

# Anagram Trees

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Steffan Christ Sølvesten



# Wordrow

[wordrow.io](https://wordrow.io)

get\_game();



`get_game();`



Reason: (1.) Simple backend (2.) Small file size

# Contents

Motivation

Wordrow

Anagrams

Binary Anatree

`contains(x)`

`anagrams(x)`

`subanagrams(x)`

`insert(x)`

Multi-valued Anatree

Letter Ordering

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## Anagrams

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# Anagrams

Consider an *alphabet*  $\Sigma = \{\sigma_1, \sigma_2, \dots, \sigma_k\}$  and words  $x, y, \dots$  from a *language*  $L \subseteq \Sigma^*$ .

## Definition (Rohit Parikh, 1961)

The *Parikh vector* of a word  $x \in \Sigma^*$  is  $\Psi(x) \triangleq \langle |\sigma_1|, |\sigma_2|, \dots, |\sigma_k| \rangle$ .

## Example

For  $\Sigma = \{a, b, c\}$ ,  $\Psi(abb) = \langle 1, 2, 0 \rangle$  and  $\Psi(abab) = \Psi(abba) = \langle 2, 2, 0 \rangle$ .

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## Theorem (Rohit Parikh, 1961)

Given a Context-Free Language,  $L \subseteq \Sigma^*$ , one can efficiently construct the set of all Parikh vectors. One can use this to identify that  $x \in \Sigma^*$  **cannot** be in the language.

**More Details:** [cs.umu.se/kurser/TDBC92/VT06/final/3.pdf](http://cs.umu.se/kurser/TDBC92/VT06/final/3.pdf)



# Anagrams

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## Example

For  $\Sigma = \{a, b, c\}$ ,  $\Psi(abb) = \langle 1, 2, 0 \rangle$  and  $\Psi(abab) = \Psi(abba) = \langle 2, 2, 0 \rangle$ .

## Definition (Anagram)

$x, y \in \Sigma^*$  are *anagrams* if  $\Psi(x) = \Psi(y)$ .

## Definition (Subanagram)

$x \in \Sigma^*$  is a *subanagram* of  $y \in \Sigma^*$  if  $\Psi(x) \leq \Psi(y)$ .

# Anagrams

## Lemma

*Given  $x, y \in \Sigma^n$ , one can compute whether  $\Psi(x) = \Psi(y)$  in  $\mathcal{O}(n + |\Sigma|)$  time.*

## Lemma

*Given  $x, y \in \Sigma^*$ , one can compute whether  $\Psi(x) \leq \Psi(y)$  in  $\mathcal{O}(|x| + |y| + |\Sigma|)$  time.*

**Proof.**



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## Lemma

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## Proof.

Compute the Parikh vectors similar to the first half of *Counting Sort*.



## Example

Counting the number of  $a$ 's,  $b$ 's, and  $c$ 's in  $aba$  and  $aab$  both yield  $\langle 2, 1, 0 \rangle$ .

# Anagrams

## Lemma

*Given  $x, y \in \Sigma^n$ , computing whether  $\Psi(x) = \Psi(y)$  takes  $\mathcal{O}(\text{sort}(n))$  time.*

**Proof.**



# Anagrams

## Lemma

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## Proof.

Sort words  $x$  and  $y$  in  $\mathcal{O}(\text{sort}(n))$  time. Then, check whether they now are the very same word in  $\mathcal{O}(n)$  time. □

## Example

$x =$     b    a    a

$y =$     a    b    a

$x =$     c    a    b

$y =$     a    b    a

# Anagrams

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## Example

$x =$    a   a   b

$y =$    a   a   b

$x =$    c   a   b

$y =$    a   b   a

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## Example

$x = \underline{a} \ a \ b$

$y = \underline{a} \ a \ b$

$x = \ c \ a \ b$

$y = \ a \ b \ a$



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Given  $x, y \in \Sigma^n$ , computing whether  $\Psi(x) = \Psi(y)$  takes  $\mathcal{O}(\text{sort}(n))$  time.

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## Example

$x = \quad a \quad \underline{a} \quad b$

$y = \quad a \quad \underline{a} \quad b$

$x = \quad c \quad a \quad b$

$y = \quad a \quad b \quad a$

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## Example

$x = \quad a \quad a \quad \underline{b}$

$y = \quad a \quad a \quad \underline{b}$

$x = \quad c \quad a \quad b$

$y = \quad a \quad b \quad a$

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Given  $x, y \in \Sigma^n$ , computing whether  $\Psi(x) = \Psi(y)$  takes  $\mathcal{O}(\text{sort}(n))$  time.

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## Example

x =	a	a	b
y =	a	a	b

✓

x =	c	a	b
y =	a	b	a

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Given  $x, y \in \Sigma^n$ , computing whether  $\Psi(x) = \Psi(y)$  takes  $\mathcal{O}(\text{sort}(n))$  time.

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## Example

$x =$	a	a	b
$y =$	a	a	b

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$x =$	<u>a</u>	b	c
$y =$	<u>a</u>	a	b

# Anagrams

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Given  $x, y \in \Sigma^n$ , computing whether  $\Psi(x) = \Psi(y)$  takes  $\mathcal{O}(\text{sort}(n))$  time.

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## Example

$x =$	a	a	b
$y =$	a	a	b

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$x =$	a	<u>b</u>	c
$y =$	a	<u>a</u>	b

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## Example

x =	a	a	b
y =	a	a	b

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x =	a	b	c
y =	a	a	b

!

# Anagrams

## Lemma

*Given  $x, y \in \Sigma^*$ , checking  $\Psi(x) \leq \Psi(y)$  takes  $\mathcal{O}(\text{sort}(|x|) + \text{sort}(|y|))$  time.*

**Proof.**





# Anagrams

## Lemma

Given  $x, y \in \Sigma^*$ , checking  $\Psi(x) \leq \Psi(y)$  takes  $\mathcal{O}(\text{sort}(|x|) + \text{sort}(|y|))$  time.

## Proof.

Again, sort words  $x$  and  $y$ . Now, match each symbol of  $x$  with ones in  $y$ ; skip symbols of  $y$  if  $x$  is “ahead”. □

## Example

$x =$     b    a

$y =$     a    b    a

$x =$     c    a

$y =$     a    b    a

# Anagrams

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Given  $x, y \in \Sigma^*$ , checking  $\Psi(x) \leq \Psi(y)$  takes  $\mathcal{O}(\text{sort}(|x|) + \text{sort}(|y|))$  time.

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$x =$     a    b

$y =$     a    a    b

$x =$     c    a

$y =$     a    b    a

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## Example

$x = \underline{a} \quad b$

$y = \underline{a} \quad a \quad b$

$x = \quad c \quad a$

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## Example

$x =$      $a$      $b$

$y =$      $a$      $a$      $b$

$x =$      $c$      $a$

$y =$      $a$      $b$      $a$

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$x = \quad a \quad \underline{b}$

$y = \quad a \quad a \quad \underline{b}$

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## Example

$x =$	a	b	
$y =$	a	a	b

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$x =$	c	a	
$y =$	a	b	a

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## Example

$x =$	a	b	
$y =$	a	a	b

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$x =$	<u>a</u>	c	
$y =$	<u>a</u>	a	b



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$y =$	a	a	b

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$x =$	a	<u>c</u>	
$y =$	a	a	<u>b</u>

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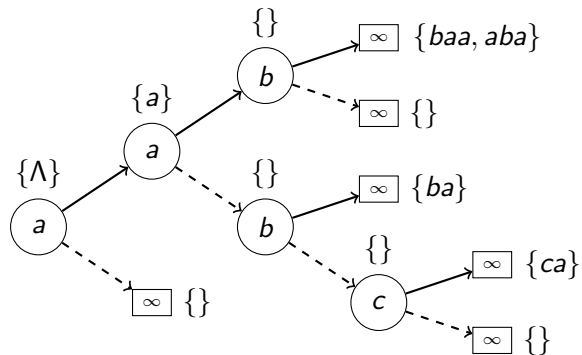
# Anatree

Given an alphabet,  $\Sigma$ , and an ordering on its symbols,  $< : \Sigma \times \Sigma \rightarrow \{\top, \perp\}$ , the *Anatree* data structure manages a set of words  $L \subseteq \Sigma^*$  on which one can do

Operation	
insert(x)	$\mathcal{O}(\text{sort}( x ) +  \Sigma )$
delete(x)	
contains(x)	$\mathcal{O}(\text{sort}( x ) +  \Sigma )$
anagrams(x)	$\mathcal{O}(\text{sort}( x ) +  \Sigma  + T)$
subanagrams(x)	$\mathcal{O}(\text{sort}( x ) + \min(N_{\text{Tree}}, 2^{ x } \cdot  \Sigma ) + T)$

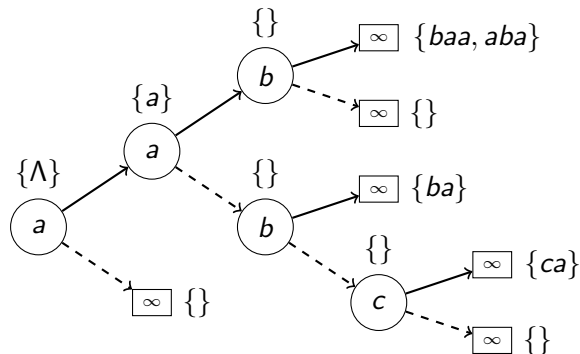
where  $N_{\text{Tree}}$  is the size of the Anagram tree and  $T$  is the output size.

# Anatree



$$L = \{\Lambda, a, ba, ca, aba, baa\}$$

Anatree.contains(ba)



$L = \{\Lambda, a, ba, ca, aba, baa\}$

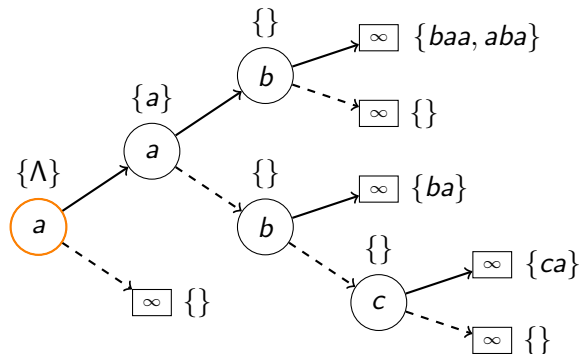
contains(x):

```
n := find(root, sort(x), 0)
return n ≠ NIL & n.contains(x)
```

find(n, x', i):



Anatree.contains(ba)



$L = \{\Lambda, a, ba, ca, aba, baa\}$

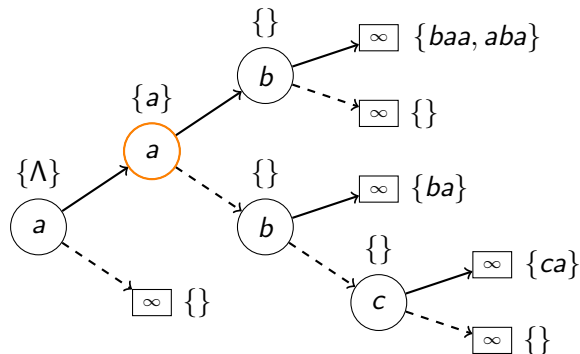
contains(x):

```
n := find(root, sort(x), 0)
return n ≠ NIL & n.contains(x)
```

find(n, x', i):

```
if x'[i] = n.char
    return find(n.true , x', i+1)
```

Anatree.contains(ba)



$L = \{\Lambda, a, ba, ca, aba, baa\}$

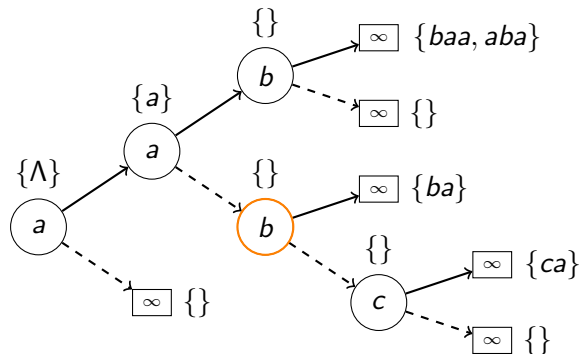
contains(x):

```
n := find(root, sort(x), 0)
return n ≠ NIL & n.contains(x)
```

find(n, x', i):

```
if x'[i] > n.char
    return find(n.false, x', i)
if x'[i] = n.char
    return find(n.true, x', i+1)
```

Anatree.contains(ba)



$L = \{\Lambda, a, ba, ca, aba, baa\}$

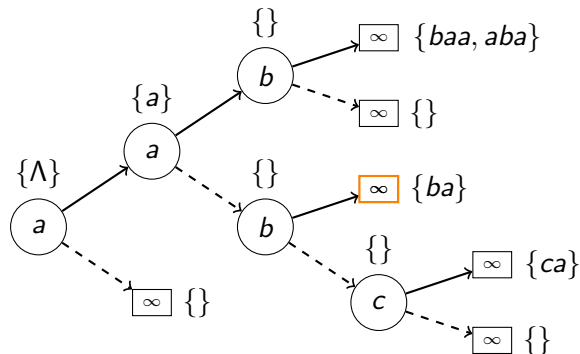
contains(x):

```
n := find(root, sort(x), 0)
return n ≠ NIL & n.contains(x)
```

find(n, x', i):

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if x'[i] > n.char
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if x'[i] = n.char
    return find(n.true, x', i+1)
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Anatree.contains(ba)



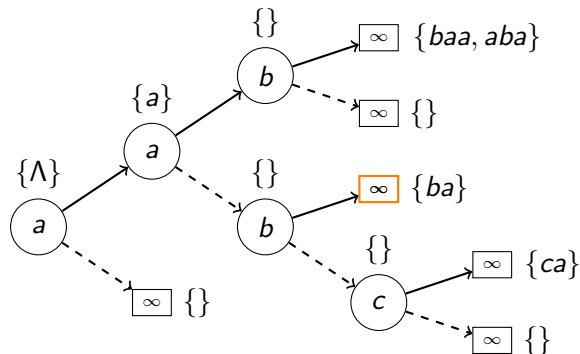
$L = \{\Lambda, a, ba, ca, aba, baa\}$

```
contains(x):
    n := find(root, sort(x), 0)
    return n ≠ NIL & n.contains(x)

find(n, x', i):
    if i = x'.length
        return n

    if x'[i] > n.char
        return find(n.false, x', i)
    if x'[i] = n.char
        return find(n.true, x', i+1)
```

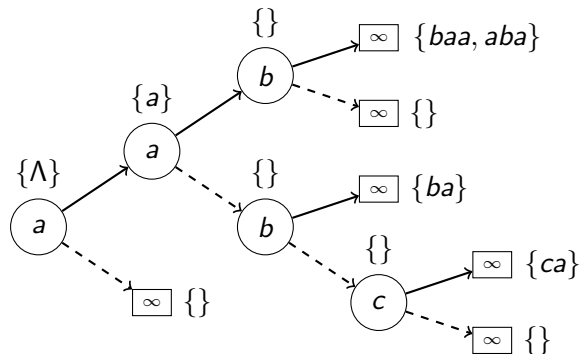
Anatree.contains(ba) = Yes



$L = \{\Lambda, a, ba, ca, aba, baa\}$

```
contains(x):  
    n := find(root, sort(x), 0)  
    return n  $\neq$  NIL & n.contains(x)  
  
find(n, x', i):  
    if i = x'.length  
        return n  
  
    if x'[i] > n.char  
        return find(n.false, x', i)  
    if x'[i] = n.char  
        return find(n.true, x', i+1)
```

Anatree.contains(aca)



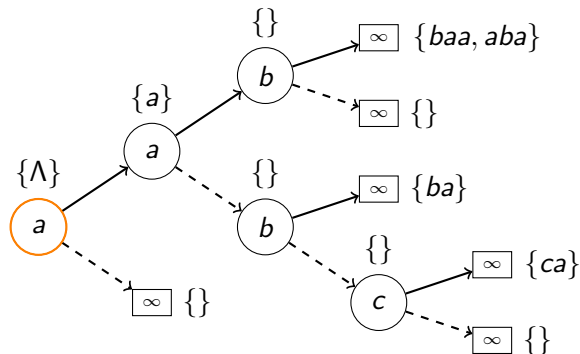
$L = \{\Lambda, a, ba, ca, aba, baa\}$

```
contains(x):
    n := find(root, sort(x), 0)
    return n ≠ NIL & n.contains(x)

find(n, x', i):
    if i = x'.length
        return n

    if x'[i] > n.char
        return find(n.false, x', i)
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Anatree.contains(aca)



$L = \{\Lambda, a, ba, ca, aba, baa\}$

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```

Anatree.contains(aca)



$L = \{\Lambda, a, ba, ca, aba, baa\}$

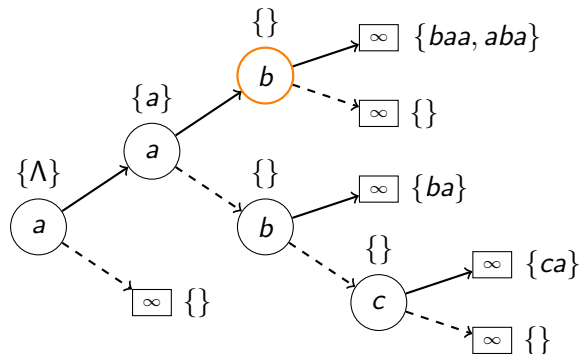
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contains(x):
    n := find(root, sort(x), 0)
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find(n, x', i):
    if i = x'.length
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        return find(n.false, x', i)
    if x'[i] = n.char
        return find(n.true, x', i+1)
```



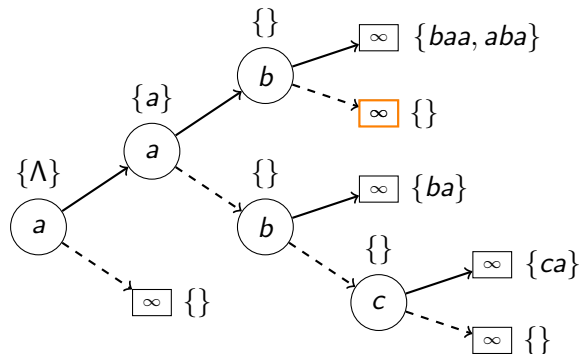
Anatree.contains(aca)



$L = \{\Lambda, a, ba, ca, aba, baa\}$

```
contains(x):  
    n := find(root, sort(x), 0)  
    return n  $\neq$  NIL & n.contains(x)  
  
find(n, x', i):  
    if i = x'.length  
        return n  
  
    if x'[i] > n.char  
        return find(n.false, x', i)  
    if x'[i] = n.char  
        return find(n.true, x', i+1)
```

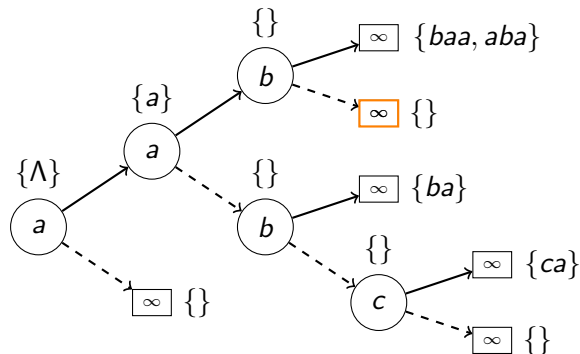
## Anatree.contains(aca)



$L = \{\Lambda, a, ba, ca, aba, baa\}$

```
contains(x):  
    n := find(root, sort(x), 0)  
    return n  $\neq$  NIL & n.contains(x)  
  
find(n, x', i):  
    if i = x'.length  
        return n  
    if x'[i] < n.char  
        return NIL  
    if x'[i] > n.char  
        return find(n.false, x', i)  
    if x'[i] = n.char  
        return find(n.true, x', i+1)
```

Anatree.contains(aca) = No

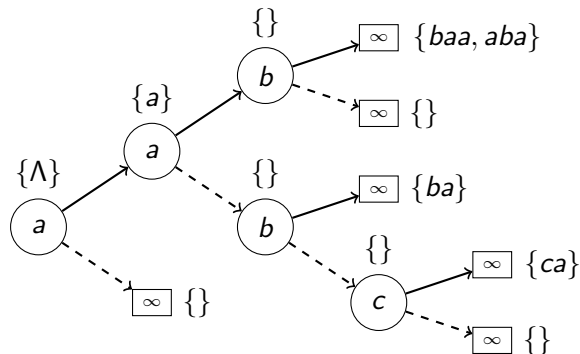


$L = \{\Lambda, a, ba, ca, aba, baa\}$

```
contains(x):
    n := find(root, sort(x), 0)
    return n ≠ NIL & n.contains(x)

find(n, x', i):
    if i = x'.length
        return n
    if x'[i] < n.char
        return NIL
    if x'[i] > n.char
        return find(n.false, x', i)
    if x'[i] = n.char
        return find(n.true, x', i+1)
```

Anatree.contains(...)



$L = \{\Lambda, a, ba, ca, aba, baa\}$

### Lemma

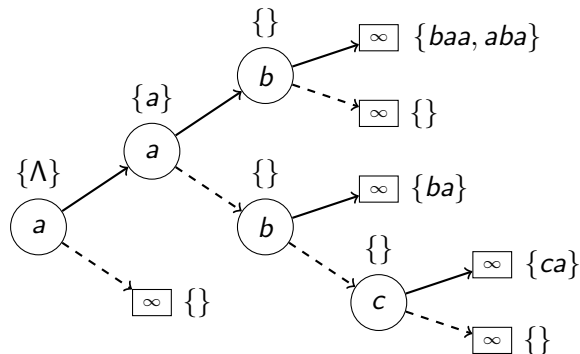
$find(n, sort(x), i)$  runs in  $\mathcal{O}(sort(|x|) + |\Sigma|)$  time.

### Proof.

$\mathcal{O}(1)$  time is spent per node. At most  $|x|$  high edges and  $|\Sigma|$  low edges are traversed, meaning at most  $|x| + |\Sigma|$  nodes are visited.

On top of this, add the  $\mathcal{O}(sort(|x|))$  time to sort  $x$  into  $x'$ . □

Anatree.contains(...)



$L = \{\Lambda, a, ba, ca, aba, baa\}$

**Lemma**

*find( $n$ , sort( $x$ ),  $i$ ) runs in  $\mathcal{O}(\text{sort}(|x|) + |\Sigma|)$  time.*

**Proof.**

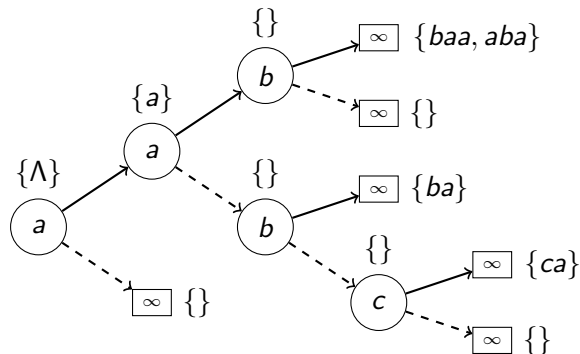
$\mathcal{O}(1)$  time is spent per node. . .

□

**Corollary**

*contains( $x$ ) runs in  $\mathcal{O}(\text{sort}(|x|) + |\Sigma|)$  time.*

## Anatree.anagrams(...)



$$L = \{\Lambda, a, ba, ca, aba, baa\}$$

anagrams(x):

$n := \text{find}(\text{root}, \text{sort}(x), 0)$

if  $n \neq \text{NIL}$

output words in  $n$

### Corollary

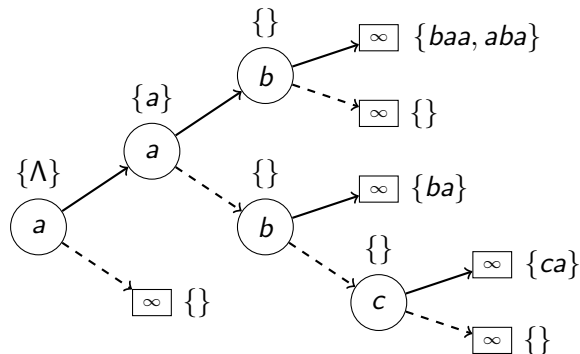
*anagrams(x) runs in*

$\mathcal{O}(\text{sort}(|x|) + |\Sigma| + T)$  time.

### Proof.

It takes  $\mathcal{O}(\text{sort}(|x|) + |\Sigma|)$  time to find  $n$  and then another  $\mathcal{O}(T)$  time to output its content.  $\square$

**Anatree.subanagrams(a) =**

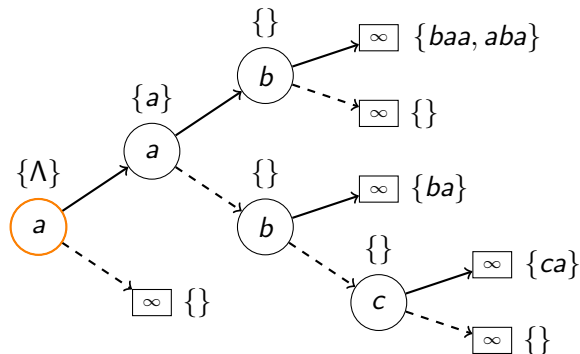


$L = \{\Lambda, a, ba, ca, aba, baa\}$

**subanagrams(x):**

**subanagrams'(root, sort(x), 0)**

`Anatree.subanagrams(a) =  $\Lambda$`



$L = \{\Lambda, a, ba, ca, aba, baa\}$

`subanagrams(x):`

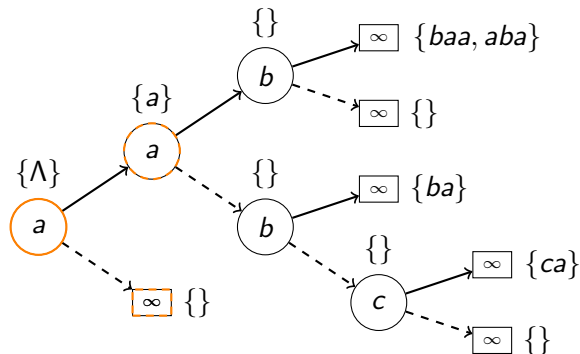
`subanagrams'(root, sort(x), 0)`

`subanagrams'(n, x', i):`

output words in n



`Anatree.subanagrams(a) =  $\Lambda$`



$L = \{\Lambda, a, ba, ca, aba, baa\}$

`subanagrams(x):`

`subanagrams'(root, sort(x), 0)`

`subanagrams'(n, x', i):`

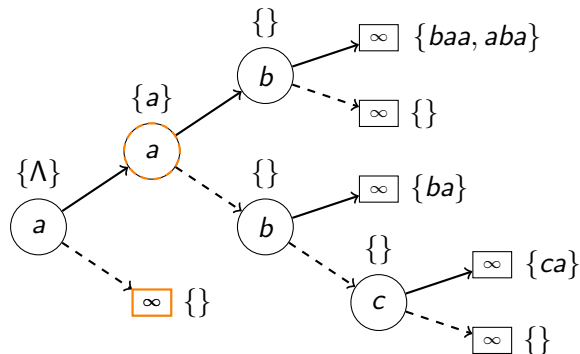
`output words in n`

`if x'[i] = n.char:`

`subanagrams'(n.false, x', i+1)`

`subanagrams'(n.true, x', i+1)`

`Anatree.subanagrams(a) =  $\Lambda$`



`subanagrams(x):`

`subanagrams'(root, sort(x), 0)`

`subanagrams'(n, x', i):`

`output words in n`

`if n.char =  $\infty$ :`

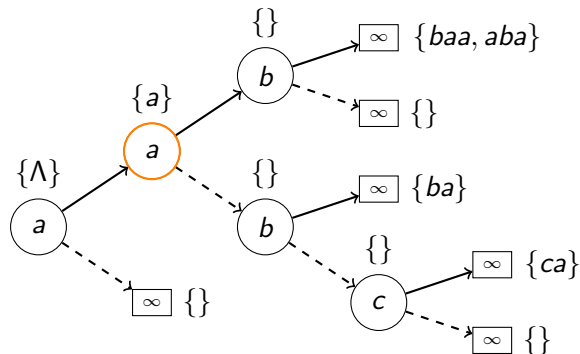
`return`

`if x'[i] = n.char:`

`subanagrams'(n.false, x', i+1)`

`subanagrams'(n.true, x', i+1)`

`Anatree.subanagrams(a) =  $\Lambda$ , a`



$L = \{\Lambda, a, ba, ca, aba, baa\}$

```
subanagrams(x):
```

```
    subanagrams'(root, sort(x), 0)
```

```
subanagrams'(n, x', i):
```

```
    output words in n
```

```
    if n.char = ∞:
```

```
        return
```

```
    if i = x'.length:
```

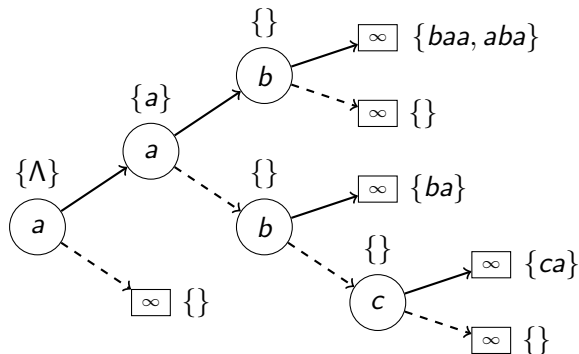
```
        return
```

```
    if x'[i] = n.char:
```

```
        subanagrams'(n.false, x', i+1)
```

```
        subanagrams'(n.true, x', i+1)
```

`Anatree.subanagrams(a) =  $\Lambda$ , a`



$L = \{\Lambda, a, ba, ca, aba, baa\}$

```
subanagrams(x):
```

```
    subanagrams'(root, sort(x), 0)
```

```
subanagrams'(n, x', i):
```

```
    output words in n
```

```
    if n.char = ∞:
```

```
        return
```

```
    if i = x'.length:
```

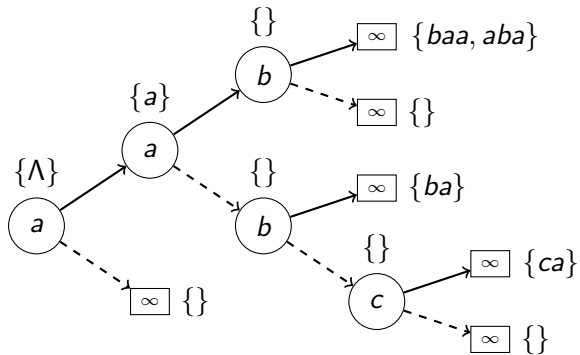
```
        return
```

```
    if x'[i] = n.char:
```

```
        subanagrams'(n.false, x', i+1)
```

```
        subanagrams'(n.true, x', i+1)
```

## Anatree.subanagrams(abb) =


$$L = \{\Lambda, a, ba, ca, aba, baa\}$$

subanagrams(x):

```
subanagrams'(root, sort(x), 0)
```

```
subanagrams'(n, x', i):
```

output words in n

```
if n.char =  $\infty$ :
```

return

```
if i == x'.length:
```

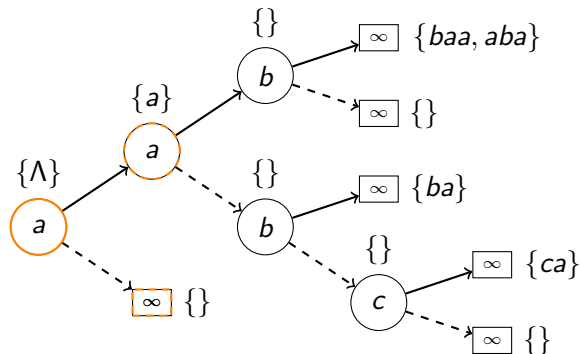
return

```
if x'[i] == n.char:
```

```
subanagrams'(n.false, x', i+1)
```

```
subanagrams'(n.true,  x', i+1)
```

`Anatree.subanagrams(abb) =  $\Lambda$`



$L = \{\Lambda, a, ba, ca, aba, baa\}$

```

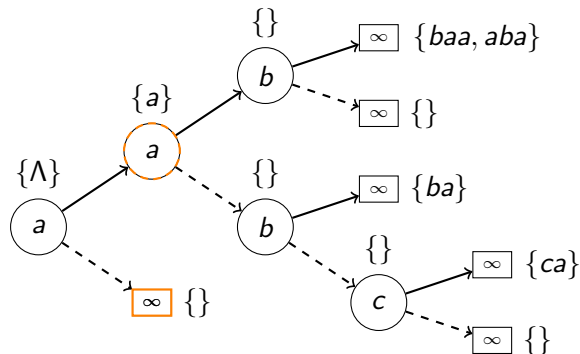
subanagrams(x):
    subanagrams'(root, sort(x), 0)

subanagrams'(n, x', i):
    output words in n
    if n.char = ∞:
        return

    if i = x'.length:
        return

    if x'[i] = n.char:
        subanagrams'(n.false, x', i+1)
        subanagrams'(n.true, x', i+1)
  
```

`Anatree.subanagrams(abb) =  $\Lambda$`



$L = \{\Lambda, a, ba, ca, aba, baa\}$

```
subanagrams(x):
```

```
    subanagrams'(root, sort(x), 0)
```

```
subanagrams'(n, x', i):
```

```
    output words in n
```

```
    if n.char =  $\infty$ :
```

```
        return
```

```
    if i = x'.length:
```

```
        return
```

```
    if x'[i] = n.char:
```

```
        subanagrams'(n.false, x', i+1)
```

```
        subanagrams'(n.true, x', i+1)
```

`Anatree.subanagrams(abb) =  $\Lambda$ , a`



$L = \{\Lambda, a, ba, ca, aba, baa\}$

```

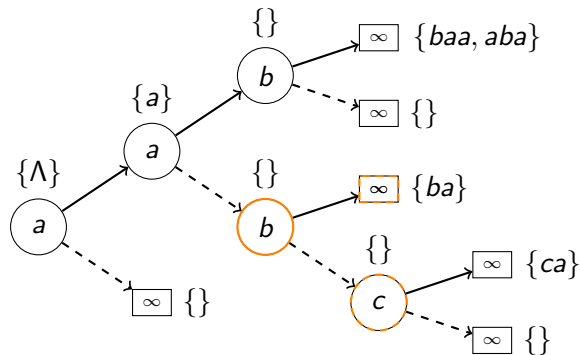
subanagrams(x):
    subanagrams'(root, sort(x), 0)

subanagrams'(n, x', i):
    output words in n
    if n.char = ∞:
        return

    if i = x'.length:
        return
    if x'[i] > n.char:
        subanagrams'(n.false, x', i)
    if x'[i] = n.char:
        subanagrams'(n.false, x', i+1)
        subanagrams'(n.true, x', i+1)
    
```



`Anatree.subanagrams(abb) =  $\Lambda$ , a`



$L = \{\Lambda, a, ba, ca, aba, baa\}$

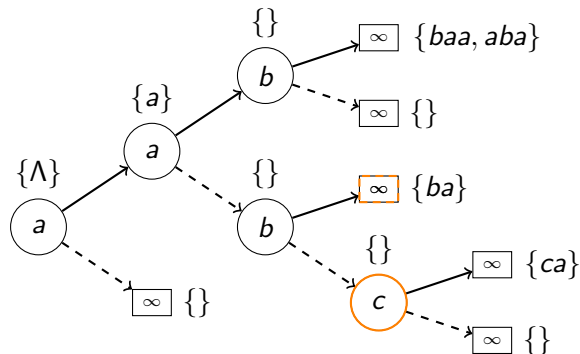
```

subanagrams(x):
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    if i = x'.length:
        return
    if x'[i] > n.char:
        subanagrams'(n.false, x', i)
    if x'[i] = n.char:
        subanagrams'(n.false, x', i+1)
        subanagrams'(n.true, x', i+1)
  
```

`Anatree.subanagrams(abb) =  $\Lambda$ , a`

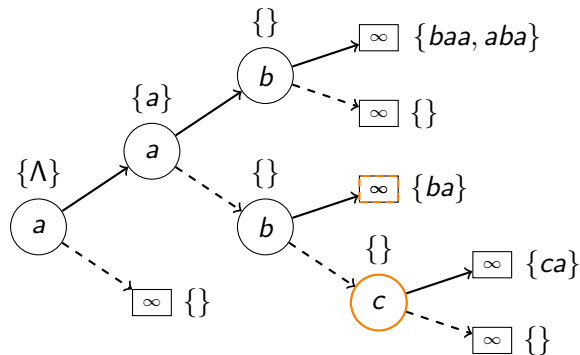


$L = \{\Lambda, a, ba, ca, aba, baa\}$

```

subanagrams(x):
    subanagrams'(root, sort(x), 0)

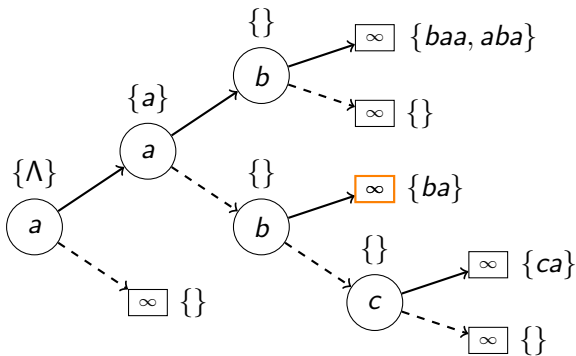
subanagrams'(n, x', i):
    output words in n
    if n.char = ∞:
        return
    while x'[i] < n.char:
        i++
    if i = x'.length:
        return
    if x'[i] > n.char:
        subanagrams'(n.false, x', i)
    if x'[i] = n.char:
        subanagrams'(n.false, x', i+1)
        subanagrams'(n.true, x', i+1)
    
```

$$\text{Anatree.subanagrams(abb)} = \Lambda, a$$

$$L = \{\Lambda, a, ba, ca, aba, baa\}$$

```
subanagrams(x):
    subanagrams'(root, sort(x), 0)

subanagrams'(n, x', i):
    output words in n
    if n.char = ∞:
        return
    while x'[i] < n.char:
        i++
    if i = x'.length:
        return
    if x'[i] > n.char:
        subanagrams'(n.false, x', i)
    if x'[i] = n.char:
        subanagrams'(n.false, x', i+1)
        subanagrams'(n.true, x', i+1)
```

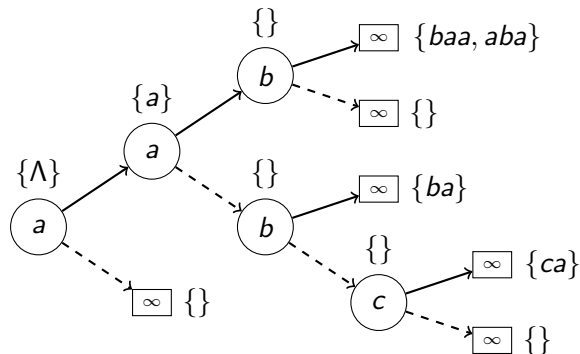
**Anatree.subanagrams(abb) =  $\Lambda$ , a, ab**


$$L = \{\Lambda, a, ba, ca, aba, baa\}$$

```
subanagrams(x):
    subanagrams'(root, sort(x), 0)

subanagrams'(n, x', i):
    output words in n
    if n.char = ∞:
        return
    while x'[i] < n.char:
        i++
    if i = x'.length:
        return
    if x'[i] > n.char:
        subanagrams'(n.false, x', i)
    if x'[i] = n.char:
        subanagrams'(n.false, x', i+1)
        subanagrams'(n.true, x', i+1)
```

`Anatree.subanagrams(abb) =  $\Lambda$ , a, ab`



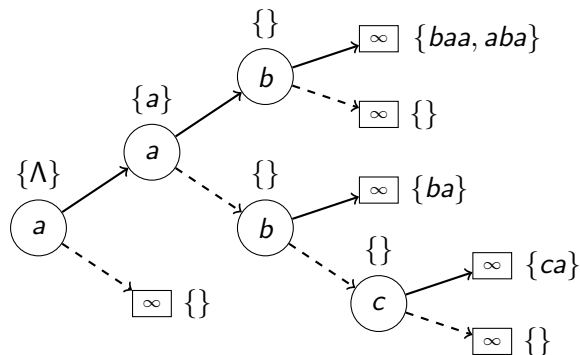
$L = \{\Lambda, a, ba, ca, aba, baa\}$

```

subanagrams(x):
    subanagrams'(root, sort(x), 0)

subanagrams'(n, x', i):
    output words in n
    if n.char = ∞:
        return
    while x'[i] < n.char:
        i++
    if i = x'.length:
        return
    if x'[i] > n.char:
        subanagrams'(n.false, x', i)
    if x'[i] = n.char:
        subanagrams'(n.false, x', i+1)
        subanagrams'(n.true, x', i+1)
  
```

## Anatree.subanagrams(...)

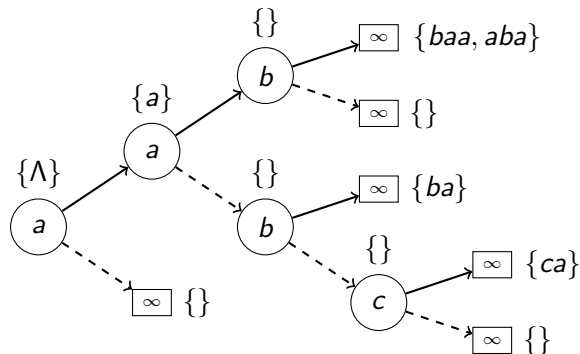


$$L = \{\Lambda, a, ba, ca, aba, baa\}$$

### Lemma

For  $N = \sum_{i=1}^k |x_i|$ , the anatree has size,  $N_{tree}$ , at most  $N$ .

## Anatree.subanagrams(...)



$$L = \{\Lambda, a, ba, ca, aba, baa\}$$

### Lemma

For  $N = \sum_{i=1}^k |x_i|$ , the anatree has size,  $N_{tree}$ , at most  $N$ .

### Theorem

*subanagrams(x)* runs in  $\mathcal{O}(\text{sort}(|x|) + \min(N_{tree}, 2^{|x|} \cdot |\Sigma|) + T)$  time.

### Proof.

It takes  $\mathcal{O}(\text{sort}(|x|))$  time to sort  $x$  and another  $\mathcal{O}(T)$  to write the output.

For every match, the recursion splits in two. Each of these  $2^{|x|}$  matches have  $|\Sigma|$  or fewer mismatches. □

**Anatree.keys(...)**

**Definition**

The subset  $L'$  of  $L \subseteq \Sigma^*$  is a set of keys w.r.t.  $\Psi$  if for all  $x, y \in L'$  then  $\Psi(x) \neq \Psi(y)$ .



**Anatree.keys(...)**

**Definition**

The subset  $L'$  of  $L \subseteq \Sigma^*$  is a set of keys w.r.t.  $\Psi$  if for all  $x, y \in L'$  then  $\Psi(x) \neq \Psi(y)$ .

**Theorem**

*keys(length) runs in  $\mathcal{O}(\min(N_{tree}, 2^{length} \cdot |\Sigma|) + T)$  time.*

**Proof.**

Left as an exercise to the reader...



# Anatree.insert( $\Lambda$ )

```
insert(x):  
    root = insert'(root, sort(x), 0, x)  
  
insert'(n, x', i, x):
```

{ }

$\infty$

## Anatree.insert( $\Lambda$ )

```
insert(x):  
    root = insert'(root, sort(x), 0, x)
```

```
insert'(n, x', i, x):  
    if i = x'.length:  
        n.insert(x)
```

```
    return n
```

$\{\Lambda\}$

$\infty$

Anatree.insert(*ba*)

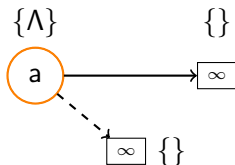
```
insert(x):  
    root = insert'(root, sort(x), 0, x)  
  
insert'(n, x', i, x):  
    if i = x'.length:  
        n.insert(x)
```

$\{\Lambda\}$

$\infty$

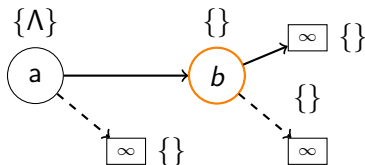
```
return n
```

## Anatree.insert(*ba*)



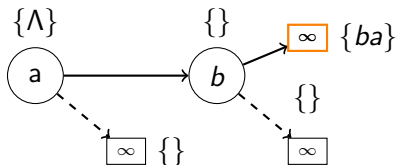
```
insert(x):  
    root = insert'(root, sort(x), 0, x)  
  
insert'(n, x', i, x):  
    if i = x'.length:  
        n.insert(x)  
    else if n.char =  $\infty$ :  
        n = node{ char: x'[i], false:  $\infty$ , true:  $\infty$  }  
        n.true = insert'(n.true, x', i+1, x)  
  
    return n
```

## Anatree.insert(*ba*)



```
insert(x):  
    root = insert'(root, sort(x), 0, x)  
  
insert'(n, x', i, x):  
    if i = x'.length:  
        n.insert(x)  
    else if n.char = ∞:  
        n = node{ char: x'[i], false: ∞, true: ∞ }  
        n.true = insert'(n.true, x', i+1, x)  
  
return n
```

## Anatree.insert(*ba*)



```
insert(x):
```

```
    root = insert'(root, sort(x), 0, x)
```

```
insert'(n, x', i, x):
```

```
    if i = x'.length:
```

```
        n.insert(x)
```

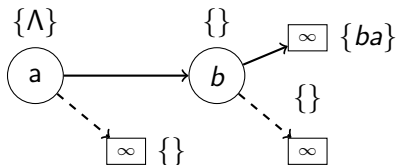
```
    else if n.char =  $\infty$ :
```

```
        n = node{ char: x'[i], false:  $\infty$ , true:  $\infty$  }
```

```
        n.true = insert'(n.true, x', i+1, x)
```

```
    return n
```

## Anatree.insert(*a*)

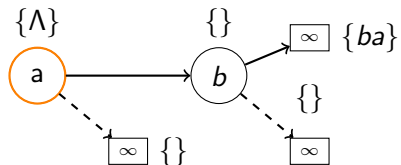


```
insert(x):  
    root = insert'(root, sort(x), 0, x)  
  
insert'(n, x', i, x):  
    if i = x'.length:  
        n.insert(x)  
    else if n.char =  $\infty$ :  
        n = node{ char: x'[i], false:  $\infty$ , true:  $\infty$  }  
        n.true = insert'(n.true, x', i+1, x)
```

```
return n
```



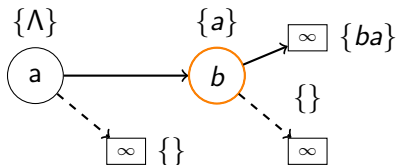
## Anatree.insert(a)



```
insert(x):  
    root = insert'(root, sort(x), 0, x)  
  
insert'(n, x', i, x):  
    if i == x'.length:  
        n.insert(x)  
    else if n.char ==  $\infty$ :  
        n = node{ char: x'[i], false:  $\infty$ , true:  $\infty$  }  
        n.true = insert'(n.true, x', i+1, x)
```

```
else if x'[i] == m.char:  
    n.true = insert'(n.true, x', i+1, x)  
return n
```

## Anatree.insert(a)



```
insert(x):
```

```
    root = insert'(root, sort(x), 0, x)
```

```
insert'(n, x', i, x):
```

```
    if i = x'.length:
```

```
        n.insert(x)
```

```
    else if n.char =  $\infty$ :
```

```
        n = node{ char: x'[i], false:  $\infty$ , true:  $\infty$  }
```

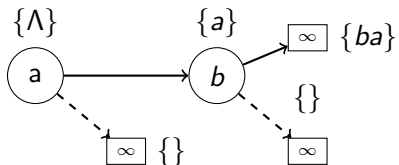
```
        n.true = insert'(n.true, x', i+1, x)
```

```
    else if x'[i] == m.char:
```

```
        n.true = insert'(n.true, x', i+1, x)
```

```
    return n
```

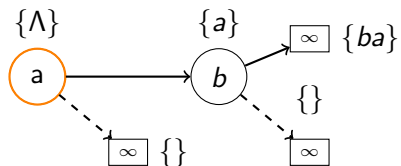
## Anatree.insert(*baa*)



```
insert(x):  
    root = insert'(root, sort(x), 0, x)  
  
insert'(n, x', i, x):  
    if i == x'.length:  
        n.insert(x)  
    else if n.char ==  $\infty$ :  
        n = node{ char: x'[i], false:  $\infty$ , true:  $\infty$  }  
        n.true = insert'(n.true, x', i+1, x)
```

```
    else if x'[i] == m.char:  
        n.true = insert'(n.true, x', i+1, x)  
    return n
```

## Anatree.insert(*baa*)

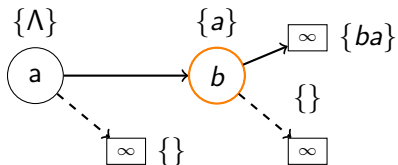


```
insert(x):
    root = insert'(root, sort(x), 0, x)

insert'(n, x', i, x):
    if i == x'.length:
        n.insert(x)
    else if n.char == ∞:
        n = node{ char: x'[i], false: ∞, true: ∞ }
        n.true = insert'(n.true, x', i+1, x)
```

```
else if x'[i] == m.char:
    n.true = insert'(n.true, x', i+1, x)
return n
```

## Anatree.insert(*baa*)



```
insert(x):
```

```
    root = insert'(root, sort(x), 0, x)
```

```
insert'(n, x', i, x):
```

```
    if i = x'.length:
```

```
        n.insert(x)
```

```
    else if n.char =  $\infty$ :
```

```
        n = node{ char: x'[i], false:  $\infty$ , true:  $\infty$  }
```

```
        n.true = insert'(n.true, x', i+1, x)
```

```
    else if x'[i] < m.char:
```

```
        n' = node{ char: x'[i], false: n, true:  $\infty$  }
```

```
        move n.words into n'.words
```

```
        n'.true = insert'(n'.true, x', i+1, x)
```

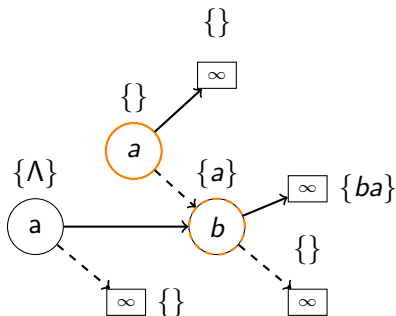
```
        return n'
```

```
    else if x'[i] == m.char:
```

```
        n.true = insert'(n.true, x', i+1, x)
```

```
    return n
```

## Anatree.insert(*baa*)



```
insert(x):
```

```
root = insert'(root, sort(x), 0, x)
```

```
insert'(n, x', i, x):
```

```
if i == x'.length:
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```
n.insert(x)
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else if n.char =  $\infty$ :
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n = node{ char: x'[i], false:  $\infty$ , true:  $\infty$  }
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n.true = insert'(n.true, x', i+1, x)
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n' = node{ char: x'[i], false: n, true:  $\infty$  }
```

```
move n.words into n'.words
```

```
n'.true = insert'(n'.true, x', i+1, x)
```

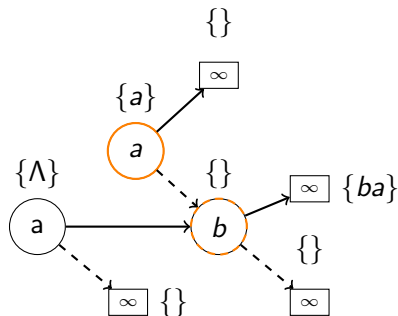
```
return n'
```

```
else if x'[i] == m.char:
```

```
n.true = insert'(n.true, x', i+1, x)
```

```
return n
```

## Anatree.insert(*baa*)



```
insert(x):
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```
insert'(n, x', i, x):
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```
    if i = x'.length:
```

```
        n.insert(x)
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        n = node{ char: x'[i], false: ∞, true: ∞ }
```

```
        n.true = insert'(n.true, x', i+1, x)
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    else if x'[i] < m.char:
```

```
        n' = node{ char: x'[i], false: n, true: ∞ }
```

```
        move n.words into n'.words
```

```
        n'.true = insert'(n'.true, x', i+1, x)
```

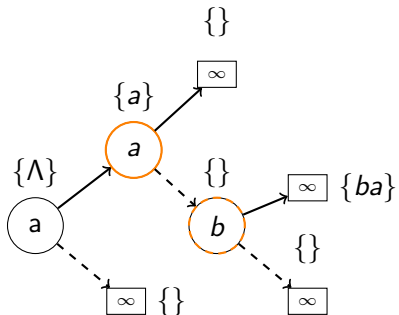
```
        return n'
```

```
    else if x'[i] == m.char:
```

```
        n.true = insert'(n.true, x', i+1, x)
```

```
    return n
```

## Anatree.insert(*baa*)



```
insert(x):
```

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    if i = x'.length:
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```

```
        move n.words into n'.words
```

```
        n'.true = insert'(n'.true, x', i+1, x)
```

```
        return n'
```

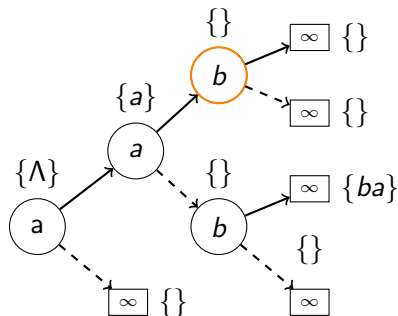
```
    else if x'[i] == m.char:
```

```
        n.true = insert'(n.true, x', i+1, x)
```

```
    return n
```



## Anatree.insert(*baa*)



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insert(x):
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        n' = node{ char: x'[i], false: n, true: ∞ }
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        move n.words into n'.words
```

```
        n'.true = insert'(n'.true, x', i+1, x)
```

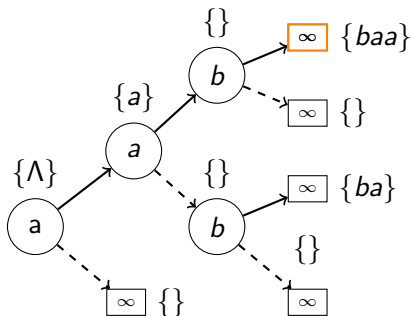
```
        return n'
```

```
    else if x'[i] == m.char:
```

```
        n.true = insert'(n.true, x', i+1, x)
```

```
    return n
```

## Anatree.insert(*baa*)



```
insert(x):
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```

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        n'.true = insert'(n'.true, x', i+1, x)
```

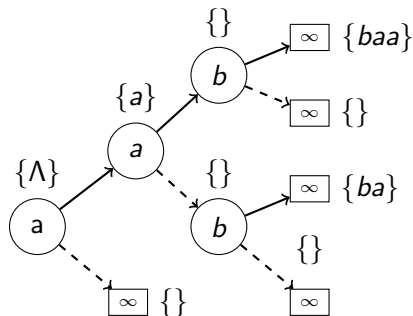
```
        return n'
```

```
    else if x'[i] == m.char:
```

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        n.true = insert'(n.true, x', i+1, x)
```

```
    return n
```

## Anatree.insert(*aba*)



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```

```
        n'.true = insert'(n'.true, x', i+1, x)
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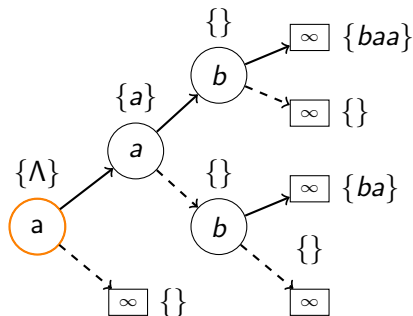
```
        return n'
```

```
    else if x'[i] == m.char:
```

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        n.true = insert'(n.true, x', i+1, x)
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    return n
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## Anatree.insert(*aba*)



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```

```
        move n.words into n'.words
```

```
        n'.true = insert'(n'.true, x', i+1, x)
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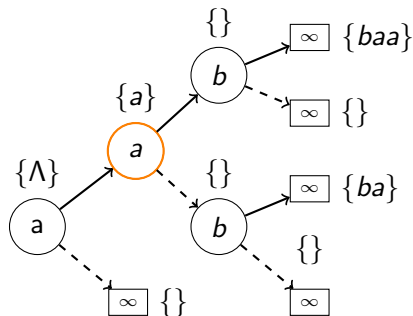
```
        return n'
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        n.true = insert'(n.true, x', i+1, x)
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## Anatree.insert(*aba*)



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        move n.words into n'.words
```

```
        n'.true = insert'(n'.true, x', i+1, x)
```

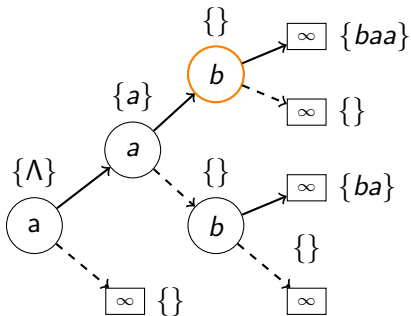
```
        return n'
```

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    else if x'[i] == m.char:
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        n.true = insert'(n.true, x', i+1, x)
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## Anatree.insert(*aba*)



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n = node{ char: x'[i], false:  $\infty$ , true:  $\infty$  }
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n.true = insert'(n.true, x', i+1, x)
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```

```
move n.words into n'.words
```

```
n'.true = insert'(n'.true, x', i+1, x)
```

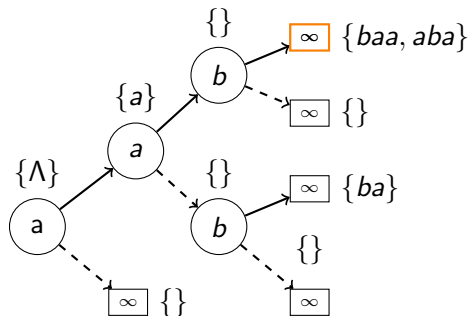
```
return n'
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```
else if x'[i] == m.char:
```

```
n.true = insert'(n.true, x', i+1, x)
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```
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## Anatree.insert(*aba*)



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        n' = node{ char: x'[i], false: n, true: ∞ }
```

```
        move n.words into n'.words
```

```
        n'.true = insert'(n'.true, x', i+1, x)
```

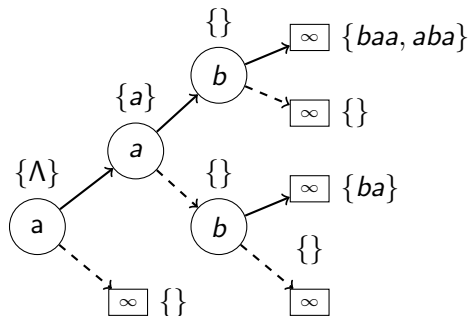
```
        return n'
```

```
    else if x'[i] == m.char:
```

```
        n.true = insert'(n.true, x', i+1, x)
```

```
    return n
```

## Anatree.insert(ca)



```
insert(x):
```

```
    root = insert'(root, sort(x), 0, x)
```

```
insert'(n, x', i, x):
```

```
    if i == x'.length:
```

```
        n.insert(x)
```

```
    else if n.char ==  $\infty$ :
```

```
        n = node{ char: x'[i], false:  $\infty$ , true:  $\infty$  }
```

```
        n.true = insert'(n.true, x', i+1, x)
```

```
    else if x'[i] < m.char:
```

```
        n' = node{ char: x'[i], false: n, true:  $\infty$  }
```

```
        move n.words into n'.words
```

```
        n'.true = insert'(n'.true, x', i+1, x)
```

```
        return n'
```

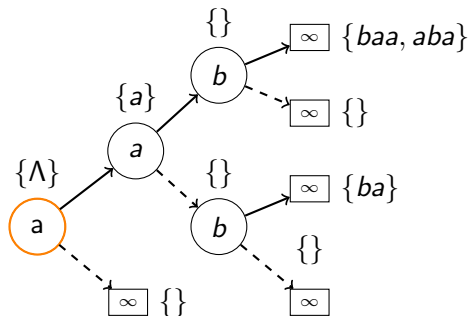
```
    else if x'[i] == m.char:
```

```
        n.true = insert'(n.true, x', i+1, x)
```

```
    return n
```



## Anatree.insert(ca)



```
insert(x):
```

```
    root = insert'(root, sort(x), 0, x)
```

```
insert'(n, x', i, x):
```

```
    if i == x'.length:
```

```
        n.insert(x)
```

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    else if n.char == ∞:
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        n = node{ char: x'[i], false: ∞, true: ∞ }
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    else if x'[i] < m.char:
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        n' = node{ char: x'[i], false: n, true: ∞ }
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```
        move n.words into n'.words
```

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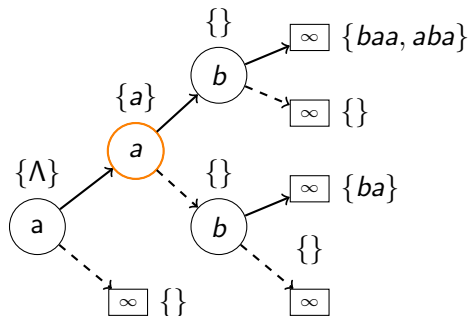
```
        return n'
```

```
    else if x'[i] == m.char:
```

```
        n.true = insert'(n.true, x', i+1, x)
```

```
    return n
```

## Anatree.insert(ca)



```
insert(x):
```

```
    root = insert'(root, sort(x), 0, x)
```

```
insert'(n, x', i, x):
```

```
    if i == x'.length:
```

```
        n.insert(x)
```

```
    else if n.char == ∞:
```

```
        n = node{ char: x'[i], false: ∞, true: ∞ }
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```
        n.true = insert'(n.true, x', i+1, x)
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    else if x'[i] < m.char:
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```
        n' = node{ char: x'[i], false: n, true: ∞ }
```

```
        move n.words into n'.words
```

```
        n'.true = insert'(n'.true, x', i+1, x)
```

```
        return n'
```

```
    else if x'[i] > m.char:
```

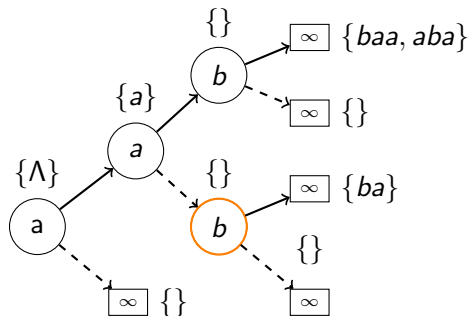
```
        n.false = insert'(n.false, x', i, x)
```

```
    else if x'[i] == m.char:
```

```
        n.true = insert'(n.true, x', i+1, x)
```

```
    return n
```

## Anatree.insert(ca)



```
insert(x):
```

```
    root = insert'(root, sort(x), 0, x)
```

```
insert'(n, x', i, x):
```

```
    if i == x'.length:
```

```
        n.insert(x)
```

```
    else if n.char == ∞:
```

```
        n = node{ char: x'[i], false: ∞, true: ∞ }
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        n.true = insert'(n.true, x', i+1, x)
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    else if x'[i] < m.char:
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        n' = node{ char: x'[i], false: n, true: ∞ }
```

```
        move n.words into n'.words
```

```
        n'.true = insert'(n'.true, x', i+1, x)
```

```
        return n'
```

```
    else if x'[i] > m.char:
```

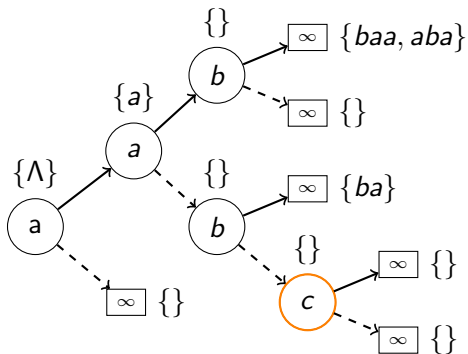
```
        n.false = insert'(n.false, x', i, x)
```

```
    else if x'[i] == m.char:
```

```
        n.true = insert'(n.true, x', i+1, x)
```

```
    return n
```

## Anatree.insert(ca)



```
insert(x):
```

```
    root = insert'(root, sort(x), 0, x)
```

```
insert'(n, x', i, x):
```

```
    if i == x'.length:
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        n.insert(x)
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    else if n.char ==  $\infty$ :
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        n = node{ char: x'[i], false:  $\infty$ , true:  $\infty$  }
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```
        n'.true = insert'(n'.true, x', i+1, x)
```

```
        return n'
```

```
    else if x'[i] > m.char:
```

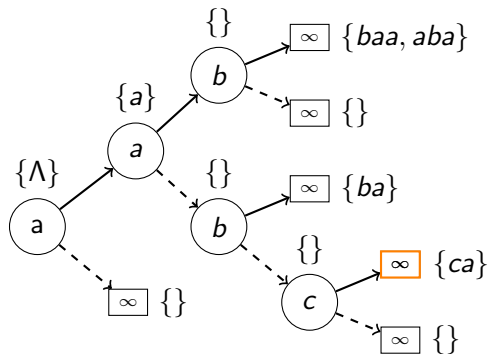
```
        n.false = insert'(n.false, x', i, x)
```

```
    else if x'[i] == m.char:
```

```
        n.true = insert'(n.true, x', i+1, x)
```

```
    return n
```

## Anatree.insert(ca)



```
insert(x):
```

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    root = insert'(root, sort(x), 0, x)
```

```
insert'(n, x', i, x):
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    if i == x'.length:
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        n' = node{ char: x'[i], false: n, true:  $\infty$  }
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```
        move n.words into n'.words
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```
        n'.true = insert'(n'.true, x', i+1, x)
```

```
        return n'
```

```
    else if x'[i] > m.char:
```

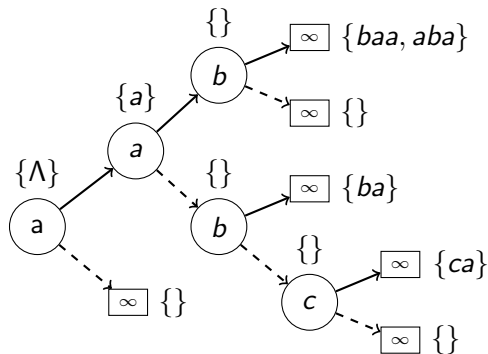
```
        n.false = insert'(n.false, x', i, x)
```

```
    else if x'[i] == m.char:
```

```
        n.true = insert'(n.true, x', i+1, x)
```

```
    return n
```

## Anatree.insert(...)



```
insert(x):
```

```
    root = insert'(root, sort(x), 0, x)
```

```
insert'(n, x', i, x):
```

```
    if i = x'.length:
```

```
        n.insert(x)
```

```
    else if n.char =  $\infty$ :
```

```
        n = node{ char: x'[i], false:  $\infty$ , true:  $\infty$  }
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        n.true = insert'(n.true, x', i+1, x)
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    else if x'[i] < m.char:
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        n' = node{ char: x'[i], false: n, true:  $\infty$  }
```

```
        move n.words into n'.words
```

```
        n'.true = insert'(n'.true, x', i+1, x)
```

```
        return n'
```

```
    else if x'[i] > m.char:
```

```
        n.false = insert'(n.false, x', i, x)
```

```
    else if x'[i] == m.char:
```

```
        n.true = insert'(n.true, x', i+1, x)
```

```
    return n
```

**Anatree.insert(...)**

**Theorem**

*insert( $x$ ) runs in  $\mathcal{O}(\text{sort}(|x|) + \Sigma)$  time.*

**Proof.**

Similar argument as for `find( $n, x', i$ )`.



**Anatree.insert(...)**

**Theorem**

*insert( $x$ ) runs in  $\mathcal{O}(\text{sort}(|x|) + \Sigma)$  time.*

**Proof.**

Similar argument as for `find( $n, x', i$ )`. □

**Corollary**

*For  $N = \sum_{i=1}^k |x_i|$ , `insert( $x_1, x_2, \dots, x_k$ )` requires  $\mathcal{O}(\text{sort}(N) + k \cdot |\Sigma|)$  time.*

**Proof.**

Follows from complexity of `insert( $x_i$ )` and `sort` distributes over  $+$  in  $\mathcal{O}$ -notation:

$$\mathcal{O}(\text{sort}(N_1) + \text{sort}(N_2)) = \mathcal{O}(\text{sort}(N_1 + N_2))$$
□



**Anatree.delete(...)**

**Theorem**

*delete(x) runs in  $\mathcal{O}(\text{sort}(|x|) + |\Sigma|)$  time.*





**Proof.**

Left as an exercise to the reader...





# Anatree

		Dictionary		Anatree			
		# Words	# Symbols	Size	#Keys	insert (s)	subanagrams (s)
	DK	32863	177308	62687	8513	12.62	1.05
	DE	23587	127562	55047	8201	9.46	0.88
	EN	40804	218342	75697	11741	10.62	1.43
	ES	39650	219776	56103	7502	8.45	0.89

# Contents

Motivation

Wordrow

Anagrams

Binary Anatree

`contains(x)`

`anagrams(x)`

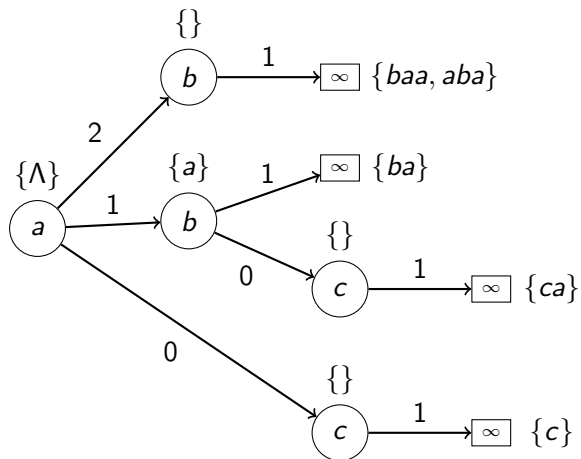
`subanagrams(x)`

`insert(x)`

**Multi-valued Anatree**

Letter Ordering

## Multi-valued Anatrie



$$L = \{\Lambda, a, c, ba, ca, aba, baa\}$$

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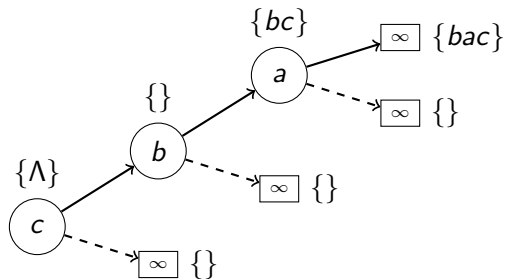
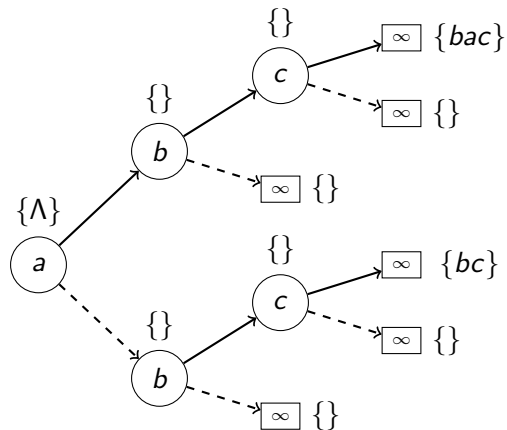
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`insert(x)`

Multi-valued Anatree

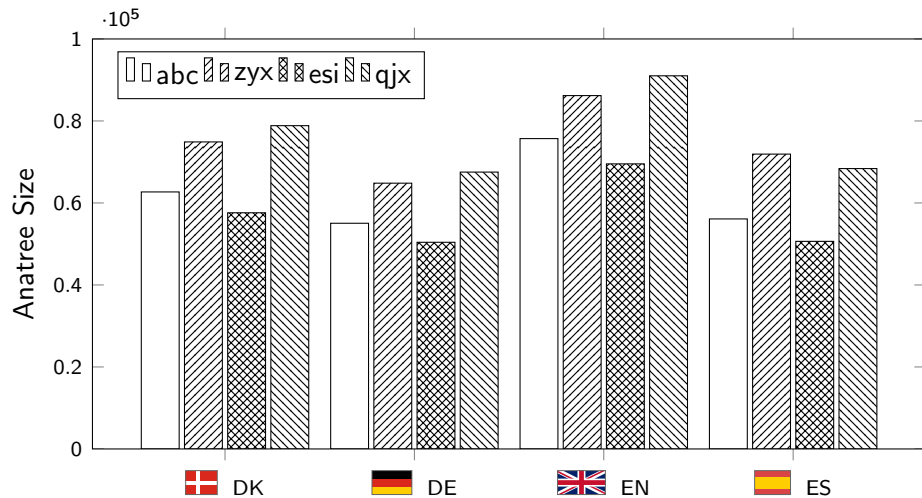
Letter Ordering

## Letter Ordering



$$L = \{\Lambda, bc, bac\}$$

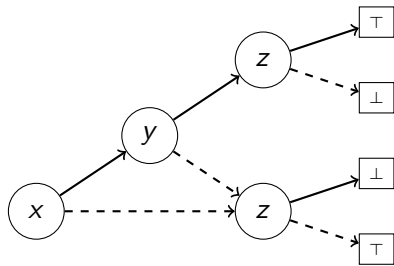
# Letter Ordering





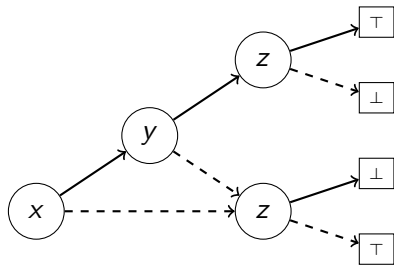


## Binary Decision Diagrams



$$f(x, y, z) \equiv \neg((x \wedge y) \oplus z)$$

# Binary Decision Diagrams

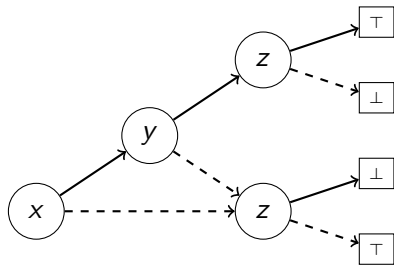


$$f(x, y, z) \equiv \neg((x \wedge y) \oplus z)$$

Used in the context of:

- Model Checking
- Compilers
- Game Solving

# Binary Decision Diagrams



$$f(x, y, z) \equiv \neg((x \wedge y) \oplus z)$$

Used in the context of:

- Model Checking
- Compilers
- Game Solving

Features of BDDs:

- (Often) Smaller than Formula/Set
- Operation Complexity depends on BDD Size
- Size depends on Variable Ordering

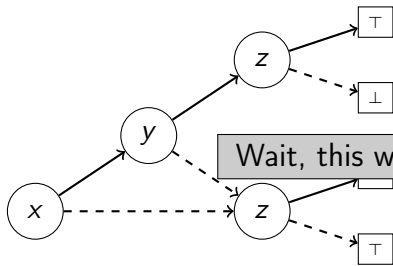
# Binary Decision Diagrams

Always has been.

Used in the context of:

- Model Checking
- Compilers
- Game Solving

Wait, this was about BDDs?



$$f(x, y, z) \equiv \neg((x \wedge y) \oplus z)$$

Properties of BDDs:

(n) Size depends on Variable Order



# Steffan Christ Sølvsten

✉ [soelvsten@cs.au.dk](mailto:soelvsten@cs.au.dk)

## Wordrow

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🎲 [wordrow.io](http://wordrow.io)

🔗 [github.com/ssoelvsten/wordrow](https://github.com/ssoelvsten/wordrow)

## Anatree

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🔗 [github.com/ssoelvsten/anatree](https://github.com/ssoelvsten/anatree)