Wormhole: A Fast Ordered Index Data Structure

Xingbo Wu

UIC
UNIVERSITY OF ILLINOIS AT CHICAGO

Fan Ni Song Jiang

UNIVERSITY OF TEXAS ARLINGTON

Index for In-memory Large-scale Data Stores

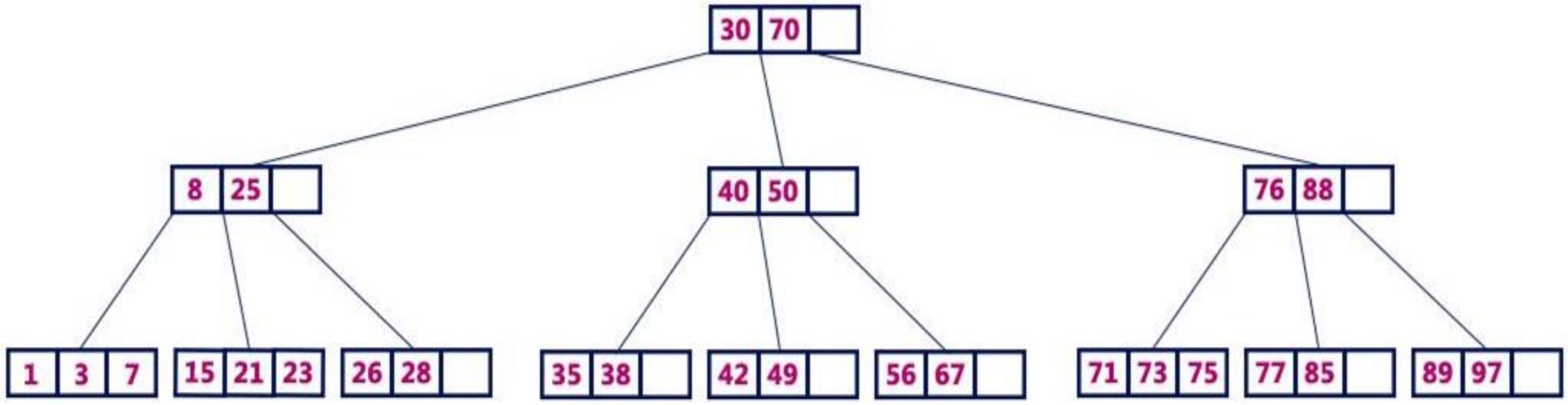
- The index can be very big.
  - The memory becomes increasing large.
  - The indexed data (key-value items) can be small.
  - Many billions of keys have to be indexed.

- The index operations can be very expensive.

"The TPC-H queries spend up to 94% (35% on average) and TPC-DS queries spend up to 77% (45% on average) of their execution time on indexing." Kocberber, et al. at IEEE/ACM MICRO'13

- The index needs to be sorted.
  - Hash table with O(1) operations often isn't a choice.
  - **But we will leverage it to accelerate search in a sorted index.**

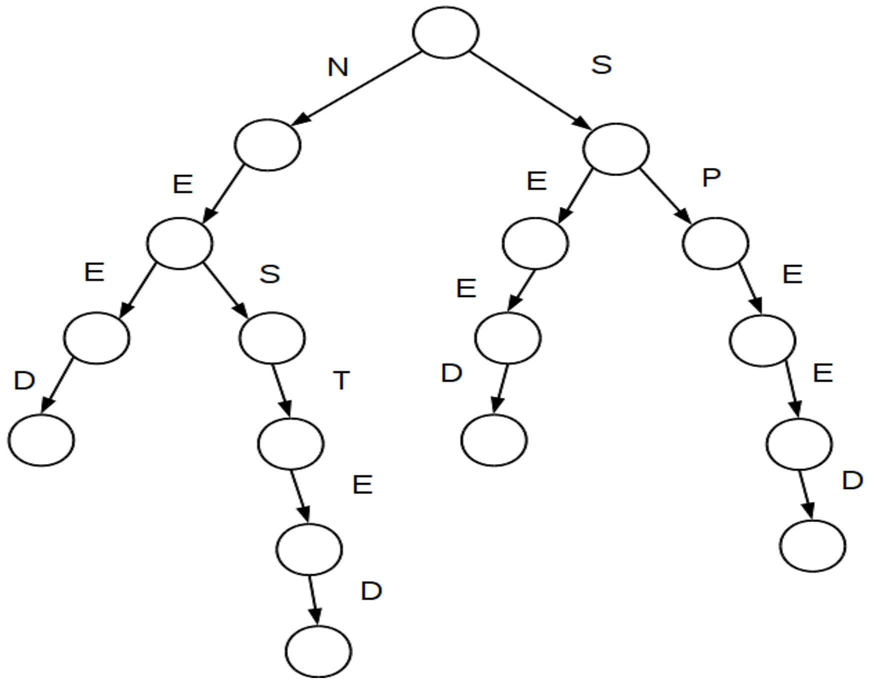
B+-tree Can be too Expensive



- O(***log N***) search cost (***N*** is the number of keys)
  - ~30 key-comparisons for one billion keys.

- A key comparison may induce multiple cache misses.
- An index search may end up with 50-100 memory accesses.

Prefix Tree Can be Time- and Space-inefficient



- O(***L***) search cost (***L*** is token count in a search key).
  - 100+ tokens in a key (e.g, URL)
- High space cost due to small node size.

The Dilemma and our Solution

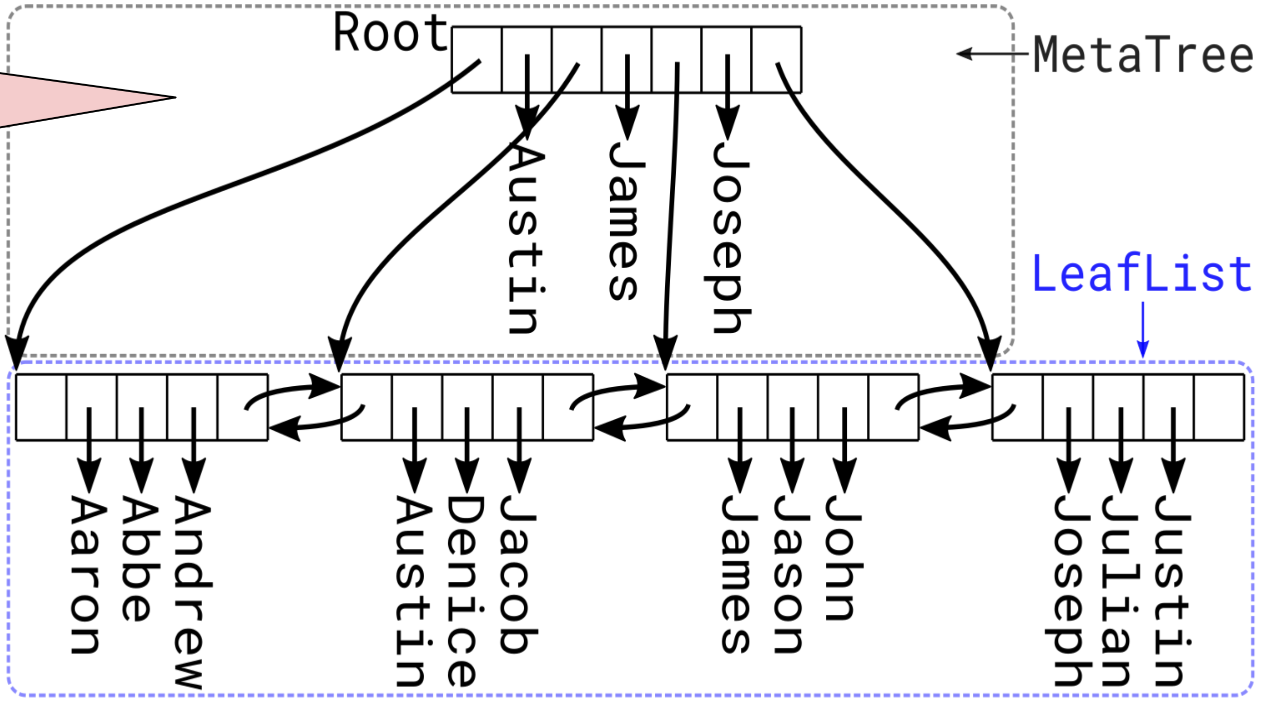
Data Structure	Pros	Cons
B+ Tree	* Space efficient (large leaf nodes) * Support of range operations	High lookup cost with a large *N*
Prefix Tree	Lookup cost not correlated with N	* High lookup cost even with a moderate L * Space inefficiency
Hash Table	O(1) lookup cost	No support of range operations

We will orchestrate **B+-tree, prefix tree, and hash table** in one index structure that:

- **has O(log L) search cost;**
- **is memory-efficient;**
- **supports range search.**

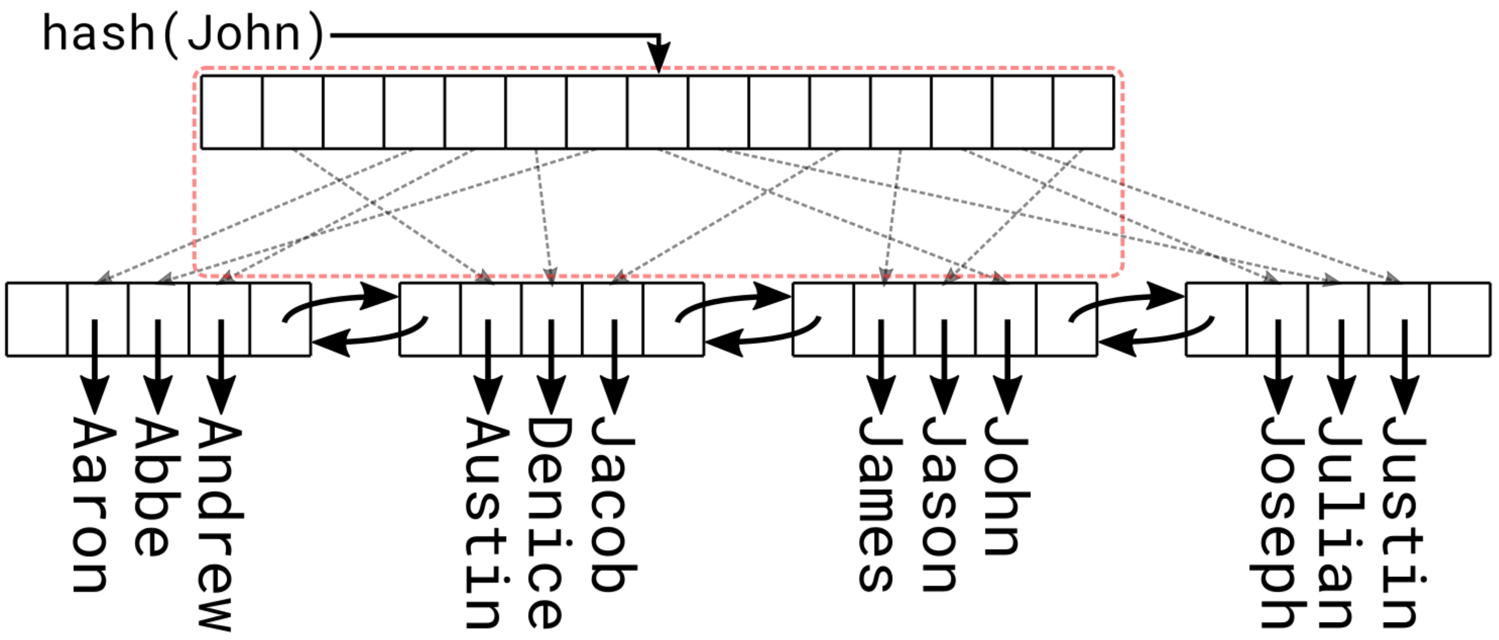
A Closer Look at B+-tree

The tree of internal nodes:
- O(log *N*) lookup cost
- Operations for maintaining tree balance



The list of leaf nodes:
- All keys in sorted order
- Fast range operations
- Constant lookup cost within each node

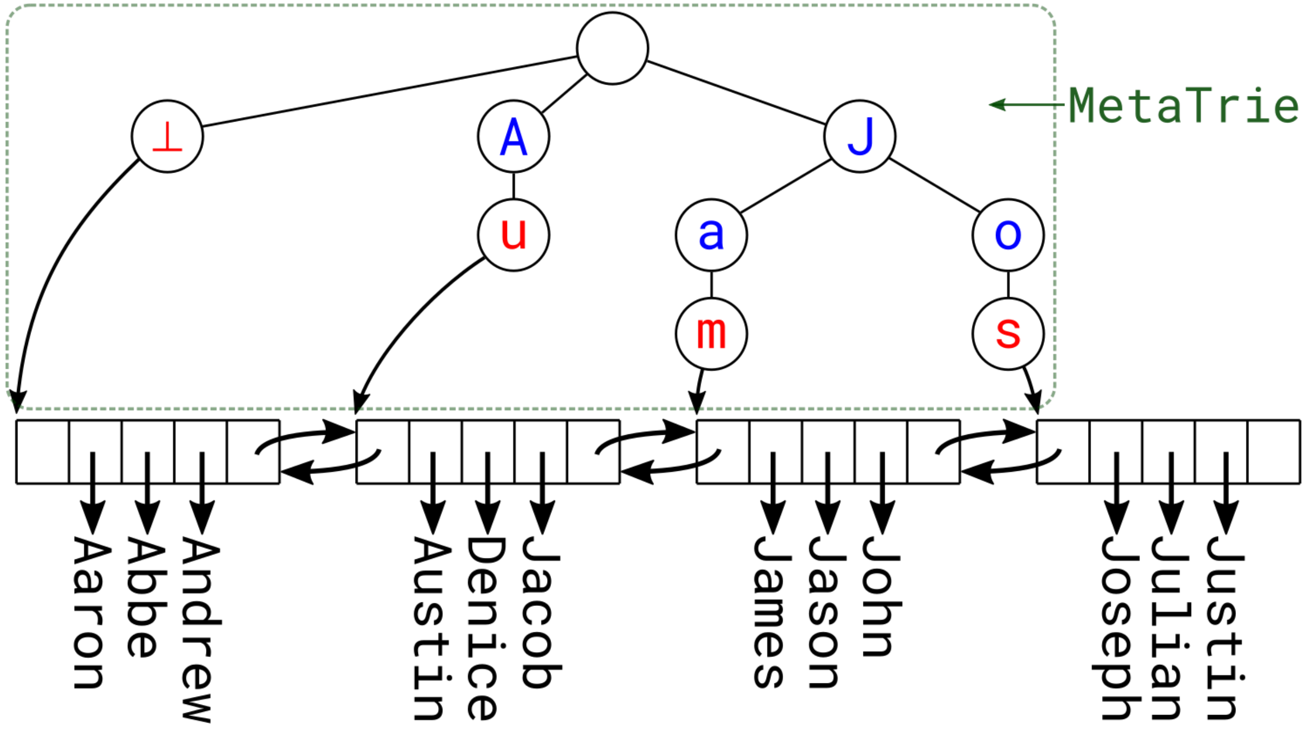
Replace MetaTree with a Hash Table?



However, this doesn't work:

- No support of insert;
- No full support of range search.

Replace MetaTree with MetaTrie (a Prefix Tree)

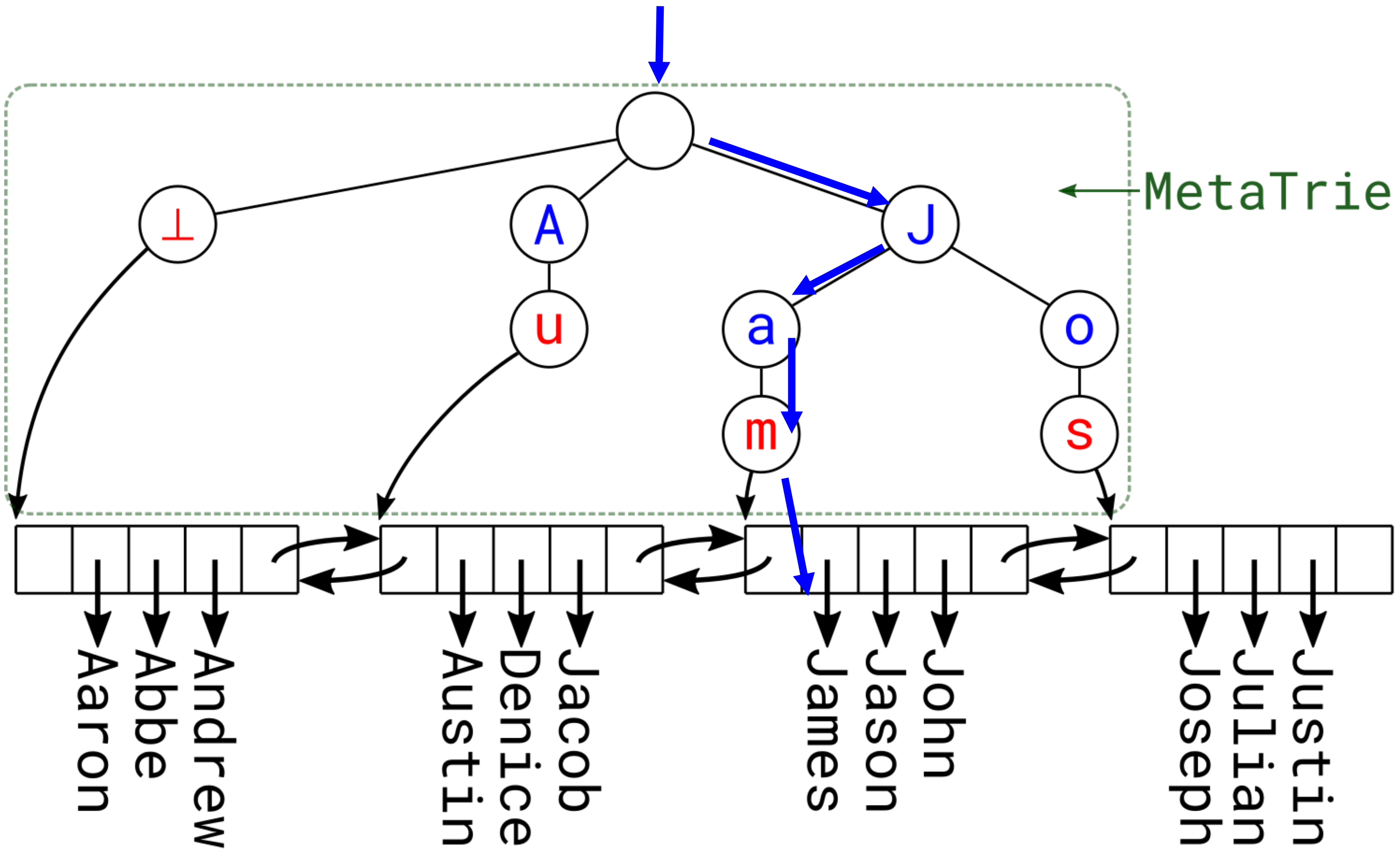


- Keys-at-its-left < ***anchor*** ≤ keys-at-its-right

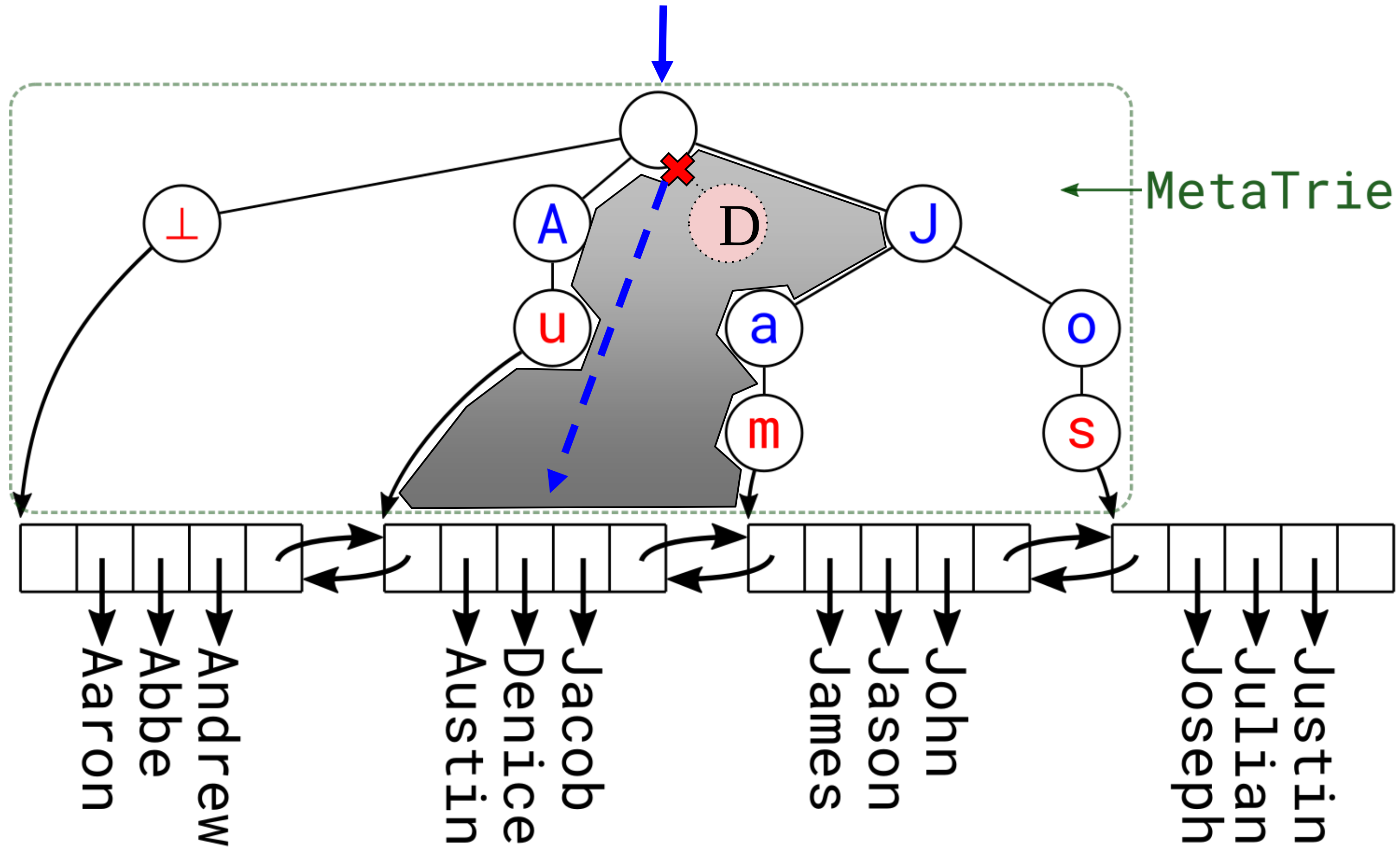
  - Example anchors: “Au”, “Jam”, “Jos”

- All prefixes of anchors are in MetaTrie.

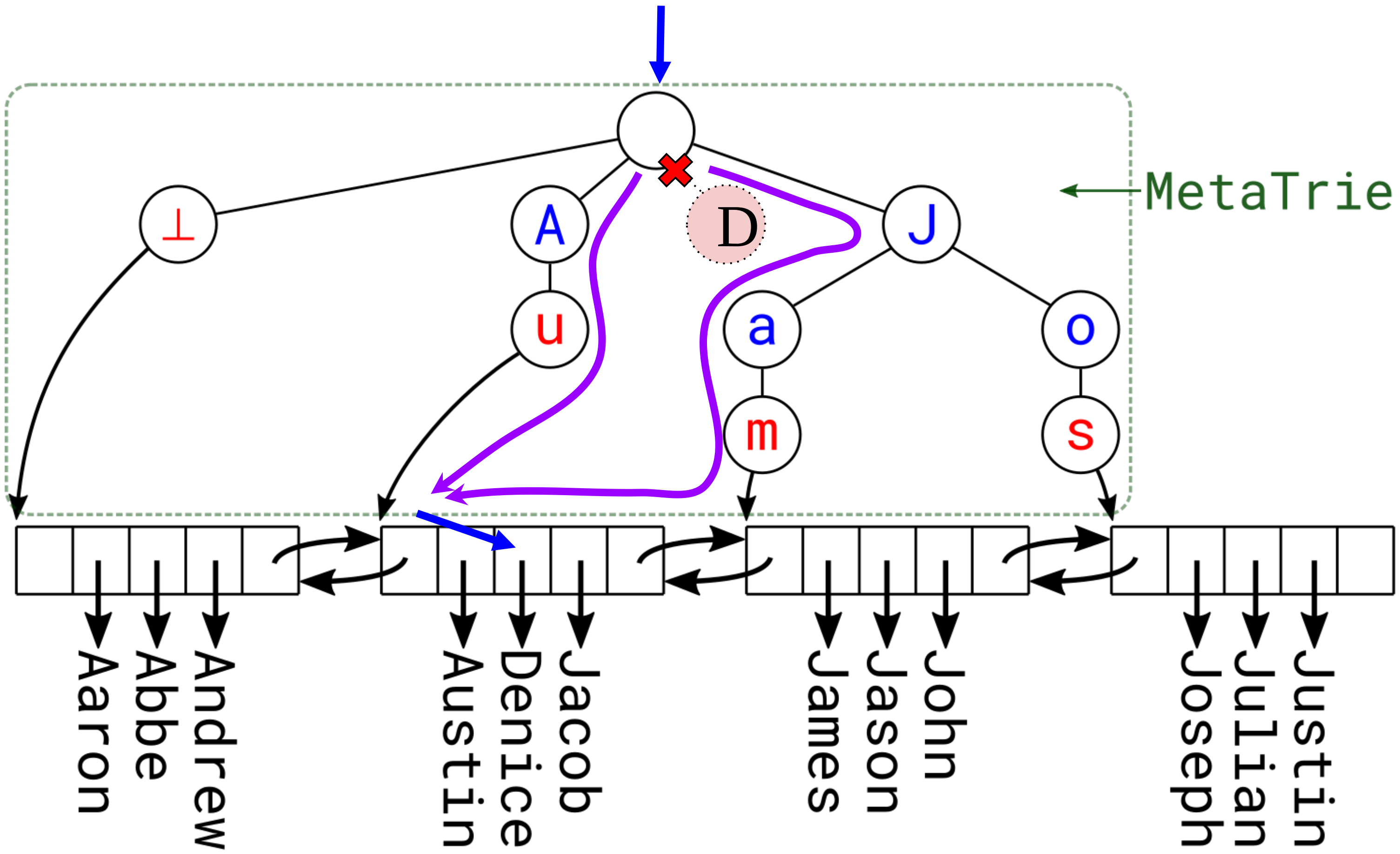
Search for “*James*” …….



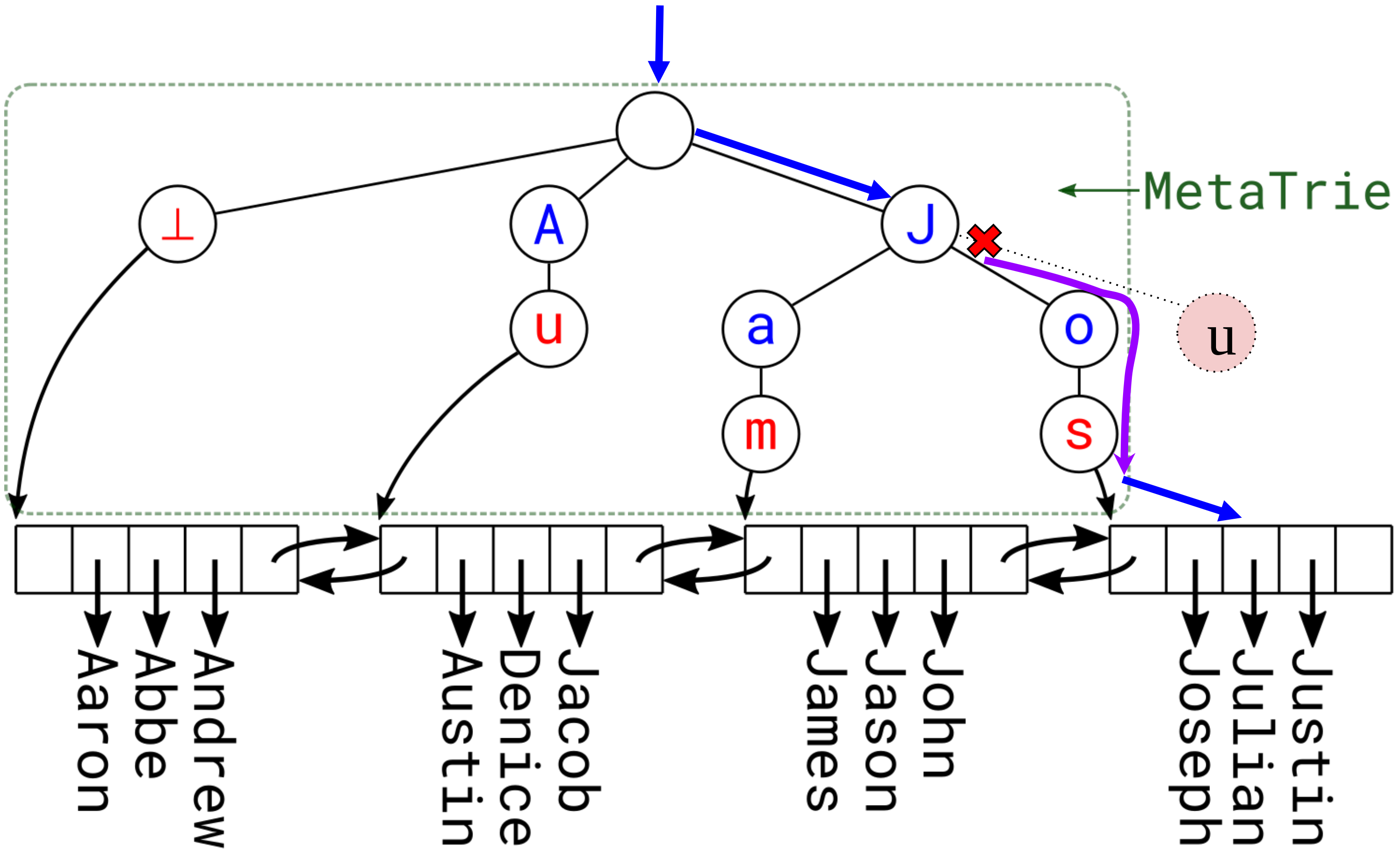
Search for “*Denice*” …….



Search for "*Denice*" ....



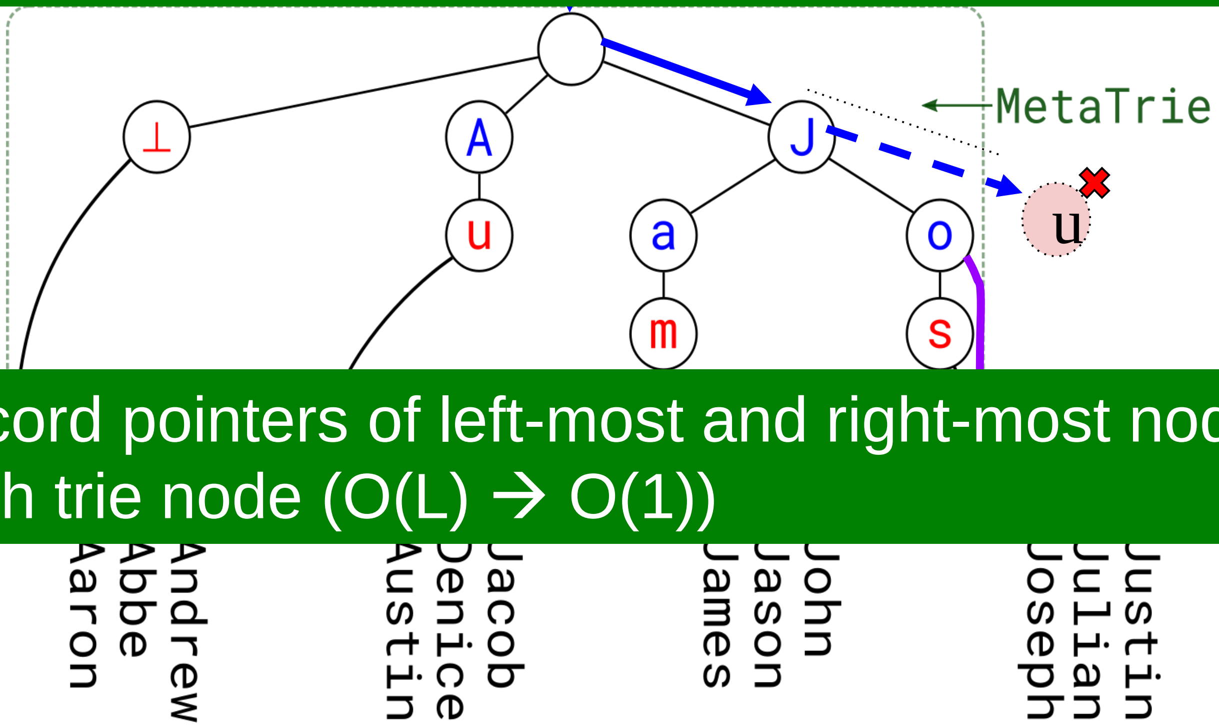
Search for “*Julian*” …….



But the Search Cost is Still *O(L)*

- Two phases in a search:
  - Find the longest prefix match (LPM) on the trie [1st phase].
  - Reach the right-most leaf of the missing node's left sibling, or the left-most leaf of the missing node's right sibling [2nd phase].

Binary search on the prefix length (O(L) → O(log L))



Record pointers of left-most and right-most nodes at each trie node (O(L) → O(1))

An Example: Binary Search on the Key with a Hash Table

- The anchor is "**Alexander**"
- All prefixes of the anchor are inserted to the hash table.
  - "A", "Al", "Ale", ... , "Alexander"
- Binary search of LPM for key "**Alexandria**"
  - Len = 5 ($\lceil (0+9)/2 \rceil$): "Alexa" exists.

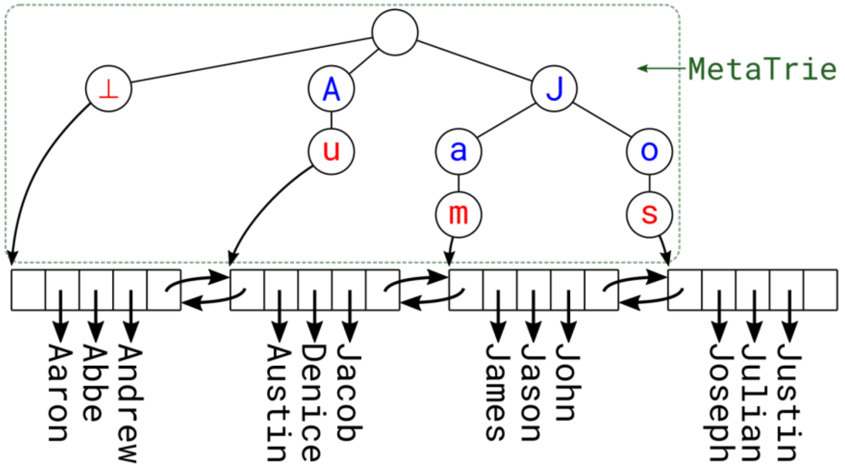
An Example: Binary Search on the Key with a Hash Table

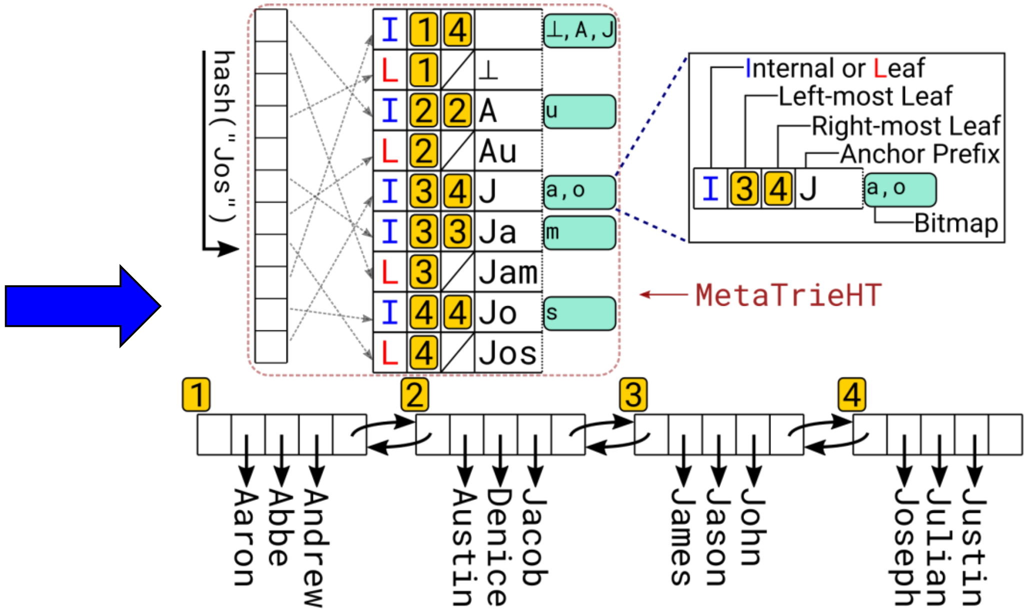
- The anchor is "$\boxed{\text{Alexand}}$er"
- All prefixes of the anchor are inserted to the hash table.
  - "A", "Al", "Ale", ... , "Alexander"
- Binary search of LPM for key "$\boxed{\text{Alexand}}$ria"
  - Len = 5 ($\lceil (0+9)/2 \rceil$): "Alexa" exists.
  - Len = 7 ($\lceil (5+9)/2 \rceil$): "Alexand" exists

An Example: Binary Search on the Key with a Hash Table

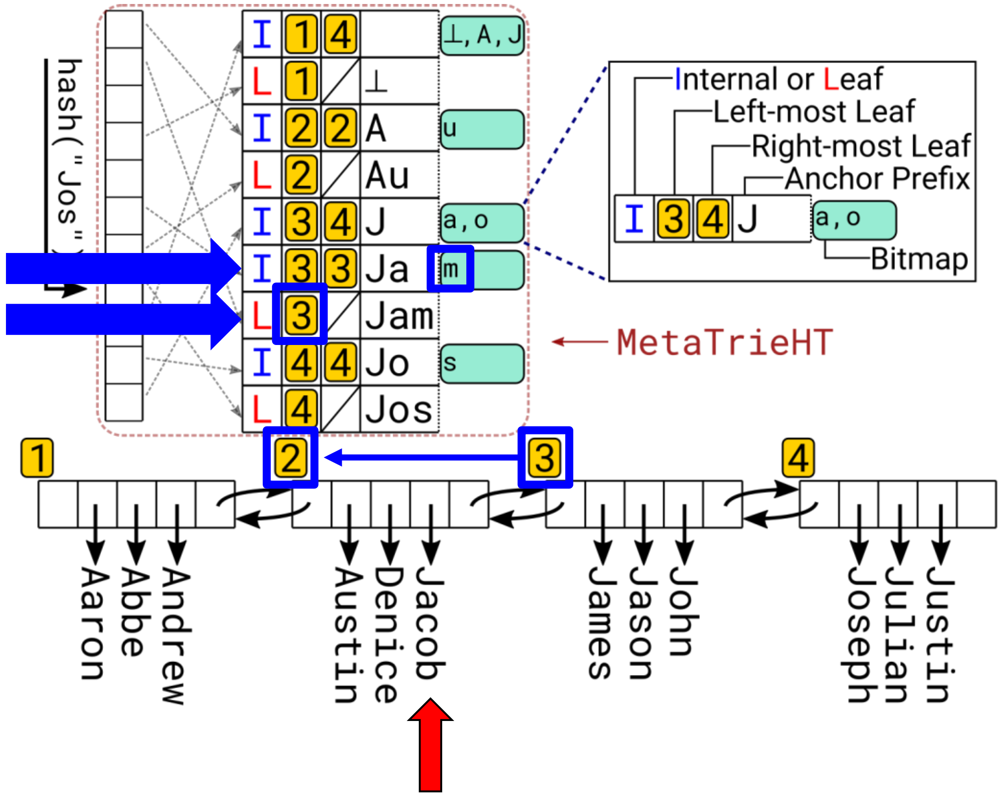
- The anchor is “$\boxed{\textbf{Alexande}}$**r**”
- All prefixes of the anchor are inserted to the hash table.
  - “A”, “Al”, “Ale”, ... , “Alexander”
- Binary search of LPM for key “$\boxed{\textbf{Alexandr}}$**a**”
  - Len = 5 ($\lceil (0+9)/2 \rceil$): “Alexa” exists.
  - Len = 7 ($\lceil (5+9)/2 \rceil$): “Alexand” exists
  - Len = 8 ($\lceil (7+9)/2 \rceil$): “Alexandr” does not exist.
  - so LPM is “Alexand” of length 7.

Wormhole:
Replace MetaTree with MetaTrieHT (a Prefix on a Hash Table)





Search for “*Jacob*” …….



- Search “**Ja**”
- But “**Jac**” is not in the table.
- Go to **Jam**’s left-most leaf node, which is Node 3
- Go to the node’s left sibling, which is Node 2
- Search for “**Jacob**” in Node 2.

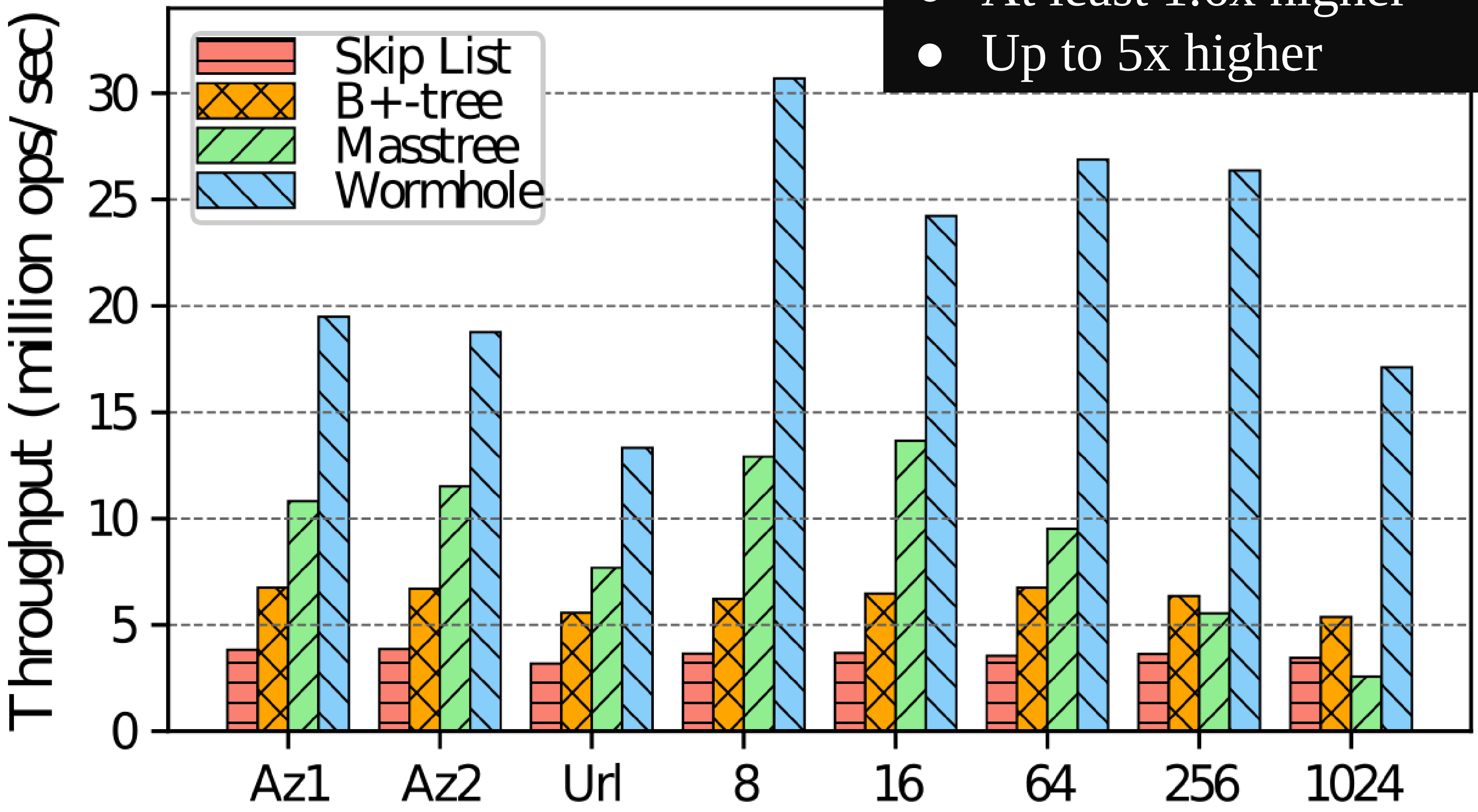
A Recap of Wormhole

- Its lookup cost is O(log L)
  - Asymptotically (much) better than O(log *N*) and O(*L*)
- Its space cost is comparable to B+ tree
  - One anchor per leaf node
- Efficient support of range Search
- Conduct split/Merge of leaf nodes (for insertion/deletion)
  - Same as B+-tree (But do not need to maintain tree balance)
  - Efficient concurrency control (see the paper)

Performance Evaluation

- The workload
  - Amazon reviews metadata (143M keys)
  - URLs from (“http://zwischenruf.at/?p=1012”) (192M keys)
  - Randomly generated keys of different sizes (8B, 16B, ... 1024B)
- The server
  - 16-core Intel Xeon E5-2697A, 40MB shared LLC, 256GB DRAM@2400MHz
- Indexes in comparison
  - Skiplist
  - B+-tree
  - Masstree
  - Cuckoo Hash Table

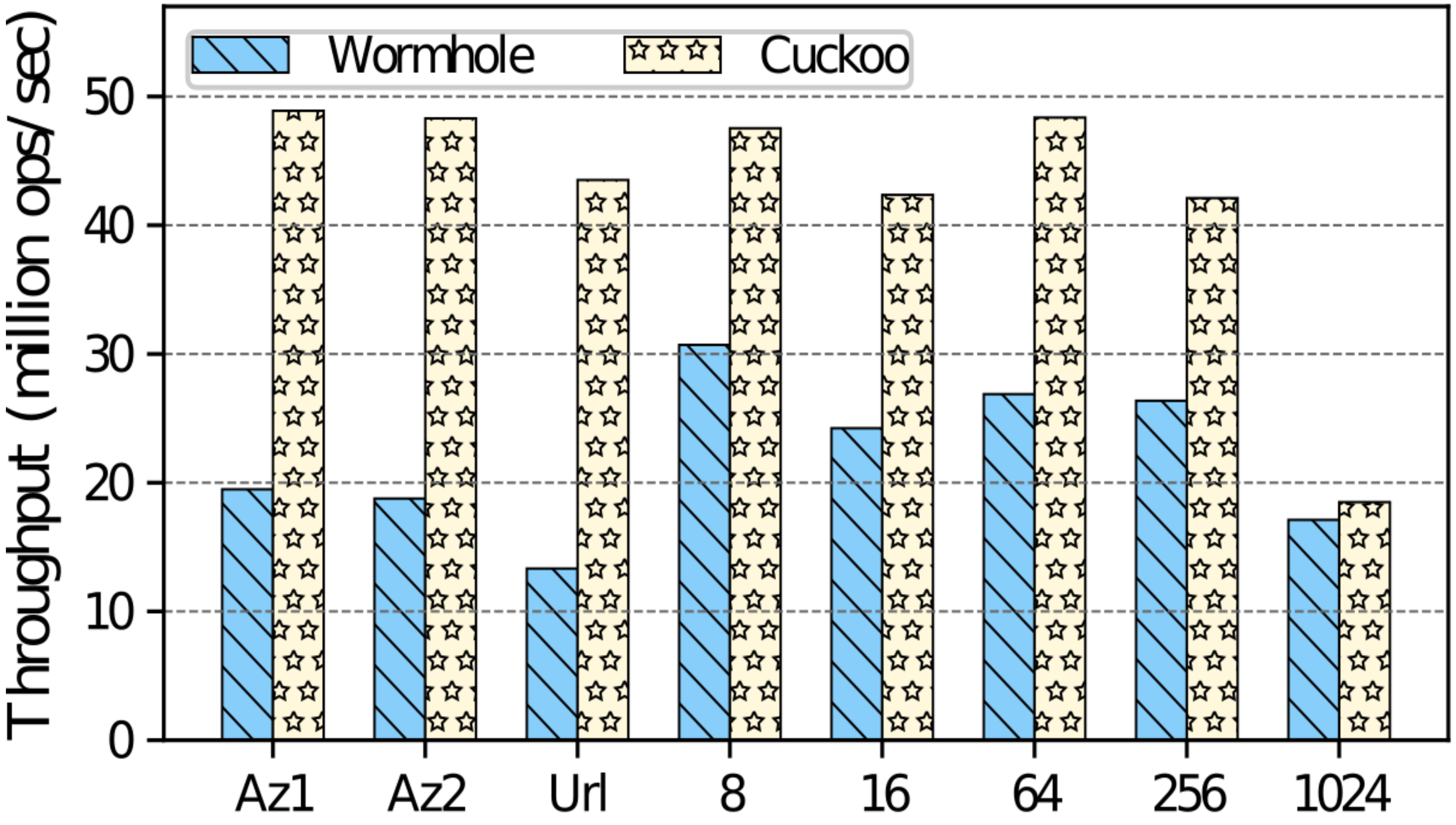
Lookup Performance



- At least 1.6x higher
- Up to 5x higher

Compare to Cuckoo Hash Table (w/ Point Search)

ONLY 2x ~ 3x slower



Conclusions

- A new index data structure for sorted keys with an asymptotically low cost of **O(log L)**.
- A well optimized implementation delivers **throughput multiple times higher**.
- A promising data structure for fine-grain-indexed big data store.

Source code is available for downloading at *https://github.com/wuxb45/wormhole*