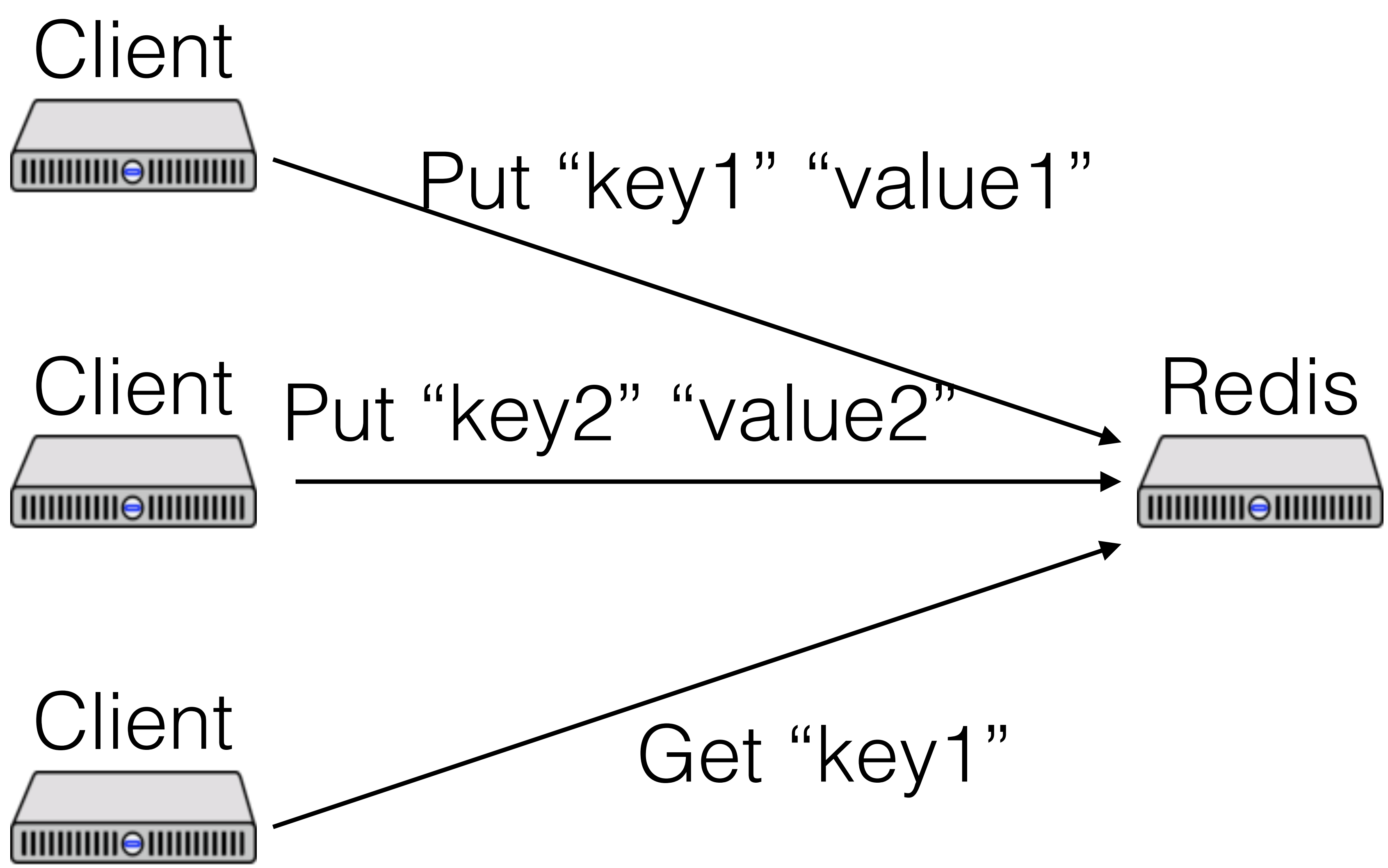
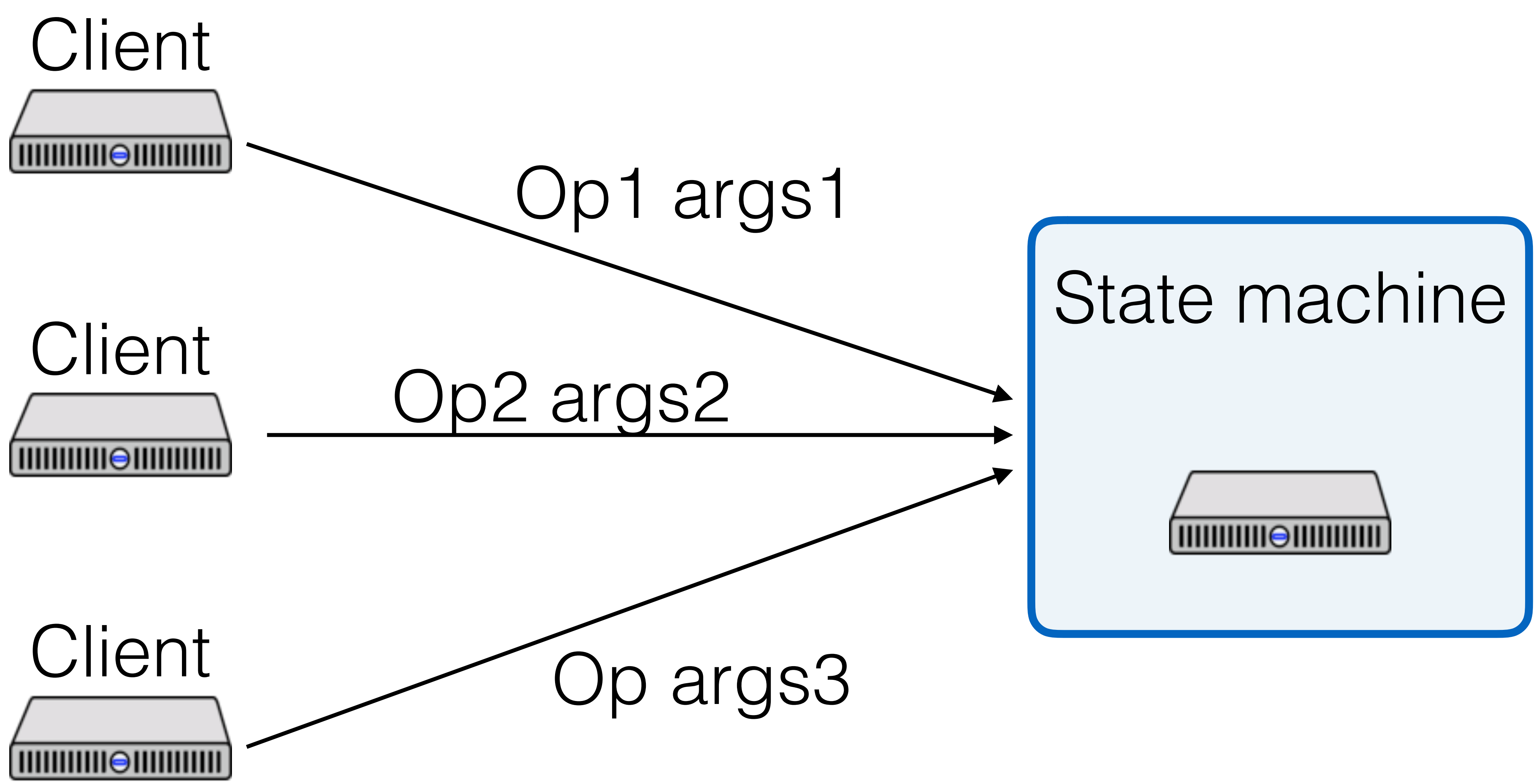
Primary/Backup

CS 452

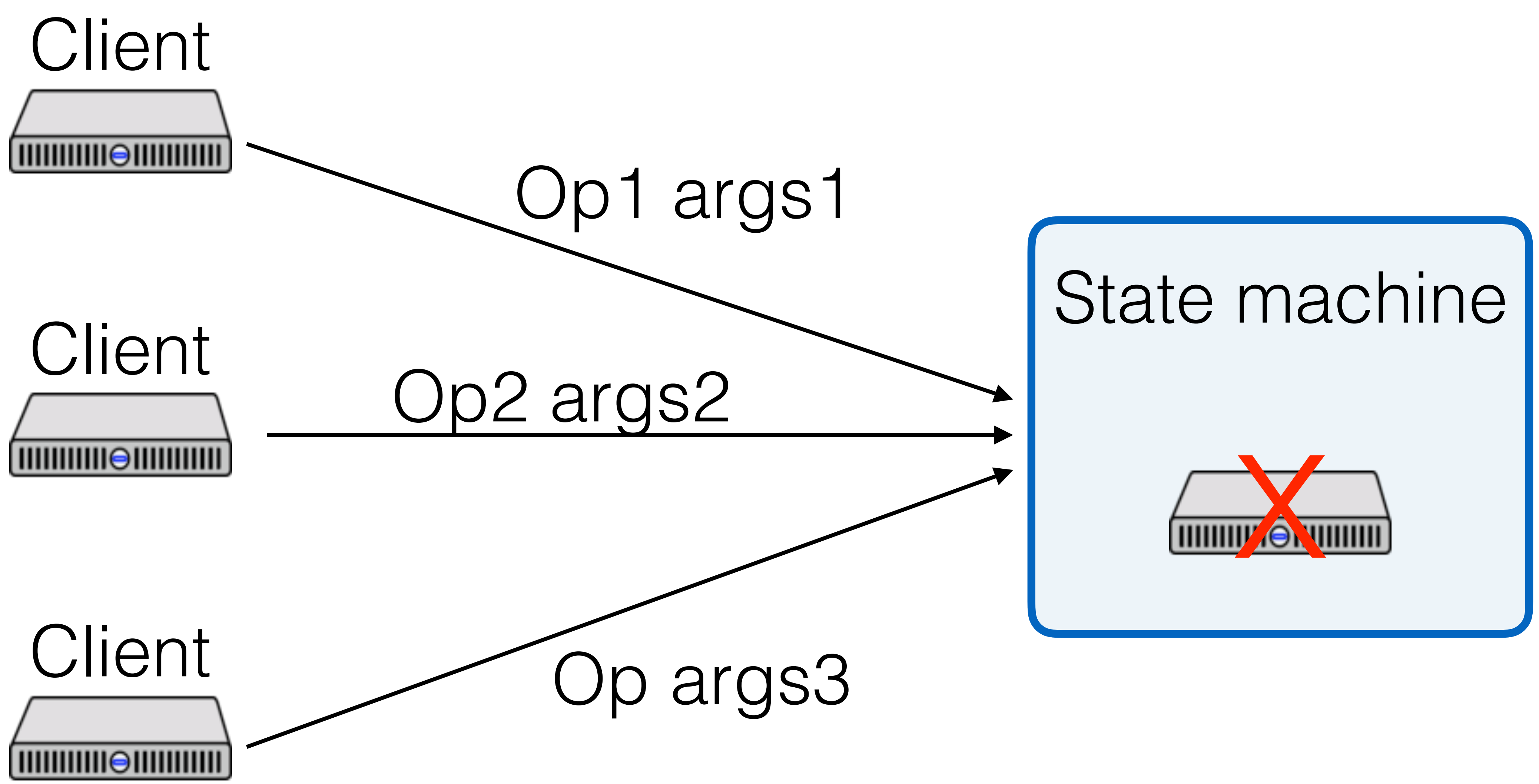
Single-node key/value store



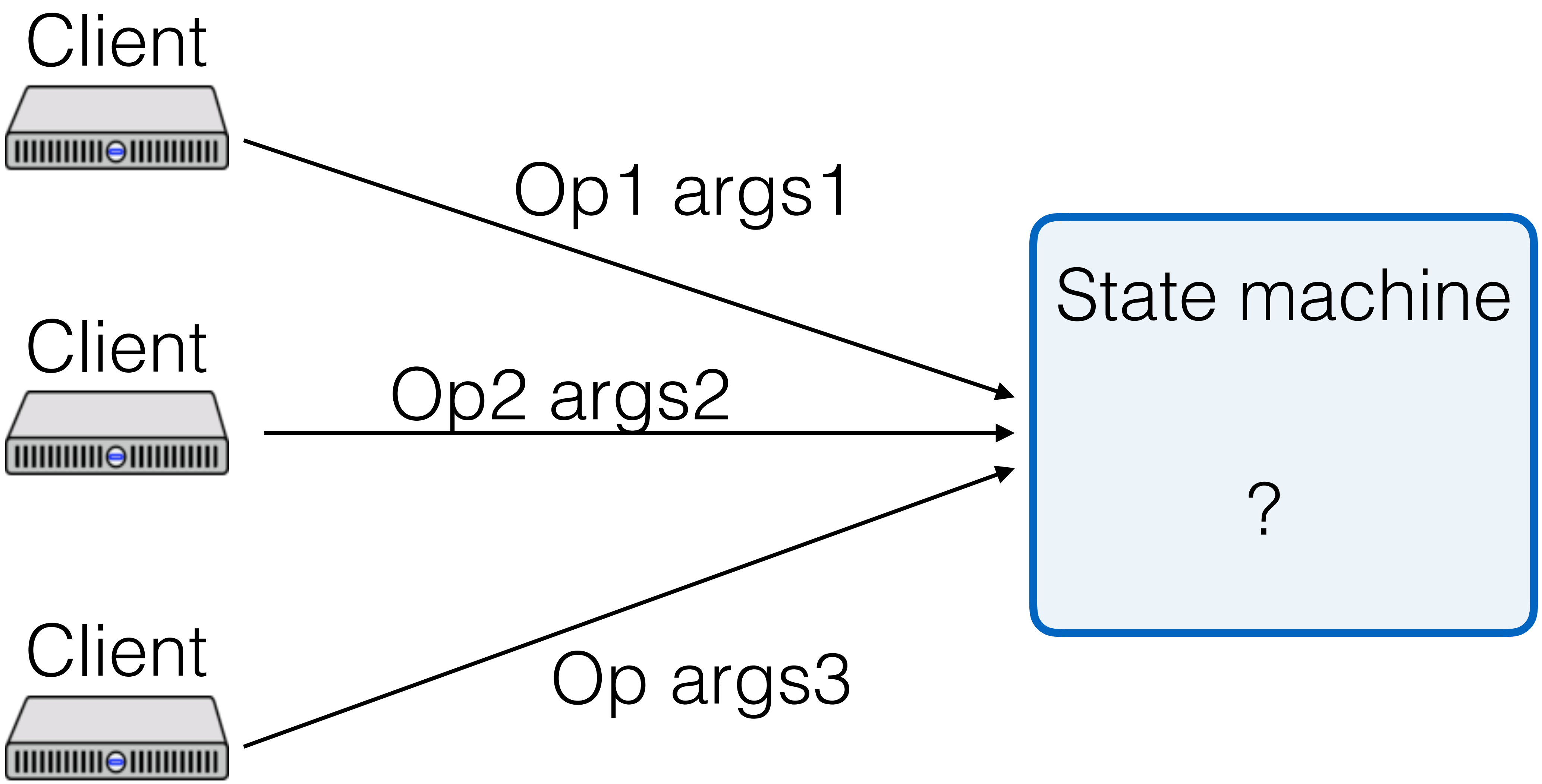
Single-node state machine



Single-node state machine



Single-node state machine



State machine replication

Replicate the state machine across multiple servers

Clients can view all servers as one state machine

What’s the simplest form of replication?

Two servers!

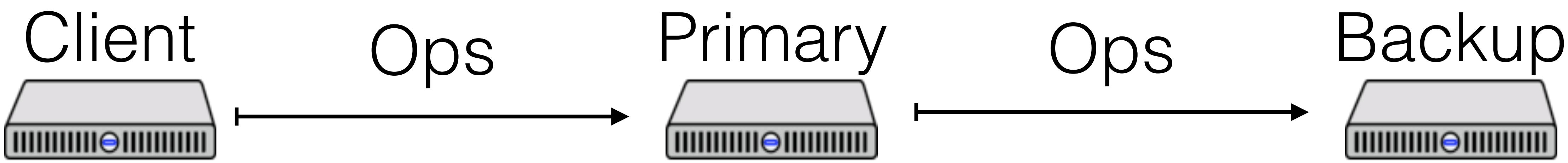
At a given time:

- Clients talk to one server, the primary
- Data are replicated on primary and backup
- If the primary fails, the backup becomes primary

Goals:

- Correct and available
- Despite *some* failures

Basic operation



Clients send operations (Put, Get) to primary

Primary decides on order of ops

Primary forwards sequence of ops to backup

Backup performs ops in same order (hot standby)

- Or just saves the log of operations (cold standby)

After backup has saved ops, primary replies to client

Challenges

Non-deterministic operations

Dropped messages

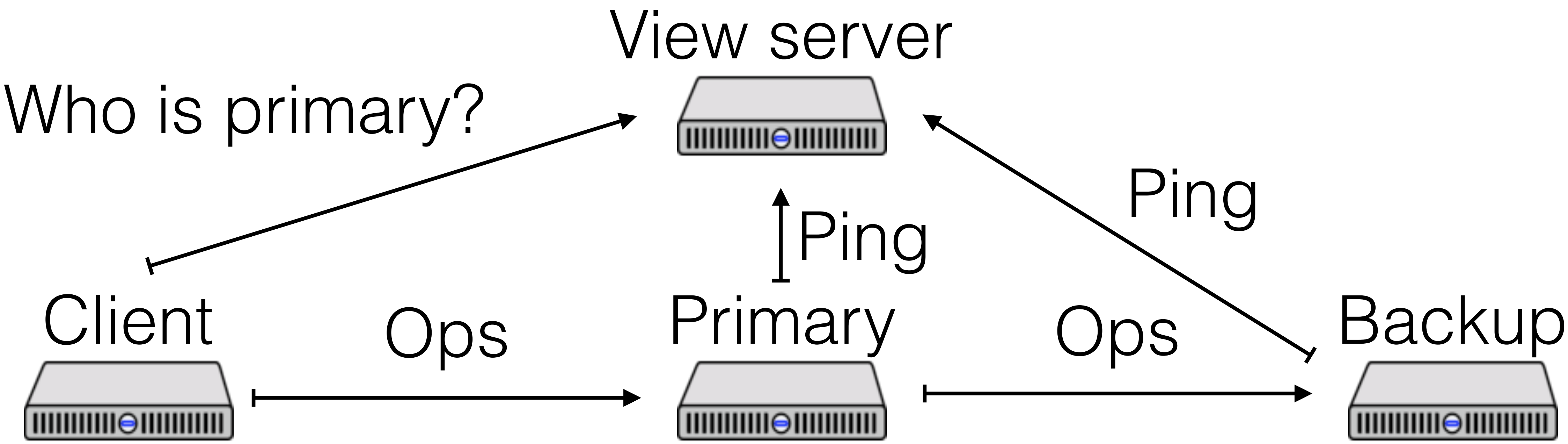
State transfer between primary and backup

- Write log? Write state?

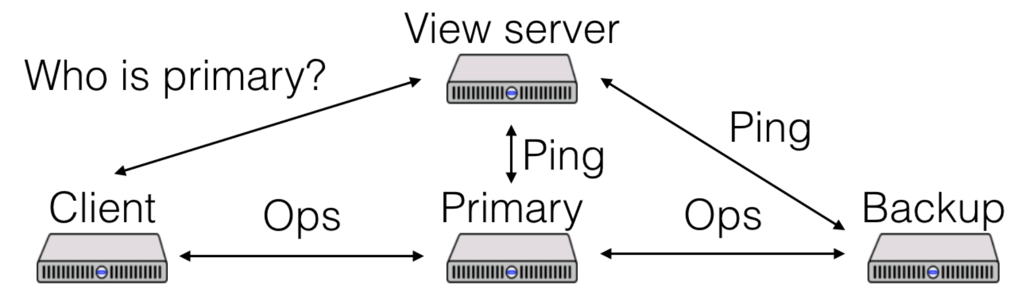
There can be only one primary at a time

- Clients, primary and backup need to agree

The View Service



The View service



View server decides who is primary and backup

- Clients and servers depend on view server

The hard part:

- Must be only one primary at a time

- Clients shouldn't communicate with view server on every request

- Careful protocol design

View server is a single point of failure (fixed in Lab 3)

On failure

Primary fails

View server declares a new “view”, moves backup to primary

View server promotes an idle server as new backup

Primary initializes new backup’s state

Now ready to process ops, OK if primary fails

“Views”

A view is a statement about the current roles in the system

Views form a sequence in time

View 1
Primary = A
Backup = B

View 2
Primary = B
Backup = C

View 3
Primary = C
Backup = D

Detecting failure

Each server periodically pings (Ping RPC) view server

To the view server, a node is

- "dead" if missed *n* Pings
- "live" after a single Ping

Can a server ever be up but declared dead?

Managing servers

Any number of servers can send Pings

- If more than two servers are live, extras are “idle”
- Idle servers can be promoted to backup

If primary dies

- New view with old backup as primary, idle as backup

If backup dies

- New view with idle server as backup

OK to have a view with a primary and no backup

- But can lead to getting stuck later

View 1
Primary = A
Backup = B

A stops pinging

View 2
Primary = B
Backup = C

B *immediately* stops pinging

View 3
Primary = C
Backup = _

Can’t move to View 3 until C gets state
How does view server know C has state?

Viewserver waits for primary ack

Track whether primary has acked (with ping) current view

MUST stay with current view until ack

Even if primary seems to have failed

This is another weakness of this protocol

Question

Can more than one server think it is the primary at the same time?

Split brain

1:A,B

A is still up, but can't reach view server
(or is unlucky and pings get dropped)

2:B,_

B learns it is promoted to primary
A still thinks it is primary

Split brain

Can more than one server *act* as primary?

- Act as = respond to clients

Rules

1. Primary in view *i+1* must have been backup or primary in view *i*
2. Primary must wait for backup to accept/execute each op before doing op and replying to client
3. Backup must accept forwarded requests only if view is correct
4. Non-primary must reject client requests
5. Every operation must be before or after state transfer

Rules

1. Primary in view *i+1* must have been backup or primary in view *i*
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Incomplete state

1:A,B

A is still up, but can't reach view server

2:C,D

C learns it is promoted to primary
A still thinks it is primary
C doesn't know previous state

Rules

1. Primary in view *i+1* must have been backup or primary in view *i*

2. Primary must wait for backup to accept/execute each op before doing op and replying to client

3. Backup must accept forwarded requests only if view is correct

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1. Missing writes

1:A,B

Client writes to A, receives response
A crashes before writing to B

2:B,C

Client reads from B
Write is missing

2. “Fast” Reads?

Does the primary need to forward reads to the backup?

(This is a common “optimization”)

Stale reads

1:A,B

A is still up, but can't reach view server

2:B,C

Client 1 writes to B
Client 2 reads from A
A returns outdated value

Reads vs. writes

Reads treated as state machine operations too

But: can be executed more than once

RPC library can handle them differently

Rules

1. Primary in view *i+1* must have been backup or primary in view *i*

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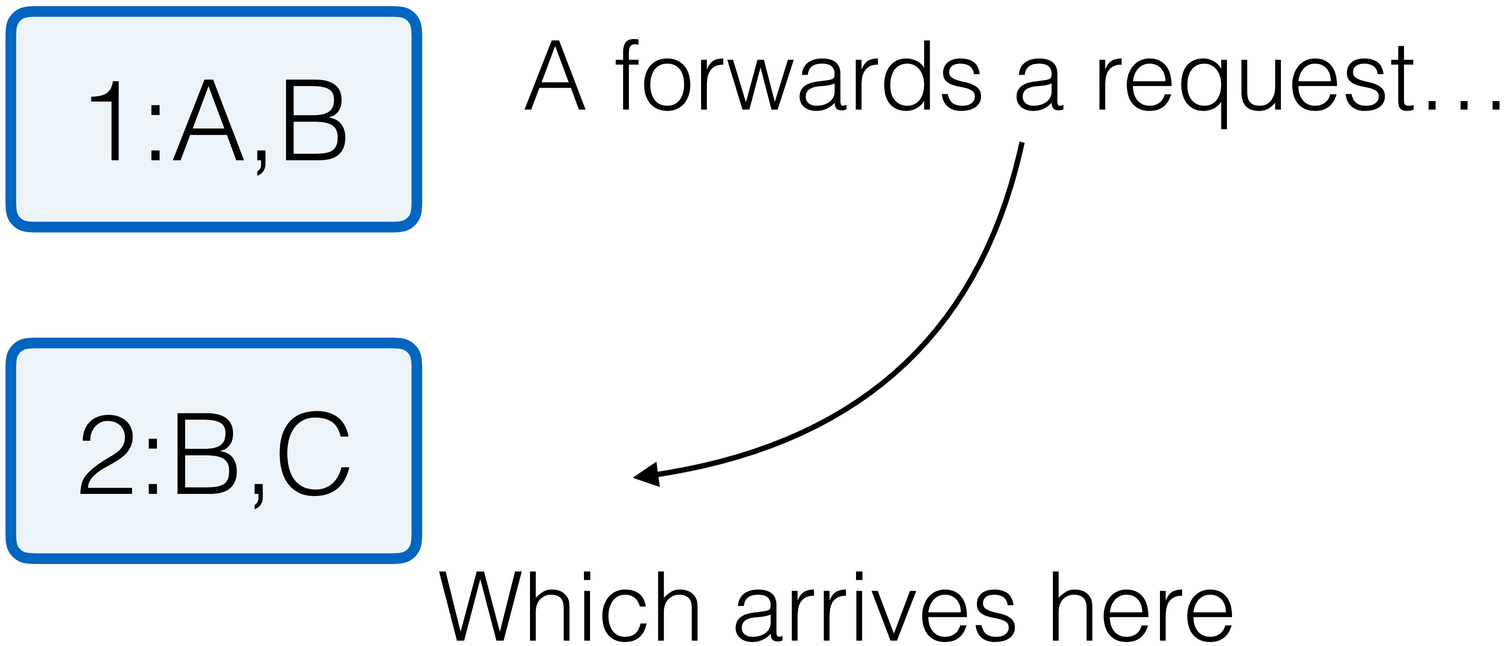
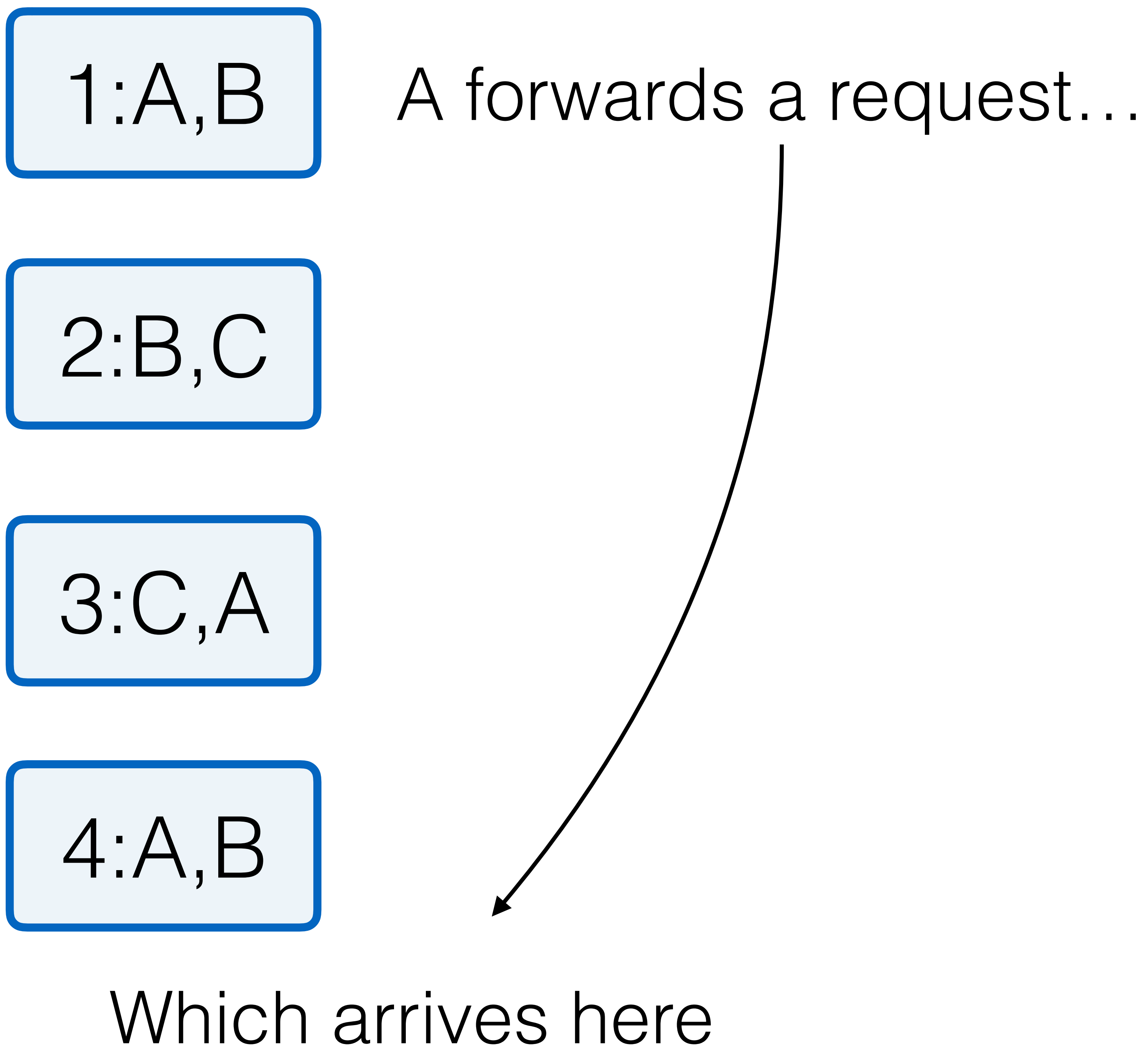
Partially split brain



Old messages



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Inconsistencies

1:A,B

2:B,C

3:B,A

Outdated client sends request to A
A shouldn't respond!

What about old messages to primary?

1:A,B

2:B,C

3:B,A

4:A,D

Outdated client sends request to A

Rules

1. Primary in view *i+1* must have been backup or primary in view *i*
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Inconsistencies

1:A,B

A starts sending state to B
Client writes to A
A forwards op to B
A sends rest of state to B

Rules

1. Primary in view *i+1* must have been backup or primary in view *i*

2. Primary must wait for backup to accept/execute each op before doing op and replying to client

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Progress

Are there cases when the system can’t make further progress (i.e. process new client requests)?

Progress

- View server fails
- Network fails entirely (hard to get around this one)
- Client can’t reach primary but it can ping VS
- No backup and primary fails
- Primary fails before completing state transfer

State transfer and RPCs

State transfer must include RPC data

Duplicate writes

1:A,B

Client writes to A
A forwards to B
A replies to client
Reply is dropped

2:B,C

B transfers state to C, crashes

3:C,D

Client resends write. Duplicated!

One more corner case

1:A,B

View server stops hearing from A
A and B, and clients, can still communicate

2:B,C

B hasn't heard from view server
Client in view 1 sends a request to A
What should happen?
Client in view 2 sends a request to B
What should happen?

Replicated Virtual Machines

Whole system replication

Completely transparent to applications and clients

High availability for any existing software

Challenge: Need state at backup to exactly mirror primary

Restricted to a uniprocessor VMs

Deterministic Replay

Key idea: state of VM depends only on its input

- Content of all input/output
- Precise instruction of every interrupt
- Only a few exceptions (e.g., timestamp instruction)

Record all hardware events into a log

- Modern processors have instruction counters and can interrupt after (precisely) x instructions
- Trap and emulate any non-deterministic instructions

Replicated Virtual Machines

Replay I/O, interrupts, etc. at the backup

- Backup executes events at primary with a lag
- Backup stalls until it knows timing of next event
- Backup does not perform external events

Primary stalls until it knows backup has copy of every event up to (and incl.) output event

- Then it is safe to perform output

On failure, inputs/outputs will be replayed at backup (idempotent)

Example

Primary receives network interrupt

- hypervisor forwards interrupt plus data to backup
- hypervisor delivers network interrupt to OS kernel
- OS kernel runs, kernel delivers packet to server
- server/kernel write response to network card
- hypervisor gets control and sends response to backup
- hypervisor delays sending response to client until backup acks

Backup receives log entries

- backup delivers network interrupt
- …
- hypervisor does *not* put response on the wire
- hypervisor ignores local clock interrupts