The RAMCloud Storage System

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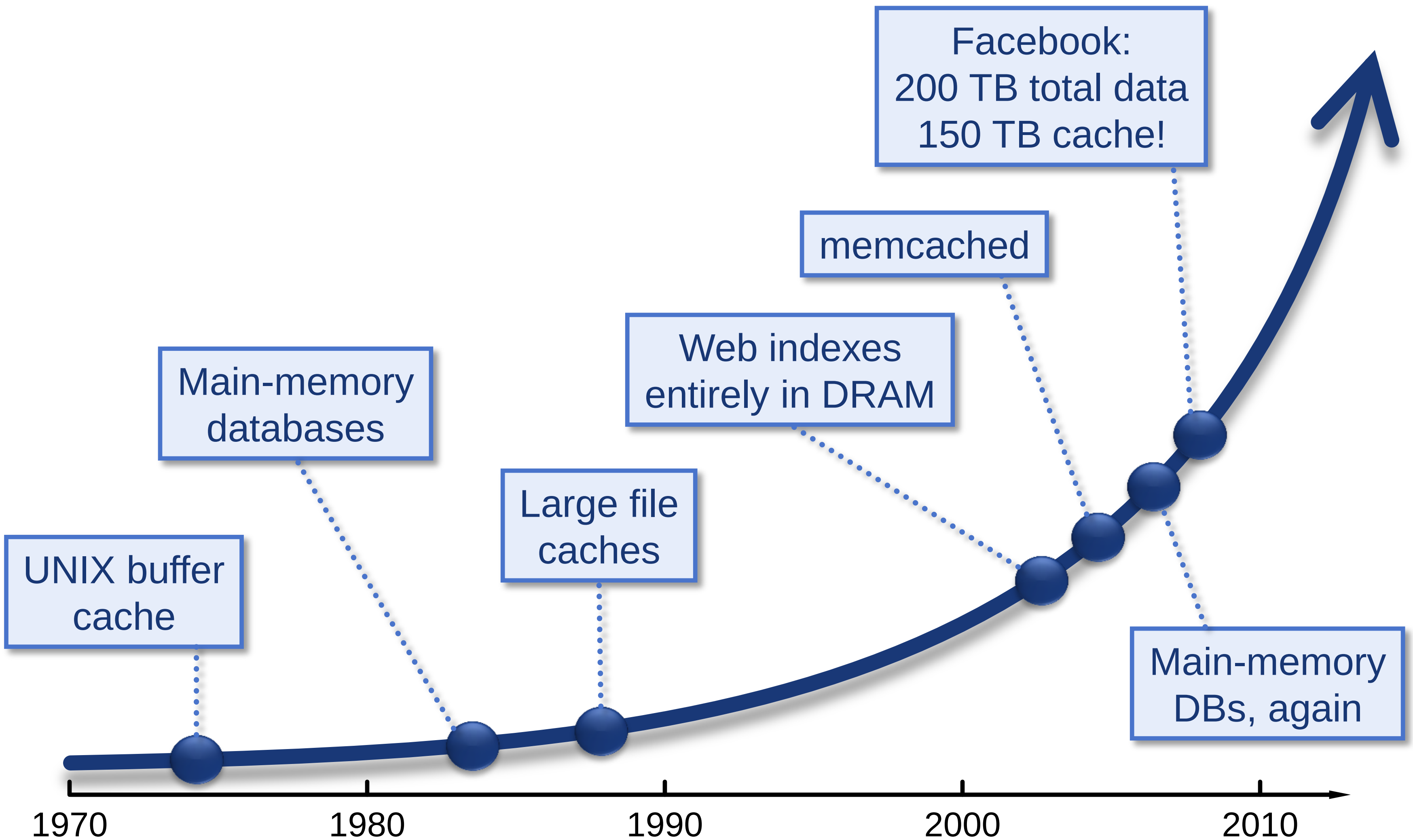
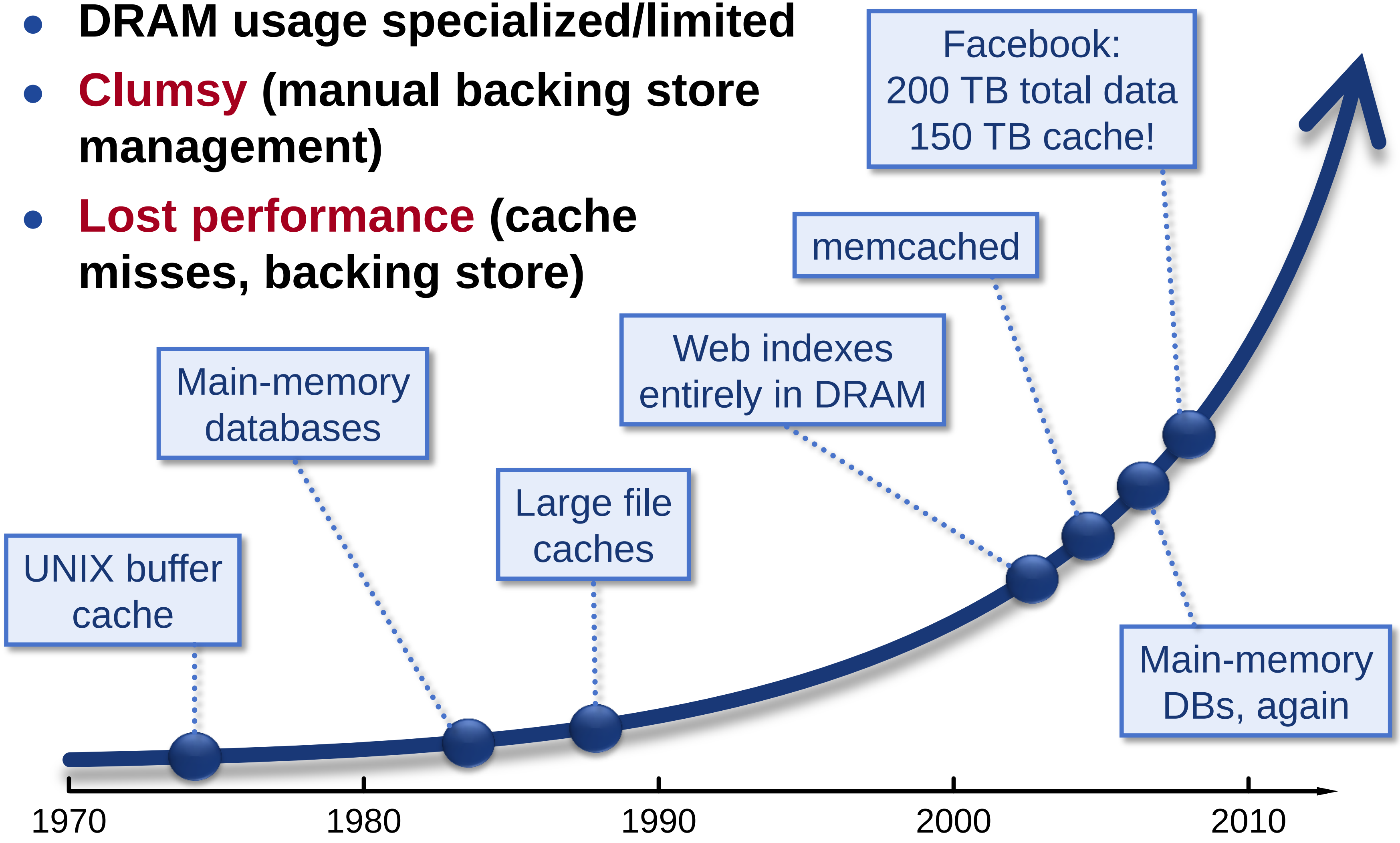
Slides available for download at http://goo.gl/13zote

DRAM in Storage Systems



DRAM in Storage Systems

- **DRAM usage specialized/limited**
- **Clumsy (manual backing store management)**
- **Lost performance (cache misses, backing store)**



RAMCloud

General-purpose DRAM-based storage for large-scale applications:

- **All data is stored in DRAM at all times**
- **As durable and available as disk**
- **Simple key-value data model**
- **Large scale: 1000+ servers, 100+ TB**
- **Low latency: 5-10 µs remote access time**

Potential impact: enable new class of applications

Performance (Infiniband)

Read 100B object	4.7 µs
Read bandwidth (large objects)	2.7 GB/s
Write 100B object (3x replication)	13.5 µs
Write bandwidth (large objects)	430 MB/s
Single-server throughput:	
Read 100B objects	900 Kobj/s
Multi-read 100B objects	6 Mobj/s
Multi-write 100B objects	450 Kobj/s
Log replay for crash recovery	800 MB/s or 2.3 Mobj/s
Crash recovery time (40 GB data, 80 servers)	1.9 s

Additional Topics To Cover

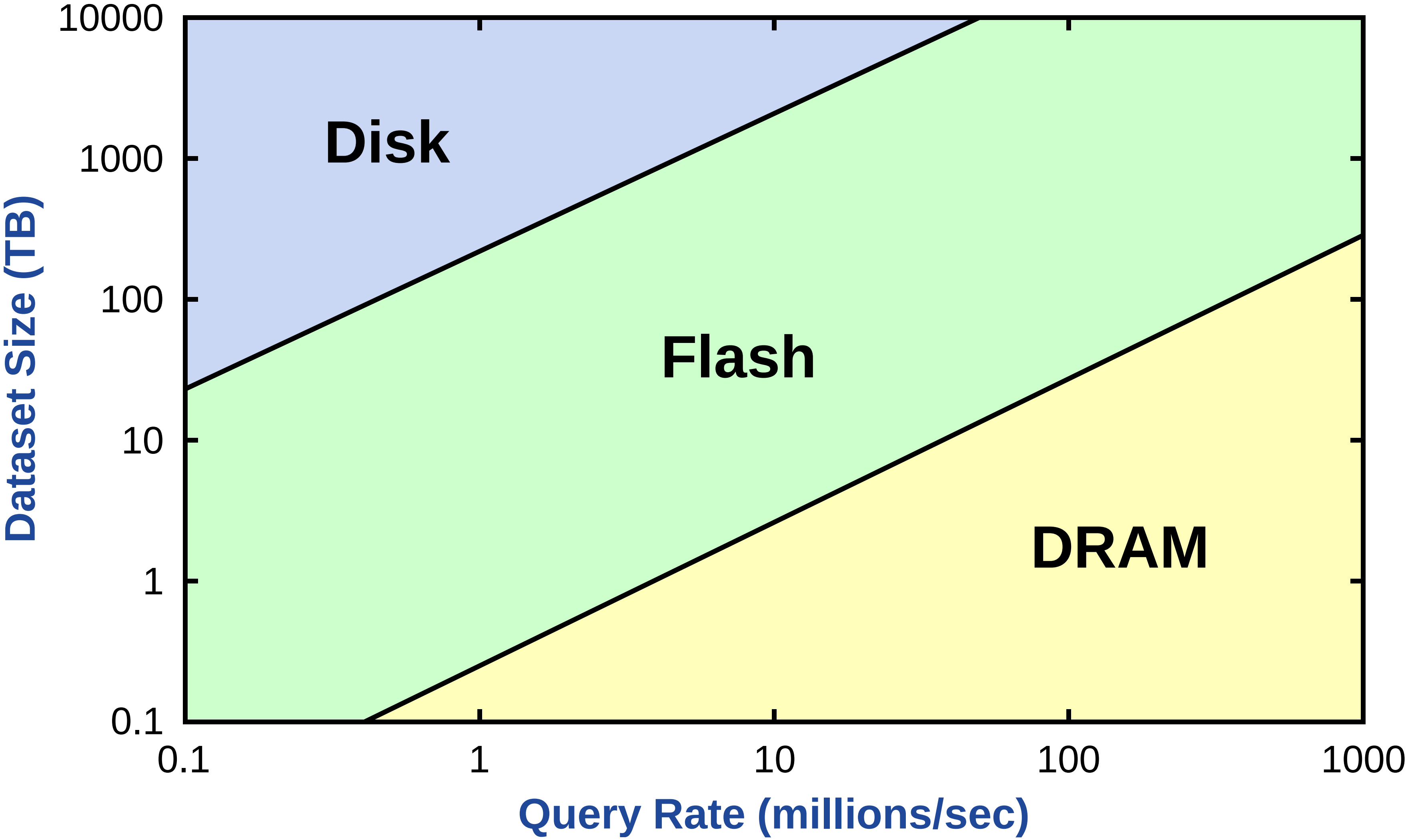
- Server lists
- History

Tutorial Outline

Part I:	**Motivation, Potential Impact**
Part II:	**Overall Architecture**
Part III:	**Log-Structured Storage**
Part IV:	**Low-Latency RPCs**
Part V:	**Crash Recovery**
Part VI:	**Status and Limitatioins**
Part VII:	**Application Experience**
Part VIII:	**Lessons Learned**

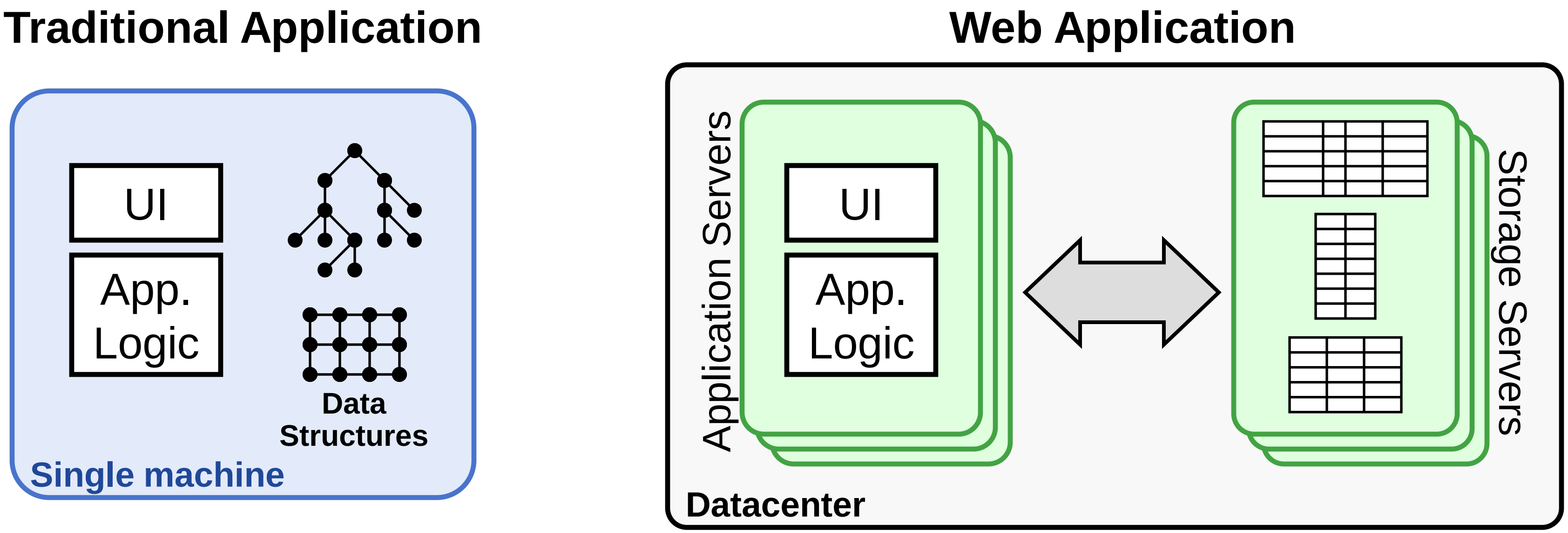
Part I: Motivation, Potential Impact

Lowest TCO



from "Andersen et al., "FAWN: A Fast Array of Wimpy Nodes",
Proc. 22nd Symposium on Operating System Principles, 2009, pp. 1-14.

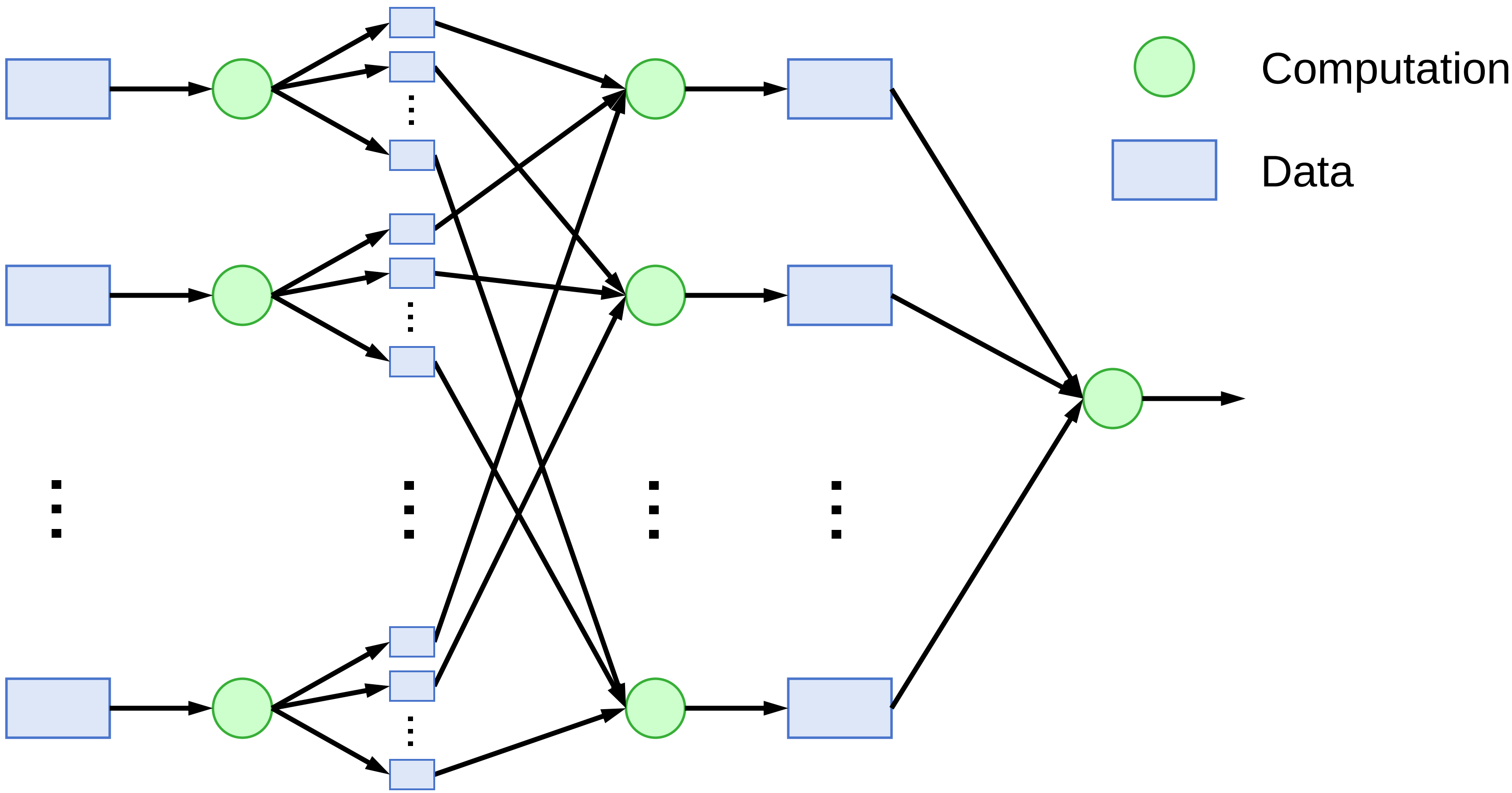
Why Does Latency Matter?



<< 1µs latency | **0.5-10ms latency**

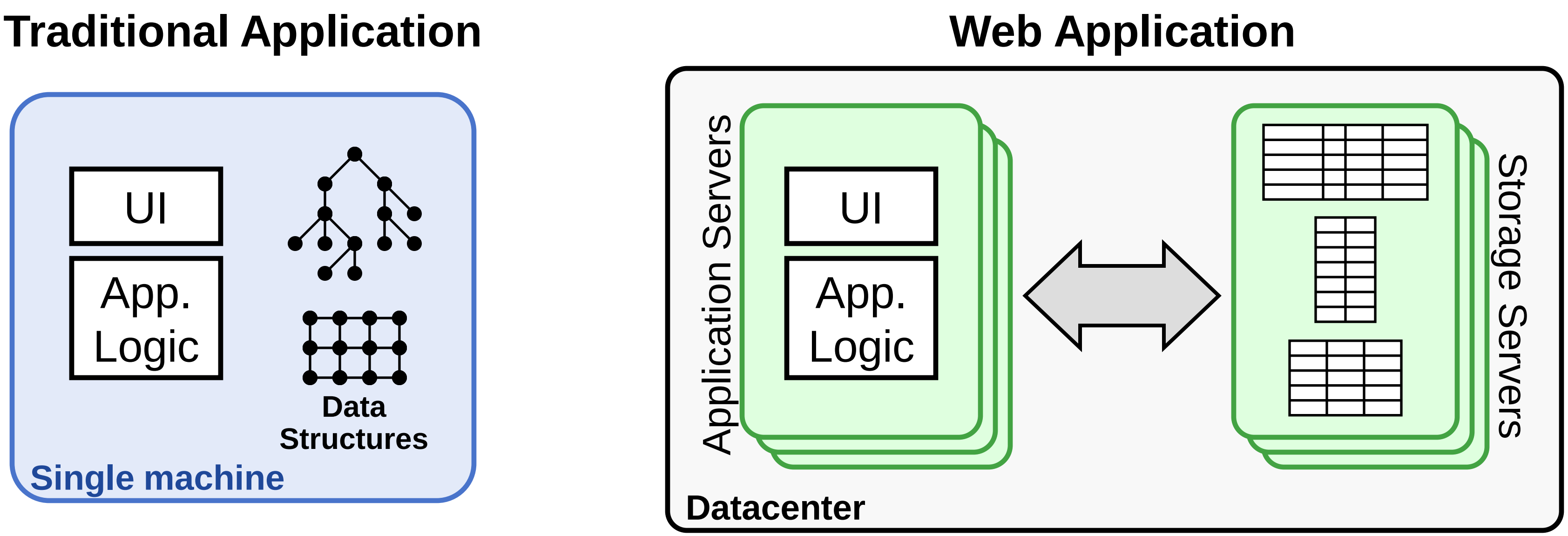
- **Large-scale apps struggle with high latency**
  - Random access data rate has not scaled!
  - Facebook: can only make 100-150 internal requests per page

MapReduce



- ✓ **Sequential data access → high data access rate**
- ✗ **Not all applications fit this model**
- ✗ **Offline**

Goal: Scale and Latency



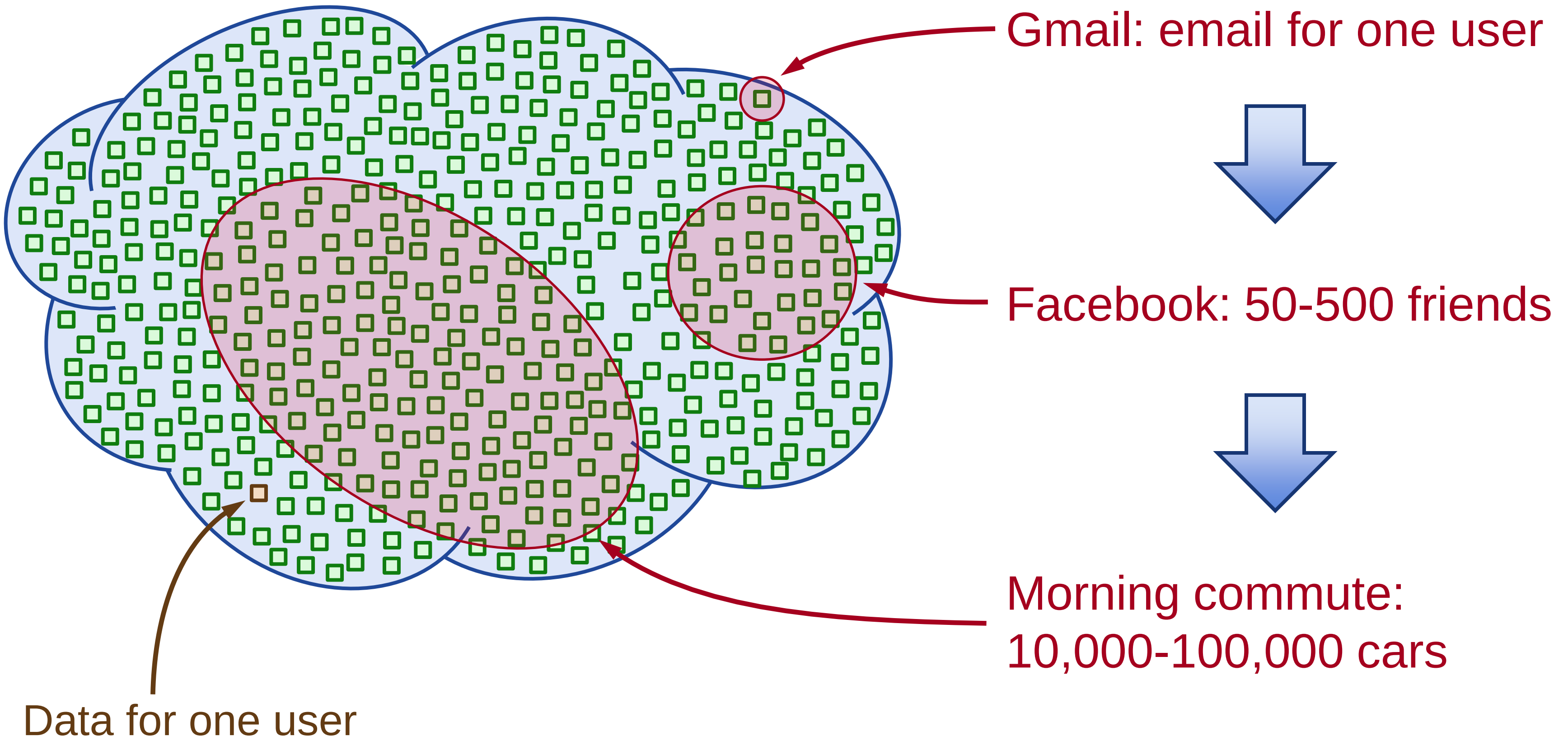
<< 1µs latency

~~0.5-10ms~~ latency
5-10µs

- **Enable new class of applications:**
  - Large-scale graph algorithms (machine learning?)
  - Collaboration at scale?

Large-Scale Collaboration

"Region of Consciousness"



Internet of Things?

Part II: Overall Architecture

Data Model: Key-Value Store

TABLE OPERATIONS

createTable(*name*) → *id*
getTableId(*name*) → *id*
dropTable(*name*)

BASIC OPERATIONS

read(*tableId, key*) → *value, version*
write(*tableId, key, value*) → *version*
delete(*tableId, key*)

BULK OPERATIONS

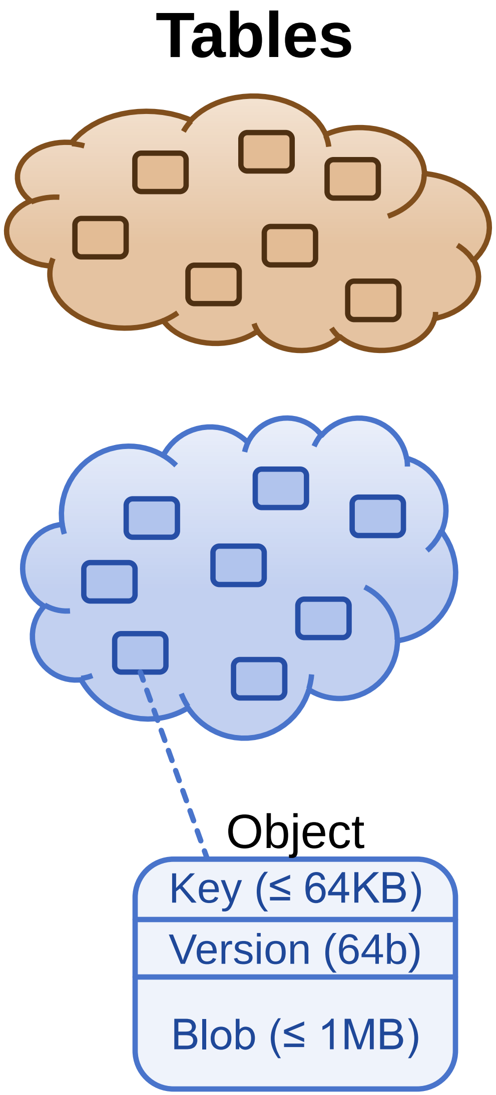
multiRead([*tableId, key*]*) → [*value*, *version*]*
multiWrite([*tableId, key, value*]*) → [*version*]*
multiDelete([*tableId*, *key*]*)
enumerateTable(tableId) → [*key, value*, *version*]*

ATOMIC OPERATIONS

increment(*tableId, key, amount*) → *value, version*
conditionalWrite(*tableId, key, value, version*) → *version*

MANAGEMENT OPERATIONS

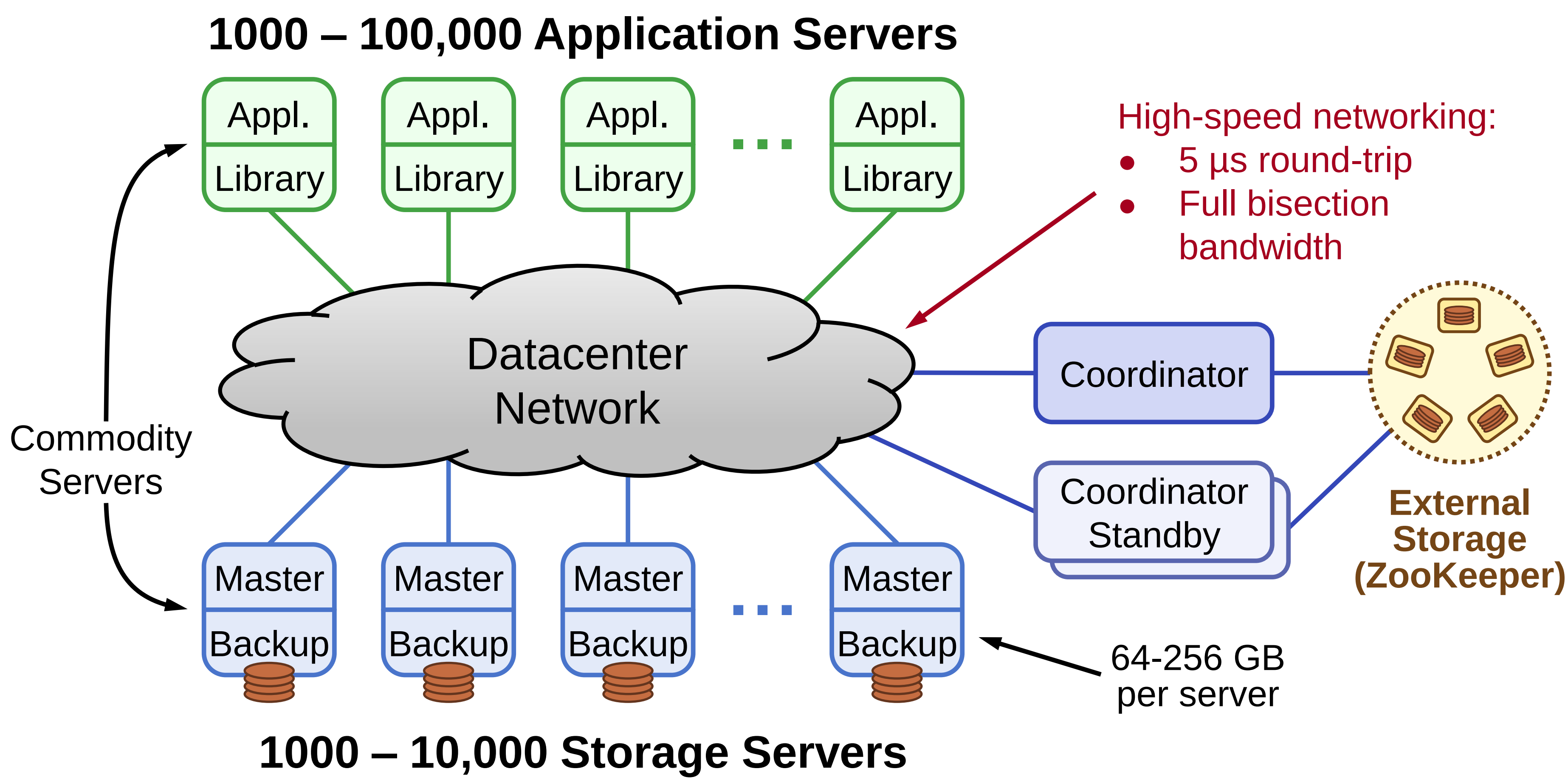
splitTablet(*tableId, keyHash*)
migrateTablet(*tableId, keyHash, newMaster*)



RAMCloud Data Model, cont'd

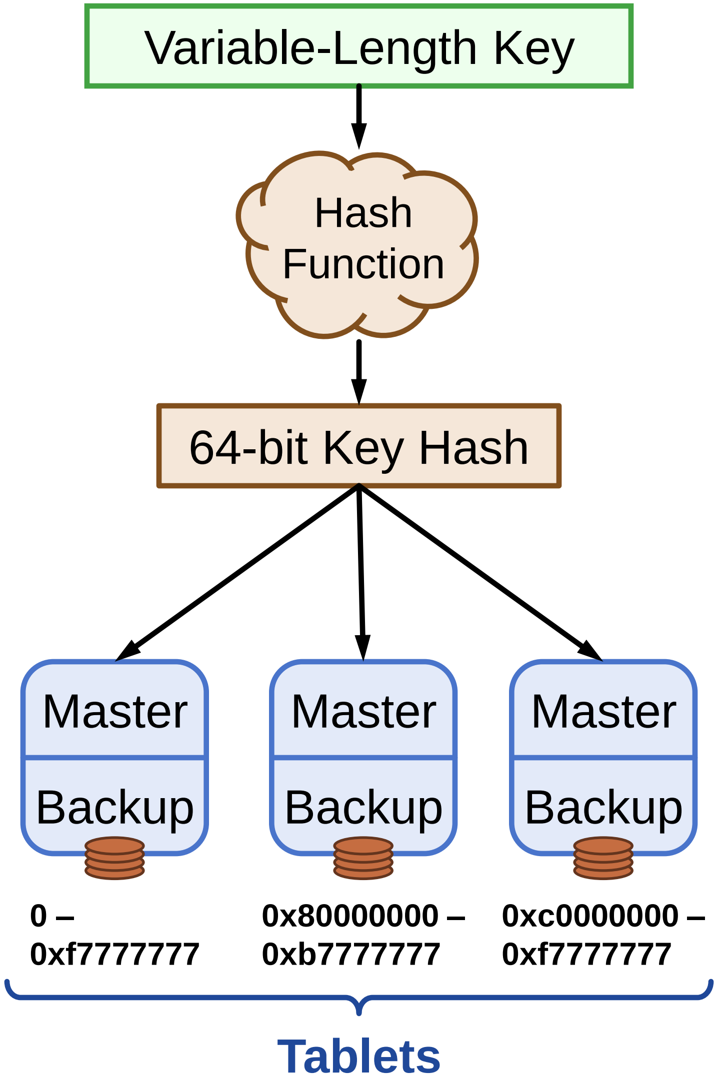
- **Goal: strong consistency (linearizability)**
  - Not yet fully implemented
- **Secondary indexes and multi-object transactions:**
  - Useful for developers
  - Not implemented in RAMCloud 1.0
  - Currently under development

RAMCloud Architecture



Hash Partitioning

- **Tables divided into tablets by key hash**
- **Tablet: unit of allocation to servers**
- **Small tables: single tablet**
- **Large tables: multiple tablets on different servers**
- **Each server stores multiple tablets**
- **Currently no automatic reconfiguration**



Example Configurations

	2010	2015–2020
# servers	2000	4000
GB/server	24GB	256GB
Total capacity	48TB	1PB
Total server cost	$3.1M	$6M
$/GB	$65	$6

For $100-200K today:

- One year of Amazon customer orders
- One year of United flight reservations

Part III: Log-Structured Storage

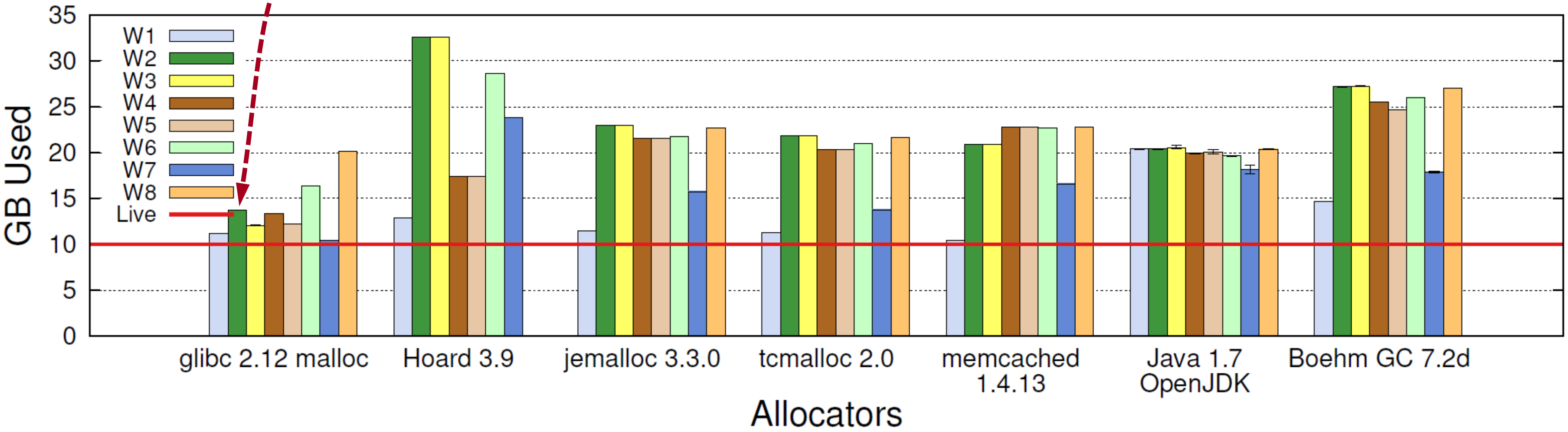
Storage System Requirements

- **High performance**
  - Read/write performance not impacted by secondary storage speed
- **Durability/availability ≥ replicated disk**
- **Efficient use of DRAM**
  - DRAM ≈ 50% of system cost
  - Goal: 80-90% DRAM utilization
- **Scalable**
  - Increase capacity/performance by adding servers
  - Centralized functionality → scalability bottleneck

Existing Allocators Waste Memory

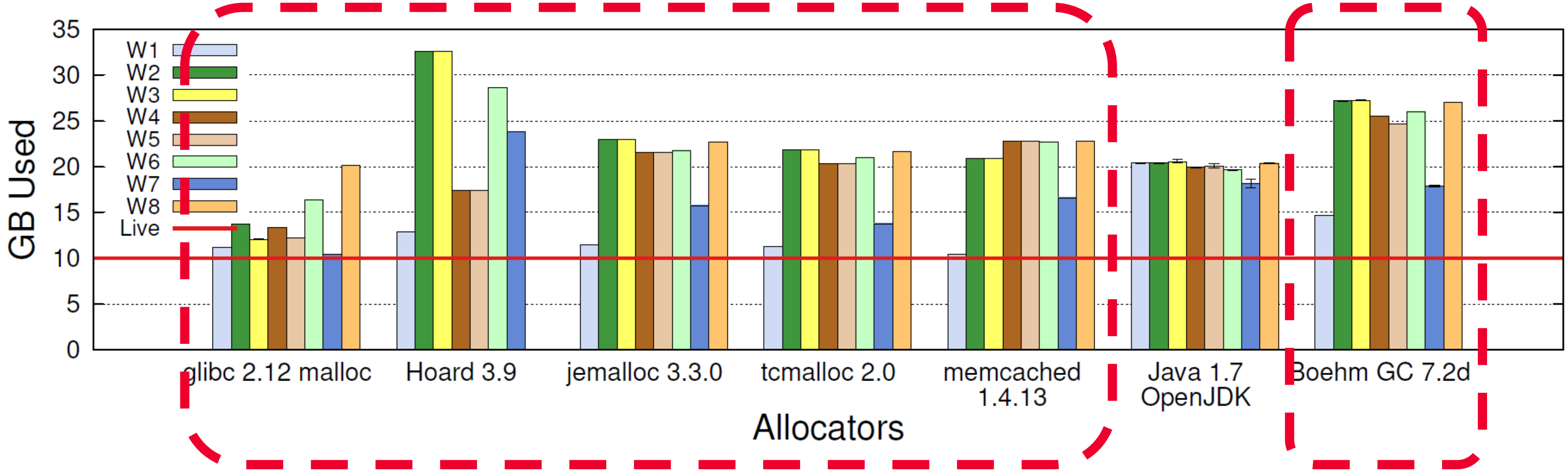
glibc malloc: 13.7 GB memory to hold 10 GB data under workload W2:

- Allocate many 100B objects
- Gradually overwrite with 130B objects

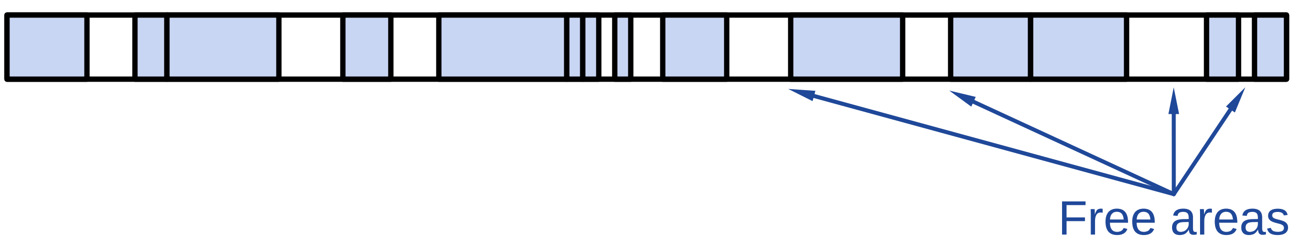


- **7 memory allocators, 8 synthetic workloads**
  - Total live data constant (10 GB)
  - But workload changes (except W1)
- **All allocators waste at least 50% of memory in some situations**

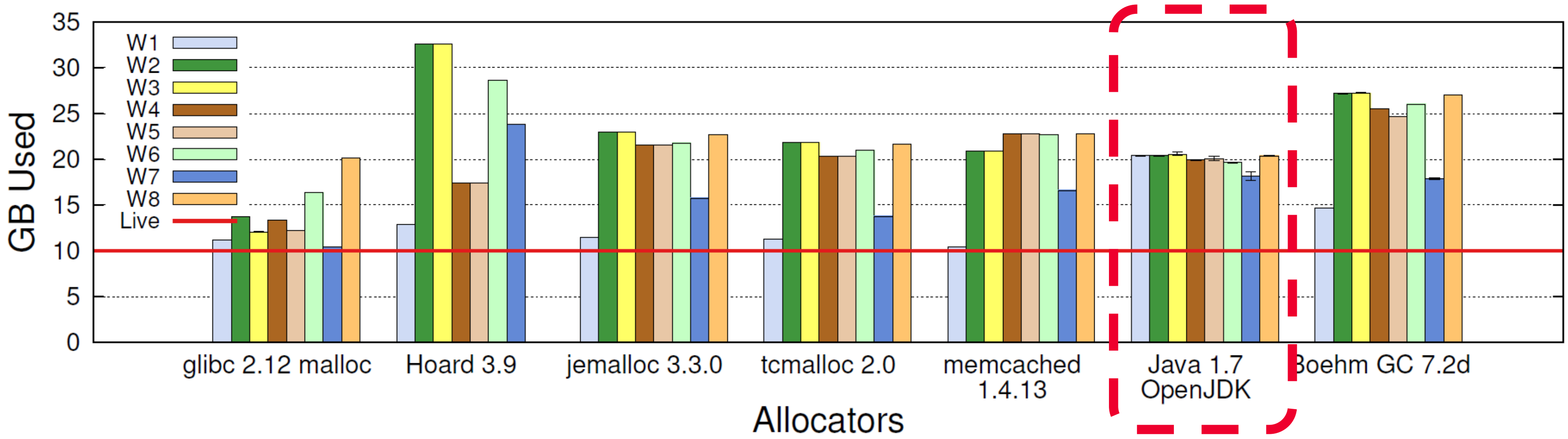
Non-Copying Allocators



- **Blocks cannot be moved once allocated**
- **Result: fragmentation**

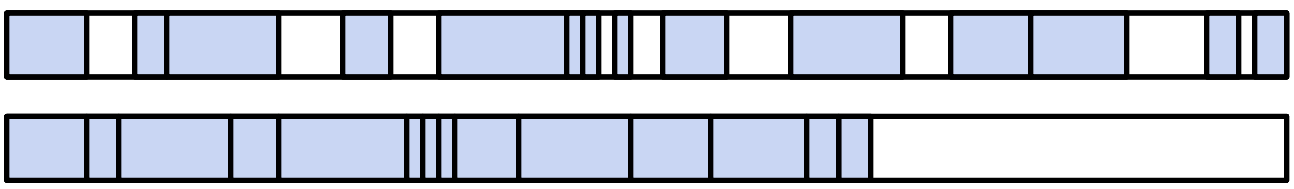


Copying Garbage Collectors



Before collection:

After collection:



- **Must scan all memory to update pointers**
  - Expensive, scales poorly
  - Wait for lots of free space before running GC
- **State of the art: 3-5x overallocation of memory**
- **Long pauses: 3+ seconds for full GC**

Allocator for RAMCloud

- **Requirements:**
  - Must use copying approach
  - Must collect free space incrementally
- **Storage system advantage: pointers restricted**
  - Pointers stored in index structures
  - Easy to locate pointers for a given memory block
  - Enables incremental copying
- **Solution: log-structured storage**

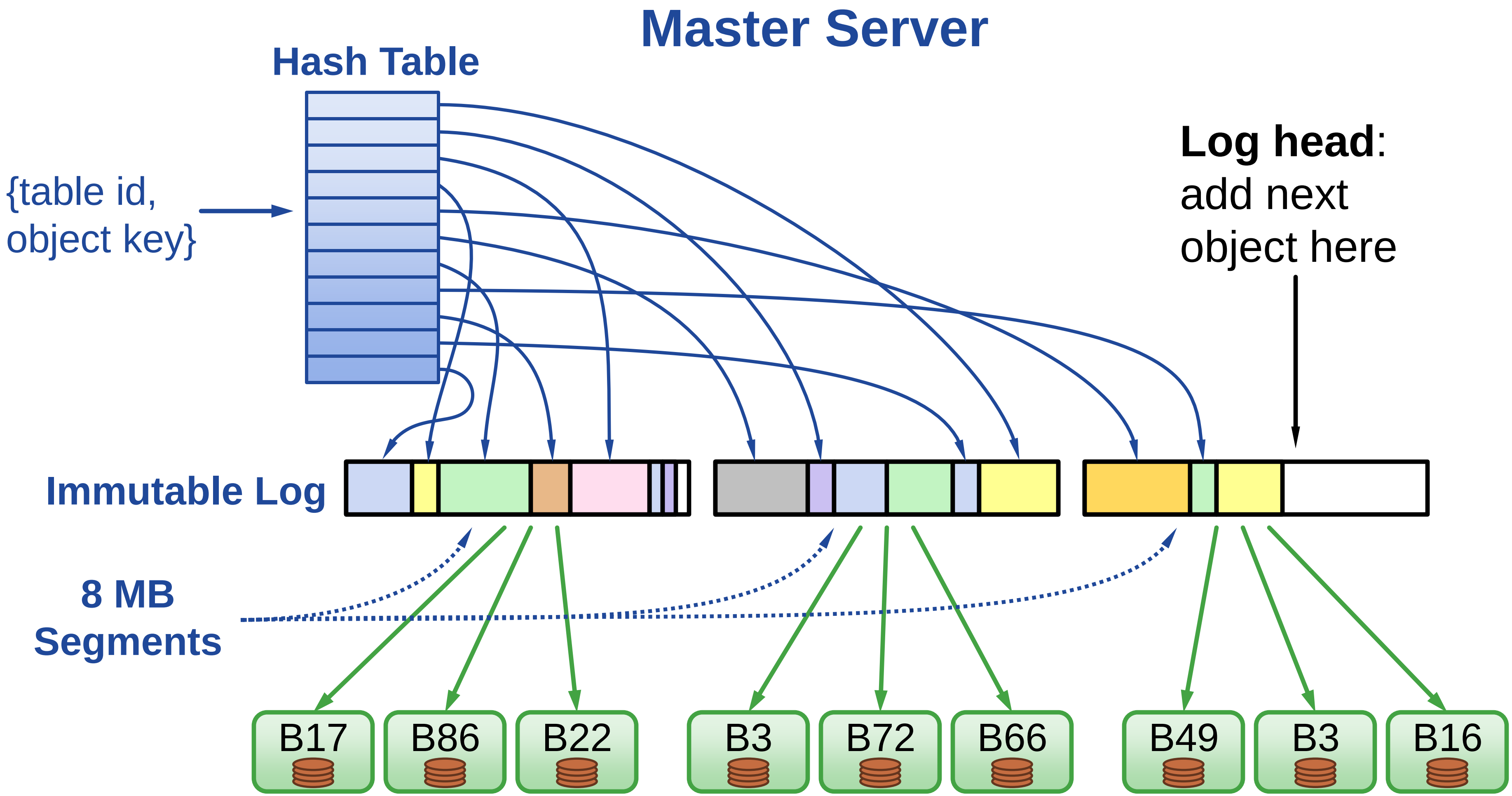
Durability/Availability

- **All data must be replicated**
- **Replication in DRAM?**
  - Expensive
  - Insufficient (power failures)
- **RAMCloud: primary-backup approach:**
  - One copy in DRAM
  - Multiple copies on secondary storage (disk/flash)
  - Must recover quickly after crashes
- **Challenge: secondary storage latency**
  - Must not affect RAMCloud access times

Log-Structured Storage

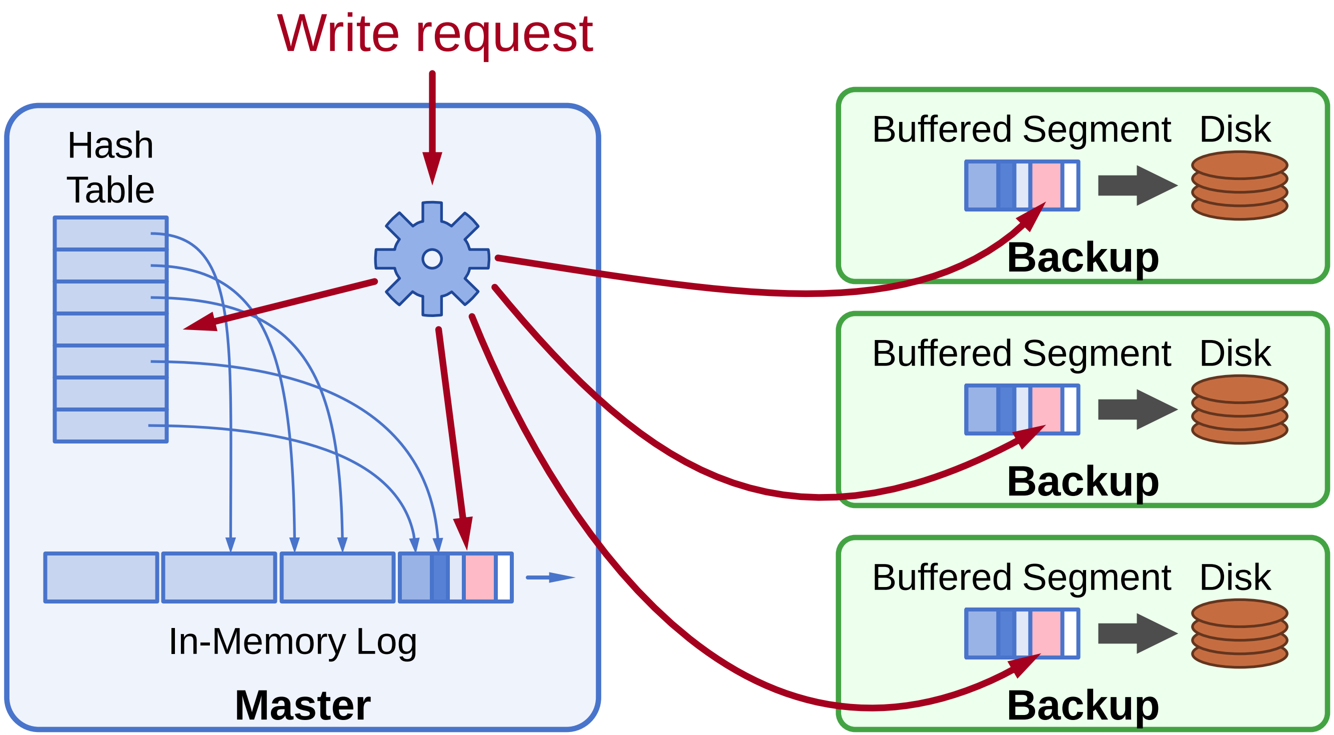
- **Store all data in append-only logs:**
  - One log per master
  - Both DRAM and secondary storage
  - Techniques similar to log-structured file systems
- **Benefits:**
  - Fast allocation
  - High throughput: batched updates to secondary storage
  - 80-90% memory utilization
  - Insensitive to workload changes
  - Crash recovery: replay log
  - Consistency: serializes operations

Log-Structured Storage



Each segment replicated on disks of 3 backup servers

Durable Writes



- **No disk I/O during write requests**
- **Backups perform I/O in background**
- **Buffer memory must be non-volatile (NVDIMMs?)**

Logs on Secondary Storage

Never read from disk or flash ...

except during crash recovery ...

then read master's entire log.

Log Entry Types

Object

Table Id	Key	Version	Timestamp	Value

Tombstone (identifies dead object)

Table Id	Key	Version	Segment Id

Segment Header

Master Id	Segment Id

Log Digest (identifies all segments in log)

Segment Id	Segment Id	...	Segment Id

Tablet Statistics

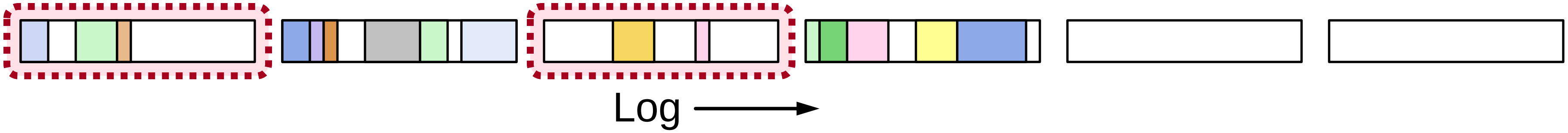
For each tablet: # log entries, log bytes (compressed)

Safe Version

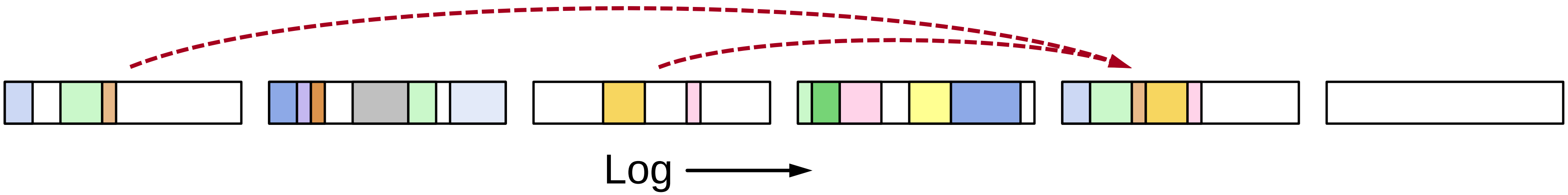
Version # larger than any used on master

Log Cleaning

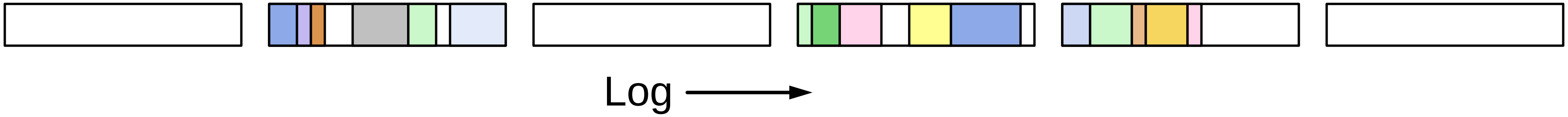
1. **Pick segments with lots of free space:**



2. **Copy live objects (survivors):**



3. **Free cleaned segments (and backup replicas)**



Cleaning is incremental

Tombstones

- **How to prevent reincarnation during crash recovery?**
- **Tombstones:**
  - Written into log when object deleted or overwritten:
    - Table id
    - Object key
    - Version of dead object
    - Id of segment where object stored
- **When can tombstone be cleaned?**
  - After segment containing object has been cleaned (and replicas deleted on backups)
- **Note: tombstones are a mixed blessing**

Cleaning Cost

U: fraction of live bytes in cleaned segments

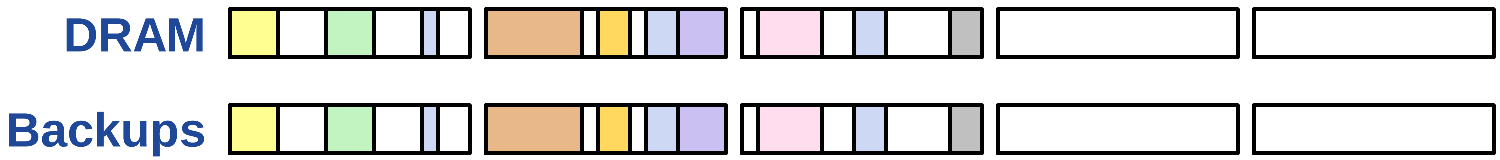
	0.5	0.9	0.99
Bytes copied by cleaner (U)	0.5	0.9	0.99
Bytes freed (1-U)	0.5	0.1	0.01
Bytes copied/byte freed (U/(1-U))	1.0	9.0	99.0

Conflicting Needs:

	Capacity	Bandwidth
Memory	expensive	cheap
Disk	cheap	expensive

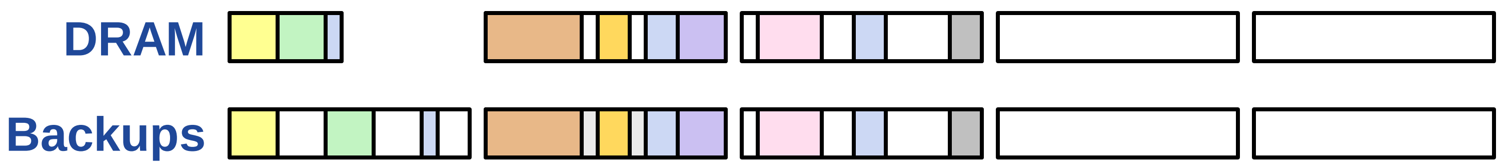
Need different policies for cleaning disk and memory

Two-Level Cleaning



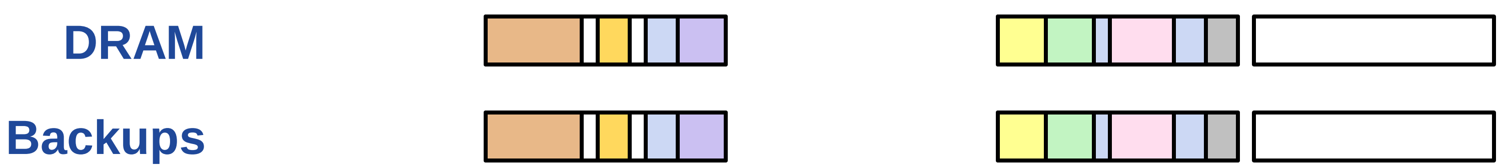
Compaction:

- Clean single segment in memory
- No change to replicas on backups



Combined Cleaning:

- Clean multiple segments
- Free old segments (disk & memory)

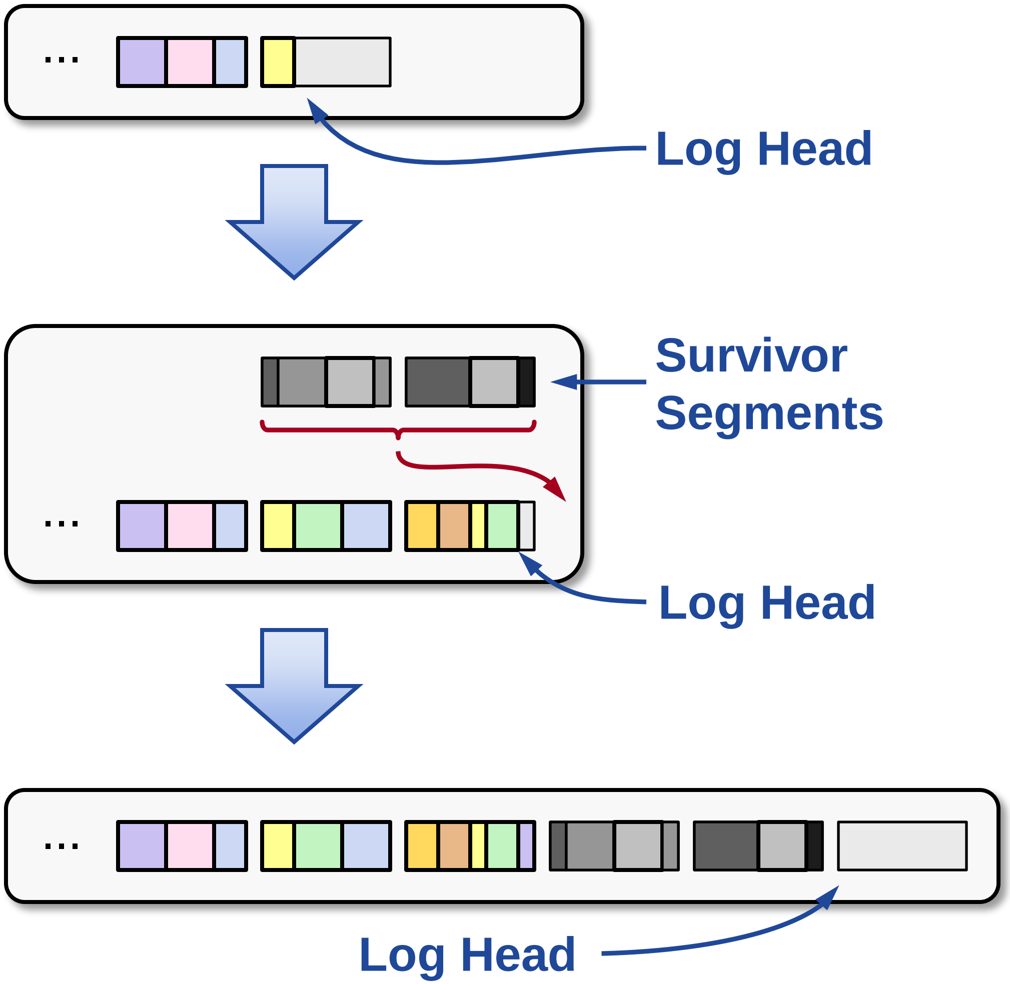


Two-Level Cleaning, cont'd

- **Best of both worlds:**
  - Optimize utilization of memory
    (can afford high bandwidth cost for compaction)
  - Optimize disk bandwidth
    (can afford extra disk space to reduce cleaning cost)
- **But:**
  - Segments in DRAM no longer fixed-size
    (implement with 128 KB seglets)
  - Compaction cannot clean tombstones
    (must eventually perform combined cleaning)

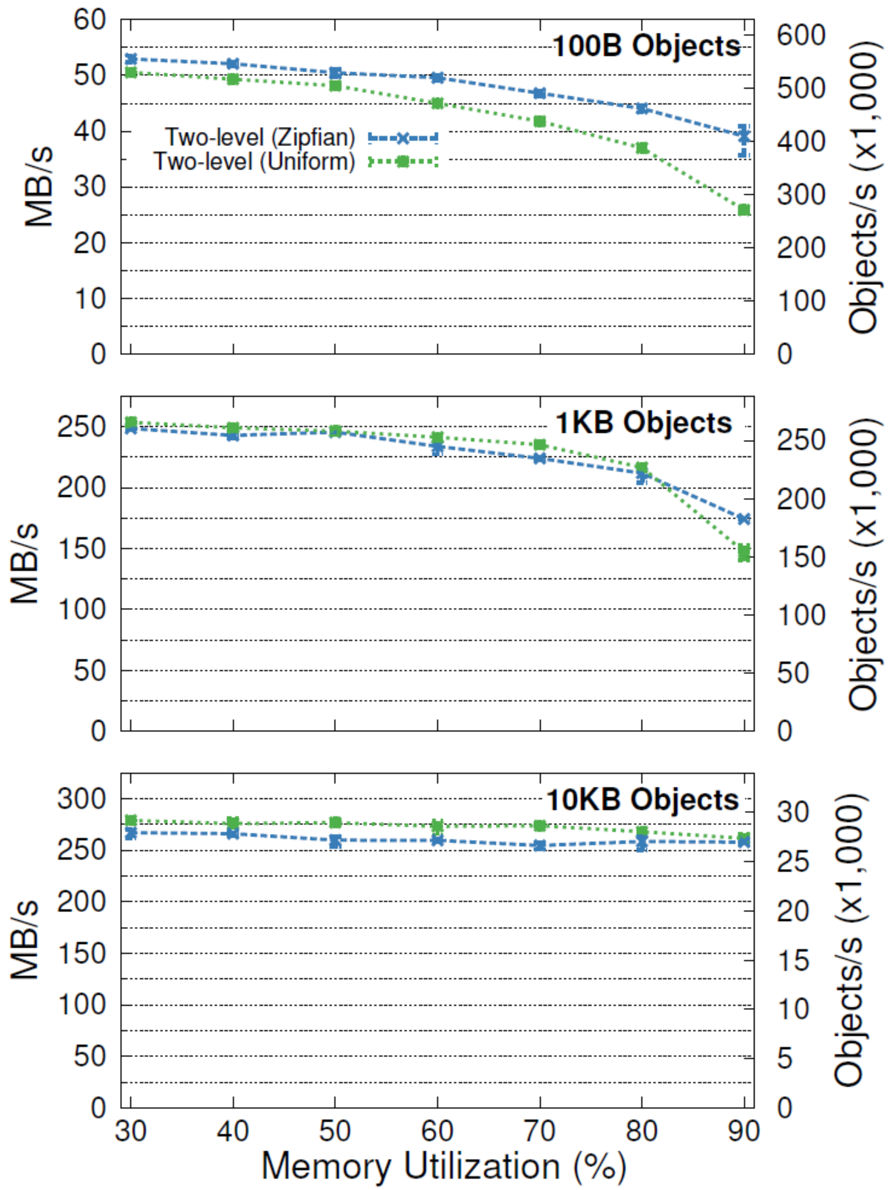
Parallel Cleaning

- **Survivor data written to "side log"**
  - No competition for log head
  - Different backups for replicas
- **Synchronization points:**
  - Updates to hash table
  - Adding survivor segments to log
  - Freeing cleaned segments



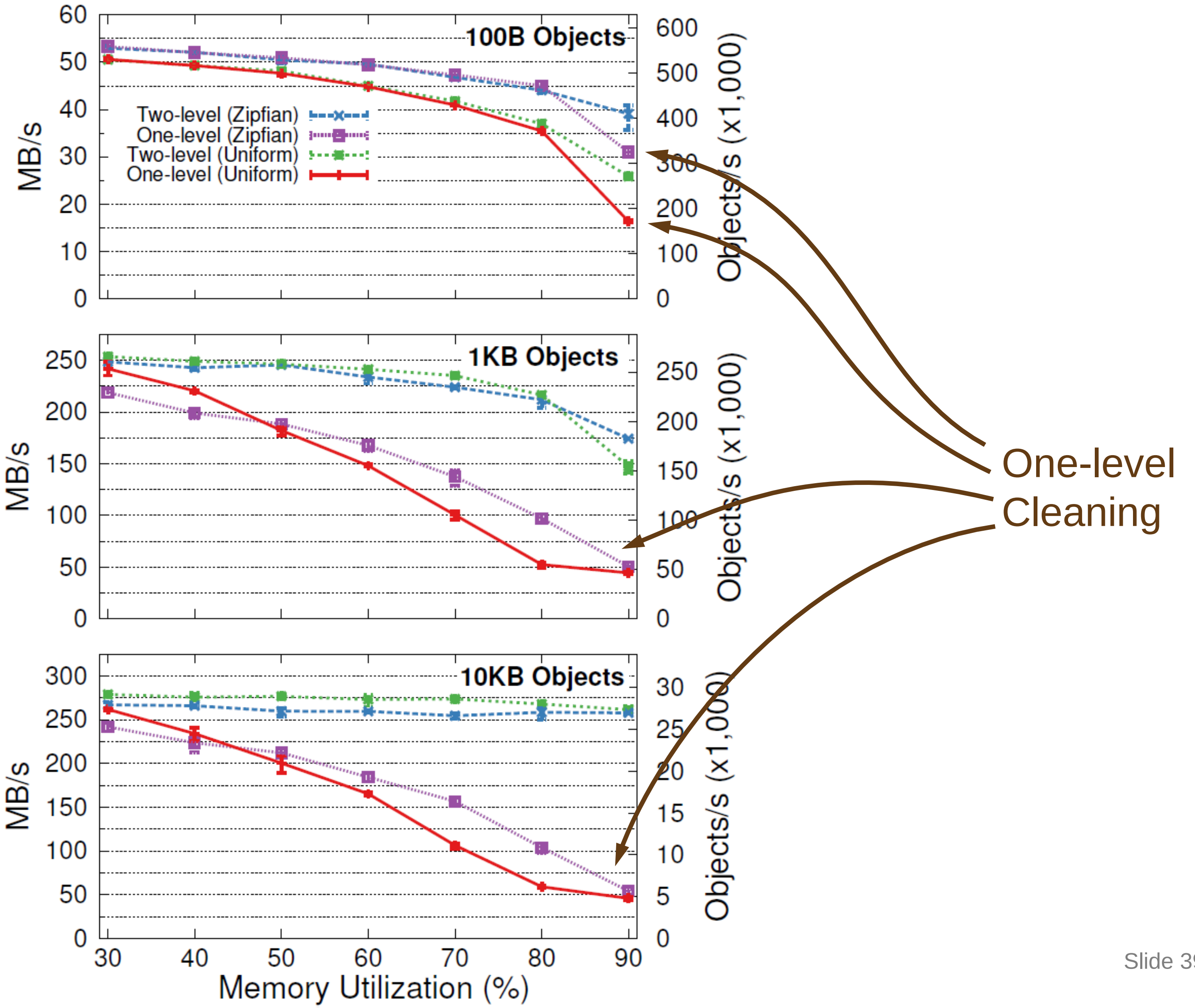
Throughput vs. Memory Utilization

1 master,
3 backups,
1 client,
concurrent
multi-writes



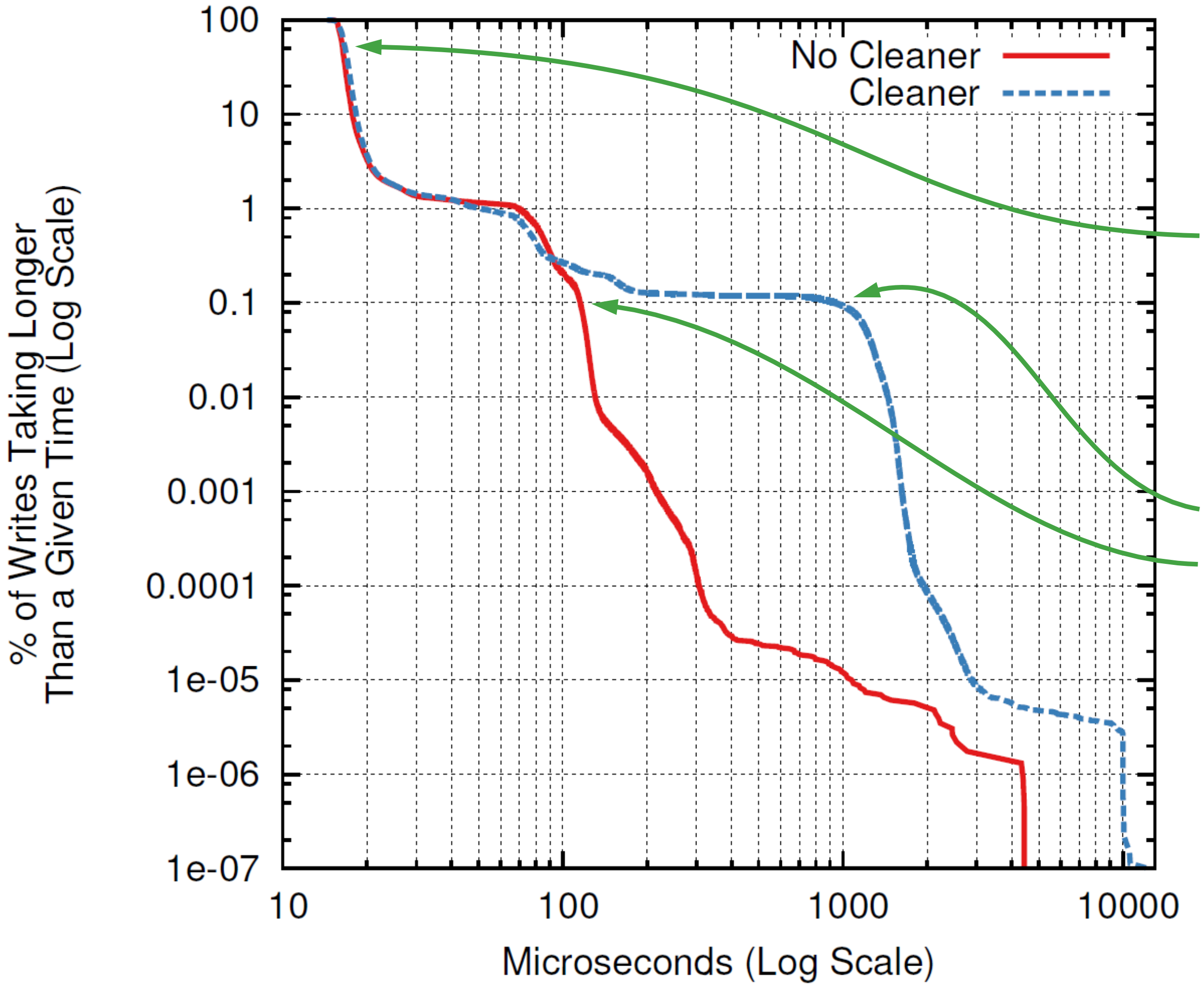
Memory Utilization	Performance Degradation
80%	17-27%
90%	26-49%
80%	14-15%
90%	30-42%
80%	3-4%
90%	3-6%

1-Level vs. 2-Level Cleaning



Cleaner's Impact on Latency

1 client, sequential 100B overwrites, no locality, 90% utilization



Median:

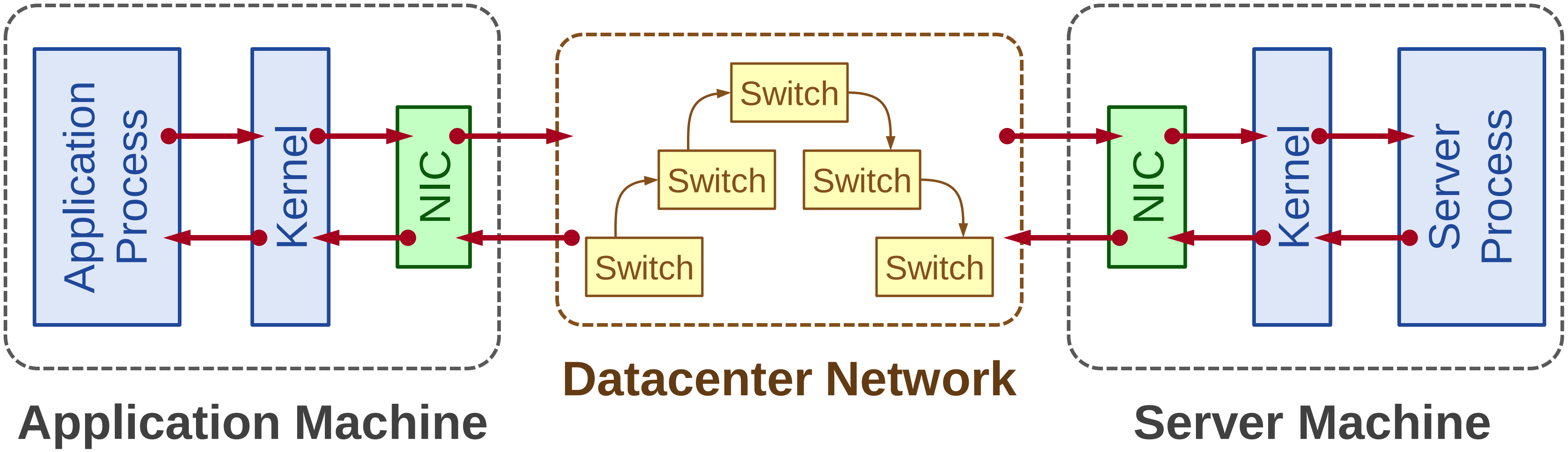
- With cleaning: 16.70 µs
- No cleaner: 16.35 µs

99.9th %ile:

- With cleaning: 900 µs
- No cleaner: 115 µs

Part IV: Low-Latency RPCs

Datacenter Latency in 2009



Component	Delay	Round-trip
Network switch	10-30 µs	100-300 µs
OS protocol stack	15 µs	60 µs
Network interface controller (NIC)	2.5-32 µs	2-128 µs
Propagation delay	0.5 µs	1.0 µs

Typical in 2009: 200-400 µs **RAMCloud goal: 5-10 µs**

How to Improve Latency

- **Network switches (10-30 µs per switch in 2009):**
  - 10Gbit switches: 500 ns per switch
  - Radical redesign: 30 ns per switch
  - Must eliminate buffering
- **Software (60 µs total in 2009):**
  - Kernel bypass: 2 µs
    - Direct NIC access from applications
    - Polling instead of interrupts
  - New protocols, threading architectures: 1µs
- **NIC (2-32 µs per transit in 2009):**
  - Optimize current architectures: 0.75 µs per transit
  - Radical NIC CPU integration: 50 ns per transit

Round-Trip Delay, Revisited

Component	2009	2015	Limit
Switching fabric	100-300 µs	5 µs	0.2 µs
Operating system	60 µs	0 µs	0 µs
Application/server	2 µs	2 µs	1 µs
NIC	8-128 µs	3 µs	0.2 µs
Propagation delay	1 µs	1 µs	1 µs
Total	200-400 µs	11 µs	2.4 µs

- **Biggest remaining hurdles:**
  - Software
  - Speed of light

RAMCloud Goal: 1 µs Service Time

- **Can't afford many L3 cache misses (< 10?)**
- **Can't afford much synchronization**
  - Acquire-release spin lock (no cache misses): 16 ns
- **Can't afford kernel calls**
- **Can't afford batching**
  - Trade-off between bandwidth and latency

Low Latency in RAMCloud

- **Kernel bypass:**
  - Map virtual NIC into application address space
  - Originally developed for Infiniband (Mellanox)
  - Now becoming available for 10 GigE (Intel, SolarFlare, etc.)
    - Driven by demand for faster virtual machines
    - Newer Mellanox NICs also support 10 GigE
    - Latency unimpressive for many NICs (RPC round-trip 2x Mellanox)
- **Polling:**
  - Client spins while waiting for RPC response
    - Response time < context switch time
    - Condition variable wakeup takes 2 µs
  - Server spins while waiting for incoming request
    - Burns 1 core even when idle

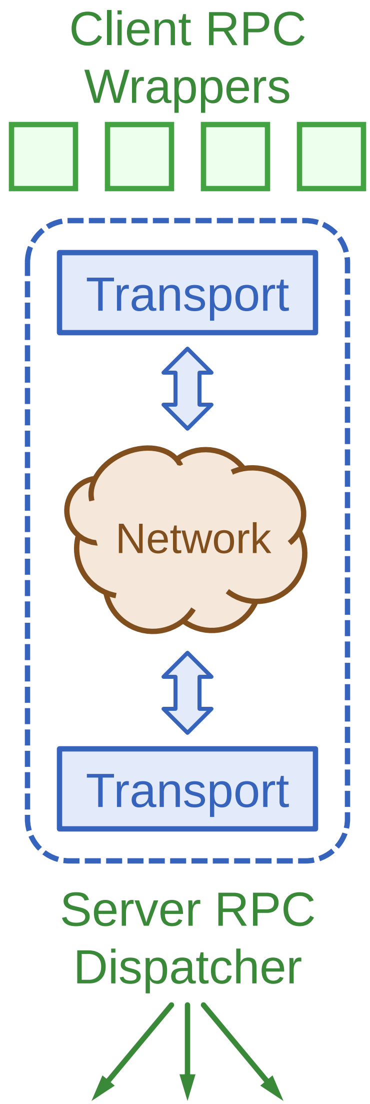
Transports

- **Encapsulate different approaches to networking**
  - Service naming
  - Reliable delivery of request & response messages
- **Client APIs:**

```
session = transport->getSession(
    serviceLocator);
session->sendRequest(request,
    response);
response->isReady();
```

- **Server API (callout):**

```
handleRpc(request) → response
```



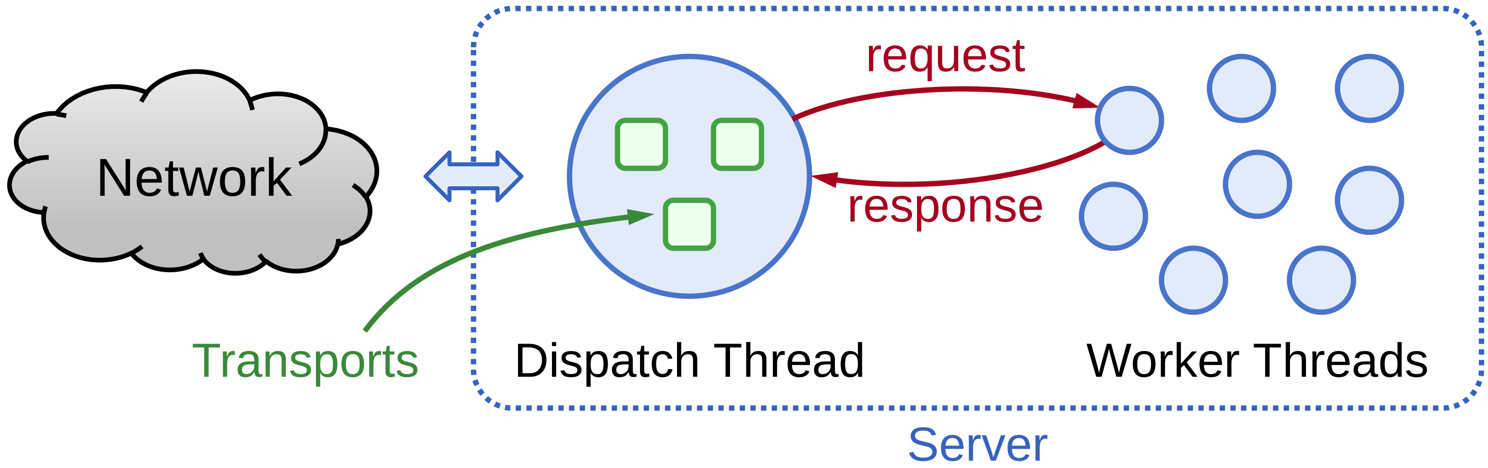
Current Transports

- **InfRcTransport**
  - Uses Infiniband Verbs APIs (reliable connected queue pairs)
  - Supports kernel bypass
  - Our workhorse transport (4.7 µs for 100B reads)
- **TcpTransport**
  - Uses kernel TCP sockets
  - Slow (50-150 µs for 100B reads)
- **FastTransport**
  - Custom protocol (reliable, flow-controlled, in-order delivery)
  - Layered on unreliable datagram drivers
  - Current drivers:
    - Kernel UDP
    - Infiniband unreliable datagrams (kernel bypass)
    - SolarFlare (10 GigE with kernel bypass)
  - Not yet as fast as InfRcTransport....

Threading Architecture

- **Initial implementation: single-threaded**
  - No synchronization overhead
  - Minimizes latency
- **Fragile:**
  - Can't process heartbeats during long-running requests
  - Callers will assume server crashed
  - "Crashes" cascade
- **Vulnerable to distributed deadlock:**
  - Nested RPCs sometimes needed:
    - E.g, replication during writes
  - All resources can be consumed with top-level requests

Dispatch Thread and Workers



- **Dispatch thread:**
  - Runs all transports
  - Polls network for input; never sleeps
  - Dispatches requests to workers
  - Thread limits for different request classes: prevent deadlock
- **Worker thread:**
  - Processes RPC requests
  - Returns responses to dispatch thread
  - Polls to wait for next request; eventually sleeps

Threads are Expensive!

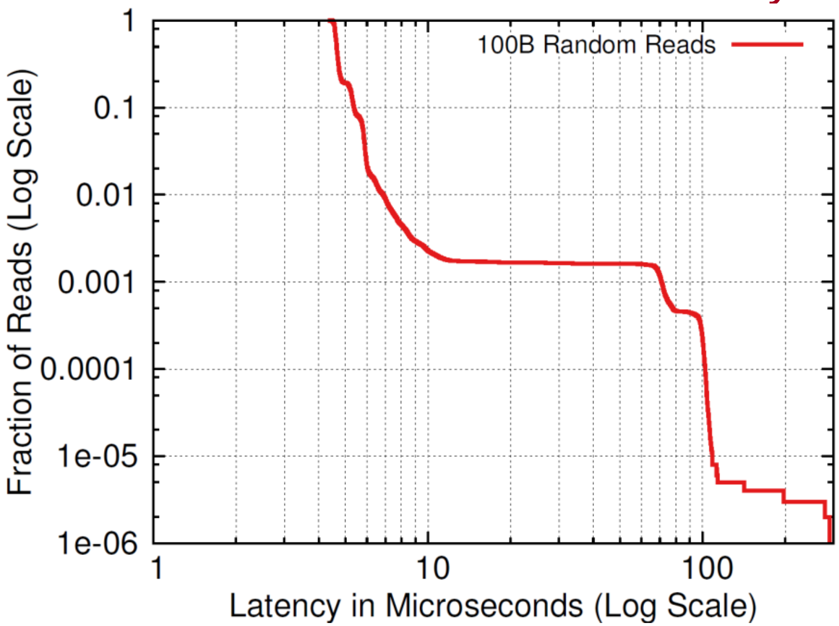
- **Latency for thread handoffs:**
  - 100ns in each direction
- **Shared state between dispatch and worker threads:**
  - Request/response buffers, etc.
  - >20 L2 additional cache misses to migrate state
- **Total cost of threading: ~450 ns in latency**
- **Dispatch thread is also throughput bottleneck**

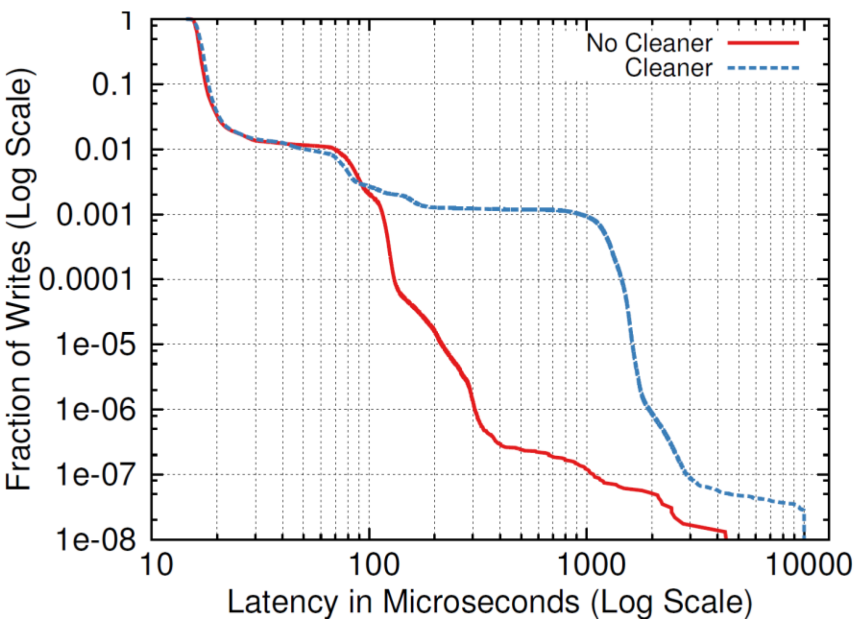
We are still looking for better alternatives...

Infiniband Latency (µs)

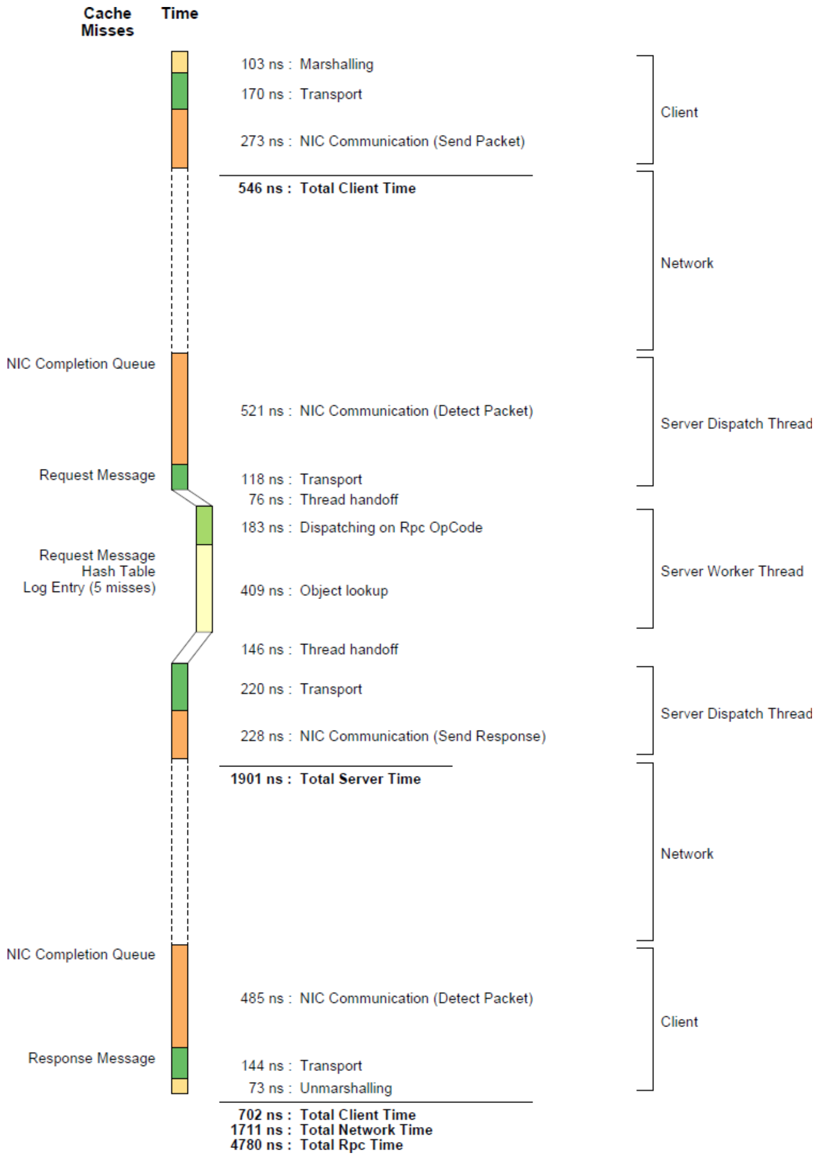
Object Size	Reads Median	Reads 90%	Reads 99%	Reads 99.9%	Writes Median	Writes 90%	Writes 99%	Writes 99.9%
100	4.7	5.4	6.4	9.2	13.4	14.7	75.6	148
1000	7.0	7.7	8.9	12.0	18.5	20.8	105	176
10000	10.1	11.1	12.3	28.5	35.3	37.7	209	287
100000	42.8	44.0	45.3	85.6	228	311	426	489
1000000	358	364	367	401	2200	2300	2400	2700

2.8 Gbytes/sec





Infiniband Read Timeline (100B)

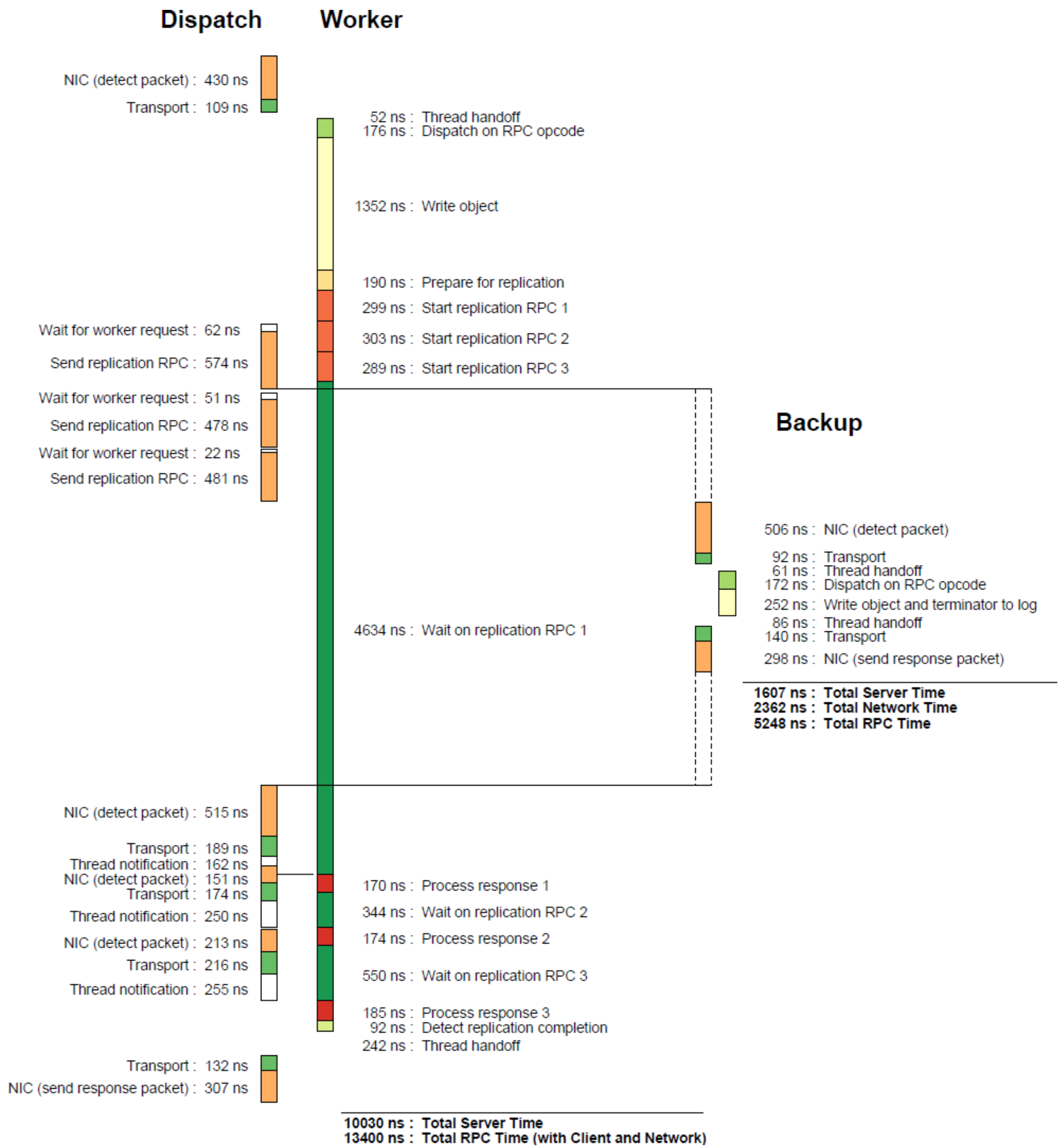


- **3.2 µs in network and NICs**
- **9 L3 cache misses on server (up to 86 ns each)**

Time on server:

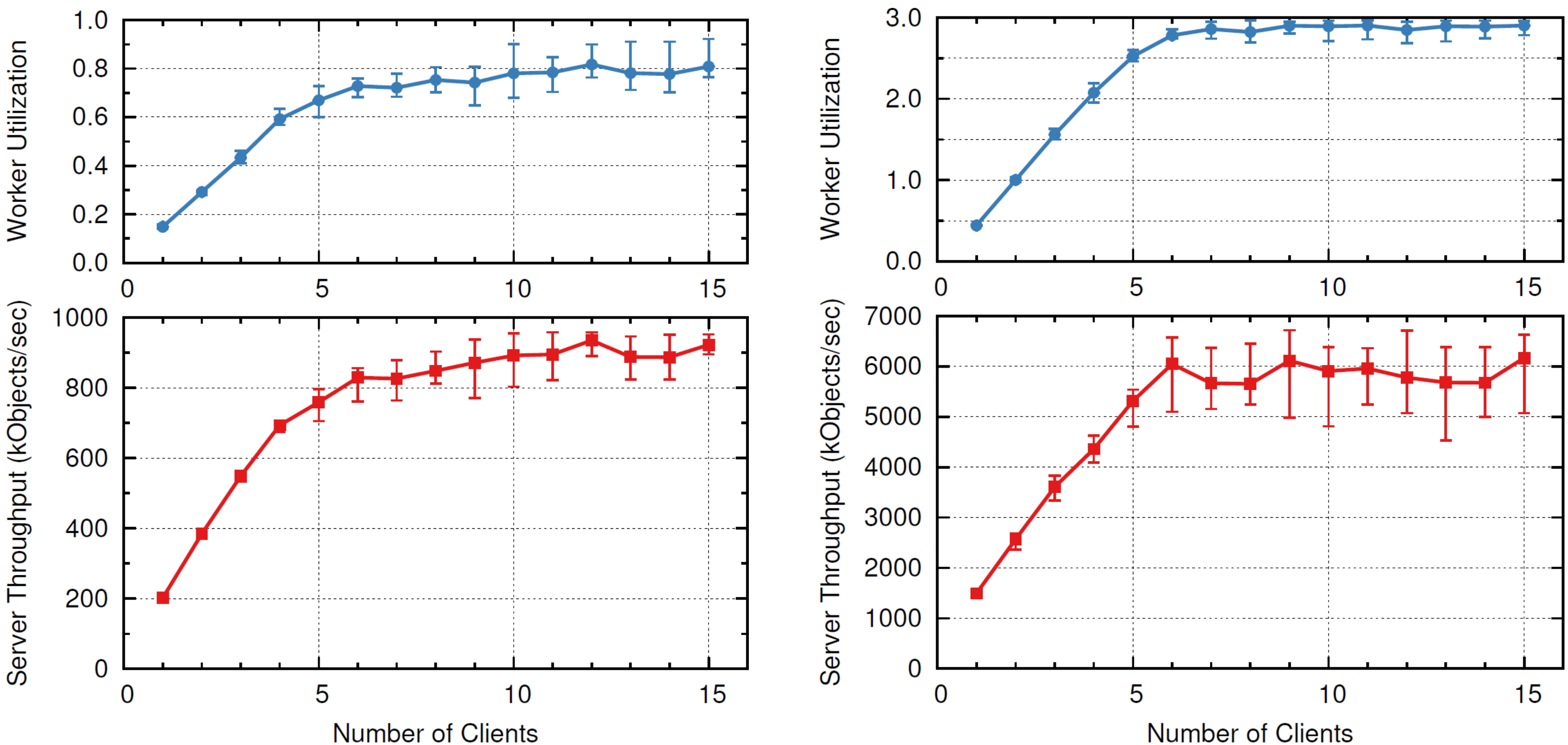
NIC communication:	749 ns	39%
Thread handoffs:	470 ns	25%
Cache misses (est.):	300 ns	16%
Other:	382 ns	20%
Total:	1901 ns	100%

Infiniband Write Timeline (100B)



Single-Server Read Throughput

Individual Reads (100B) | **Multi-reads (70 × 100B)**



Part V: Crash Recovery

Fault Tolerance Introduction

- **Failures to handle:**
  - Networking failures (e.g. packet loss, partitions)
  - Storage server crashes (masters/backups)
  - Coordinator crashes
  - Corruption of segments (DRAM and disk/flash)
  - Multiple failures
  - Zombies: “dead” server keeps operating
- **Assumptions:**
  - Fail-stop (no Byzantine failures)
  - Secondary storage survives crashes
  - Asynchronous network

Fault Tolerance Goals

- **Individual server failures? Continue normal operation:**
  - Near-continuous availability
  - High performance
  - Correct operation
  - No data loss
- **Multiple failures also OK if:**
  - Only a small fraction of servers fail
  - Failures randomly distributed
- **Large-scale outages:**
  - May cause unavailability
  - No data loss (assuming sufficient replication)

Error Handling Philosophy

- **Error handling: huge source of complexity**
  - Must write code 3 times
  - Must handle secondary/simultaneous failures
  - Hard to test
  - Rarely exercised

  } May not work when needed

- **Goal: minimize distinct cases to handle**
- **Technique #1: masking**
  - Deal with errors at a low level
- **Technique #2: failure promotion**
  - E.g., promote all internal server errors to "server failure"

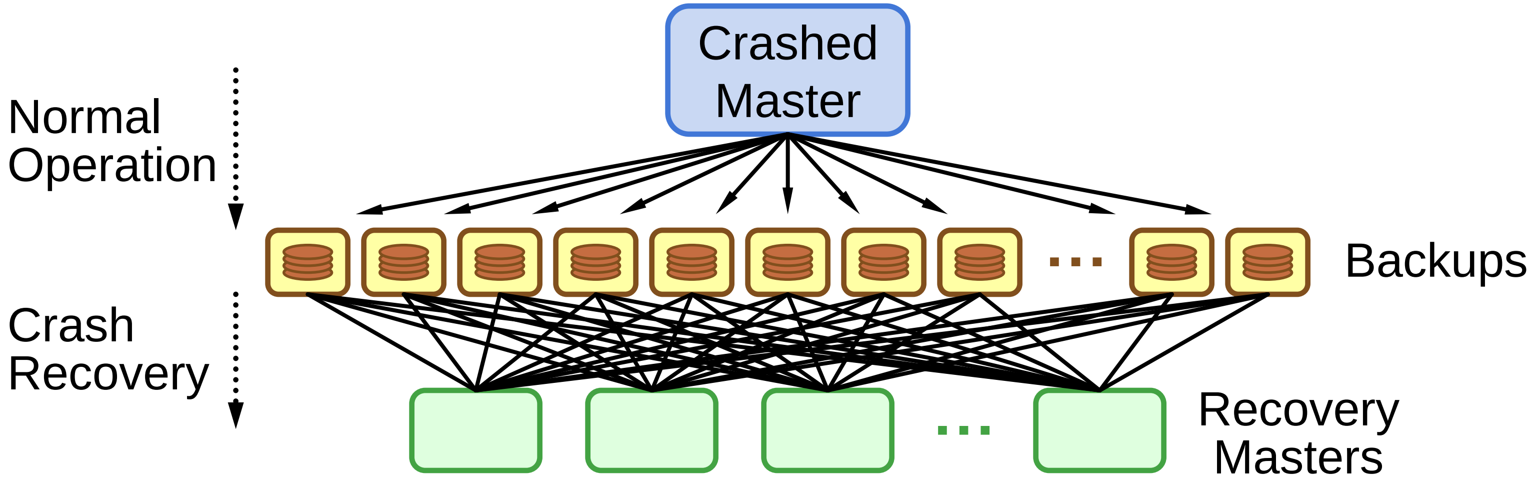
Master Crash Recovery

Additional challenges:

- **Speed: must recover in 1-2 seconds**
  - Data unavailable during recovery
- **Avoid creating scalability bottlenecks**
  - Distributed operations

Fast Master Recovery

- **Goal: recover 256 GB data in 1-2 seconds:**
  - Read from one flash drive? — 1000 seconds
  - Transmit over 10 GigE connection? — 250 seconds
  - Replay log on one CPU? — 500 seconds
- **Solution: concurrency**
  (take advantage of cluster scale)

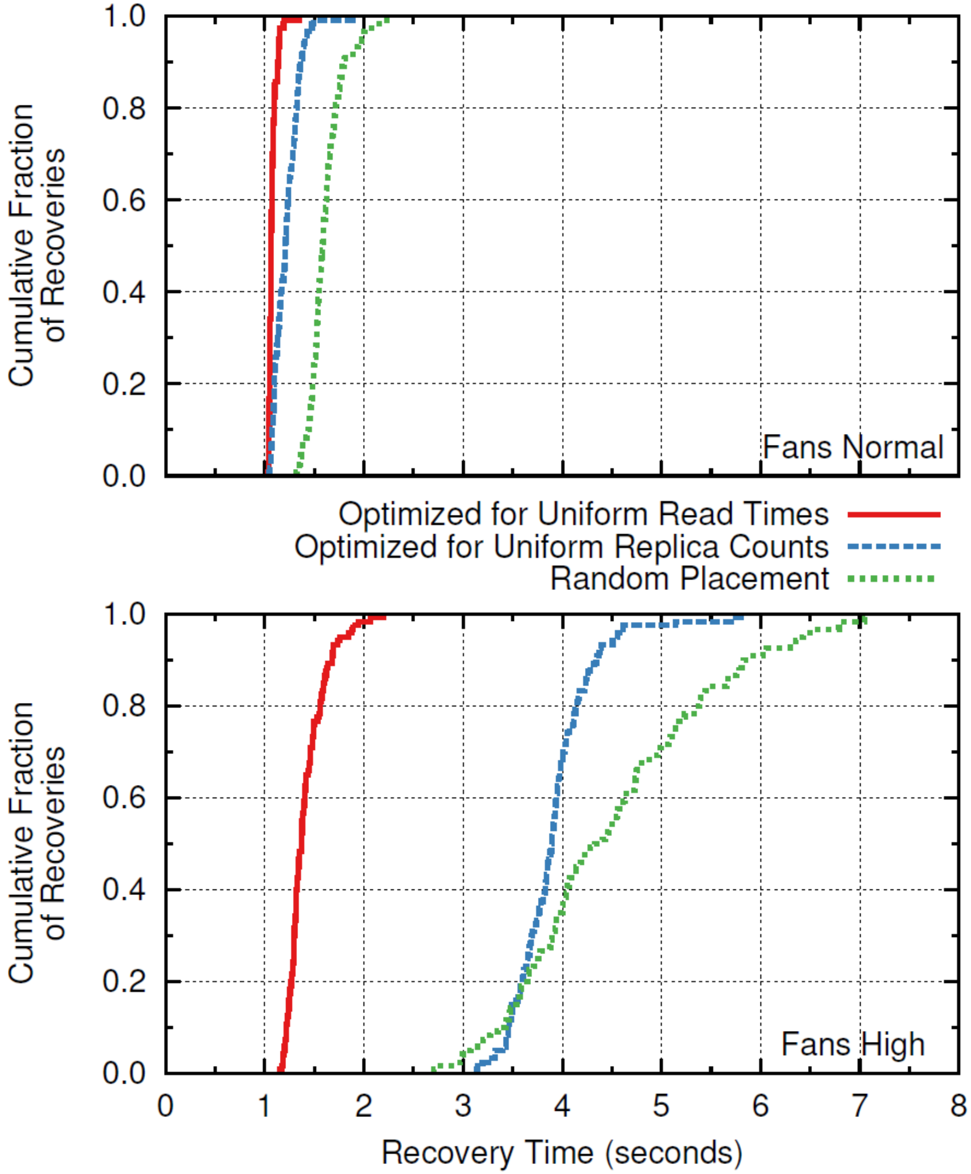


Scattering Replicas

- **Requirements for replica placement:**
  - Distribute replicas for each master uniformly
  - Use backup bandwidth and space evenly
  - Reflect failure modes (replicas in different racks)
  - Backups may have different device capacities/speeds
  - Backups enter and leave cluster
  - Each master must place its replicas independently
- **Solution: randomization with refinement**
  - Mitzenmacher’s “power of two choices”
  - Pick several candidate backups at random
  - Select best choice(s)
    (minimize worst-case read time for a backup)

Placement Effectiveness

- **120 recoveries per graph**
- **Replicas stored on disk**



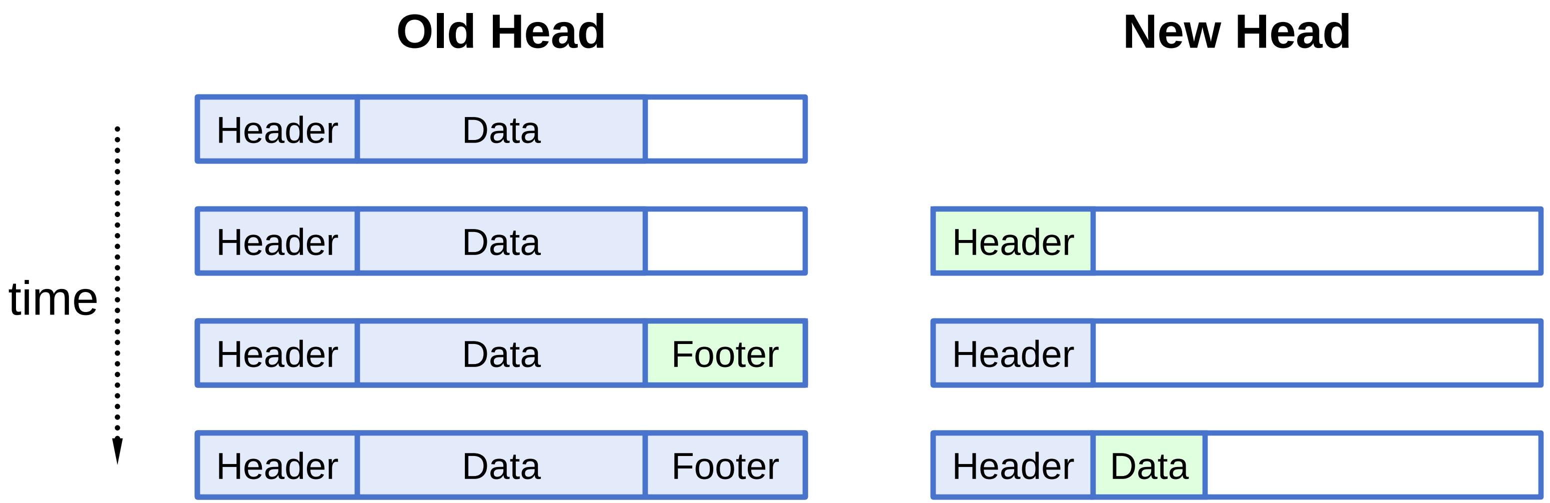
Fast Failure Detection

- **Goal: detect failures in a few hundred ms**
- **Distributed randomized approach:**
  - Every 100ms each server pings another at random
  - No response in 10-20ms? Report to coordinator
  - Coordinator pings again before declaring death
- **Probability of detecting crashed server:**
  - 63% in first round
  - 99% after 5 rounds
- **Problems:**
  - Performance glitches may be treated as failures (overloaded servers)
  - Protocol interactions (200 ms retry interval in TCP)

Master Recovery Overview

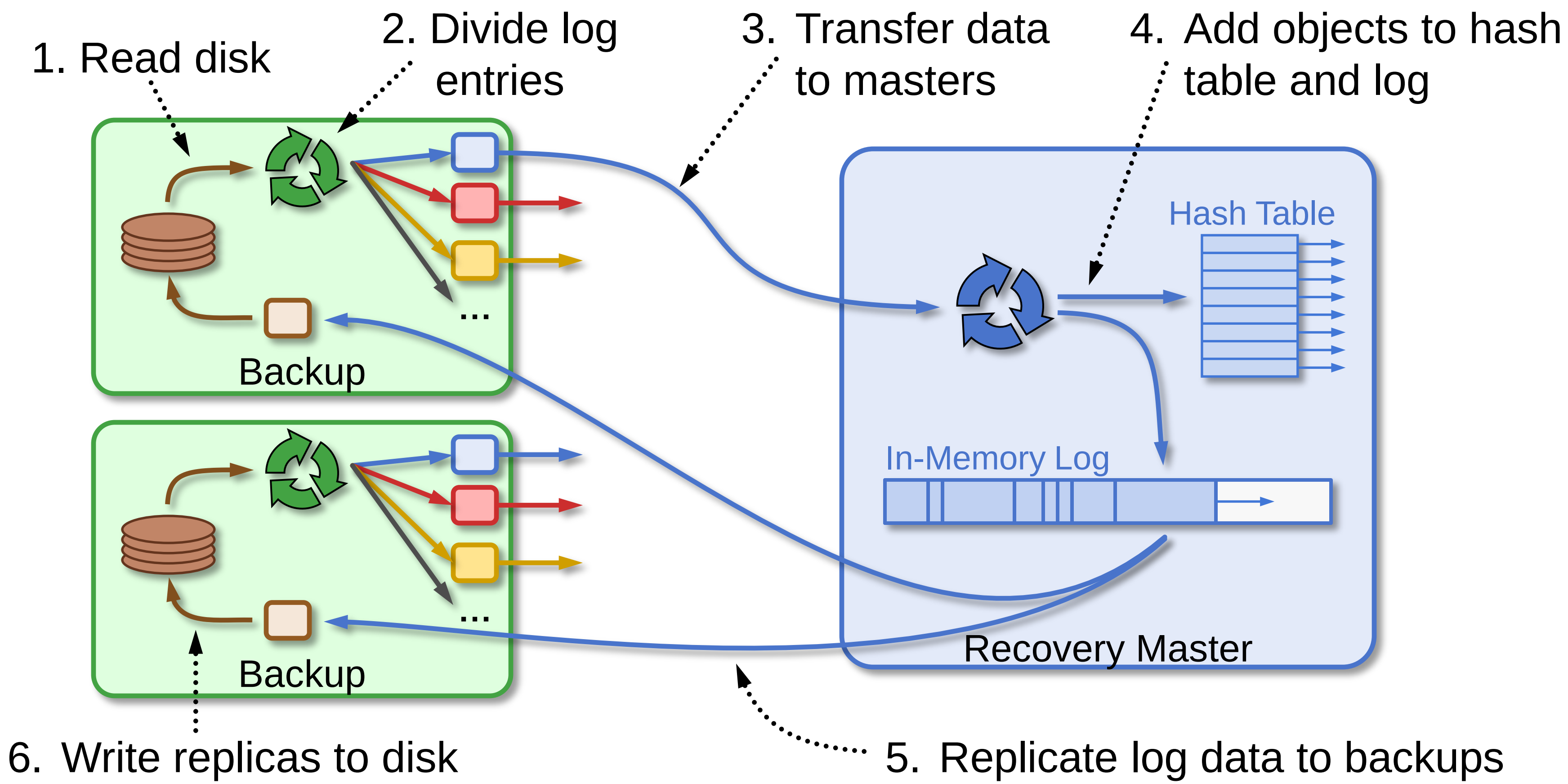
1. **Coordinator collects log metadata from all backups**
2. **Coordinator divides recovery work (tablet partitions)**
3. **Coordinator chooses recovery masters, assigns partitions**
4. **Recovery masters, backups replay log entries**
   - Recovery masters incorporate data into their logs
5. **Coordinator updates tablet configuration info to make tablets available again**

Ensuring Log Completeness



- **Invariants:**
  - Header names all other segments in log (log digest)
  - At least one open segment (header but no footer)
  - If multiple open segments, only oldest contains data
- **Defer recovery until log complete:**
  - Open segment available
  - One replica available for each segment in log digest

Log Replay



- **Concurrency in two dimensions:**
  - Pipelining
  - Data parallelism

Segment Replay Order

- **Backups and masters work independently**
  - Backups read segments, divide log entries
  - Masters fetch partitioned data, replay
- **To avoid pipeline stalls:**
  - Backups publish read order
  - Masters fetch in order of expected availability
  - Masters maintain multiple outstanding fetches
- **Log data replayed out of order:**
  - Version numbers identify most up-to-date information

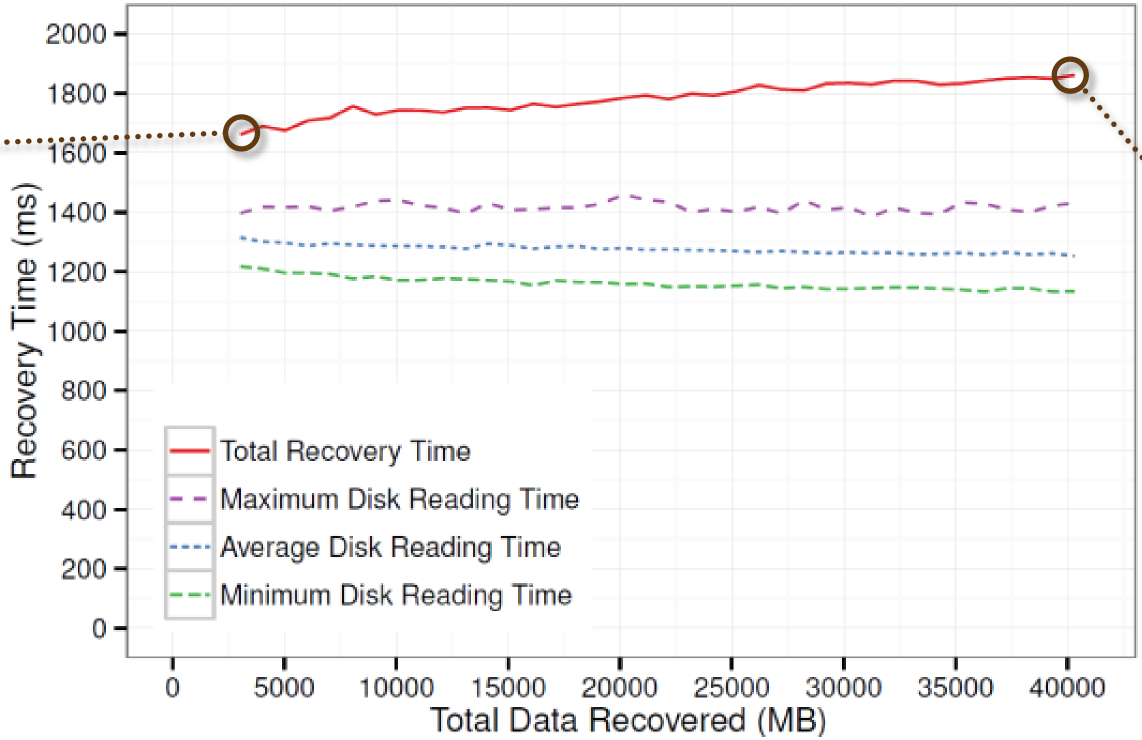
Replay Throughput

Single recovery master (Infiniband):

Object Size (bytes)	Throughput (Mobjs/sec)	(MB/sec)
1	2.32	84
64	2.18	210
128	2.03	319
256	1.71	478
1024	0.81	824
2048	0.39	781
4096	0.19	754

Recovery Scalability

1 master
2 backups
2 SSDs
500 MB



80 masters
160 backups
160 SSDs
40 GB

- **Will improve with newer machines**
  - Need more cores (our nodes: 4 cores)
  - Need more memory bandwidth (our nodes: 11 GB/sec)

Secondary Failures

Recovery complications:

- **Multiple master failures**
- **Recovery masters:**
  - Crash during recovery
  - Insufficient memory
  - Not enough recovery masters available
- **Backup crashes:**
  - Before recovery
  - During recovery

  } Replicas not available
- **Coordinator crashes**

Handling Multiple Failures

- **Recovery is organized incrementally:**
  - Make progress in small independent pieces (one partition for one crashed master)
  - Retry until done
- **Coordinator recovery loop:**
  - Pick a dead master
  - Collect replica info from backups, see if complete log available
  - Choose (some) partitions, assign to recovery masters
  - For recovery masters that complete, update tablet assignments
  - If dead master has no tablets assigned, remove it from cluster
- **This approach also handles cold start, partitions**

Zombies

- **“Dead” servers may not be dead!**
  - Temporary network partition causes ping timeouts
  - RAMCloud recovers “dead” server: tablets reconstructed elsewhere
  - Partition resolved, “dead” server continues to serve requests
  - Some clients use zombie, some use new servers: inconsistency!
- **Preventing writes to zombies:**
  - Coordinator must contact backups for head segment during recovery
  - Backups reject replication writes from zombie; zombie suicides
- **Preventing reads from zombies:**
  - Zombie learns of its status during pings for failure detection
  - Only probabilistically safe...

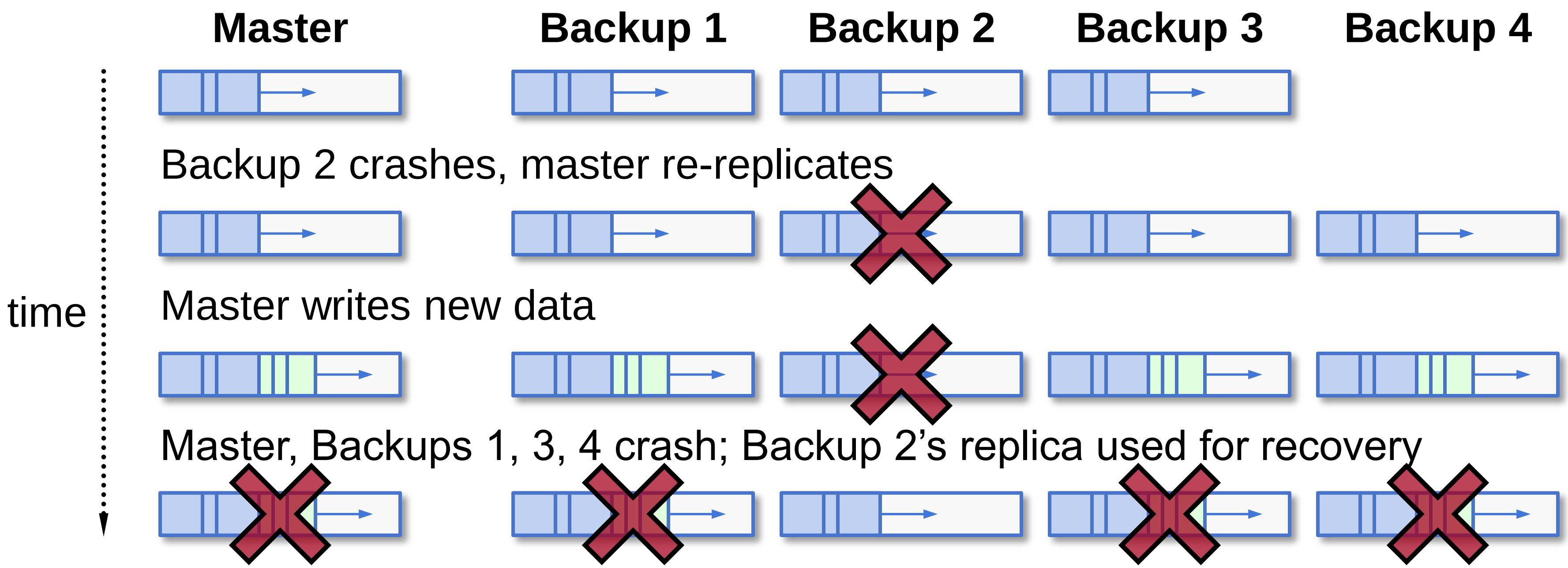
Backup Crashes

- **Basic mechanism:**
  - Coordinator notifies masters of crashes
  - Each master independently re-replicates lost segments
  - Mechanism not time-critical (no loss of availability)
- **Complications:**
  - Backup restart: replica garbage collection
  - Write-all-read-any approach requires replica consistency
  - Replica consistency problems:
    - When backup for head segment crashes
    - When master crashes during re-replication

Replica Garbage Collection

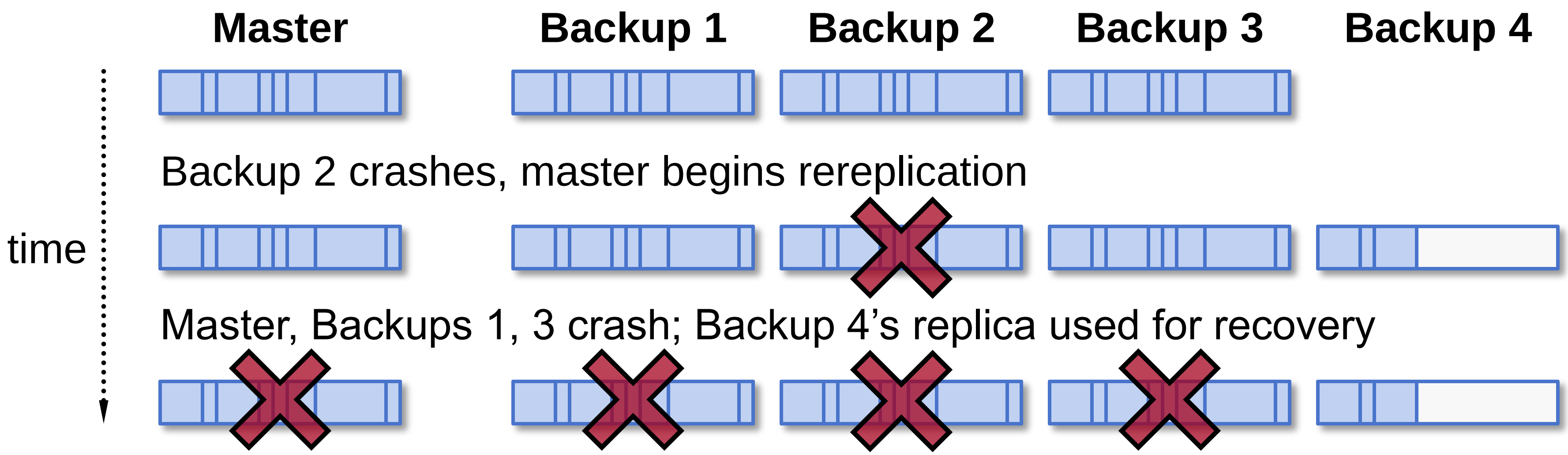
- **Backup restart:**
  - Normal case: can discard existing replicas (all masters have re-replicated)
  - But, sometimes need replicas (e.g. cold start, master crash)
- **For each replica, check state of master**
  - Not in cluster: free replica (master crashed, was recovered)
  - Crashed: retain replica
  - Master up: check with master (“do you still need this replica?”)
  - Repeat until all replicas freed

Head Segment Consistency



- **Must prevent use of out-of-date replicas**
  - Master sends info to coordinator after crash recovery (new log epoch number)
  - Coordinator ignores out-of-date replica during recovery

Crash During Rereplication



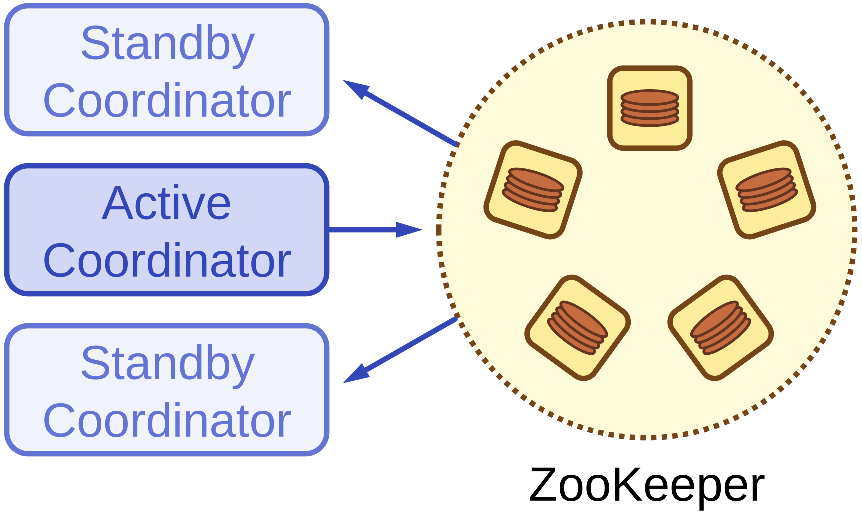
- **Must prevent use of incomplete replicas**
  - During rereplication, new replica marked "incomplete"
  - Once rereplication complete, new replica marked "complete"
  - During recovery, backup doesn't report incomplete replicas

Coordinator Crash Recovery

- **Must protect coordinator metadata:**
  - Server list (active/crashed storage servers)
  - Information for each table:
    - Name
    - Identifier
    - Mapping of tablets to storage servers
- **Store metadata in RAMCloud?**
  - Need server list before recovery
- **Instead, use separate external storage:**
  - Key-value data model
  - Must be highly reliable
  - Doesn't need to be very large or very fast
  - Currently using ZooKeeper

Active/Standby Model

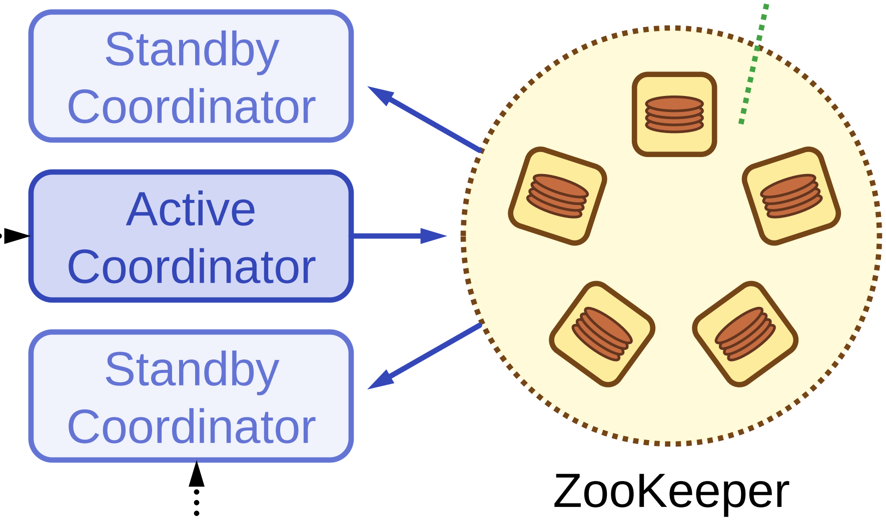
- **One active coordinator:**
  - Record state on external storage
- **Multiple standbys:**
  - Watch activity of active coordinator
  - If active coordinator stops making progress, compete to become new leader
- **New leader:**
  - Read state from external storage
  - Cleanup incomplete operations



Leader Election & Lease

- Identifies active coordinator
- Version must change within lease time

- Update leader object to maintain leadership (conditional write based on version)
- If update fails, stop acting as coordinator



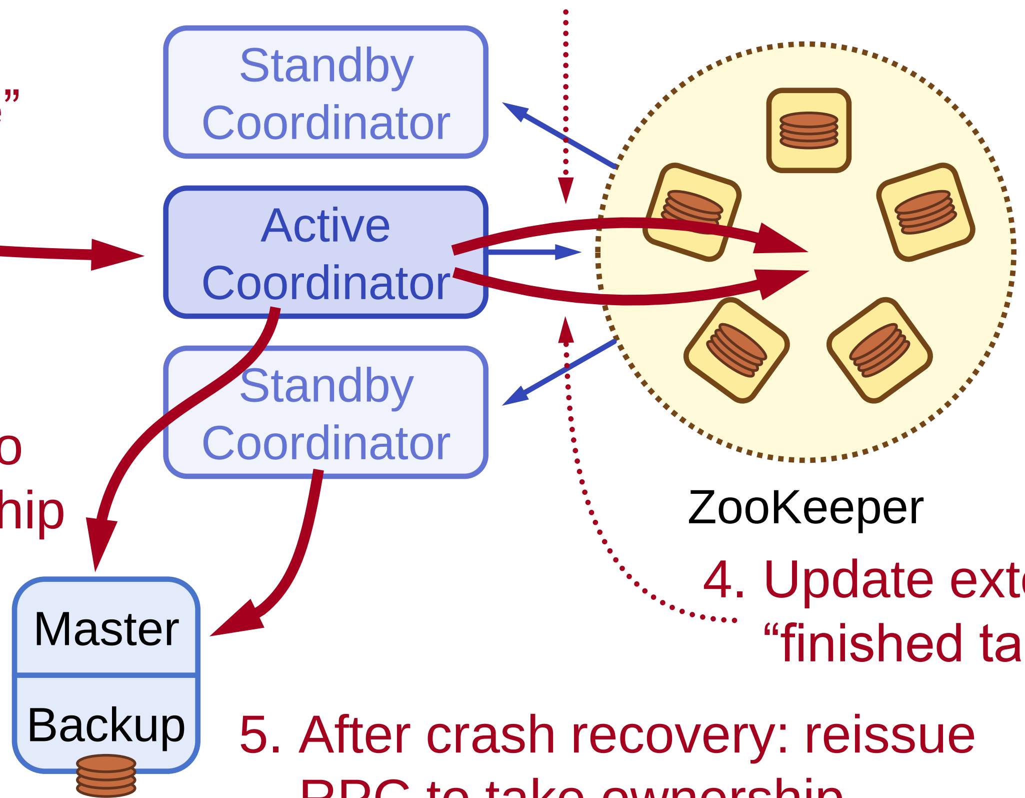
- Check leader object occasionally
- If lease time elapses with no version change, conditional write to become leader

Distributed Updates

Must maintain consistency between coordinator, other servers, external storage

1. Client request:
   “create new table”

2. Create external storage object for
   table: “intend to place on server X”



3. Tell master to
   take ownership

Must be idempotent!

4. Update external storage:
   “finished table creation”

5. After crash recovery: reissue
   RPC to take ownership

Part VI: Status and Limitations

RAMCloud History

- **First design discussions: Spring 2009**
- **Began serious coding: Spring 2010**
- **Version 1.0 in January 2014**
  - Includes all features described here
  - Usable for applications
- **Available in open-source form at RAMCloud Wiki: https://ramcloud.stanford.edu/**
- **Goal: ~~research prototype~~ production-quality system**

Limitations

- No geo-replication
- Key-value data model
- Linearizability support incomplete
- No protection
- Incomplete configuration management (mechanisms but no policies)

Current Work

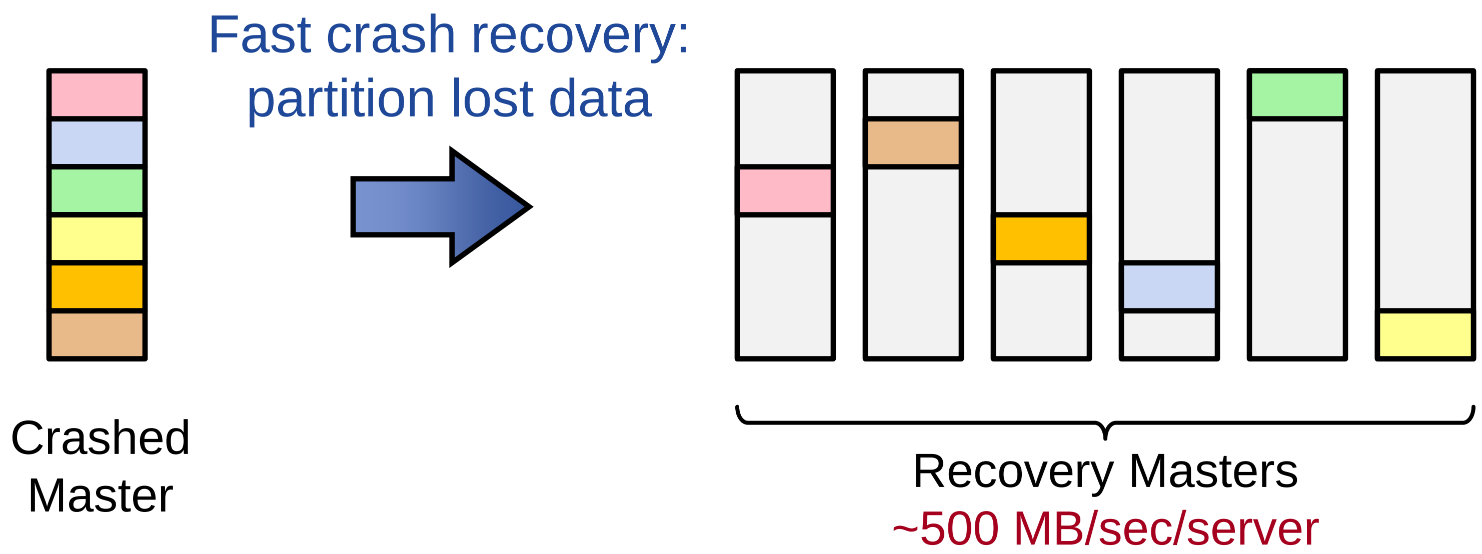
- **Higher-level data model:**
  - Secondary indexes
  - Multi-object transactions
  - Full linearizability
  - Research question: achievable at low latency and large scale??
- **New transport layer:**
  - New protocol for low-latency datacenter RPC (replace TCP)
  - New threading architecture
  - Better scalability

Part VII: Application Experience

Applications?

- **No applications in production, but several experiments:**
  - Stanford: natural language processing, graph algorithms
  - Open Networking Laboratory: ONOS (operating system for software defined networks)
  - CERN: high energy physics (visiting scientist, summer 2014)
  - Huawei: real-time device management
- **Challenges**
  - Low-latency networking not yet commonplace
  - RAMCloud not cost-effective at small scale
  - RAMCloud is too slow (!!)

Scale and Recovery



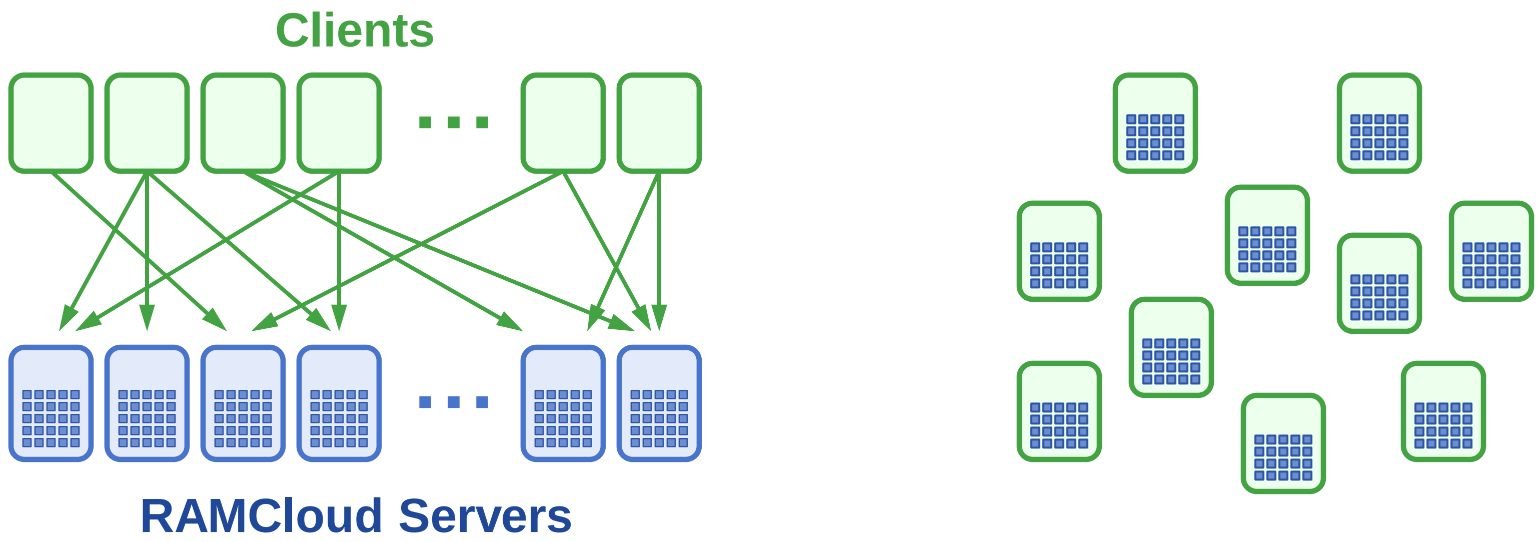
Cluster Size	Server Capacity	Cluster Capacity	Recovery Time
101 servers	50 GB	5 TB	1 sec
201 servers	100 GB	20 TB	1 sec
6 servers	100 GB	600 GB	40 sec
6 servers	2.5 GB	15 GB	1 sec
11 servers	5 GB	55 GB	1 sec

Small clusters can't have both fast recovery and large capacity/server

Fast But Not Fastest

Choice #1:
5-10 µs remote access

Choice #2:
50-100ns local access



- **Choice #2 is 100x faster than RAMCloud**
  - And, can store data in application-specific fashion
  - But, data must partition
  - What about persistence?

Application Philosophy

- **Technology transfer is a numbers game:**
  - Must try many experiments to find the right fit
- **Our goals:**
  - Learn something from every test case
  - Keep improving RAMCloud
- **Application issues suggest new research opportunities**

Part VIII: Lessons Learned

Logging

- **Initially chosen for performance (batch writes to disk/flash)**
- **Many other advantages:**
  - Crash recovery: self-identifying records that can be replayed
  - Convenient place for additional metadata (log digest, tablet usage stats)
  - Consistent replication: mark consistent points
  - Immutable: simplifies concurrent access
  - Neutralize zombies (disable head segment)
  - Manages memory quite efficiently
- **Disadvantage:**
  - Only one insertion point per master: limits throughput

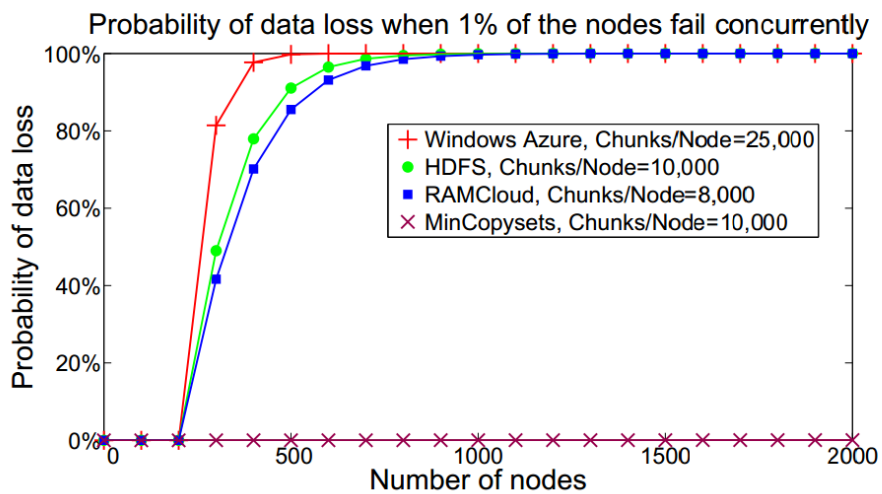
Randomization

Essential tool for large-scale systems:

- **Replace centralized decisions with distributed ones:**
  - Choosing backups for replicas
  - Failure detection
- **Simple and efficient algorithms for managing large numbers of objects**
  - Coordinator dividing tablets among partitions during recovery
- **Many “pretty good” decisions produces nearly optimal result**

Sometimes Randomization is Bad!

- **Select 3 backups for segment at random?**
- **Problem:**
  - In large-scale system, any 3 machine failures results in data loss
  - After power outage, ~1% of servers don't restart
  - Every power outage loses a few segments!
- **Solution: derandomize backup selection**
  - Pick first backup at random (for load balancing)
  - Other backups deterministic (replication groups)
  - Result: data safe for hundreds of years
  - (but, lose more data in each loss)



Ubiquitous Retry

Assume operations may not succeed at first: provide mechanism for retries

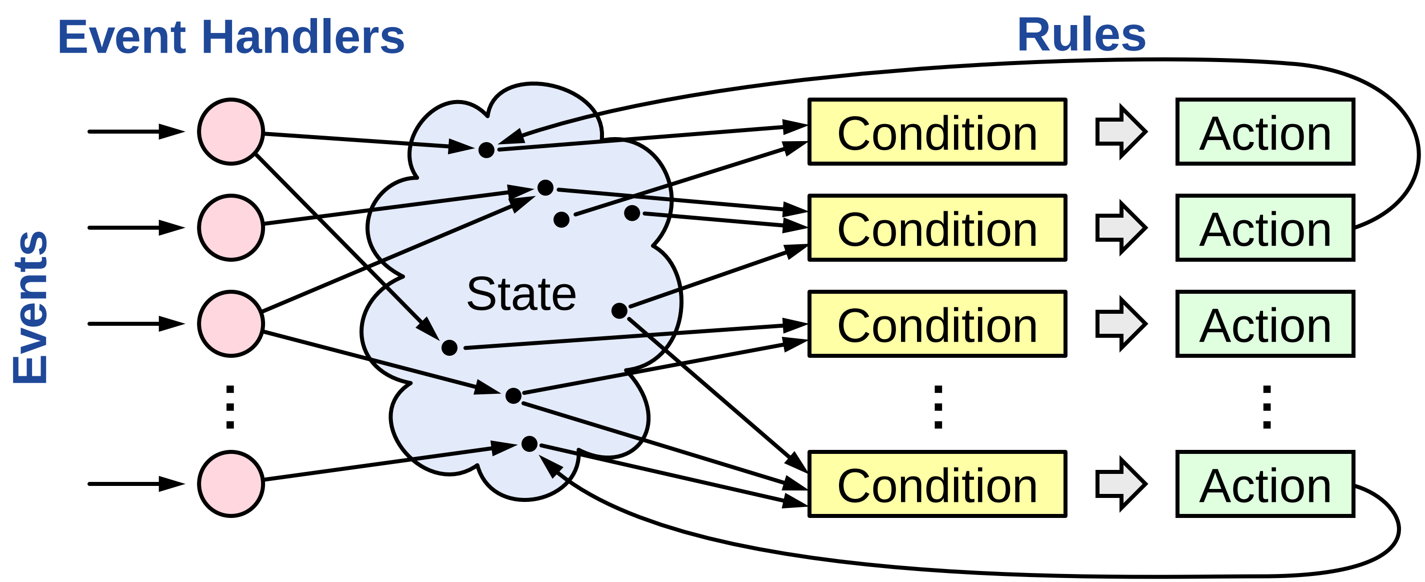
- **Fault tolerance:**
  - After crash, reconstruct data and retry
  - Incomplete recovery
- **Configuration changes (e.g., tablet moved)**
- **Blocking:**
  - Don’t block operations on servers (resource exhaustion, deadlock)
  - Return STATUS_RETRY error; client retries later
- **Retries now built into RPC system**
  - All RPCs transparently retry-able
  - Can define reusable retry modules (e.g. for “tablet moved”)

Rules-Based Programming

- **RAMCloud contains many DCFT modules (Distributed, Concurrent, Fault-Tolerant)**
  - Segment replica manager
  - Cluster membership notifier
  - Main loop of recovery masters
  - Multi-read dispatcher
  - ...
- **Very hard to implement! (nondeterminism)**

Rules-Based Programming, cont'd

- **Solution: decompose code into rules**
  - Rule = condition to check against state, action to execute
  - Each rule makes incremental progress towards a goal
  - DCFT module = retry loop
  - Execute rules until goal reached



Layering Conflicts With Latency

- **Layering:**
  - Essential for decomposing large systems
  - Each crossing adds delay
  - Many layers → high latency
  - Granular interfaces especially problematic
- **For low latency, must rethink system architecture**
  - Minimize layer crossings
  - Thick interfaces: lots of useful work for each crossing
  - Fast paths that bypass layers (e.g., kernel bypass for NICs)

Conclusion

- **RAMCloud: general-purpose DRAM-based storage**
  - Scale
  - Latency
- **Goals:**
  - Harness full performance potential of DRAM-based storage
  - Enable new applications: intensive manipulation of large-scale data
- **What could you do with:**
  - 1M cores
  - 1 petabyte data
  - 5-10µs flat access time

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[7] R. Stutsman, C. Lee, and J. Ousterhout, “Experience with Rules-Based Programming for Distributed, Concurrent, Fault-Tolerant Code,” Stanford technical report, https://ramcloud.atlassian.net/wiki/display/RAM/RAMCloud+Papers?preview=/6848671/12058674/dcft.pdf

Palette