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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?

What is a Distributed System?

A distributed system is one where a machine I've never 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
- peer-to-peer: BitTorrent, Blockchain

Other courses:

- **CS 542**: Computer Networks
- **CS 55*0***: Advanced Operating Systems (this is really a DS course)

Why Go Distributed?

More computing power

More storage capacity

Fault tolerance

Data sharing

Decentralized trust

New Challenges

System failure: need to worry about partial failure

Consistency: do nodes have most up-to-date copies of data?

Data location: who owns what?

Dynamic Systems: nodes come and go

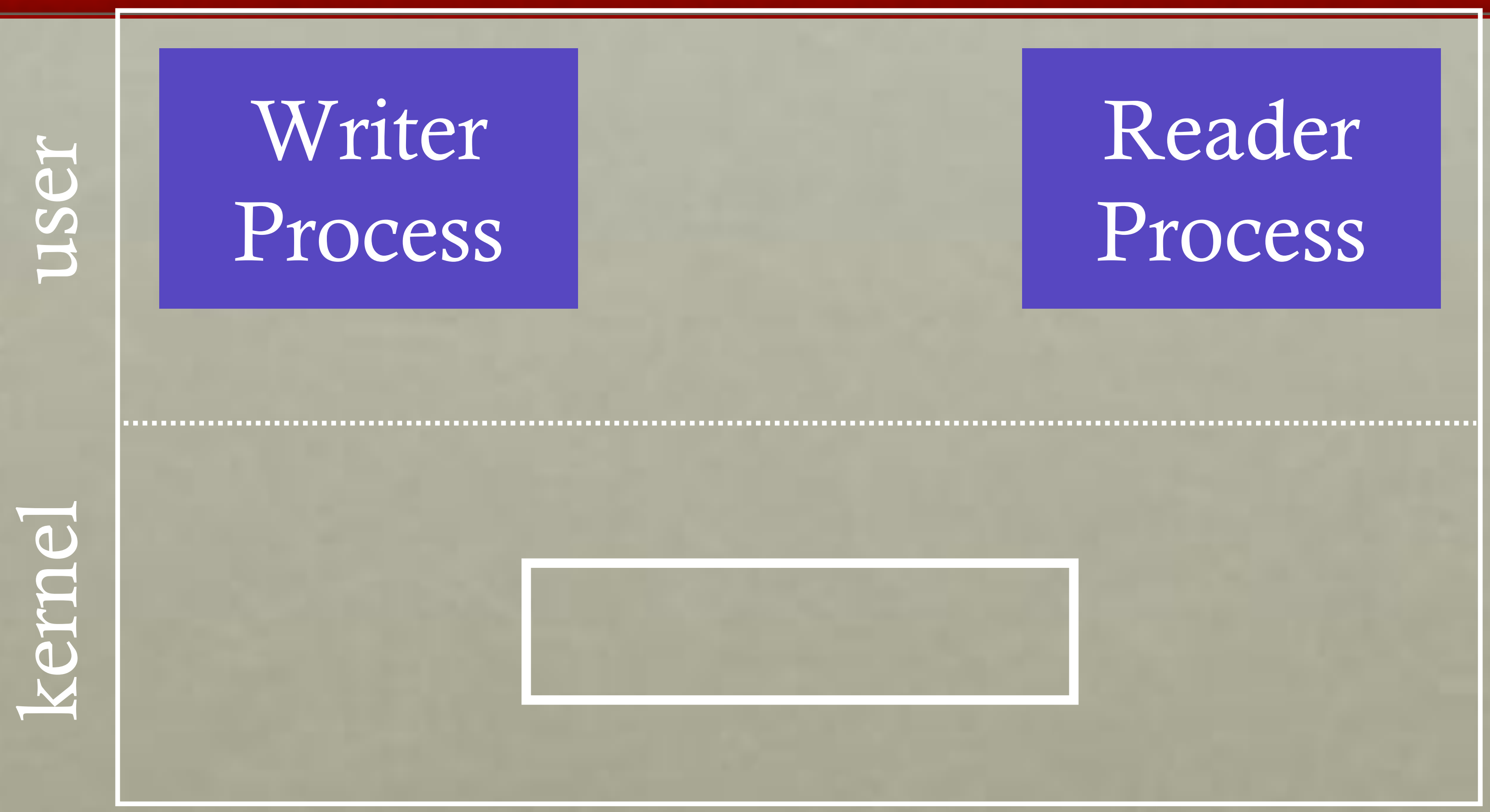
Communication failure: links unreliable

- bit errors
- packet loss
- node/link failure

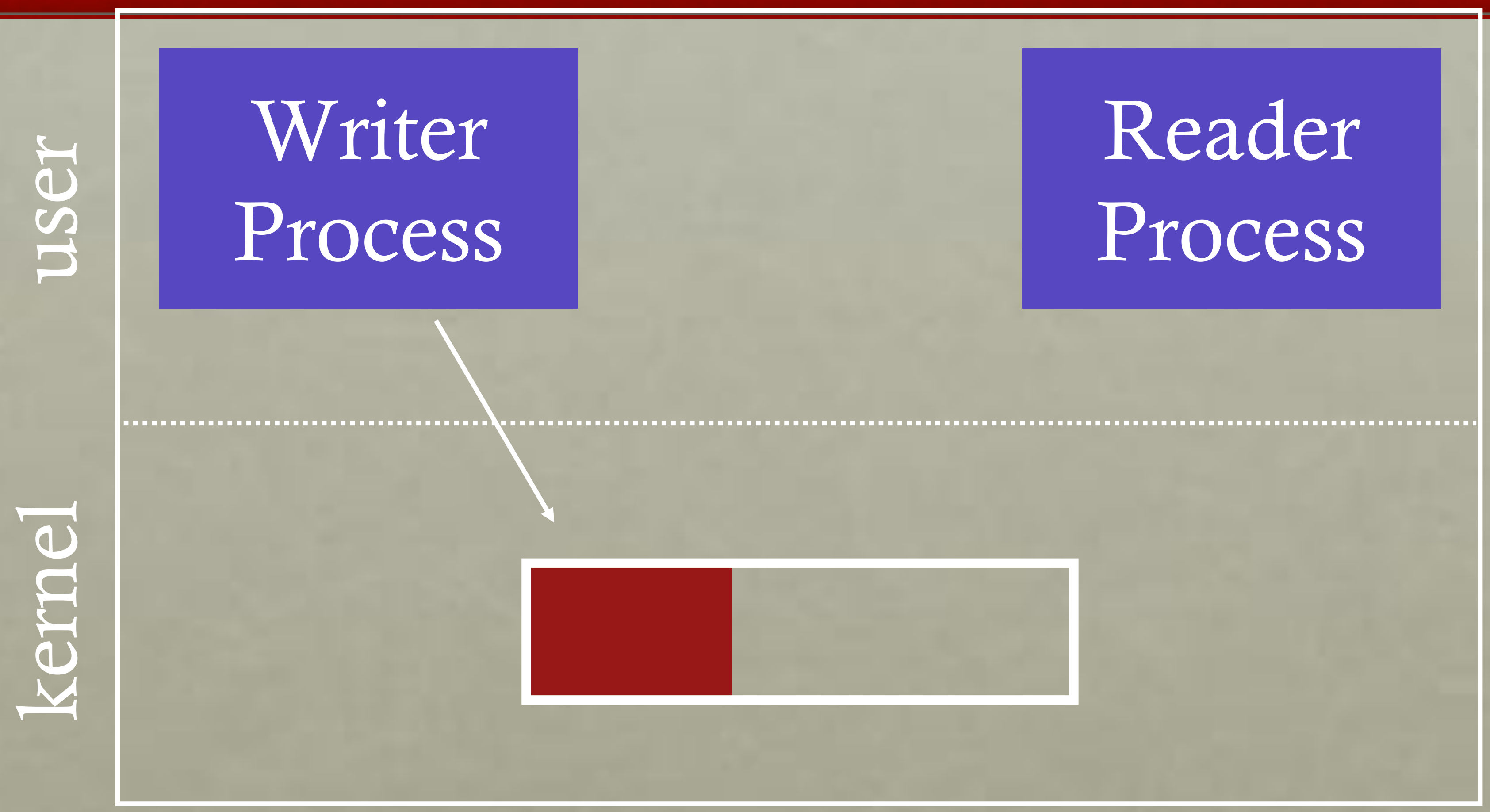
Motivating example:

Why are network sockets less reliable than pipes?

PIPE



PIPE



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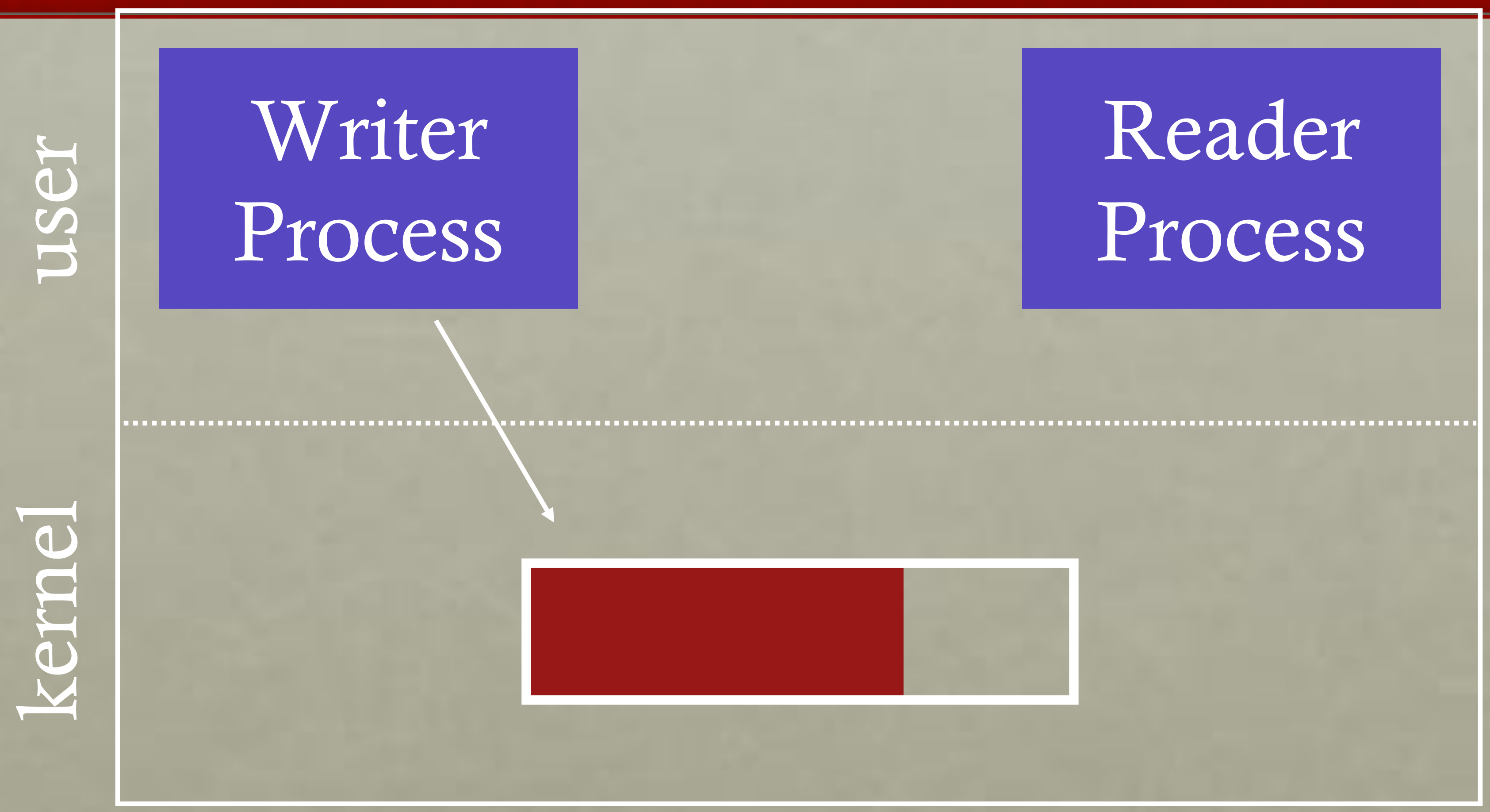

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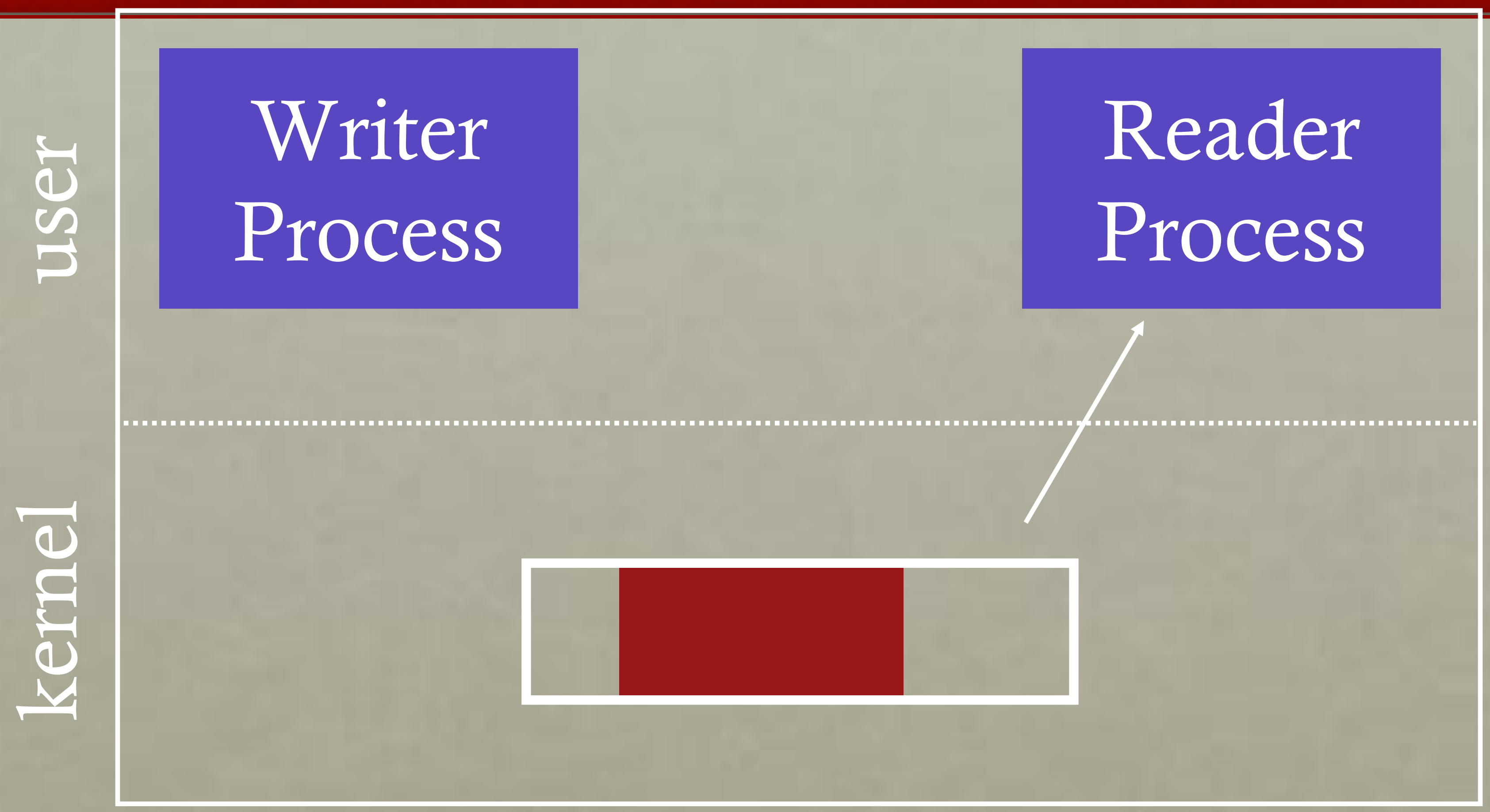

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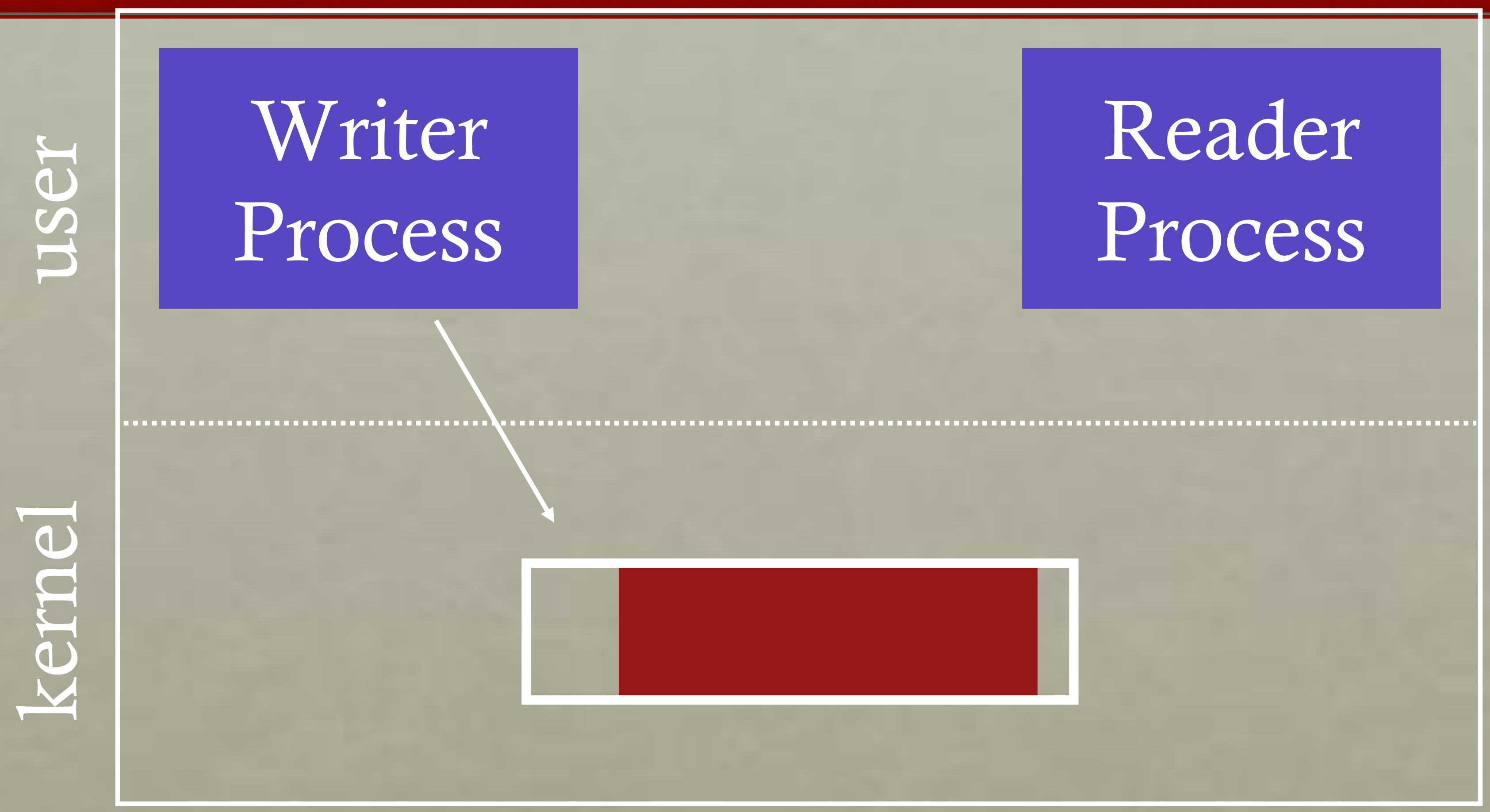

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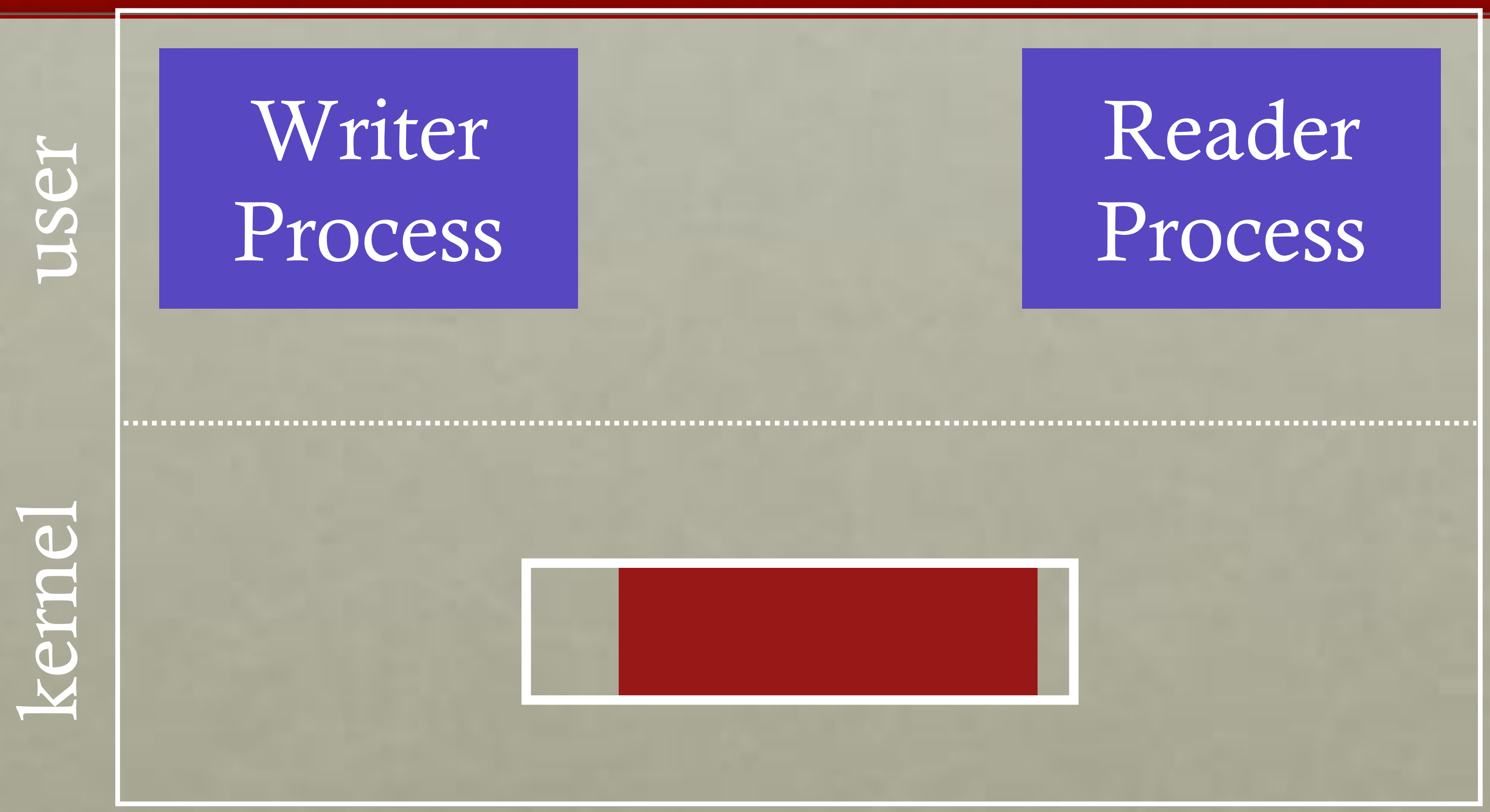
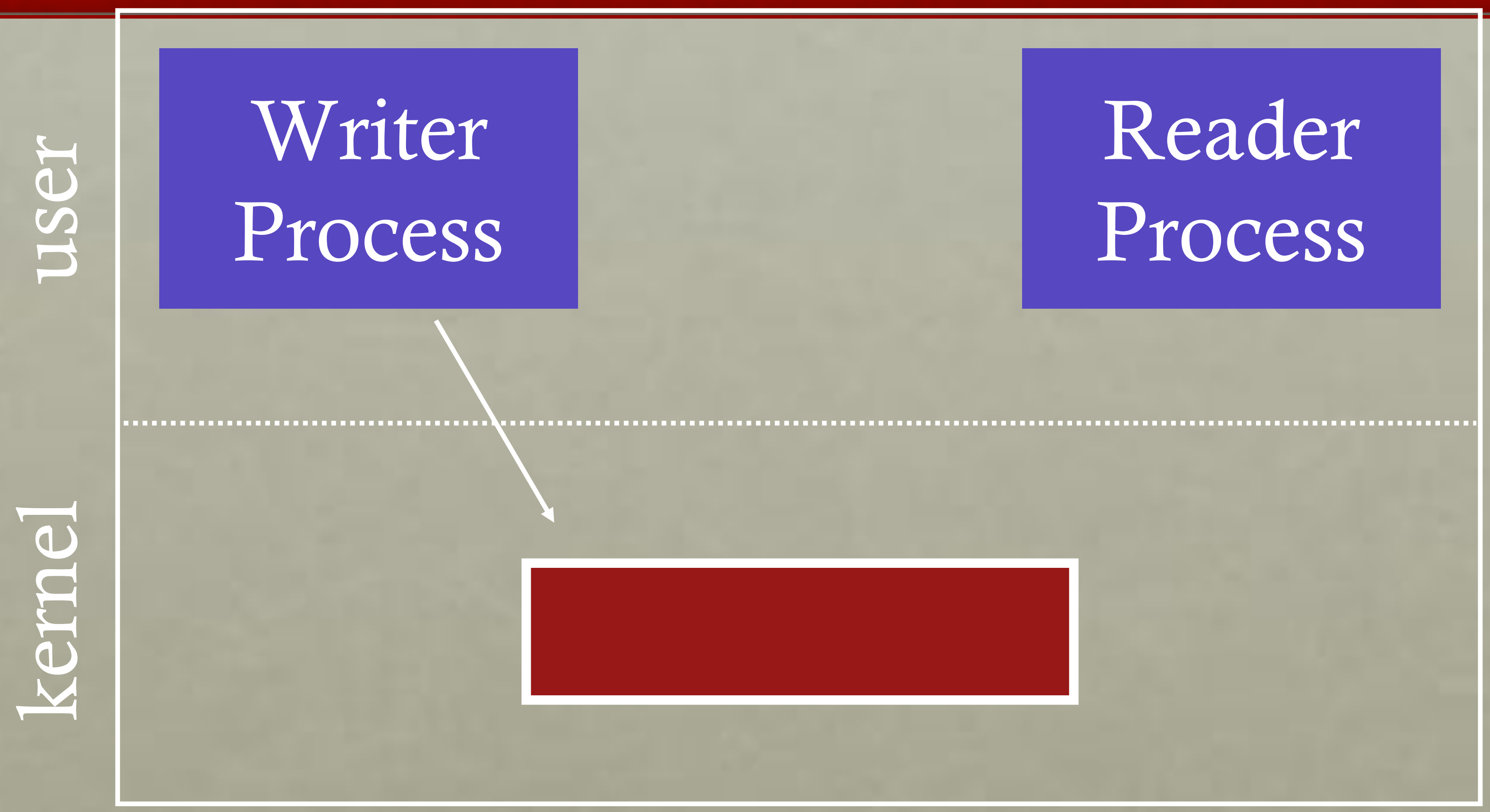


PIPE



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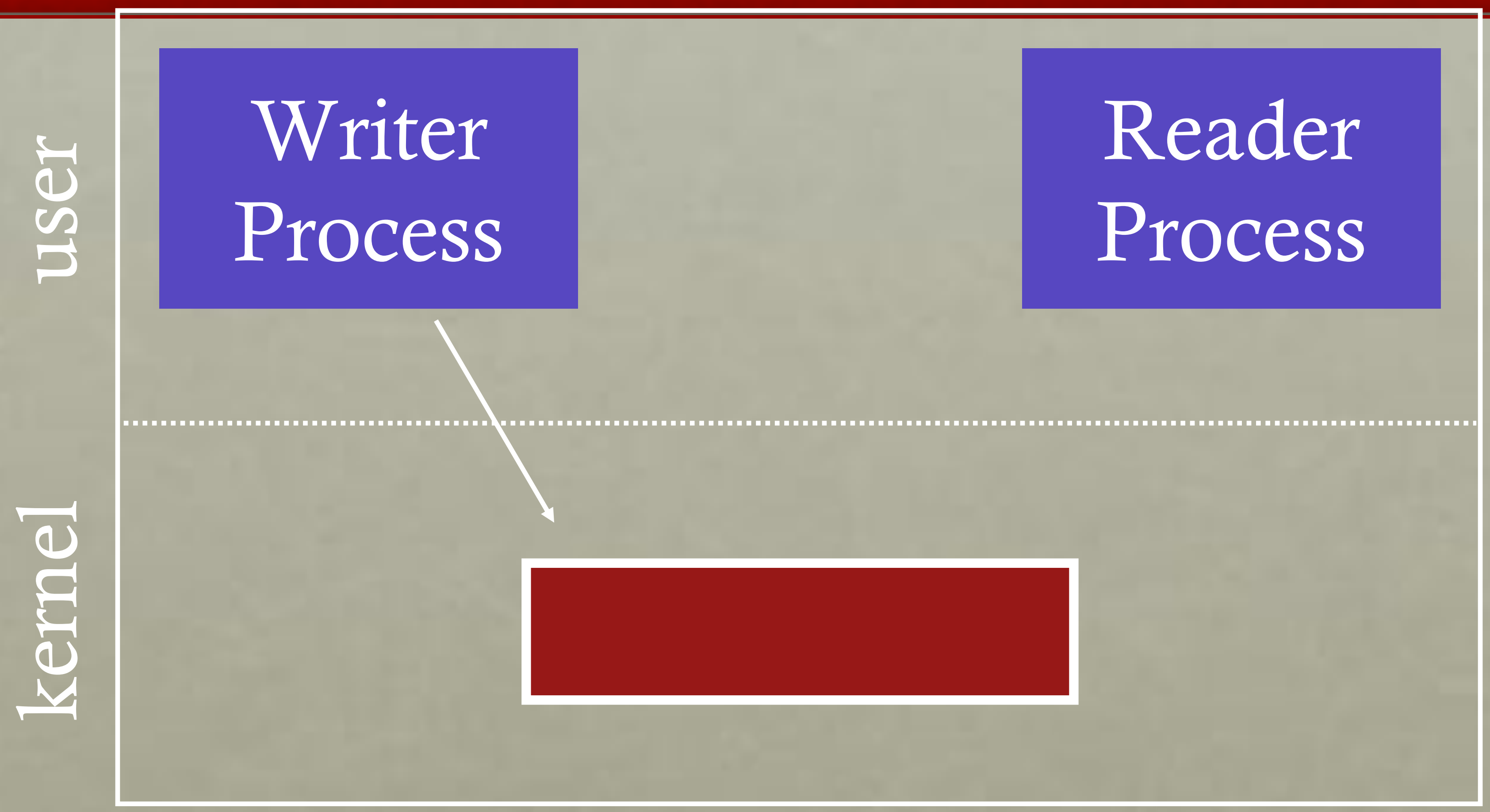
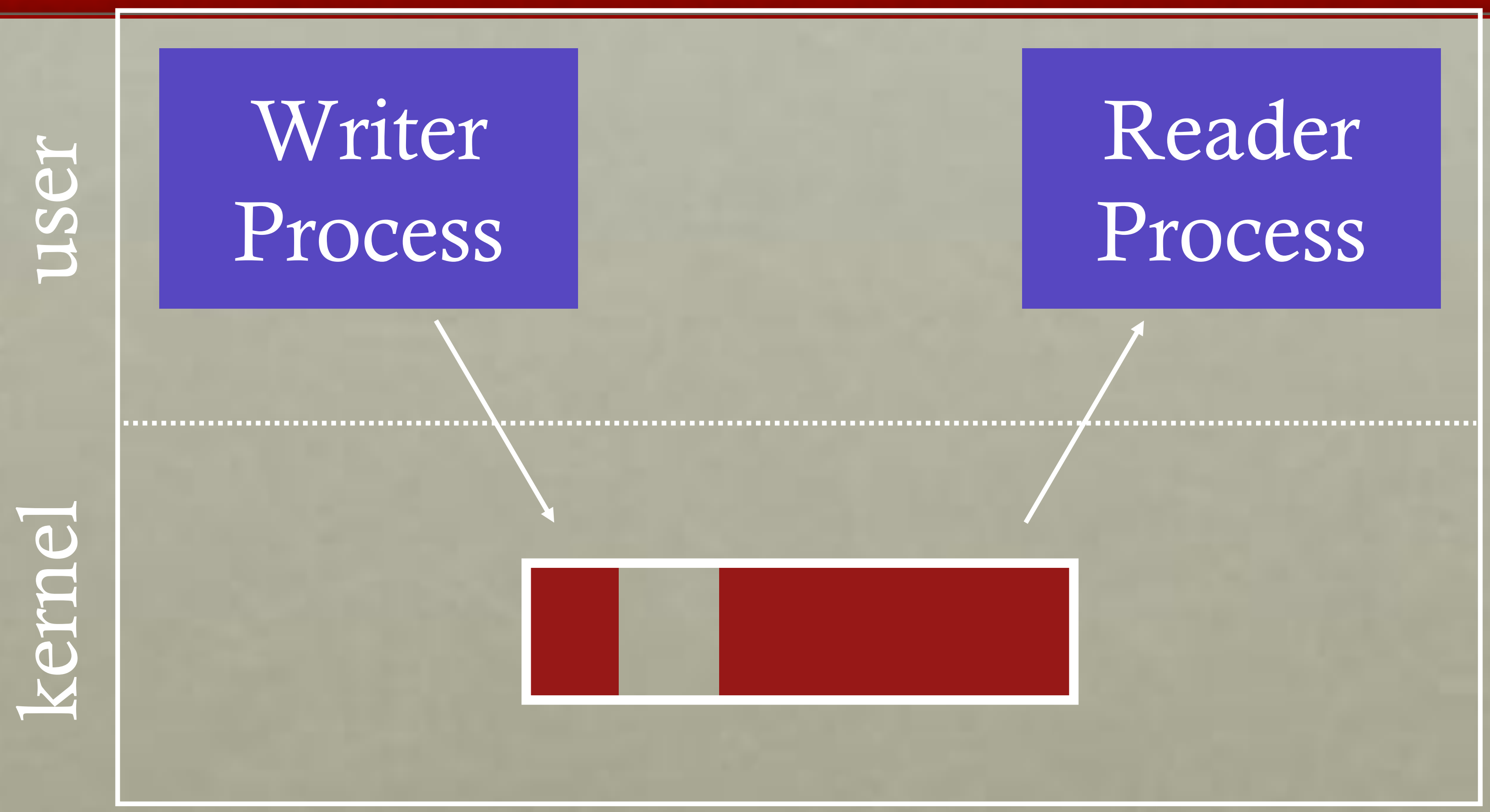


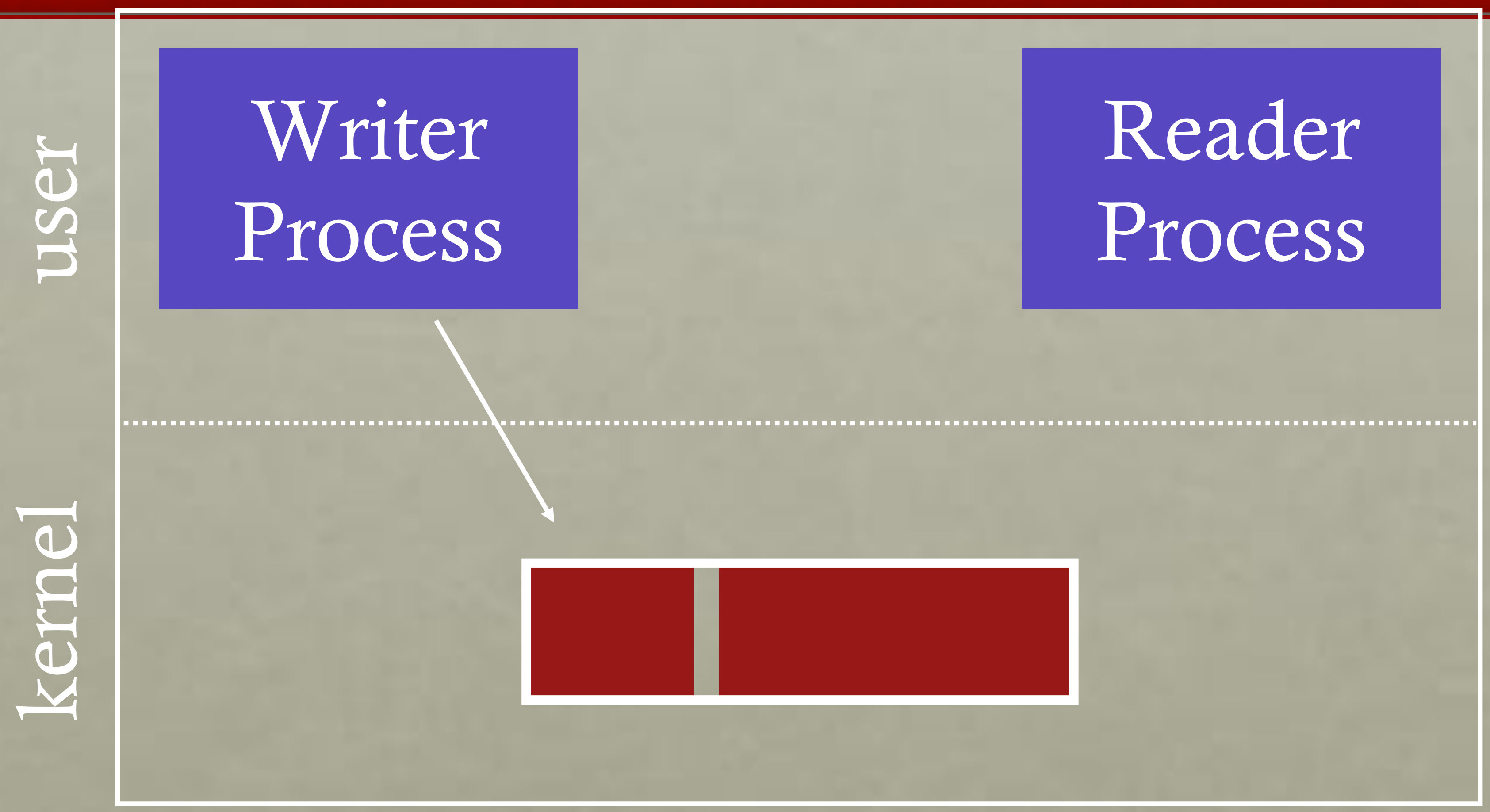
write waits for space

PIPE

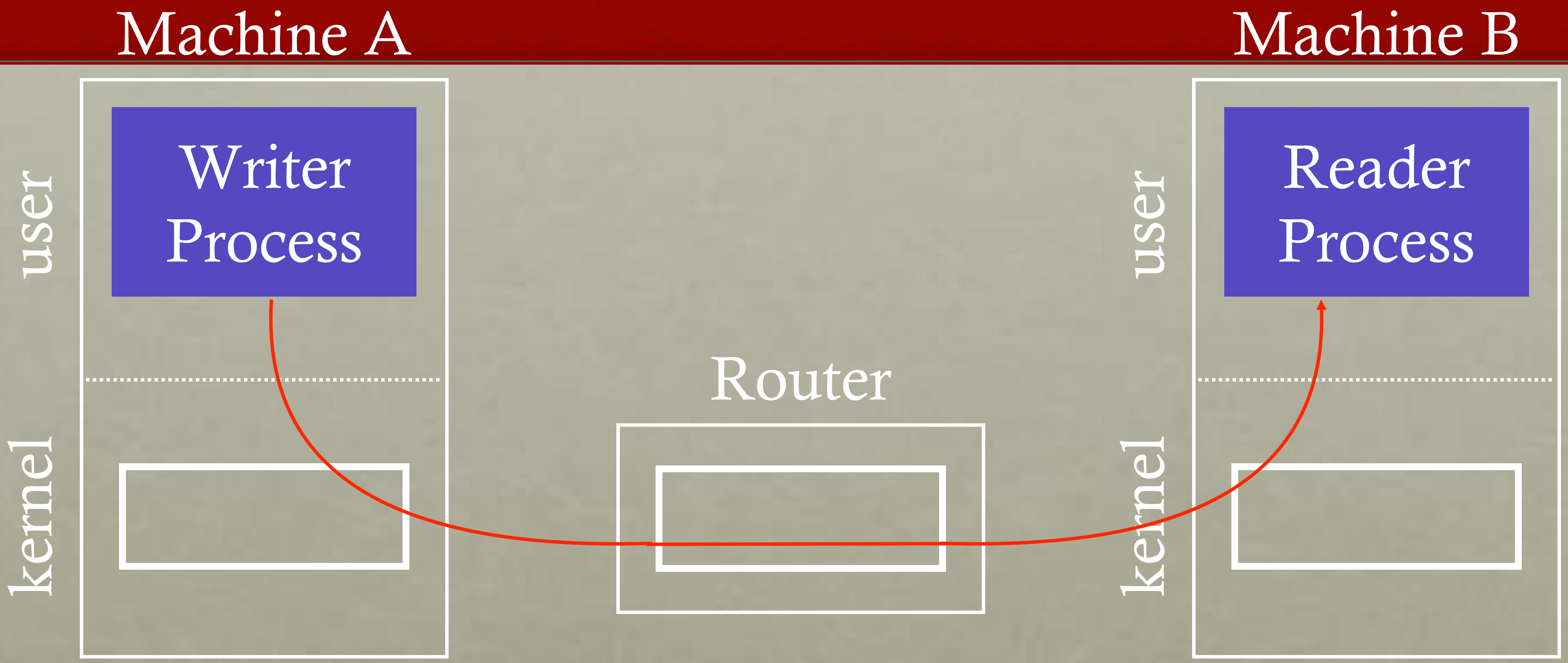


write waits for space

PIPE

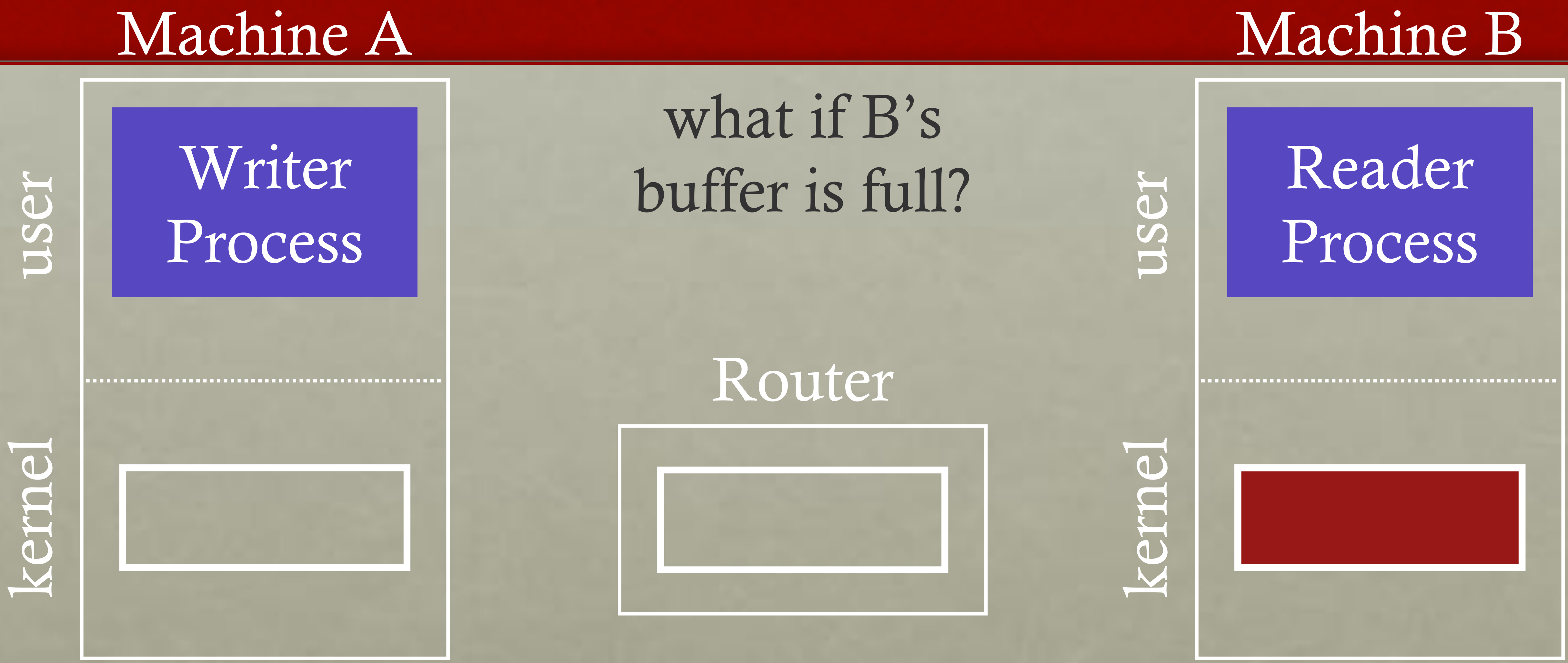


Network Socket

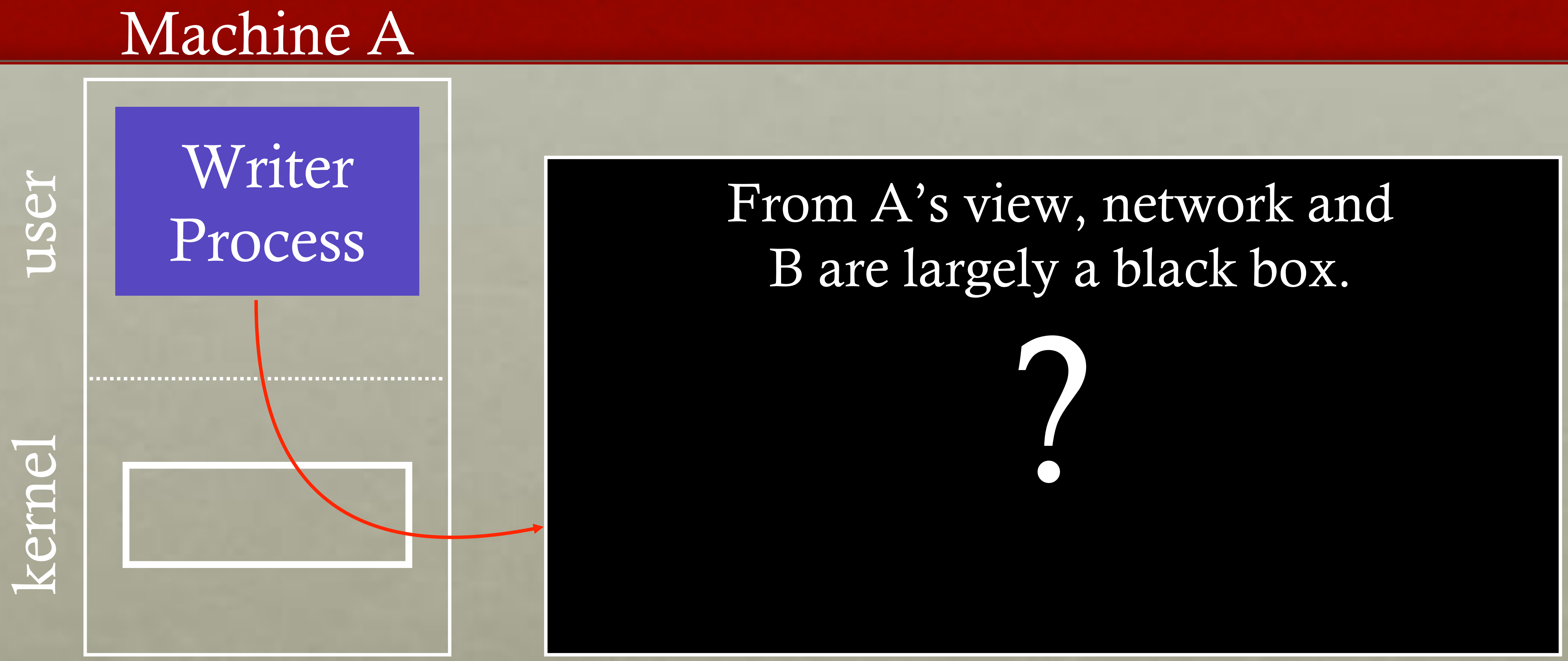


Network Socket

Network Socket



Network Socket



Communication Overview

Raw messages: UDP

Reliable messages: TCP

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

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

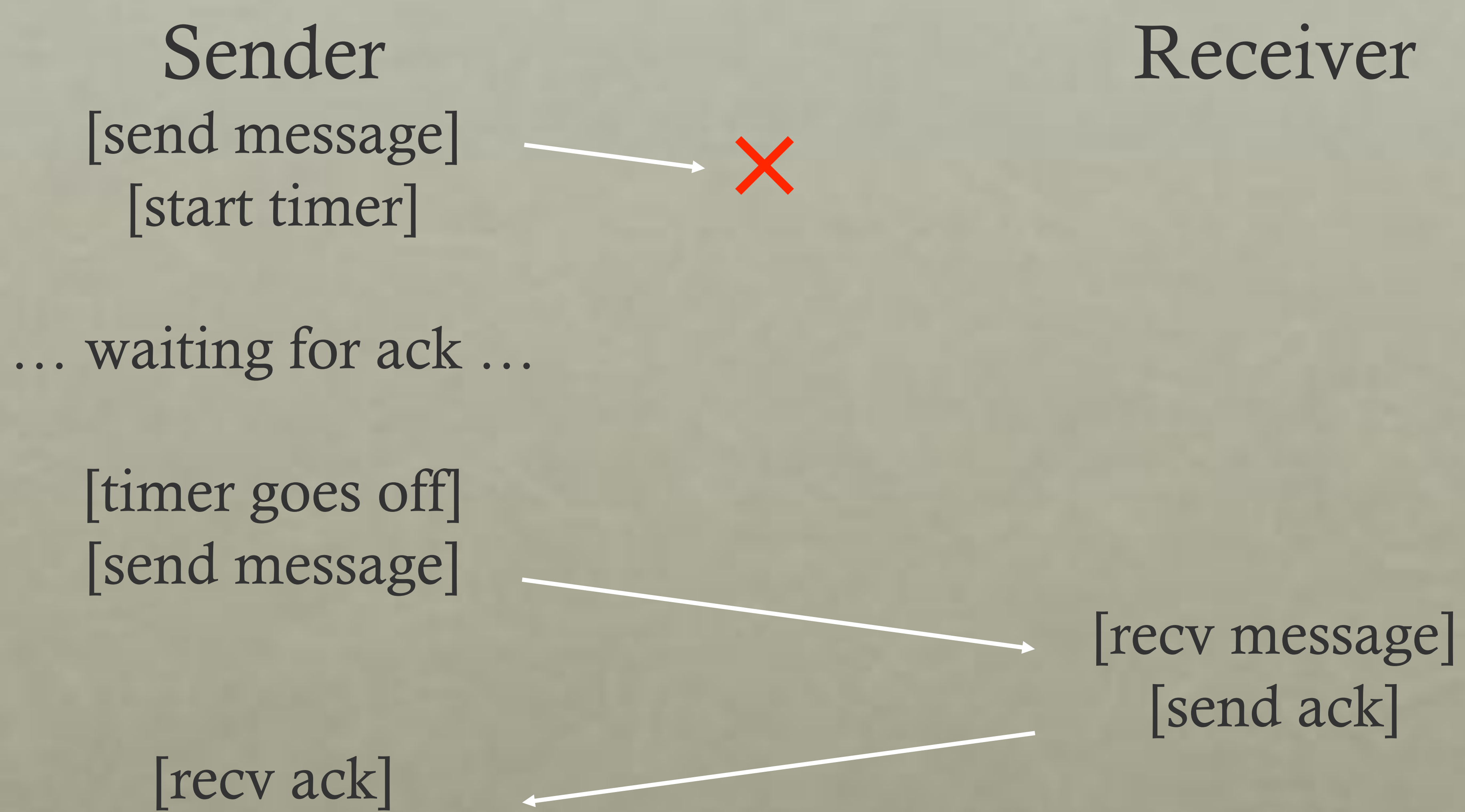
Sender

[send message]

Receiver

Sender doesn't receive ACK…
What to do?

Technique #2: Timeout



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

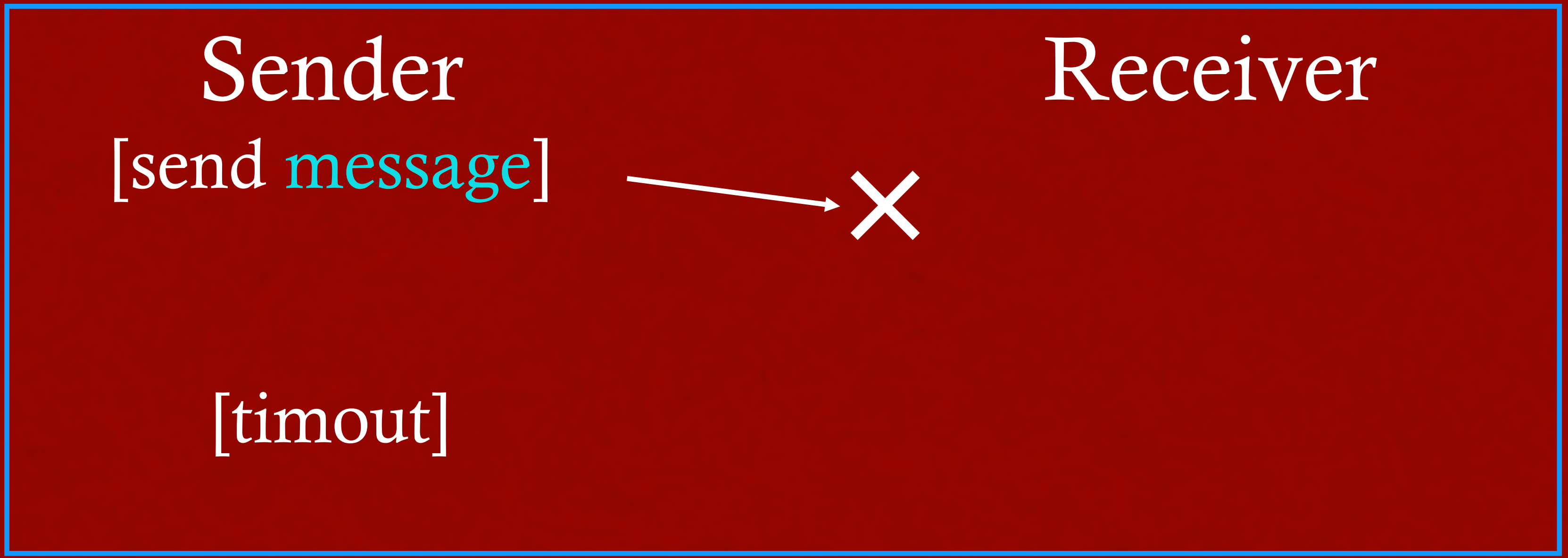
Adjust time based on how long acks usually take

For each missing ack, wait longer between retries

Lost Ack: Issue 2

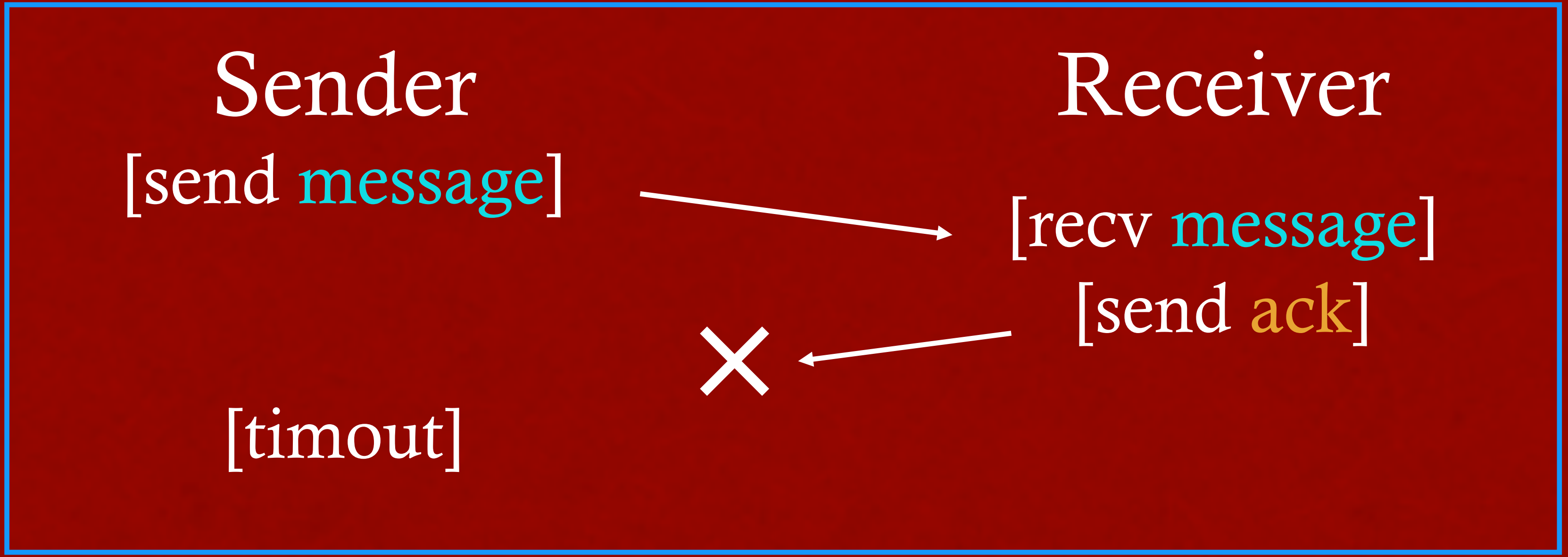
What does a lost ack really mean?

Case 1



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

Case 2

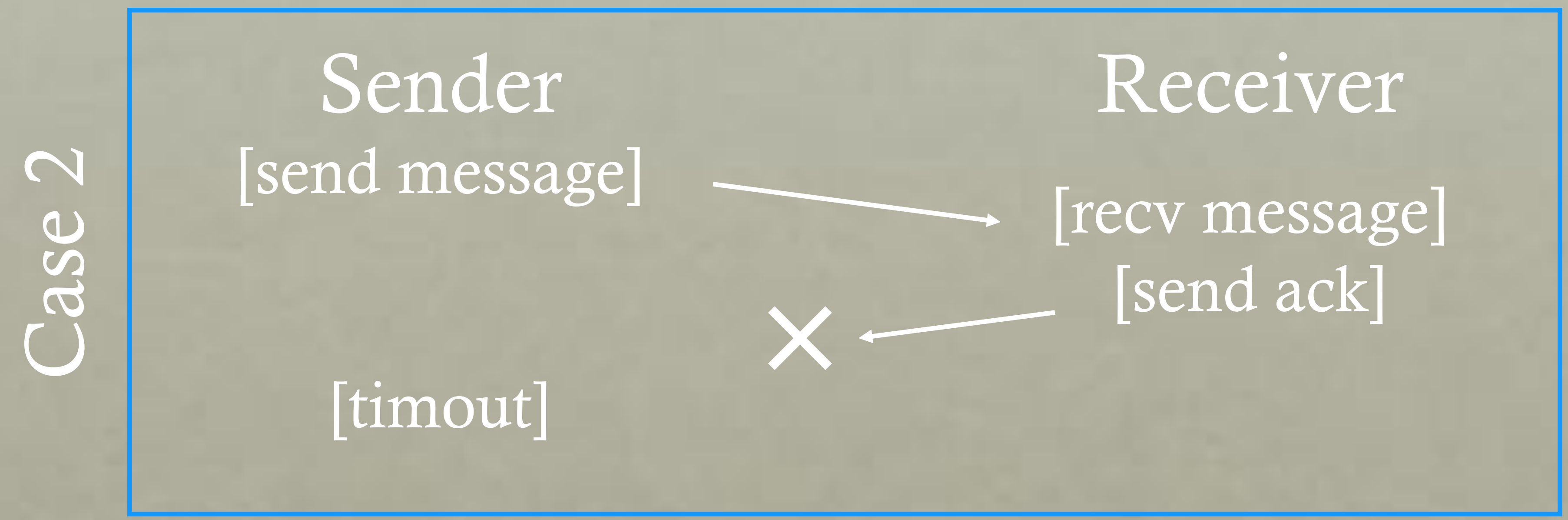


ACK: message received exactly once

No ACK: message may or may not have been received

What if message is command to increment counter?

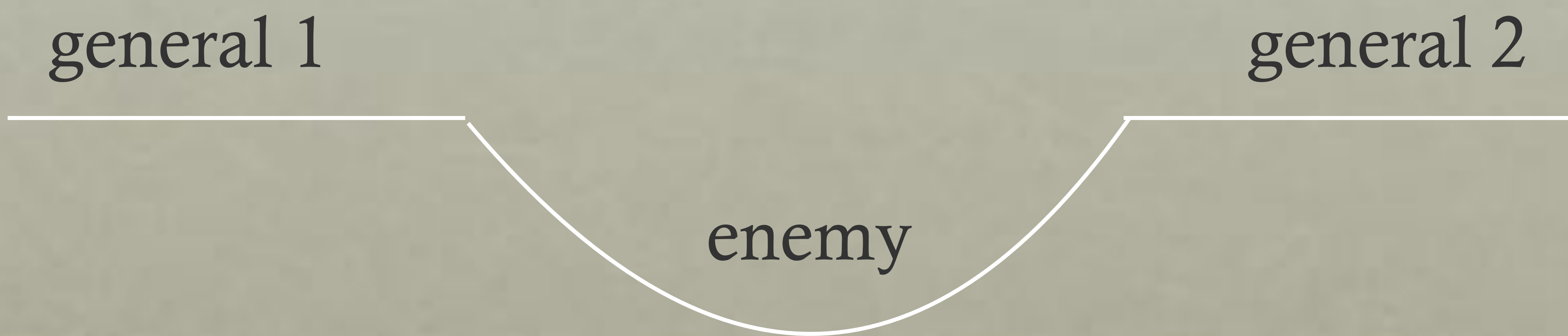
PROPOSED SOLUTION



Proposal:
Sender could send an AckAck so receiver knows whether to retry sending an Ack

Sound good?

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?

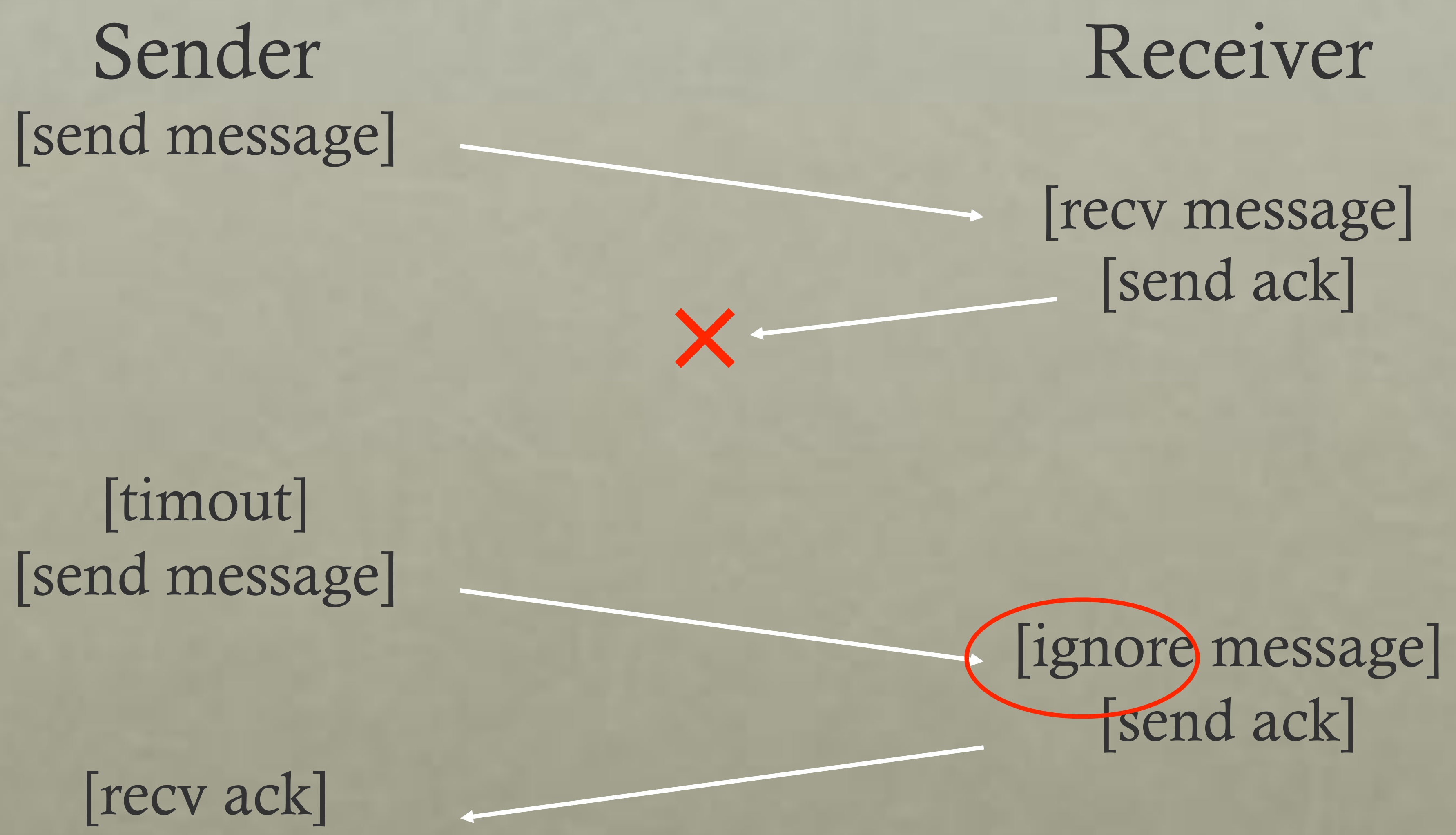
Reliable Messages: Layering Strategy

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

Communications Overview

Raw messages: UDP

Reliable messages: TCP

Remote procedure call: RPC

RPC

Remote **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) Runtime library

- Thread pool
- Socket listeners call functions on server

(2) Stub generation

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

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 serializing/deserializing

Wrapper Generation: Pointers

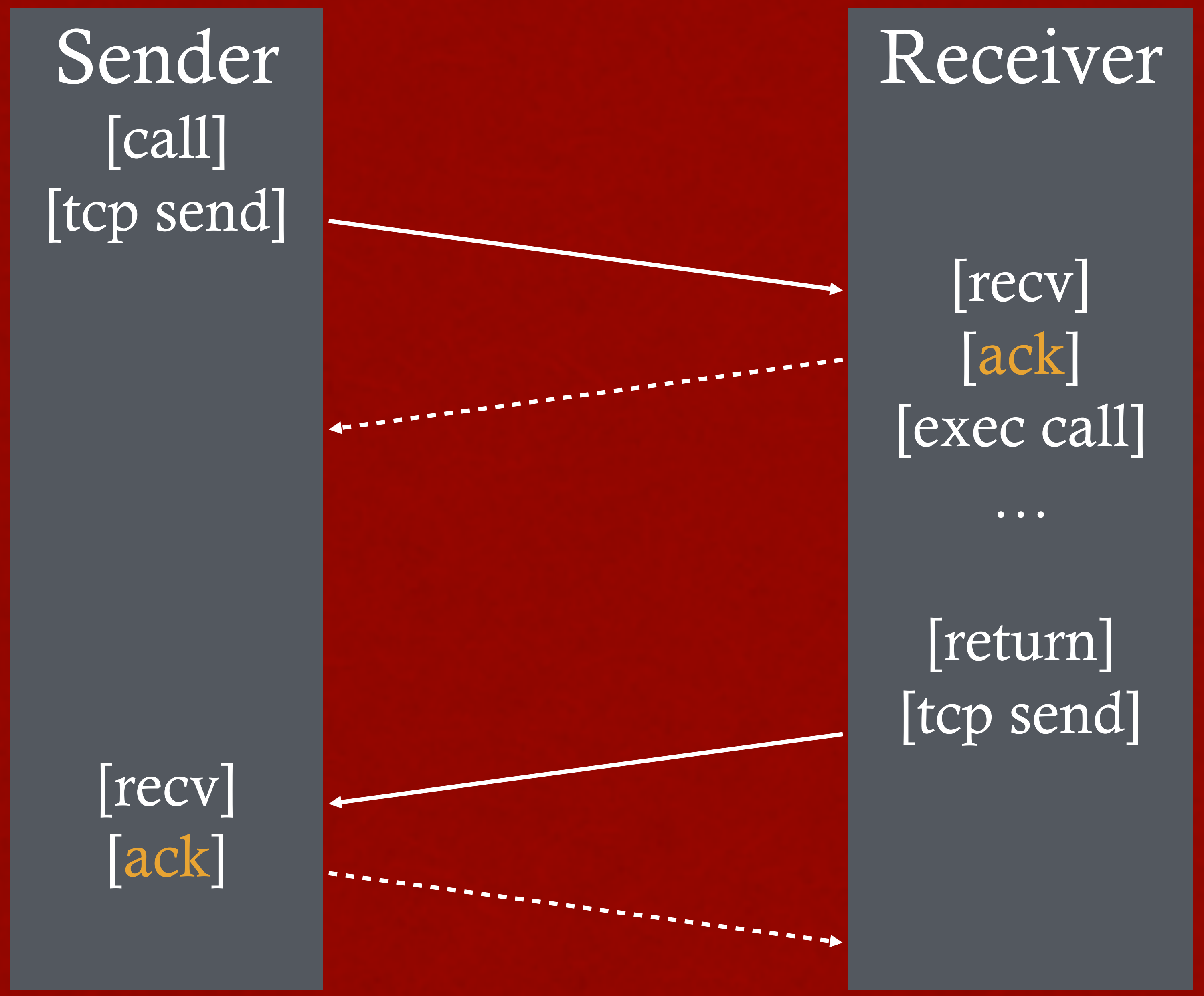
Why are pointers problematic?

Address passed from client not valid on server

Solutions?

- smart RPC package: follow pointers and copy data

RPC OVER TCP?



Why wasteful?

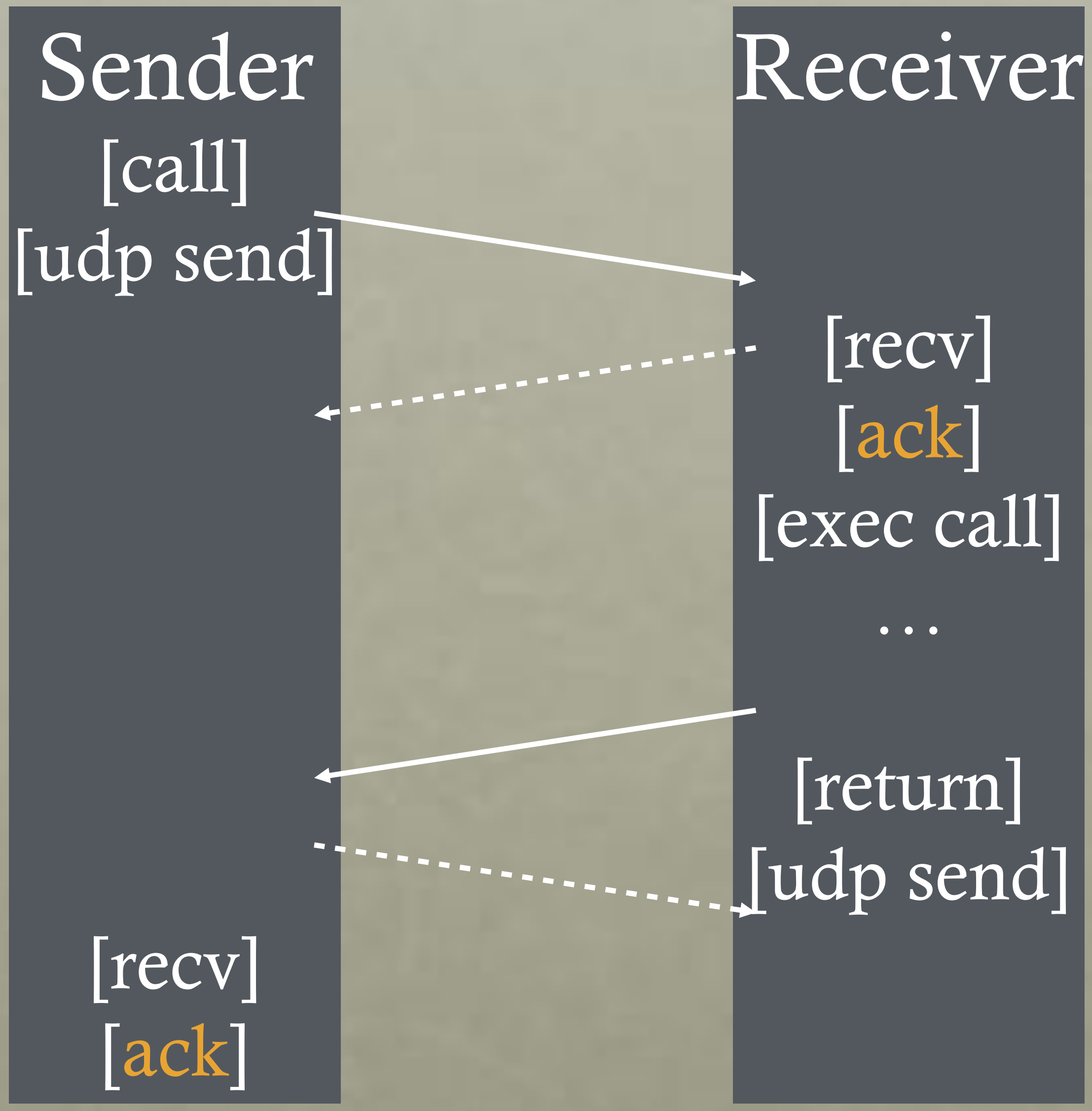
RPC OVER UDP

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 file 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

Overview

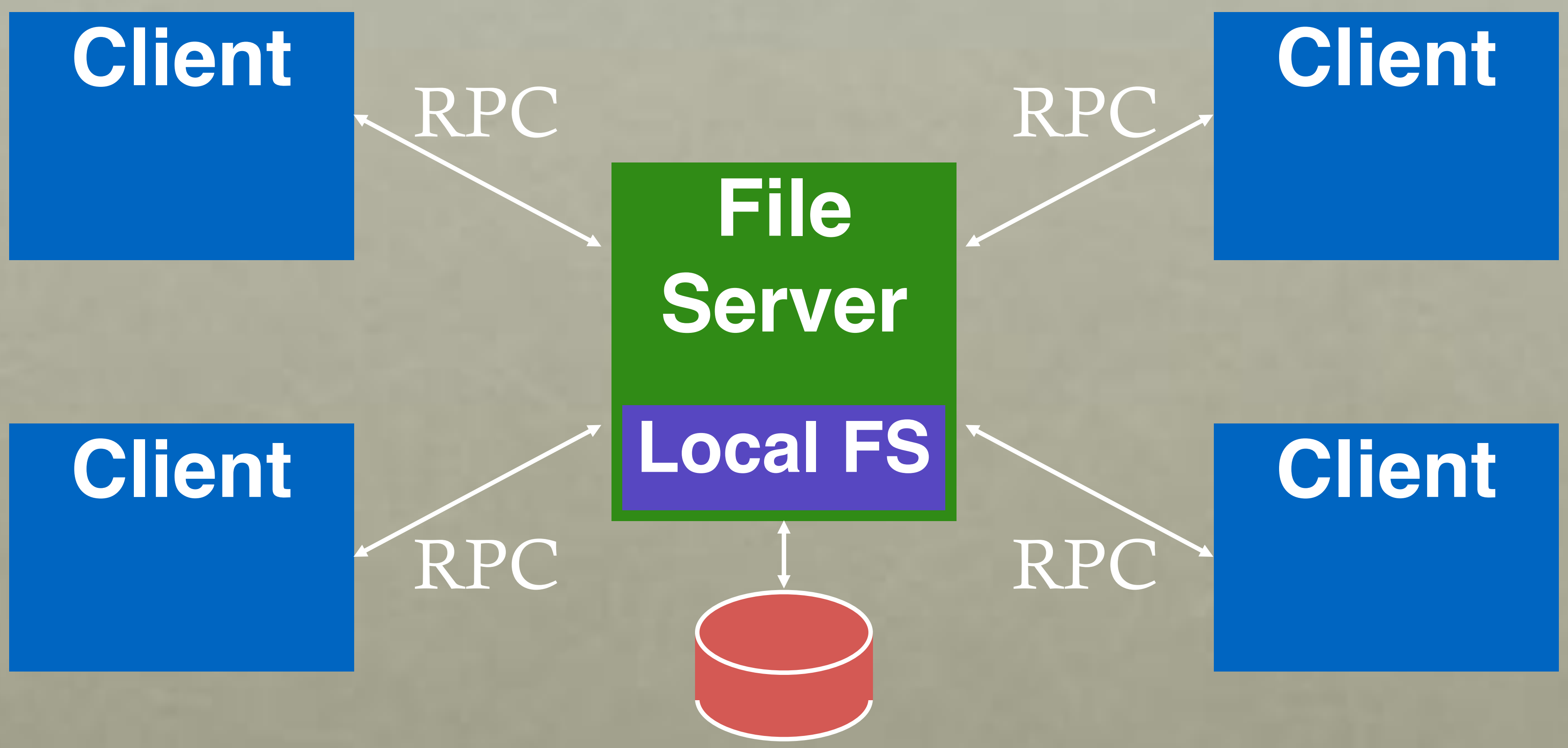
Architecture

Network API

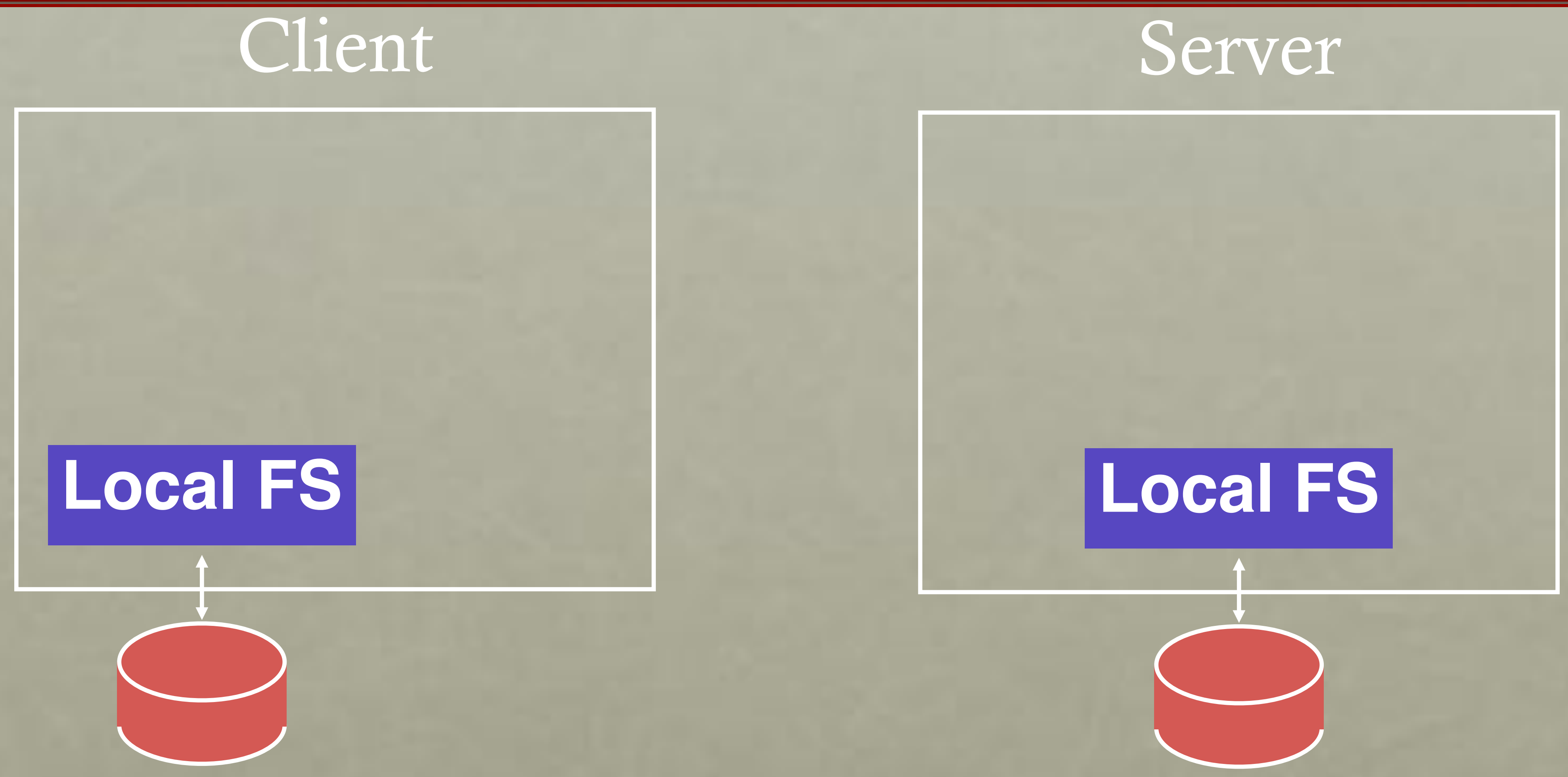
Write Buffering

Cache

NFS Architecture



General Strategy: Export FS



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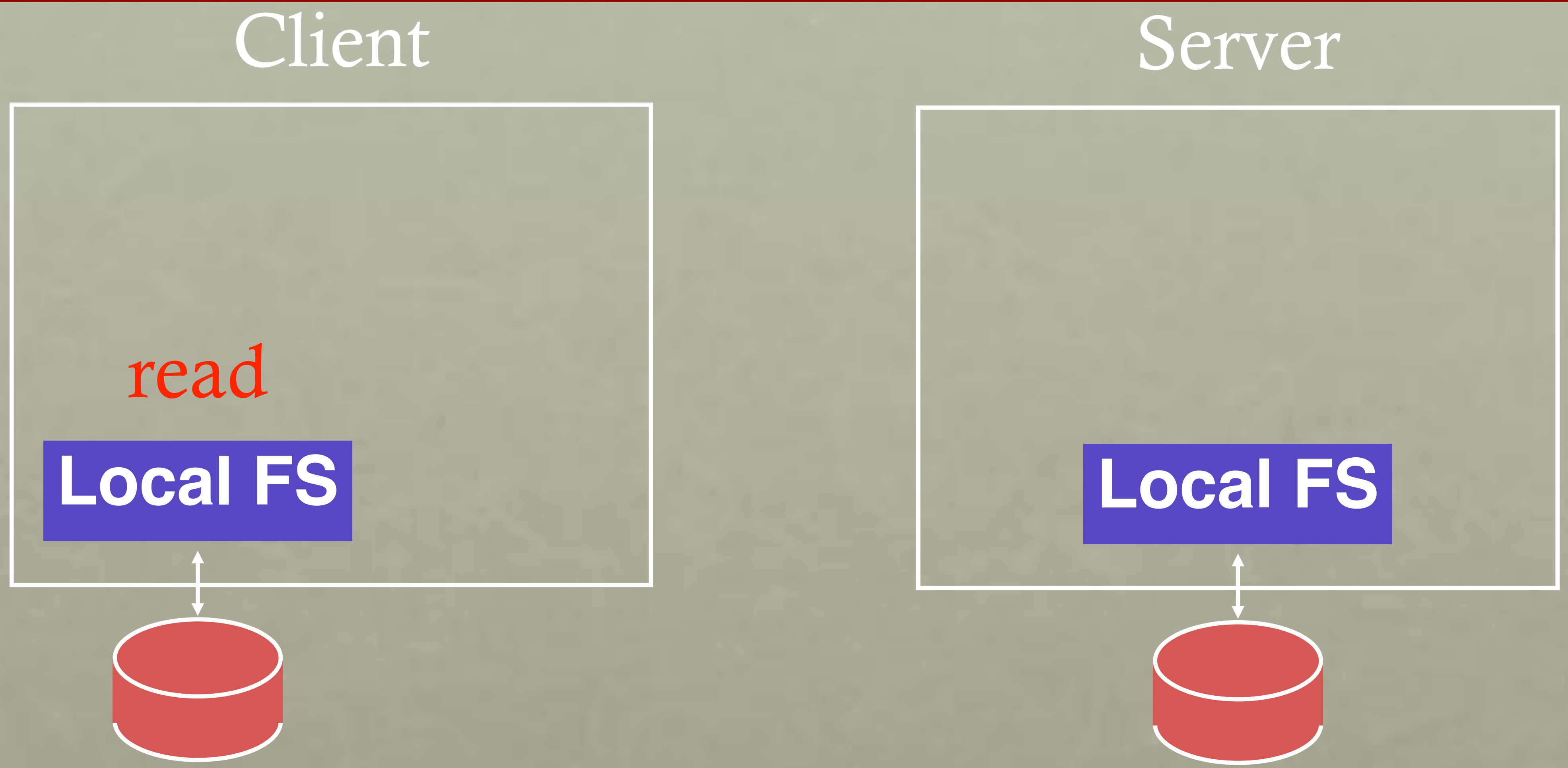
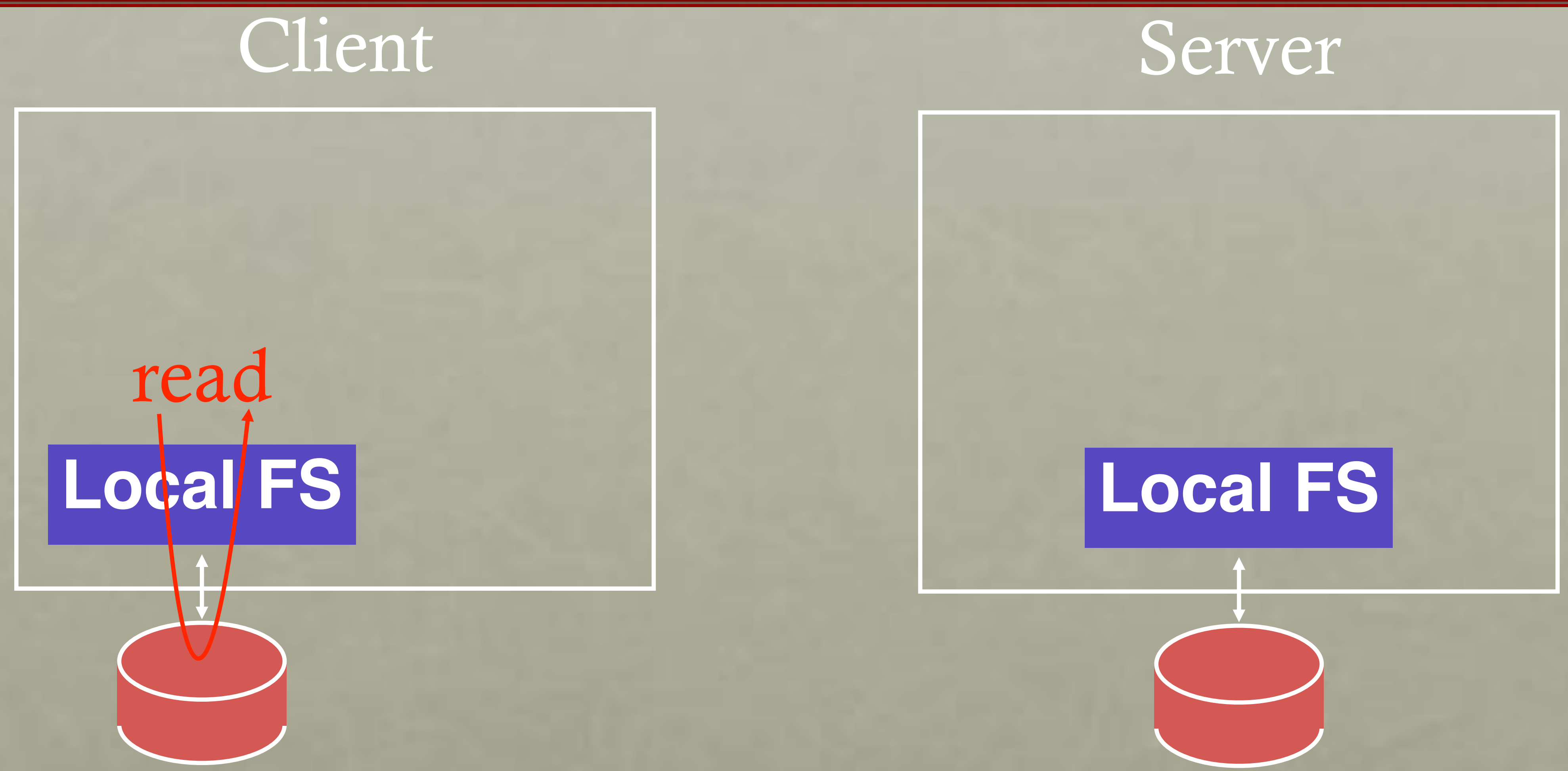


General Strategy: Export FS



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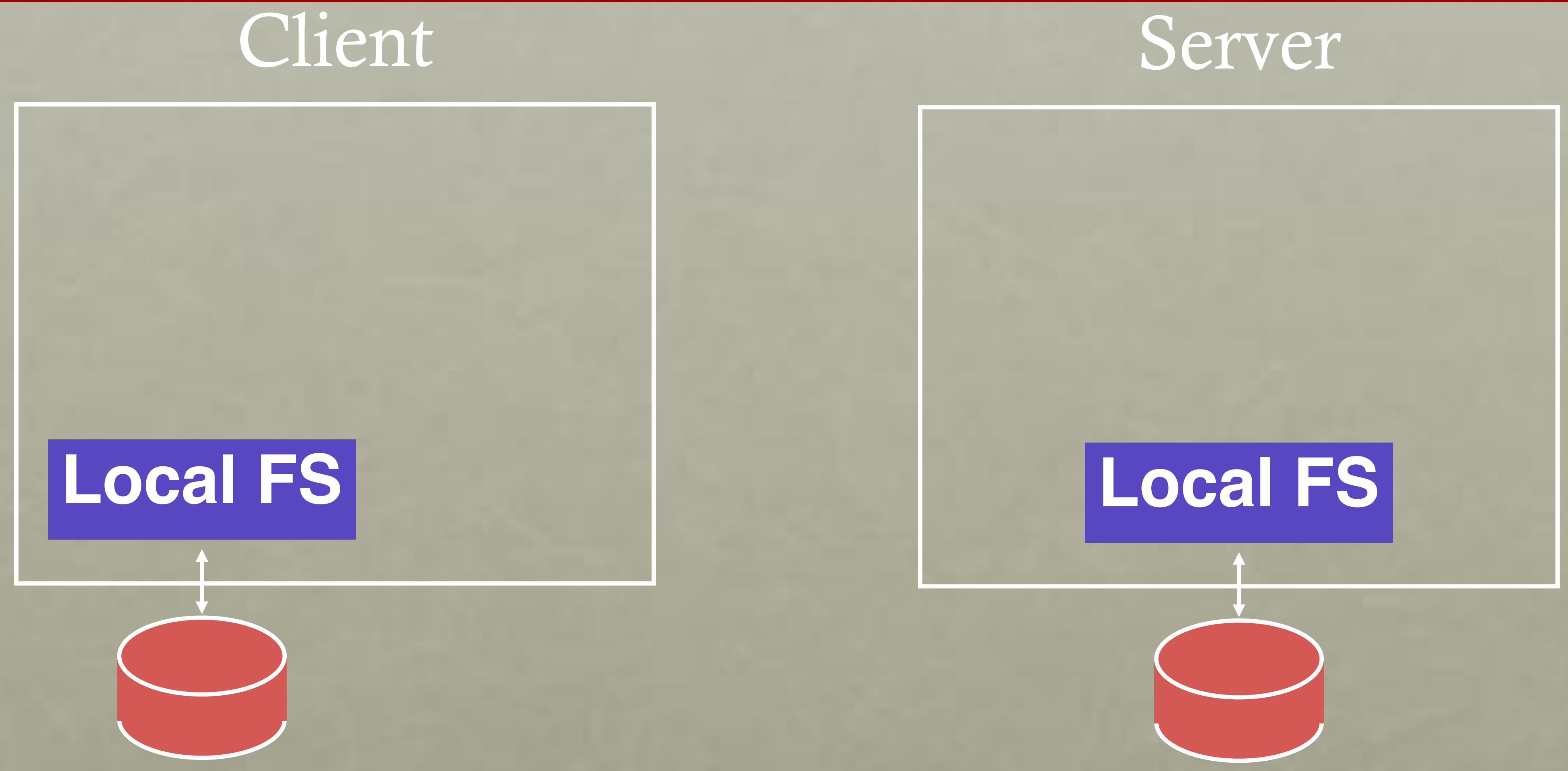
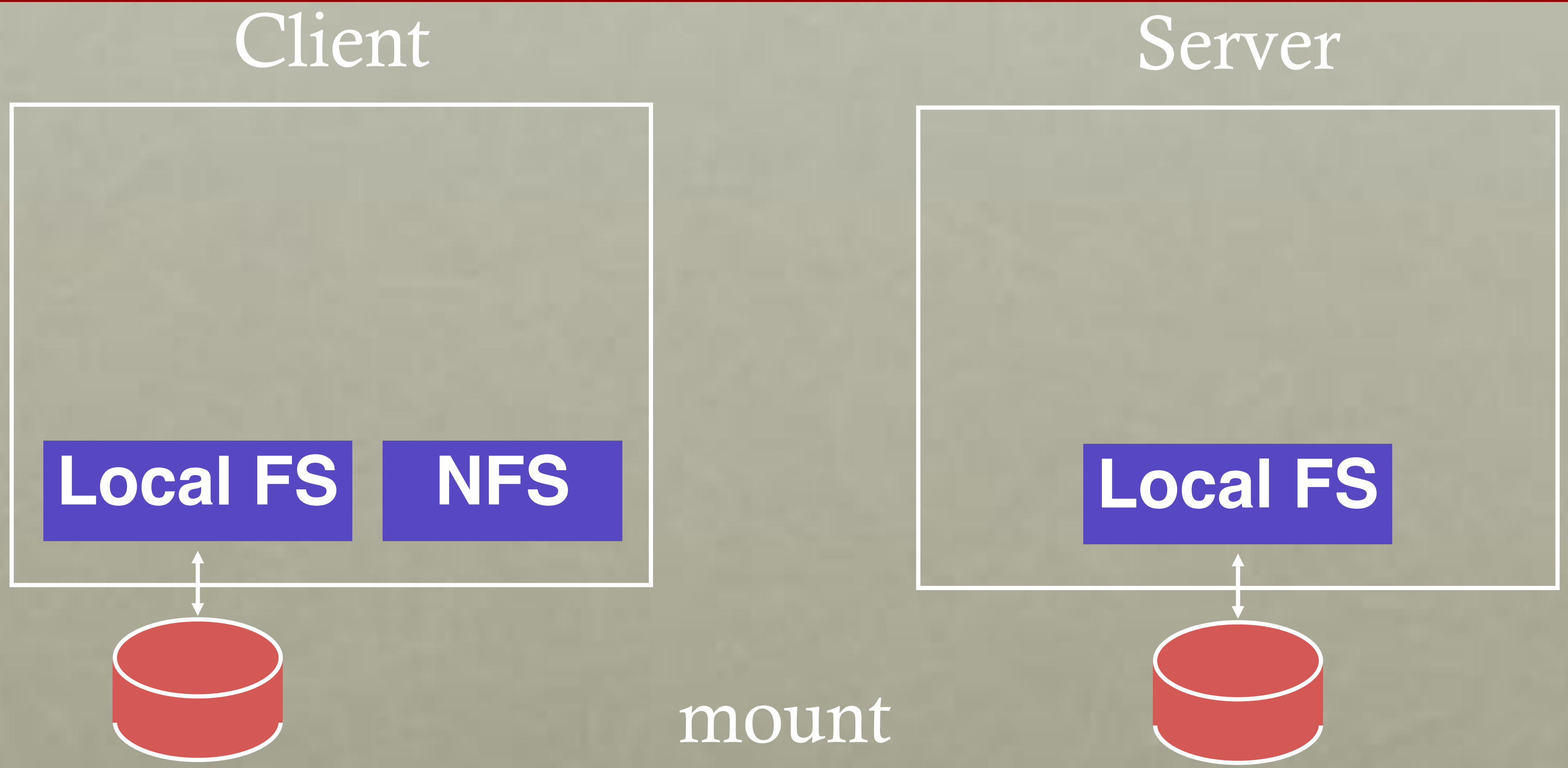
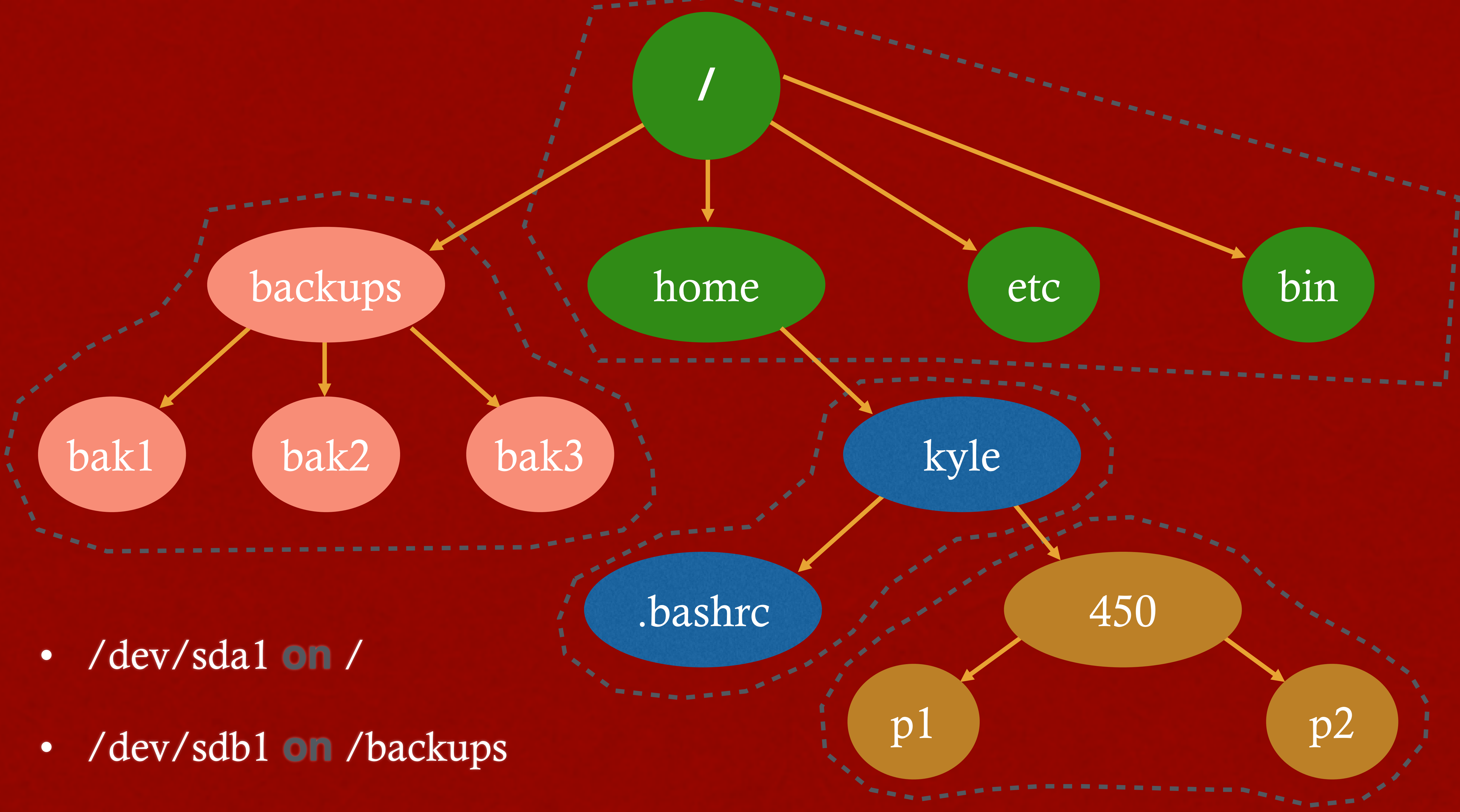


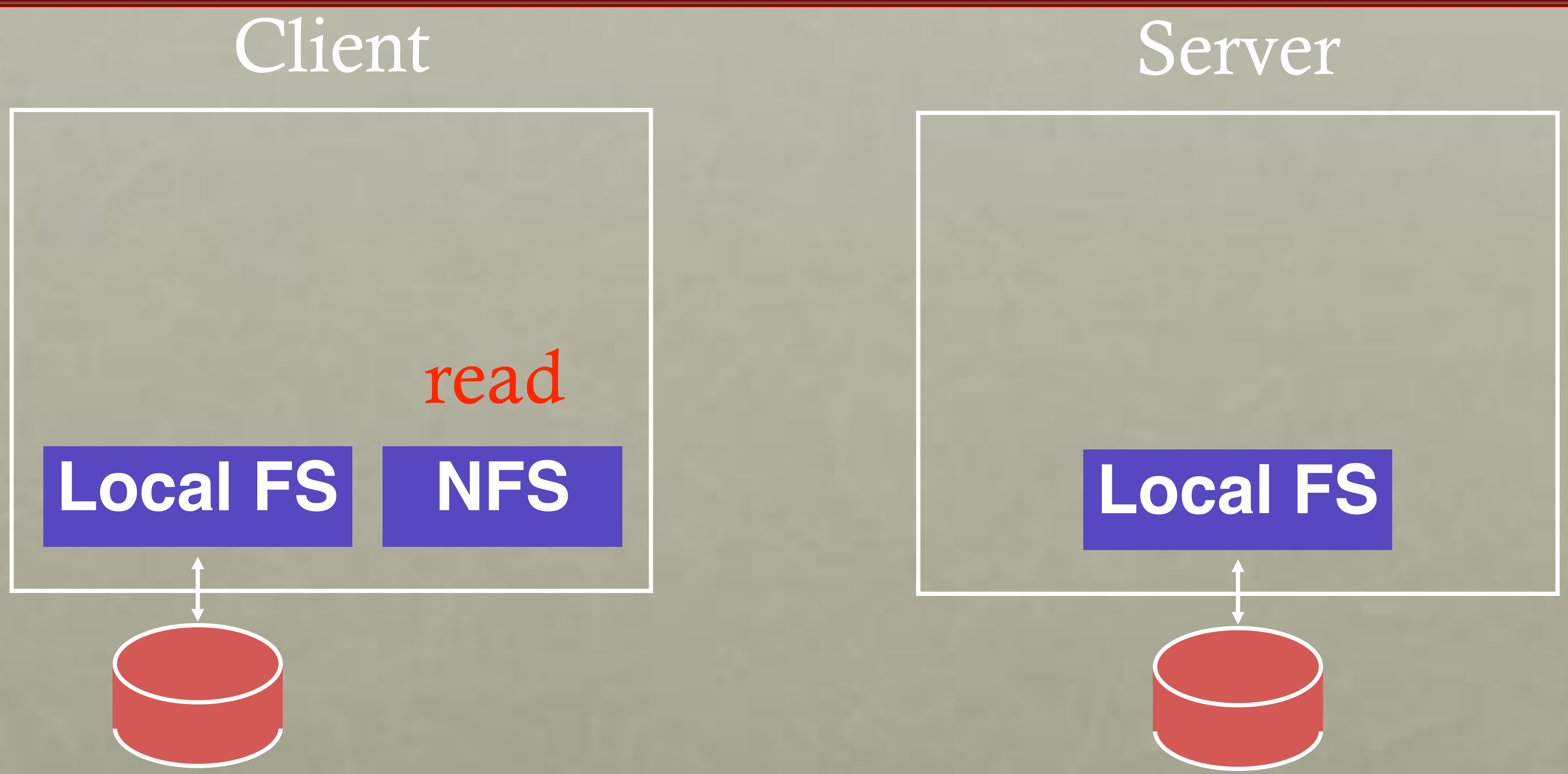
General Strategy: Export FS





- /dev/sda1 on /
- /dev/sdb1 on /backups
- NFS on /home/kyle

General Strategy: Export FS



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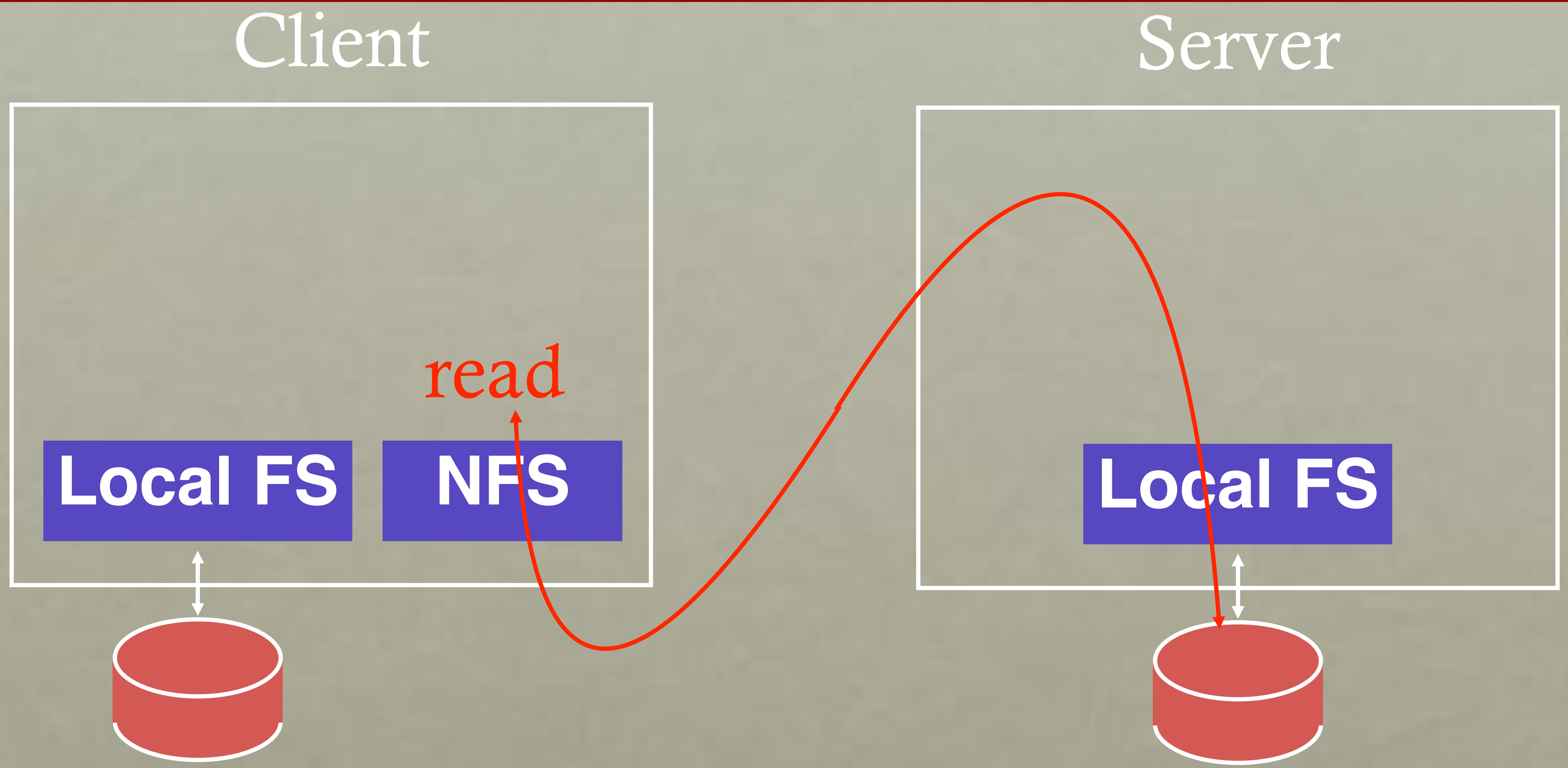


Goals for NFS

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

STRATEGY 1

Attempt: Wrap regular UNIX system calls using RPC

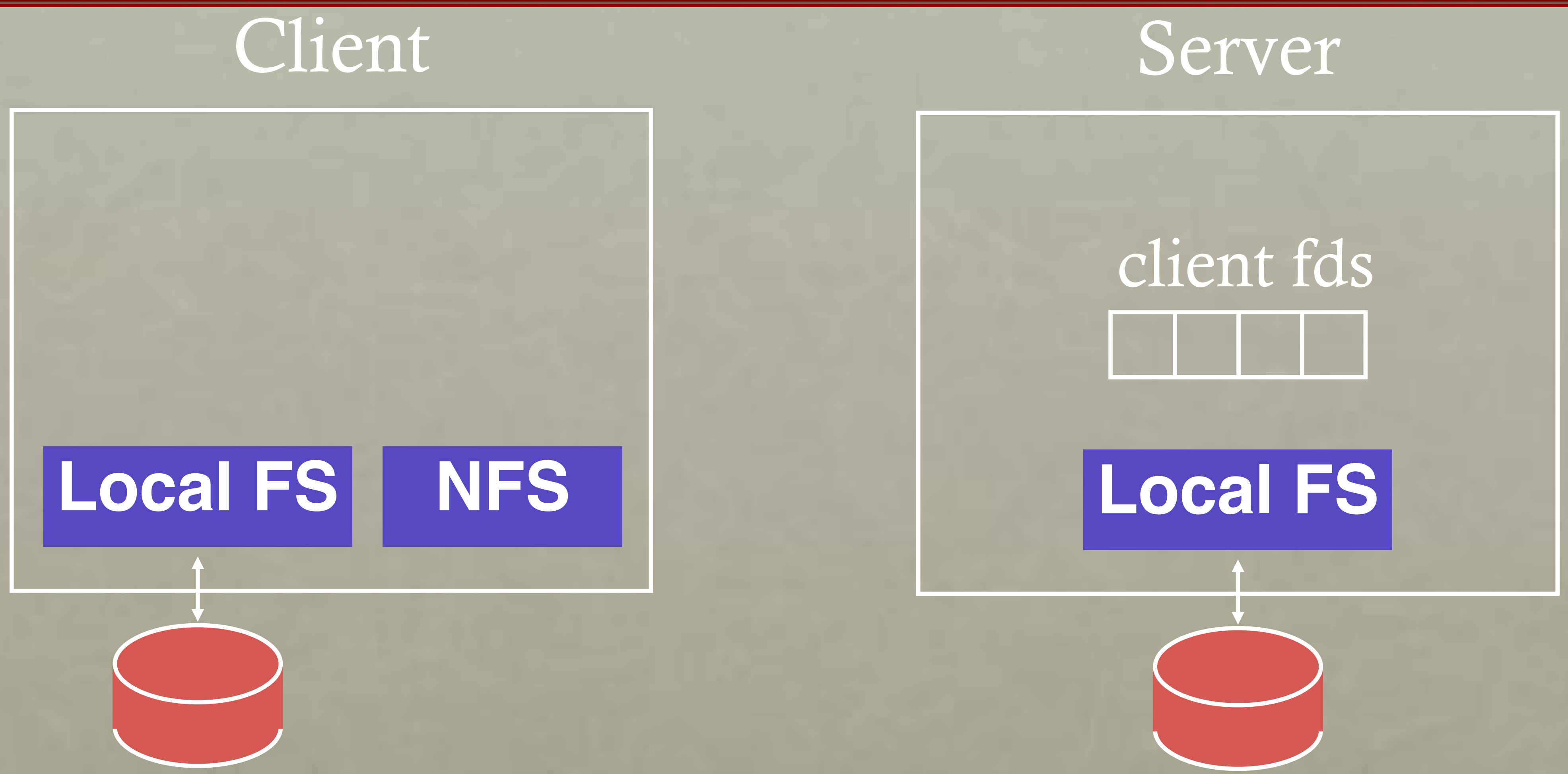
open() on client calls open() on server

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



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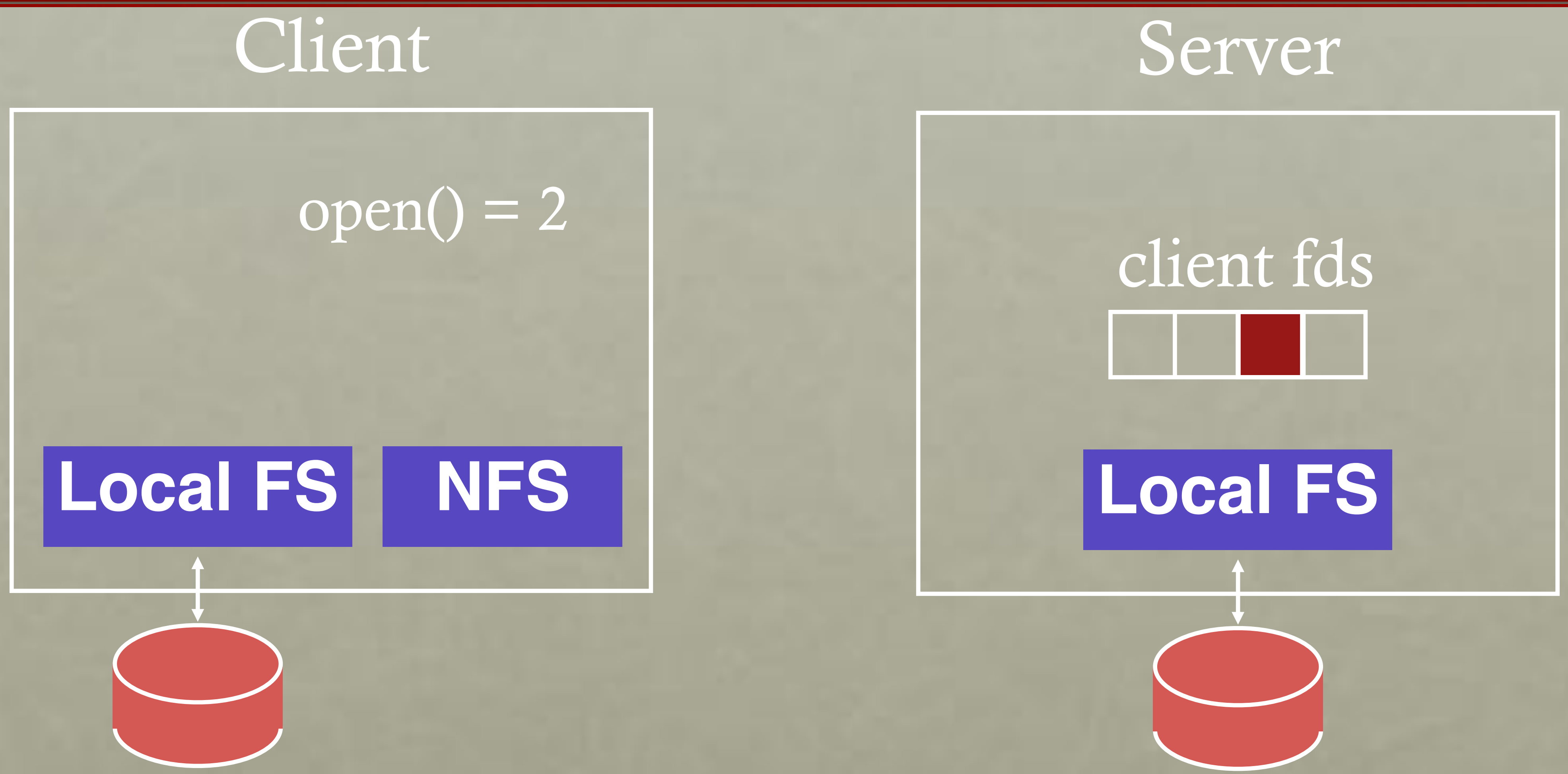

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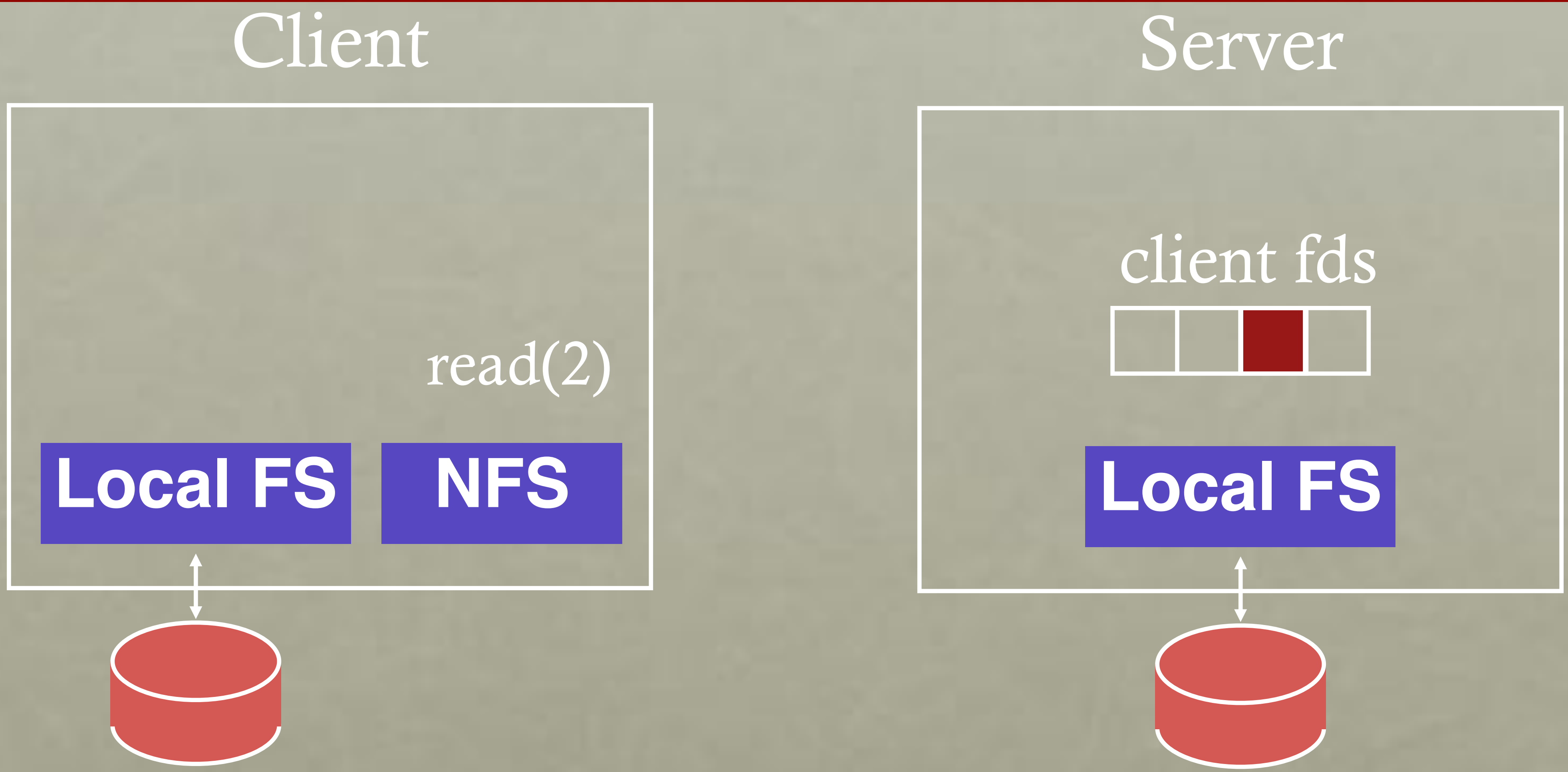

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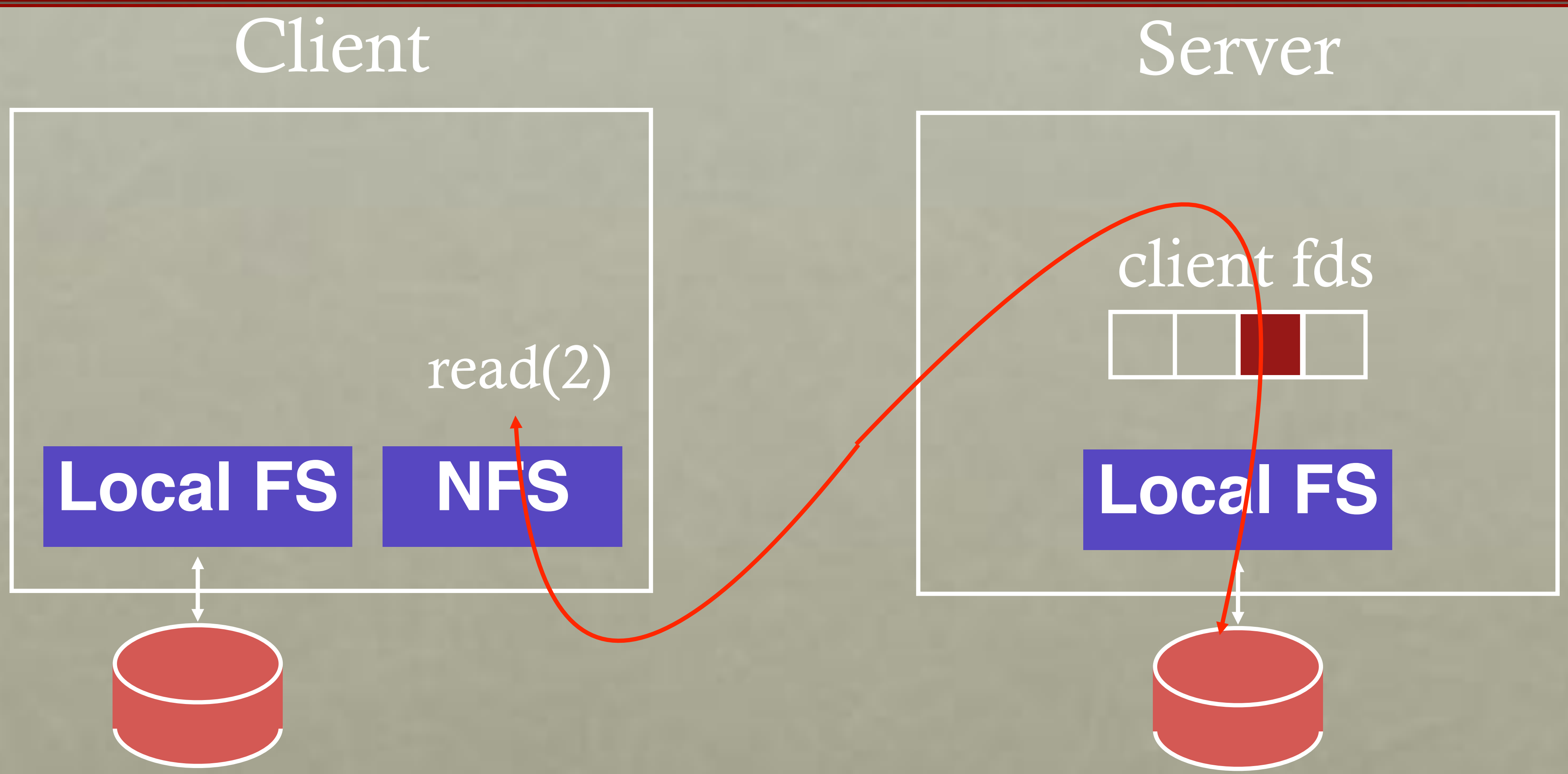


Strategy 1 Problems

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…

Potential Solutions

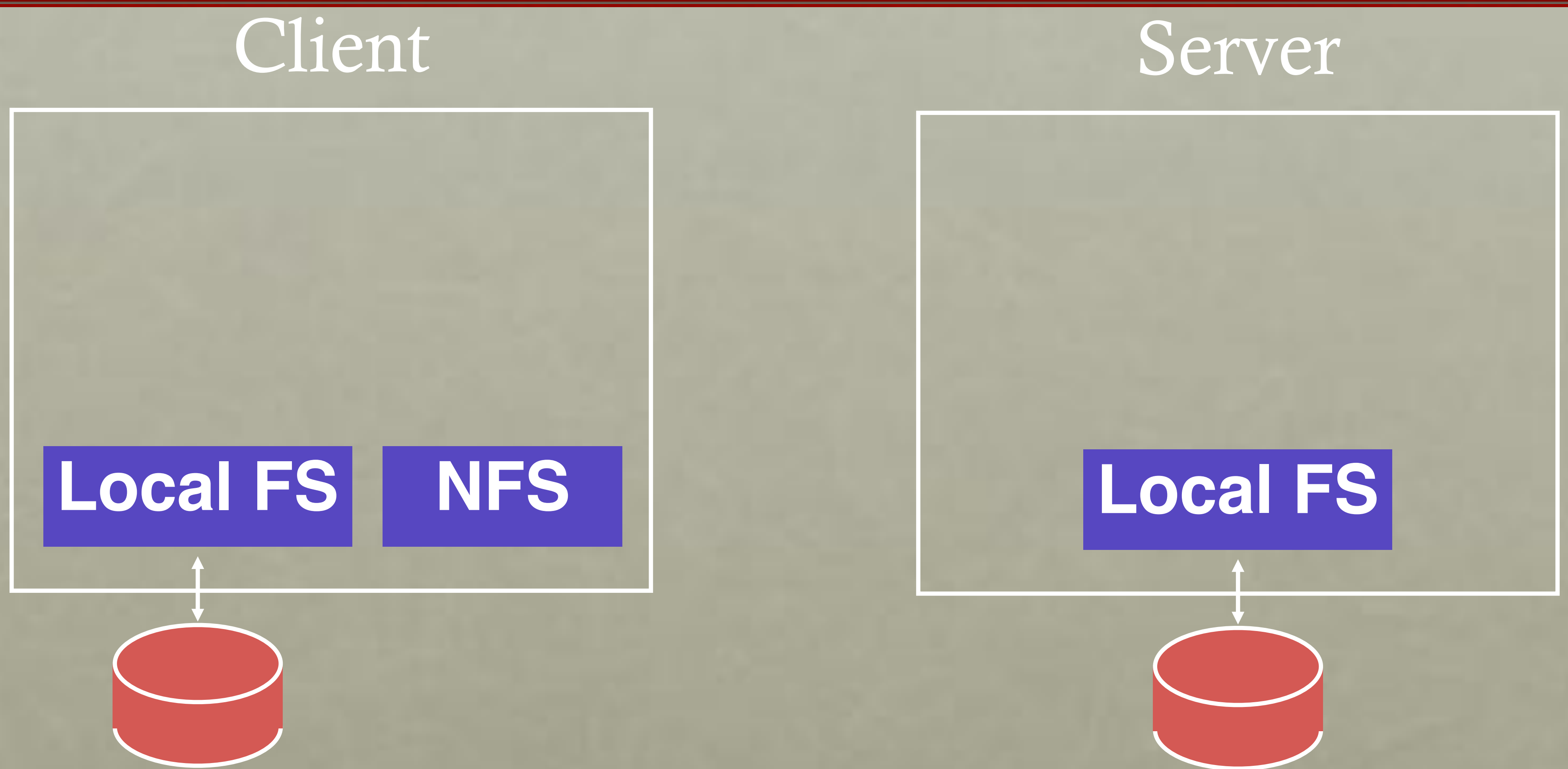
1. Run some crash recovery protocol upon reboot
   - Complex
2. Persist fds on server disk.
   - Slow
   - What if client crashes? When can fds be garbage collected?

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(char *path, buf, size, offset);
pwrite(char *path, buf, size, offset);
```

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

Pros?

Server can crash and reboot transparently to clients.

Cons?

Too many path lookups.

Strategy 3: Inode Requests

```
inode = open(char *path);

pread(inode, buf, size, offset);

pwrite(inode, buf, size, offset);
```

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(char *path);

pread(fh, buf, size, offset);

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

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

Opaque to client (client should not interpret internals)

Can NFS Protocol Include Append?

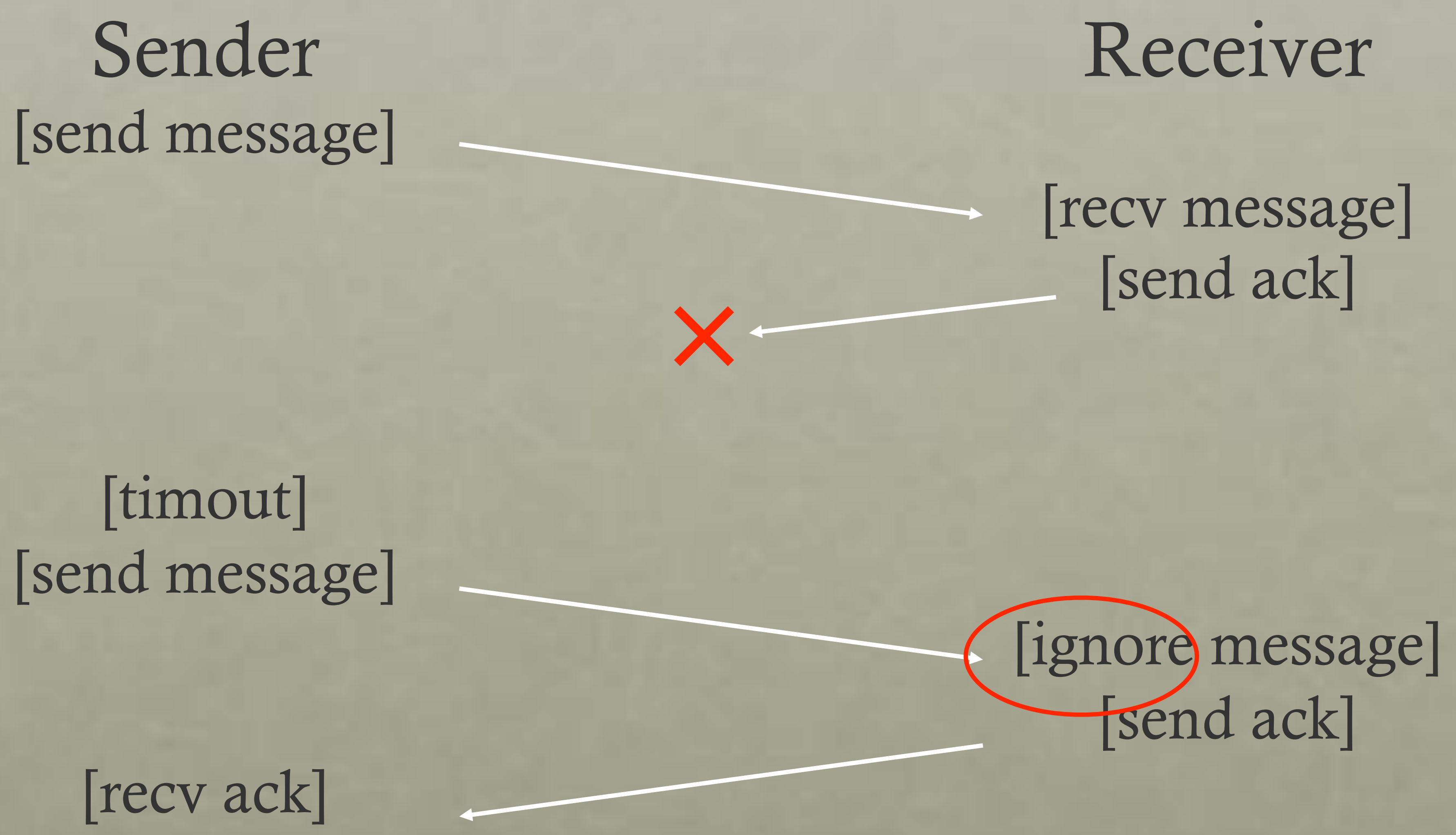
```
fh = open(char *path);

pread(fh, buf, size, offset);

pwrite(fh, buf, size, offset);

append(fh, buf, size);
```

Problem with append()?

If RPC library retries, what happens when append() is retried?

Problem: Why is it difficult to replay append()?

Replica Suppression is Stateful



TCP suppresses repeated message

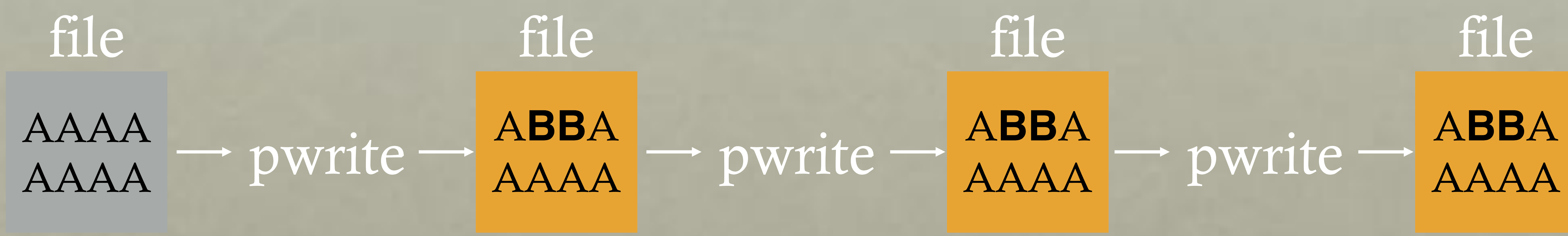
Problem: TCP is stateful
If server crashes, forgets which RPC's have been executed!

Idempotent Operations

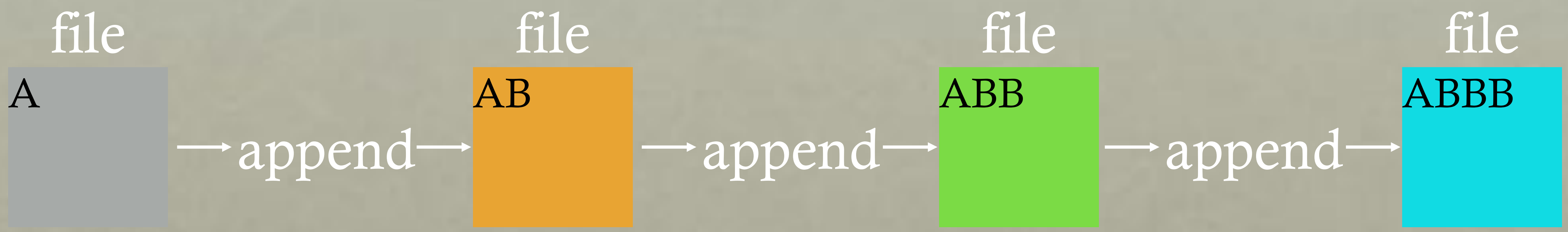
Solution:
Design API so no harm to executing function more than once

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 #>

Strategy 5: Client Logic

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

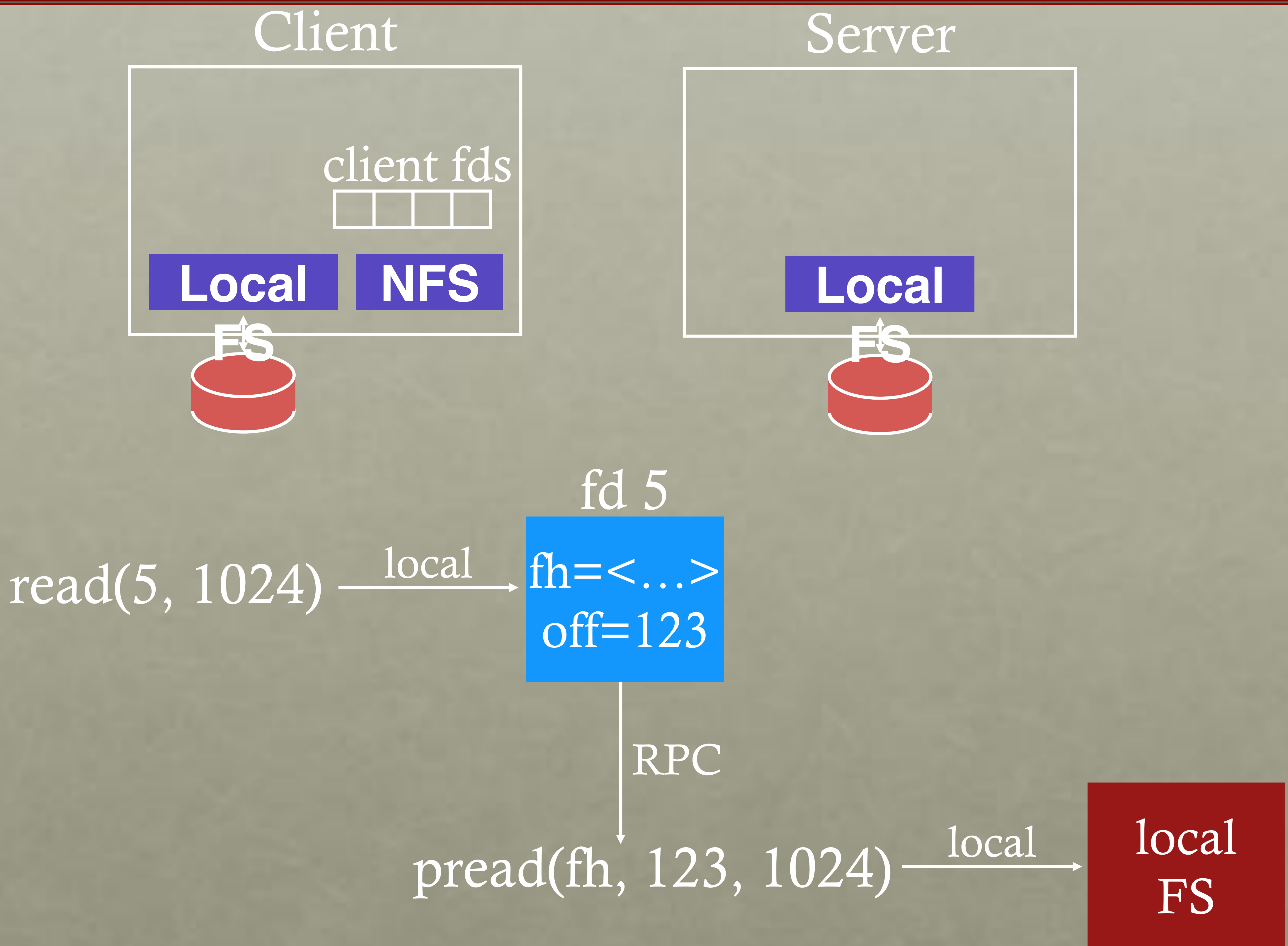
Client open() creates a local fd object

It contains:

- file handle

- offset

FILE DESCRIPTORS



Overview

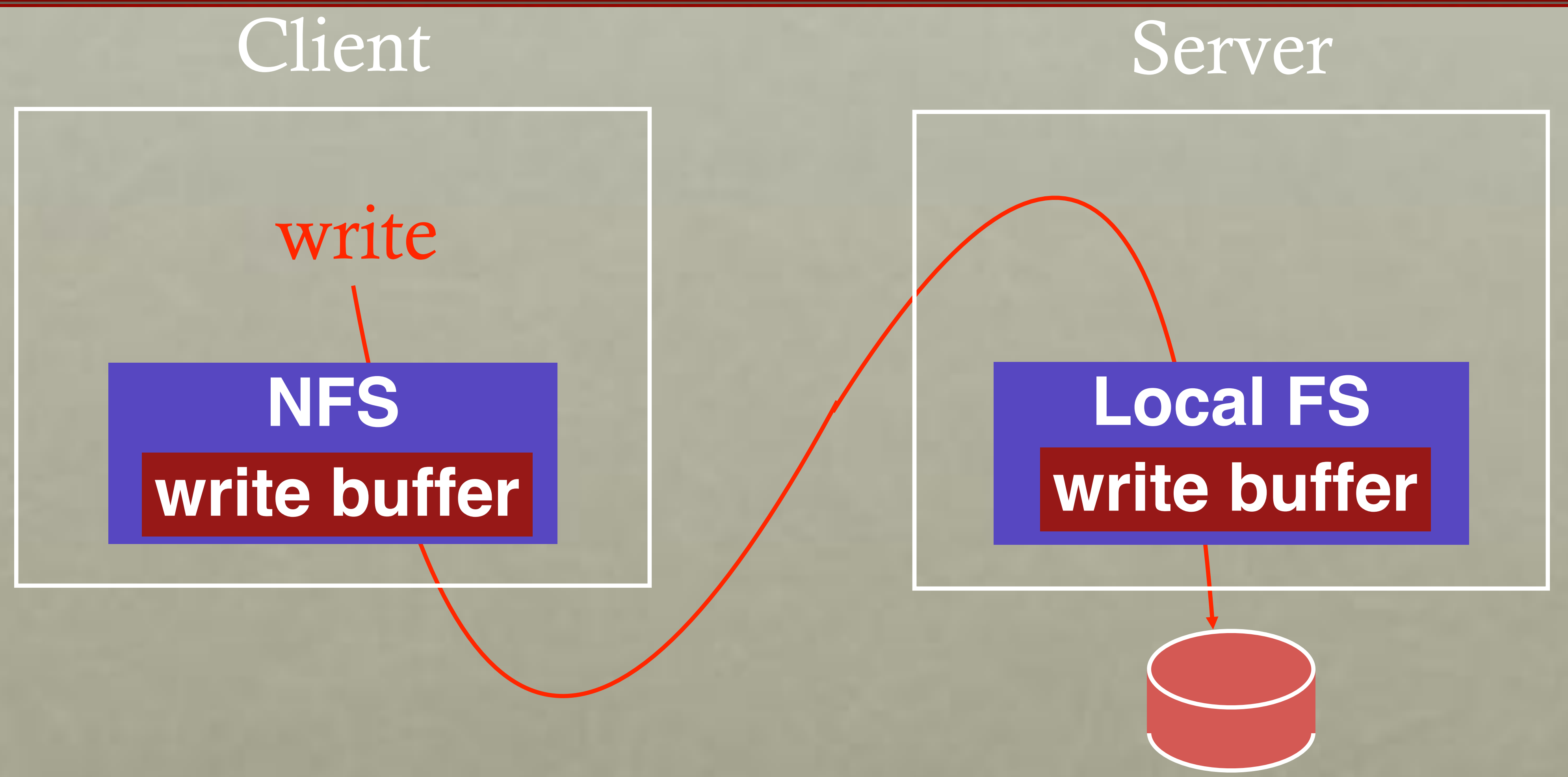
~~Architecture~~

~~Network API~~

Write Buffering

Cache

Write Buffers

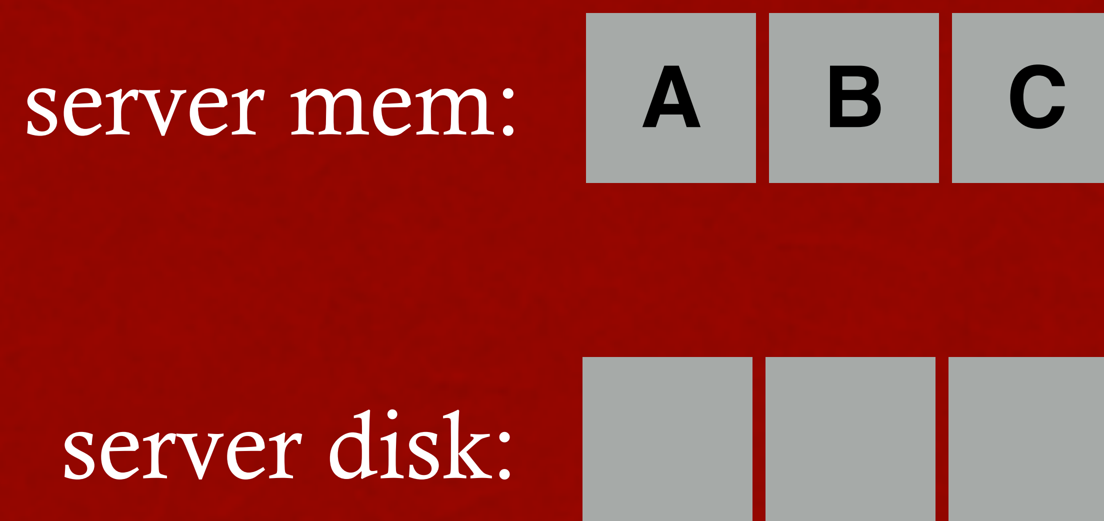


server acknowledges write before write is pushed to disk;
what happens if server crashes?

Server Write Buffer Lost

client:

```
write A to 0

write B to 1

write C to 2
```



server 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
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```
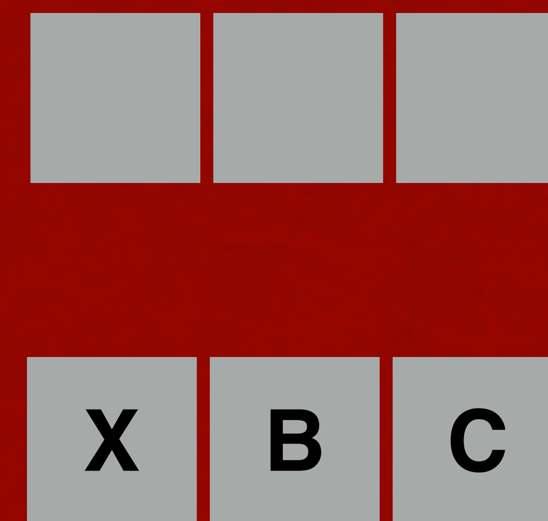

server mem:

server disk:



crash!

server acknowledges write before write is pushed to disk

Server Write Buffer Lost

client:

```
write A to 0
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```
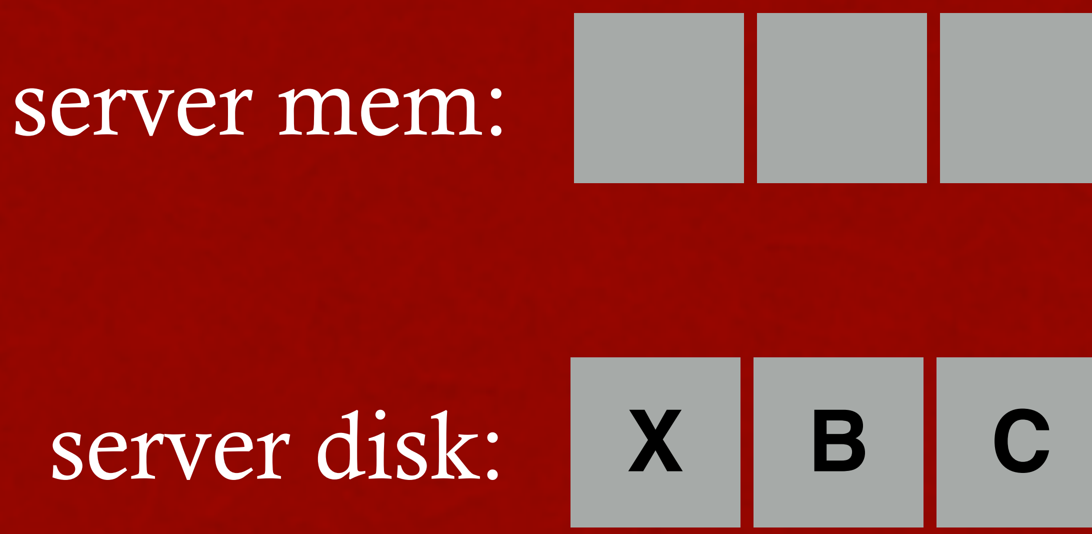



server acknowledges write before write is pushed to disk

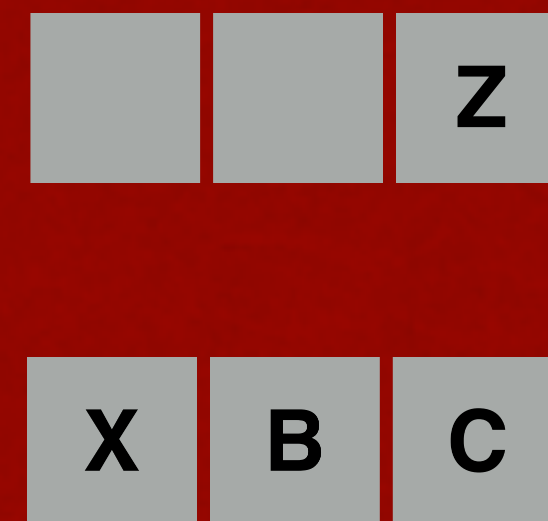
Server Write Buffer Lost

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
```

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
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write X to 0
write Y to 1
write Z to 2
```

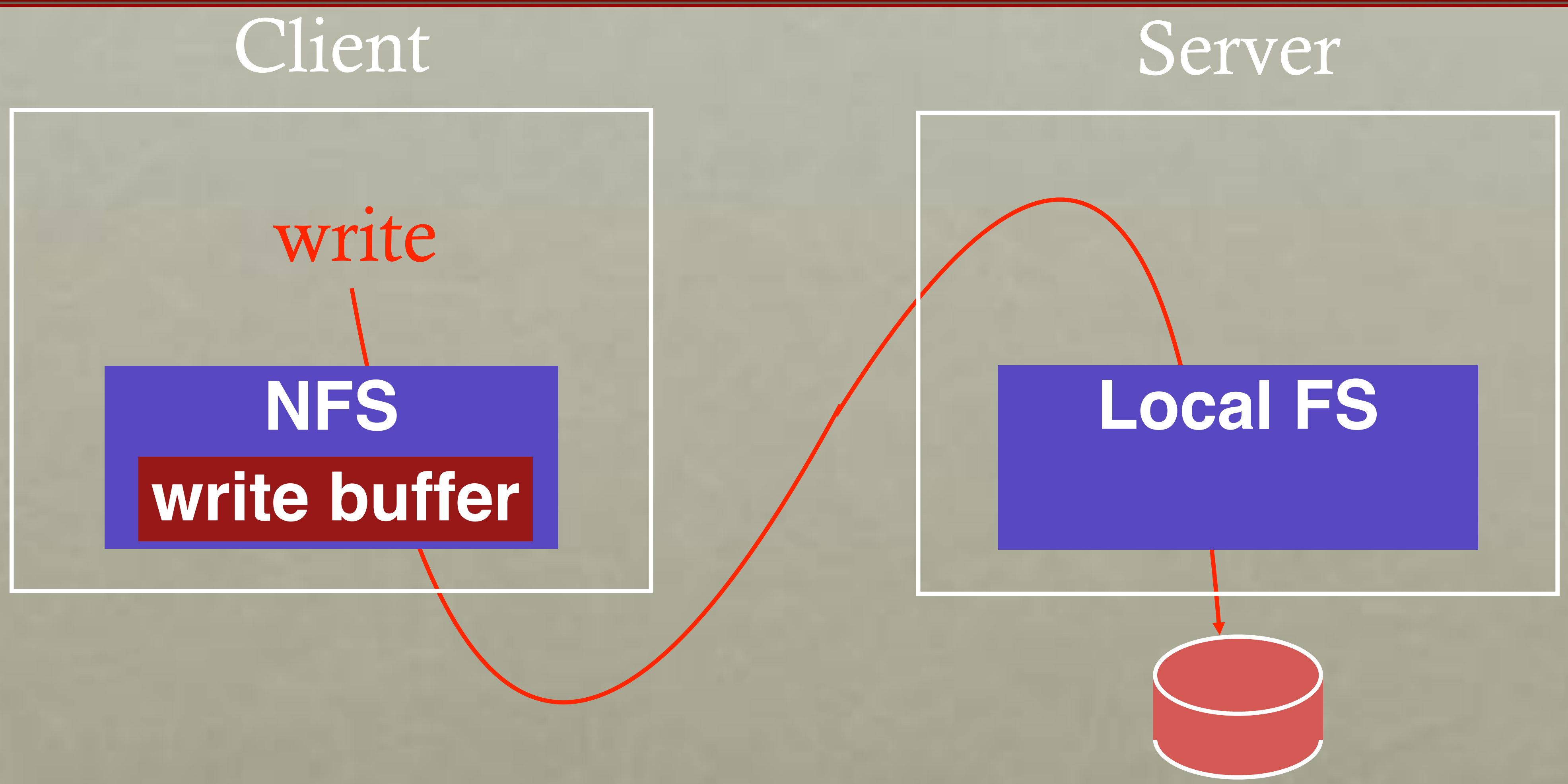
server mem: | | | Z |

server disk: | X | B | Z |

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

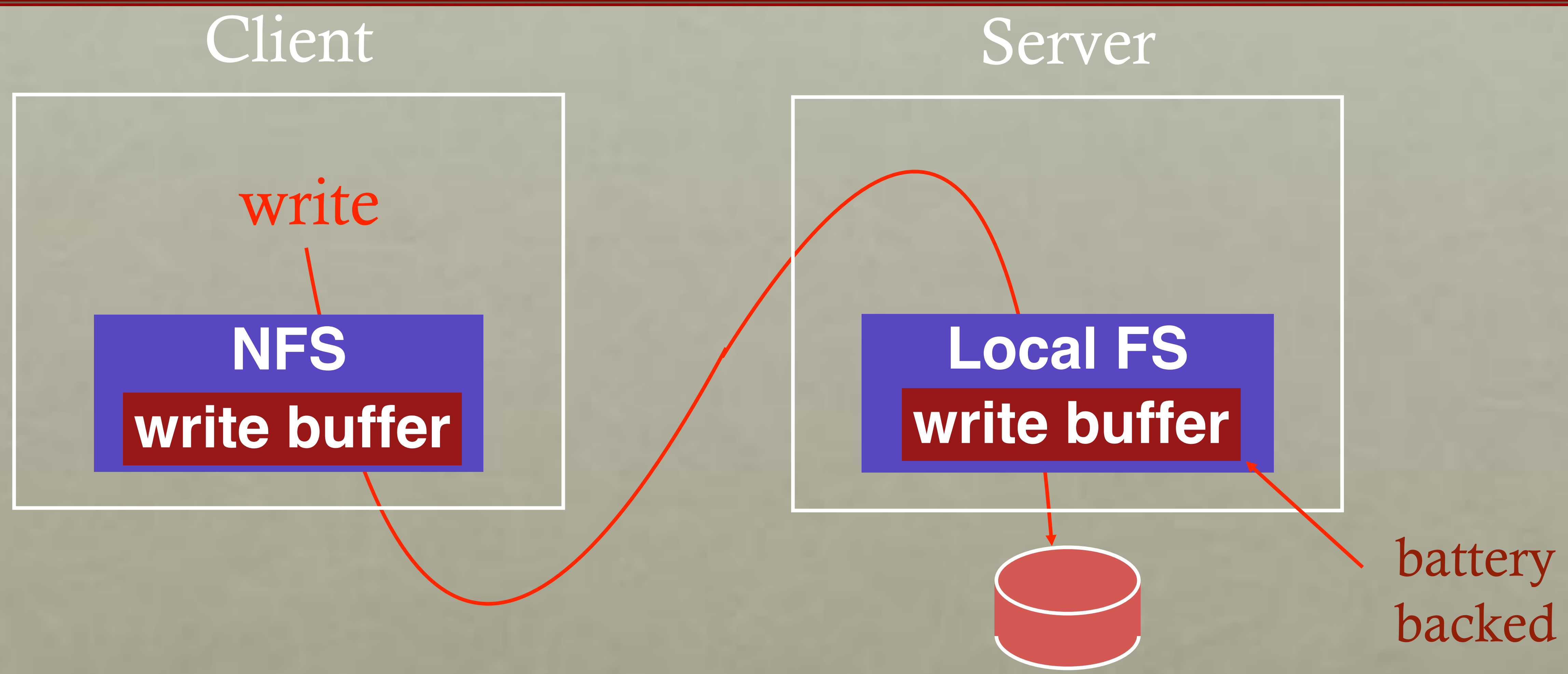
Solutions????

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

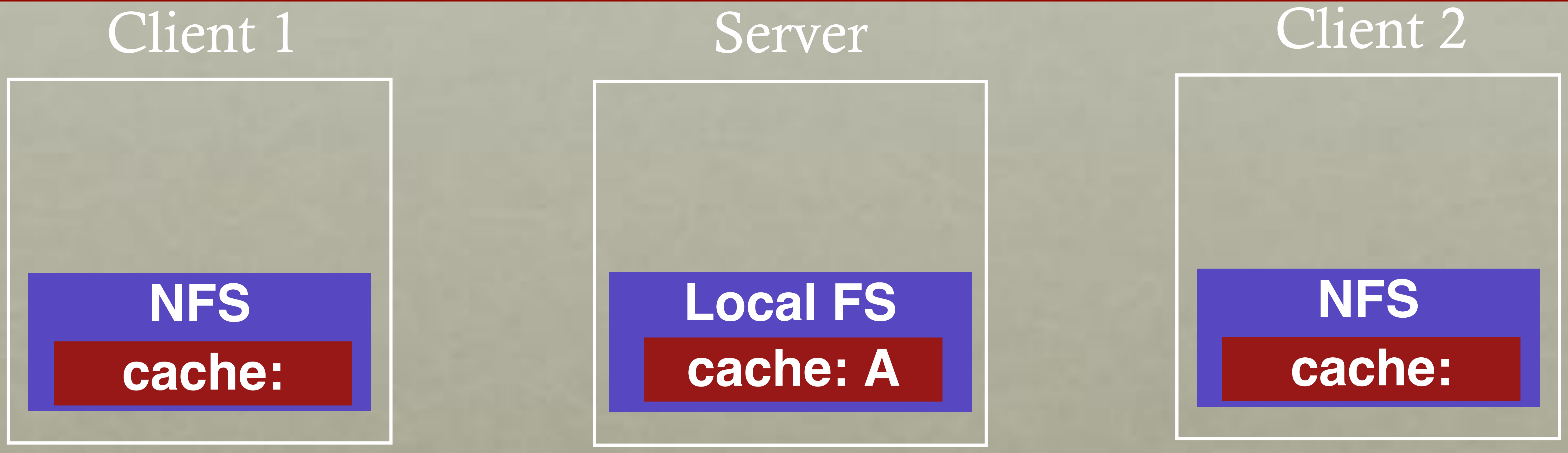
Cache Consistency

NFS can cache data in three places:

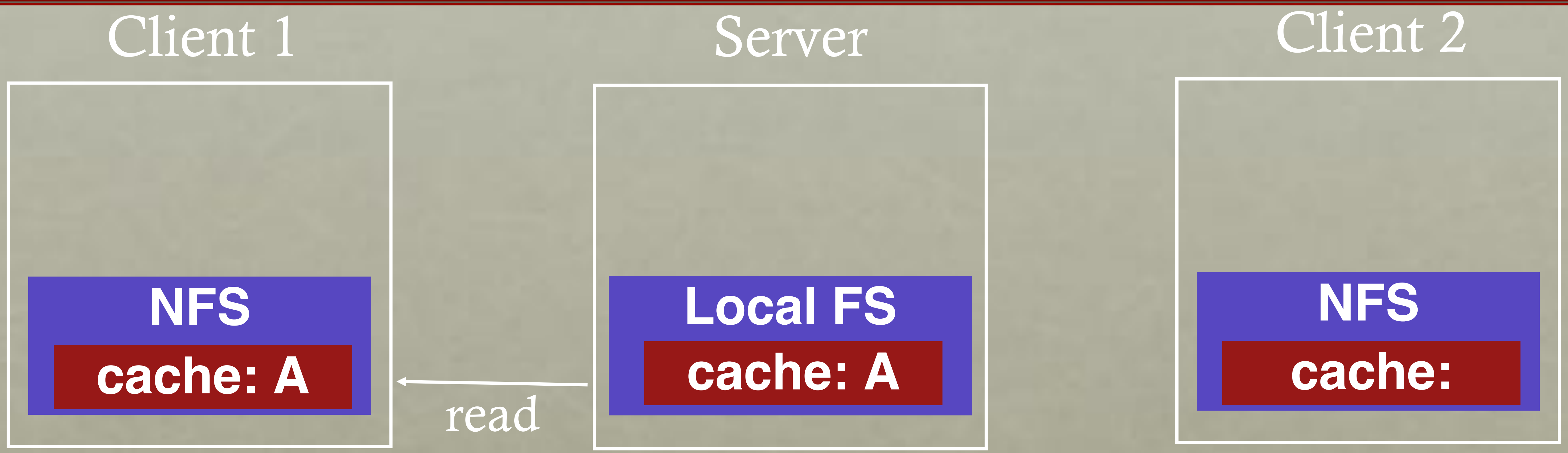
- server memory
- client disk
- client memory

How to make sure all versions are in sync?

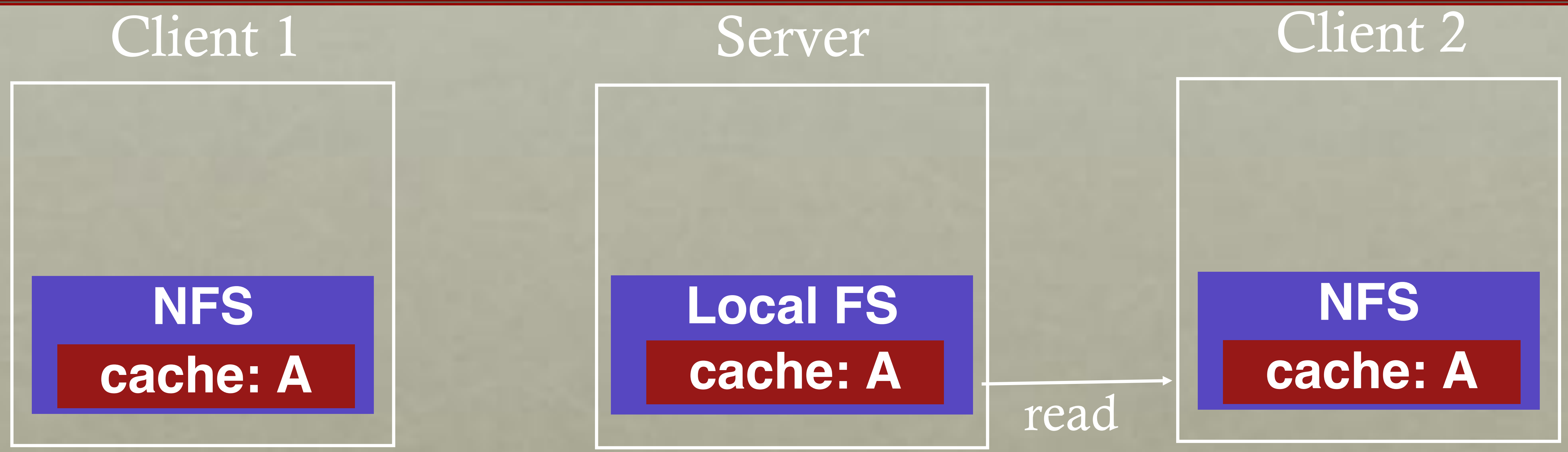
Distributed Cache



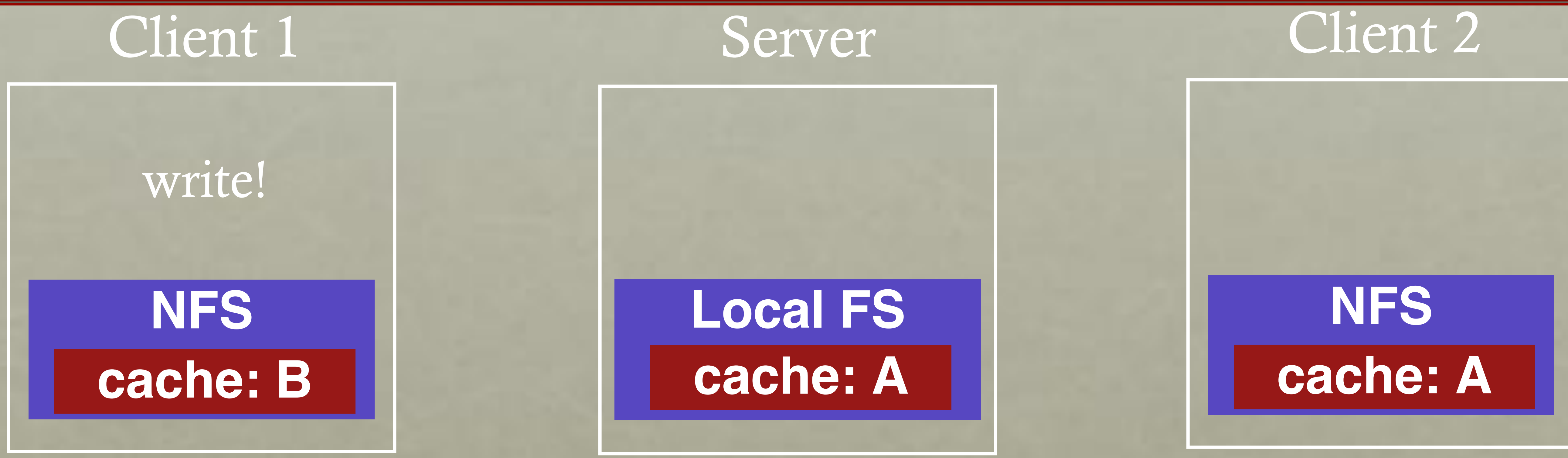
CACHE


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

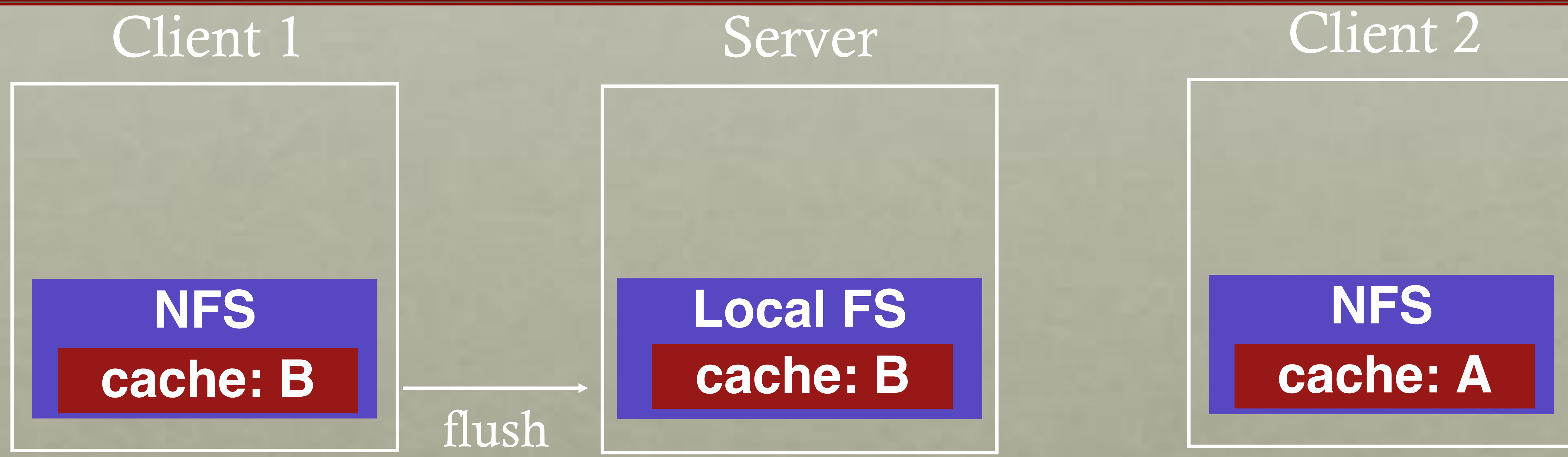
CACHE



"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)

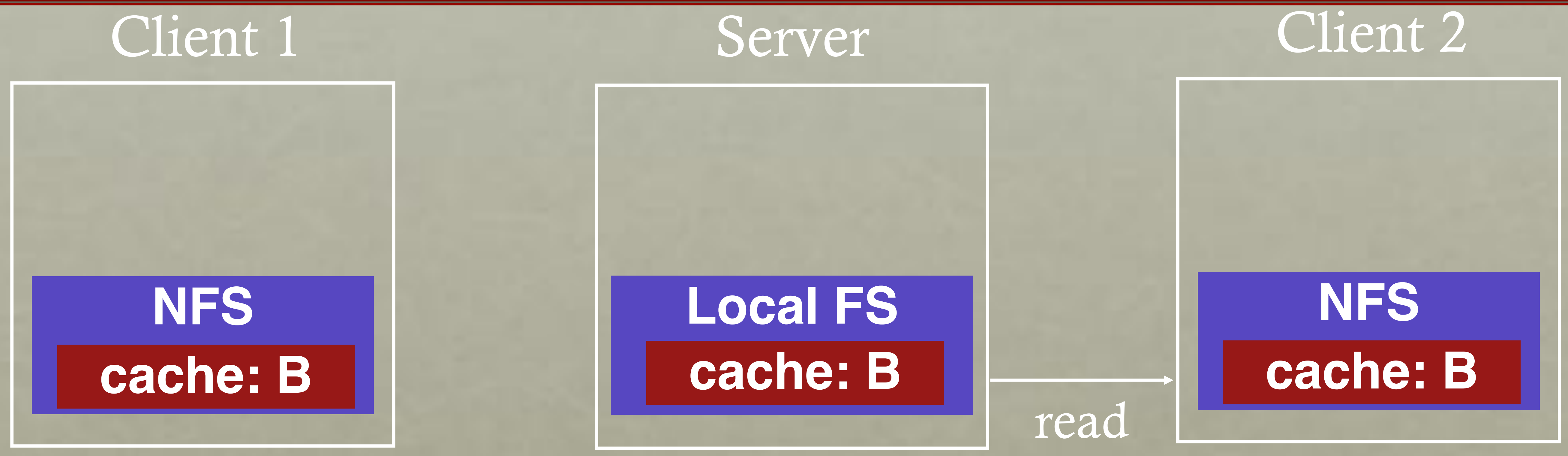
CACHE



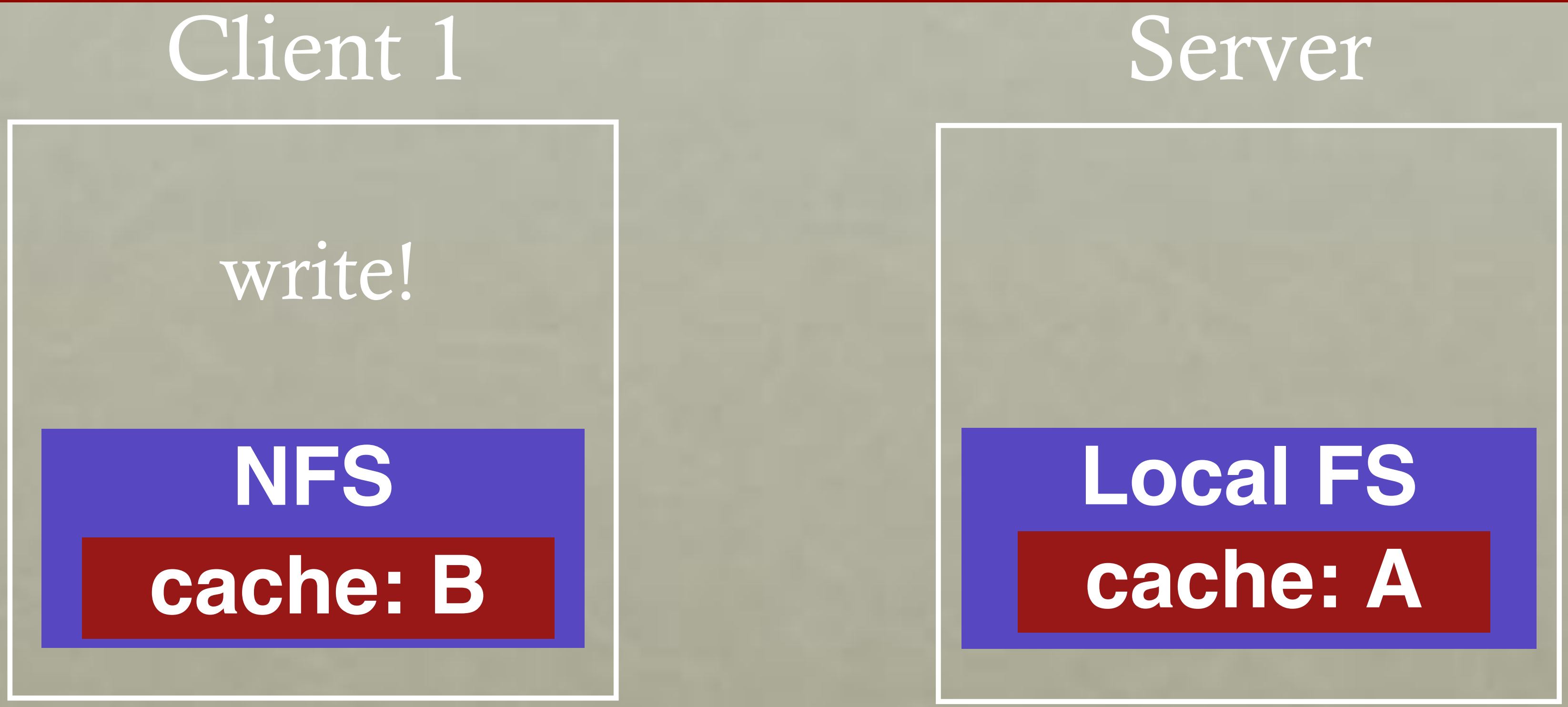
"Stale Cache" problem:
client 2 doesn't have latest version

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



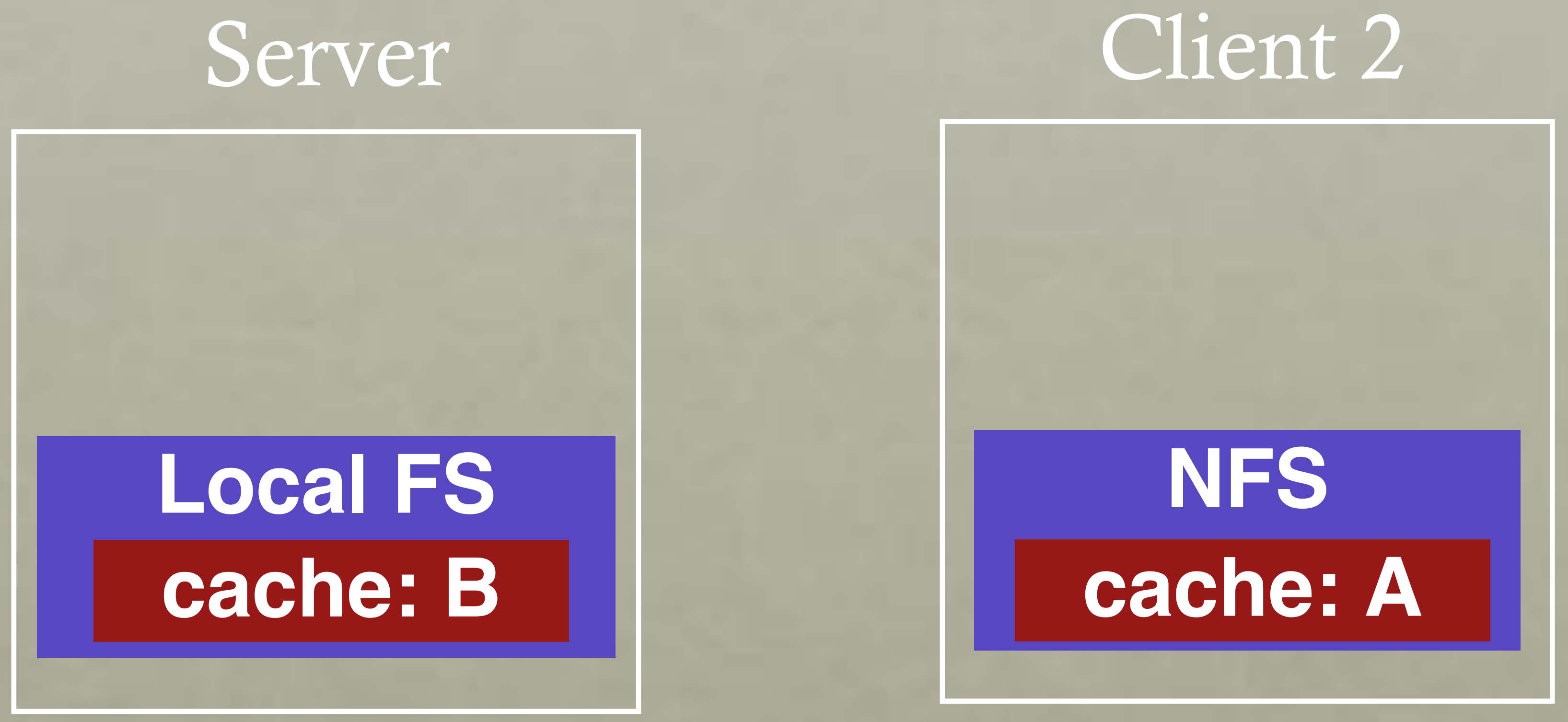
When client buffers a write, how can server (and other clients) see update?

- Client flushes cache entry to server

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

NFS solution: flush on fd close

Problem 2: Stale Cache



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

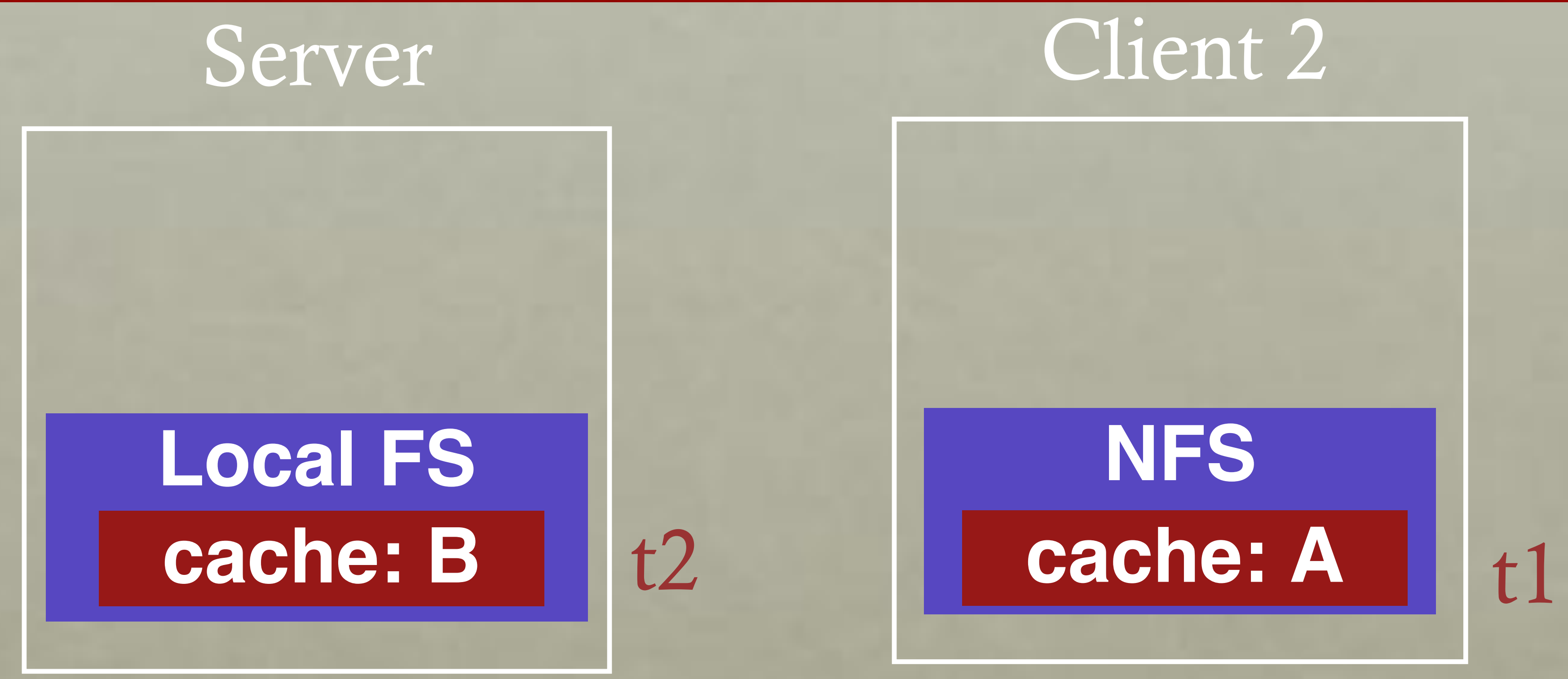
One possible solution:

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

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 time (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 systems, especially with crashes

Problems:

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