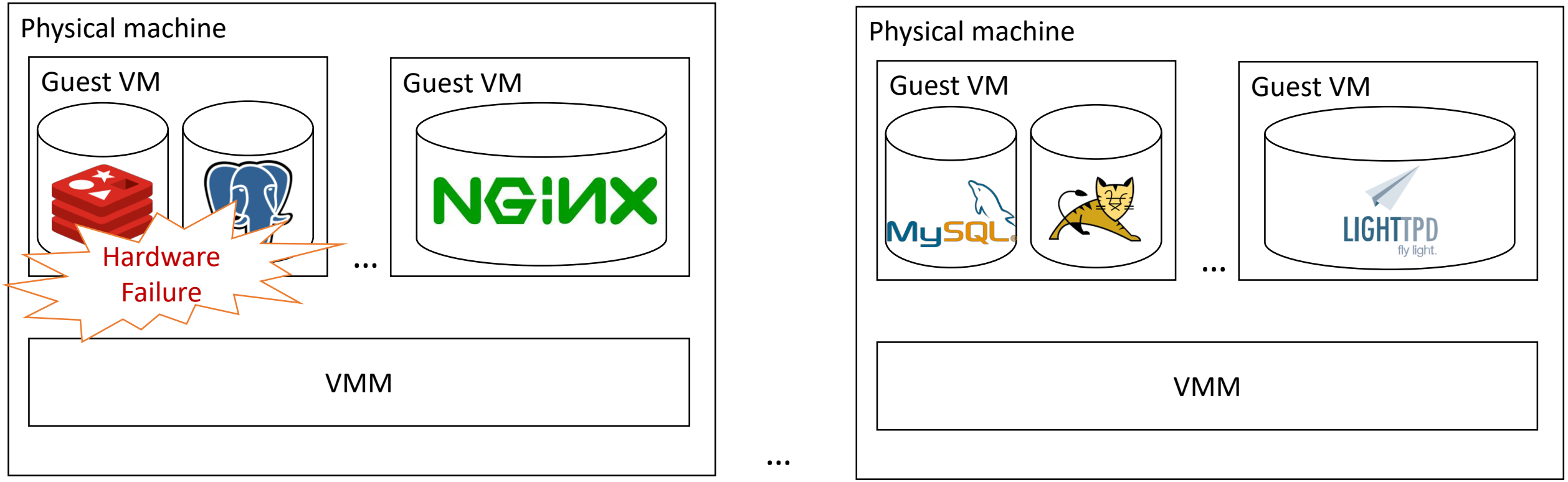
PLOVER: Fast, Multi-core Scalable Virtual Machine Fault-tolerance

Cheng Wang, Xusheng Chen, Weiwei Jia, Boxuan Li, Haoran Qiu, Shixiong Zhao, and Heming Cui

The University of Hong Kong

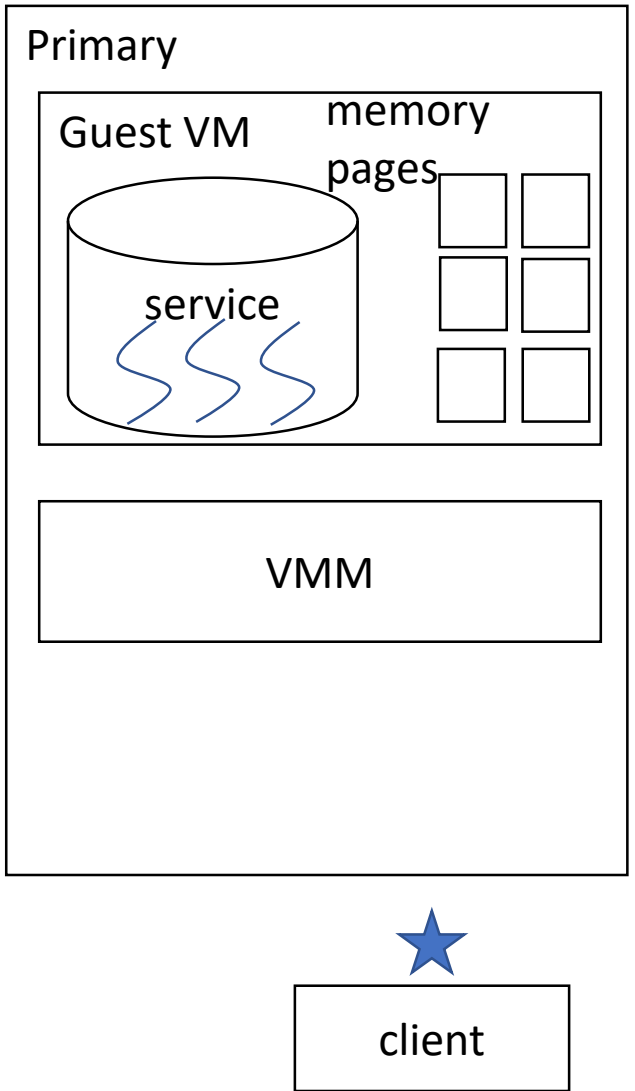
Virtual machines are pervasive in datacenters



VM fault tolerance is **crucial**!

Classic VM replication - primary/backup approach

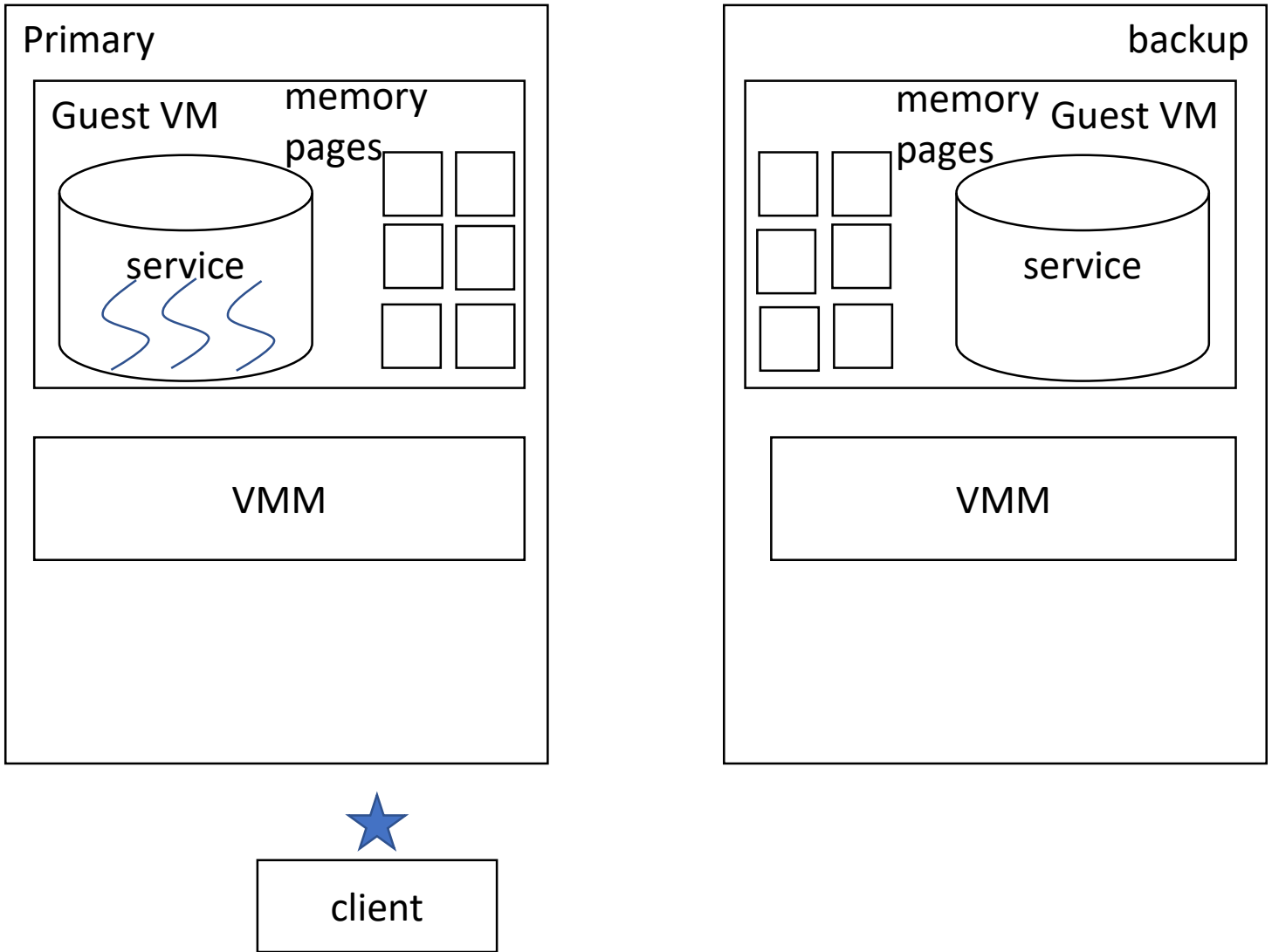
Remus [NSDI'08]



client

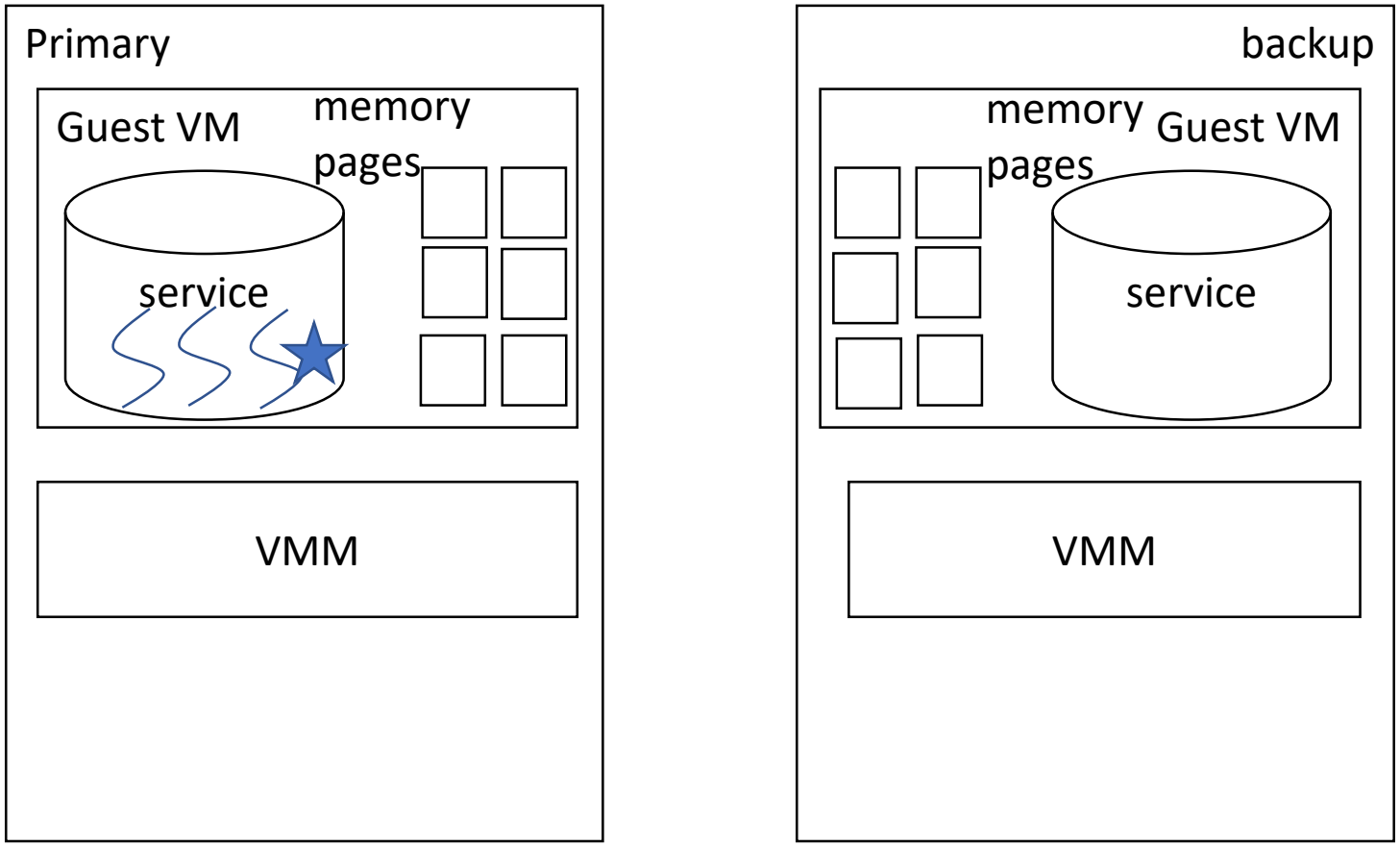
Classic VM replication - primary/backup approach

Remus [NSDI'08]



Classic VM replication - primary/backup approach

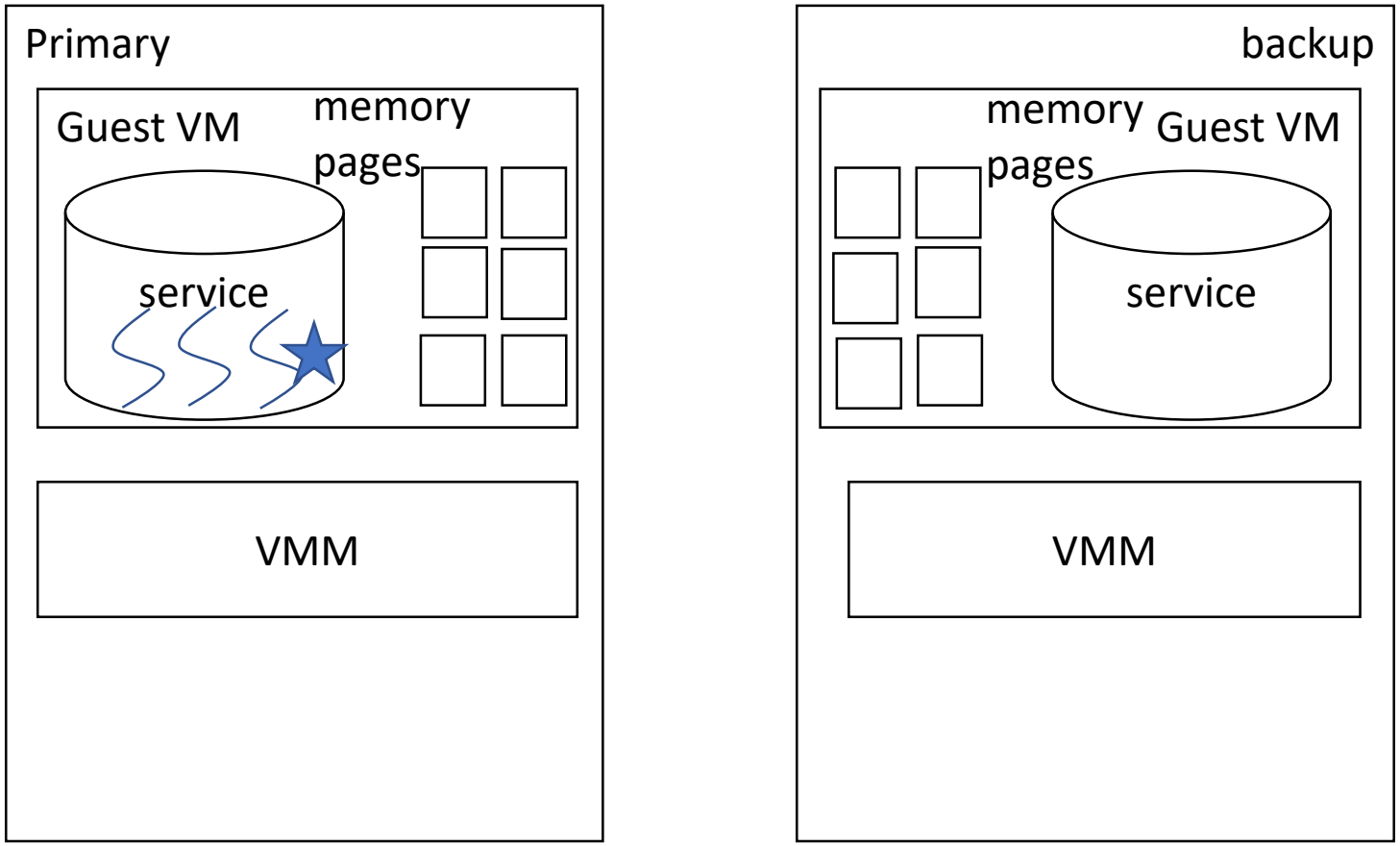
Remus [NSDI'08]



client

Classic VM replication - primary/backup approach

Remus [NSDI'08]

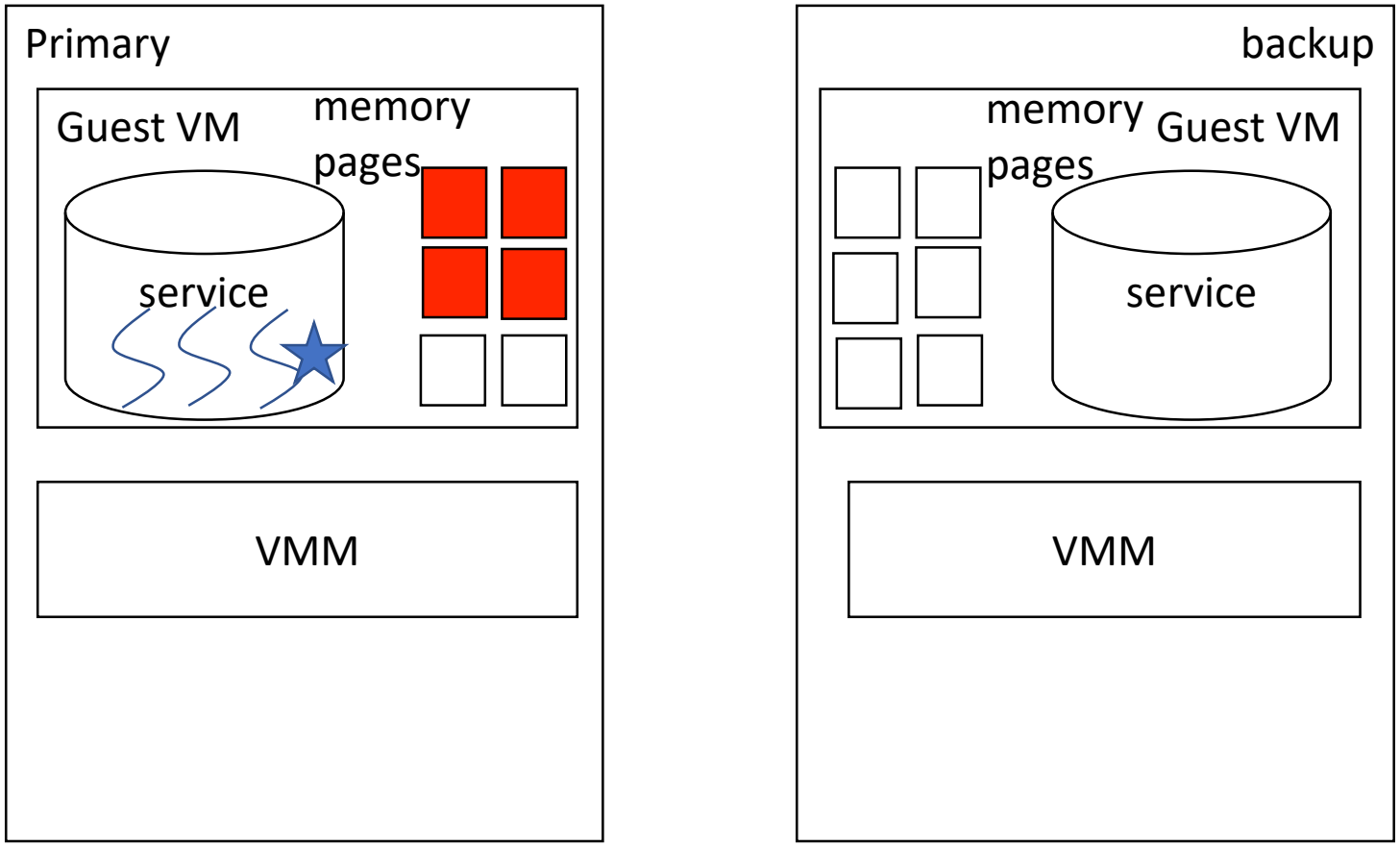


Synchronize primary/backup every 25ms

1. Pause primary VM (every 25ms) and transmit all changed state (e.g., memory pages) to backup.

Classic VM replication - primary/backup approach

Remus [NSDI'08]

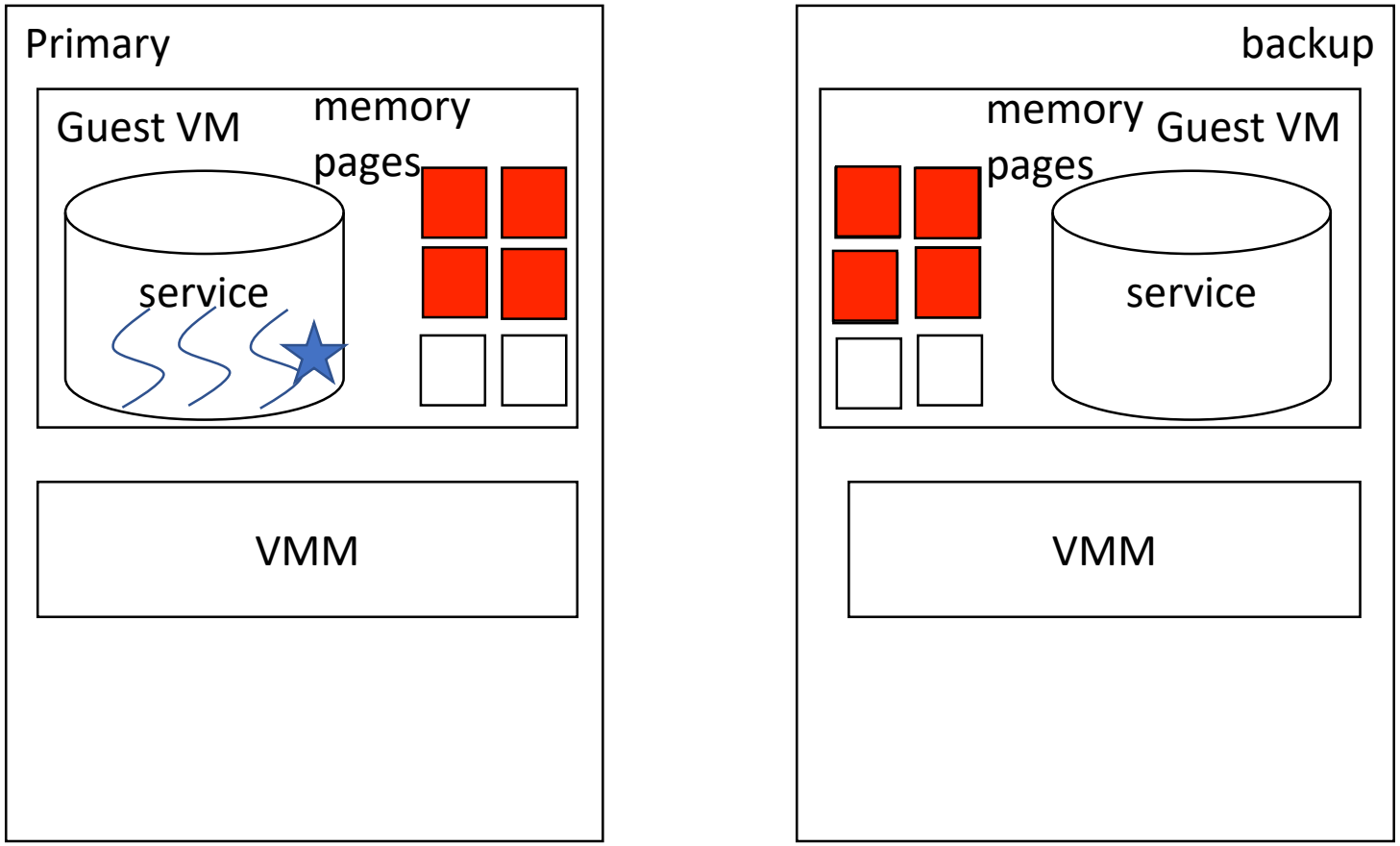


Synchronize primary/backup every 25ms

1. Pause primary VM (every 25ms) and transmit all changed state (e.g., memory pages) to backup.

Classic VM replication - primary/backup approach

Remus [NSDI'08]

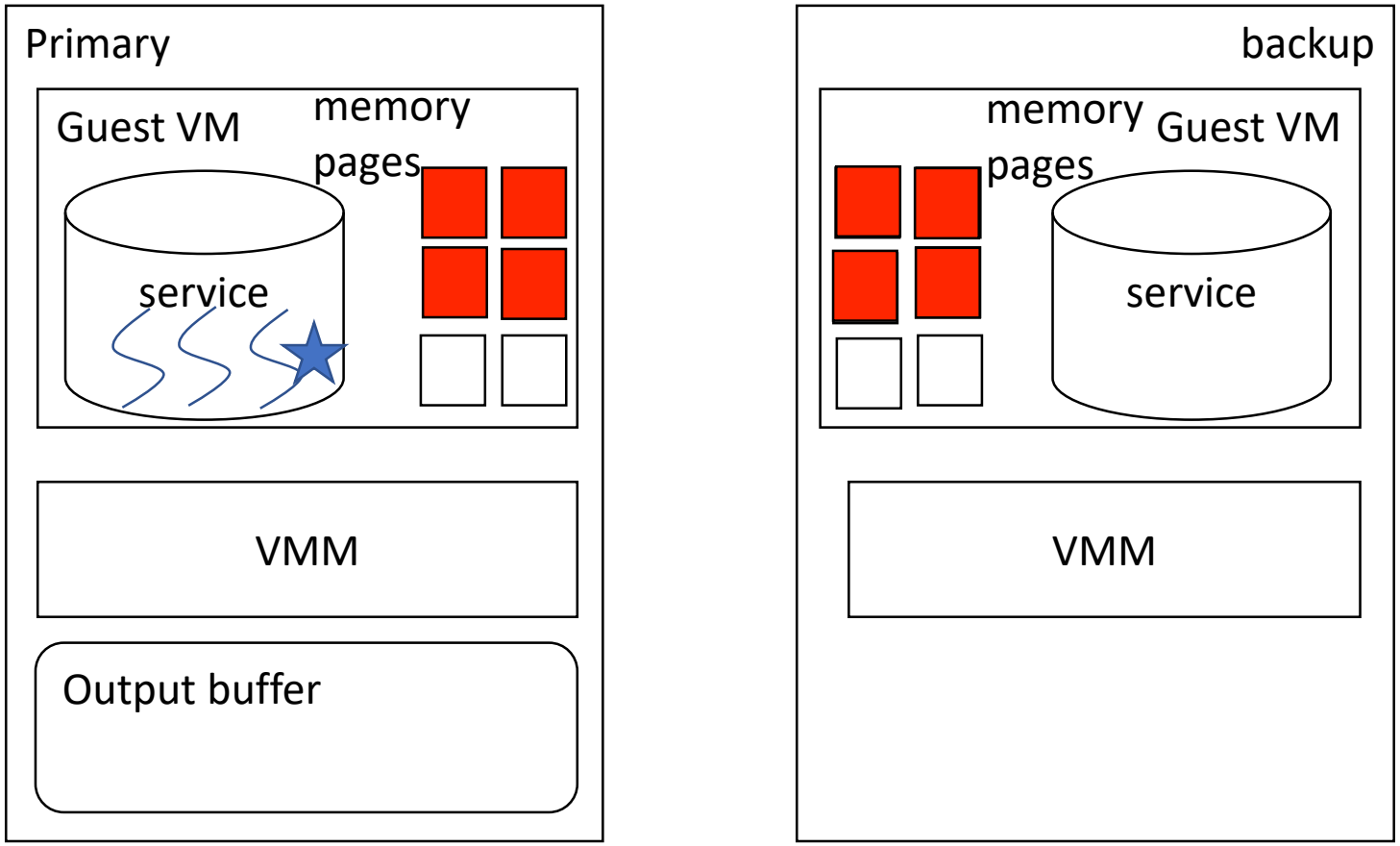


Synchronize primary/backup every 25ms

1. Pause primary VM (every 25ms) and transmit all changed state (e.g., memory pages) to backup.

Classic VM replication - primary/backup approach

Remus [NSDI'08]

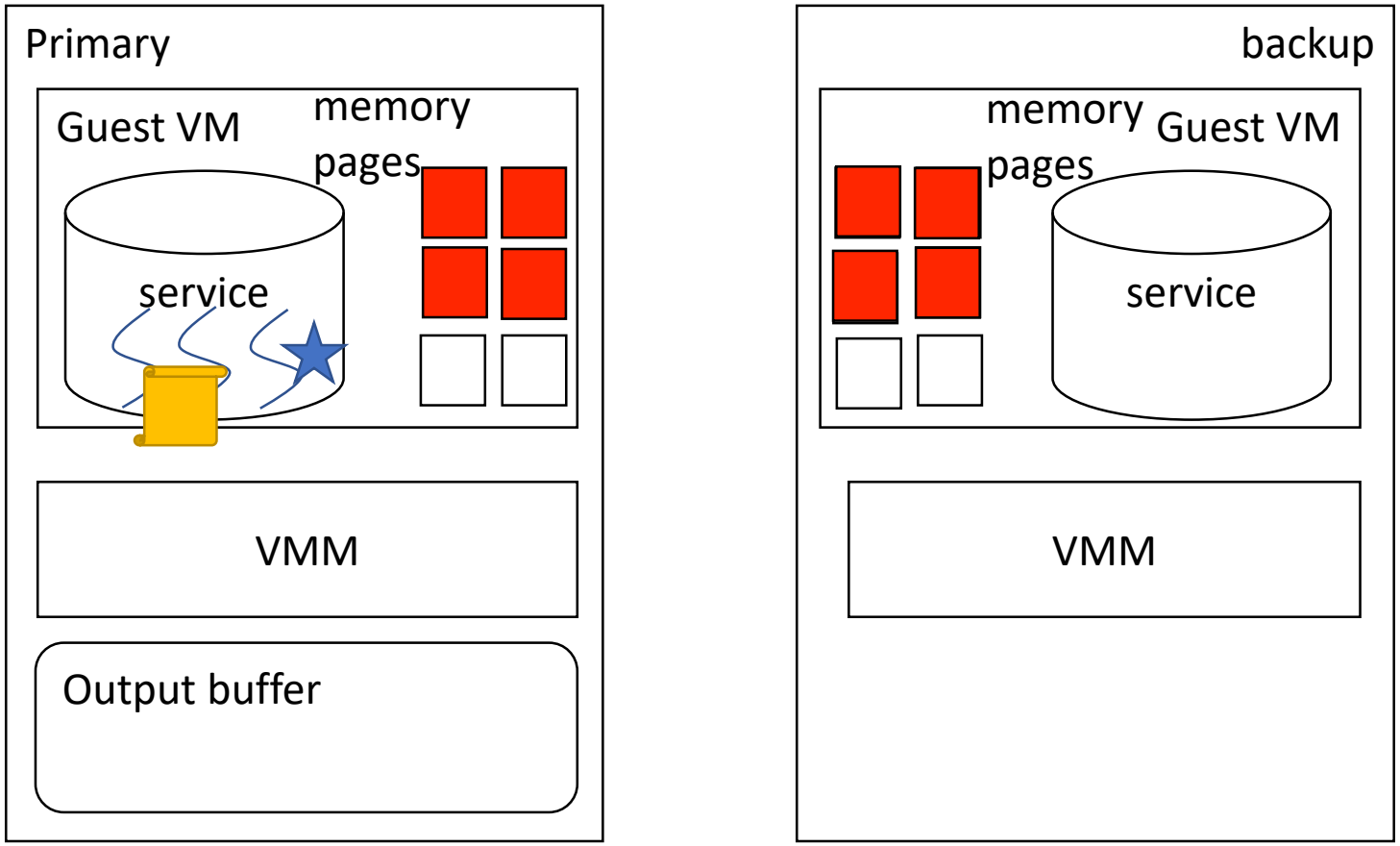


Synchronize primary/backup every 25ms

1. Pause primary VM (every 25ms) and transmit all changed state (e.g., memory pages) to backup.

Classic VM replication - primary/backup approach

Remus [NSDI'08]

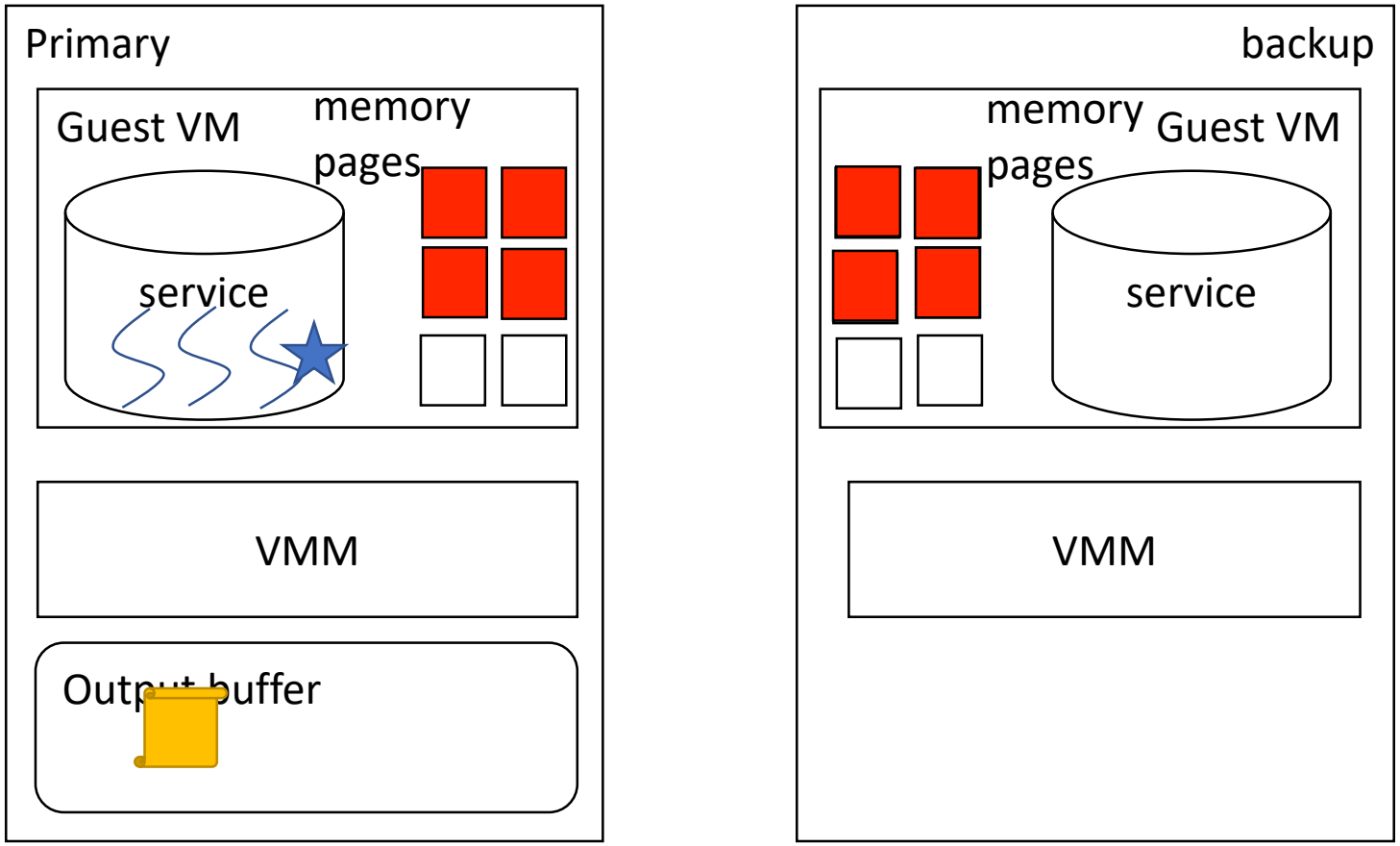


Synchronize primary/backup every 25ms

1. Pause primary VM (every 25ms) and transmit all changed state (e.g., memory pages) to backup.

Classic VM replication - primary/backup approach

Remus [NSDI'08]

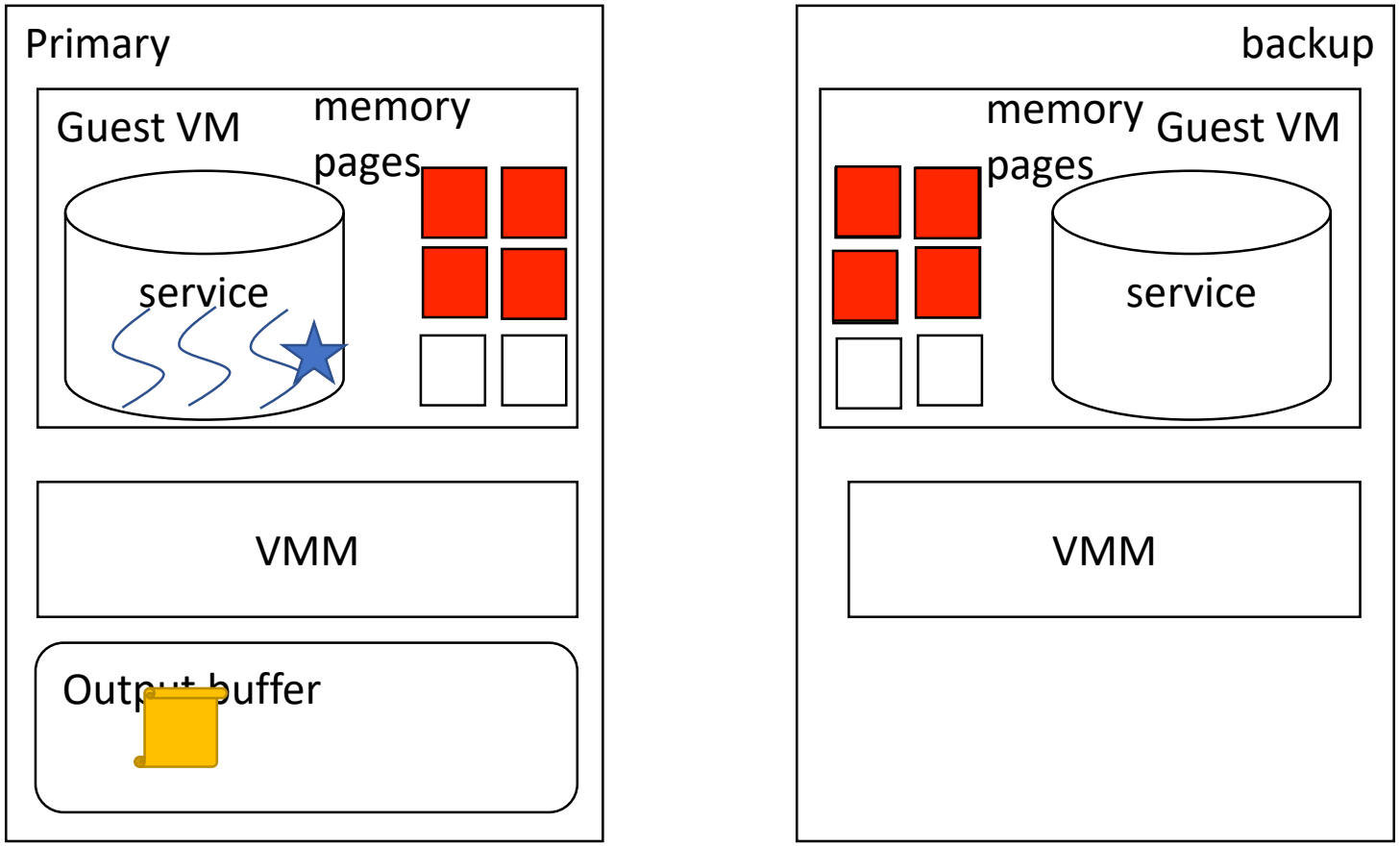


Synchronize primary/backup every 25ms

1. Pause primary VM (every 25ms) and transmit all changed state (e.g., memory pages) to backup.

Classic VM replication - primary/backup approach

Remus [NSDI'08]

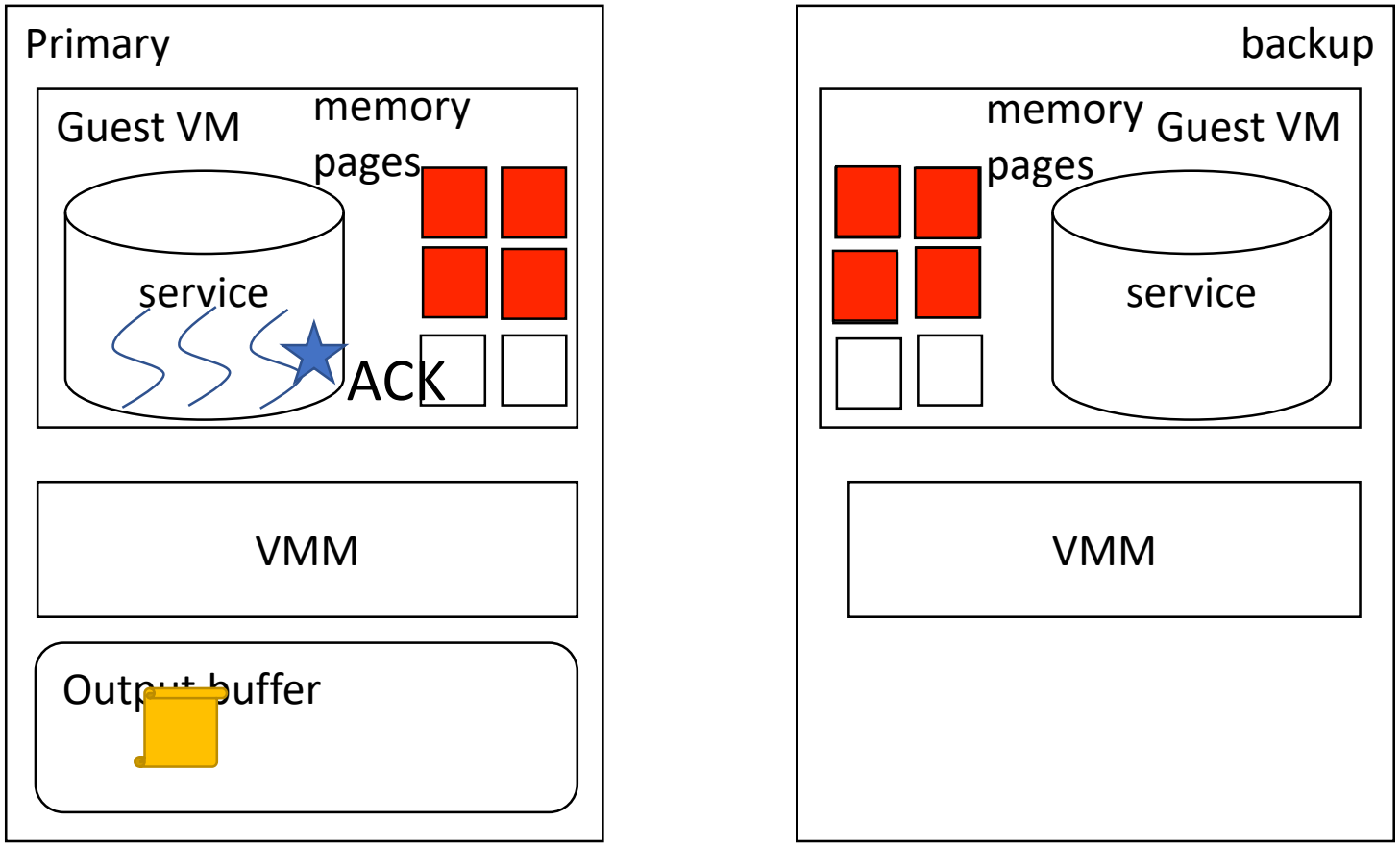


Synchronize primary/backup every 25ms

1. Pause primary VM (every 25ms) and transmit all changed state (e.g., memory pages) to backup.
2. Backup acknowledges to the primary when complete state has been received.

Classic VM replication - primary/backup approach

Remus [NSDI'08]

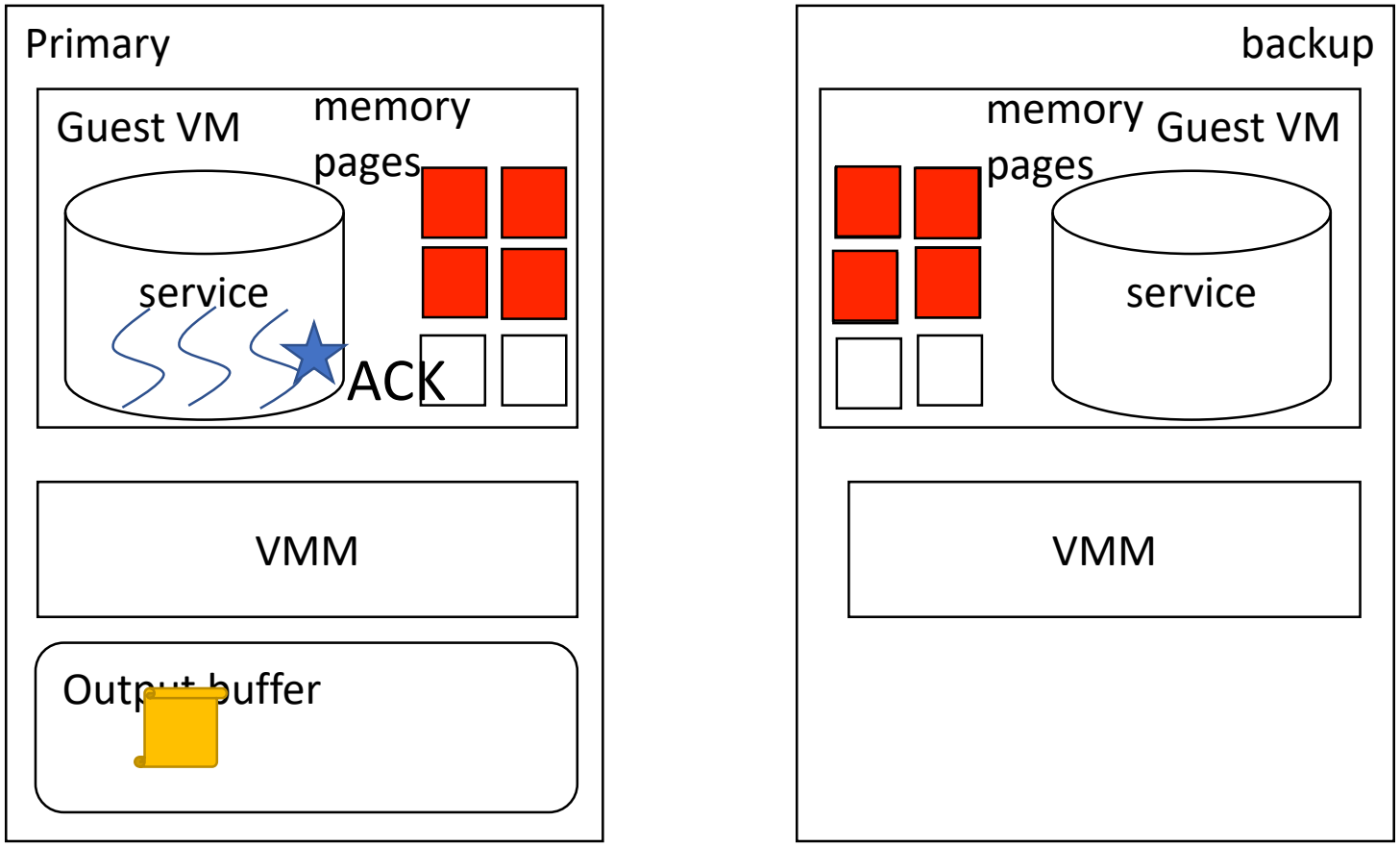


Synchronize primary/backup every 25ms

1. Pause primary VM (every 25ms) and transmit all changed state (e.g., memory pages) to backup.
2. Backup acknowledges to the primary when complete state has been received.

Classic VM replication - primary/backup approach

Remus [NSDI'08]

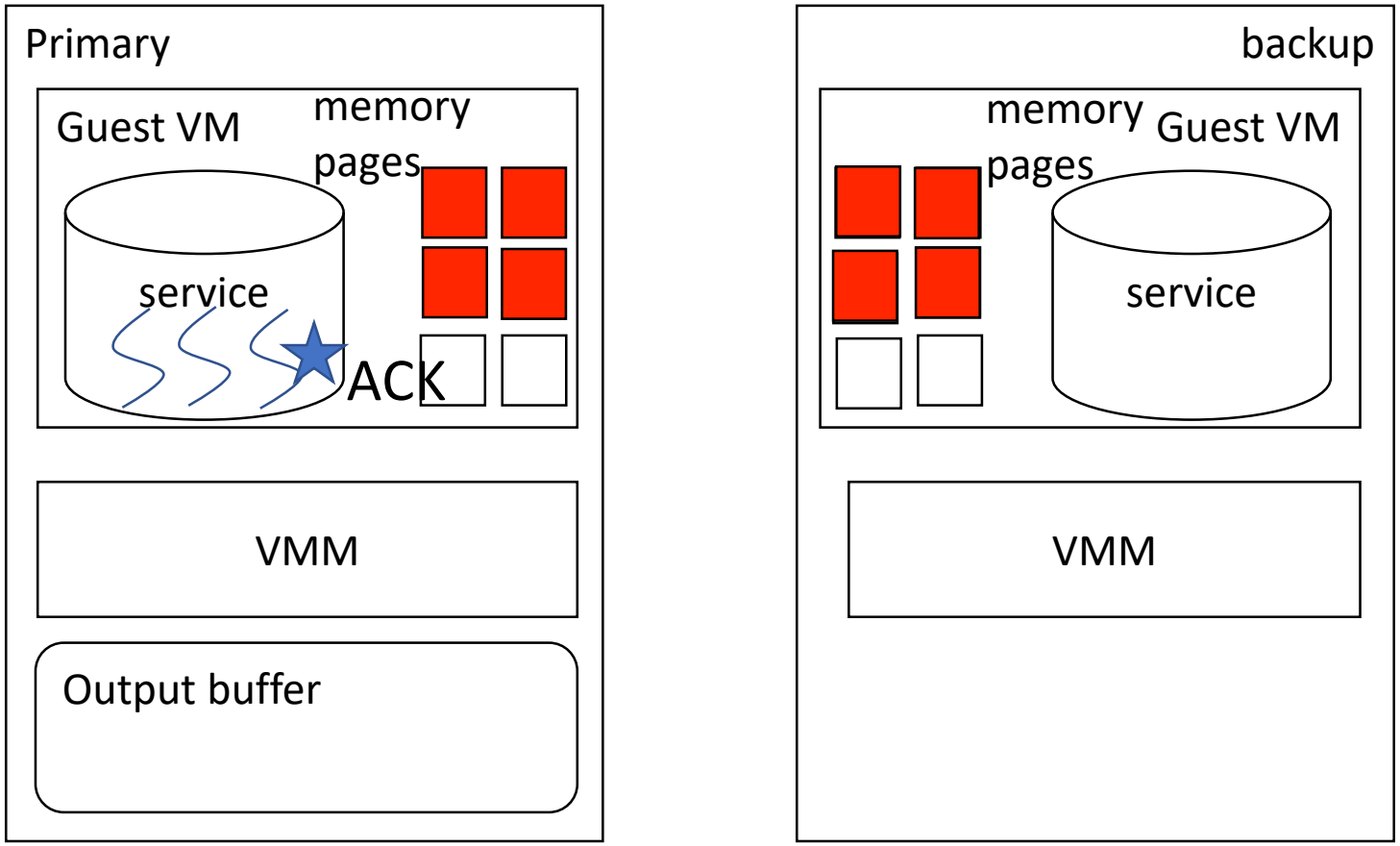


Synchronize primary/backup every 25ms

1. Pause primary VM (every 25ms) and transmit all changed state (e.g., memory pages) to backup.
2. Backup acknowledges to the primary when complete state has been received.
3. Primary's buffered network output is released.

Classic VM replication - primary/backup approach

Remus [NSDI'08]

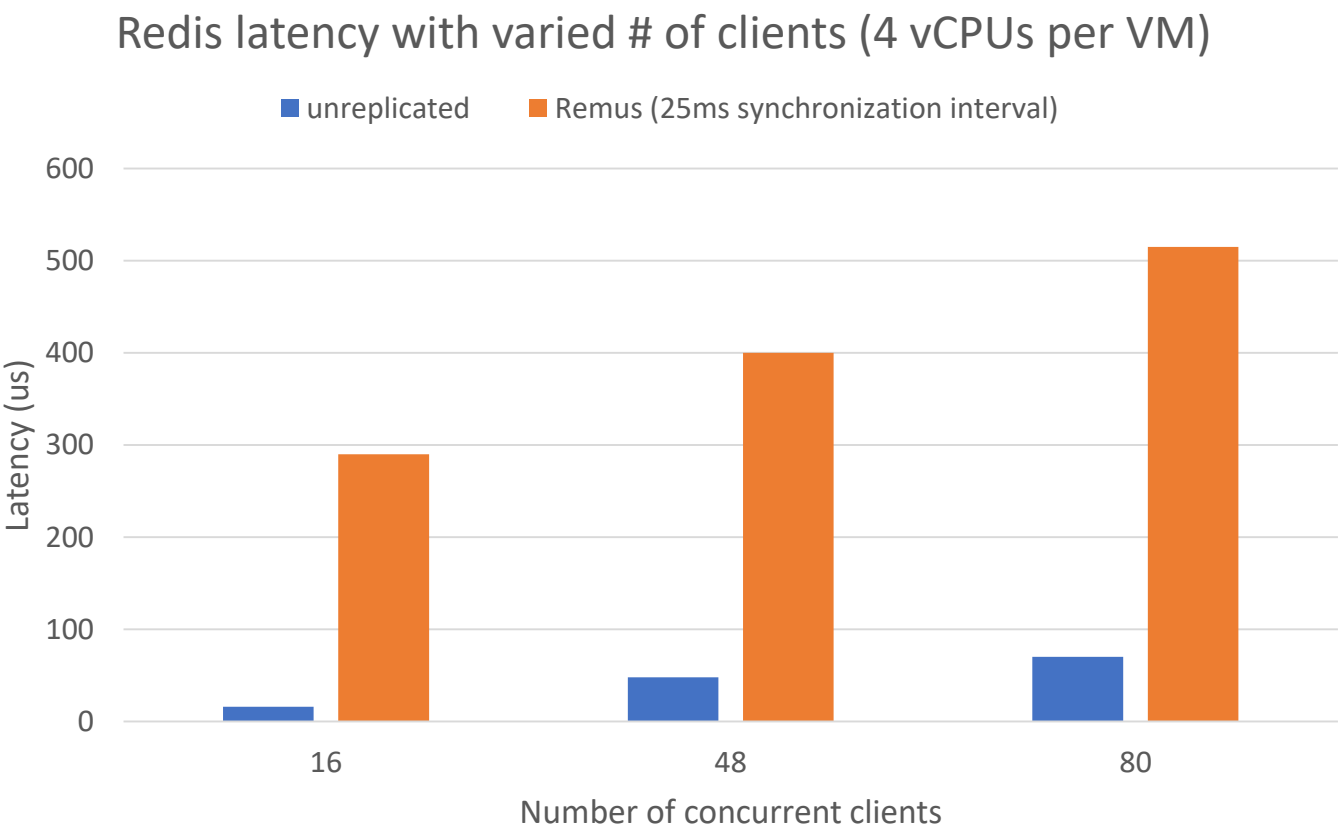


Synchronize primary/backup every 25ms

1. Pause primary VM (every 25ms) and transmit all changed state (e.g., memory pages) to backup.
2. Backup acknowledges to the primary when complete state has been received.
3. Primary's buffered network output is released.

Two limitations of primary/backup approach (1)

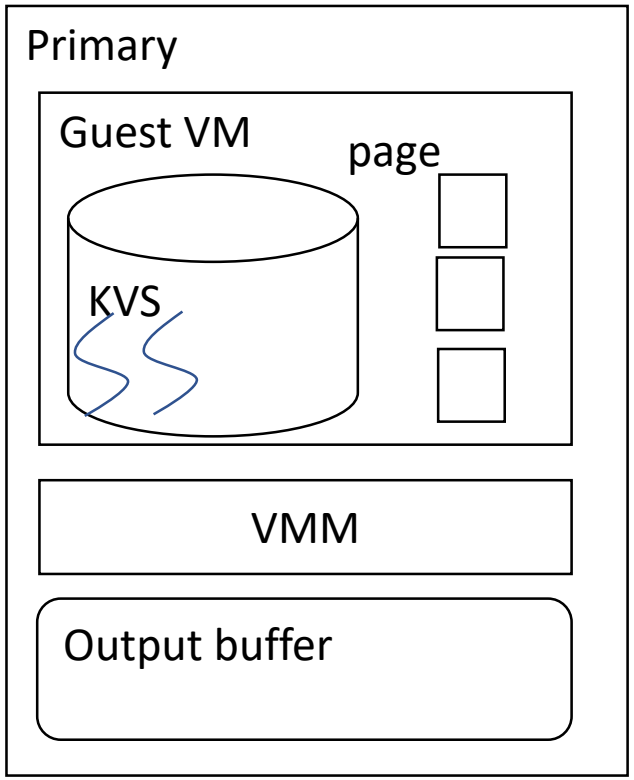
- Too many memory pages have to be copied and transferred, greatly ballooned client-perceived latency

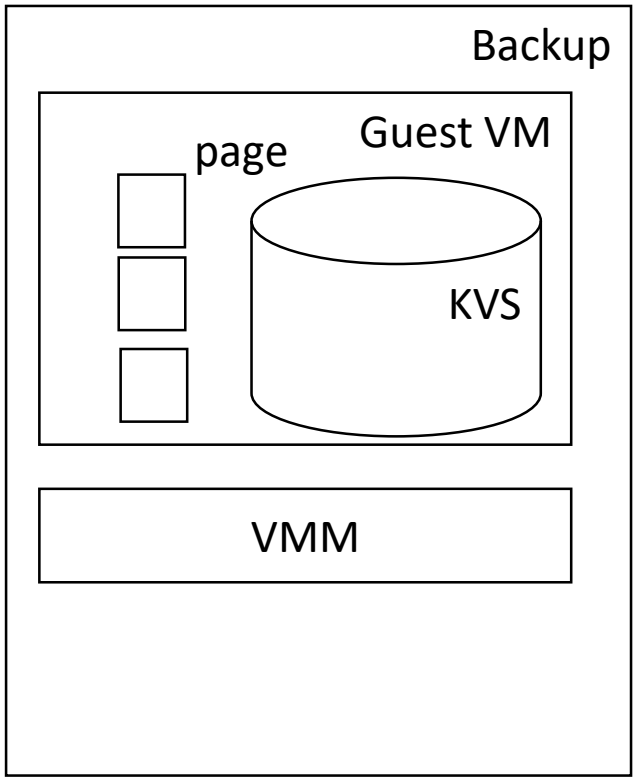


# of concurrent clients	Page transfer size (MB)
16	20.9
48	68.4
80	110.5

Two limitations of primary/backup approach (2)

- The split-brain problem



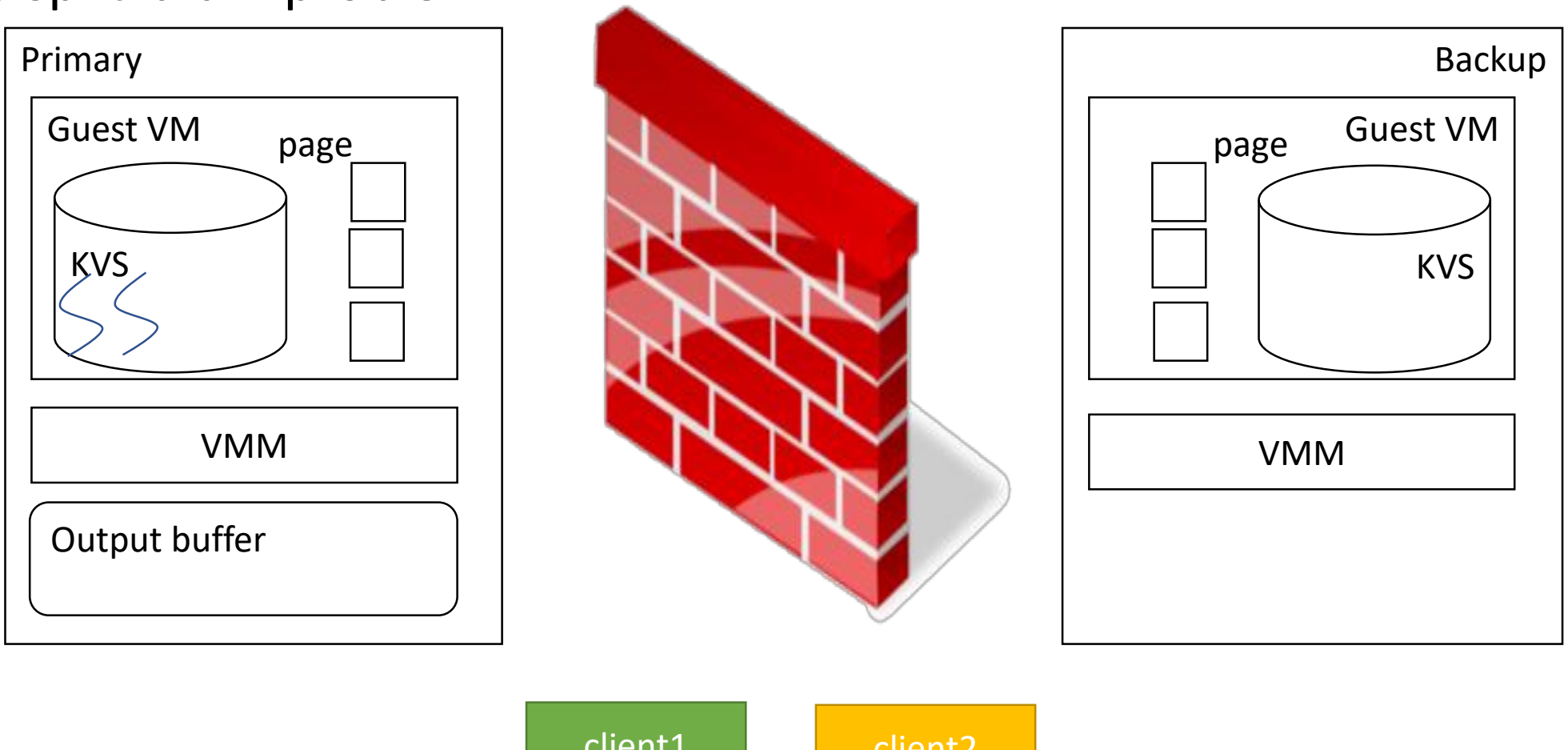


client1

client2

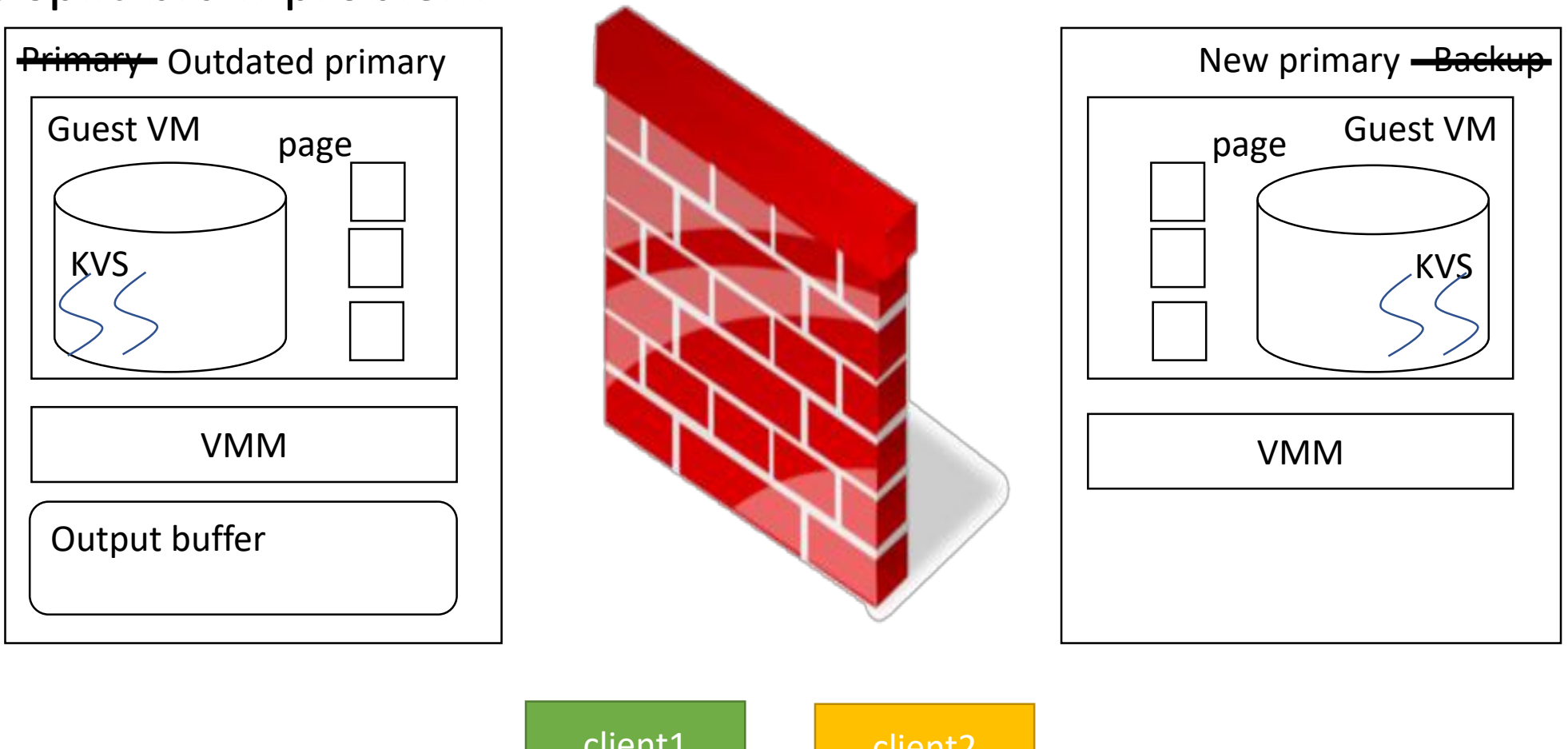
Two limitations of primary/backup approach (2)

- The split-brain problem



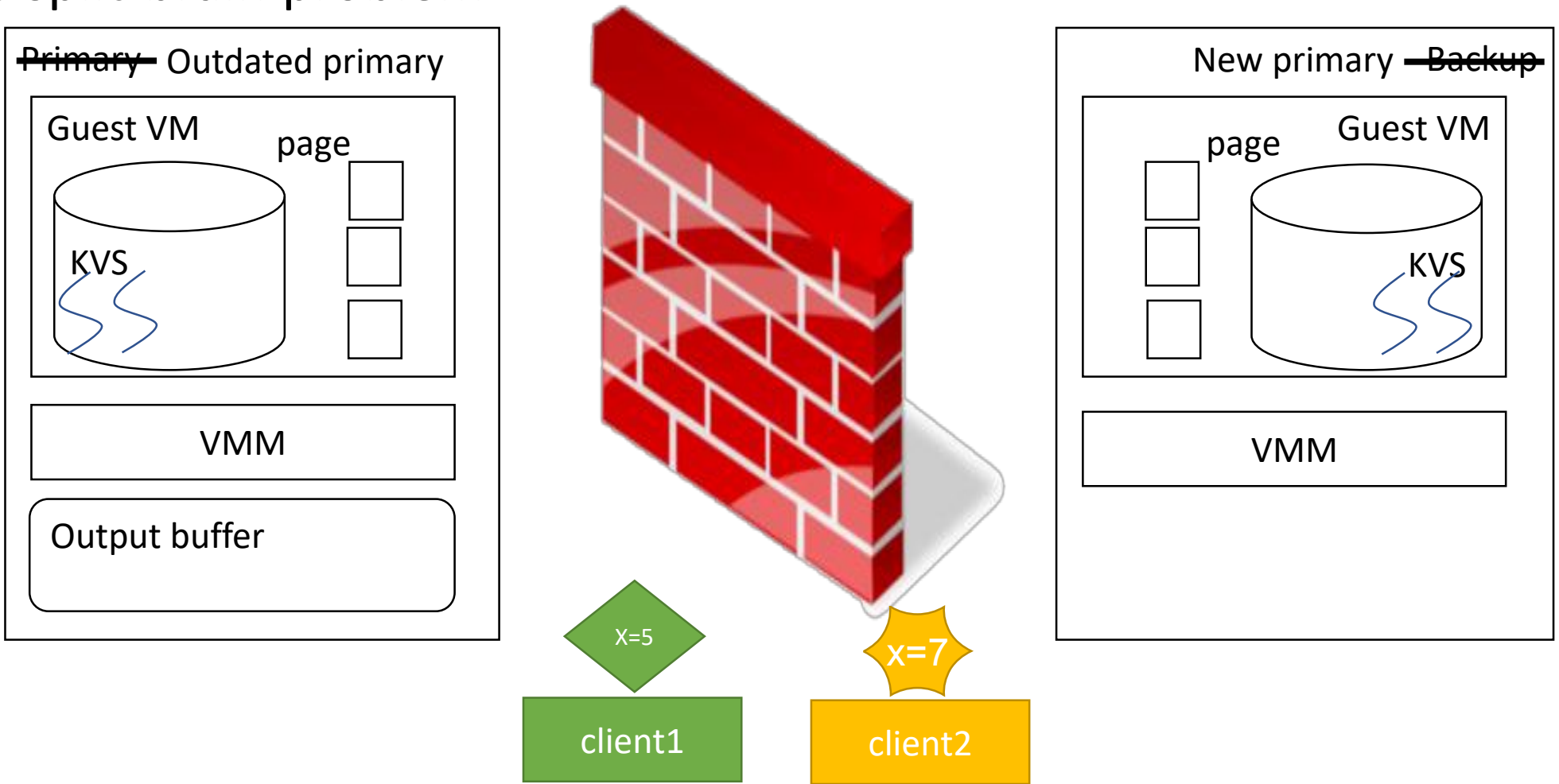
Two limitations of primary/backup approach (2)

- The split-brain problem



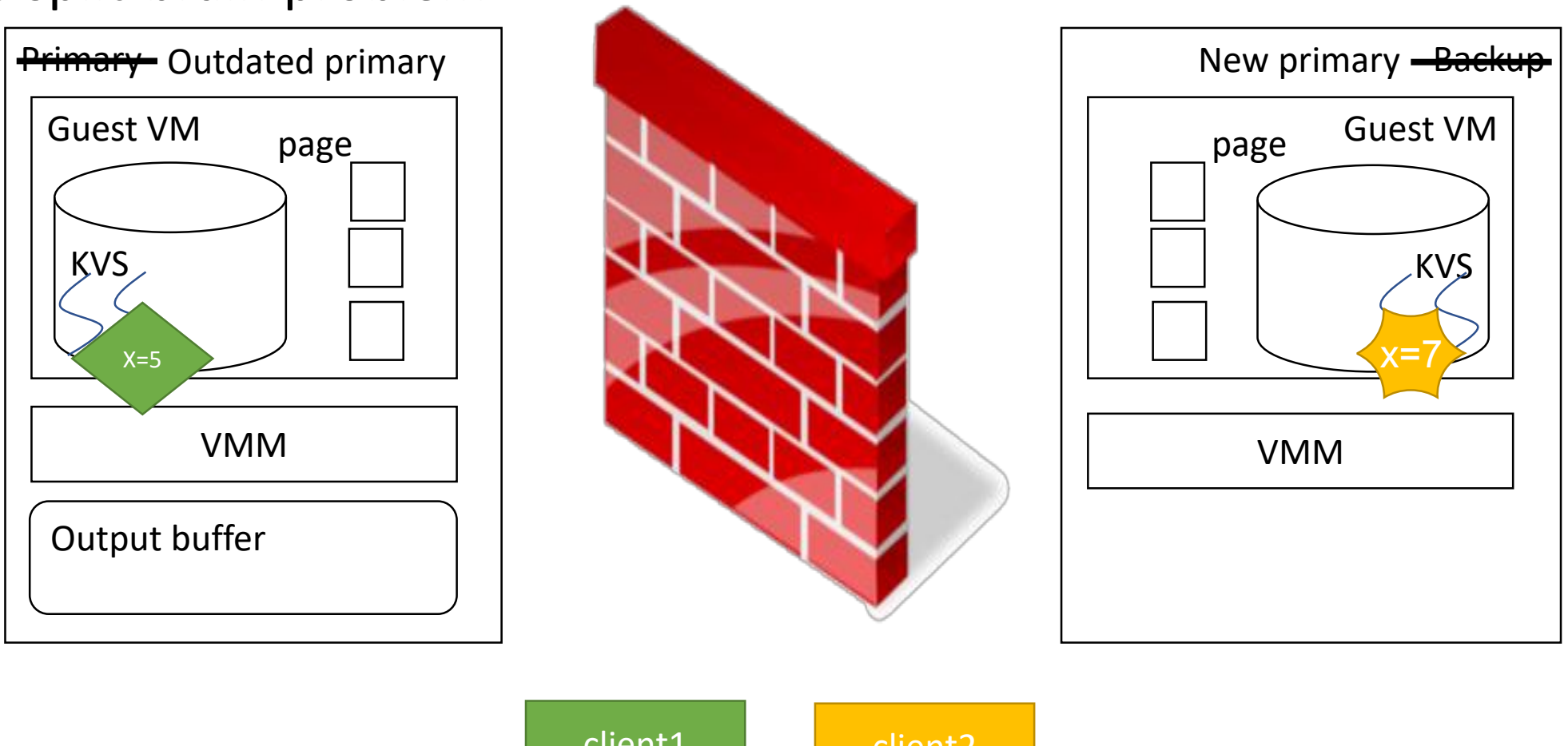
Two limitations of primary/backup approach (2)

- The split-brain problem



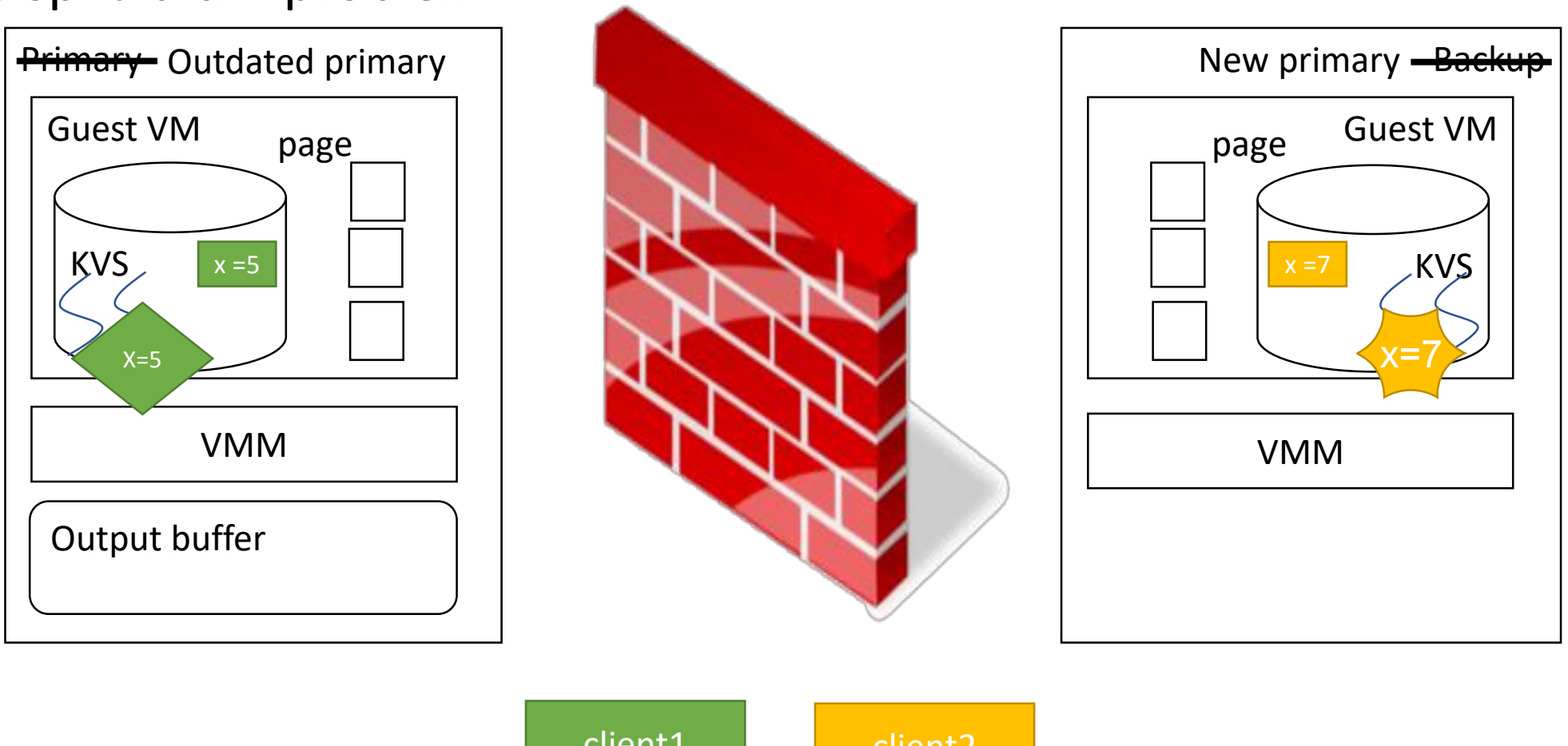
Two limitations of primary/backup approach (2)

- The split-brain problem

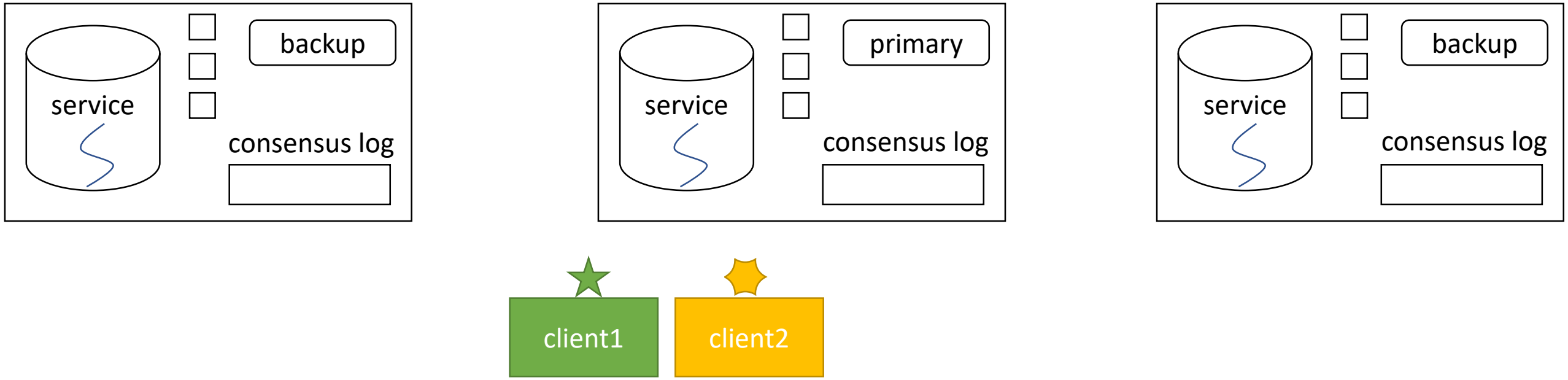


Two limitations of primary/backup approach (2)

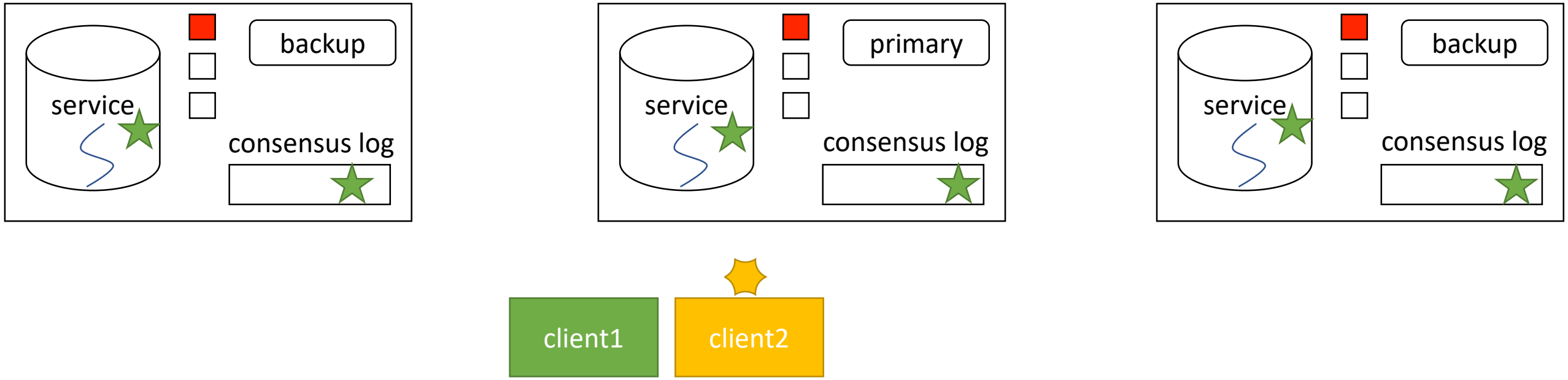
- The split-brain problem



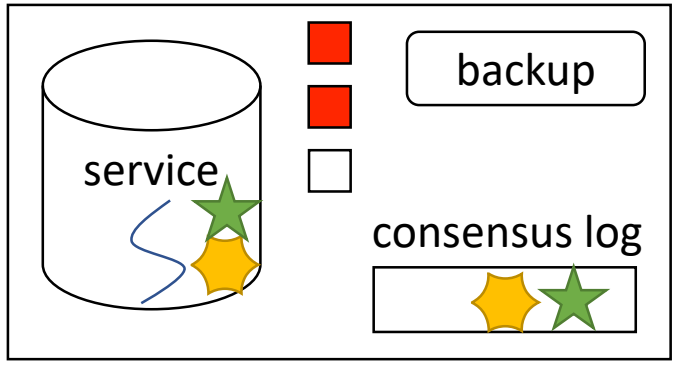
State Machine Replication (SMR): Powerful

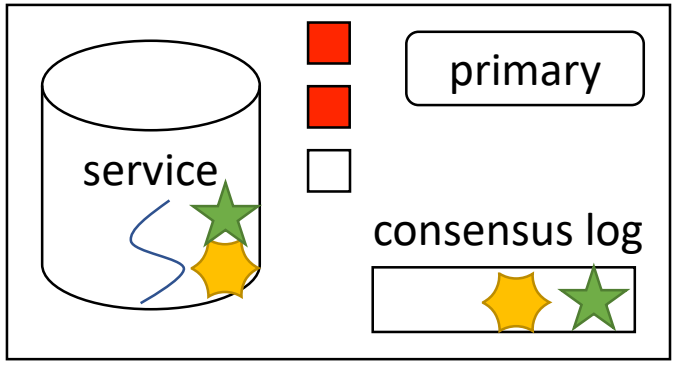


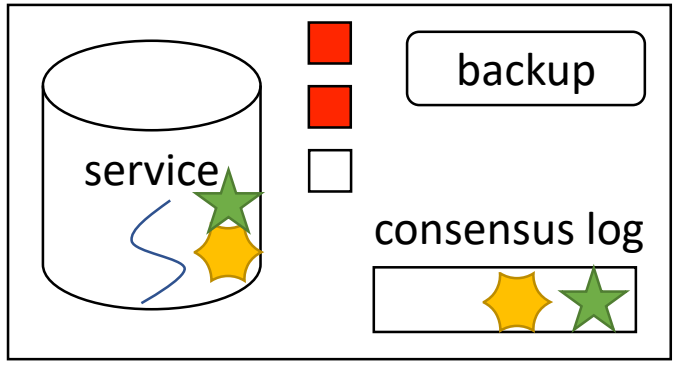
State Machine Replication (SMR): Powerful



State Machine Replication (SMR): Powerful

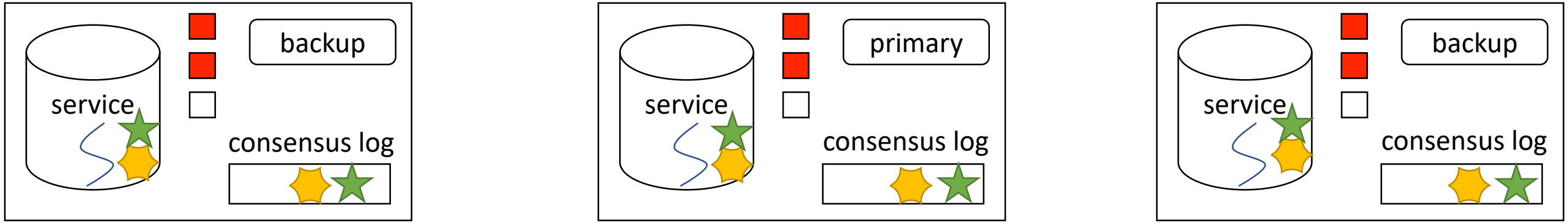






client1 client2

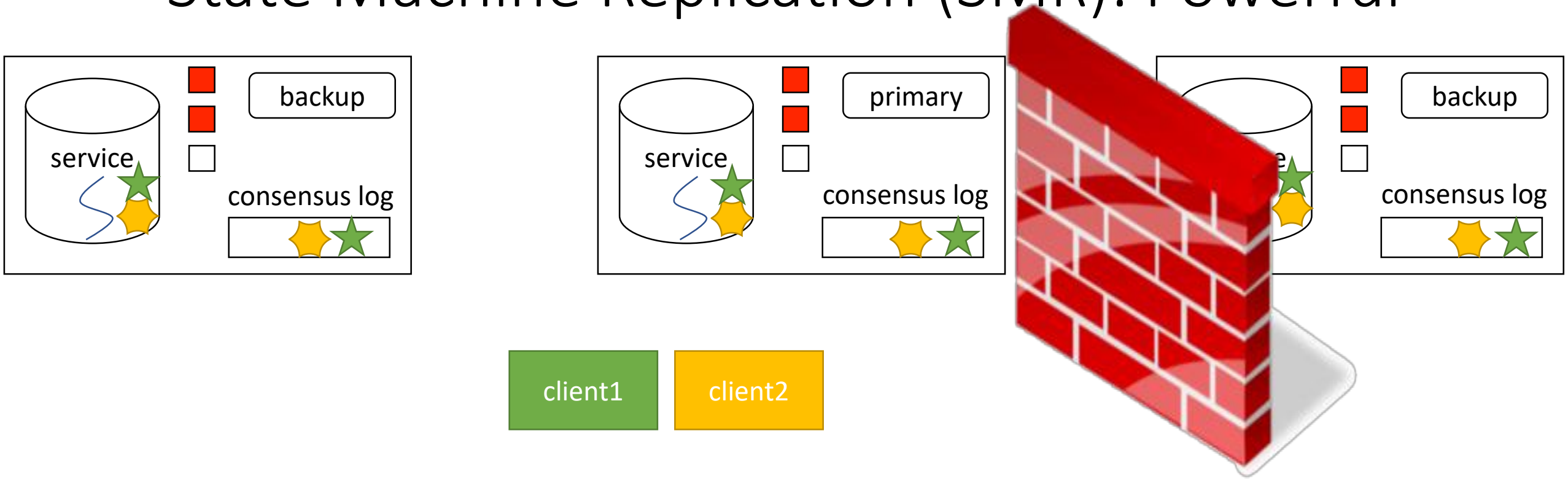
State Machine Replication (SMR): Powerful



- SMR systems: Chubby, Zookeeper, Raft [ATC'14], Consensus in a box [NSDI'15], NOPaxos[OSDI'16], APUS [SoCC'17]

Ensure same execution states

State Machine Replication (SMR): Powerful

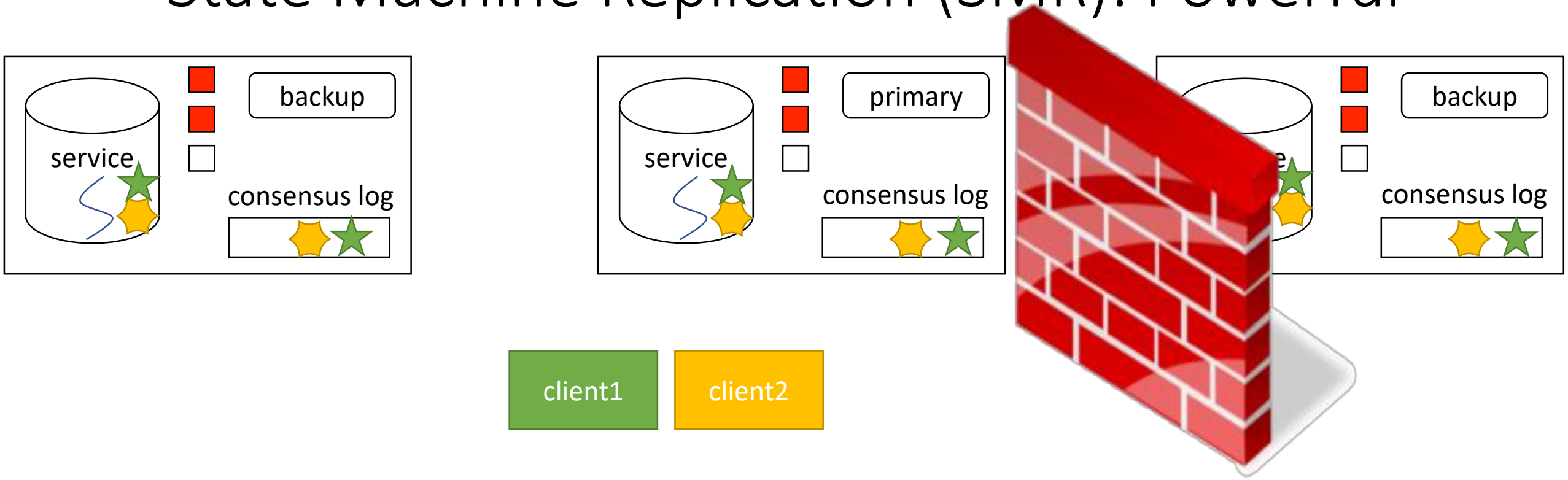


- SMR systems: Chubby, Zookeeper, Raft [ATC'14], Consensus in a box [NSDI'15], NOPaxos[OSDI'16], APUS [SoCC'17]

Ensure same execution states

Strong fault tolerance guarantee without split-brain problem

State Machine Replication (SMR): Powerful



- SMR systems: Chubby, Zookeeper, Raft [ATC'14], Consensus in a box [NSDI'15], NOPaxos[OSDI'16], APUS [SoCC'17]

Ensure same execution states

Strong fault tolerance guarantee without split-brain problem

Need to handle non-determinism

- Deterministic multithreading (e.g., CRANE [SOSP'15]) - slow
- Manually annotate service code to capture non-determinism (e.g., Eve [OSDI'12]) - error prone

Making a choice

State machine replication

Pros:

- Good performance by ensuring the same execution states
- Solve the split-brain problem

Cons:

- Hard to handle non-determinism

Primary/backup approach

Pros:

- Automatically handle non-determinism

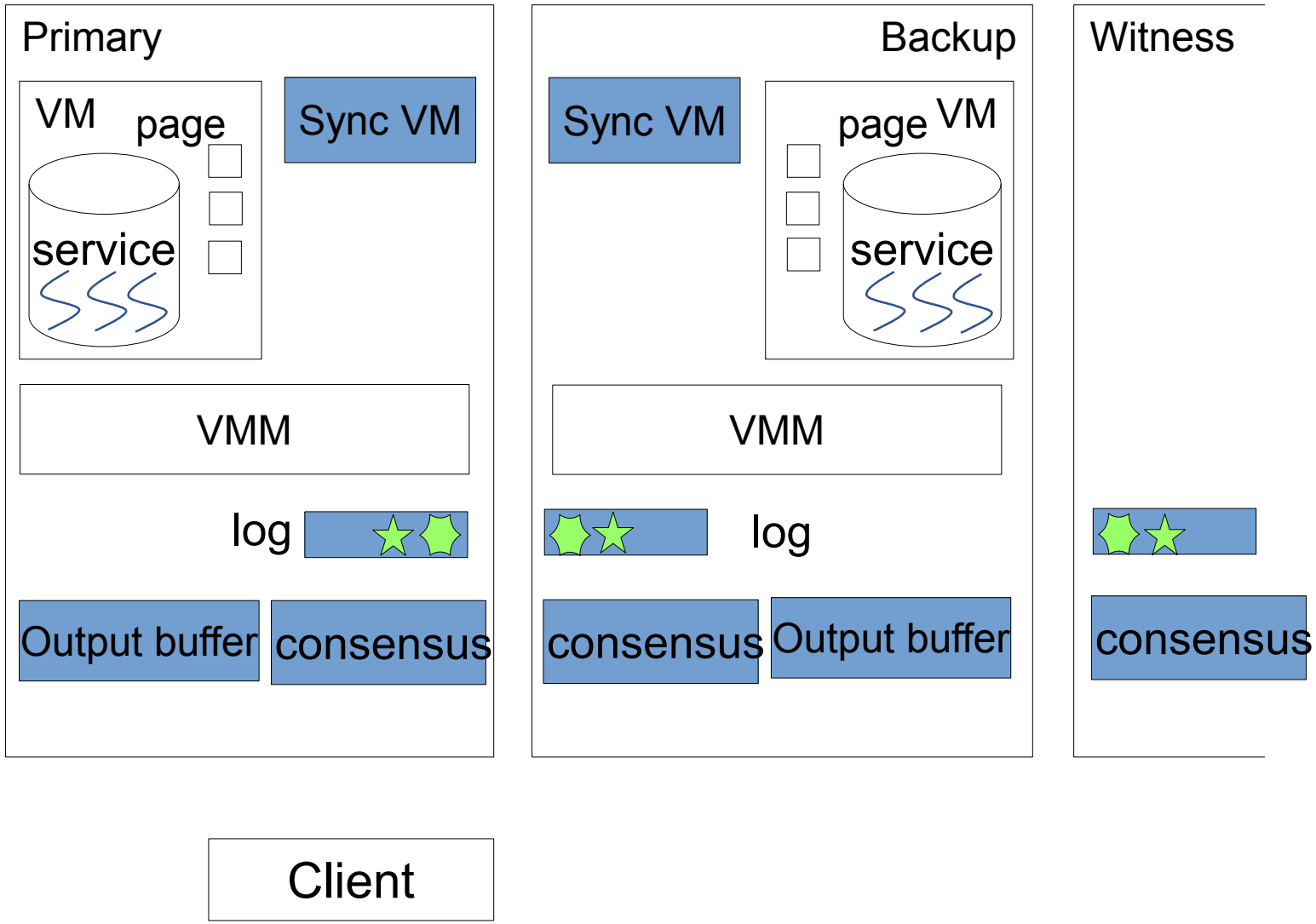
Cons:

- Unsatisfactory performance due to transferring large amount of state
- Have the split-brain problem

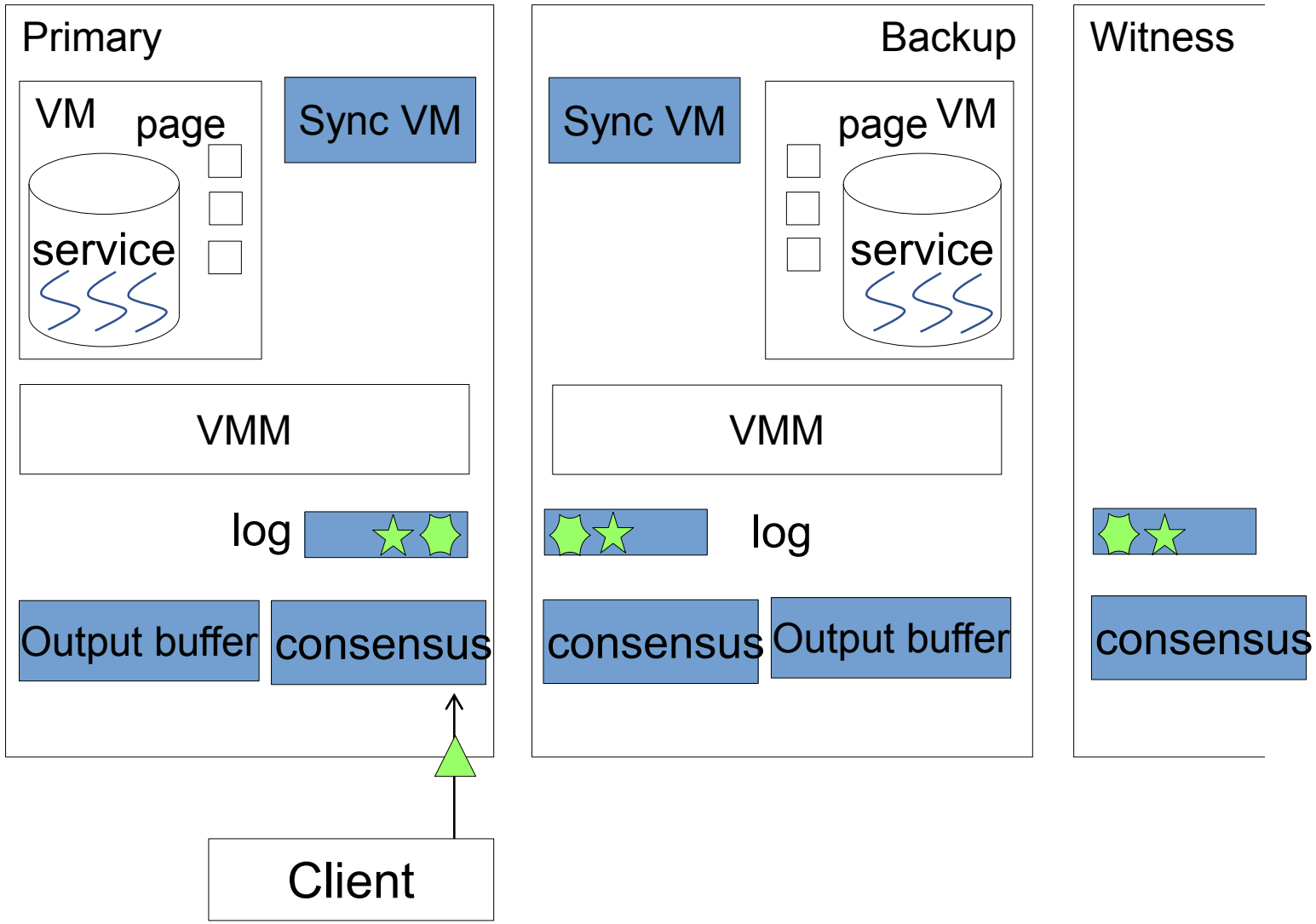
PLOVER: Combining SMR and primary/backup

- Simple to achieve by carefully designing the consensus protocol
  - Step 1: Use Paxos to ensure the same total order of requests for replicas
  - Step 2: Invoke VM synchronization periodically and then release replies
- Combines the benefits of SMR and primary/backup
  - Step 1 makes primary/backup have mostly the same memory (up to 97%), then PLOVER need only copy and transfer a small portion of the memory
  - Step 2 automatically addresses non-determinism and ensures external consistency
- Challenges:
  - How to achieve consensus and synchronize VM efficiently?
  - When to do the VM synchronization for primary/backup to maximize the same memory pages?

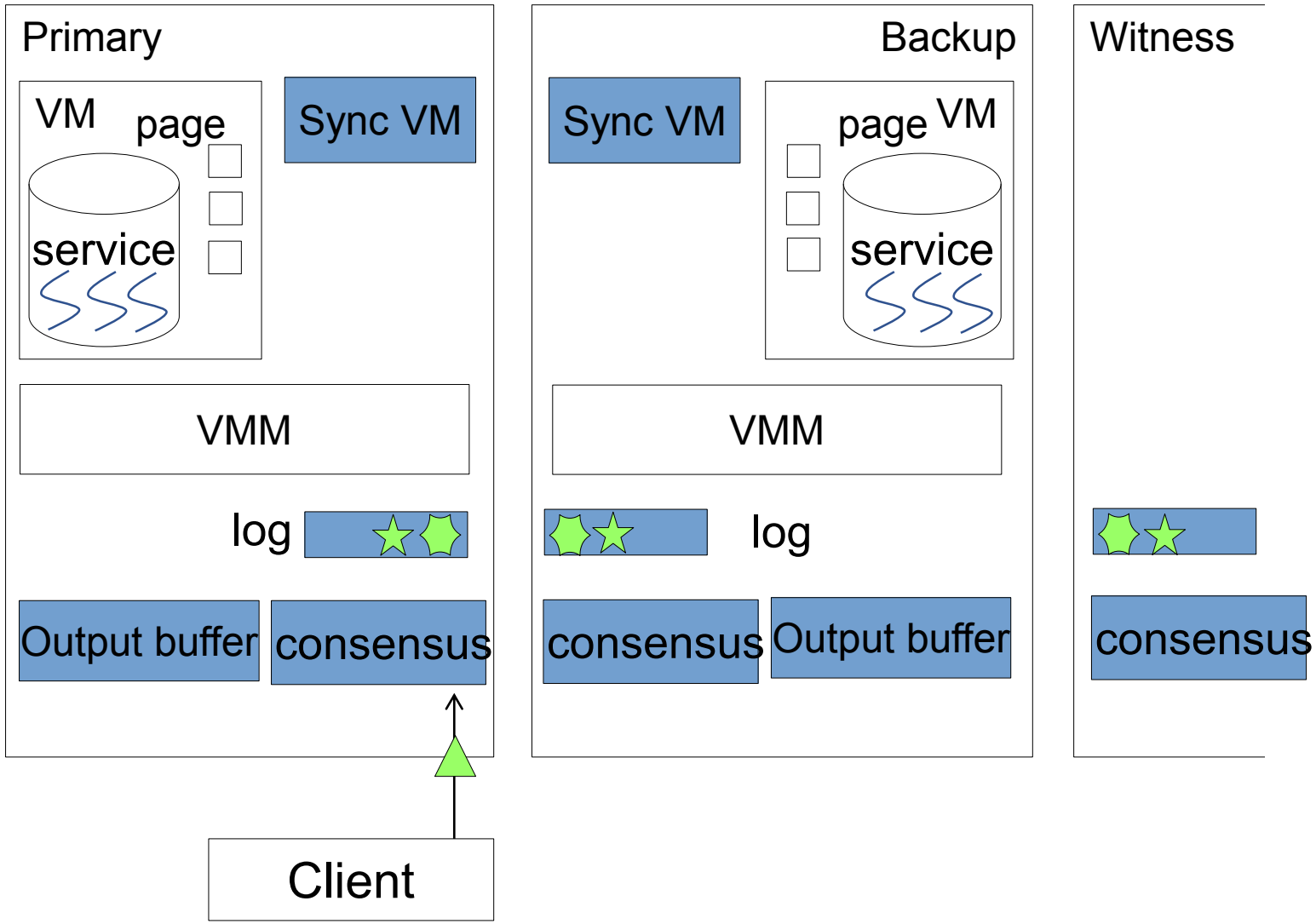
PLOVER architecture



PLOVER architecture



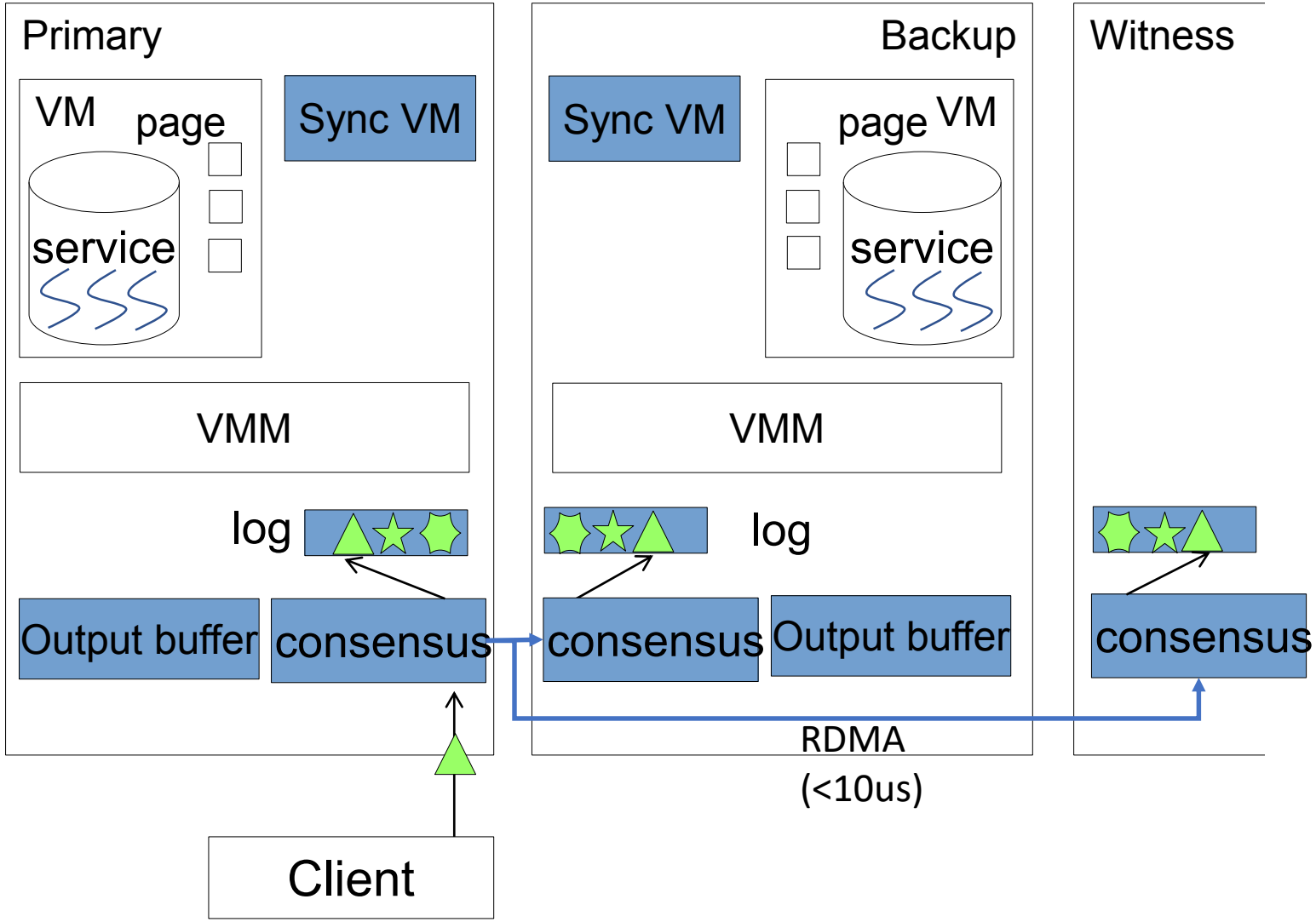
PLOVER architecture



RDMA-based input consensus:

- Primary: propose request and execute
- Backup: agree on request and execute
- Witness: agree on request and ignore

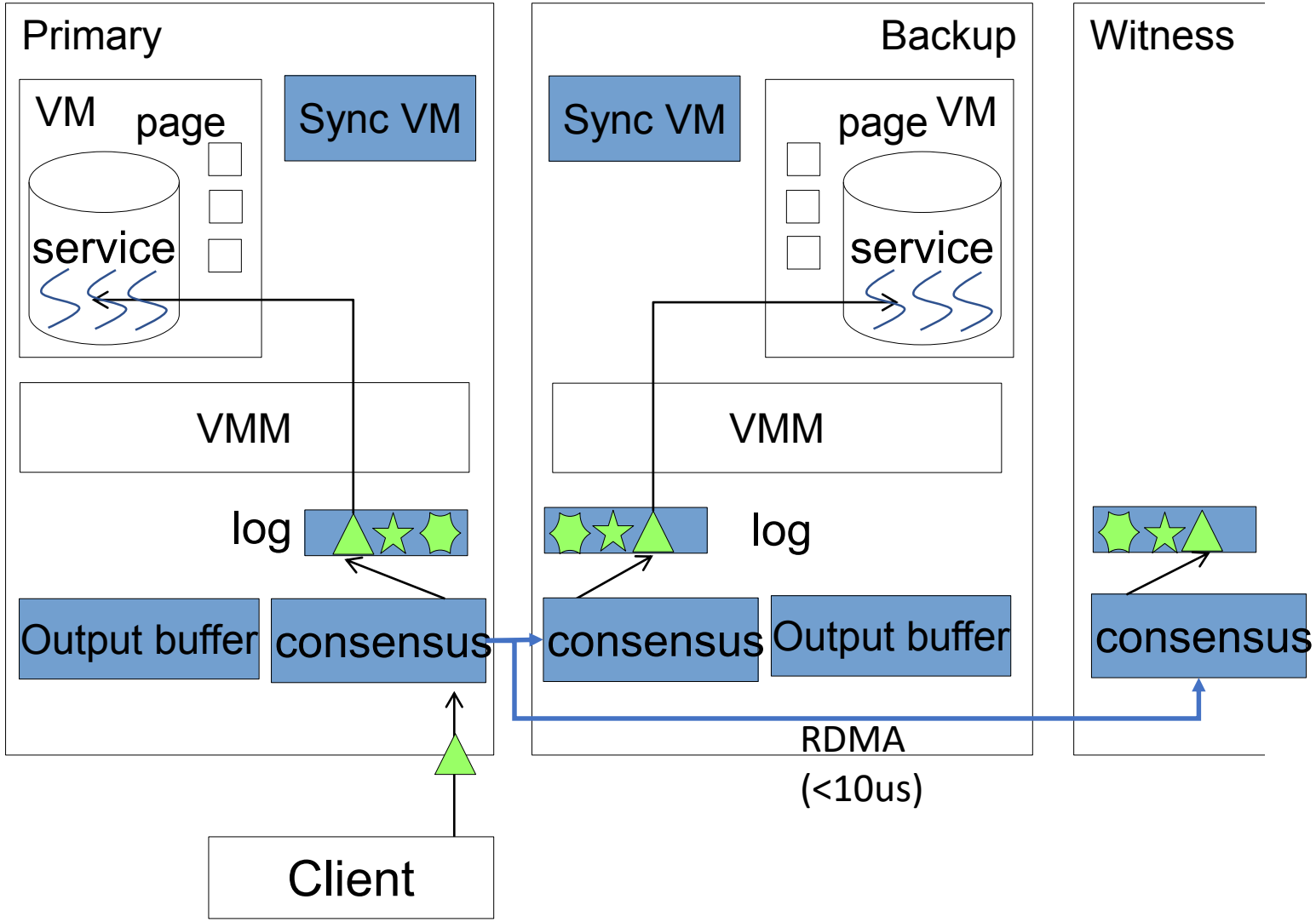
PLOVER architecture



RDMA-based input consensus:

- Primary: propose request and execute
- Backup: agree on request and execute
- Witness: agree on request and ignore

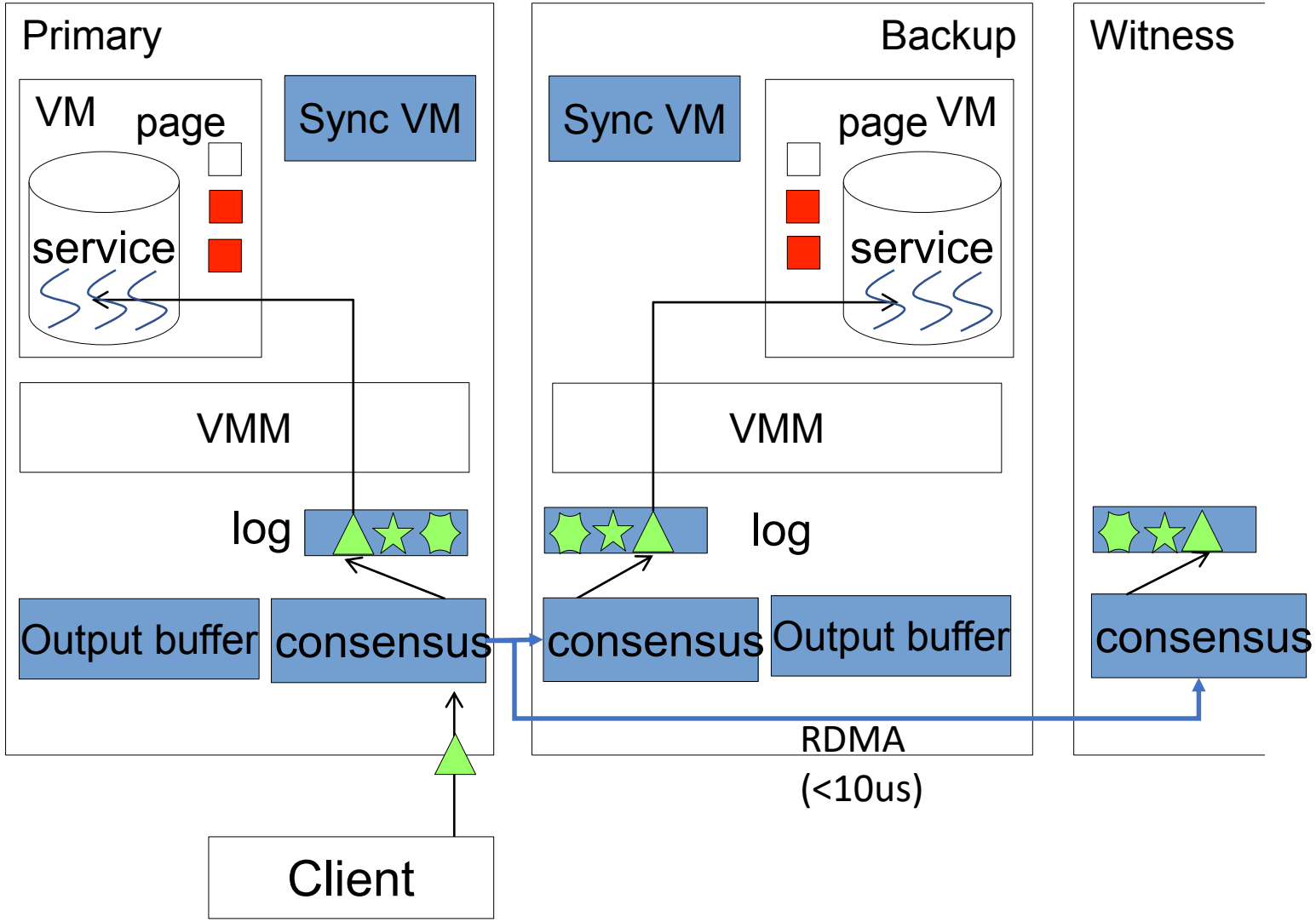
PLOVER architecture



RDMA-based input consensus:

- Primary: propose request and execute
- Backup: agree on request and execute
- Witness: agree on request and ignore

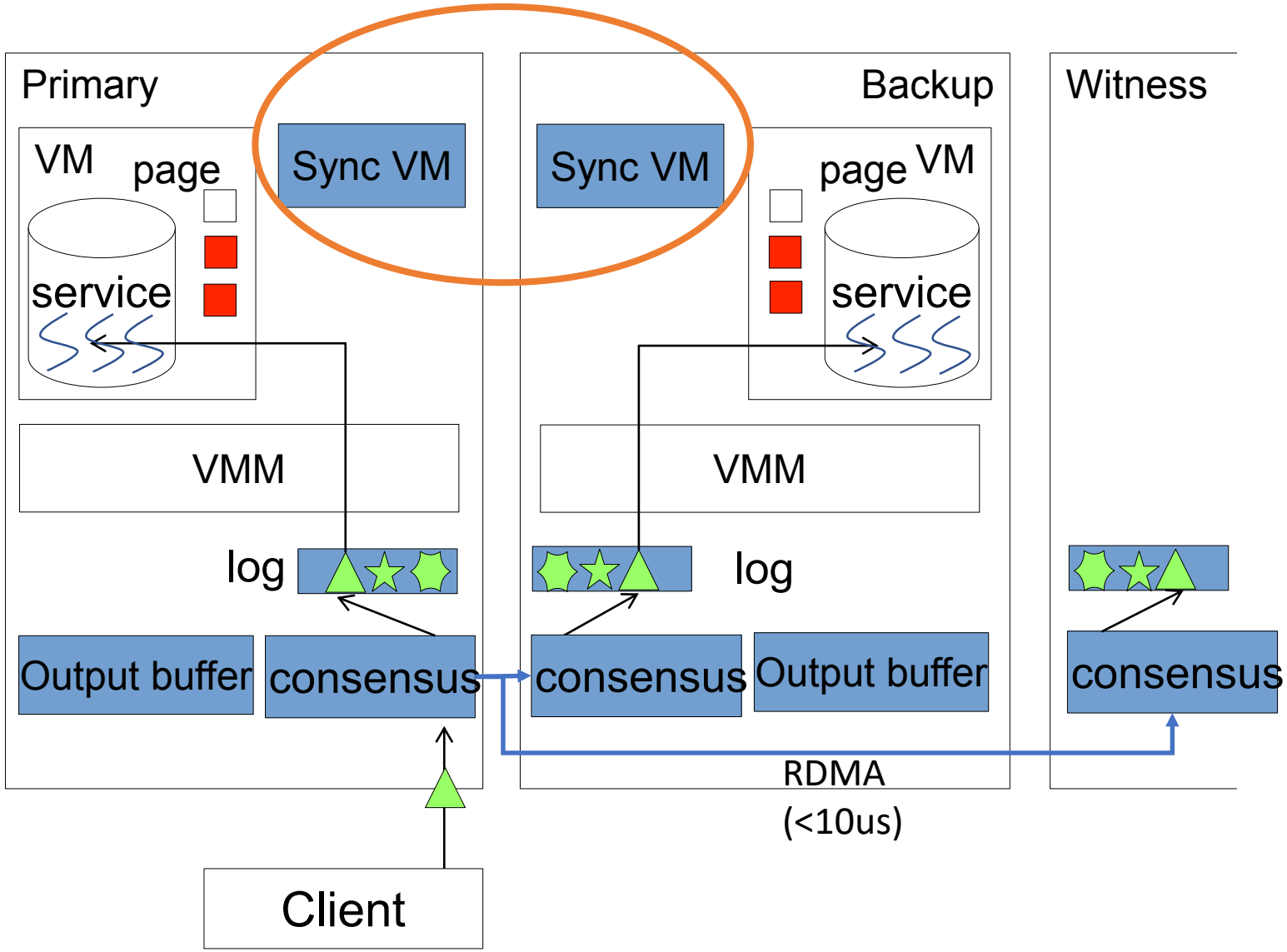
PLOVER architecture



RDMA-based input consensus:

- Primary: propose request and execute
- Backup: agree on request and execute
- Witness: agree on request and ignore

PLOVER architecture

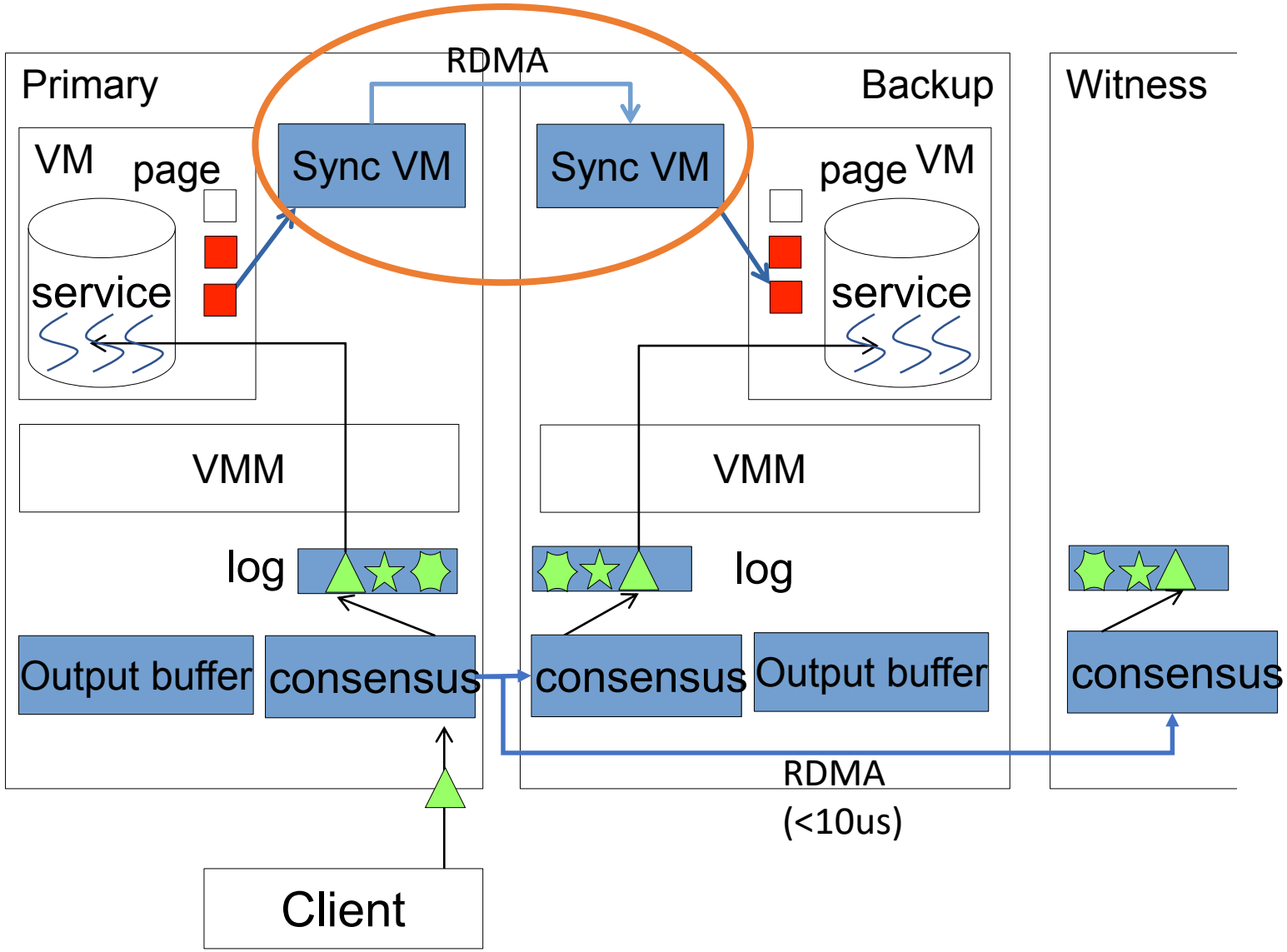


RDMA-based input consensus:

- Primary: propose request and execute
- Backup: agree on request and execute
- Witness: agree on request and ignore

RDMA-based VM synchronization:

PLOVER architecture



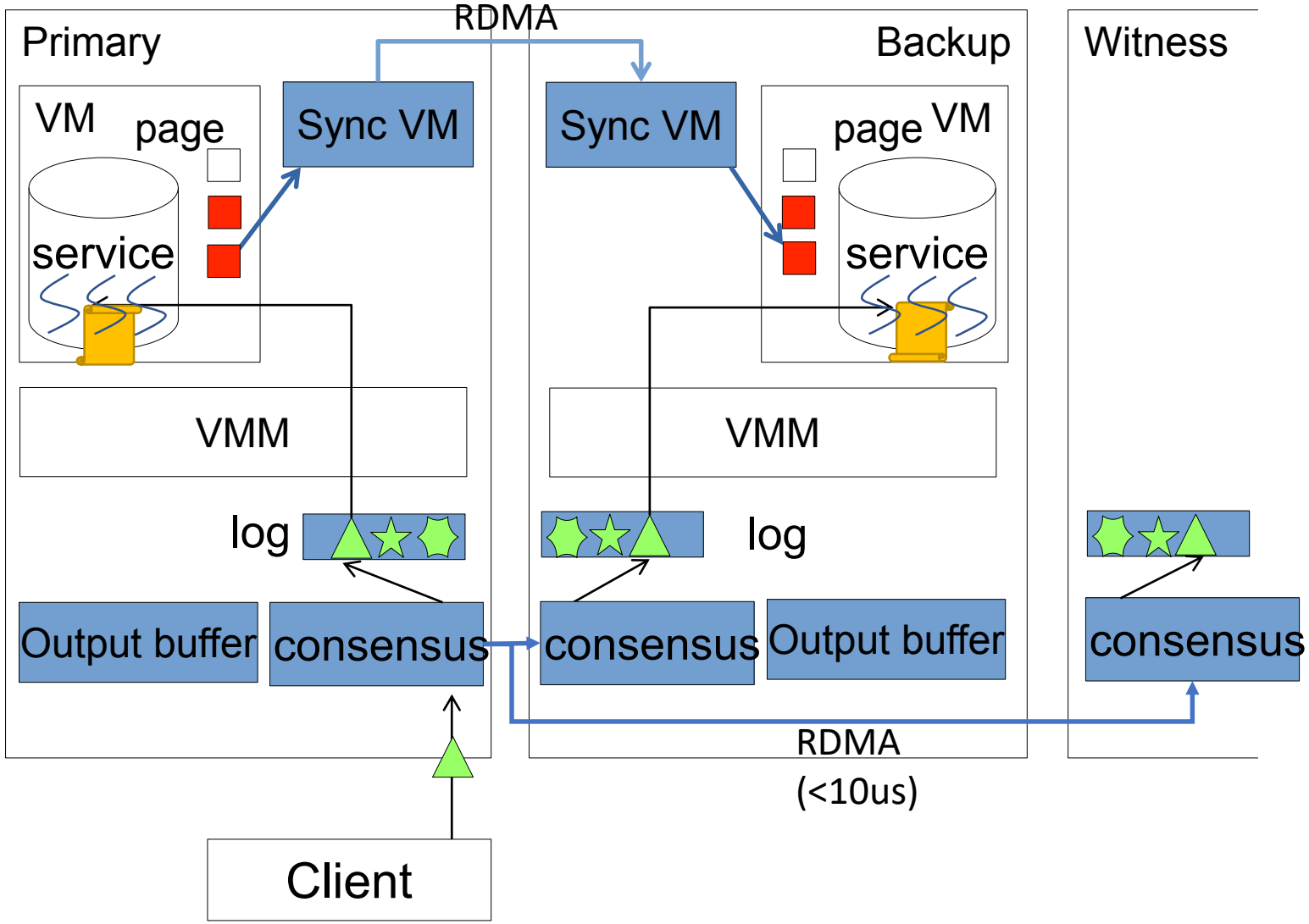
RDMA-based input consensus:

- Primary: propose request and execute
- Backup: agree on request and execute
- Witness: agree on request and ignore

RDMA-based VM synchronization:

1. Exchange and union dirty page bitmap
2. Compute hash of each dirty page
3. Compare hashes
4. Transfer divergent pages

PLOVER architecture



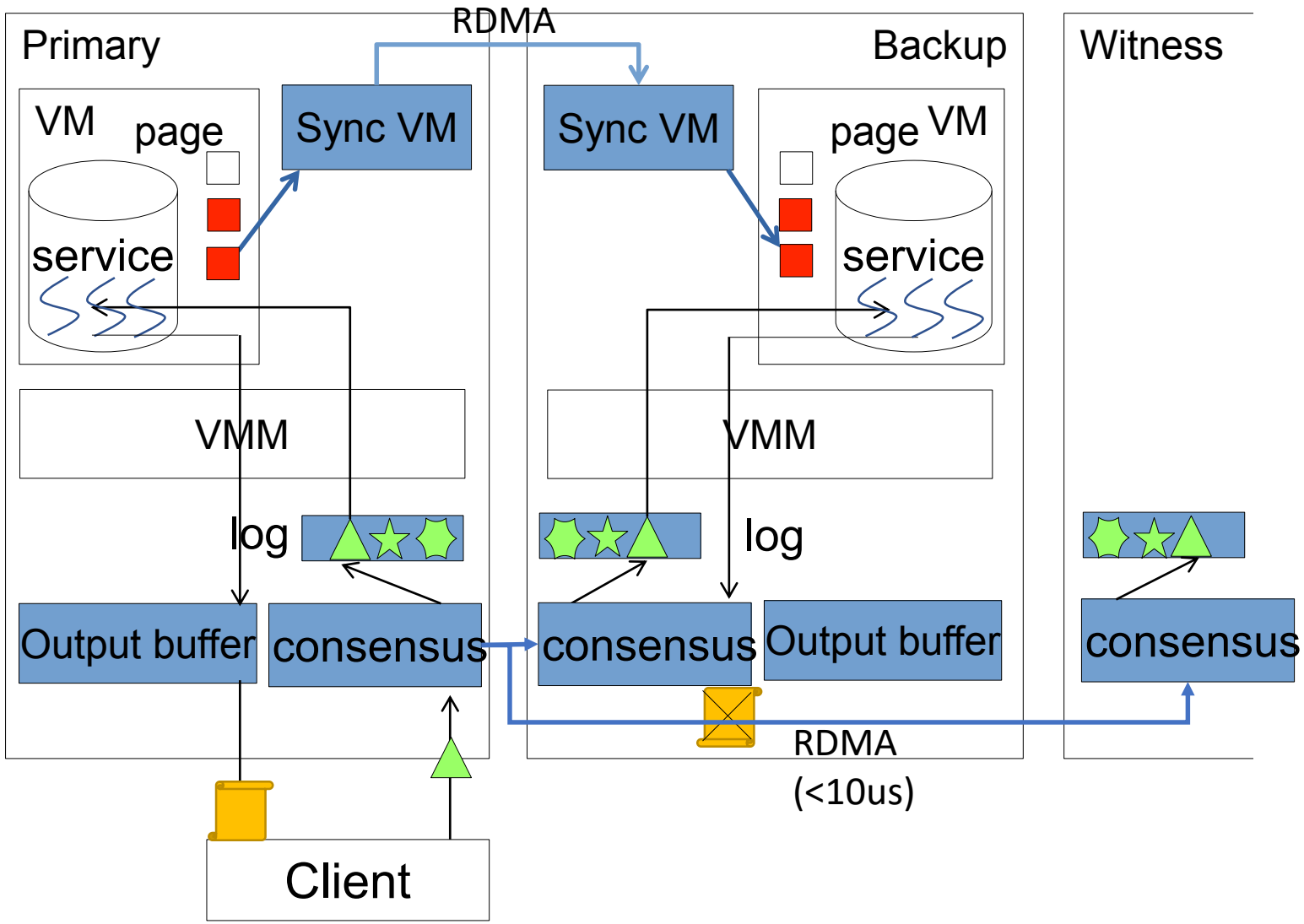
RDMA-based input consensus:

- Primary: propose request and execute
- Backup: agree on request and execute
- Witness: agree on request and ignore

RDMA-based VM synchronization:

1. Exchange and union dirty page bitmap
2. Compute hash of each dirty page
3. Compare hashes
4. Transfer divergent pages

PLOVER architecture



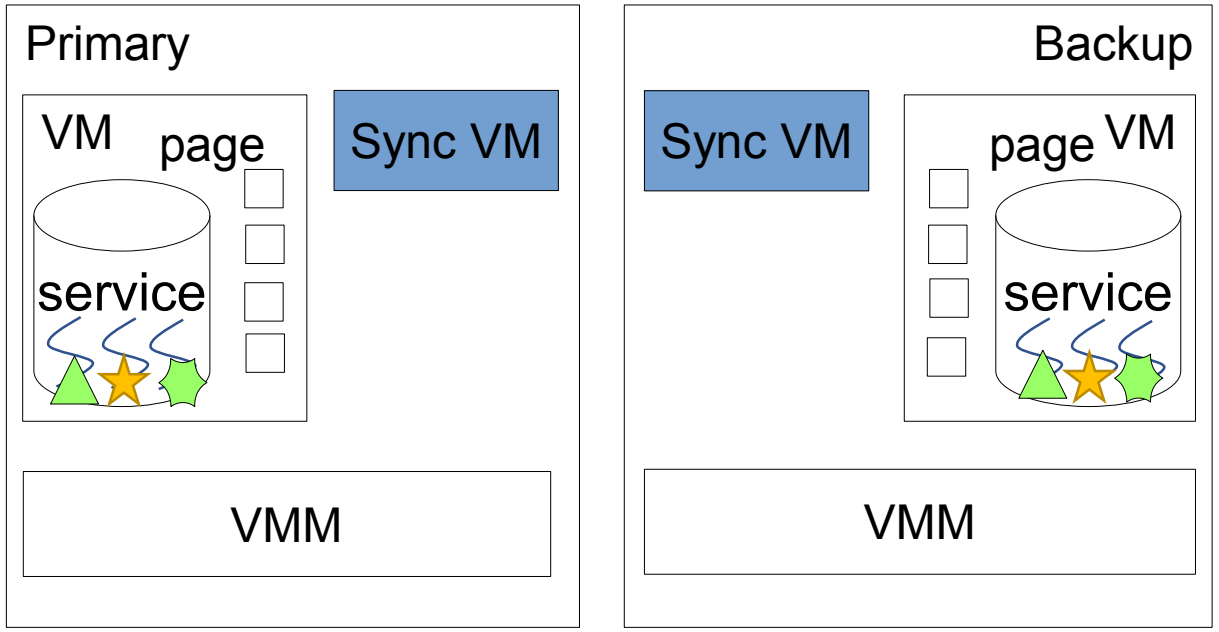
RDMA-based input consensus:

- Primary: propose request and execute
- Backup: agree on request and execute
- Witness: agree on request and ignore

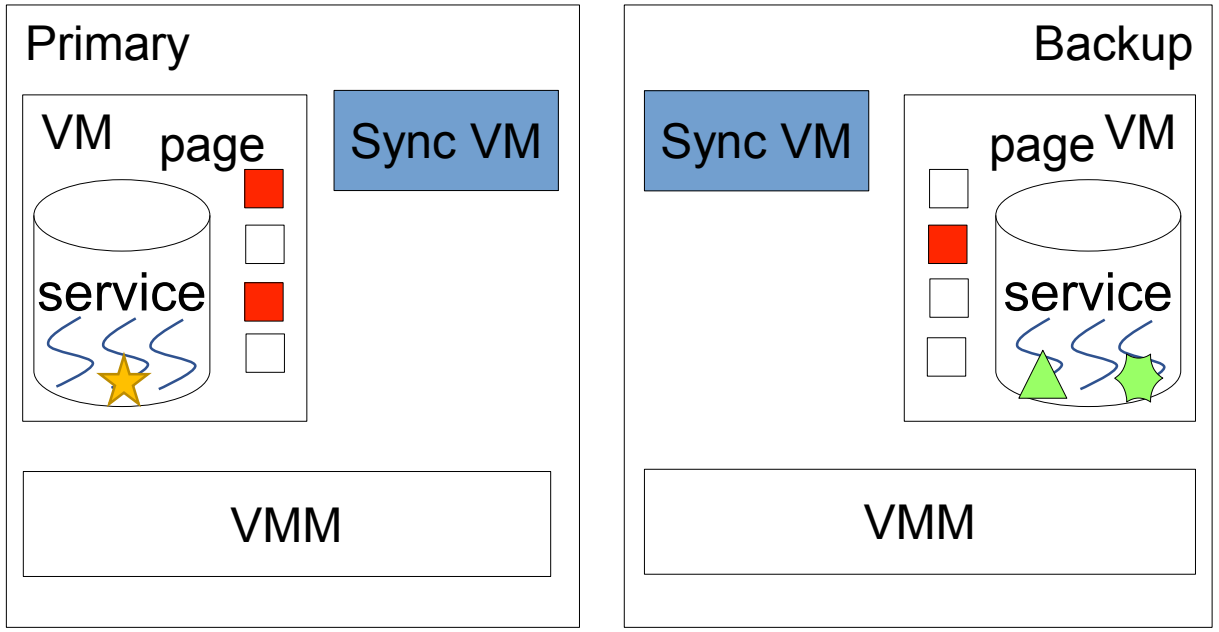
RDMA-based VM synchronization:

1. Exchange and union dirty page bitmap
2. Compute hash of each dirty page
3. Compare hashes
4. Transfer divergent pages

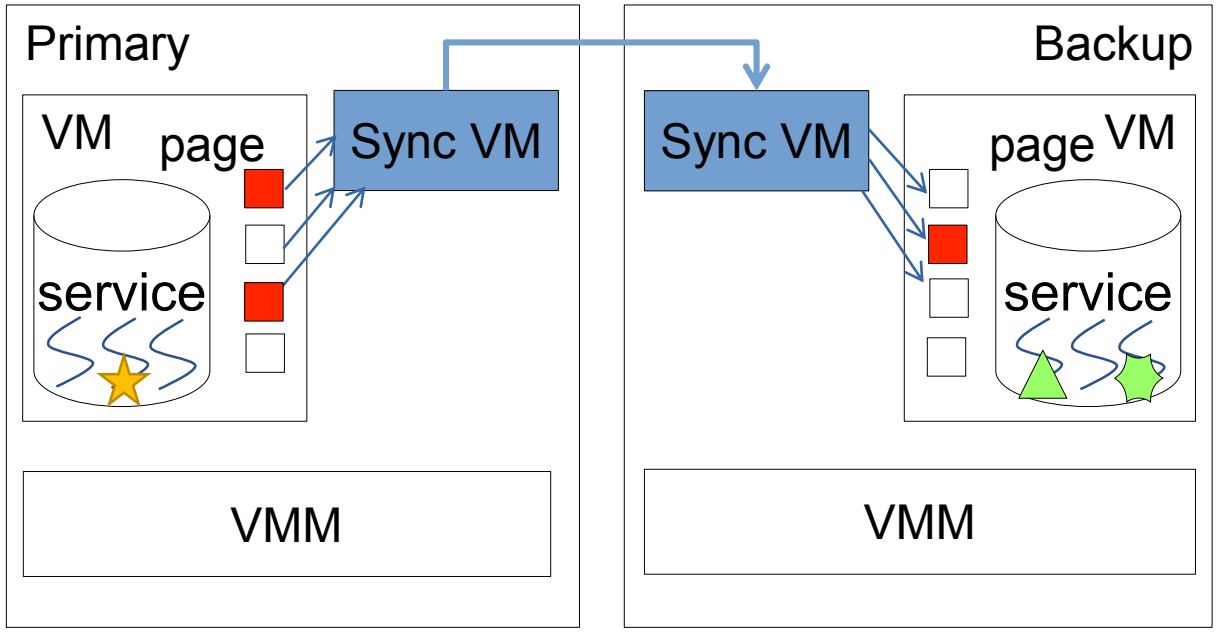
When to decide VM synchronization period?



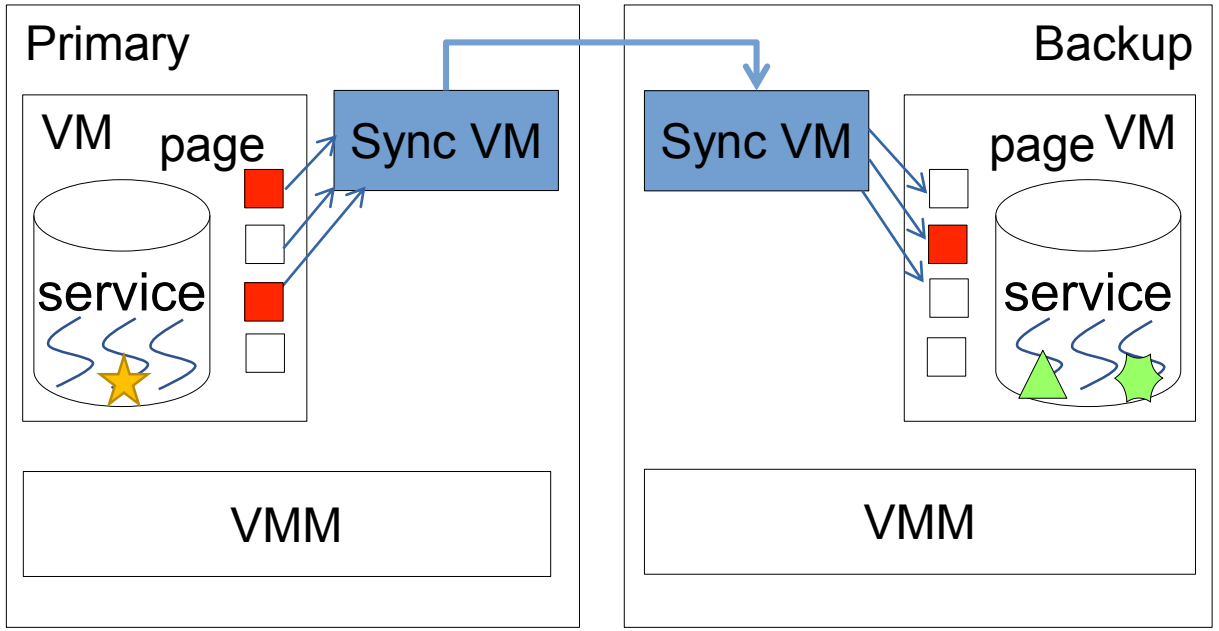
When to decide VM synchronization period?



When to decide VM synchronization period?



When to decide VM synchronization period?



Issue of not choosing synchronization timing carefully

- Large amount of divergent state

Synchronize when processing is almost finished!

- CPU and disk usage is almost zero when service finishes processing
- Non-intrusive scheme to monitor service state
- Invoke synchronization when CPU and disk usage is nearly zero

PLOVER addressed other practical challenges

- Concurrent hash computation of dirty pages
- Fast consensus without interrupting the VMM's I/O event loop
- Collect service running state from VMM without hurting performance
- Full integration with KVM-QEMU
- …

Evaluation setup

- Three replica machines
  - Dell R430 server
  - Connected with 40Gbps network
  - Guest VM configured with 4 vCPU and 16GB memory
- Metrics: measured both throughput and latency with 95% percentile
- Compared with three state-of-the-art VM fault tolerance systems
  - Remus (NSDI'08): use its latest KVM-based implementation developed by KVM
  - STR (DSN'09) and COLO (SoCC'13): various optimizations of Remus. E.g., COLO skips synchronization if network outputs from two VMs are the same

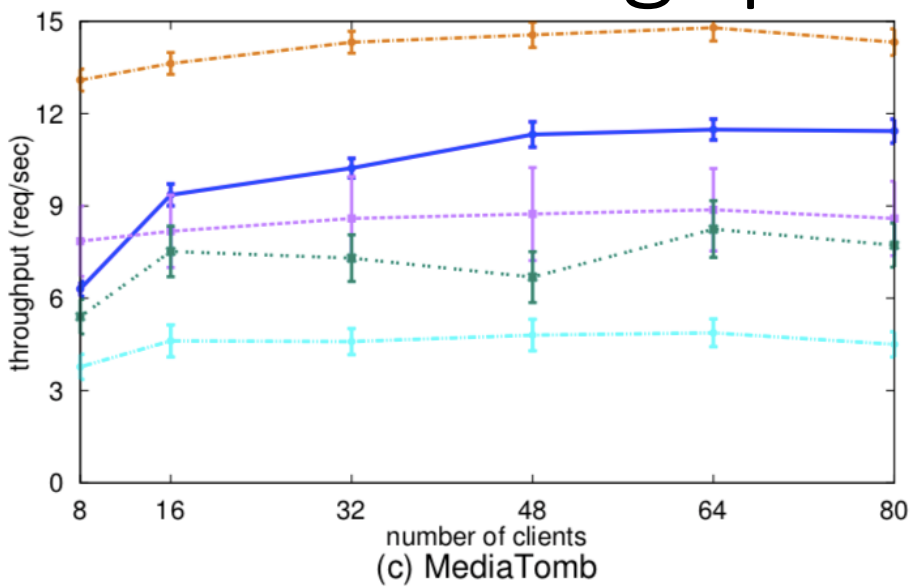
- Evaluated PLOVER on 12 programs, grouped into 8 services

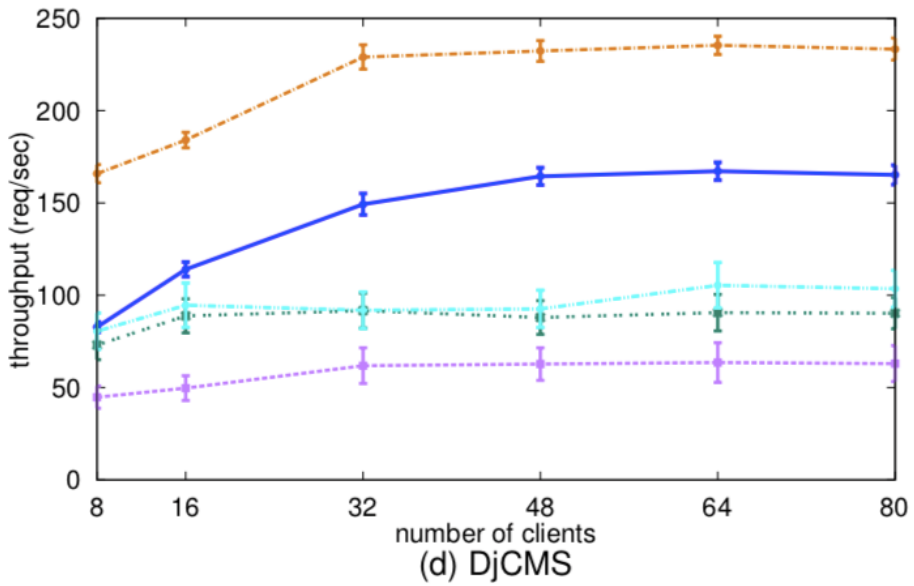
service	Program type	Benchmark	Workload
Redis	Key value store	self	50% SET, 50% GET
SSDB	Key value store	self	50% SET, 50% GET
MediaTomb	Multimedia storage server	ApacheBench	Transcoding videos
pgSQL	Database server	pgbench	TPC-B
DjCMS (Nginx, Python, MySQL)	Content management system	ApacheBench	Web requests on a dashboard page
Tomcat	HTTP web server	ApacheBench	Web requests on a shopping store page
lighttpd	HTTP web server	ApacheBench	Watermark image with PHP
Node.js	HTTP web server	ApacheBench	Web requests on a messenger bot

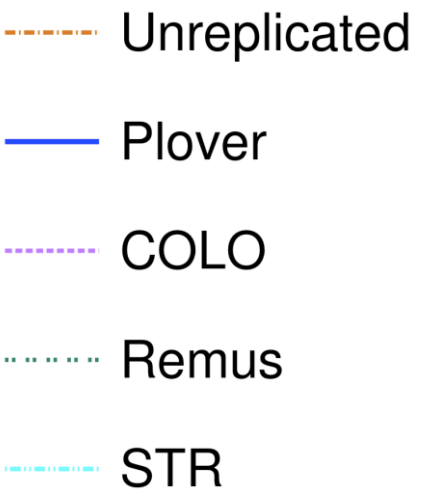
Evaluation questions

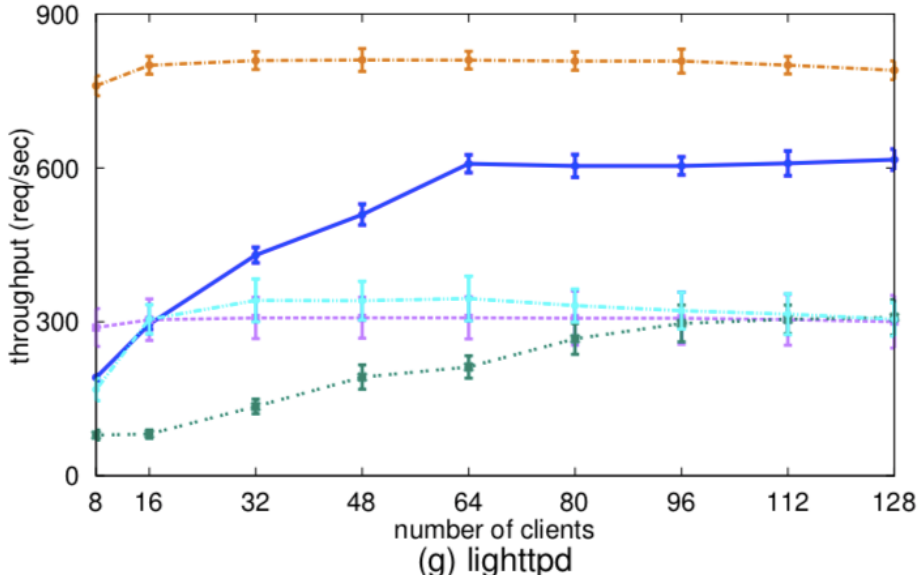
- How does PLOVER compare to unreplicated VM and state-of-the-art VM fault tolerance systems?
- How does PLOVER scale to multi-core?
- What is PLOVER's CPU footprint?
- How robust is PLOVER to failures?
  - Handle network partition, leader failure, etc, efficiently
- Comparison of PLOVER and other three systems on different parameter settings?
  - PLOVER is still much faster than the three systems

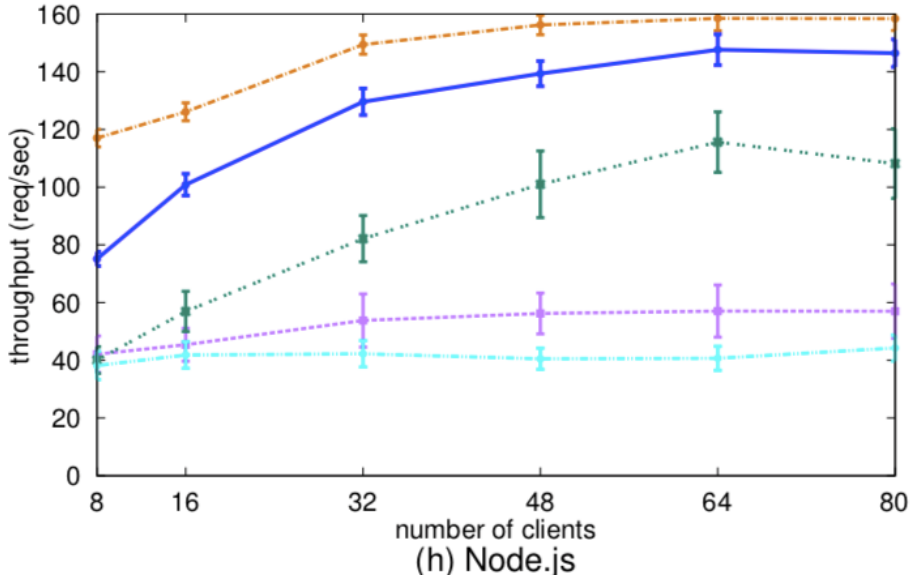
Throughput on four services



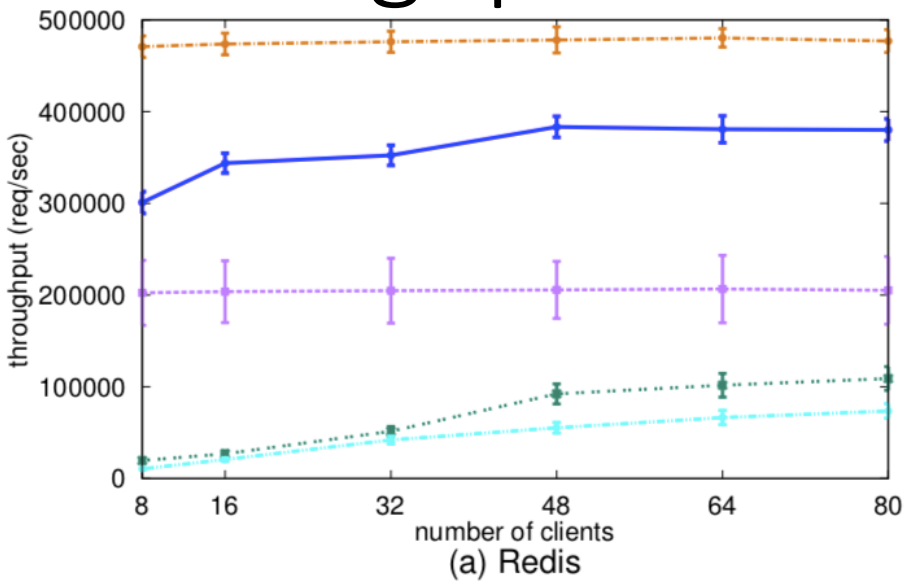




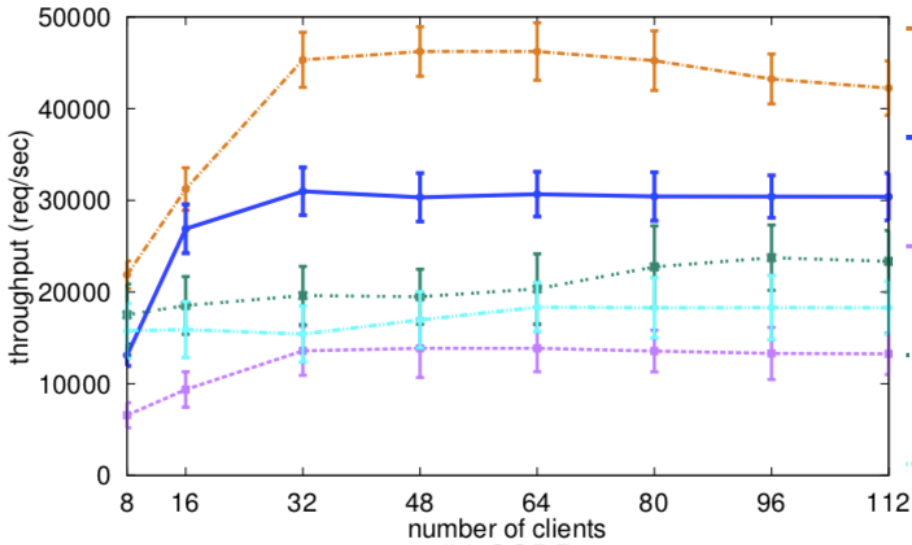




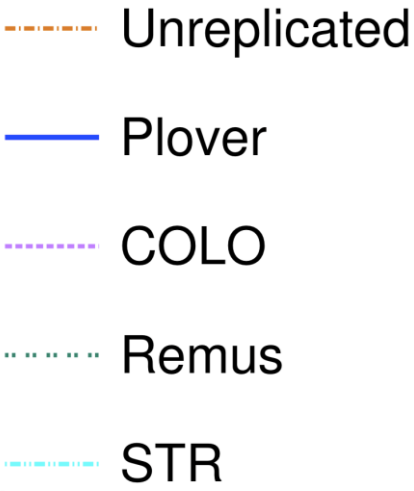
Throughput on the other four services

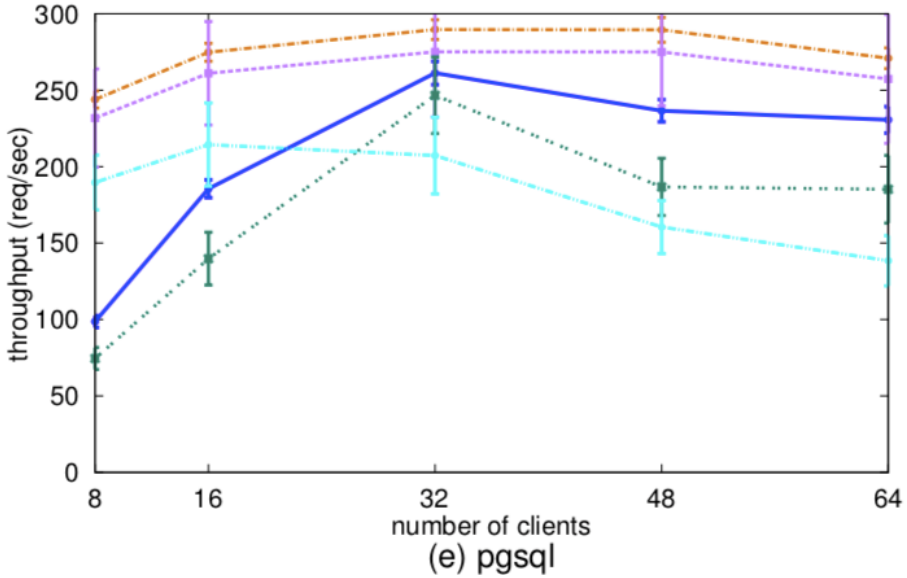


(a) Redis

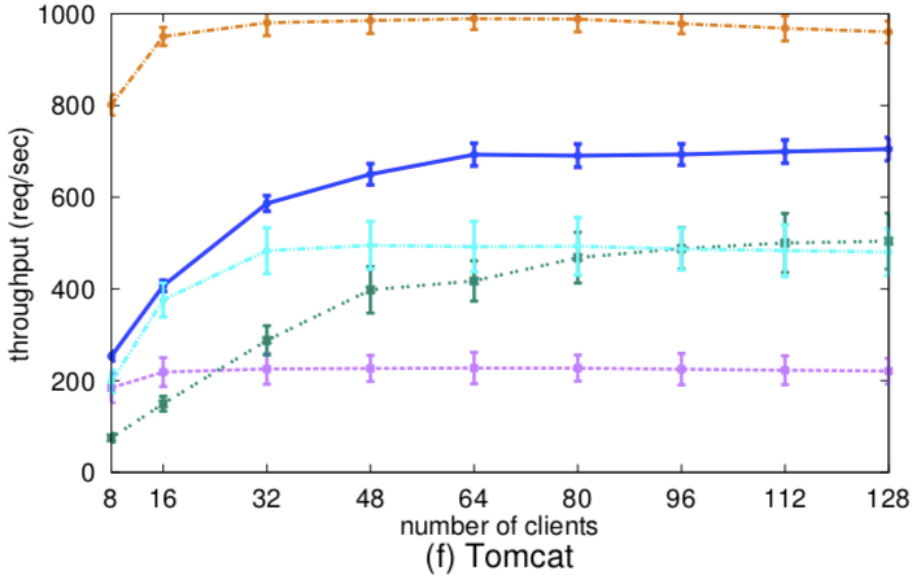


(b) SSDB



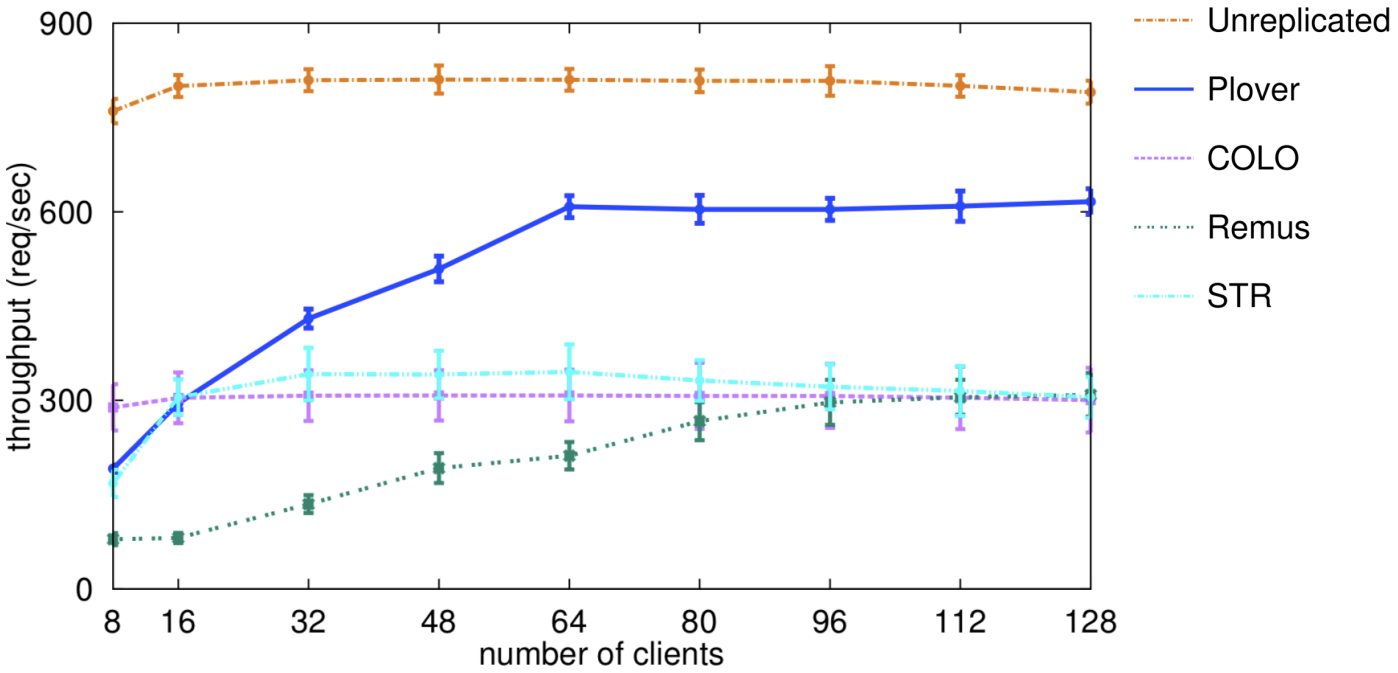


(e) pgsql



(f) Tomcat

Lighttpd+PHP performance analysis



lighttpd + PHP

PLOVER:

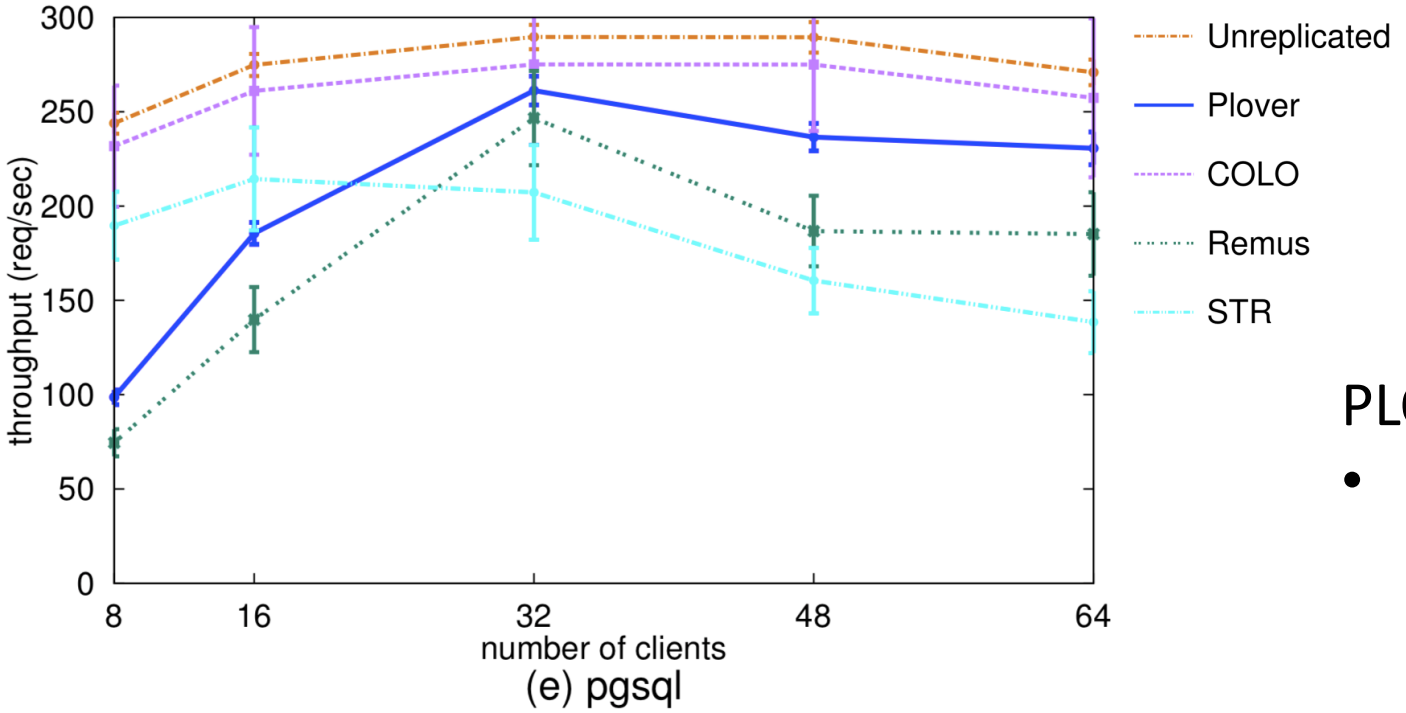
Interval	Dirty Page	Same	Transfer
86ms	33.9K	97%	2.8ms

Remus:

Sync-interval	Dirty Page	Transfer
25ms (Remus-Xen default)	33.3K	53.5ms
100ms (Remus-KVM default)	33.9K	55.7ms

Analysis:
PLOVER needs to transfer only 33.9k * 3% = 1.0K pages, But Remus, STR, and COLO need to transfer all or most of the 33K dirty pages. E.g., since most network outputs from two VMs differ, COLO has to do synchronizations for almost every output packet.

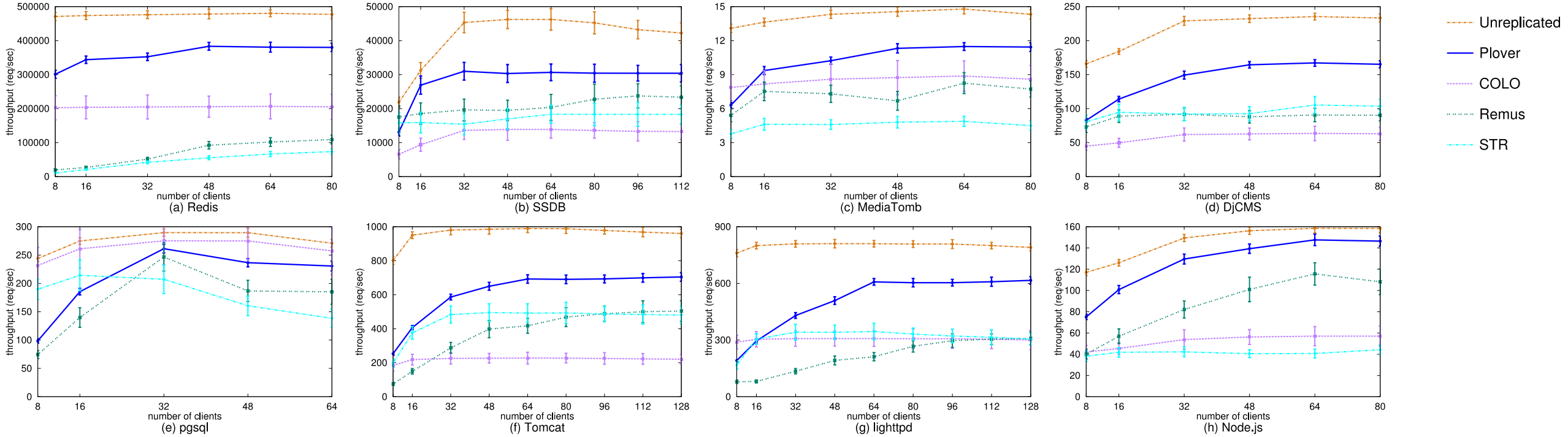
pgSQL performance analysis



PLOVER is slower than COLO on pgSQL

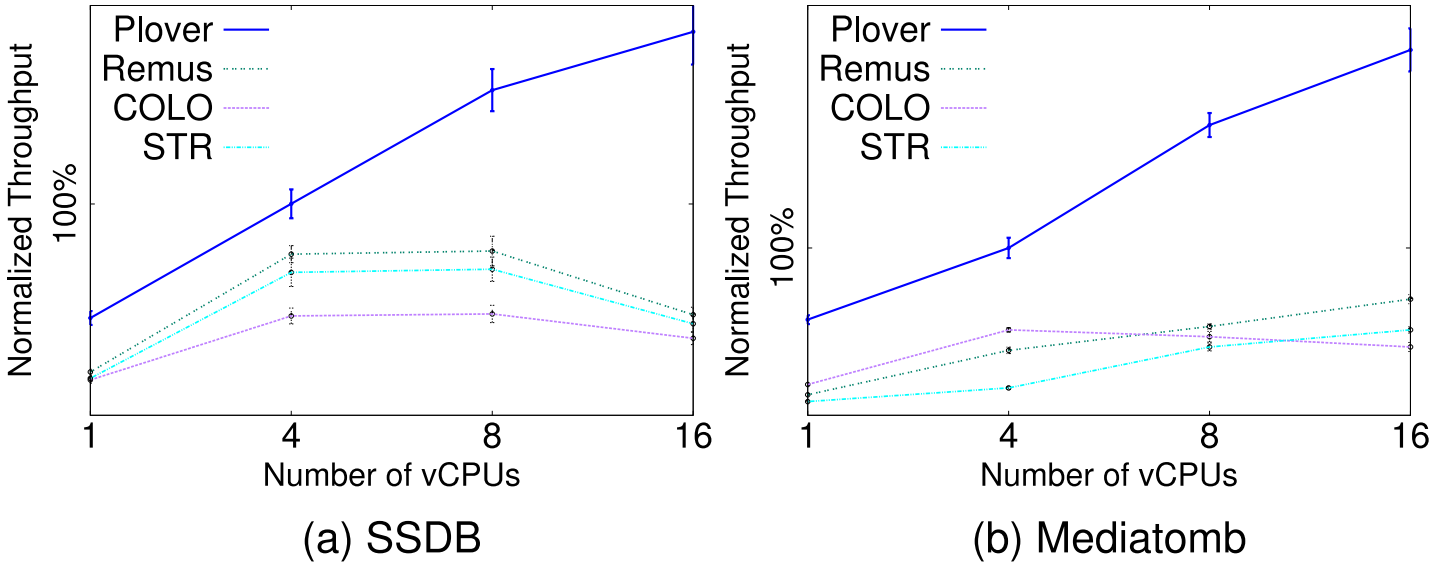
- COLO safely skips synchronization because most network outputs from two VMs are the same

Performance Summary (4 vCPU per VM)



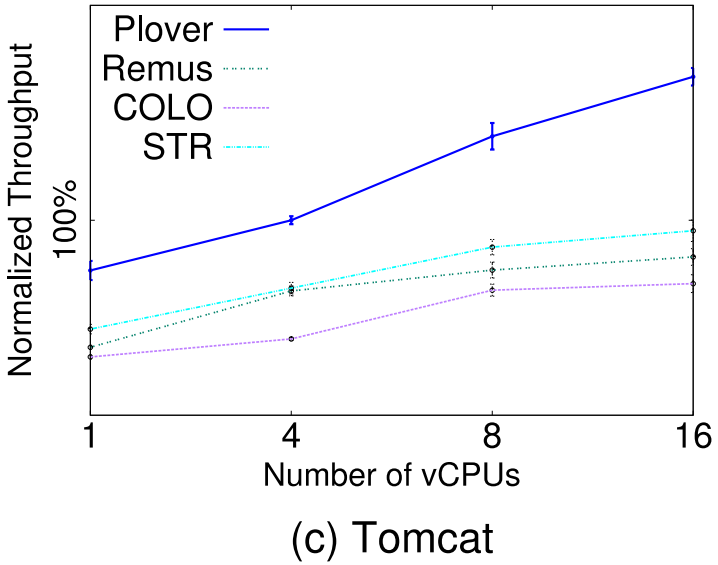
- PLOVER's throughput is 21% lower than unreplicated, 0.9X higher than Remus, 1.0X higher than COLO, 1.4X higher than STR
  - 72% ~ 97% dirty memory pages between PLOVER's primary and backup are the same
  - PLOVER's TCP implementation throughput is still 0.9X higher the three systems on average

Multi-core Scalability (4vCPU - 16vCPU per VM)

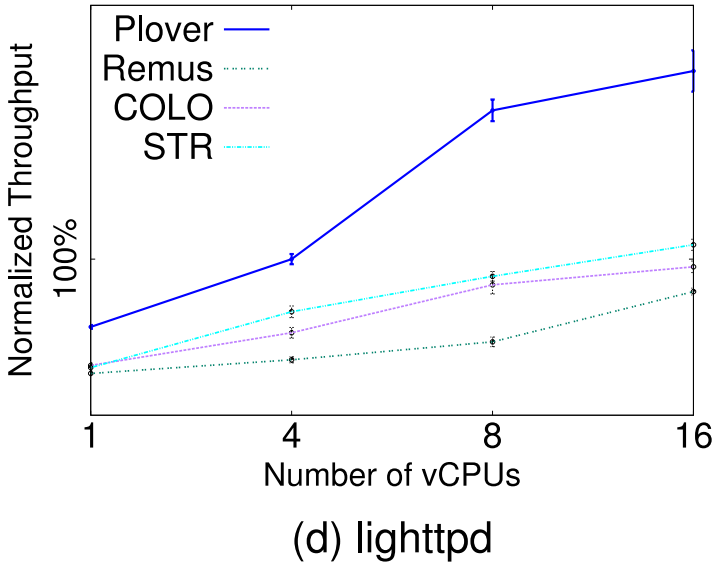


(a) SSDB

(b) Mediatomb



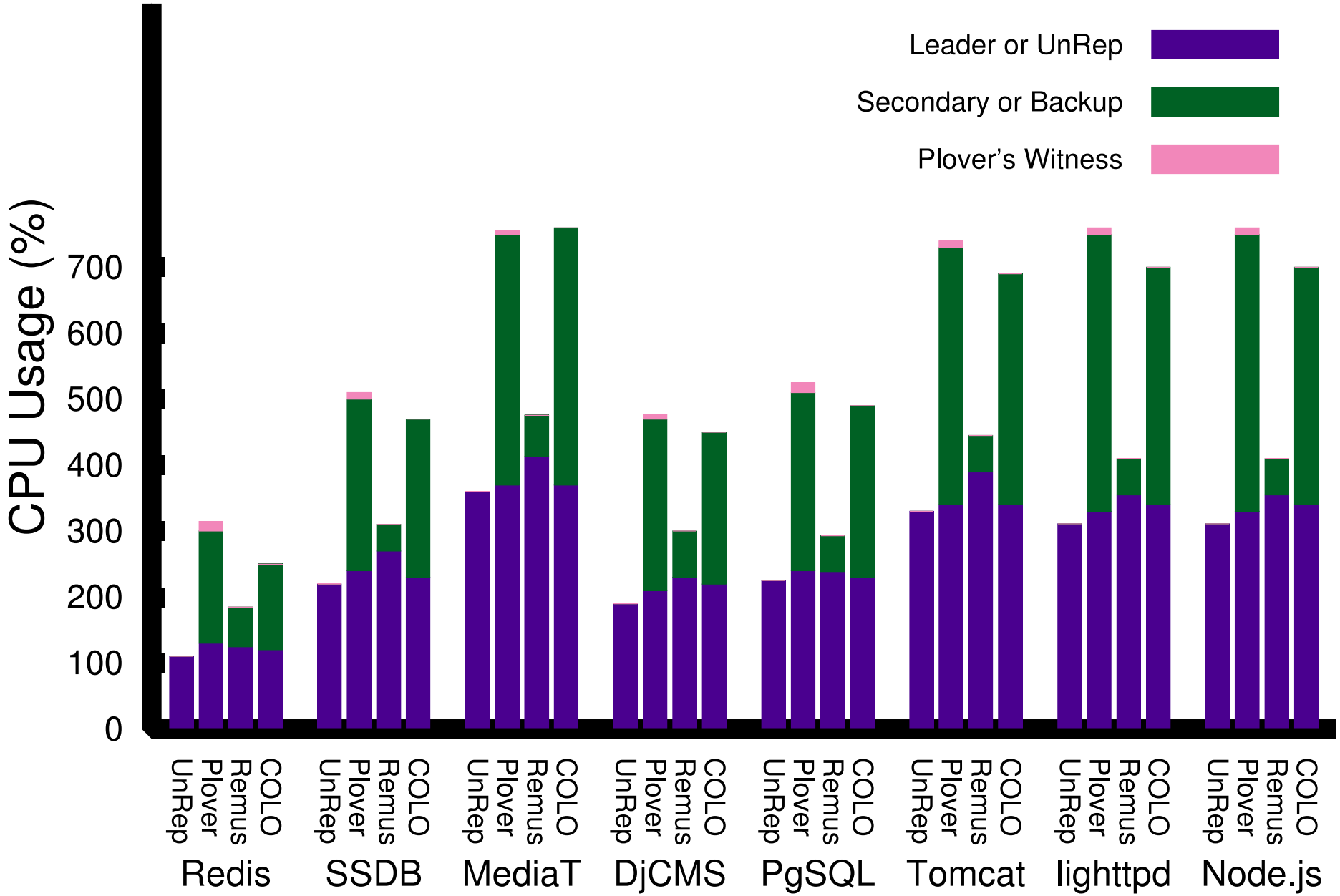
(c) Tomcat



(d) lighttpd

- Redis, DjCMS, pgSQL, and Node.js are not listed because they don't need many vCPUs per VM to improve throughput
  - E.g., Redis is single-threaded

CPU footprint



Conclusion and Ongoing Work

- PLOVER: efficiently replicate VM with strong fault tolerance
  - Low performance overhead, scalable to multi-core, robust to replica failures
- Collaborating with Huawei for technology transfer
  - Funded by Huawei Innovation Research Program 2017
  - Submitted a patent (Patent Cooperation Treaty ID: 85714660PCT01)
- https://github.com/hku-systems/plover