pRedis: Penalty and Locality Aware Memory Allocation in Redis

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Outline

• Background
• Motivation Example
• pRedis: Penalty and Locality Aware Memory Allocation
• Long-term Locality Handling
• Evaluation
• Conclusion
Background

• In modern web services, the use of KV cache often help improve service performance.
  • Redis
  • Memcached
Background

- **Hardware Cache**: Recency-based policy: LRU, Approx-LRU
- **Key-Value Cache**: Recency-based policy: LRU, Approx-LRU
  - Not efficient

**Hidden assumption**: miss penalty is uniform

**Not correct** in KV Cache

- small strings, big images, static pages, dynamic pages, from remote server, from local computation, etc.
Penalty Aware Policies

• The issue of miss penalty has drawn widespread attention:
  • GreedyDual [Young’s PhD thesis, 1991]
  • GD-Wheel [EuroSys’15]
  • PAMA [ICPP’15]
  • Hyperbolic Caching [ATC’17]

  \[ p_i = c_i \times \frac{n_i}{t_i} \]

• Hyperbolic Caching (HC) delivers a better cache replacement scheme.
  • combines the miss penalty, access count and residency time of data item.
  • shows its advantage over other schemes on request service time.
  • but it is short of a global view of access locality
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Motivation Example

- We define the **miss penalty** as the time interval between the miss of a `GET` request and the `SET` of the same key immediately following the `GET`.

Access rates of these three classes are 5 : 3 : 2.

Assume that each item’s **hit time** is 1 ms, and the **total memory** size is 5.
Motivation Example – LRU Policy

Every access to class 1 will be a hit (except first 2 access).
Other accesses to class 2 and class 3 will all be misses.
Average request latency = 0.5*1 + 0.3*(200+1) + 0.2*(200+1) = 101 ms.
The elements in class 1 are chosen to evict except for their first load. The newest class 3 elements stay in cache even there is no reuse. Average request latency = $0.5 \times (10 + 1) + 0.3 \times 1 + 0.2 \times (200 + 1) = 46$ ms
Motivation Example – pRedis Policy

- Key Problems:
  - LRU: doesn’t consider miss penalty (e.g. class 2, class 3)
  - HC: doesn’t consider locality (e.g. class 3)
- We combine Locality (Miss Ratio Curve, MRC) and Miss Penalty.

\[
\begin{align*}
mr_1(c_1) &= \begin{cases} 
1 & c_1 < 2 \\
0 & c_1 \geq 2 
\end{cases} \\
mr_2(c_2) &= \begin{cases} 
1 & c_2 < 3 \\
0 & c_2 \geq 3 
\end{cases} \\
mr_3(c_3) &= 1
\end{align*}
\]

\[
W = 0.5*mr_1(c_1)*10 + 0.3*mr_2(c_2)*200 + 0.2*mr_3(c_3)*200, \quad \text{s.t. } c_1+c_2+c_3 = 5
\]

\[
c_1 = 2, \quad c_2 = 3, \quad c_3 = 0, \quad W_{\text{min}} = 40,
\]

average request latency = 0.5 \times 1 + 0.3 \times 1 + 0.2 \times (200 + 1) = 41 \text{ ms}
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pRedis: Penalty and Locality Aware Memory Allocation

- In pRedis design, a workload can be divided into a series of fixed-size time windows (or phases). In a time window:

  - During the time window:
    - Miss Penalty Tracking
    - Class Decision
    - Trace Tracking

  - At the end of each time window:
    - MRC Construction
    - Memory reallocation

  - Track miss penalty
  - Divide penalty into classes
  - Generate sub-trace for each class
  - Use EAET Model
  - Use dynamic programming
pRedis System Design

Redis Kernel

- request
- cmd dispatch
- mem_evict
- cmd->proc()

pRedis Driver

pRedis Module

- op & key
- key
- cmd monitor
- key & cid
- sampling RTH
- RTHs
- EAET model
- MRCs
- class_mem allocation

Penalty Class ID Filter

EAET Model

Class Memory Allocation
pRedis – Penalty Class 1

• Track the miss penalty for each KV.
• Divide them into different classes.
• But how to maintain these information efficiently?
  • store an additional field for each stored key? too

Penalty Class ID Filter

1 million keys
Pr(false positive) = 0.01

Overhead: 1 MB
pRedis – Penalty Class ID Filter

• Two different ways to decide the Penalty Class ID:
  • 1) Auto-detecting: pRedis(auto)
     • set the range of each penalty class in advance.
     • each KV will be automatically assigned to the class it belongs to based on the measured miss penalty.
  • 2) User-hinted: pRedis(hint)
     • provides an interface for user to specify the class of an item.
     • aggregates the latency of all items of a penalty class in a time period.
pRedis – EAET Model

- Enhanced AET (EAET) model is a cache locality model (APSys 2018):
  - support read, write, update, deletion operations
  - support non-uniform object sizes

**Input:** KVs access workload

```
SET key1 123
GET key1
SET key2 "test"
GET key2
...
```

**Output:** Miss Ratio Curve (MRC)
pRedis – Class Memory Allocation

• If we allocate penalty class $i$ with $M_i$ memory units, then this class’s overall miss penalty (or latency) $MP_i$ can be estimated as:

$$MP_i = mr_i(M_i) \times p_i \times N_i$$

  - $mr_i(M_i)$: miss rate given memory size $M_i$
  - $p_i$: average miss penalty
  - $N_i$: access count

• Our final goal:

$$\min \sum_{i=1}^{n} MP_i = \min \sum_{i=1}^{n} mr_i(M_i) \times p_i \times N_i \quad \text{s.t.} \quad \sum_{i=1}^{n} M_i = M$$

Dynamic programming to obtain the optimal memory allocation: enforced through object replacements.
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Long-term Locality Handling

**Periodic Pattern:** The number of requests changes periodically over time, and the long-term reuse is accompanied by the emergence of request peaks.

**Non-Periodic Pattern:** The number of requests remains relatively stable over time, or there are no long-term reuses.
Auto Load/Dump Mechanism

• Obviously, when these two types of workloads share Redis,
  • with the LRU strategy, the memory usage of the two types of data will change during the access peaks and valleys.
  • the passive evictions during the valley periods and the passive loadings (because of GET misses) during the peak periods will cause considerable latency.

• Auto load/dump mechanism
  • Proactively dump some of the memory to a local SSD (or hard drives) when a valley arrives.
  • Proactively load the previously dumped content before arrival of a peak.
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Experimental Setup

• We evaluate pRedis and other strategies using **six cluster nodes**.
• Each node: Intel(R) Xeon(R) E5-2670 v3 2.30GHz processor with 30MB shared LLC and 200 GB of memory, the OS is Ubuntu 16.04 with Linux-4.15.0.
Latency – Experimental Design

- We use the MurmurHash3 function to randomly distribute the data to two backend MySQL servers, one **local** and one **remote**.
  - access latency are $\sim 120 \mu s$ and $\sim 1000 \mu s$, respectively.

- We set a series of ranges, $[1\mu s, 10\mu s)$, $[10\mu s, 30\mu s)$, $[30\mu s, 70\mu s)$, ..., $[327670\mu s, 655350\mu s)$, 16 penalty classes in total.

- Additionally, in order to compare two different variants of pRedis, we run a **stress test** (mysqlslap) in the remote MySQL server after the workload reaches 40% of the trace.
  - causing the remote latency to rise from $\sim 1000 \mu s$ to $\sim 2000 \mu s$. 
pRedis(auto) is 34.8% and 20.5% lower than Redis and Redis-HC, pRedis(hint) cuts another 1.6%.

<table>
<thead>
<tr>
<th></th>
<th>Redis</th>
<th>Redis-HC</th>
<th>pRedis(auto)</th>
<th>pRedis(hint)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg (μs)</td>
<td>519.0</td>
<td>425.4</td>
<td>338.1</td>
<td>332.7</td>
</tr>
</tbody>
</table>
Latency

- We summarize the average response latency of the six YCSB workloads in the right figure.

- pRedis(auto) vs. Redis-HC: 12.1% ~ 51.9%.

- pRedis(hint) vs. Redis-HC: 14.0% ~ 52.3%.
Tail Latency

• YCSB Workload A
• using pRedis(hint)
• 0~99.99%: pRedis are the same as or lower than Redis and Redis-HC.
• 99.999%~99.9999%: three methods have their pros and cons.
• next 0.00009%: pRedis performs better than others.

<table>
<thead>
<tr>
<th></th>
<th>min</th>
<th>90th</th>
<th>95th</th>
<th>99th</th>
<th>99.9th</th>
<th>99.99th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redis</td>
<td>19</td>
<td>1335</td>
<td>1415</td>
<td>1561</td>
<td>1712</td>
<td>1789</td>
</tr>
<tr>
<td>Redis-HC</td>
<td>19</td>
<td>1295</td>
<td>1369</td>
<td>1506</td>
<td>1664</td>
<td>1766</td>
</tr>
<tr>
<td>pRedis</td>
<td>19</td>
<td>540</td>
<td>1349</td>
<td>1490</td>
<td>1647</td>
<td>1747</td>
</tr>
</tbody>
</table>
Auto Dump/Load in Periodic Pattern

- We use two traces from the collection of Redis traces
  - one trace has periodic pattern (the e-commerce trace),
  - the other has non-periodic pattern (a system monitoring service trace).

- The data objects are also distributed to both the local and remote MySQL databases.
Auto Dump/Load in Periodic Pattern

• In general, the use of auto-dump/load can smooth the access latency caused by periodic pattern switching.

• pRedis(with d/l) vs. Redis-HC: 13.3%

• pRedis(with d/l) vs. pRedis(without d/l): 8.4%
## Overhead

### Time Overhead

<table>
<thead>
<tr>
<th>Phase No.</th>
<th>RTH (μs)</th>
<th>MRC (μs)</th>
<th>DP (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.87</td>
<td>275</td>
<td>118</td>
</tr>
<tr>
<td>2</td>
<td>1.19</td>
<td>288</td>
<td>97</td>
</tr>
<tr>
<td>3</td>
<td>1.52</td>
<td>282</td>
<td>109</td>
</tr>
<tr>
<td>4</td>
<td>1.87</td>
<td>274</td>
<td>109</td>
</tr>
<tr>
<td>5</td>
<td>1.60</td>
<td>273</td>
<td>98</td>
</tr>
<tr>
<td>6</td>
<td>1.71</td>
<td>272</td>
<td>95</td>
</tr>
<tr>
<td>7</td>
<td>2.01</td>
<td>301</td>
<td>120</td>
</tr>
<tr>
<td>8</td>
<td>1.89</td>
<td>290</td>
<td>112</td>
</tr>
<tr>
<td><strong>avg</strong></td>
<td><strong>1.58</strong></td>
<td><strong>280</strong></td>
<td><strong>107</strong></td>
</tr>
</tbody>
</table>

RTH sampling time takes about 0.01% of access time, MRC construction and re-allocation DP occur at the end of each phase (in minutes), that’s negligible.

### Space Overhead

<table>
<thead>
<tr>
<th>Space Details</th>
<th>Total Space Overhead</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling Table</td>
<td>100 K * 32 B = 3.2 MB</td>
</tr>
<tr>
<td>RTH Arrays</td>
<td>120 KB * 16 = 1.88 MB</td>
</tr>
<tr>
<td>MRC Arrays</td>
<td>1 K * 4 B = 4 KB</td>
</tr>
<tr>
<td>Penalty Table</td>
<td>16 * 4 B = 64 B</td>
</tr>
<tr>
<td>Class IDs Filter</td>
<td>1 MB * 16 = 16 MB</td>
</tr>
<tr>
<td>KV Size Cache</td>
<td>1 M * 4 B = 4 MB</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>25.08 MB</strong></td>
</tr>
</tbody>
</table>

Working set is 10 GB (using YCSB Workload A), total space overhead is 25.08 MB, 0.24% of the total working set size, that’s acceptable.
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- We have presented a systematic design and implementation of pRedis:
  - A penalty and locality aware memory allocation scheme for Redis.
  - It exploits the data locality and miss penalty, in a quantitative manner, to guide the memory allocation in Redis.

- pRedis shows good performance:
  - It can predict MRC for each penalty class with a 98.8% accuracy and has the ability to adapt the phase change.
  - It outperforms a state-of-the-art penalty aware cache management scheme, HC, by reducing 14~52% average response time.
  - Its time and space overhead is low.
Thanks for your attention!

Q & A

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Workloads

- MSR Workloads
  - One week of block I/O traces from the Microsoft Research Cambridge Enterprise servers

- YCSB Workloads
  - A framework and common set of workloads for evaluating the performance of different "key-value" and "cloud" serving stores.

- A Collection of Real-world Redis Workloads
  - They are obtained from a set of Redis servers used for E-commerce, cluster performance monitoring, and other services.

- Memtier Benchmark
  - A high throughput benchmarking tool for Redis and Memcached.
**MRC Accuracy**

- pRedis relies on accurate MRCs.
- We compare the pRedis MRC, obtained by EAET using 1% set sampling, with the actual MRC, obtained by measuring the full-trace reuse distances.

- The average absolute error of EAET is **1.2%**, which is accurate enough.
Throughput – Worst Case

• A stress test using Memtier benchmark
• The memory-limit is set to $\infty$, so all of the GET queries will be hits.
• We setup 2 to 10 threads to send requests, each thread will drive 50 clients, each client send 1000000 requests total. The ratio of SET and GET is 1:10, and default data size is 32 bytes.

<table>
<thead>
<tr>
<th>Threads</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio (%)</td>
<td>97.8</td>
<td>97.5</td>
<td>98.6</td>
<td>98.8</td>
<td>99.5</td>
</tr>
</tbody>
</table>

The average degradation is only 1.5%