Order maintenance problem

Dietz, Sleator 1987

Bender, Demaine, Farach, Zito 2001
Problem definition

Perform a sequence of the following operations on a list L

**Insert(x,y)** : Insert record y after x into the list

**Delete(x)** : delete record x from the list

**Order(x,y)** : Return true if x is before y in the list. Otherwise return false
First attempt

Insert(x,y)  \[\text{\textbullet} \quad \text{\textbullet} \]

Insert(x,z)  \[\text{\textbullet} \quad \text{\textbullet} \quad \text{\textbullet} \quad \text{\textbullet} \]

Insert(x,u)  \[\text{\textbullet} \quad \text{\textbullet} \quad \text{\textbullet} \quad \text{\textbullet} \]
First attempt

Insert(x,y)

Insert(x,z)

Insert(x,u)
Bender et al’s solution

Imagine your list items reside at the leaves of a complete binary tree. $M$ leaves, item labeled $i$ reside at the $i^{th}$ leaf.

When a “phase” starts we relabel $n$ items so they are equally spaced among the leaves.

Phase goes on as long as

$$\frac{n}{2} \leq \#\text{items} \leq 2n$$
Remember the data structure is only a linked list

How do we choose M?
Associate **maximum density** with the nodes, 1, \( T^1 \), \( T^2 \) \ldots
\( T \in (1,2) \)

\[
\begin{align*}
1/4 \\
2^{-3/2} &= 0.35 \\
2^{-1} &= 0.5 \\
2^{-1/2} &= 0.71 \\
1 &\substack{x \ y \ z}
\end{align*}
\]

We pick the tree large enough such that density of the root breaks only when the # of items grow by a factor of 2.
Lemma 1:
We use $O(\log n)$ bits per tag.

Proof.

At the start of a phase, we choose $M$ such that:

$T^{-\log(M)} = \frac{2n}{M}$

So we use $\log(2n)/(1-\log T)$ bits
Insert(x, z) : Choose any label between l(x) and l(s(x)) if they are not consecutive
Insert\((x,z')\) : Choose any label between \(l(x)\) and \(l(s(x))\) if they are not consecutive. Otherwise, find the lowest ancestor of \(x\) such that the density of items in its subtree is below the threshold and relabel them evenly. Then continue as before.
Insert$(x, z^1)$: Choose any label between $l(x)$ and $l(s(x))$ if they are not consecutive. Otherwise, find the least ancestor of $x$ such that the density of items in its subtree is below the threshold and relabel them evenly. Then continue as before.
Insert(x, z^2)

1/4

2^{-3/2} = 0.35

2^{-1} = 0.5

2^{-1/2} = 0.71

1

x Z^1 Z y
Insert($x, z^2$)
Few important observations:

- **The tree does not exist!** We do the density calculations as we go up just by going to the right and to the left in the list.

- Once the density of the root overflows we “create” a new tree twice as large, then we relabel all nodes evenly.

- We do the same if the number of nodes decrease by a factor of 2 since the last time we fixed the tree.
Complexity analysis

• How much time it takes to relabel a subtree rooted at x with $2^i$ leaves?
  \[ O\left(\frac{2^i}{T^i}\right) \]

• What is the density of the children of x after the relabeling?
  At most $\frac{1}{T^i}$

• Before we relabel x again the density of one of its children must grow to?
  At least $\frac{1}{T^{i-1}}$

• So between relabeling we have inserted
  \[ \left(\frac{1}{T^{i-1}} - \frac{1}{T^i}\right) 2^{i-1} \] nodes.
Complexity analysis

• Charge the relabeling work to the new nodes inserted since the last relabeling. How much do we charge to each node?

\[
\frac{2^i}{T^i} \frac{2^i}{(1/T^{i-1} - 1/T^i) 2^{i-1}} = \frac{2}{T-1}
\]

• How many relabelings charge a node x?

At most \(\log M = O(\log n)\)