

**Disadvantage of balanced search trees:**

## Disadvantage of balanced search trees:

- worst case; no advantage for easy inputs

## Disadvantage of balanced search trees:

- worst case; no advantage for easy inputs
- additional memory required

## Disadvantage of balanced search trees:

- worst case; no advantage for easy inputs
- additional memory required
- complicated implementation

# Splay Trees

## Disadvantage of balanced search trees:

- worst case; no advantage for easy inputs
- additional memory required
- complicated implementation

## Splay Trees:

# Splay Trees

## Disadvantage of balanced search trees:

- worst case; no advantage for easy inputs
- additional memory required
- complicated implementation

## Splay Trees:

- + after access, an element is moved to the root;  $\text{splay}(x)$   
repeated accesses are faster

# Splay Trees

## Disadvantage of balanced search trees:

- worst case; no advantage for easy inputs
- additional memory required
- complicated implementation

## Splay Trees:

- + after access, an element is moved to the root;  $\text{splay}(x)$   
repeated accesses are faster
- only amortized guarantee

# Splay Trees

## Disadvantage of balanced search trees:

- worst case; no advantage for easy inputs
- additional memory required
- complicated implementation

## Splay Trees:

- + after access, an element is moved to the root;  $\text{splay}(x)$   
repeated accesses are faster
- only amortized guarantee
- read-operations change the tree



# Splay Trees

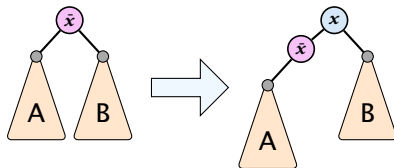
## **find( $x$ )**

- ▶ search for  $x$  according to a search tree
- ▶ let  $\tilde{x}$  be last element on search-path
- ▶  $\text{splay}(\tilde{x})$

# Splay Trees

## insert( $x$ )

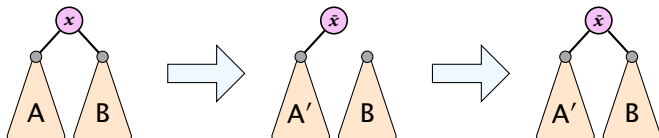
- ▶ search for  $x$ ;  $\bar{x}$  is last visited element during search (successor or predecessor of  $x$ )
- ▶ splay( $\bar{x}$ ) moves  $\bar{x}$  to the root
- ▶ insert  $x$  as new root



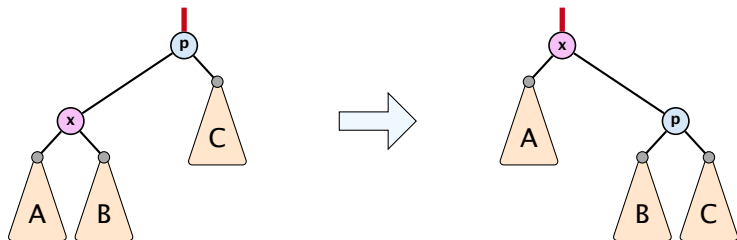
# Splay Trees

## delete( $x$ )

- ▶ search for  $x$ ; splay( $x$ ); remove  $x$
- ▶ search largest element  $\bar{x}$  in  $A$
- ▶ splay( $\bar{x}$ ) (on subtree  $A$ )
- ▶ connect root of  $B$  as right child of  $\bar{x}$



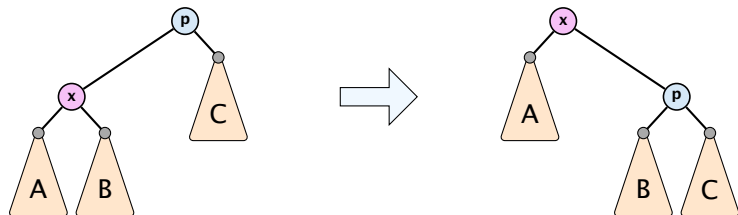
# Move to Root



## How to bring element to root?

- ▶ one (bad) option: `moveToRoot( $x$ )`
- ▶ iteratively do rotation around parent of  $x$  until  $x$  is root
- ▶ if  $x$  is left child do right rotation otw. left rotation

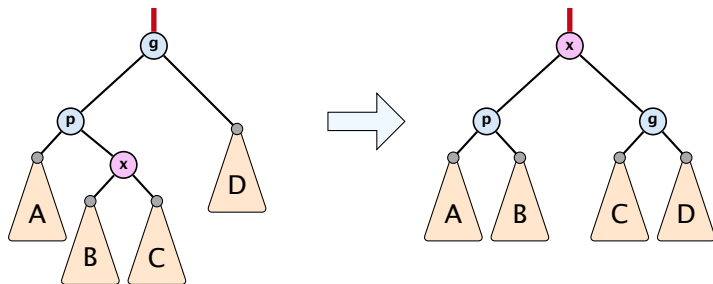
## Splay: Zig Case



**better option  $\text{splay}(x)$ :**

- ▶ zig case: if  $x$  is child of root do left rotation or right rotation around parent

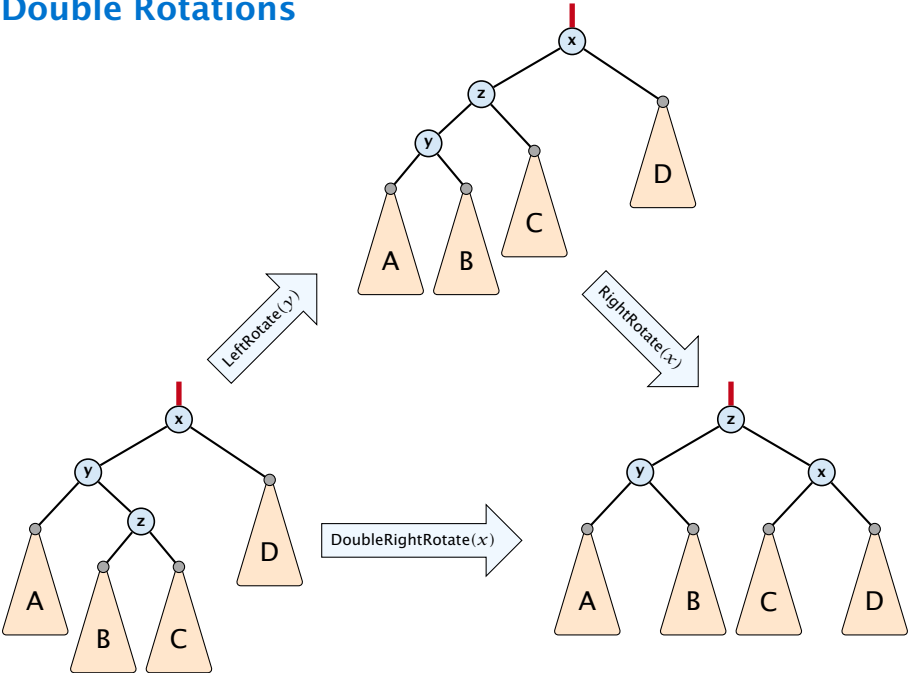
## Splay: Zigzag Case



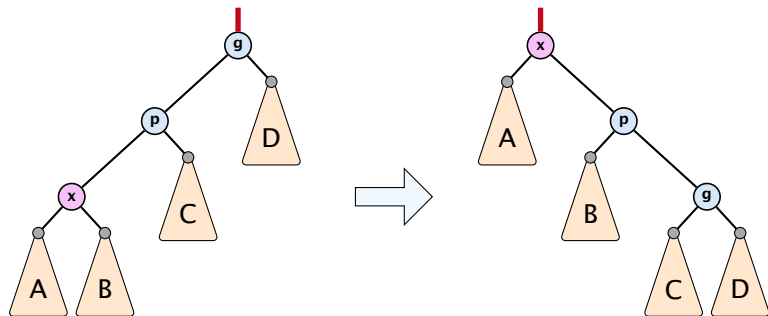
### better option $\text{splay}(x)$ :

- ▶ zigzag case: if  $x$  is right child and parent of  $x$  is left child (or  $x$  left child parent of  $x$  right child)
- ▶ do double right rotation around grand-parent (resp. double left rotation)

# Double Rotations



## Splay: Zigzig Case

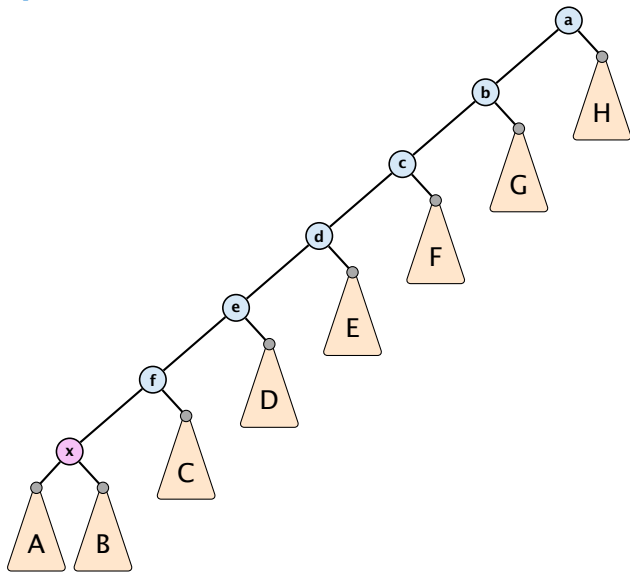


### better option $\text{splay}(x)$ :

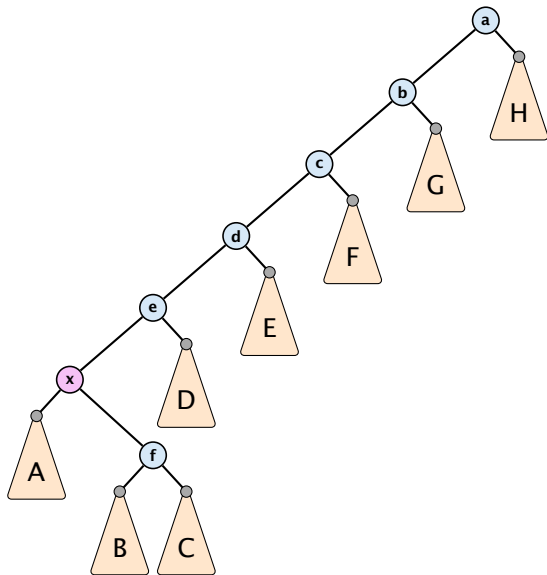
- ▶ zigzig case: if  $x$  is left child and parent of  $x$  is left child (or  $x$  right child, parent of  $x$  right child)
- ▶ do right rotation around grand-parent followed by right rotation around parent (resp. left rotations)



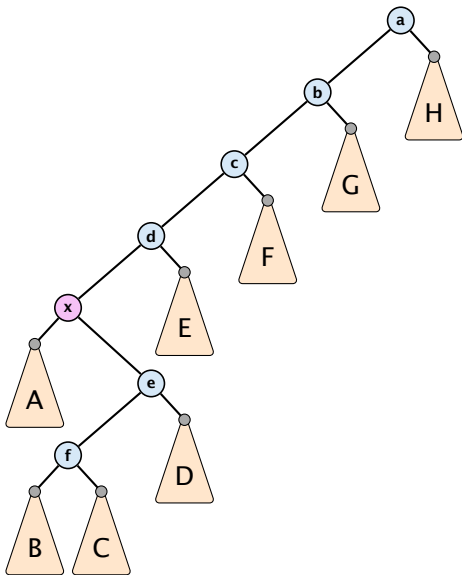
# Splay vs. Move to Root



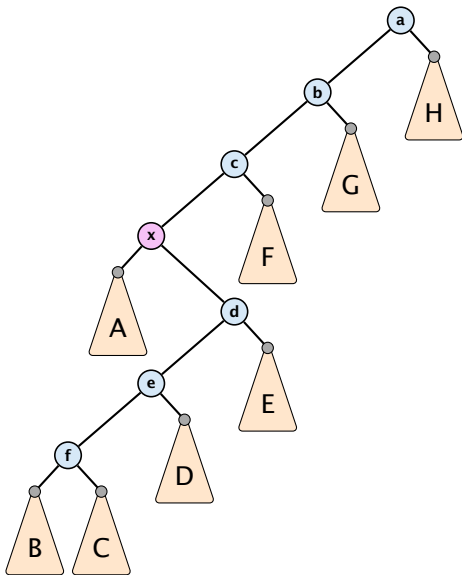
# Splay vs. Move to Root



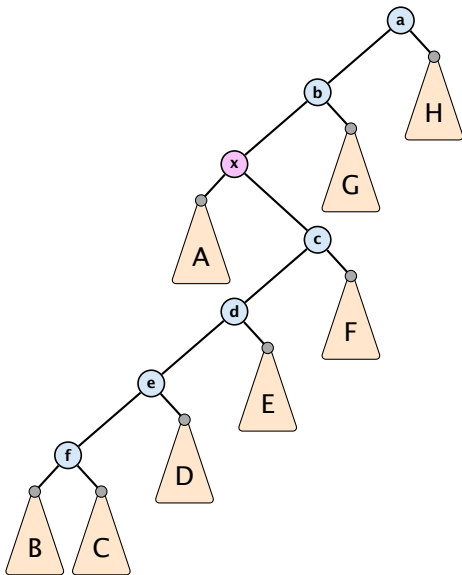
# Splay vs. Move to Root



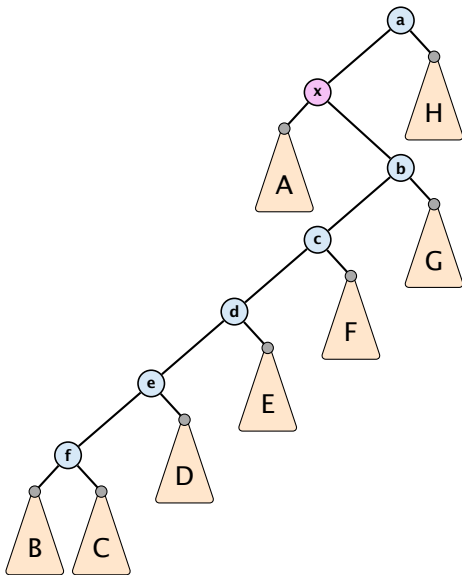
# Splay vs. Move to Root



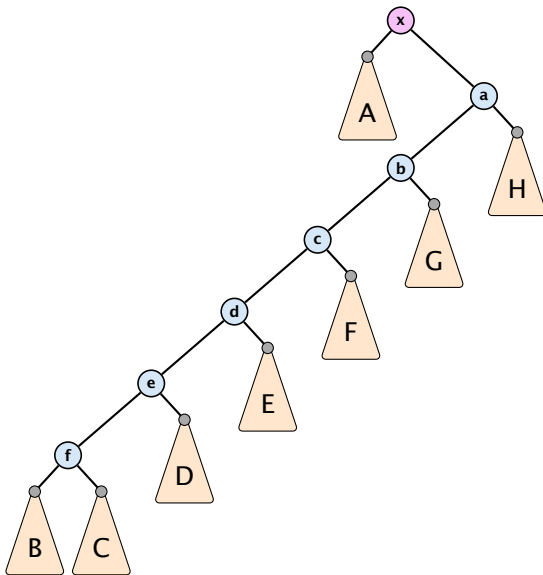
# Splay vs. Move to Root



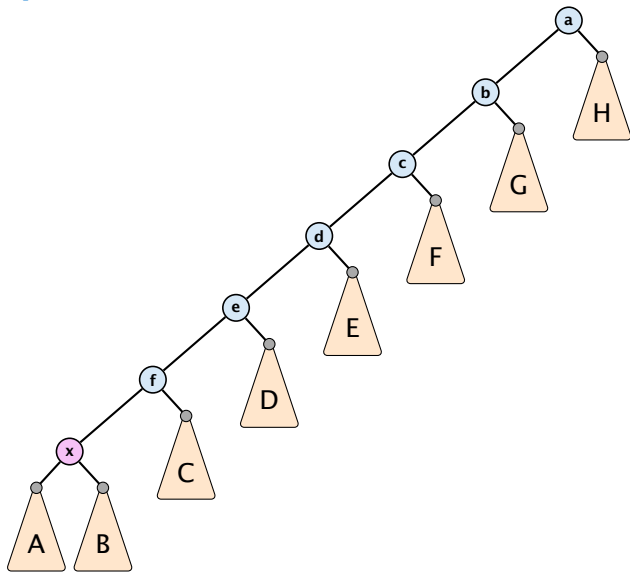
# Splay vs. Move to Root



# Splay vs. Move to Root

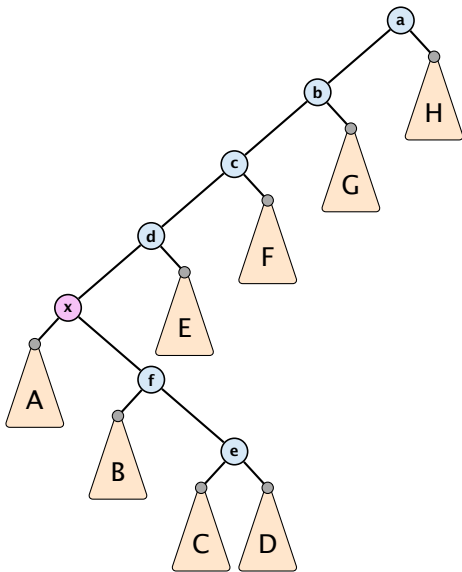


# Splay vs. Move to Root

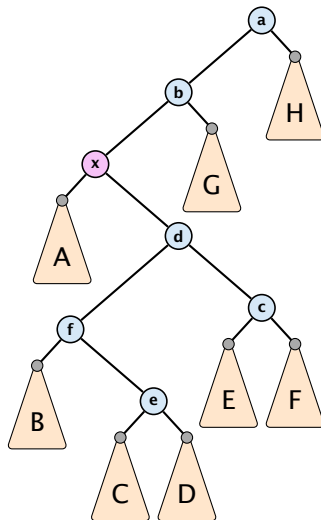




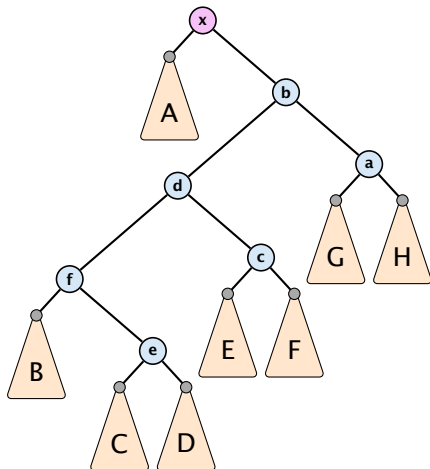
# Splay vs. Move to Root



# Splay vs. Move to Root



# Splay vs. Move to Root



# Static Optimality

Suppose we have a sequence of  $m$  find-operations.  $\text{find}(x)$  appears  $h_x$  times in this sequence.

The cost of a **static** search tree  $T$  is:

$$\text{cost}(T) = m + \sum_x h_x \text{depth}_T(x)$$

The total cost for processing the sequence on a splay-tree is  $\mathcal{O}(\text{cost}(T_{\min}))$ , where  $T_{\min}$  is an **optimal static search tree**.

# Dynamic Optimality

Let  $S$  be a sequence with  $m$  find-operations.

Let  $A$  be a data-structure based on a search tree:

- ▶ the cost for accessing element  $x$  is  $1 + \text{depth}(x)$ ;
- ▶ after accessing  $x$  the tree may be re-arranged through rotations;

## Conjecture:

A splay tree that only contains elements from  $S$  has cost  $\mathcal{O}(\text{cost}(A, S))$ , for processing  $S$ .

## Lemma 9

*Splay Trees have an **amortized** running time of  $\mathcal{O}(\log n)$  for all operations.*

# Amortized Analysis

## Definition 10

A data structure with operations  $\text{op}_1(), \dots, \text{op}_k()$  has amortized running times  $t_1, \dots, t_k$  for these operations if the following holds.

Suppose you are given a sequence of operations (**starting with an empty data-structure**) that operate on at most  $n$  elements, and let  $k_i$  denote the number of occurrences of  $\text{op}_i()$  within this sequence. Then the actual running time must be at most  $\sum_i k_i \cdot t_i(n)$ .

# Potential Method

**Introduce a potential for the data structure.**



# Potential Method

**Introduce a potential for the data structure.**

- ▶  $\Phi(D_i)$  is the potential after the  $i$ -th operation.

# Potential Method

**Introduce a potential for the data structure.**

- ▶  $\Phi(D_i)$  is the potential after the  $i$ -th operation.
- ▶ Amortized cost of the  $i$ -th operation is

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

# Potential Method

**Introduce a potential for the data structure.**

- ▶  $\Phi(D_i)$  is the potential after the  $i$ -th operation.
- ▶ Amortized cost of the  $i$ -th operation is

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

- ▶ Show that  $\Phi(D_i) \geq \Phi(D_0)$ .

# Potential Method

**Introduce a potential for the data structure.**

- ▶  $\Phi(D_i)$  is the potential after the  $i$ -th operation.
- ▶ Amortized cost of the  $i$ -th operation is

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

- ▶ Show that  $\Phi(D_i) \geq \Phi(D_0)$ .

Then

$$\sum_{i=1}^k c_i$$

# Potential Method

**Introduce a potential for the data structure.**

- ▶  $\Phi(D_i)$  is the potential after the  $i$ -th operation.
- ▶ Amortized cost of the  $i$ -th operation is

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

- ▶ Show that  $\Phi(D_i) \geq \Phi(D_0)$ .

Then

$$\sum_{i=1}^k c_i \leq \sum_{i=1}^k c_i + \Phi(D_k) - \Phi(D_0)$$

# Potential Method

**Introduce a potential for the data structure.**

- ▶  $\Phi(D_i)$  is the potential after the  $i$ -th operation.
- ▶ Amortized cost of the  $i$ -th operation is

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

- ▶ Show that  $\Phi(D_i) \geq \Phi(D_0)$ .

Then

$$\sum_{i=1}^k c_i \leq \sum_{i=1}^k c_i + \Phi(D_k) - \Phi(D_0) = \sum_{i=1}^k \hat{c}_i$$

This means the amortized costs can be used to derive a bound on the total cost.

# Example: Stack

## Stack

- ▶  $S.$  push()
- ▶  $S.$  pop()
- ▶  $S.$  multipop( $k$ ): removes  $k$  items from the stack. If the stack currently contains less than  $k$  items it empties the stack.
- ▶ The user has to ensure that pop and multipop do not generate an underflow.

# Example: Stack

## Stack

- ▶  $S.$  push()
- ▶  $S.$  pop()
- ▶  $S.$  multipop( $k$ ): removes  $k$  items from the stack. If the stack currently contains less than  $k$  items it empties the stack.
- ▶ The user has to ensure that pop and multipop do not generate an underflow.

## Actual cost:

- ▶  $S.$  push(): cost 1.
- ▶  $S.$  pop(): cost 1.
- ▶  $S.$  multipop( $k$ ): cost  $\min\{\text{size}, k\} = k$ .



## Example: Stack

Use potential function  $\Phi(S) = \text{number of elements on the stack}$ .

## Example: Stack

Use potential function  $\Phi(S) = \text{number of elements on the stack}$ .

**Amortized cost:**

►  $S.\text{push}()$ : cost

$$\hat{C}_{\text{push}} = C_{\text{push}} + \Delta\Phi = 1 + 1 \leq 2 .$$

## Example: Stack

Use potential function  $\Phi(S)$  = number of elements on the stack.

### Amortized cost:

- ▶  $S.\text{push}()$ : cost

$$\hat{C}_{\text{push}} = C_{\text{push}} + \Delta\Phi = 1 + 1 \leq 2 .$$

- ▶  $S.\text{pop}()$ : cost

$$\hat{C}_{\text{pop}} = C_{\text{pop}} + \Delta\Phi = 1 - 1 \leq 0 .$$

## Example: Stack

Use potential function  $\Phi(S)$  = number of elements on the stack.

### Amortized cost:

- ▶  **$S$ . push():** cost

$$\hat{C}_{\text{push}} = C_{\text{push}} + \Delta\Phi = 1 + 1 \leq 2 .$$

- ▶  **$S$ . pop():** cost

$$\hat{C}_{\text{pop}} = C_{\text{pop}} + \Delta\Phi = 1 - 1 \leq 0 .$$

- ▶  **$S$ . multipop( $k$ ):** cost

$$\hat{C}_{\text{mp}} = C_{\text{mp}} + \Delta\Phi = \min\{\text{size}, k\} - \min\{\text{size}, k\} \leq 0 .$$

## Example: Binary Counter

### **Incrementing a binary counter:**

Consider a computational model where each bit-operation costs one time-unit.

## Example: Binary Counter

### Incrementing a binary counter:

Consider a computational model where each bit-operation costs one time-unit.

Incrementing an  $n$ -bit binary counter may require to examine  $n$ -bits, and maybe change them.

## Example: Binary Counter

### Incrementing a binary counter:

Consider a computational model where each bit-operation costs one time-unit.

Incrementing an  $n$ -bit binary counter may require to examine  $n$ -bits, and maybe change them.

### Actual cost:

- ▶ Changing bit from 0 to 1: cost 1.
- ▶ Changing bit from 1 to 0: cost 1.
- ▶ Increment: cost is  $k + 1$ , where  $k$  is the number of consecutive ones in the least significant bit-positions (e.g, 001101 has  $k = 1$ ).

## Example: Binary Counter



## Example: Binary Counter

Choose potential function  $\Phi(x) = k$ , where  $k$  denotes the number of ones in the binary representation of  $x$ .

**Amortized cost:**

## Example: Binary Counter

Choose potential function  $\Phi(x) = k$ , where  $k$  denotes the number of ones in the binary representation of  $x$ .

**Amortized cost:**

- ▶ Changing bit from 0 to 1:

$$\hat{C}_{0 \rightarrow 1} = C_{0 \rightarrow 1} + \Delta\Phi = 1 + 1 \leq 2 .$$

## Example: Binary Counter

Choose potential function  $\Phi(x) = k$ , where  $k$  denotes the number of ones in the binary representation of  $x$ .

### Amortized cost:

- ▶ Changing bit from 0 to 1:

$$\hat{C}_{0 \rightarrow 1} = C_{0 \rightarrow 1} + \Delta\Phi = 1 + 1 \leq 2 .$$

- ▶ Changing bit from 1 to 0:

$$\hat{C}_{1 \rightarrow 0} = C_{1 \rightarrow 0} + \Delta\Phi = 1 - 1 \leq 0 .$$

## Example: Binary Counter

Choose potential function  $\Phi(x) = k$ , where  $k$  denotes the number of ones in the binary representation of  $x$ .

### Amortized cost:

- ▶ Changing bit from 0 to 1:

$$\hat{C}_{0 \rightarrow 1} = C_{0 \rightarrow 1} + \Delta\Phi = 1 + 1 \leq 2 .$$

- ▶ Changing bit from 1 to 0:

$$\hat{C}_{1 \rightarrow 0} = C_{1 \rightarrow 0} + \Delta\Phi = 1 - 1 \leq 0 .$$

- ▶ **Increment:** Let  $k$  denotes the number of consecutive ones in the least significant bit-positions. An increment involves  $k$   $(1 \rightarrow 0)$ -operations, and one  $(0 \rightarrow 1)$ -operation.

Hence, the amortized cost is  $k\hat{C}_{1 \rightarrow 0} + \hat{C}_{0 \rightarrow 1} \leq 2$ .

# Splay Trees

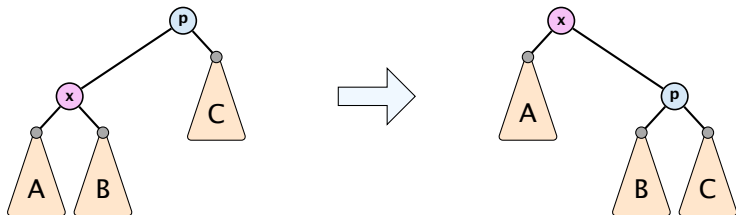
## potential function for splay trees:

- ▶ size  $s(x) = |T_x|$
- ▶ rank  $r(x) = \log_2(s(x))$
- ▶  $\Phi(T) = \sum_{v \in T} r(v)$

amortized cost = real cost + potential change

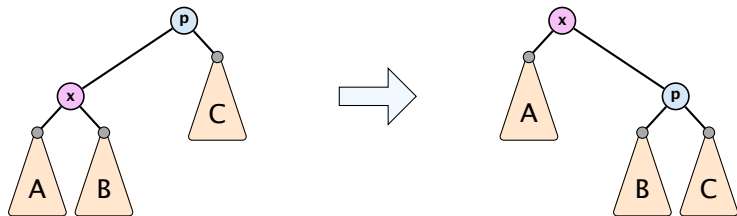
The cost is essentially the cost of the splay-operation, which is 1 plus the number of rotations.

## Splay: Zig Case



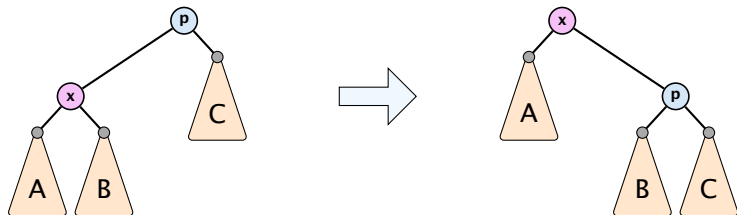
$$\Delta\Phi =$$

## Splay: Zig Case



$$\Delta\Phi = r'(x) + r'(p) - r(x) - r(p)$$

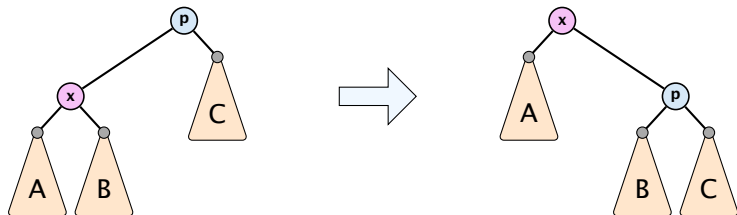
## Splay: Zig Case



$$\begin{aligned}\Delta\Phi &= r'(x) + r'(p) - r(x) - r(p) \\ &= r'(p) - r(x)\end{aligned}$$

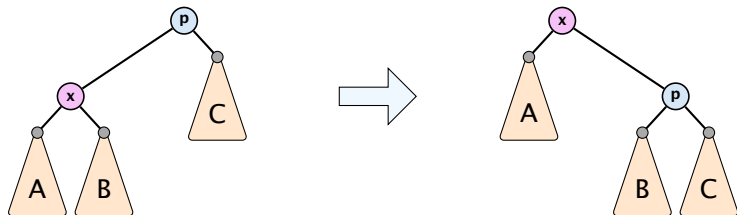


## Splay: Zig Case



$$\begin{aligned}\Delta\Phi &= r'(x) + r'(p) - r(x) - r(p) \\ &= r'(p) - r(x) \\ &\leq r'(x) - r(x)\end{aligned}$$

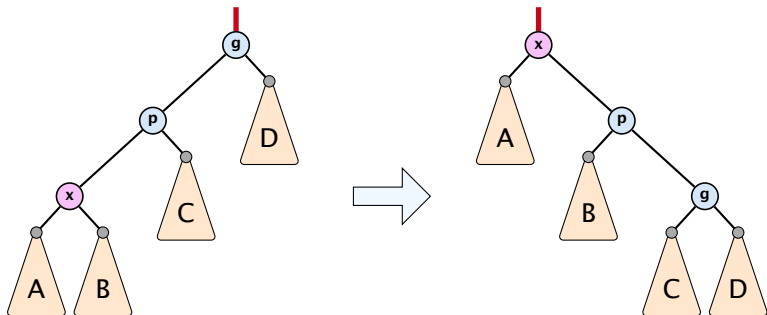
## Splay: Zig Case



$$\begin{aligned}\Delta\Phi &= r'(x) + r'(p) - r(x) - r(p) \\ &= r'(p) - r(x) \\ &\leq r'(x) - r(x)\end{aligned}$$

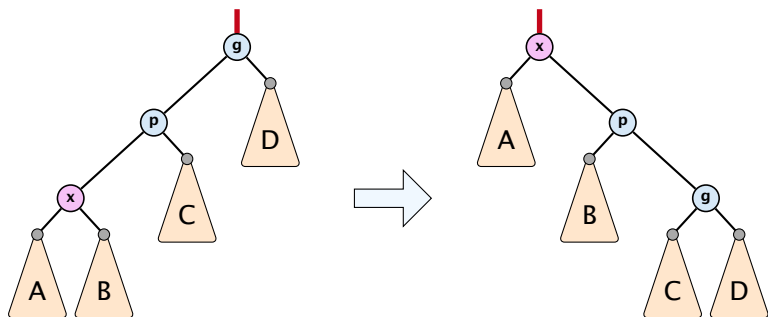
$$\text{cost}_{\text{zig}} \leq 1 + 3(r'(x) - r(x))$$

## Splay: Zigzig Case



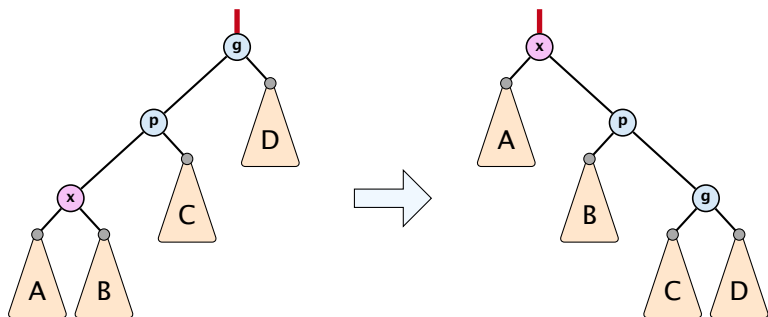
$$\Delta\Phi =$$

## Splay: Zigzig Case



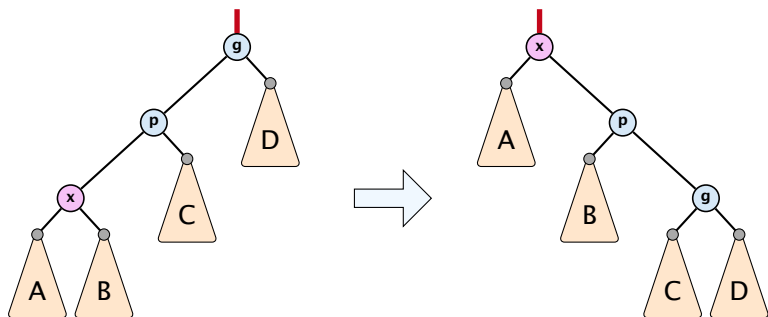
$$\Delta\Phi = r'(x) + r'(p) + r'(g) - r(x) - r(p) - r(g)$$

## Splay: Zigzig Case



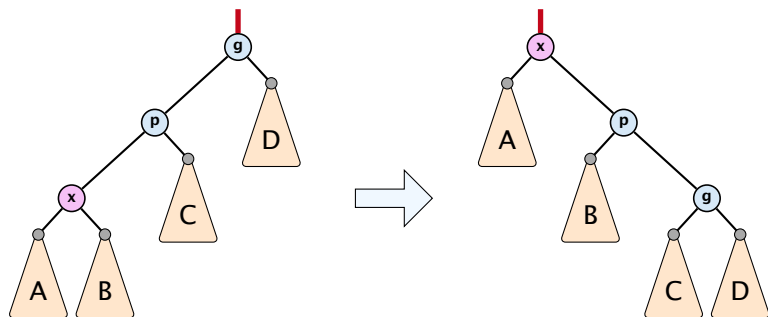
$$\begin{aligned}\Delta\Phi &= r'(x) + r'(p) + r'(g) - r(x) - r(p) - r(g) \\ &= r'(p) + r'(g) - r(x) - r(p)\end{aligned}$$

## Splay: Zigzig Case



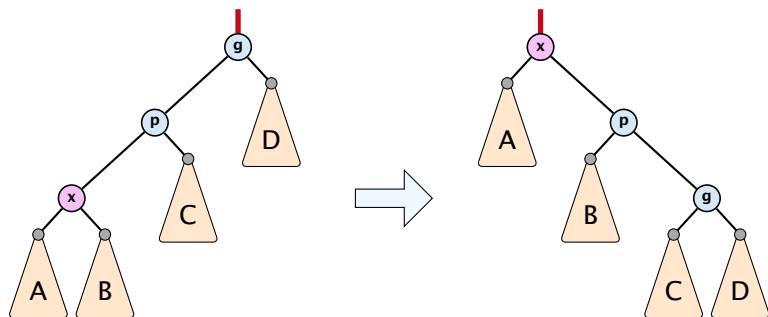
$$\begin{aligned}\Delta\Phi &= r'(x) + r'(p) + r'(g) - r(x) - r(p) - r(g) \\ &= r'(p) + r'(g) - r(x) - r(p) \\ &\leq r'(x) + r'(g) - r(x) - r(x)\end{aligned}$$

## Splay: Zigzig Case



$$\begin{aligned}\Delta\Phi &= r'(x) + r'(p) + r'(g) - r(x) - r(p) - r(g) \\ &= r'(p) + r'(g) - r(x) - r(p) \\ &\leq r'(x) + r'(g) - r(x) - r(x) \\ &= r'(x) + r'(g) + r(x) - 3r'(x) + 3r'(x) - r(x) - 2r(x)\end{aligned}$$

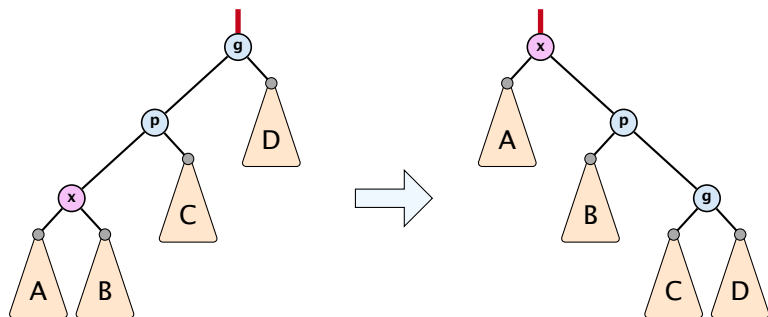
## Splay: Zigzig Case



$$\begin{aligned}\Delta\Phi &= r'(x) + r'(p) + r'(g) - r(x) - r(p) - r(g) \\ &= r'(p) + r'(g) - r(x) - r(p) \\ &\leq r'(x) + r'(g) - r(x) - r(x) \\ &= r'(x) + r'(g) + r(x) - 3r'(x) + 3r'(x) - r(x) - 2r(x) \\ &= -2r'(x) + r'(g) + r(x) + 3(r'(x) - r(x))\end{aligned}$$

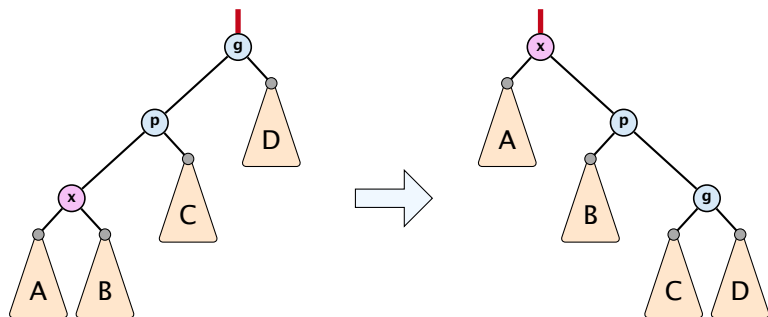


## Splay: Zigzig Case



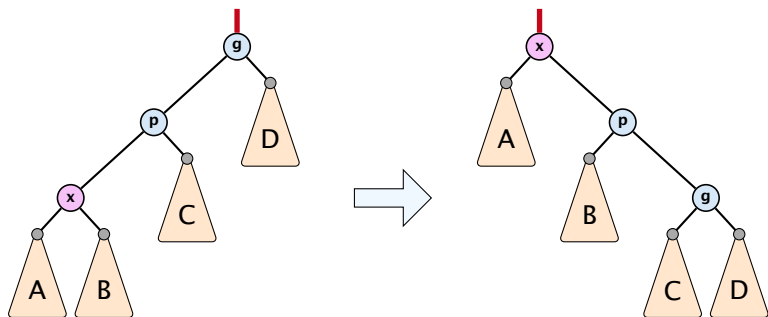
$$\begin{aligned}\Delta\Phi &= r'(x) + r'(p) + r'(g) - r(x) - r(p) - r(g) \\ &= r'(p) + r'(g) - r(x) - r(p) \\ &\leq r'(x) + r'(g) - r(x) - r(x) \\ &= r'(x) + r'(g) + r(x) - 3r'(x) + 3r'(x) - r(x) - 2r(x) \\ &= -2r'(x) + r'(g) + r(x) + 3(r'(x) - r(x)) \\ &\leq -2 + 3(r'(x) - r(x))\end{aligned}$$

## Splay: Zigzig Case



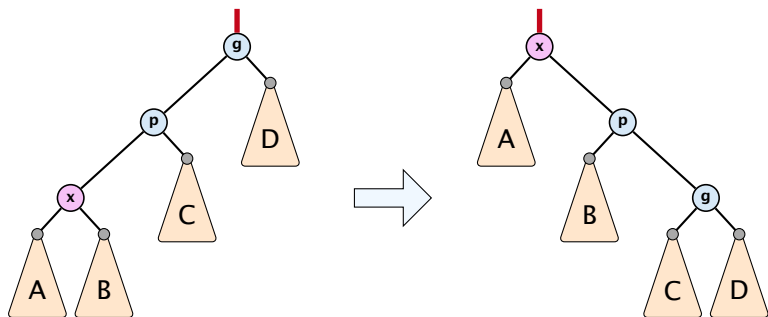
$$\begin{aligned}\Delta\Phi &= r'(x) + r'(p) + r'(g) - r(x) - r(p) - r(g) \\ &= r'(p) + r'(g) - r(x) - r(p) \\ &\leq r'(x) + r'(g) - r(x) - r(x) \\ &= r'(x) + r'(g) + r(x) - 3r'(x) + 3r'(x) - r(x) - 2r(x) \\ &= -2r'(x) + r'(g) + r(x) + 3(r'(x) - r(x)) \\ &\leq -2 + 3(r'(x) - r(x)) \Rightarrow \text{COST}_{\text{zigzig}} \leq 3(r'(x) - r(x))\end{aligned}$$

## Splay: Zigzig Case



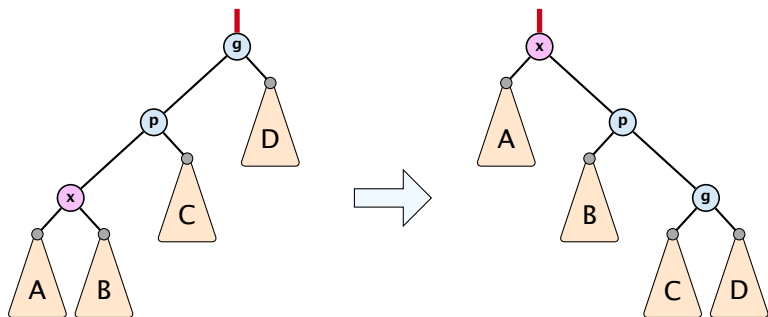
$$\frac{1}{2}(r(x) + r'(g) - 2r'(x))$$

## Splay: Zigzig Case



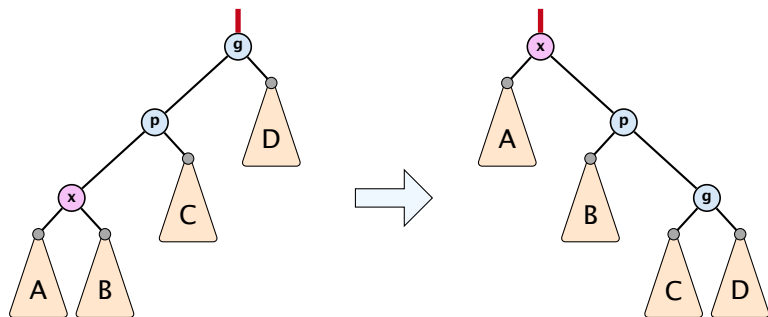
$$\begin{aligned} & \frac{1}{2} (r(x) + r'(g) - 2r'(x)) \\ &= \frac{1}{2} (\log(s(x)) + \log(s'(g)) - 2\log(s'(x))) \end{aligned}$$

## Splay: Zigzig Case



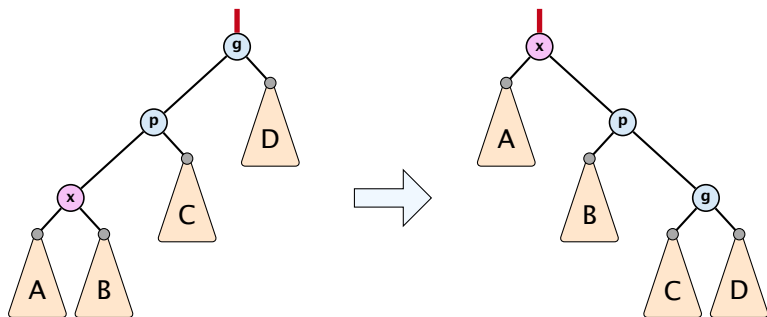
$$\begin{aligned} & \frac{1}{2} (r(x) + r'(g) - 2r'(x)) \\ &= \frac{1}{2} (\log(s(x)) + \log(s'(g)) - 2\log(s'(x))) \\ &= \frac{1}{2} \log\left(\frac{s(x)}{s'(x)}\right) + \frac{1}{2} \log\left(\frac{s'(g)}{s'(x)}\right) \end{aligned}$$

## Splay: Zigzig Case



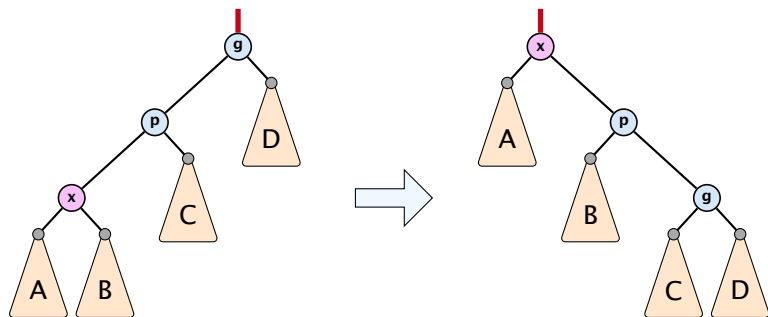
$$\begin{aligned} & \frac{1}{2} (r(x) + r'(g) - 2r'(x)) \\ &= \frac{1}{2} \left( \log(s(x)) + \log(s'(g)) - 2 \log(s'(x)) \right) \\ &= \frac{1}{2} \log \left( \frac{s(x)}{s'(x)} \right) + \frac{1}{2} \log \left( \frac{s'(g)}{s'(x)} \right) \\ &\leq \log \left( \frac{1}{2} \frac{s(x)}{s'(x)} + \frac{1}{2} \frac{s'(g)}{s'(x)} \right) \end{aligned}$$

## Splay: Zigzig Case



$$\begin{aligned} & \frac{1}{2} (r(x) + r'(g) - 2r'(x)) \\ &= \frac{1}{2} \left( \log(s(x)) + \log(s'(g)) - 2 \log(s'(x)) \right) \\ &= \frac{1}{2} \log \left( \frac{s(x)}{s'(x)} \right) + \frac{1}{2} \log \left( \frac{s'(g)}{s'(x)} \right) \\ &\leq \log \left( \frac{1}{2} \frac{s(x)}{s'(x)} + \frac{1}{2} \frac{s'(g)}{s'(x)} \right) \leq \log \left( \frac{1}{2} \right) \end{aligned}$$

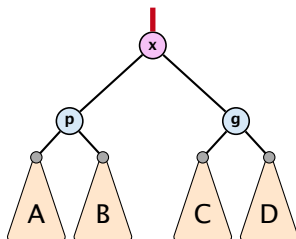
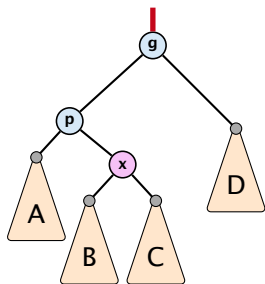
## Splay: Zigzig Case



$$\begin{aligned} & \frac{1}{2} (r(x) + r'(g) - 2r'(x)) \\ &= \frac{1}{2} \left( \log(s(x)) + \log(s'(g)) - 2 \log(s'(x)) \right) \\ &= \frac{1}{2} \log \left( \frac{s(x)}{s'(x)} \right) + \frac{1}{2} \log \left( \frac{s'(g)}{s'(x)} \right) \\ &\leq \log \left( \frac{1}{2} \frac{s(x)}{s'(x)} + \frac{1}{2} \frac{s'(g)}{s'(x)} \right) \leq \log \left( \frac{1}{2} \right) = -1 \end{aligned}$$

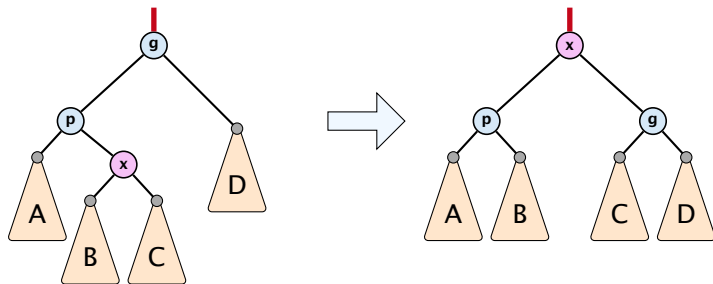


## Splay: Zigzag Case



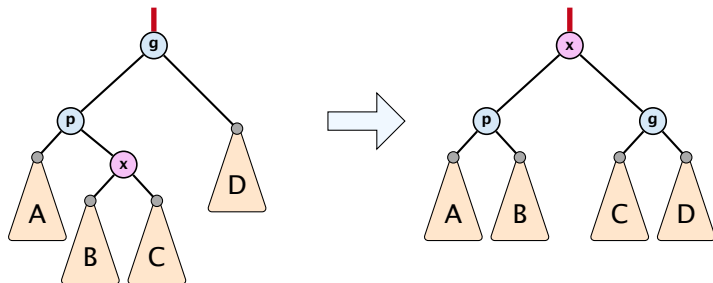
$\Delta\Phi =$

## Splay: Zigzag Case



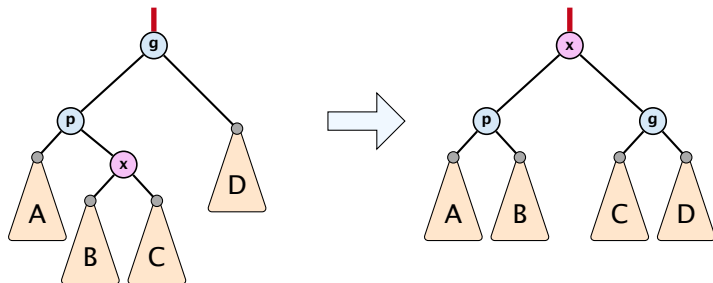
$$\Delta\Phi = r'(x) + r'(p) + r'(g) - r(x) - r(p) - r(g)$$

## Splay: Zigzag Case



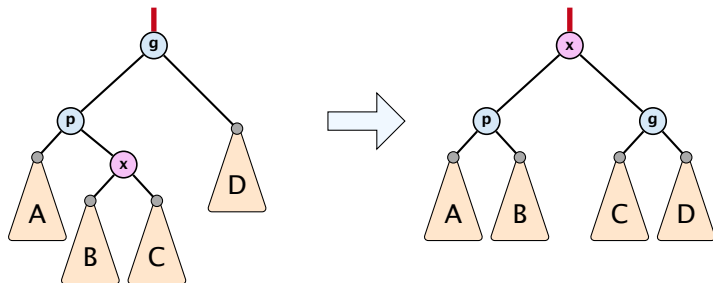
$$\begin{aligned}\Delta\Phi &= r'(x) + r'(p) + r'(g) - r(x) - r(p) - r(g) \\ &= r'(p) + r'(g) - r(x) - r(p)\end{aligned}$$

## Splay: Zigzag Case



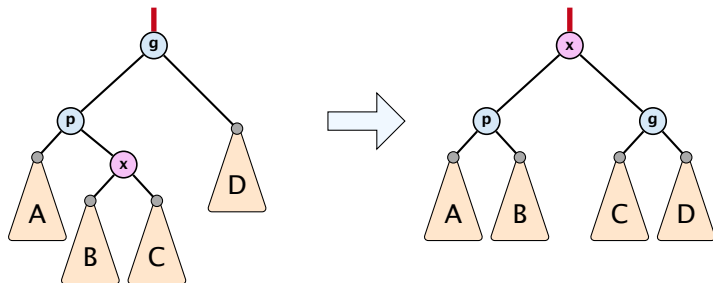
$$\begin{aligned}\Delta\Phi &= r'(x) + r'(p) + r'(g) - r(x) - r(p) - r(g) \\ &= r'(p) + r'(g) - r(x) - r(p) \\ &\leq r'(p) + r'(g) - r(x) - r(x)\end{aligned}$$

## Splay: Zigzag Case



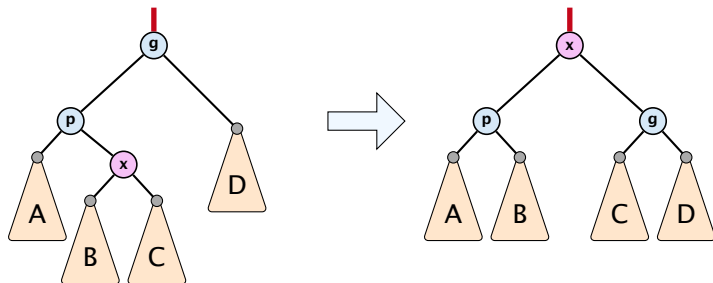
$$\begin{aligned}\Delta\Phi &= r'(x) + r'(p) + r'(g) - r(x) - r(p) - r(g) \\ &= r'(p) + r'(g) - r(x) - r(p) \\ &\leq r'(p) + r'(g) - r(x) - r(x) \\ &= r'(p) + r'(g) - 2r'(x) + 2r'(x) - 2r(x)\end{aligned}$$

## Splay: Zigzag Case



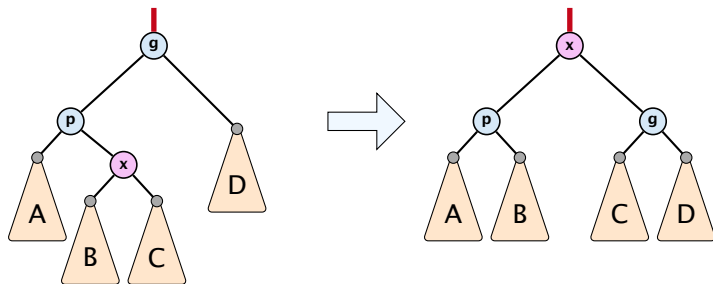
$$\begin{aligned}\Delta\Phi &= r'(x) + r'(p) + r'(g) - r(x) - r(p) - r(g) \\ &= r'(p) + r'(g) - r(x) - r(p) \\ &\leq r'(p) + r'(g) - r(x) - r(x) \\ &= r'(p) + r'(g) - 2r'(x) + 2r'(x) - 2r(x) \\ &\leq -2 + 2(r'(x) - r(x))\end{aligned}$$

## Splay: Zigzag Case



$$\begin{aligned}\Delta\Phi &= r'(x) + r'(p) + r'(g) - r(x) - r(p) - r(g) \\ &= r'(p) + r'(g) - r(x) - r(p) \\ &\leq r'(p) + r'(g) - r(x) - r(x) \\ &= r'(p) + r'(g) - 2r'(x) + 2r'(x) - 2r(x) \\ &\leq -2 + 2(r'(x) - r(x)) \Rightarrow \text{COST}_{\text{zigzag}} \leq 3(r'(x) - r(x))\end{aligned}$$

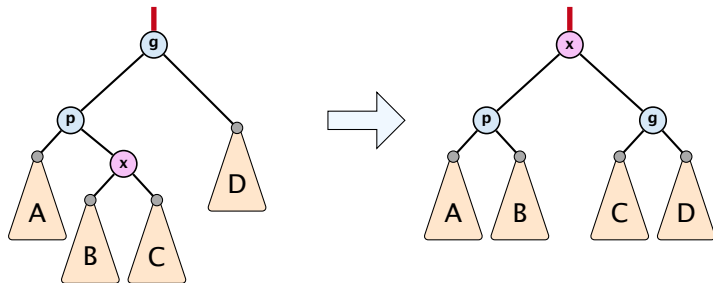
## Splay: Zigzag Case



$$\frac{1}{2}(r'(p) + r'(g) - 2r'(x))$$

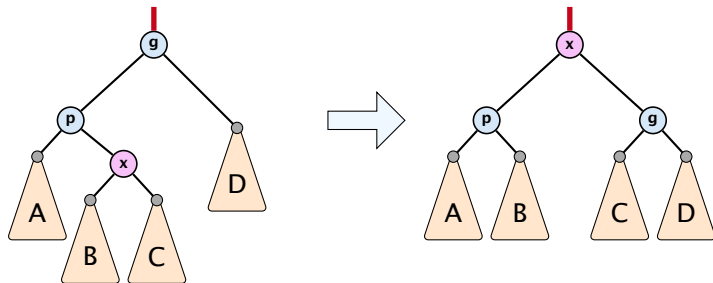


## Splay: Zigzag Case



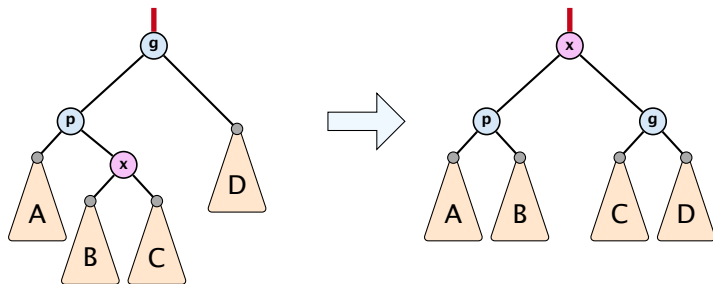
$$\begin{aligned} & \frac{1}{2} (r'(p) + r'(g) - 2r'(x)) \\ &= \frac{1}{2} (\log(s'(p)) + \log(s'(g)) - 2\log(s'(x))) \end{aligned}$$

## Splay: Zigzag Case



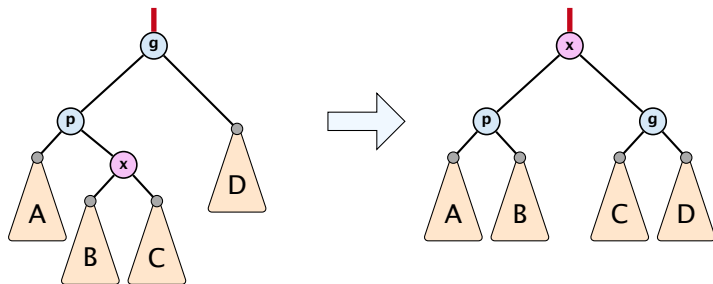
$$\begin{aligned} & \frac{1}{2} (r'(p) + r'(g) - 2r'(x)) \\ &= \frac{1}{2} (\log(s'(p)) + \log(s'(g)) - 2\log(s'(x))) \\ &\leq \log\left(\frac{1}{2} \frac{s'(p)}{s'(x)} + \frac{1}{2} \frac{s'(g)}{s'(x)}\right) \end{aligned}$$

## Splay: Zigzag Case



$$\begin{aligned} & \frac{1}{2} (r'(p) + r'(g) - 2r'(x)) \\ &= \frac{1}{2} (\log(s'(p)) + \log(s'(g)) - 2\log(s'(x))) \\ &\leq \log\left(\frac{1}{2} \frac{s'(p)}{s'(x)} + \frac{1}{2} \frac{s'(g)}{s'(x)}\right) \leq \log\left(\frac{1}{2}\right) \end{aligned}$$

## Splay: Zigzag Case



$$\begin{aligned} & \frac{1}{2} (r'(p) + r'(g) - 2r'(x)) \\ &= \frac{1}{2} (\log(s'(p)) + \log(s'(g)) - 2\log(s'(x))) \\ &\leq \log\left(\frac{1}{2} \frac{s'(p)}{s'(x)} + \frac{1}{2} \frac{s'(g)}{s'(x)}\right) \leq \log\left(\frac{1}{2}\right) = -1 \end{aligned}$$

Amortized cost of the whole splay operation:

$$\begin{aligned} &\leq 1 + 1 + \sum_{\text{steps } t} 3(r_t(x) - r_{t-1}(x)) \\ &= 2 + 3(r(\text{root}) - r_0(x)) \\ &\leq \mathcal{O}(\log n) \end{aligned}$$