Principles of Distributed Computing
Exercise 6: 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.](image)

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 \( T_0 \) consists of a single node. The tree \( T_i \) consists of a root together with \( i \) subtrees, which are \( T_0, \ldots, T_{i-1} \), rooted at the \( i \) children of the root, see Figure 2.

First, we will show that the number of nodes in the tree \( T_i \) is \( 2^i \). This obviously holds for \( T_0 \). The induction hypothesis is that it holds for all \( T_0, \ldots, T_{i-1} \). It follows that the number of nodes of \( T_i \) is \( n = 1 + \sum_{j=0}^{i-1} 2^j = 2^i \).

We will show now that the radius of the root of \( T_i \) is \( R(T_i) = i \). Again, this is trivially true for \( T_0 \). It is easy to see that \( R(T_i) = 1 + R(T_{i-1}) \), because \( T_{i-1} \) is the child with the largest radius. Inductively, it follows that \( R(T_i) = i \).

By definition, when cutting of the subtree \( T_{i-1} \) from \( T_i \), the resulting tree is again \( T_{i-1} \). Let \( C : T_i \mapsto T_{i-1} \) denote this cutting operation. For all \( i > 0 \), we thus have that \( C(T_i) = T_{i-1} \). We will now start a request at the single node \( v \) with a distance of \( i \) from the root in \( T_i \). On its path to
the root, the request passes nodes that are roots of the trees $T_1, \ldots, T_i$. 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 $C(T_1), \ldots, C(T_i) = T_0, \ldots, T_{i-1}$. 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 $\log n$. 

Figure 2: The trees $T_0, \ldots, T_5$. 

\[ \begin{array}{c} T_0 \quad T_1 \quad T_2 \quad T_3 \end{array} \]