Cheap and Available State Machine Replication

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Protect data from failures

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  - Durability: data is never lost
  - Availability: data can be accessed at any time

- Failures
  - Power loss, DRAM bit errors, disk corruption, software bugs, …

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Replication

Basic idea of replication

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Redundancy => fault tolerance

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Data replication => availability and durability

Stronger replication requires more replicas

- Primary-backup: f+1 replicas => f crash failures

  Data: GFS [Ghemawat SOSP’03], HDFS [Shvachko MSST’10], …

- Paxos: 2f+1 replicas => f crash failures and timing errors (e.g. long message delay)

  Lock service: Boxwood [MacCormick OSDI’04], Chubby [Burrows OSDI’06], …

  Data: SMART [Lorch Eurosys’06], …

  Metadata: MS Azure [Calder SOSP’11], …

  Data + metadata: Megastore [Baker CIDR’11], Spanner [Corbett OSDI’12], …

- BFT: 3f+1 replicas => f arbitrary failures

  Data + metadata: FARSITE [Adya OSDI’02], UpRight [Clement SOSP’09], …

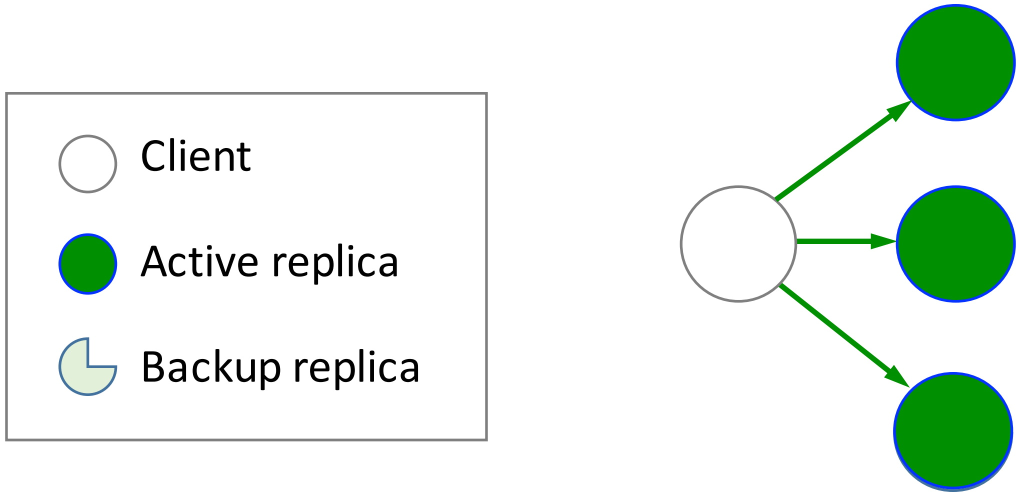
Stronger replication requires more replicas

- Are we willing to pay a higher cost for stronger guarantees?

Existing work made other tradeoffs

- On-demand instantiation for asynchronous replication protocols

  Cheap Paxos [Lamport DSN'04], ZZ [Wood Eurosys'11], …



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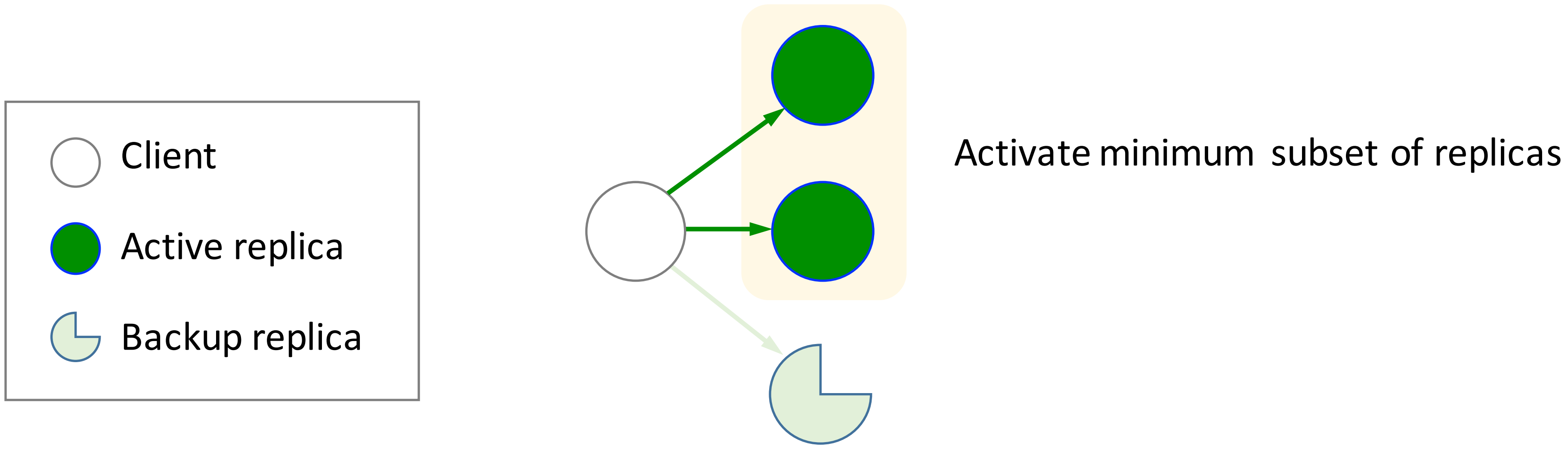

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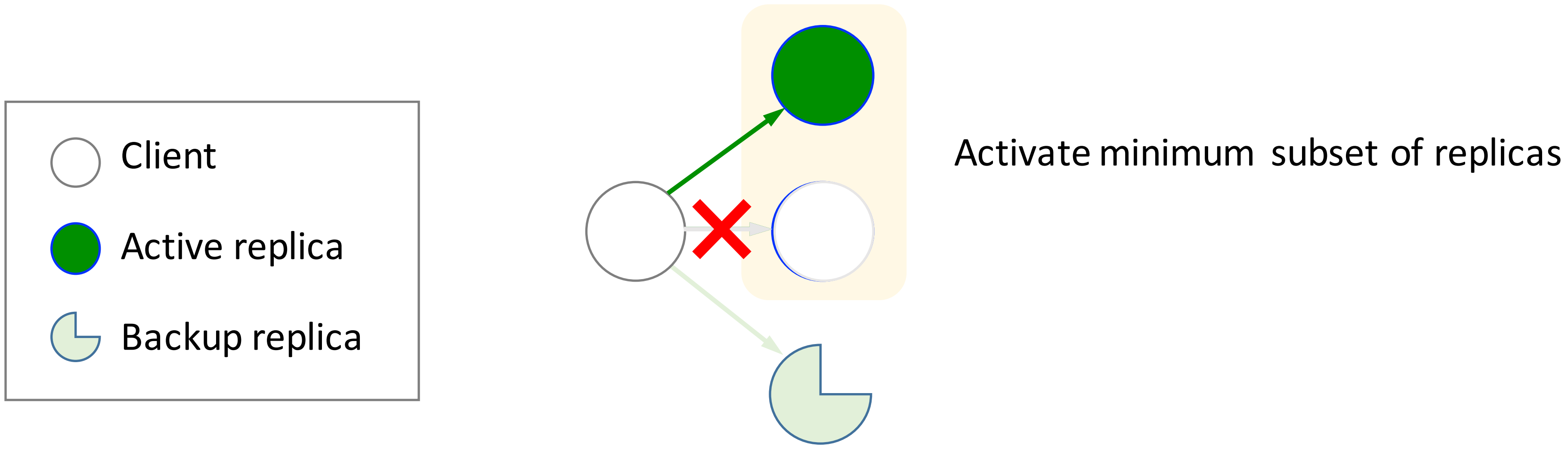

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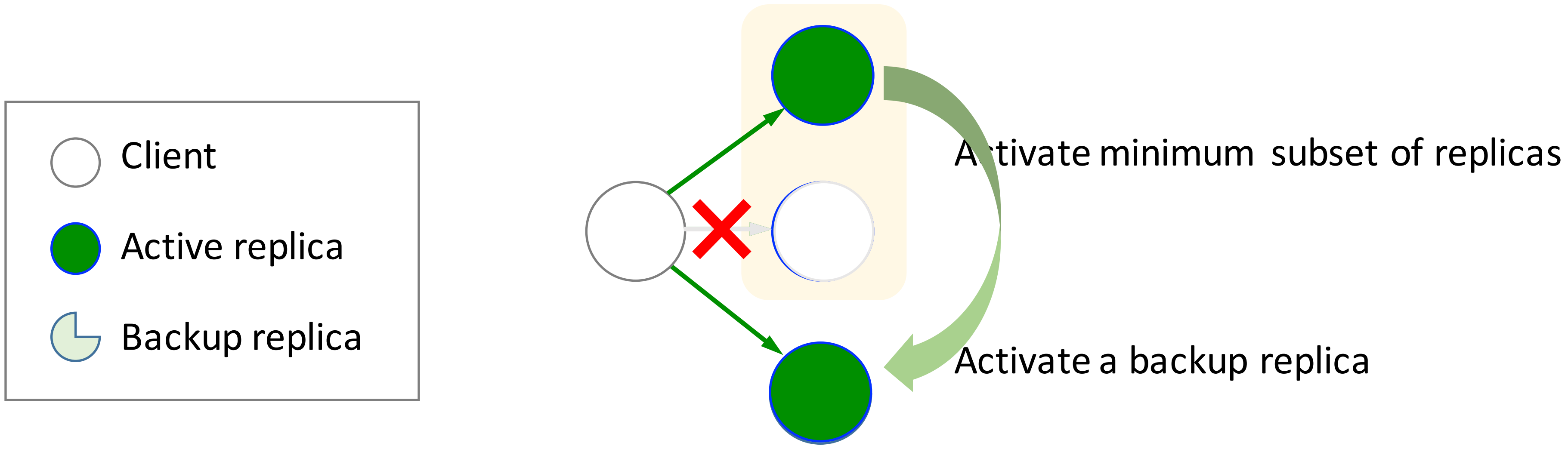

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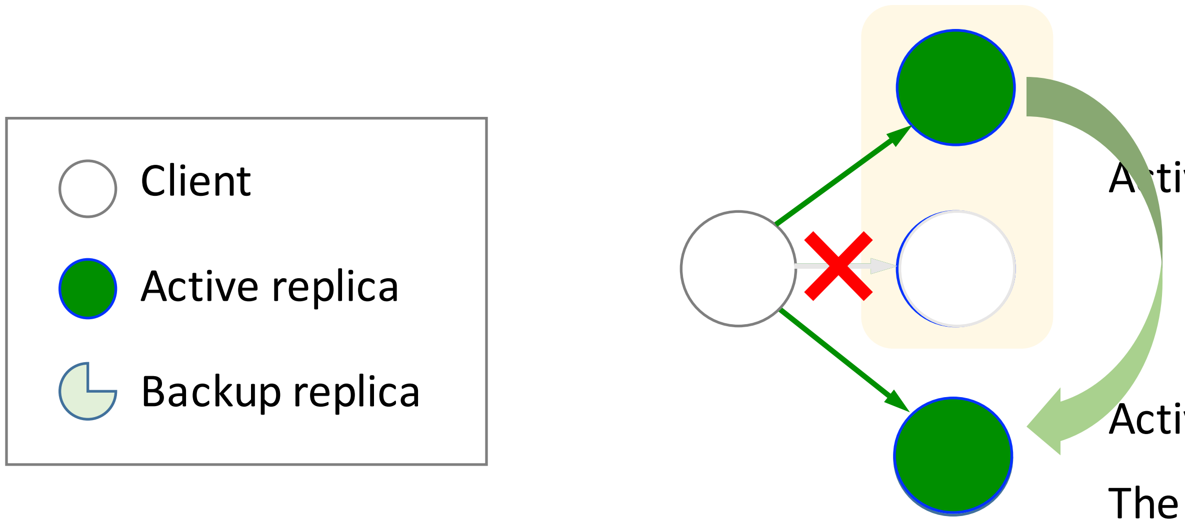

Activate minimum subset of replicas

Activate a backup replica

The system is unavailable when activating a backup replica (transfer data)

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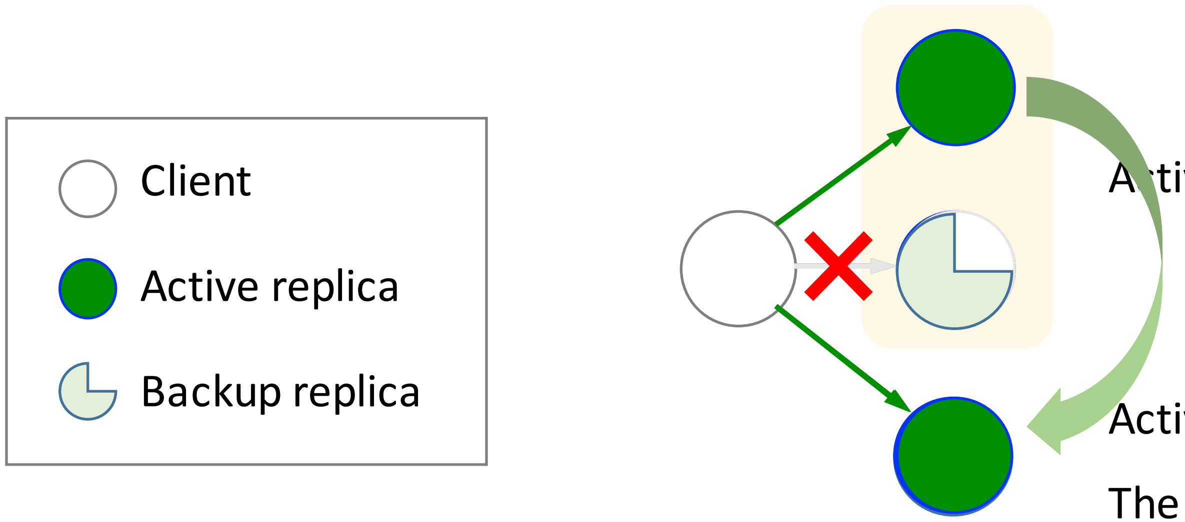

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- Separating agreement from execution ([Yin SOSP'03])
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  - Not effective for applications that are heavy in agreement or using Paxos

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  - Not effective for applications that are heavy in agreement or using Paxos
- Separating metadata from data (Gnothi [Wang ATC'12])
  - Full replication of metadata and partial replication of data
  - Only effective for block storage
- ……

Is it possible to reduce replication cost without hurting availability and correctness?

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Yes for many popular protocols (e.g. Paxos, UpRight)

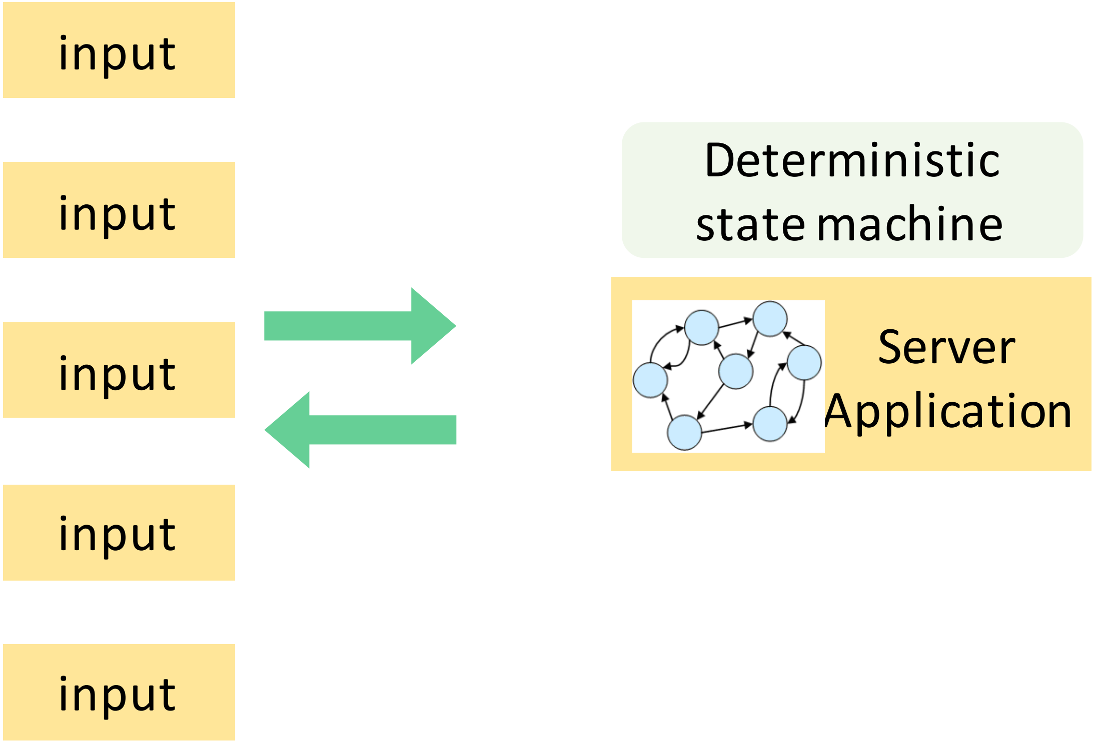
Highlights

Protocol	Original	Our approach
Paxos	**2f + 1**	**f + 1**
UpRight Execution	**u + max(u, r) + 1**	**u + r + 1**

u: number of omission failures

r: number of commission failures

Background: State Machine Replication (SMR)



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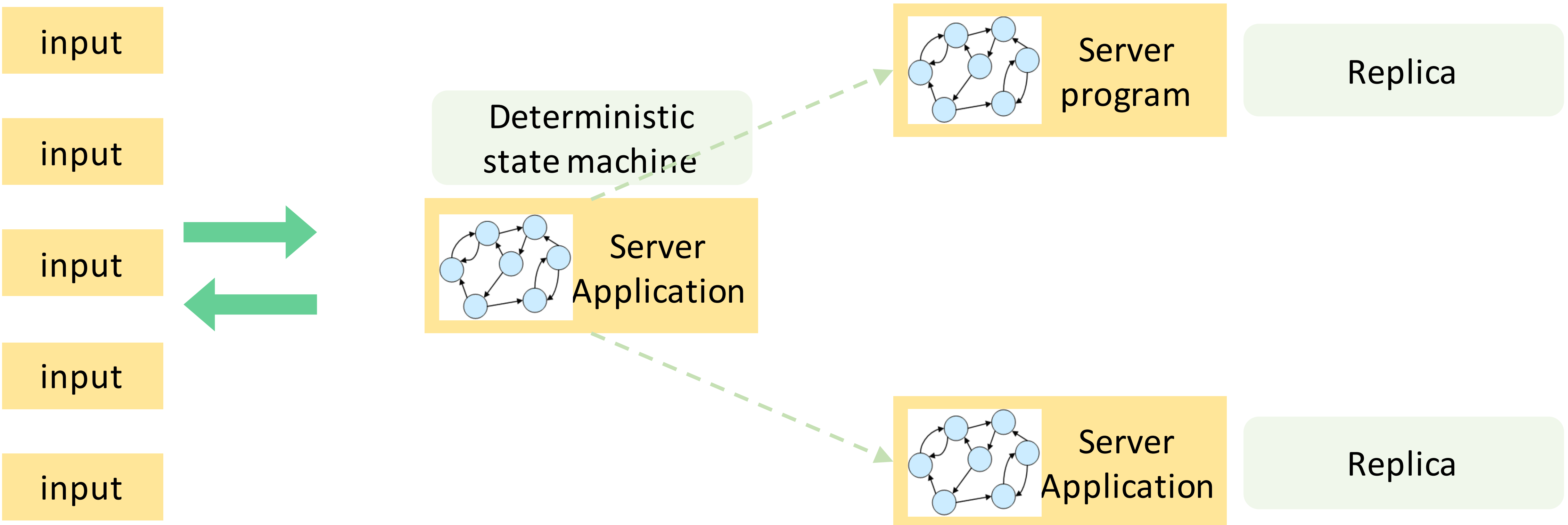

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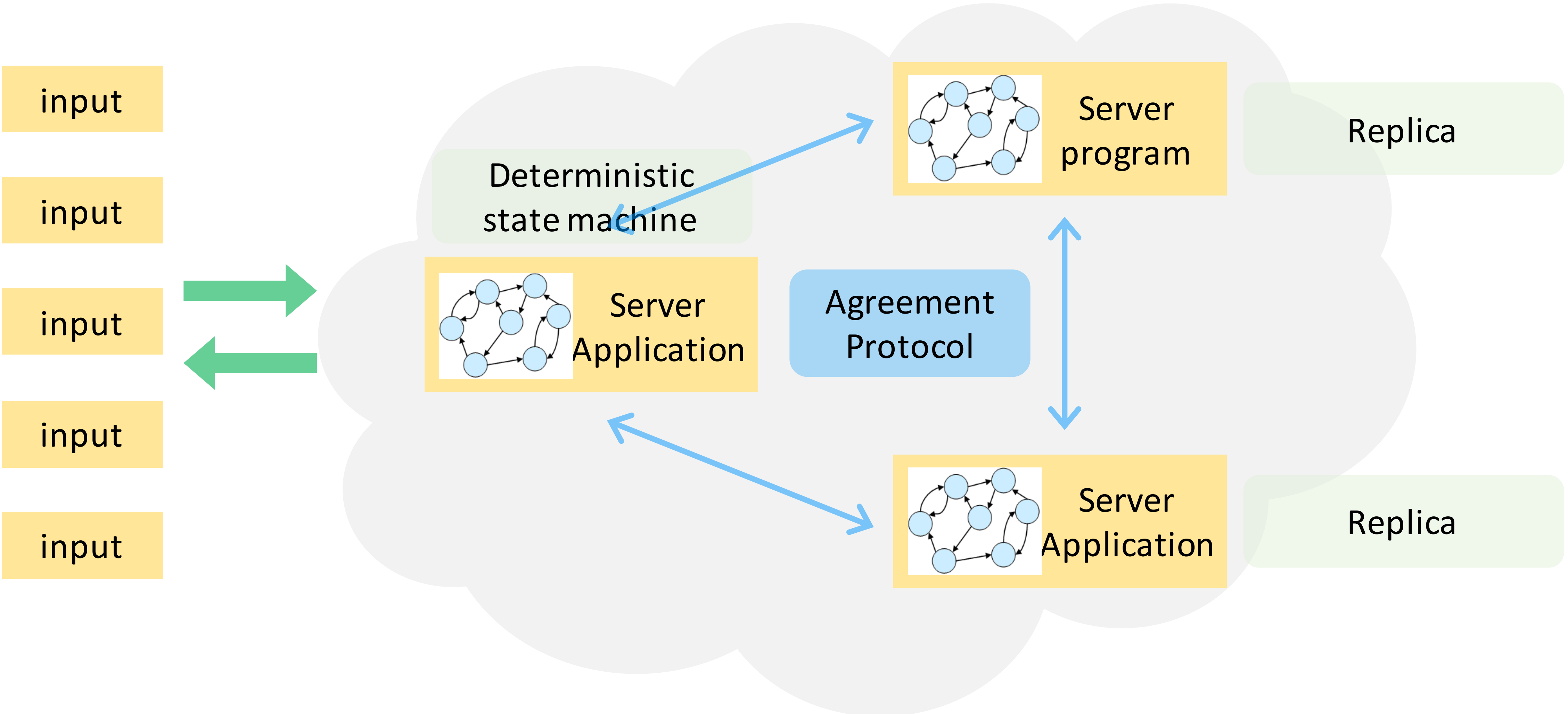

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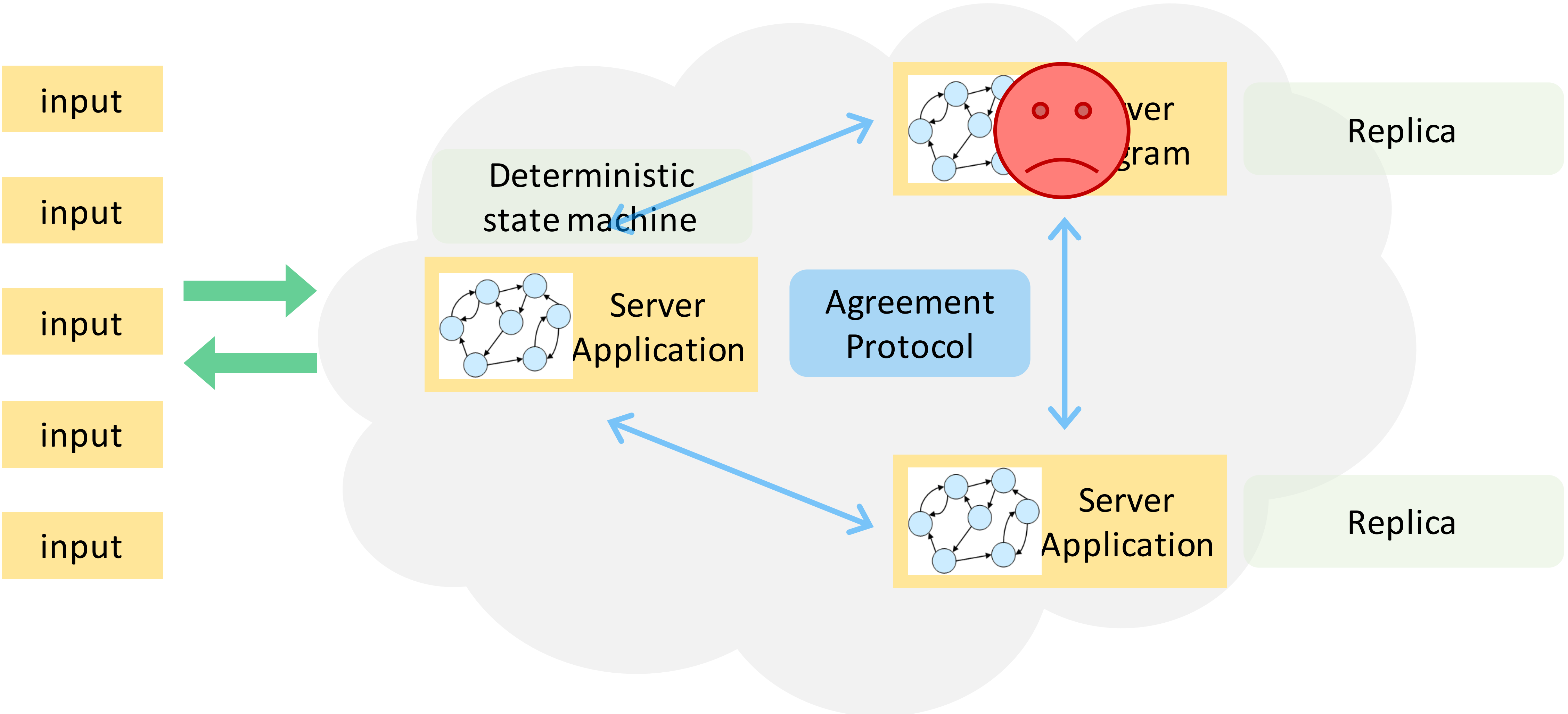

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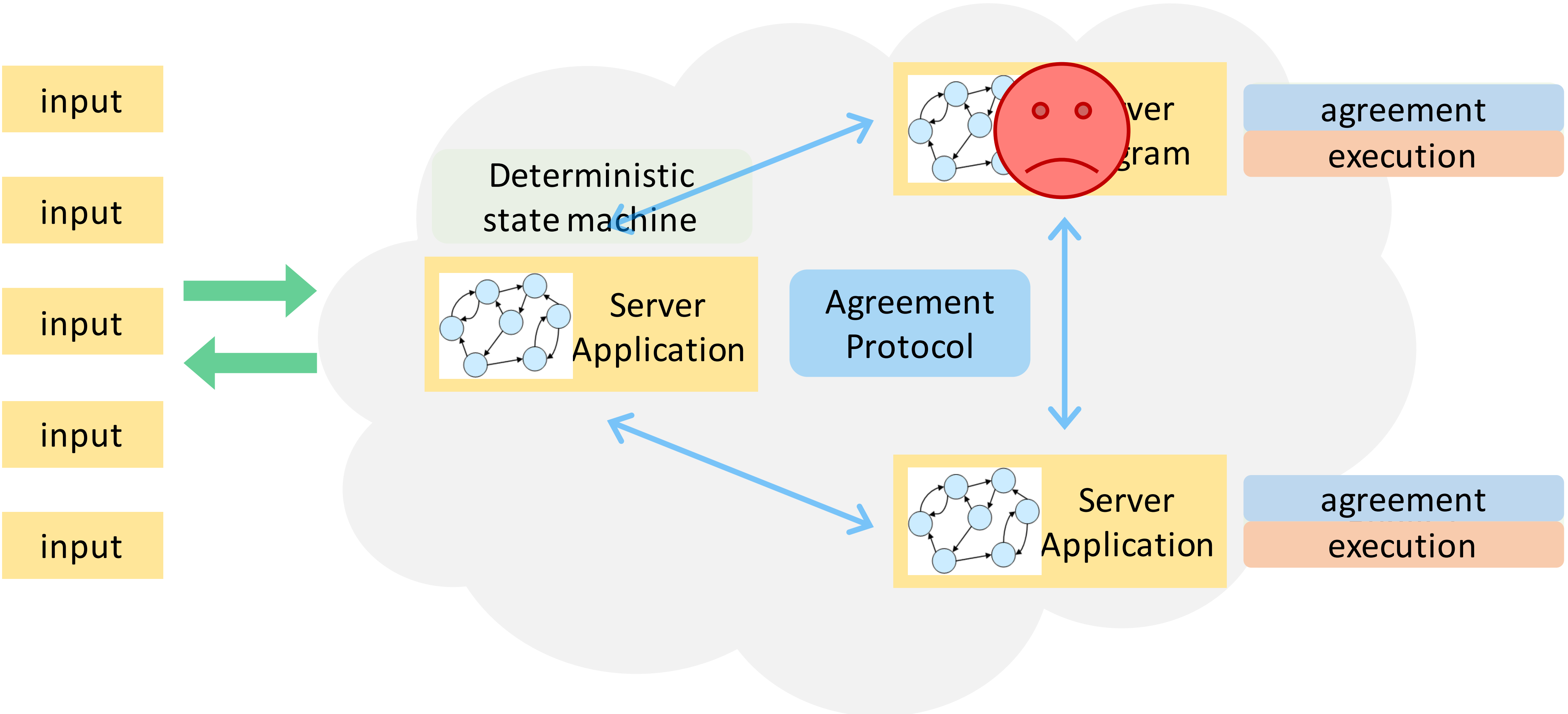

Our solution: on-demand instantiation + lazy recovery

- Reduce cost with on-demand instantiation
  - Activate minimum set of replicas and wakeup backup ones when active ones fail
  - Problem: system is unavailable when rebuilding backup replica

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- Challenge

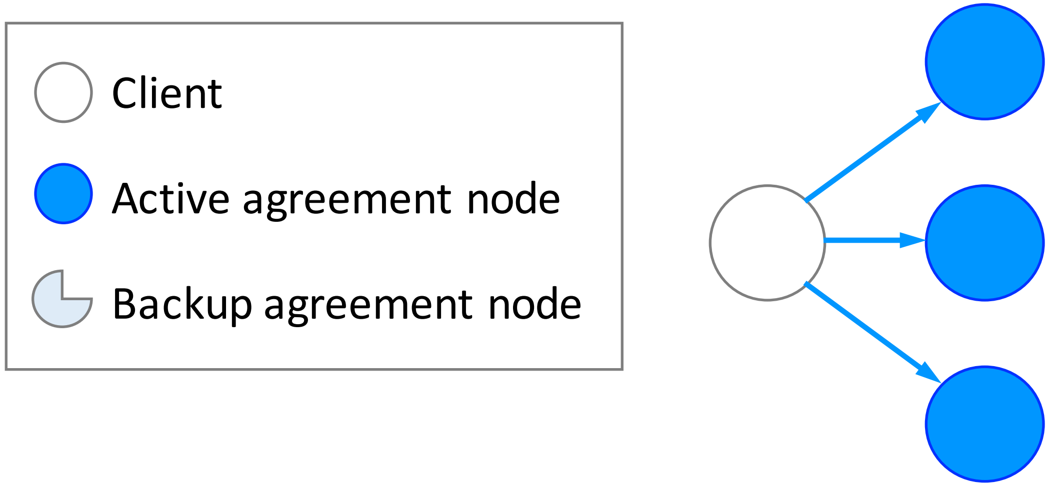
  How to ensure the system is able to function correctly even when some nodes have only partial state?

Key observation: when agreement and execution are separated, they each presents a unique property that enables lazy recovery

Instant activation for agreement nodes

- Agreement: decide the next request to execute
- Observation: agreement protocol is memoryless

  A node does not need to know prior requests when agreeing on the next one



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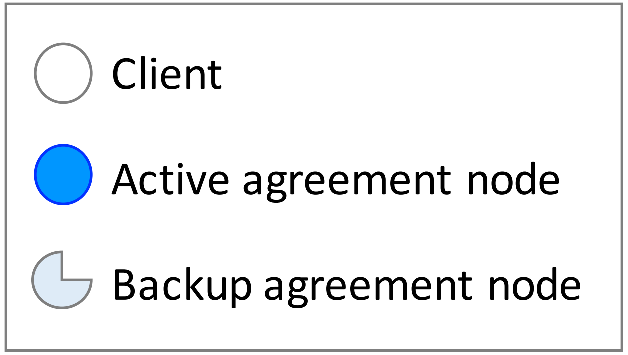

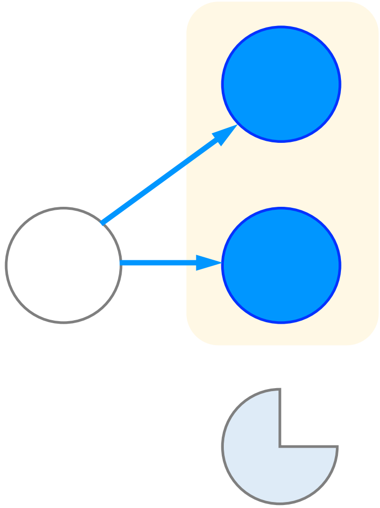

Activate minimum number of agreement nodes that can reach agreement N^A_{active} = N^A_{normal}

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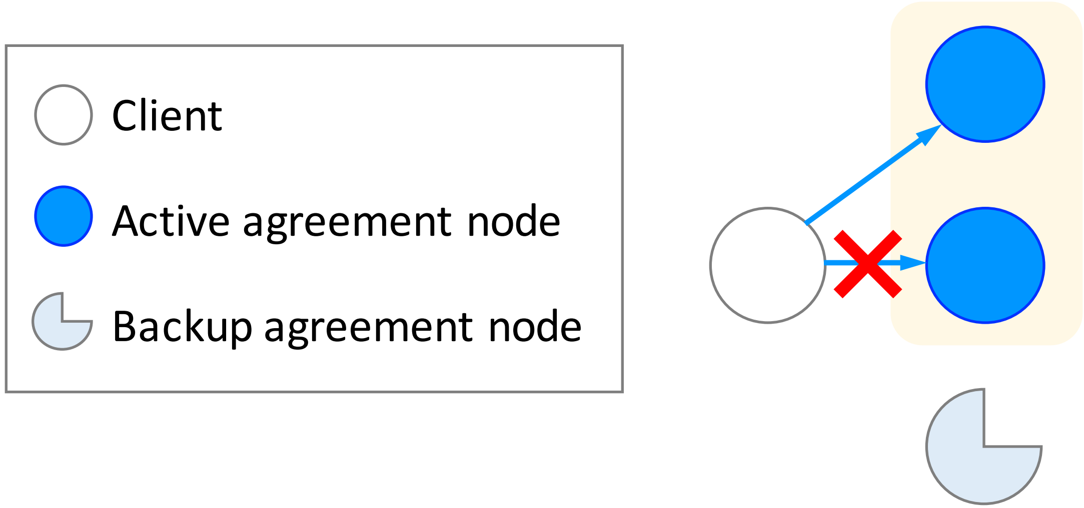

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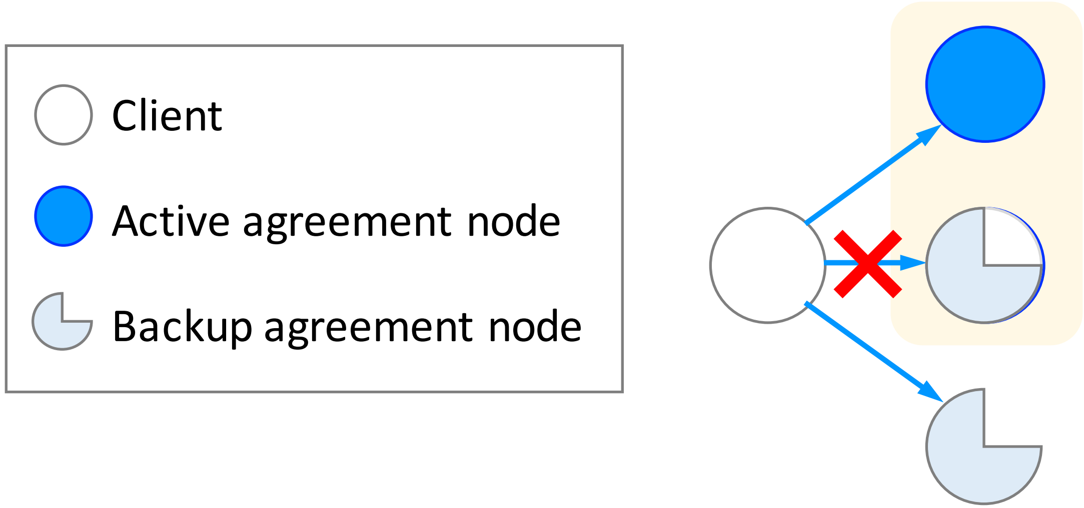

Activate minimum number of agreement nodes that can reach agreement N^{A}_{active} = N^{A}_{normal}

Ask a blank backup node to join agreement Immediately

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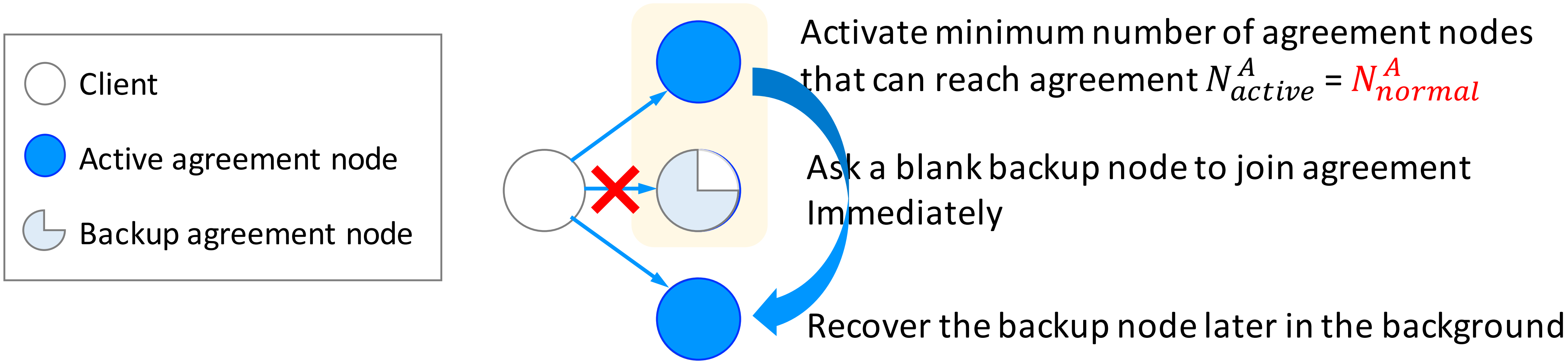

Separating critical and flexible tasks for execution

- Execution: execute requests and other applications' tasks

  Critical task (e.g. executing a request, sending replies to clients)

  Flexible task (e.g. taking a snapshot for garbage collection)

- Observation:

  Number of replicas required to execute critical tasks ($N^E_{critical}$) is sometimes fewer than that required to execute flexible tasks ($N^E_{flexible}$)

Separating critical and flexible tasks for execution

- Our strategy

  Activate N^{E}_{active} = max ($N^{E}_{critical} + f$, $N^{E}_{flexible}$) nodes

Separating critical and flexible tasks for execution

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  Activate $N^E_{active} = \max(N^E_{critical} + f, N^E_{flexible})$ nodes

  Can always perform critical tasks

Separating critical and flexible tasks for execution

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Can perform flexible tasks when there are no failures

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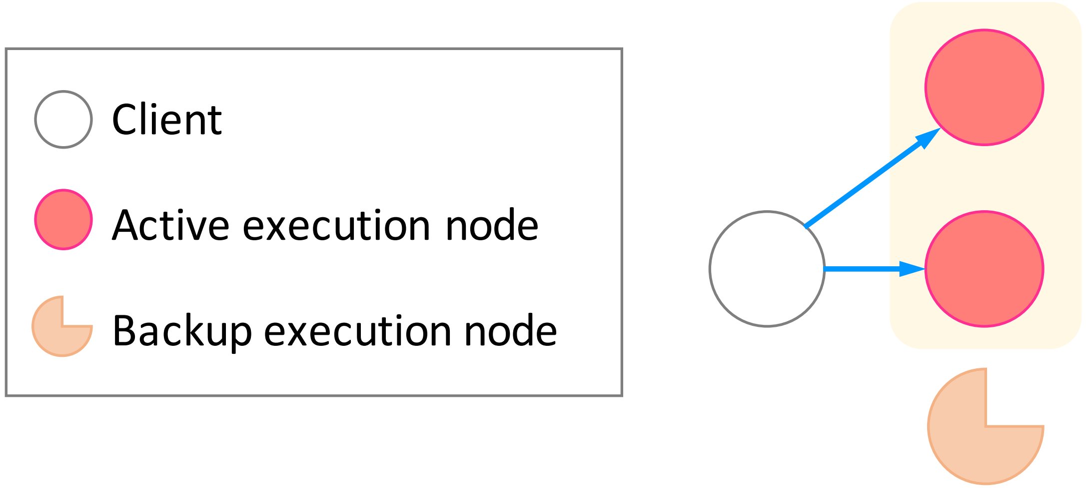

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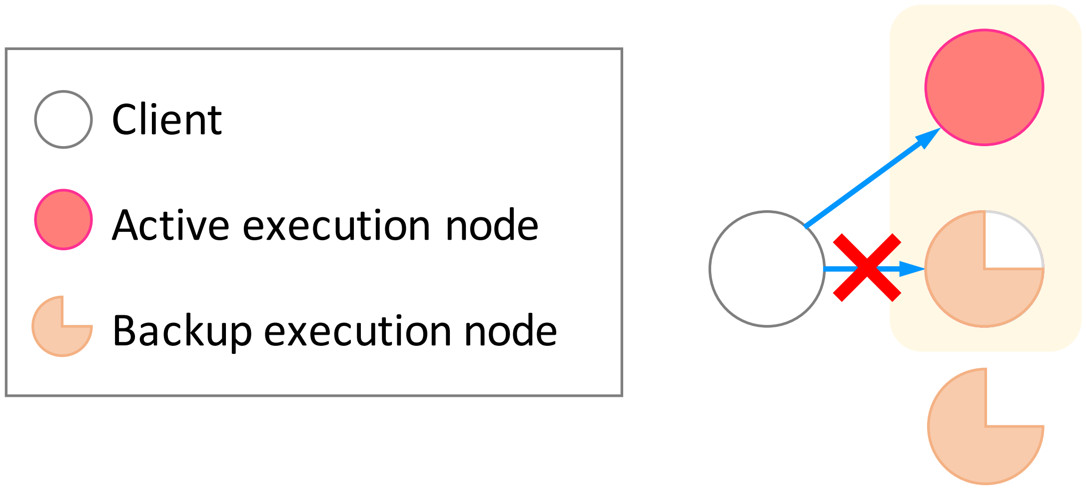

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Can perform critical tasks, but not flexible tasks

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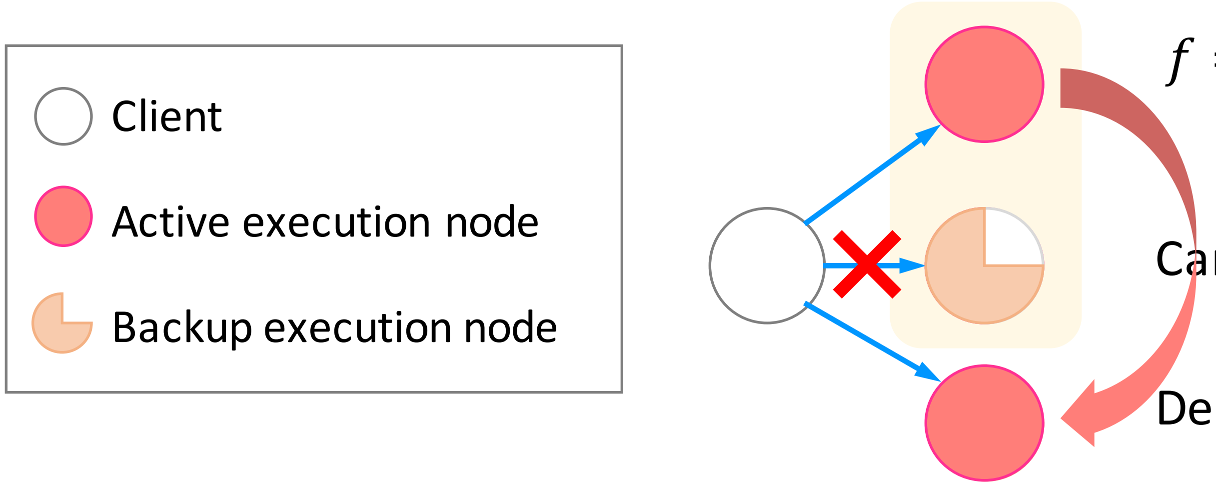

$f = 1, N^E_{critical} = 1, N^E_{flexible} = 2$ => $N^E_{active} = 2$

Can perform critical tasks, but not flexible tasks

Delay flexible tasks after recovery completes

Summary

- Activate a subset of agreement and execution nodes
- When an agreement node fails, ask a blank one to join agreement immediately
- When an execution node fails, keep processing requests with remaining execution nodes
- Recover nodes later in the background

Case studies

Protocol	Original	Our approach
Paxos	2f+1 / 2f+1	f+1 / f+1
UpRight Execution	u + max(u, r) + 1	u + r + 1
Zyzzyva	3f+1 / 2f+1	3f+1 / 2f+1

- Paxos

$N^A_{normal} = f + 1 \rightarrow N^A_{active} = f + 1$

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- UpRight Execution

$$N^E_{critical} = r + 1, N^E_{flexible} = \max(u, r) + 1 \Rightarrow N^E_{active} = u + r + 1$$

Case studies

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- Zyzzyva [Kotla SOSP'07]

  $N^A_{normal} = 3f + 1$ (Speculation) ➔ $N^A_{active} = 3f + 1$

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Our approach is not always effective

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Our approach is not always effective

Adaptive recovery

- Challenge: how to finish recovery in a timely manner?
- Why necessary?
  - Delayed recovery results in higher probability of data loss
  - Long delayed flexible tasks (e.g. garbage collection) will block the system

- Our solution
  - An adaptive approach to meet the deadline specified by the administrator

Evaluation

- Build ThriftyPaxos from scratch in Java

- Questions
  - What is the performance of ThriftyPaxos when there are no failures?
    Compare to standard Paxos

  - What is the availability of ThriftyPaxos when failures occur?
    Compare to standard Paxos and Cheap Paxos

  - Can adaptive recovery meet the deadline with different configurations?
    Use various deadlines and state sizes

Evaluation setup

- Machines

  Dell R220 with 8 cores, 16GB RAM and two hard drivers

- Evaluate replicated H2 and RemoteHashMap

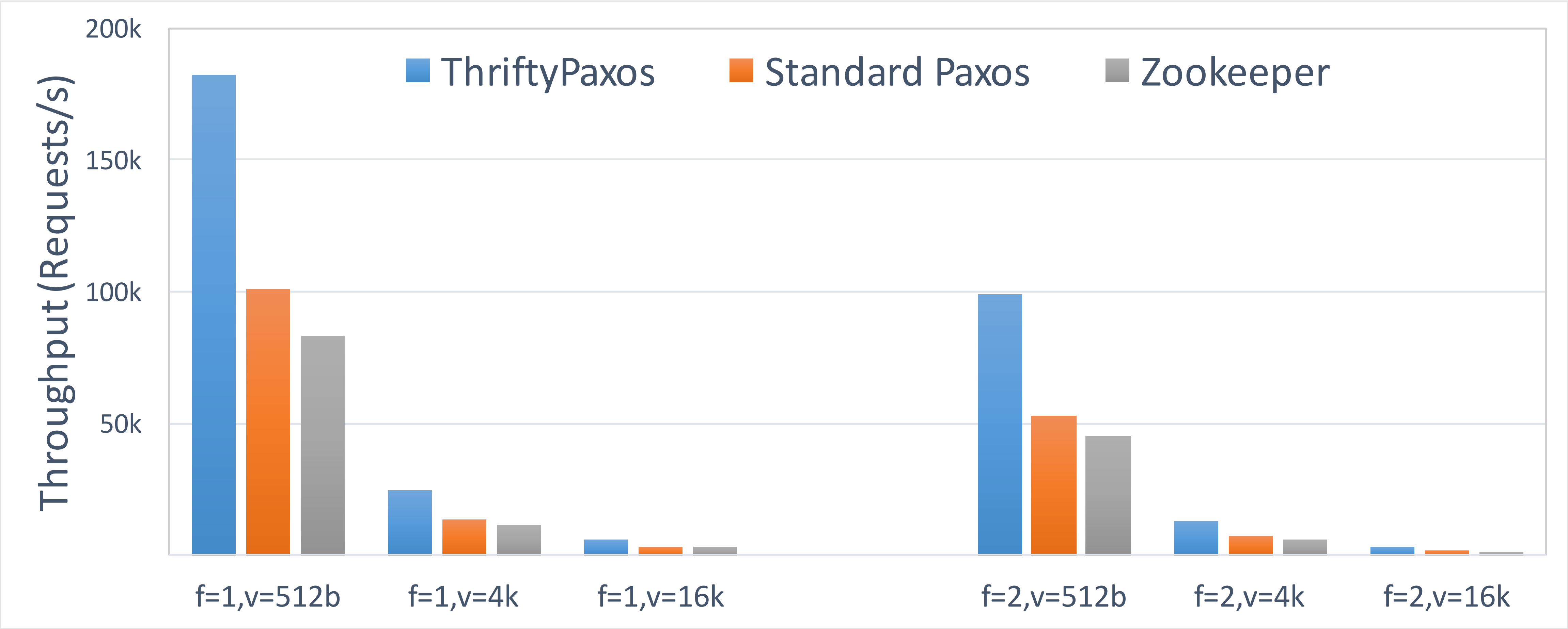
  H2: database system, ran TPC-C over H2

  RemoteHashMap: benchmark application built by us

- Methodology

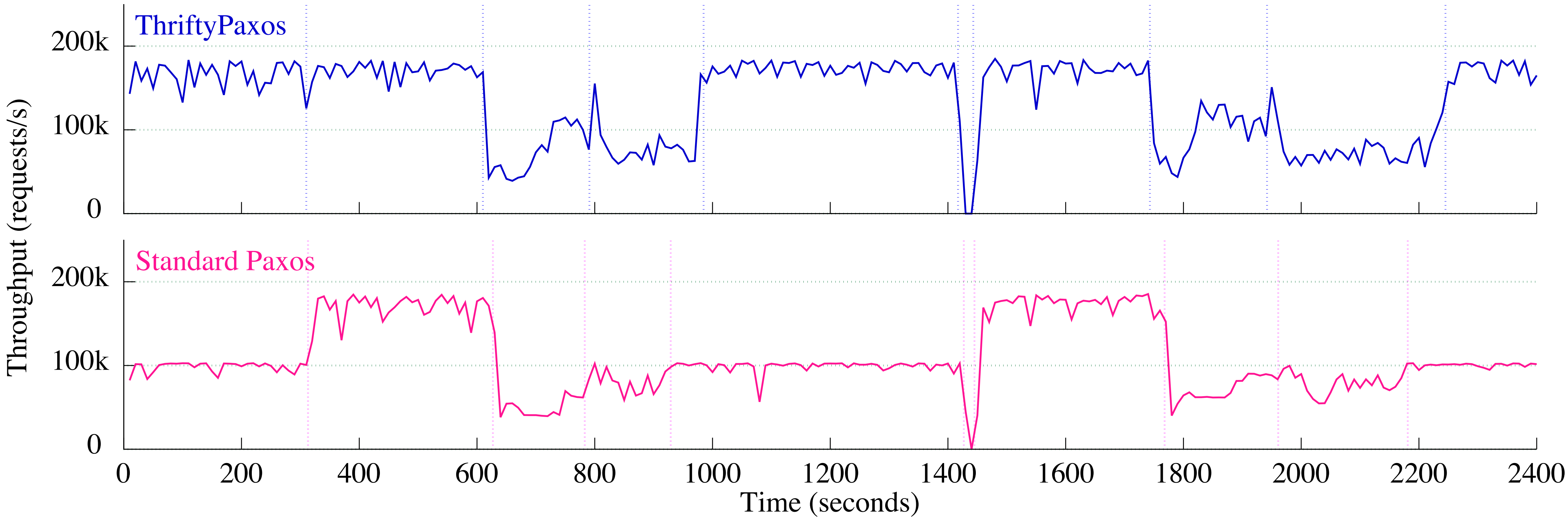
  To evaluate availability, kill agreement and execution nodes to emulate failures

ThriftyPaxos achieves higher throughput



ThriftyPaxos achieves 73%~88% more write throughput

Maintaining availability during failure recovery



f=1, v=512b, snapshot=5G

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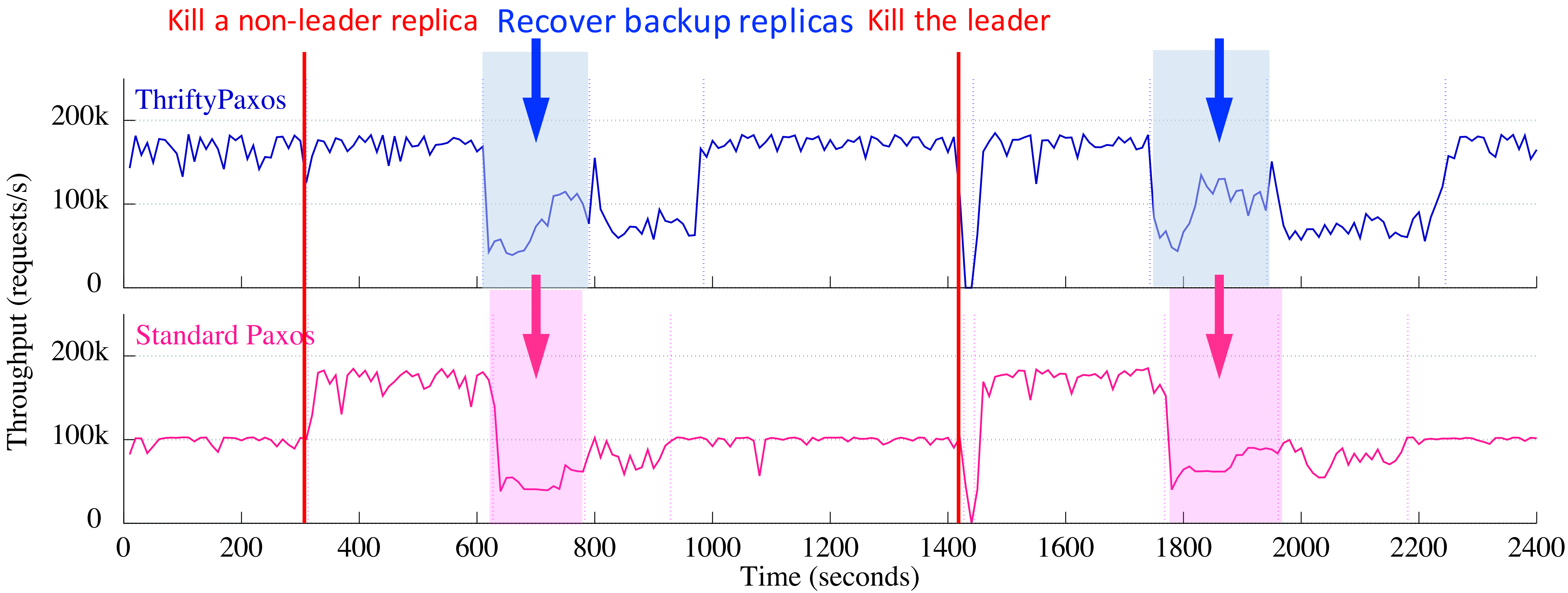

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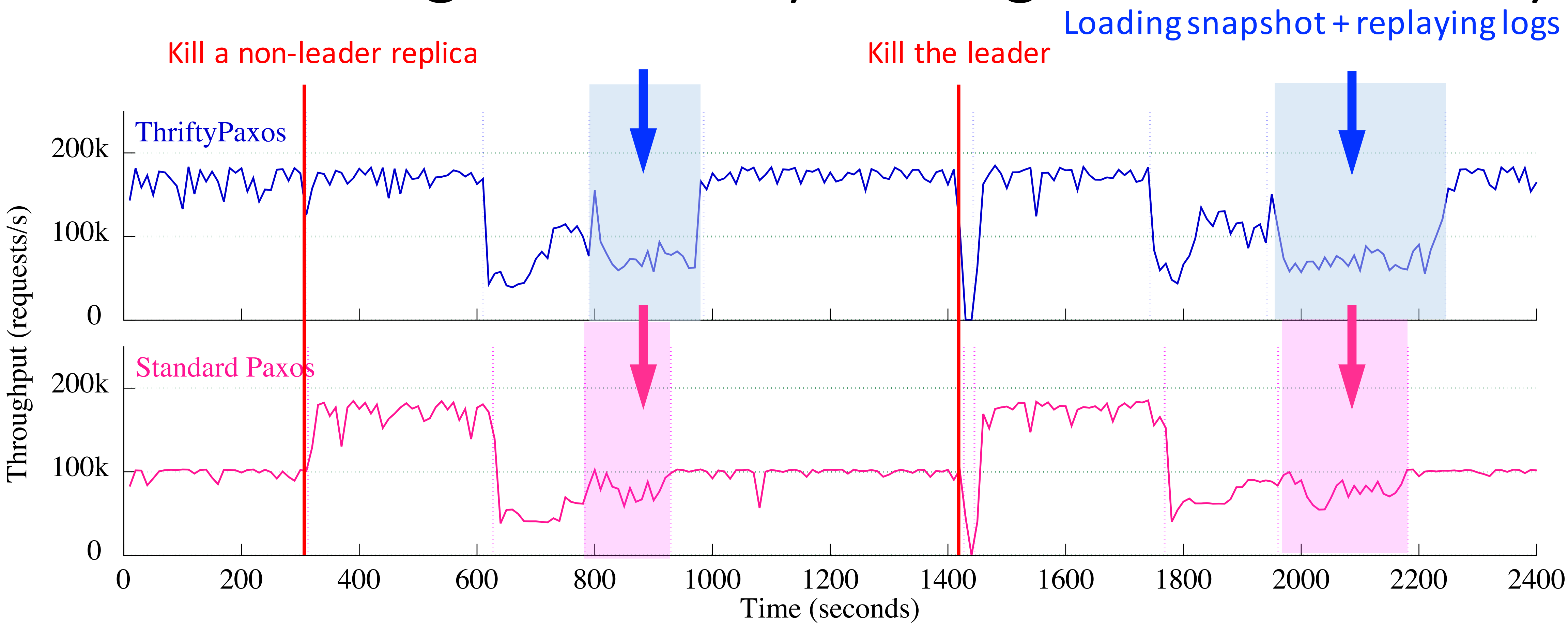

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Related work

- On-demand instantiation
  Cheap Paxos[Lamport DSN'04], ZZ [Wood Eurosys'11]
- Accurate failure detection
  Falcon[Leners SOSP'11], …
- Higher read throughput
  ZooKeeper[Hunt ATC'10], Gaios[Bolosky NSDI'11], …
- Lower latency
  Fast Paxos[Lamport DC'06], Speculative Paxos[Ports NSDI'15], Zyzzyva [Kotla SOSP'07], …
- Multi-leader load balance
  Mencius [Mao OSDI'08], EPaxos [Moraru SOSP'13], …

Conclusion

- Strong replication does not have to be expensive

- No need to invent new protocols
  - Examine conditions for correctness and availability in existing protocols
  - Combine on-demand instantiation and lazy recovery

https://github.com/vdr007/ThriftyPaxos