CS 561, Randomized Data Structures: Hash Tables, Skip Lists, Bloom Filters, Count-Min sketch

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Outline

- Hash Tables
- Skip Lists
- Count-Min Sketch
A dictionary ADT implements the following operations

- $\text{Insert}(x)$: puts the item $x$ into the dictionary
- $\text{Delete}(x)$: deletes the item $x$ from the dictionary
- $\text{IsIn}(x)$: returns true iff the item $x$ is in the dictionary
Dictionary ADT

- Frequently, we think of the items being stored in the dictionary as keys
- The keys typically have records associated with them which are carried around with the key but not used by the ADT implementation
- Thus we can implement functions like:
  - \( \text{Insert}(k,r) \): puts the item \((k,r)\) into the dictionary if the key \(k\) is not already there, otherwise returns an error
  - \( \text{Delete}(k) \): deletes the item with key \(k\) from the dictionary
  - \( \text{Lookup}(k) \): returns the item \((k,r)\) if \(k\) is in the dictionary, otherwise returns null
Implementing Dictionaries

- The simplest way to implement a dictionary ADT is with a linked list
- Let $l$ be a linked list data structure, assume we have the following operations defined for $l$
  - $\text{head}(l)$: returns a pointer to the head of the list
  - $\text{next}(p)$: given a pointer $p$ into the list, returns a pointer to the next element in the list if such exists, null otherwise
  - $\text{previous}(p)$: given a pointer $p$ into the list, returns a pointer to the previous element in the list if such exists, null otherwise
  - $\text{key}(p)$: given a pointer into the list, returns the key value of that item
  - $\text{record}(p)$: given a pointer into the list, returns the record value of that item
At-Home Exercise

Implement a dictionary with a linked list

- Q1: Write the operation Lookup(k) which returns a pointer to the item with key k if it is in the dictionary or null otherwise
- Q2: Write the operation Insert(k,r)
- Q3: Write the operation Delete(k)
- Q4: For a dictionary with $n$ elements, what is the runtime of all of these operations for the linked list data structure?
- Q5: Describe how you would use this dictionary ADT to count the number of occurrences of each word in an online book.
Dictionaries

- This linked list implementation of dictionaries is very slow
- Q: Can we do better?
- A: Yes, with hash tables, AVL trees, etc
Hash Tables

Hash Tables implement the Dictionary ADT, namely:

- Insert(x) - $O(1)$ expected time, $\Theta(n)$ worst case
- Lookup(x) - $O(1)$ expected time, $\Theta(n)$ worst case
- Delete(x) - $O(1)$ expected time, $\Theta(n)$ worst case
Direct Addressing

• Suppose universe of keys is $U = \{0, 1, \ldots, m - 1\}$, where $m$ is not too large
• Assume no two elements have the same key
• We use an array $T[0..m - 1]$ to store the keys
• Slot $k$ contains the elem with key $k$
Direct Address Functions

DA-Search(T, k) { return T[k]; }
DA-Insert(T, x) { T[key(x)] = x; }
DA-Delete(T, x) { T[key(x)] = NIL; }

Each of these operations takes $O(1)$ time
Direct Addressing Problem

- If universe $U$ is large, storing the array $T$ may be impractical
- Also much space can be wasted in $T$ if number of objects stored is small
- Q: Can we do better?
- A: Yes we can trade time for space
Hash Tables

- “Key” Idea: An element with key $k$ is stored in slot $h(k)$, where $h$ is a hash function mapping $U$ into the set $\{0, \ldots, m-1\}$
- Main problem: Two keys can now hash to the same slot
- Q: How do we resolve this problem?
- A1: Try to prevent it by hashing keys to “random” slots and making the table large enough
- A2: Chaining
- A3: Open Addressing
Chained Hash

In chaining, all elements that hash to the same slot are put in a linked list.

CH-Insert(T,x){Insert x at the head of list T[h(key(x))];}
CH-Search(T,k){search for elem with key k in list T[h(k)];}
CH-Delete(T,x){delete x from the list T[h(key(x))];}
Analysis

- CH-Insert takes $O(1)$ time if the list is doubly linked and there are no duplicate keys
- Q: How long does CH-Search and CH-Delete take?
- A: It depends. In particular, depends on the load factor, $\alpha = n/m$ (i.e. average number of elems in a list)
CH-Search Analysis

- Worst case analysis: everyone hashes to one slot so \( \Theta(n) \)
- For average case, make the *simple uniform hashing* assumption: any given elem is equally likely to hash into any of the \( m \) slots, indep. of the other elems
- Let \( n_i \) be a random variable giving the length of the list at the \( i \)-th slot
- Then time to do a search for key \( k \) is \( 1 + n_h(k) \)
Q: What is $E(n_{h(k)})$?
A: We know that $h(k)$ is uniformly distributed among $\{0, \ldots, m-1\}$
Thus, $E(n_{h(k)}) = \sum_{i=0}^{m-1} (1/m)n_i = n/m = \alpha$
Hash Functions

- Want each key to be equally likely to hash to any of the $m$ slots, independently of the other keys
- Key idea is to use the hash function to “break up” any patterns that might exist in the data
- We will always assume a key is a natural number (can e.g. easily convert strings to naturaly numbers)
Division Method

- \( h(k) = k \mod m \)
- Want \( m \) to be a prime number, which is not too close to a power of 2
- Why? Reduces collisions in the case where there is periodicity in the keys inserted
Hash Tables implement the Dictionary ADT. Assuming \( n = O(m) \) we have:

- Insert(\( x \)) - \( O(1) \) expected time, \( \Theta(n) \) worst case
- Lookup(\( x \)) - \( O(1) \) expected time, \( \Theta(n) \) worst case
- Delete(\( x \)) - \( O(1) \) expected time, \( \Theta(n) \) worst case
Skip List

- Enables insertions and searches for ordered keys in $O(\log n)$ expected time
- Very elegant randomized data structure, simple to code but analysis is subtle
- They guarantee that, with high probability, all the major operations take $O(\log n)$ time (e.g. Find-Max, Predecessor/Sucessor)
- Can even enable ”find-i-th value” if store with each edge the number of elements that edge skips
A skip list is basically a collection of doubly-linked lists, $L_1, L_2, \ldots, L_x$, for some integer $x$.

Each list has a special head and tail node, the keys of these nodes are assumed to be $-\text{MAXNUM}$ and $+\text{MAXNUM}$ respectively.

The keys in each list are in sorted order (non-decreasing).
Skip List

• Every node is stored in the bottom list
• For each node in the bottom list, we flip a coin over and over until we get tails. For each heads, we make a duplicate of the node.
• The duplicates are stacked up in levels and the nodes on each level are strung together in sorted linked lists
• Each node $v$ stores a search key ($\text{key}(v)$), a pointer to its next lower copy ($\text{down}(v)$), and a pointer to the next node in its level ($\text{right}(v)$).
Example
Search

• To do a search for a key, $x$, we start at the leftmost node $L$ in the highest level
• We then scan through each level as far as we can without passing the target value $x$ and then proceed down to the next level
• The search ends either when we find the key $x$ or fail to find $x$ on the lowest level
SkipListFind(x, L) {
    v = L;
    while (v != NULL) and (Key(v) != x) {
        if (Key(Right(v)) > x)
            v = Down(v);
        else
            v = Right(v);
    }
    return v;
}
Search Example
Insert

$p$ is a constant between 0 and 1, typically $p = 1/2$, let rand() return a random value between 0 and 1

Insert(k){
First call Search(k), let pLeft be the leftmost elem $\leq k$ in $L_1$
Insert $k$ in $L_1$, to the right of pLeft
i = 2;
while (rand()$\leq p$){
    insert $k$ in the appropriate place in $L_i$;
}

Deletion

- Deletion is very simple
- First do a search for the key to be deleted
- Then delete that key from all the lists it appears in from the bottom up, making sure to “zip up” the lists after the deletion
Analysis

- Intuitively, each level of the skip list has about half the number of nodes of the previous level, so we expect the total number of levels to be about $O(\log n)$
- Similarly, each time we add another level, we cut the search time in half except for a constant overhead
- So after $O(\log n)$ levels, we would expect a search time of $O(\log n)$
- We will now formalize these two intuitive observations
Height of Skip List

- For some key, \( i \), let \( X_i \) be the maximum height of \( i \) in the skip list.
- Q: What is the probability that \( X_i \geq 2\log n \)?
- A: If \( p = \frac{1}{2} \), we have:

\[
P(X_i \geq 2 \log n) = \left( \frac{1}{2} \right)^{2\log n} = \frac{1}{(2^{\log n})^2} = \frac{1}{n^2}
\]

- Thus the probability that a particular key \( i \) achieves height \( 2 \log n \) is \( \frac{1}{n^2} \)
Height of Skip List

- Q: What is the probability that any key achieves height 2 \log n?
  - A: We want
    \[ P(X_1 \geq 2 \log n \text{ or } X_2 \geq 2 \log n \text{ or } \ldots \text{ or } X_n \geq 2 \log n) \]
- By a Union Bound, this probability is no more than
  \[ P(X_1 \geq k \log n) + P(X_2 \geq k \log n) + \cdots + P(X_n \geq k \log n) \]
  - Which equals:
    \[ \sum_{i=1}^{n} \frac{1}{n^2} = \frac{n}{n^2} = \frac{1}{n} \]
Height of Skip List

- This probability gets small as $n$ gets large
- In particular, the probability of having a skip list of size exceeding $2 \log n$ is $o(1)$
- If an event occurs with probability $1 - o(1)$, we say that it occurs with high probability
- Key Point: The height of a skip list is $O(\log n)$ with high probability.
In-Class Exercise Trick

A trick for computing expectations of discrete positive random variables:

• Let $X$ be a discrete r.v., that takes on values from $1$ to $n$

$$E(X) = \sum_{i=1}^{n} P(X \geq i)$$
Why?

\[
\sum_{i=1}^{n} P(X \geq i) = P(X = 1) + P(X = 2) + P(X = 3) + \ldots \\
+ P(X = 2) + P(X = 3) + P(X = 4) + \ldots \\
+ P(X = 3) + P(X = 4) + P(X = 5) + \ldots \\
+ \ldots \\
= 1 \cdot P(X = 1) + 2 \cdot P(X = 2) + 3 \cdot P(X = 3) + \ldots \\
= E(X)
\]
In-Class Exercise

Q: How much memory do we expect a skip list to use up?

• Let $X_i$ be the number of lists that element $i$ is inserted in.
• Q: What is $P(X_i \geq 1)$, $P(X_i \geq 2)$, $P(X_i \geq 3)$?
• Q: What is $P(X_i \geq k)$ for general $k$?
• Q: What is $E(X_i)$?
• Q: Let $X = \sum_{i=1}^{n} X_i$. What is $E(X)$?
Search Time

- It's easier to analyze the search time if we imagine running the search backwards.
- Imagine that we start at the found node $v$ in the bottommost list and we trace the path backwards to the top leftmost sentinel, $L$.
- This will give us the length of the search path from $L$ to $v$ which is the time required to do the search.
Backwards Search

SLFback(v){
    while (v != L){
        if (Up(v)!=NIL)
            v = Up(v);
        else
            v = Left(v);
    }
}
Backward Search

- For every node $v$ in the skip list $Up(v)$ exists with probability $1/2$. So for purposes of analysis, SLFBack is the same as the following algorithm:

```java
FlipWalk(v){
    while (v != L){
        if (COINFLIP == HEADS)
            v = Up(v);
        else
            v = Left(v);
    }
}
```
Analysis

- For this algorithm, the expected number of heads is exactly the same as the expected number of tails.
- Thus the expected run time of the algorithm is twice the expected number of upward jumps.
- Since we already know that the number of upward jumps is $O(\log n)$ with high probability, we can conclude that the expected search time is $O(\log n)$. 
Bloom Filters

- Randomized data structure for representing a set. Implements:
  - Insert(x):
  - IsMember(x):
- Allow false positives but require very little space
- Used frequently in: Databases, networking problems, p2p networks, packet routing
Bloom Filters

- Have $m$ slots, $k$ hash functions, $n$ elements; assume hash functions are all independent
- Each slot stores 1 bit, initially all bits are 0
- Insert($x$) : Set the bit in slots $h_1(x), h_2(x), ..., h_k(x)$ to 1
- IsMember($x$) : Return yes iff the bits in $h_1(x), h_2(x), ..., h_k(x)$ are all 1
Analysis Sketch

- $m$ slots, $k$ hash functions, $n$ elements; assume hash functions are all independent
- Then $P(\text{fixed slot is still 0}) = (1 - 1/m)^{kn}$
- Useful fact from Taylor expansion of $e^{-x}$:
  \[ e^{-x} - x^2/2 \leq 1 - x \leq e^{-x} \text{ for } x < 1 \]
- Then if $x \leq 1$
  \[ e^{-x}(1 - x^2) \leq 1 - x \leq e^{-x} \]
• Thus we have the following to good approximation.

\[ Pr(\text{fixed slot is still 0}) = (1 - 1/m)^{kn} \]

\[ \approx e^{-kn/m} \]

• Let \( p = e^{-kn/m} \) and let \( \rho \) be the fraction of 0 bits after \( n \) elements inserted then

\[ Pr(\text{false positive}) = (1 - \rho)^k \approx (1 - p)^k \]

• Where this last approximation holds because \( \rho \) is very close to \( p \) (by a Martingale argument beyond the scope of this class)
• Want to minimize \((1-p)^k\), which is equivalent to minimizing 
  \[ g = k \ln(1 - p) \]
• Trick: Note that 
  \[ g = -(m/n) \ln(p) \ln(1 - p) \]
• By symmetry, this is minimized when \(p = 1/2\) or equivalently 
  \[ k = (m/n) \ln 2 \]
• False positive rate is then 
  \[ (1/2)^k \approx (.6185)^{m/n} \]
• Can get the union of two sets by just taking the bitwise-or of the bit-vectors for the corresponding Bloom filters
• Can easily half the size of a bloom filter - assume size is power of 2 then just bitwise-or the first and second halves together
• Can approximate the size of the intersection of two sets - inner product of the bit vectors associated with the Bloom filters is a good approximation to this.
Extensions

- Bloomier Filters: Also allow for data to be inserted in the filter - similar functionality to hash tables but less space, and the possibility of false positives.
Data Streams

- A router forwards packets through a network
- A natural question for an administrator to ask is: what is the list of substrings of a fixed length that have passed through the router more than a predetermined threshold number of times
- This would be a natural way to try to, for example, identify worms and spam
- Problem: the number of packets passing through the router is *much* too high to be able to store counts for every substring that is seen!
This problem motivates the data stream model
Informally: there is a stream of data given as input to the algorithm
The algorithm can take at most one pass over this data and must process it sequentially
The memory available to the algorithm is much less than the size of the stream
In general, we won’t be able to solve problems exactly in this model, only approximate
Our Problem

- We are presented with a stream of items $i$
- We want to get a good approximation to the value $\text{Count}(i,T)$, which is the number of times we have seen item $i$ up to time $T$
Count-Min Sketch

- Our solution will be to use a data structure called a *Count-Min Sketch*
- This is a randomized data structure that will keep approximate values of Count(i,T)
- It is implemented using $k$ hash functions and $m$ counters
Count-Min Sketch

- Think of our $m$ counters as being in a 2-dimensional array, with $m/k$ counters per row and $k$ rows
- Let $C_{a,b}$ be the counter in row $a$ and column $b$
- Our hash functions map items from the universe into counters
- In particular, hash function $h_a$ maps item $i$ to counter $C_{a,h_a(i)}$
Updates

- Initially all counters are set to 0
- When we see item \( i \) in the data stream we do the following
- For each \( 1 \leq a \leq k \), increment \( C_{a,h_a(i)} \)
Count Approximations

- Let $C_{a,b}(T)$ be the value of the counter $C_{a,b}$ after processing $T$ tuples.
- We approximate Count$(i, T)$ by returning the value of the smallest counter associated with $i$.
- Let $m(i, T)$ be this value.
Main Theorem:

- For any item $i$, $m(i, T) \geq \text{Count}(i, T)$
- With probability at least $1 - e^{-m\epsilon/e}$ the following holds: $m(i, T) \leq \text{Count}(i, T) + \epsilon T$
Proof

- Easy to see that \( m(i, T) \geq \text{Count}(i, T) \), since each counter \( C_{a,h_a(i)} \) incremented by \( c_t \) every time pair \((i, c_t)\) is seen.
- Hard Part: Showing \( m(i, T) \leq \text{Count}(i, T) + \epsilon T \).
- To see this, we will first consider the specific counter \( C_{1,h_1(i)} \) and then use symmetry.
Proof

- Let $Z_1$ be a random variable giving the amount the counter is incremented by items other than $i$
- Let $X_t$ be an indicator r.v. that is 1 if $j$ is the $t$-th item, and $j \neq i$ and $h_1(i) = h_1(j)$
- Then $Z_1 = \sum_{t=1}^{T} X_t$
- But if the hash functions are “good”, then if $i \neq j$, $Pr(h_1(i) = h_1(j)) \leq k/m$ (specifically, we need the hash functions to come from a 2-universal family, but we won’t get into that in this class)
- Hence, $E(X_t) \leq k/m$
Proof

- Thus, by linearity of expectation, we have that:

\[ E(Z_1) = \sum_{t=1}^{T} \left( \frac{k}{m} \right) \leq Tk/m \]  

(1)

(2)

- We now need to make use of a very important inequality: Markov’s inequality
Markov’s Inequality

- Let $X$ be a random variable that only takes on non-negative values
- Then for any $\lambda > 0$:
  \[ Pr(X \geq \lambda) \leq \frac{E(X)}{\lambda} \]
- Proof of Markov’s: Assume instead that there exists a $\lambda$ such that $Pr(X \geq \lambda)$ was actually larger than $E(X)/\lambda$
- But then the expected value of $X$ would be at least $\lambda \times Pr(X \geq \lambda) > E(X)$, which is a contradiction!!!
Proof

- Now, by Markov’s inequality,

\[
Pr(Z_1 \geq \epsilon T') \leq \frac{(Tk/m)/\epsilon T')}{k/(m\epsilon)} = k/(m\epsilon)
\]

- This is the event where \(Z_1\) is “bad” for item \(i\).
Proof (Cont’d)

• Now again assume our $k$ hash functions are “good” in the sense that they are independent
• Then we have that

$$\prod_{i=1}^{k} Pr(Z_j \geq \epsilon T') \leq \left( \frac{k}{m\epsilon} \right)^k$$
Proof

- Finally, we want to choose a \( k \) that minimizes this probability
- Using calculus, we can see that the probability is minimized when \( k = m\epsilon/e \), in which case

\[
\left( \frac{k}{m\epsilon} \right)^k = e^{-m\epsilon/e}
\]

- This completes the proof!
Recap

- Our Count-Min Sketch is very good at giving estimating counts of items with very little external space
- Tradeoff is that it only provides approximate counts, but we can bound the approximation!
- Note: Can use the Count-Min Sketch to keep track of all the items in the stream that occur more than a given threshold (“heavy hitters”)
- Basic idea is to store an item in a list of “heavy hitters” if its count estimate ever exceeds some given threshold