CS 361, Lecture 23

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Outline

- B-Trees
- Skip Lists

B-Trees

- B-Trees are balanced search trees designed to work well on disks
- B-Trees are *not* binary trees: each node can have many children
- Each node of a B-Tree contains *several* keys, not just one
- When doing searches, we decide which child link to follow by finding the correct interval of our search key in the key set of the current node.

Disk Accesses

- Consider any search tree
- The number of disk accesses per search will dominate the run time
- Unless the entire tree is in memory, there will usually be a disk access every time an arbitrary node is examined
- The number of disk accesses for most operations on a B-tree is proportional to the height of the B-tree
- I.e. The info on each node of a B-tree can be stored in main memory

B-Tree Properties

The following is true for every node x

- x stores keys, $key_1(x), \ldots key_l(x)$ in sorted order (nondecreasing)
- x contains pointers, $c_1(x), \ldots, c_{l+1}(x)$ to its children
- Let k_i be any key stored in the subtree rooted at the i-th child of x, then $k_1 \leq key_1(x) \leq k_2 \leq key_2(x) \cdots \leq key_l(x) \leq k_{l+1}$

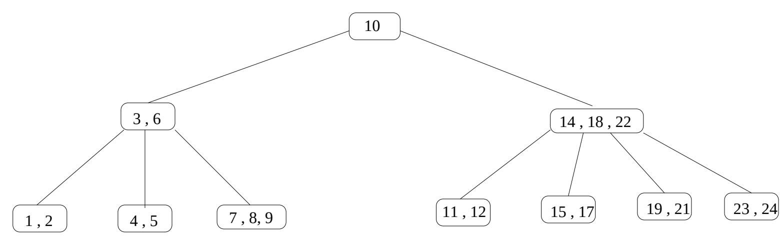
B-Tree Properties

- All leaves have the same depth
- Lower and upper bounds on the number of keys a node can contain, given as a function of a fixed integer t:
  - Every node other than the root must have $\geq (t-1)$ keys, and t children. If the tree is non-empty, the root must have at least one key (and 2 children)
  - Every node can contain at most $2t-1$ keys, so any internal node can have at most $2t$ children

Note

- The above properties imply that the height of a B-tree is no more than $\log_t \frac{n+1}{2}$, for $t \geq 2$, where n is the number of keys.
- If we make t, larger, we can save a larger (constant) fraction over RB-trees in the number of nodes examined
- A (2-3-4)-tree is just a B-tree with $t = 2$

Example B-Tree



In-Class Exercise

We will now show that for any B-Tree with height h and n keys, $h \leq \log_t \frac{n+1}{2}$, where $t \geq 2$.

Consider a B-Tree of height $h > 1$

- Q1: What is the minimum number of nodes at depth 1, 2, and 3
- Q2: What is the minimum number of nodes at depth i?
- Q3: Now give a lowerbound for the total number of *keys* (e.g. $n \geq ???$)
- Q4: Show how to solve for h in this inequality to get an upperbound on h

Splay Trees

- A Splay Tree is a kind of BST where the standard operations run in $O(\log n)$ *amortized* time
- This means that over l operations (e.g. Insert, Lookup, Delete, etc), the total cost is $O(l * \log n)$
- In other words, the average cost per operation is $O(\log n)$
- However a single operation could still take $O(n)$ time
- In practice, they are very fast

Skip Lists

- Technically, not a BST, but they implement all of the same operations
- 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

High Level Analysis

Comparison of various BSTs

- RB-Trees: + guarantee $O(\log n)$ time for each operation, easy to augment, − high constants
- AVL-Trees: + guarantee $O(\log n)$ time for each operation, − high constants
- B-Trees: + works well for trees that won't fit in memory, − inserts and deletes are more complicated
- Splay Tress: + small constants, − amortized guarantees only
- Skip Lists: + easy to implement, − runtime guarantees are probabilistic only

Which Data Structure to use?

- Splay trees work very well in practice, the "hidden constants" are small
- Unfortunately, they can not guarantee that *every* operation takes $O(\log n)$
- When this guarantee is required, B-Trees are best when the entire tree will not be stored in memory
- If the entire tree will be stored in memory, RB-Trees, AVL-Trees, and Skip Lists are good

Skip List

- Technically, not a BST, but they implement all of the same operations
- 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

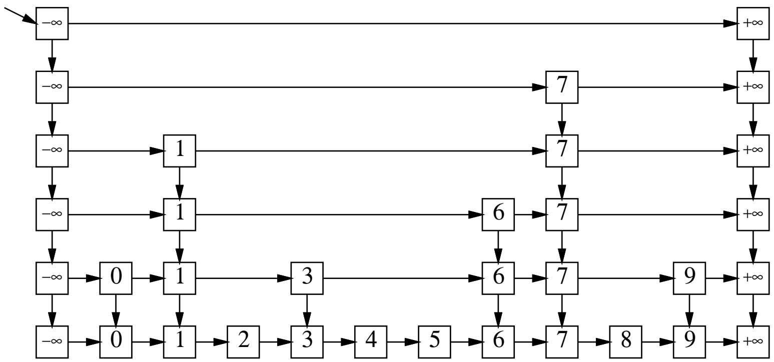
Skip List

- 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 $-$MAXINT and $+$MAXINT 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 (key(v)), a pointer to its next lower copy (down(v)), and a pointer to the next node in its level (right(v)).

Example



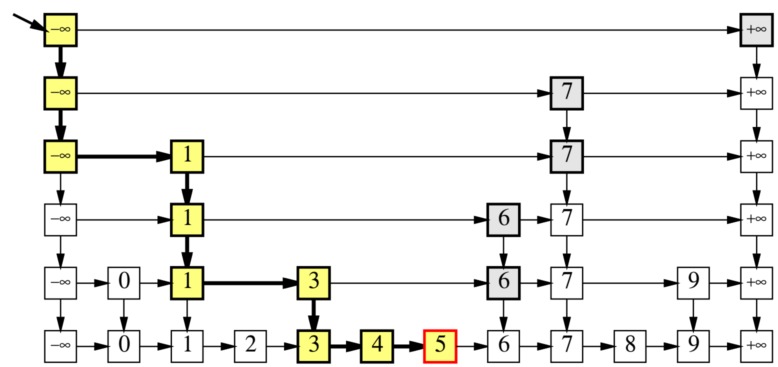
Search

- 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

Search

```
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 <= k in L_1
Insert k in L_1, to the right of pLeft
i = 2;
while (rand()<= 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 $p = 1/2$, we have:

$$
\begin{aligned}
P(X_i \geq 2 \log n) &= \left(\frac{1}{2}\right)^{2 \log n} \\
&= \frac{1}{(2^{\log n})^2} \\
&= \frac{1}{n^2}
\end{aligned}
$$

- 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:

$$\sum_{i=1}^{n} \frac{1}{n^2} = \frac{n}{n^2} = 1/n$$

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.

Expected Space

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???

In-Class Exercise

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

- Let X_i be the number of lists elem 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

- Its 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 senitel, 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:

```
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 $O(\log n)$