Fast Crash Recovery in RAMCloud

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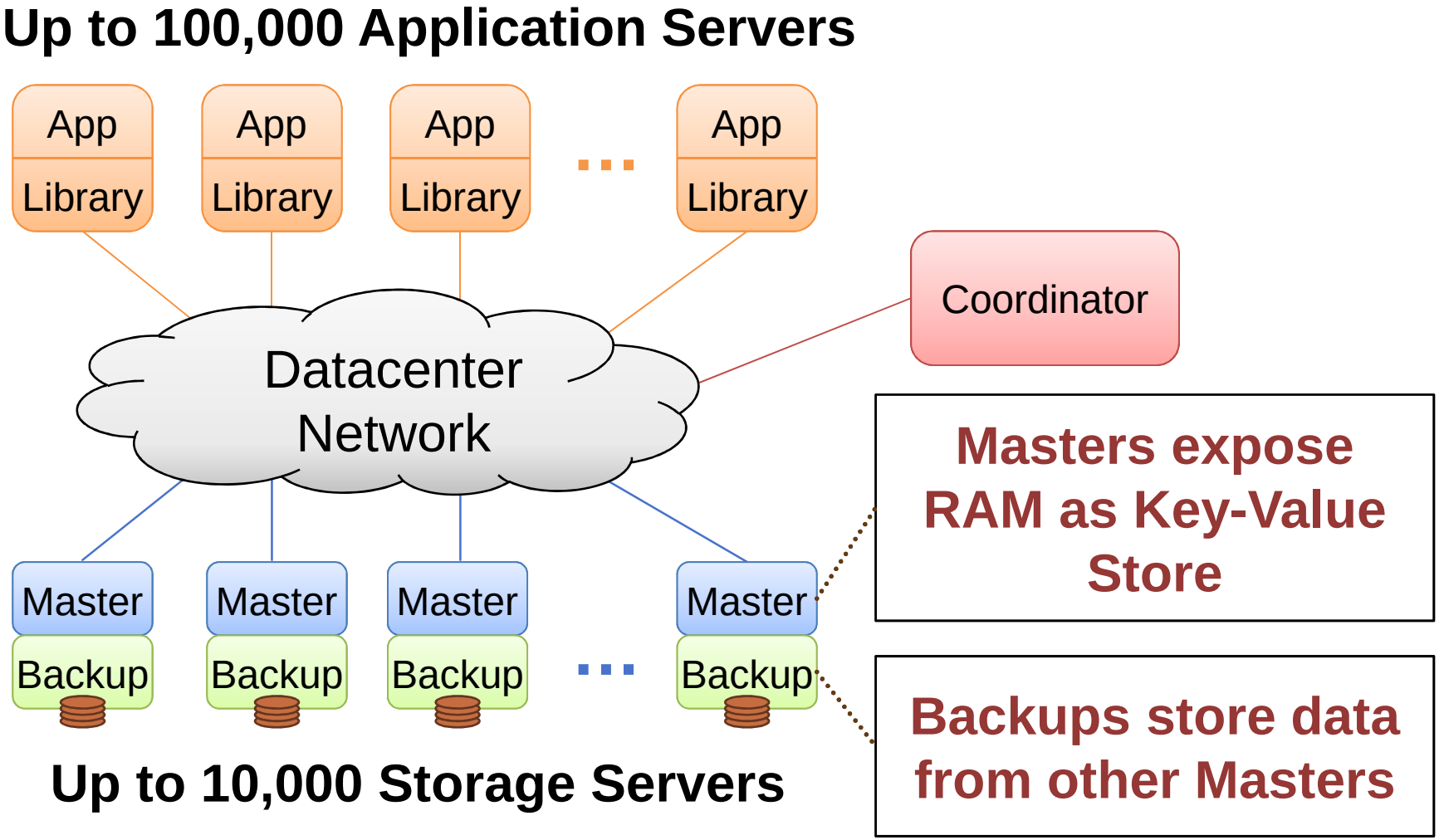
Overview

- **RAMCloud: General purpose storage in RAM**
  - Low latency: **5-10 µs** remote access
  - Large scale: 10,000 nodes, 100 TB to 1 PB
- **Key Problem: RAM's lack of durability**
- **Durability: Pervasive log structure, even in RAM**
  - Uses inexpensive disk-based replication
  - RAM performance by eliminating synchronous disk writes
- **Availability: Fast crash recovery in 1 to 2 s**
  - Recovers **35 GB to RAM in 1.6 s** using 60 nodes
  - Leverages the scale of the cluster
    - Balances work evenly across hosts
    - Avoids centralized control

RAMCloud Architecture



Durability & Availability

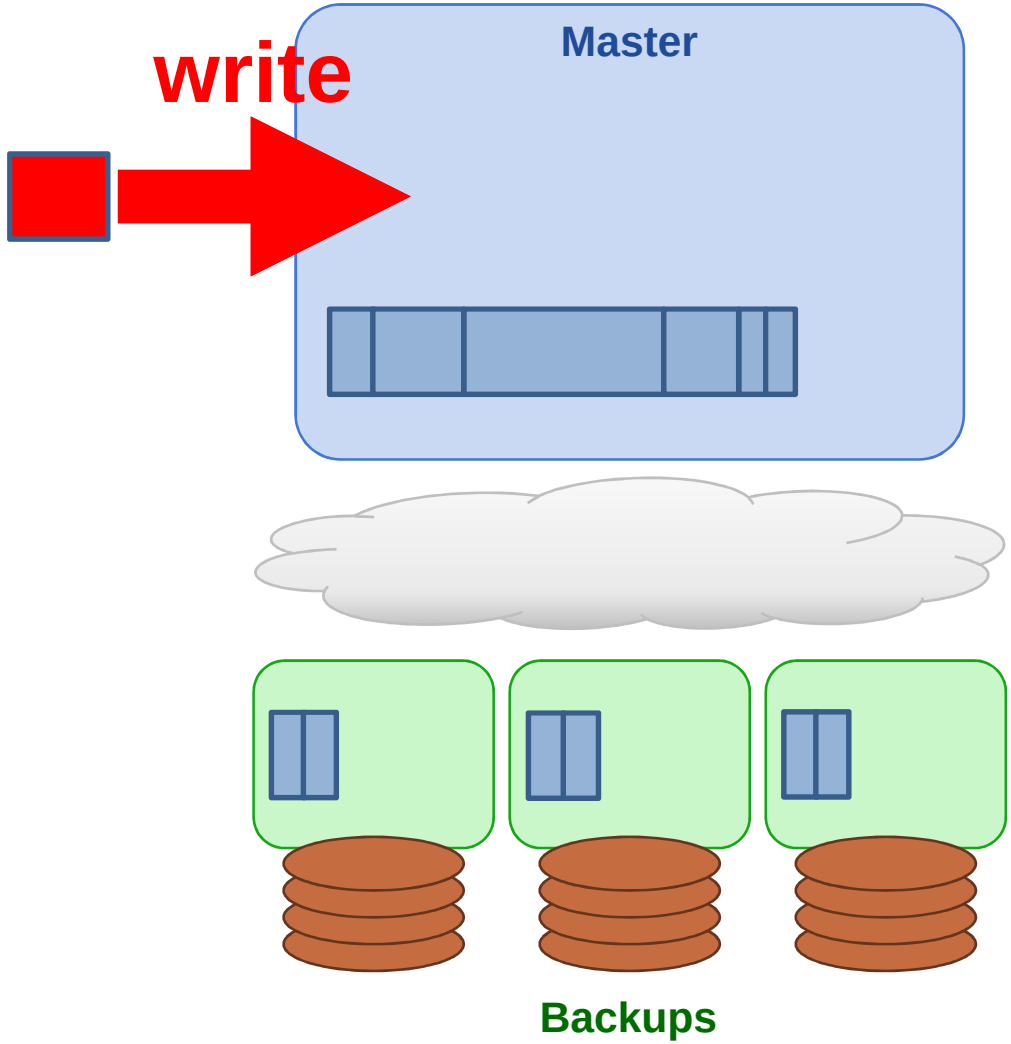
- **Requirements**
  - Retain high performance
  - Minimum cost, energy

- **Replicate in RAM of other masters?**
  - 3x system cost, energy
  - Still have to handle power failures

The RAMCloud Approach

- **1 copy in RAM**
- **Backup copies on disk/flash: durability ~ free!**
- **Problem: Synchronous disk writes too slow**
  - **Pervasive log structure, even in RAM**
- **Problem: Data is unavailable on crash**
  - **Fast Crash Recovery in 1 to 2 s**
    - Fast enough that applications won't notice

Durability with RAM performance



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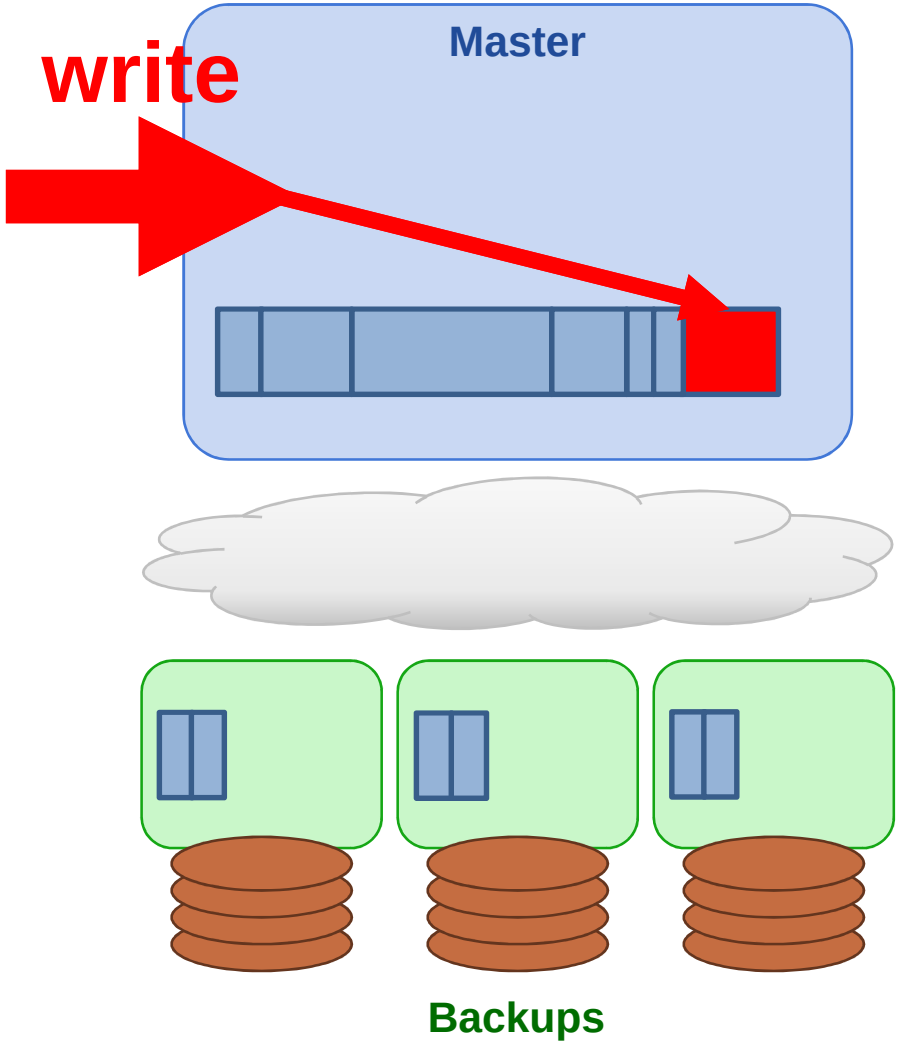

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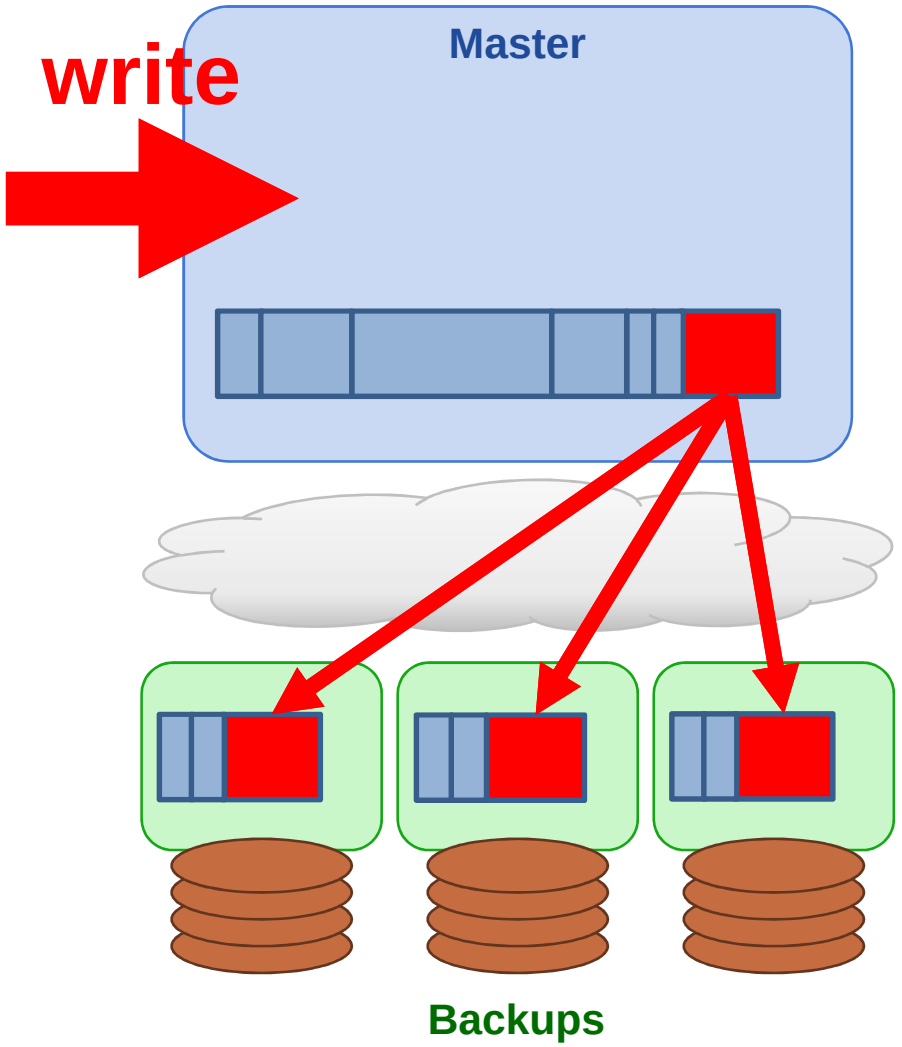
  - No synchronous disk write



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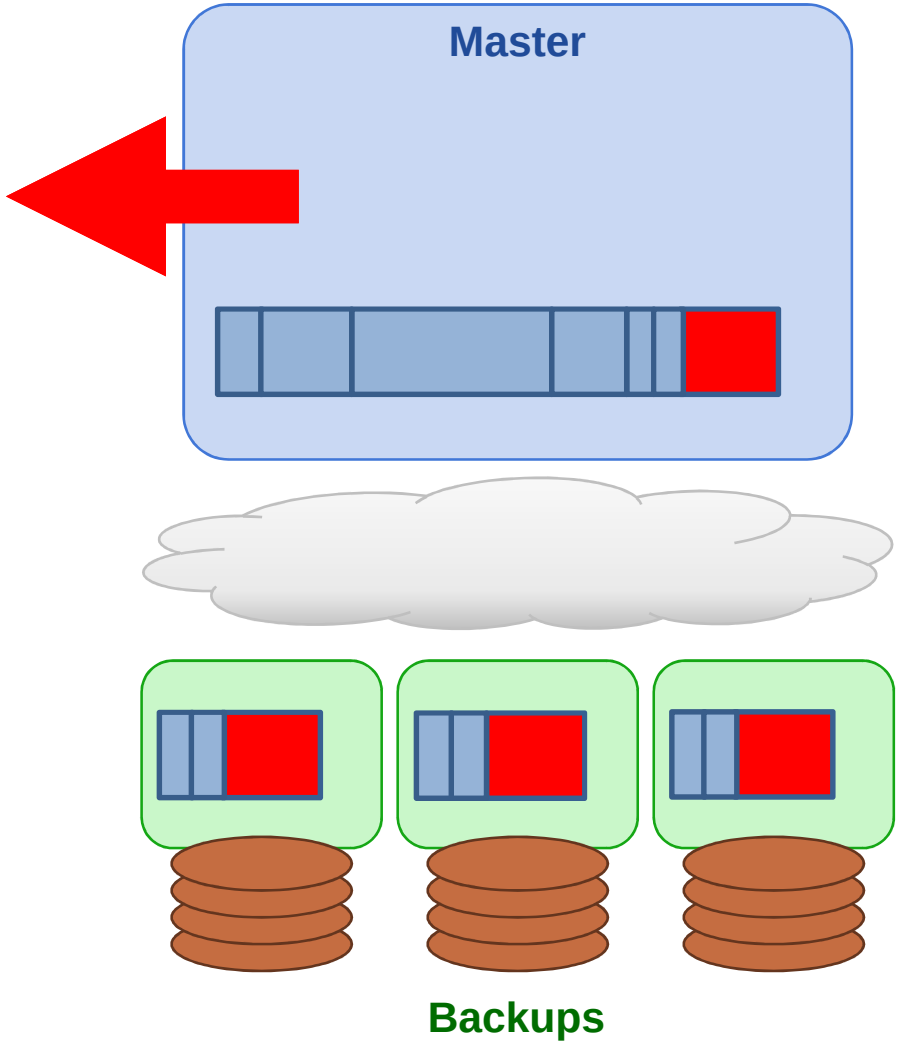

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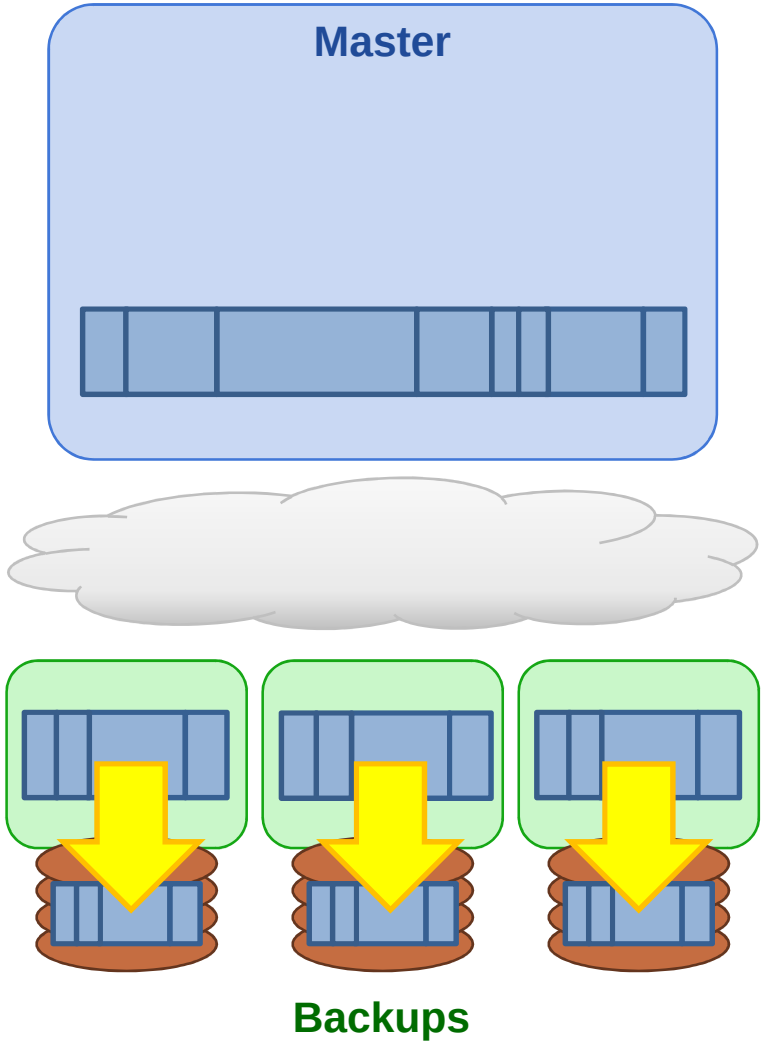

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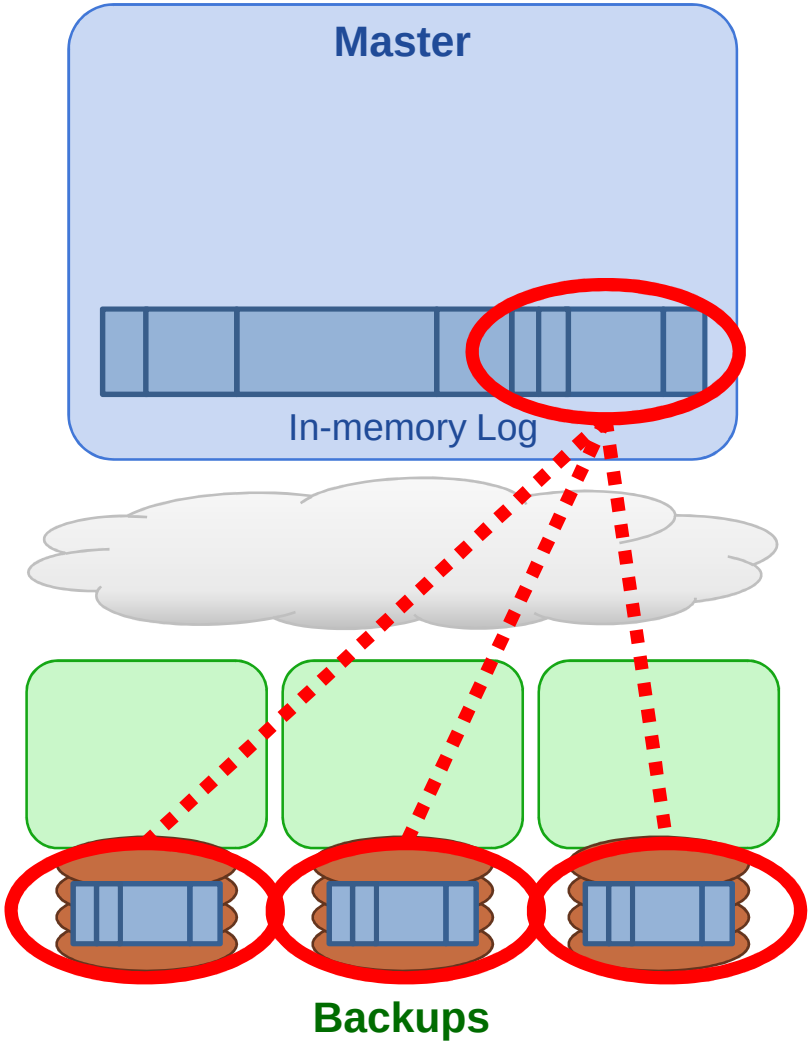
- **Pervasive log structure**
  - Even RAM is a log
  - Log cleaner



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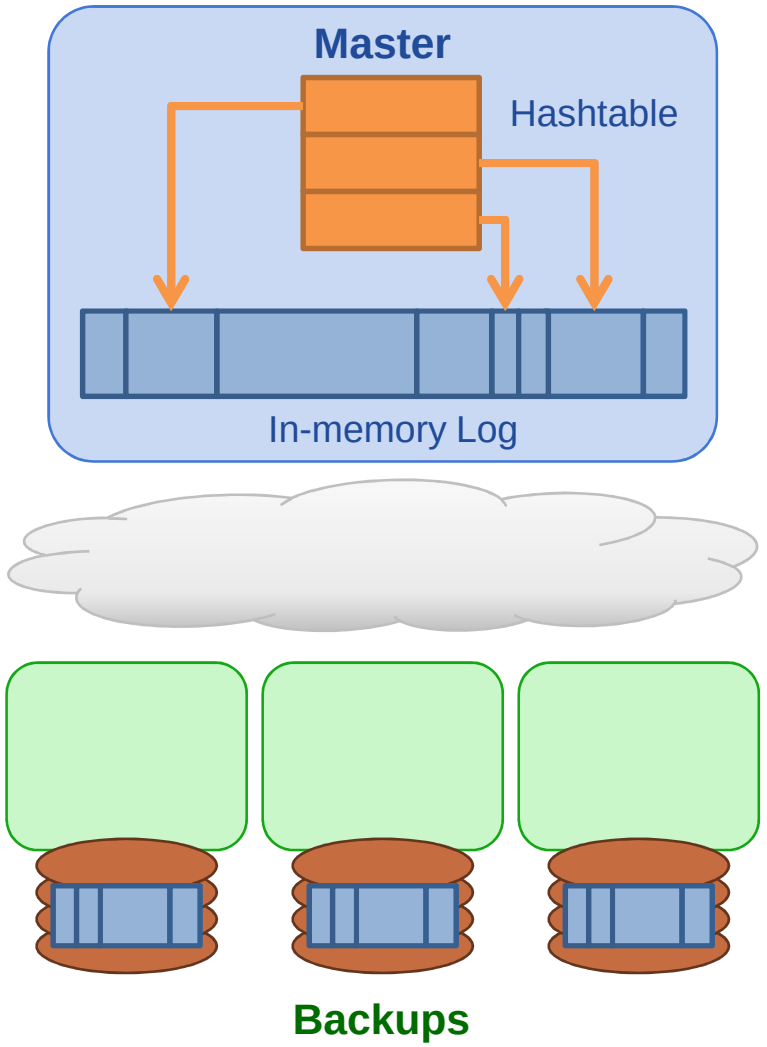
- **Hashtable, key → location**



Fast Crash Recovery

- **What is left when a Master crashes?**
  - Log data stored on disk on backups

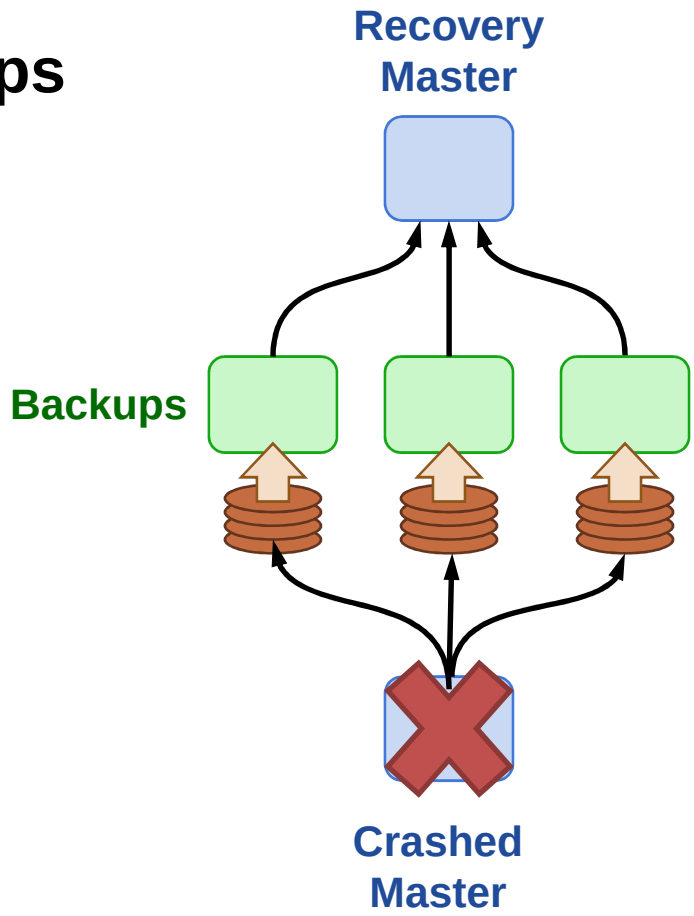
- **What must be done to restart servicing requests?**
  - Replay log data into RAM
  - Reconstruct the hashtable

- **Recover fast: 64 GB in 1-2 seconds**
- **Key to fast recovery: use system scale**

Recovery without Scale

- **Masters backed up to 3 Backups**
  - Each backup stores entire log
- **Problem: Disk bandwidth**
- **64 GB / 300 MB/sec**
  ≈ 210 seconds

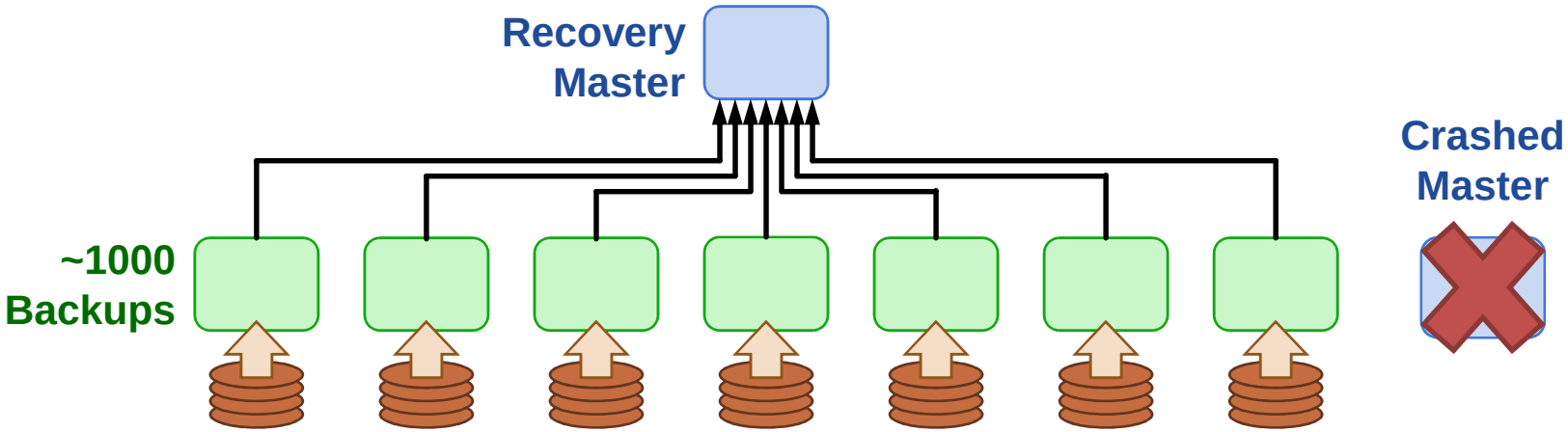
- **Solution: more disks**
  (more backups)



Solution: Scatter Log Data

- **Each log divided into 8MB segments**
- **Master chooses different backups for each segment (randomly)**
- **Segments scattered across all servers in the cluster**

- **Crash recovery:**
  - All backups read from disk in parallel
  - 64 GB / (1000 backups * 100 MB/s/backup) = **0.6 seconds**



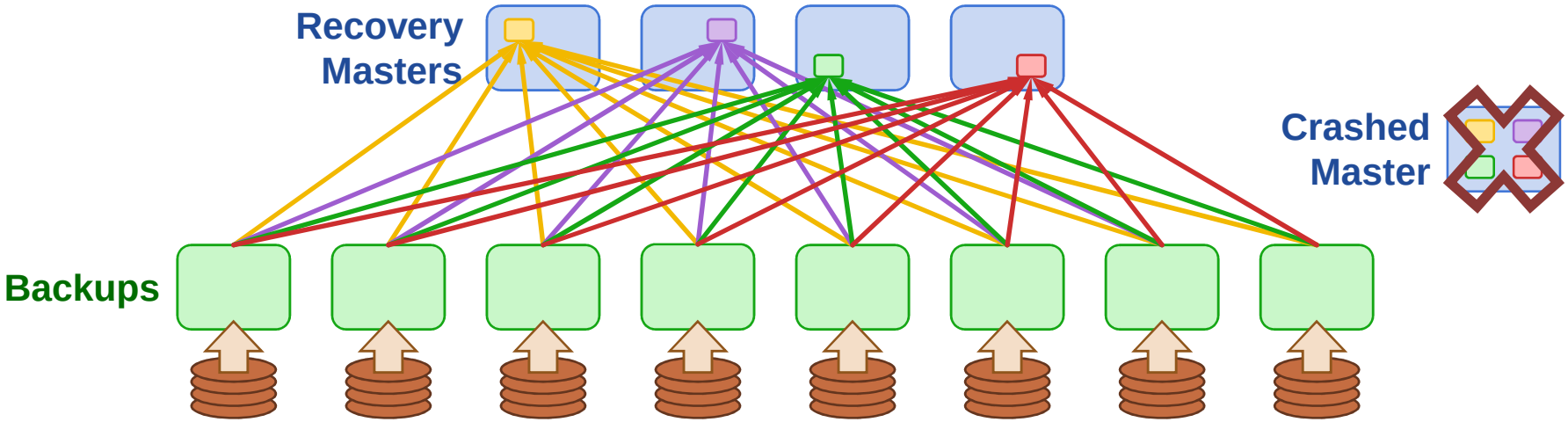
Problem: Network bandwidth

- **Second bottleneck: NIC on recovery master**
  - 64 GB / 10 Gbits/second ≈ 60 seconds
  - CPU and memory bandwidth a limitation

- **Solution: more recovery masters**
  - Spread work over 100 recovery masters
  - 60 seconds / 100 masters ≈ 0.6 seconds

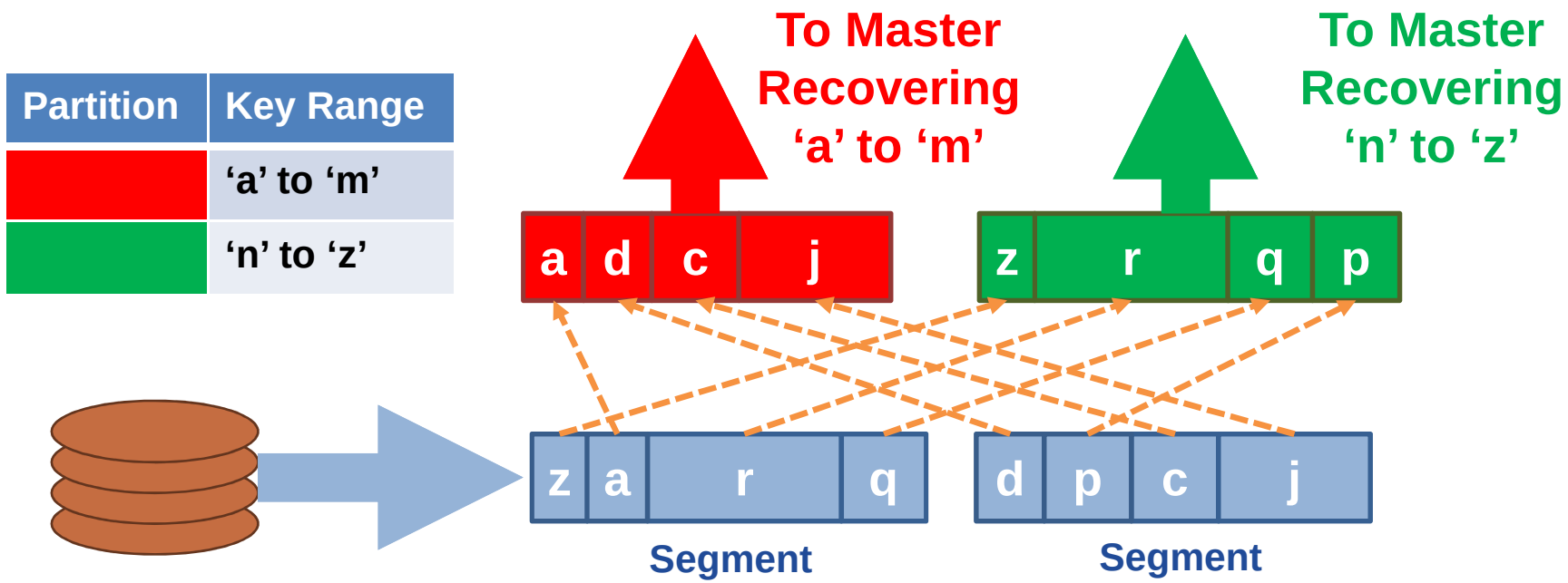
Solution: Partitioned Recovery

- **Divide each master's data into partitions**
  - Recover each partition on separate Recovery Master
  - Partitions based on key ranges, *not log segment*
  - Eliminates need for idle, empty Recovery Masters



Partitioning During Recovery

- **Backups receive a partition list at the start of recovery**
- **Backups load segments from disk and partition log entries**
- **Each recovery master replays only relevant log entries**



Issues Harnessing Scale

- **Balancing work evenly**
  - Parallel work is only as fast as the slowest unit
- **Avoiding centralized control**
  - Centralized control eventually becomes a bottleneck
  - Nodes often work without perfect/global knowledge

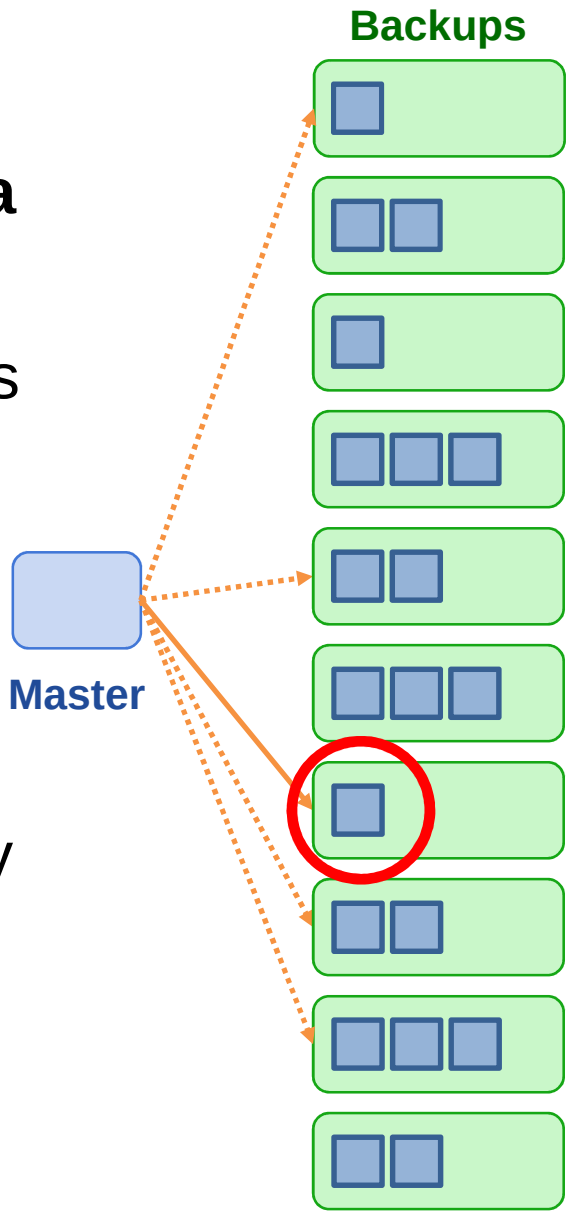
Balancing Partitions

- **Problem: Balancing work of each recovery master**
  - Recovery will be slow if a single Master is given
    - Too much data
    - Too many objects

- **Solution: Profiler tracks density of key ranges**
  - Done locally on each master
  - Balance size and number of objects per partition

Segment Scattering

- **Problem: Balancing time reading data across disks**
  - Recovery is slow if just one Backup is slow
- **Solution: Use similar approach to [Mitzenmacher 1996]**
  - Choose candidate Backups randomly
  - Select the “best”
  - Minimize worst-case disk read time



Detecting Incomplete Logs

- **Problem: Ensure entire log is found during recovery**
  - Centrally cataloging segments for each log expensive

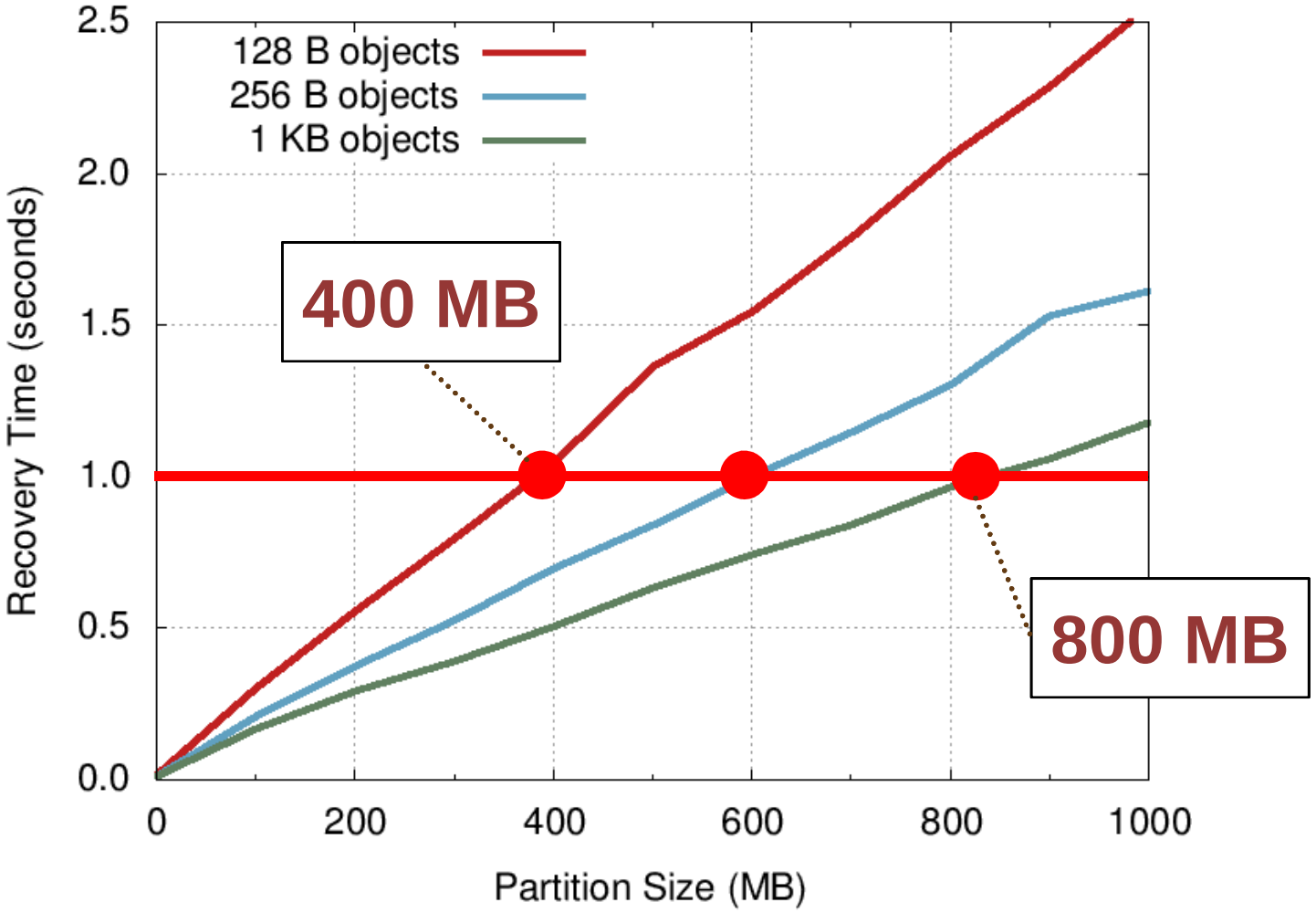
- **Solution: Self-describing log**
  - Masters record catalog of log segments in segments
  - Coordinator talks to each Backup at start of recovery
    - Finds most recent catalog
  - Can detect if all copies of most recent catalog are lost

Experimental Setup

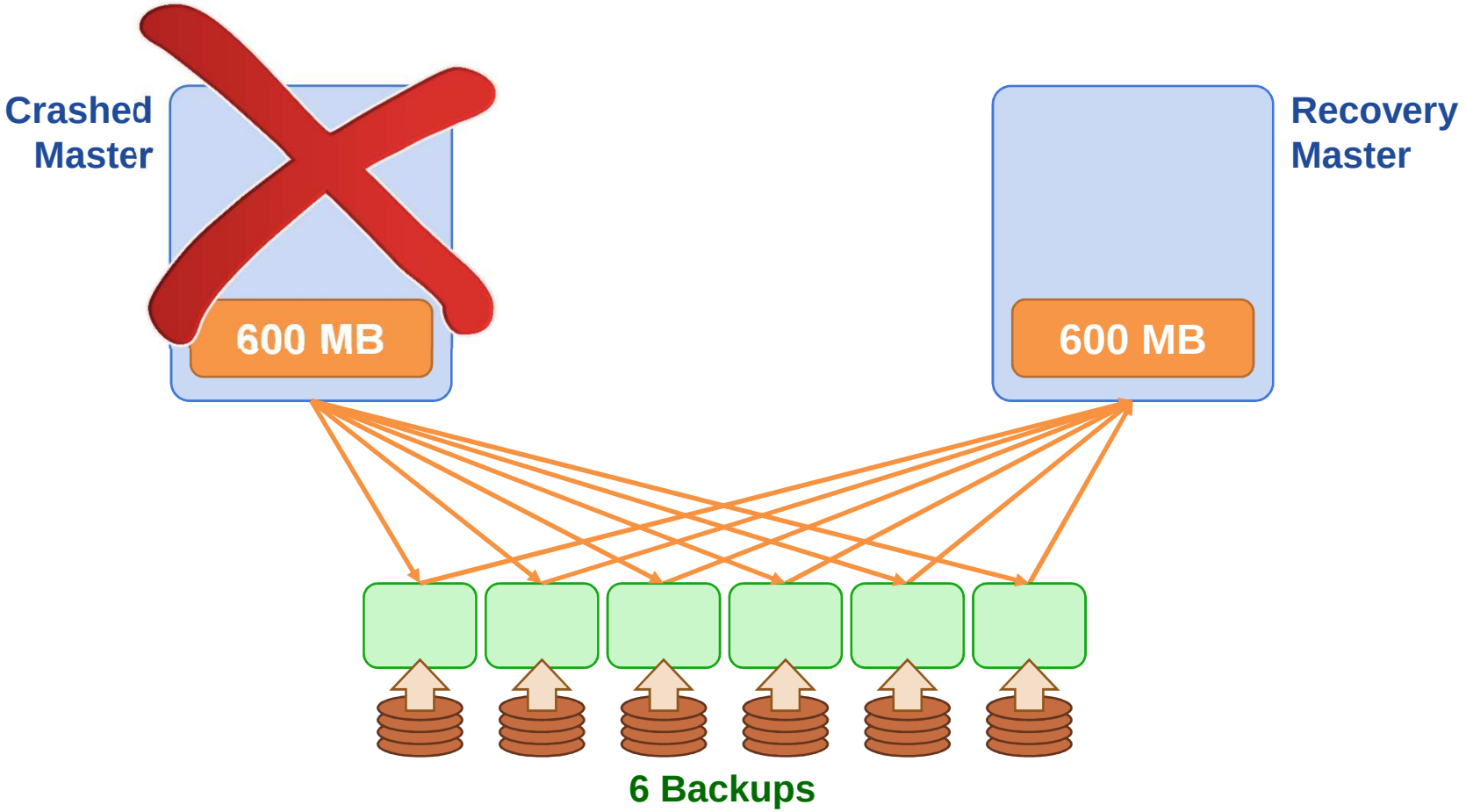
Cluster Configuration
60 Machines
2 Disks per Machine (100 MB/s/disk)
Mellanox Infiniband HCAs (25 Gbps, PCI Express limited)
5 Mellanox Infiniband Switches Two layer topology Nearly full bisection bandwidth

- **Approx. for datacenter networks in 3-5 years**
- **5.2 µs round trip from 100 B read operations**

How much can a Master recover in 1s?



How well does recovery scale?



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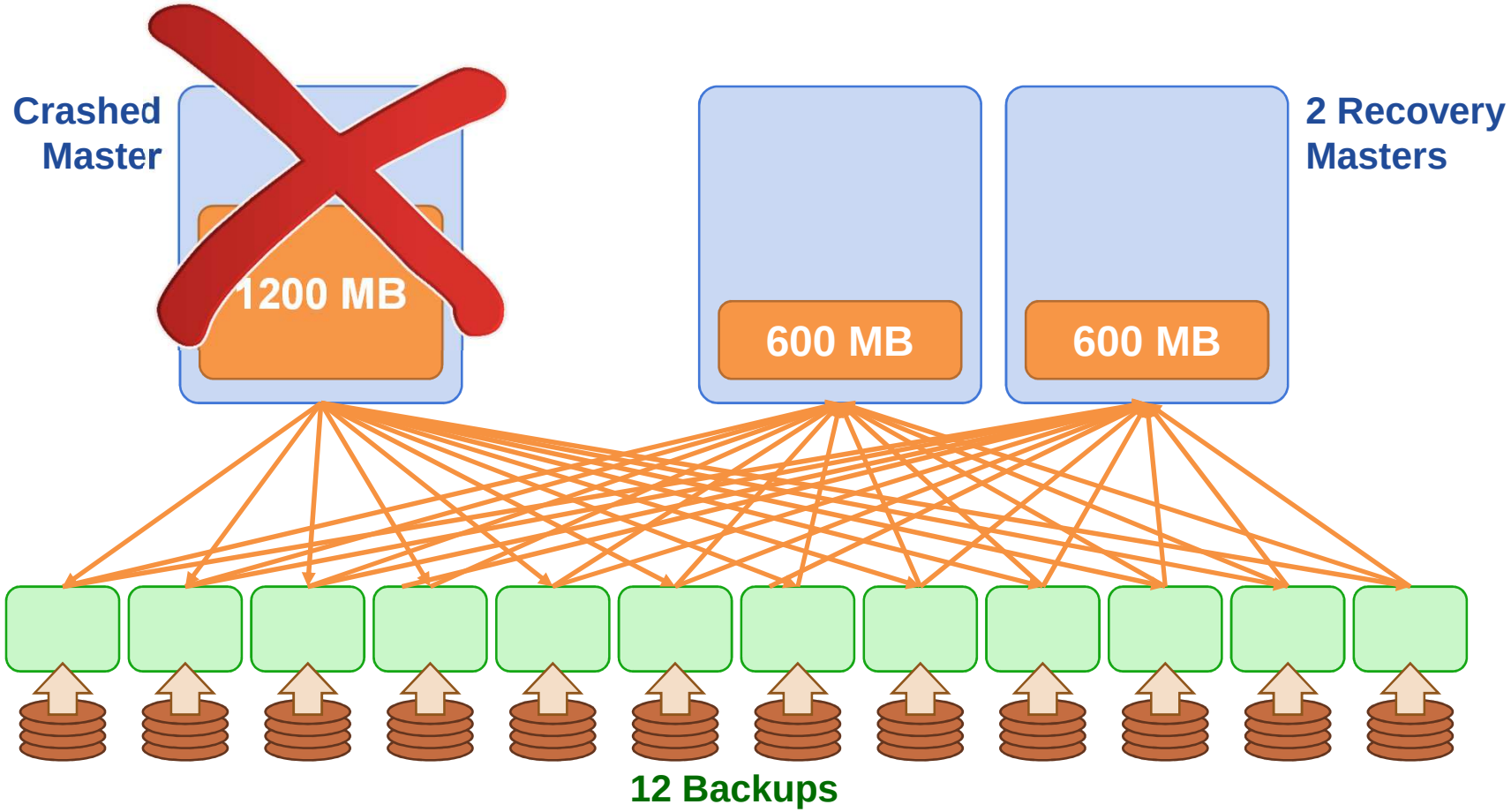

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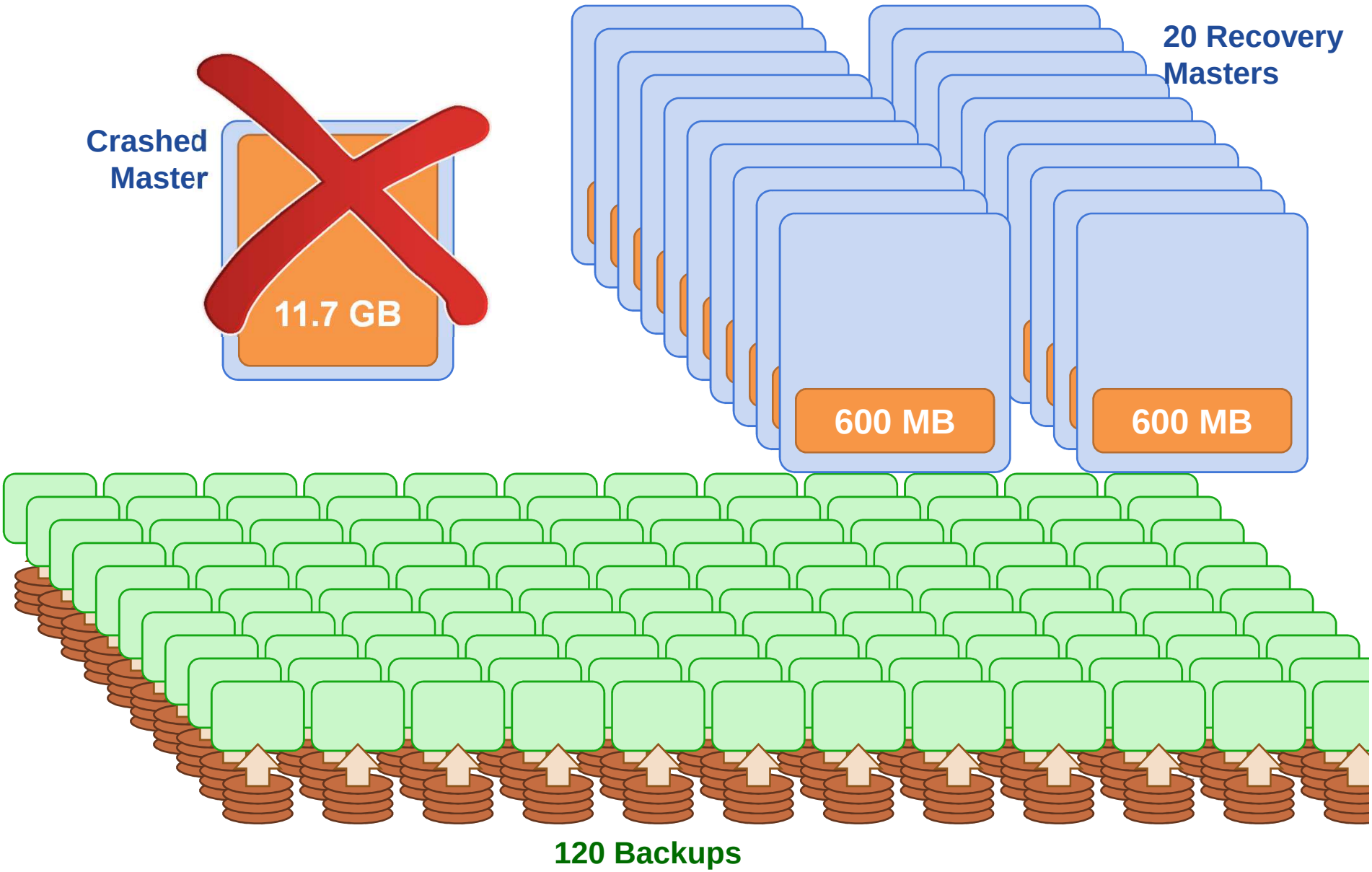

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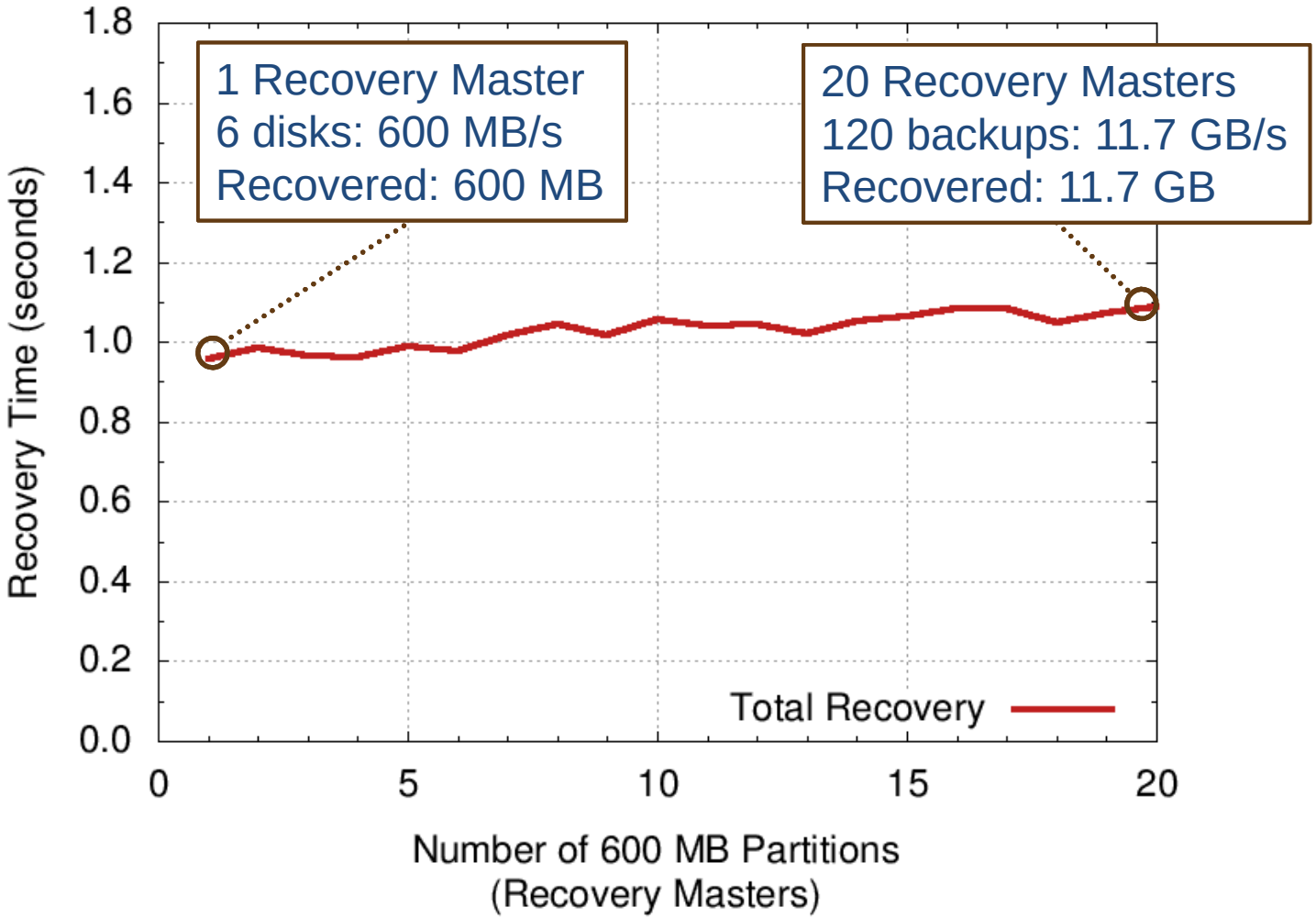

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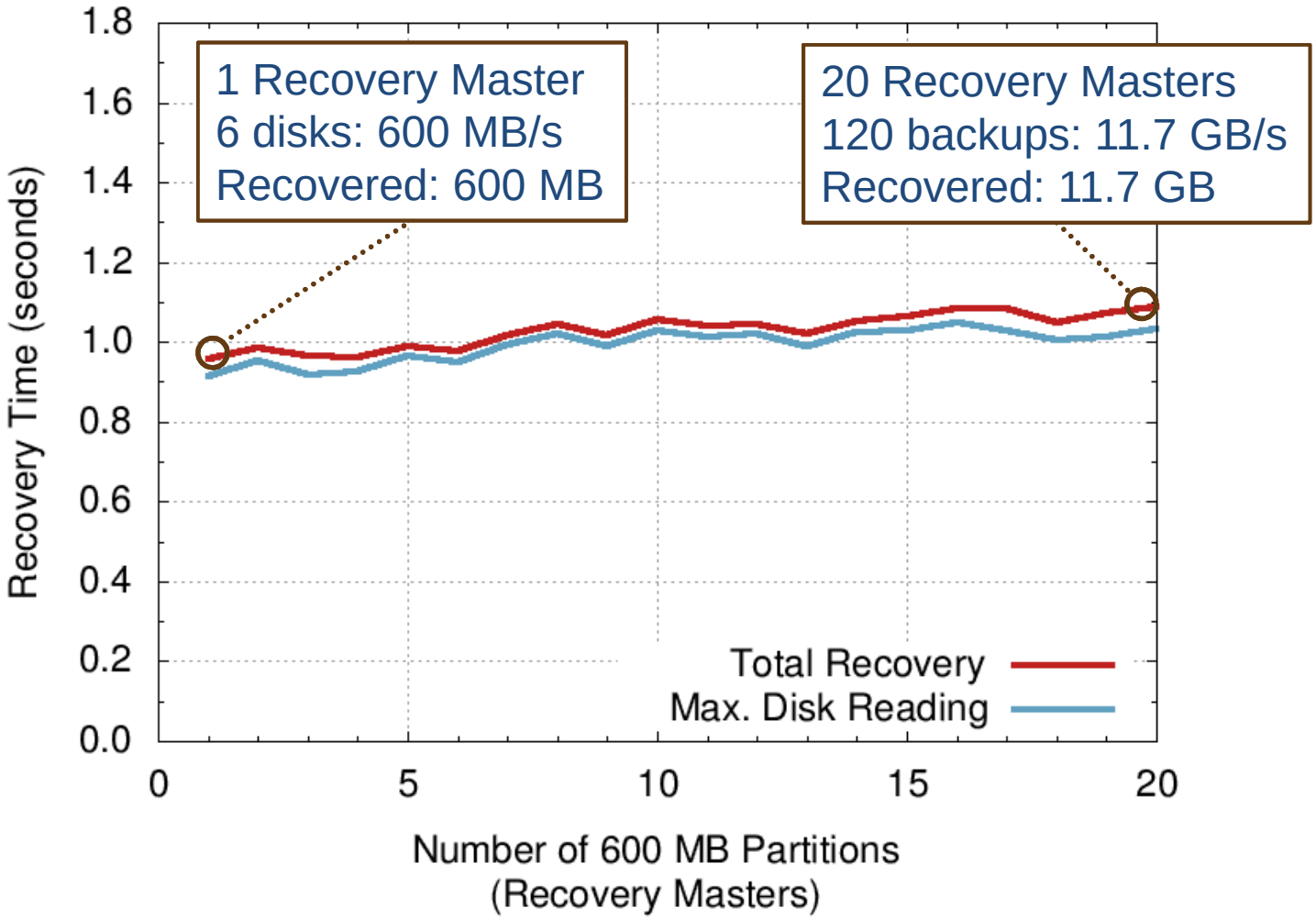
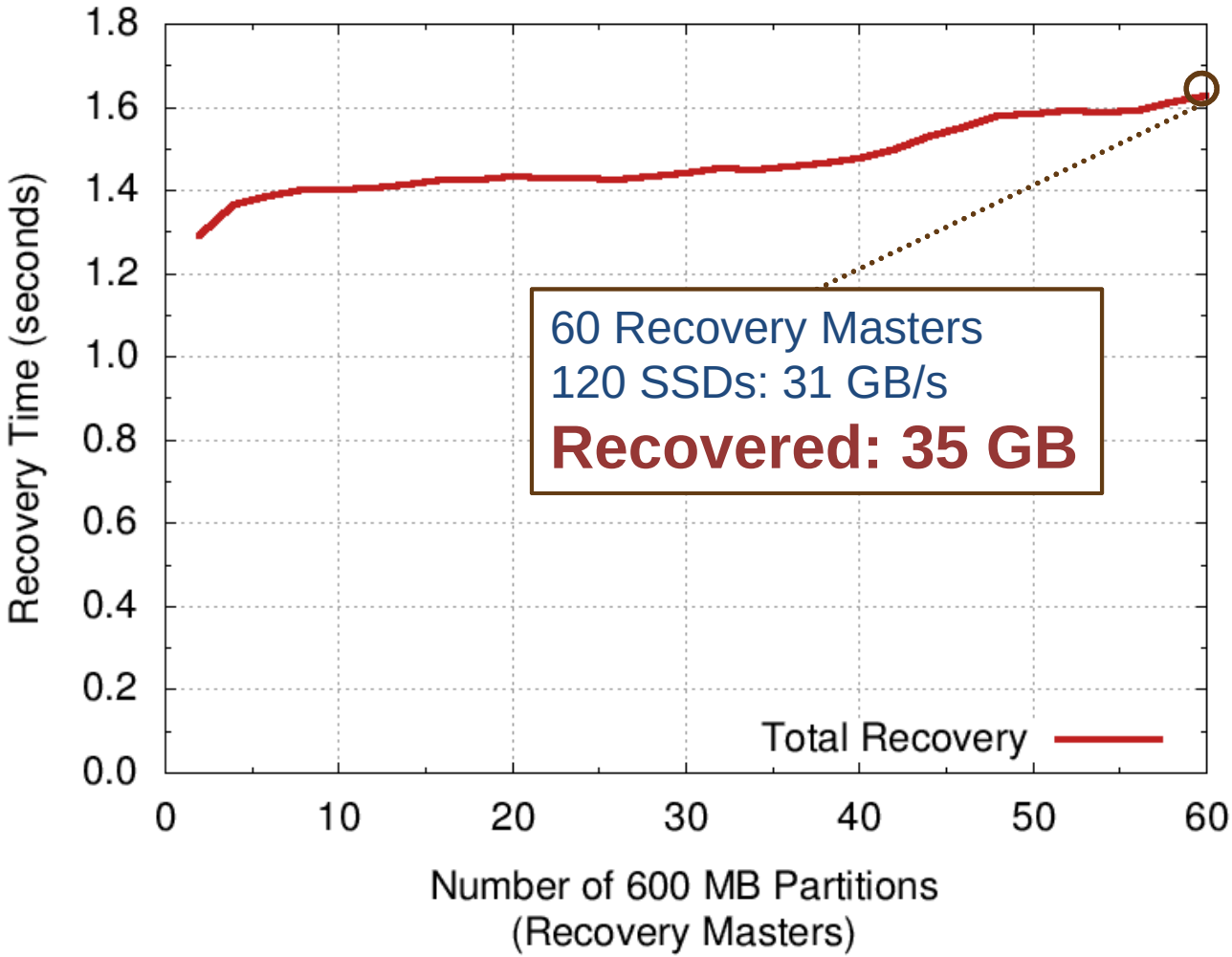


Total recovery time tightly tracks straggling disks

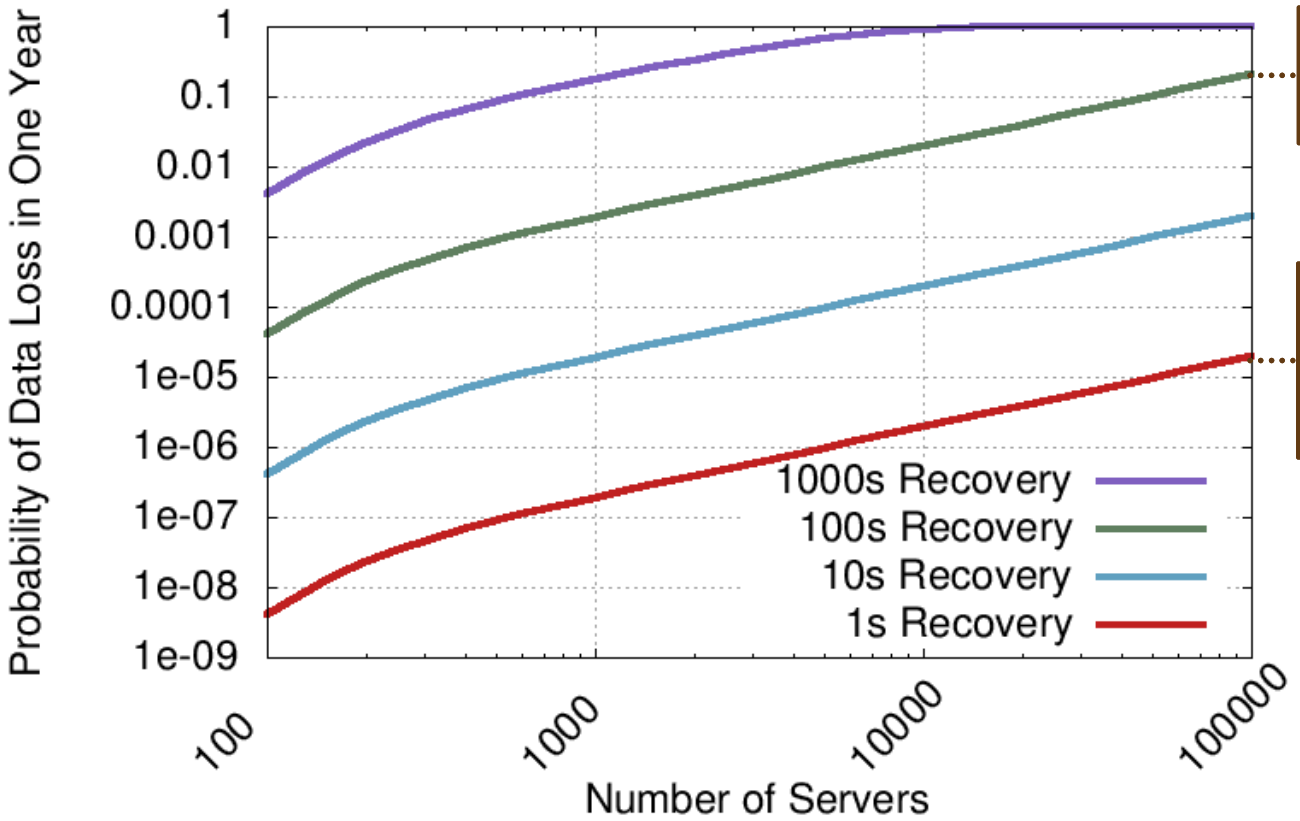
Flash Allows Higher Scalability



2x270 MB/s SSDs per recovery master

(vs. 6x100 MB/s disks per recovery master)

Fast Recovery Improves Durability



GFS (SOSP '03)
3-Copies on Disk

RAMCloud with
1-Copy in RAM
2-Copies on Disk

Assumptions:

- **2 failures/server/year**
- **Failures are independent**
- **Failures lose all contents of both RAM and disk**
- **Replication factor 3**

Related Work

- **Log-structured Filesystem (LFS)**
  - RAMCloud keeps log in-memory and on disk
  - More efficient cleaner; cleans from RAM instead of disk
- **memcached**
  - Apps must deal with backing store and consistency
  - Reduced performance from misses, cold caches
- **Bigtable + GFS**
  - Primarily disk based
  - Scatters across disks for durability
  - Bigtable uses a logging approach on GFS
  - Stores indexes, eliminates need for replay on recovery

Conclusions

- **Pervasive log structure**
  - Fast writes, inexpensive
- **Fast crash recovery in 1 to 2 s**
  - Recovers **35 GB to RAM in 1.6 s** using 60 nodes
  - Leverages the scale of the cluster
- **Potential Impact**
  - Easy to harness performance of RAM at scale
    - 5-10 µs access time
    - 100 TB to 1 PB
    - **As durable and available as disk**
  - Enable a new class data-intensive applications

Questions?

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Recovery Flow