DistCache: Provable Load Balancing for Large-Scale Storage Systems with Distributed Caching

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Large-scale cloud services need large storage clusters

- Major cloud services serve billions of users.
Storage servers have load imbalance issue

- **Typical workloads** [Sigmetrics’12]:
  - Highly skewed.
  - Dynamic.

The skewness of the workload brings imbalance.
Solutions to mitigate the load imbalance

- Consistent hashing and related.
  - Do not handle dynamic and skewed workloads.

- Data migration or replication.
  - Large system and storage overhead.
  - High cache coherence cost.

- Front-end cache as a load balancer.
  - Low update overhead.
  - Work for arbitrary workloads.
Solutions to mitigate the load imbalance

- Consistent hashing and related.
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- Front-end cache as a load balancer.
  - Low update overhead.
  - Work for arbitrary workloads.
Prior work: Fast, small cache alleviates load imbalance

Cache hottest $O(n \log n)$ items [SoCC’11]

Server load is balanced

Application to cluster-scale: [NSDI’16, SOSP’17]

A cache node brings load balancing in a cluster.
Strawman: Big, fast cache for inter-cluster load balancing
One “Big” cache is infeasible

41 Tbps

32 Clusters of 32 Servers

40G  40G  40G

One big cache is not scalable.
First, balance the load within each cluster.
Second, balance the load between clusters

Cache hottest $O(m \log m)$ items.

We need to avoid using big node anywhere.
DistCache: Distributed caching as load balancer

Cache hottest $O(m \log m)$ items.

Upper-layer cache nodes

Lower-layer cache nodes

$m$ clusters

Provable, Practical, General mechanism.
Natural goals on a distributed caching mechanism

Ideally, DistCache should be as good as “one big cache” to absorb $O(m \log m)$ hottest items.
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To achieve “one big cache”:

- Support **ANY** query workload to hottest $O(m \log m)$ items.
- Each cache node is **NOT** overloaded.
- Keep cache coherence with **MINIMAL** cost.
Design Challenges of DistCache

- Challenge #1: How to allocate cached items?
  - Do not overload any cache node.
  - Do not incur high cache coherence cost.

- Challenge #2: How to query the cached items?
  - Provide best and stable cache query distribution.

- Challenge #3: How to update the cached items?
  - Two-phase update to ensure cache coherence.
Design Challenges of DistCache

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Challenge #1: How to allocate the cached items?

Strawman Sol #1: Cache-Replication

Upper layer cache nodes

\{A, B, C, D, E\}

Update cache

\{A, B, C, D, E\}

Update cache

\{A, B, C, D, E\}

Update cache

Lower layer cache nodes

\{A, B, C\}

Update cache

\{D, E\}

Update cache

\{F\}

Cache-Replication incurs high cache coherence cost.
Challenge #1: How to allocate the cached items?

Strawman Sol #2: Cache-Partition

Upper layer cache nodes: {A, B, C} (Overload)  
Lower layer cache nodes: {A, B, C} (Overload)

Cache-Partition could put too many hottest items into the same cache node.
Independent hashes to allocate the cached items

Two independent hashes H1 and H2 to allocate hot items

- Stable and best cache allocation.
- Small cache coherence cost.
Challenge #2: How to query the cached items?

Get(C) with upper layer first

Upper layer cache nodes
{B, E}

{A, B, C}

Lower layer cache nodes

{A}

{D, E}

{C, D, F}

{F}

Querying item with upper layer first does not guarantee best throughput.
Power-of-two-choices to query the cached items

Get(C) with upper layer first

Upper layer cache nodes

{B, E}

{A}

{C, D, F}

Lower layer cache nodes

{A, B, C}

{D, E}

{F}

Power-of-two-choices to route the queries guarantee stable throughput.
Putting together: DistCache

- Independent hashes to allocate cache items.
- Power-of-two-choices of current cache loads to route queries.
Theoretical Guarantee behind DistCache

For $m$ storage clusters:
- DistCache absorbs any query workload to the hottest $O(m \log m)$ items.

with the following condition:
- Query rate for a single item is no larger than $\frac{1}{2}$ of one cache node’s throughput. (No more half of a cluster!)
Proof Sketch: Convert to a perfect matching problem

Proofs leverage tools from **expander graph, network flow, and querying theory**

Our PoT query can find a perfect match for any query workload distribution.

Hottest items →

Upper layer cache nodes →

Lower layer cache nodes →
Remarks of the DistCache Analysis

- The numbers of cache nodes in two layers can be different as long as \( m \) isn’t too small.
- The throughput of cache nodes can be different.
- Aggregated throughput is almost same as “big cache”.

Example Deployment Scenarios of DistCache

Cache

DRAM/SSD Array

O(10) MQPS each

Programmable Switch

O(1) BQPS each

Servers

Flash / Disk

O(100) KQPS each

+ 

DRAM

O(10) MQPS each
Case Study: Switch-based distributed caching

1. Client sends query
2. Client side switch decides which cache node to access (PoT)
3. If cache hit, switch will reply

When cache hit, cache switch will reply the query immediately.

Programmable switches

Redis Storage Clusters

Client Cluster
Case Study: Switch-based distributed caching

1. Client sends query
2. Client side switch decides which cache node to access (PoT)
3. If cache miss, query is forwarded to server
4. Server handles the query to Redis, and replies.

When cache miss, query is handled by the server.
Implementation Overview

Controller
- Cache Management
- Network Management

- Key-Value Cache
- Heavy Hitter Detector
- Query Routing

Cache Switch

Client-side Switch

Servers

Clients

Query Load Statistics
Query Routing
P4: Programmable Protocol-Independent Packet Processing

User-defined Packet Format:

<table>
<thead>
<tr>
<th>ETH</th>
<th>IP</th>
<th>TCP</th>
<th>SEQ</th>
<th>OP</th>
<th>KEY</th>
<th>VALUE</th>
</tr>
</thead>
</table>

Existing Packet Header

Packet Header for Caching

Header/Metadata in Shared Memory

Parser

Match-Action Table

Match-Action Table

Match-Action Table

Deparser
P4: Programmable Protocol-Independent Packet Processing

User-defined Packet Format:

- ETH
- IP
- TCP
- SEQ
- OP
- KEY
- VALUE

Existing Packet Header

Packet Header for Caching

Parser

Match: \( \text{OP} \equiv \text{GET} \)
Action: \( \text{Get\_Load} \) ++

Match: \( \text{KEY} \equiv \text{A} \& \text{Vaild} \)
Action: \( \text{Get value of A} \)

Match: Val of A is fetched
Action: Update to header

Deparser
Evaluation Setup

- Baselines: NoCache, Cache-Partition, Cache-Replication.
Evaluation Takeaways

- For read queries, DistCache works as good as Cache-Replication.

- For write queries, DistCache has performed significantly better:
  - When write ratio (<0.3), better throughput.
  - When write ratio (>0.3), as good as Cache-Partition.
DistCache balances the loads of different clusters

DistCache offers nearly perfect throughput for skewed workloads
DistCache scales linearly with the number of nodes. DistCache can support very large storage clusters.
DistCache incurs small cache coherence cost

Under Zipf-0.99 workload, DistCache offers best write throughput.
Conclusions

- DistCache is a general distributed caching mechanism to ensure load balancing across many storage clusters.

- DistCache requires simple primitives (independent hashing, power-of-two-choices routing).

- DistCache provides near-perfect throughput with rigorous theoretical guarantees.