A Forest-structured Bloom Filter with Flash Memory

Guanlin Lu, Biplob Debnath, David H.C. Du
Department of Computer Science and Engineering
University of Minnesota Twin Cities

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Introduction to Bloom Filter

- What’s it?
  - A bit vector that compactly represents a set of items (keys)
    - Support key query/insert operations
    - Tell definitely if a key is NOT present; couldn’t tell with guarantee that a key is indeed present (a few false positives may exist)

- Where is Bloom Filter (BF) used for?
  - Database applications
  - Network applications
    - E.g., router
  - Backup applications
    - E.g., chunking based data dedupe (not found → new chunk!)
Extending BF to Secondary Storage Device

- **Why?**
  - In-RAM BF size is limited by the available RAM size on the machine. However, some Apps like dedupe needs BF size beyond RAM capacity.

- **Main concept**
  - Utilize a limited amount of RAM space combined with a much larger secondary storage space to form a BF

- **Secondary storage device choices**
  - flash memory vs. magnetic disk
Building a BF with Flash Memory

- Special characteristics of flash memory:
  - page-level read/write but block-level erase
  - random page read is almost as fast as sequential page read
  - page write is slower than page read; page update needs a flash erase first
  - each flash cell has a limited number of writes due to wearout during life-cycle

How is the BF design optimized for flash characteristics?
Existing Works

- Single-layer Design

```
+----------+  +----------+  +----------+  +----------+  +----------+  +----------+
| subBF 1  | H | ...       |   | ...       |   | ...       |   | SubBF N   |
```

- Query key $k_i$
- Hash function $h() \% N$

**Pros**
- It requires only 1 flash page read/write per key query → best for key query

**Cons**
- Buffer space is very limited for each sub-BF → many flash read-then-write ops are required for each sub-BF during the run.
- Some sub-BFs tend to receive more keys than others (by single hash function), but buffer space is equally pre-partitioned.
- BF size has to be determined in advance and could not be changed during the run.
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Existing Works

■ Single-layer Design

```
| subBF 1 |   |   | ... | ... | ... | Miss! |   | Sub BF N |
```

■ Pros

□ It requires only 1 flash page read/write for key query → best for key query

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Existing Works

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| subBF 1 | ... | ... | ... | Sub BF N |

RAM write buffer

- Pros
  - It requires only 1 flash page read/write, makes it best for key query

- Cons
  - Buffer space is very limited for each sub-BF, many flash read-then-write ops are required for each sub-BF during the run.
  - Some sub-BFs tend to receive more keys than others (by single hash function), but buffer space is equally pre-partitioned.
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Existing Works

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  ![Diagram of Single-layer Design](image)

- Pros
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  - Buffer space is very limited for each sub-BF \(\rightarrow\) many flash read-then-write ops are required for each sub-BF during the run.
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Existing Works

- Linear-chaining Design

  ![Diagram of RAM Miss](image)

  - Pros
    - best for key insertion: each chained BF will be only written once, hence the flash write # is minimized
    - BF size grows dynamically as the # of chained BFs increased
  
  - Cons
    - Querying a key may require traverse all chained BFs
    - False positive errors tend to be much higher than single-layer design
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  ![Diagram](attachment:existing_works.png)

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  ![Diagram showing RAM and FLASH with BF 1 and BF 2]

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  ![Diagram showing RAM and FLASH with BF 1 and Miss!]

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Proposed Forest-structured BF (FBF) Design

- **Goal:** To strike a balance between key query and insert performance
- Partition flash space into a collection of sub-BFs of flash-page sized and organize them into a forest structure.
- **Key features**:
  - Overall BF size can grow by extending another layer of forest.
  - Each key query will at most require # of flash reads equal to forest height.
  - Key insertions are buffered temporarily in RAM buffer, which is designed to minimize flash write counts (explained in next page).
Proposed Buffer Space Management Scheme for FBF Design

- FBF inserts new keys into the lowest-layer of the forest only, which optimizes for
  - allowing larger buffer space per sub-BF
  - Minimize the target address range for flash writes

- FBF manages buffer space by
  - grouping consecutive sub-BFs into blocks
  - buffering key insertions per block in a in-RAM set data structure
  - keeping all sets into a linked-list
  - selecting the block corresponding to the set containing most insertions to update when the entire buffer space is used up.
Experimental Evaluation Results

- **Workload description:**
  - A sequence (20 millions) of SHA1 hash value of 160-bit length. Each of which represents a chunk-id produced by standard content-defined chunking algorithm; 57% are unique chunk-ids
  - BF access pattern: Key query & insert are interleaved

- **TR vs. buffer size for both cache managing schemes:**

<table>
<thead>
<tr>
<th>buffer schemes</th>
<th>fixed-size compartment</th>
<th>set-list</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of flash writes</td>
<td>2,024</td>
<td>1,053</td>
</tr>
<tr>
<td>ops/sec</td>
<td>8,405</td>
<td>8,657</td>
</tr>
</tbody>
</table>
Experimental Evaluation Results

- Throughput Rate (TR) vs. buffer sizes for forest-structure BF and single-layer BF
Summary of Contributions

- We present a novel BF design (FBF) with flash memory that
  - strikes a balance between key query and key insert performance
  - achieves a significantly higher TR with the same buffer size compared with existing designs.
- Furthermore, our proposed buffer space managing scheme reduces the number of flash writes remarkably (e.g., 50% less), even with the same existing BF design.
Thank you!
Thank you!
Background Works

- **Single-layer Design**

  ![Diagram of Single-layer Design]

  - Pros
    - Requires only 1 flash page read/key query \( \rightarrow \) best for key query

  - Cons
    - Buffer space is very limited for each sub-BF \( \rightarrow \) many flash read-then-write ops are required for each sub-BF during the run.
    - Some sub-BFs tend to receive more keys than others (by single hash function), but buffer space is equally partitioned ahead.
    - BF size should be determined in advance and could not be changed during the run.