

3-2 Amortized Analysis

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Robert Tarjan



John Hopcroft

*For fundamental achievements
in the design and analysis of algorithms and data structures.*

— Turing Award, 1986

AMORTIZED COMPUTATIONAL COMPLEXITY*

ROBERT ENDRE TARJAN†

Abstract. A powerful technique in the complexity analysis of data structures is *amortization*, or averaging over time. Amortized running time is a realistic but robust complexity measure for which we can obtain surprisingly tight upper and lower bounds on a variety of algorithms. By following the principle of designing algorithms whose amortized complexity is low, we obtain “self-adjusting” data structures that are simple, flexible and efficient. This paper surveys recent work by several researchers on amortized complexity.

“Amortized Computational Complexity”, 1985

Amortized analysis is
an algorithm analysis technique for
analyzing a sequence of operations
irrespective of the input to show that
the average cost per operation is small, even though
a single operation within the sequence might be expensive.

By *averaging the cost per operation over a worst-case sequence*,
amortized analysis can yield a time complexity that is
more *robust* than *average-case analysis*, since
its *probabilistic assumptions on inputs* may be false,
and more *realistic* than *worst-case analysis*, since it may be
impossible for every operation to take the worst-case time,
as occurs often in manipulation of data structures.



EXAMPLE

Dynamic Tables

- (I) Summation Method
- (II) Accounting Method
- (III) Potential Method



EXAMPLE

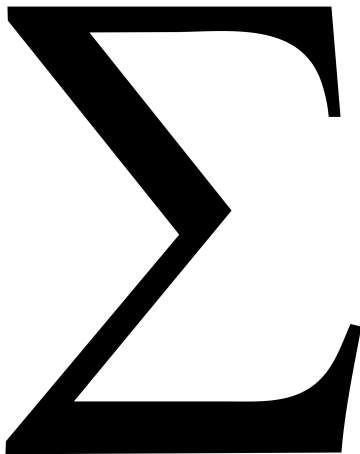
Dynamic Tables

“Move-to-Front” List

Splay Tree

- (I) Summation Method
- (II) Accounting Method
- (III) Potential Method

The Summation Method



$$O_1, O_2, \dots, O_n$$

$$C_1, C_2, \dots, C_n$$

$$O_1, O_2, \dots, O_n$$

$$C_1, C_2, \dots, C_n$$

$$\forall i, \hat{c}_i = \frac{\left(\sum_{i=1}^n c_i \right)}{n}$$

The Summation Method for Array Doubling

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On **any sequence** of n INSERTs on an **initially empty** array.

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$o_i :$	o_1	o_2	o_3	o_4	o_5	o_6	o_7	o_8	o_9	o_{10}
$c_i :$	1	2	3	1	5	1	1	1	9	1

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$$c_i = \begin{cases} (i-1) + 1 = i & \text{if } i-1 \text{ is an exact power of 2} \\ 1 & \text{o.w.} \end{cases}$$

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$$\begin{array}{cccccccccc} o_i : & o_1 & o_2 & o_3 & o_4 & o_5 & o_6 & o_7 & o_8 & o_9 & o_{10} \\ c_i : & 1 & 2 & 3 & 1 & 5 & 1 & 1 & 1 & 9 & 1 \end{array}$$

$$c_i = \begin{cases} (i-1) + 1 = i & \text{if } i-1 \text{ is an exact power of 2} \\ 1 & \text{o.w.} \end{cases}$$

$$\sum_{i=1}^n c_i \leq n + \sum_{j=0}^{\lceil \lg n \rceil - 1} 2^j = n + (2^{\lceil \lg n \rceil} - 1) \leq n + 2n = 3n$$

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$$\boxed{\forall i, \hat{c}_i = 3}$$

The Accounting Method



O_1, O_2, \dots, O_m

C_1, C_2, \dots, C_m

a_1, a_2, \dots, a_m

$$O_1, O_2, \dots, O_m$$

$$C_1, C_2, \dots, C_m$$

$$a_1, a_2, \dots, a_m$$

$$\hat{c}_i = c_i + a_i, \quad a_i \geq 0$$

Amortized Cost = Actual Cost + Accounting Cost

$$O_1, O_2, \dots, O_m$$

$$C_1, C_2, \dots, C_m$$

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$$O_1, O_2, \dots, O_m$$

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$$C_1, C_2, \dots, C_m$$

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Amortized Cost = Actual Cost + Accounting Cost

$$\forall m, \sum_{i=1}^m c_i \leq \sum_{i=1}^m \hat{c}_i \implies \forall m, \sum_{i=1}^m a_i \geq 0$$

Key Point: Put the accounting cost on specific objects.

The Accounting Method for Array Doubling

$$Q : \hat{c}_i = 3 \text{ vs. } \hat{c}_i = 2$$

The Accounting Method for Array Doubling

$Q : \hat{c}_i = 3$ vs. $\hat{c}_i = 2$

$$\hat{c}_i = 3 = \underbrace{1}_{\text{insert}} + \underbrace{1}_{\text{move itself}} + \underbrace{1}_{\text{help move another}}$$

The Accounting Method for Array Doubling

$Q : \hat{c}_i = 3 \text{ vs. } \hat{c}_i = 2$

$$\hat{c}_i = 3 = \underbrace{1}_{\text{insert}} + \underbrace{1}_{\text{move itself}} + \underbrace{1}_{\text{help move another}}$$

	\hat{c}_i	c_i (<i>actual cost</i>)	a_i (<i>accounting cost</i>)
INSERT (<i>normal</i>)	3	1	2
INSERT (<i>expansion</i>)	3	$1 + t$	$-t + 2$

The Potential Method

$$D_0, o_1, D_1, o_2, \dots, \underbrace{D_{i-1}, o_i, D_i}_{\text{the } i\text{-th operation}}, \dots, D_{m-1}, o_m, D_m$$

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$$\Phi : \{D_i \mid 0 \leq i \leq m\} \rightarrow \mathcal{R}$$

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$$\hat{c}_i = c_i + \left(\Phi(D_i) - \Phi(D_{i-1}) \right)$$

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$$\sum_{1 \leq i \leq m} \hat{c}_i = \left(\sum_{1 \leq i \leq m} c_i \right) + \left(\Phi(D_m) - \Phi(D_0) \right)$$

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$$\forall m, \sum_{i=1}^m c_i \leq \sum_{i=1}^m \hat{c}_i \iff \boxed{\forall i : \Phi(D_i) \geq \Phi(D_0)}$$

$$D_0, o_1, D_1, o_2, \dots, \underbrace{D_{i-1}, o_i, D_i}_{\text{the } i\text{-th operation}}, \dots, D_{m-1}, o_m, D_m$$

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$$\forall m, \sum_{i=1}^m c_i \leq \sum_{i=1}^m \hat{c}_i \quad \Longleftarrow \quad \boxed{\forall i : \Phi(D_i) \geq \Phi(D_0)}$$

$$\Phi(D_0) = 0, \quad \forall i : \Phi(D_i) \geq 0$$

$$D_0, o_1, D_1, o_2, \dots, \underbrace{D_{i-1}, o_i, D_i}_{\text{the } i\text{-th operation}}, \dots, D_{m-1}, o_m, D_m$$

$$\Phi : \{D_i \mid 0 \leq i \leq m\} \rightarrow \mathcal{R}$$

$$\hat{c}_i = c_i + \left(\Phi(D_i) - \Phi(D_{i-1}) \right)$$

$$\sum_{1 \leq i \leq m} \hat{c}_i = \left(\sum_{1 \leq i \leq m} c_i \right) + \left(\Phi(D_m) - \Phi(D_0) \right)$$

$$\forall m, \sum_{i=1}^m c_i \leq \sum_{i=1}^m \hat{c}_i \quad \Longleftarrow \quad \boxed{\forall i : \Phi(D_i) \geq \Phi(D_0)}$$

$$\Phi(D_0) = 0, \quad \forall i : \Phi(D_i) \geq 0 \quad (\text{Typically})$$

The Potential Method for Dynamic Tables

$$\alpha = \frac{T.num}{T.size}$$

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EXPANSION : $\begin{cases} \text{When to expand?} \\ \text{How large to expand?} \end{cases}$

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EXPANSION : $\begin{cases} \text{When to expand?} & \alpha = 1 \\ \text{How large to expand?} & \alpha = 1/2 \end{cases}$

The Potential Method for Dynamic Tables

$$\alpha = \frac{T.num}{T.size}$$

EXPANSION : $\begin{cases} \text{When to expand?} & \alpha = 1 \\ \text{How large to expand?} & \alpha = 1/2 \end{cases}$

CONTRACTION : $\begin{cases} \text{When to contract?} \\ \text{How small to contract?} \end{cases}$

The Potential Method for Dynamic Tables

$$\alpha = \frac{T.num}{T.size}$$

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The Potential Method for Dynamic Tables

$$\alpha = \frac{T.num}{T.size}$$

EXPANSION : $\begin{cases} \text{When to expand?} & \alpha = 1 \\ \text{How large to expand?} & \alpha = 1/2 \end{cases}$

CONTRACTION : $\begin{cases} \text{When to contract?} & \alpha = 1/4 \\ \text{How small to contract?} & \alpha = 1/2 \end{cases}$

$$\frac{1}{4} \leq \alpha \leq 1$$

$$\Phi(T) = \begin{cases} 2 \cdot T.num - T.size & \text{if } \alpha(T) \geq 1/2 \\ T.size/2 - T.num & \text{if } \alpha(T) < 1/2 \end{cases}$$

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$$\Phi(T_0) = 0, \quad \Phi(T_i) \geq 0$$

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$$\alpha = 1/2 \rightsquigarrow \alpha = 1 \implies \Phi(T) : 0 \rightsquigarrow T.num$$

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$$\alpha = 1/2 \rightsquigarrow \alpha = 1/4 \implies \Phi(T) : 0 \rightsquigarrow T.num$$

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By Case Analysis.

$$\Phi(T) = \begin{cases} 2 \cdot T.num - T.size & \text{if } \alpha(T) \geq 1/2 \\ T.size/2 - T.num & \text{if } \alpha(T) < 1/2 \end{cases}$$

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By Case Analysis.

TABLE-INSERT

$$\begin{cases} \alpha_{i-1} < 1/2 & \begin{cases} \alpha_i < 1/2 \\ \alpha_i \geq 1/2 \end{cases} \\ \alpha_{i-1} \geq 1/2 & \begin{cases} \alpha_{i-1} < 1 \\ \alpha_{i-1} = 1 \end{cases} \end{cases}$$

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$$\begin{cases} \alpha_{i-1} < 1/2 \begin{cases} \alpha_i < 1/2 \\ \alpha_i \geq 1/2 \end{cases} \\ \alpha_{i-1} \geq 1/2 \begin{cases} \alpha_{i-1} < 1 \\ \alpha_{i-1} = 1 \end{cases} \end{cases}$$

TABLE-DELETE

$$\begin{cases} \alpha_{i-1} < 1/2 \begin{cases} \frac{num_{i-1}-1}{size_{i-1}} \geq \frac{1}{4} \\ \frac{num_{i-1}-1}{size_{i-1}} < \frac{1}{4} \end{cases} \\ \alpha_{i-1} \geq 1/2 \begin{cases} \alpha_i < 1/2 \left(\frac{num_{i-1}-1}{size_{i-1}} < \frac{1}{4} \right) \\ \alpha_i \geq 1/2 \end{cases} \end{cases}$$

TABLE-DELETE

$$\alpha_{i-1} < 1/2 \wedge \frac{num_{i-1} - 1}{size_{i-1}} < \frac{1}{4}$$

$$\hat{c}_i = c_i + \left(\Phi_i - \Phi_{i-1} \right)$$

TABLE-DELETE

$$\alpha_{i-1} < 1/2 \wedge \frac{num_{i-1} - 1}{size_{i-1}} < \frac{1}{4}$$

$$\begin{aligned}\hat{c}_i &= c_i + (\Phi_i - \Phi_{i-1}) \\ &= 1 + (size_i/2 - num_i) - (size_{i-1}/2 - num_{i-1})\end{aligned}$$

TABLE-DELETE

$$\alpha_{i-1} < 1/2 \wedge \frac{num_{i-1} - 1}{size_{i-1}} < \frac{1}{4}$$

$$\begin{aligned}\hat{c}_i &= c_i + (\Phi_i - \Phi_{i-1}) \\ &= 1 + (size_i/2 - num_i) - (size_{i-1}/2 - num_{i-1}) \\ &= 2\end{aligned}$$

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$$\alpha_{i-1} < 1/2 \wedge \frac{num_{i-1} - 1}{size_{i-1}} < \frac{1}{4}$$

$$\begin{aligned}\hat{c}_i &= c_i + (\Phi_i - \Phi_{i-1}) \\ &= 1 + (size_i/2 - num_i) - (size_{i-1}/2 - num_{i-1}) \\ &= 2\end{aligned}$$

Why?

TABLE-DELETE

$$\alpha_{i-1} \geq 1/2 \wedge \alpha_i \geq 1/2$$

$$\hat{c}_i = c_i + (\Phi_i - \Phi_{i-1})$$

TABLE-DELETE

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TABLE-INSERT

$$\left\{ \begin{array}{l} \alpha_{i-1} < 1/2 \left\{ \begin{array}{l} \alpha_i < 1/2 \text{ (0)} \\ \alpha_i \geq 1/2 \text{ (3)} \end{array} \right. \\ \alpha_{i-1} \geq 1/2 \left\{ \begin{array}{l} \alpha_{i-1} < 1 \text{ (3)} \\ \alpha_{i-1} = 1 \text{ (3)} \end{array} \right. \end{array} \right.$$

TABLE-DELETE

$$\left\{ \begin{array}{l} \alpha_{i-1} < 1/2 \left\{ \begin{array}{l} \frac{num_{i-1}-1}{size_{i-1}} \geq \frac{1}{4} \text{ (1)} \\ \frac{num_{i-1}-1}{size_{i-1}} < \frac{1}{4} \text{ (2)} \end{array} \right. \\ \alpha_{i-1} \geq 1/2 \left\{ \begin{array}{l} \alpha_i < 1/2 \text{ (1/2)} \\ \alpha_i \geq 1/2 \text{ (-1)} \end{array} \right. \end{array} \right.$$

TABLE-INSERT

$$\left\{ \begin{array}{l} \alpha_{i-1} < 1/2 \left\{ \begin{array}{l} \alpha_i < 1/2 \text{ (0)} \\ \alpha_i \geq 1/2 \text{ (3)} \end{array} \right. \\ \alpha_{i-1} \geq 1/2 \left\{ \begin{array}{l} \alpha_{i-1} < 1 \text{ (3)} \\ \alpha_{i-1} = 1 \text{ (3)} \end{array} \right. \end{array} \right.$$

TABLE-DELETE

$$\left\{ \begin{array}{l} \alpha_{i-1} < 1/2 \left\{ \begin{array}{l} \frac{\text{num}_{i-1}-1}{\text{size}_{i-1}} \geq \frac{1}{4} \text{ (1)} \\ \frac{\text{num}_{i-1}-1}{\text{size}_{i-1}} < \frac{1}{4} \text{ (2)} \end{array} \right. \\ \alpha_{i-1} \geq 1/2 \left\{ \begin{array}{l} \alpha_i < 1/2 \text{ (1/2)} \\ \alpha_i \geq 1/2 \text{ (-1)} \end{array} \right. \end{array} \right.$$



Array Merging Dictionary: the summation method

CREATE (1); MERGE ($2m$)

Array Merging Dictionary: the summation method

CREATE (1); MERGE ($2m$)

$i \quad c_i$

1 1

2 $1 + 2$

3 1

4 $1 + 2 + 4$

5 1

6 $1 + 2$

7 1

8 $1 + 2 + 4$

$\vdots \quad \dots$

Array Merging Dictionary: the summation method

CREATE (1); MERGE (2*m*)

i *c_i*

1 1

2 1 + 2

3 1

4 1 + 2 + 4

5 1

6 1 + 2

7 1

8 1 + 2 + 4

⋮ ...

$$\sum_{i=1}^n c_i = \sum_{j=0}^{\lfloor \log n \rfloor} \lfloor \frac{n}{2^j} \rfloor 2^j \leq n(\lfloor \log n \rfloor + 1)$$

Array Merging Dictionary: the summation method

CREATE (1); MERGE (2*m*)

i *c_i*

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7 1

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⋮ ...

$$\sum_{i=1}^n c_i = \sum_{j=0}^{\lfloor \log n \rfloor} \lfloor \frac{n}{2^j} \rfloor 2^j \leq n(\lfloor \log n \rfloor + 1)$$

$$\forall i, \hat{c}_i = 1 + \lfloor \log n \rfloor$$

Array Merging Dictionary: the accounting method

$$\hat{c}_i = 1 + \lfloor \log n \rfloor$$

Array Merging Dictionary: the accounting method

$$\hat{c}_i = 1 + \lfloor \log n \rfloor$$

What does it mean?

Array Merging Dictionary: the accounting method

$$\hat{c}_i = 1 + \lfloor \log n \rfloor$$

What does it mean?

$$\forall n, \sum_{i=1}^n a_i \geq 0$$

What work are you proudest of?



What work are you proudest of?



Proudest? It's hard to choose.

What work are you proudest of?



Proudest? It's hard to choose.

*I like the **self-adjusting search tree** data structure
that Danny Sleator and I developed.*

Self-Adjusting Binary Search Trees

DANIEL DOMINIC SLEATOR AND ROBERT ENDRE TARJAN

AT&T Bell Laboratories, Murray Hill, NJ

Abstract. The *splay* tree, a self-adjusting form of binary search tree, is developed and analyzed. The binary search tree is a data structure for representing tables and lists so that accessing, inserting, and deleting items is easy. On an n -node splay tree, all the standard search tree operations have an amortized time bound of $O(\log n)$ per operation, where by “amortized time” is meant the time per operation averaged over a worst-case sequence of operations. Thus splay trees are as efficient as balanced trees when total running time is the measure of interest. In addition, for sufficiently long access sequences, splay trees are as efficient, to within a constant factor, as static optimum search trees. The efficiency of splay trees comes not from an explicit structural constraint, as with balanced trees, but from applying a simple restructuring heuristic, called *splaying*, whenever the tree is accessed. Extensions of splaying give simplified forms of two other data structures: lexicographic or multidimensional search trees and link/cut trees.

“Self-Adjusting Binary Search Trees – *Splay Tree*”, *JACM*, 1985

Self-Adjusting Binary Search Trees



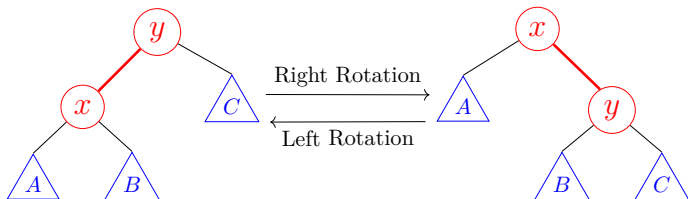
vs. Balanced Binary Search Trees

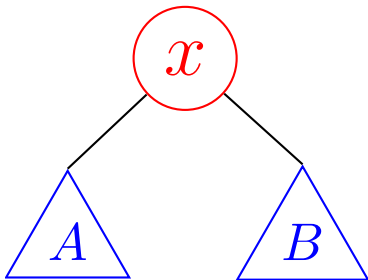
$\text{SPLAY}(x)$:

Moving node x to the root of the tree by performing a sequence of **rotations** along the path from x to the root.

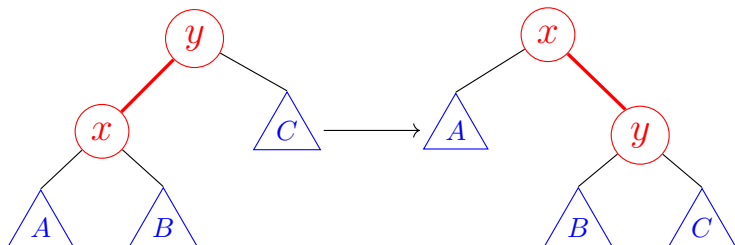
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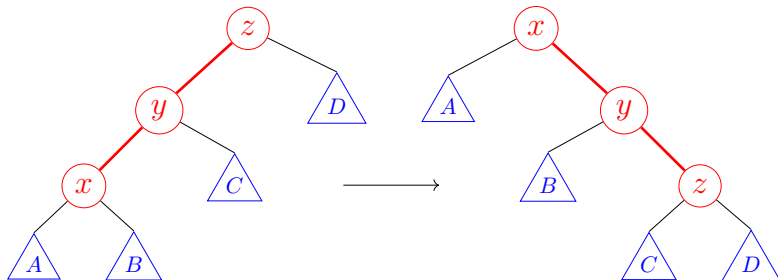


CASE 0: x is the root



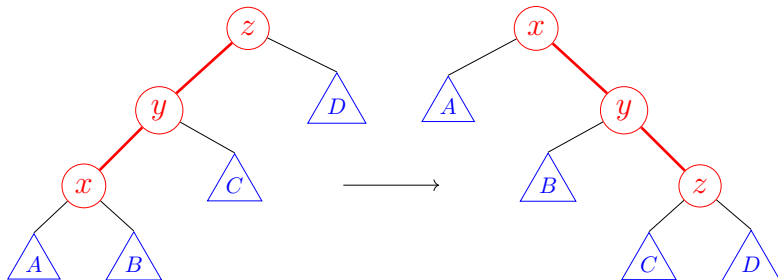
CASE 1: zig

$y = p(x)$ is the root



CASE 2: zig-zig

$$\begin{aligned}
 y &= p(x) & z &= p(y) \\
 x &= lc(y) & y &= lc(z)
 \end{aligned}$$

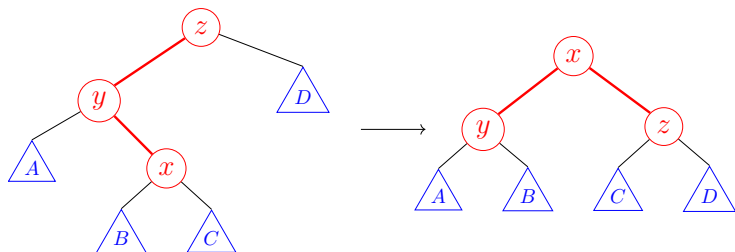


CASE 2: zig-zig

$$y = p(x) \quad z = p(y)$$

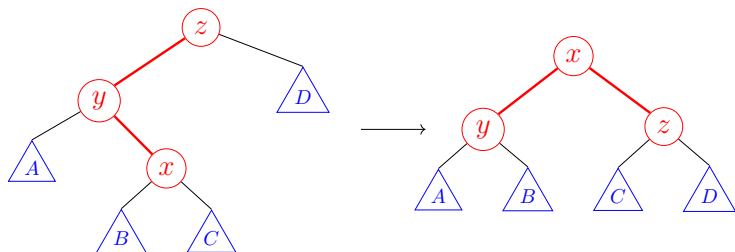
$$x = lc(y) \quad y = lc(z)$$

$$(1) : y - z \quad (2) : x - y$$



CASE 3: zig-zag

$$\begin{aligned}
 y &= p(x) & z &= p(y) \\
 x &= rc(y) & y &= lc(z)
 \end{aligned}$$

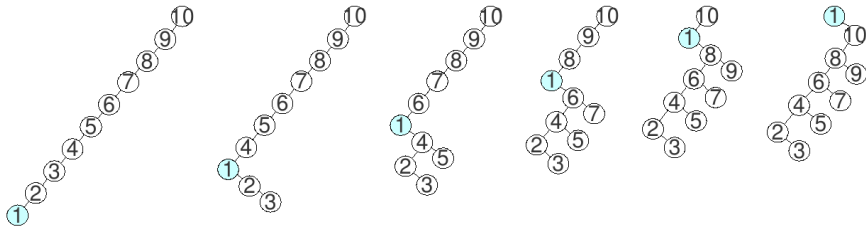


CASE 3: zig-zag

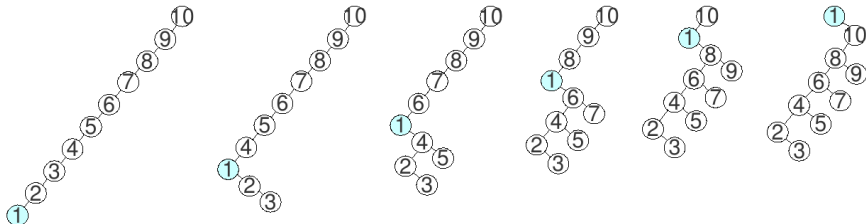
$$y = p(x) \quad z = p(y)$$

$$x = rc(y) \quad y = lc(z)$$

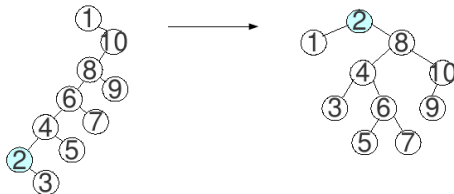
$$(1) : x - y \quad (2) : x - z$$



SPLAY(1)



SPLAY(1)



SPLAY(2)

Amortized analysis of SPLAY

Amortized analysis of SPLAY

A splay tree T of n -node

An arbitrary sequence of m SPLAY operations

Amortized analysis of SPLAY

A splay tree T of n -node

An arbitrary sequence of m SPLAY operations

of rotations

Amortized analysis of SPLAY

A splay tree T of n -node

An arbitrary sequence of m SPLAY operations

of rotations

Theorem

$$\hat{c}_{\text{SPLAY}} = O(\log n).$$

$$\Phi_0 \text{ SPLAY}_1 \Phi_1 \text{ SPLAY}_2 \Phi_2 \cdots \underbrace{\Phi_{i-1} \text{ SPLAY}_i \Phi_i}_{\text{the } i\text{-th SPLAY}} \cdots \text{SPLAY}_m \Phi_m$$

$$\hat{c}_{\text{SPLAY}_i} = c_{\text{SPLAY}_i} + (\Phi_{\text{SPLAY}_i} - \Phi_{\text{SPLAY}_{i-1}})$$

$$\Phi_0 \text{ SPLAY}_1 \Phi_1 \text{ SPLAY}_2 \Phi_2 \cdots \underbrace{\Phi_{i-1} \text{ SPLAY}_i \Phi_i}_{\text{the } i\text{-th SPLAY}} \cdots \text{SPLAY}_m \Phi_m$$

$$\hat{c}_{\text{SPLAY}_i} = c_{\text{SPLAY}_i} + (\Phi_{\text{SPLAY}_i} - \Phi_{\text{SPLAY}_{i-1}})$$

How to define Φ ?

$s(x)$: # of nodes in the subtree rooted at x

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$$r(x) = \log s(x)$$

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$$\Phi = \sum_{x \in T} r(x)$$

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$$\hat{c}_{\text{SPLAY}_i} = c_{\text{SPLAY}_i} + (\Phi_{\text{SPLAY}_i} - \Phi_{\text{SPLAY}_{i-1}})$$

How to calculate $(\Phi_{\text{SPLAY}_i} - \Phi_{\text{SPLAY}_{i-1}})$ and c_{SPLAY_i} ?

$$\Phi_0 \text{ SPLAY}_1 \Phi_1 \text{ SPLAY}_2 \Phi_2 \cdots \underbrace{\Phi_{i-1} \text{ SPLAY}_i \Phi_i}_{\text{the } i\text{-th SPLAY}} \cdots \text{SPLAY}_m \Phi_m$$

$$\Phi_0 \text{ SPLAY}_1 \Phi_1 \text{ SPLAY}_2 \Phi_2 \cdots \underbrace{\Phi_{i-1} \text{ SPLAY}_i \Phi_i}_{\text{the } i\text{-th SPLAY}} \cdots \text{SPLAY}_m \Phi_m$$

$$\underbrace{\Phi_{i-1} \text{ SPLAY}_i \Phi_i}_{\text{the } i\text{-th SPLAY}} :$$

$$\Phi_{i-1} \triangleq \Phi_{0'} \text{ ITER}_1 \Phi_{1'} \cdots \underbrace{\Phi_{k-1} \text{ ITER}_k \Phi_k}_{\text{the } k\text{-th ITERATION}} \cdots \text{ITER}_l \Phi_l \triangleq \Phi_i$$

$$\Phi_0 \text{ SPLAY}_1 \Phi_1 \text{ SPLAY}_2 \Phi_2 \cdots \underbrace{\Phi_{i-1} \text{ SPLAY}_i \Phi_i}_{\text{the } i\text{-th SPLAY}} \cdots \text{SPLAY}_m \Phi_m$$

$$\underbrace{\Phi_{i-1} \text{ SPLAY}_i \Phi_i}_{\text{the } i\text{-th SPLAY}} :$$

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$$\begin{aligned} \hat{c}_{\text{SPLAY}_i} &= \sum_{1 \leq j \leq l} \hat{c}_{\text{ITER}_j} \\ &= \sum_{1 \leq j \leq l} c_{\text{ITER}_j} + (\Phi_{\text{ITER}_j} - \Phi_{\text{ITER}_{j-1}}) \end{aligned}$$

$$\hat{c}_{\text{ITER}_j} = c_{\text{ITER}_j} + (\Phi_{\text{ITER}_j} - \Phi_{\text{ITER}_{j-1}})$$

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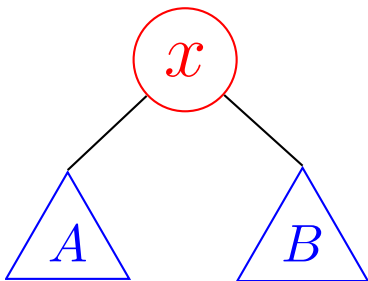
By Case Analysis.

$$\hat{c}_{\text{ITER}_j} = c_{\text{ITER}_j} + (\Phi_{\text{ITER}_j} - \Phi_{\text{ITER}_{j-1}})$$

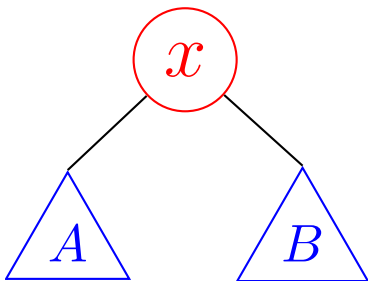
By Case Analysis.

$$\hat{c}_j = c_j + (\Phi_j - \Phi_{j-1})$$

Remember: ITER

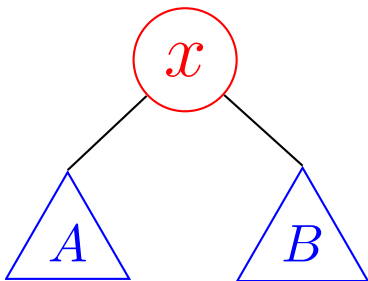


CASE 0



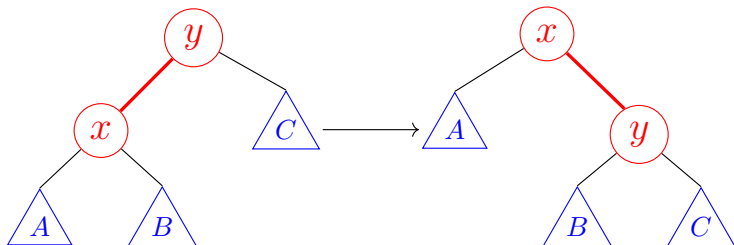
CASE 0

$$\hat{c}_j = c_j + (\Phi_j - \Phi_{j-1})$$



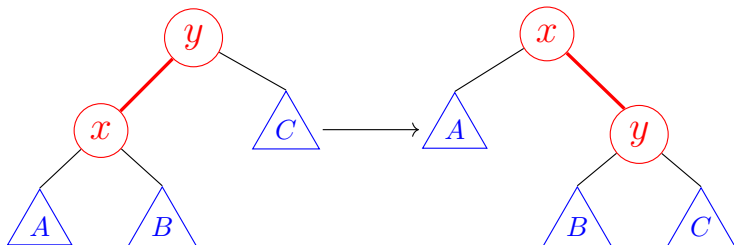
CASE 0

$$\begin{aligned}\hat{c}_j &= c_j + (\Phi_j - \Phi_{j-1}) \\ &= 0 + 0 \\ &= 0\end{aligned}$$



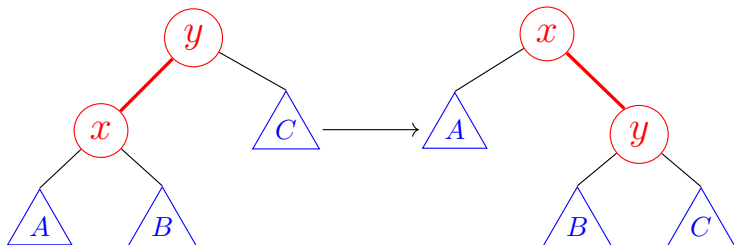
CASE 1: zig

$$\hat{c}_j = c_j + (\Phi_j - \Phi_{j-1})$$



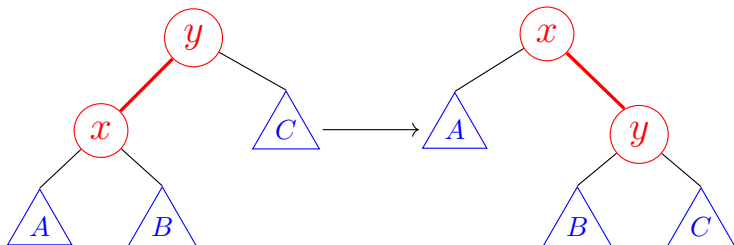
CASE 1: zig

$$\begin{aligned}
 \hat{c}_j &= c_j + (\Phi_j - \Phi_{j-1}) \\
 &= 1 + r_j(x) + r_j(y) - r_{j-1}(x) - r_{j-1}(y)
 \end{aligned}$$



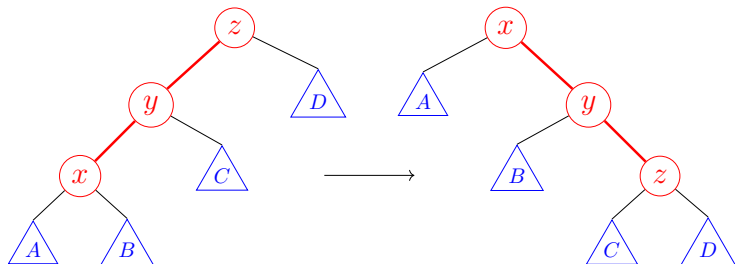
CASE 1: zig

$$\begin{aligned}
 \hat{c}_j &= c_j + (\Phi_j - \Phi_{j-1}) \\
 &= 1 + r_j(x) + r_j(y) - r_{j-1}(x) - r_{j-1}(y) \\
 &\leq 1 + r_j(x) - r_{j-1}(x)
 \end{aligned}$$



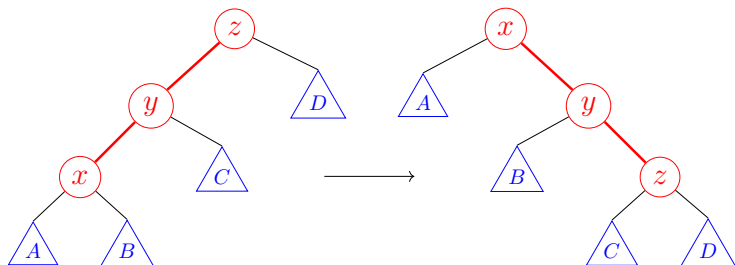
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 \hat{c}_j &= c_j + (\Phi_j - \Phi_{j-1}) \\
 &= 1 + r_j(x) + r_j(y) - r_{j-1}(x) - r_{j-1}(y) \\
 &\leq 1 + r_j(x) - r_{j-1}(x) \\
 &\leq 1 + 3(r_j(x) - r_{j-1}(x))
 \end{aligned}$$



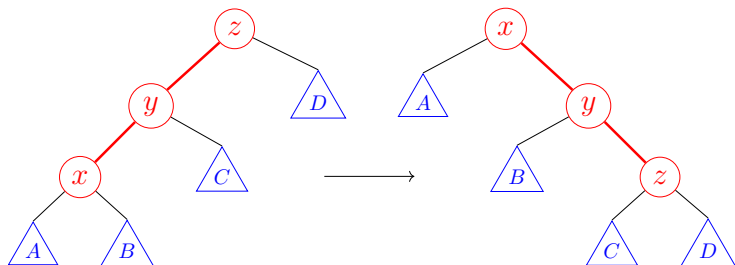
CASE 2: zig-zig

$$\hat{c}_j = c_j + (\Phi_j - \Phi_{j-1})$$



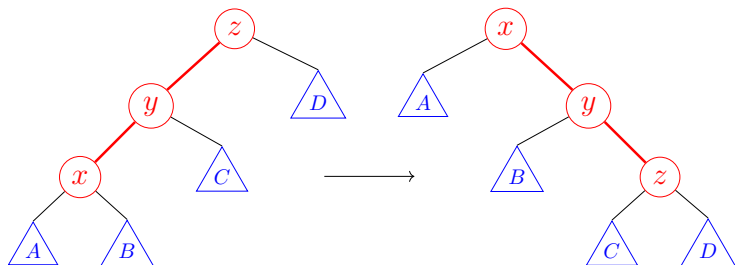
CASE 2: zig-zig

$$\begin{aligned}
 \hat{c}_j &= c_j + (\Phi_j - \Phi_{j-1}) \\
 &= 2 + r_j(x) + r_j(y) + r_j(y) - r_{j-1}(x) - r_{j-1}(y) - r_{j-1}(z)
 \end{aligned}$$



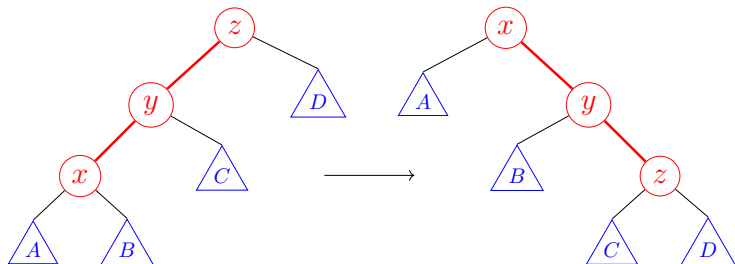
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 \end{aligned}$$



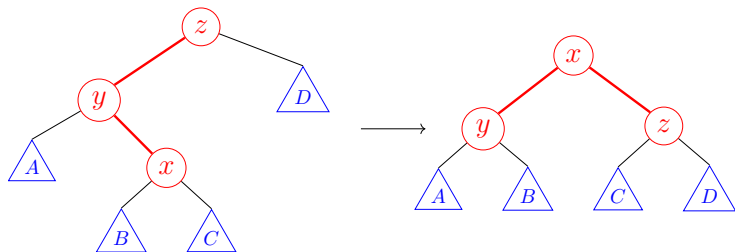
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 &= 2 + r_j(x) + r_j(y) + r_j(y) - r_{j-1}(x) - r_{j-1}(y) - r_{j-1}(z) \\
 &= 2 + r_j(y) + r_j(y) - r_{j-1}(x) - r_{j-1}(y) \\
 &\leq 2 + r_j(x) + r_j(z) - 2r_{j-1}(x)
 \end{aligned}$$



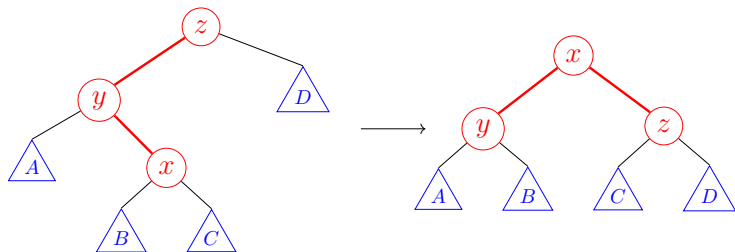
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 &= 2 + r_j(y) + r_j(y) - r_{j-1}(x) - r_{j-1}(y) \\
 &\leq 2 + r_j(x) + r_j(z) - 2r_{j-1}(x) \\
 &\leq 3(r_j(x) - r_{j-1}(x))
 \end{aligned}$$



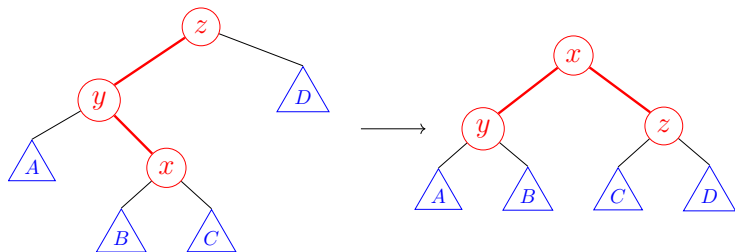
CASE 3: zig-zag

$$\hat{c}_j = c_j + (\Phi_j - \Phi_{j-1})$$



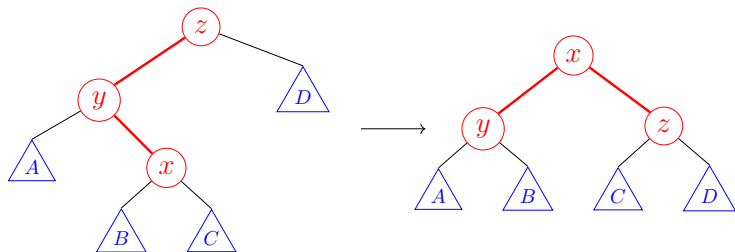
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 &\leq 2 + r_j(y) + r_j(z) - 2r_{j-1}(x)
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 \hat{c}_j &= c_j + (\Phi_j - \Phi_{j-1}) \\
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 &\leq 2 + r_j(y) + r_j(z) - 2r_{j-1}(x) \\
 &\leq 3(r_j(x) - r_{j-1}(x))
 \end{aligned}$$

$$\hat{c}_{\text{ITER}_j} \leq \begin{cases} 0, & \text{CASE 0} \\ 1 + 3(r_j(x) - r_{j-1}(x)), & \text{CASE 1} \\ 3(r_j(x) - r_{j-1}(x)), & \text{CASE 2} \\ 3(r_j(x) - r_{j-1}(x)), & \text{CASE 3} \end{cases}$$

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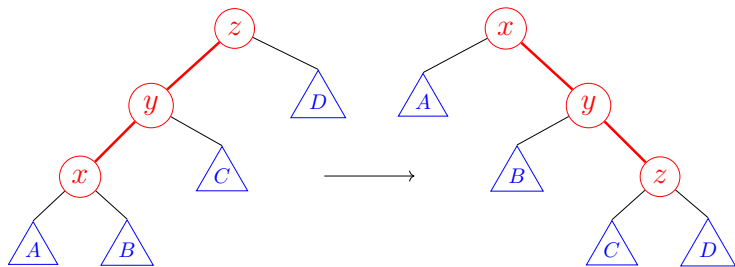
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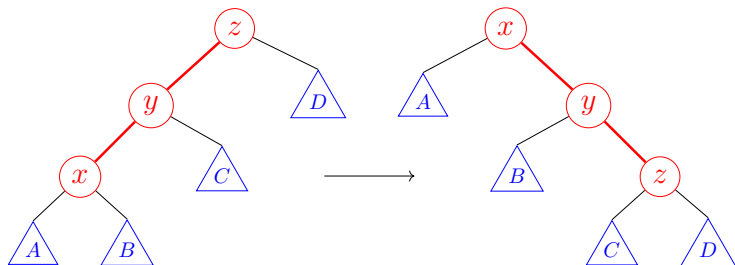
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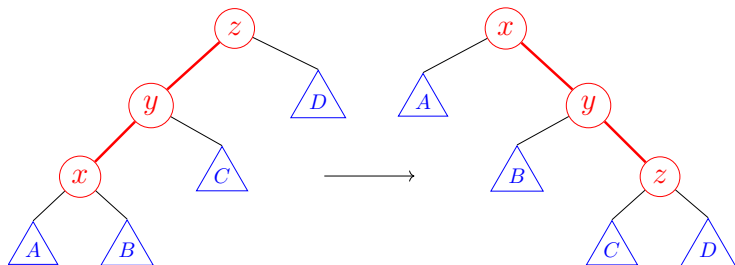
$$\begin{aligned} \hat{c}_{\text{SPLAY}_i} &= \sum_{1 \leq j \leq l} \hat{c}_{\text{ITER}_j} \\ &= \sum_{1 \leq j \leq l} c_{\text{ITER}_j} + (\Phi_{\text{ITER}_j} - \Phi_{\text{ITER}_{j-1}}) \\ &\leq 3(r_{\text{ITER}_l}(x) - r_{\text{ITER}_0}(x)) + 1 \\ &= 3(\log n - r_{\text{ITER}_0}(x)) + 1 \\ &\leq 3 \log n + 1 \\ &= O(\log n) \end{aligned}$$





MTR (Move To Root) heuristic:

Keeping rotate the edge joining x to its parent.



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Keeping rotate the edge joining x to its parent.

Does this work?

$$\Phi = \sum_{x \in T} r(x)$$



$$\Phi = \sum_{x \in T} r(x)$$



$\text{SPLAY}(x)$

SPLAY(x)

SEARCH(x, t)

INSERT(x, t)

DELETE(x, t)

JOIN(t_1, t_2)

SPLIT(x, t)

SPLAY(x)

SEARCH(x, t)

INSERT(x, t)

DELETE(x, t)

JOIN(t_1, t_2)

SPLIT(x, t)

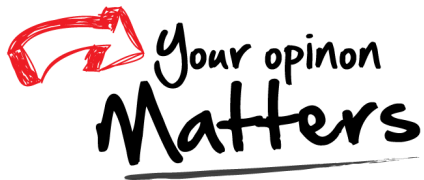
Self-Adjusting Binary Search Trees

DANIEL DOMINIC SLEATOR AND ROBERT ENDRE TARJAN

AT&T Bell Laboratories, Murray Hill, NJ

Abstract. The *splay* tree, a self-adjusting form of binary search tree, is developed and analyzed. The binary search tree is a data structure for representing tables and lists so that accessing, inserting, and deleting items is easy. On an n -node splay tree, all the standard search tree operations have an amortized time bound of $O(\log n)$ per operation, where by “amortized time” is meant the time per operation averaged over a worst-case sequence of operations. Thus splay trees are as efficient as balanced trees when total running time is the measure of interest. In addition, for sufficiently long access sequences, splay trees are as efficient, to within a constant factor, as static optimum search trees. The efficiency of splay trees comes not from an explicit structural constraint, as with balanced trees, but from applying a simple restructuring heuristic, called *splaying*, whenever the tree is accessed. Extensions of splaying give simplified forms of two other data structures: lexicographic or multidimensional search trees and link/cut trees.





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