Suffix Tree Application 4 - Build Linear Time Suffix Array - GeeksforGeeks

Suffix Tree Application 4 – Build Linear Time Suffix Array

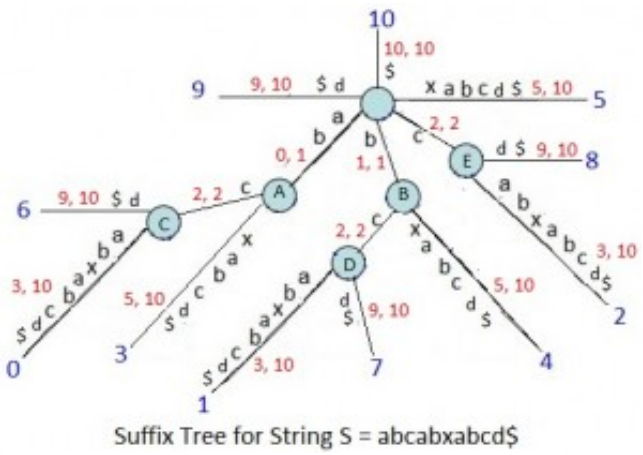
Given a string, build it's Suffix Array
We have already discussed following two ways of building suffix array:

Please go through these to have the basic understanding.
Here we will see how to build suffix array in linear time using suffix tree.

Lets consider string abcabxabcd.
It's suffix array would be:

```
0 6 3 1 7 4 2 8 9 5
```

Lets look at following figure:



This is suffix tree for String "abcabxabcd$"
If we do a DFS traversal, visiting edges in lexicographic order (we have been doing the same traversal in other Suffix Tree Application articles as well) and print suffix indices on leaves, we will get following:

```
10 0 6 3 1 7 4 2 8 9 5
```

"$" is lexicographically lesser than [a-zA-Z].
The suffix index 10 corresponds to edge with "$" label.
Except this 1st suffix index, the sequence of all other numbers gives the suffix array of the string.

So if we have a suffix tree of the string, then to get it's suffix array, we just need to do a lexicographic order DFS traversal and store all the suffix indices in resultant suffix array, except the very 1st suffix

index.

```
// A C program to implement Ukkonen's Suffix Tree Construction// And and
then create suffix array in linear time#include <stdio.h>#include
<string.h>#include <stdlib.h>#define MAX_CHAR 256
struct SuffixTreeNode {
    struct SuffixTreeNode *children[MAX_CHAR];
    //pointer to other node via suffix link
    struct SuffixTreeNode *suffixLink;
    /*(start, end) interval specifies the edge, by which the
      node is connected to its parent node. Each edge will
      connect two nodes,  one parent and one child, and
      (start, end) interval of a given edge  will be stored
      in the child node. Lets say there are two nods A and B
      connected by an edge with indices (5, 8) then this
      indices (5, 8) will be stored in node B. */
    int start;
    int *end;
    /*for leaf nodes, it stores the index of suffix for
        the path  from root to leaf*/
    int suffixIndex;
};
typedef struct SuffixTreeNode Node;
char text[100]; //Input string
Node *root = NULL; //Pointer to root node
/*lastNewNode will point to newly created internal node,
  waiting for it's suffix link to be set, which might get
  a new suffix link (other than root) in next extension of
  same phase. lastNewNode will be set to NULL when last
  newly created internal node (if there is any) got it's
  suffix link reset to new internal node created in next
  extension of same phase. */
Node *lastNewNode = NULL;Node *activeNode = NULL;/*activeEdge is represeted
as input string character
  index (not the character itself)*/
int activeEdge = -1;
int activeLength = 0;
// remainingSuffixCount tells how many suffixes yet to// be added in tree
int remainingSuffixCount = 0;
int leafEnd = -1;
int *rootEnd = NULL;
int *splitEnd = NULL;
```

```
int size = -1; //Length of input string
Node *newNode(int start, int *end)
{
    Node *node =(Node*) malloc(sizeof(Node));
    int i;
    for (i = 0; i < MAX_CHAR; i++)
        node->children[i] = NULL;
    /*For root node, suffixLink will be set to NULL
    For internal nodes, suffixLink will be set to root
    by default in  current extension and may change in
    next extension*/
    node->suffixLink = root;
    node->start = start;
    node->end = end;
    /*suffixIndex will be set to -1 by default and
      actual suffix index will be set later for leaves
      at the end of all phases*/
    node->suffixIndex = -1;
    return node;
}
int edgeLength(Node *n) {
    if(n == root)
        return 0;
    return *(n->end) - (n->start) + 1;
}
int walkDown(Node *currNode)
{
    /*activePoint change for walk down (APCFWD) using
      Skip/Count Trick  (Trick 1). If activeLength is greater
      than current edge length, set next  internal node as
      activeNode and adjust activeEdge and activeLength
      accordingly to represent same activePoint*/
    if (activeLength >= edgeLength(currNode))
    {
        activeEdge += edgeLength(currNode);
        activeLength -= edgeLength(currNode);
        activeNode = currNode;
        return 1;
    }
    return 0;
}
void extendSuffixTree(int pos)
```

```
{
    /*Extension Rule 1, this takes care of extending all
    leaves created so far in tree*/
    leafEnd = pos;
    /*Increment remainingSuffixCount indicating that a
    new suffix added to the list of suffixes yet to be
    added in tree*/
    remainingSuffixCount++;
    /*set lastNewNode to NULL while starting a new phase,
     indicating there is no internal node waiting for
     it's suffix link reset in current phase*/
    lastNewNode = NULL;
    //Add all suffixes (yet to be added) one by one in tree
    while(remainingSuffixCount > 0) {
        if (activeLength == 0)
            activeEdge = pos; //APCFALZ
        // There is no outgoing edge starting with
        // activeEdge from activeNode
        if (activeNode->children[text[activeEdge]] == NULL)
        {
            //Extension Rule 2 (A new leaf edge gets created)
            activeNode->children[text[activeEdge]] =
                                        newNode(pos, &leafEnd);
            /*A new leaf edge is created in above line starting
             from  an existng node (the current activeNode), and
             if there is any internal node waiting for it's suffix
             link get reset, point the suffix link from that last
             internal node to current activeNode. Then set lastNewNode
             to NULL indicating no more node waiting for suffix link
             reset.*/
            if (lastNewNode != NULL)
            {
                lastNewNode->suffixLink = activeNode;
                lastNewNode = NULL;
            }
        }
        // There is an outgoing edge starting with activeEdge
        // from activeNode
        else
        {
            // Get the next node at the end of edge starting
            // with activeEdge
```

```
            Node *next = activeNode->children[text[activeEdge]];
            if (walkDown(next))//Do walkdown
            {
                //Start from next node (the new activeNode)
                continue;
            }
            /*Extension Rule 3 (current character being processed
              is already on the edge)*/
            if (text[next->start + activeLength] == text[pos])
            {
                //If a newly created node waiting for it's
                //suffix link to be set, then set suffix link
                //of that waiting node to curent active node
                if(lastNewNode != NULL && activeNode != root)
                {
                    lastNewNode->suffixLink = activeNode;
                    lastNewNode = NULL;
                }
                //APCFER3
                activeLength++;
                /*STOP all further processing in this phase
                and move on to next phase*/
                break;
            }
            /*We will be here when activePoint is in middle of
              the edge being traversed and current character
              being processed is not  on the edge (we fall off
              the tree). In this case, we add a new internal node
              and a new leaf edge going out of that new node. This
              is Extension Rule 2, where a new leaf edge and a new
              internal node get created*/
            splitEnd = (int*) malloc(sizeof(int));
            *splitEnd = next->start + activeLength - 1;
            //New internal node
            Node *split = newNode(next->start, splitEnd);
            activeNode->children[text[activeEdge]] = split;
            //New leaf coming out of new internal node
            split->children[text[pos]] = newNode(pos, &leafEnd);
            next->start += activeLength;
            split->children[text[next->start]] = next;
            /*We got a new internal node here. If there is any
              internal node created in last extensions of same
```

```
            phase which is still waiting for it's suffix link
            reset, do it now.*/
        if (lastNewNode != NULL)
        {
        /*suffixLink of lastNewNode points to current newly
            created internal node*/
            lastNewNode->suffixLink = split;
        }
        /*Make the current newly created internal node waiting
            for it's suffix link reset (which is pointing to root
            at present). If we come across any other internal node
            (existing or newly created) in next extension of same
            phase, when a new leaf edge gets added (i.e. when
            Extension Rule 2 applies is any of the next extension
            of same phase) at that point, suffixLink of this node
            will point to that internal node.*/
        lastNewNode = split;
    }
    /* One suffix got added in tree, decrement the count of
        suffixes yet to be added.*/
    remainingSuffixCount--;
    if (activeNode == root && activeLength > 0) //APCFER2C1
    {
        activeLength--;
        activeEdge = pos - remainingSuffixCount + 1;
    }
    else if (activeNode != root) //APCFER2C2
    {
        activeNode = activeNode->suffixLink;
    }
  }
}
void print(int i, int j)
{
  int k;
  for (k=i; k<=j; k++)
    printf("%c", text[k]);
}//Print the suffix tree as well along with setting suffix index//So tree
will be printed in DFS manner//Each edge along with it's suffix index will
be printed
void setSuffixIndexByDFS(Node *n, int labelHeight)
{
```

```
    if (n == NULL)  return;
    if (n->start != -1) //A non-root node
    {
        //Print the label on edge from parent to current node
        //Uncomment below line to print suffix tree
       // print(n->start, *(n->end));
    }
    int leaf = 1;
    int i;
    for (i = 0; i < MAX_CHAR; i++)
    {
        if (n->children[i] != NULL)
        {
            //Uncomment below two lines to print suffix index
           // if (leaf == 1 && n->start != -1)
            //   printf(" [%d]\n", n->suffixIndex);
            //Current node is not a leaf as it has outgoing
            //edges from it.
            leaf = 0;
            setSuffixIndexByDFS(n->children[i], labelHeight +
                                edgeLength(n->children[i]));
        }
    }
    if (leaf == 1)
    {
        n->suffixIndex = size - labelHeight;
        //Uncomment below line to print suffix index
        //printf(" [%d]\n", n->suffixIndex);
    }
}
void freeSuffixTreeByPostOrder(Node *n)
{
    if (n == NULL)
        return;
    int i;
    for (i = 0; i < MAX_CHAR; i++)
    {
        if (n->children[i] != NULL)
        {
            freeSuffixTreeByPostOrder(n->children[i]);
        }
    }
```

```
    if (n->suffixIndex == -1)
        free(n->end);
    free(n);
}/*Build the suffix tree and print the edge labels along with suffixIndex.
suffixIndex for leaf edges will be >= 0 and for non-leaf edges will be -1*/
void buildSuffixTree()
{
    size = strlen(text);
    int i;
    rootEnd = (int*) malloc(sizeof(int));
    *rootEnd = - 1;
    /*Root is a special node with start and end indices as -1,
    as it has no parent from where an edge comes to root*/
    root = newNode(-1, rootEnd);
    activeNode = root; //First activeNode will be root
    for (i=0; i<size; i++)
        extendSuffixTree(i);
    int labelHeight = 0;
    setSuffixIndexByDFS(root, labelHeight);
}
void doTraversal(Node *n, int suffixArray[], int *idx)
{
    if(n == NULL)
    {
        return;
    }
    int i=0;
    if(n->suffixIndex == -1) //If it is internal node
    {
        for (i = 0; i < MAX_CHAR; i++)
        {
            if(n->children[i] != NULL)
            {
                doTraversal(n->children[i], suffixArray, idx);
            }
        }
    }
    //If it is Leaf node other than "$" label
    else if(n->suffixIndex > -1 && n->suffixIndex < size)
    {
        suffixArray[(*idx)++] = n->suffixIndex;
    }
```

```
}
void buildSuffixArray(int suffixArray[])
{
    int i = 0;
    for(i=0; i< size; i++)
        suffixArray[i] = -1;
    int idx = 0;
    doTraversal(root, suffixArray, &idx);
    printf("Suffix Array for String ");
    for(i=0; i<size; i++)
        printf("%c", text[i]);
    printf(" is: ");
    for(i=0; i<size; i++)
        printf("%d ", suffixArray[i]);
    printf("\n");
}// driver program to test above functions
int main(int argc, char *argv[])
{
    strcpy(text, "banana$");
    buildSuffixTree();
    size--;
    int *suffixArray =(int*) malloc(sizeof(int) * size);
    buildSuffixArray(suffixArray);
    //Free the dynamically allocated memory
    freeSuffixTreeByPostOrder(root);
    free(suffixArray);
    strcpy(text, "GEEKSFORGEEKS$");
    buildSuffixTree();
    size--;
    suffixArray =(int*) malloc(sizeof(int) * size);
    buildSuffixArray(suffixArray);
    //Free the dynamically allocated memory
    freeSuffixTreeByPostOrder(root);
    free(suffixArray);
    strcpy(text, "AAAAAAAAAA$");
    buildSuffixTree();
    size--;
    suffixArray =(int*) malloc(sizeof(int) * size);
    buildSuffixArray(suffixArray);
    //Free the dynamically allocated memory
    freeSuffixTreeByPostOrder(root);
    free(suffixArray);
```

```
    strcpy(text, "ABCDEFG$");
    buildSuffixTree();
    size--;
    suffixArray =(int*) malloc(sizeof(int) * size);
    buildSuffixArray(suffixArray);
    //Free the dynamically allocated memory
    freeSuffixTreeByPostOrder(root);
    free(suffixArray);
    strcpy(text, "ABABABA$");
    buildSuffixTree();
    size--;
    suffixArray =(int*) malloc(sizeof(int) * size);
    buildSuffixArray(suffixArray);
    //Free the dynamically allocated memory
    freeSuffixTreeByPostOrder(root);
    free(suffixArray);
    strcpy(text, "abcabxabcd$");
    buildSuffixTree();
    size--;
    suffixArray =(int*) malloc(sizeof(int) * size);
    buildSuffixArray(suffixArray);
    //Free the dynamically allocated memory
    freeSuffixTreeByPostOrder(root);
    free(suffixArray);
    strcpy(text, "CCAAACCCGATTA$");
    buildSuffixTree();
    size--;
    suffixArray =(int*) malloc(sizeof(int) * size);
    buildSuffixArray(suffixArray);
    //Free the dynamically allocated memory
    freeSuffixTreeByPostOrder(root);
    free(suffixArray);
    return 0;
}
```

Output:

```
Suffix Array for String banana is: 5 3 1 0 4 2
Suffix Array for String GEEKSFORGEEKS is: 9 1 10 2 5 8 0 11 3 6 7 12 4
Suffix Array for String AAAAAAAAAA is: 9 8 7 6 5 4 3 2 1 0
Suffix Array for String ABCDEFG is: 0 1 2 3 4 5 6
Suffix Array for String ABABABA is: 6 4 2 0 5 3 1
Suffix Array for String abcabxabcd is: 0 6 3 1 7 4 2 8 9 5
```

```
Suffix Array for String CCAAACCCGATTA is: 12 2 3 4 9 1 0 5 6 7 8 11 10
```

Ukkonen’s Suffix Tree Construction takes O(N) time and space to build suffix tree for a string of length N and after that, traversal of tree take O(N) to build suffix array.
So overall, it’s linear in time and space.
Can you see why traversal is O(N) ?? Because a suffix tree of string of length N will have at most N-1 internal nodes and N leaves. Traversal of these nodes can be done in O(N).

We have published following more articles on suffix tree applications:

This article is contributed by **Anurag Singh**. Please write comments if you find anything incorrect, or you want to share more information about the topic discussed above