



# Principles of Distributed Computing

## Exercise 4: Sample Solution

### 1 Concurrent Ivy

- a) The three nodes are served in the order  $v_2, v_3, v_1$ .
- b) Figure 1 depicts the structure of the tree after the requests have been served. Since  $v_1$  is served last, it is the holder of the token at the end.

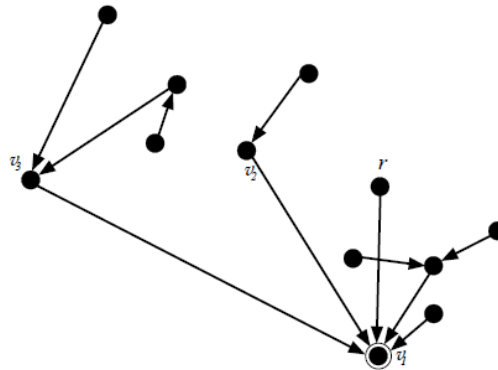


Figure 1: Tree after the requests have been served.

### 2 Tight Ivy

In order to show that the bound of  $\log n$  steps on average is tight, we construct a special tree which is defined recursively as follows. The tree  $\mathcal{T}_0$  consists of a single node. The tree  $\mathcal{T}_i$  consists of a root together with  $i$  subtrees, which are  $\mathcal{T}_0, \dots, \mathcal{T}_{i-1}$ , rooted at the  $i$  children of the root, see Figure 2.

First, we will show that the number of nodes in the tree  $\mathcal{T}_i$  is  $2^i$ . This obviously holds for  $\mathcal{T}_0$ . The induction hypothesis is that it holds for all  $\mathcal{T}_0, \dots, \mathcal{T}_{i-1}$ . It follows that the number of nodes of  $\mathcal{T}_i$  is  $n = 1 + \sum_{j=0}^{i-1} 2^j = 2^i$ .

We will show now that the radius of the root of  $\mathcal{T}_i$  is  $\mathcal{R}(\mathcal{T}_i) = i$ . Again, this is trivially true for  $\mathcal{T}_0$ . It is easy to see that  $\mathcal{R}(\mathcal{T}_i) = 1 + \mathcal{R}(\mathcal{T}_{i-1})$ , because  $\mathcal{T}_{i-1}$  is the child with the largest radius. Inductively, it follows that  $\mathcal{R}(\mathcal{T}_i) = i$ .

By definition, when cutting of the subtree  $\mathcal{T}_{i-1}$  from  $\mathcal{T}_i$ , the resulting tree is again  $\mathcal{T}_{i-1}$ . Let  $\mathcal{C} : \mathcal{T}_i \mapsto \mathcal{T}_{i-1}$  denote this cutting operation. For all  $i > 0$ , we thus have that  $\mathcal{C}(\mathcal{T}_i) = \mathcal{T}_{i-1}$ . We will now start a request at the single node  $v$  with a distance of  $i$  from the root in  $\mathcal{T}_i$ . On its path to

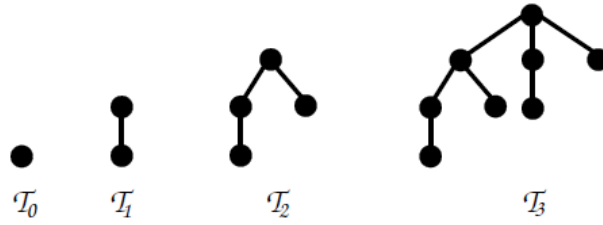


Figure 2: The trees  $\mathcal{T}_0, \dots, \mathcal{T}_3$ .

the root, the request passes nodes that are roots of the trees  $\mathcal{T}_1, \dots, \mathcal{T}_i$ . All of those nodes become children of the new root  $v$  according to the Ivy protocol. The new children lose their largest “child” subtree in the process, thus the children of node  $v$  have the structures  $\mathcal{C}(\mathcal{T}_1), \dots, \mathcal{C}(\mathcal{T}_i) = \mathcal{T}_0, \dots, \mathcal{T}_{i-1}$ . Hence, the structure of the tree does not change due to the request and all subsequent requests can also cost  $i$  steps. Since  $n = 2^i$ , each request costs exactly  $\log n$ .