Filters (Bloom & Quotient)

CSCI 256
Announcements/Logistics

• Last day of classes!!!!

• Review session: Monday @ 7pm, room TBA

• TA office hours: Tuesday @ around 3:30pm (Johnathan after Ward prize presentations)

• Office hours: Wednesday 10:30-noon, 1:30-2:30pm

• Final Exam: Thursday @ 9:30
  • Any questions about the exam?
Today’s Outline: Filters

• Filter Operations
• Filter Motivation
• Filter Designs
  • Bloom Filter
    • Parameters
    • Example
    • Limitations
  • Quotient Filter
    • Quotienting idea
    • Data structure
    • Example
Filter Operations

• Filters *approximately* answer questions about set membership. Therefore, a filter *must* support:
  • Insertions: `insert(key)`
  • Queries: `lookup(key)`

• Filters *may* also support other operations:
  • Deletion: `remove(key)`
  • Union: `merge(filter_a, filter_b)`
Filter Motivation

- Sometimes, we’re asked to perform an operation on a piece of data that doesn’t actually exist
  - Consider a library. If we know the call number of a book we want, we can: (1) walk to the correct floor, (2) find the shelf with the correct range, and (3) scan for the book on the shelf.
    - If the book was checked out, all of that work was wasted!
  - These steps are surprisingly similar to the process of looking for an item in a data structure so large that it exceeds RAM

- What does this have to do with filters?
  - Filters compactly represent a set so we can check for the existence of an item. **If the filter can confirm that the item does not exist, then we don’t need to do the expensive search!**
Filters: the BIG idea

• Filters are not exact.

• By embracing approximation, filters can be memory efficient data structures
  • Some false positives are allowed
  • But false negatives are never allowed

• Many applications are OK with this behavior
  • Typically filters are used in applications where a wrong answer just wastes work, but does not harm correctness
    • Recall the library example from before:
      • If we confirm the book doesn’t exist, we don’t search (correct)
      • If we mistakenly say the book exists, all we do is waste the time that we would have needed in the absence of the filter (correct, but slow)
Filter Case Study: Bloom
Bloom Filters

**Goal**: approximately represent a set of \( n \) elements using a bit array

- Queries return one of two answers:
  - Item is definitely NOT in the set
  - Item is Possibly in the set

**Parameters**: \( m, k \)

- \( m \): Number of bits in the array (i.e., buckets)
- \( k \): Set of \( k \) hash functions \( \{ h_1, h_2, ..., h_k \} \), each with range \( \{0...m-1\} \)
Concrete Example: $k=3$, $m=10$

\[
M = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

INSERT( )

$h_1( )$

$h_2( )$

$h_3( )$
Concrete Example: $k=3$, $m=10$

\[
M = \begin{bmatrix}
0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\]

Set:
Concrete Example: \( k=3, \ m=10 \)

\[
\begin{align*}
M &= \begin{bmatrix}
0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\
\end{bmatrix} \\
\text{INSERT}( \star ) \\
\h_1 ( \star ) \\
\h_2 ( \star ) \\
\h_3 ( \star )
\end{align*}
\]
Concrete Example: $k=3, m=10$

\[
M = \begin{bmatrix}
0 & 1 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 1 \\
\end{bmatrix}
\]

Note: bit was already set
Concrete Example: $k=3$, $m=10$

$$M = \begin{bmatrix} 0 & 1 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 1 \end{bmatrix}$$

LOOKUP( )

$h_1$ ( )

$h_2$ ( )

$h_3$ ( )

Set: 🌟

All $k$ bits are 1: return “possibly in set”
Concrete Example: $k=3$, $m=10$

Not all $k$ bits are 1: return "definitely NOT in set"
Concrete Example: $k=3$, $m=10$

M = \begin{bmatrix} 0 & 1 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 1 \end{bmatrix}

LOOKUP( )

All k bits are 1: return 
"possibly in set"

False Positive!

Set: ✝️
Tuning False Positives

• What happens if we increase $m$?
• What happens if we increase $k$?

• False positive rate $f$ is:

$$f = \left(1 - \left(1 - \frac{1}{m}\right)^{kn}\right)^k \approx \left(1 - e^{-\frac{kn}{m}}\right)^k$$

$P$ (a given bit is still 0 after $n$ insertions with $k$ independent hash functions)
Bloom Filters

• Are there any problems with Bloom filters?
  • What operations do they support/not support?
  • How do you grow a Bloom filter?
  • What if your filter itself exceeds RAM (how bad is locality)?
    • What does the cache behavior look like?
Bloom Filters: Challenges

• How do you grow a Bloom filter?
  • Short answer: you can’t
    • Filter only stores bits: no way to “invert” bits to recover items
  • Longer answer: rebuild
    • If you wanted to grow a Bloom filter, you could allocate a new (empty) filter of the target size, then read through all items and insert them to the new filter
      • Note: the underlying data may or may not be available!
Bloom Filters: Challenges

• What if your filter itself exceeds RAM?
  • What does the cache behavior look like?
    • Good hash functions intentionally create a uniform distribution to avoid “clumping”
    • So even if the filter fits in RAM, the cache locality is poor

• If the data set is truly large, there are a few options:
  • Use fewer bits per item (sacrifice precision)
  • Tolerate higher false positive rates
  • Use caching techniques, adding potential for expensive misses
Bloom Filters: Challenges

• What operations do they support/not support?
  • insert?
    Yes!
  • query?
    Yes!
  • delete?
    No! (Multiple items may have “set” any given bit)
  • rename?
    No! (rename = delete + insert)
  • “count”? 
    No! (maybe/no answers only)

Bloom filter extensions that add support for additional operations do exist, but these operations are not supported by the standard data structure.
Filter Case Study: Quotient
Quotient Filters

• Based on a technique from a homework question in Donald Knuth’s “The Art of Computer Programming: Sorting and Searching, volume 3” (Section 6.4, exercise 13)

• Quotienting Idea:

```
Hash: 1 0 1 1 0 0 1 0 1 1 0 1 1 1 0 0 1 0 1
```
Quotient Filters

- Based on a technique from a homework question in Donald Knuth’s “The Art of Computer Programming: Sorting and Searching, volume 3” (Section 6.4, exercise 13)

- Quotienting Idea:

  | Hash: | 1 0 1 1 0 0 1 0 1 1 0 1 1 1 0 0 1 0 1 |
  |

  Quotient: \( q \) most significant bits  
  Remainder: \( r \) least significant bits

  Remaining bits are discarded/lost
Building a Quotient Filter

• The quotient is used as an index into an \( m \)-bucket array, where the remainder is stored.
  • Essentially, filter is a hashtable that stores a remainder as the value
  • The quotient is implicitly stored because it is the bucket index

• Collisions are resolved using linear probing and 3 extra bits per bucket
  • \texttt{is\_occupied}: whether a slot is the canonical slot for some value currently stored in the filter
  • \texttt{is\_continuation}: whether a slot holds a remainder that is part of a run (but not the first element in the run)
  • \texttt{is\_shifted}: whether a slot holds a remainder that is not in its canonical slot

• A canonical slot is an element’s “home bucket”, i.e., where it belongs in the absence of collisions.
Quotient Filter Example

Figure 1: An example quotient filter and its representation.

[https://www.usenix.org/conference/hotstorage11/dont-thrash-how-cache-your-hash-flash]
Quotient Filter Example

Parameters:
- $q = 1$ “bit”
- $r = 3$ “bits”

<table>
<thead>
<tr>
<th>Quotient (Bucket Index)</th>
<th>Remainder (Item Stored)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>132</td>
</tr>
<tr>
<td>2</td>
<td>859</td>
</tr>
<tr>
<td>2</td>
<td>609</td>
</tr>
<tr>
<td>3</td>
<td>402</td>
</tr>
</tbody>
</table>

Example uses decimal digits for readability.
Quotient Filter Example

is_occupied

is_shifted

is_continuation

402 did not collide with any elements, but it was shifted from its canonical slot by 609 and 859.

859 collided with 609, so 859 is both shifted and part of a run. 402 would live here, so this bucket is occupied.

Collision, but 609 is in its canonical slot, so is_occupied is set.
Quotient Filter Concept-check

• What are the possible reasons for a collision?
  • Which collisions are treated as “false positives”

• What parameters does the QF give the user? In other words:
  • What knobs can you turn to control the size of the filter?
  • What knobs can you turn to control the false positive rate of the filter?
Quotient Filter Concept-check

• What are the possible reasons for a collision?
  • Collisions in the hashtable
    • Same quotient, but different remainders cause shifting
  • Collisions in the hashspace
    • Different keys may produce identical quotients/remainders
      • If a hash function collision -> not the QF’s fault
      • If due to dropped bits during “quotienting” -> that is the QF’s fault
  • Which collisions are treated as “false positives”
    • Collisions in the hash space

• What parameters does the QF give the user? In other words:
  • What knobs can you turn to control the size of the filter?
  • What knobs can you turn to control the false positive rate of the filter?
    • Quotient bits (number of buckets)
    • Remainder bits (how many unique bits per element to store)
Why QF over BF?

- QF supports deletes
- QF supports “merges”
- QF has good cache locality
  - How many locations accessed per operation?
  - Some math can show that runs/clusters are expected to be small

- **Don’t Thrash, How to Cache Your Hash on Flash** also introduces the Cascade filter, a *write-optimized* filter made up of increasingly large QFs that spill over to disk.
  - Similar idea to Log-structured merge trees, which are an exciting data structure for large key-value stores!
Cascade Filter

Figure 2: Merging QFs. Three QFs of different sizes are shown above, and they are merged into a single large QF below. The

Inserts are fast (duplicates are OK, so inserts only touch RAM level)
Lookups do 1 I/O per level
What next?

• CS256 Unlocks new Williams CS courses:
  • [https://www.cs.williams.edu/~jannen/teaching/cs-prereqs.svg](https://www.cs.williams.edu/~jannen/teaching/cs-prereqs.svg)
• CS256 Prepares you for CS research
  • NSF REUs
  • Williams Summer Research
  • Thesis
• CS256 helps you think in new ways about the world
Thank you!

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