Distributed Adaptive Radix Tree for Efficient Metadata Search on HPC Systems

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Abstract
- Affix-based keyword search is fundamental to metadata search on HPC systems.
- Building inverted index to boost the performance of affix-based keyword search is a common practice but is challenging in distributed system like HPC.
- We propose Distributed Adaptive Radix Tree (DART) to address the challenge of building such index in distributed environment.
- Our experimental evaluation exhibits the effectiveness and efficiency of DART.

Methods
- **DART Partition Tree Initialization**
  While initializing DART on character set with \( k \) characters, we have to make sure the total number of leaf nodes in DART is larger than the total number of machines \( M \). Thus, we initialize the height of the DART partition tree \( d \) as:
  \[
  d = \lceil \log_k M \rceil + 1
  \]
  Then, we have the following partition tree:

- **DART Base Virtual Node Selection**
  Then, for a given string, starting from the root node of the partition tree, we locate the leaf node by following the path containing the sequence of first \( k \) characters in the given string. We choose such node as the base virtual node.

- **DART Alternative Virtual Node Selection**
  For load balance purpose, we choose an alternative virtual node. We defined a different function for selecting the alternative virtual node.
<table>
<thead>
<tr>
<th>Keyword</th>
<th>Base Virtual Node</th>
<th>Alternative Virtual Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>A (Begin at 0)</td>
<td>C (Begin at 45)</td>
</tr>
<tr>
<td>ABF</td>
<td>A (Begin at 0)</td>
<td>C (Begin at 45)</td>
</tr>
<tr>
<td>B</td>
<td>B (Begin at 45)</td>
<td>A (Begin at 0)</td>
</tr>
<tr>
<td>BB</td>
<td>B (Begin at 90)</td>
<td>A (Begin at 0)</td>
</tr>
<tr>
<td>CRB</td>
<td>C (Begin at 180)</td>
<td>B (Begin at 90)</td>
</tr>
</tbody>
</table>

- **DART Eventual Node Selection**
  After selecting the base virtual node and alternative node, we detect the number of keywords indexed on them, and select the one with less keywords indexed as the eventual node.

- **DART Operation Complexity**

<table>
<thead>
<tr>
<th>Operations</th>
<th>Computation Complexity</th>
<th>Communication Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insertion</td>
<td>( O(1) )</td>
<td>( O(1) )</td>
</tr>
<tr>
<td>Deletion</td>
<td>( O(1) )</td>
<td>( O(1) )</td>
</tr>
<tr>
<td>Exact Search</td>
<td>( O(1) )</td>
<td>( O(1) )</td>
</tr>
<tr>
<td>Prefix Search</td>
<td>( O(1) )</td>
<td>( O(1) )</td>
</tr>
<tr>
<td>Suffix Search</td>
<td>( O(1) )</td>
<td>( O(1) )</td>
</tr>
<tr>
<td>infix Search</td>
<td>( O(1) )</td>
<td>( O(1) )</td>
</tr>
</tbody>
</table>

Search Performance at Scale
- **Search Throughput**
  DART is able to achieve efficient affix-based keyword search at scale. As compared to two DHT cases, DART performs up to 55 times better in prefix search and suffix search while maintaining comparable performance in exact search and infix search.

- **Query Latency**
  As the number of server increases, DART is able to maintain decent query latency which remains under 250 microseconds for prefix search, suffix search and exact search. For infix query, the latency on DART still remains within 20 milliseconds on 256 servers, which is the largest scale we have ever tested.

Load Balance at Scale
- DART is able to maintain load balance at scale. With different number of servers and different dataset, the dispersion of keyword distribution and query request distribution of DART is always between “full string hashing” and “initial hashing”.

Conclusion
- We have developed a trie-based inverted indexing technique, called DART, by which efficient affix-based keyword search can be performed.
- Our evaluation result shows that DART can successfully facilitate affix-based keyword search and achieve up to 55 times better search performance than “Full String Hashing” DHT use case, while maintaining load balance introduced by imbalanced keyword distribution by different leading characters and uneven query workload of different keyword.

References:

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Background
- Building inverted index for keyword search problem is a common practice.
- In distributed system, building inverted index for keywords involves two different paradigms – document-partitioned approach and term-partitioned approach.
- Document-partitioned approach suffers from heavy overhead introduced by query broadcasting.
- “Full String Hashing” in term-based approach still suffers from query broadcasting in prefix search and suffix search.
- “Initial Hashing” in term-based approach suffers from imbalanced workload introduced by uneven keyword distribution led by different leading character.

Search Performance at Scale
- Also, uneven query workload on popular keyword is noticeable.