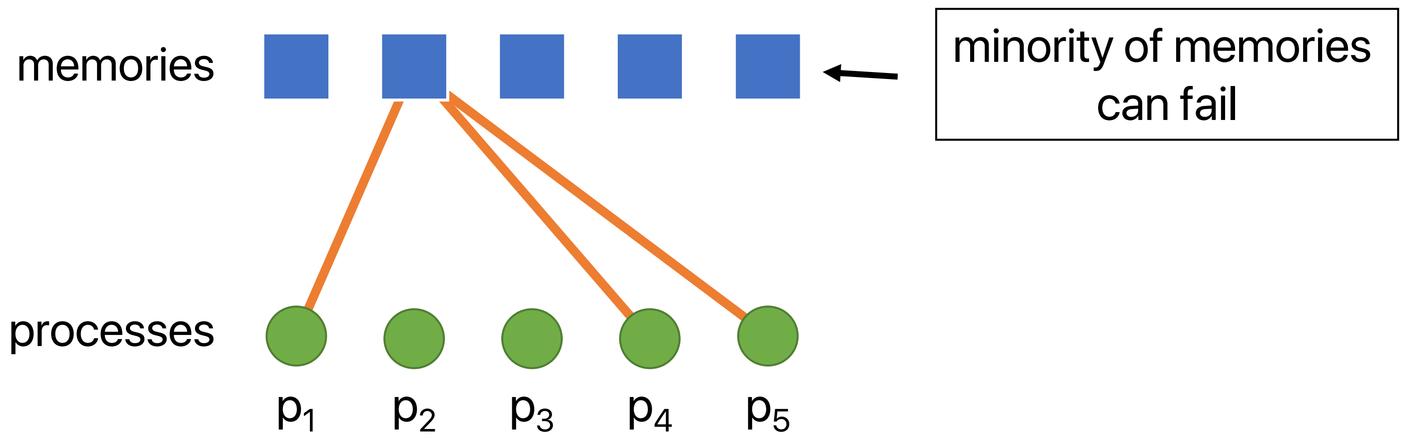


Outline

- Introduction
- 3 remarkable results with RDMA:
  - Consensus with crash faults
  - Broadcast with Byzantine faults
  - Fast memory replication

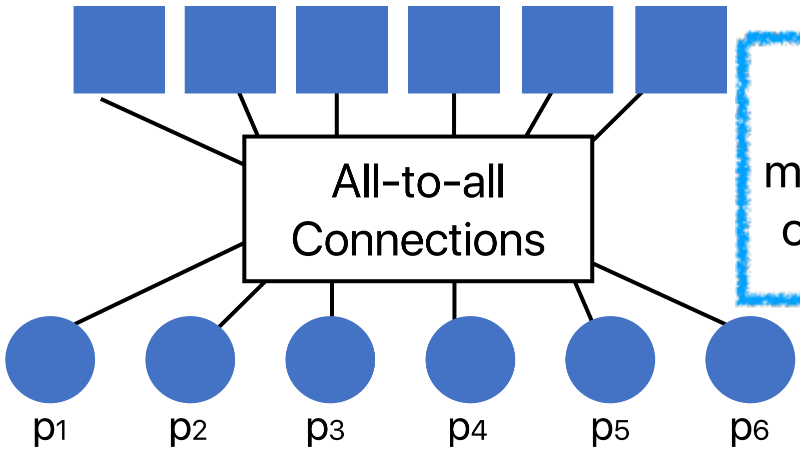
Recall: Disaggregated Memory



Handling Memory Failures

Replication: Treat all memories the same

Send all write/read requests to all memories, wait to hear acknowledgement from majority



Instead of many faulty memories, we can now think of one non-faulty memory!

Exercise Show that this implements a regular register, but not an atomic register!

Reliable MRMW Atomic Register

- We want to implement an atomic MRMW register on a set of unreliable (fault-prone) memories
- We want to minimize the number of round trips (RTTs) per operation.
- Proven: cannot be solved s.t. each operation always takes 1 RTT.
- But can it be done s.t. operations take 1 RTT most of the time?
- To simplify the problem, we assume each memory has plenty of **max registers.**

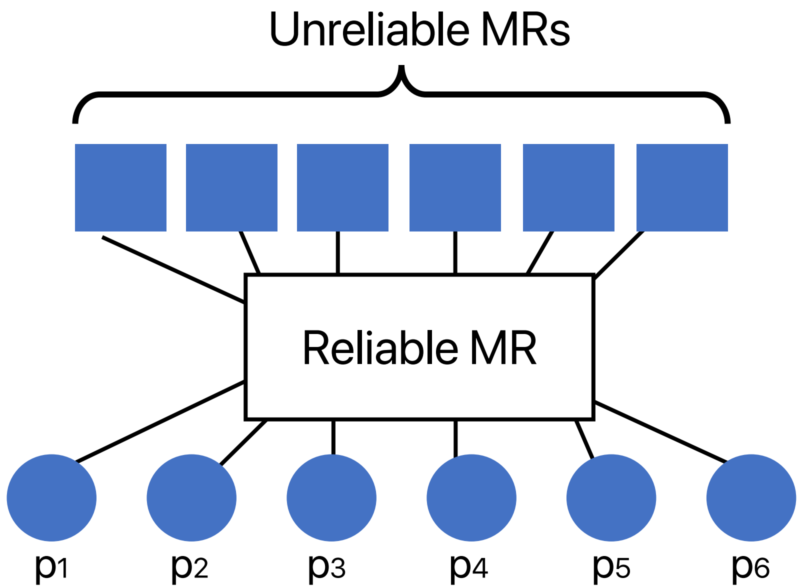
Max Registers

- Two operations: read and write
- Intuitively: read returns highest value written so far
- Formally:
  - **Validity**: If read R returns v, then either (a) $v = \bot$, or (b) some operation write(v) was invoked before R returns.
  - **Read-read monotonicity**: If a read returns value y and a preceding read returns value x, then $x \leq y$.
  - **Write-read monotonicity**: If a read returns value y and a preceding write writes value x, then $x \leq y$.
  - **Liveness (wait-freedom):** Every invoked operation eventually returns.

Exercise

Step 1: Reliable Max Register

- Implement a reliable max register from a set of unreliable max registers
- Writes should complete in 0-1 RTTs, reads should complete in 1-2 RTTs.
- Common case: both operations should take 1 RTT.
- Hint: use caching.



Step 2: Atomic MRMW Register

Classic Algorithm

M = Reliable max register. Each value is a tuple (timestamp, id, value). Lexicographic ordering.

```
def WRITE(v): // this block is not atomic
  fresh_ts = (M.READ().ts.i + 1, tid)
  M.WRITE((fresh_ts, v))

def READ():
  return M.READ().v
```

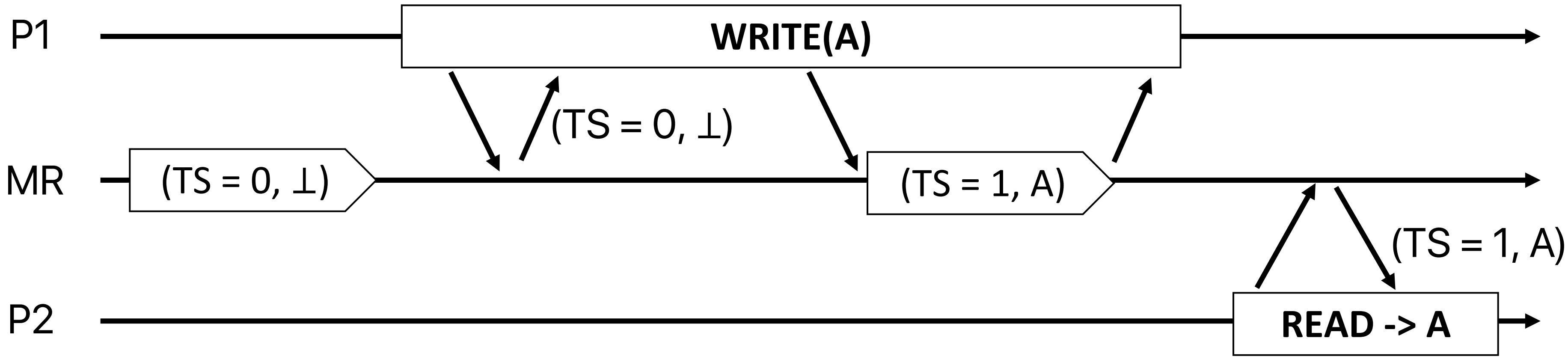
2 RTTs

1 RTT

Why 2 RTTs for WRITE? Can we do better?

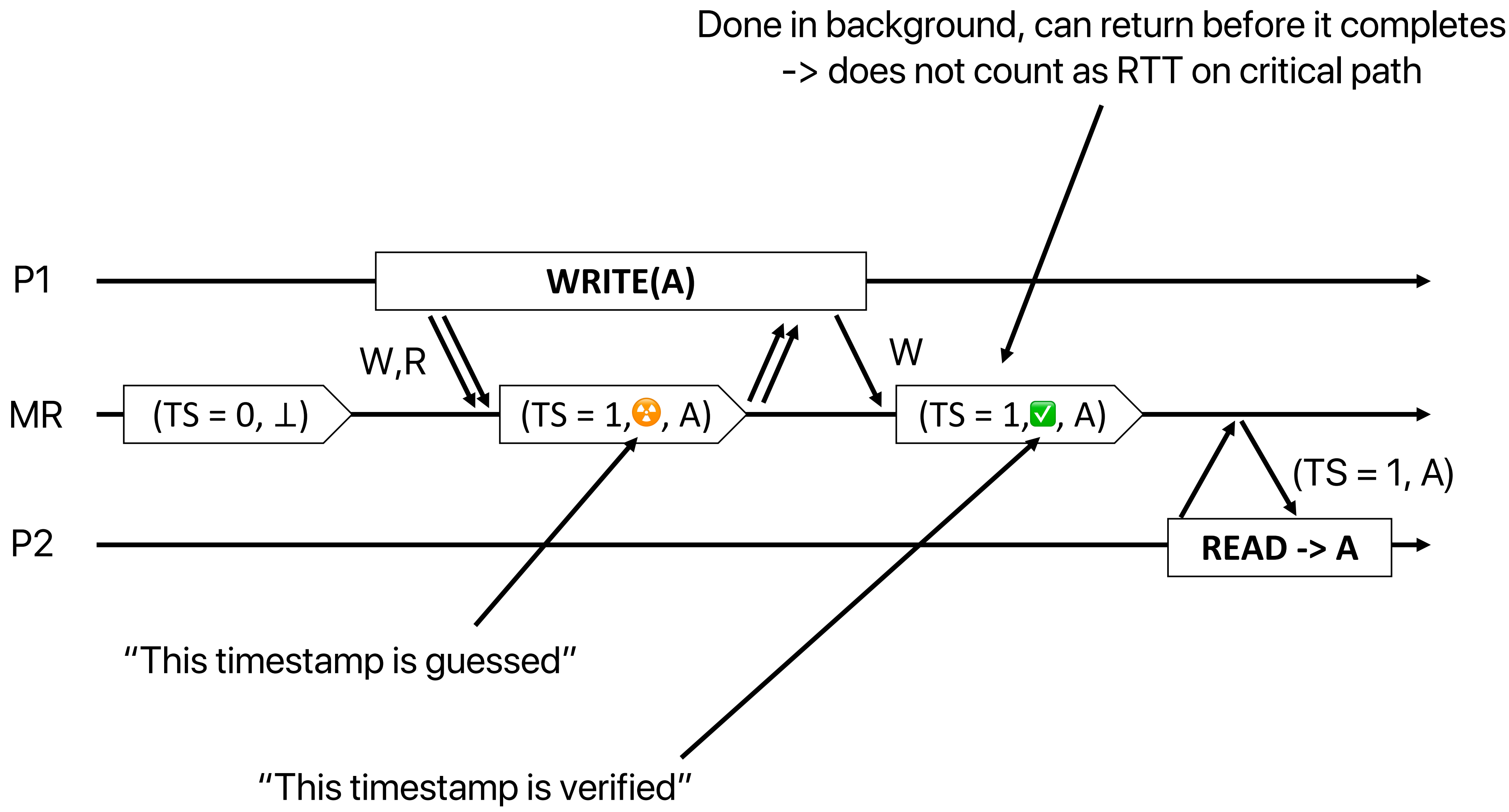
Example

- Each write needs to use a fresh timestamp, i.e., higher than all preceding (why?)
- Finding a fresh timestamp takes 1 RTT.



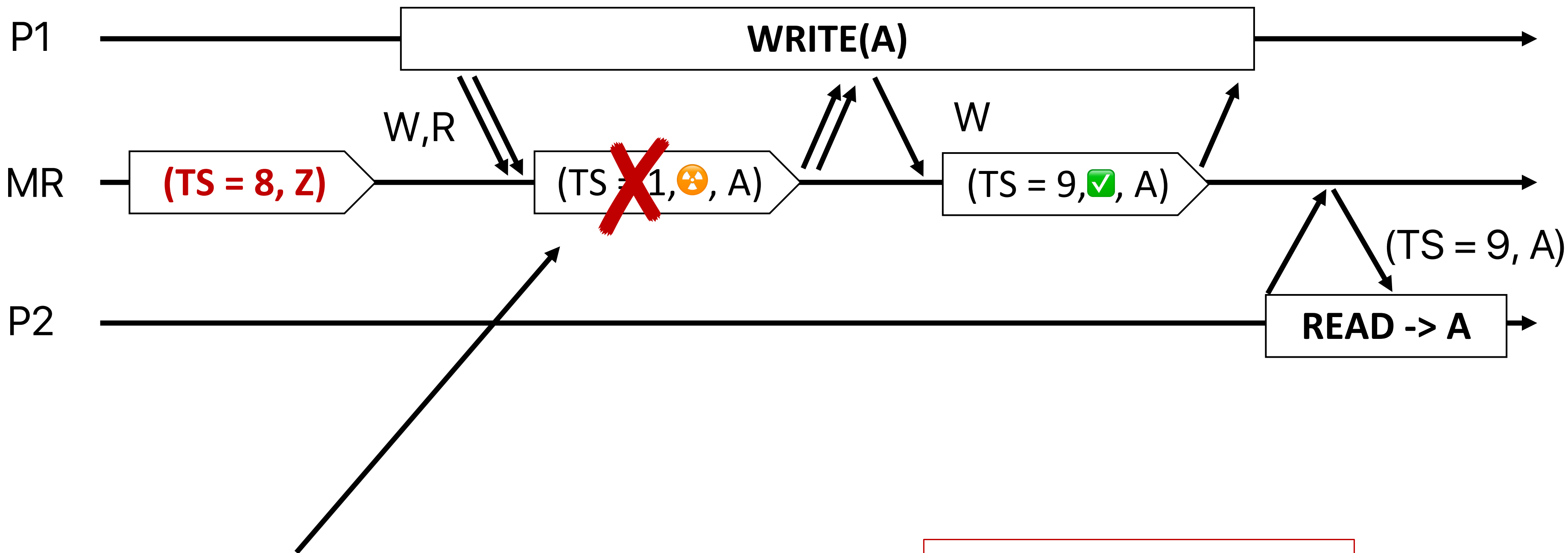
2nd WRITE RTT is unavoidable.
1st WRITE RTT: Could we guess the timestamp?

Guessing Timestamps



Guessing Timestamps

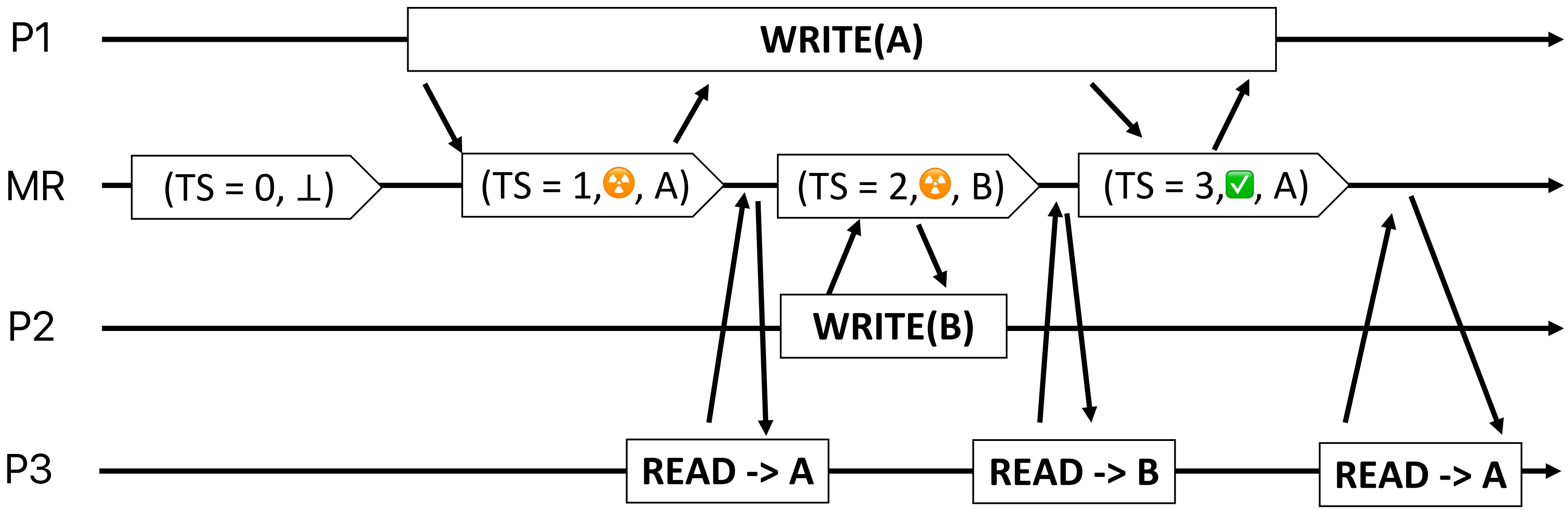
What if guessed timestamp is wrong?



P1 attempts to write this but fails

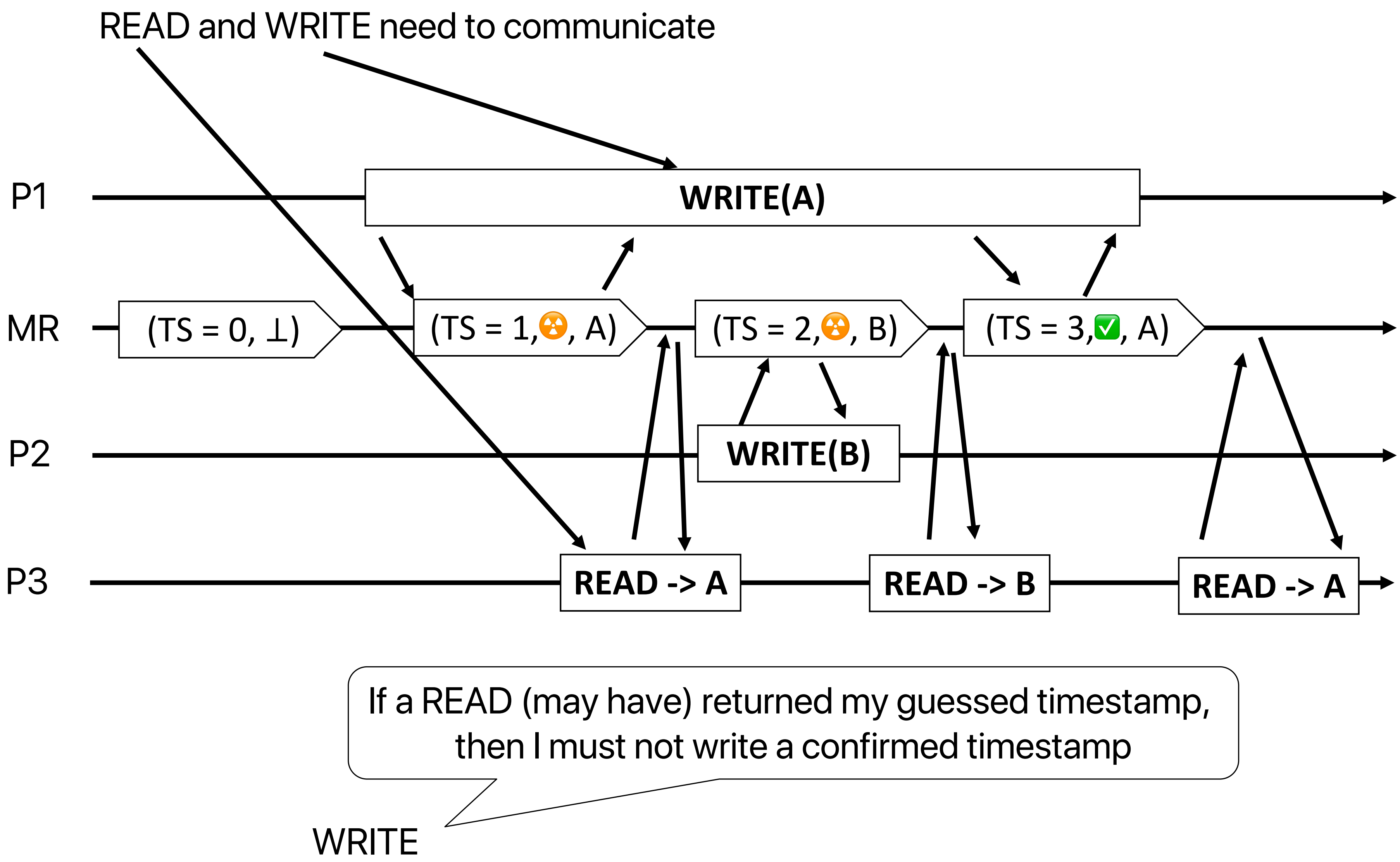
This is not (yet) correct!

Guessing Timestamps



Not atomic/linearizable ☹

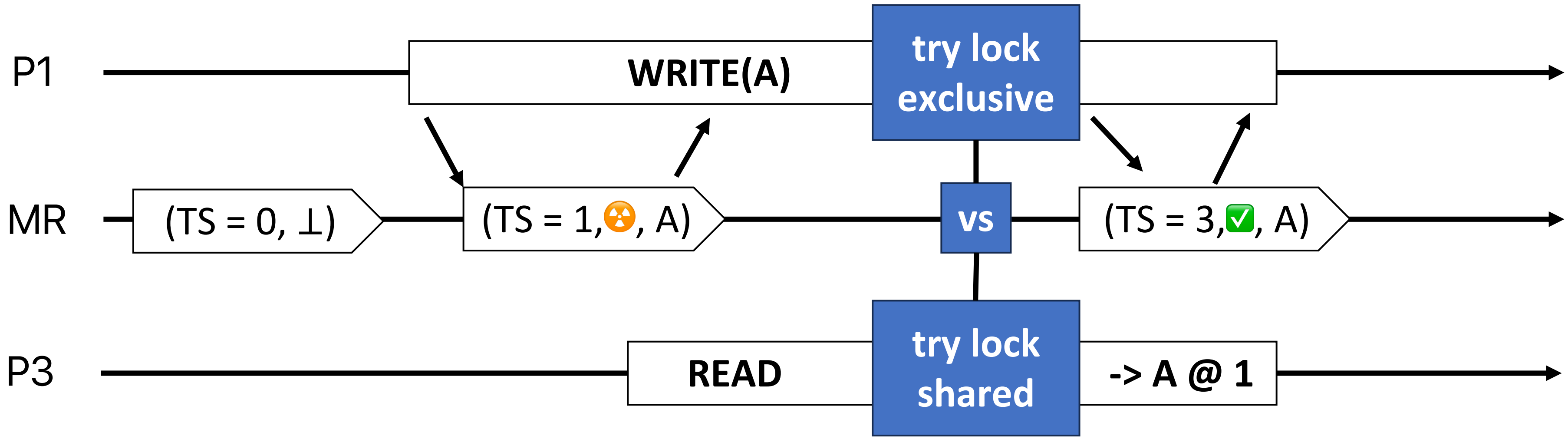
Solution:


READ and WRITE need to communicate
P1
WRITE(A)
MR
(TS = 0, ⊥)
(TS = 1,☢, A)
(TS = 2,☢, B)
(TS = 3,✅, A)
P2
WRITE(B)
P3
READ -> A
READ -> B
READ -> A
If a READ (may have) returned my guessed timestamp,
then I must not write a confirmed timestamp
WRITE

Solution

If a READ (may have) returned my guessed timestamp, then I must not write a confirmed timestamp

WRITE



Putting It All Together

Write algorithm

```
M = ((0, ⊥), VERIFIED, ⊥) // Max Register
TSL[tid] = {} // Timestamp Lock

def WRITE(v):
  w = (guessTs(), GUESSED, v)
  in parallel {m = M.READ(), M.WRITE(w)}
  if m <= w: // Fast path (fresh timestamp)
    in bg: M.WRITE(w with VERIFIED) // Spdup reads
  else: // Slow path (potentially stale timestamp)
    if TSL[tid].TRYLOCK(w.ts, WRITE):
      M.WRITE(((m.ts.i+1, tid), VERIFIED, v))
```

guess a timestamp
write guessed ts + read current ts
if guessed ts is fresh:
write verified ts in bg
if guessed ts is stale:
try to take exclusive lock
if successful, write fresh ts

Common case: 1 RTT!

Putting It All Together

Read algorithm

```
def READ():
  seen: dict<ThreadId, MValue> = {}
  while True:
    m = M.READ()
    if m is VERIFIED: return m.v // Fast path
    if m in seen.values: // Fresh timestamp
      if TSL[m.ts.tid].TRYLOCK(m.ts, READ):
        in bg: M.WRITE(m with VERIFIED) // Spdup rds
        return m.v
    elif m.ts.tid in seen.keys: // Wait-free path
      return seen[m.ts.tid].v
    seen[m.ts.tid] = m
```

read from MR
if ts is verified, return it

try to take shared lock
if successful, help reads & return

Common case: 1 RTT!

Putting It All Together

Read algorithm

```
def READ():
 seen: dict<ThreadId, MValue> = {}
 while True:
  m = M.READ()
  if m is VERIFIED: return m.v // Fast path
  if m in seen.values: // Fresh timestamp
   if TSL[m.ts.tid].TRYLOCK(m.ts, READ):
    in bg: M.WRITE(m with VERIFIED) // Spdup rds
    return m.v
  elif m.ts.tid in seen.keys: // Wait-free path
   return seen[m.ts.tid].v
  seen[m.ts.tid] = m
```

What about all this other stuff?

It's for wait-freedom. Check out the paper for the full explanation:

"SWARM: Replicating Shared Disaggregated-Memory Data in No Time"

Further Reading

1. ABGMZ. *The Impact of RDMA on Agreement*. PODC 2019.
2. ABGMXZ. *Microsecond Consensus for Microsecond Applications*. OSDI 2020.
3. ABGPXZ. *Frugal Byzantine Computing*. DISC 2021.
4. ABGMXZ. *uBFT: Microsecond-Scale BFT using Disaggregated Memory*. ASPLOS 2023.
5. MBXZAG. *SWARM: Replicating Shared Disaggregated-Memory Data in No Time*. SOSP 2024