Karma: Cost-effective Geo-replicated Cloud Storage with Dynamic Enforcement of Causal Consistency

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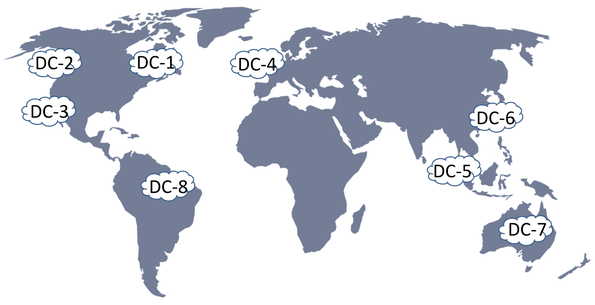
Motivation

Modern Cloud Storage Systems



- Span multiple geo-distributed DCs
  - Twitter, Facebook, Google, Amazon
  - Amazon has 8 worldwide DCs
- Replicate data for low latency
- Use asynchronous write propagation
- Have to handle failures, and partitions

The Consistency Spectrum

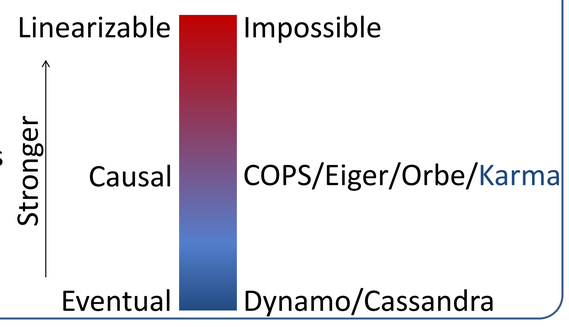
Replication, asynchronous write propagation create ordering issues

- Weak "eventually consistent" systems
  Widely deployed, but ordering can be confusing
- Strong ordering of all reads and writes across all clients
  CAP Theorem ⇒ unavailable on partition

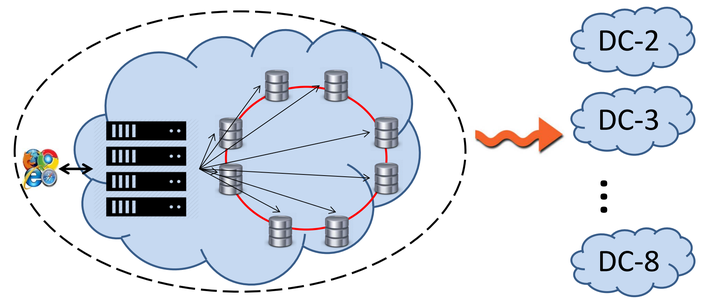
Causal consistency:
Partial order that preserves causality

Not confusing for users

Available under partition



Problems with Existing Causal Approaches

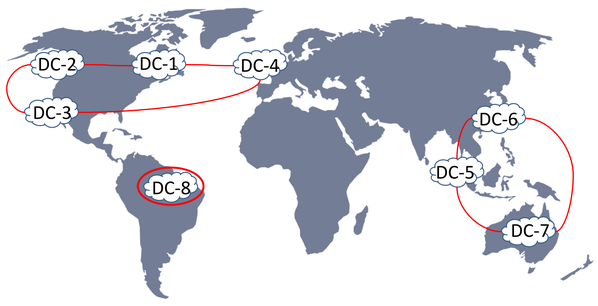


- Static binding: A user is allowed to access only one DC
- Full replication: Expensive, scalability issues
- Simple solutions do not work
  - Spreading data across DCs ⇒ Availability issues
  - Allowing users to switch DCs ⇒ Consistency violation

Karma: First causally consistent geo-replicated cloud storage system with partial replication while preserving consistency and availability

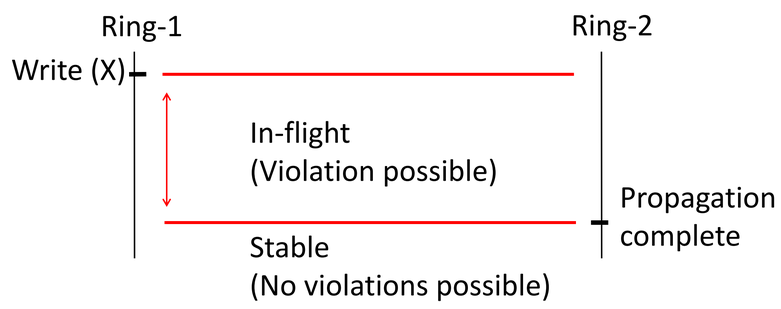
Karma's Key Ideas

Partial Replication



- Decouple rings and DCs
- Rings span multiple DCs
  Each ring contains full replica of dataset
- Availability in wide-area rings guaranteed by causality-preserving dynamic ring binding
- DC level caching used for fast reads of remote objects

Dynamic Ring Binding



- Karma's novel mechanism: Dynamic Ring Restrictions (DRR)
- If a client reads an in-flight object from Ring-1
  Temporarily restrict client to read all objects from Ring-1
  Client can access any ring once in-flight objects are stable

Caching/Write Buffers

- Partial replication ⇒ Remote objects, slow
- DC-level storage caches enable fast reads:
  - Problem: Normal cache operation violates causality
  - Solution: Stable value caching
- Persistent thread-private write buffers enable fast writes
  - All writes are local
  - Reads check write-buffer to avoid violations

Performance Evaluation (R/W : 95/5)

Experimental Setup
- 64-node testbed on PRObE cluster
- 8 data centers, 8 nodes each
- Amazon AWS emulation using DummyNet

Four Schemes:

	COPS-Ideal	Karma	COPS-PR	Karma-NC
Replication	Full	Partial	Partial	Partial
Ring binding	Static	Dynamic	Static	Dynamic
Write buffers	-	✓	✓	✓
Caching	-	✓	✗	✗

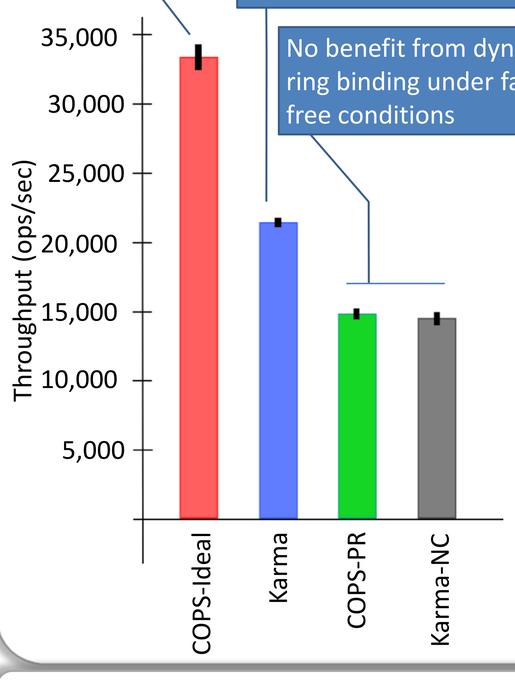
COPS-Ideal looks better, incurs high (impractical) cost of full replication

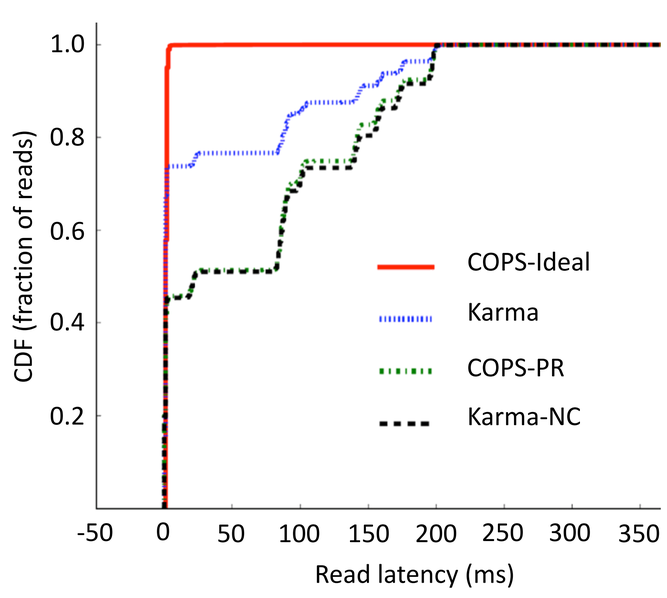
Karma has ≈30% cache misses

Karma's advantage diminished here since writes are only 5%

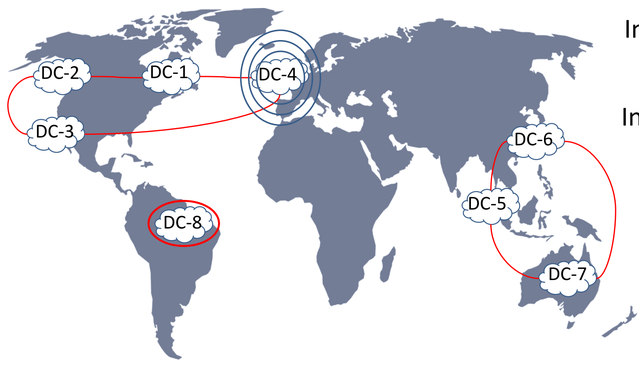
Karma achieves 43% higher throughput than COPS-PR

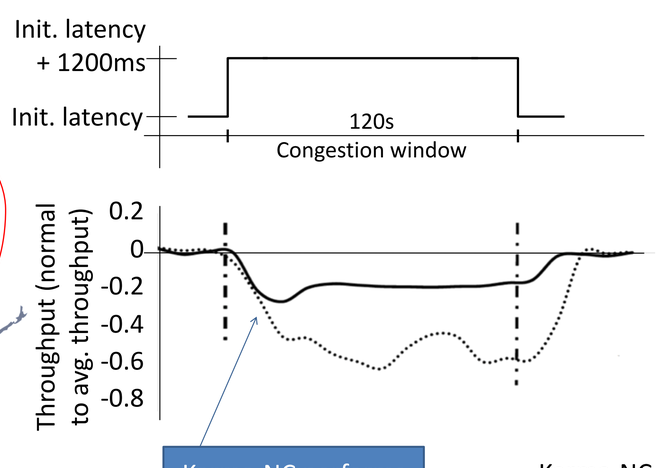
No benefit from dynamic ring binding under fault free conditions





Performance with Faults





Importance of Dynamic Ring Binding
- Induce congestion in Europe DC
- All traffic (in and out) is affected
- Table below shows avg. performance hit

	Karma-NC	COPS-PR
Throughput degradation	≈ 20%	≈ 50%
Latency increase	≈ 20%	≈ 85%

Fault Tolerance Analysis

Failure	Availability	Contrast to Full Repl.	Contrast to COPS-PR	Protection Mechanism
Backend Server	✓	=	=	Chain replication
Cache Server	✓	Not applicable		Stable state
Frontend Server	✓	=	=	Chain replication
Rack	✓	=	=	Chain replication
Single AZ	✓	=	↑	Dynamic binding
Partition	✓	=	↑	Dynamic binding

Cost Savings

Summary

- First causally-consistent cloud storage system with:
  - ✓ Partial replication ⇒ Practical, cost effective
  - ✓ Dynamic ring switching ⇒ Stronger availability guarantees
- 43% throughput improvement iso-cost
- Significant reduction in operational and capital expenditures

ACM Symposium on Cloud Computing 2016

This material is based upon work supported by the National Science Foundation under Grant No. CSR-1618921