

Lecture Notes on Skip Lists

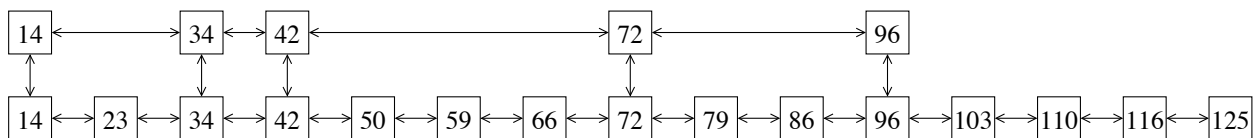
Lecture 12 — March 18, 2004

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- Balanced tree structures we know at this point: B-trees, red-black trees, treaps.
- Could you implement them right now? Probably, with time... but without looking up any details in a book?
- Skip lists are a simple randomized structure you'll never forget.

Starting from scratch

- Initial goal: *just searches* — ignore updates (Insert/Delete) for now
- Simplest data structure: linked list
- Sorted linked list: $\Theta(n)$ time
- 2 sorted linked lists:
 - Each element can appear in 1 or both lists
 - How to speed up search?
 - **Idea:** Express and local subway lines
 - **Example:** 14, 23, 34, 42, 50, 59, 66, 72, 79, 86, 96, 103, 110, 116, 125
(What is this sequence?)
 - Boxed values are “express” stops; others are normal stops
 - Can quickly jump from express stop to next express stop, or from any stop to next normal stop
 - Represented as two linked lists, one for express stops and one for all stops:



- Every element is in linked list 2 (LL2); some elements also in linked list 1 (LL1)
- Link equal elements between the two levels
- To search, first search in LL1 until about to go too far, then go down and search in LL2

- Cost:

$$\text{len}(\text{LL1}) + \frac{\text{len}(\text{LL2})}{\text{len}(\text{LL1})} = \text{len}(\text{LL1}) + \frac{n}{\text{len}(\text{LL1})}$$

- Minimized when

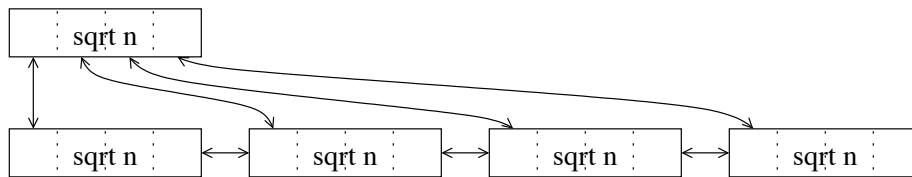
$$\text{len}(\text{LL1}) = \frac{n}{\text{len}(\text{LL1})}$$

$$\Rightarrow \text{len}(\text{LL1})^2 = n$$

$$\Rightarrow \text{len}(\text{LL1}) = \sqrt{n}$$

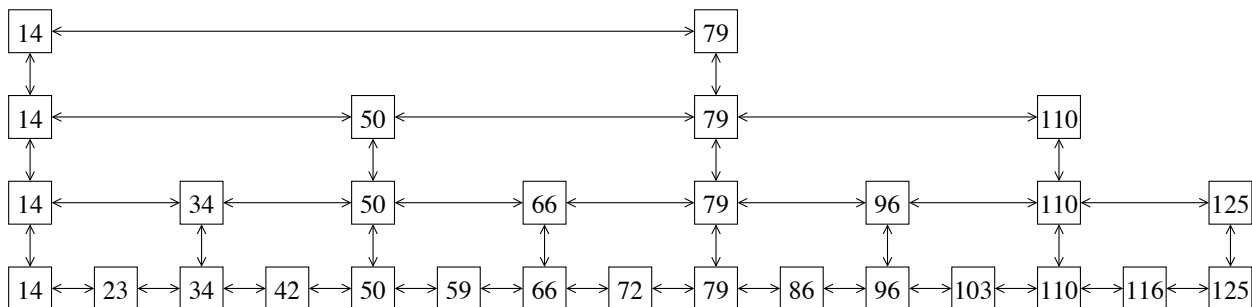
$$\Rightarrow \text{search cost} = 2\sqrt{n}$$

- Resulting 2-level structure:



- 3 linked lists: $3 \cdot \sqrt[3]{n}$
- k linked lists: $k \cdot \sqrt[k]{n}$
- $\lg n$ linked lists: $\lg n \cdot \sqrt[\lg n]{n} = \lg n \cdot \underbrace{n^{1/\lg n}}_{=2} = \Theta(\lg n)$

- Becomes like a binary tree:



- **Example:** Search for 72

- * Level 1: 14 too small, 79 too big; go down 14
- * Level 2: 14 too small, 50 too small, 79 too big; go down 50
- * Level 3: 50 too small, 66 too small, 79 too big; go down 66
- * Level 4: 66 too small, 72 spot on

Insert

- New element should certainly be added to bottommost level
(Invariant: Bottommost list contains all elements)
- Which other lists should it be added to?
(Is this the entire balance issue all over again?)
- **Idea:** Flip a coin
 - With what probability should it go to the next level?
 - To mimic a balanced binary tree, we'd like half of the elements to advance to the next-to-bottommost level
 - So, when you insert an element, flip a fair coin
 - If heads: add element to next level up, and flip another coin (repeat)
- Thus, on average:
 - 1/2 the elements go up 1 level
 - 1/4 the elements go up 2 levels
 - 1/8 the elements go up 3 levels
 - Etc.
- Thus, “approximately even”

Example

- Get out a real coin and try an example
- You should put a special value $-\infty$ at the beginning of each list, and always promote this special value to the highest level of promotion
- This forces the leftmost element to be present in every list, which is necessary for searching

... many coins are flipped ...
(Isn't this easy?)

- The result is a skip list.
- It probably isn't as balanced as the ideal configurations drawn above.
- It's clearly good on average.
- Claim it's really really good, almost always.

Analysis: Claim of With High Probability

- **Theorem:** *With high probability, every search costs $\Theta(\lg n)$ in a skip list with n elements*
- What do we need to do to prove this? [Calculate the probability, and show that it's high!]
- We need to define the notion of “with high probability”; this is a powerful technical notion, used throughout randomized algorithms
- **Informal definition:** An event occurs *with high probability* if, for any $\alpha \geq 1$, there is an appropriate choice of constants for which E occurs with probability at least $1 - O(1/n^\alpha)$
- In reality, the constant hidden within $\Theta(\lg n)$ in the theorem statement actually depends on c .
- **Precise definition:** A (parameterized) event E_α occurs *with high probability* if, for any $\alpha \geq 1$, E_α occurs with probability at least $1 - c_\alpha/n^\alpha$, where c_α is a “constant” depending only on α .
- The term $O(1/n^\alpha)$ or more precisely c_α/n^α is called the *error probability*
- The idea is that the error probability can be made very very very small by setting α to something big, e.g., 100

Analysis: Warmup

- **Lemma:** With high probability, skip list with n elements has $O(\lg n)$ levels
- (In fact, the number of levels is $\Theta(\log n)$, but we only need an upper bound.)
- **Proof:**

– $\Pr[\text{element } x \text{ is in more than } c \lg n \text{ levels}] = 1/2^{c \lg n} = 1/n^c$

– Recall Boole’s inequality / union bound:

$$\Pr[E_1 \cup E_2 \cup \dots \cup E_n] \leq \Pr[E_1] + \Pr[E_2] + \dots + \Pr[E_n]$$

– Applying this inequality:

$$\Pr[\text{any element is in more than } c \lg n \text{ levels}] \leq n \cdot 1/n^c = 1/n^{c-1}$$

– Thus, error probability is polynomially small and exponent ($\alpha = c - 1$) can be made arbitrarily large by appropriate choice of constant in level bound of $O(\lg n)$

Analysis: Proof of Theorem

- **Cool idea:** Analyze search backwards—from leaf to root
 - Search starts at leaf (element in bottommost level)
 - At each node visited:
 - * If node wasn't promoted higher (got TAILS here), then we go [came from] left
 - * If node wasn't promoted higher (got HEADS here), then we go [came from] top
 - Search stops at root of tree
- Know height is $O(\lg n)$ with high probability; say it's $c \lg n$
- Thus, the number of “up” moves is at most $c \lg n$ with high probability
- Thus, search cost is at most the following quantity:

How many times do we need to flip a coin to get $c \lg n$ heads?
- Intuitively, $\Theta(\lg n)$

Analysis: Coin Flipping

- **Claim:** Number of flips till $c \lg n$ heads is $\Theta(\lg n)$ with high probability
- Again, constant in $\Theta(\lg n)$ bound will depend on α
- **Proof of claim:**

– Say we make $10c \lg n$ flips

– When are there at least $c \lg n$ heads?

$$\text{Pr}[\text{exactly } c \lg n \text{ heads}] = \underbrace{\binom{10c \lg n}{c \lg n}}_{\substack{\text{orders} \\ \text{HHHTTT vs. HTHTHT}}} \cdot \underbrace{\left(\frac{1}{2}\right)^{c \lg n}}_{\text{heads}} \cdot \underbrace{\left(\frac{1}{2}\right)^{9c \lg n}}_{\text{tails}}$$

$$\text{Pr}[\text{at most } c \lg n \text{ heads}] = \underbrace{\binom{10c \lg n}{c \lg n}}_{\substack{\text{overestimate} \\ \text{on orders}}} \cdot \underbrace{\left(\frac{1}{2}\right)^{9c \lg n}}_{\text{tails}}$$

– Recall bounds on $\binom{y}{x}$:

$$\left(\frac{y}{x}\right)^x \leq \binom{y}{x} \leq \left(e \frac{y}{x}\right)^x$$

[Michael's “deathbed” formula: even on your deathbed, if someone gives you a binomial and says “simplify”, you should know this!]

– Applying this formula to the previous equation:

$$\begin{aligned}
 \Pr[\text{at most } c \lg n \text{ heads}] &\leq \binom{10c \lg n}{c \lg n} \left(\frac{1}{2}\right)^{9c \lg n} \\
 &\leq \left(\frac{e \cdot 10c \lg n}{c \lg n}\right)^{c \lg n} \cdot \left(\frac{1}{2}\right)^{9c \lg n} \\
 &= (10e)^{c \lg n} \cdot \left(\frac{1}{2}\right)^{9c \lg n} \\
 &= 2^{\lg(10e) \cdot c \lg n} \cdot \left(\frac{1}{2}\right)^{9c \lg n} \\
 &= 2^{(\lg(10e) - 9)c \lg n} \\
 &= 2^{-\alpha \lg n} \\
 &= 1/n^\alpha
 \end{aligned}$$

– The point here is that, as $10 \rightarrow \infty$, $\alpha = 9 - \lg(10e) \rightarrow \infty$, independent of (for all) c

- End of proof of claim and theorem

Acknowledgments

The mysterious “Michael” is Michael Bender at SUNY Stony Brook. This lecture is based on discussions with him.