# Advanced Topics: Distributed Systems and NFS

**Questions answered in this lecture:**

What is **challenging** about distributed systems?

How can a **reliable messaging protocol** be built on unreliable layers?

What is **RPC**?

What is the **NFS stateless protocol**?

What are **idempotent** operations and why are they useful?

What state is tracked on NFS clients?

# File-System Case Studies

Local

- **FFS**: Fast File System
- **LFS**: Log-Structured File System

Network

- **Intro**: communication basics [today]
- **NFS**: Network File System
- **AFS**: Andrew File System

# Review

# Atomicity

Say we want to do several things.

Atomicity means we don’t get interrupted when partially done (or at least that we can make it appear that way to the user).

**Concurrency**: we’re worried about other threads
**Persistence**: we’re worried about crashes

# Atomic Update

Say we want to update a file foo.txt. If we crash, we want one of the following:

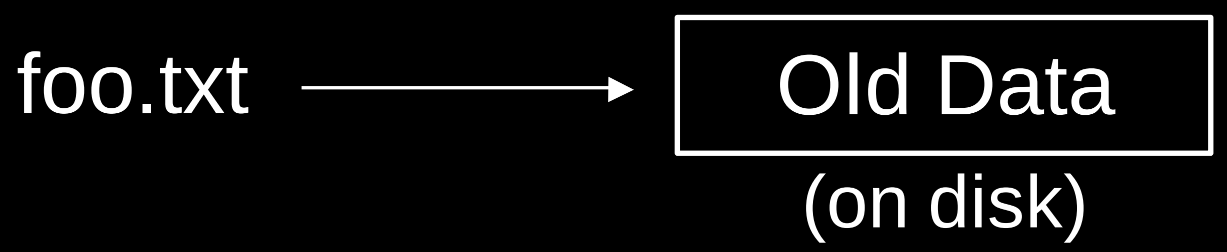
- all old data
- all new data

**Strategy**: write new data to foo.tmp, and only after that's complete, replace foo.txt by switching names.

# Bad Protocol

copy foo.txt to foo.tmp (with changes)
rename foo.tmp to foo.txt

# Bad Protocol



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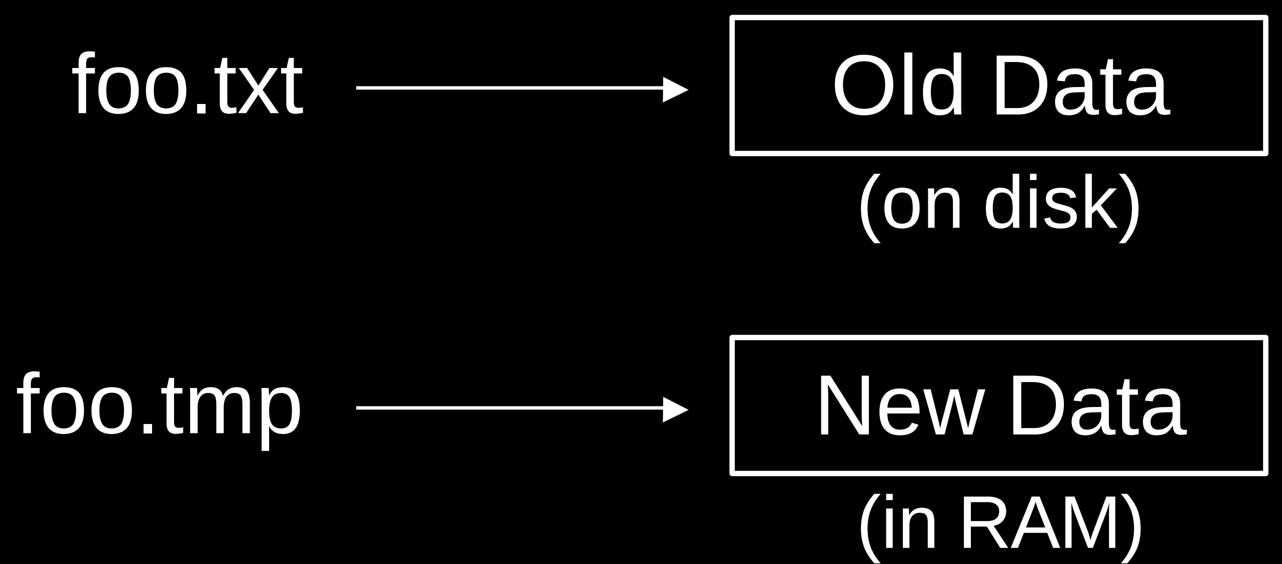

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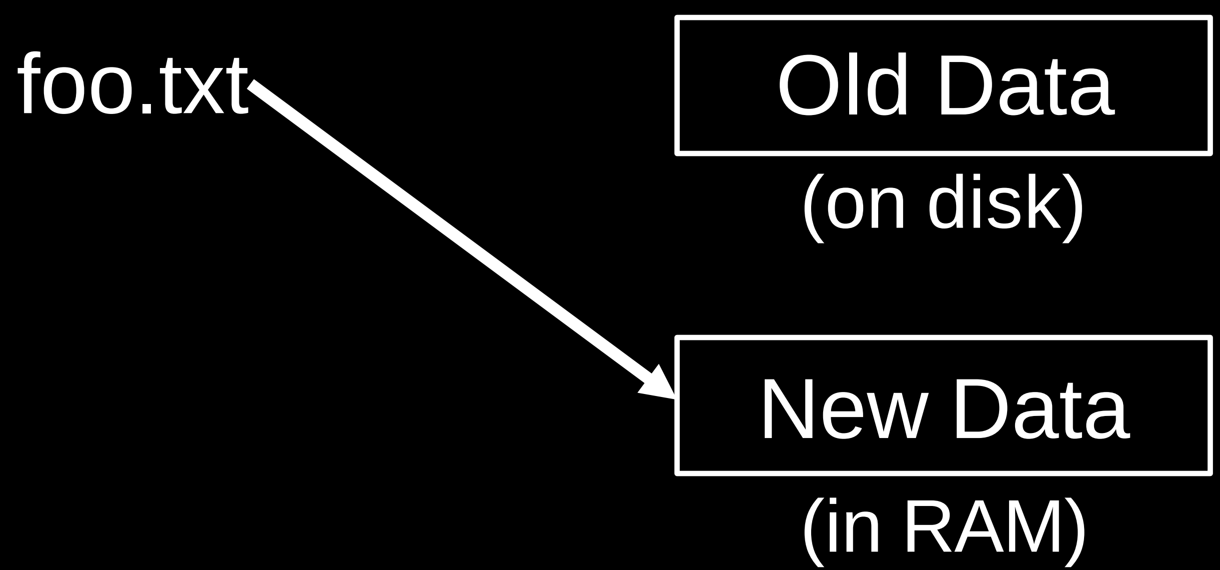

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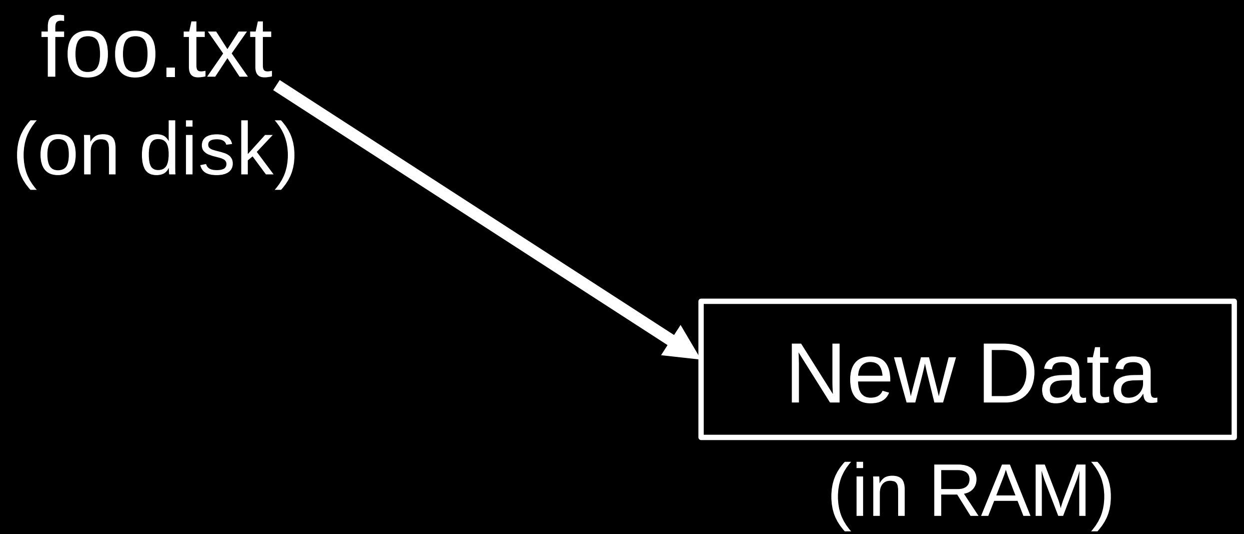

# Good Protocol

copy foo.txt to foo.tmp (with changes)

fsync foo.tmp

rename foo.tmp to foo.txt

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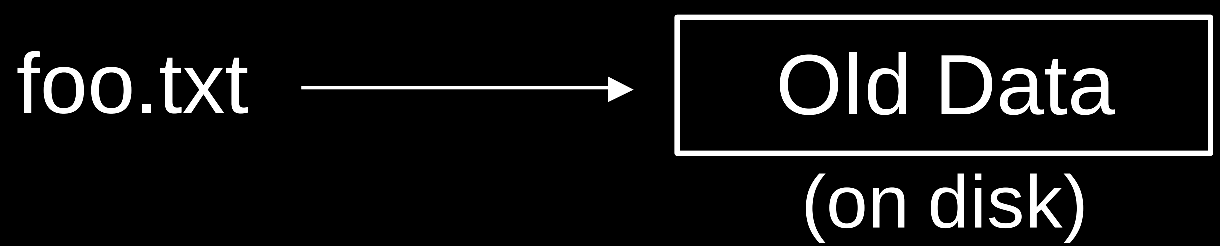

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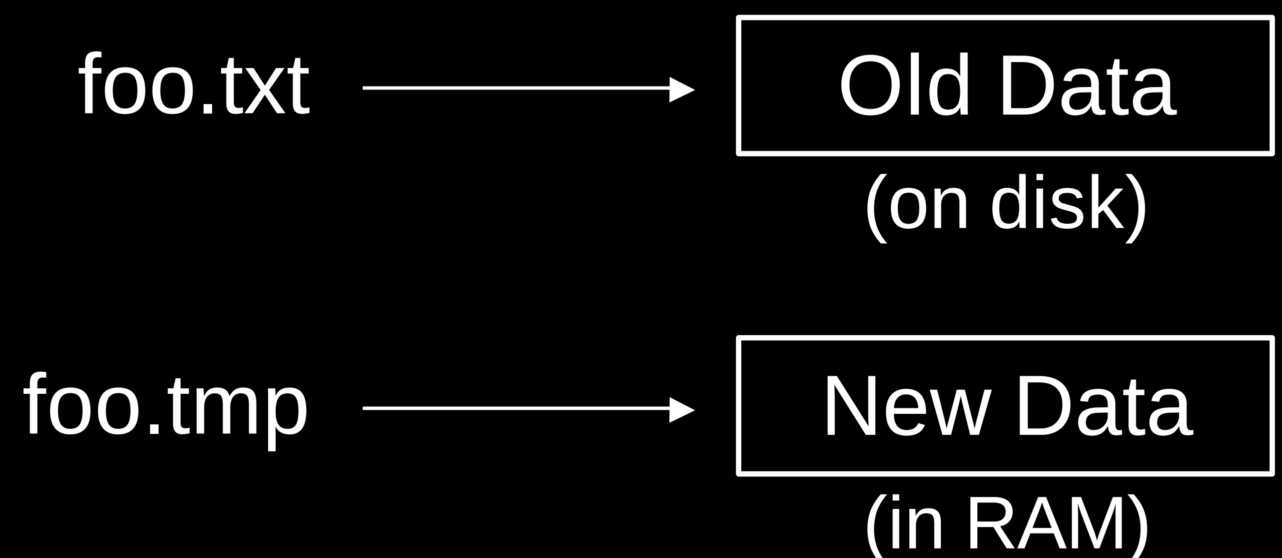
copy foo.txt to foo.tmp (with changes)



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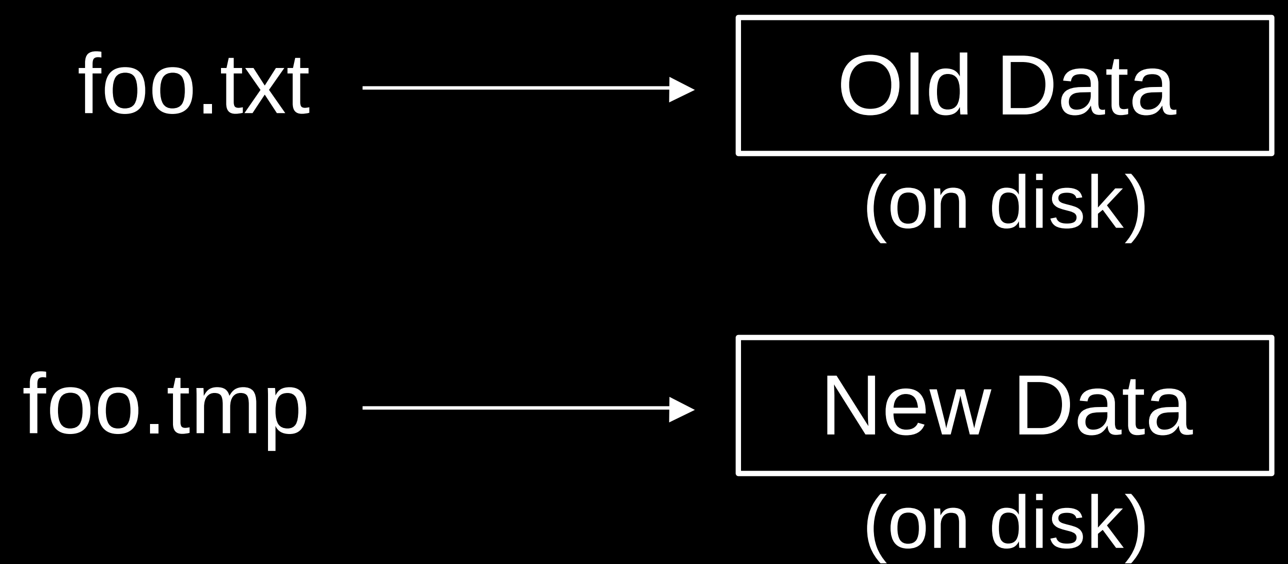

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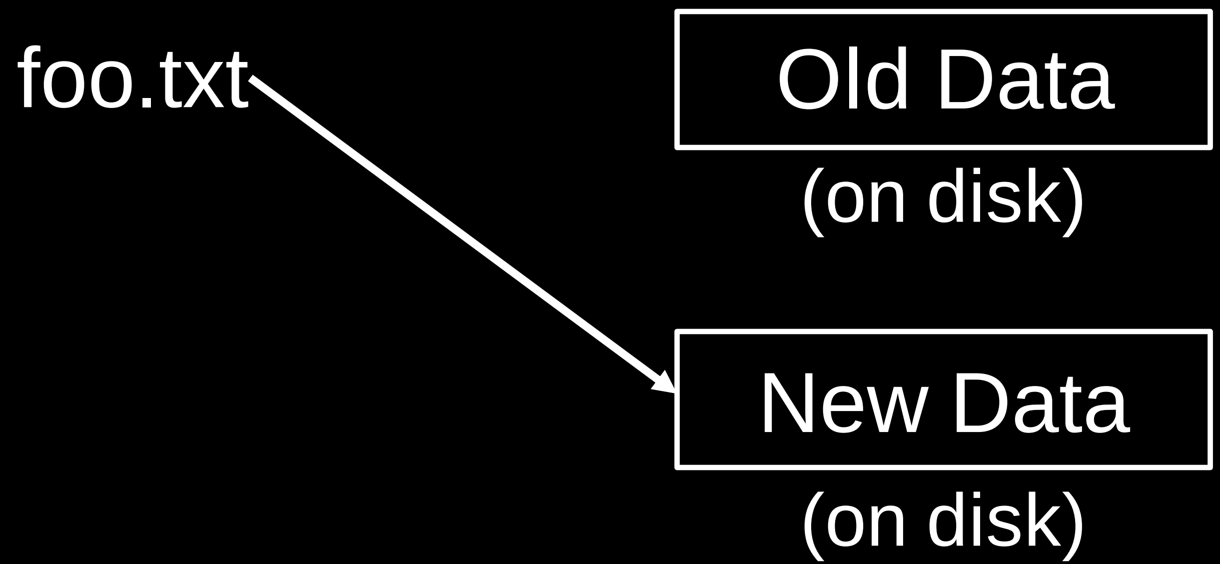

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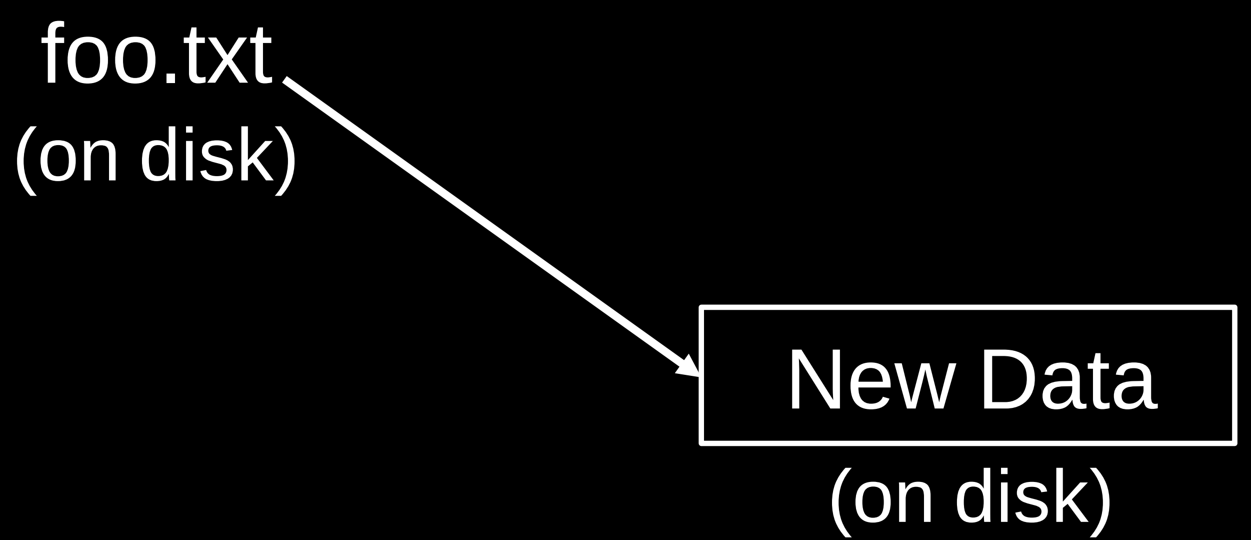


# Local FS Comparison

FFS+Journal:
- must write data twice (writes expensive)
- can put data exactly where we like (reads cheaper)

LFS:
- all writes sequential (writes cheaper)
- reads may be very random (reads expensive)

# Local FS Comparison

In what ways is FFS more complex?

In what ways is LFS more complex?

Compare group descriptor to segment summary.

LFS: why don’t we need to update root inode upon updating any file?

# Distributed Systems

# What is a Distributed System?

*A distributed system is one where a machine I've n ever heard of can cause my program to fail.*
— *Leslie Lamport*

Definition:
More than 1 machine working together to solve a problem

Examples:
- client/server: web server and web client
- cluster: page rank computation

Other courses:
- Networking
- Distributed Systems

# Why Go Distributed?

More computing power

More storage capacity

Fault tolerance

Data sharing

# New Challenges

**System failure**: need to worry about partial failure

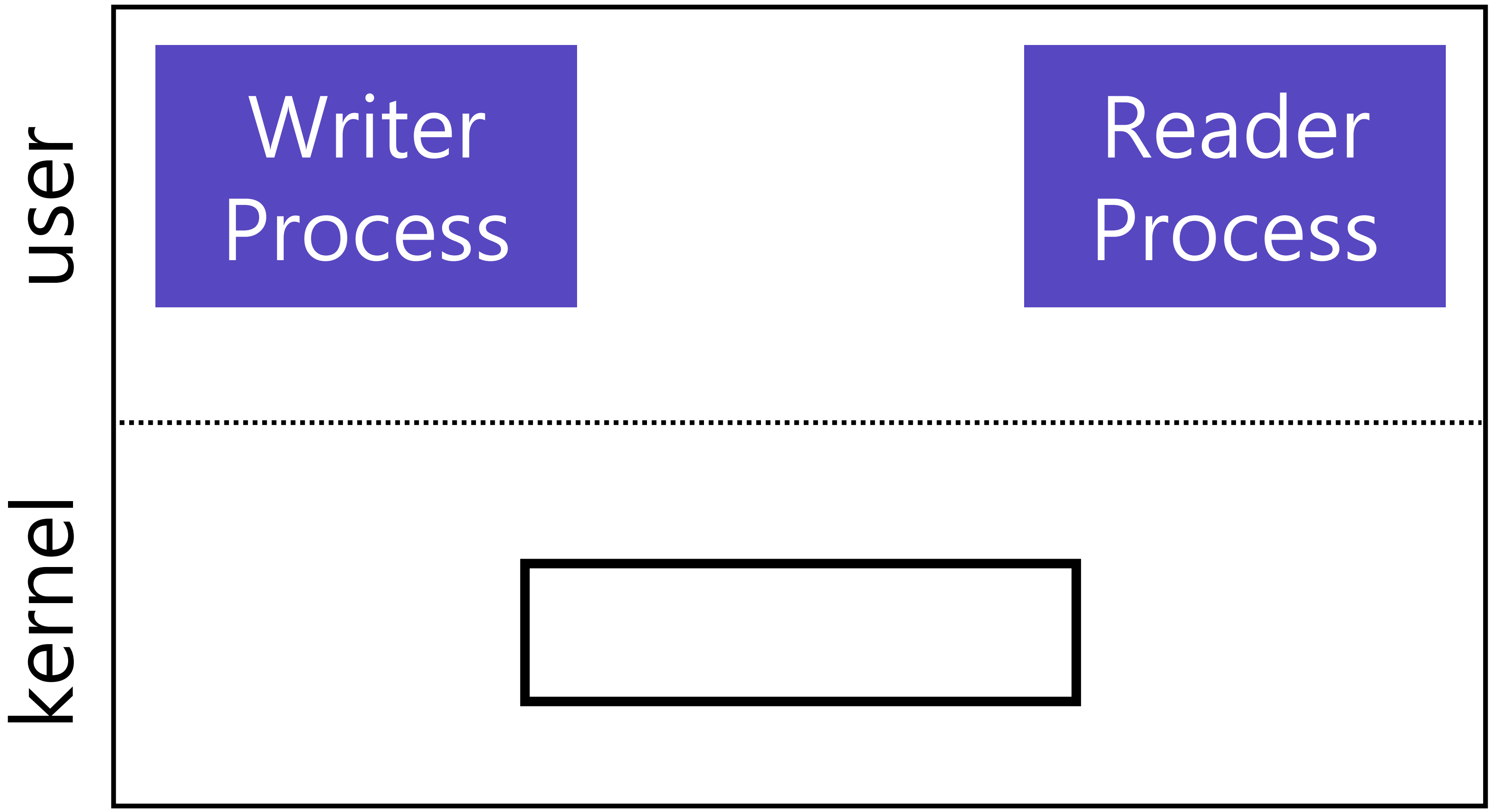
**Communication failure**: links unreliable

- bit errors
- packet loss
- node/link failure

Motivation example:

Why are network sockets less reliable than pipes?

# Pipe



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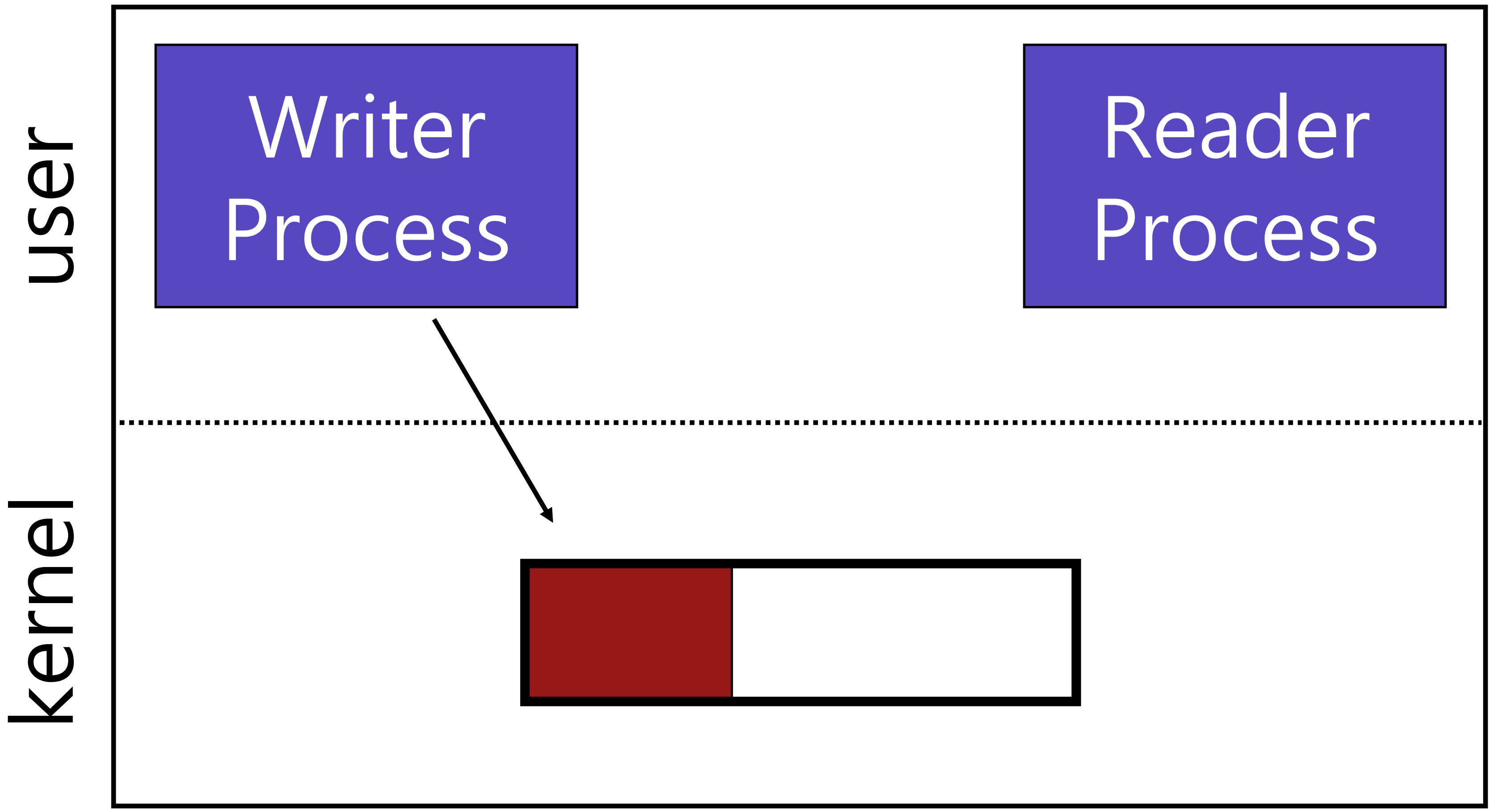

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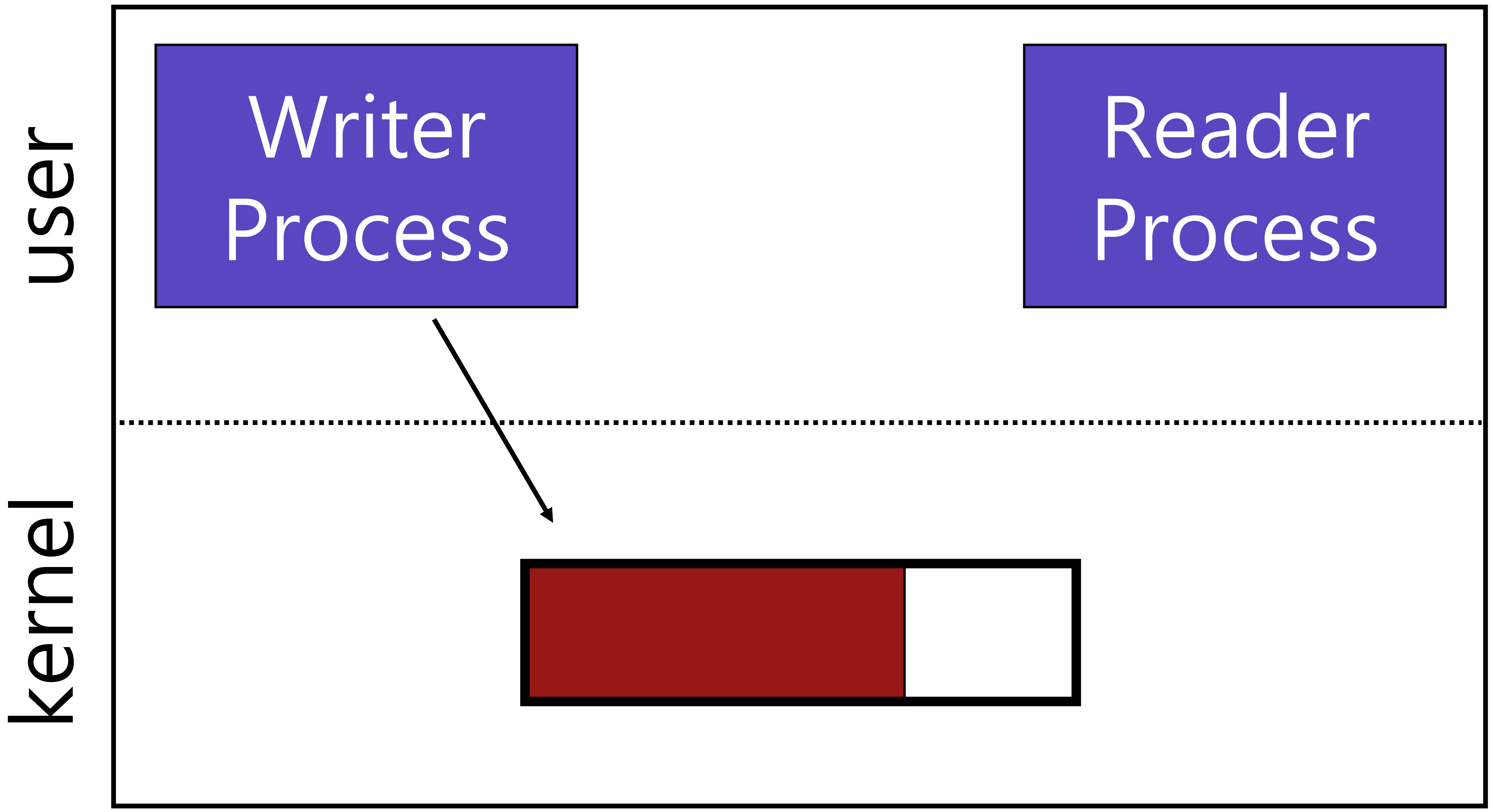

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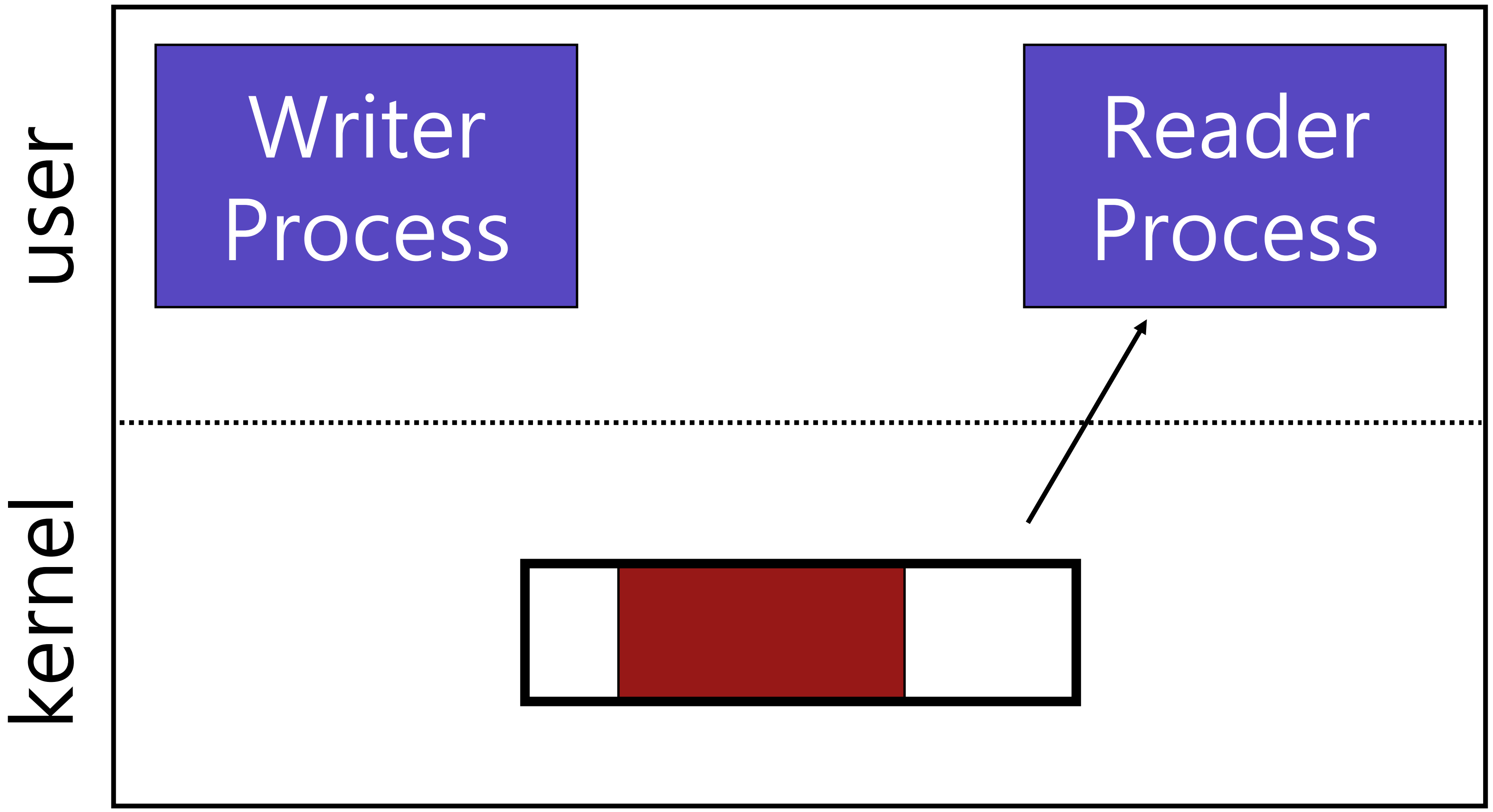

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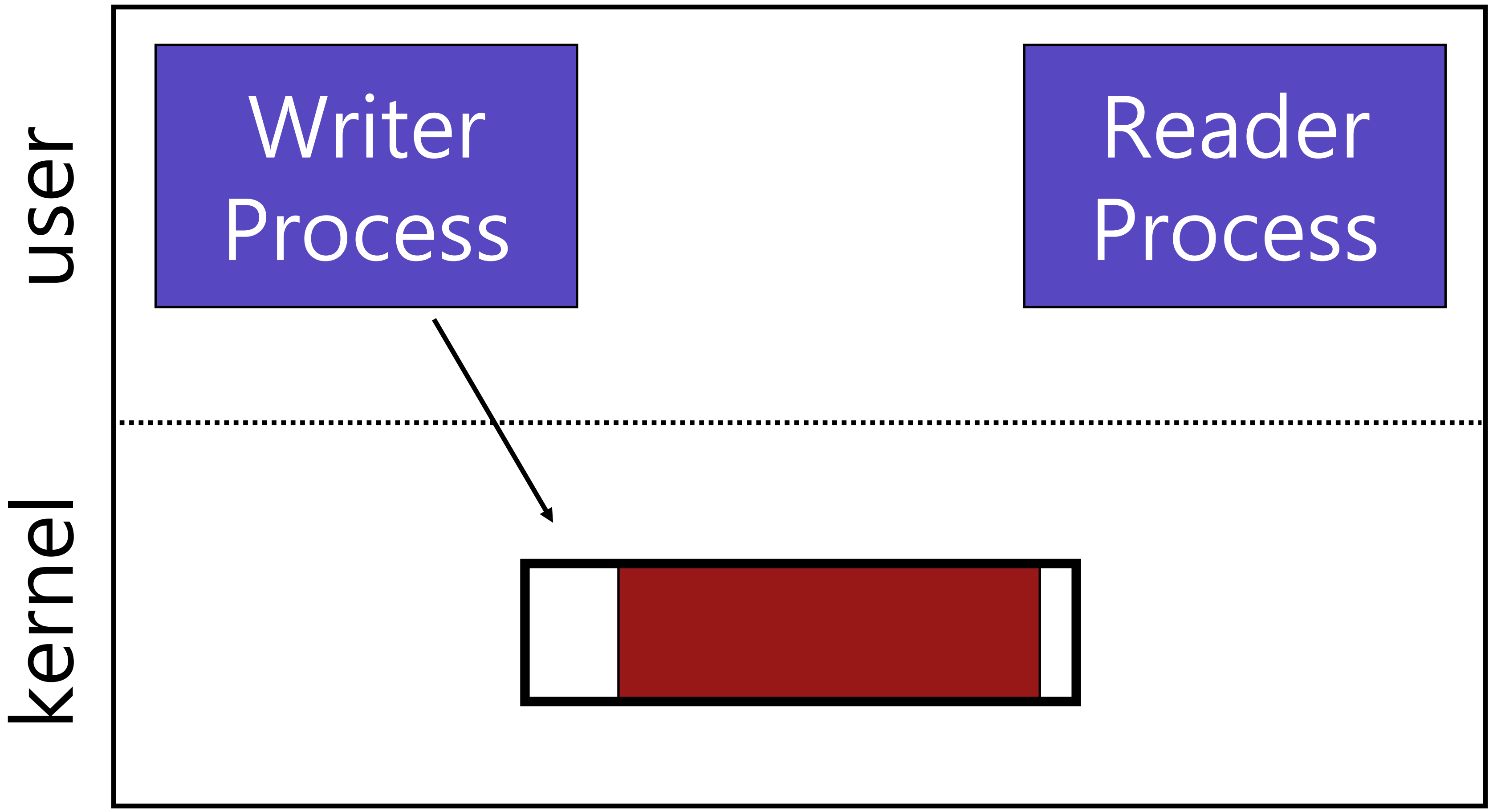

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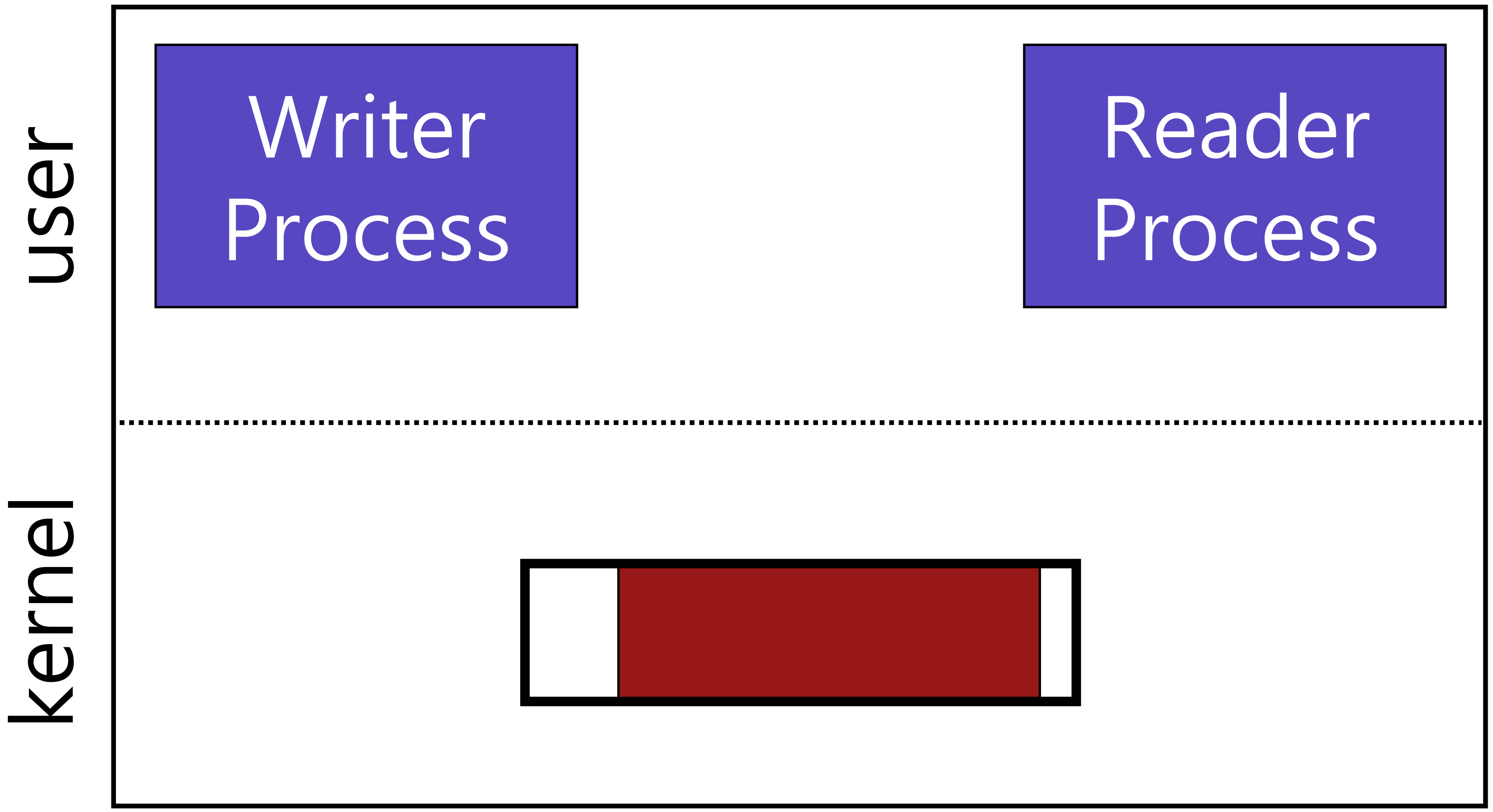

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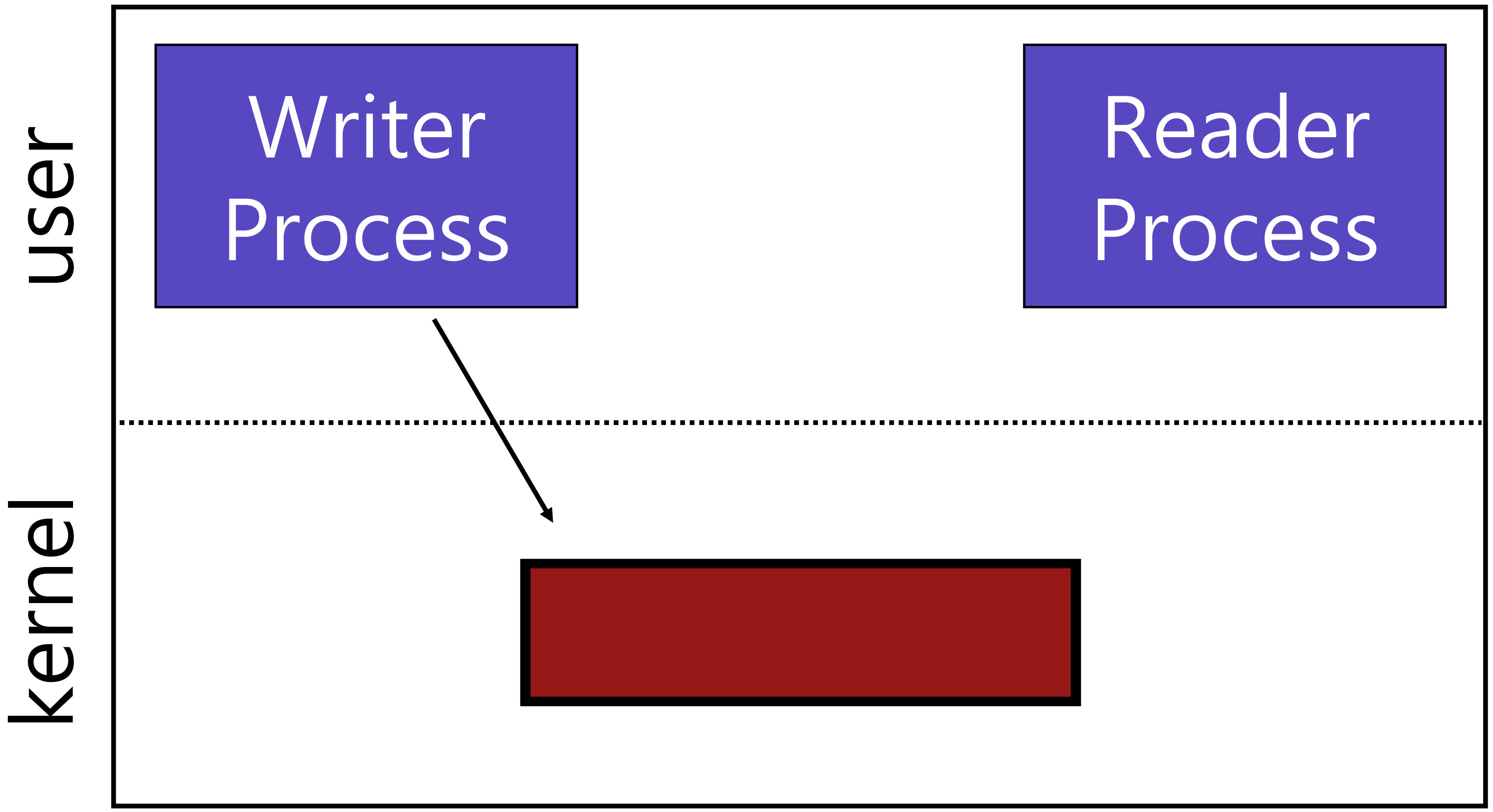

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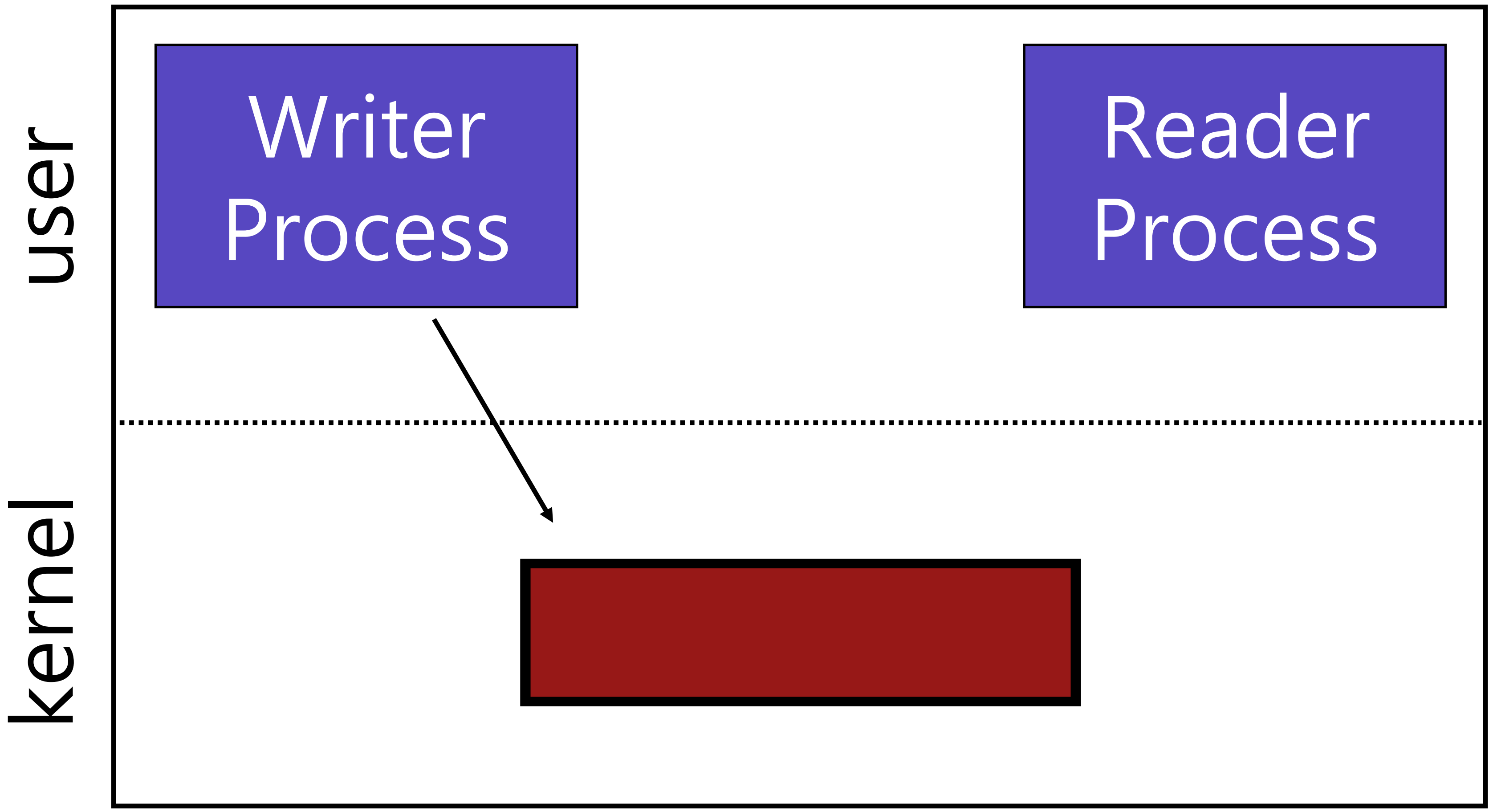
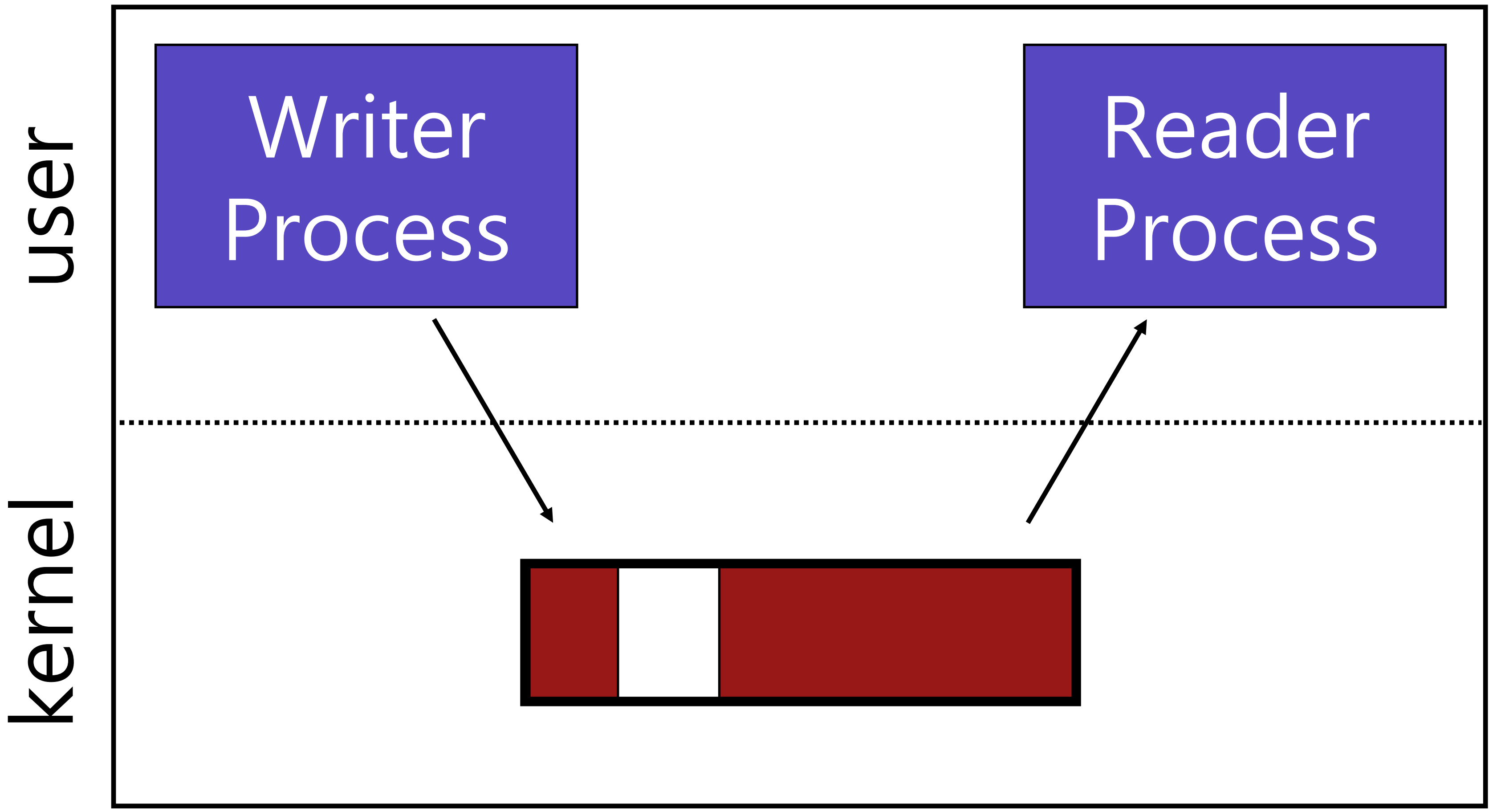


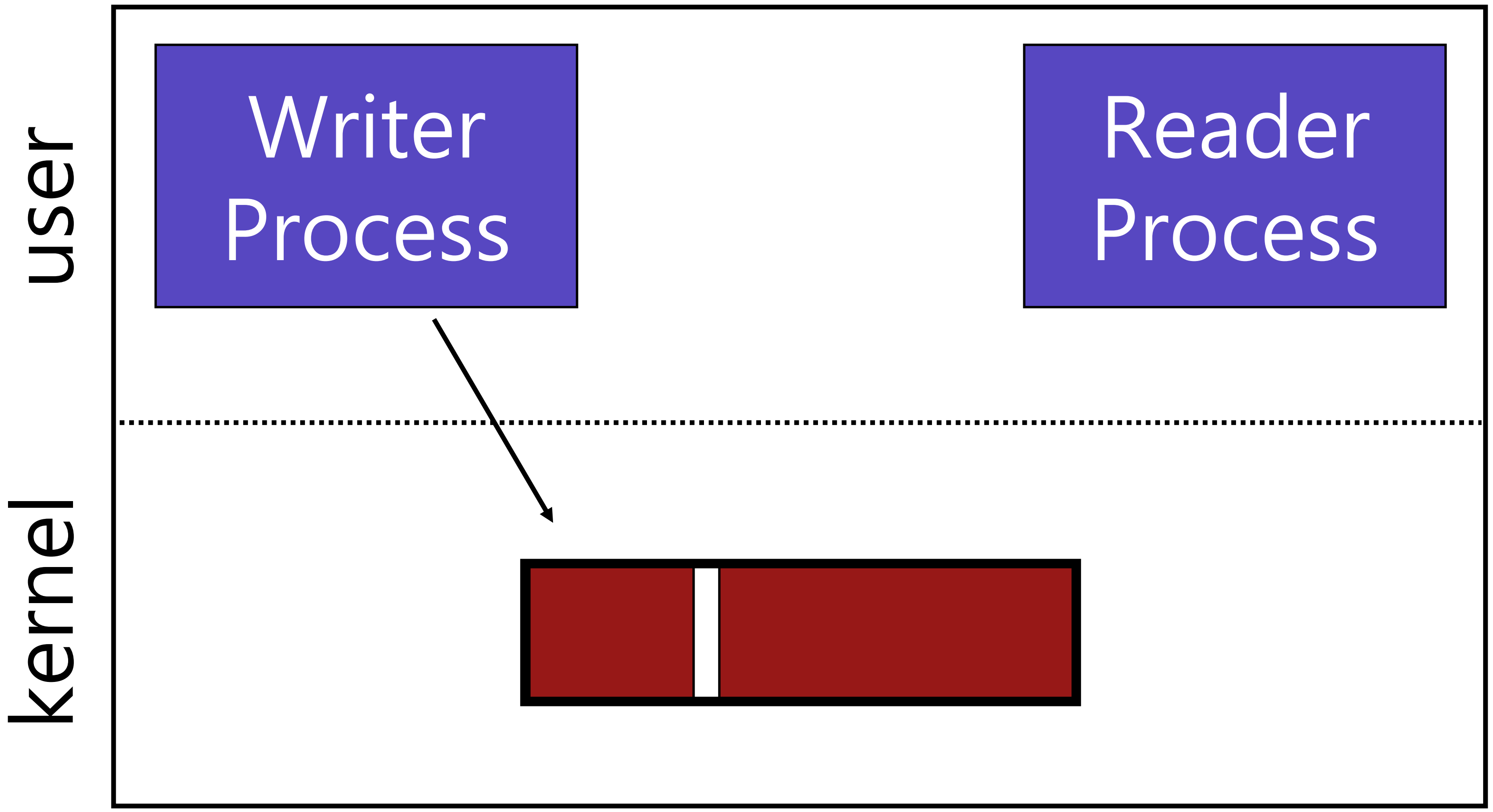

write waits for space

# Pipe

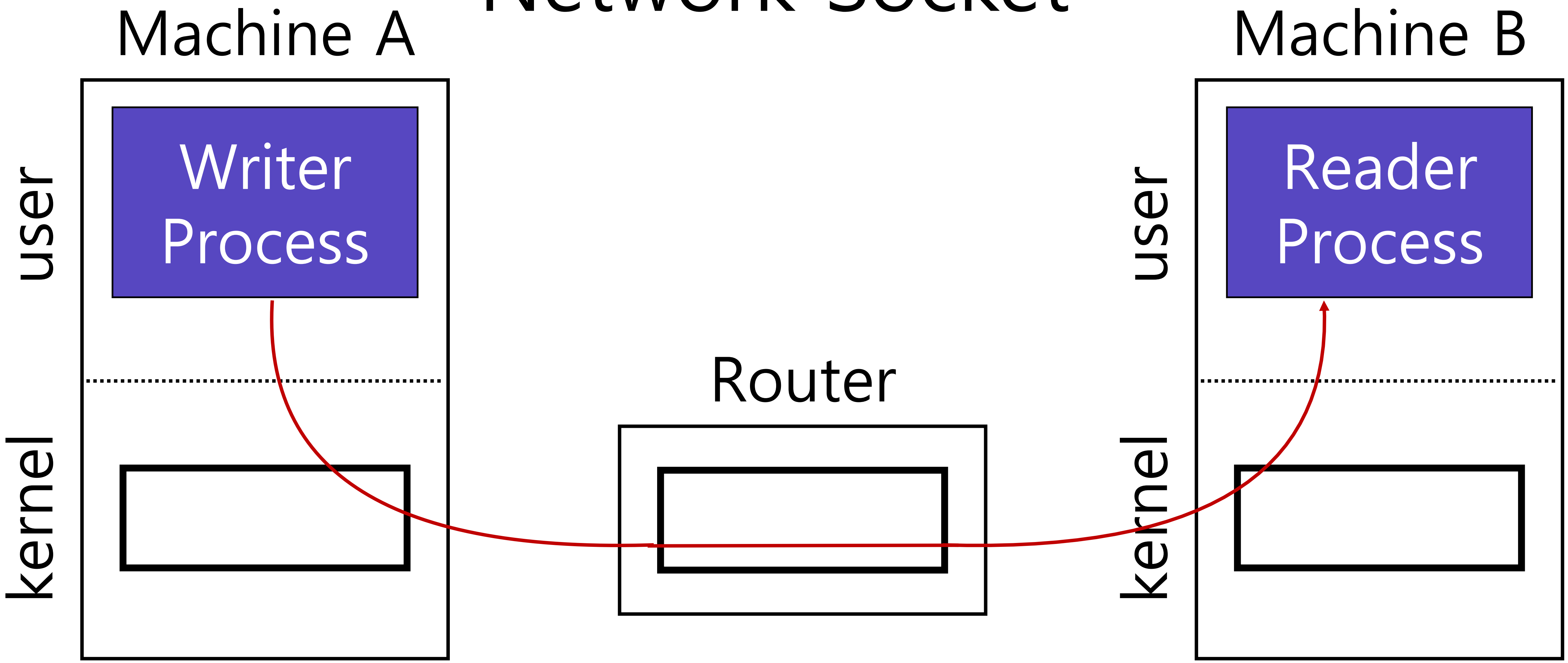



write waits for space

# Pipe



# Network Socket



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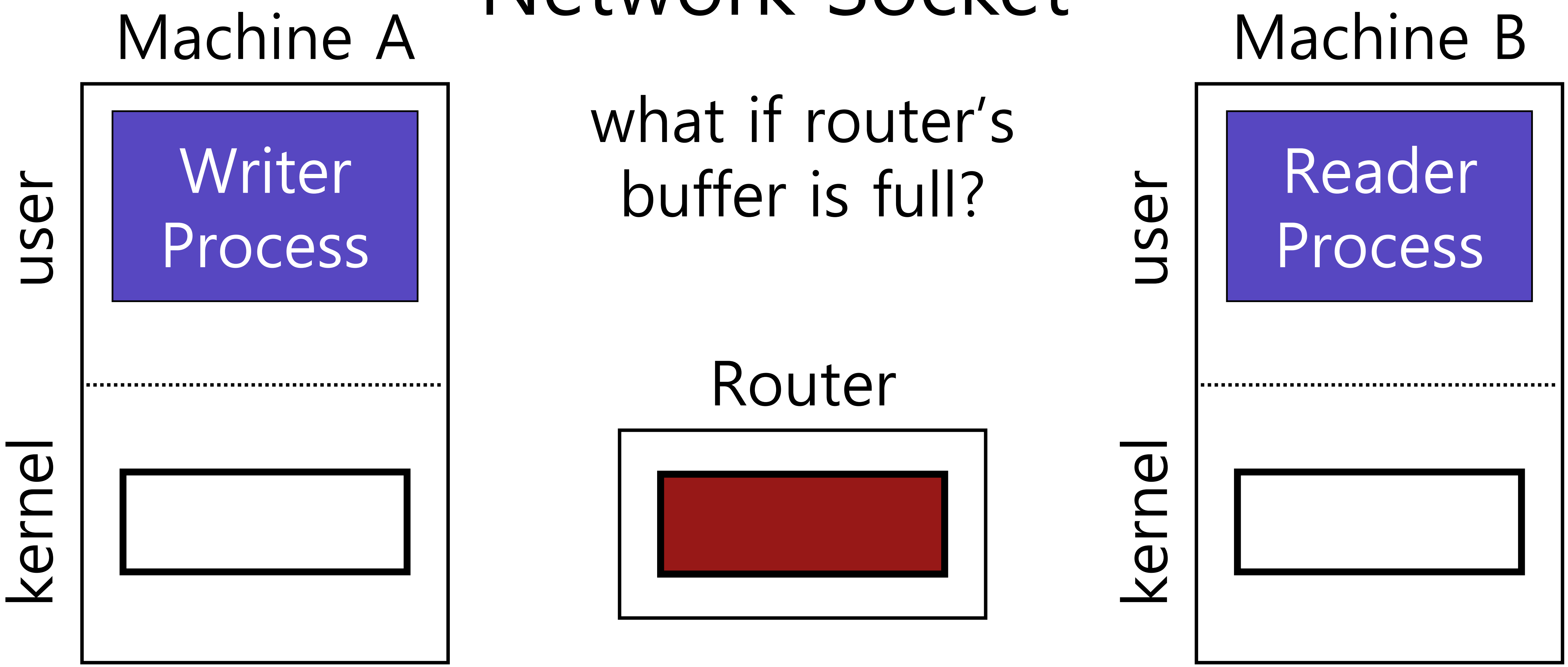
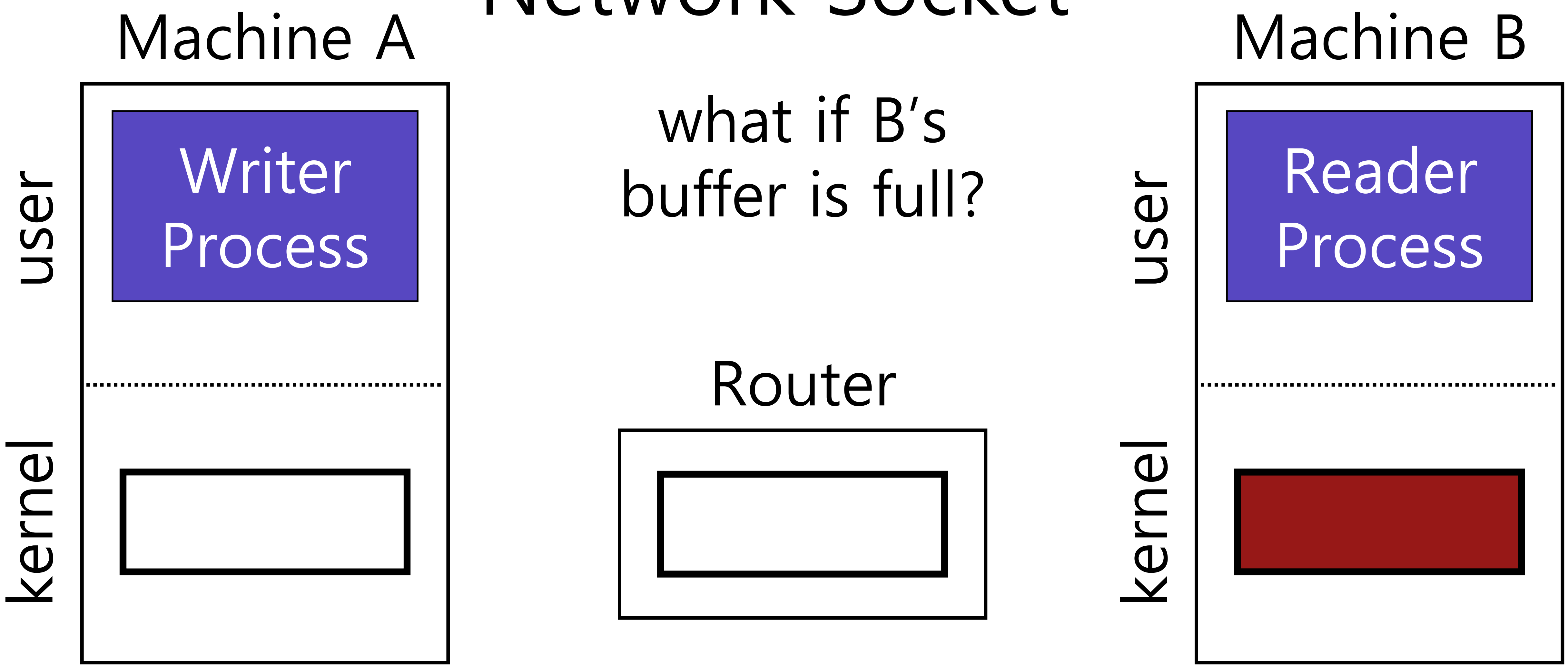


# Network Socket

what if B's buffer is full?



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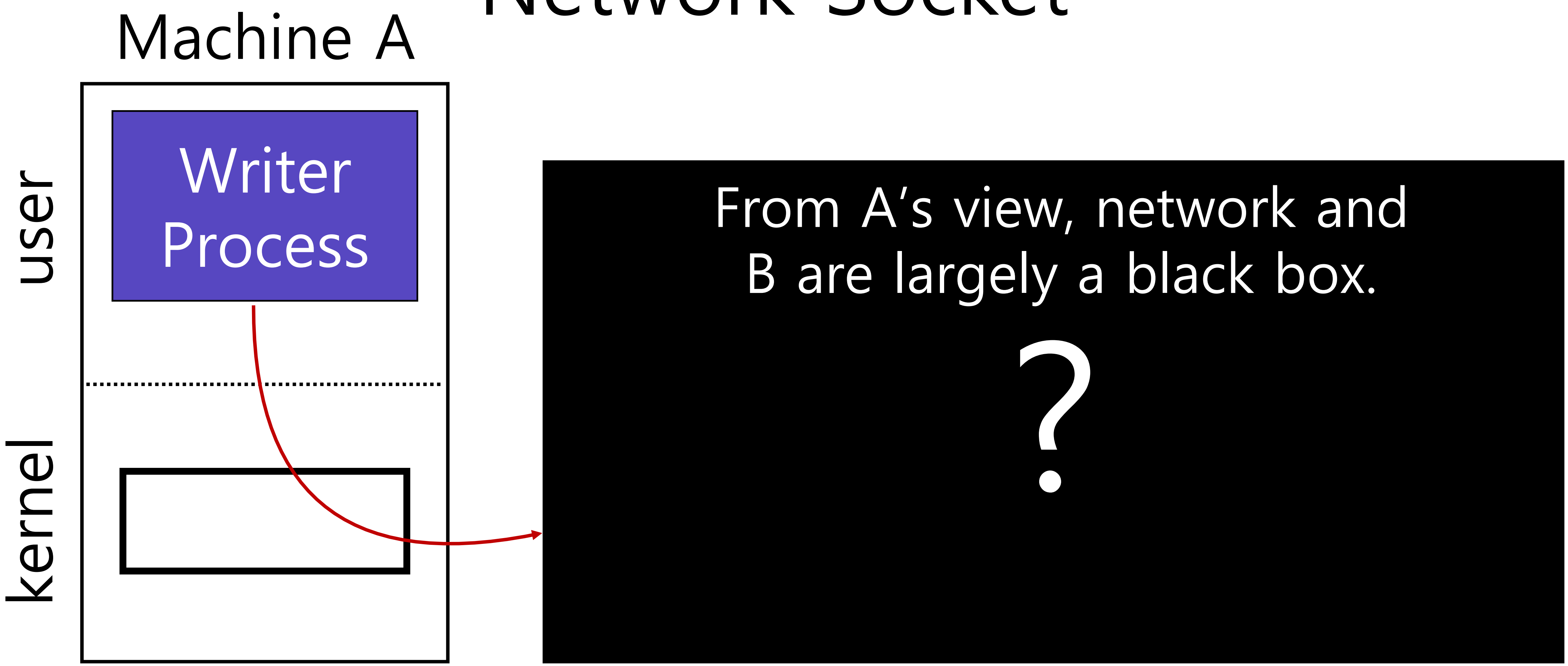

# Communication Overview

Raw messages: UDP

Reliable messages: TCP

OS abstractions
- virtual memory
- global file system

Programming-language abstractions
- Remote procedure call: RPC

# Raw Messages: UDP

UDP : User Datagram Protocol

API:

- reads and writes over socket file descriptors
- messages sent from/to ports to target a process on machine

Provide minimal reliability features:

- messages may be lost
- messages may be reordered
- messages may be duplicated
- only protection: checksums to ensure data not corrupted

# Raw Messages: UDP

Advantages

- Lightweight
- Some applications make better reliability decisions themselves (e.g., video conferencing programs)

Disadvantages

- More difficult to write applications correctly

# Communication Overview

Raw messages: UDP

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# Reliable Messages: Layering strategy

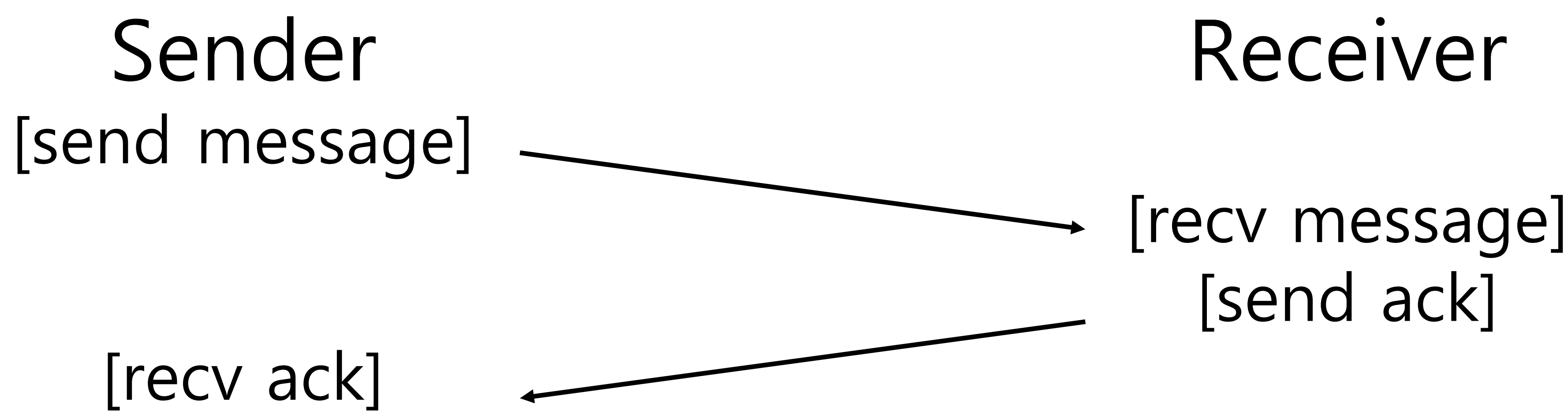
TCP: Transmission Control Protocol

Using software, build reliable, logical connections over unreliable connections

Techniques:

- acknowledgment (ACK)

# Technique #1: ACK



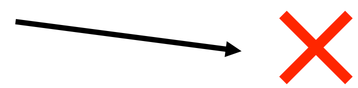

Sender knows message was received

# ACK

Sender

Receiver

[send message]



Sender doesn’t receive ACK…

What to do?

# Reliable Messages: Layering strategy

TCP: Transmission Control Protocol

Using software, build reliable, logical connections ov
er unreliable connections

Techniques:

- acknowledgment (ACK)
- timeout

# Technique #2: Timeout

| Sender | Receiver |
|---|---|
| [send message]<br>[start timer] | |
| … waiting for ack … | |
| [timer goes off]<br>[send message] | |
| | [recv message]<br>[send ack] |
| [recv ack] | |

# Lost ACK: Issue 1

How long to wait?

Too long?

- System feels unresponsive

Too short?

- Messages needlessly re-sent
- Messages may have been dropped due to overloaded server. Resending makes overload worse!

# Lost Ack: Issue 1

How long to wait?

One strategy: be adaptive

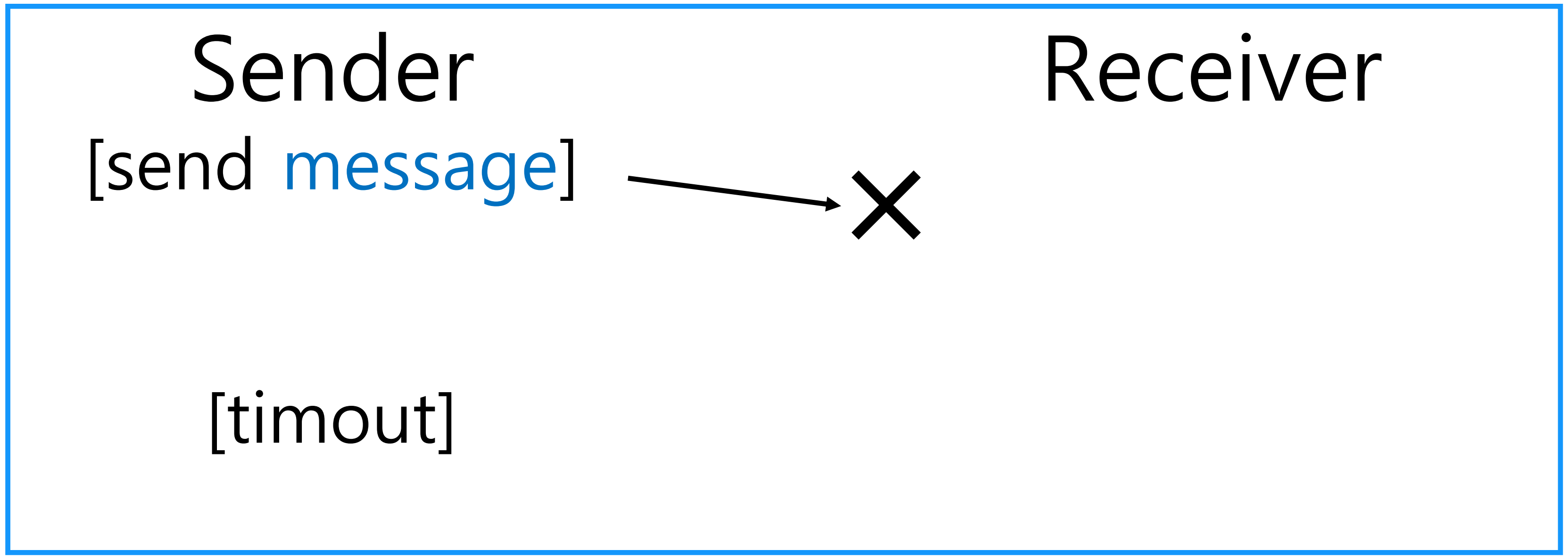
Adjust time based on how long acks usually take

For each missing ack, wait longer between retries

# Lost Ack: Issue 2

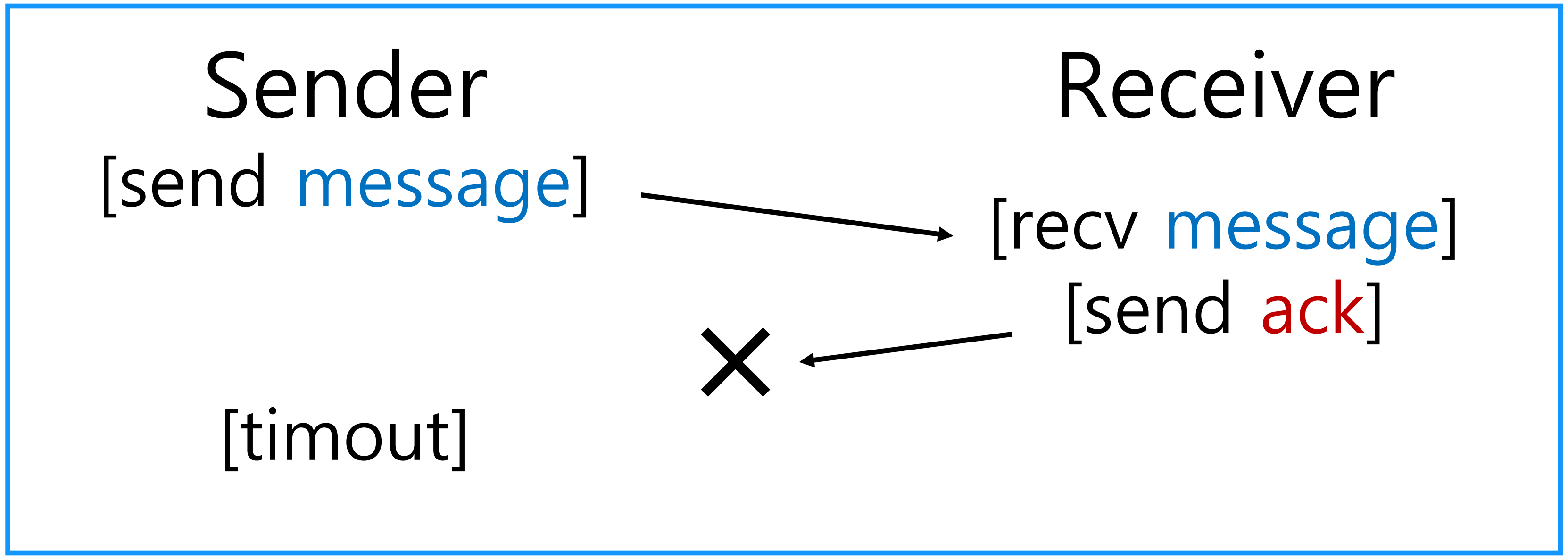
What does a lost ack really mean?

Case 1




Lost ACK:
How can sender tell between these two cases?

Case 2

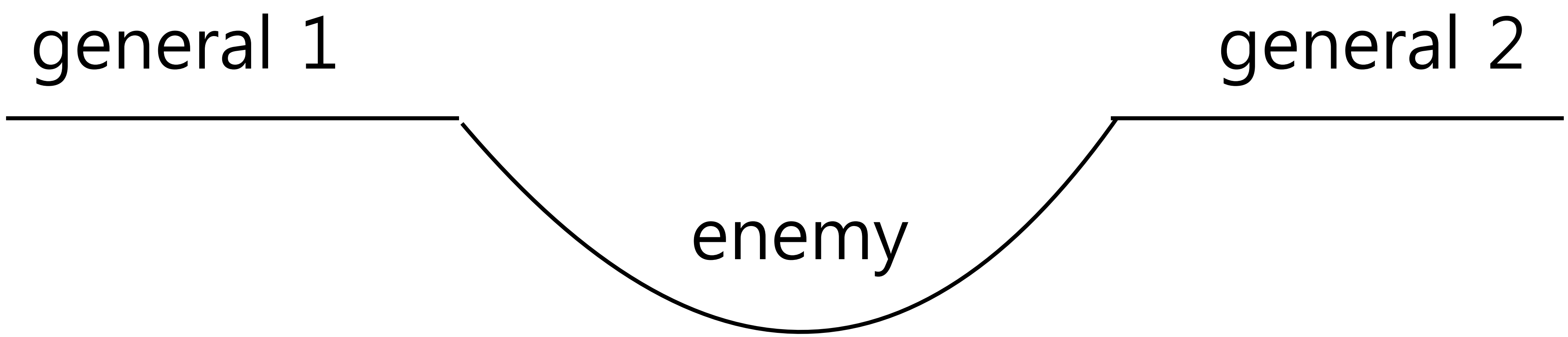



ACK: message received exactly once

No ACK: message may or may not have been received (at most one)

What if message is command to increment counter?

# Aside:
# Two Generals' Problem




Suppose generals agree after N messages

Did the arrival of the N'th message change decision?

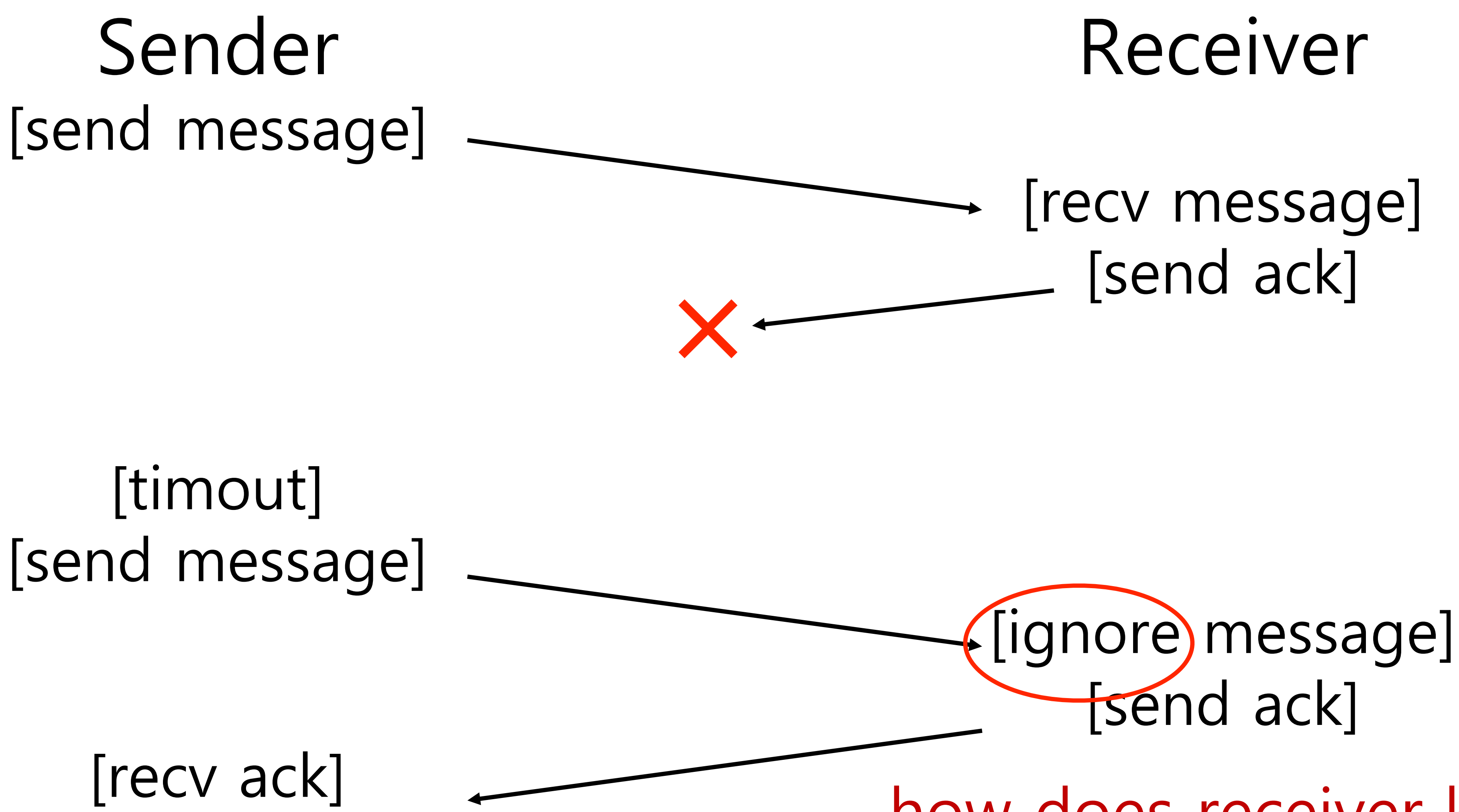
- if yes: then what if the N'th message had been lost?
- if no: then why bother sending N messages?

# Reliable Messages: Layering Strategy

Using software, build reliable, logical connections over unreliable connections

Techniques:
- acknowledgment
- timeout
- remember sent messages

# Technique #3: Receiver Remembers Messages




how does receiver know to ignore?

# Solutions

Solution 1: remember every message ever received

Solution 2: sequence numbers

- senders gives each message an increasing unique seq number
- receiver knows it has seen all messages before N
- receiver remembers messages received after N

Suppose message K is received.  Suppress message if:

- K < N
- Msg K is already buffered

# TCP

TCP: Transmission Control Protocol

Most popular protocol based on seq nums

Buffers messages so arrive in order

Timeouts are adaptive

# Communication Overview

Raw messages: UDP

Reliable messages: TCP

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- global file system

Programming-language abstractions
- Remote procedure call: RPC

# Virtual Memory

**Inspiration**: threads share memory

**Idea**: processes on different machines share mem

# Virtual Memory

**Inspiration**: threads share memory

**Idea**: processes on different machines share mem

**Strategy**:

- a bit like swapping we saw before
- instead of swap to disk, swap to other machine
- sometimes multiple copies may be in memory on different machines

## Process on Machine A

| PFN | valid | present |
|---|---|---|
| - | 0 | - |
| - | 0 | - |
| - | 0 | - |
| - | 0 | - |

… …

5 6 7 8

## Process on Machine B

| PFN | valid | present |
|---|---|---|
| - | 0 | - |
| - | 0 | - |
| - | 0 | - |
| - | 0 | - |

… …

21 22 23 24

## Process on Machine A

| PFN | valid | present |
|---|---|---|
| - | 0 | - |
| - | 1 | 0 |
| - | 1 | 0 |
| - | 1 | 0 |

… …

5 6 7 8

## Process on Machine B

| PFN | valid | present |
|---|---|---|
| - | 0 | - |
| - | 1 | 0 |
| - | 1 | 0 |
| - | 1 | 0 |

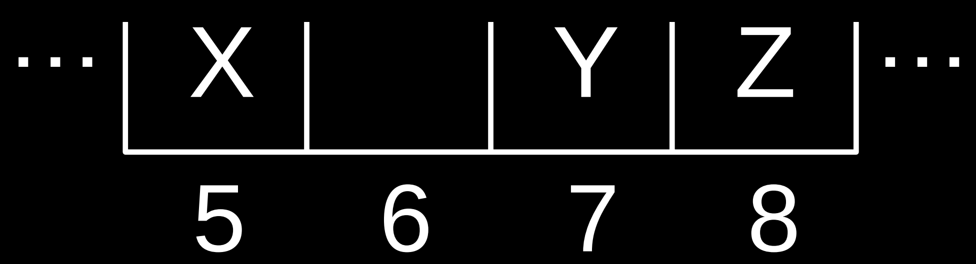
… …

21 22 23 24

map 3-page region into both memories.

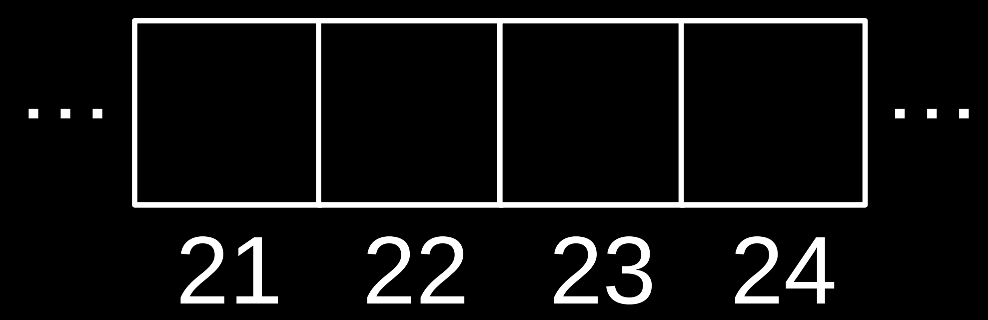
## Process on Machine A

| PFN | valid | present |
|---|---|---|
| - | 0 | - |
| 5 | 1 | 1 |
| 7 | 1 | 1 |
| 8 | 1 | 1 |




## Process on Machine B

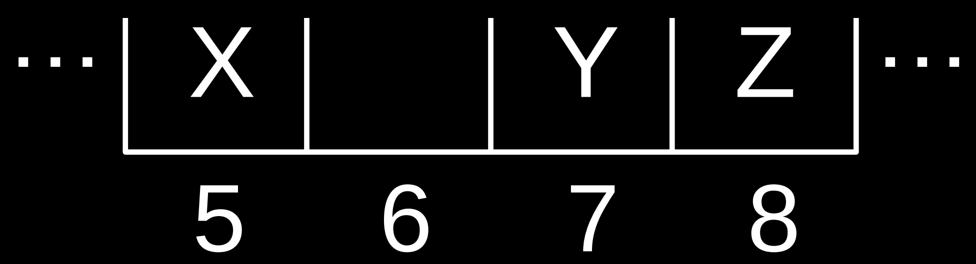
| PFN | valid | present |
|---|---|---|
| - | 0 | - |
| - | 1 | 0 |
| - | 1 | 0 |
| - | 1 | 0 |




A writes X,Y,Z

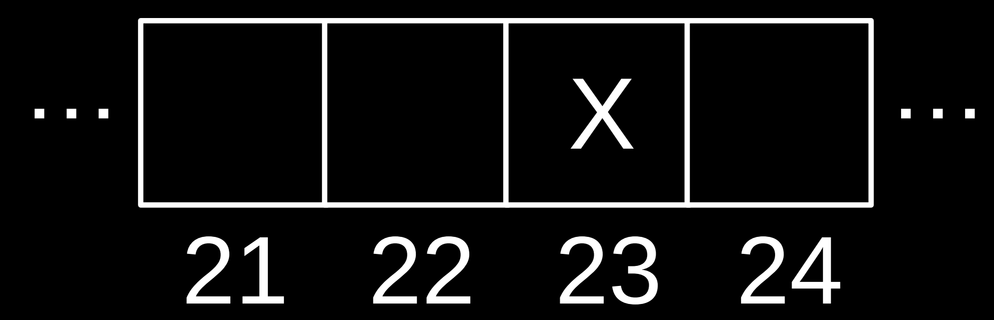
## Process on Machine A

| PFN | valid | present |
|---|---|---|
| - | 0 | - |
| 5 | 1 | 1 |
| 7 | 1 | 1 |
| 8 | 1 | 1 |




## Process on Machine B

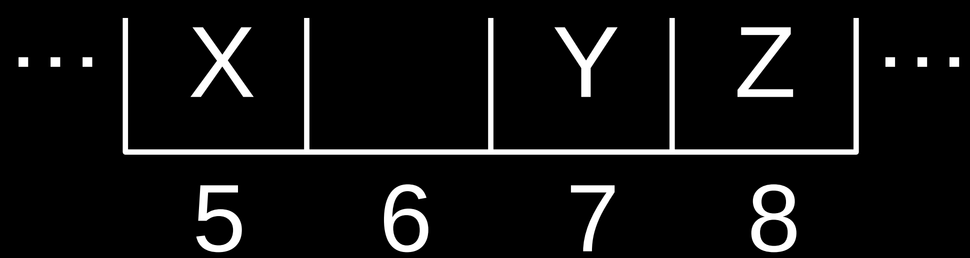
| PFN | valid | present |
|---|---|---|
| - | 0 | - |
| 23 | 1 | 1 |
| - | 1 | 0 |
| - | 1 | 0 |




B reads 1st page

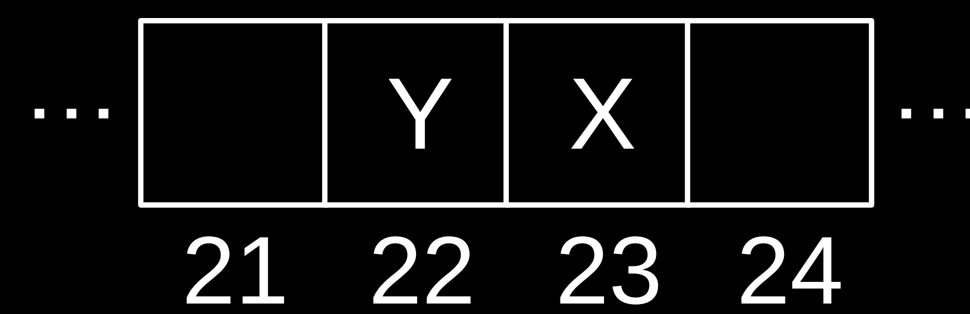
## Process on Machine A

| PFN | valid | present |
|---|---|---|
| - | 0 | - |
| 5 | 1 | 1 |
| 7 | 1 | 1 |
| 8 | 1 | 1 |




## Process on Machine B

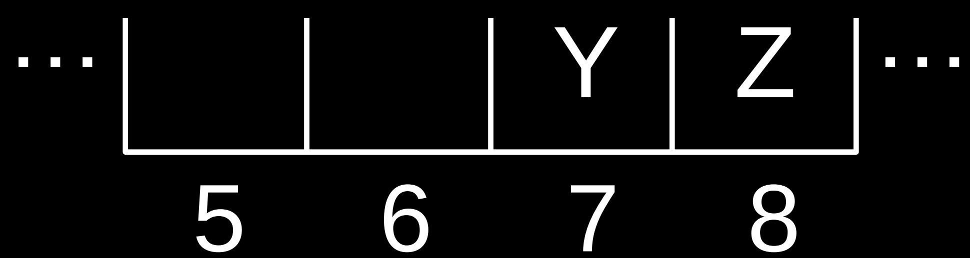
| PFN | valid | present |
|---|---|---|
| - | 0 | - |
| 23 | 1 | 1 |
| 22 | 1 | 1 |
| - | 1 | 0 |




B reads 2st page

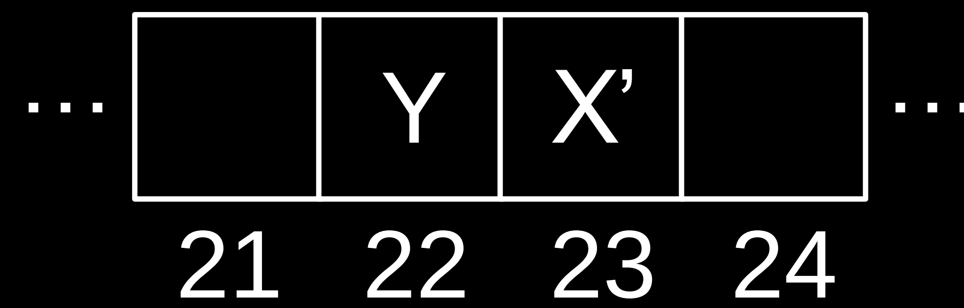
## Process on Machine A

| PFN | valid | present |
|---|---|---|
| - | 0 | - |
| - | 1 | 0 |
| 7 | 1 | 1 |
| 8 | 1 | 1 |




## Process on Machine B

| PFN | valid | present |
|---|---|---|
| - | 0 | - |
| 23 | 1 | 1 |
| 22 | 1 | 1 |
| - | 1 | 0 |




B writes X’ to 1st page

## Process on Machine A

| PFN | valid | present |
|---|---|---|
| - | 0 | - |
| 6 | 1 | 1 |
| 7 | 1 | 1 |
| 8 | 1 | 1 |

| … | 5 | 6 | 7 | 8 | … |
|---|---|---|---|---|---|
| … | | X’ | Y | Z | … |

## Process on Machine B

| PFN | valid | present |
|---|---|---|
| - | 0 | - |
| 23 | 1 | 1 |
| 22 | 1 | 1 |
| - | 1 | 0 |

| … | 21 | 22 | 23 | 24 | … |
|---|---|---|---|---|---|
| … | | Y | X’ | | … |

A reads 1st page

# Virtual Memory Problems

What if a machine crashes?
- mapping disappears in other machines
- how to handle?

Performance?
- when to prefetch?
- loads/stores expected to be fast

DSM (distributed shared memory) not used today.

# Global File System

Advantages

- file access is already expected to be slow
- use common API
- no need to modify applications (sorta true, flocks over NFS don’t work)

Disadvantages

- doesn’t always make sense, e.g., for video app

# Communication Overview

Raw messages: UDP

Reliable messages: TCP

OS abstractions
- virtual memory
- global file system

Programming-language abstractions
- Remote procedure call: RPC

# RPC

**R**emote **P**rocedure **C**all

What could be easier than calling a function?

**Strategy**: create wrappers so calling a function on another machine feels just like calling a local function

Very common abstraction

# RPC

Machine A

```
int main(...) {
    int x = foo("hello");
}

int foo(char *msg) {
    send msg to B
    recv msg from B
}
```

Machine B

```
int foo(char *msg) {
    ...
}

void foo_listener() {
    while(1) {
        recv, call foo
    }
}
```

What it feels like for programmer

# RPC

Machine A

```
int main(...) {
    int x = foo("hello");
}

int foo(char *msg) {
    send msg to B
    recv msg from B
}
```

Machine B

```
int foo(char *msg) {
    ...
}

void foo_listener() {
    while(1) {
        recv, call foo
    }
}
```

Actual calls

# RPC

Machine A

```
int main(...) {
     int x = foo("hello");
}

int foo(char *msg) {
     send msg to B
     recv msg from B
}
```

client wrapper

Machine B

```
int foo(char *msg) {
     ...
}

void foo_listener() {
     while(1) {
          recv, call foo
     }
}
```

server wrapper

Wrappers

# RPC Tools

RPC packages help with two components

**(1) Stub generation**

- Create wrappers automatically
- Many tools available (rpcgen, thrift, protobufs)

(2) Runtime library

- Thread pool
- Socket listeners call functions on server

# Stub Generation

Many tools will automatically generate wrappers:
- rpcgen
- thrift
- protobufs

Programmer fills in generated stubs.

# Wrapper Generation

Wrappers must do conversions:

- client arguments to message
- message to server arguments
- convert server return value to message
- convert message to client return value

Need uniform endianness (wrappers do this)

Conversion is called marshaling/unmarshaling, or serializi ng/deserializing

# Wrapper Generation: Pointers

Why are pointers problematic?

Address passed from client not valid on server

Solutions?

- smart RPC package: follow pointers and copy data
- distribute generic data structs with RPC package

# RPC Tools

RPC packages help with two components

(1) Stub generation

- Create wrappers automatically
- Many tools available (rpcgen, thrift, protobufs)

**(2) Runtime library**

- Thread pool
- Socket listeners call functions on server

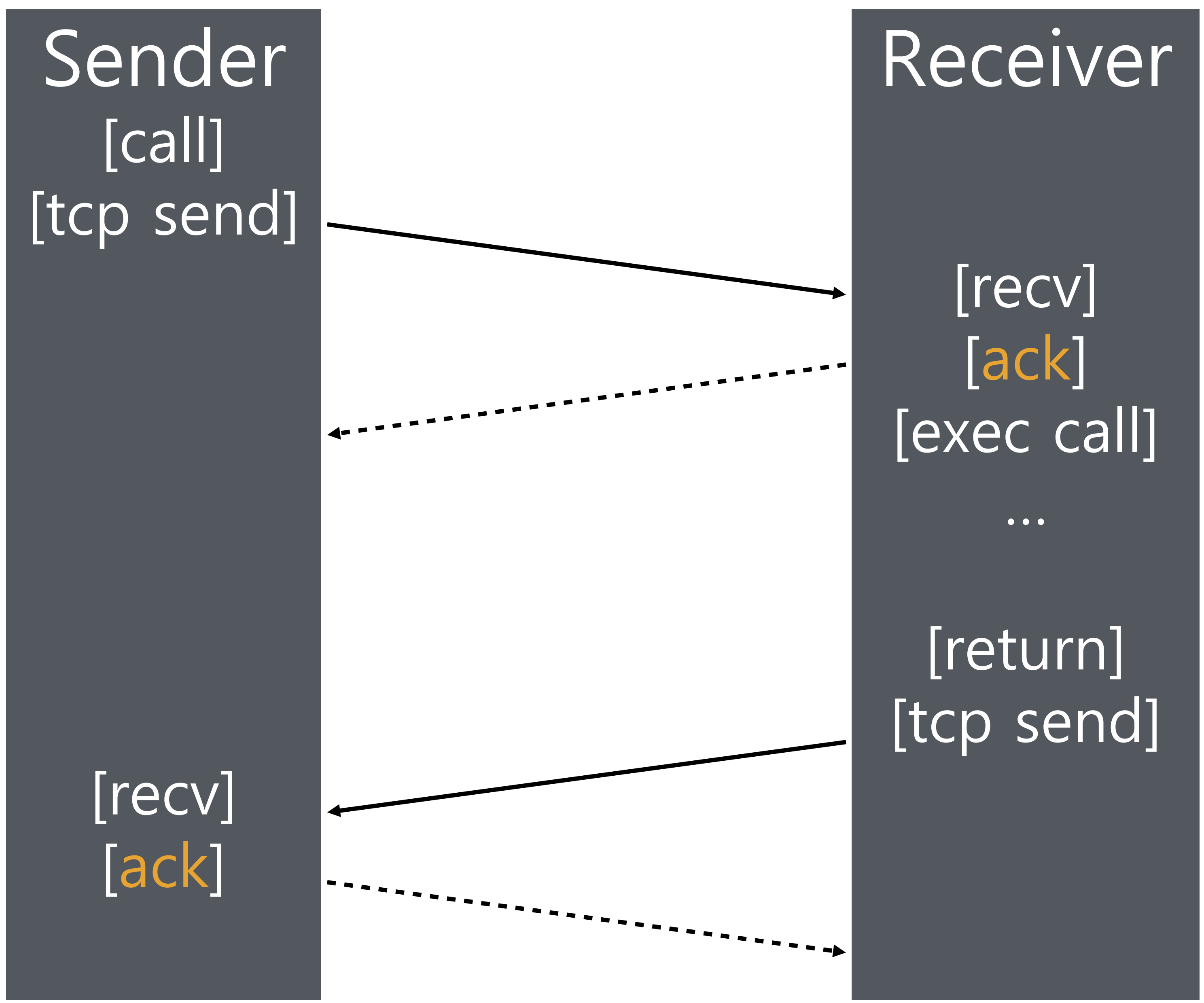
# Runtime Library

Design decisions:

How to serve calls?
- usually with a thread pool

What underlying protocol to use?
- usually UDP

# RPC over TCP?



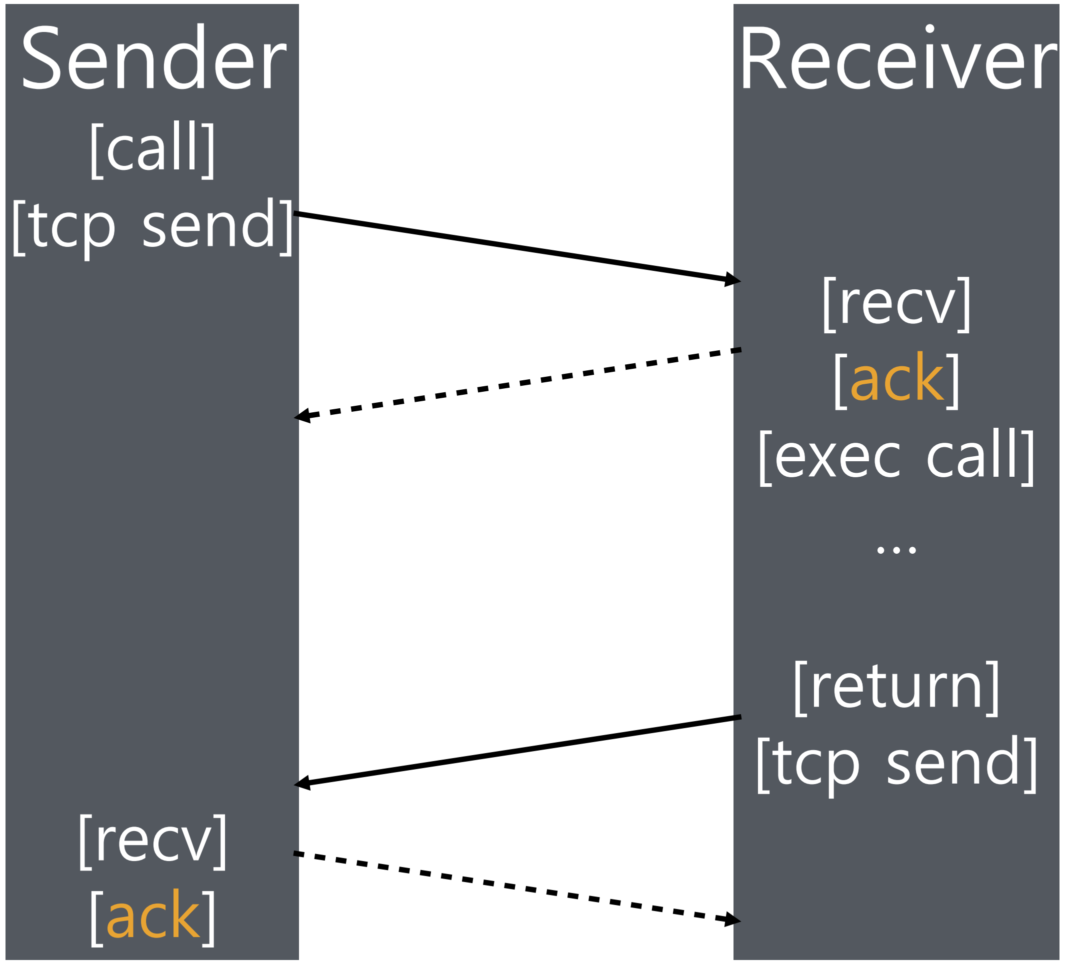

Why wasteful?

# RPC over UDP

Strategy: use function return as implicit ACK

Piggybacking technique

What if function takes a long time?
 - then send a separate ACK



# Distributed File Systems

**File systems are great use case for distributed systems**

**Local FS**:
processes on same machine access shared files

**Network FS**:
processes on different machines access shared files in same way

# Goals for distributed file systems

Fast + simple crash recovery
- both clients and file server may crash

Transparent access
- can’t tell accesses are over the network
- normal UNIX semantics

Reasonable performance

# NFS

Think of NFS as more of a protocol than a particular f
ile system

Many companies have implemented NFS:
Oracle/Sun, NetApp, EMC, IBM

We're looking at NFSv2
- NFSv4 has many changes

Why look at an older protocol?
- Simpler, focused goals
- To compare and contrast NFS with AFS (next lecture)

# Overview

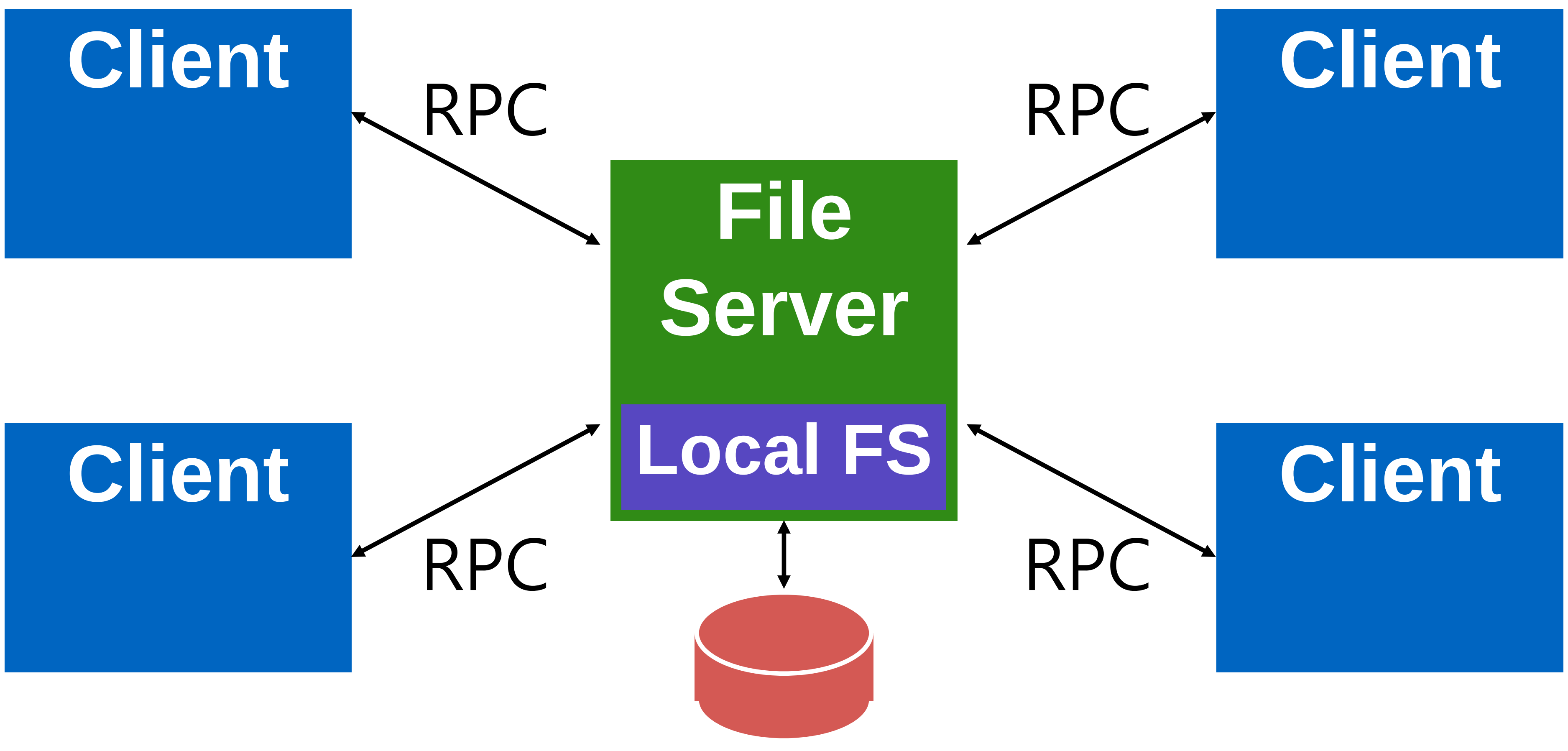
Architecture

Network API

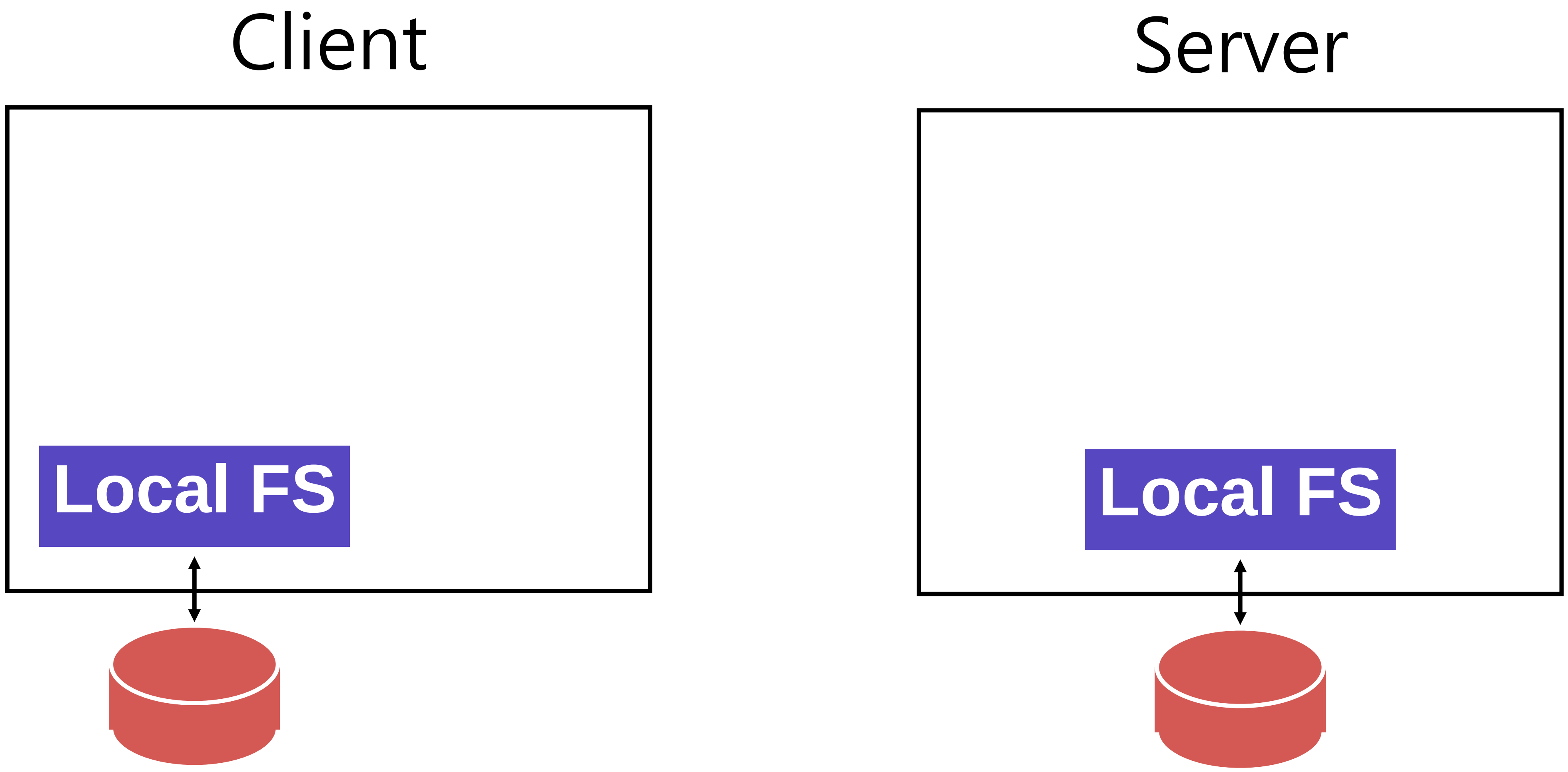
Write Buffering

Cache

# NFS Architecture



# General Strategy: Export FS



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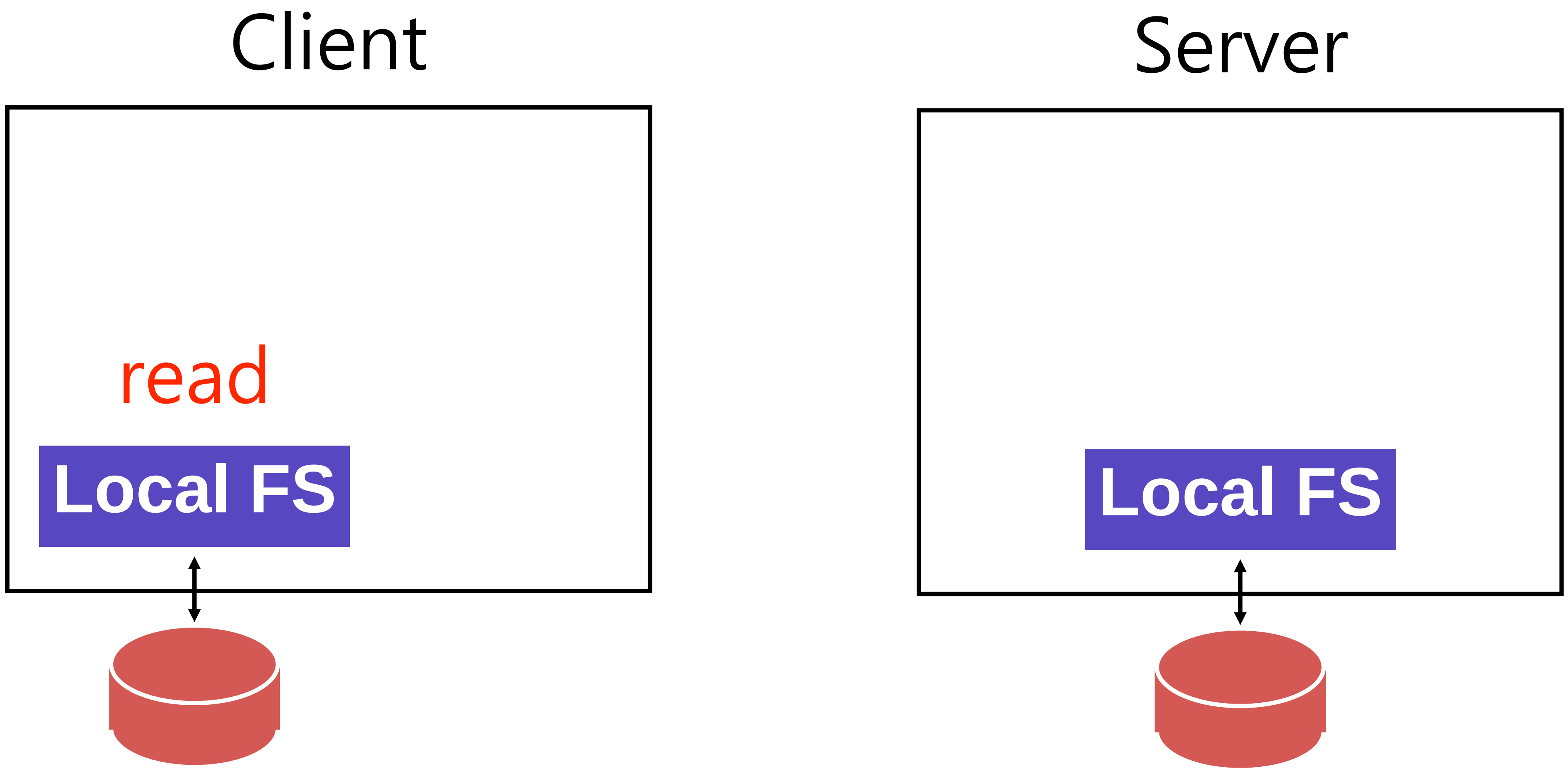

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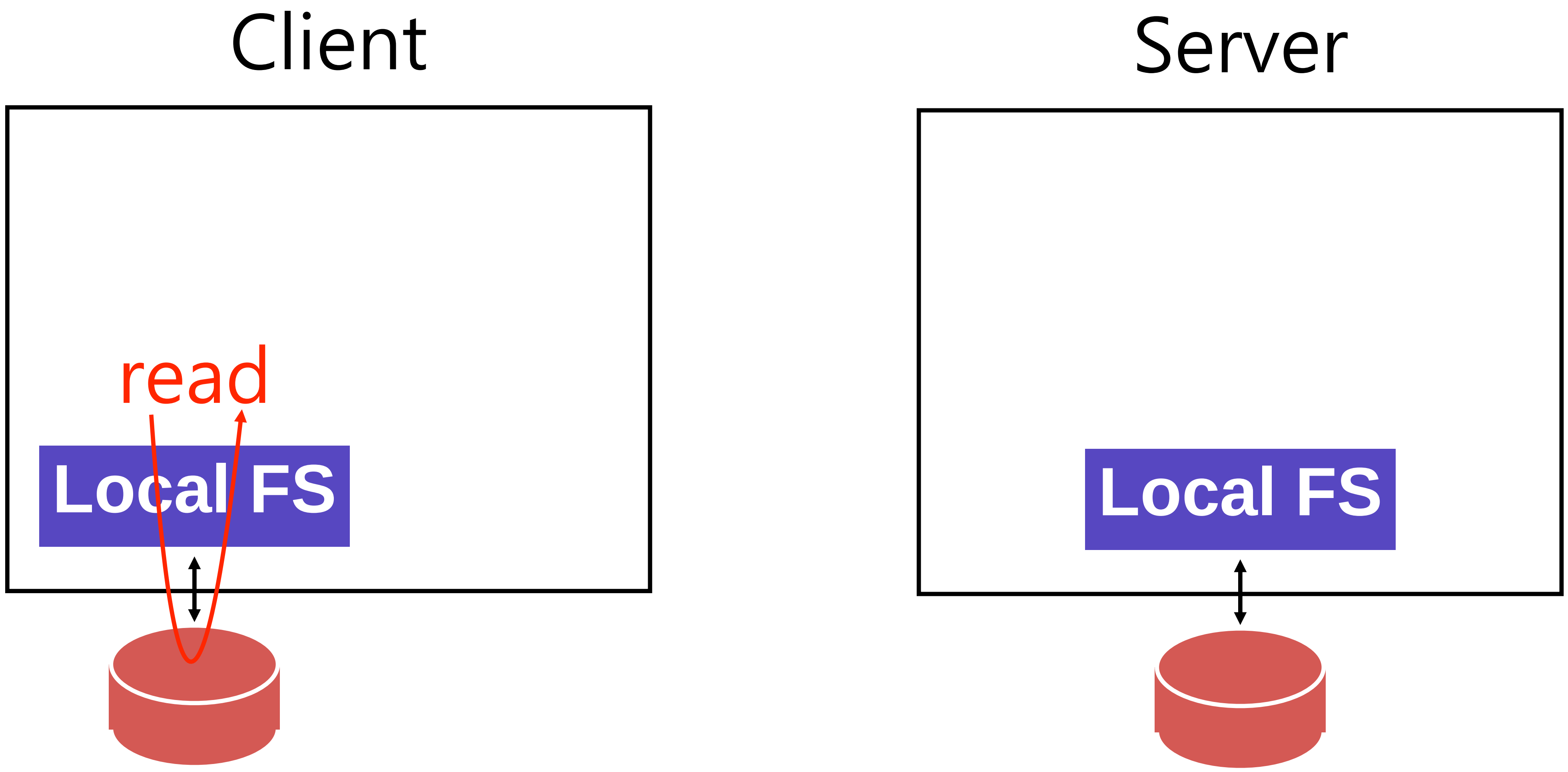
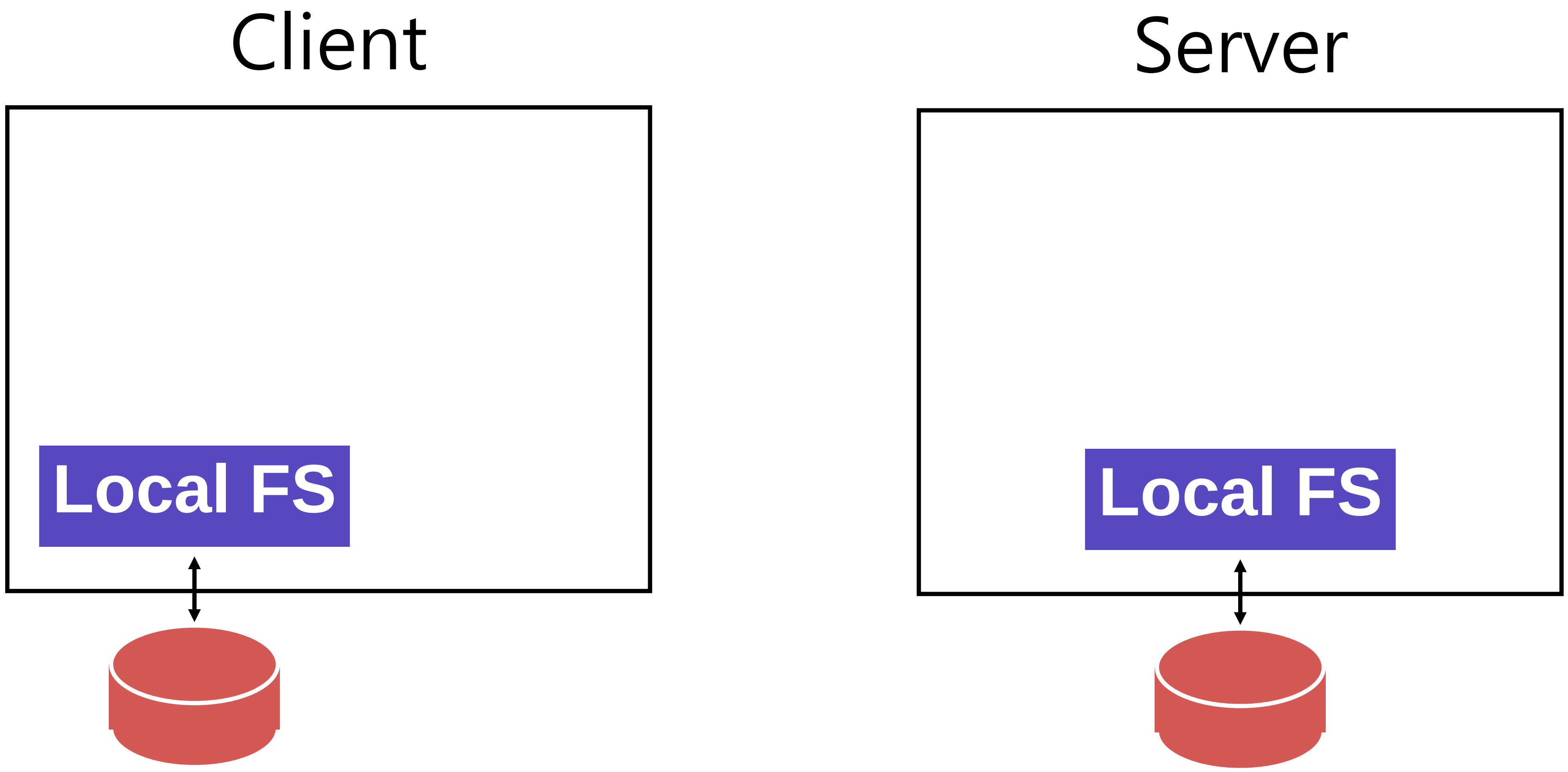


# General Strategy: Export FS



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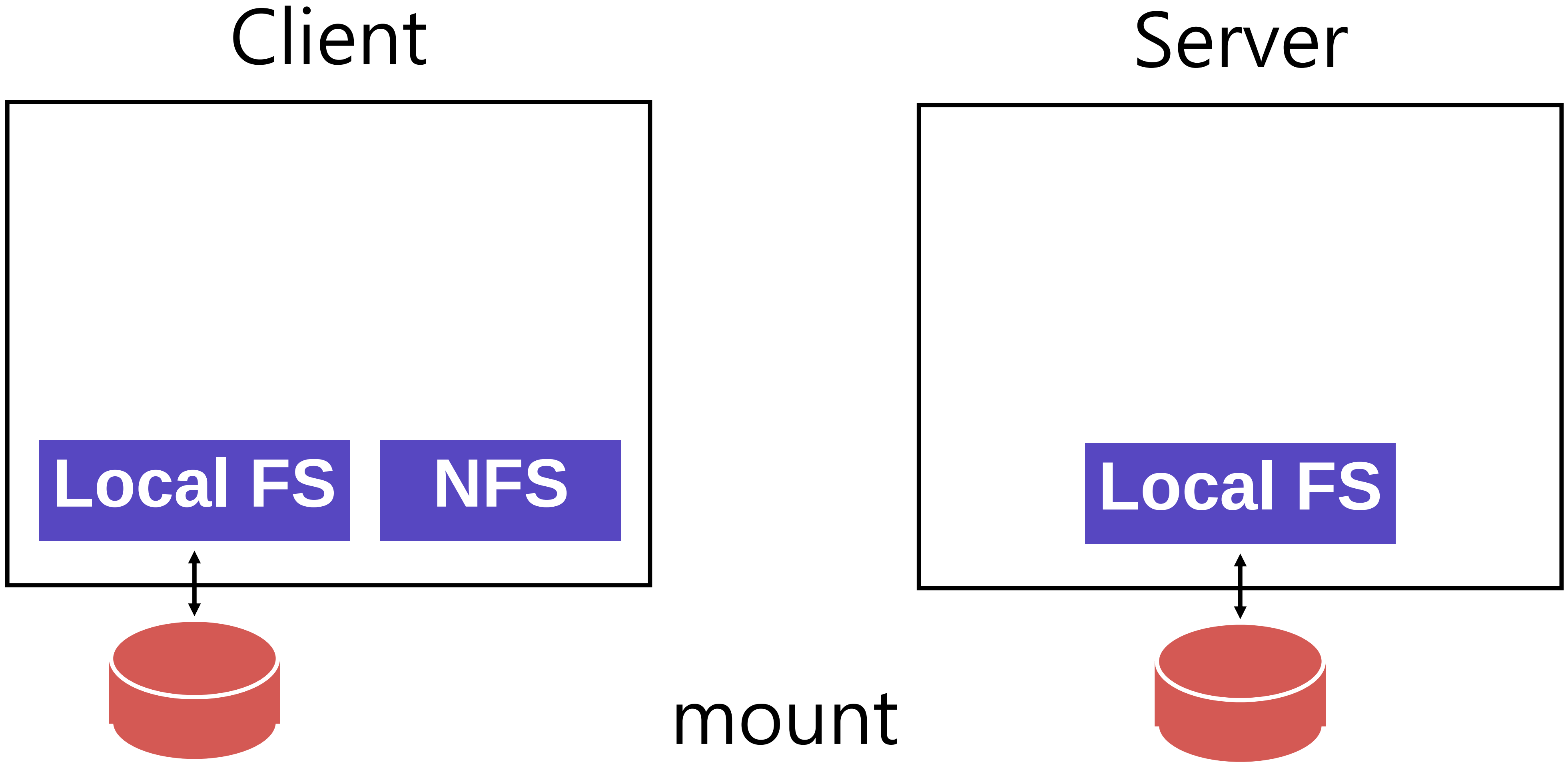
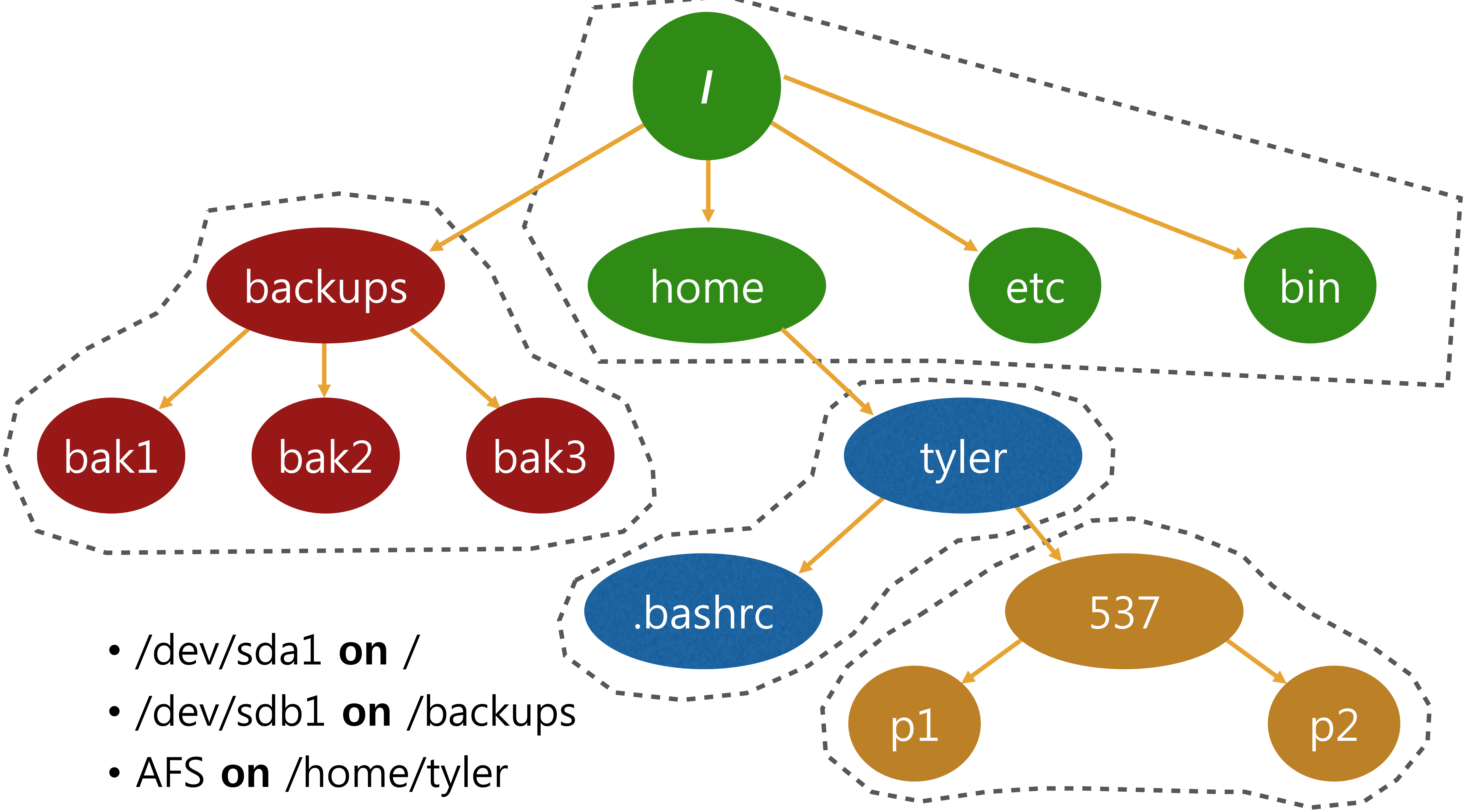
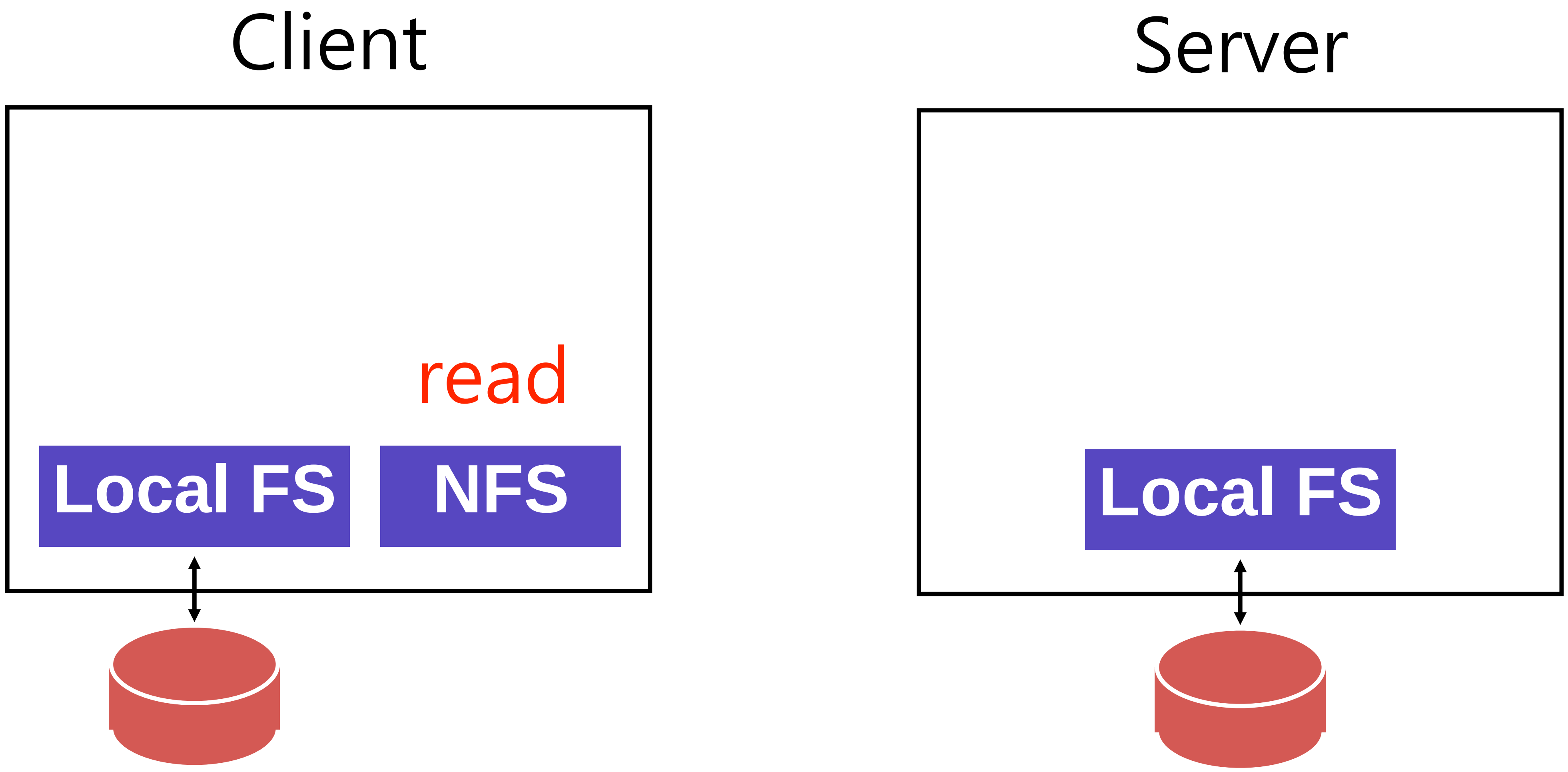


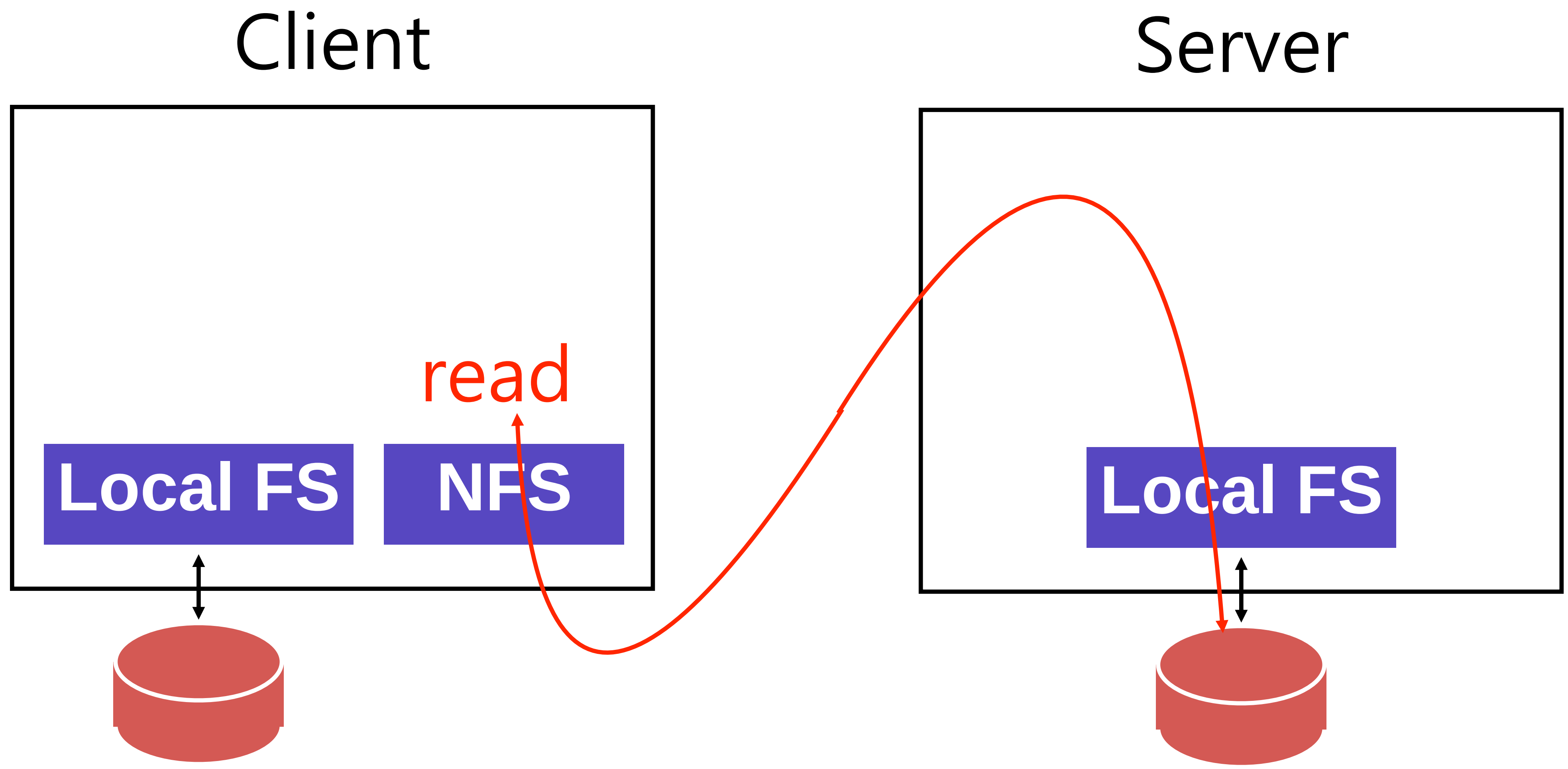



- /dev/sda1 **on** /
- /dev/sdb1 **on** /backups
- AFS **on** /home/tyler

# General Strategy: Export FS



# General Strategy: Export FS



# OSTEP
# Advanced Topics:
# NFS and AFS

**Questions answered in this lecture:**

What is the **NFS stateless protocol**?

What are **idempotent** operations and why are they useful?

What state is tracked on NFS clients?

What is the **NFS cache consistency** model?

How does AFS improve **scalability**?  What is a **callback**?

What is the **AFS cache consistency** model?

# Primary goals for NFS

**Local FS**: processes on same machine access shared files.

**Network FS**: processes on different machines access shared files in same way.

# Sub goals for NFS

Fast + simple crash recovery
 - both clients and file server may crash

Transparent access
 - can't tell accesses are over the network
 - normal UNIX semantics

Reasonable performance

# Overview

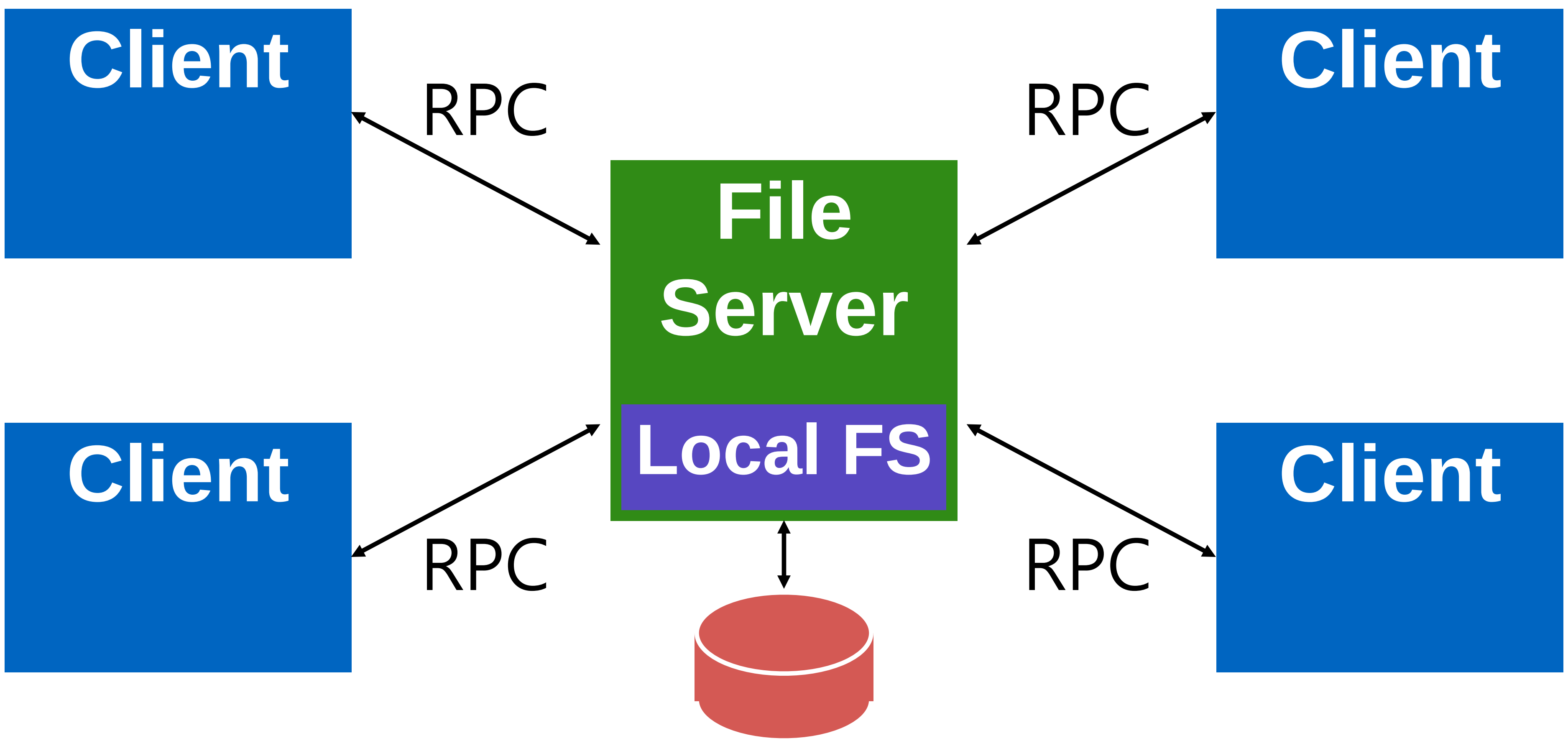
Architecture

Network API

Write Buffering

Cache

# NFS Architecture



# Main Design Decisions

What functions to expose via RPC?

Think of NFS as more of a protocol than a particular file system.

Many companies have implemented NFS: Oracle/Sun, NetApp, EMC, IBM, etc

# Today's Lecture

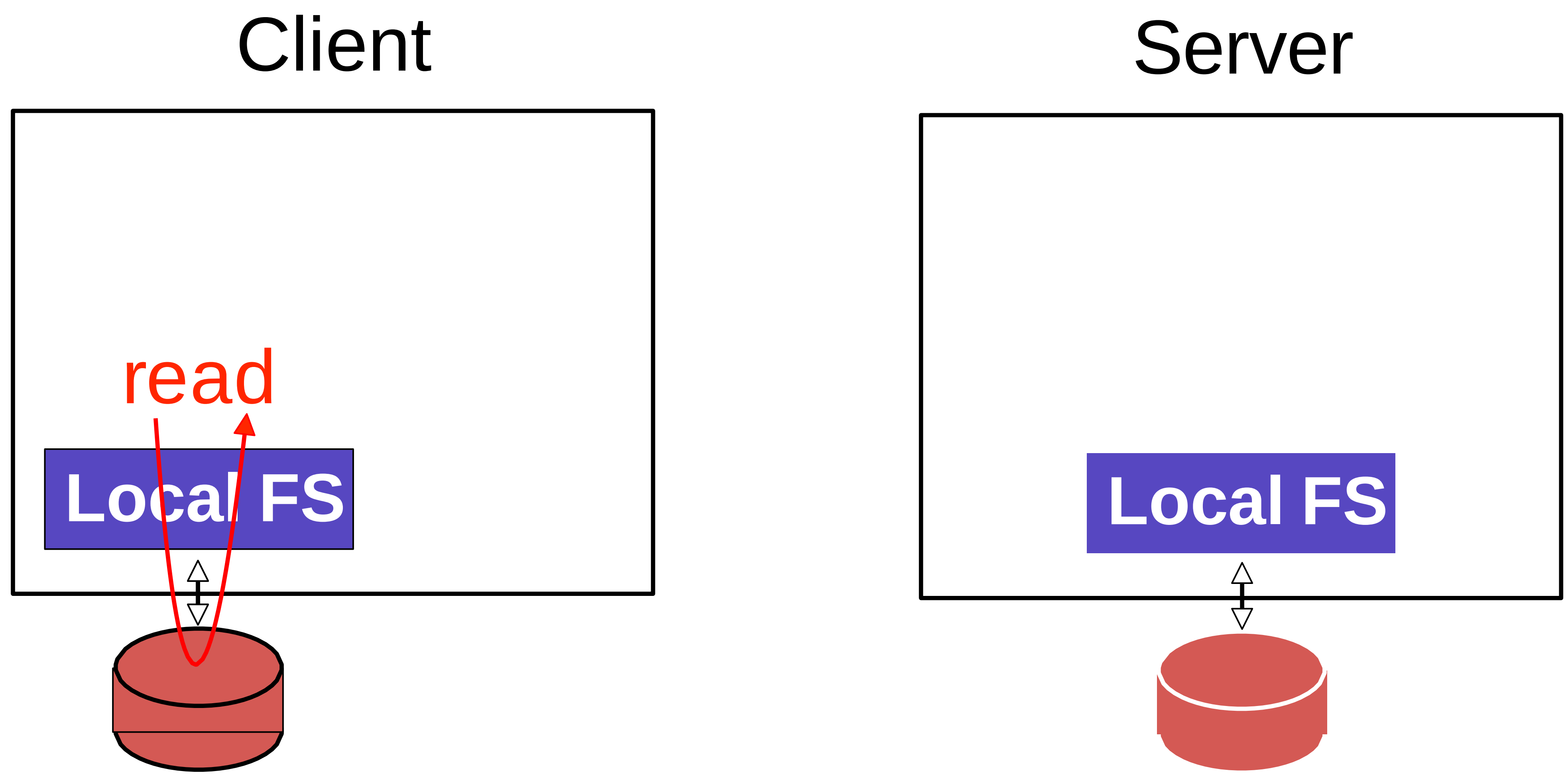
We're looking at NFSv2.

There is now an NFSv4 with many changes. Why

look at an older protocol?

To compare and contrast NFS with AFS.

# General Strategy: Export FS



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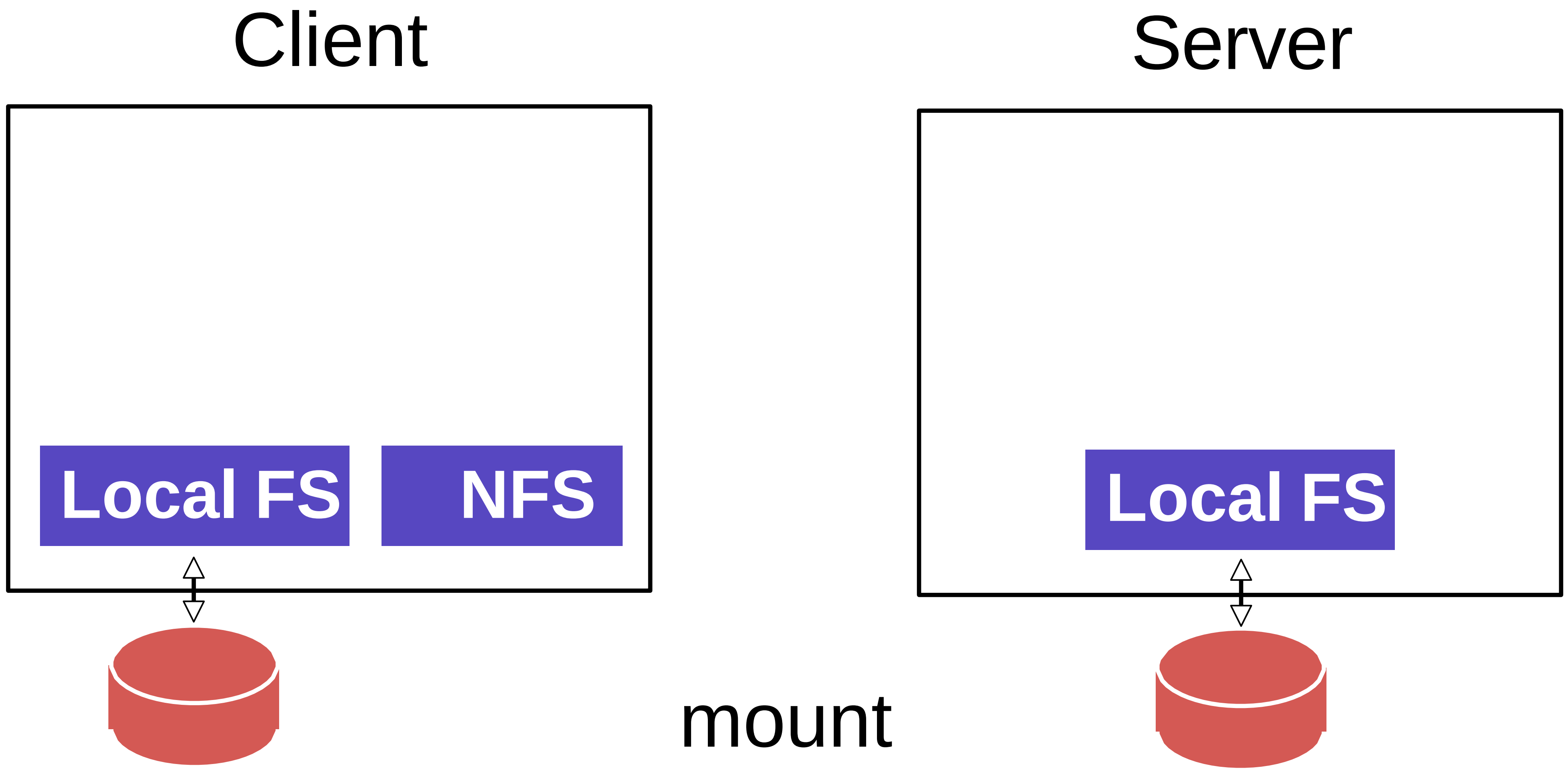
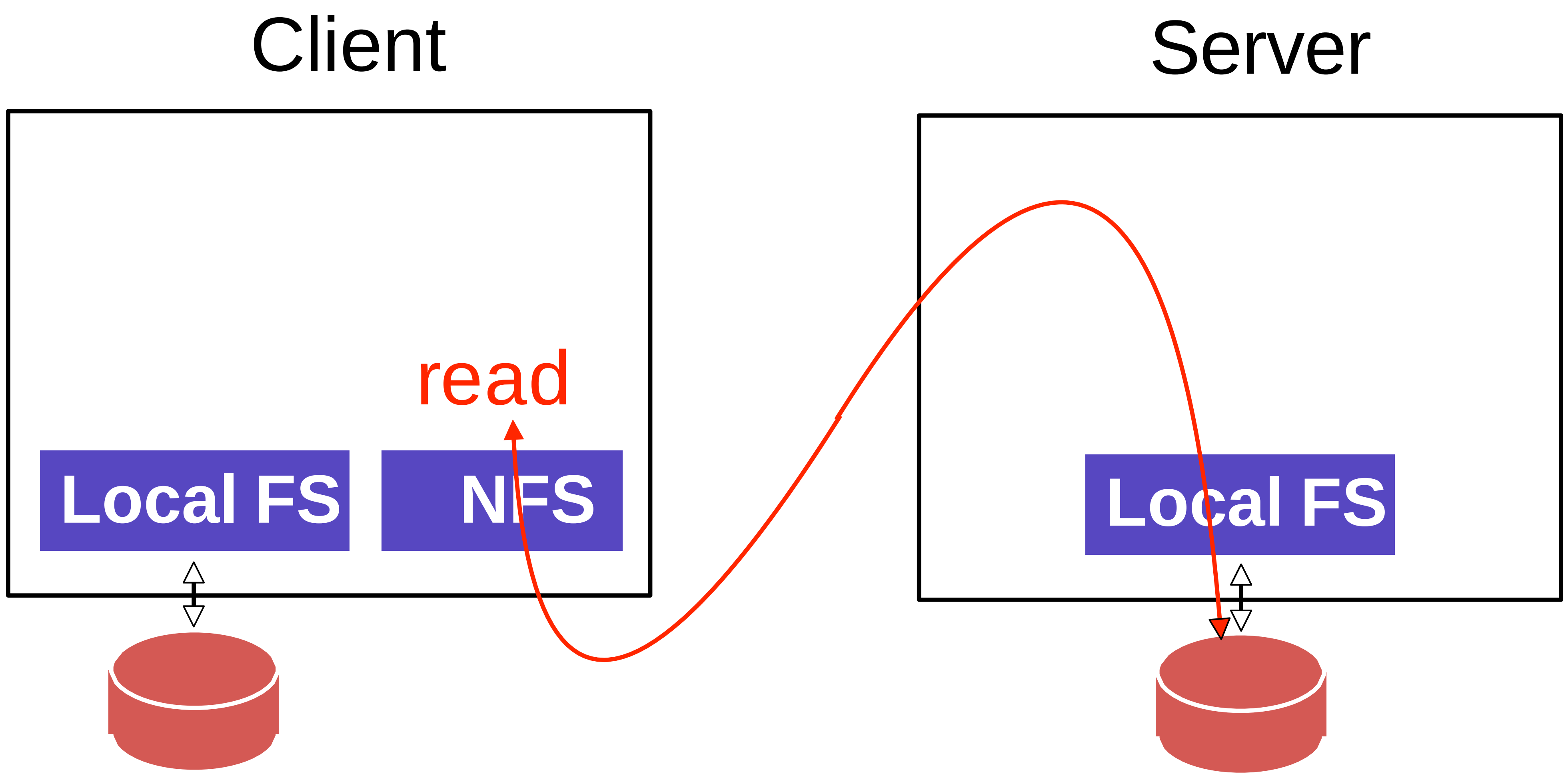


# General Strategy: Export FS



# Overview

~~Architecture~~

Network API

Write Buffering

Cache

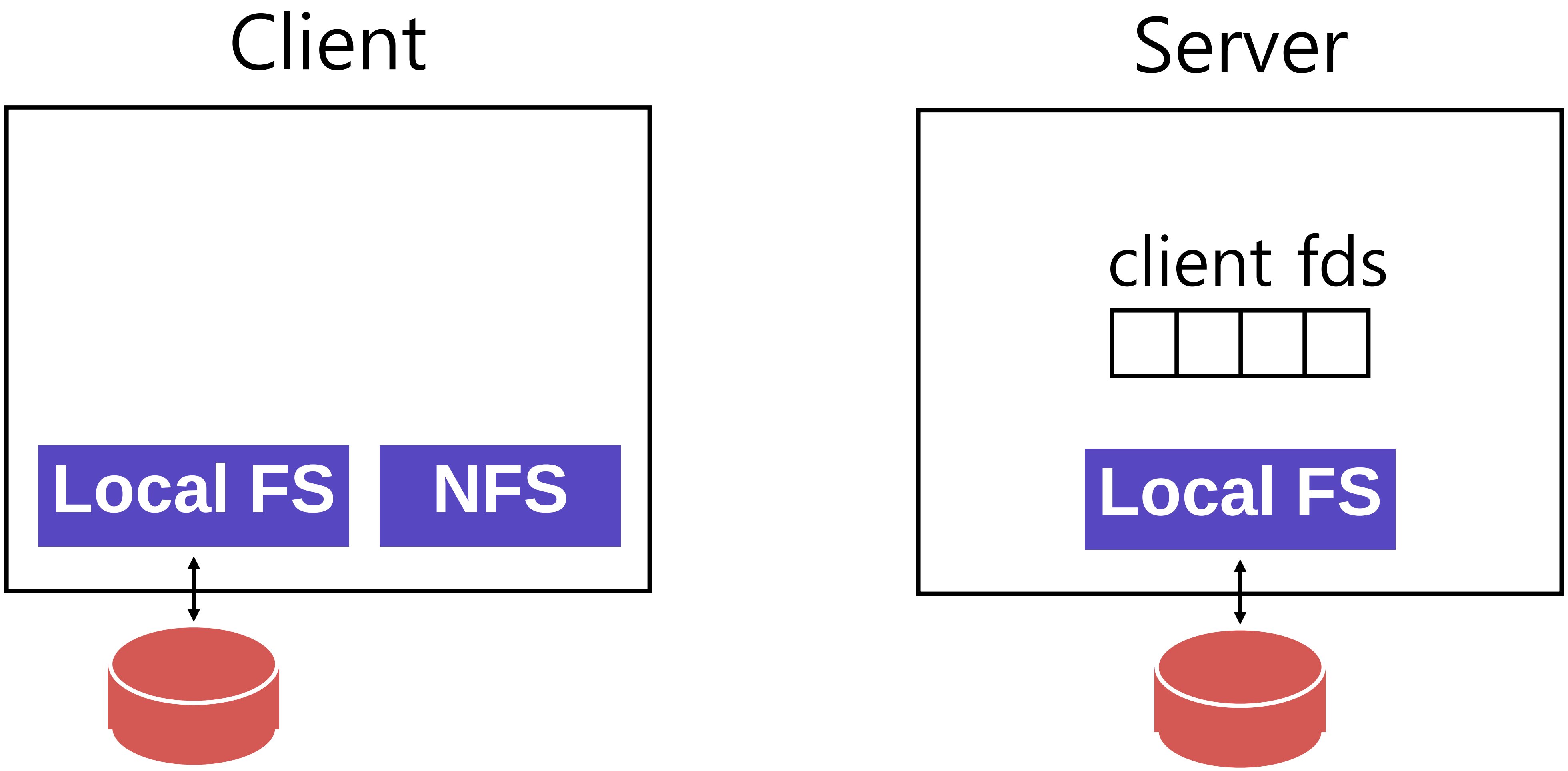
# Strategy 1

Attempt: Wrap regular UNIX system calls using RPC

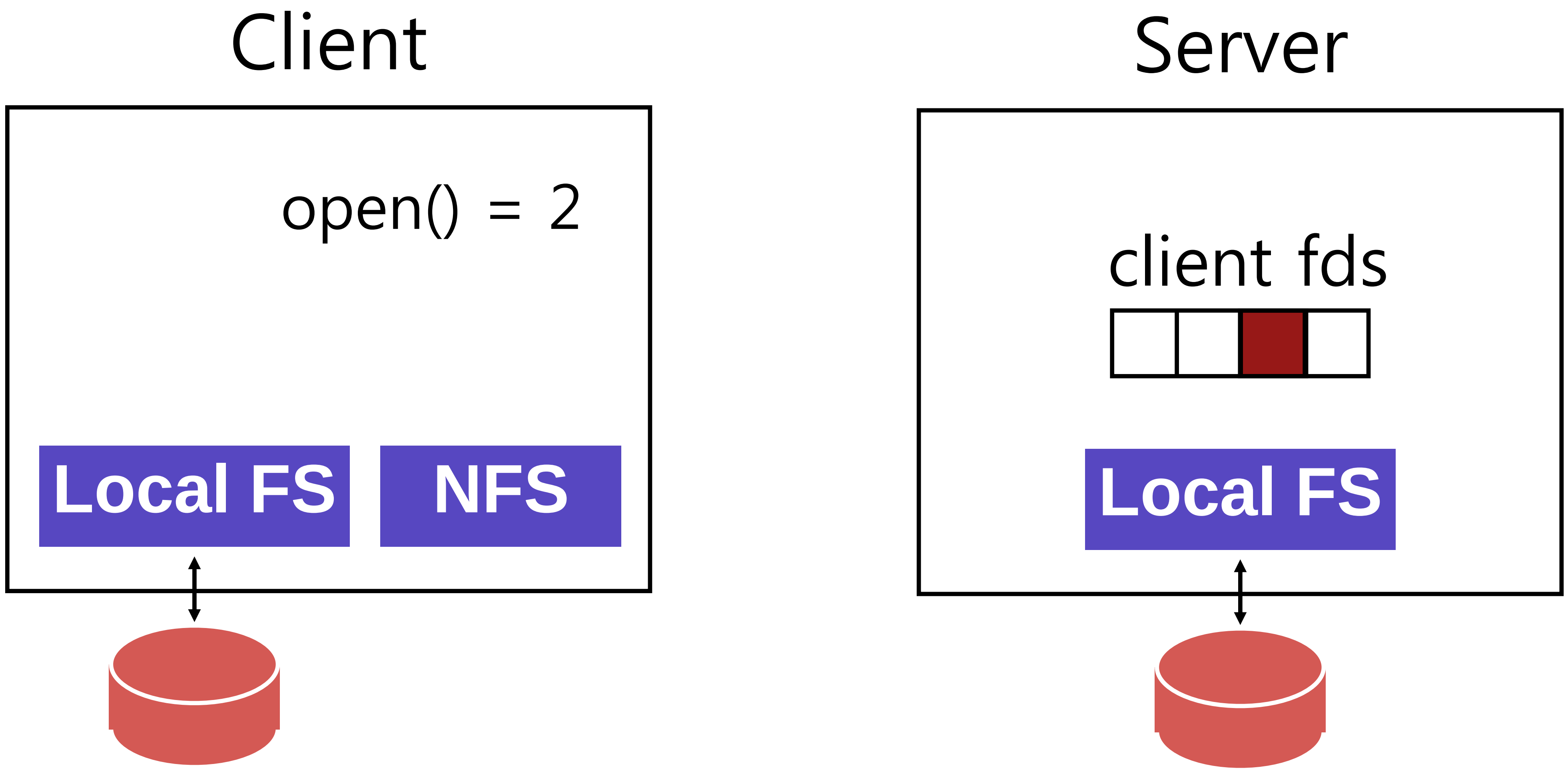
open() on client calls open() on server
open() on server returns fd back to client

read(fd) on client calls read(fd) on server
read(fd) on server returns data back to client

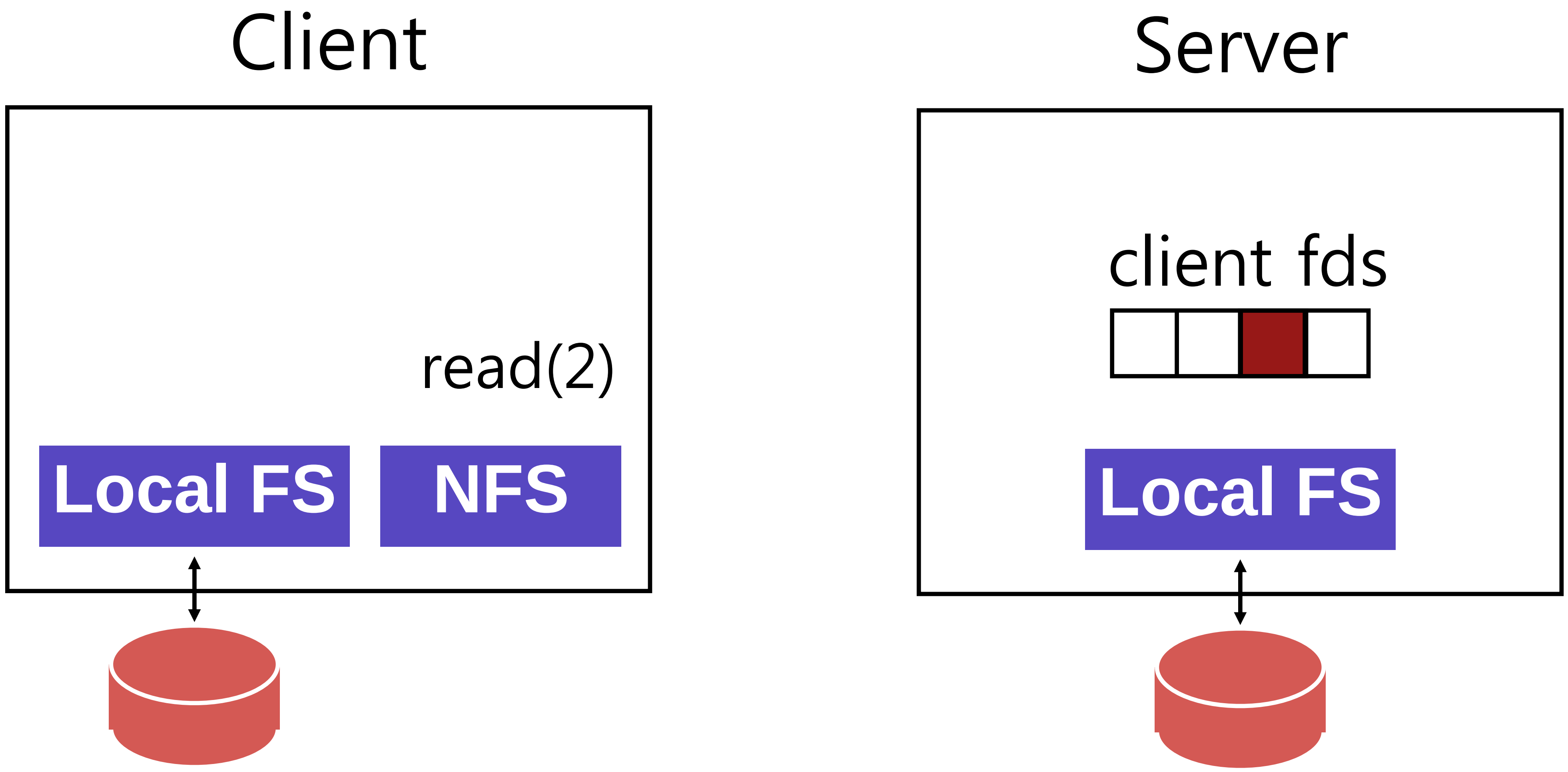
# File Descriptors



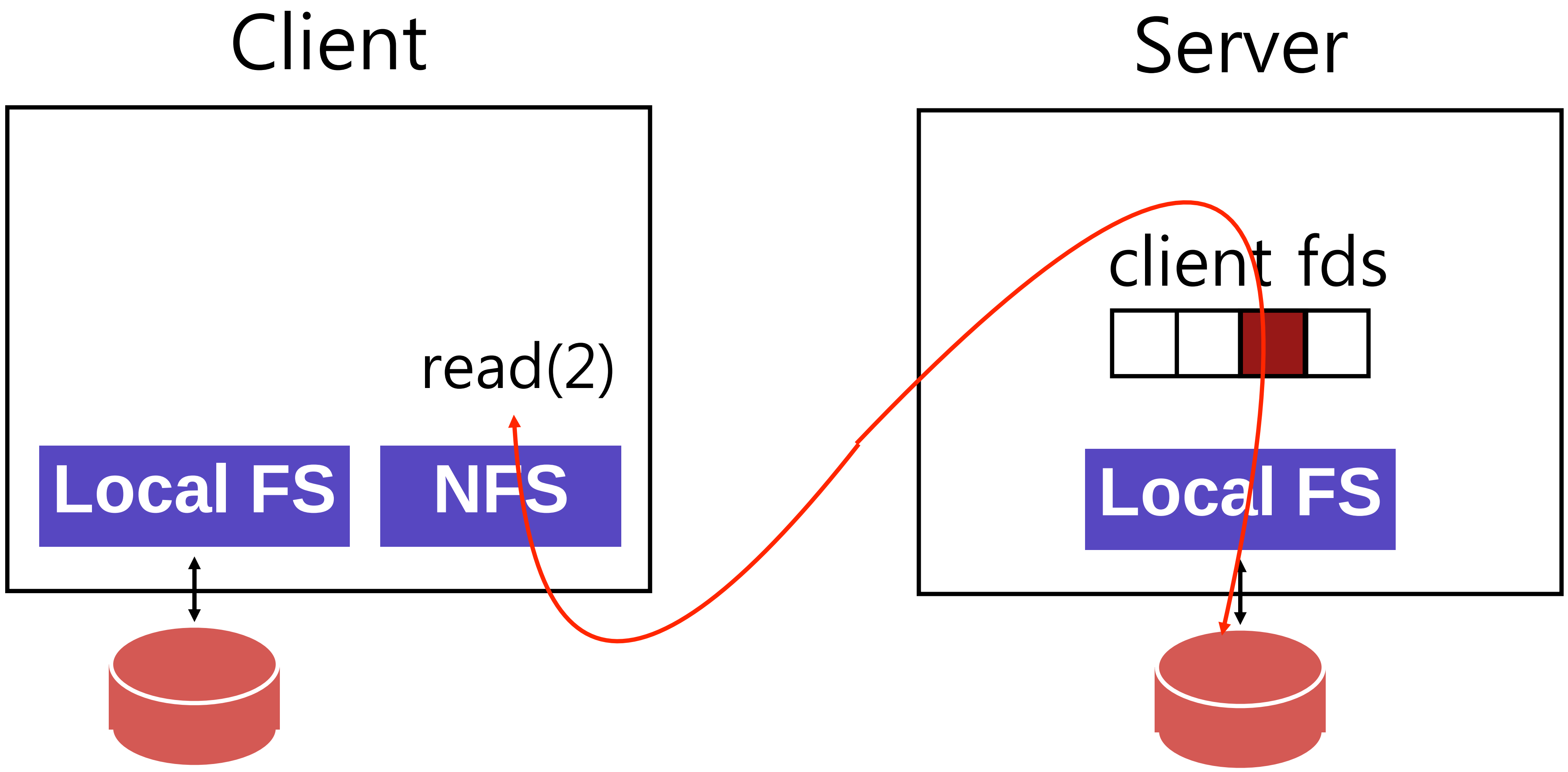
# File Descriptors



# File Descriptors



# File Descriptors



# Strategy 1 Problems

What about crashes?

```
int fd = open("foo", O_RDONLY);
read(fd, buf, MAX);
read(fd, buf, MAX);
...
read(fd, buf, MAX);
```

Server crash!

nice if acts like a slow read

Imagine server crashes and reboots during reads

...

# Sub goals for NFS

Fast + simple crash recovery
- both clients and file server may crash

Transparent access
- can’t tell accesses are over the network
- normal UNIX semantics

Reasonable performance

# Potential Solutions

1. Run some crash recovery protocol upon reboot
   - Complex

2. Persist fds on server disk.
   - Slow
   - What if client crashes? When can fds be garbage collected?

# Sub goals for NFS

Fast + simple crash recovery
 - both clients and file server may crash

Transparent access
 - can’t tell accesses are over the network
 - normal UNIX semantics

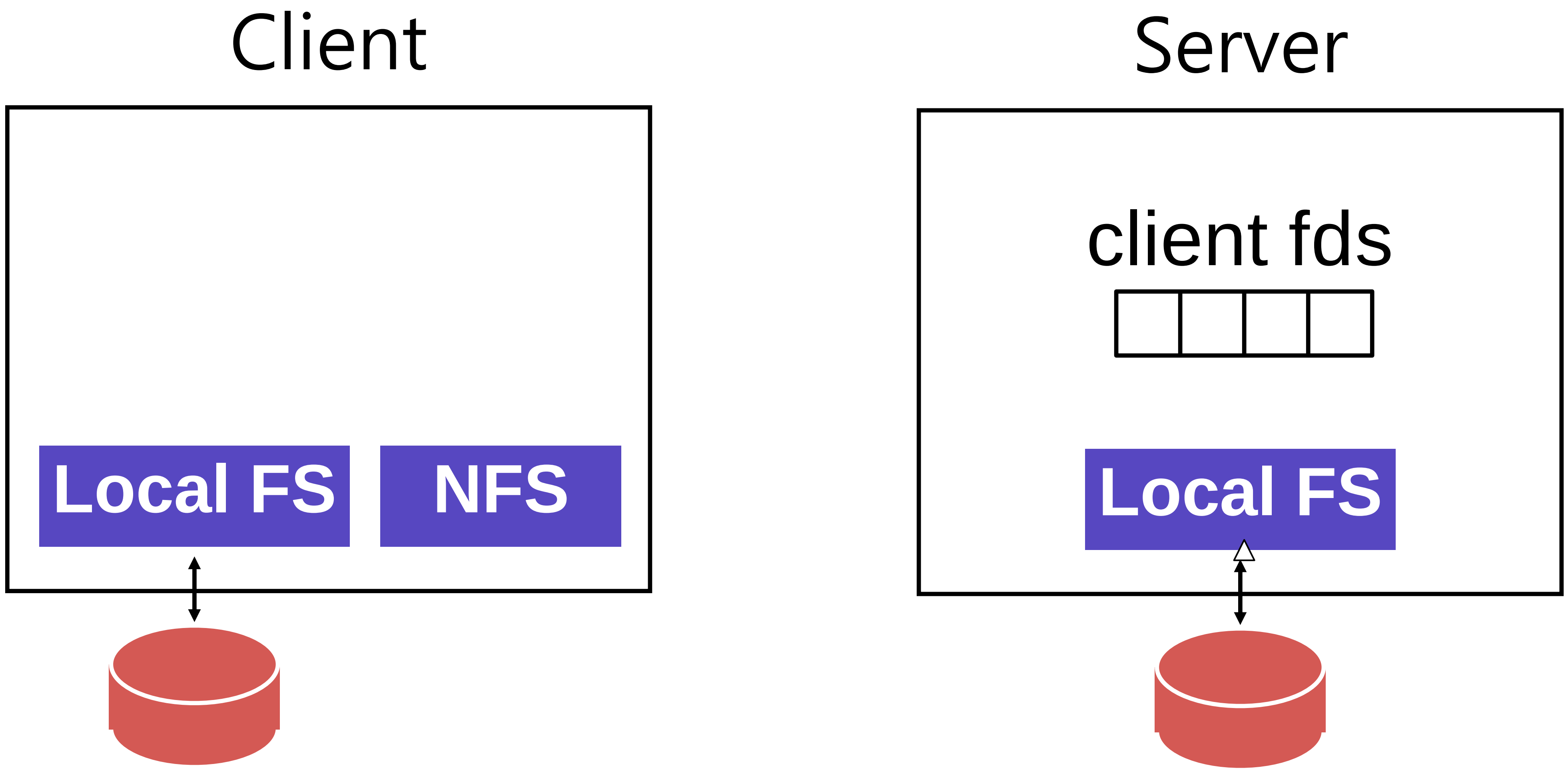
Reasonable performance

# Strategy 2: put all info in requests

Use "stateless" protocol!

- server maintains no state about clients
- server still keeps other state, of course

# Eliminate File Descriptors



# Strategy 2: put all info in requests

Use "stateless" protocol!

- server maintains no state about clients

Need API change. One possibility:

**pread**(<u>char *path</u>, <u>buf</u>, <u>size</u>, <u>offset</u>);
**pwrite**(<u>char *path</u>, <u>buf</u>, <u>size</u>, <u>offset</u>);

Specify path and offset each time. Server need not remem ber anything from clients.

Pros? Server can crash and reboot transparently to clients.

Cons? Too many path lookups.

# Strategy 3: inode requests

**pread**(<u>char *path</u>, <u>buf</u>, <u>size</u>, <u>offset</u>);
**pwrite**(<u>char *path</u>, <u>buf</u>, <u>size</u>, <u>offset</u>);

# Strategy 3: inode requests

inode = **open**(<u>char *path</u>);

**pread**(<u>inode</u>, <u>buf</u>, <u>size</u>, <u>offset</u>);

**pwrite**(<u>inode</u>, <u>buf</u>, <u>size</u>, <u>offset</u>);

This is pretty good! Any correctness problems?

If file is deleted, the inode could be reused

- Inode not guaranteed to be unique over time

# Strategy 4: file handles

fh = **open**(<u>char *path</u>);

**pread**(<u>fh</u>, <u>buf</u>, <u>size</u>, <u>offset</u>);

**pwrite**(<u>fh</u>, <u>buf</u>, <u>size</u>, <u>offset</u>);

File Handle = <volume ID, inode #, **generation #**>

Opaque to client (client should not interpret internals)

# Can NFS Protocol include Append?

fh = **open**(<u>char *path</u>);

**pread**(<u>fh</u>, <u>buf</u>, <u>size</u>, <u>offset</u>);

**pwrite**(<u>fh</u>, <u>buf</u>, <u>size</u>, <u>offset</u>);

append(<u>fh</u>, <u>buf</u>, <u>size</u>);

Problem with append()?

If RPC library retries if no ACK or return, what happens when append() is retried?

Problem: Why is it difficult to not replay append()?

# Replica Suppression is Stateful

Sender

[send message]

[timout]

[send message]

[recv ack]

Receiver

[recv message]

[send ack]

[ignore message]

[send ack]

TCP suppresses repeated message

Problem: TCP is stateful

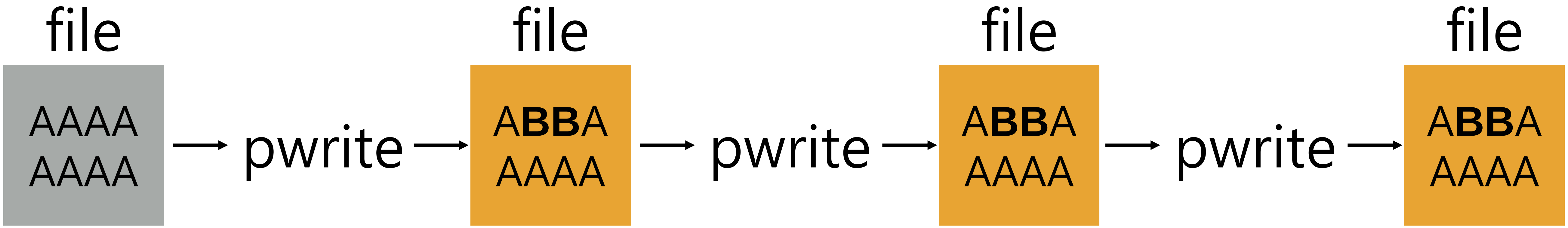
If server crashes, forgets which RPC's have been executed!

# Idempotent Operations

Solution:
Design API so no harm to executing function more tha
n once

If f() is idempotent, then:
    f() has the same effect as f(); f(); ... f(); f()

# pwrite is idempotent



# append is NOT idempotent

# What operations are Idempotent?

Idempotent
- any sort of read that doesn't change anything
- pwrite

Not idempotent
- append

What about these?
- mkdir
- creat

# Strategy 4: file handles

fh = **open**(char *path);

**pread**(fh, buf, size, offset);

**pwrite**(fh, buf, size, offset);

~~**append**(fh, buf, size);~~

File Handle = <volume ID, inode #, generation #>

# Sub goals for NFS

Fast + simple crash recovery
- both clients and file server may crash

Transparent access
- can't tell accesses are over the network
- normal UNIX semantics

Reasonable performance

# Strategy 5: client logic

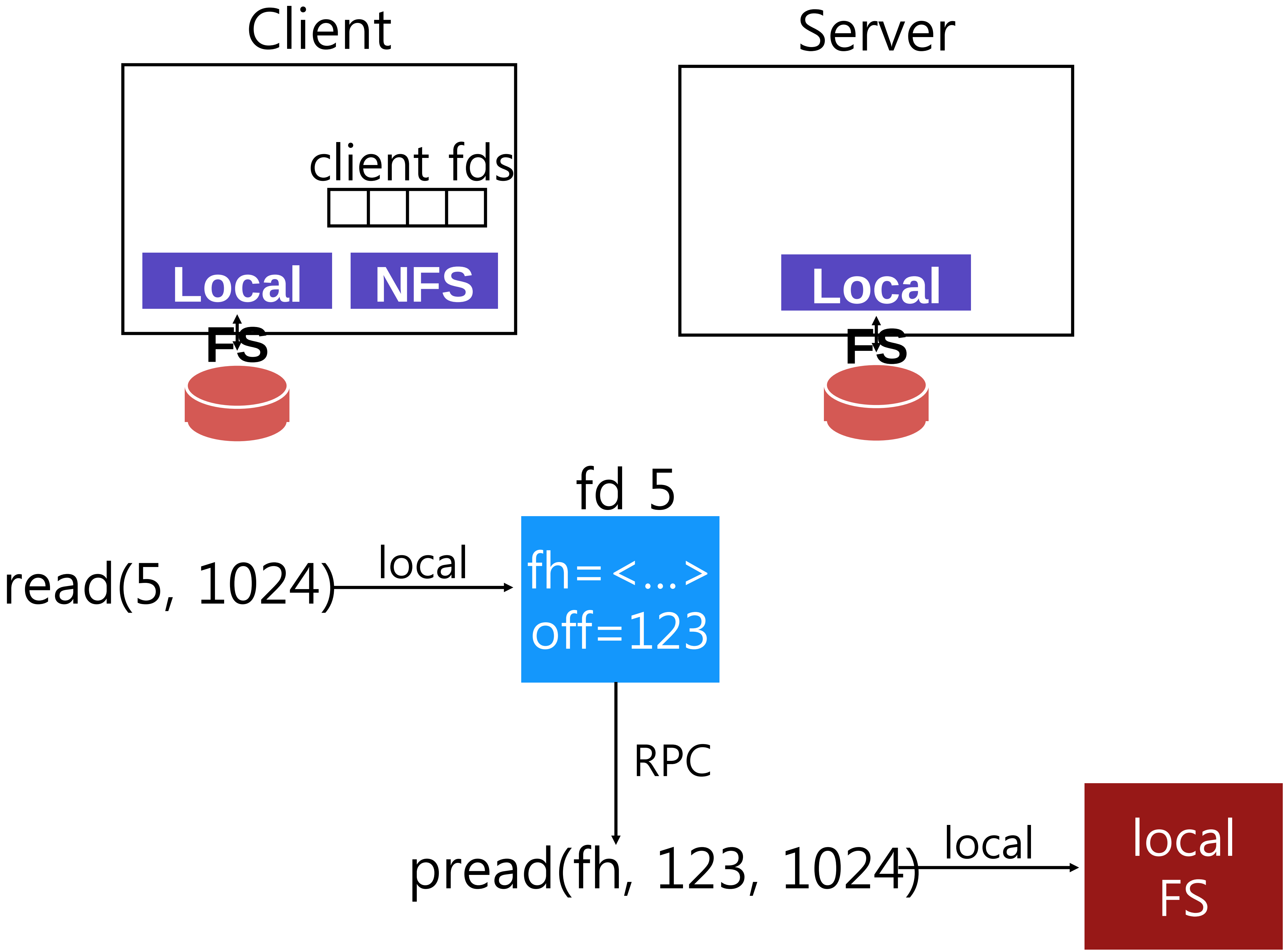
Build normal UNIX API on client side on top of idempotent, RPC-based API

Client open() creates a local fd object

It contains:

- file handle
- offset

# File Descriptors



# Overview

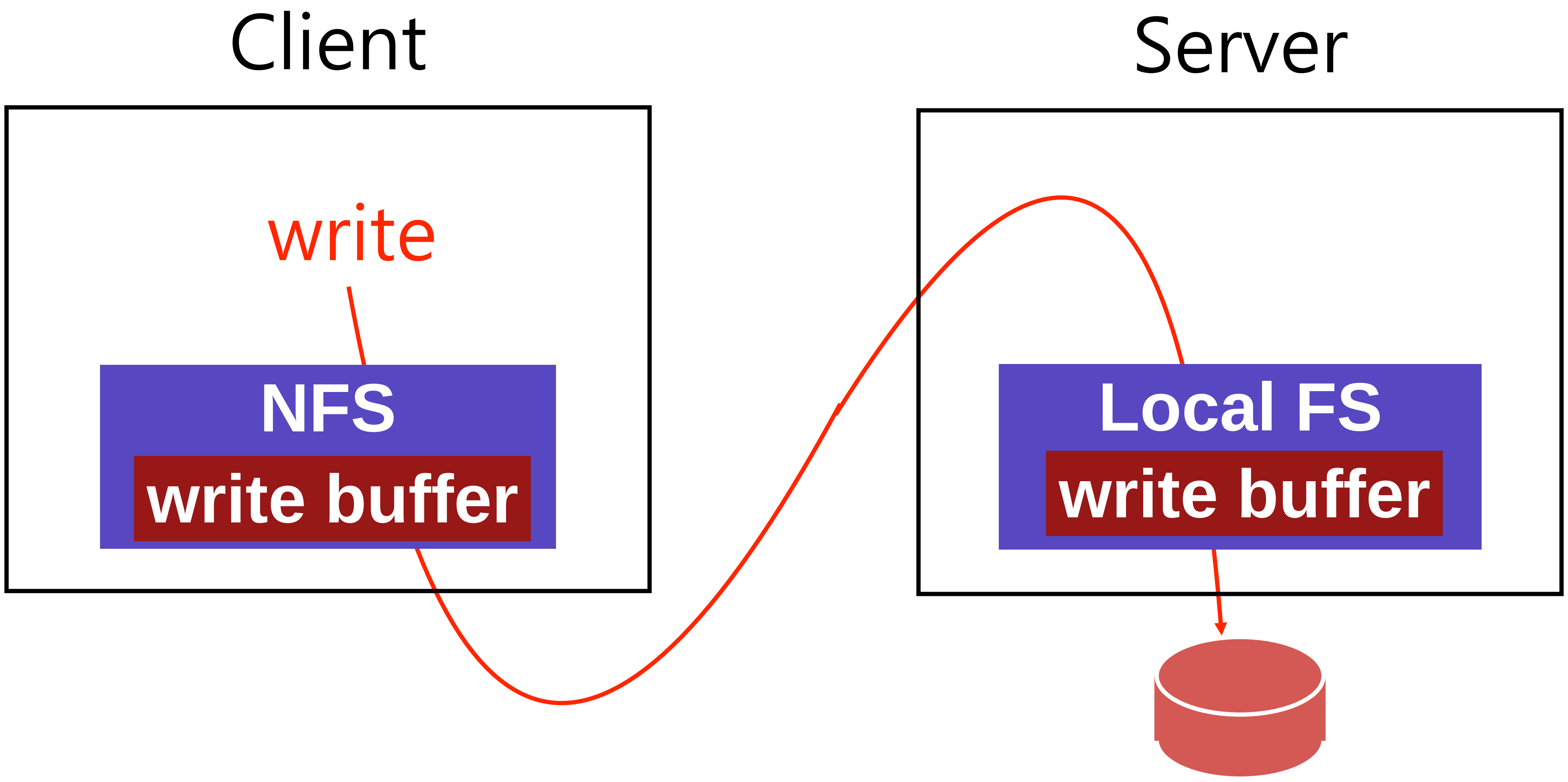
~~Architecture~~

~~Network API~~

Write Buffering

Cache

# Write Buffers




server acknowledges write before write is pushed to disk;
what happens if server crashes?

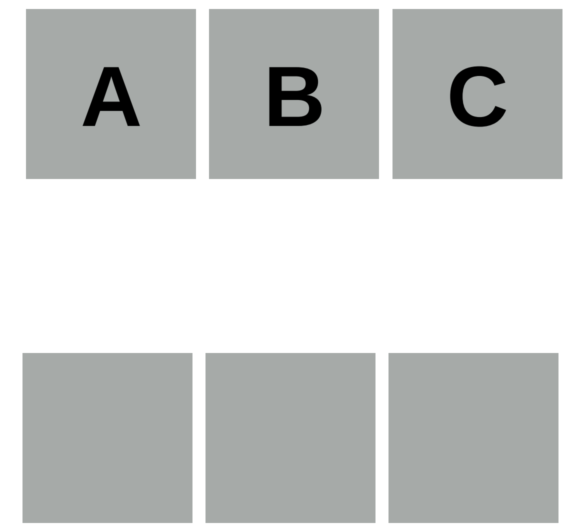
# Server Write Buffer Lost

client:

write A to 0
write B to 1
write C to 2

server mem:

server disk:




server acknowledges write before write is pushed to disk

# Server Write Buffer Lost

client:

write A to 0
write B to 1
write C to 2

server mem: | A | B | C |

server disk: | A | B | C |

server acknowledges write before write is pushed to disk

# Server Write Buffer Lost

client:

write A to 0
write B to 1
write C to 2

write X to 0

server mem: X B C

server disk: A B C

server acknowledges write before write is pushed to disk

# Server Write Buffer Lost

client:

write A to 0
write B to 1
write C to 2

write X to 0

server mem: | X | B | C |

server disk: | X | B | C |

server acknowledges write before write is pushed to disk

# Server Write Buffer Lost

client:

write A to 0
write B to 1
write C to 2

write X to 0
write Y to 1

server mem: X Y C

server disk: X B C

server acknowledges write before write is pushed to disk

# Server Write Buffer Lost

client:

write A to 0

write B to 1

write C to 2

write X to 0

write Y to 1

server mem:

| | | |
|---|---|---|
| | | |

server disk:

| | | |
|---|---|---|
| **X** | **B** | **C** |

crash!

server acknowledges write before write is pushed to disk

# Server Write Buffer Lost

client:

write A to 0

write B to 1

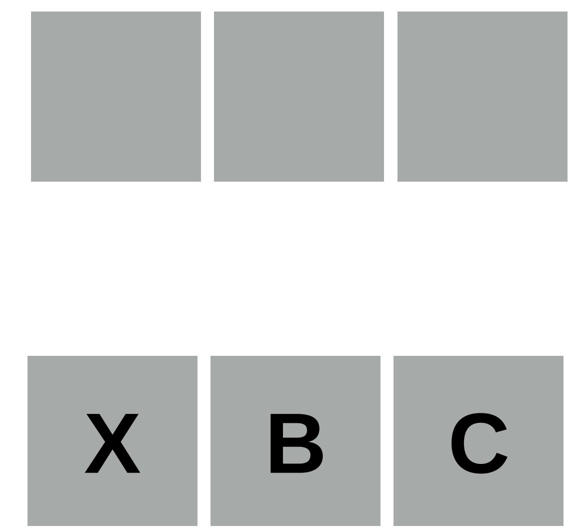
write C to 2

write X to 0

write Y to 1

server mem:

server disk:

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# Server Write Buffer Lost

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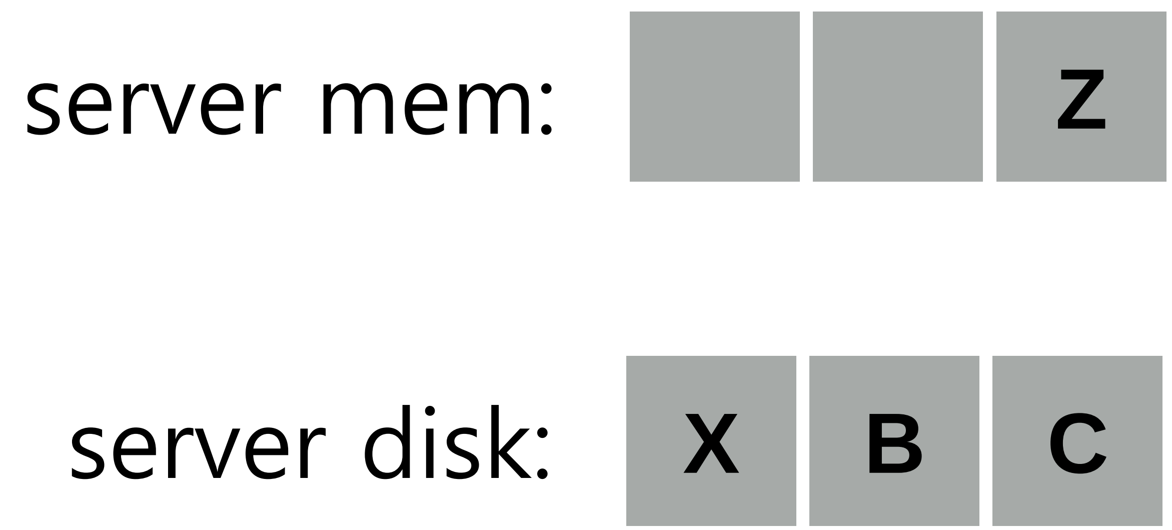



server acknowledges write before write is pushed to disk

# Server Write Buffer Lost

client:

write A to 0

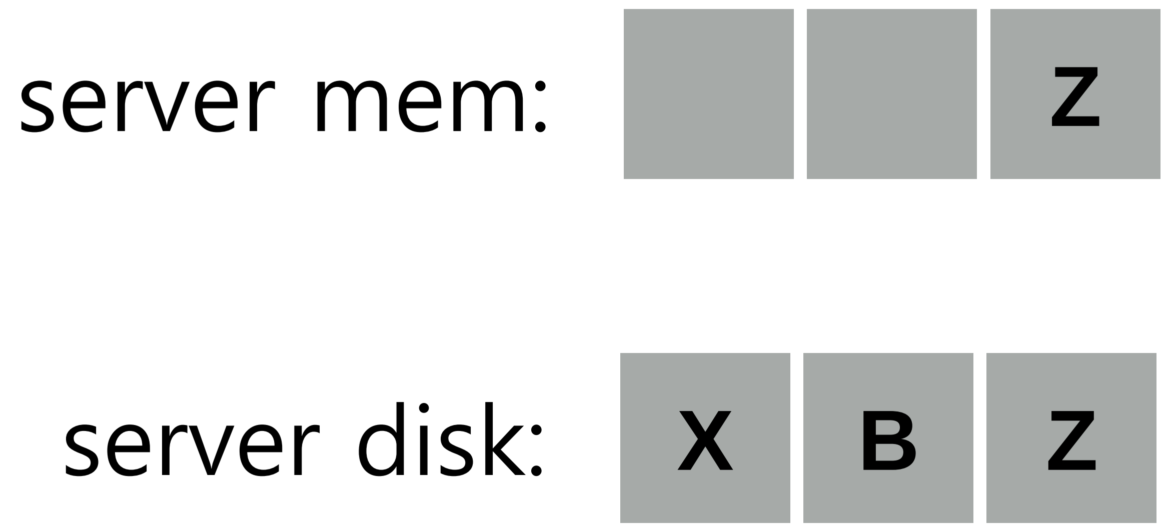
write B to 1

write C to 2

write X to 0

write Y to 1

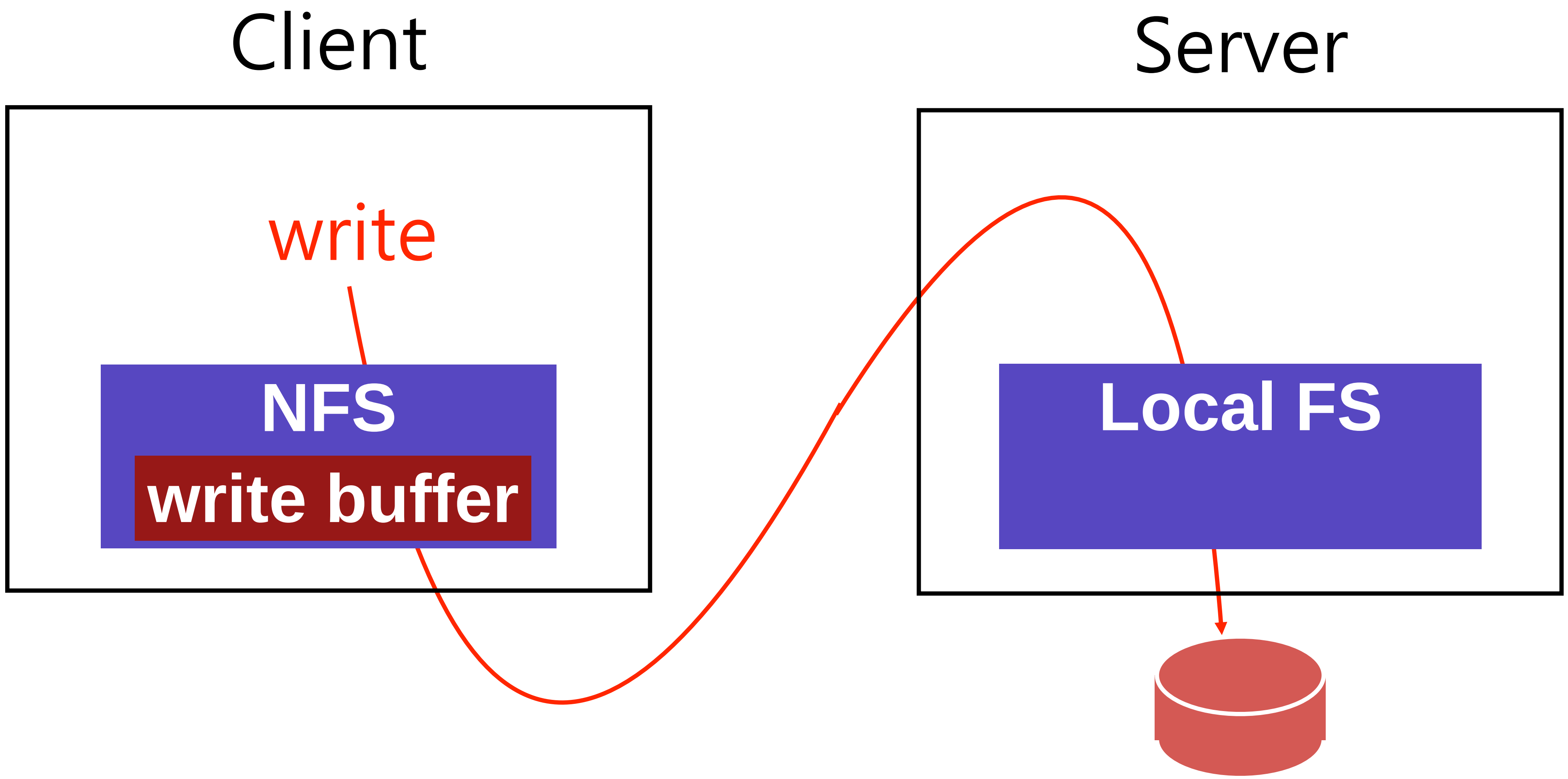
write Z to 2




Problem:
No write failed, but disk state doesn't match any point in time

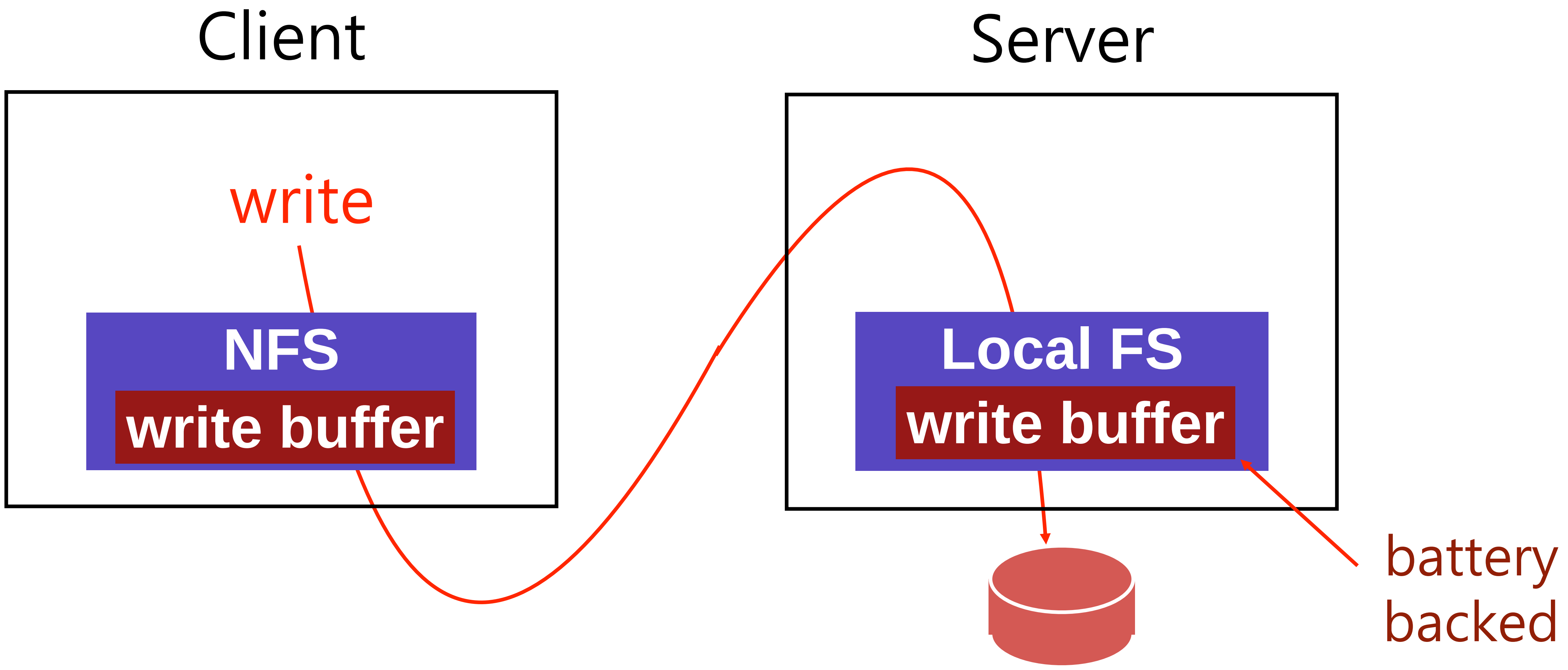
Solutions????

# Write Buffers




1. Don't use server write buffer
(persist data to disk before acknowledging write)
Problem: Slow!

# Write Buffers




2. use persistent write buffer (more expensive)

# Overview

~~Architecture~~

~~Network API~~

~~Write Buffering~~

Cache

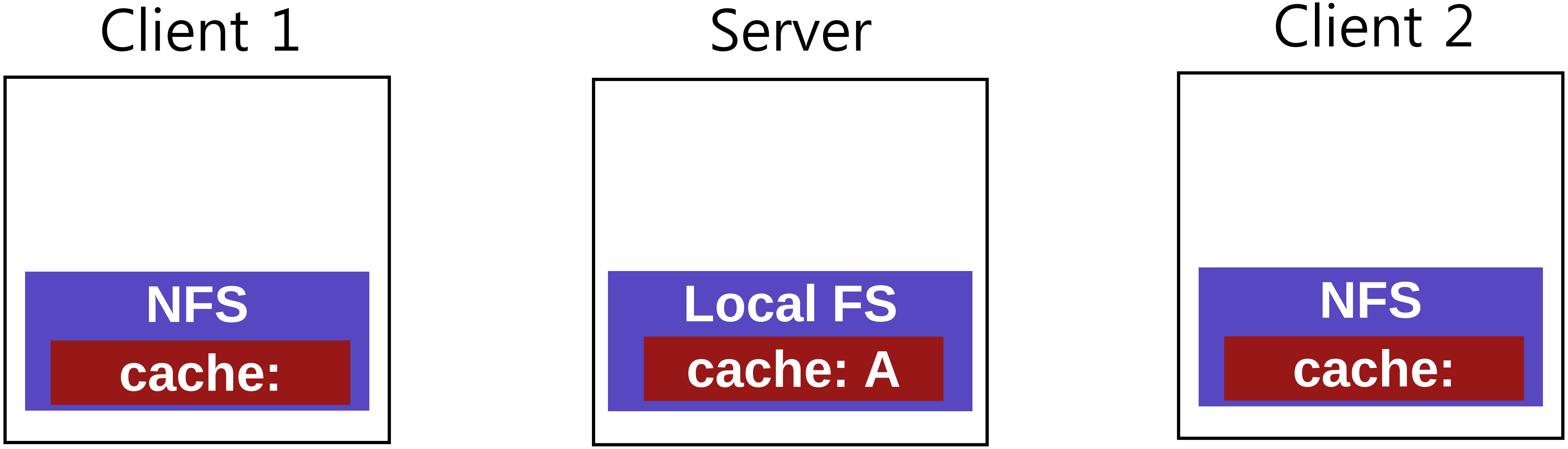
# Cache Consistency

NFS can cache data in three places:

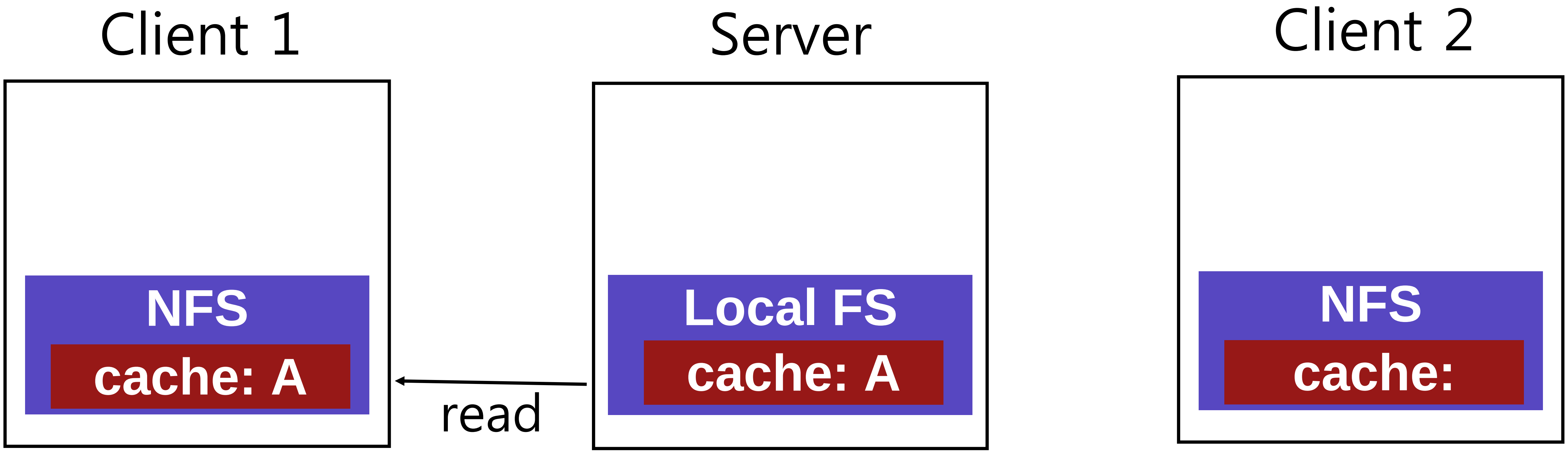
- server memory
- client disk
- client memory

How to make sure all versions are in sync?

# Distributed Cache

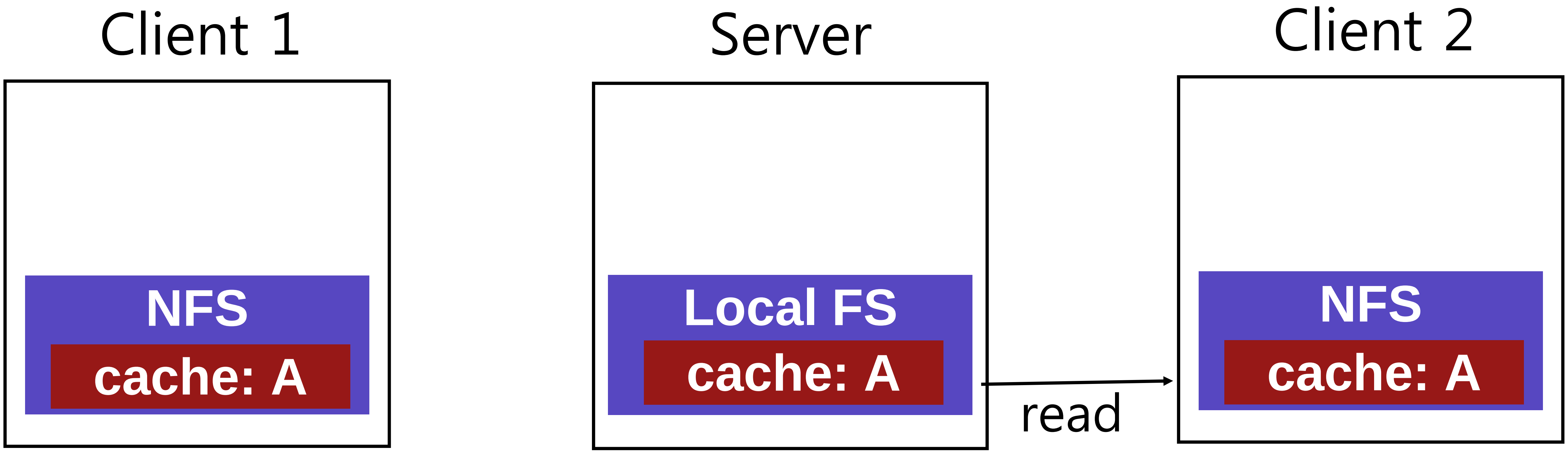


# Cache

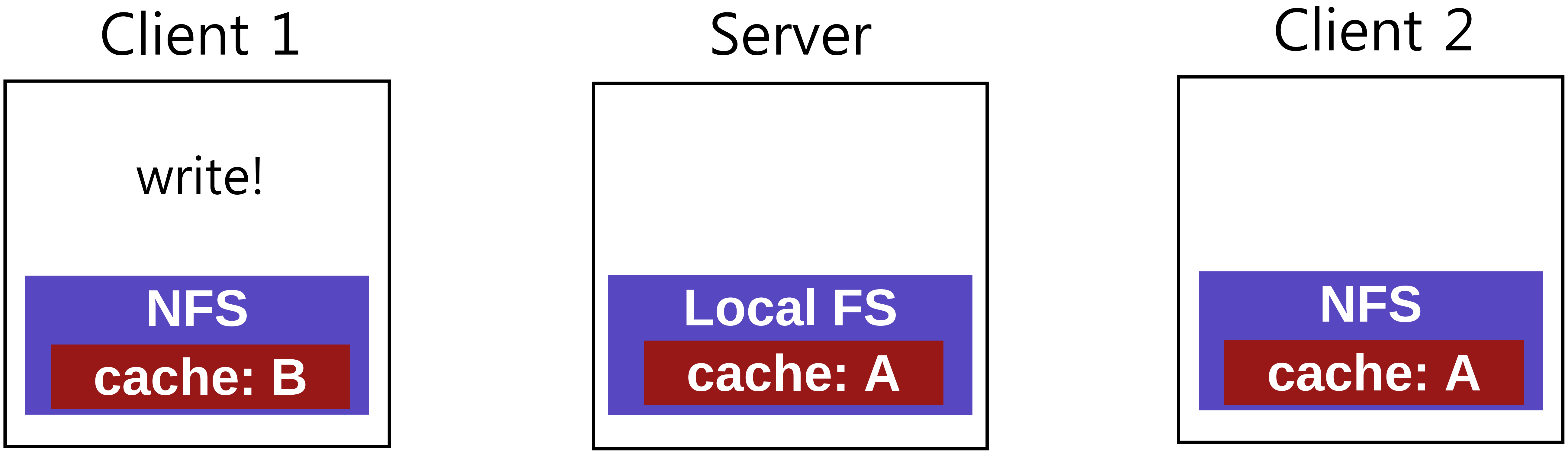


Client 1
Server
Client 2
NFS
cache: A
read
Local FS
cache: A
NFS
cache:

# Cache


Client 1
Server
Client 2
NFS
cache: A
Local FS
cache: A
read
NFS
cache: A

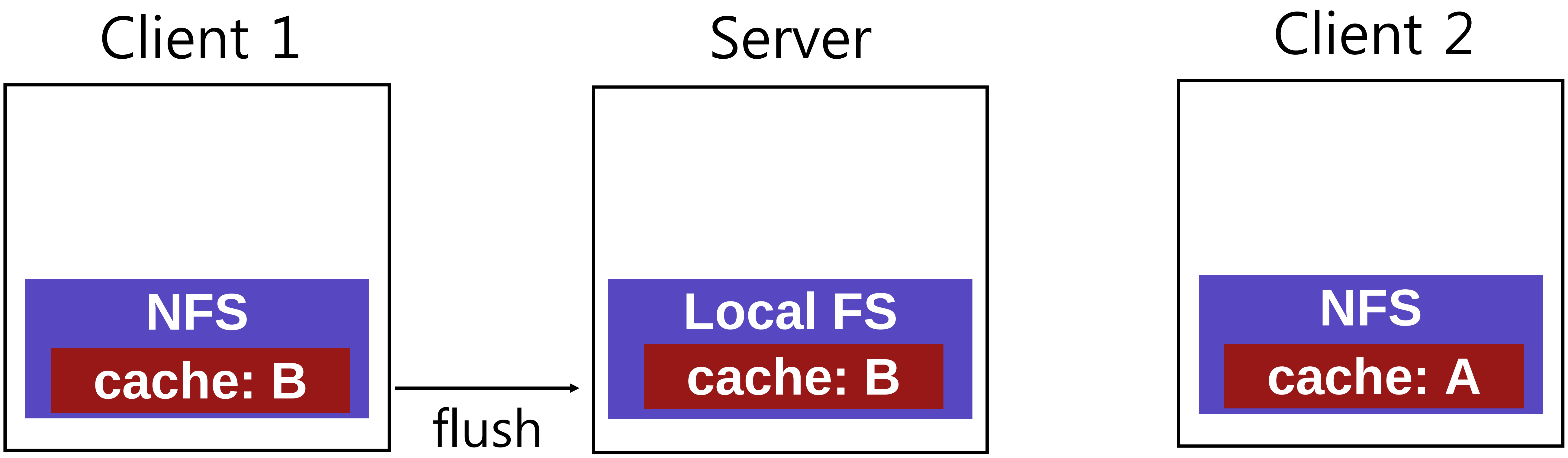
# Cache




"Update Visibility" problem:
server doesn't have latest version

What happens if Client 2 (or any other client) reads data?
Sees old version (different semantics than local FS)

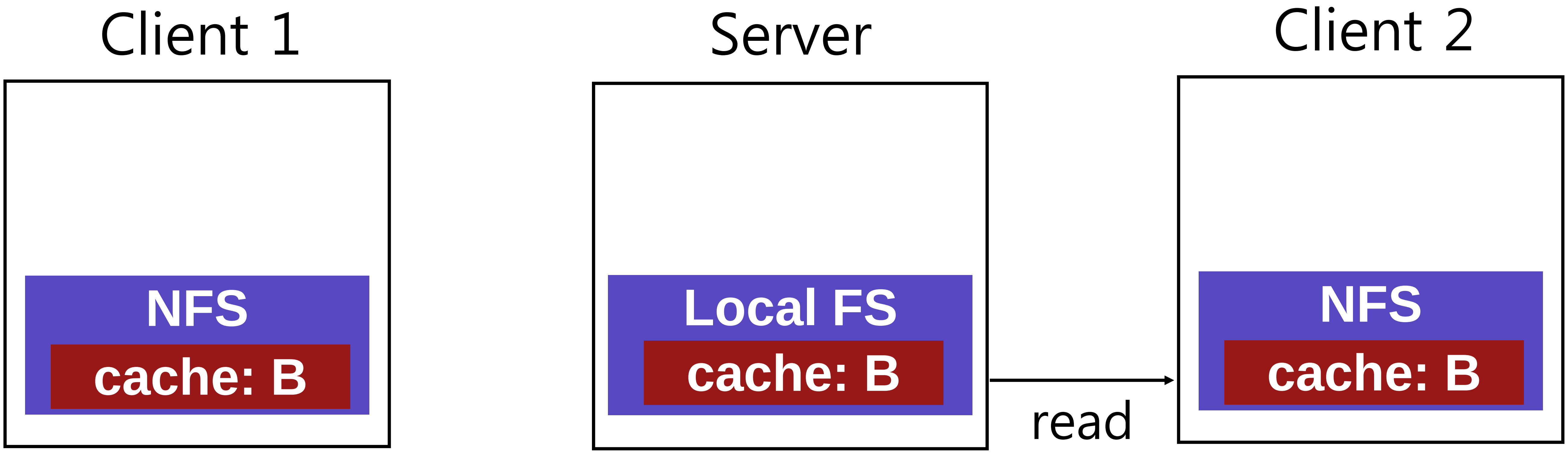
# Cache



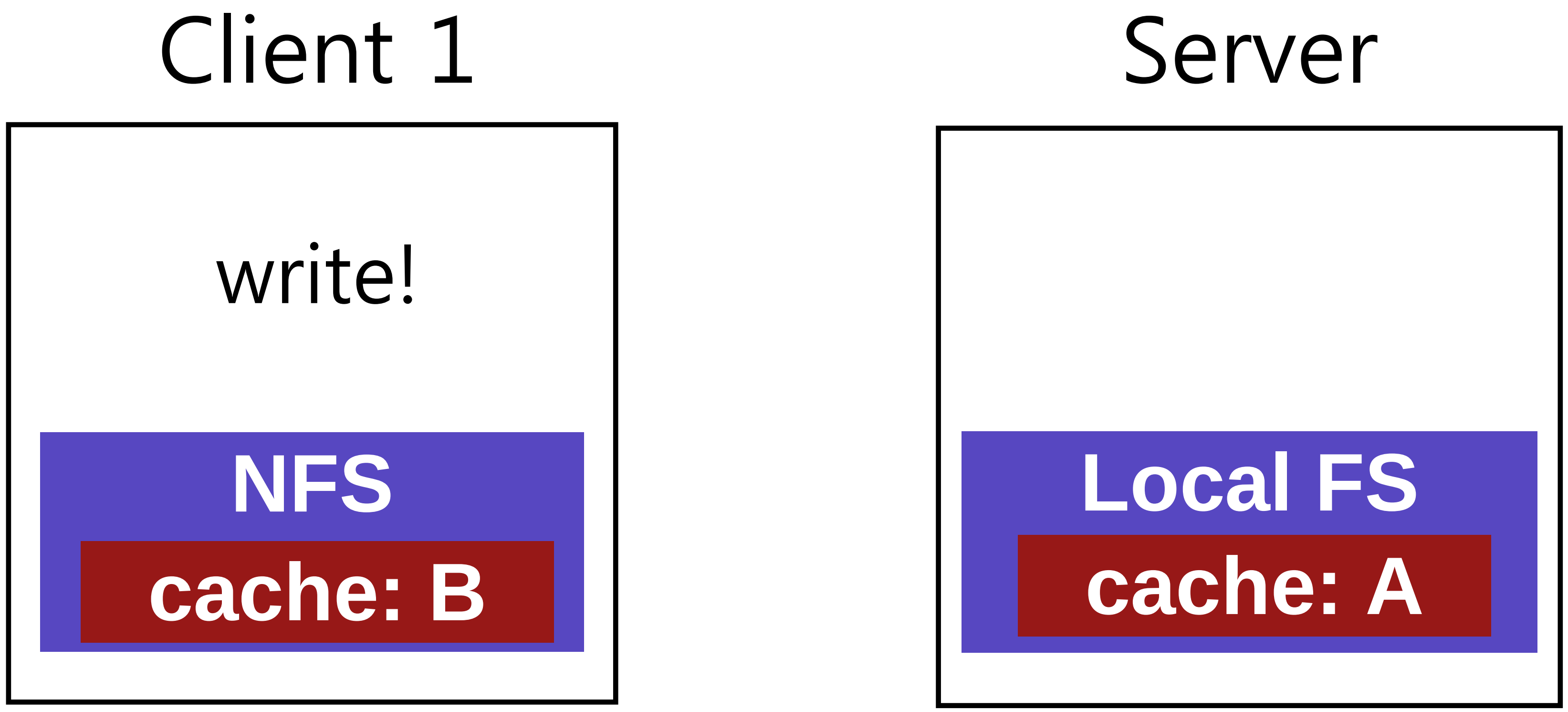

"Stale Cache" problem:
client 2 doesn't have latest version

What happens if Client 2 reads data?
Sees old version (different semantics than local FS)

# Cache


Client 1
Server
Client 2
NFS
cache: B
Local FS
cache: B
NFS
cache: B
read

# Problem 1: Update Visibility



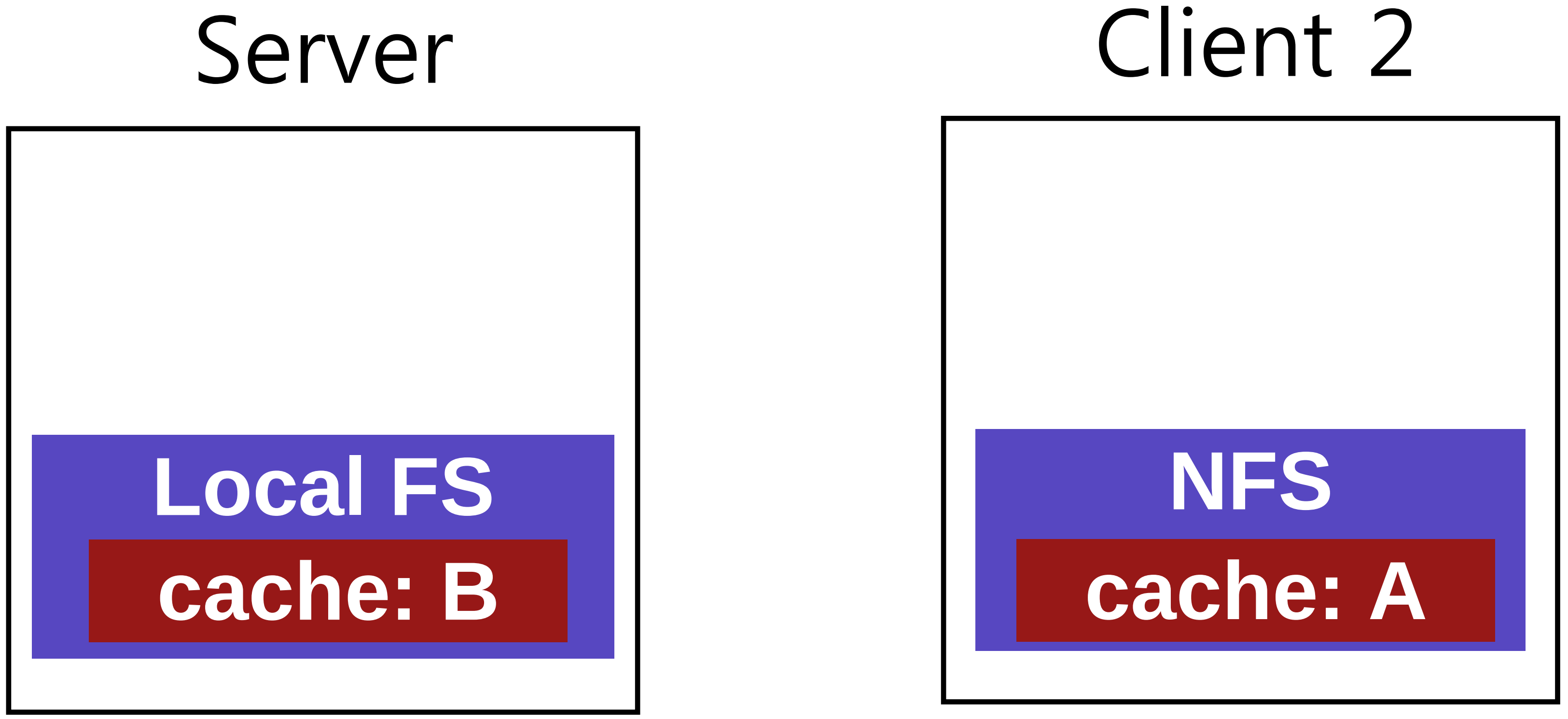

When client buffers a write, how can server (and other clients) see update?

- Client flushes cache entry to server

**When** should client perform flush????? (3 reasonable options??)

NFS solution: flush on fd close(not quite like UNIX)

# Problem 2: Stale Cache




Problem: Client 2 has stale copy of data; how can it get the latest?

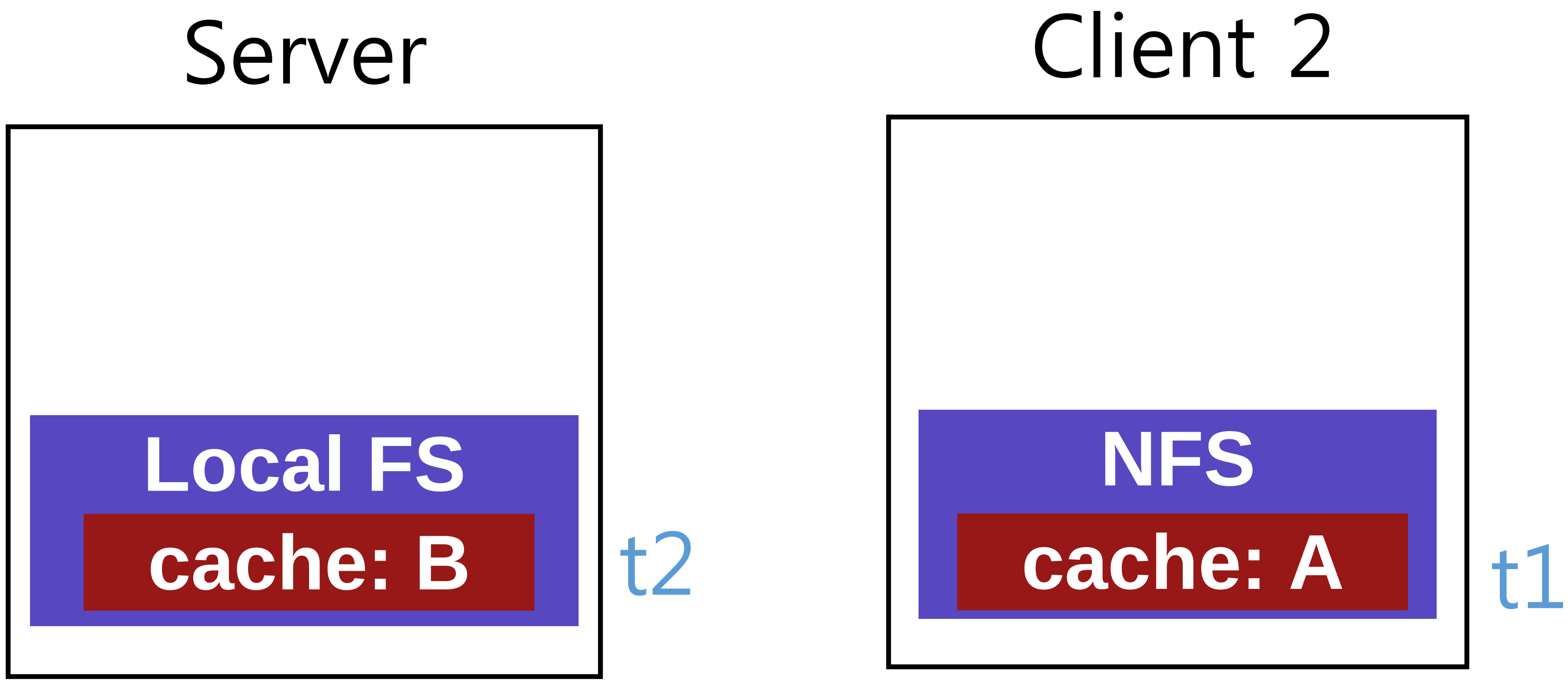
One possible solution:

- If NFS had state, server could push out update to relevant clien ts

NFS solution:

- Clients recheck if cached copy is current before using data

# Stale Cache Solution




Client cache records time when data block was fetched (t1)

Before using data block, client does a STAT request to server

- get's last modified timestamp for this file (t2) (not block…)
- compare to cache timestamp
- refetch data block if changed since timestamp (t2 > t1)

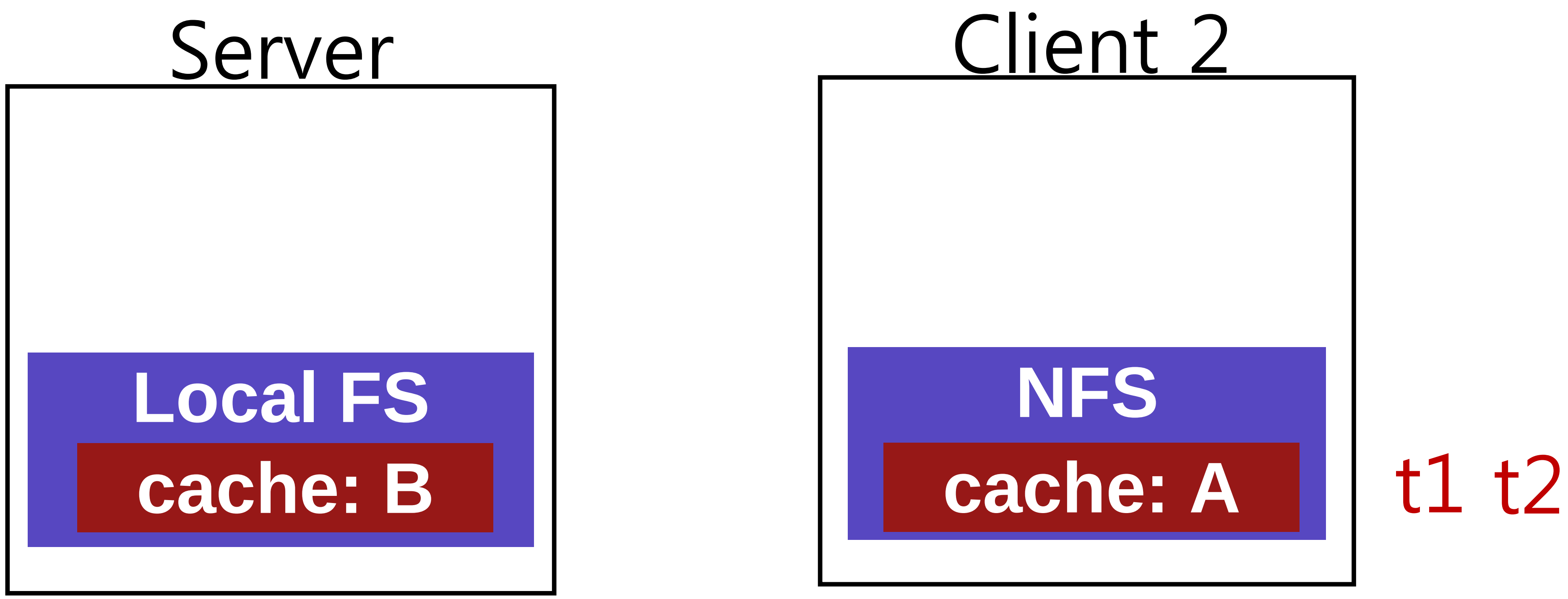
# Measure then Build

NFS developers found stat accounted for 90% of server requests

Why?

Because clients frequently recheck cache

# Reducing Stat Calls




Solution: cache results of stat calls

What is the result? Never see updates on server!

Partial Solution: Make stat cache entries expire after a given tim e (e.g., 3 seconds) (discard t2 at client 2)

What is the result? Could read data that is up to 3 seconds old

# NFS Summary

NFS handles client and server crashes very well;
robust APIs are often:

- **stateless**: servers don't remember clients
- **idempotent**: doing things twice never hurts

Caching and write buffering is harder in distributed syste ms, especially with crashes

Problems:

- Consistency model is odd (client may not see updates unt il 3 seconds after file is closed)
- Scalability limitations as more clients call stat() on server

# AFS Goals

Primary goal: scalability!  (many clients per server)

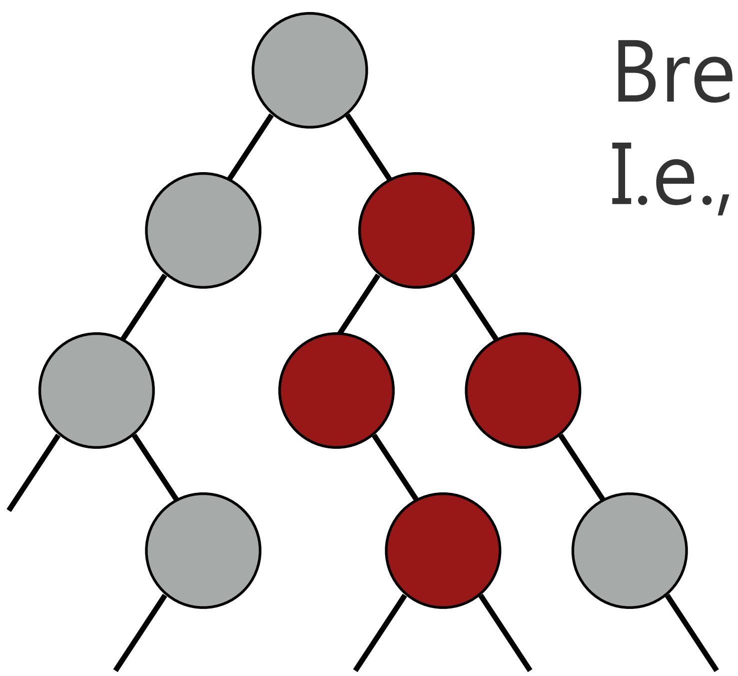
More reasonable semantics for concurrent file access

Not good about handling some failure scenarios.

# AFS Design

NFS: Server exports local FS

AFS: Directory tree stored across many server machines (helps scalability!)

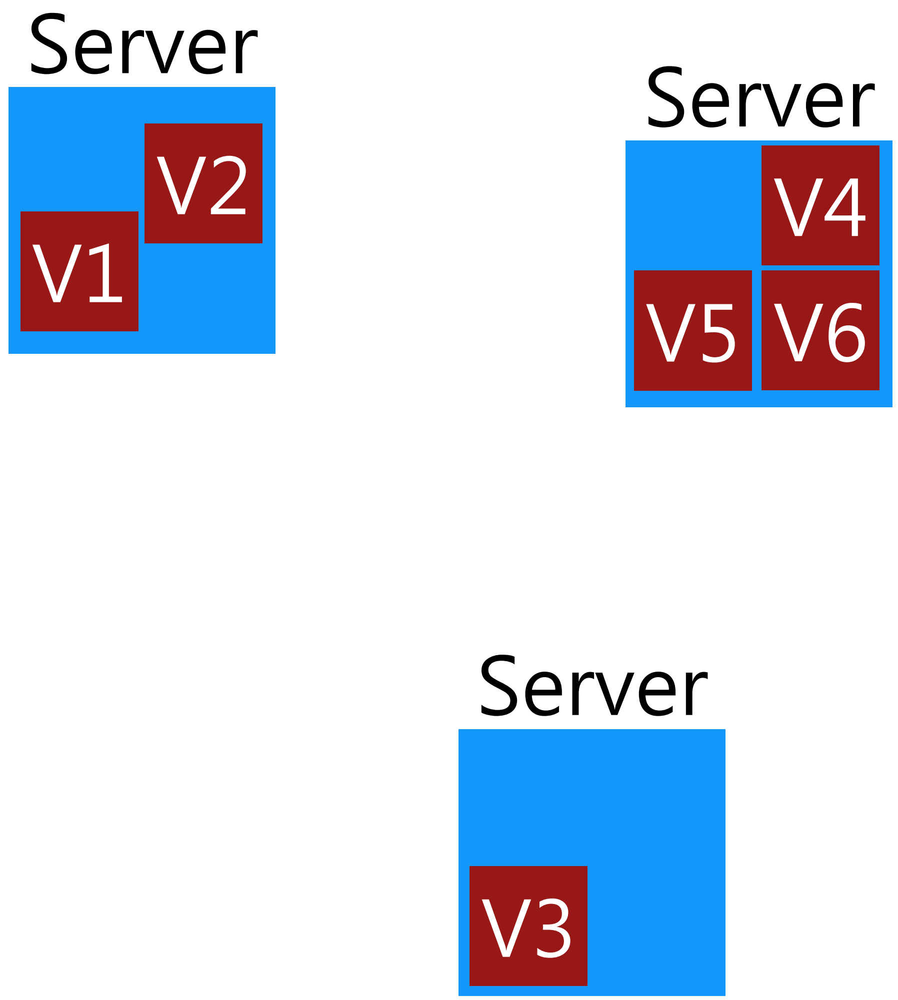


Break directory tree into "volumes"
I.e., partial sub trees

# Viewing Volumes

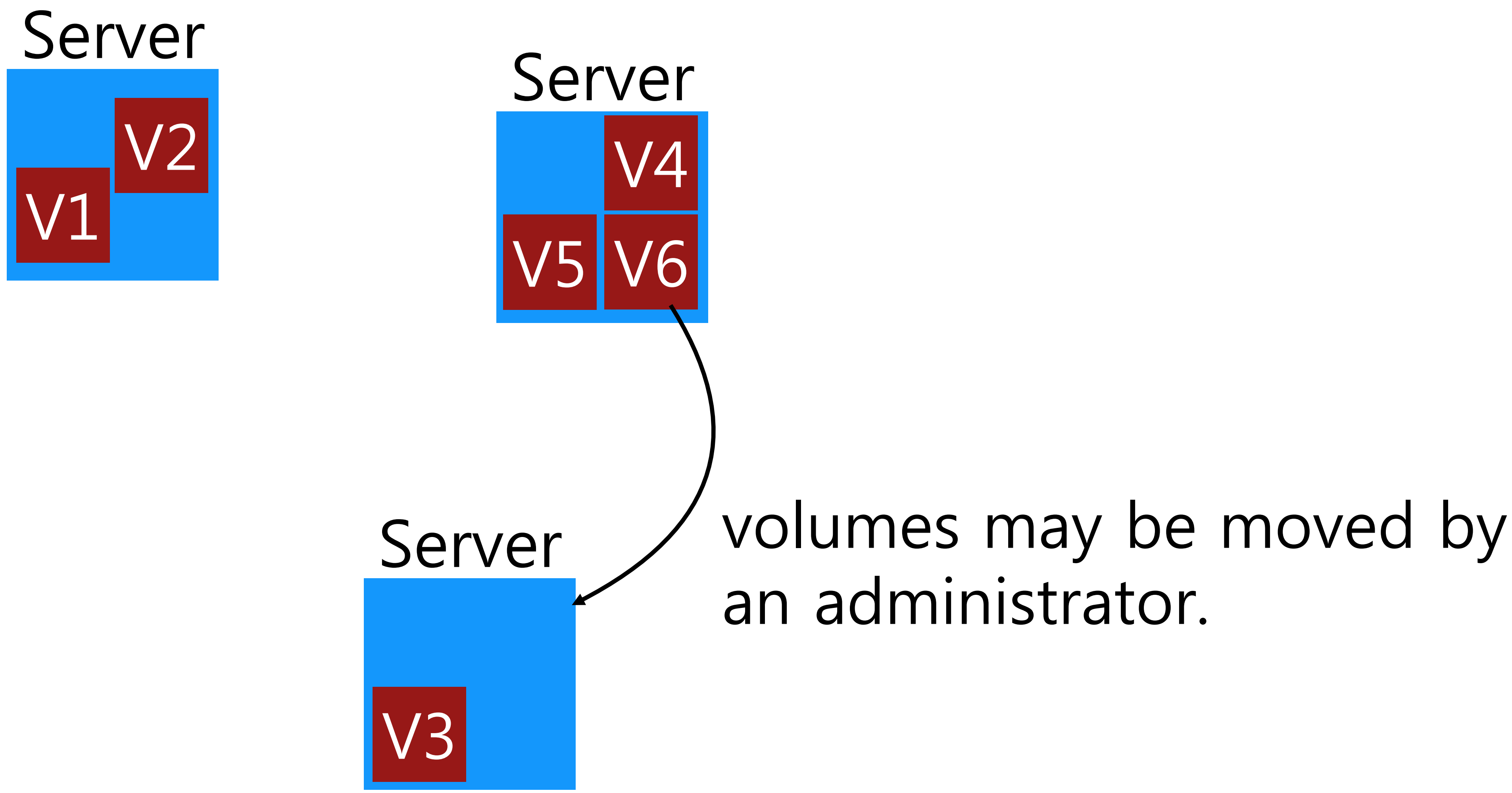
```
[harter@egg] (3)$ pwd
/u/h/a/harter
[harter@egg] (4)$ fs lq
Volume Name          Quota       Used %Used   Partition
u.harter         100000000   12964328   13%         76%
[harter@egg] (5)$ cd /p/wind/
[harter@egg] (6)$ fs lq
Volume Name          Quota       Used %Used   Partition
p.wind.root      100000000    1000208    1%          0%
```

# Volume Architecture

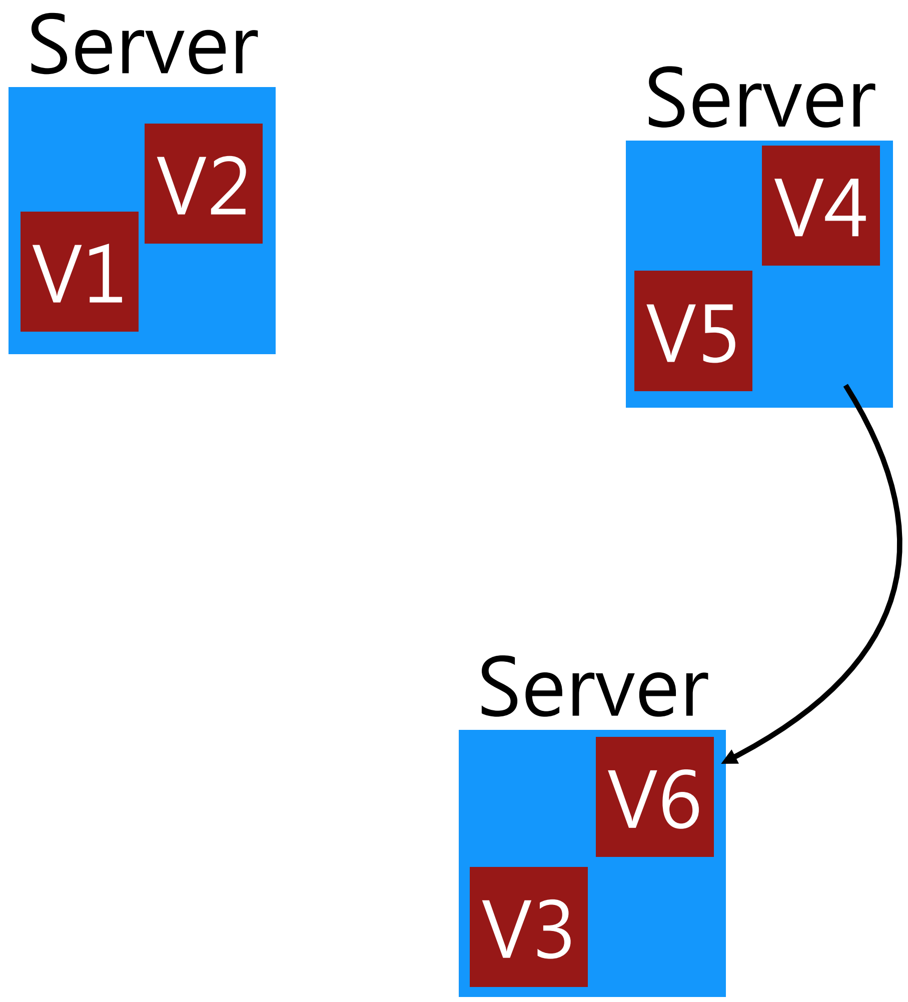



collection of servers store different volumes that together form directory tree

# Volume Architecture

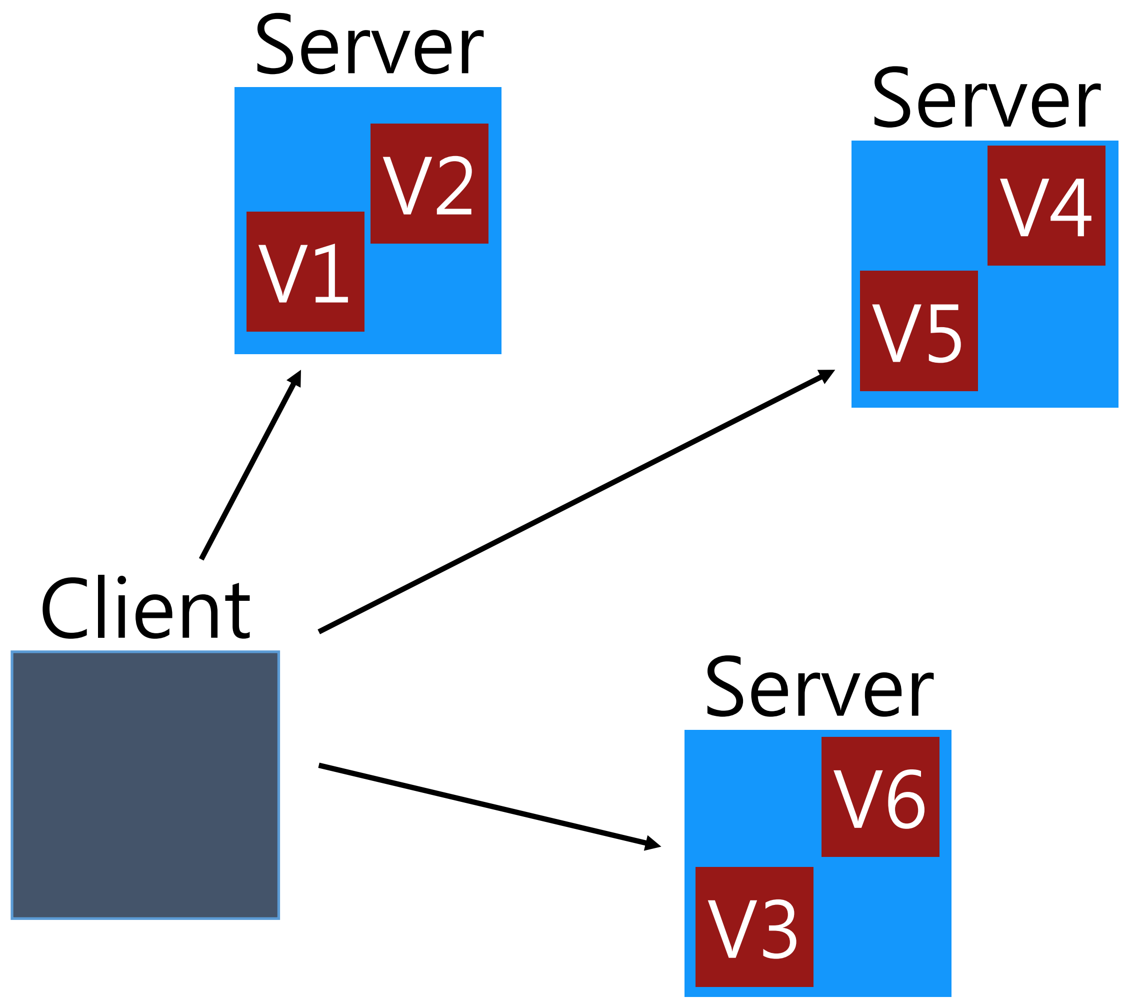


# Volume Architecture




volumes may be moved by an administrator.

# Volume Architecture




Client library gives seamless view of directory tree by automatically finding volumes

Communication via RPC
Servers store data in local file systems

# Outline

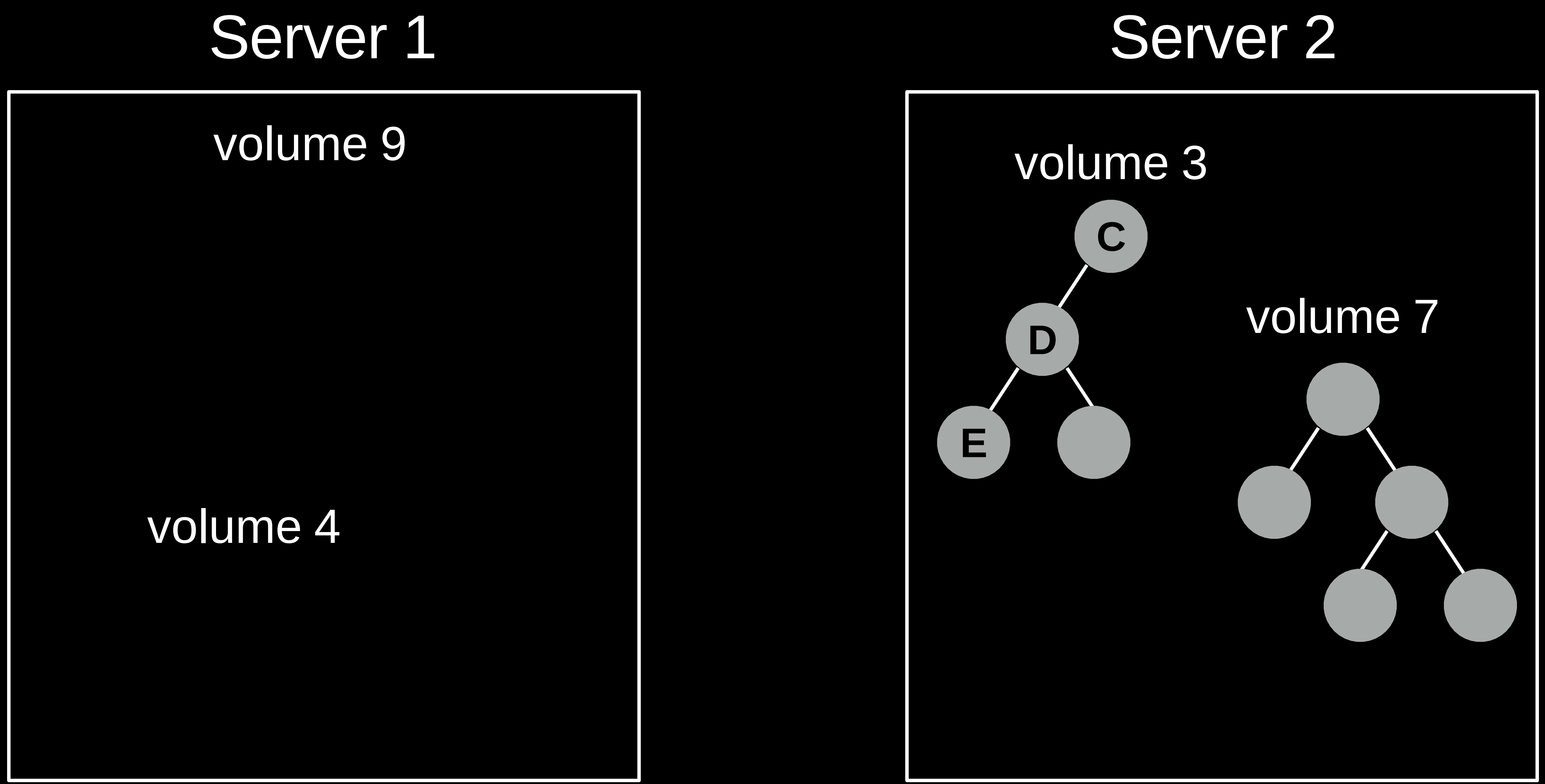
Volume management
Cache management
Name resolution
Process structure
Local-storage API
File locks.

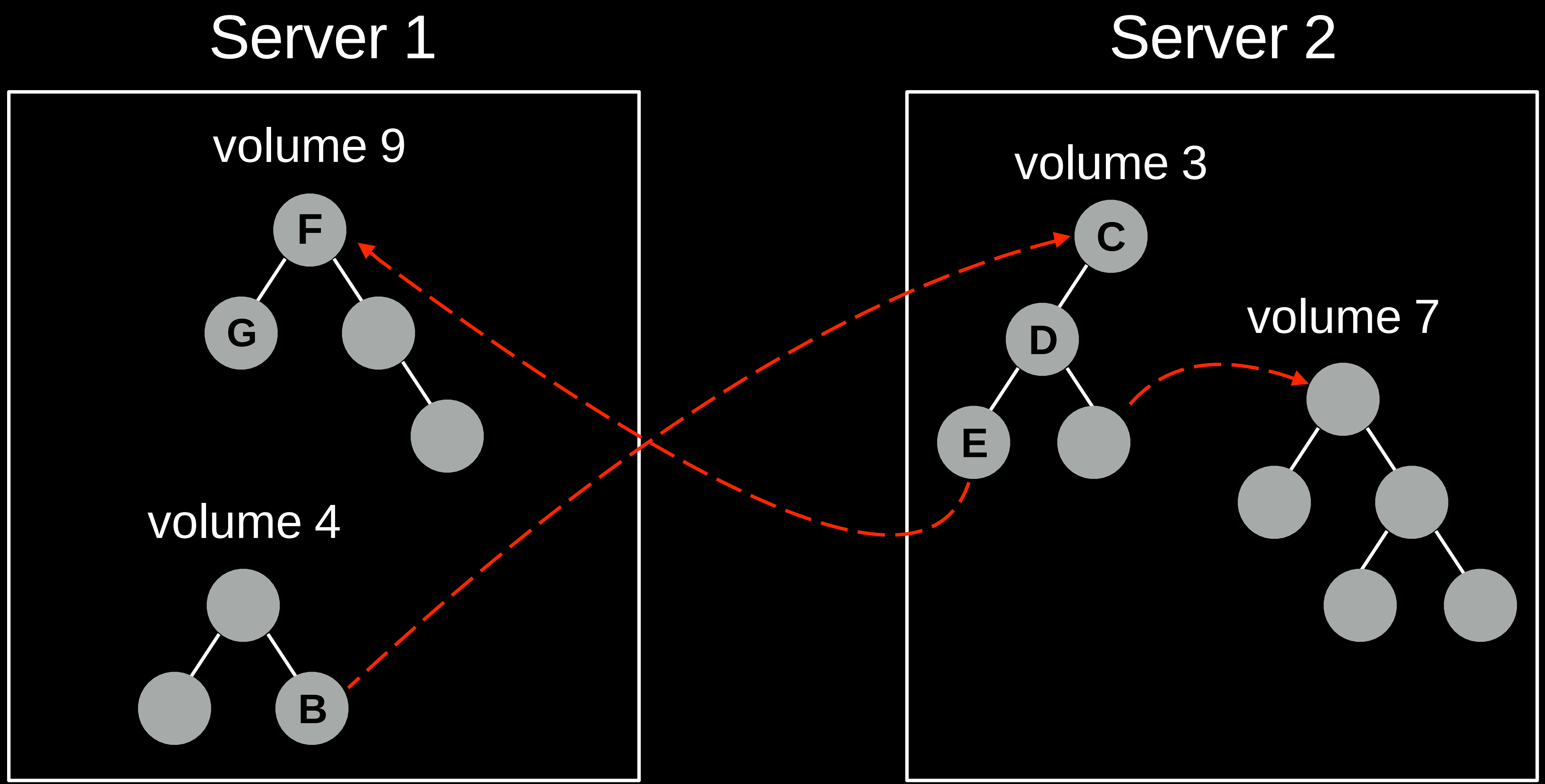
# Volume Glue

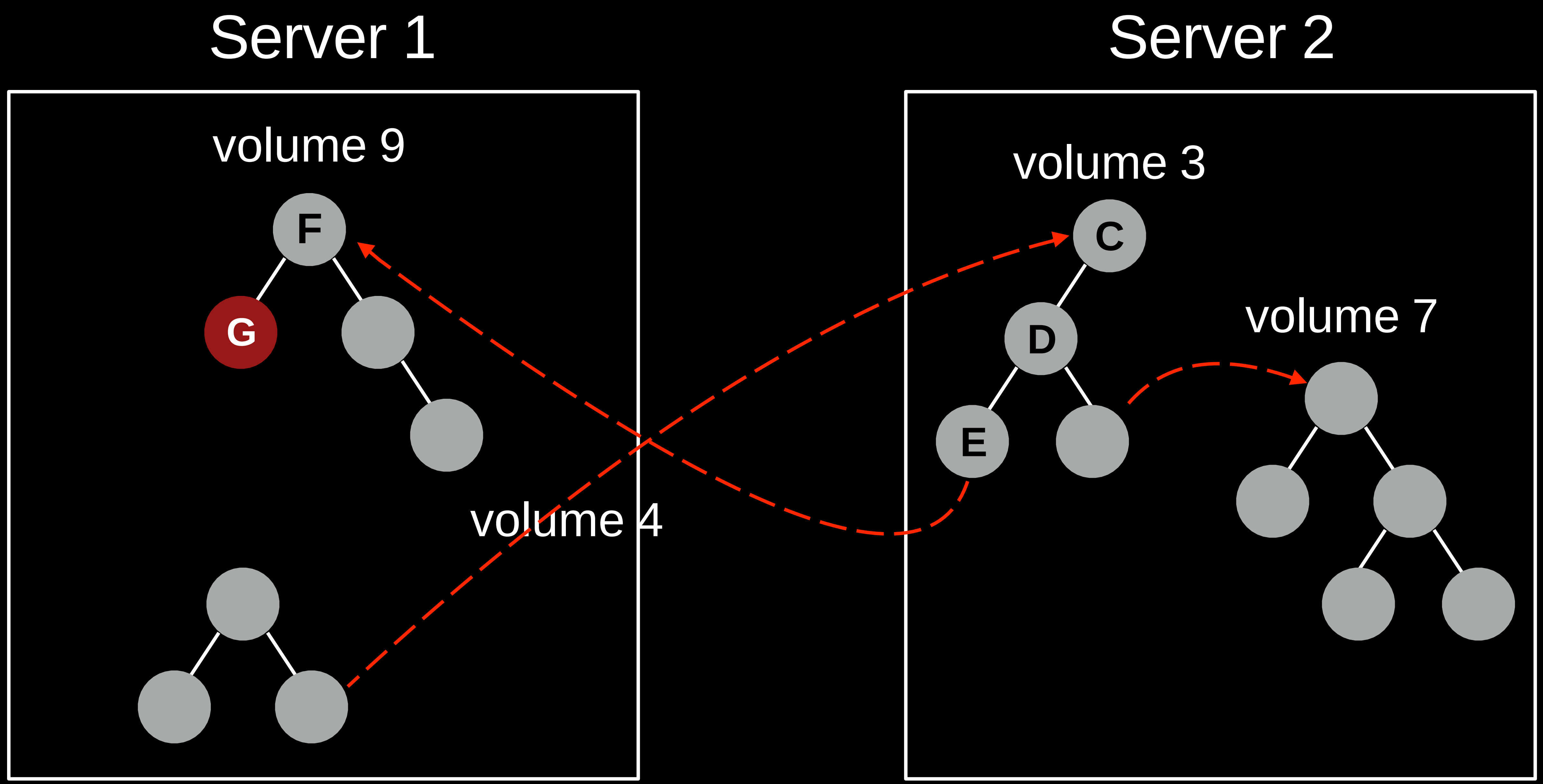
Volumes should be glued together into a seamless file tree.

Volume is a partial subtree.

Volume leaves may point to other volumes.


Server 1
volume 9
volume 4
Server 2
volume 3
C
D
E
volume 7


Server 1
Server 2
volume 9
F
G
volume 4
B
volume 3
C
D
E
volume 7




open A/B/C/D/E/F/G

# Volume Database

Given a volume name, how do we know what machine stores it?

Maintain volume database mapping volume name to locations.

Replicate to every server.
 - clients can ask any server they please

# Volume Movement

What if we want to migrate a volume to another machine?

Steps:

- copy data over
- update volume database

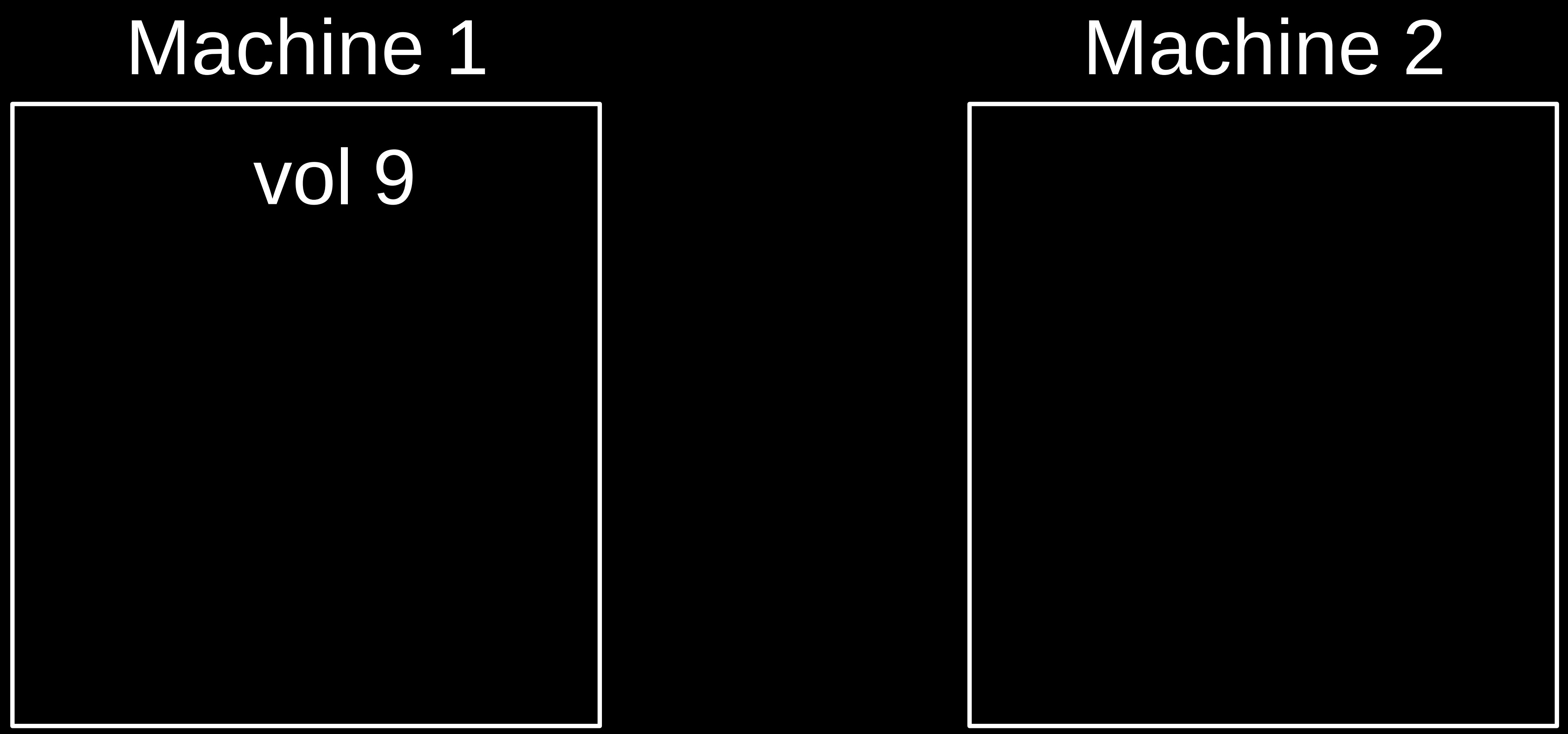
# Volume Movement

What if we want to migrate a volume to another machine?

Steps:
- copy data over ← don’t want to halt I/O during
- update volume database

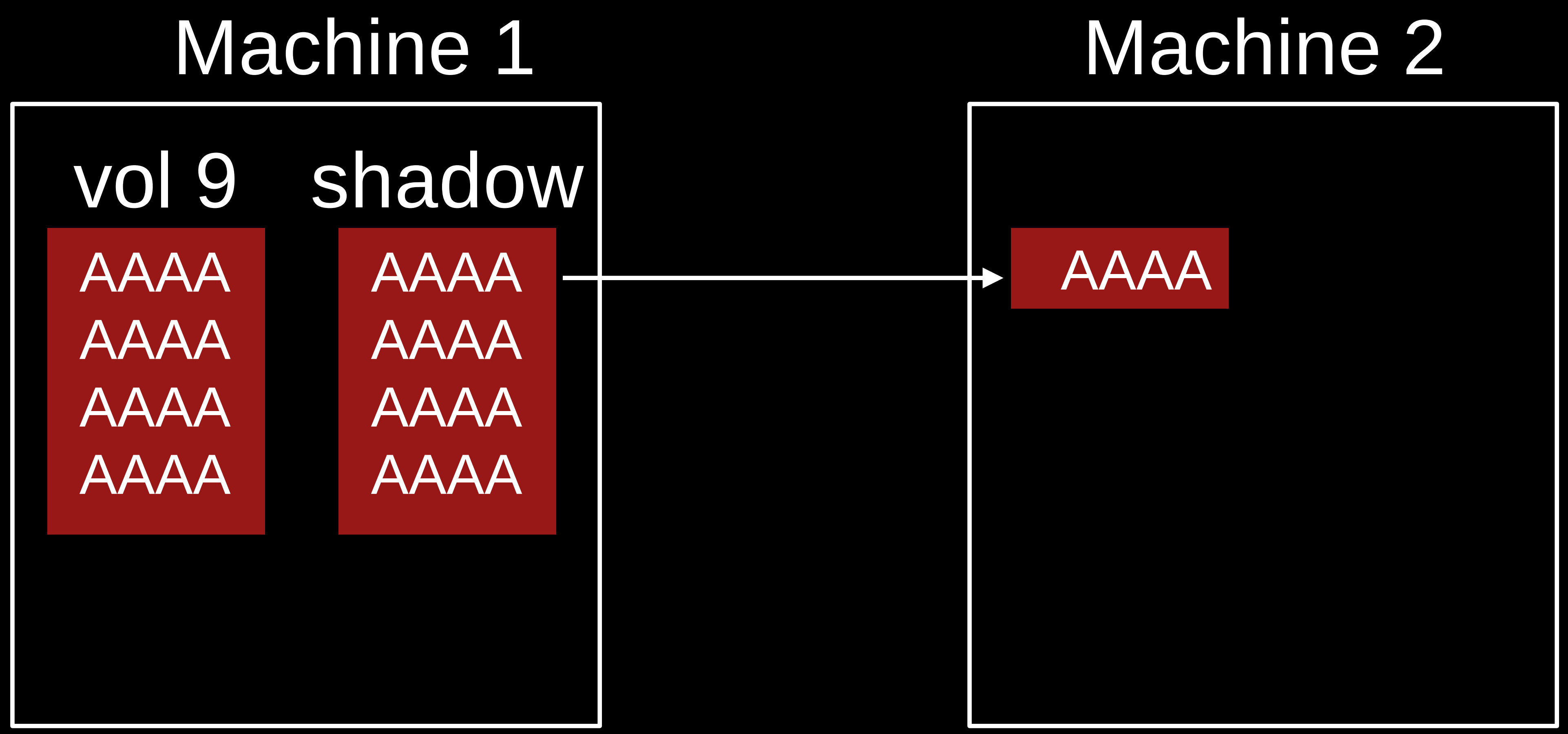
What about updates during movement?

# Copy

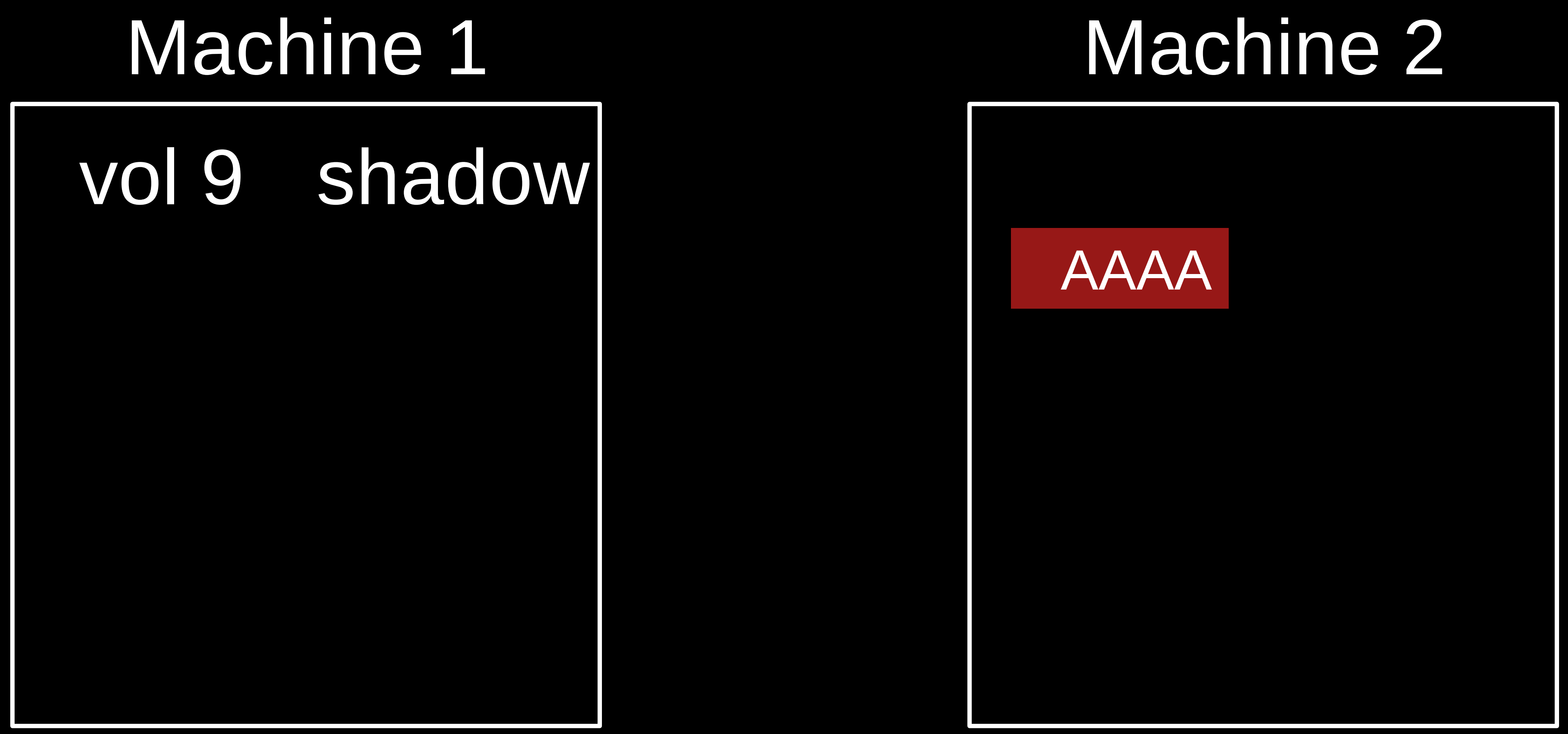


# Copy

# Copy


Machine 1
Machine 2
vol 9
shadow
AAAA
AAAA
AAAA
AAAA
AAAA
AAAA
AAAA
AAAA
AAAA

# Copy



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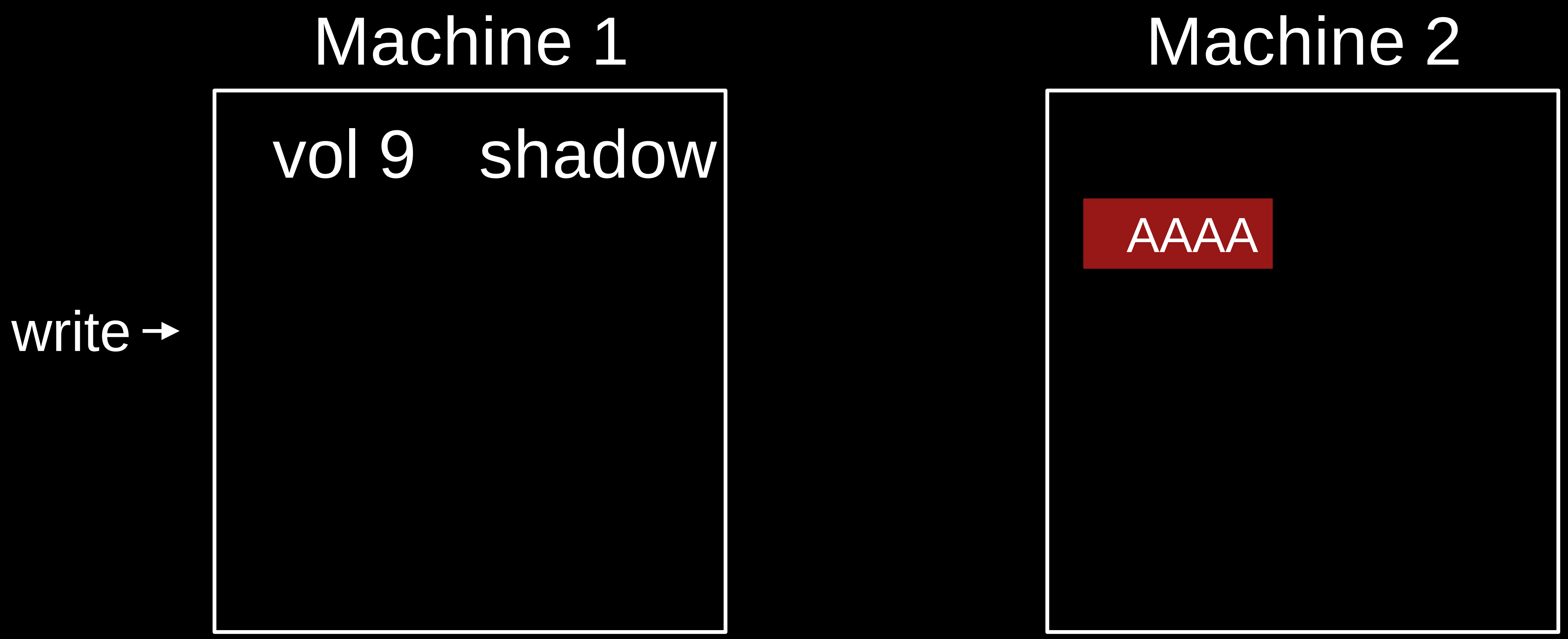

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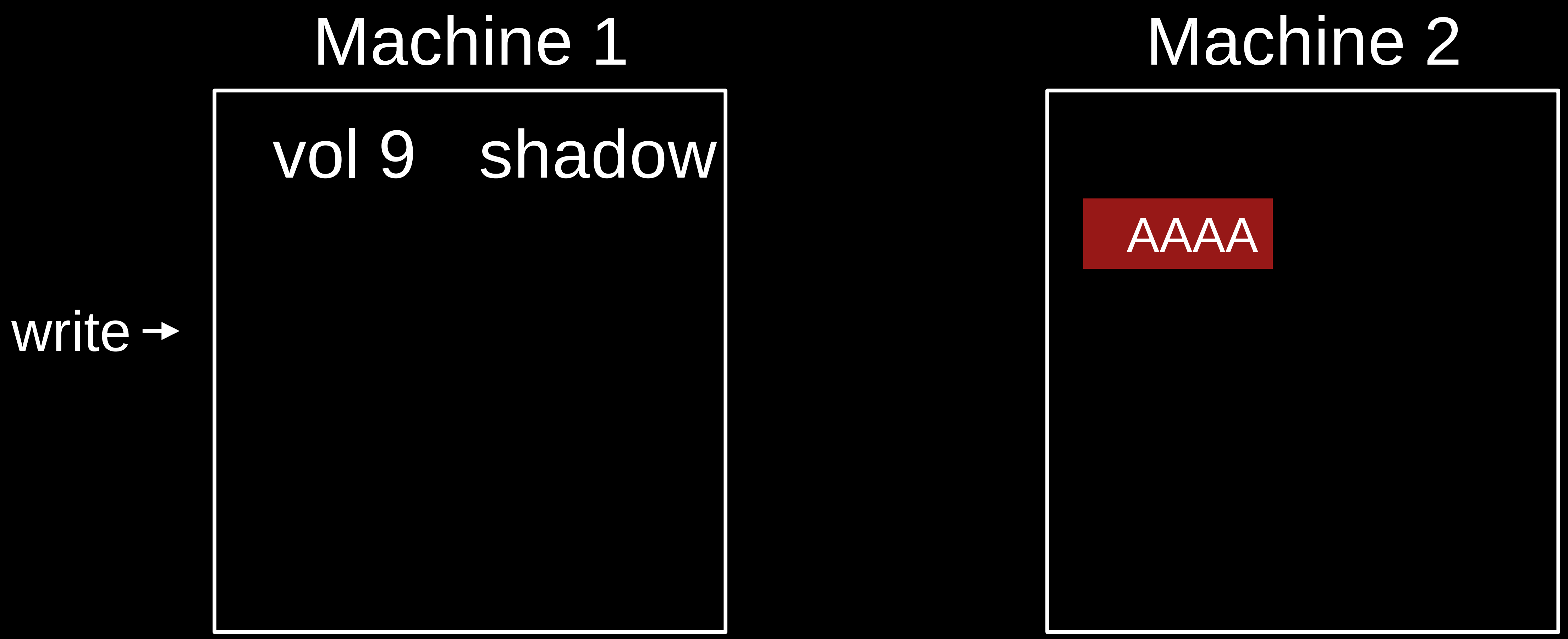

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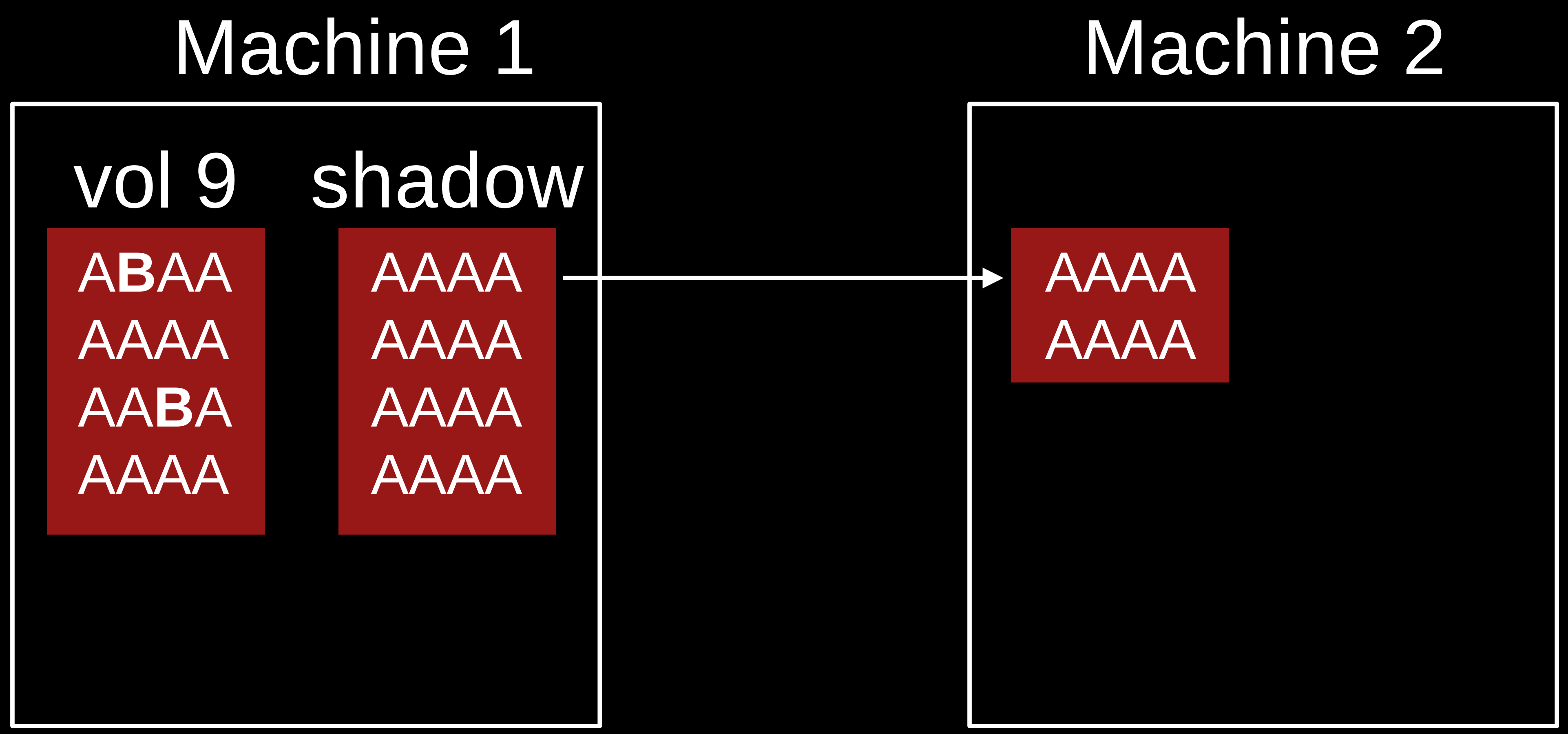
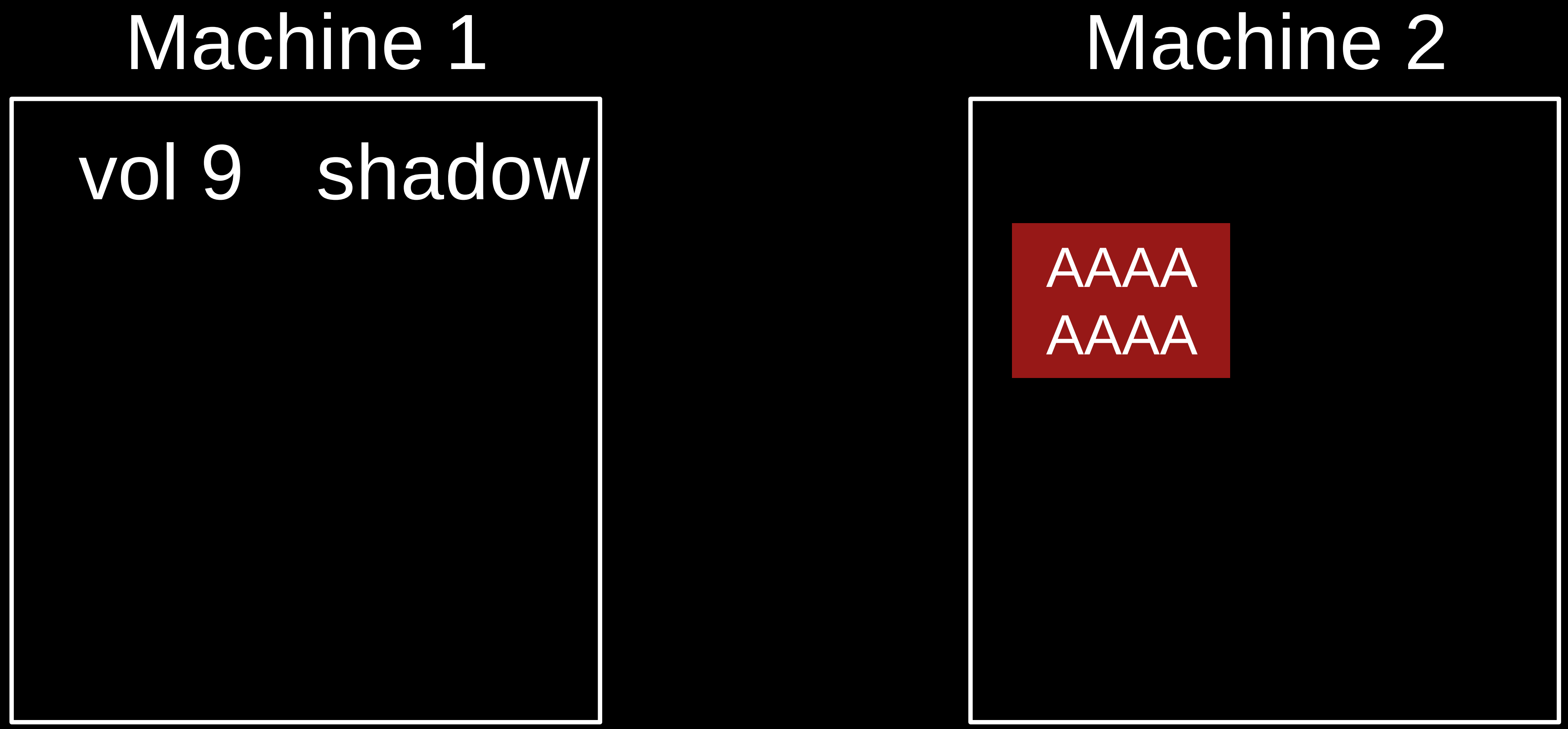
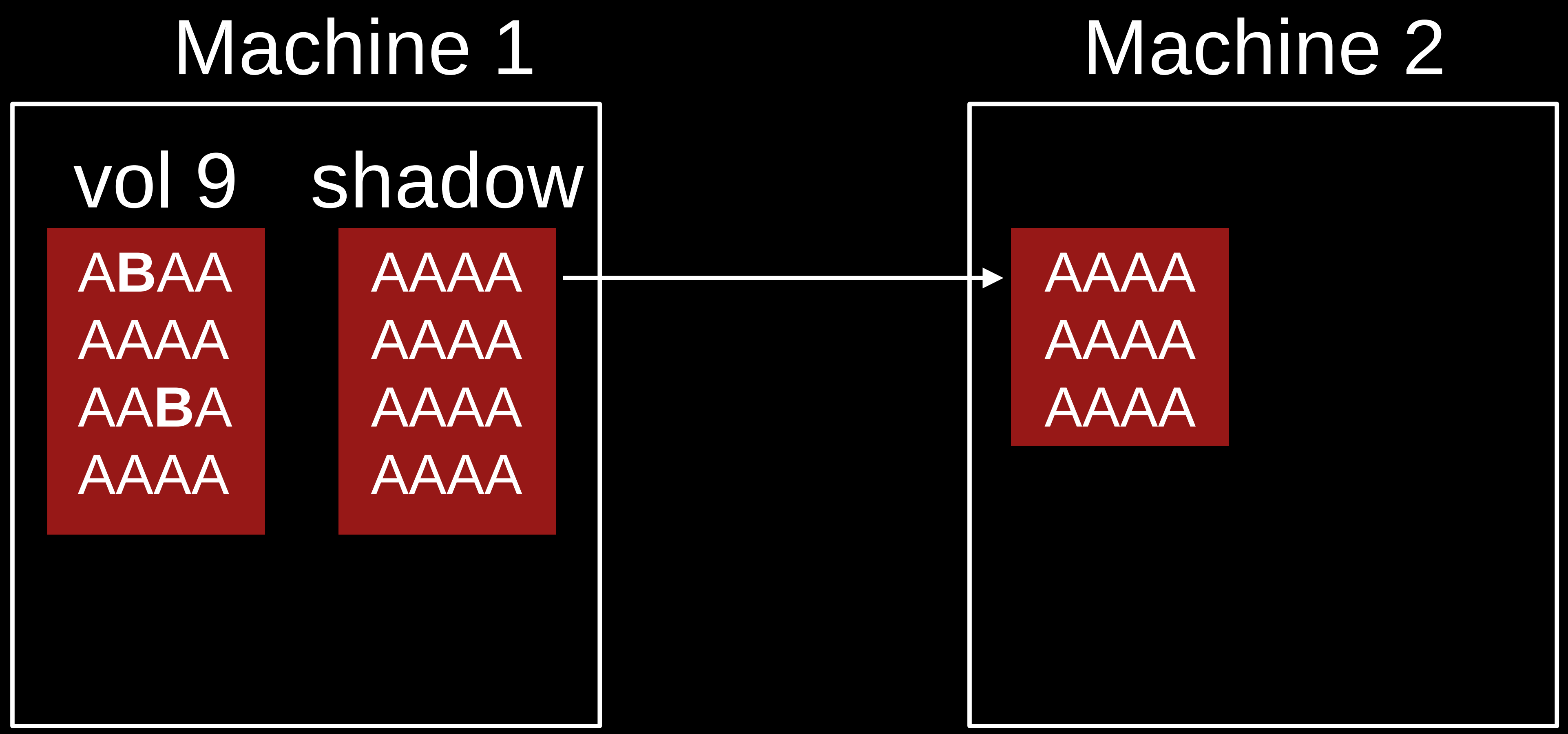

Machine 1
Machine 2
vol 9
shadow
ABAA
AAAA
AABA
AAAA
AAAA
AAAA
AAAA
AAAA
AAAA
AAAA

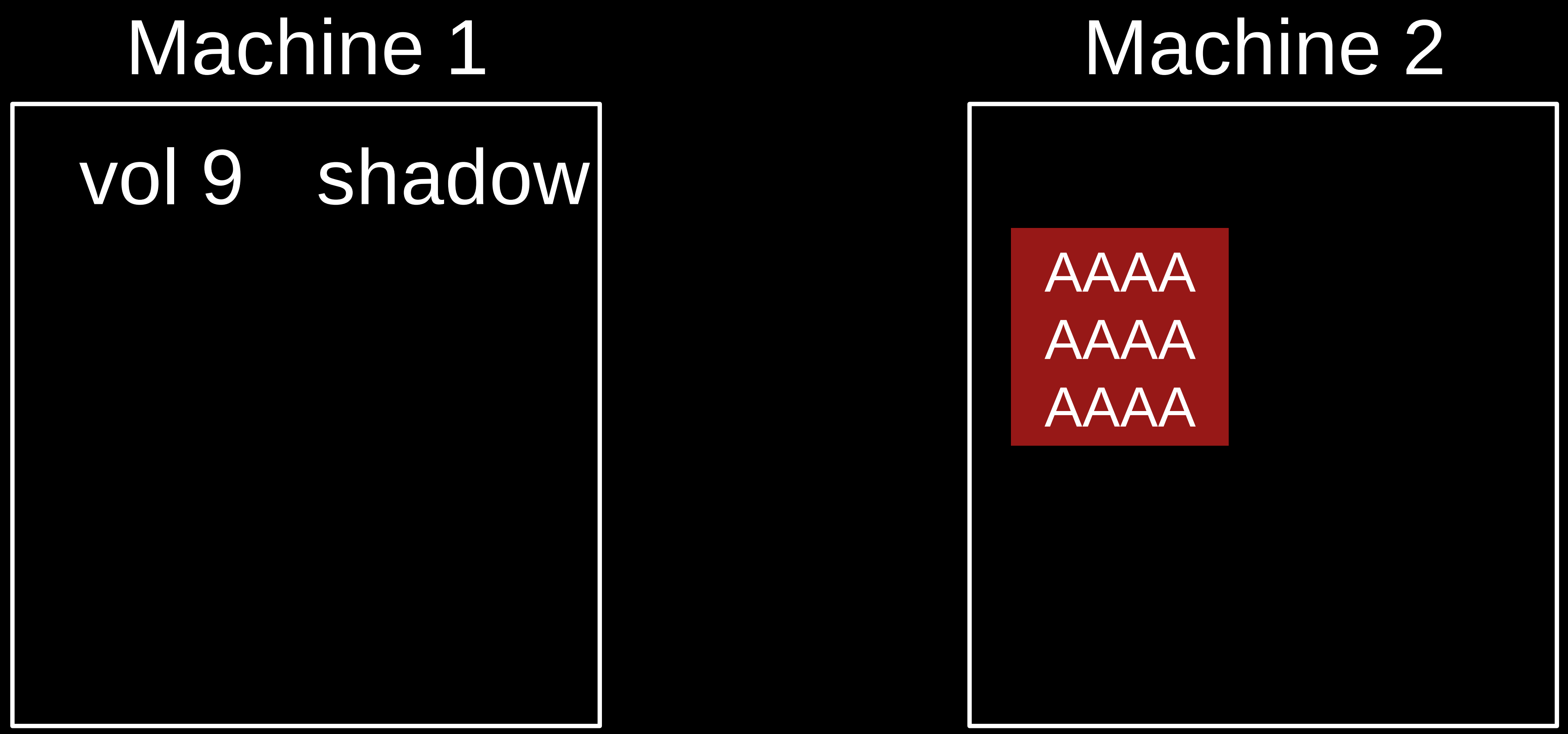
# Copy



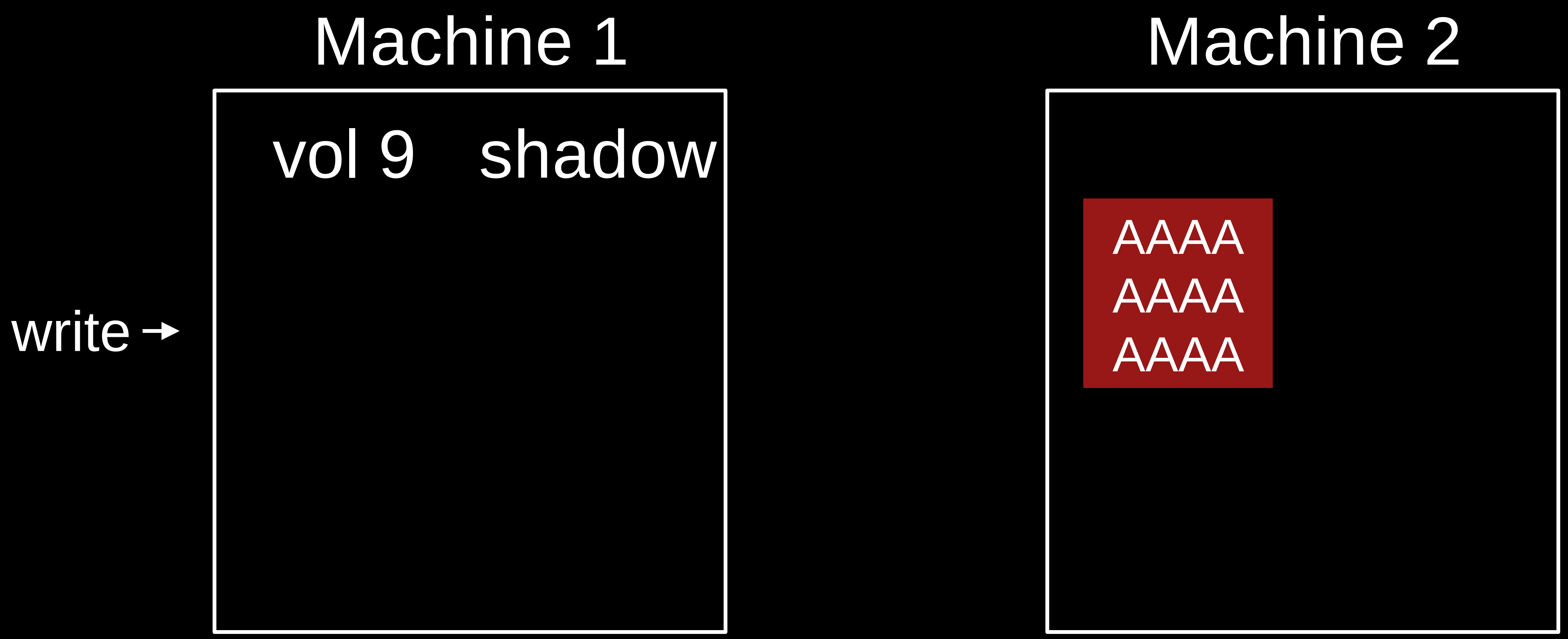
# Copy


Machine 1
Machine 2
vol 9
shadow
ABAA
AAAA
AABA
AAAA
AAAA
AAAA
AAAA
AAAA
AAAA
AAAA
AAAA

# Copy



# Copy



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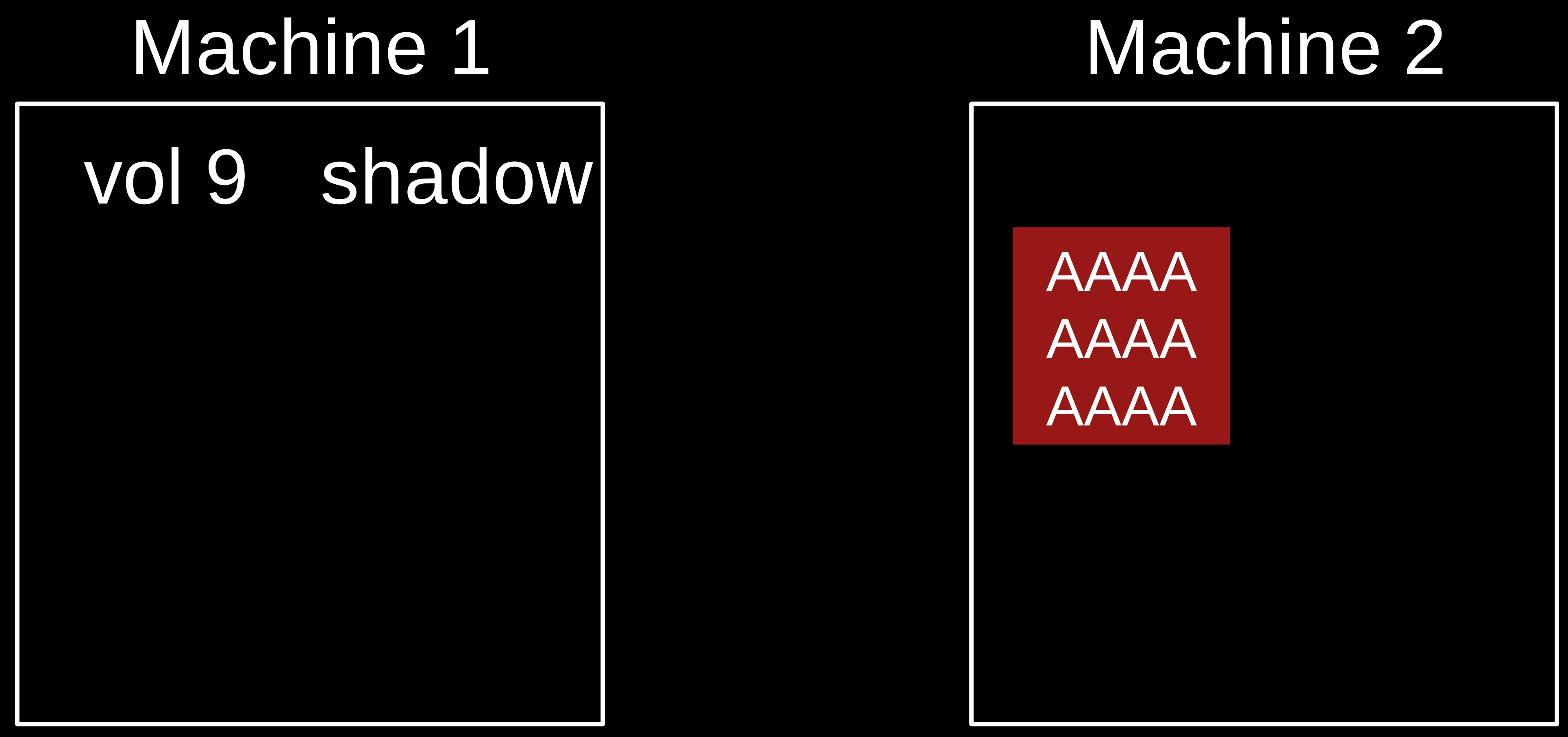
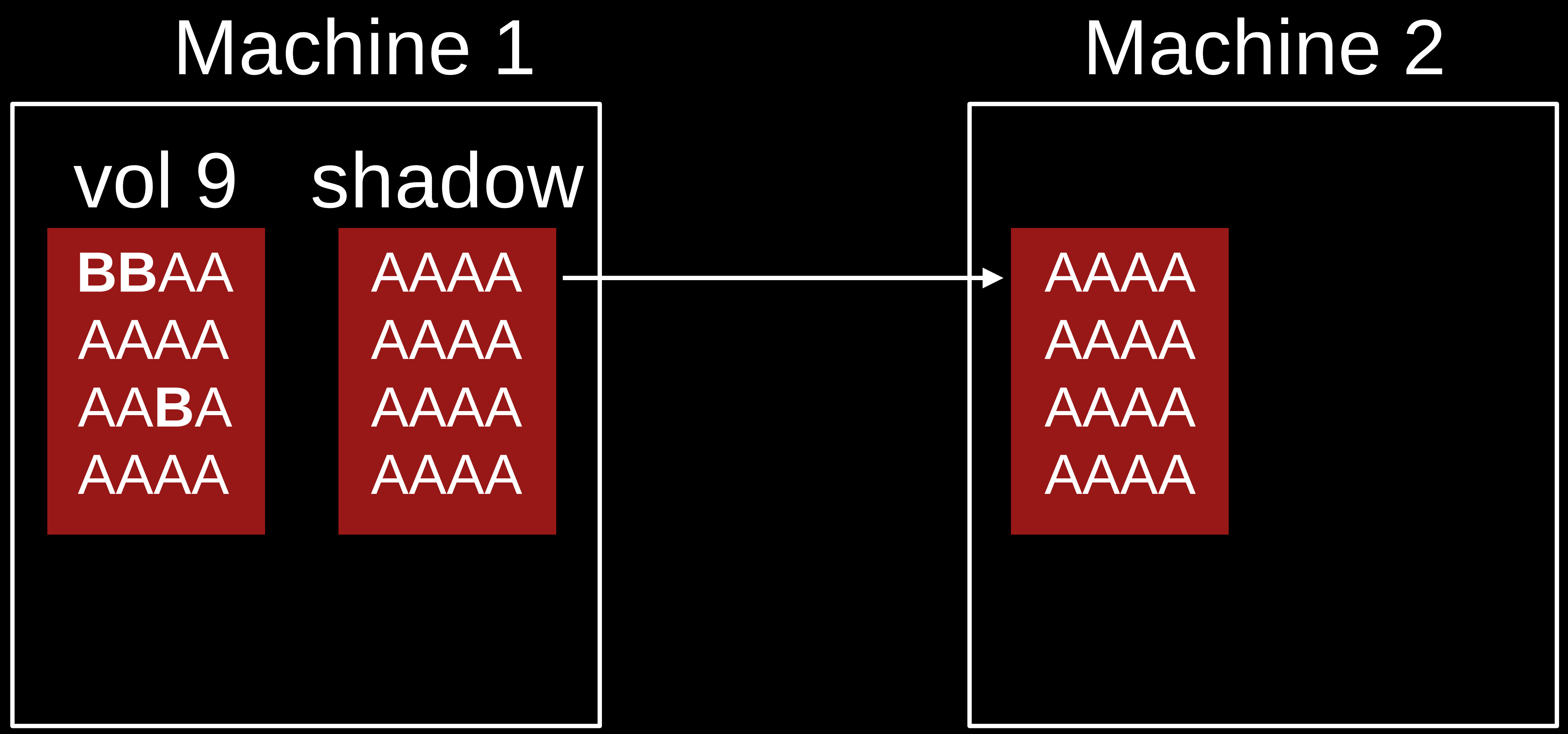


# Copy


Machine 1
Machine 2
vol 9
shadow
**BB**AA
AAAA
AA**B**A
AAAA
AAAA
AAAA
AAAA
AAAA
AAAA
AAAA
AAAA
AAAA

# Copy

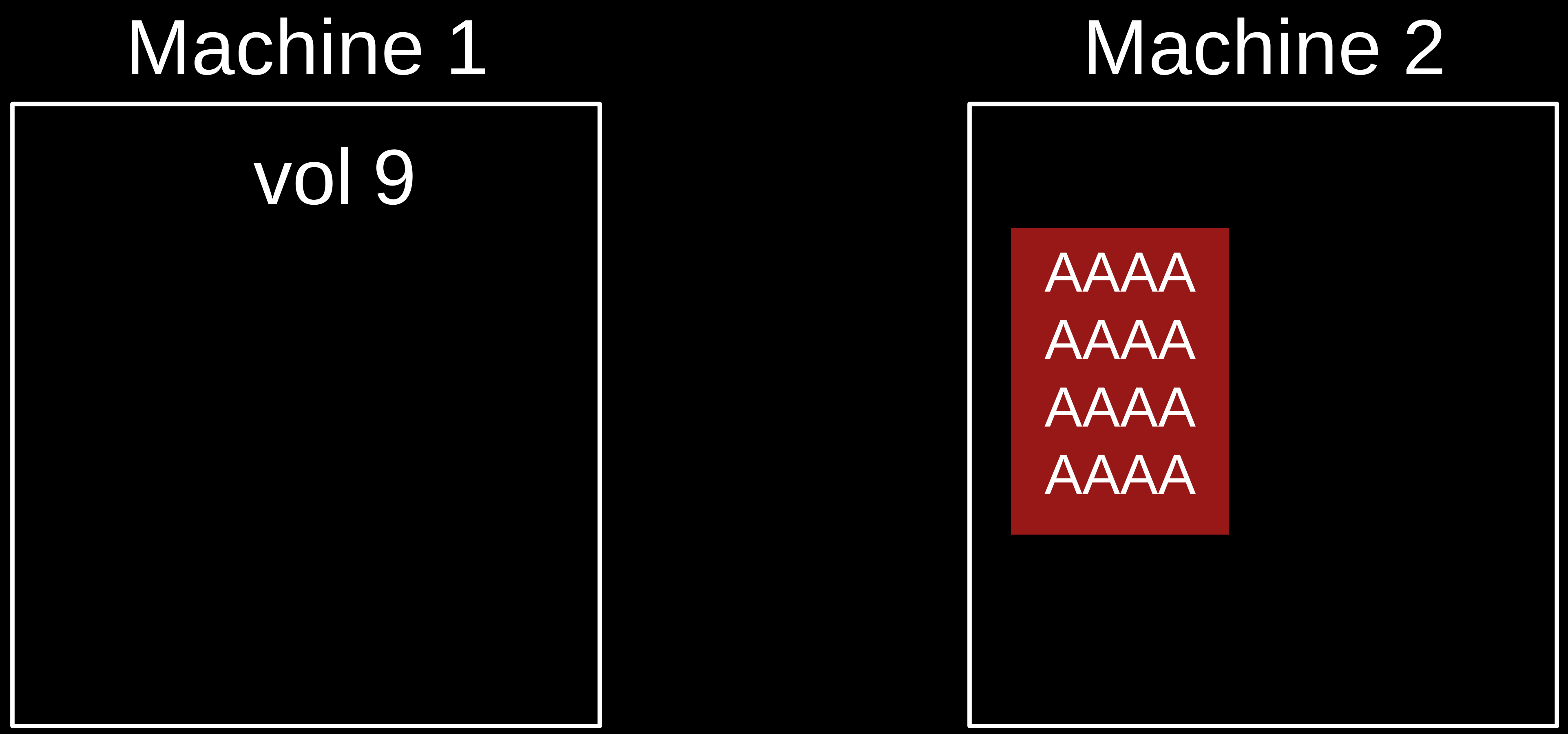
Machine 1

vol 9 shadow

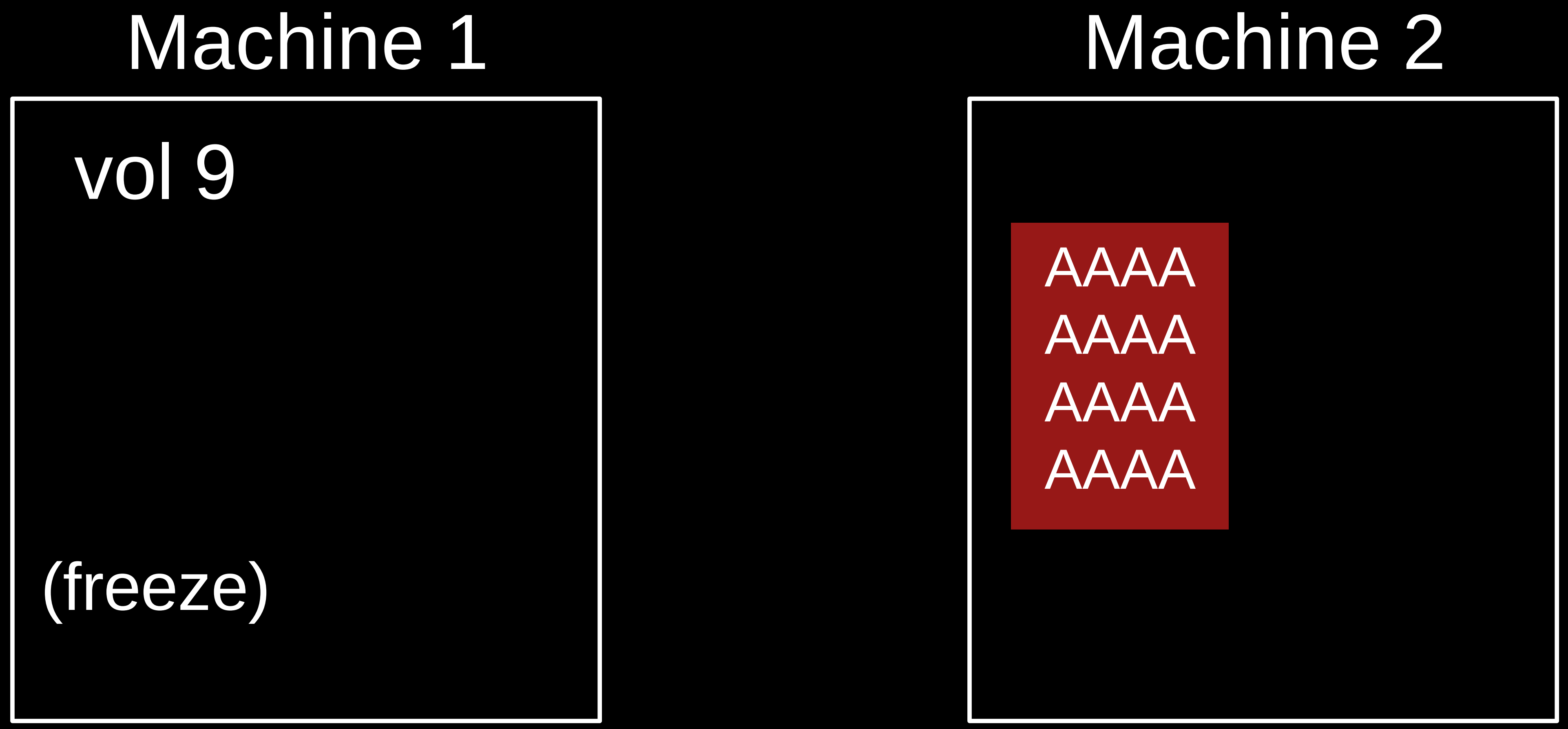
Machine 2

AAAA
AAAA
AAAA
AAAA

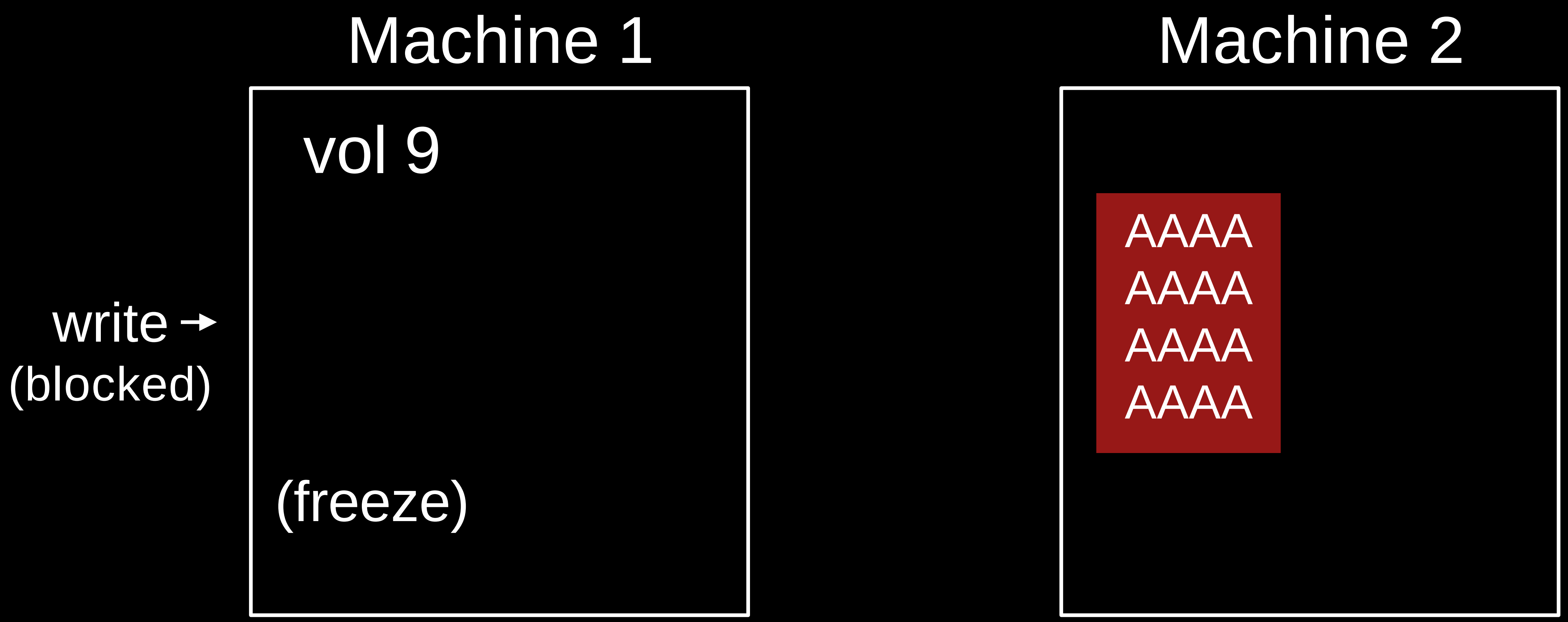
# Copy



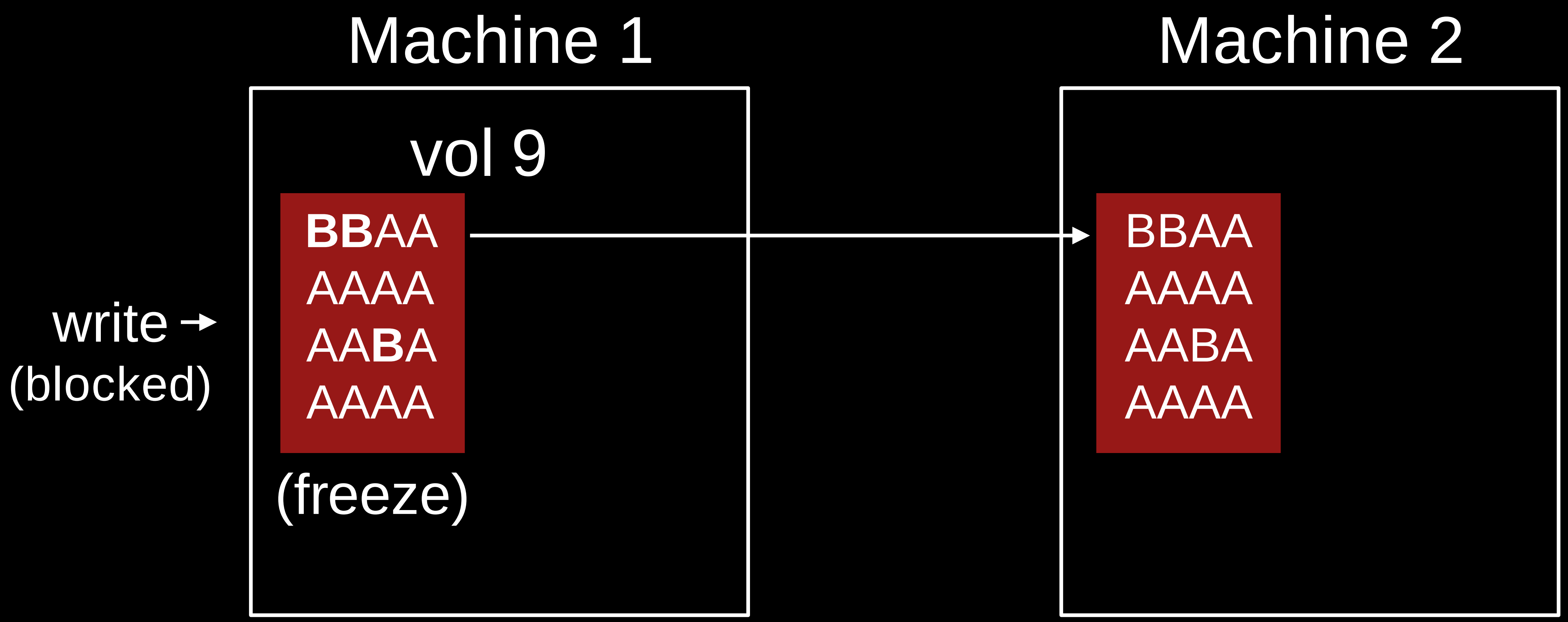
# Copy



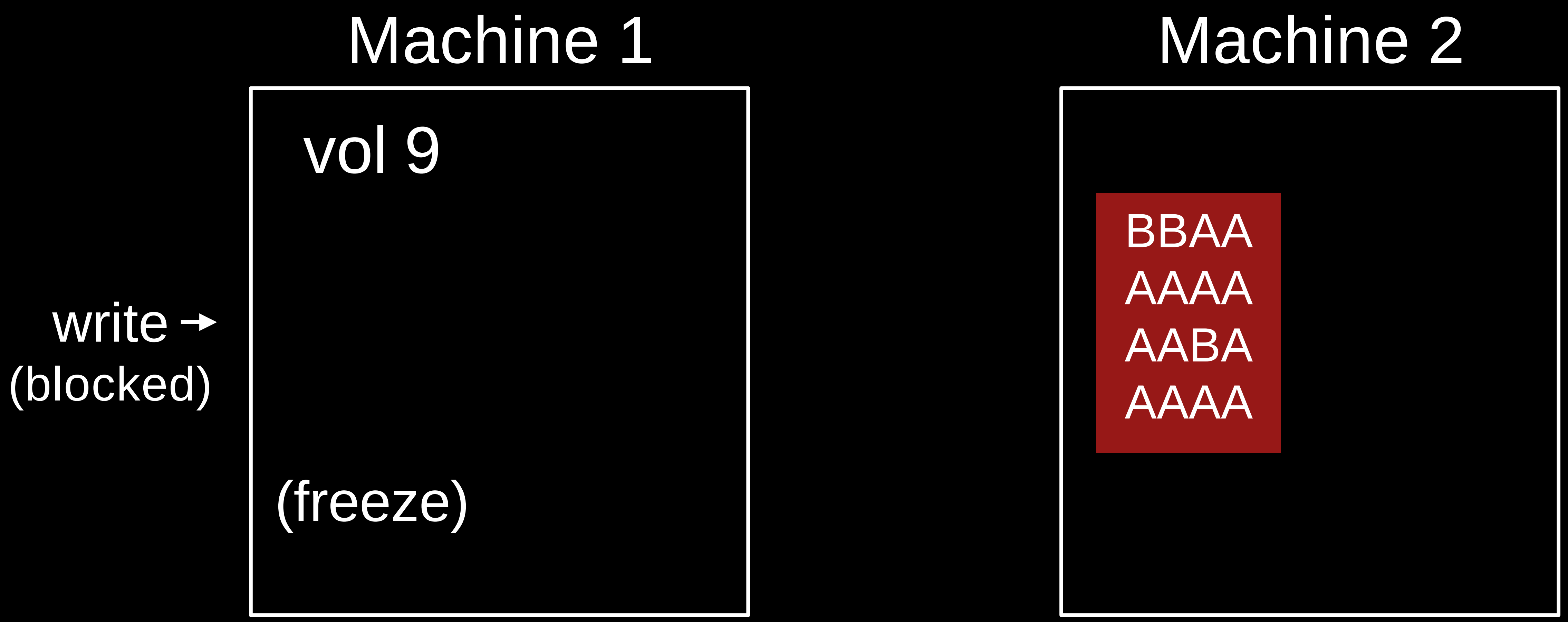
# Copy


Machine 1
Machine 2
vol 9
write
(blocked)
(freeze)
AAAA
AAAA
AAAA
AAAA

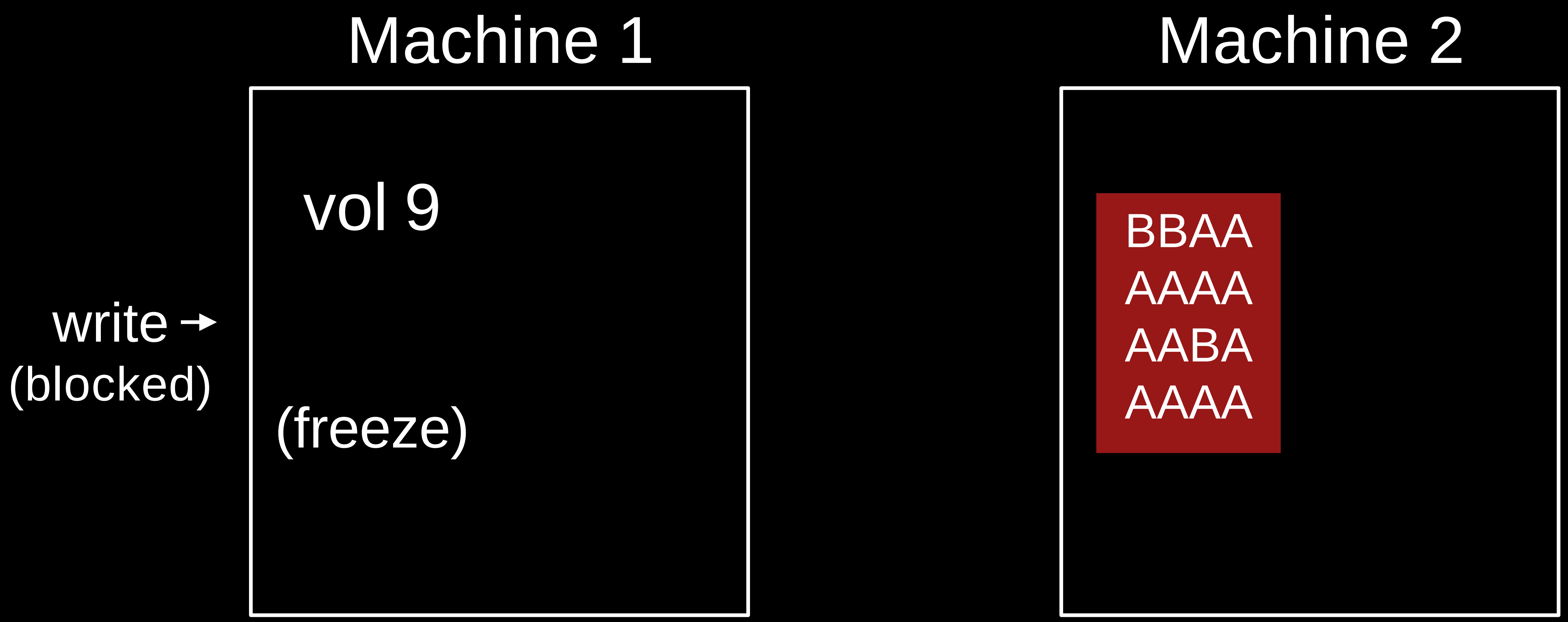
# Copy


Machine 1
Machine 2
vol 9
BBAA
AAAA
AABA
AAAA
(freeze)
write
(blocked)
BBAA
AAAA
AABA
AAAA

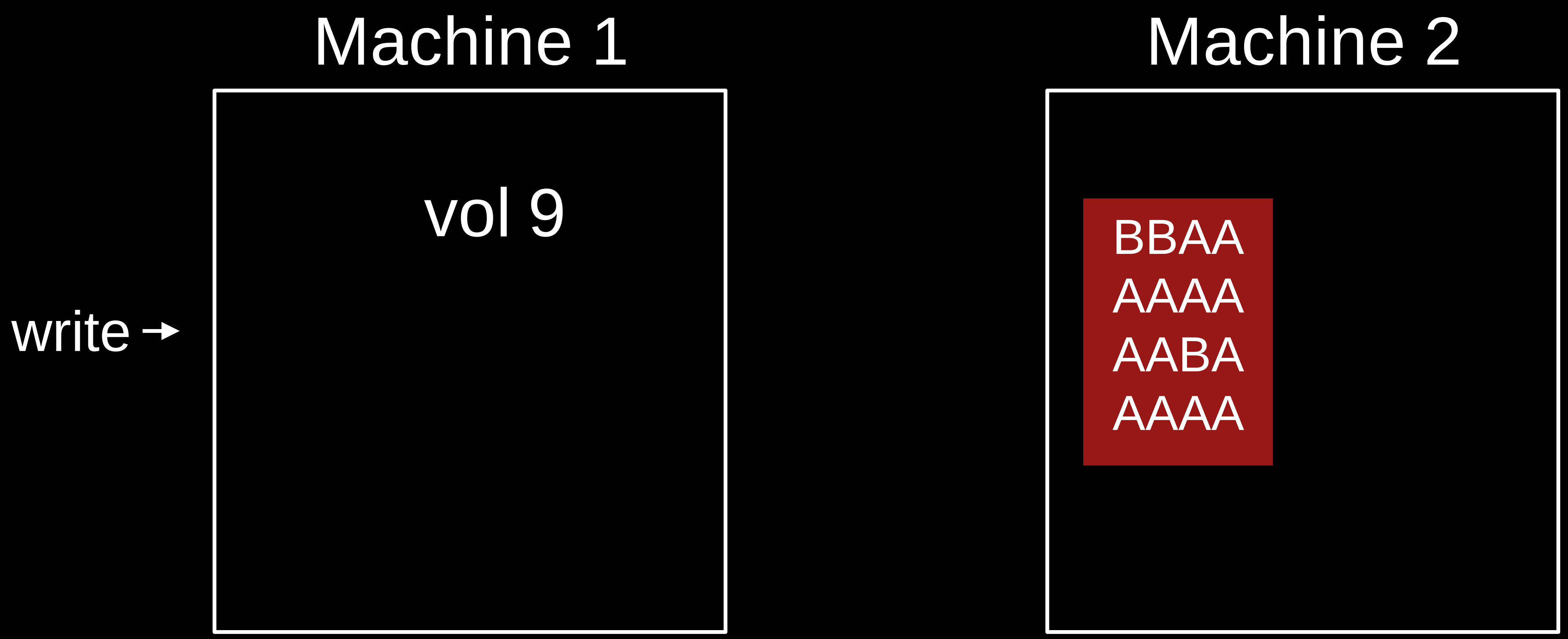
# Copy


Machine 1
vol 9
(freeze)
write
(blocked)
Machine 2
BBAA
AAAA
AABA
AAAA

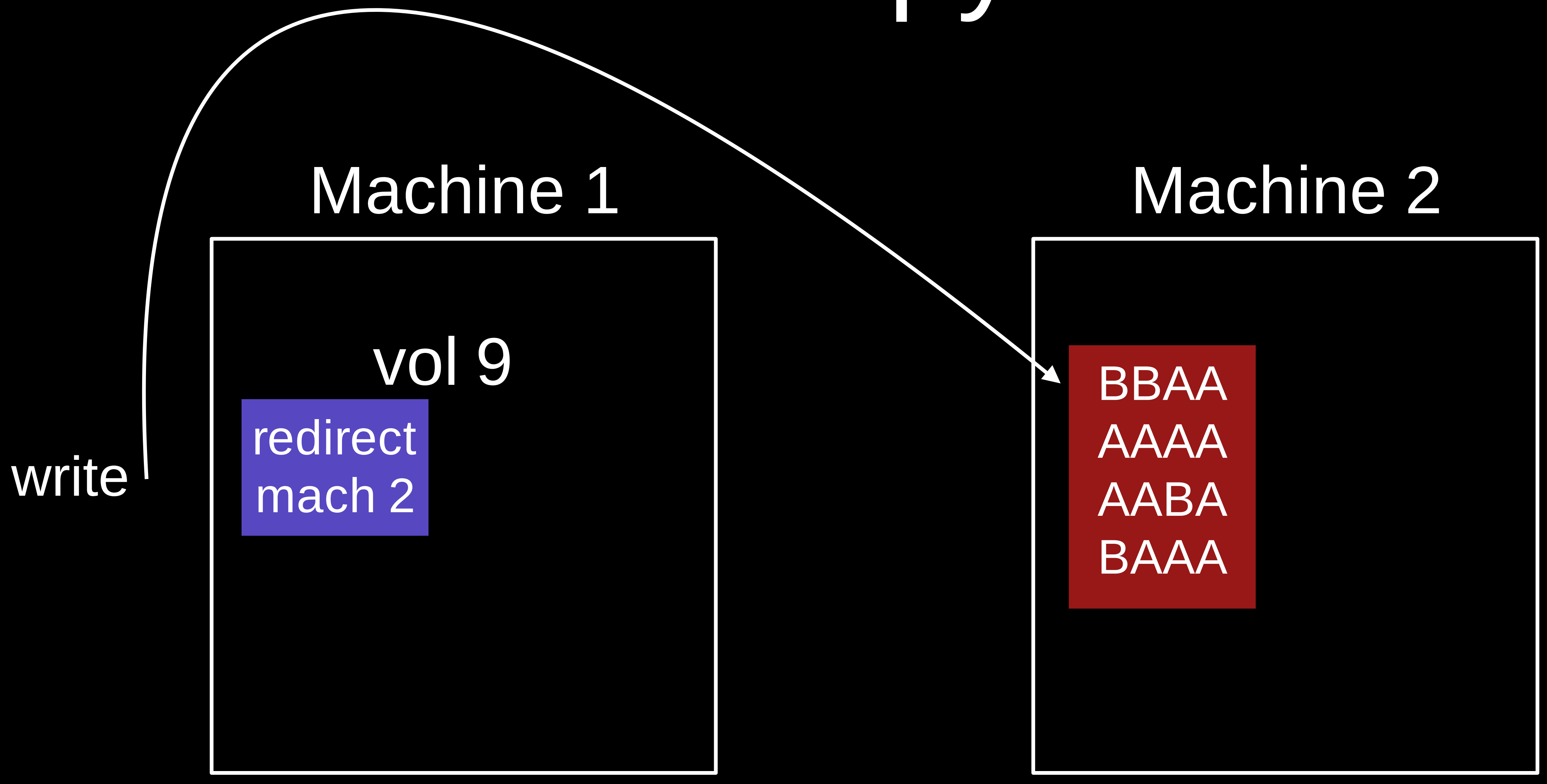
# Copy


Machine 1
Machine 2
vol 9
write
(blocked)
(freeze)
BBAA
AAAA
AABA
AAAA

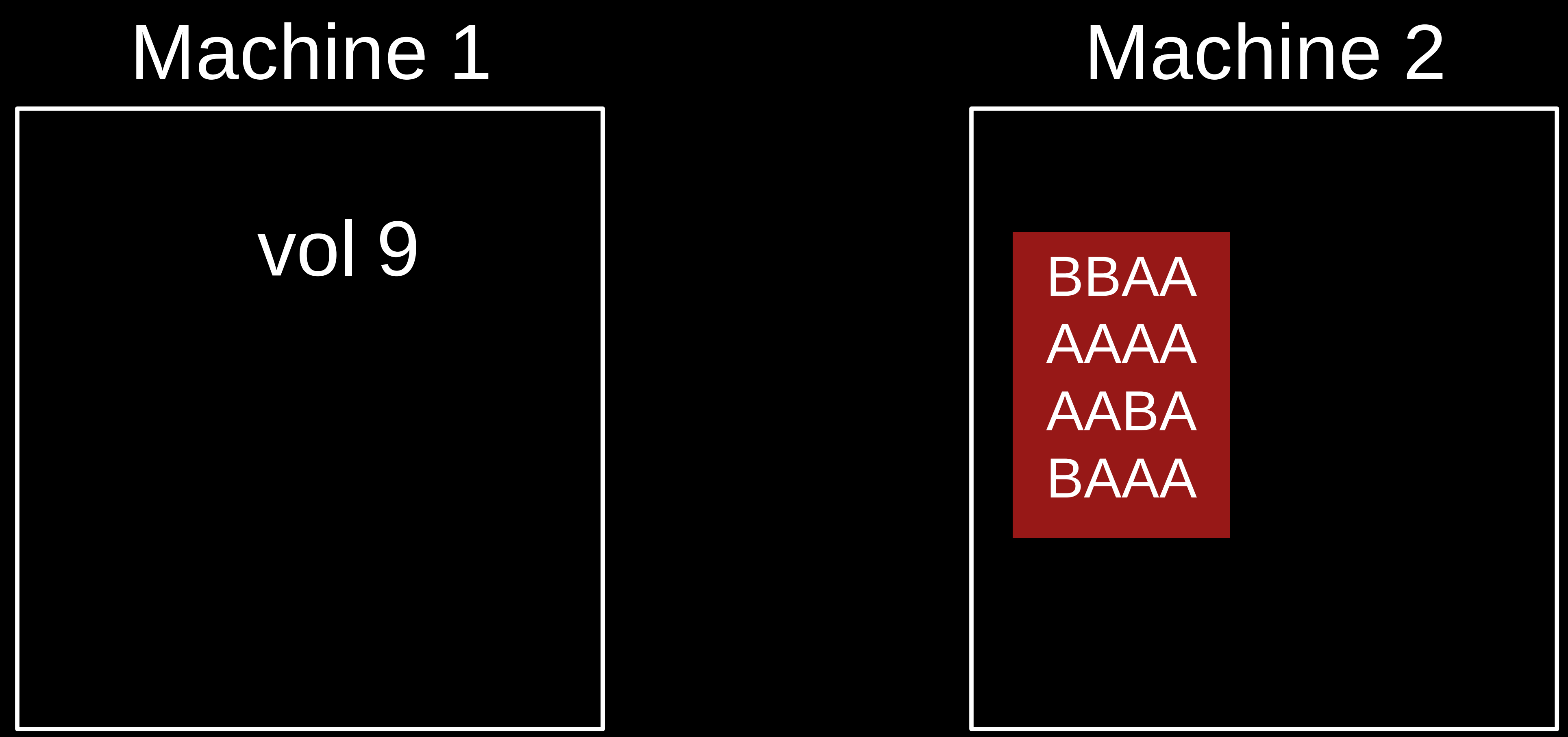
# Copy



# Copy


Machine 1
Machine 2
vol 9
redirect
mach 2
write
BBAA
AAAA
AABA
BAAA

# Copy



# Volume Movement

What if we want to migrate a volume to another machine?

Steps:

- copy data over ← don’t want to halt I/O during
- update volume database

What about updates during movement?

# Volume Movement

What if we want to migrate a volume to another machine?

Steps:

- copy data over
- update volume database ← what if somebody reads stale?

What about updates during movement?

# Volume Movement

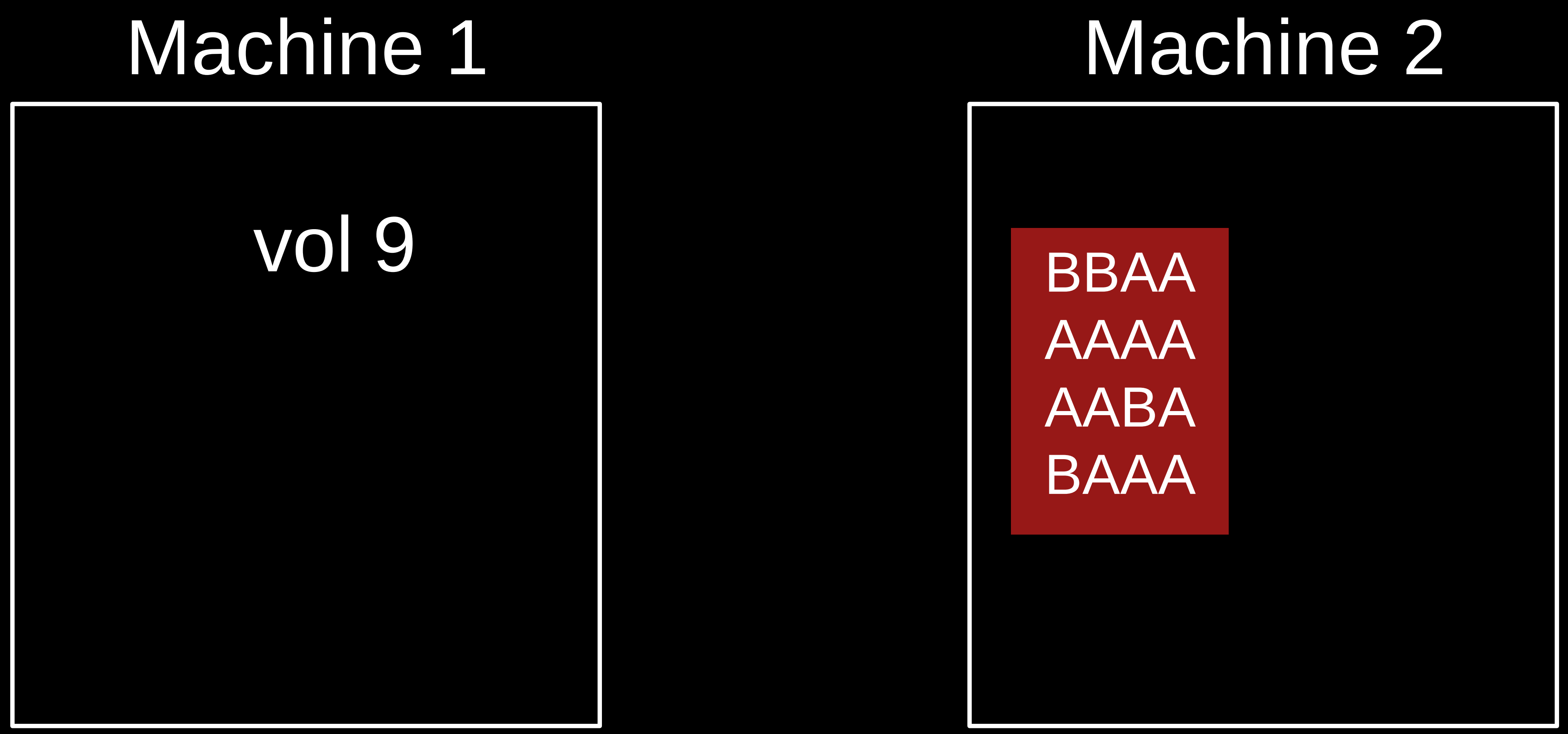
What if we want to migrate a volume to another machine?

Steps:
- copy data over
- update volume database ← what if somebody reads stale?

keep forwarding note at old location until all replicas updated

What about updates during movement?

# Copy



# Outline

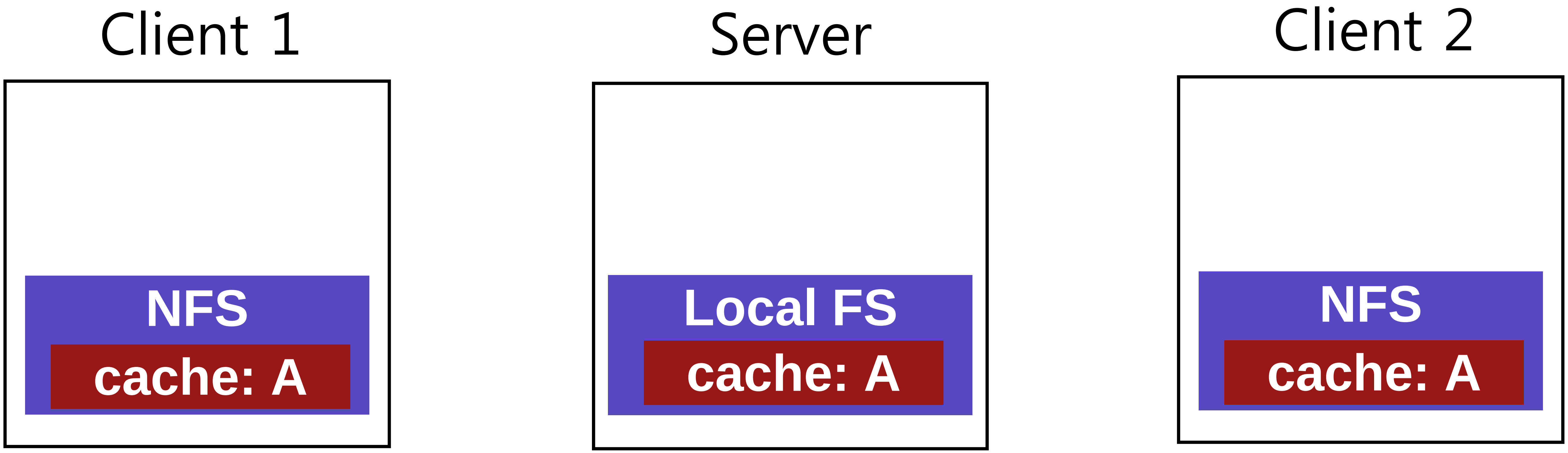
Volume management
Cache management
Name resolution
Process structure
Local-storage API
File locks.

# AFS Cache Consistency

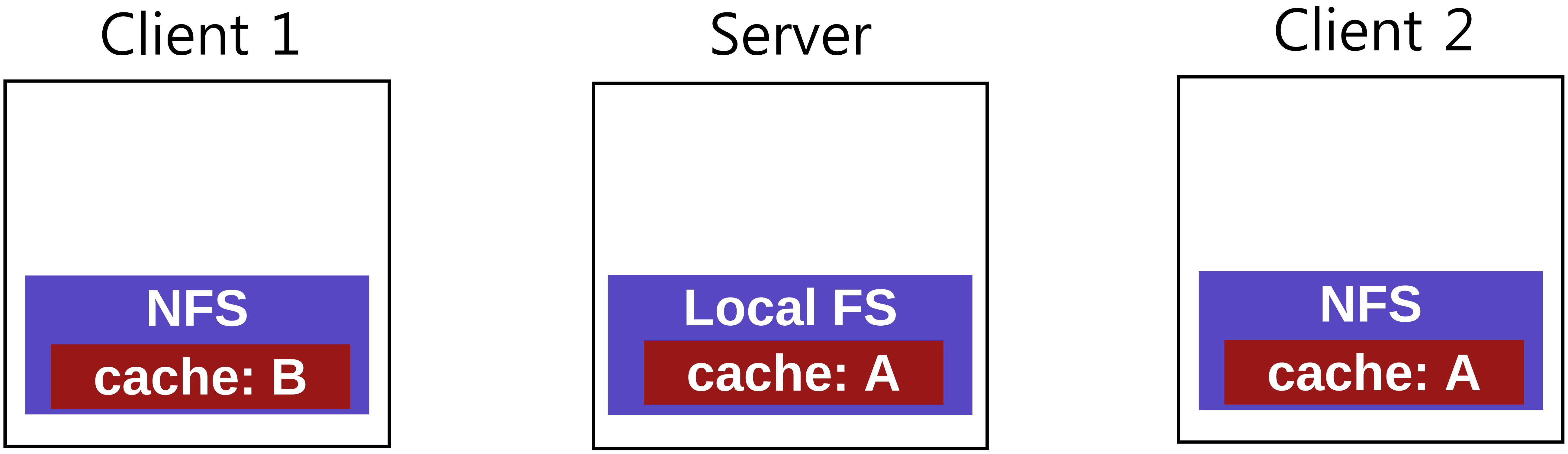
Update visibility

Stale cache

# Update Visibility



# Update Visibility




“Update Visibility” problem: server doesn’t have latest.

# Update Visibility

Clients updates not seen on servers yet.

NFS solution is to flush blocks
- on close()
- other times too – e.g., when low on memory

Problems
- flushes not atomic (one block at a time)
- two clients flush at once: mixed data

# Update Visibility

AFS solution:

- also flush on close
- buffer **whole files** on local disk; update file on server atomically

Concurrent writes?

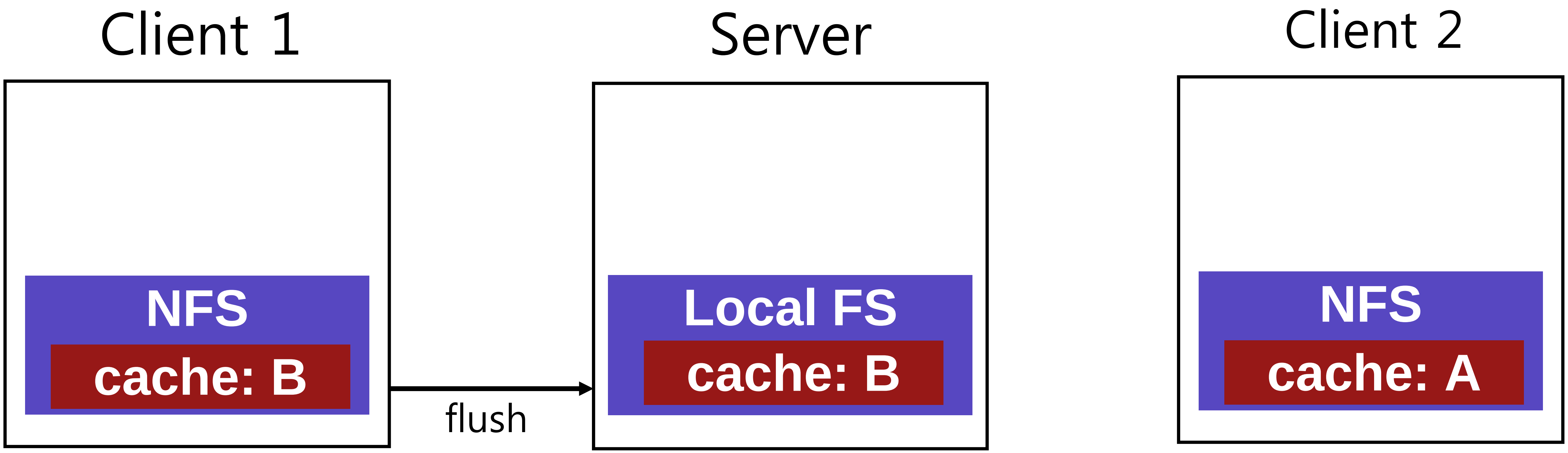
- Last writer (i.e., last file closer) wins
- Never get mixed data on server

# AFS Cache Consistency

Update visibility

Stale cache

# Cache Consistency




“Stale Cache” problem: client 2 doesn’t have latest

# Stale Cache

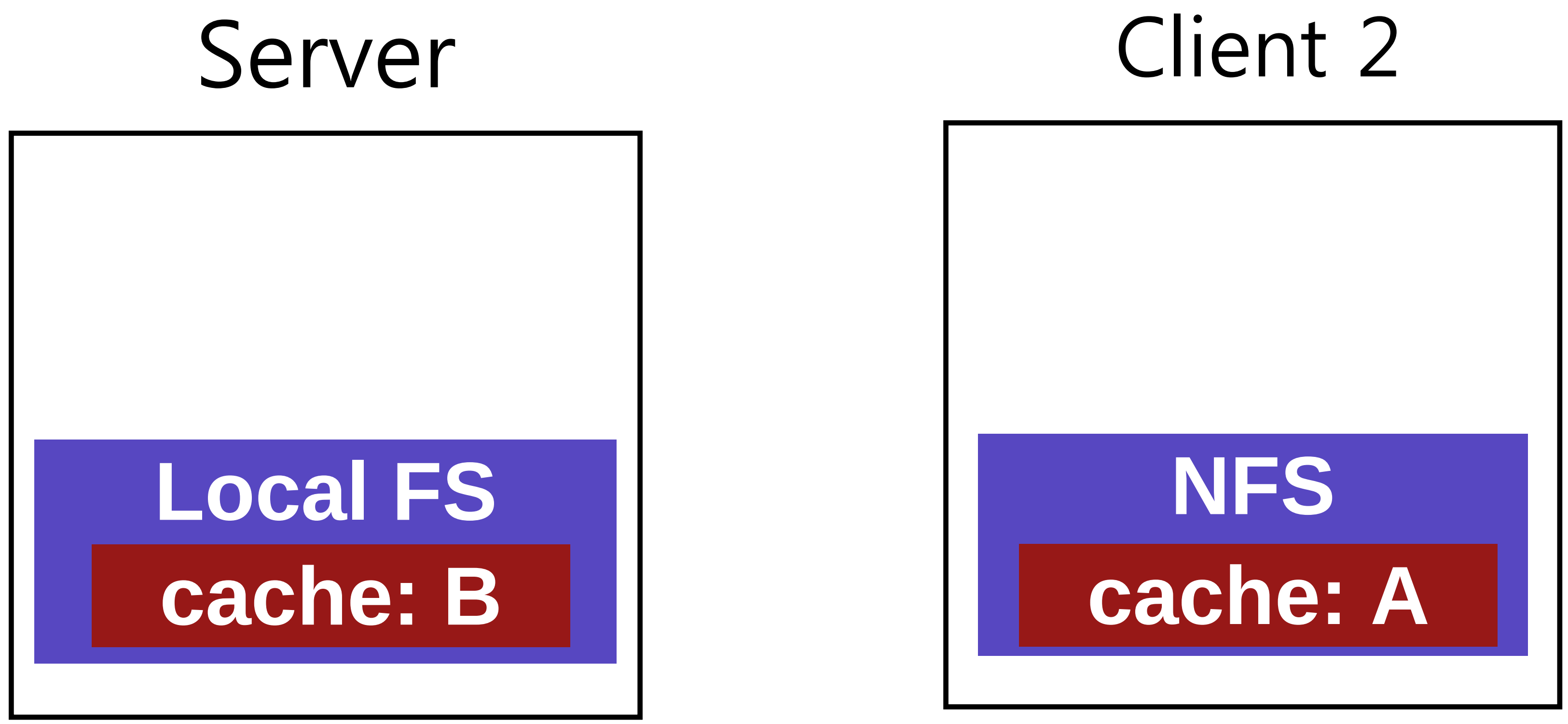
NFS rechecks cache entries compared to server before using them, assuming check hasn't been done "recently"

How to determine how recent? (about 3 seconds)

"Recent" is too long?

"Recent" is too short?

# Stale Cache




AFS solution: Tell clients when data is overwritten

- Server must remember which clients have this file open right now

When clients cache data, ask for "callback" from server if changes

- Clients can use data without checking all the time

Server no longer stateless!

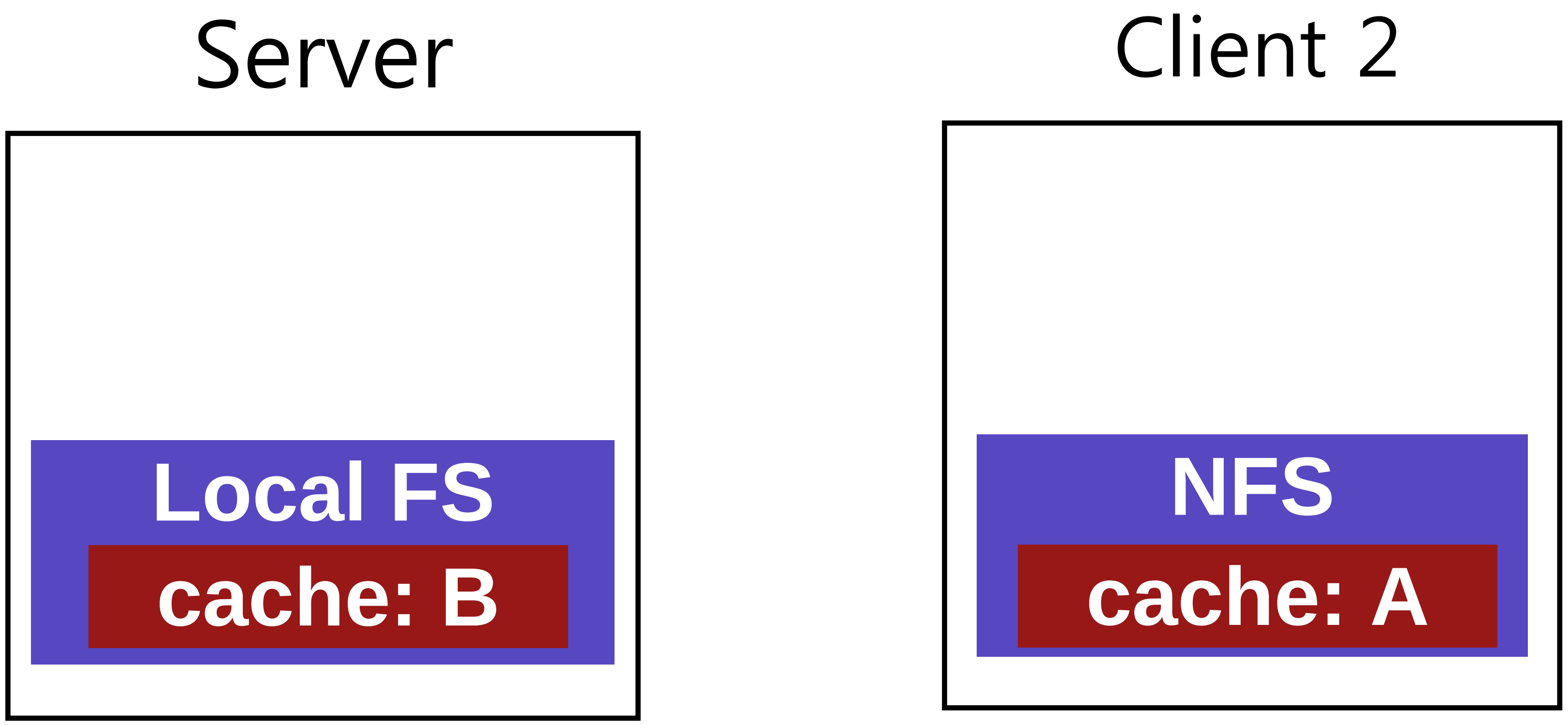
# Callbacks: Dealing with STATE

What if client crashes?

What if server runs out of memory?

What if server crashes?

# Client Crash




What should client do after reboot?
(remember cached data can be on disk too...)

Concern? may have missed notification that cached copy changed

Option 1: evict everything from cache

Option 2: ??? recheck entries before using

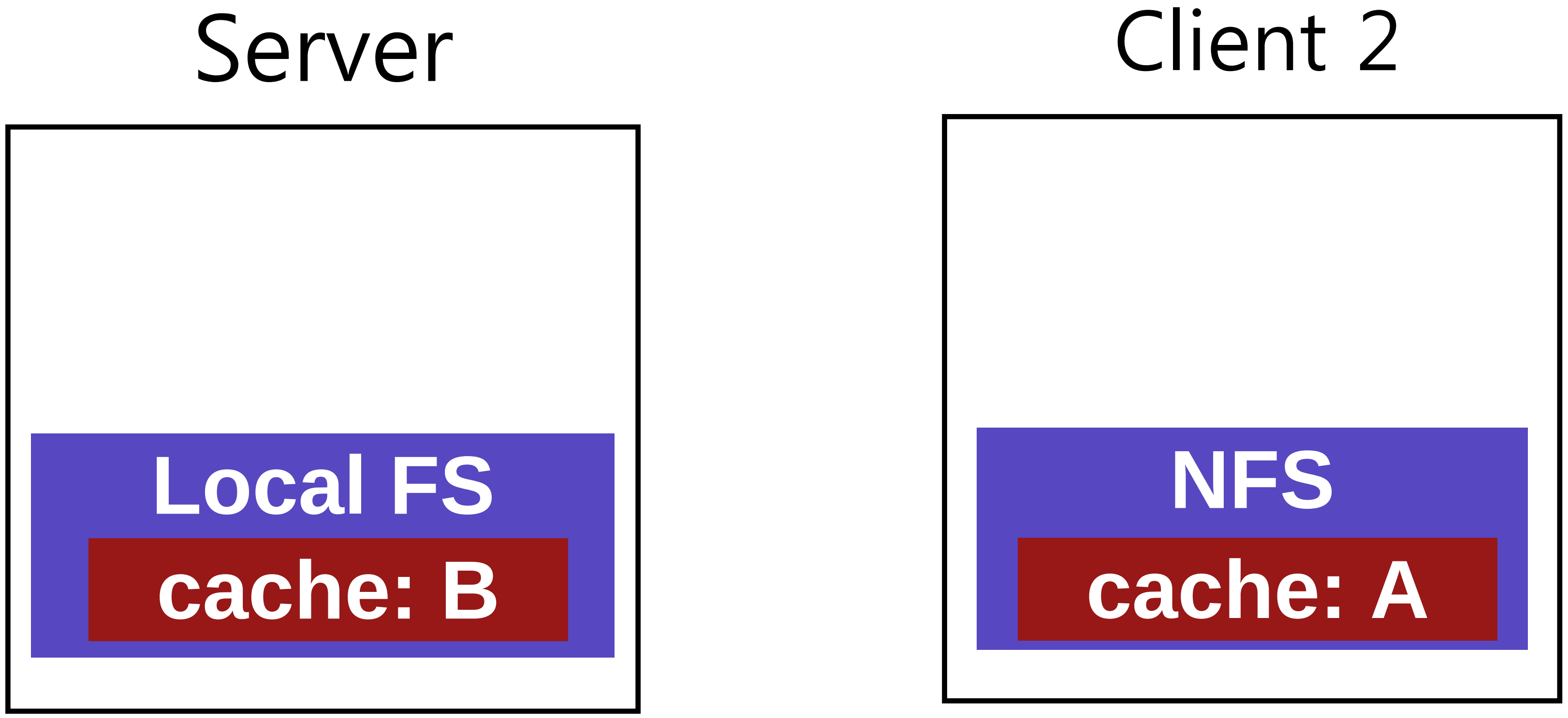
# Callbacks: Dealing with STATE

What if client crashes?

What if server runs out of memory?

What if server crashes?

# Low Server Memory




Strategy: tell clients you are dropping their callback

What should client do?

Option 1: Discard entry from cache

Option 2: ???  Mark entry for recheck

# Callbacks: Dealing with STATE

What if client crashes?

What if server runs out of memory?

What if server crashes?

# Server Crashes

What if server crashes?

Option: tell all clients to recheck all data before next read

Handling server and client crashes without inconsistencies or race conditions is very difficult…

Option: persist callbacks

# Callbacks: Dealing with STATE

What if client crashes?

What if server runs out of memory?

What if server crashes?

**AFS paper**: “there is a potential for inconsistency if the callback state maintained by a [client] gets out of sync with the [server state]”.

# Prefetching

AFS paper notes: "the study by Ousterhout *et al.* has shown that most files in a 4.2BSD environment are read in their entirety."

What are the implications for client prefetching policy?

Aggressively prefetch whole files.

# Whole-File Caching

Upon open, AFS client fetches whole file (even if huge), storing in local memory or disk

Upon close, client flushes file to server (if file was written)

Convenient and intuitive semantics:

- AFS needs to do work only for open/close
  - Only check callback on open, not every read
- reads/writes are local

- Use same version of file entire time between open and close

# Outline

Volume management
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# Why is this Inefficient?

Requests to server:

```
fd1 = open("/a/b/c/d/e/1.txt")
fd2 = open("/a/b/c/d/e/2.txt")
fd3 = open("/a/b/c/d/e/3.txt")
```

# Why is this Inefficient?

Requests to server:

```
fd1 = open(“/a/b/c/d/e/1.txt”)
fd2 = open(“/a/b/c/d/e/2.txt”)
fd3 = open(“/a/b/c/d/e/3.txt”)
```

Same inodes and dir entries repeatedly read.

Cache prevent too much disk I/O.

Too much CPU, though.

# Solution

Server returns dir entries to client.

Client caches entries, inodes.

Pro: partial traversal is the common case.

Con: first lookup requires many round trips.

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# Process Structure

For each client, a different process ran on the server.

Context switching costs were high.

Solution: ???

# Process Structure

For each client, a different process ran on the server.

Context switching costs were high.

Solution: use threads.

Shared addr space => more useful TLB entries.

# Outline

Volume management
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# Which API is faster?  More convenient?

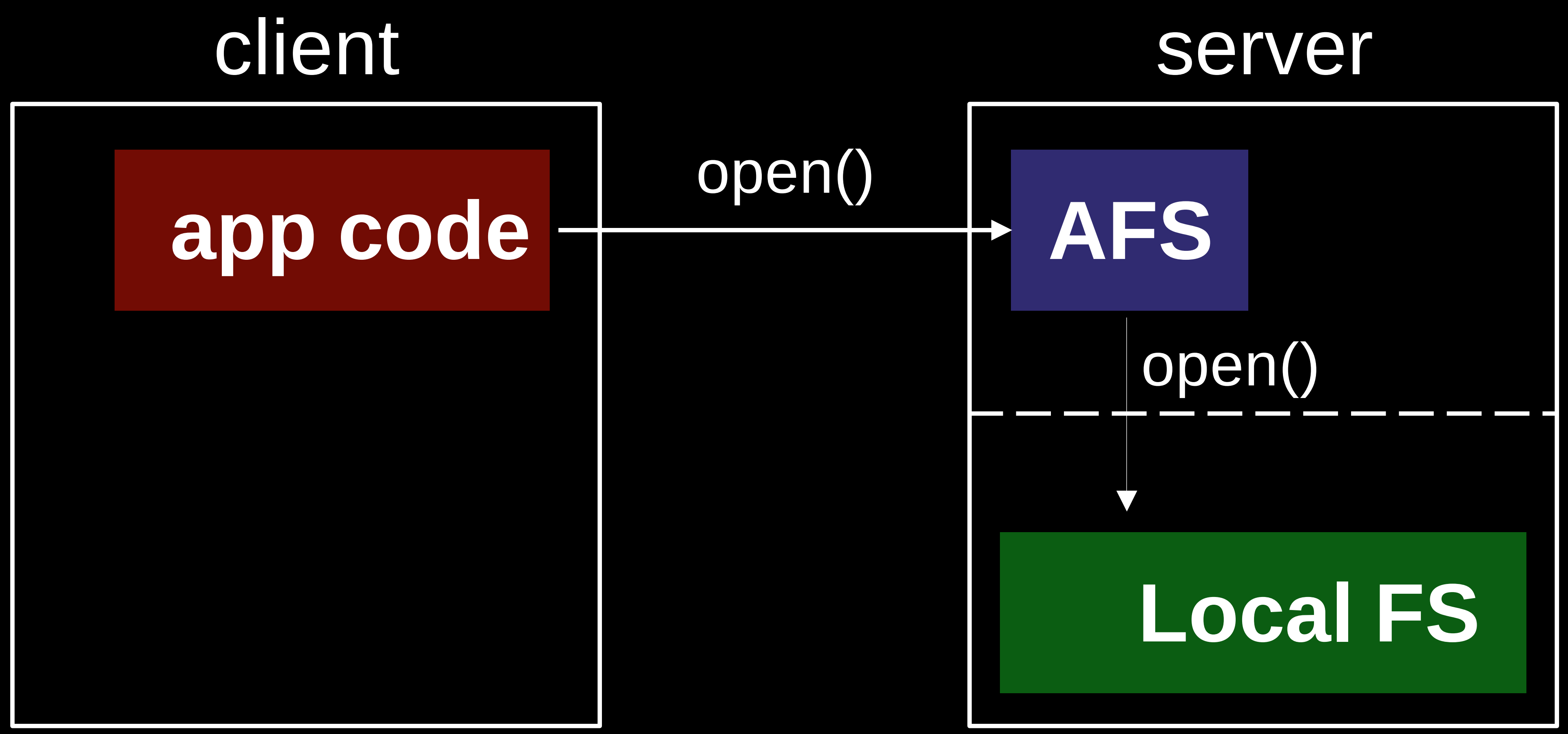
```
open(int inode, ...)

open(char *path, ...)
```

# Which API is faster? More convenient?

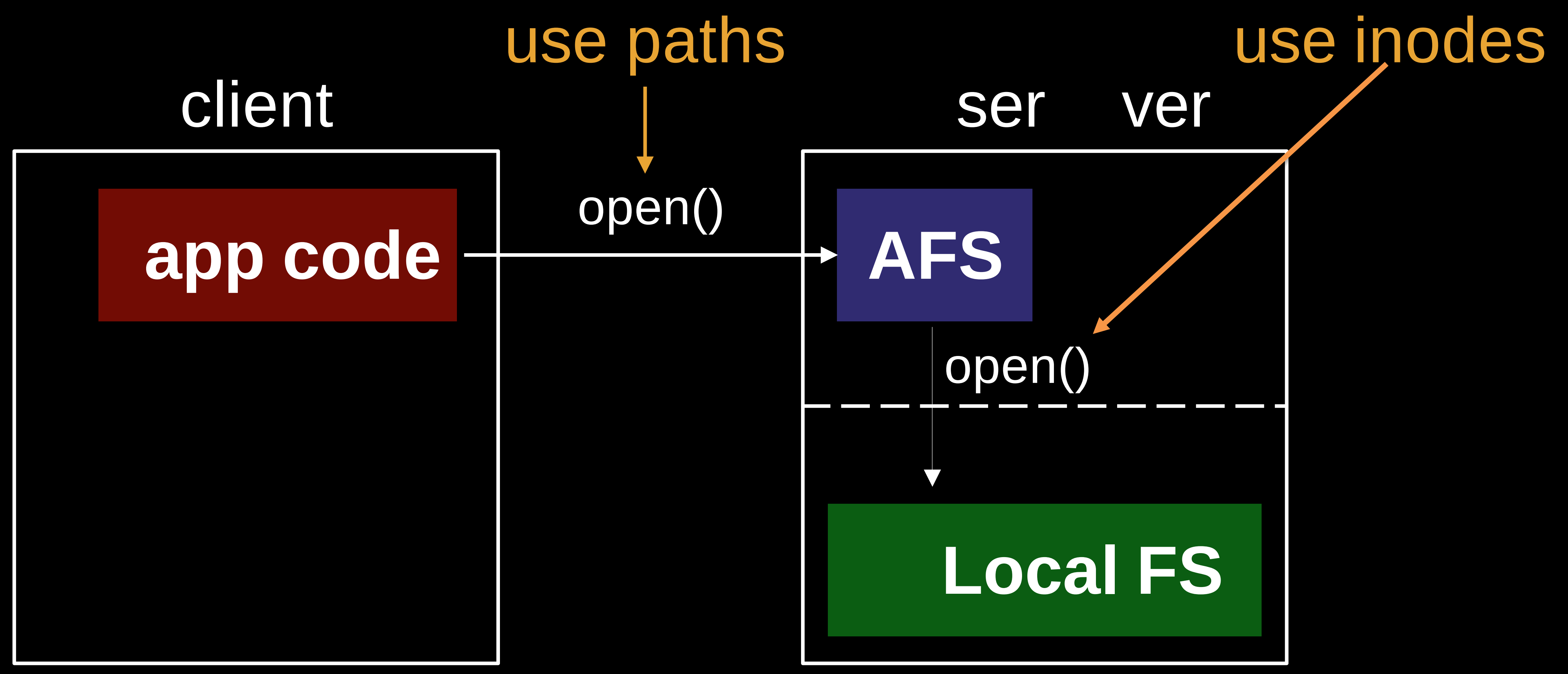
```
open(int inode, ...)

        open(char *path, ...)
```

Lookup by inodes is faster (no traversal),
but less convenient.

# Which open API is better?



# Which open API is better?



# Which API is faster? More convenient?

```
open(int inode, ...)

open(char *path, ...)
```

Lookup by inodes is faster (no traversal),
but less convenient.

AFS developers added first call so AFS could use it.

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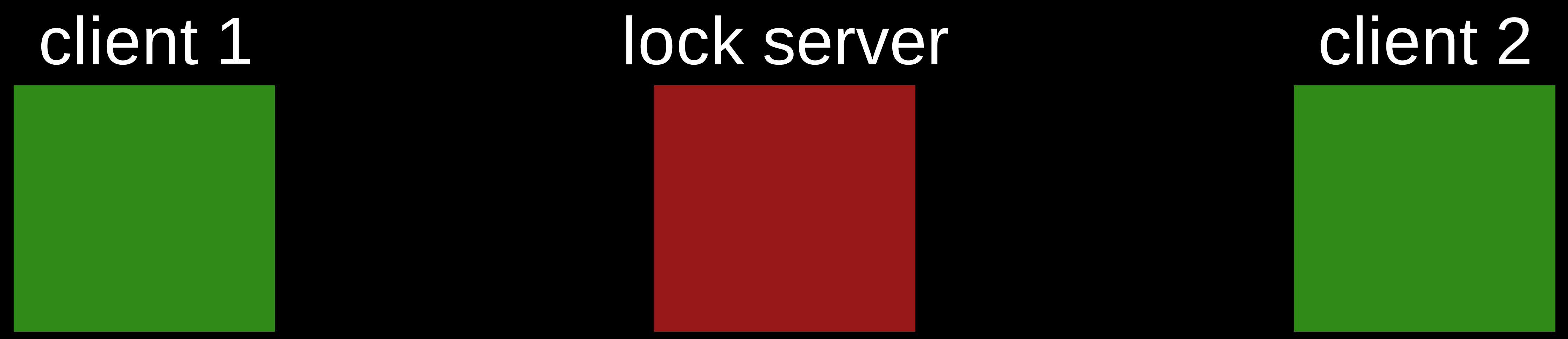
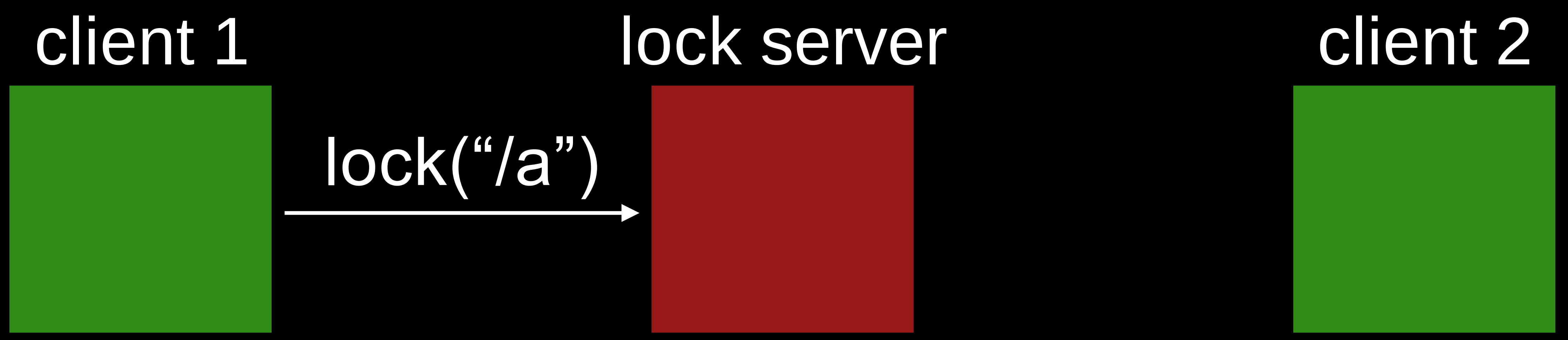
# Dedicated Lock Server



# Dedicated Lock Server



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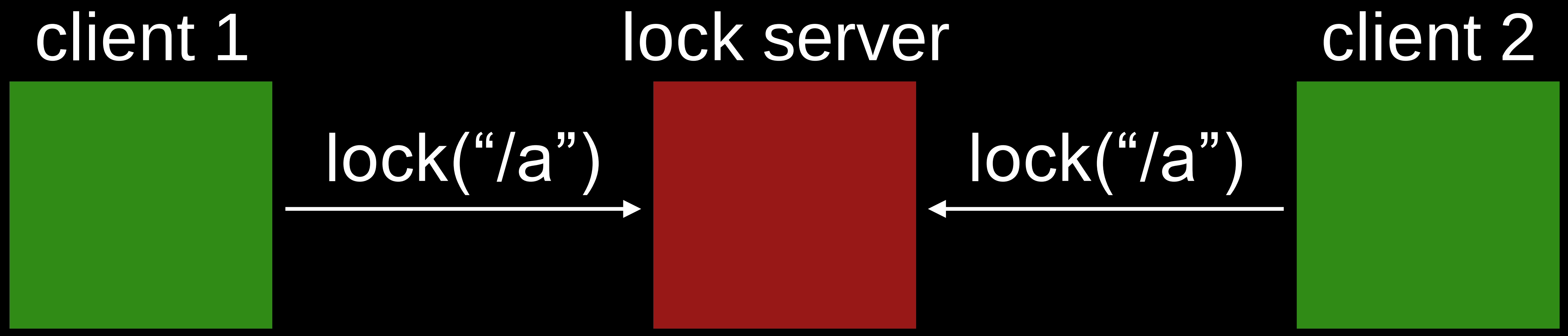

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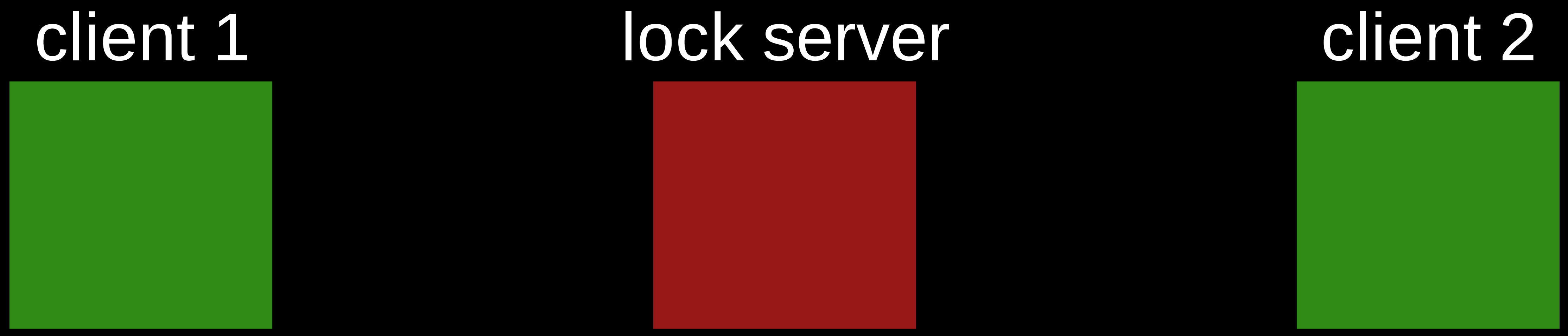
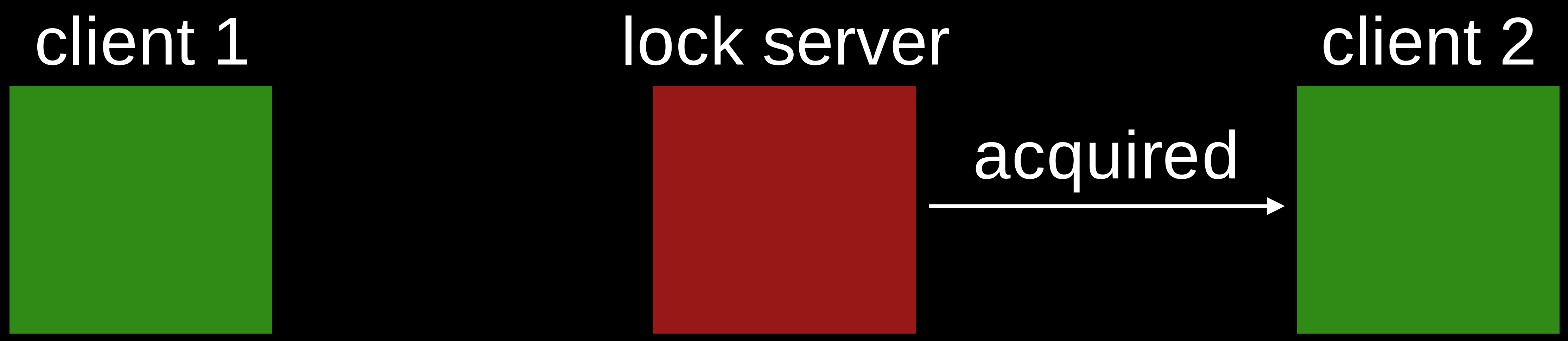
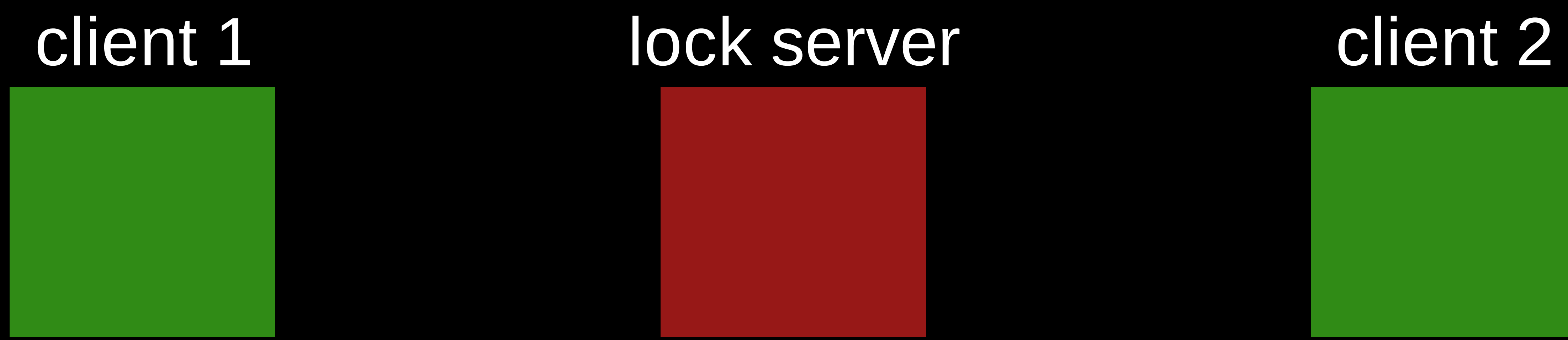


# Dedicated Lock Server



# Dedicated Lock Server



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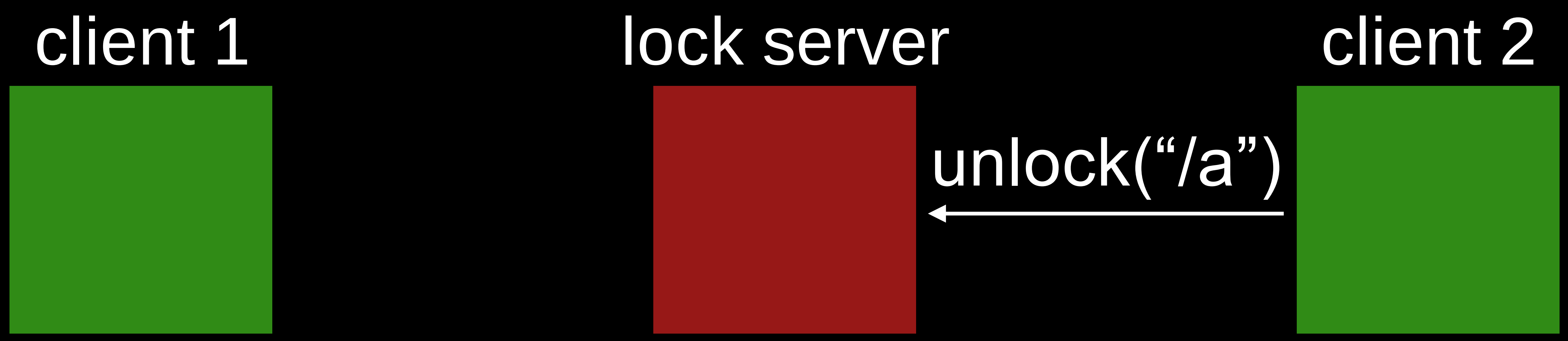

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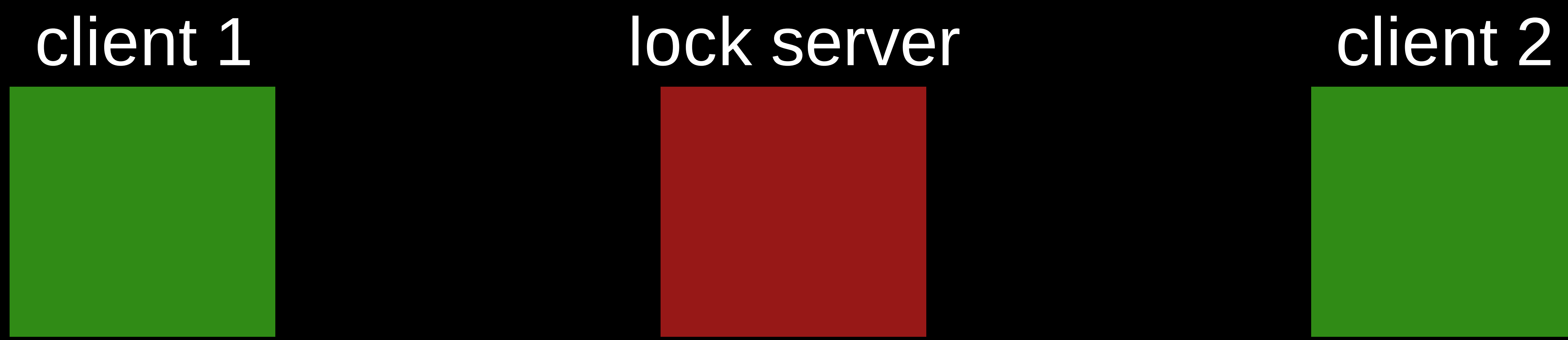
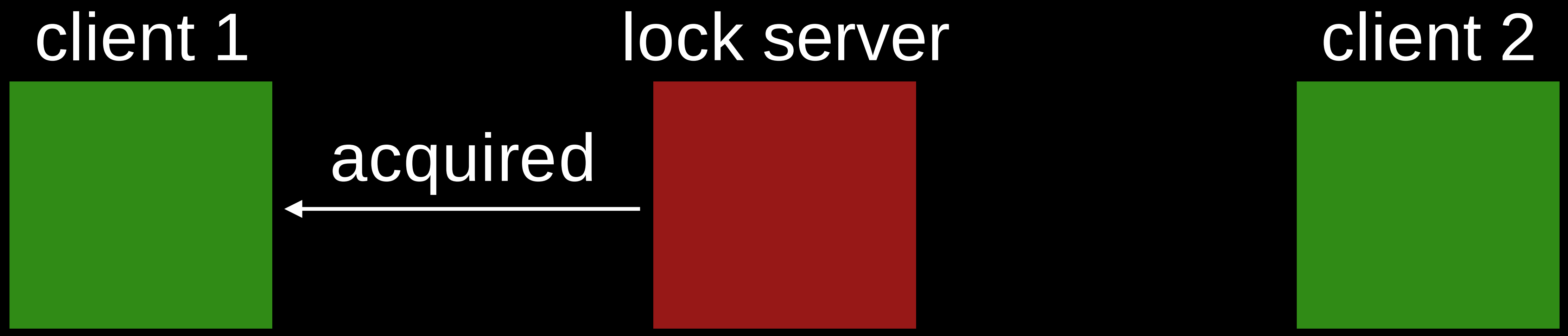
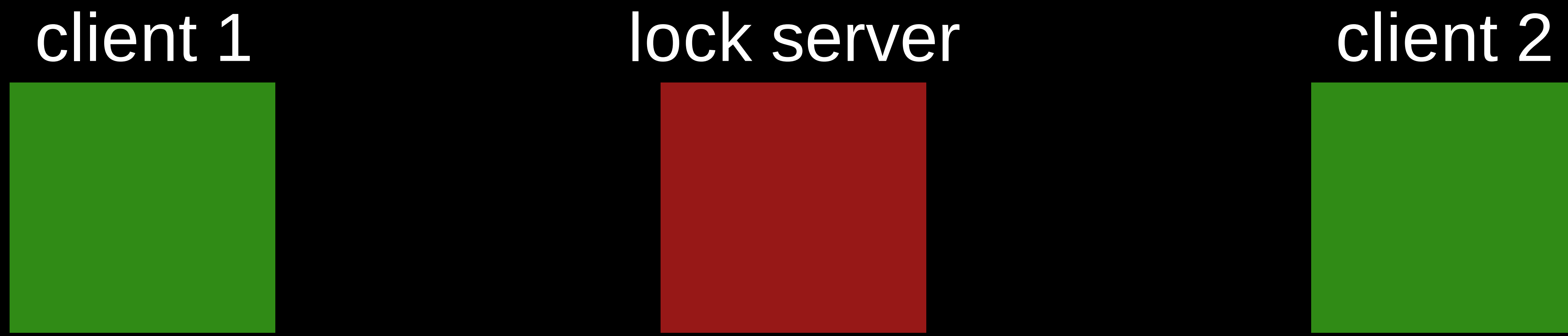


# Dedicated Lock Server



# Dedicated Lock Server



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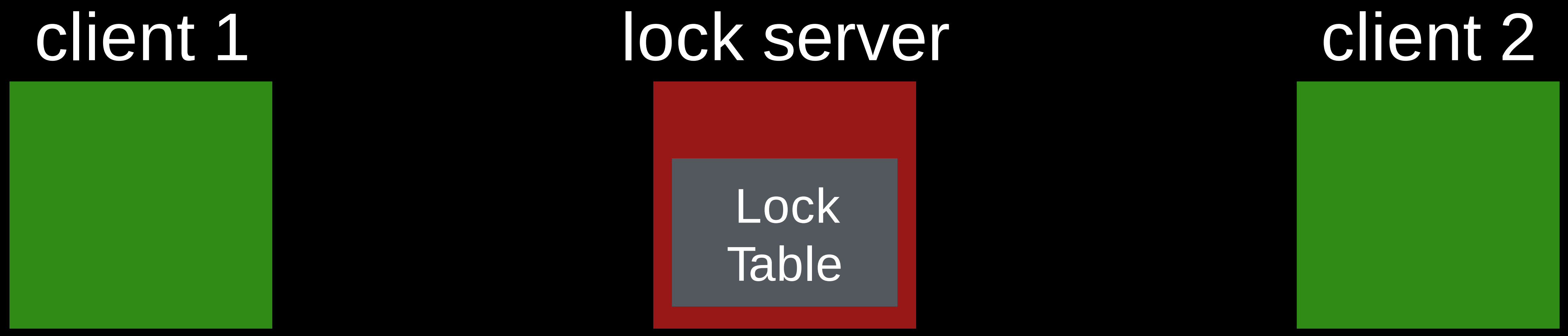

# Lock Table

```
void table_lock(char *name) {
   hash_entry_t *entry;
     acquire(guard);
   entry = find_or_create(name);
    release(guard);
   lock(entry->lock);
          }

void table_unlock(char *name) {
   hash_entry_t *entry;
     acquire(guard);
   entry = find_or_create(name);
     release(guard);
   unlock(entry->lock);
           }
```

# Lock Table

```
void table_lock(char *name) {
   hash_entry_t *entry;
   acquire(guard);
   entry = find_or_create(name)     ;
     release(guard);
   lock(entry->lock);
          }

void table_unlock(char *name) {
   hash_entry_t *entry;
     acquire(guard);
   entry = find_or_create(name);
     release(guard);
   unlock(entry->lock);
           }
```

expose these with RPCs

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Volume management
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# AFS Summary

Multi-step copy and forwarding make volume migration fast and consistent.

**State** is useful for **scalability**, but makes handling crashes hard

- Server tracks callbacks for clients that have file cached
- Lose callbacks when server crashes…

Workload drives design: **whole-file caching**

- More intuitive semantics (see version of file that existed when fil e was opened)

# AFS vs nfs Protocols

Can you summarize the consistency semantics provided by NFSv2?

| Time | Client A | Client B | Server Action? |
|---|---|---|---|
| 0 | fd = open("file A"); | | |
| 10 | read(fd, block1); | | |
| 20 | read(fd, block2); | | |
| 30 | read(fd, block1); | | |
| 31 | read(fd, block2); | | |
| 40 | | fd = open("file A"); | |
| 50 | | write(fd, block1); | |
| 60 | read(fd, block1); | | |
| 70 | | close(fd); | |
| 80 | read(fd, block1); | | |
| 81 | read(fd, block2); | | |
| 90 | close(fd); | | |
| 100 | fd = open("fileA"); | | |
| 110 | read(fd, block1); | | |
| 120 | close(fd); | | |

When will server be contacted for NFS? For AFS?
What data will be sent? What will each client see?

# Nfs Protocol

| Time | Client A | Client B | Server Action? |
|---|---|---|---|
| 0 | fd = open("file A"); | | lookup() |
| 10 | read(fd, block1); read | | read |
| 20 | read(fd, block2); read | | read |
| 30 | read(fd, block1); check cache: attr expired getattr(); okay; use local | | getattr |
| 31 | read(fd, block2); attr not expired, use local | | |
| 40 | | fd = open("file A"); | lookup |
| 50 | | write(fd, block1); keep local | |
| 60 | read(fd, block1); attr. expired use local data | | getattr() |
| 70 | | close(fd); write bl to server! | write to disk |
| 80 | read(fd, block1); attr expired: get attr. CHANGED FILE - kickout | | read() |
| 81 | read(fd, block2); not in cache → read | | read() |
| 90 | close(fd); | | |
| 100 | fd = open("fileA"); | | lookup |
| 110 | read(fd, block1); attr expire; get new attr local ok | | getattr |
| 120 | close(fd); | | |

# AFS Protocol

| Time | Client A | Client B | Server Action? |
|---|---|---|---|
| 0 | fd = open("file A"); | | setup callback for A |
| 10 | read(fd, block1); | send all of | file A |
| 20 | read(fd, block2); local!! | | |
| 30 | read(fd, block1); | | |
| 31 | read(fd, block2); | | |
| 40 | | fd = open("file A"); | setup callback |
| 50 | | write(fd, block1); send | all of A |
| 60 | read(fd, block1); local | | |
| 70 | | close(fd); send back | changes of A |
| 80 | read(fd, block1); local | | break callbacks |
| 81 | read(fd, block2); local | | |
| 90 | close(fd); nothing changed | | |
| 100 | fd = open("fileA"); no callback!! need to | fetch A again | |
| 110 | read(fd, block1); | | |
| 120 | close(fd); | send A | |