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Random search trees have the property that their depth depends on the order in which they are built. They have to be balanced in order to obtain a more efficient storage-and-retrieval data structure. Balancing a search tree is time consuming. This explains the popularity of data structures which approximate a balanced tree but have lower amortized balancing costs, such as AVL trees, Fibonacci trees and 2-3 trees. The algorithms for maintaining these data structures efficiently are complex and hard to derive. This observation has led to insertion algorithms that perform local balancing around the newly inserted node, without backtracking on the search path. This is also called a fringe heuristic. The resulting class of trees is referred to as 1-locally balanced trees, in this note referred to as hairy trees. In this note a simple analysis of their behaviour is provided.
FIGURE 1. Two hairy trees and a non-hairy one.

In general, hairy trees are not balanced. In the worst case, a hairy tree of \( n \) elements has depth \( \left\lceil \frac{n+1}{2} \right\rceil \) (see Figure 2).

2. INSERTION IN HAIRY SEARCH TREES

We present the operation \texttt{enterh} for inserting a key into a search tree, which maintains the search tree as a hairy tree by restructuring it whenever a node is inserted at the end of a twig. Its structure follows the case-distinction in the definition of is hairy.

```
PROC enterh (TREE VAR t, EL CONST e):
    { is hairy search tree (t) }
    IF is empty (t) THEN t := tree (e)
    ELSEIF e < t .key
    ELSEIF t . key < e
    FI
    {is hairy search tree (t), is in (e, t)}
ENDPROC enterh;
```

with the refinements:

```
enter left:
    IF is empty (t.left) THEN extend left
    ELIF is empty (t.right)
    THEN enter left left
    ELIF t .left.key < e
    THEN enter left right
    FI
    ELSE enterh (t. left, e)
    FI.

enter right:
    IF is empty (t.right) THEN extend right
    ELIF is empty (t.left)
    THEN enter right left
    ELIF t.right.key < e
    THEN enter right right
    FI
    ELSE enterh (t.right, e)
    FI.
```

The correctness of this algorithm is easy to prove, since it closely follows the inductive structure of the definition of is hairy. The implementation may be further optimized by transformational techniques (unfolding, specialization and elimination of recursion).

3. EFFICIENCY OF HAIRY TREES

We analyse the efficiency of hairy trees in terms of the cost of a random successful search (\( S_n \)) in a tree with \( n \) keys, and the cost of a random unsuccessful search (\( U_n \)). Let \( I_n \) be the average internal path length of all hairy trees with \( n \) keys (see [4]), so \( S_n = I_n/n \). Furthermore, let

```
FIGURE 3. Addition via single-son node.
```

\(^{1}\) The programming language used is Elan [3], an educational algorithmic language. (Obtainable from ftp://ftp.cs.kun.nl/pub/elan.)
\[ \Delta_n \text{ be the average ratio between the number of single-son nodes and the number of external nodes in hairy trees with } n \text{ keys. Then we have:} \]

\[ I_{n+1} = I_n + (U_n + 1) - 2\Delta_n \quad (1) \]

as obviously the internal path length is augmented with \( U_n + 1 \) by the insertion of a new key, and occasionally diminished by a restructuring. A restructuring is performed if and only if we start from (up to symmetry) the situation of Figure 3, which is transformed by insertion of a node at its end into the one of the cases in Figure 4. After restructuring we have Figure 5.

In both cases the internal path length decreases by 1 as a result of restructuring. The probability of this situation to occur in tree \( t \) is:

\[ \frac{2 \times \text{single}(t)}{\text{ext}(t)} = 2\Delta(t) \]

From equation (1) we derive:

\[ I_n = \sum_{k=0}^{n-1} (U_k + 1 - 2\Delta_k) \quad (2) \]

The following relation is well known:

\[ S_n = \left(1 + \frac{1}{n} U_n\right) - 1 \]

and can be rewritten as

\[ I_n = (n + 1)U_n - n \quad (3) \]

Combining (2) and (3) yields

\[ (n + 1)U_n = \sum_{k=0}^{n-1} (U_k + 2 - 2\Delta_k) \]

This is transformed into a recurrence relation by computing

\[ (n + 1)U_n - nU_{n-1} = U_{n-1} + 2 - 2\Delta_{n-1}, \]

leading to:

\[ U_n - U_{n-1} = \frac{2}{n+1}(1 - \Delta_{n-1}) \]

and thus:

\[ U_n = 2 \sum_{k=0}^{n-1} \frac{1}{k+2}(1 - \Delta_k) \]

Next we consider \( \Delta_n \). Let \( \sigma_n \) be the average number of single-son nodes in a hairy tree. When a new node is inserted via a search path through a single-son node, then the number of single-son nodes will be decremented by 1. As such a search path contains three external nodes, the probability of this event to occur equals \( 3\sigma_n/(n+1) \). If the search path does not contain a single-son node, then the number of single-son nodes will be incremented by 1. This event has a probability \( 1 - 3\sigma_n/(n+1) \). Combining these results leads to the following recurrence relation:

\[ \sigma_{n+1} = \sigma_n - \frac{3\sigma_n}{n+1} + \frac{(n + 1) - 3\sigma_n}{n + 1} \]

\[ = \frac{n - 5}{n + 1} \sigma_n + 1 \]

From this recurrence relation we derive \( \sigma_6 = 1 \), and therefore \( \sigma_n = (n + 1)/7 \) for \( n > 6 \). As \( \Delta_n = \sigma_n/(n + 1) \), we conclude:

\[ \Delta_n = \frac{1}{7} \quad \text{for } n > 6 \]

LEMMA 4.

\[ U_n = \frac{3}{4}U^*_n \approx 1.1883 \ldots 2 \log n \]

where \( U^*_n = 2 \sum_{k=0}^{n-1} 1/(k + 2) \approx 1.3863 \ldots 2 \log n - 0.8456 \ldots \) is the average cost of an unsuccessful search in a random binary tree. The result of this analysis is summarized in Table 1 (see [2, 4]).

4. CONCLUSIONS

The analysis of the complexity of hairy trees turns out to be particularly simple. Their efficiency lies about halfway between random search trees and AVL trees. Considering the simplicity of their implementation, it is surprising that this class of partially balance trees is not used widely in practice.

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REFERENCES