

# Amortized Analysis

# Outline for Today

- **Euler Tour Trees**
  - A quick bug fix from last time.
- **Cartesian Trees Revisited**
  - Why could we construct them in time  $O(n)$ ?
- **Amortized Analysis**
  - Analyzing data structures over the long term.
- **2-3-4 Trees**
  - A better analysis of 2-3-4 tree insertions and deletions.

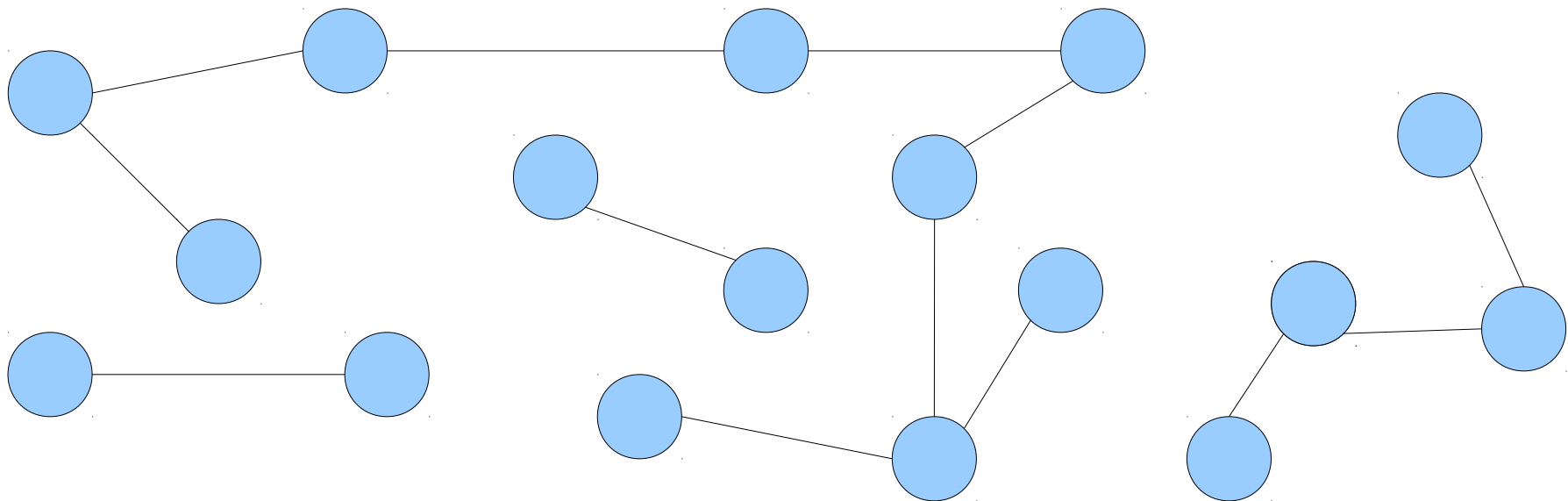
Review from Last Time

# Dynamic Connectivity in Forests

- Consider the following special-case of the dynamic connectivity problem:

Maintain an undirected **forest**  $G$  so that edges may be inserted and deleted and connectivity queries may be answered efficiently.

- Each deleted edge splits a tree in two; each added edge joins two trees and never closes a cycle.

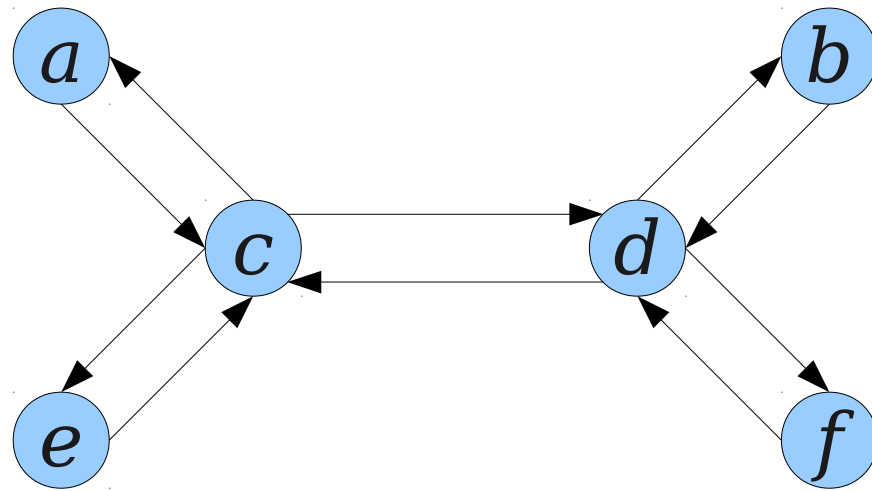


# Dynamic Connectivity in Forests

- **Goal:** Support these three operations:
  - *link*( $u, v$ ): Add in edge  $\{u, v\}$ . The assumption is that  $u$  and  $v$  are in separate trees.
  - *cut*( $u, v$ ): Cut the edge  $\{u, v\}$ . The assumption is that the edge exists in the tree.
  - *is-connected*( $u, v$ ): Return whether  $u$  and  $v$  are connected.
- The data structure we'll develop can perform these operations time  **$O(\log n)$**  each.

# Euler Tours on Trees

- In general, trees do not have Euler tours.



*a c d b d f d c e c a*

- **Technique:** replace each edge  $\{u, v\}$  with two edges  $(u, v)$  and  $(v, u)$ .
- Resulting graph has an Euler tour.

A Correction from Last Time

# The Bug

- The previous representation of Euler tour trees required us to store pointers to the first and last instance of each node in the tours.
- This can't be updated in time  $O(1)$  after rotating a tour, so the operations have the wrong time bounds.
- We need to update our approach so that this is no longer necessary.

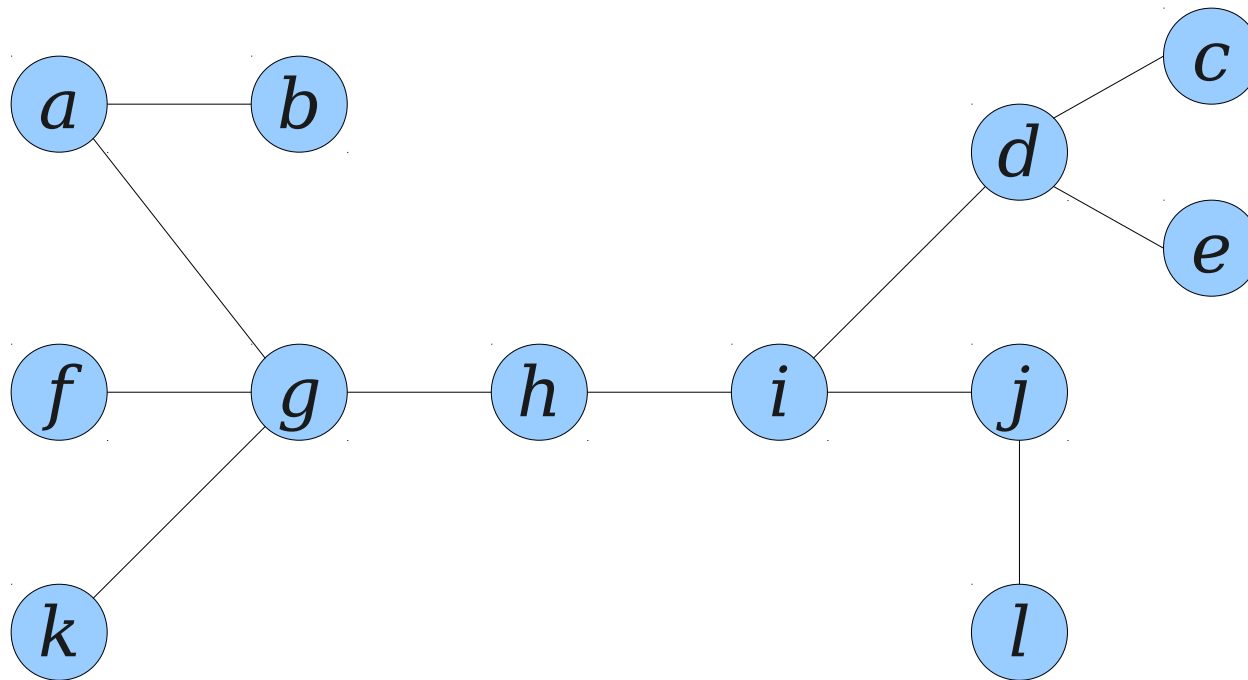


# Rerooting a Tour

- The subtrees defined by ranges in Euler tours on trees depend on the root.
- In some cases, we will need to change the root of the tree.

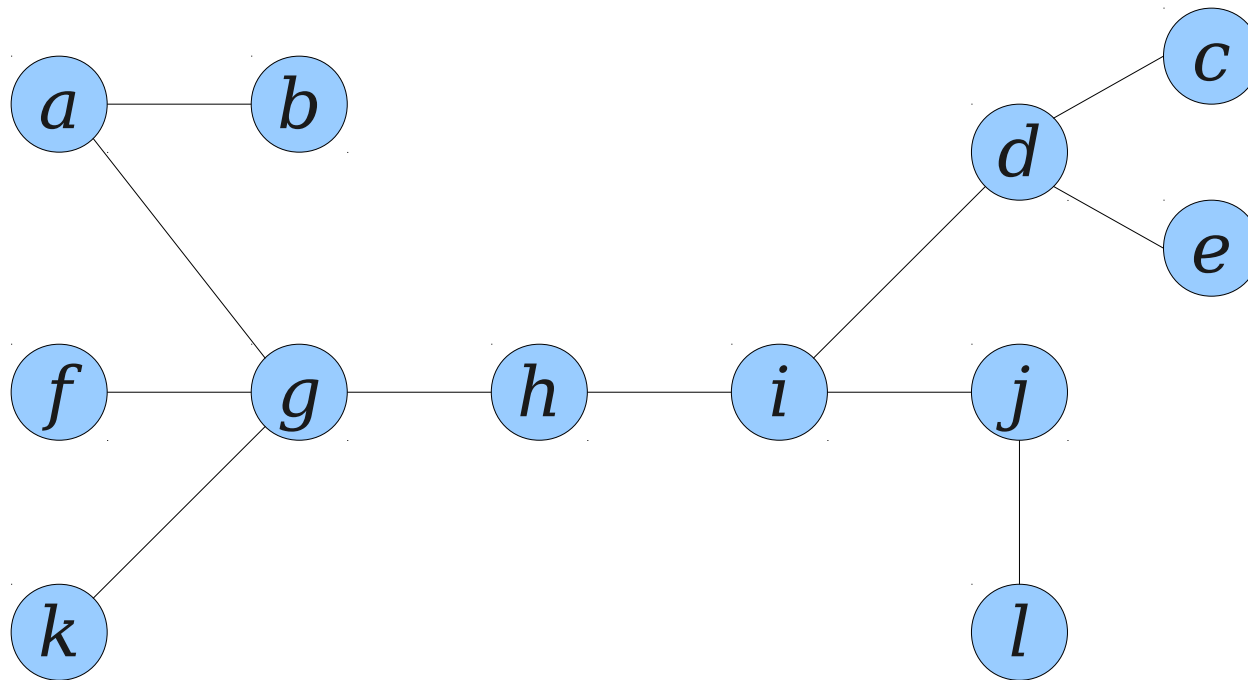
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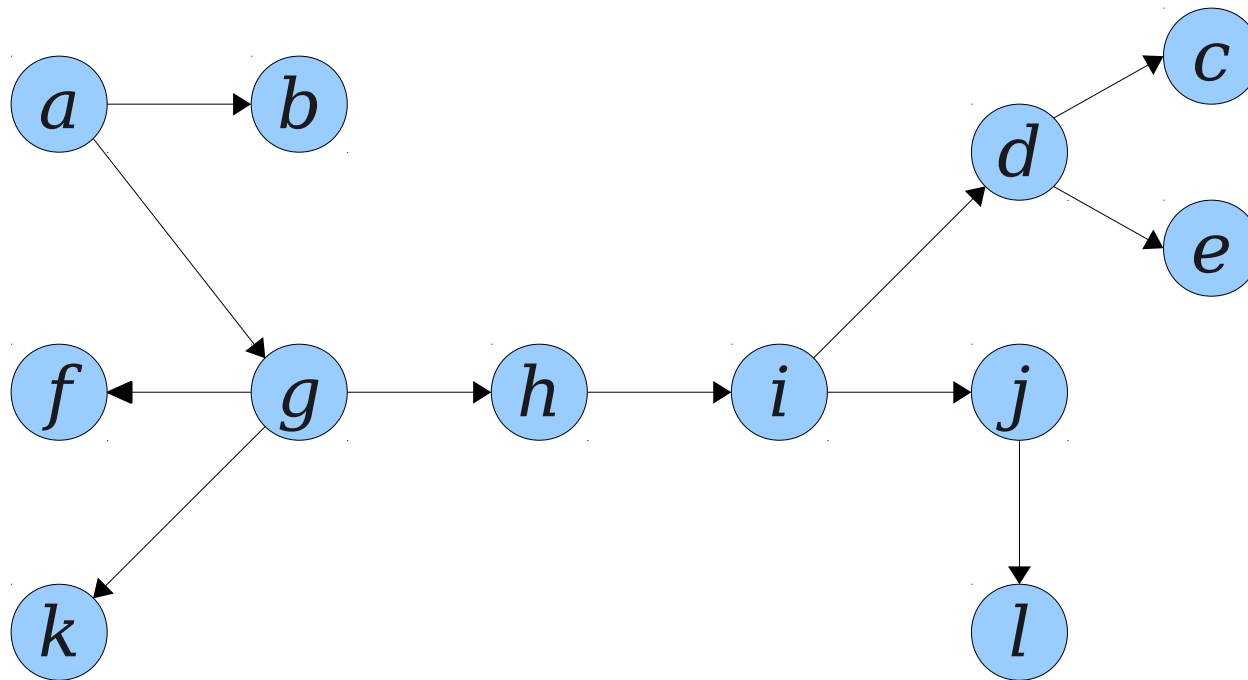
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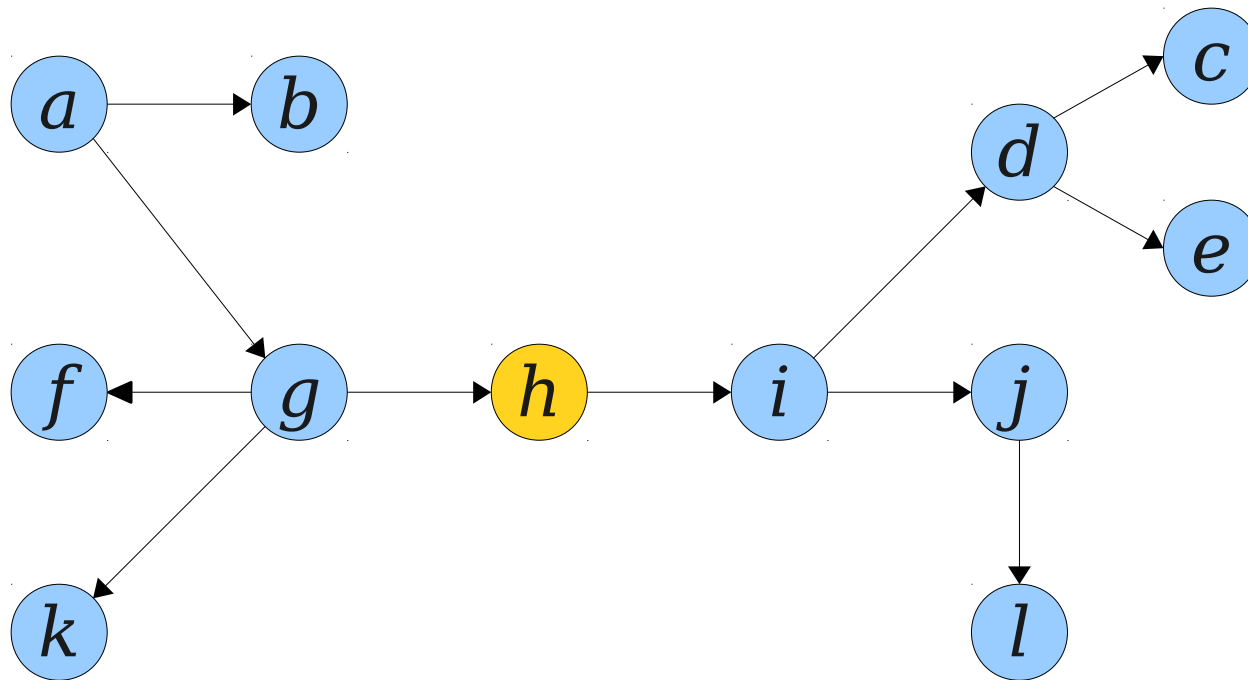
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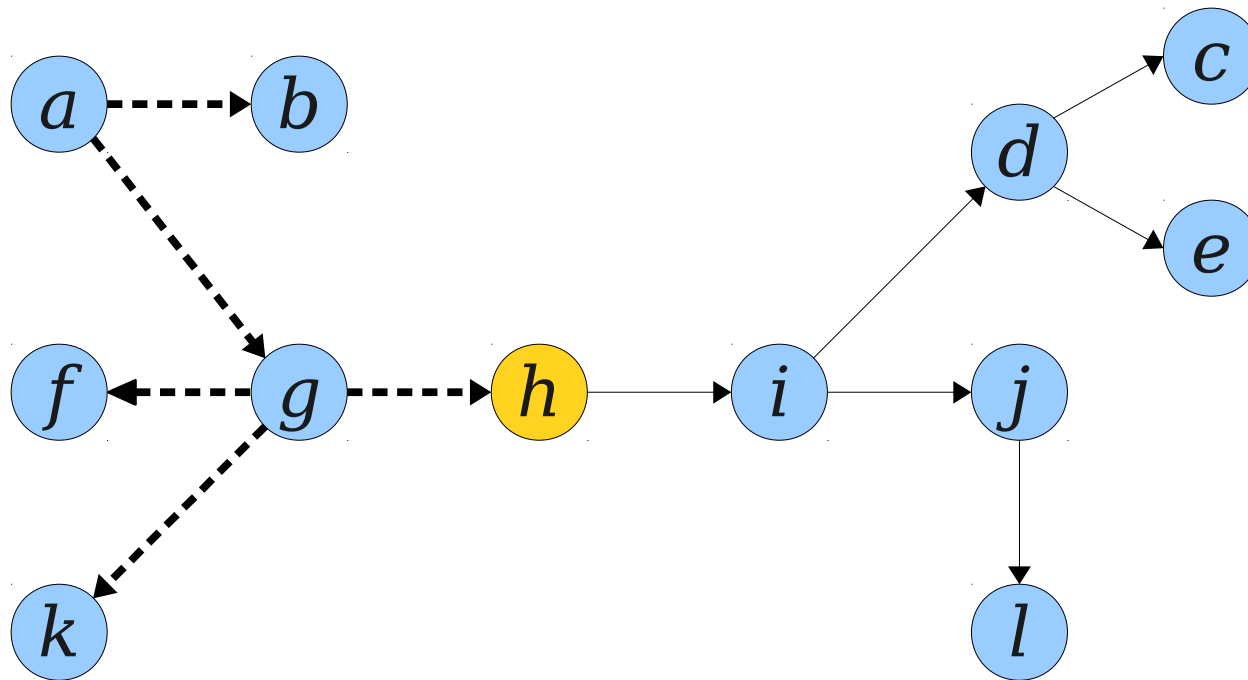
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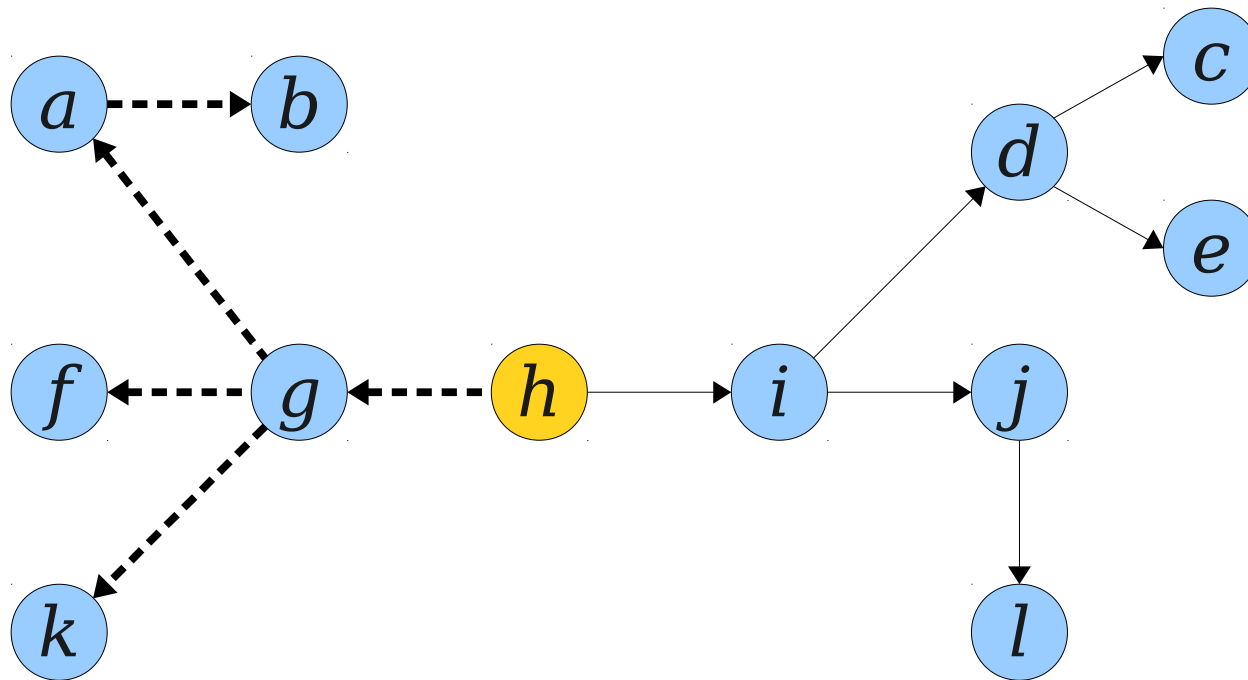
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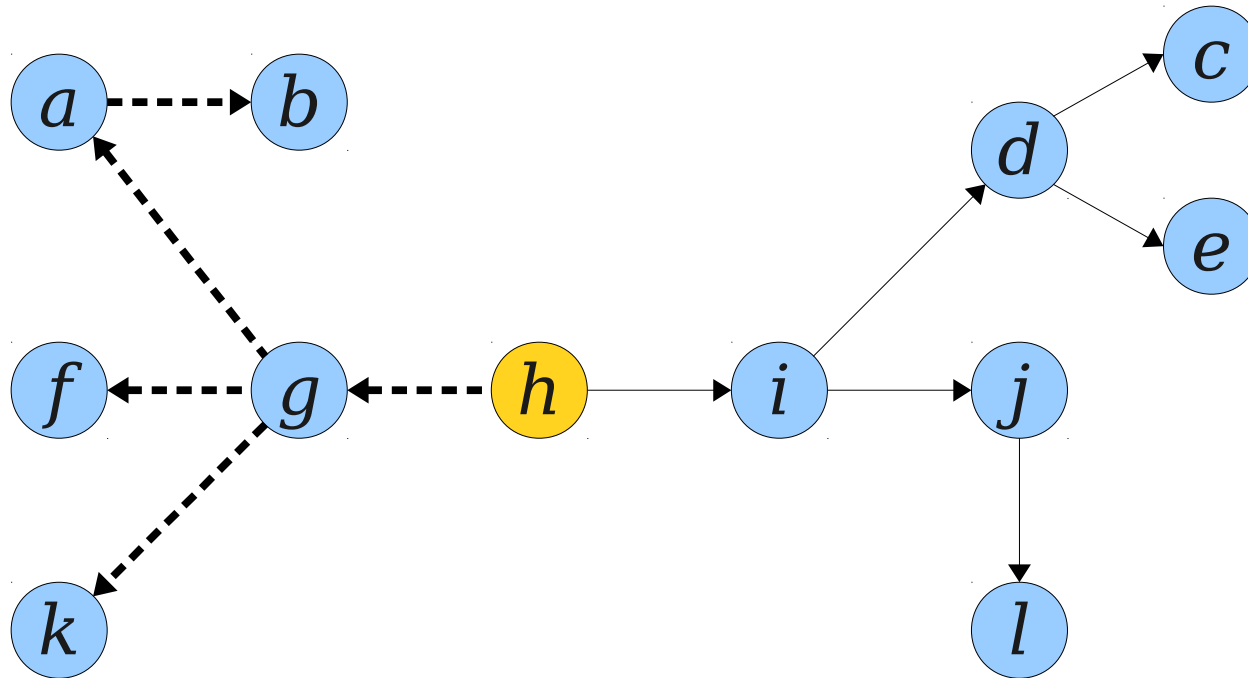
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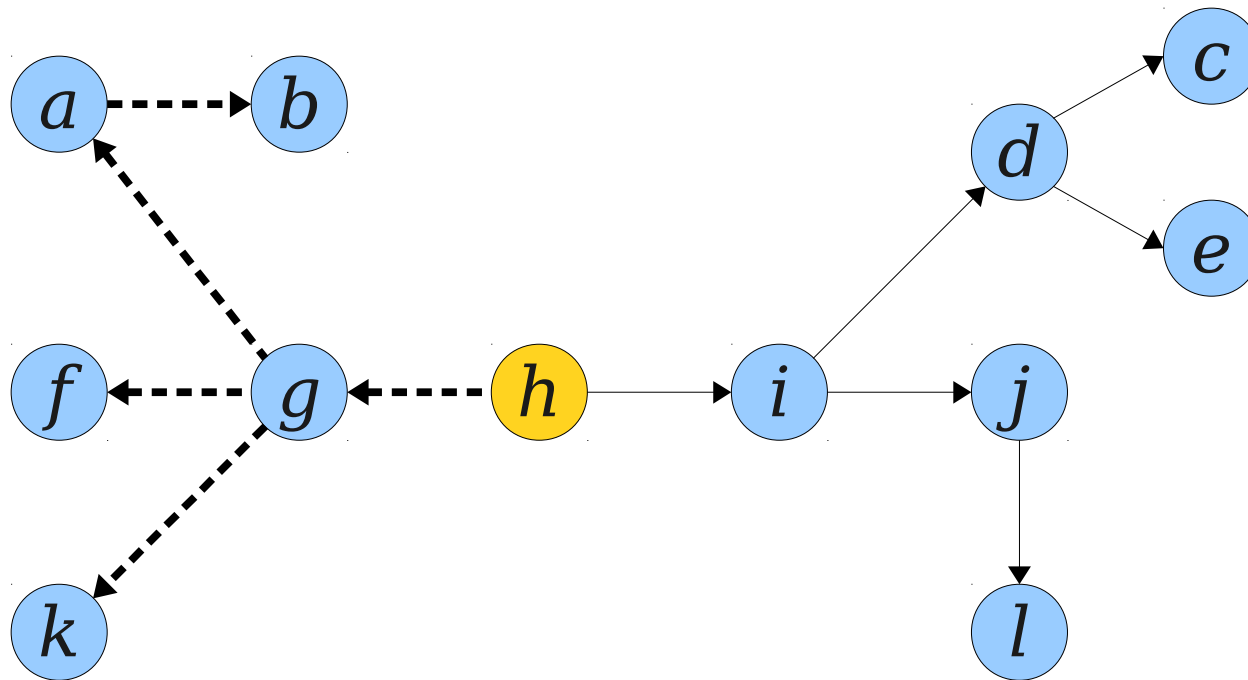


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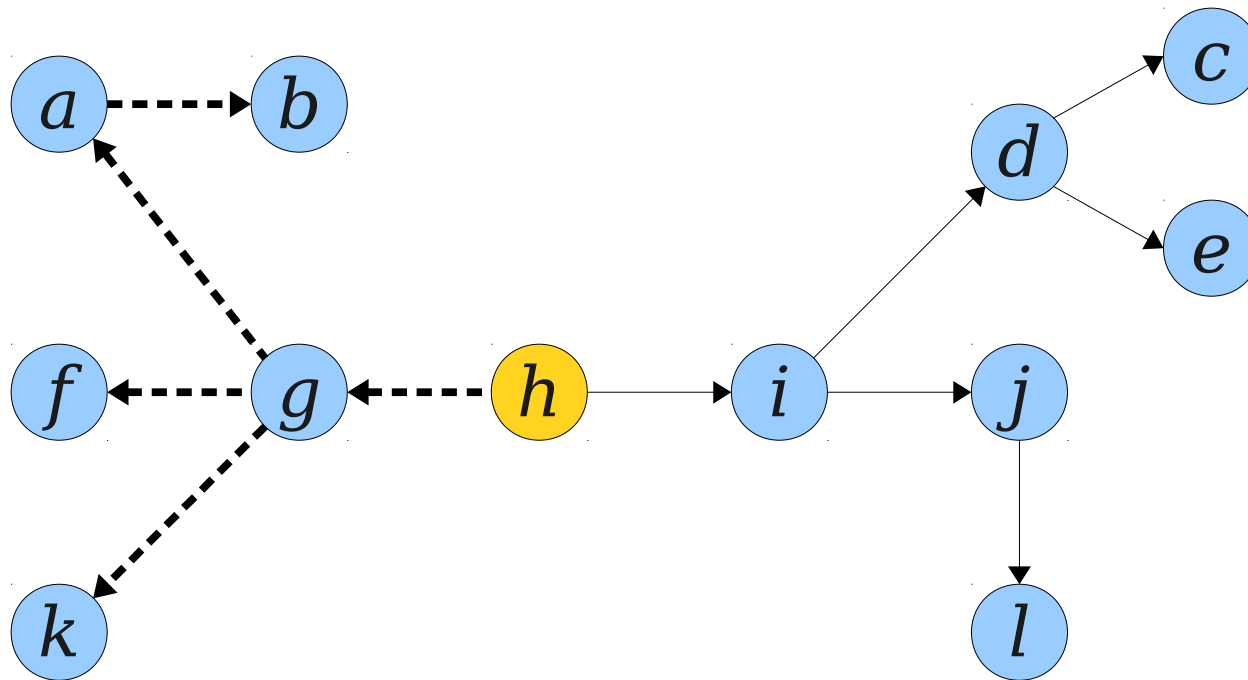
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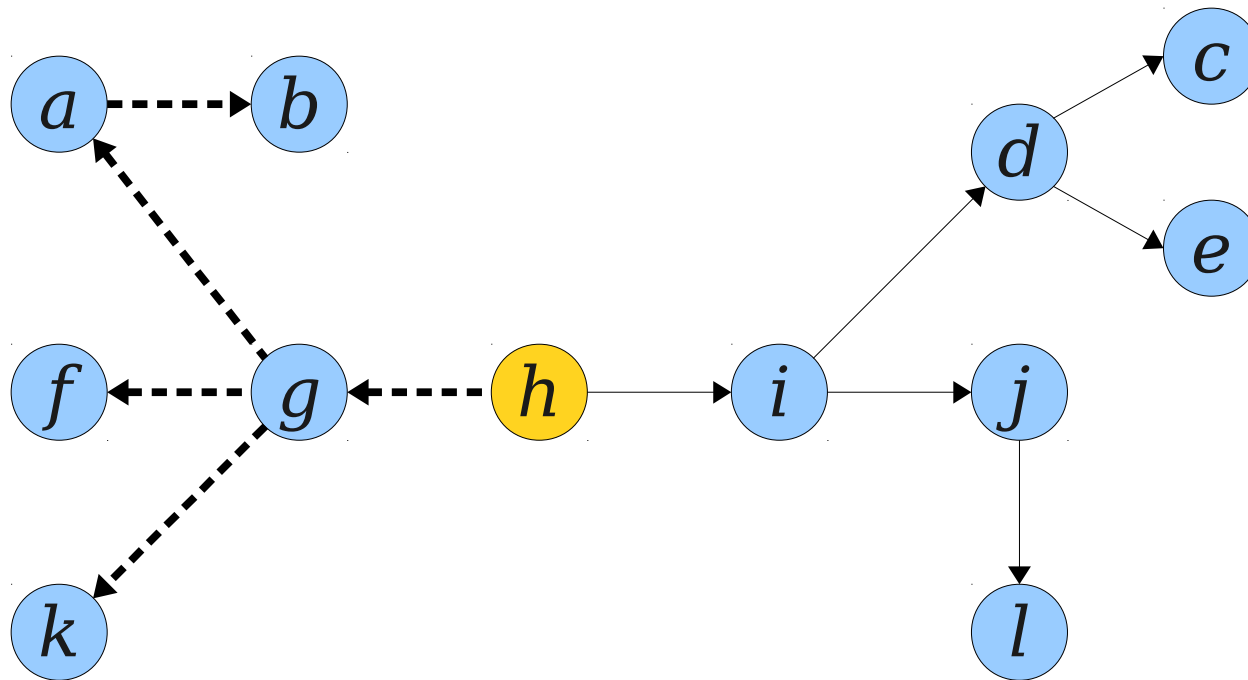
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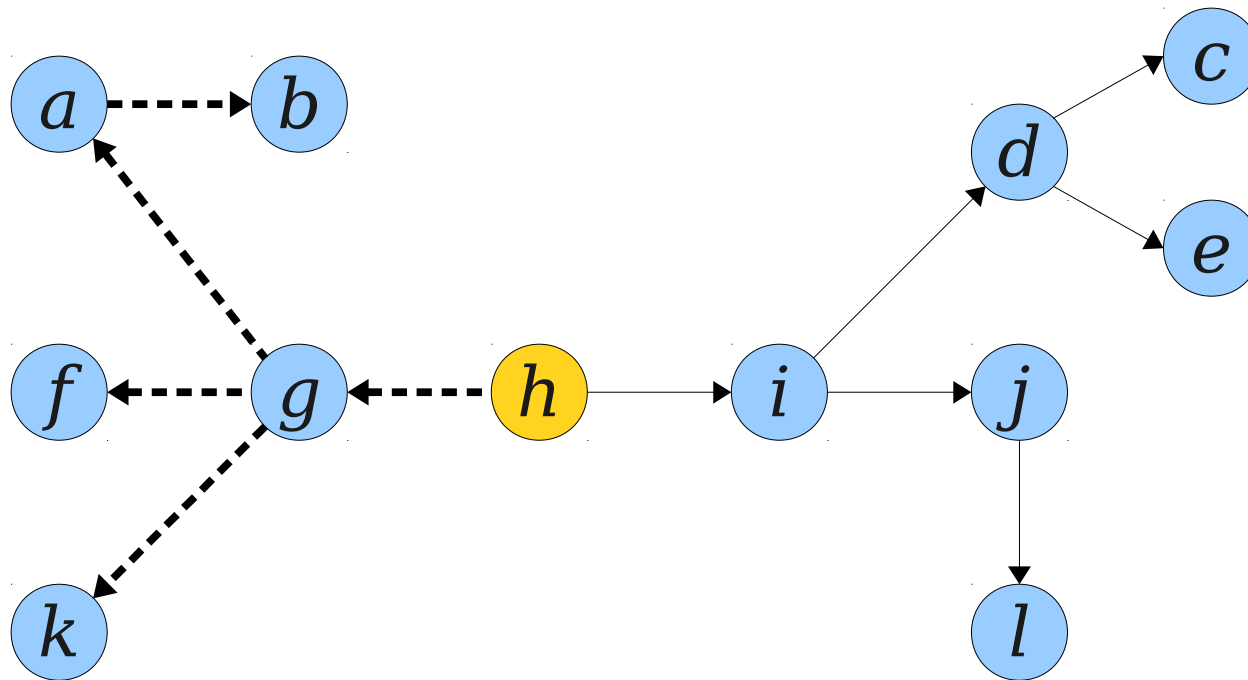
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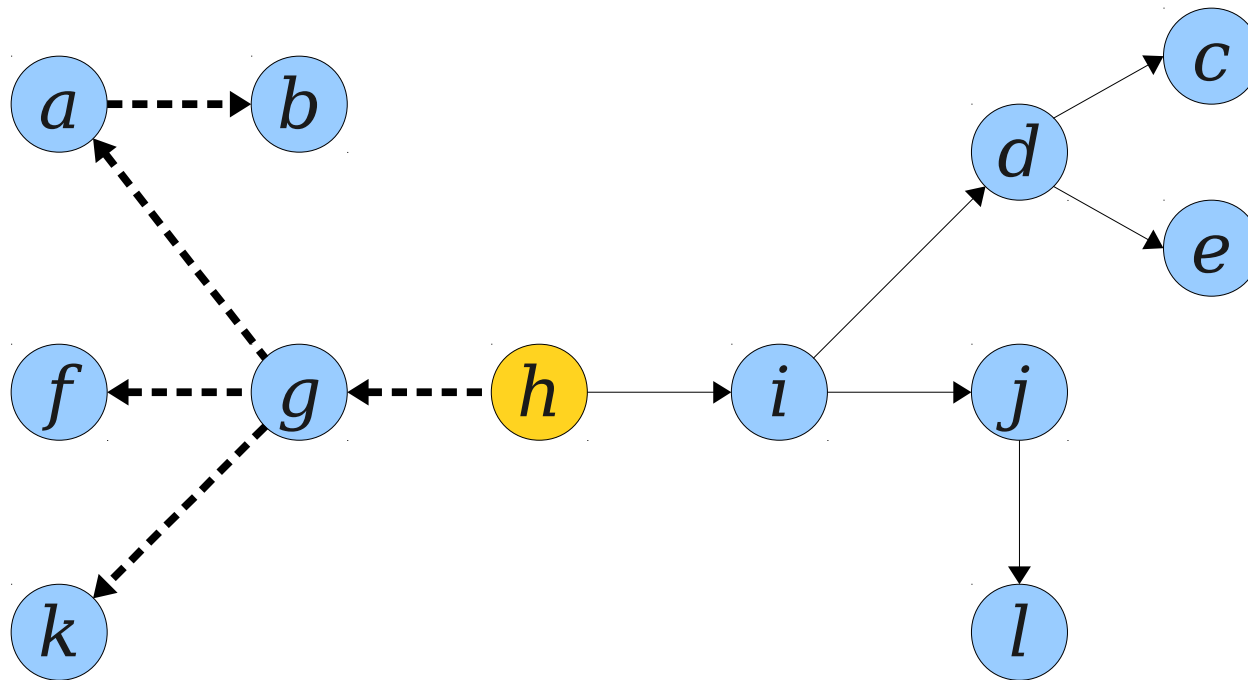
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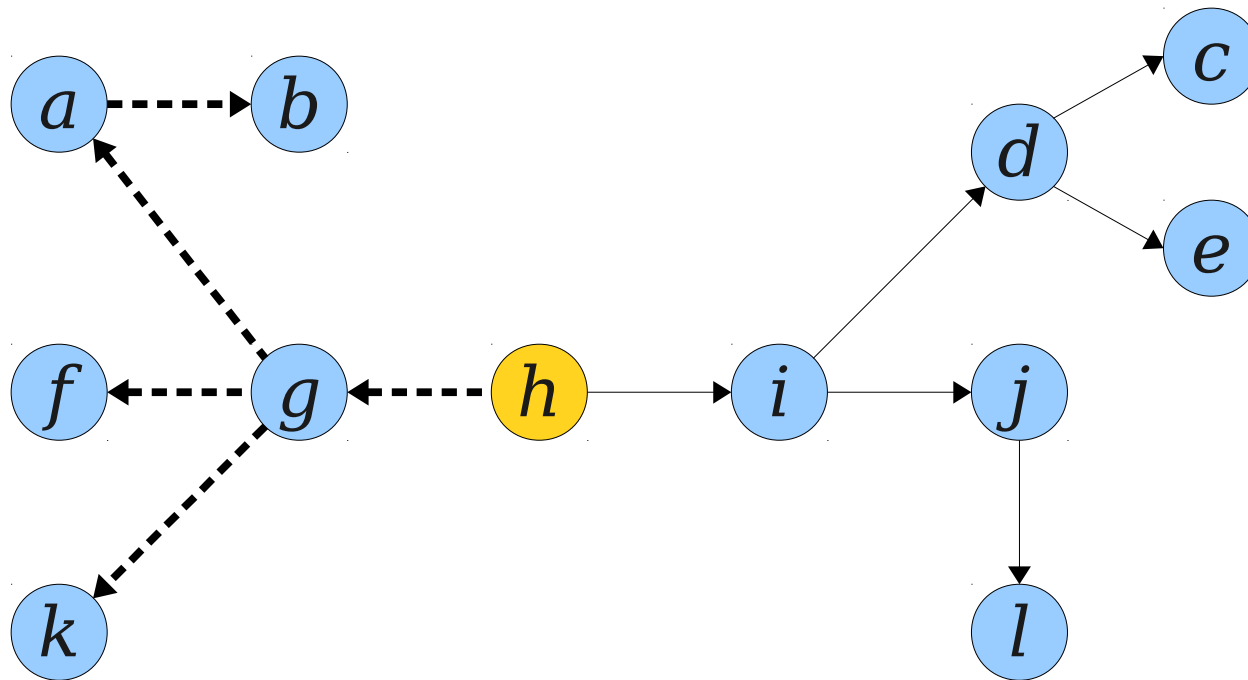


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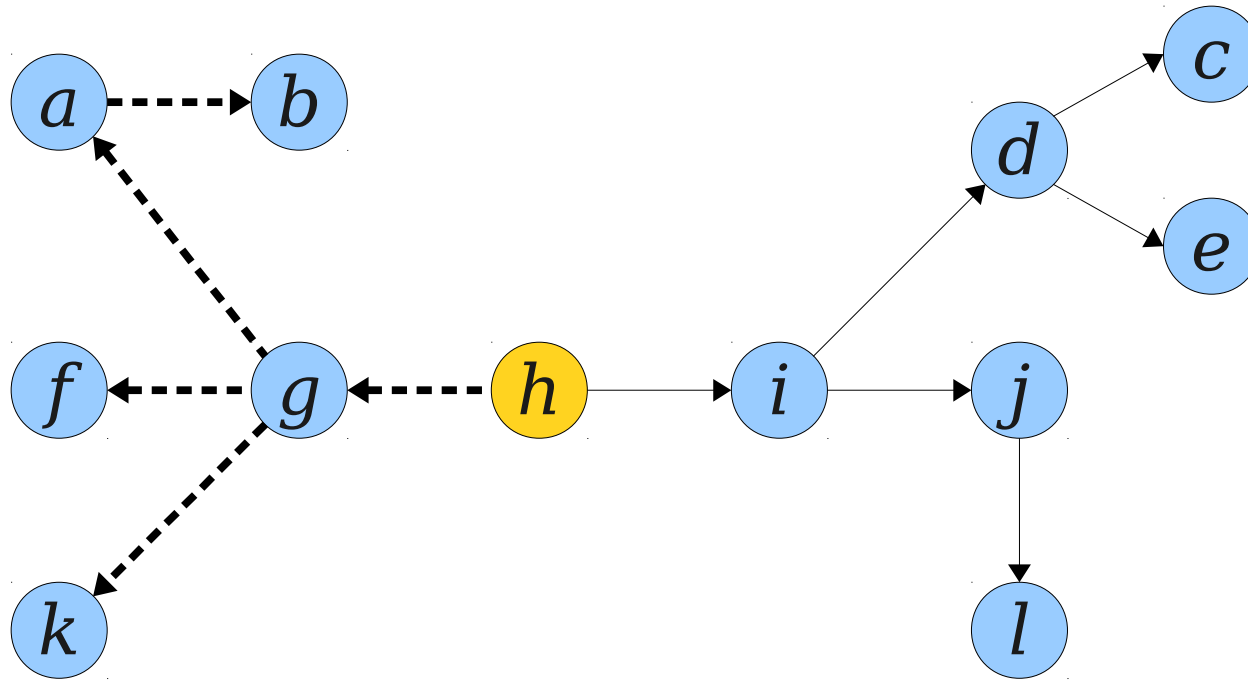


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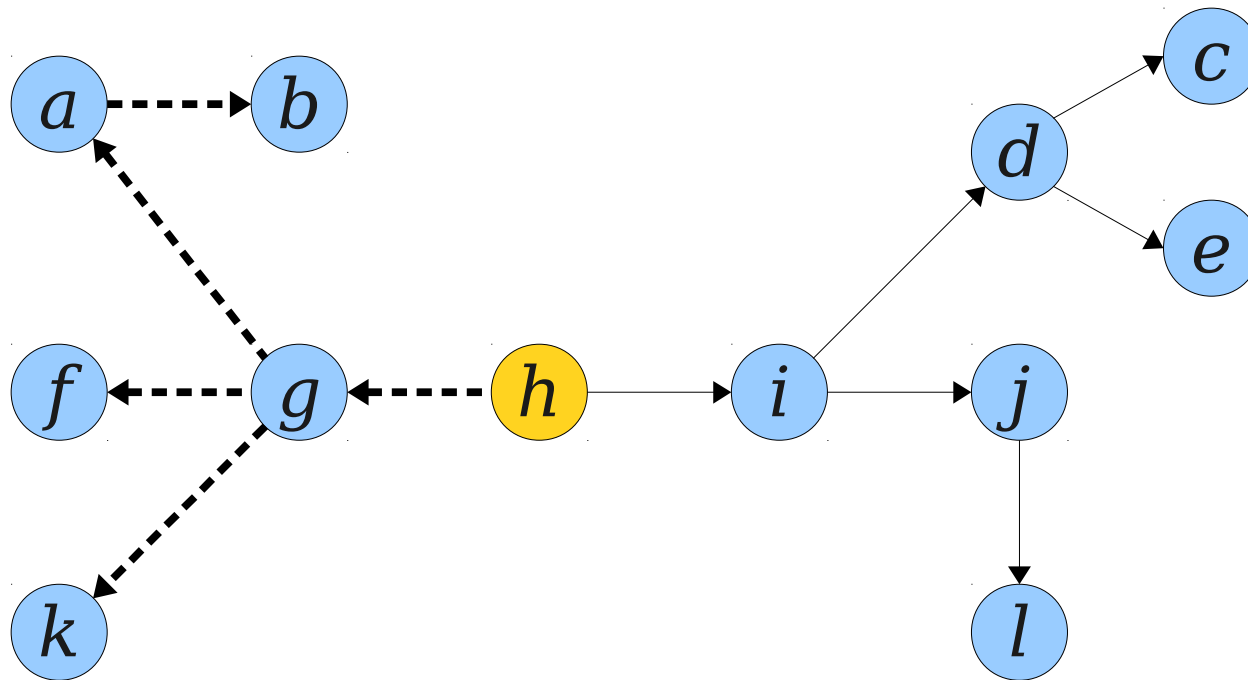
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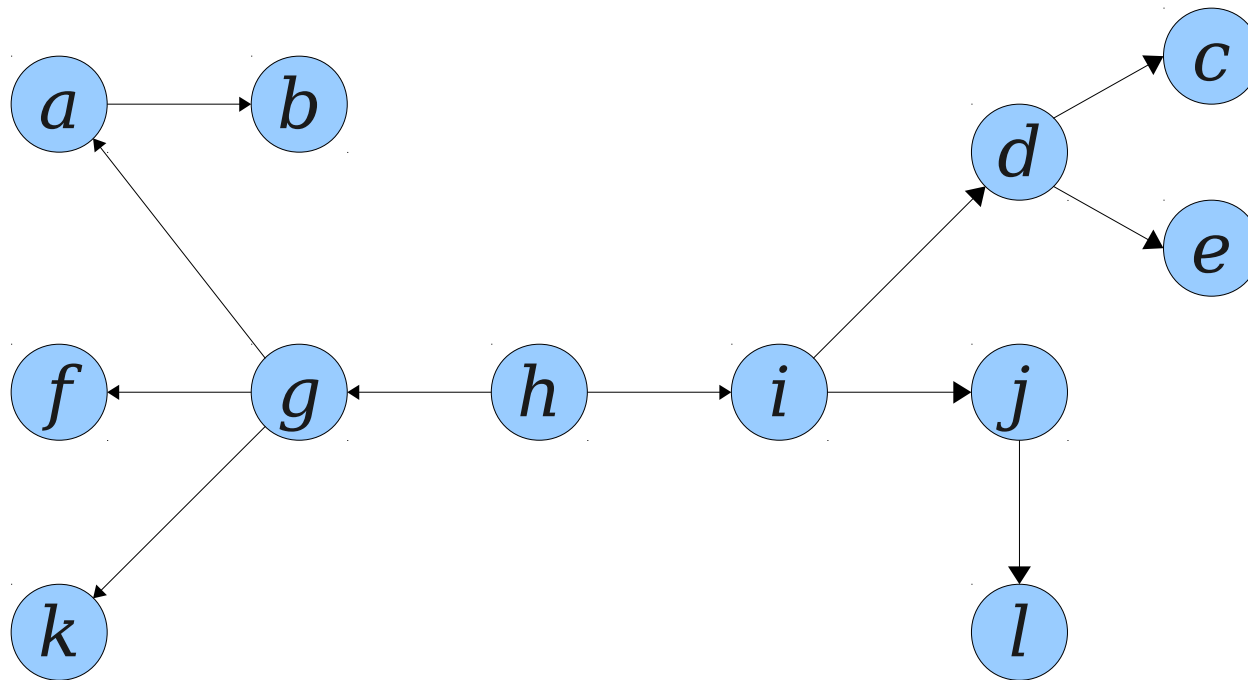


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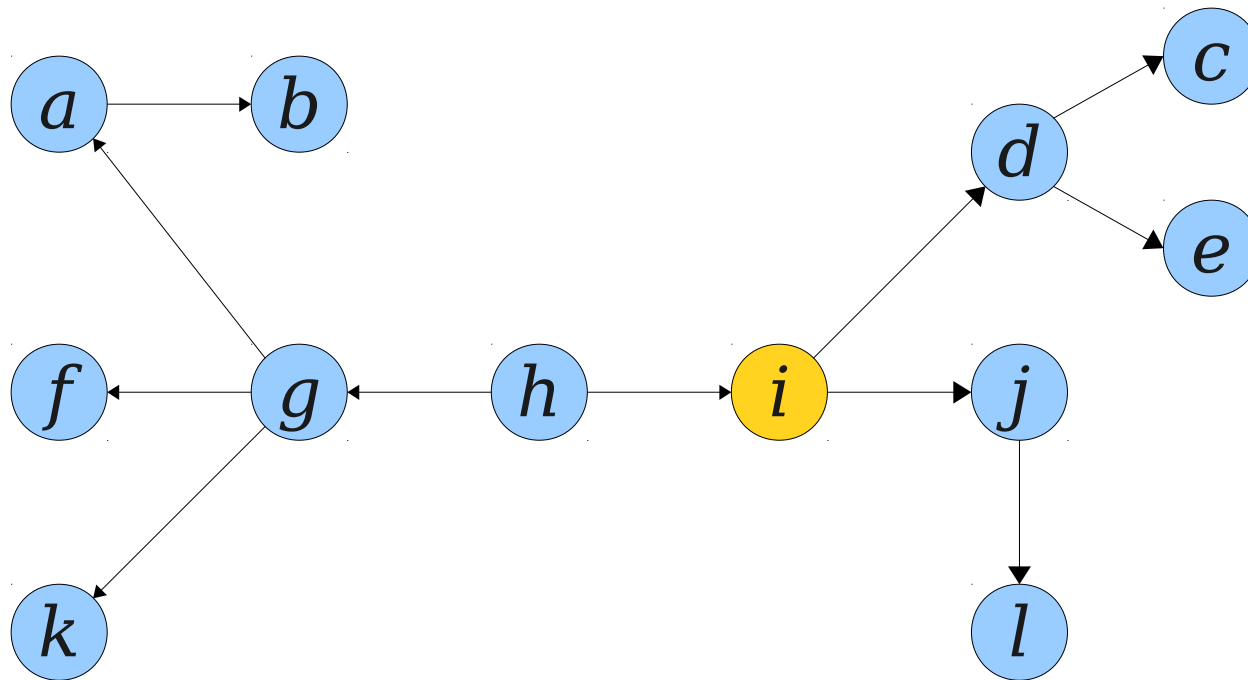
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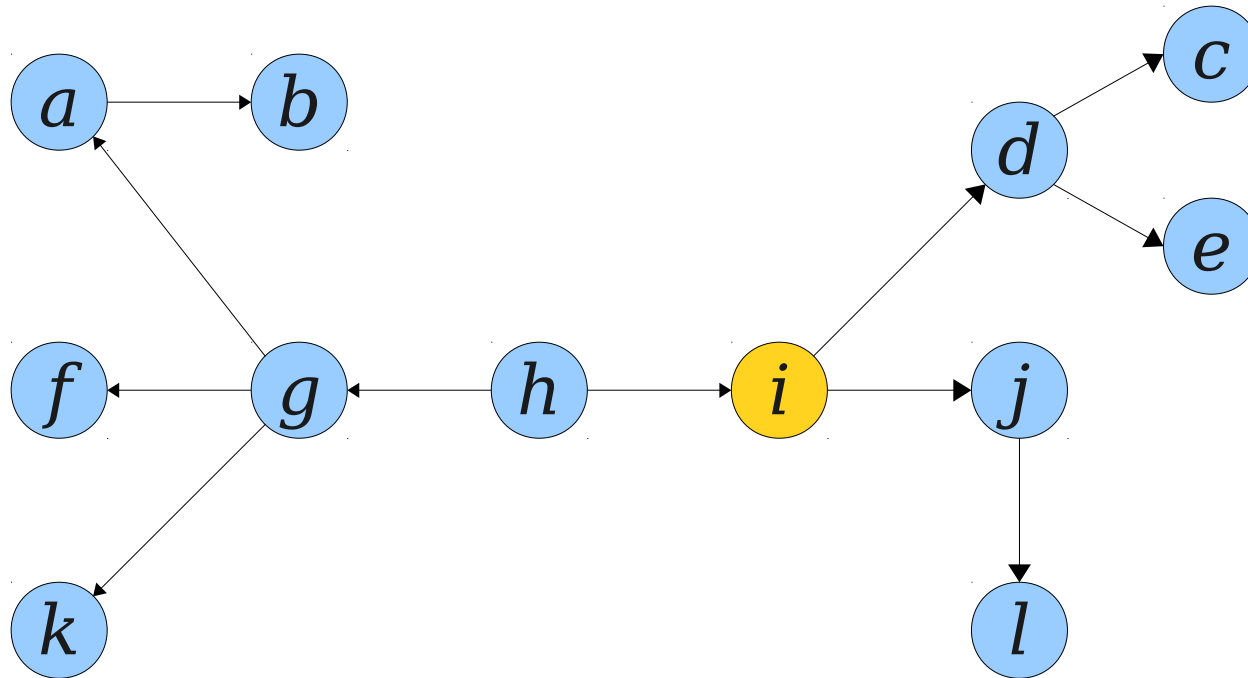
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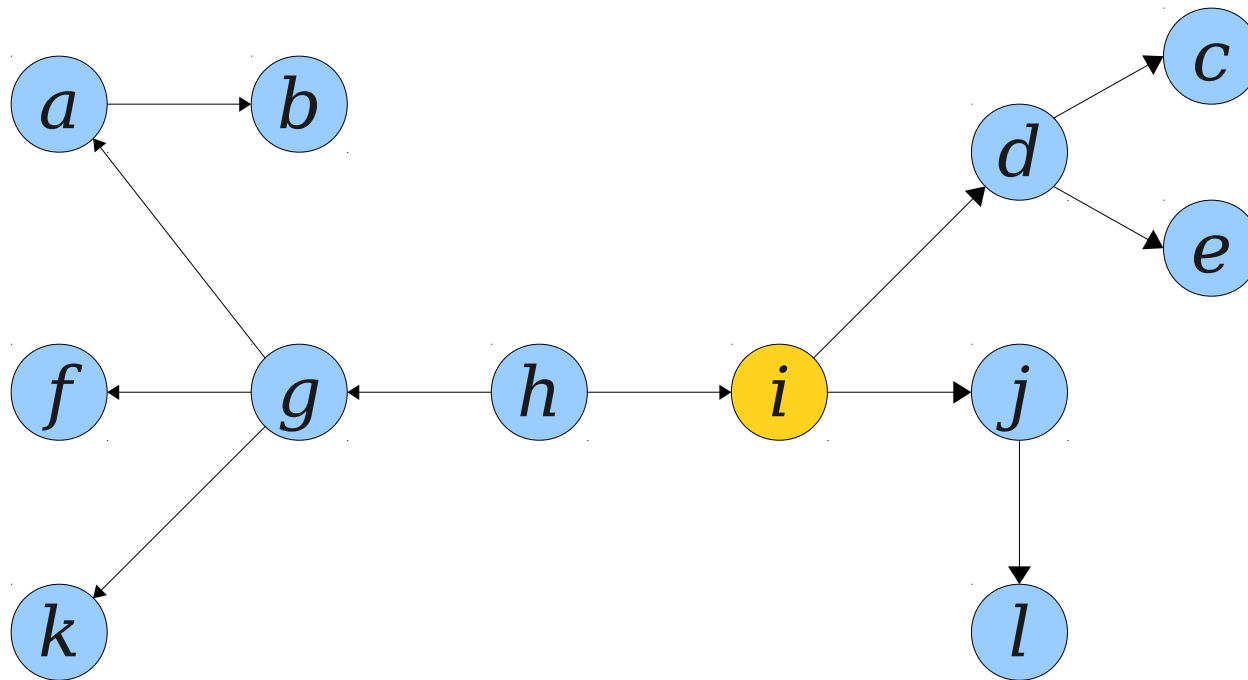
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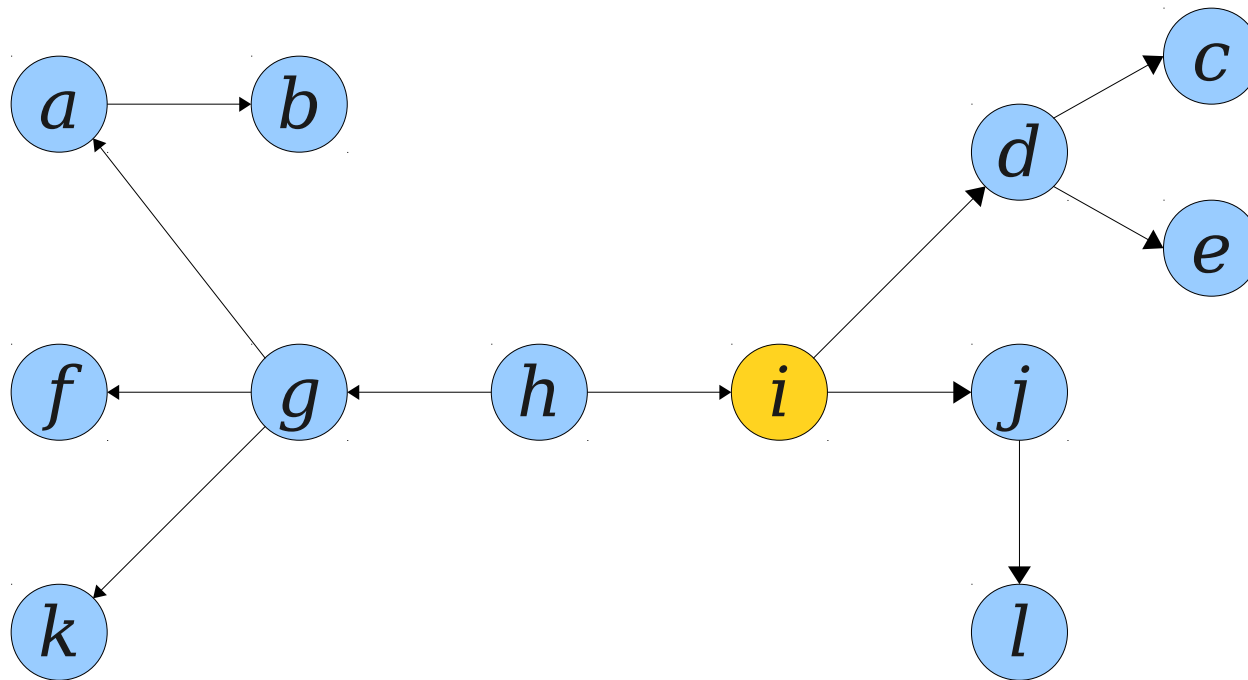
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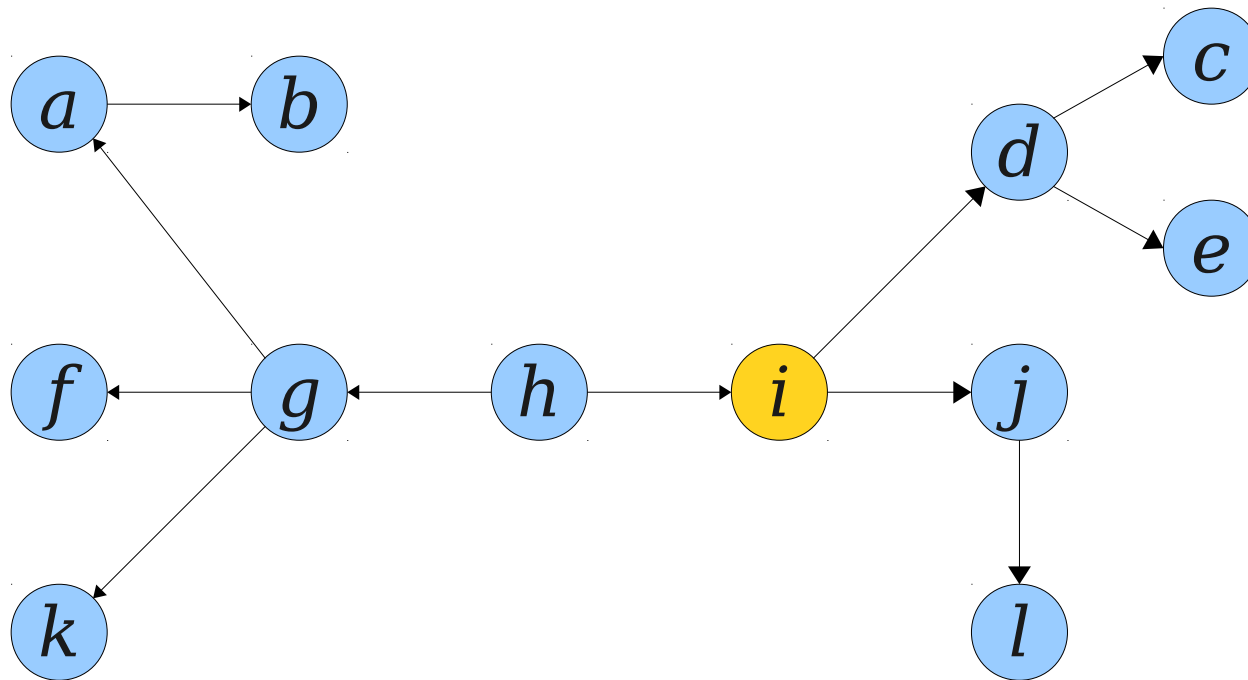
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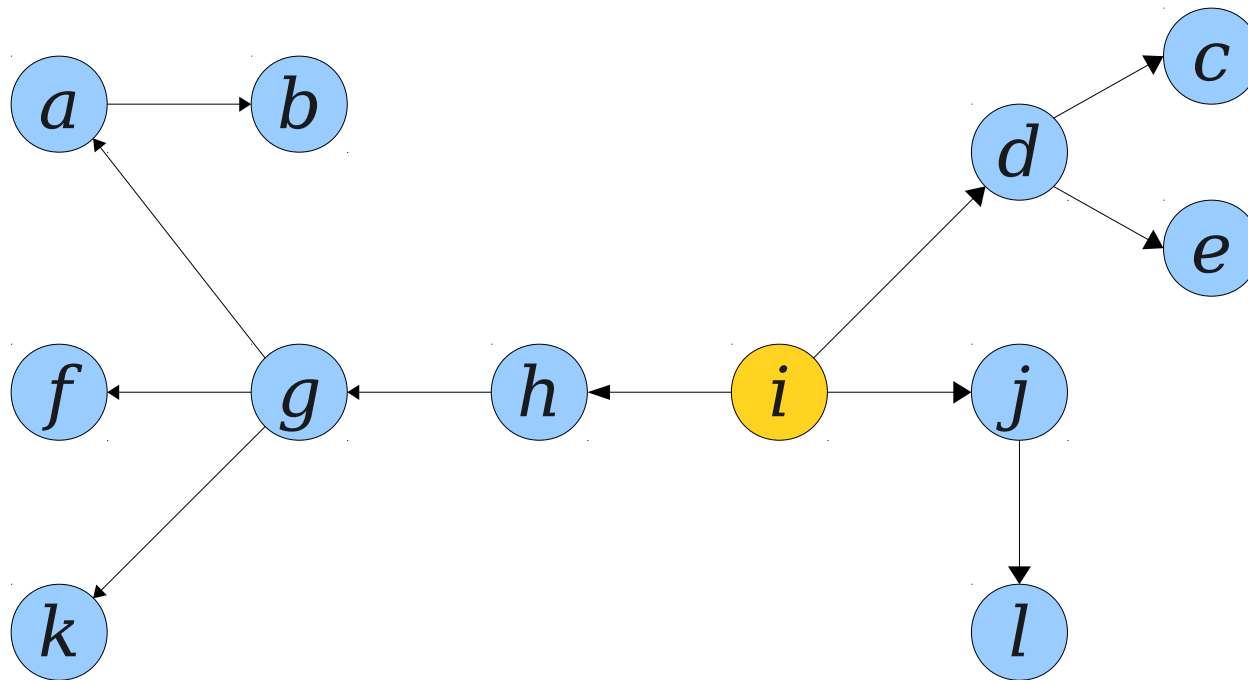
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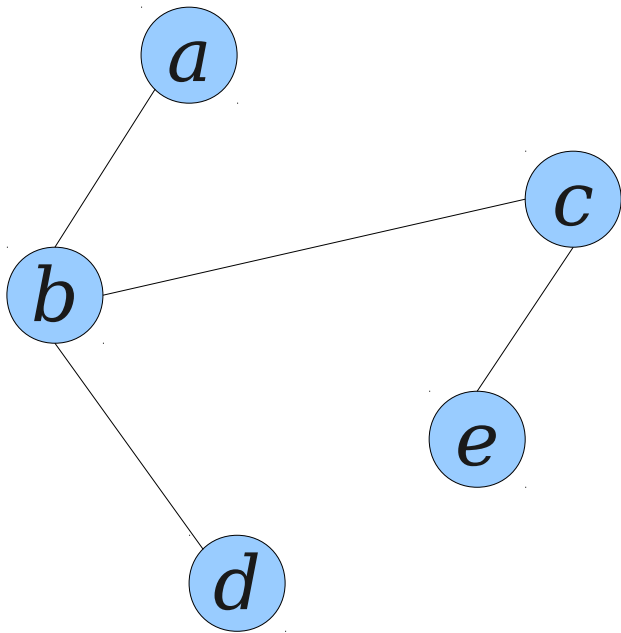
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- **Algorithm:**
  - Find *any* copy of the node  $r$  that will be the new root.
  - Split the tour  $E$  right before  $r$  into  $E_1$  and  $E_2$ .
  - Delete the first node from  $E_1$ .
  - Concatenate  $E_1, E_2, \{r\}$ .
- **Difference from before:** We only need a single pointer to  $r$ , not the full range.

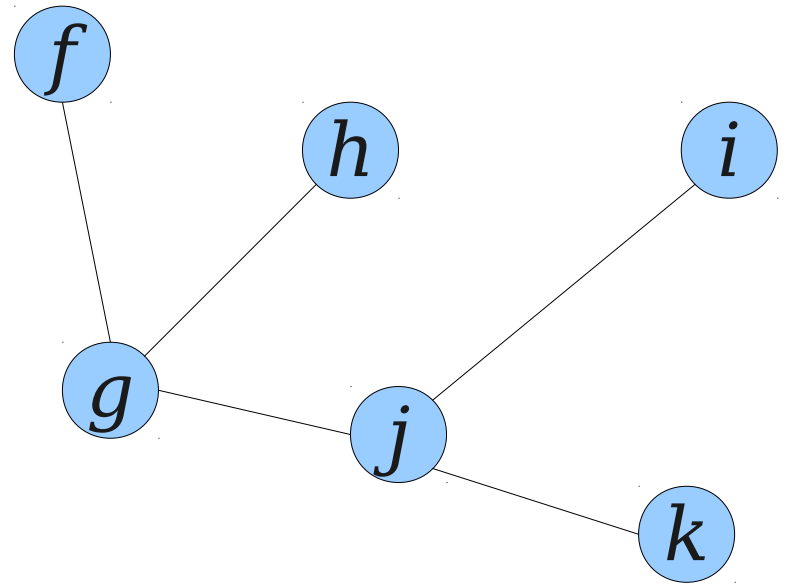


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- Watch what happens to the Euler tours:



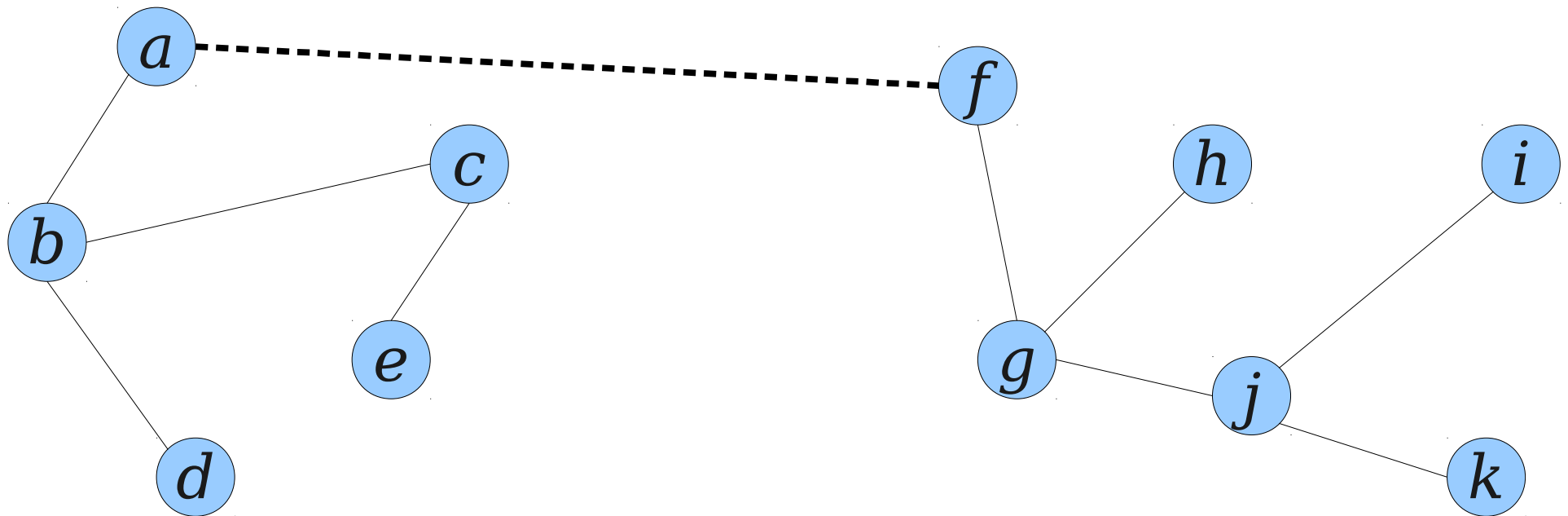
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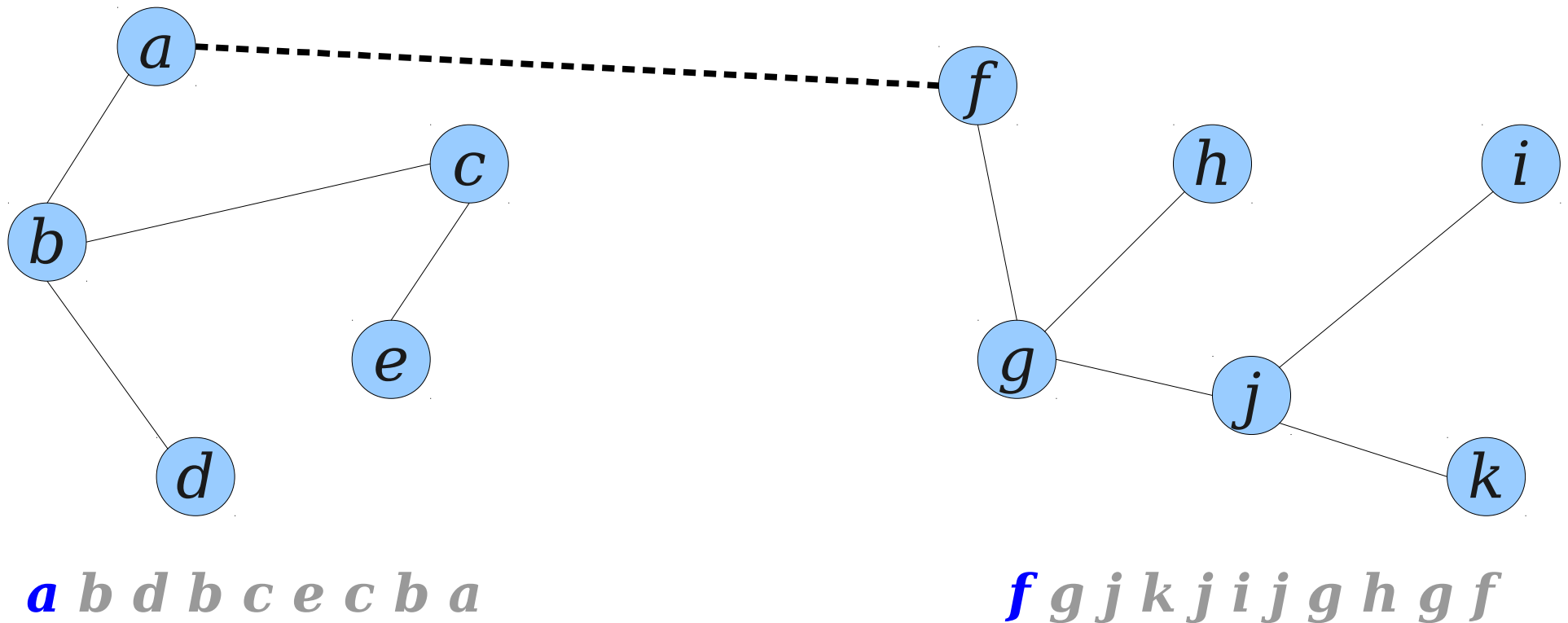


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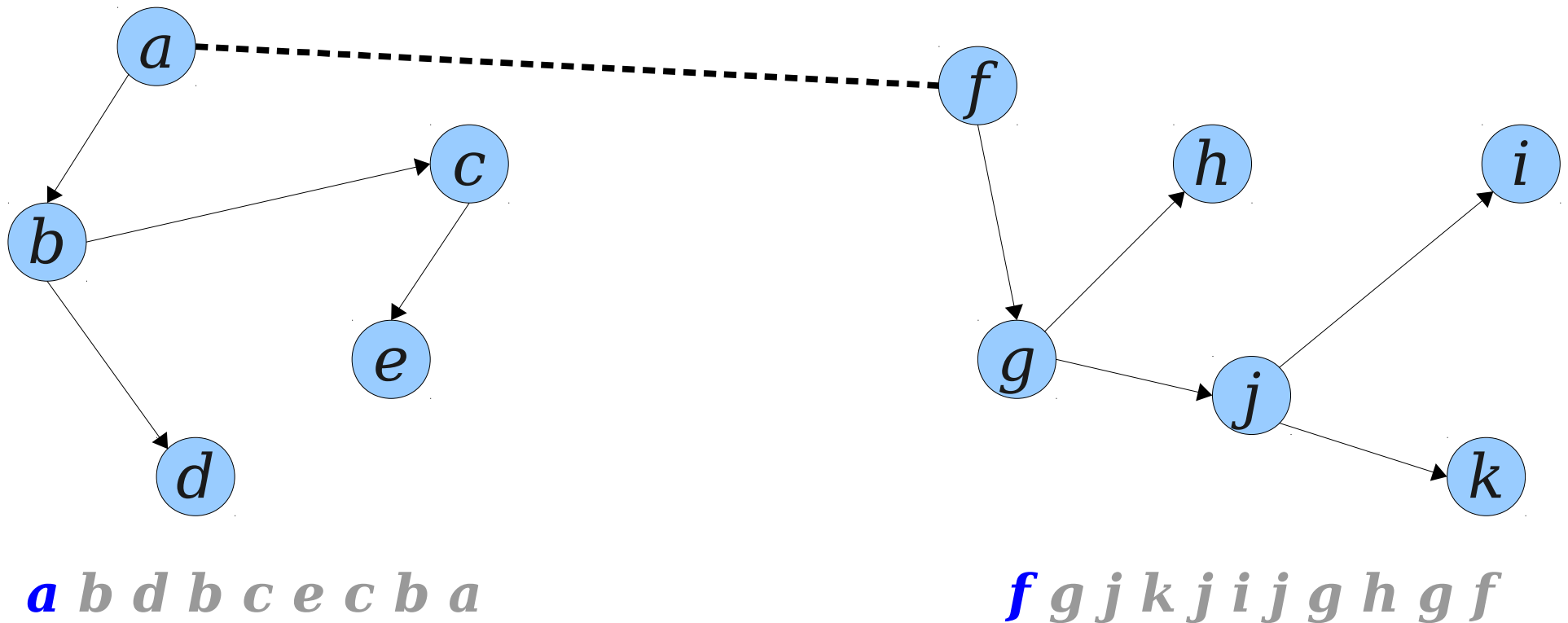
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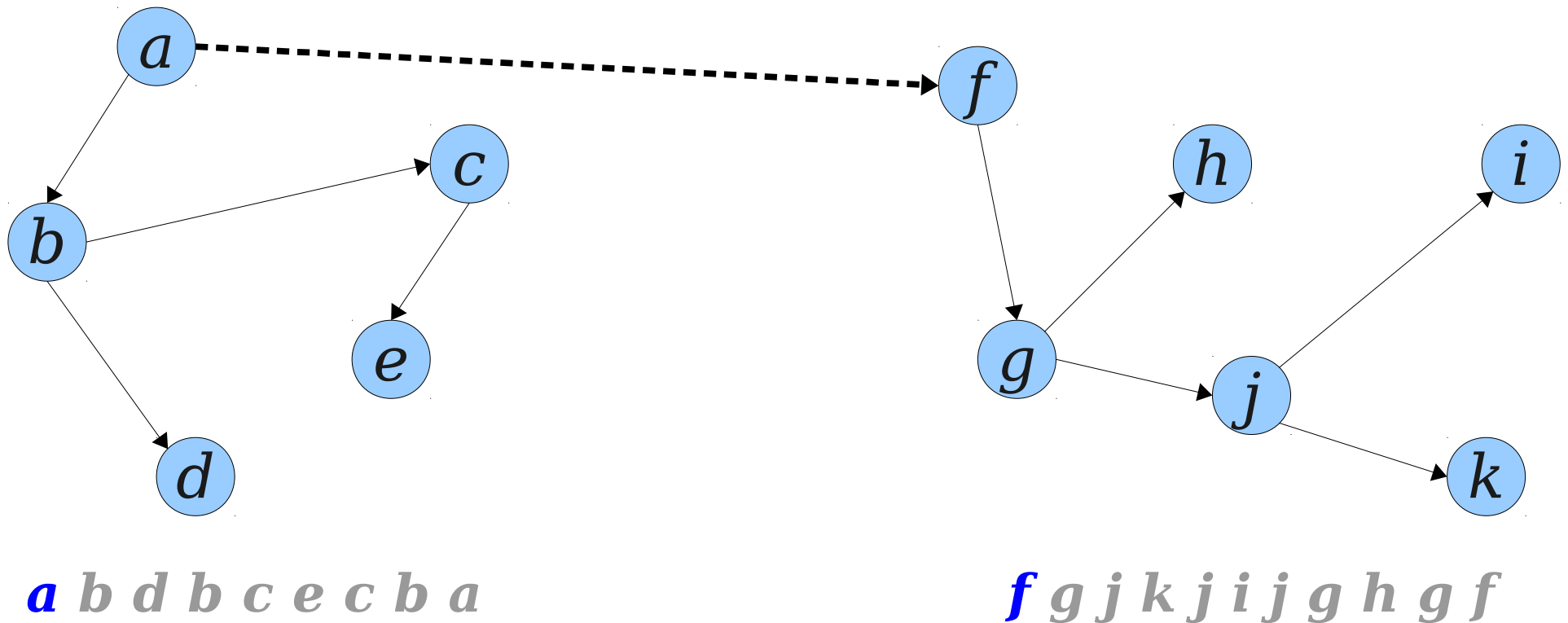
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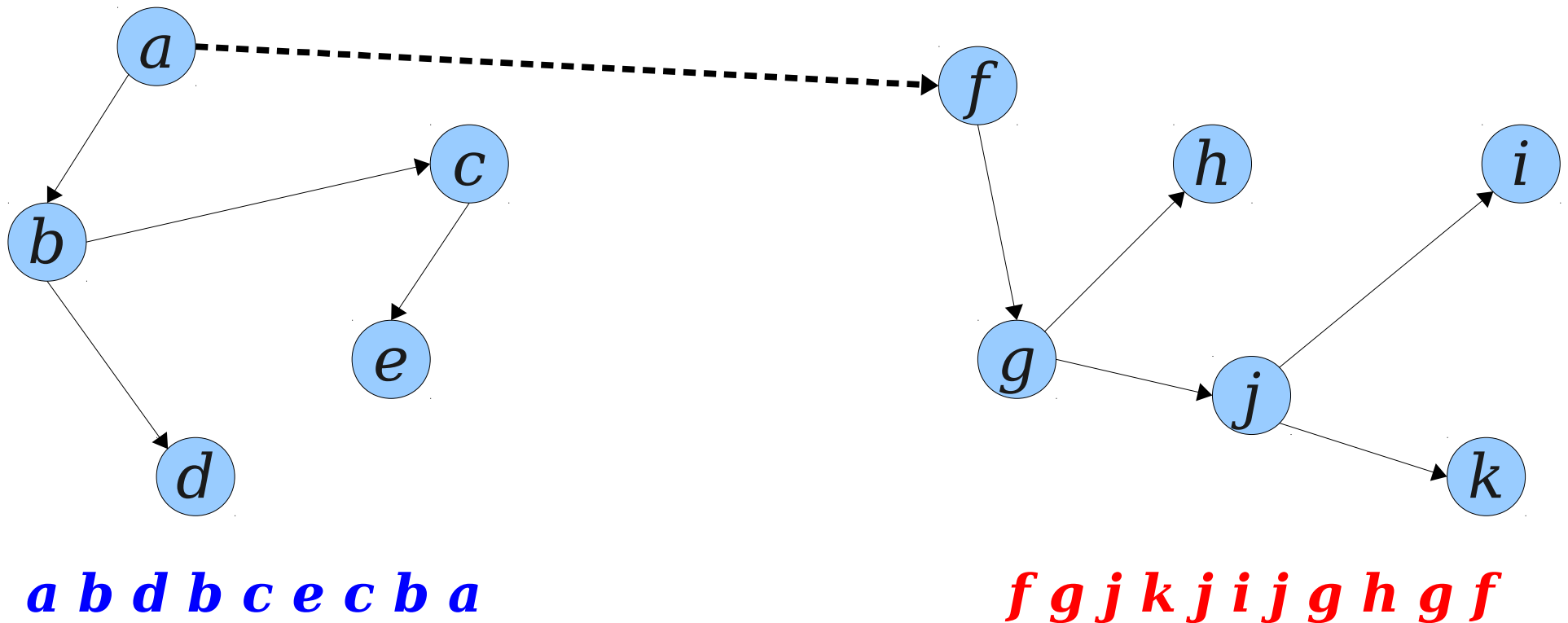
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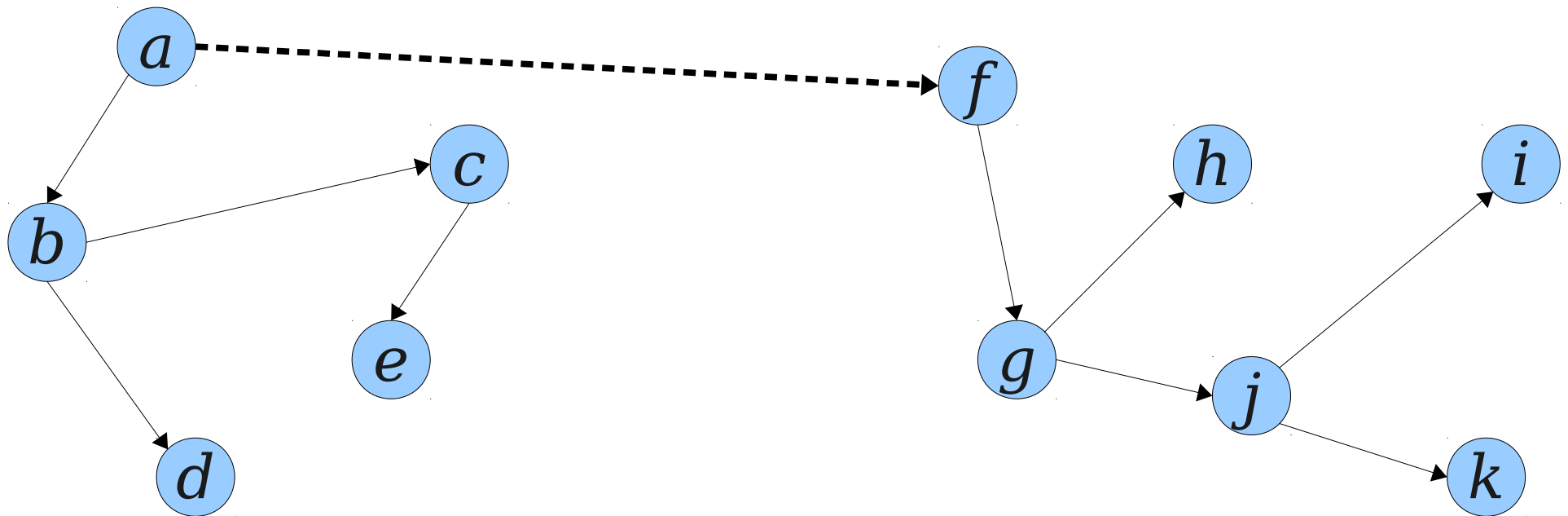
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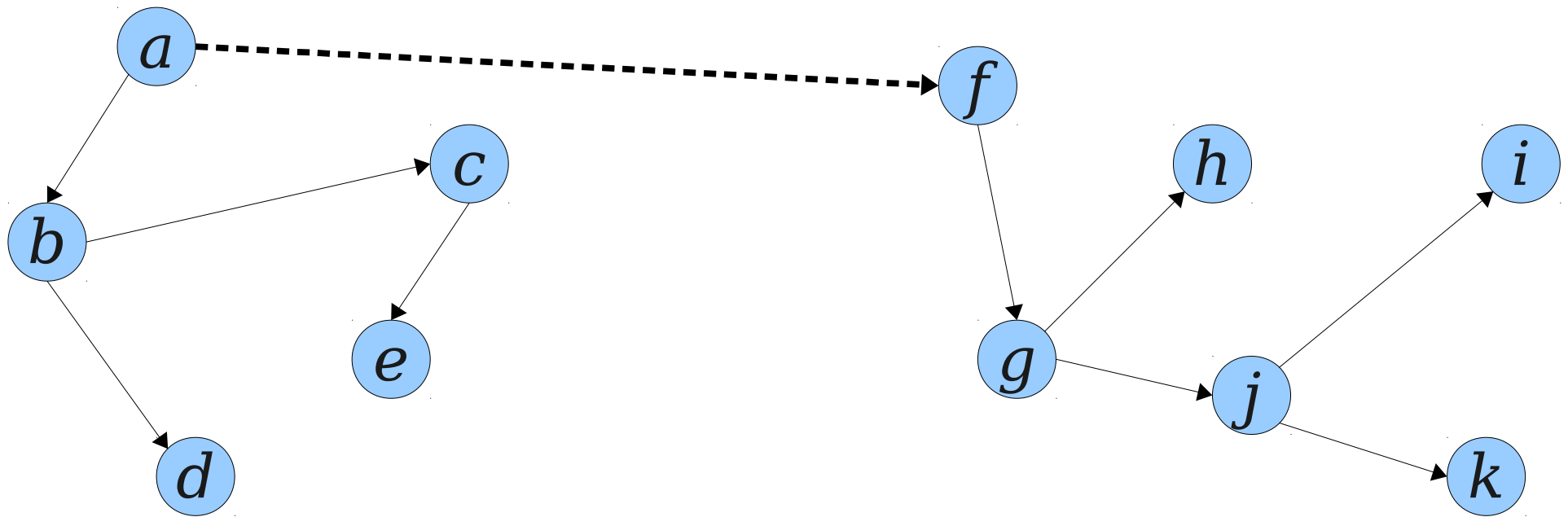
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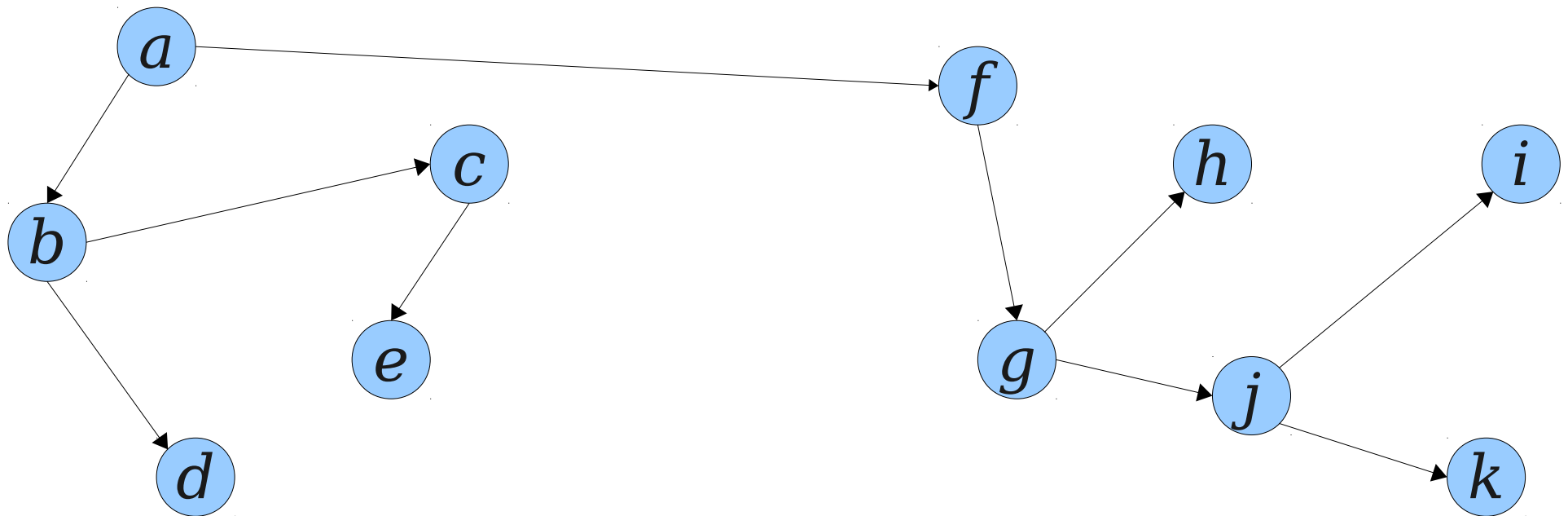


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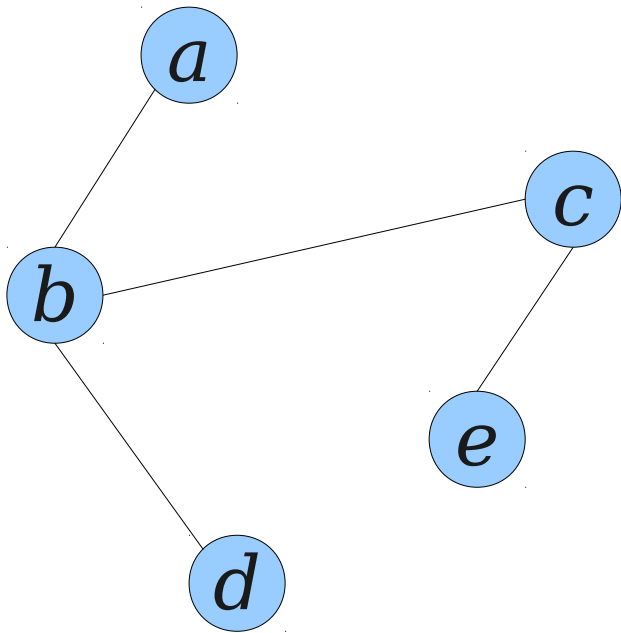
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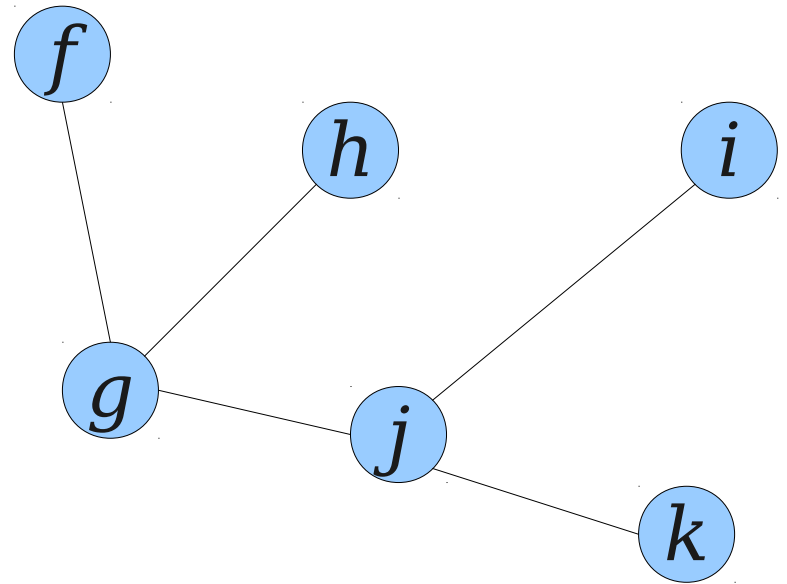
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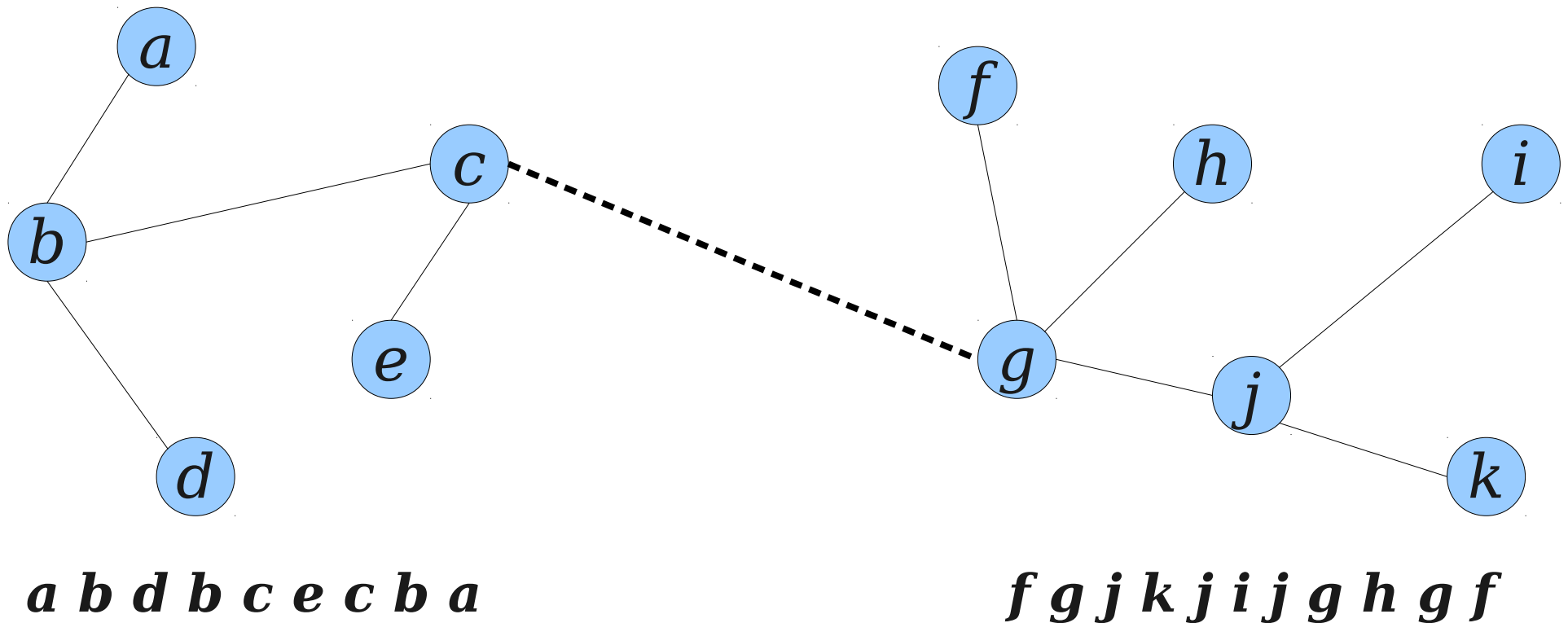
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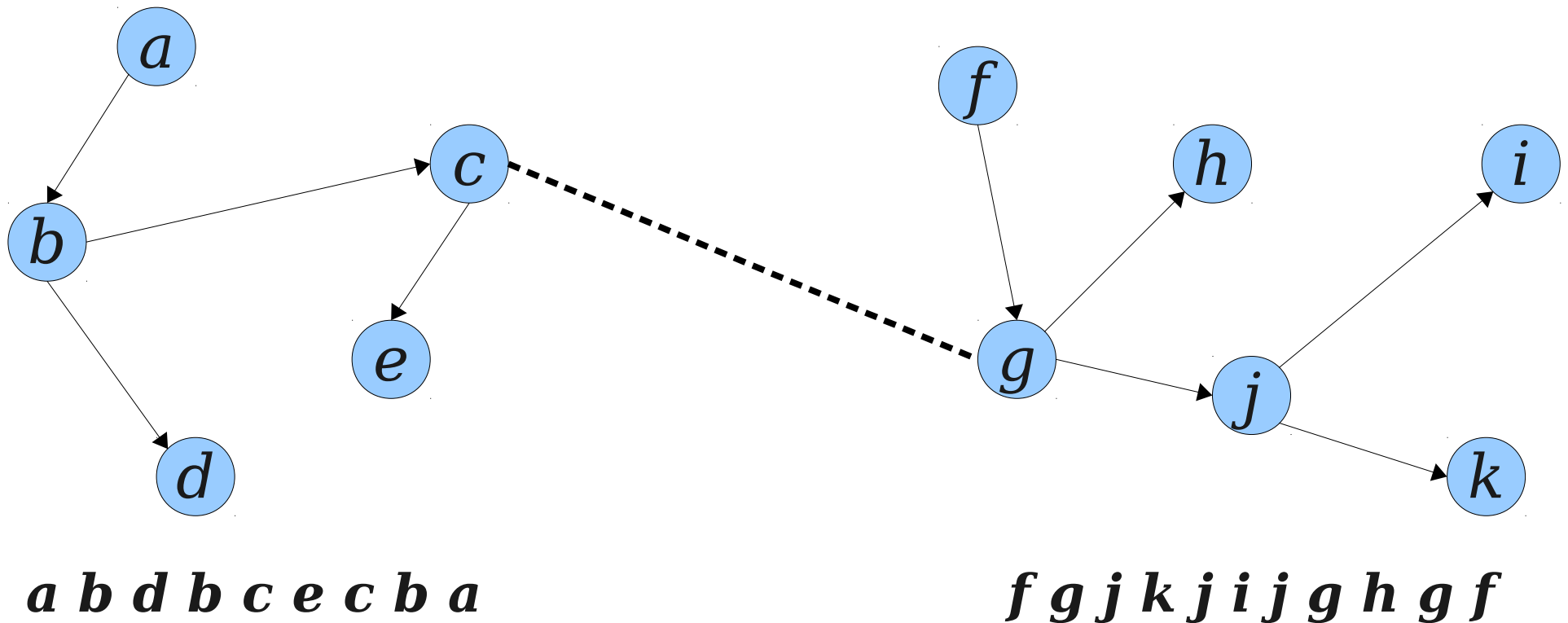
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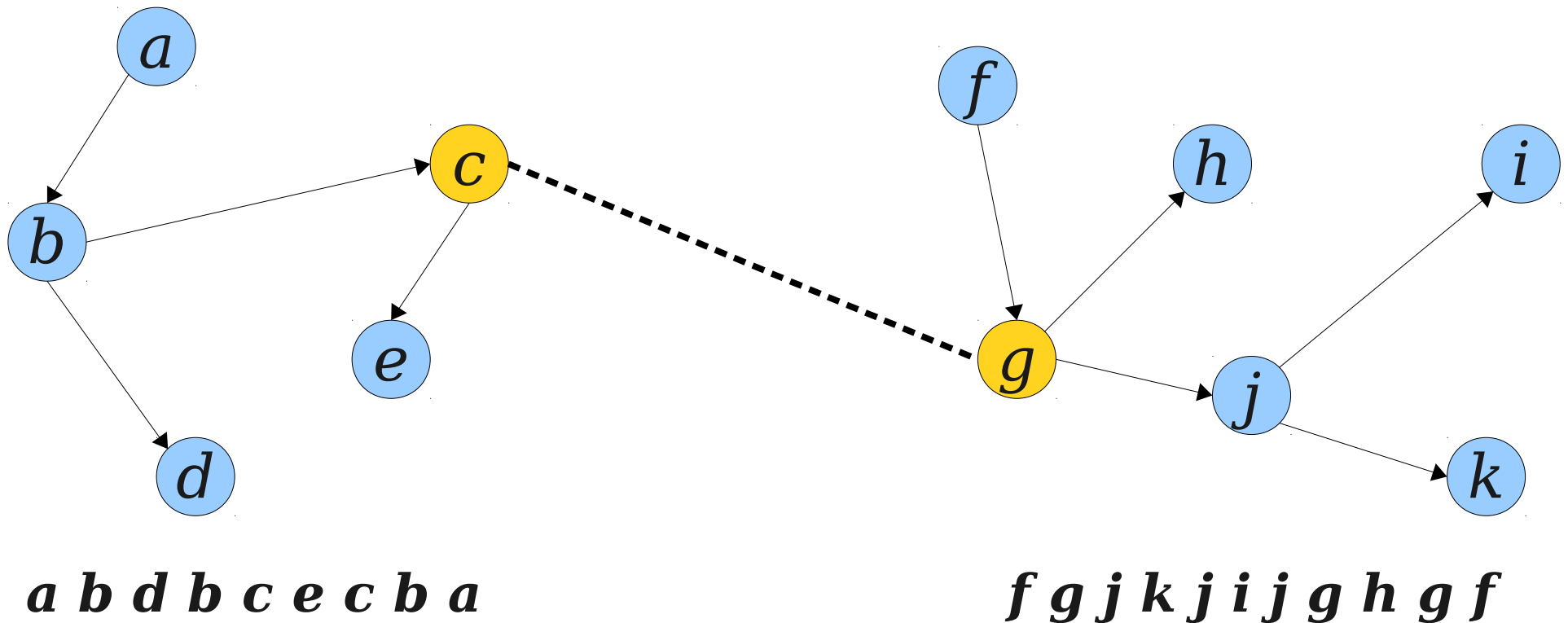
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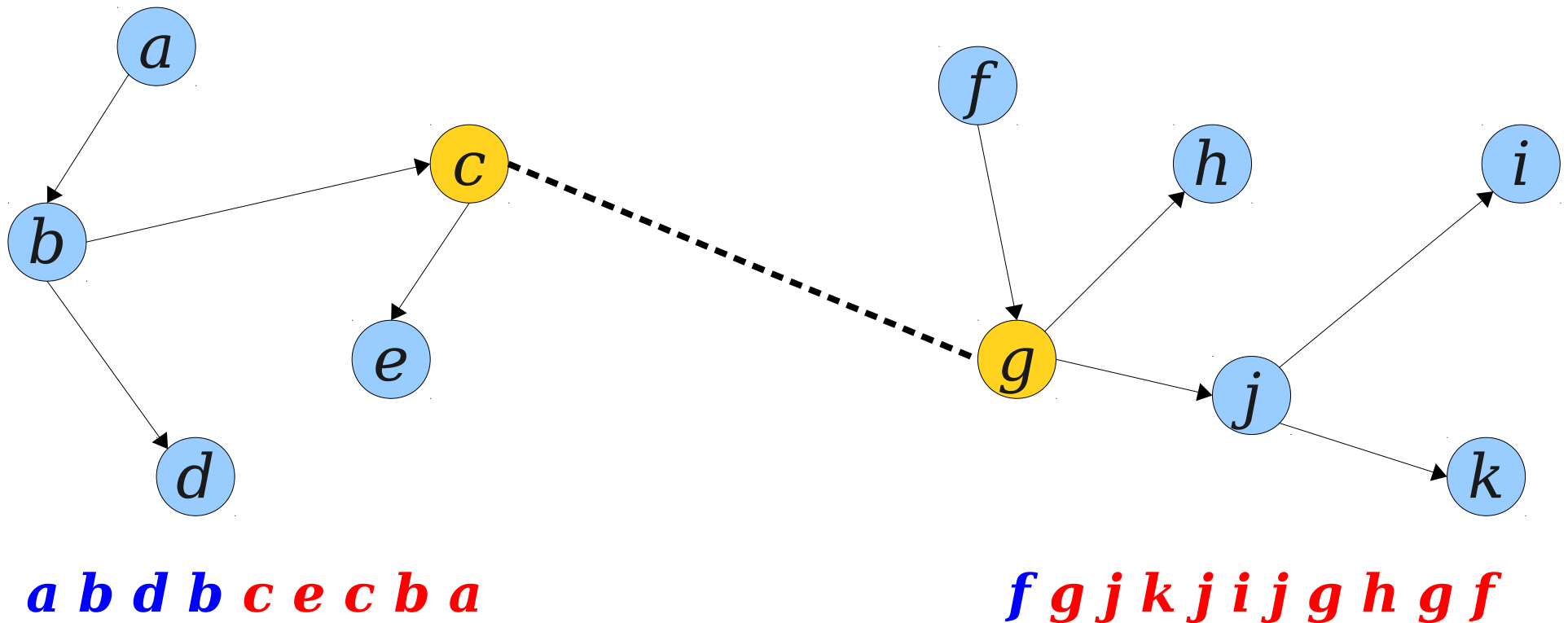
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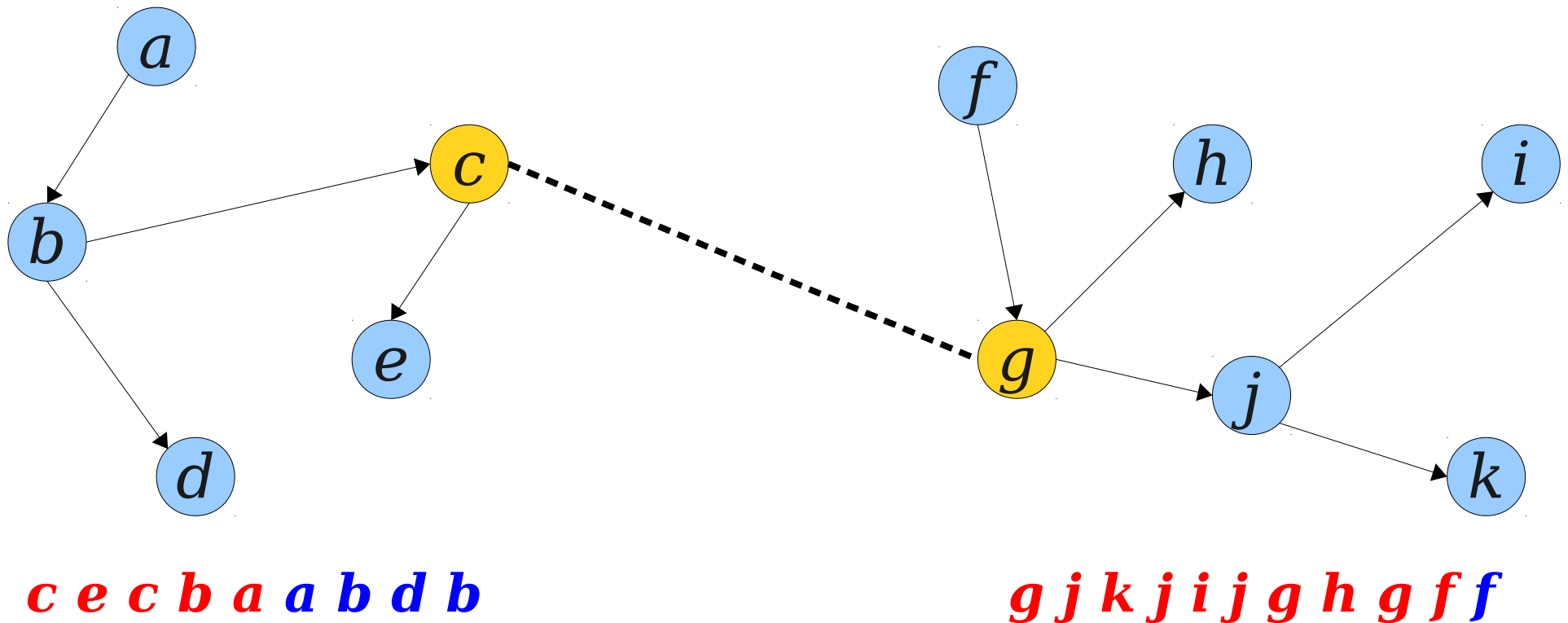
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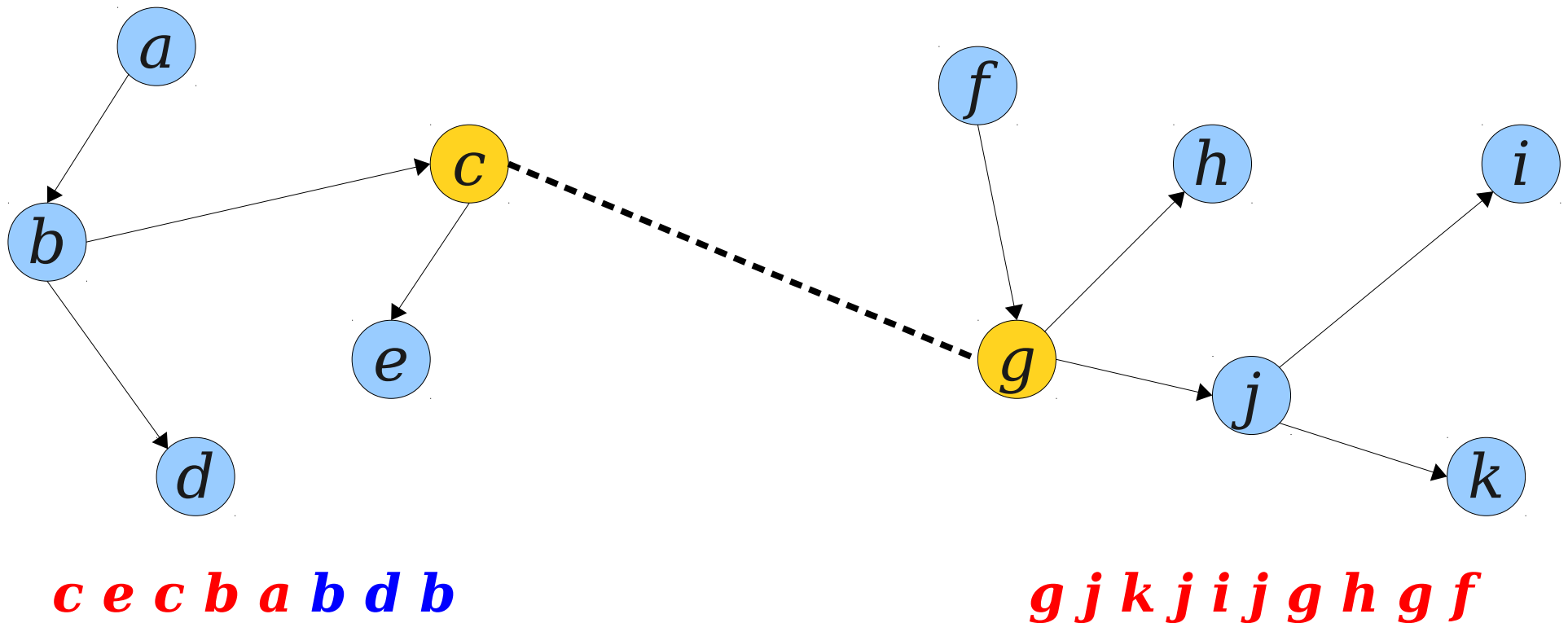
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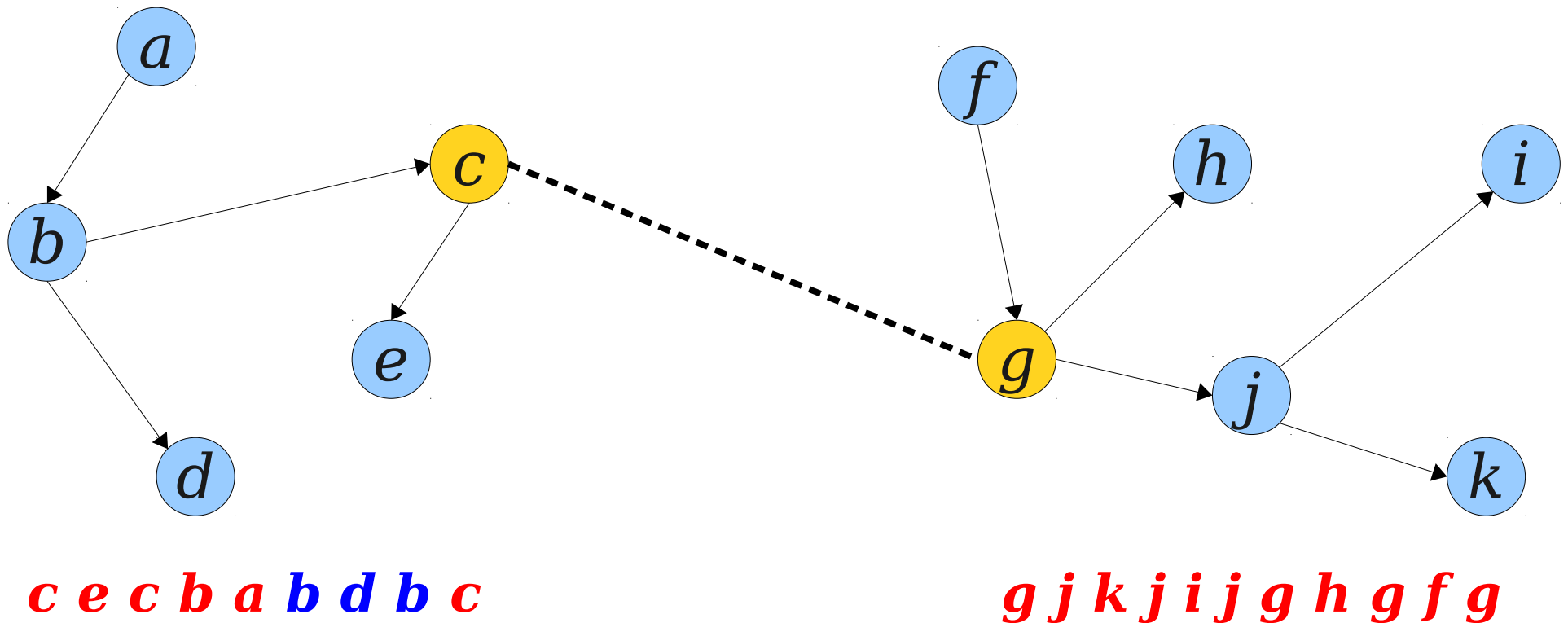
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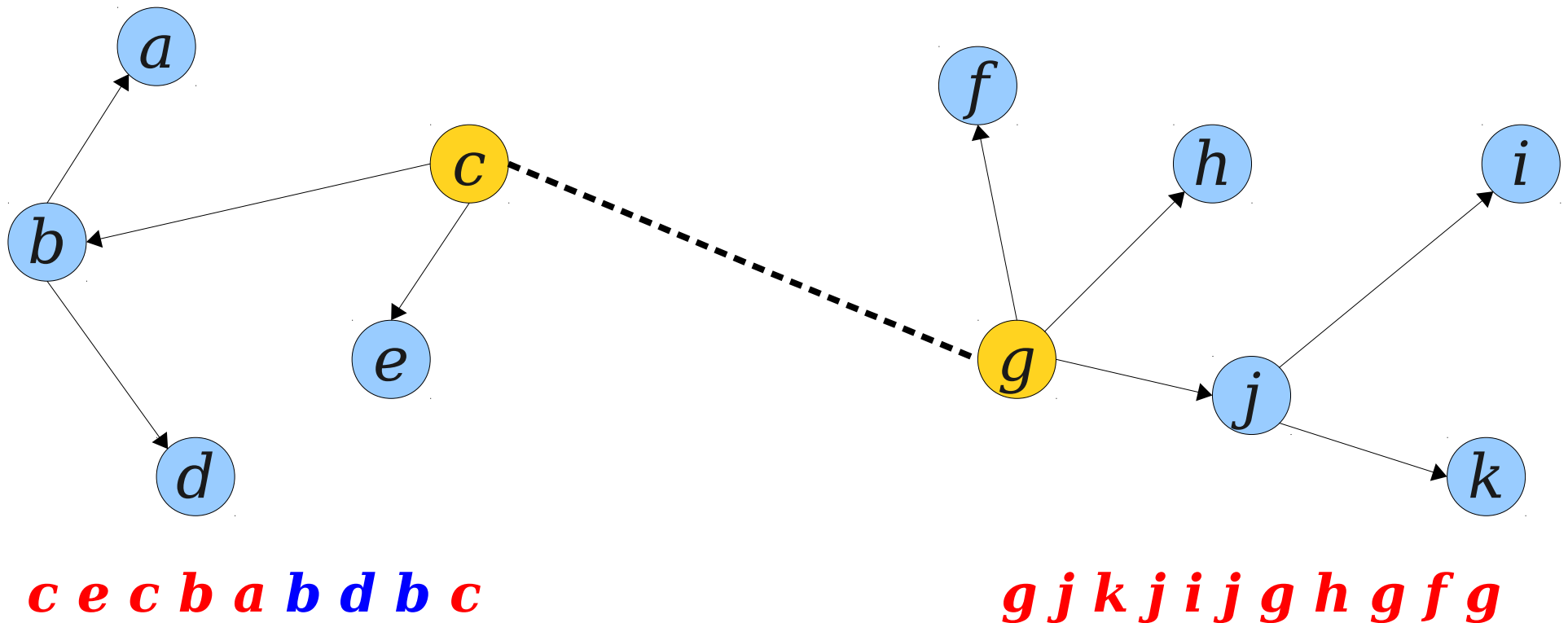
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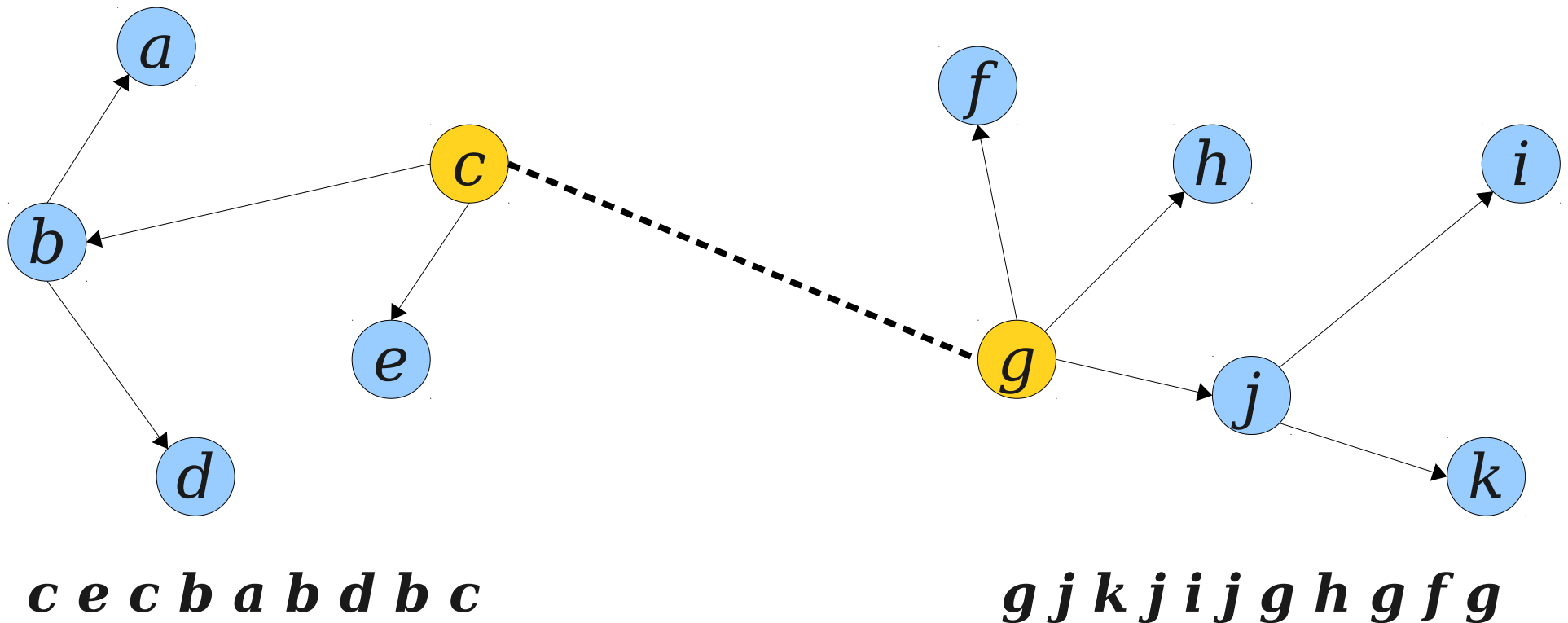
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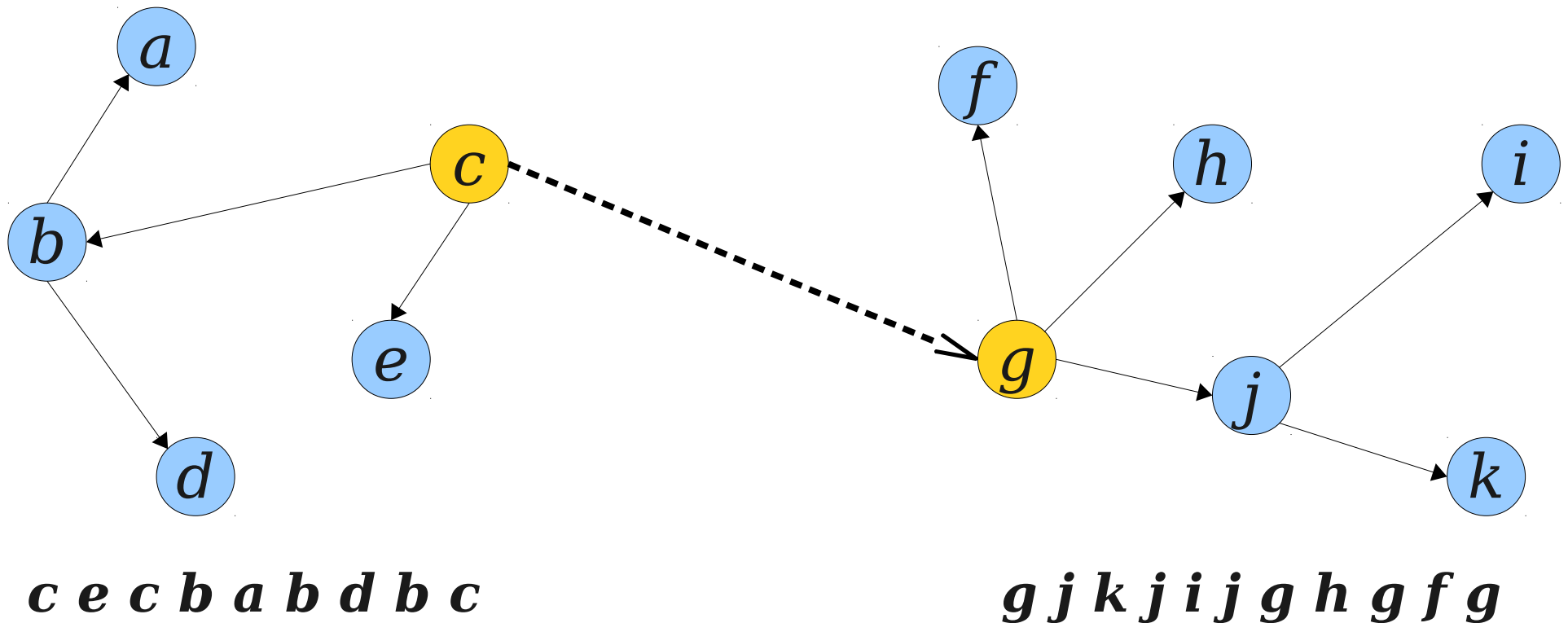
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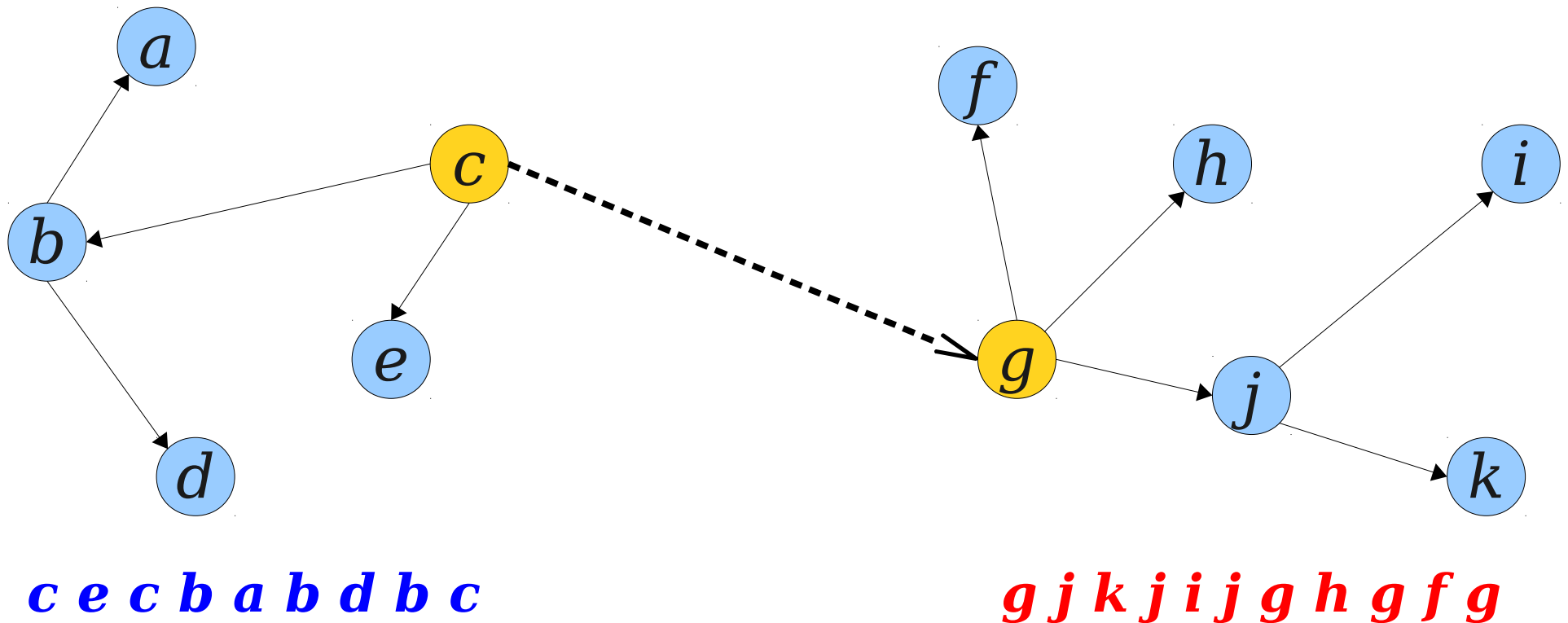
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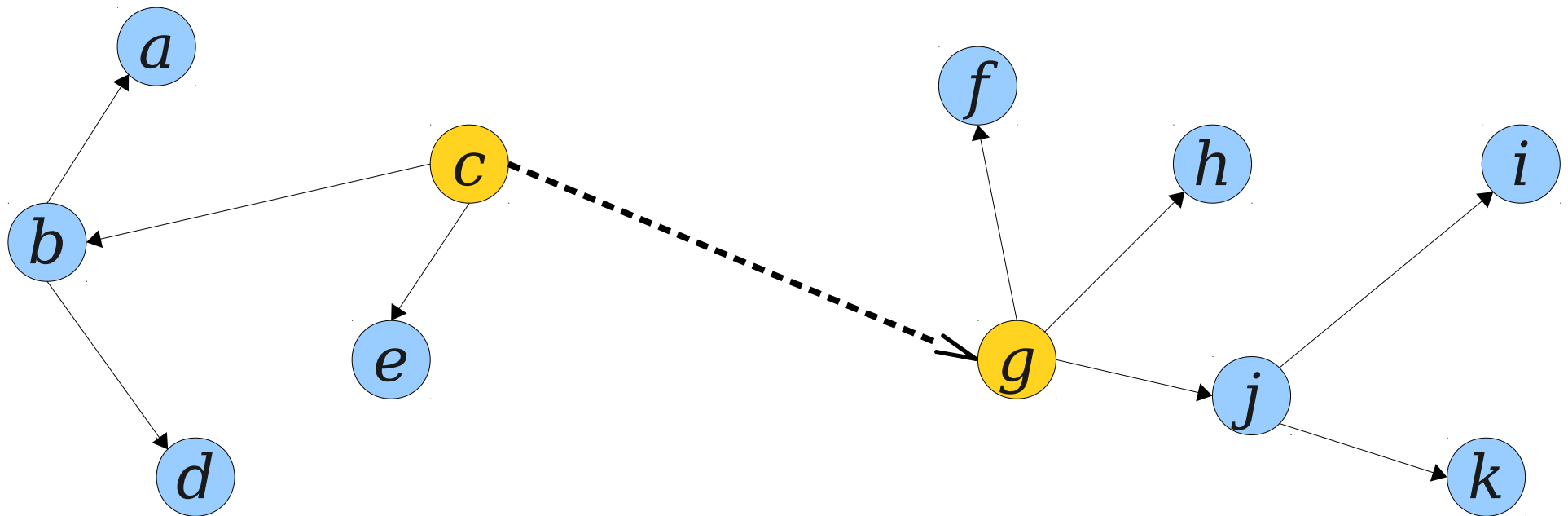
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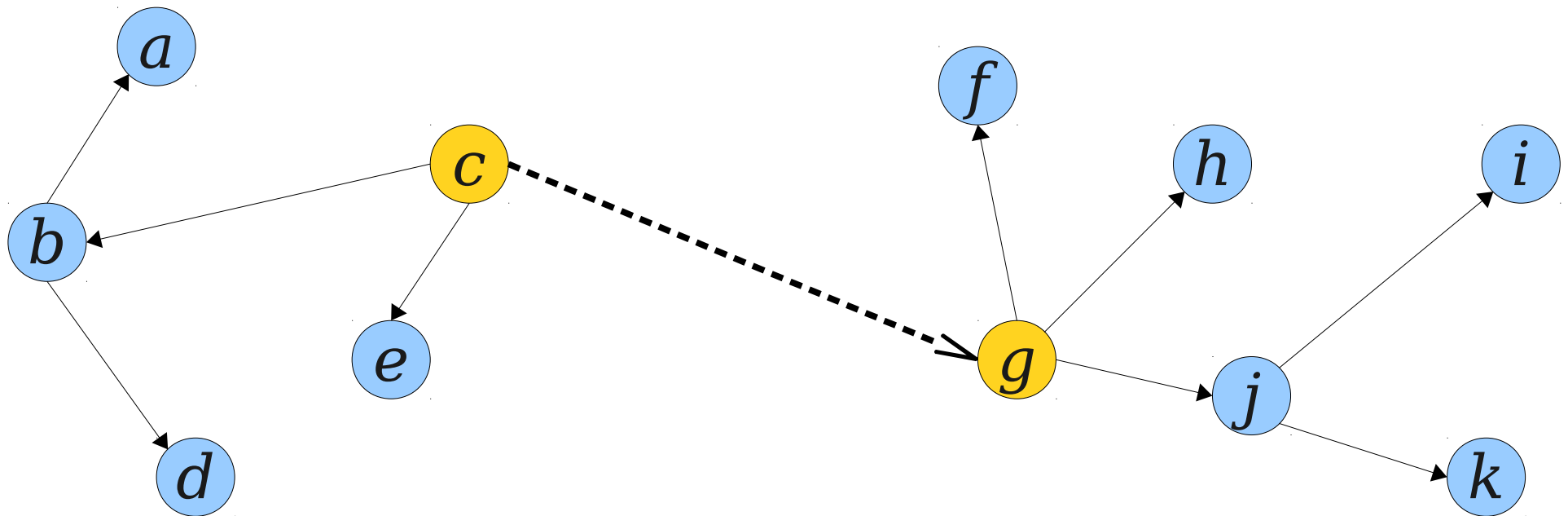
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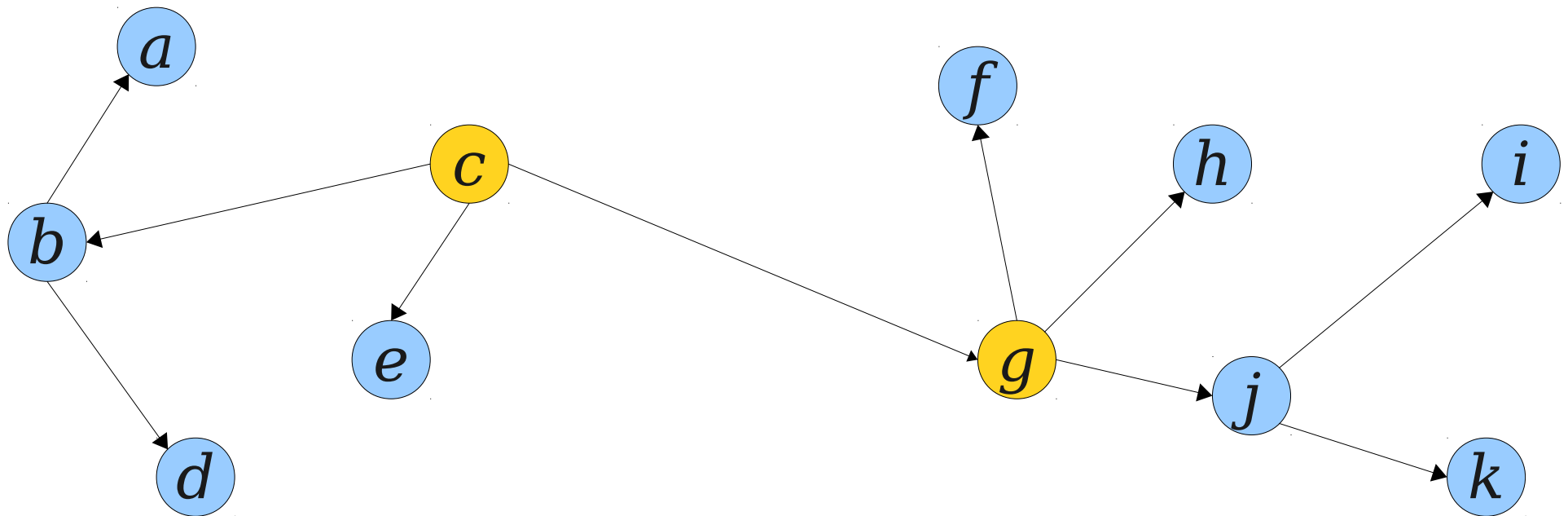


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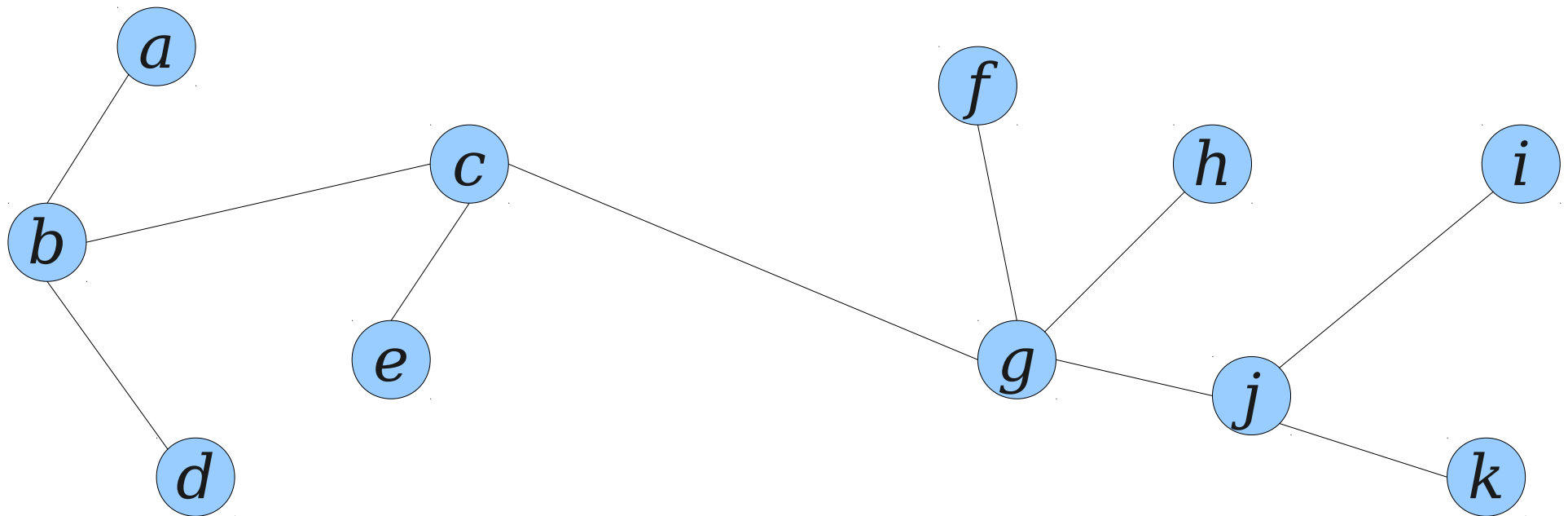
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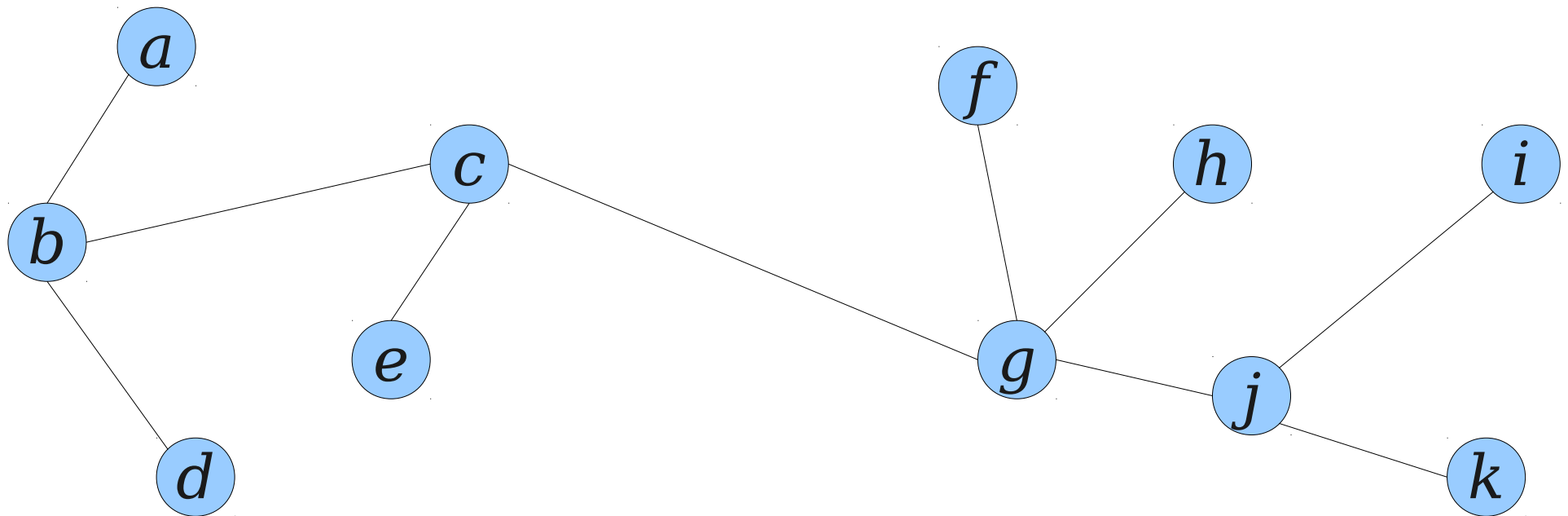
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- To link  $T_1$  and  $T_2$  by adding  $\{u, v\}$ :
  - Let  $E_1$  and  $E_2$  be Euler tours of  $T_1$  and  $T_2$ , respectively.
  - Rotate  $E_1$  to root the tour at  $u$ .
  - Rotate  $E_2$  to root the tour at  $v$ .
  - Concatenate  $E_1, E_2, \{u, v\}$ .
- **This is the same as before.**

# Euler Tours and Dynamic Trees

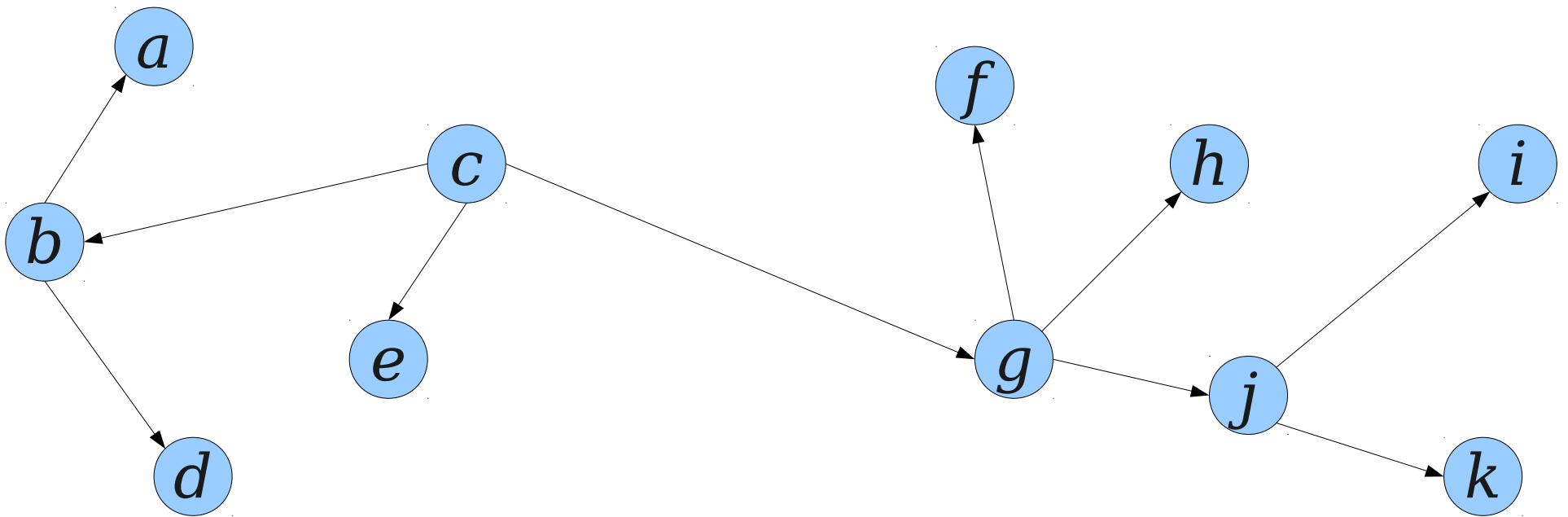
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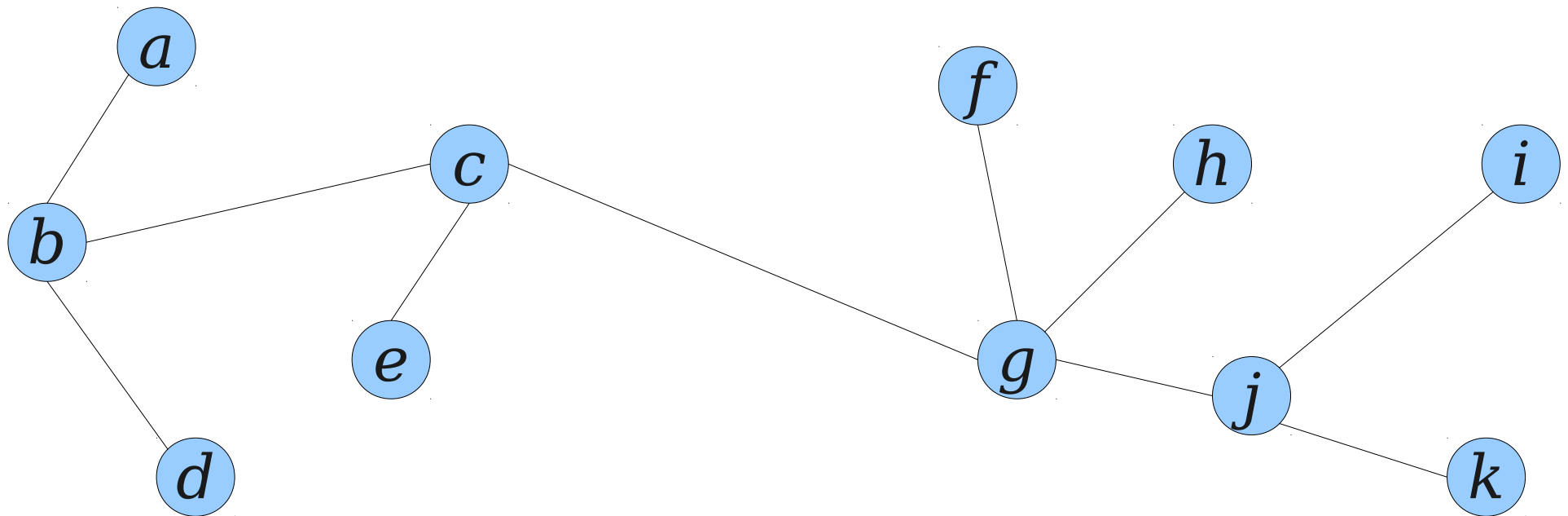
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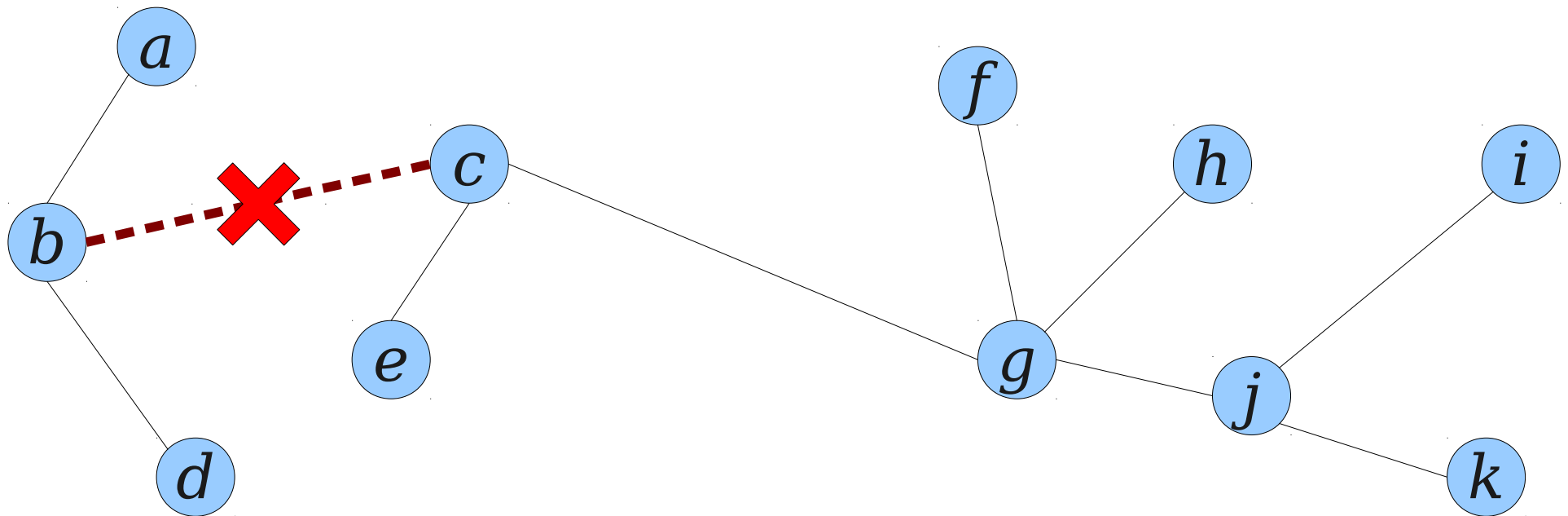
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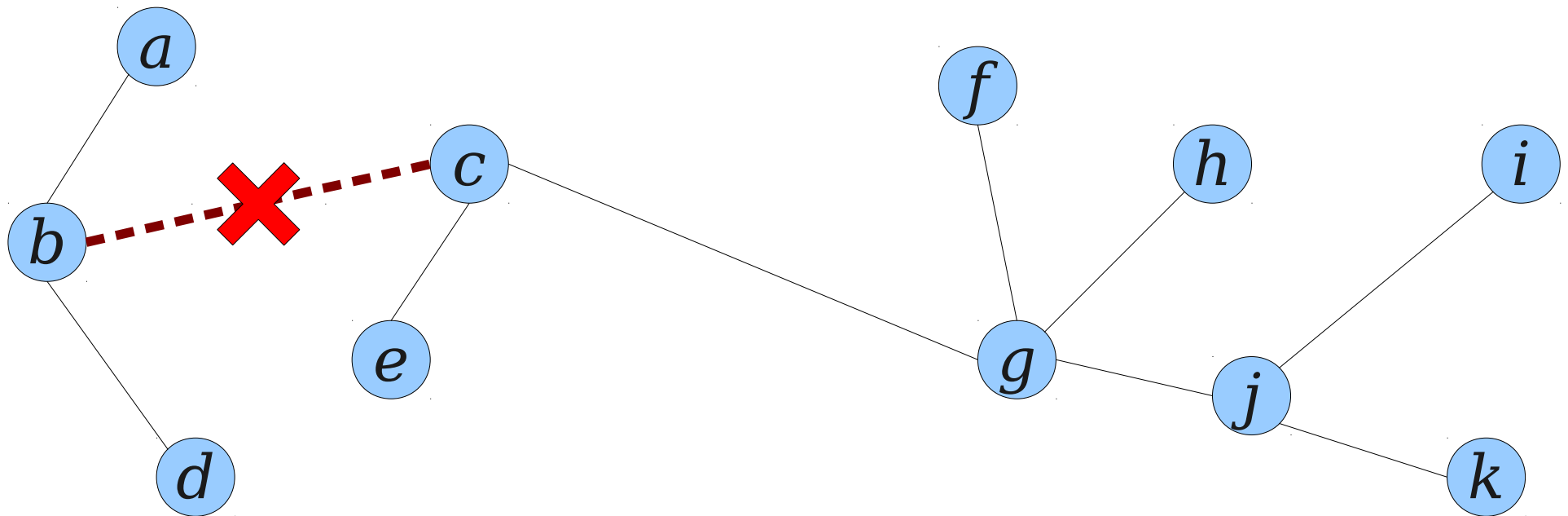
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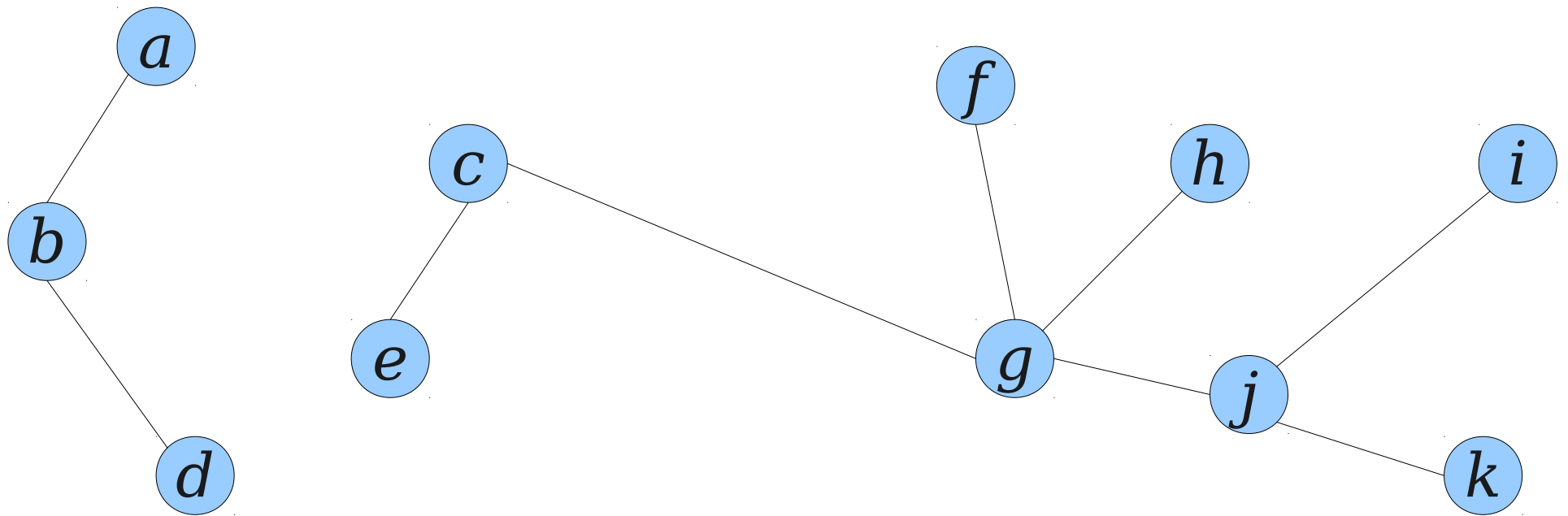


**$c e c b a b d b c g j k j i j g h g f g c$**



# Euler Tours and Dynamic Trees

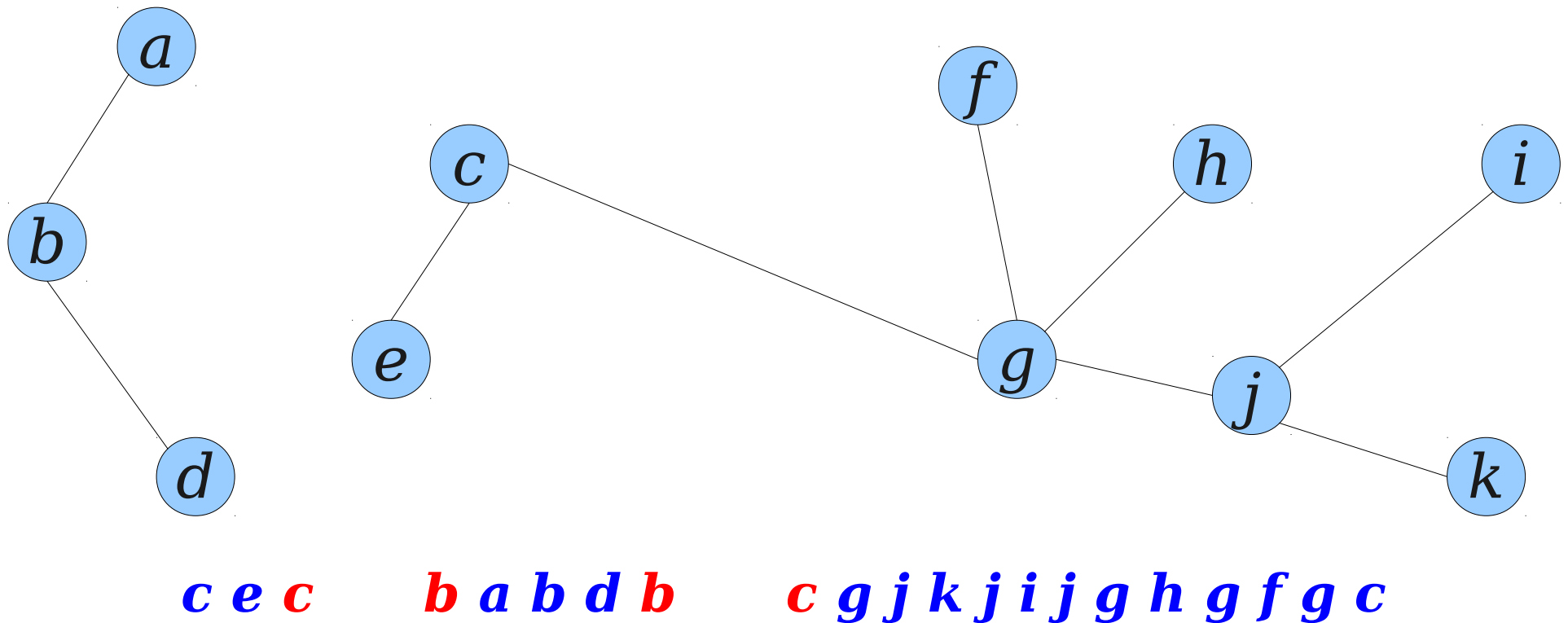
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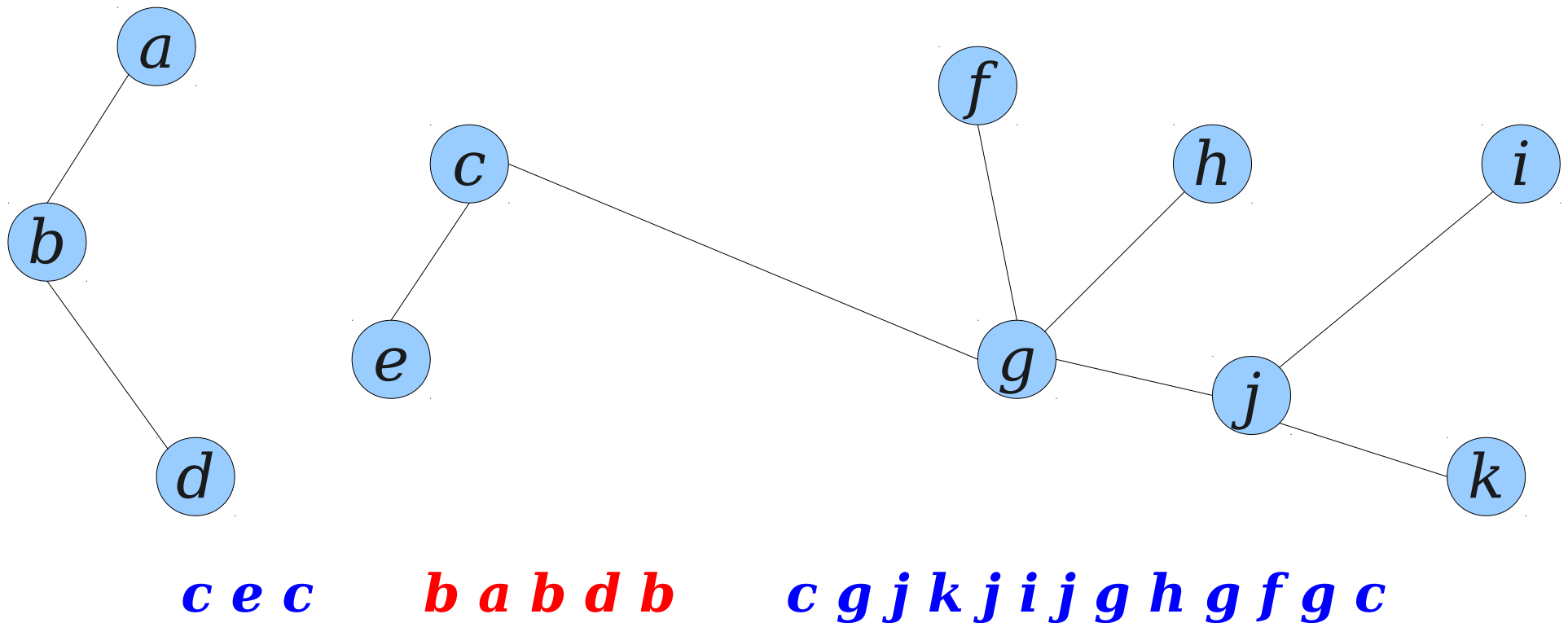
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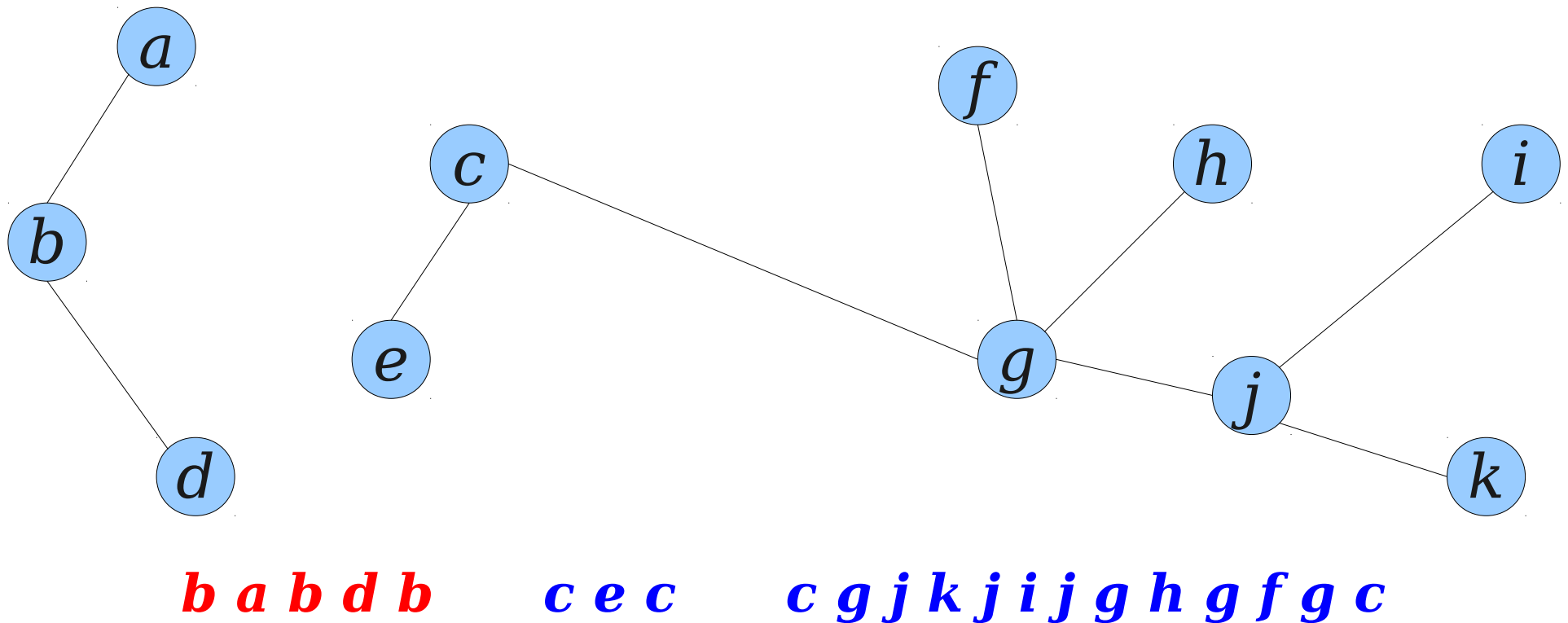
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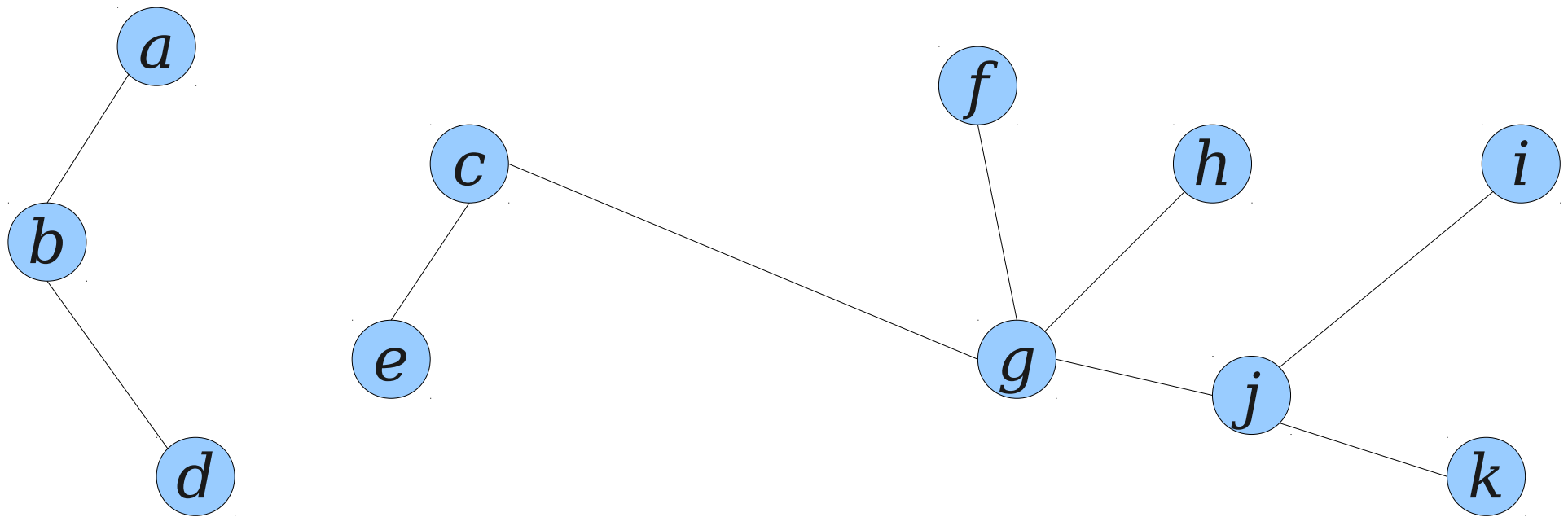
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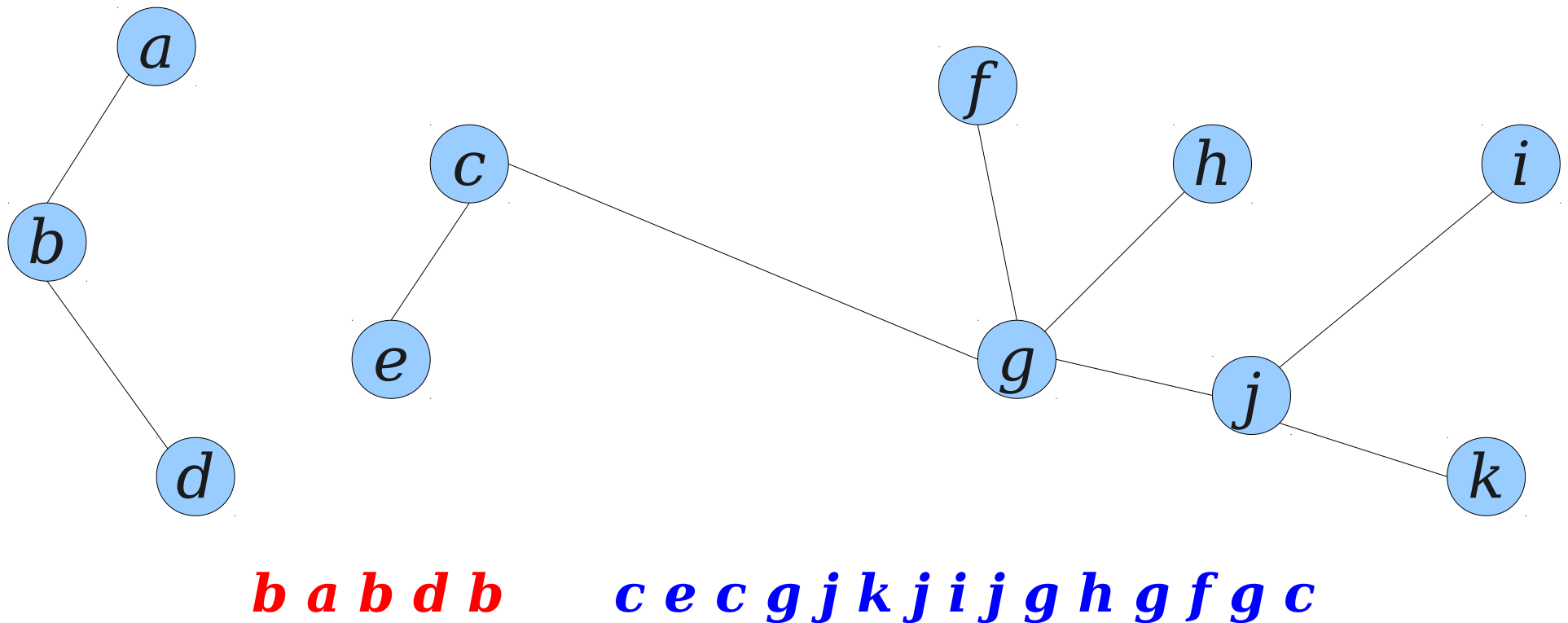


***b a b d b***

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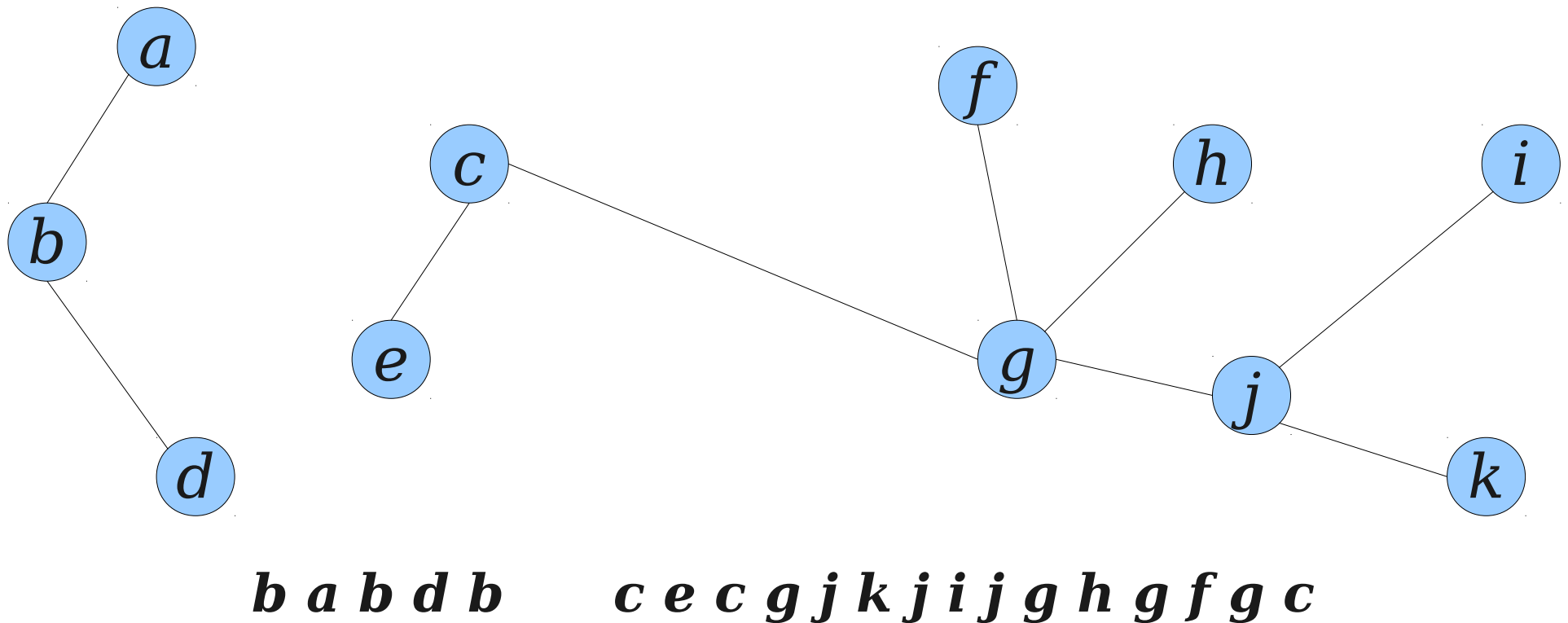
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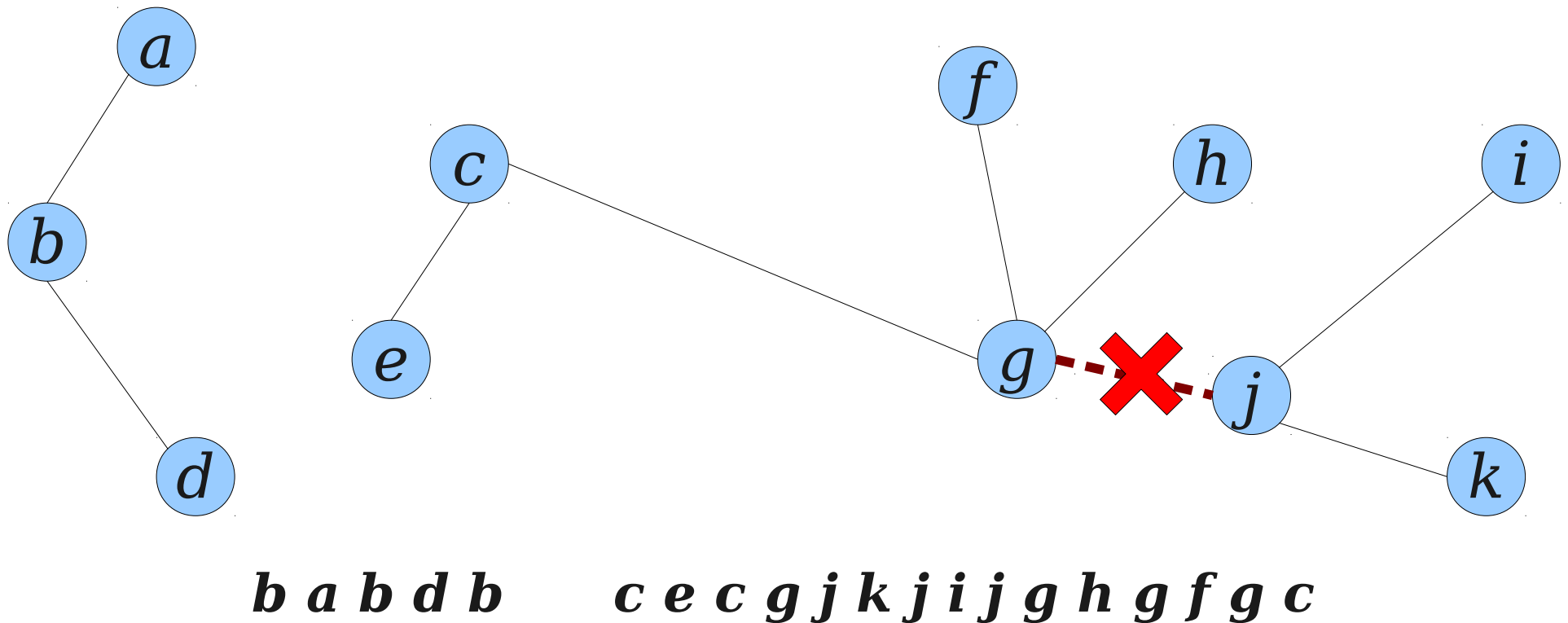
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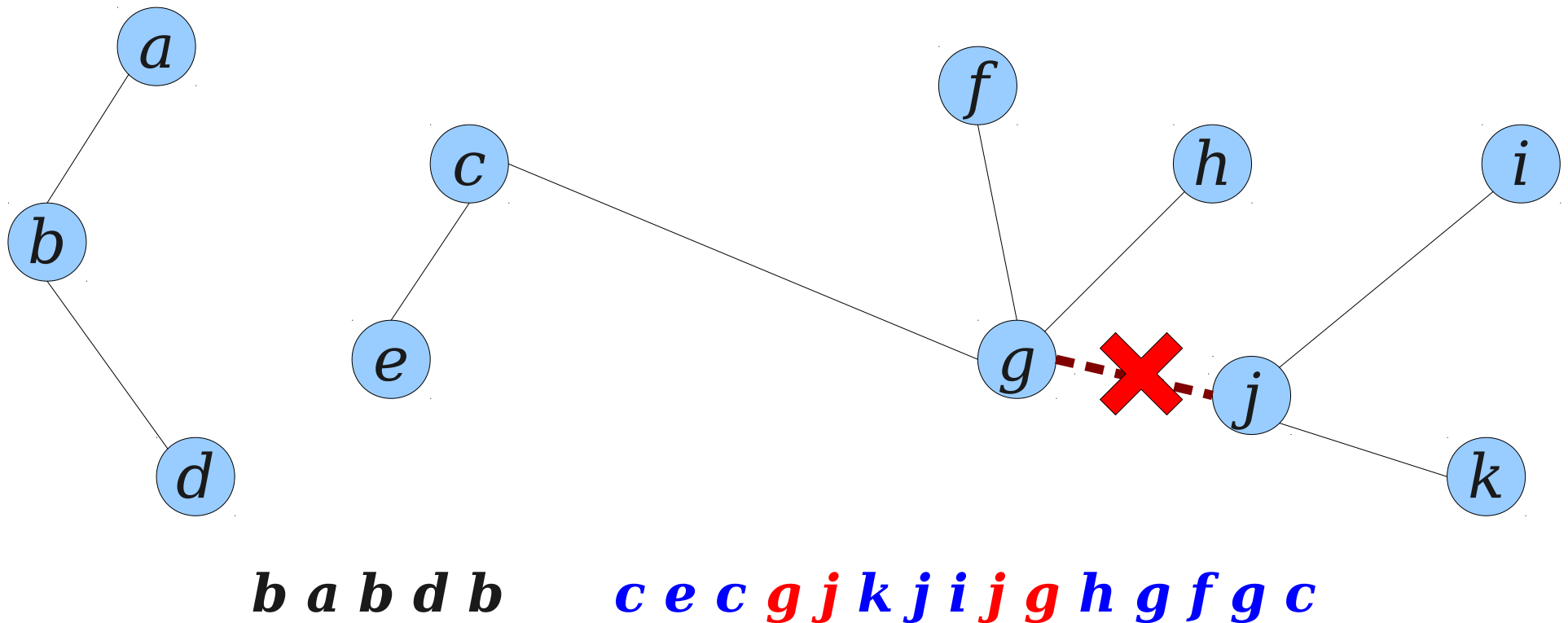
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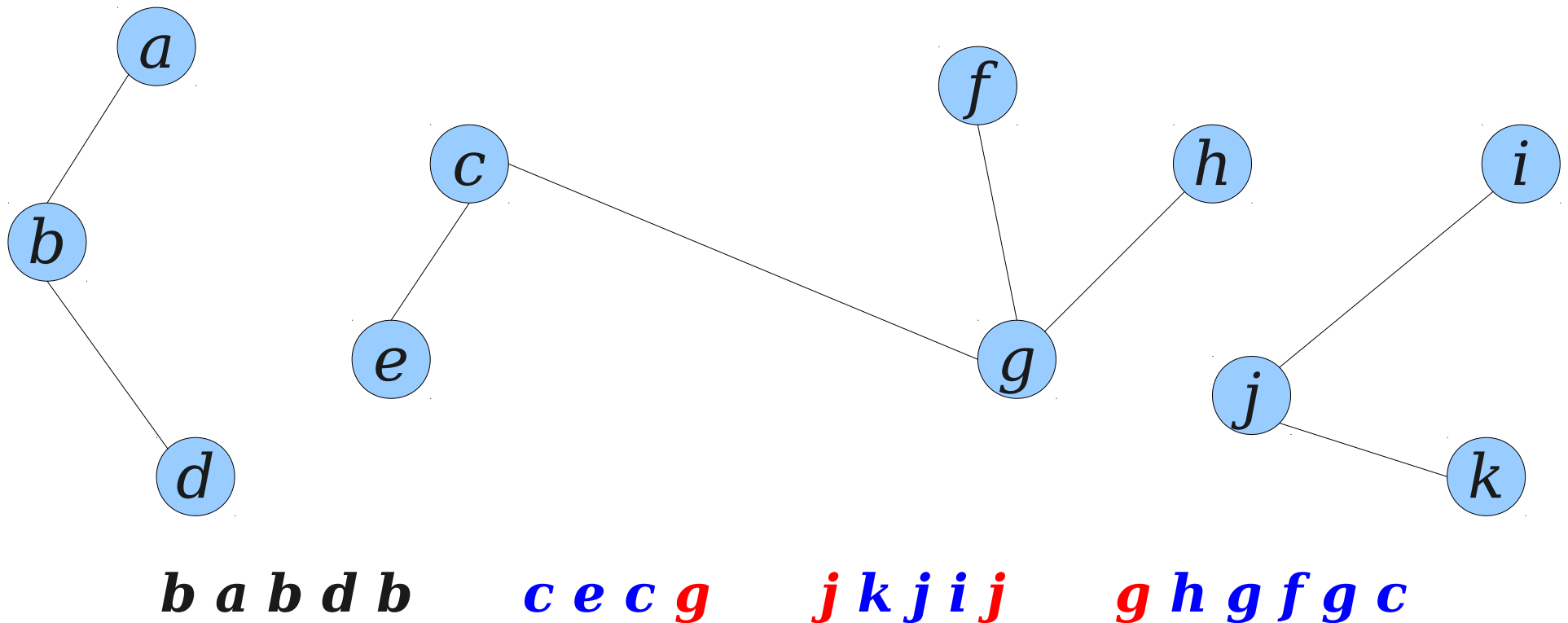
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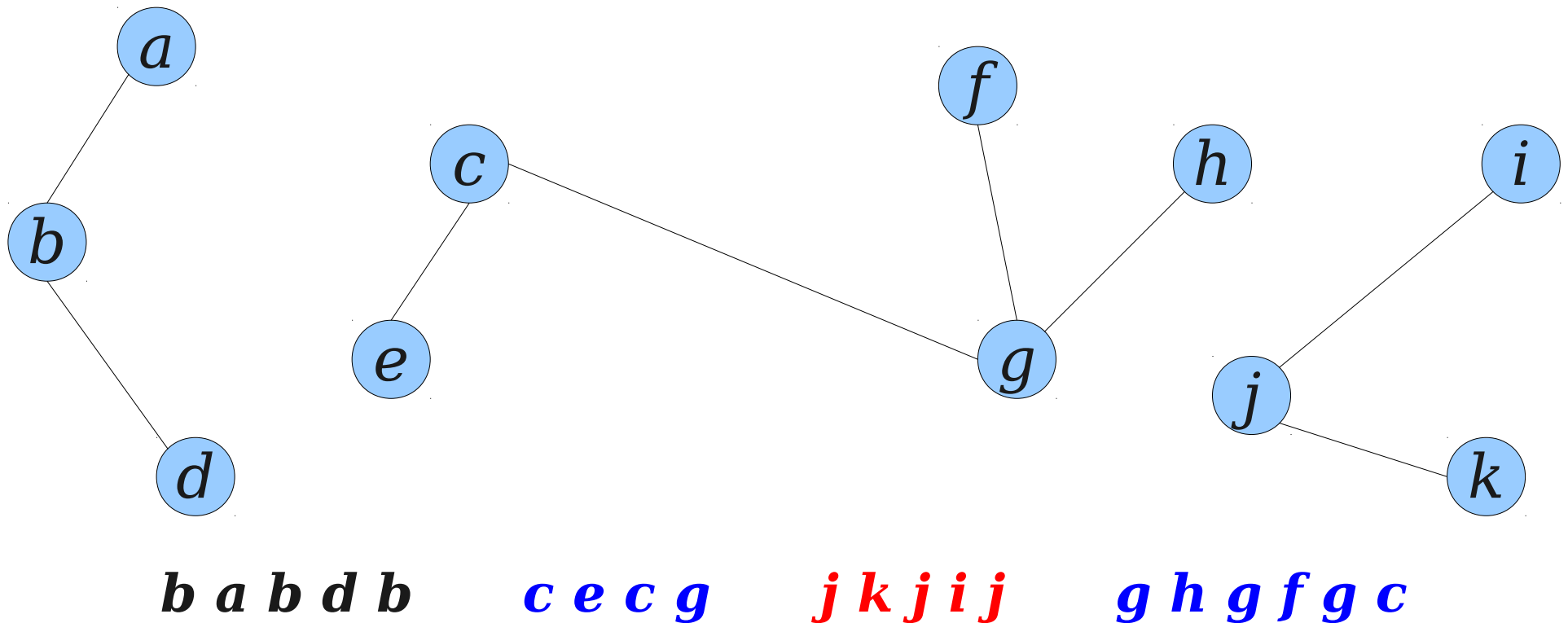
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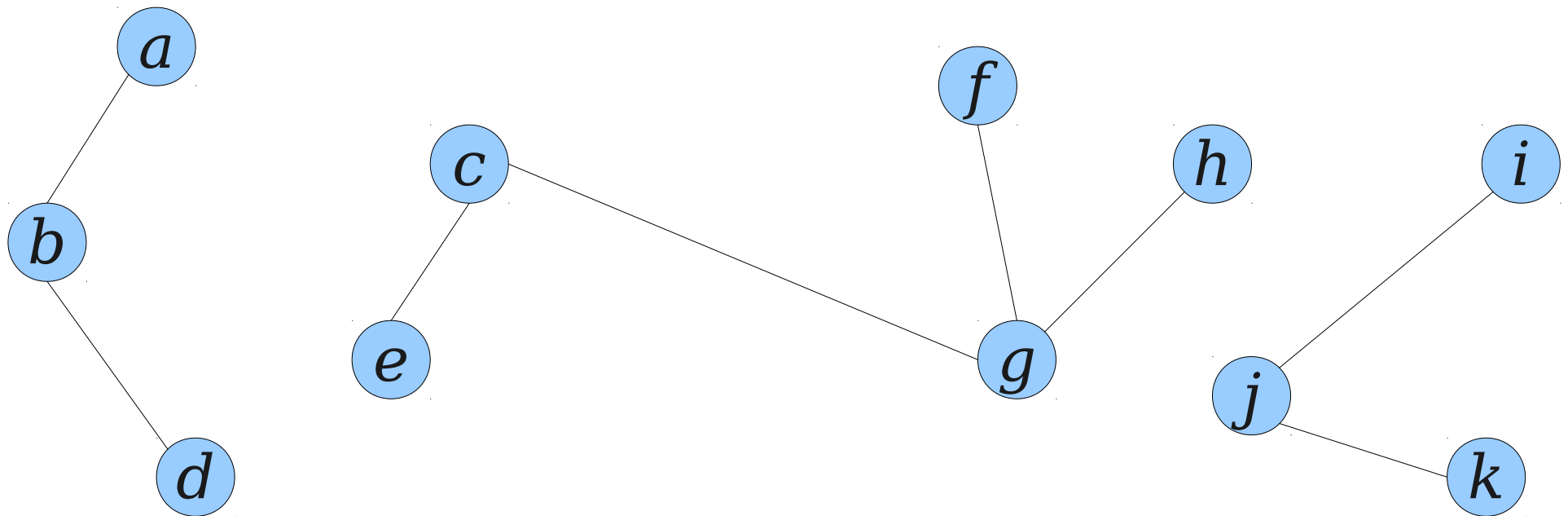
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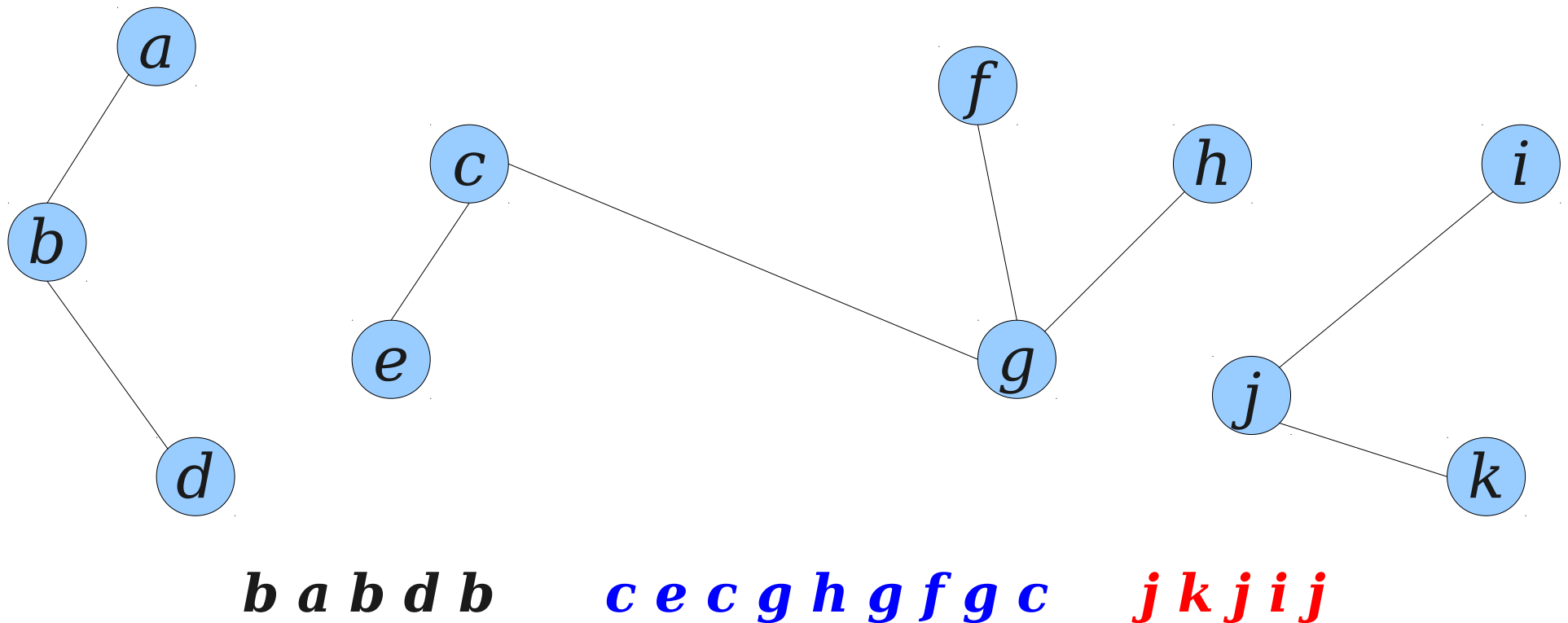
***b a b d b***

***c e c g g h g f g c***

***j k j i j***

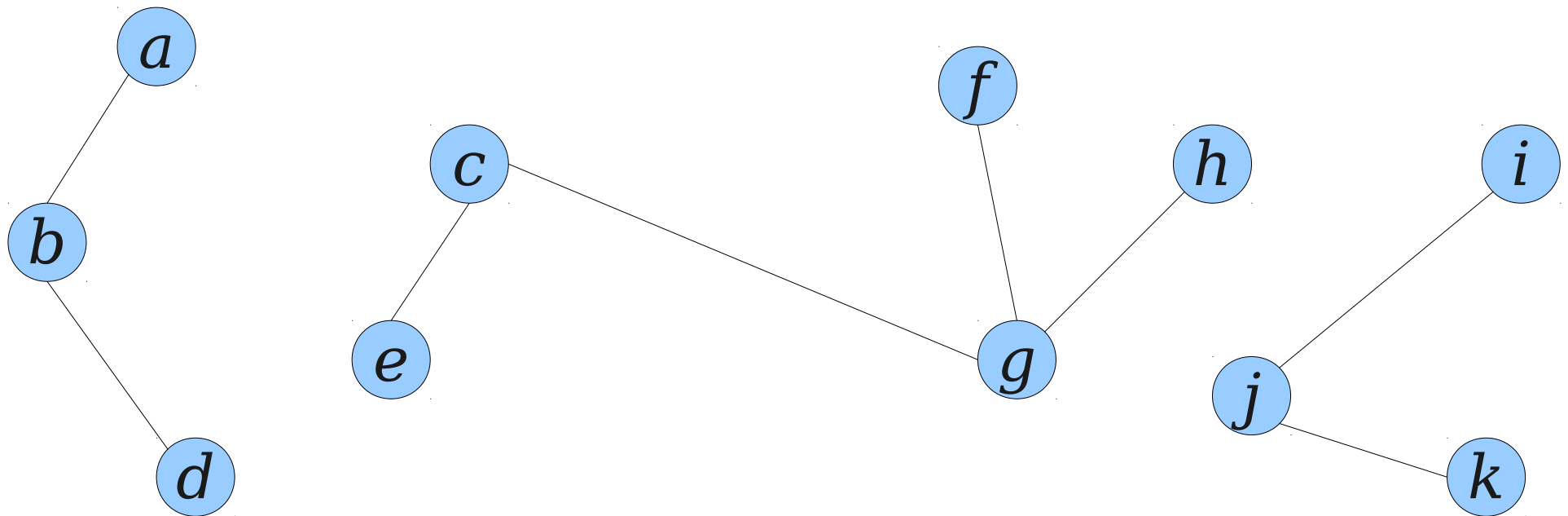
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**$b a b d b$**

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**$j k j i j$**

# Euler Tours and Dynamic Trees

- Given a tree  $T$ , executing **cut( $u, v$ )** cuts the edge  $\{u, v\}$  from the tree (assuming it exists).
- To cut  $T$  into  $T_1$  and  $T_2$  by cutting  $\{u, v\}$ :
  - Let  $E$  be an Euler tour for  $T$ .
  - Split  $E$  at  $(u, v)$  and  $(v, u)$  to get  $J, K, L$ , in that order.
  - Delete the last entry of  $J$ .
  - Then  $E_1 = K$ .
  - Then  $E_2 = J, L$
- **No longer necessary to store the full range of  $u$  and  $v$ .**
- **Now need to store pointers from the edges to the spots where the nodes appear in the trees.**

# Euler Tour Trees

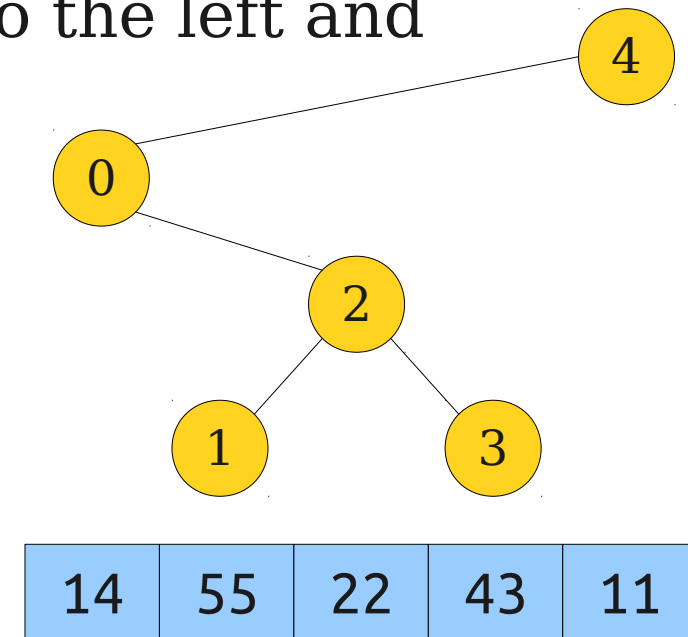
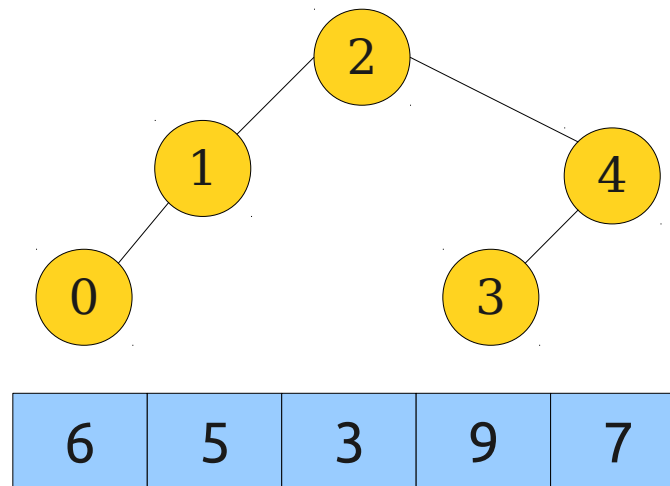
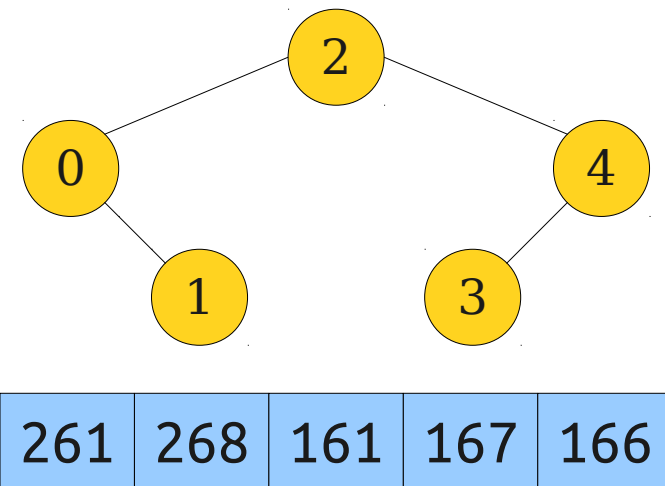
- The data structure:
  - Represent each tree as an Euler tour.
  - Store those sequences as balanced binary trees.
  - Each node in the original forest stores a pointer to some arbitrary occurrence of that node.
  - Each edge in the original forest stores pointers to the nodes appearing when that edge is visited.
    - Can store these edges in a balanced BST.
  - Each node in the balanced trees stores a pointer to its parent.
- *link*, *cut*, and *is-connected* queries take time only  **$O(\log n)$**  each.



# Cartesian Trees Revisited

# Cartesian Trees

- A **Cartesian tree** is a binary tree derived from an array and defined as follows:
  - The empty array has an empty Cartesian tree.
  - For a nonempty array, the root stores the index of the minimum value. Its left and right children are Cartesian trees for the subarrays to the left and right of the minimum.



# Constructing Cartesian Trees

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# Constructing Cartesian Trees

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# Constructing Cartesian Trees



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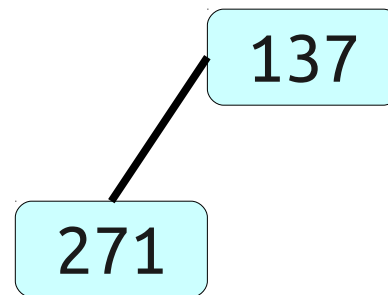
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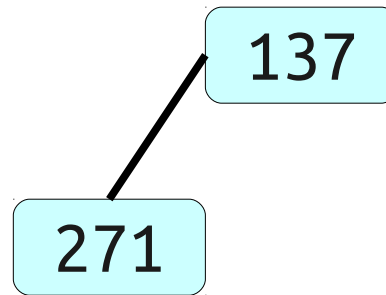
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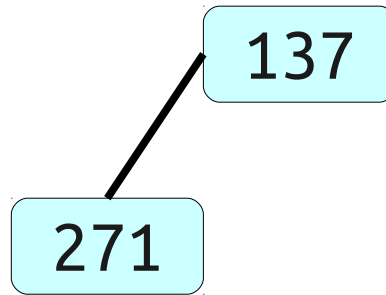


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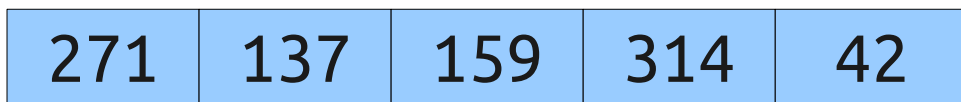
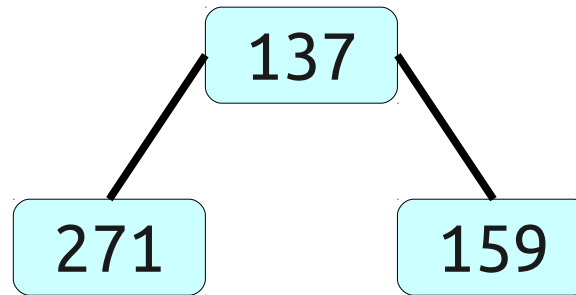
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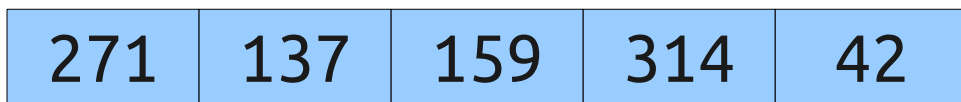
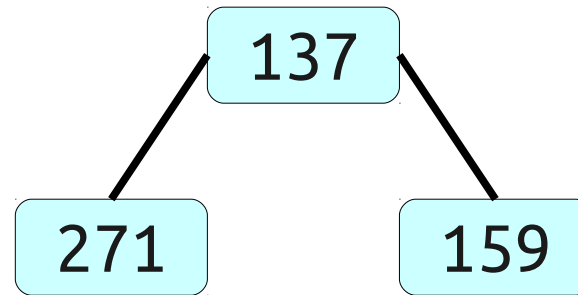
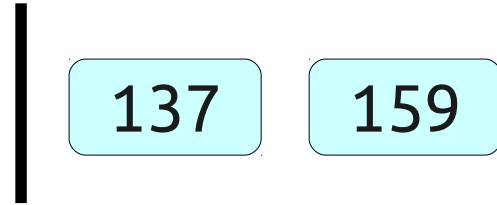
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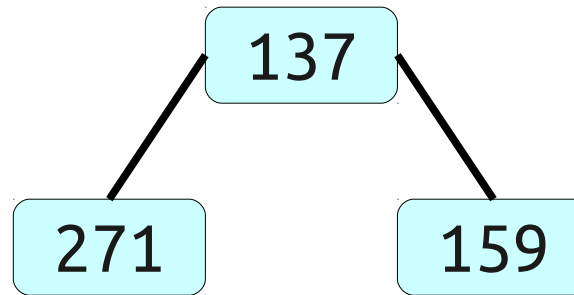


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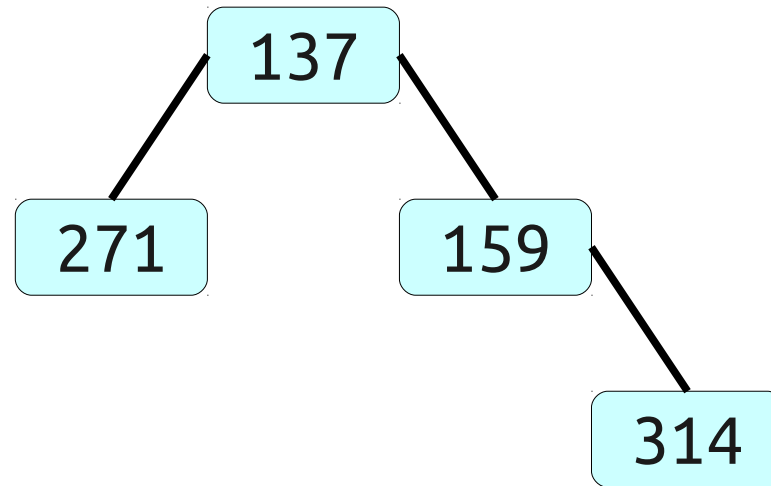
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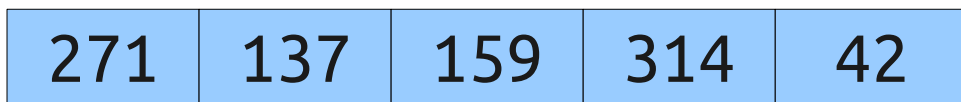
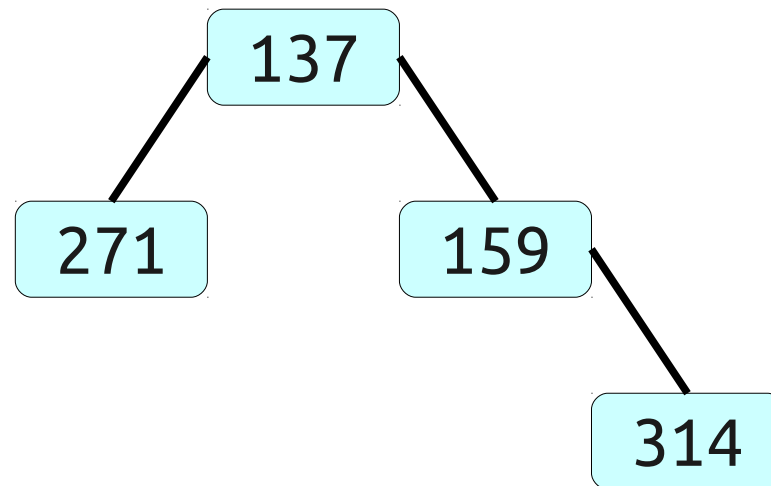
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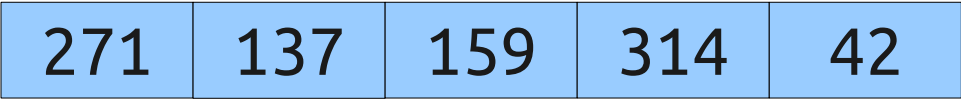
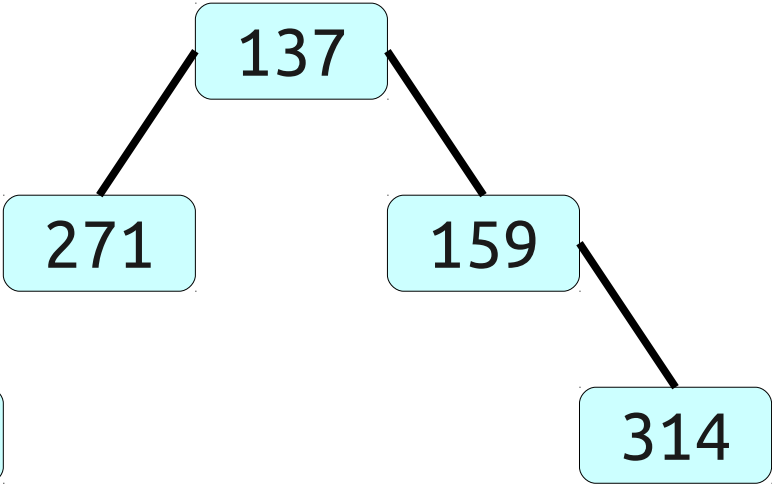


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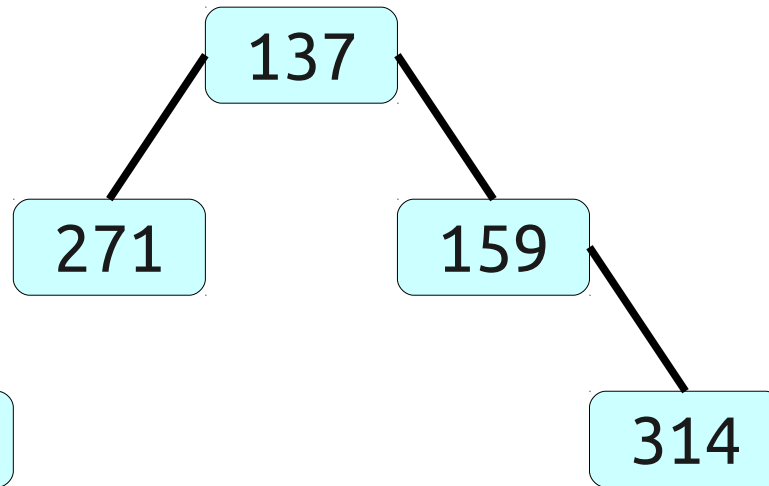


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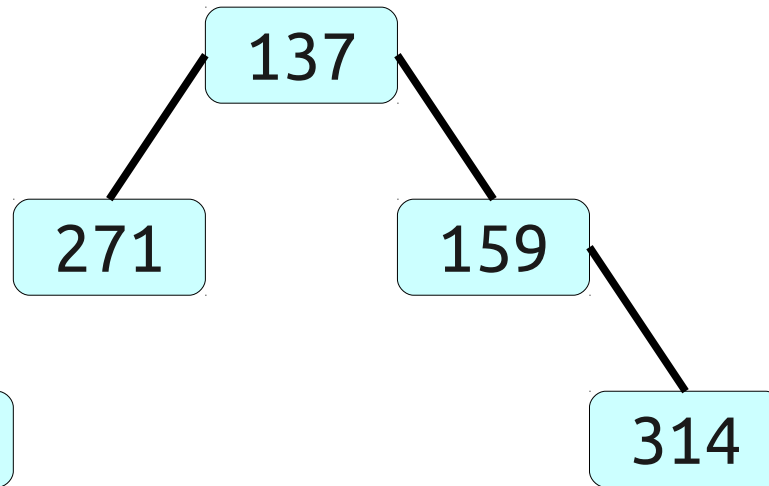


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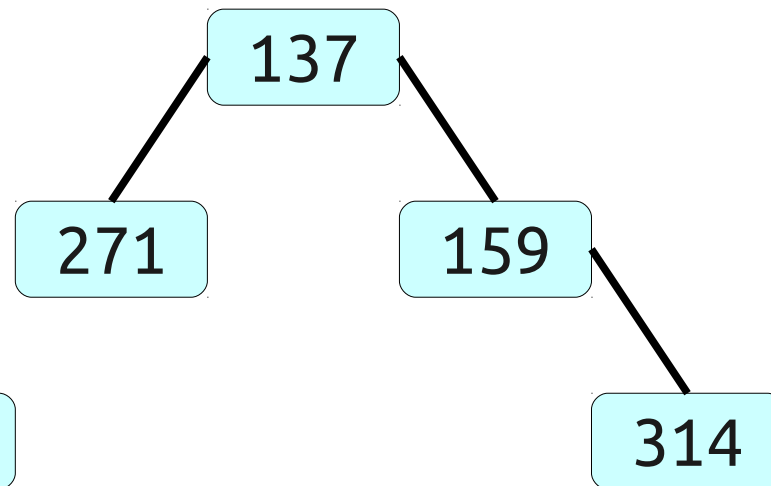
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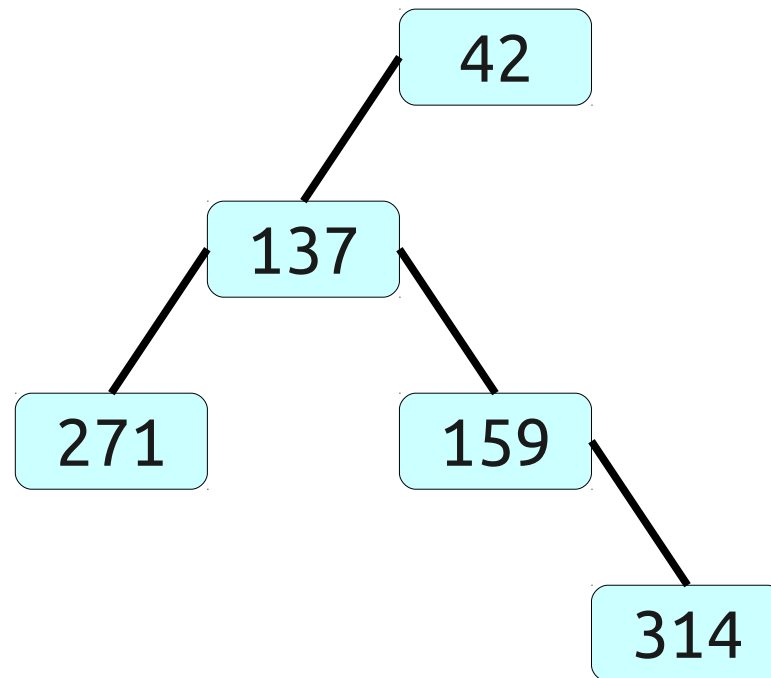
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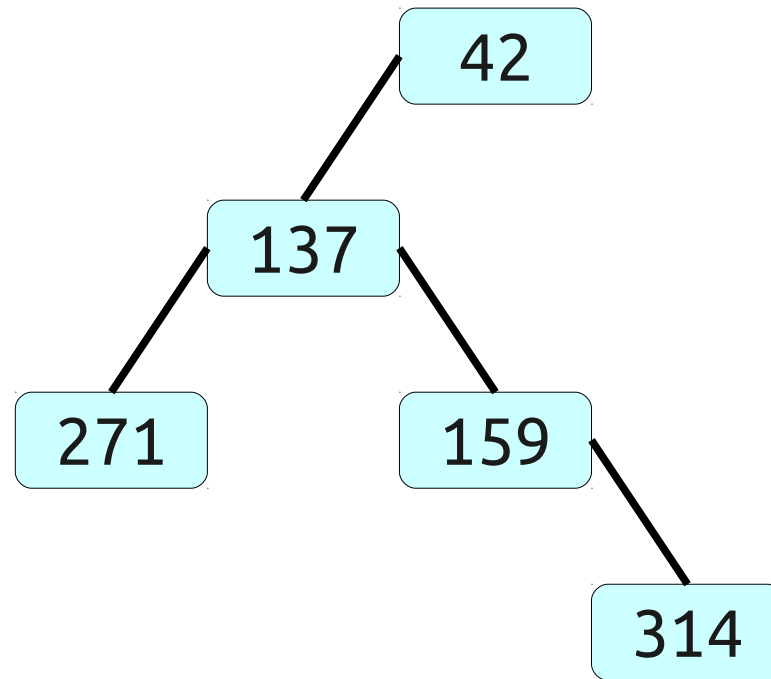


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# Constructing Cartesian Trees



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# The Runtime Analysis

- Adding an individual node to a Cartesian tree might take time  $O(n)$ .
- However, the net time spent adding new nodes across the whole tree is  $O(n)$ .
- Why is this?
  - Every node pushed at most once.
  - Every node popped at most once.
  - Work done is proportional to the number of pushes and pops.
  - Total runtime is  $O(n)$ .

# The Tradeoff

- Typically, we've analyzed data structures by bounding the worst-case runtime of each operation.
- Sometimes, all we care about is the total runtime of a sequence of  $m$  operations, not the cost of each individual operation.
- ***Trade worst-case runtime per operation for worst-case runtime overall.***
- This is a fundamental technique in data structure design.

# The Goal

- Suppose we have a data structure and perform a series of operations  $op_1, op_2, \dots, op_m$ .
  - These operations might be the same operation, or they might be different.
- Let  $t(op_k)$  denote the time required to perform operation  $op_k$ .
- **Goal:** Bound the expression

$$T = \sum_{i=1}^m t(op_i)$$

- There are many ways to do this. We'll see three recurring techniques.



# Amortized Analysis

- An **amortized analysis** is a different way of bounding the runtime of a sequence of operations.
- Each operation  $op_i$  really takes time  $t(op_i)$ .
- **Idea:** Assign to each operation  $op_i$  a new cost  $a(op_i)$ , called the **amortized cost**, such that

$$\sum_{i=1}^m t(op_i) \leq \sum_{i=1}^m a(op_i)$$

- If the values of  $a(op_i)$  are chosen wisely, the second sum can be much easier to evaluate than the first.

# The Aggregate Method

- In the **aggregate method**, we directly evaluate

$$T = \sum_{i=1}^m t(op_i)$$

and then set  $a(op_i) = T / m$ .

- Assigns each operation the average of all the operation costs.
- The aggregate method says that the cost of a Cartesian tree insertion is amortized  $O(1)$ .

# Amortized Analysis

- We will see two types of amortized analysis today:
  - The **banker's method** (also called the **accounting method**) works by placing “credits” on the data structure redeemable for units of work.
  - The **potential method** (also called the **physicist's method**) works by assigning a potential function to the data structure and factoring in changes to that potential to the overall runtime.
- All three techniques are useful at different times, so we'll see how to use all three today.

# The Banker's Method

# The Banker's Method

- In the **banker's method**, operations can place **credits** on the data structure or spend credits that have already been placed.
- Placing a credit somewhere takes time  $O(1)$ .
- Credits may be removed from the data structure to pay for  $O(1)$  units of work.
- Note: the credits don't actually show up in the data structure. It's just an accounting trick.
- The amortized cost of an operation is

$$a(op_i) = t(op_i) + O(1) \cdot (added_i - removed_i)$$

# The Banker's Method

- If we never spend credits we don't have:

$$\sum_{i=1}^m a(op_i) = \sum_{i=1}^m (t(op_i) + O(1) \cdot (added_i - removed_i))$$

# The Banker's Method

- If we never spend credits we don't have:

$$\begin{aligned}\sum_{i=1}^m a(op_i) &= \sum_{i=1}^m (t(op_i) + O(1) \cdot (added_i - removed_i)) \\ &= \sum_{i=1}^m t(op_i) + O(1) \sum_{i=1}^m (added_i - removed_i)\end{aligned}$$

# The Banker's Method

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# The Banker's Method

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# The Banker's Method

- If we never spend credits we don't have:

$$\begin{aligned}\sum_{i=1}^m a(op_i) &= \sum_{i=1}^m (t(op_i) + O(1) \cdot (added_i - removed_i)) \\ &= \sum_{i=1}^m t(op_i) + O(1) \sum_{i=1}^m (added_i - removed_i) \\ &= \sum_{i=1}^m t(op_i) + O(1) \cdot netCredits \\ &\geq \sum_{i=1}^m t(op_i)\end{aligned}$$

- The sum of the amortized costs upper-bounds the sum of the true costs.

# Constructing Cartesian Trees

|

271	137	159	314	42
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# Constructing Cartesian Trees

|

271

271

137

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314

42

# Constructing Cartesian Trees

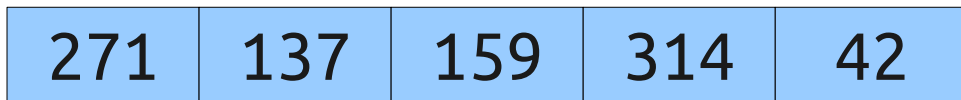
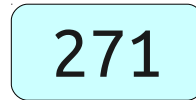
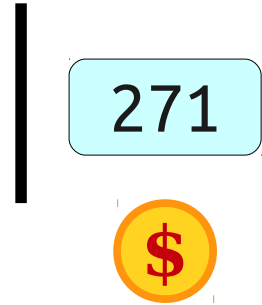


271

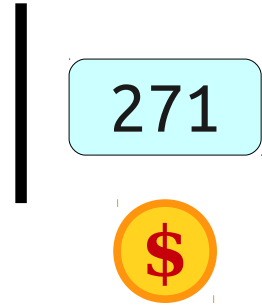
271

271	137	159	314	42
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# Constructing Cartesian Trees



# Constructing Cartesian Trees

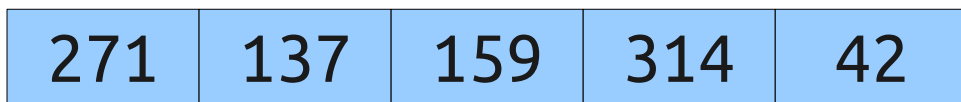
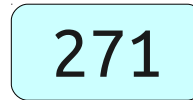
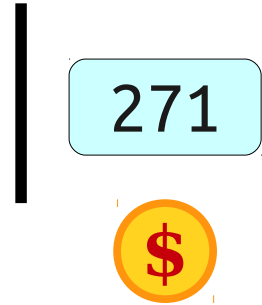


Work done: 1 push  
Credits Added: \$1  
Amortized Cost: **2**

271

271	137	159	314	42
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# Constructing Cartesian Trees





# Constructing Cartesian Trees



271



271

137

271	137	159	314	42
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# Constructing Cartesian Trees



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137

271	137	159	314	42
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# Constructing Cartesian Trees

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271

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271

137

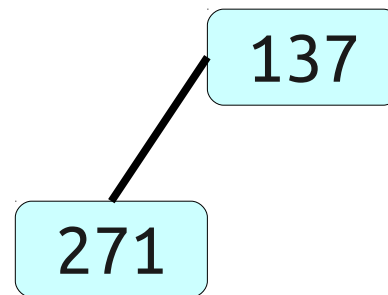
159

314

42

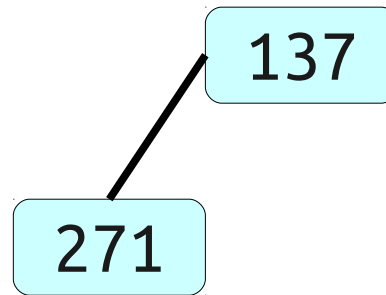
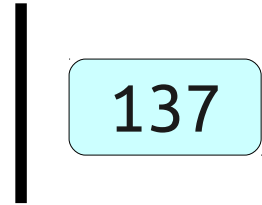
# Constructing Cartesian Trees

|



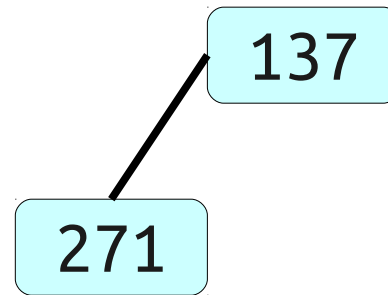
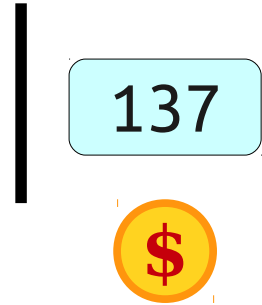
271	137	159	314	42
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# Constructing Cartesian Trees



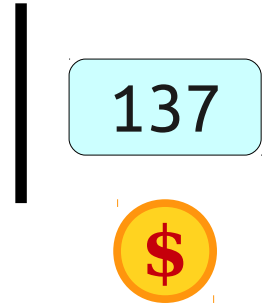
271	137	159	314	42
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# Constructing Cartesian Trees

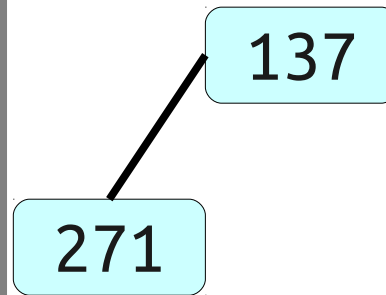


271	137	159	314	42
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# Constructing Cartesian Trees

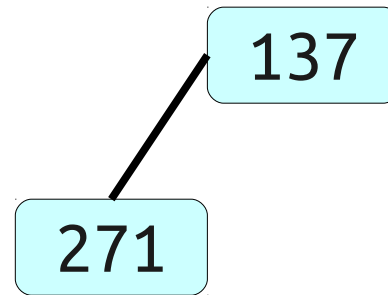
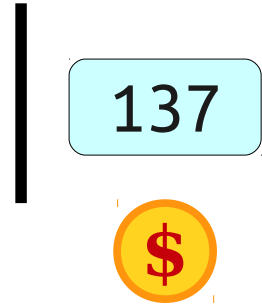


Work done: 1 push, 1 pop  
Credits Removed: \$1  
Credits Added: \$1  
Amortized Cost: **2**



271	137	159	314	42
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# Constructing Cartesian Trees



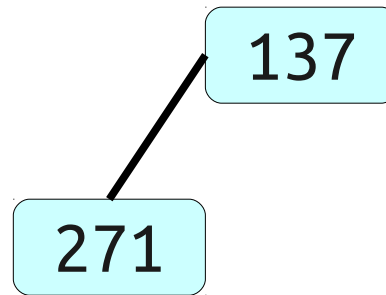
271	137	159	314	42
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# Constructing Cartesian Trees



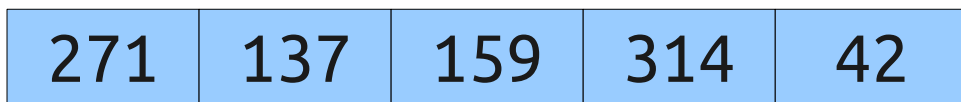
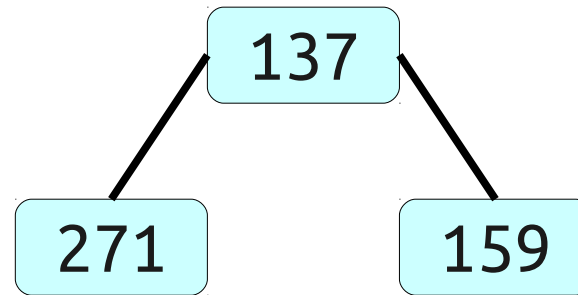
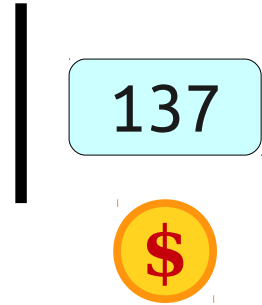
137



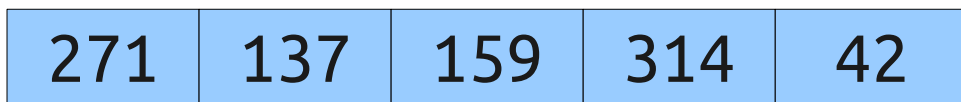
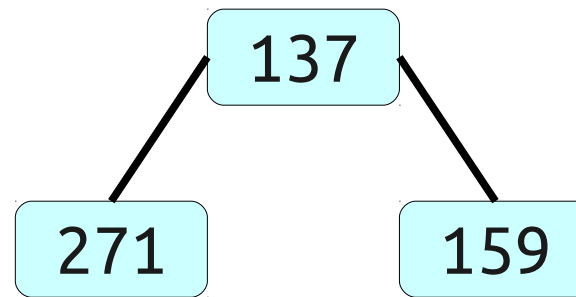
159

271	137	159	314	42
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# Constructing Cartesian Trees



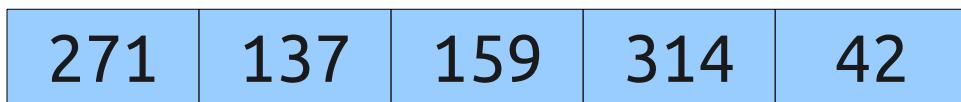
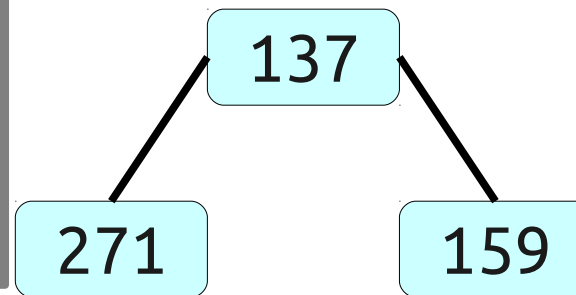
# Constructing Cartesian Trees



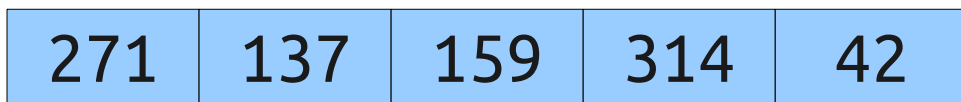
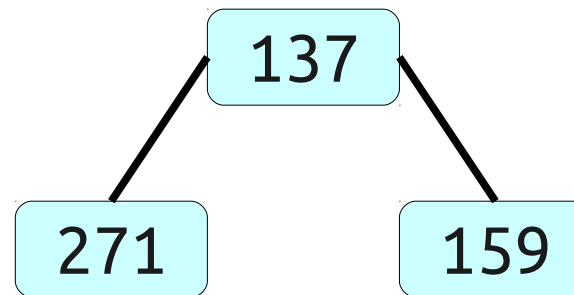
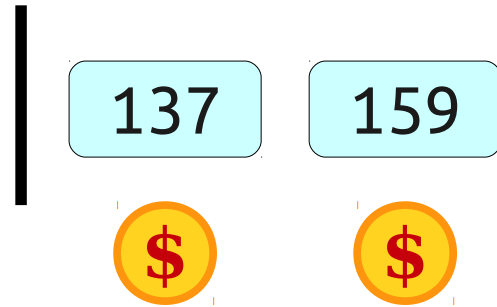
# Constructing Cartesian Trees



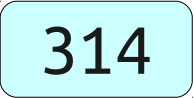
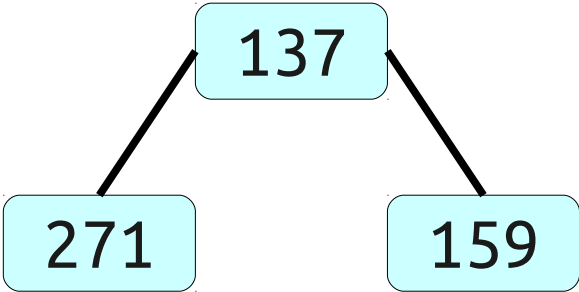
Work done: 1 push  
Credits Added: \$1  
Amortized Cost: **2**



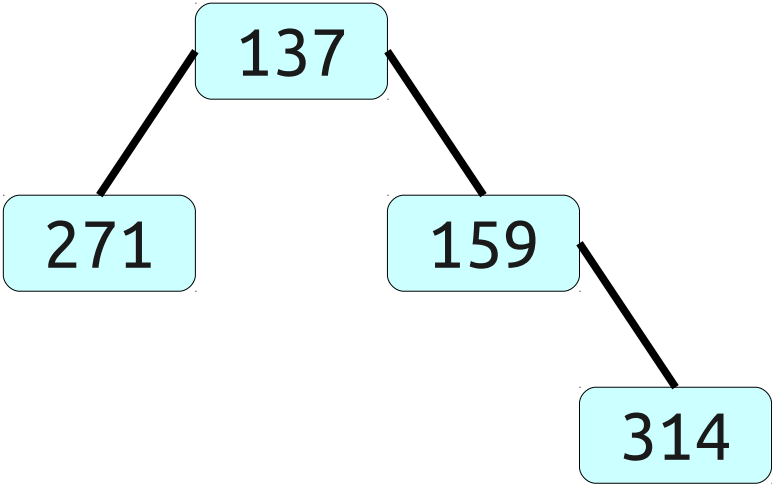
# Constructing Cartesian Trees



# Constructing Cartesian Trees

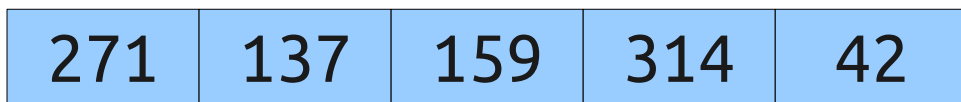
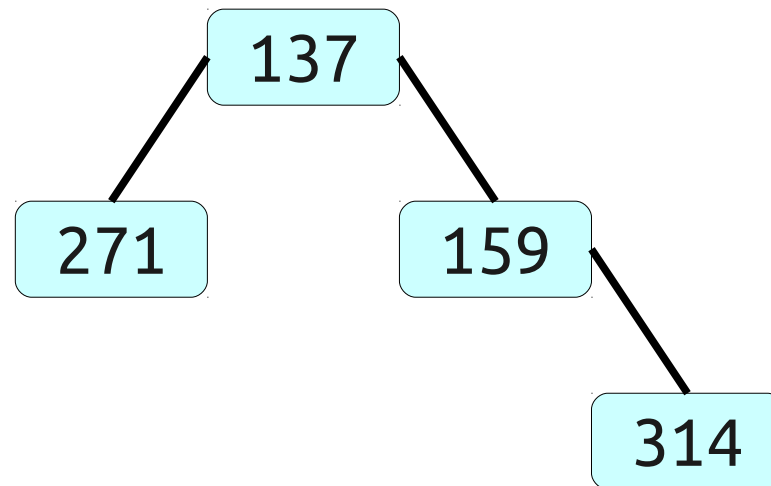


# Constructing Cartesian Trees



271	137	159	314	42
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# Constructing Cartesian Trees

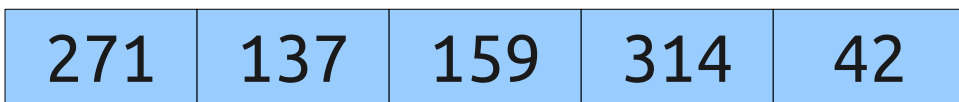
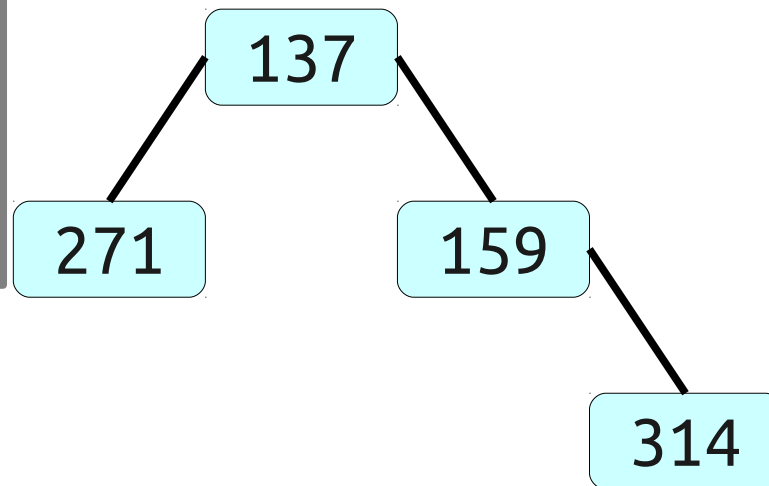




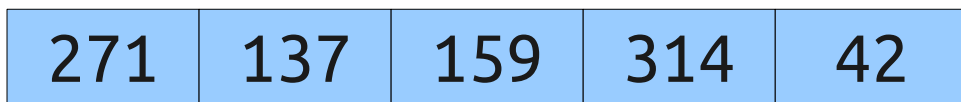
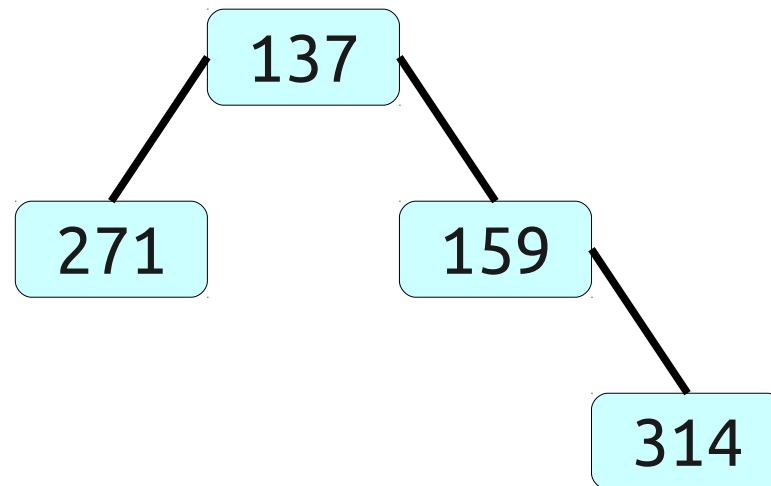
# Constructing Cartesian Trees



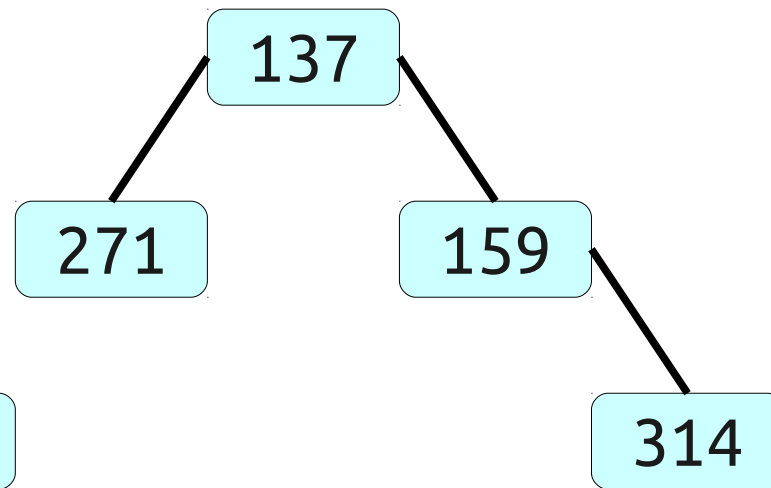
Work done: 1 push  
Credits Added: \$1  
Amortized Cost: **2**



# Constructing Cartesian Trees



# Constructing Cartesian Trees

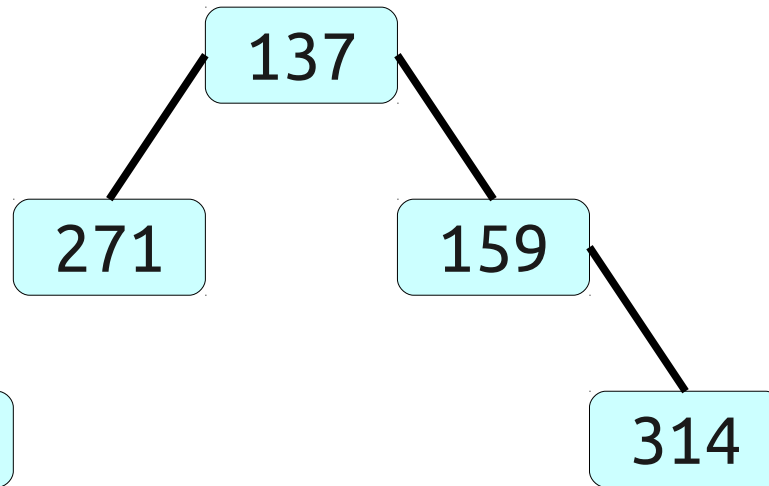


# Constructing Cartesian Trees



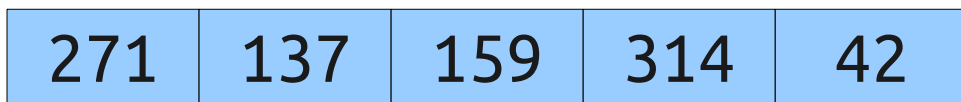
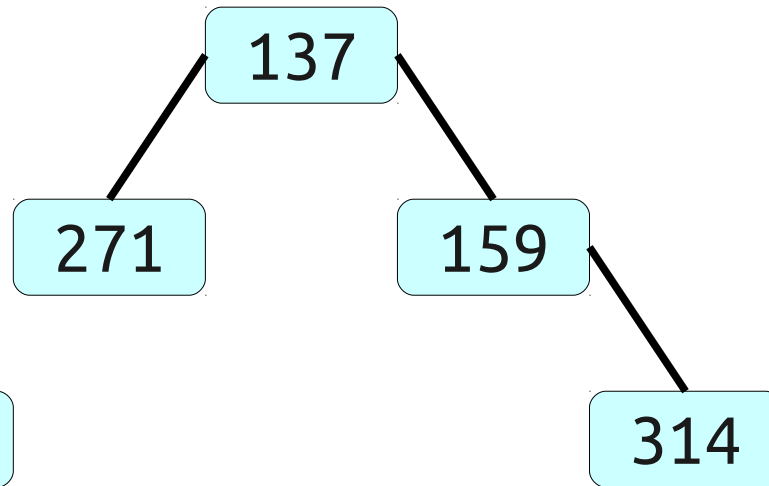
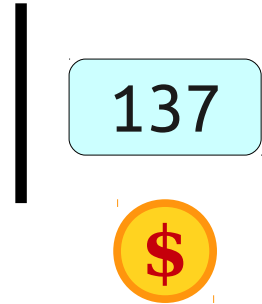
137

159



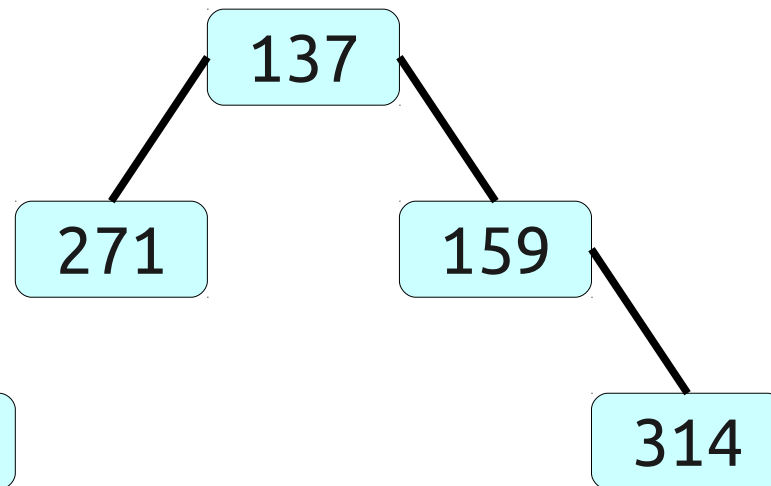
271	137	159	314	42
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# Constructing Cartesian Trees



# Constructing Cartesian Trees

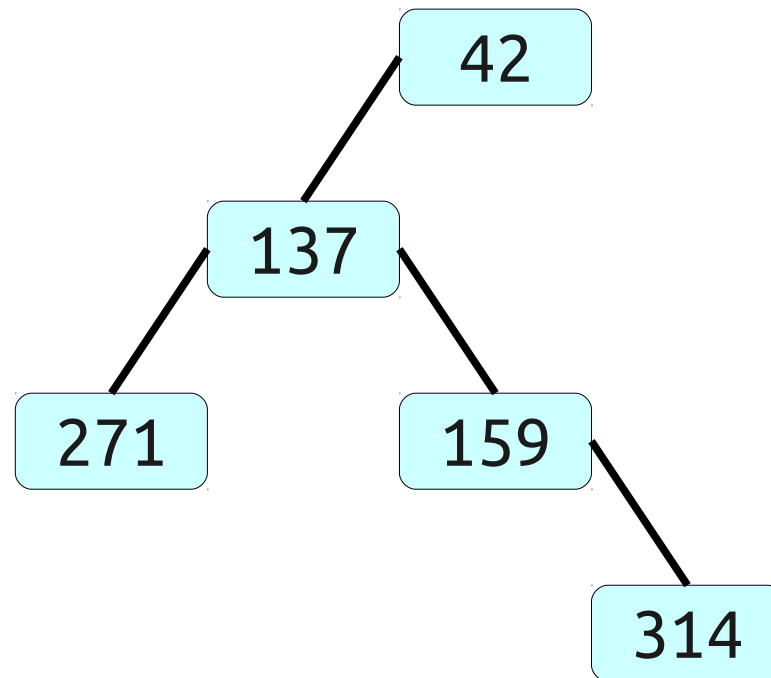
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271	137	159	314	42
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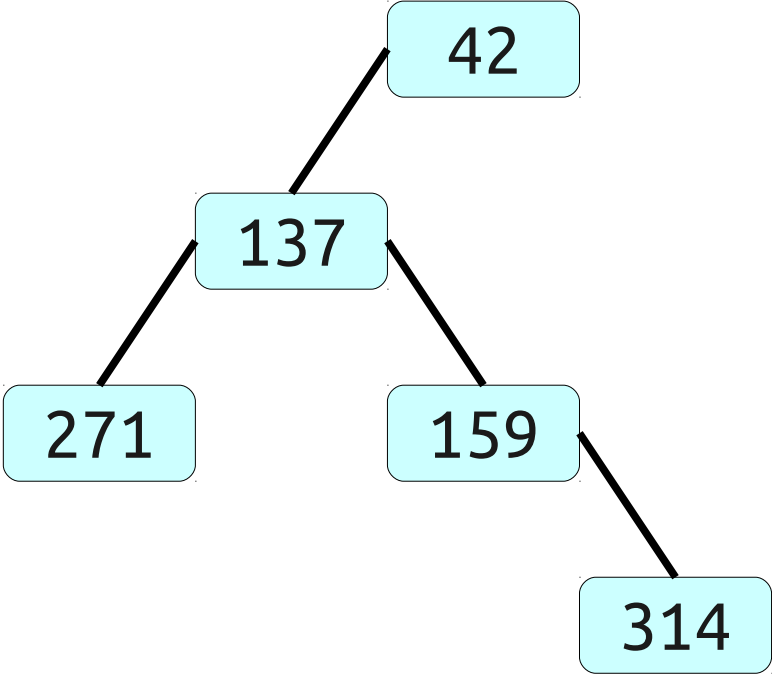
# Constructing Cartesian Trees

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271	137	159	314	42
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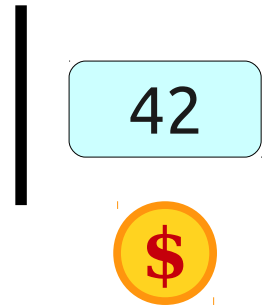
# Constructing Cartesian Trees



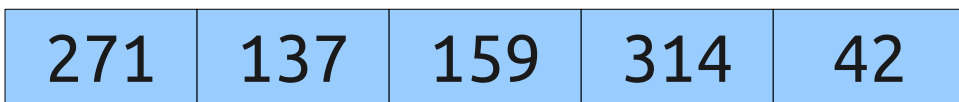
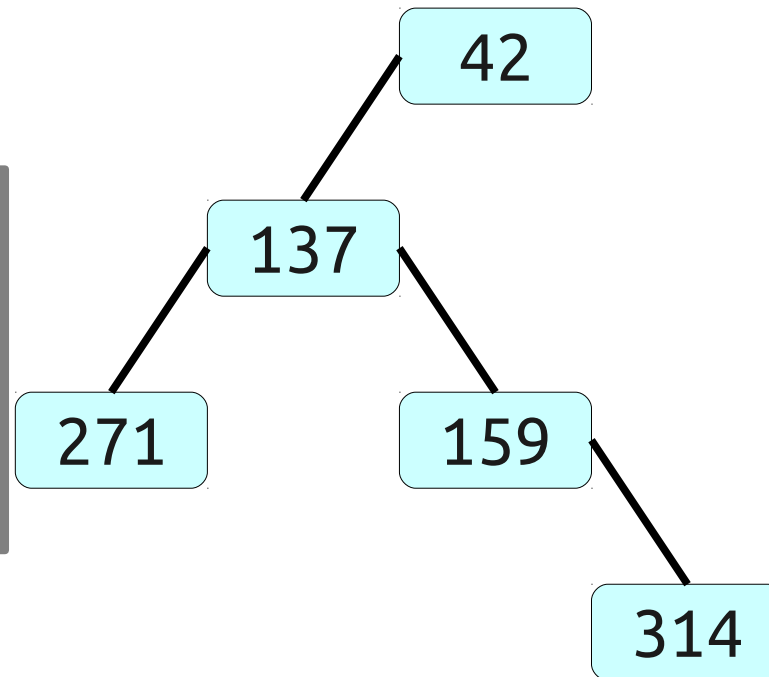
271	137	159	314	42
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# Constructing Cartesian Trees



Work done: 1 push, 3 pops  
Credits Removed: \$3  
Credits Added: \$1  
Amortized Cost: **2**



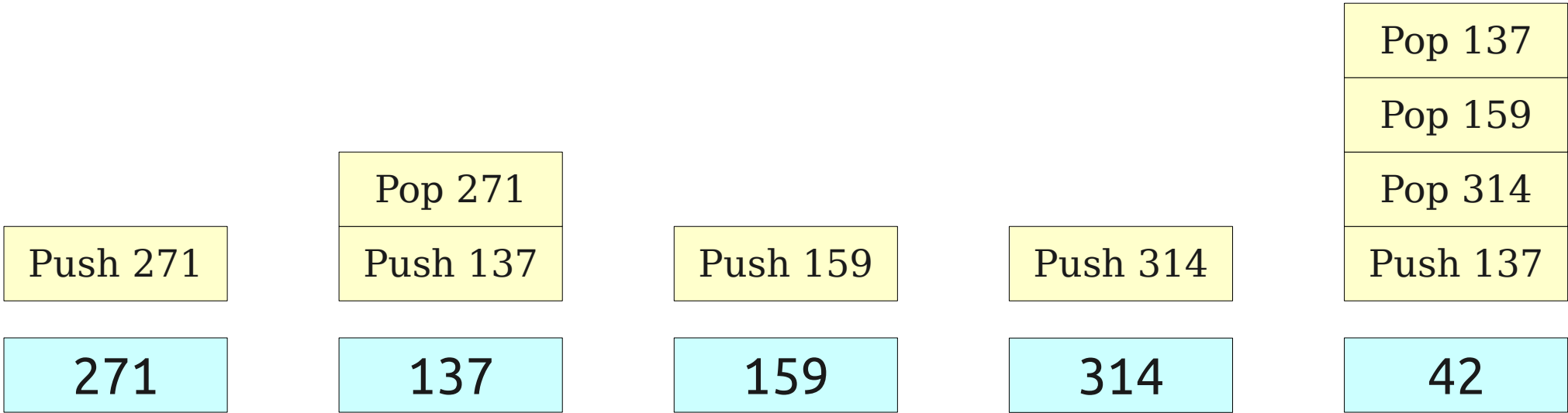
# The Banker's Method

- Using the banker's method, the cost of an insertion is

$$\begin{aligned} & t(op) + O(1) \cdot (added_i - removed_i) \\ &= 1 + k + O(1) \cdot (1 - k) \\ &= 1 + k + 1 - k \\ &= 2 \\ &= \mathbf{O(1)} \end{aligned}$$

- Each insertion has amortized cost  $O(1)$ .
- Any  $n$  insertions will take time  $O(n)$ .

# Intuiting the Banker's Method



# Intuiting the Banker's Method

Pop 271
Push 271

271

Push 137

137

Push 159

159

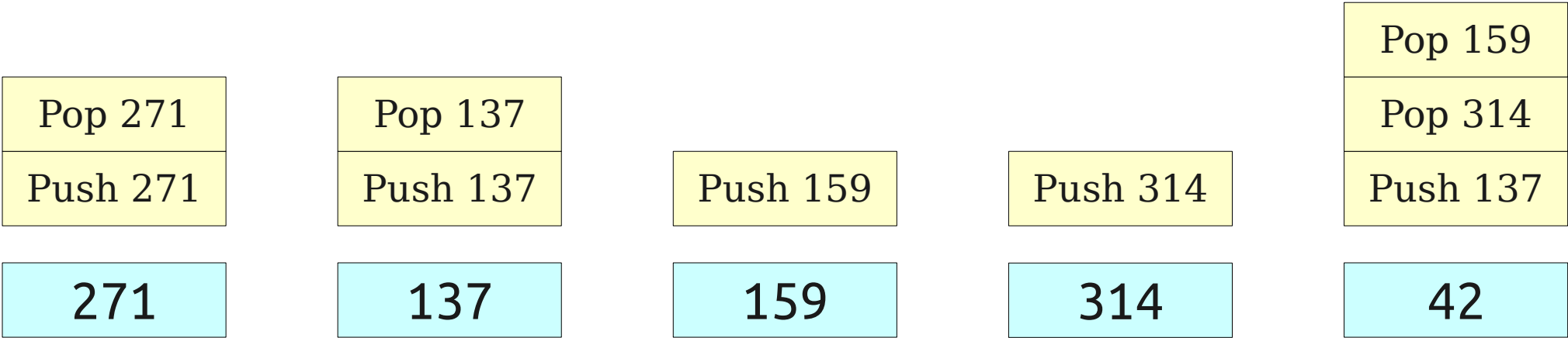
Push 314

314

Pop 137
Pop 159
Pop 314
Push 137

42

# Intuiting the Banker's Method



# Intuiting the Banker's Method

Pop 271
Push 271

Pop 137
Push 137

Pop 159
Push 159

Push 314
----------

Pop 314
Push 137

271
-----

137
-----

159
-----

314
-----

42
----

# Intuiting the Banker's Method

Pop 271
Push 271

271
-----

Pop 137
Push 137

137
-----

Pop 159
Push 159

159
-----

Pop 314
Push 314

314
-----

Push 137
----------

42
----

# Intuiting the Banker's Method

Each operation here is being “charged” for two units of work, even if didn't actually do two units of work.

Pop 271
Push 271

Pop 137
Push 137

Pop 159
Push 159

Pop 314
Push 314

Push 137
----------

271
-----

137
-----

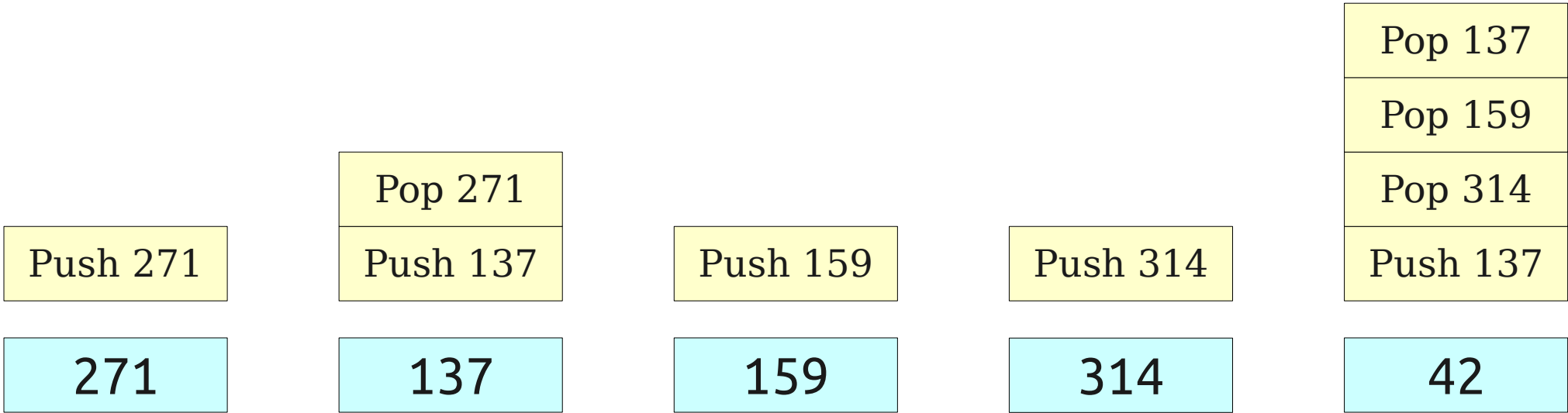
159
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314
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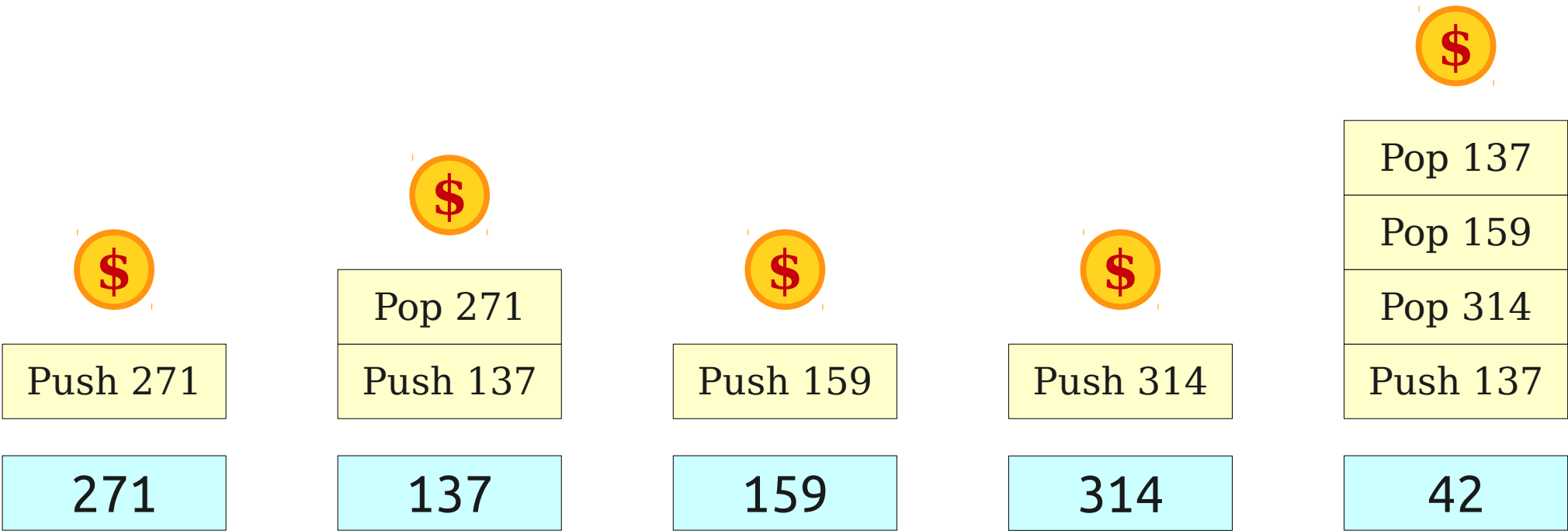
42
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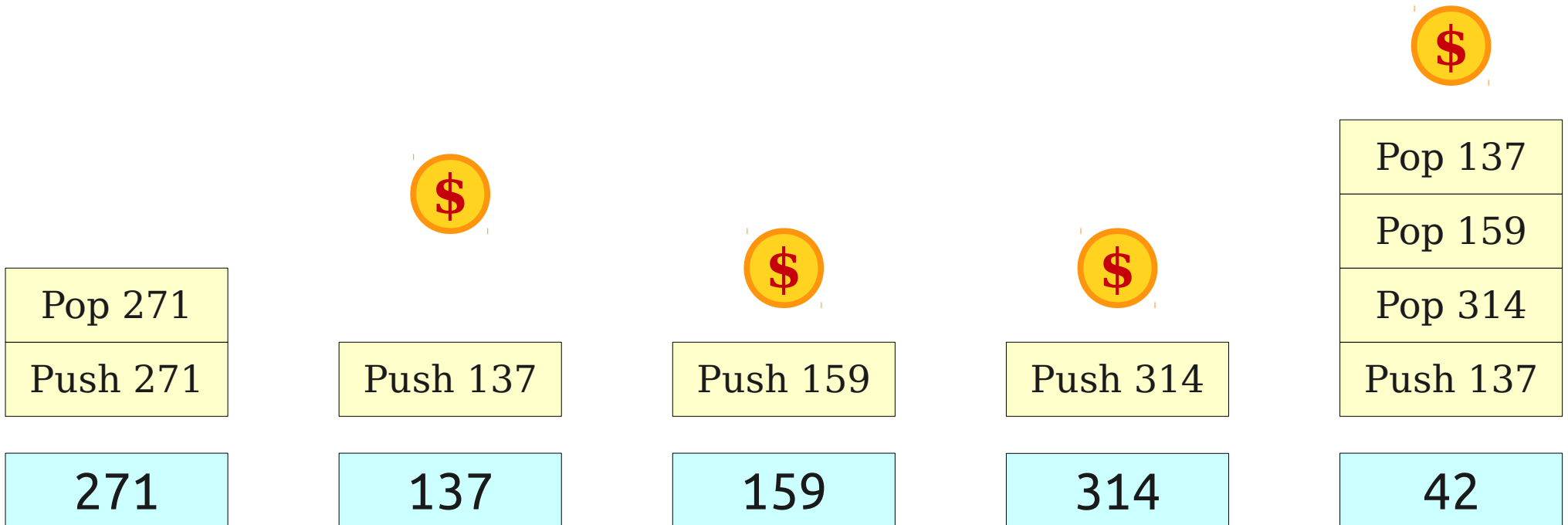
# Intuiting the Banker's Method



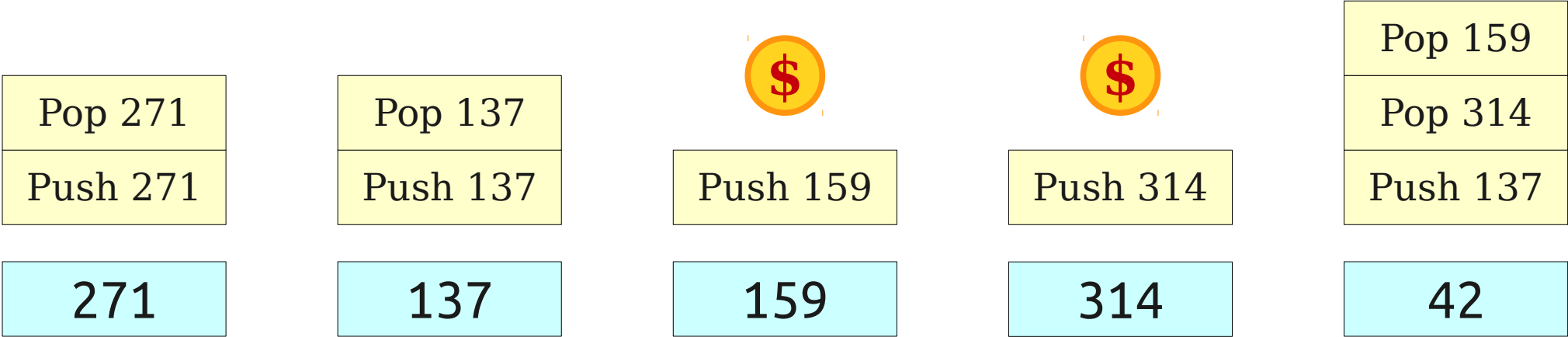
# Intuiting the Banker's Method



# Intuiting the Banker's Method



# Intuiting the Banker's Method



# Intuiting the Banker's Method



Pop 271
Push 271

271
-----

Pop 137
Push 137

137
-----

Pop 159
Push 159

159
-----



Push 314
----------

314
-----

Pop 314
Push 137

42
----

# Intuiting the Banker's Method



Pop 271
Push 271

271
-----

Pop 137
Push 137

137
-----

Pop 159
Push 159

159
-----

Pop 314
Push 314

314
-----

Push 137
----------

42
----

# Intuiting the Banker's Method

Each credit placed can be used to “move” a unit of work from one operation to another.



Pop 271
Push 271

Pop 137
Push 137

Pop 159
Push 159

Pop 314
Push 314

Push 137
----------

271
-----

137
-----

159
-----

314
-----

42
----

# An Observation

- We defined the amortized cost of an operation to be

$$a(op_i) = t(op_i) + O(1) \cdot (added_i - removed_i)$$

- Equivalently, this is

$$a(op_i) = t(op_i) + O(1) \cdot \Delta credits_i$$

- Some observations:
  - It doesn't matter where these credits are placed or removed from.
  - The total number of credits added and removed doesn't matter; all that matters is the *difference* between these two.



# The Potential Method

- In the **potential method**, we define a **potential function**  $\Phi$  that maps a data structure to a non-negative real value.
- Each operation on the data structure might change this potential.
- If we denote by  $\Phi_i$  the potential of the data structure just before operation  $i$ , then we can define  $a(op_i)$  as

$$a(op_i) = t(op_i) + O(1) \cdot (\Phi_{i+1} - \Phi_i)$$

- Intuitively:
  - Operations that increase the potential have amortized cost greater than their true cost.
  - Operations that decrease the potential have amortized cost less than their true cost.

# The Potential Method

$$\sum_{i=1}^m a(op_i) = \sum_{i=1}^m (t(op_i) + O(1)) \cdot (\Phi_{i+1} - \Phi_i)$$

# The Potential Method

$$\begin{aligned}\sum_{i=1}^m a(op_i) &= \sum_{i=1}^m (t(op_i) + O(1) \cdot (\Phi_{i+1} - \Phi_i)) \\ &= \sum_{i=1}^m t(op_i) + O(1) \cdot \sum_{i=1}^m (\Phi_{i+1} - \Phi_i)\end{aligned}$$

# The Potential Method

$$\begin{aligned}\sum_{i=1}^m a(op_i) &= \sum_{i=1}^m (t(op_i) + O(1) \cdot (\Phi_{i+1} - \Phi_i)) \\ &= \sum_{i=1}^m t(op_i) + O(1) \cdot \sum_{i=1}^m (\Phi_{i+1} - \Phi_i) \\ &= \sum_{i=1}^m t(op_i) + O(1) \cdot (\Phi_{m+1} - \Phi_1)\end{aligned}$$

# The Potential Method

$$\begin{aligned}\sum_{i=1}^m a(op_i) &= \sum_{i=1}^m (t(op_i) + O(1) \cdot (\Phi_{i+1} - \Phi_i)) \\ &= \sum_{i=1}^m t(op_i) + O(1) \cdot \sum_{i=1}^m (\Phi_{i+1} - \Phi_i) \\ &= \sum_{i=1}^m t(op_i) + O(1) \cdot (\Phi_{m+1} - \Phi_1)\end{aligned}$$

- Assuming that  $\Phi_{i+1} - \Phi_1 \geq 0$ , this means that the sum of the amortized costs upper-bounds the sum of the real costs.
- Typically,  $\Phi_1 = 0$ , so  $\Phi_{i+1} - \Phi_1 \geq 0$  holds.

# Constructing Cartesian Trees

$\Phi = \mathbf{0}$  |

271	137	159	314	42
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# Constructing Cartesian Trees

$\Phi = \mathbf{0}$  |

271

271	137	159	314	42
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# Constructing Cartesian Trees

$\Phi = 1$  | 271

271

271	137	159	314	42
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# Constructing Cartesian Trees

$$\Phi = 1 \mid \boxed{271}$$

Work done: 1 push

$\Delta\Phi$ : +1

Amortized Cost: **2**

**271**

271	137	159	314	42
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# Constructing Cartesian Trees

$\Phi = 1$  | 271

271

271	137	159	314	42
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# Constructing Cartesian Trees

$\Phi = 1$  | 271

271

137

271	137	159	314	42
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# Constructing Cartesian Trees

$\Phi = \mathbf{0}$  |

271

137

271

137

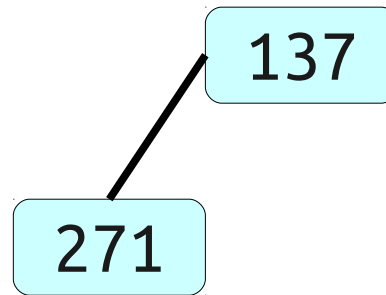
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314

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# Constructing Cartesian Trees

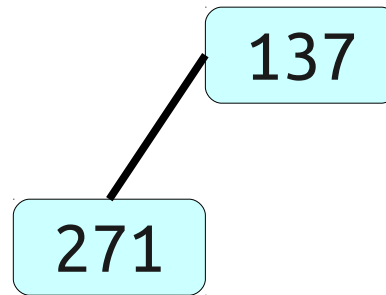
$\Phi = \mathbf{0}$  |



271	137	159	314	42
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# Constructing Cartesian Trees

$\Phi = 1$  | 137



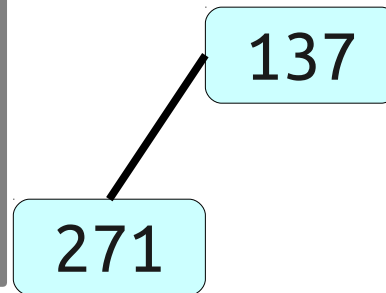
271	137	159	314	42
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# Constructing Cartesian Trees

$$\Phi = 1 \mid \boxed{137}$$

Work done: 1 push, 1 pop  
 $\Delta\Phi: 0$

Amortized Cost: **2**



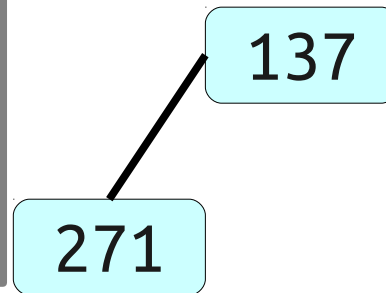
271	137	159	314	42
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# Constructing Cartesian Trees

$$\Phi = 1 \mid \boxed{137}$$

Work done: 1 push, 1 pop  
 $\Delta\Phi: 0$

Amortized Cost: **2**



271	137	159	314	42
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Notice that  $\Phi$  went

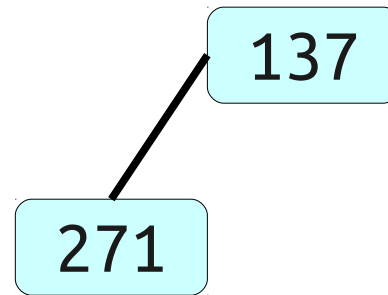
$1 \rightarrow 0 \rightarrow 1$

All that matters is the **net** change.



# Constructing Cartesian Trees

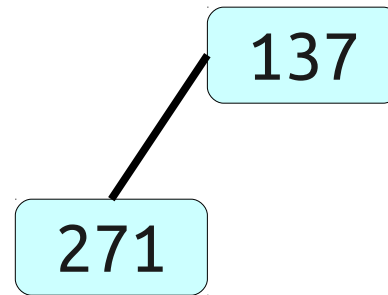
$\Phi = 1$  | 137



271	137	159	314	42
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# Constructing Cartesian Trees

$\Phi = 1$  | 137

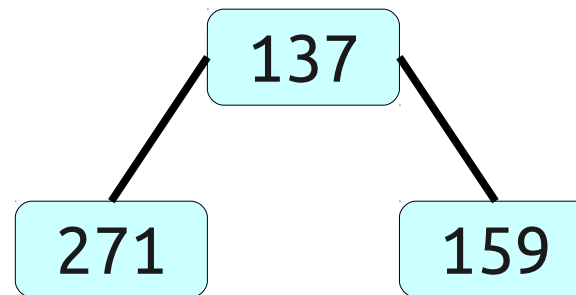


159

271	137	159	314	42
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# Constructing Cartesian Trees

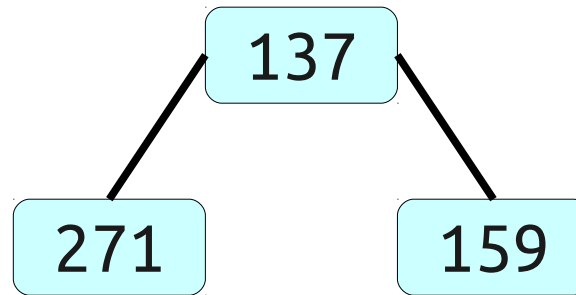
$\Phi = 1$  | 137



271	137	159	314	42
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# Constructing Cartesian Trees

$\Phi = 2$  | 137 159



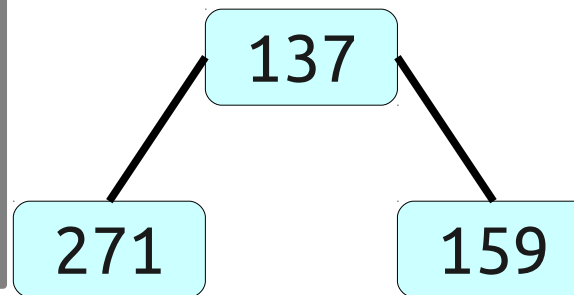
271	137	159	314	42
-----	-----	-----	-----	----

# Constructing Cartesian Trees

$$\Phi = 2 \left| \begin{array}{|c|c|} \hline 137 & 159 \\ \hline \end{array} \right.$$

Work done: 1 push  
 $\Delta\Phi: +1$

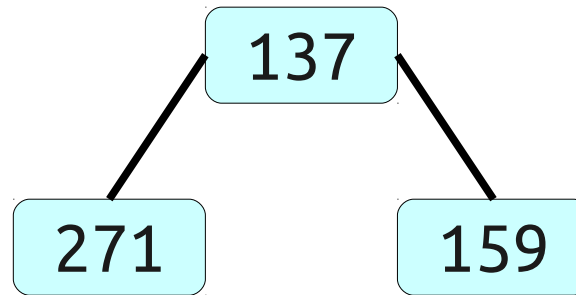
Amortized Cost: **2**



271	137	159	314	42
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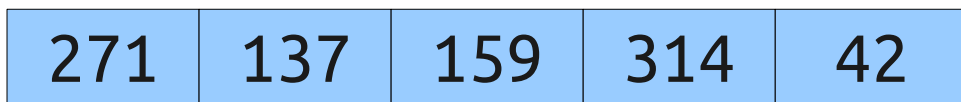
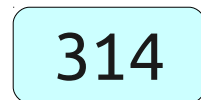
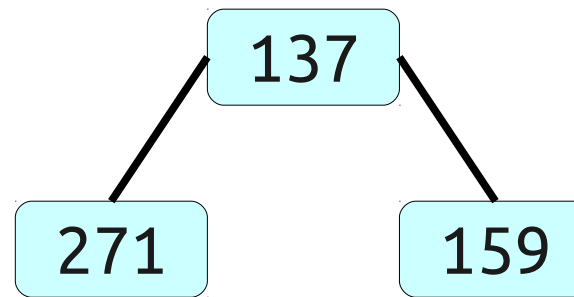
# Constructing Cartesian Trees

$\Phi = 2$  | 137 159



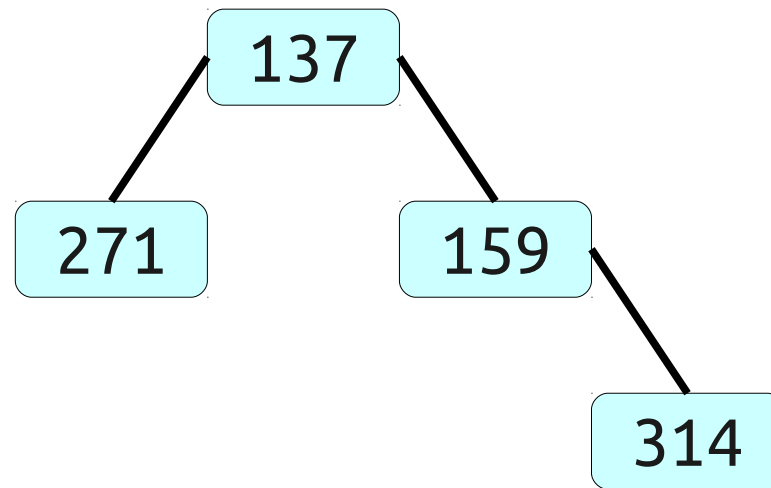
271	137	159	314	42
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# Constructing Cartesian Trees



# Constructing Cartesian Trees

$\Phi = 2$  | 137 159

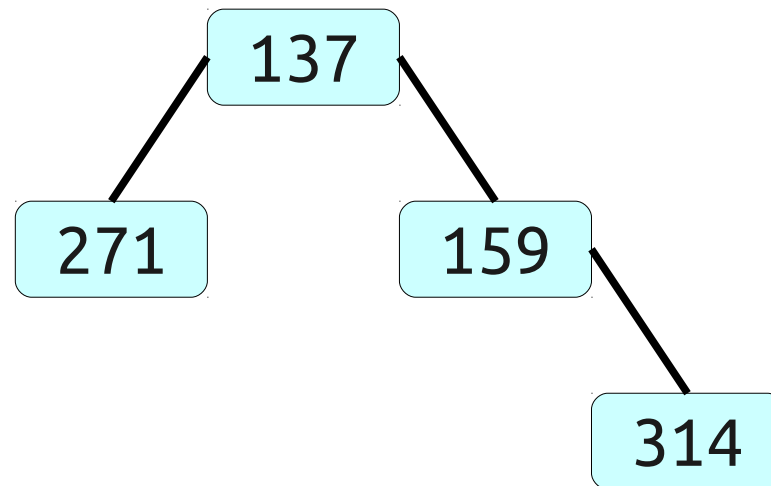


271	137	159	314	42
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# Constructing Cartesian Trees

$\Phi = 3$  | 137 159 314

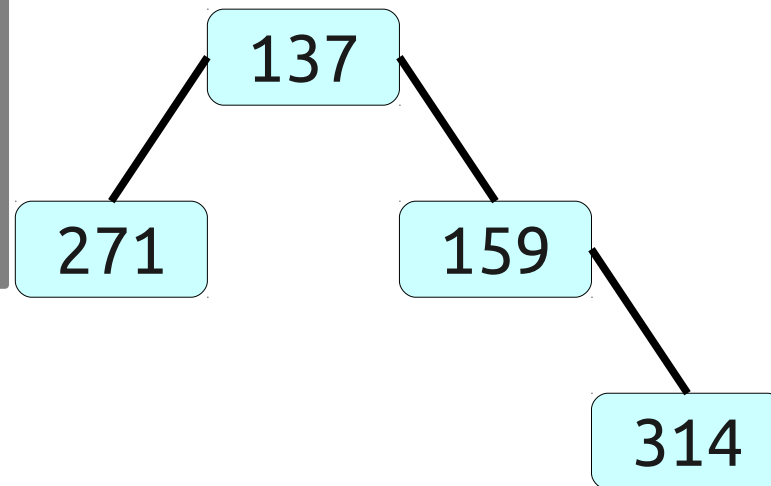


271	137	159	314	42
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# Constructing Cartesian Trees

$\Phi = 3$  | 137 159 314

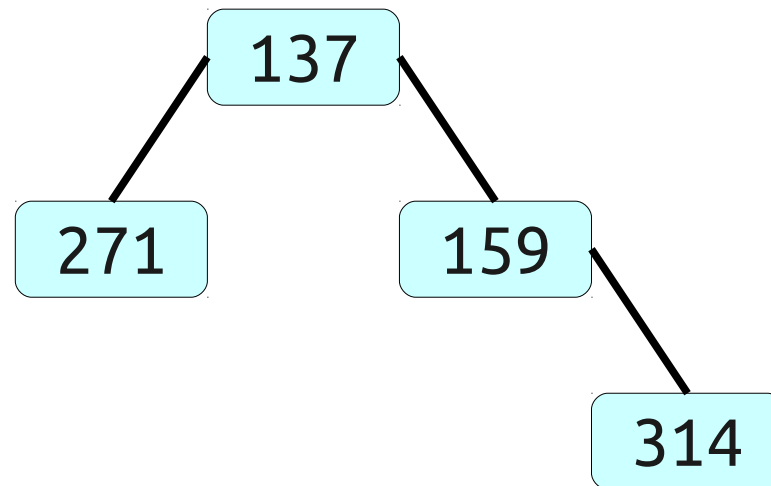
Work done: 1 push  
Credits Added:  $\Delta\Phi$ : +1  
Amortized Cost: **2**



271 137 159 314 42

# Constructing Cartesian Trees

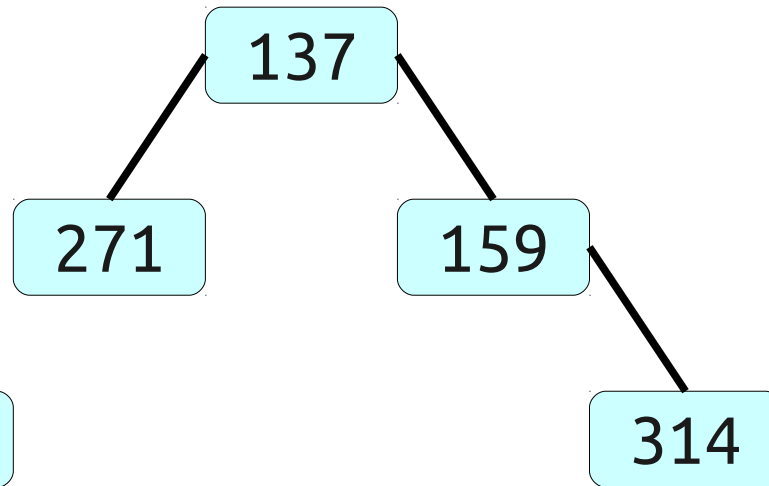
$\Phi = 3$  | 137 159 314



271	137	159	314	42
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# Constructing Cartesian Trees

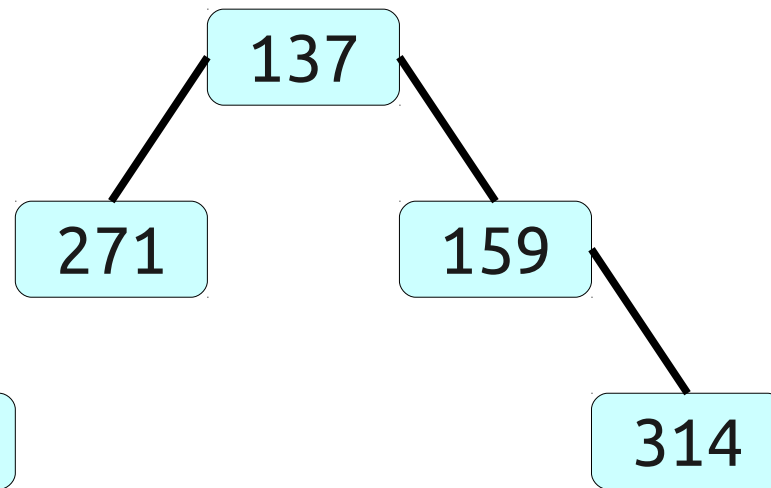
$\Phi = 3$  | 137 159 314



271	137	159	314	42
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# Constructing Cartesian Trees

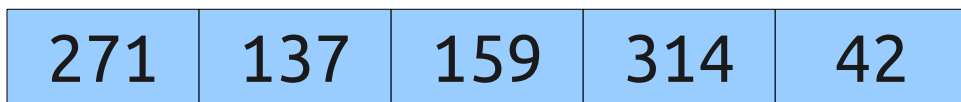
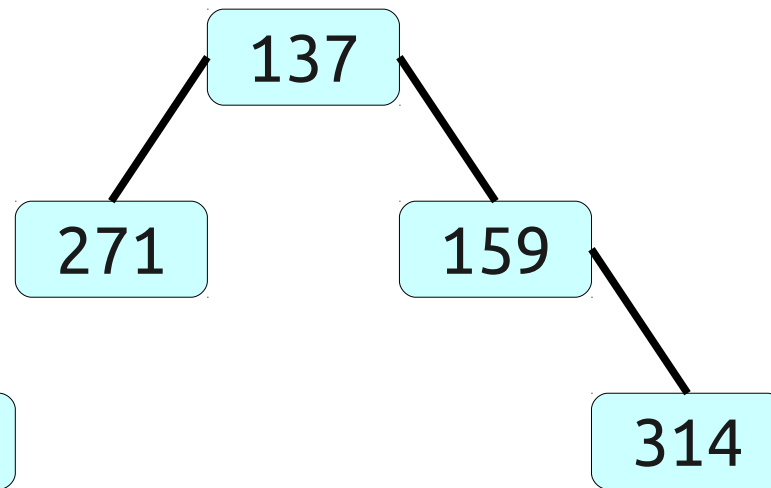
$\Phi = 2$  | 137 159



271	137	159	314	42
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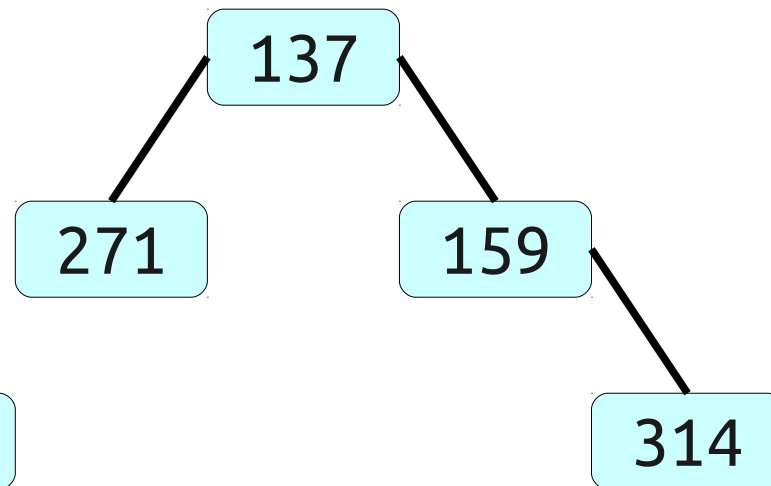
# Constructing Cartesian Trees

$$\Phi = \mathbf{1} \mid \boxed{137}$$



# Constructing Cartesian Trees

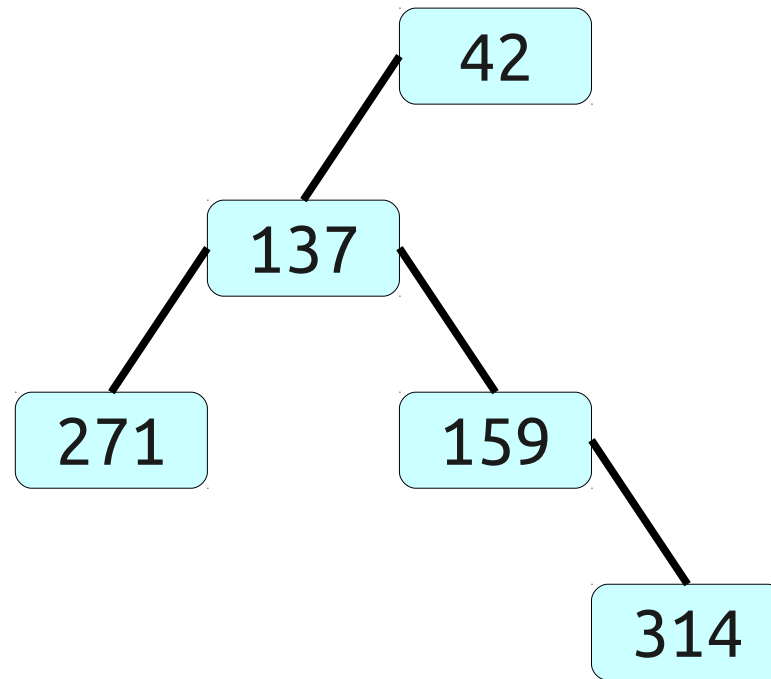
$$\Phi = \mathbf{0} \mid$$



271	137	159	314	42
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# Constructing Cartesian Trees

$$\Phi = \mathbf{0} \mid$$

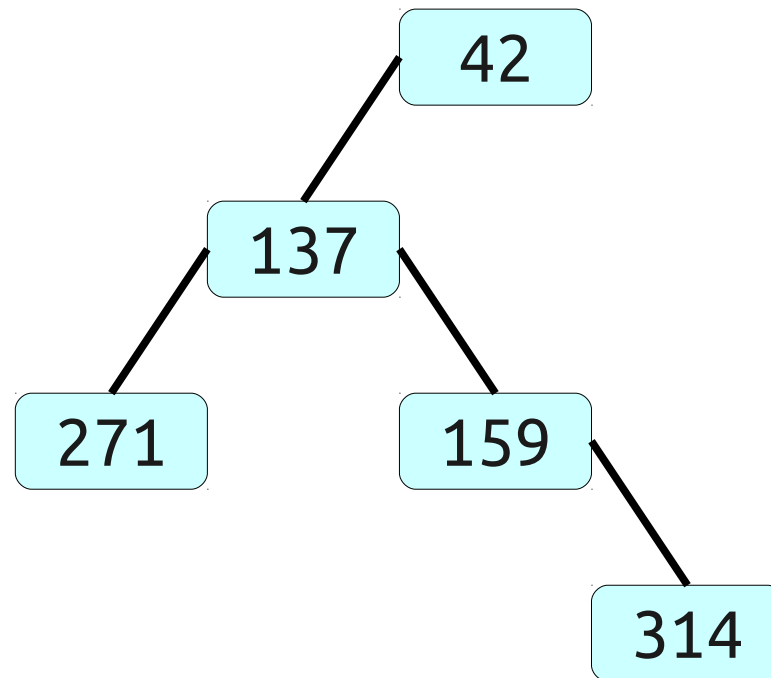


271	137	159	314	42
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# Constructing Cartesian Trees

$\Phi = \mathbf{1} \mid \boxed{42}$



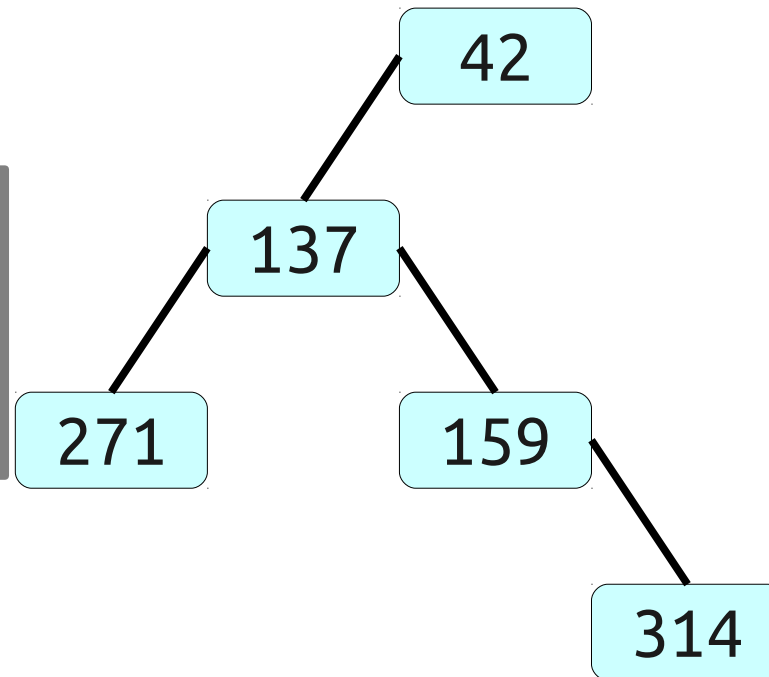
271	137	159	314	42
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# Constructing Cartesian Trees

$$\Phi = 1 \mid \boxed{42}$$

Work done: 1 push, 3 pops  
 $\Delta\Phi: -2$

Amortized Cost: **2**



271	137	159	314	42
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# The Potential Method

- Using the potential method, the cost of an insertion into a Cartesian tree can be computed as

$$\begin{aligned} & t(op) + \Delta\Phi \\ &= 1 + k + O(1) \cdot (1 - k) \\ &= 1 + k + 1 - k \\ &= 2 \\ &= \mathbf{O(1)} \end{aligned}$$

- So the amortized cost of an insertion is  $O(1)$ .
- Therefore,  $n$  total insertions takes time  $O(n)$ .

Time-Out for Announcements!

# Problem Set Three

- Problem Set Three goes out today. It's due next Wednesday at 2:15PM.
- Explore amortized analysis and a different data structure for dynamic connectivity in trees!
- Keith will be holding office hours in Gates 178 tomorrow from 2PM - 4PM.

Your Questions

“Is it possible to please get an explanation of where we lost points in the homeworks and a sample solution set?”

**Of course!** We'll release hardcopy solutions for the problem sets in lecture. You're welcome to stop by office hours to ask questions about the problem sets.

“How can we access the grades specifically for our code submissions?”

You should have received an email with your grade and feedback from your grader. If you didn't, let me know ASAP!



“Could we use a Piazza forum for the class?  
It would make answering a lot of questions,  
both practical and conceptual, much easier.  
Thanks!”

I'll think about this. In the meantime, feel  
free to email the staff list with questions!

**[cs166-spr1314-staff@lists.stanford.edu](mailto:cs166-spr1314-staff@lists.stanford.edu)**

# A Note on Questions

Back to CS166!

Another Example: **Two-Stack Queues**

# The Two-Stack Queue



**Out**



**In**

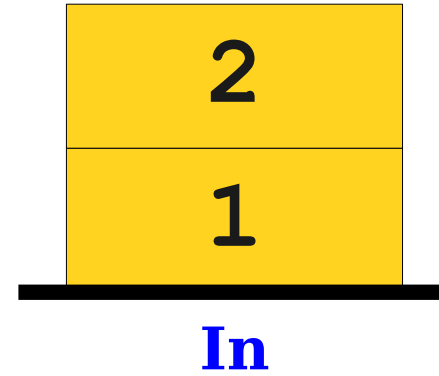
# The Two-Stack Queue

  
**Out**

  
**In**

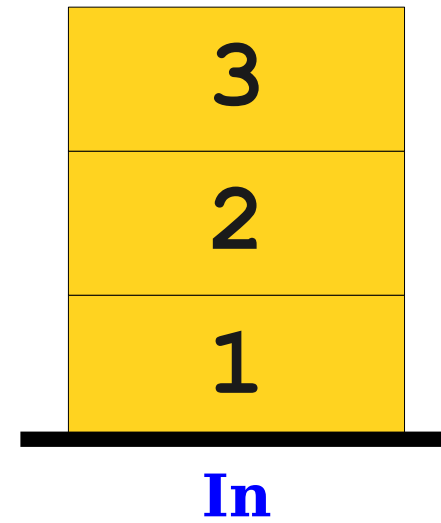
# The Two-Stack Queue

**Out**



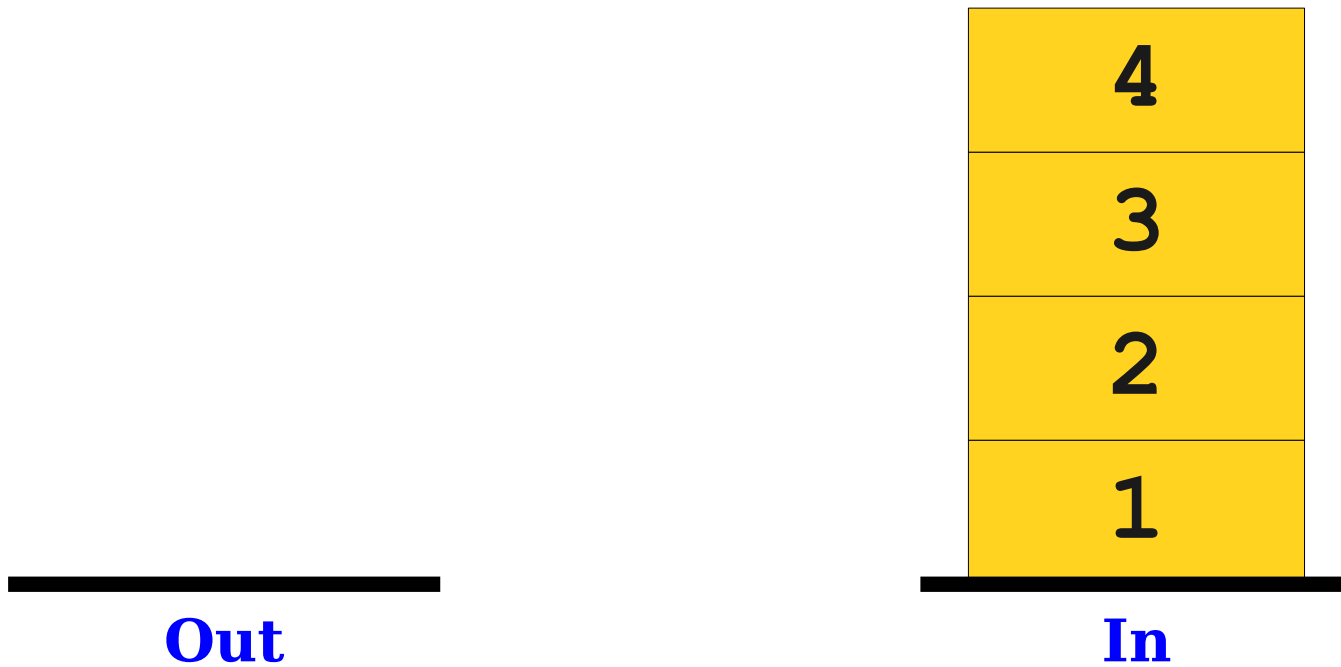
# The Two-Stack Queue

**Out**

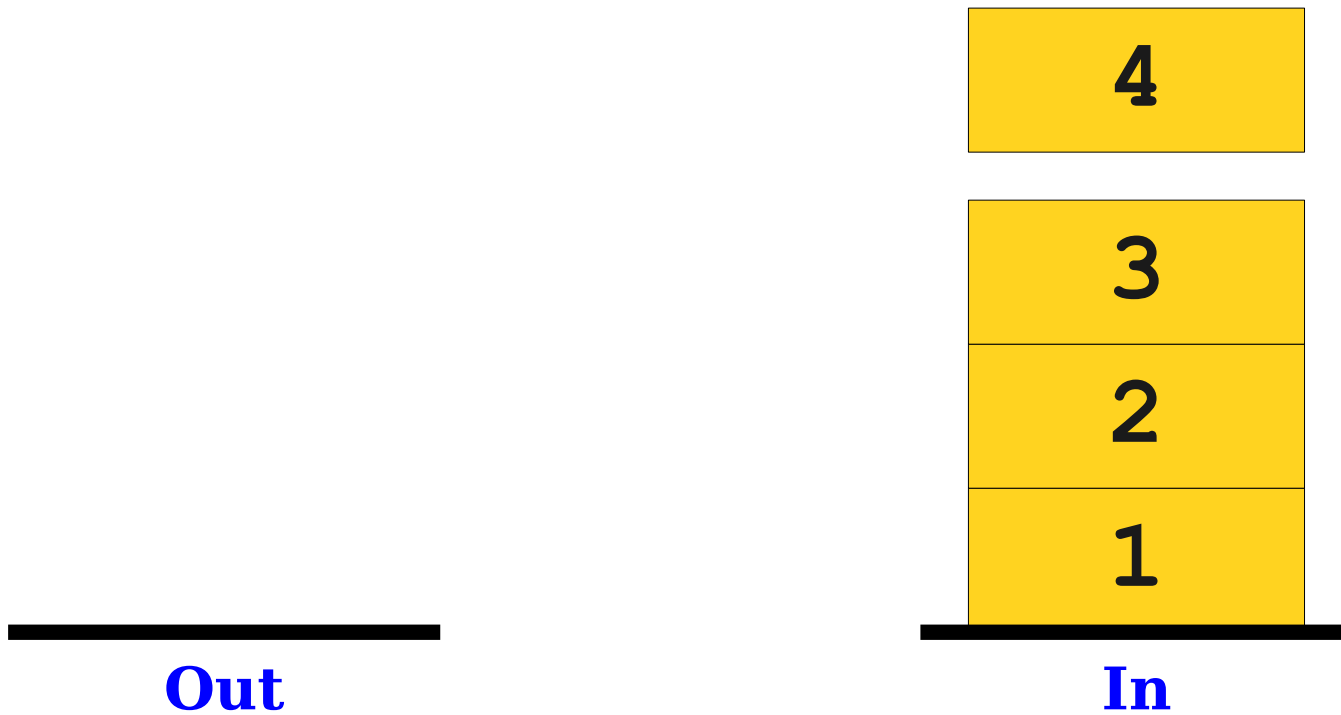




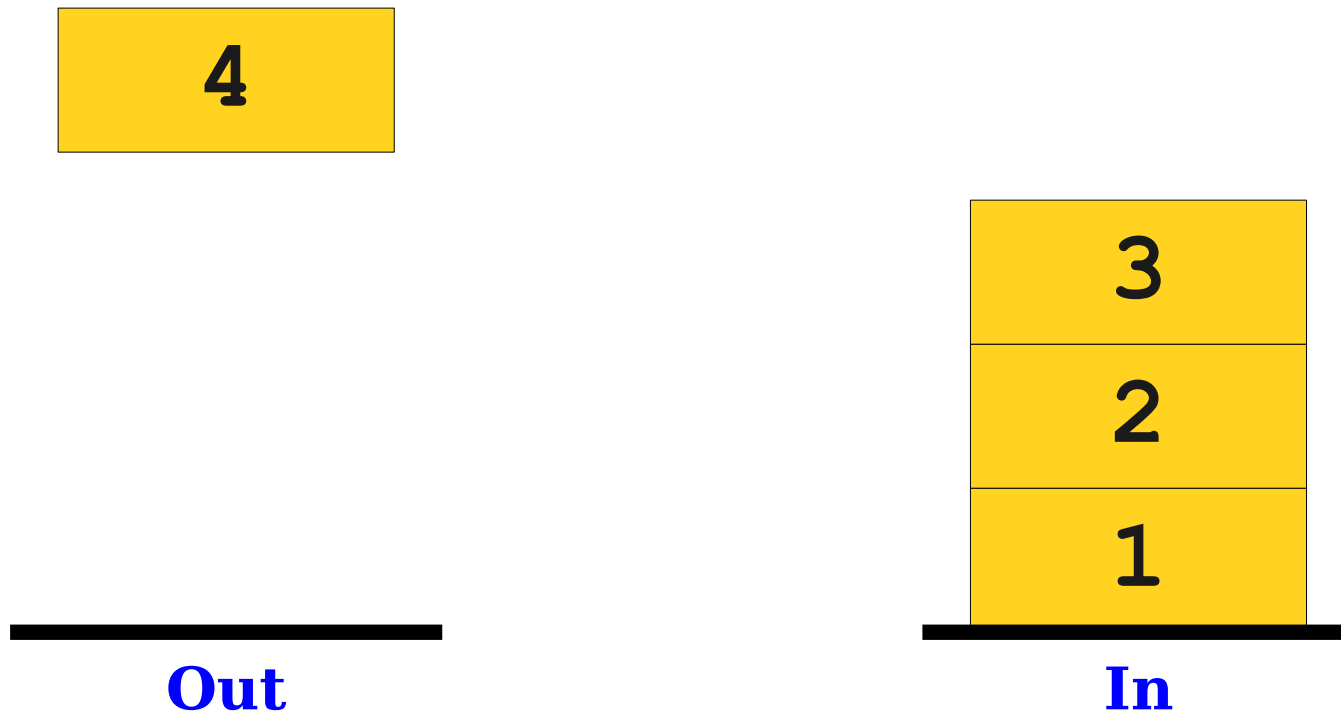
# The Two-Stack Queue



# The Two-Stack Queue



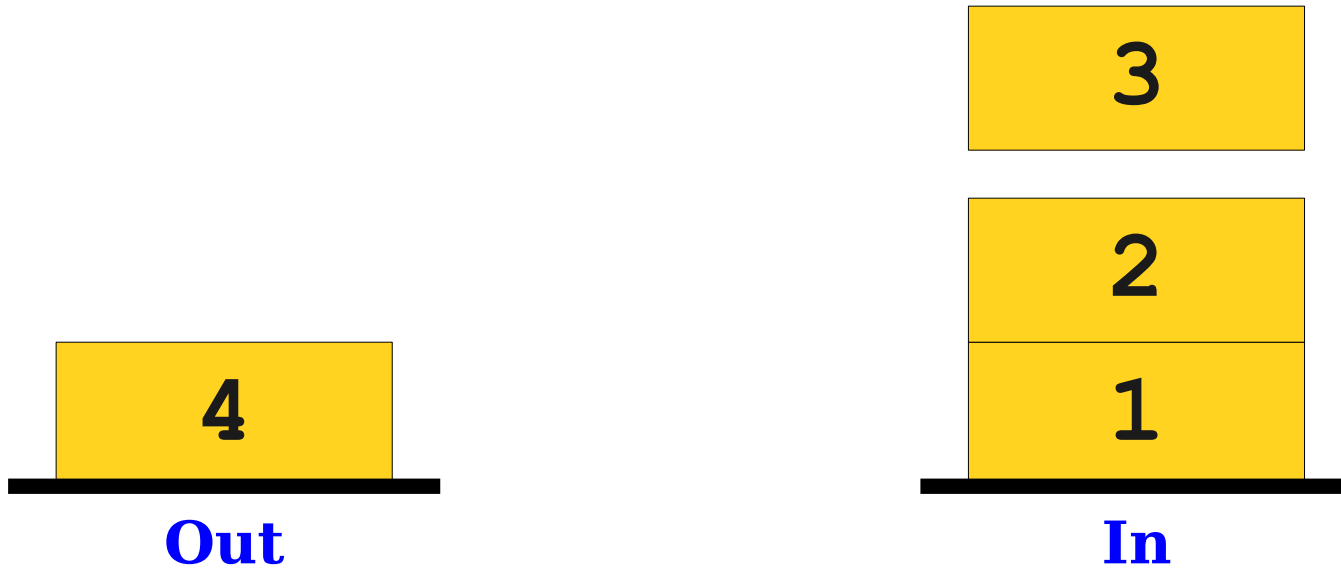
# The Two-Stack Queue



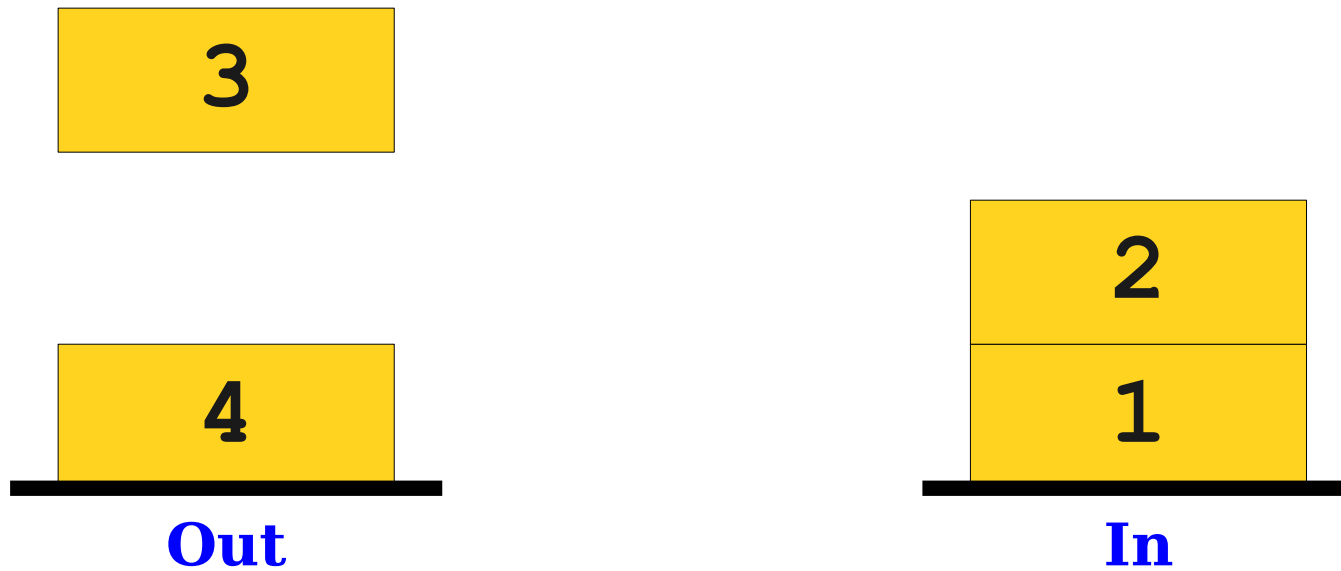
# The Two-Stack Queue



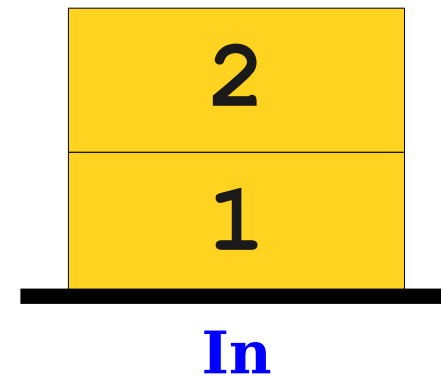
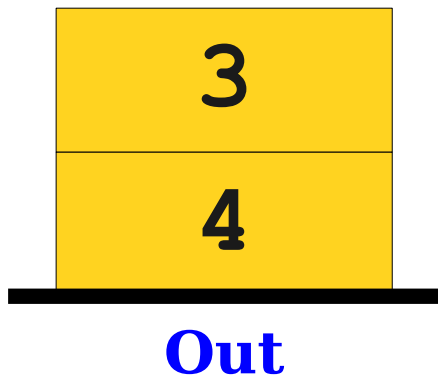
# The Two-Stack Queue



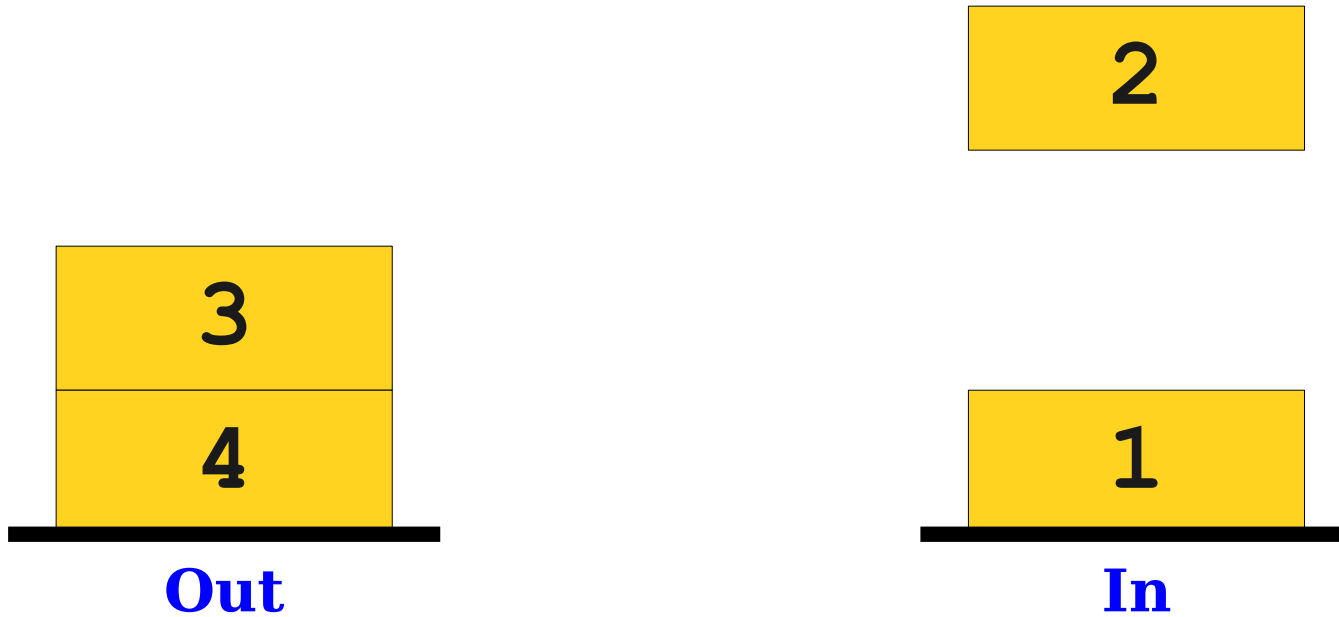
# The Two-Stack Queue



# The Two-Stack Queue

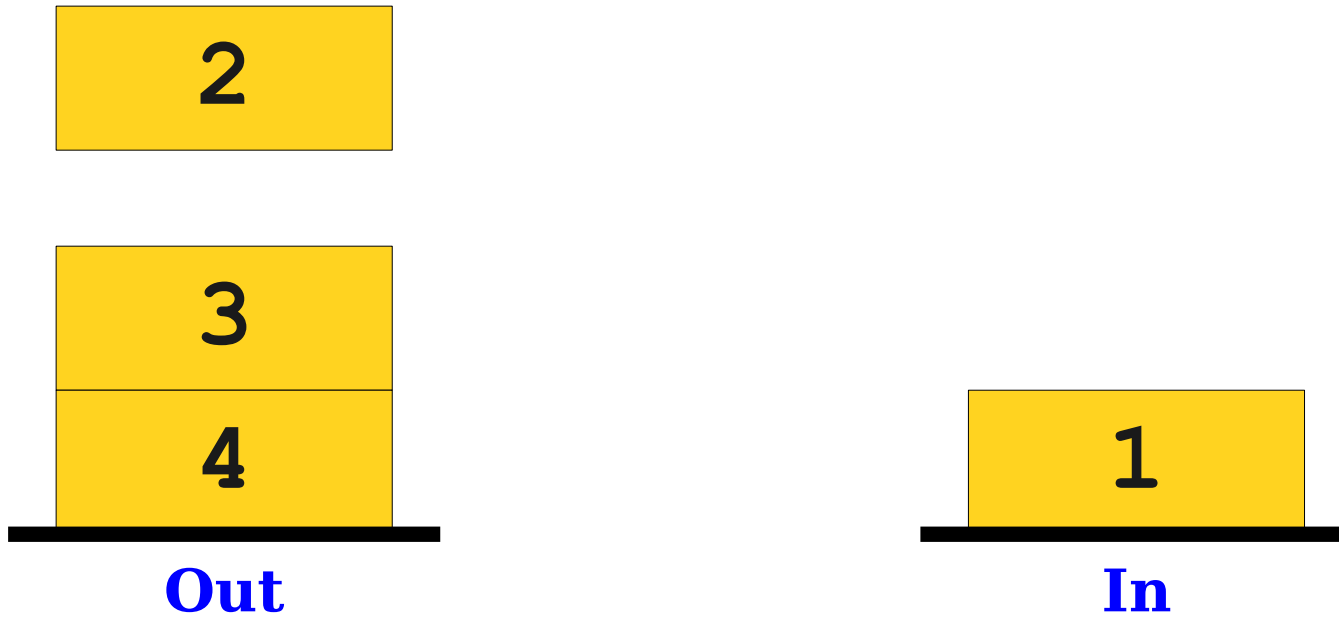


# The Two-Stack Queue





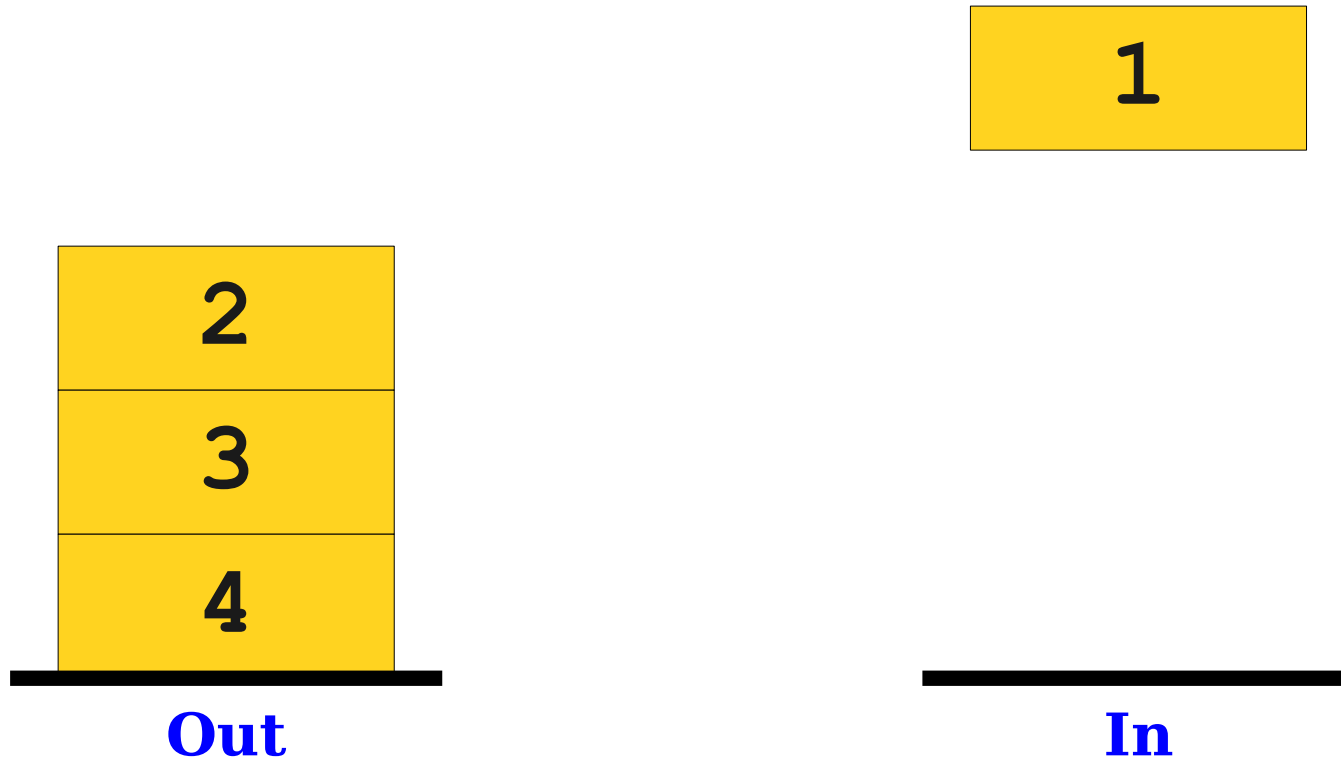
# The Two-Stack Queue



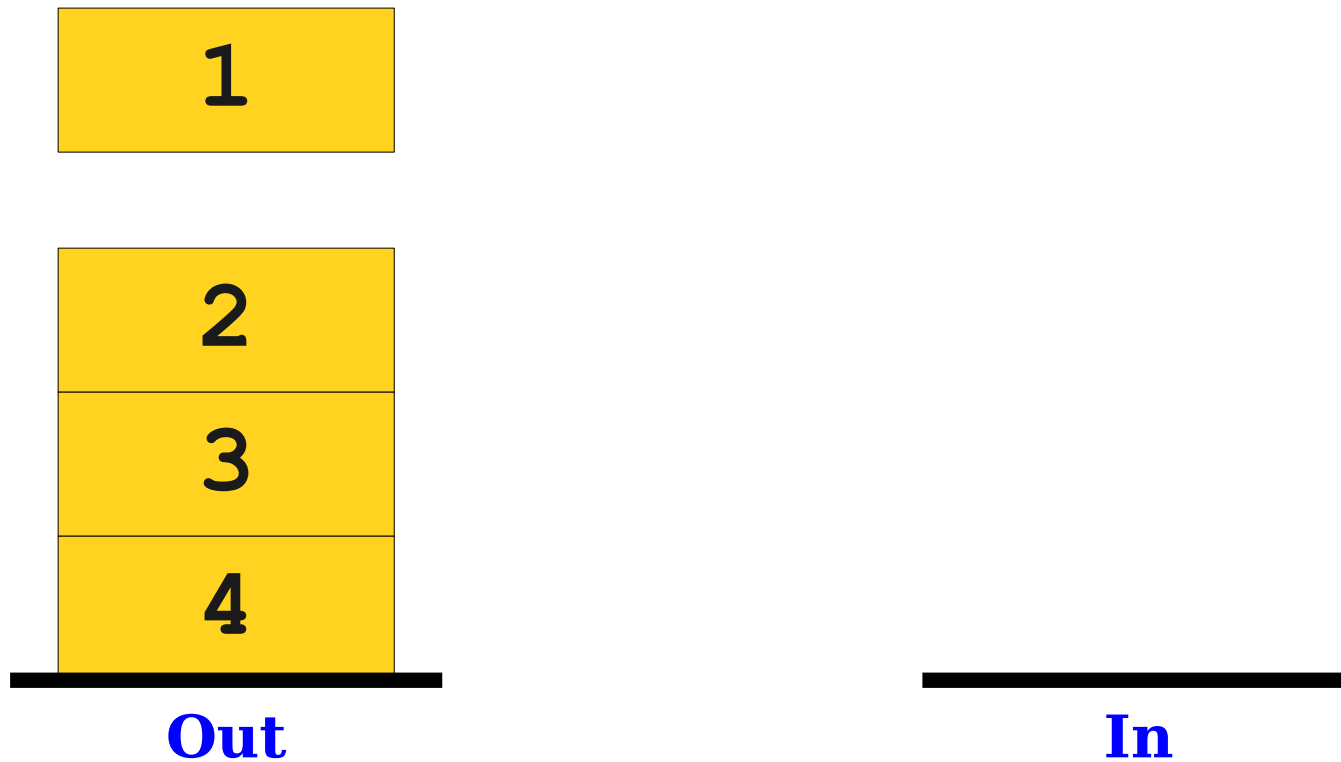
# The Two-Stack Queue



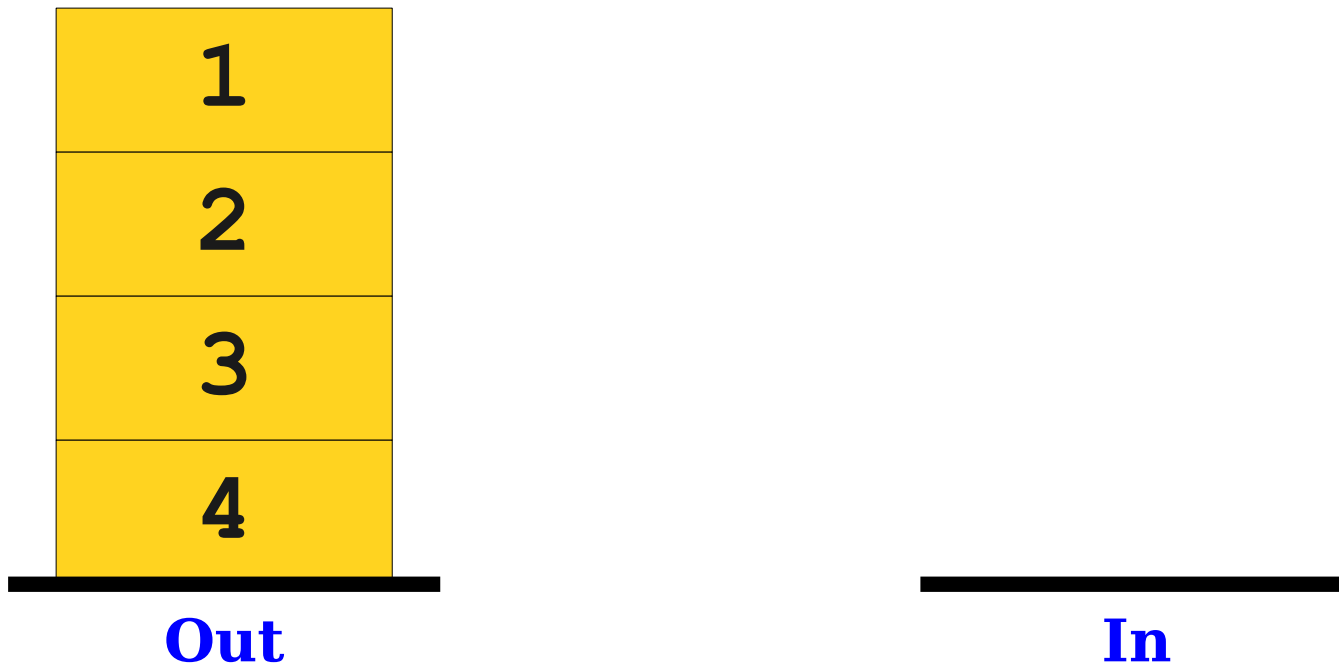
# The Two-Stack Queue



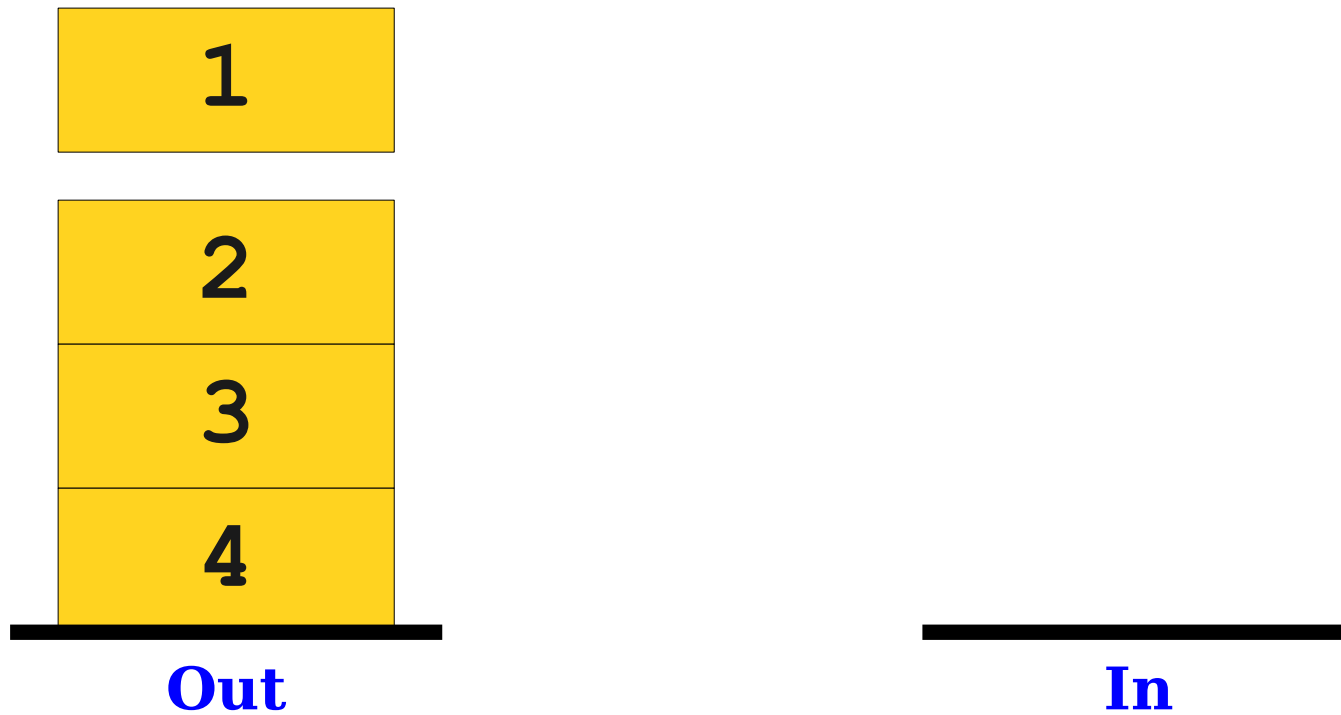
# The Two-Stack Queue



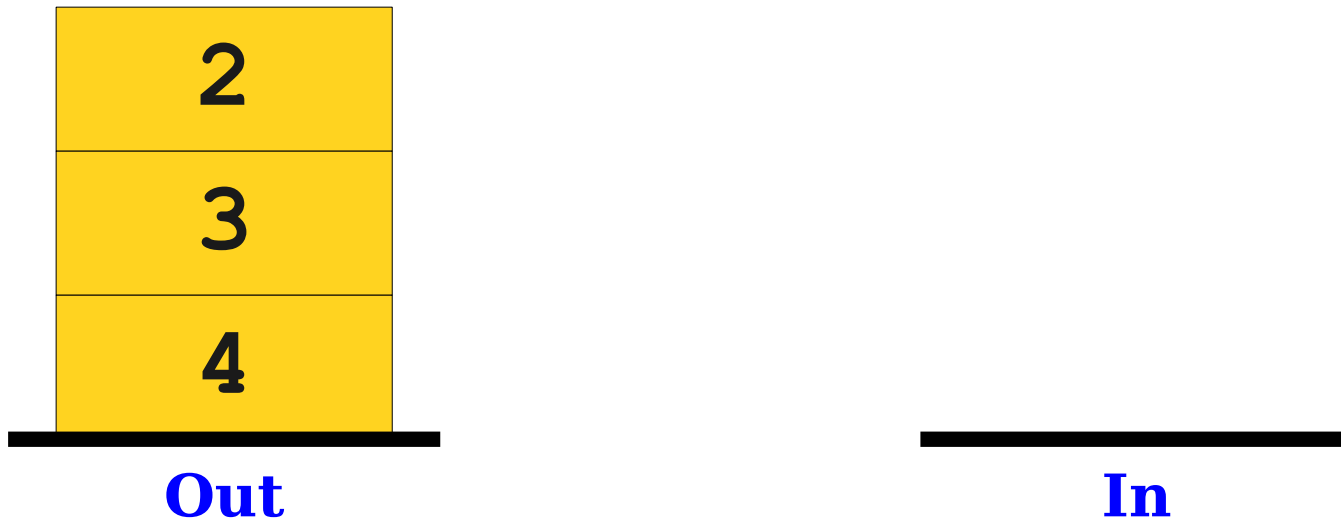
# The Two-Stack Queue



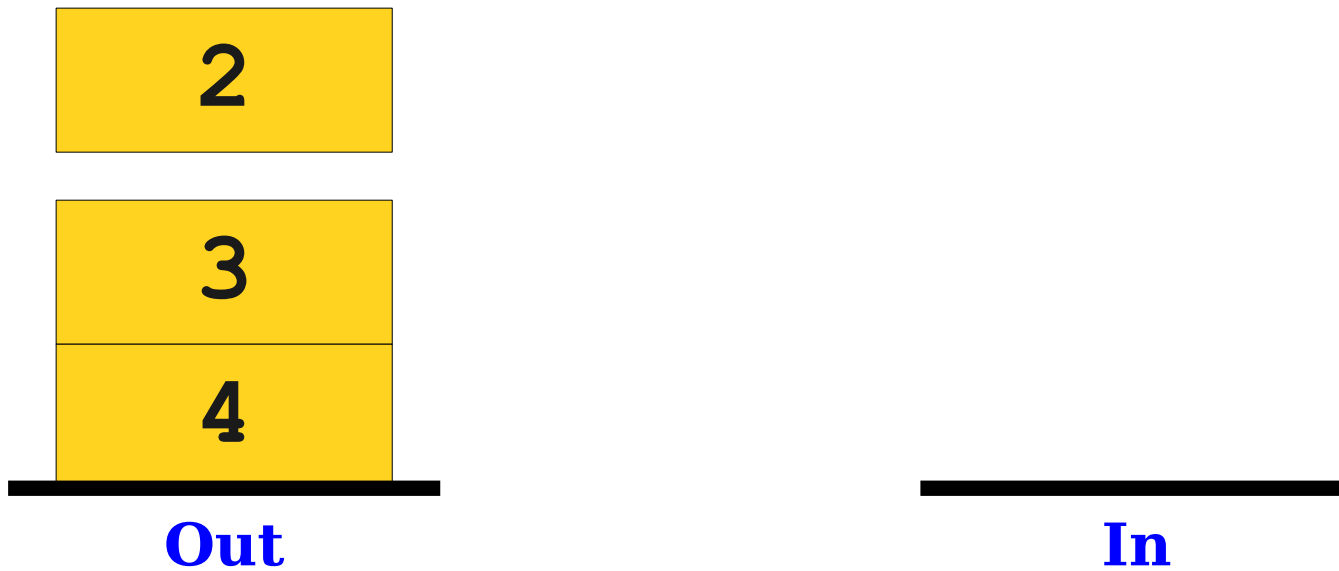
# The Two-Stack Queue



# The Two-Stack Queue

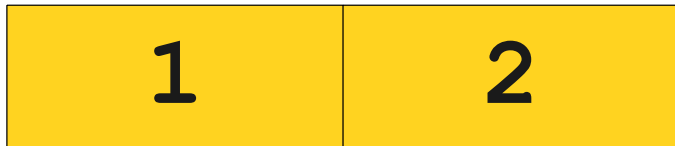
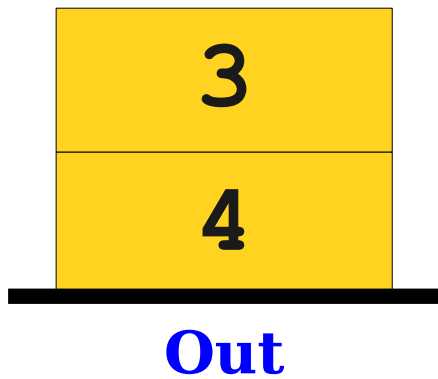


# The Two-Stack Queue

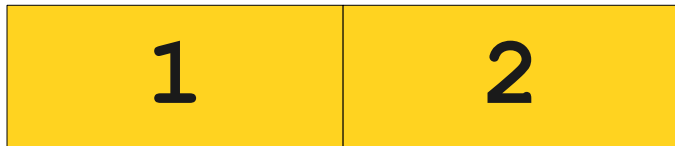
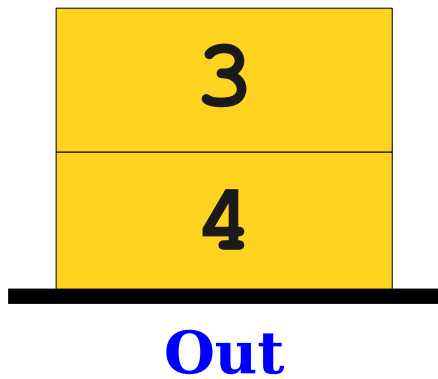




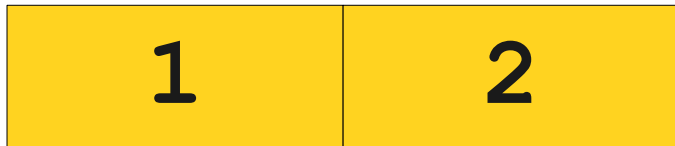
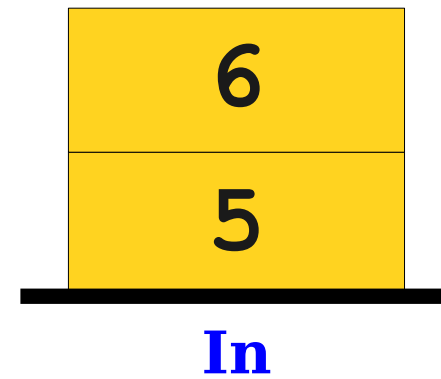
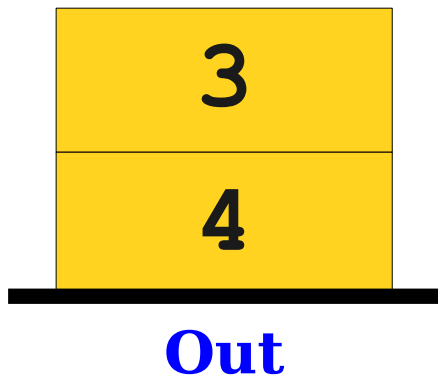
# The Two-Stack Queue



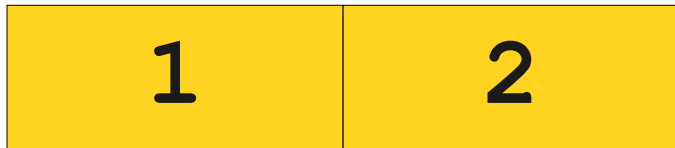
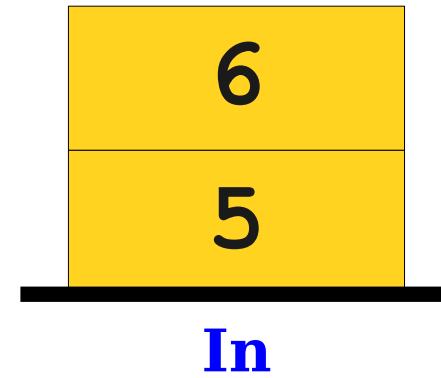
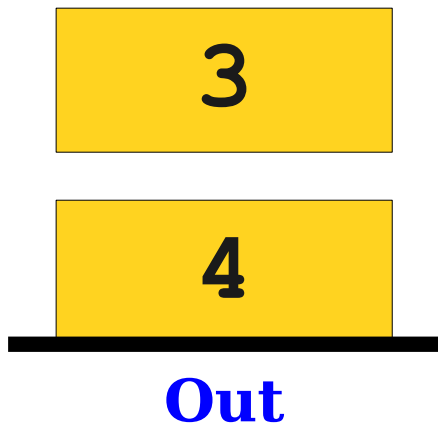
# The Two-Stack Queue



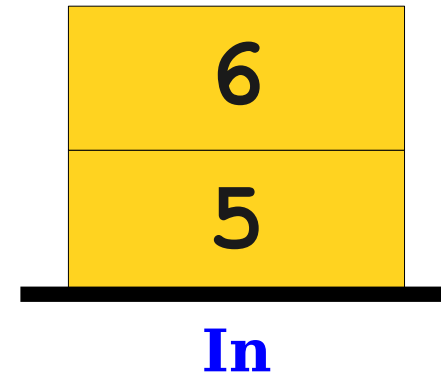
# The Two-Stack Queue



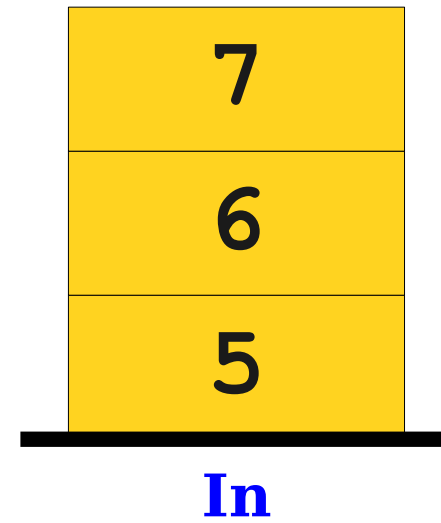
# The Two-Stack Queue



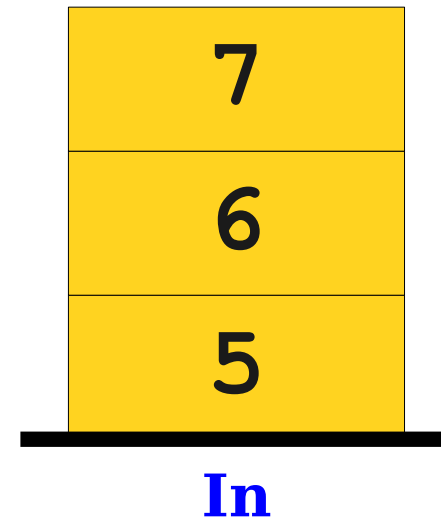
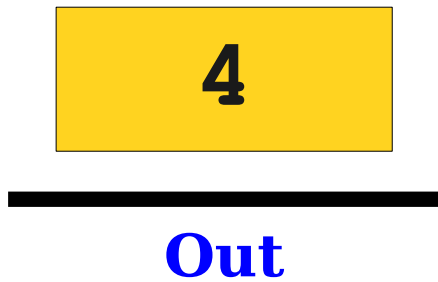
# The Two-Stack Queue



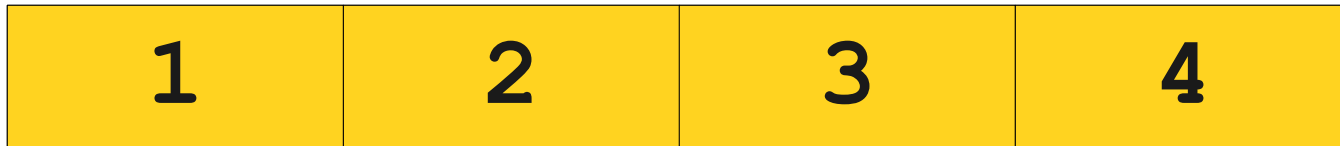
# The Two-Stack Queue



# The Two-Stack Queue

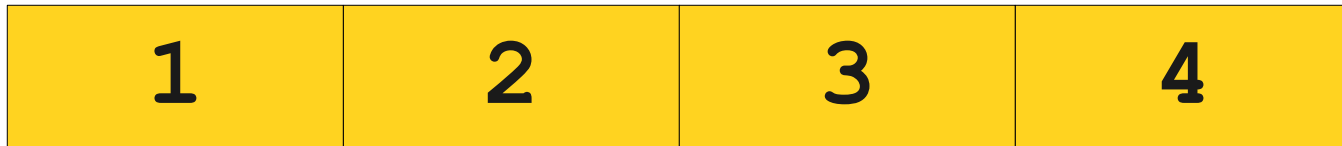


# The Two-Stack Queue





# The Two-Stack Queue



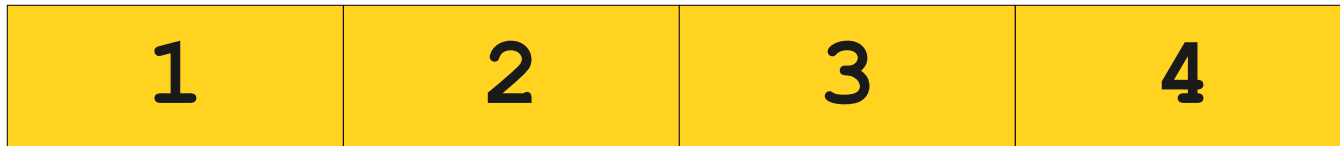
# The Two-Stack Queue



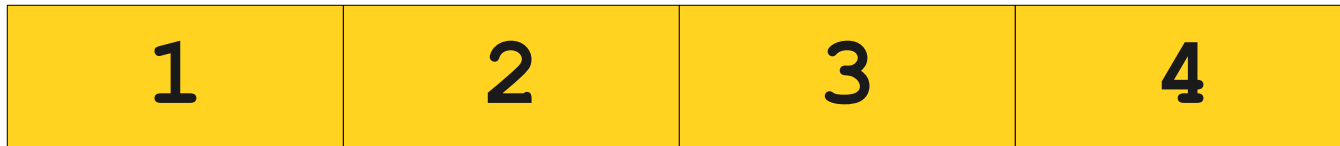
**Out**



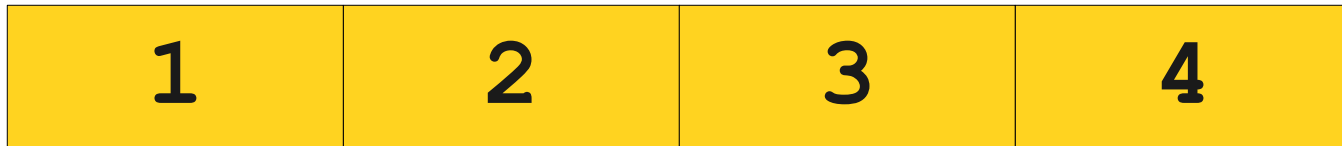
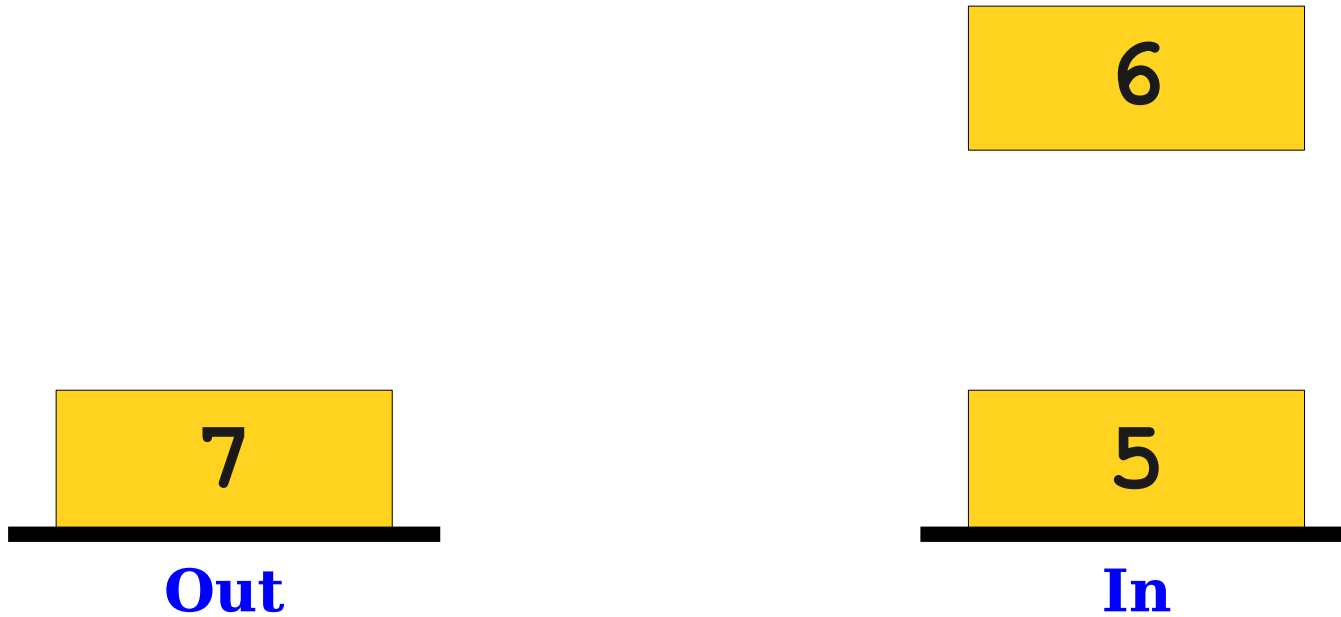
**In**



# The Two-Stack Queue



# The Two-Stack Queue



# The Two-Stack Queue

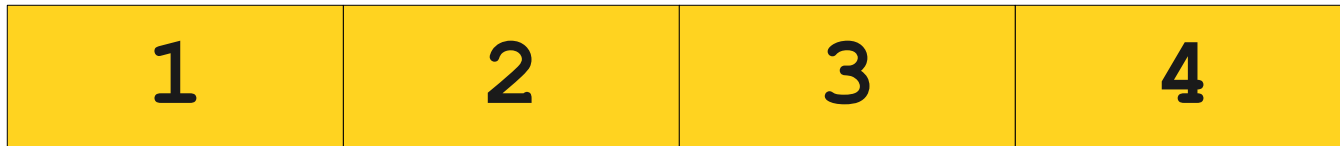
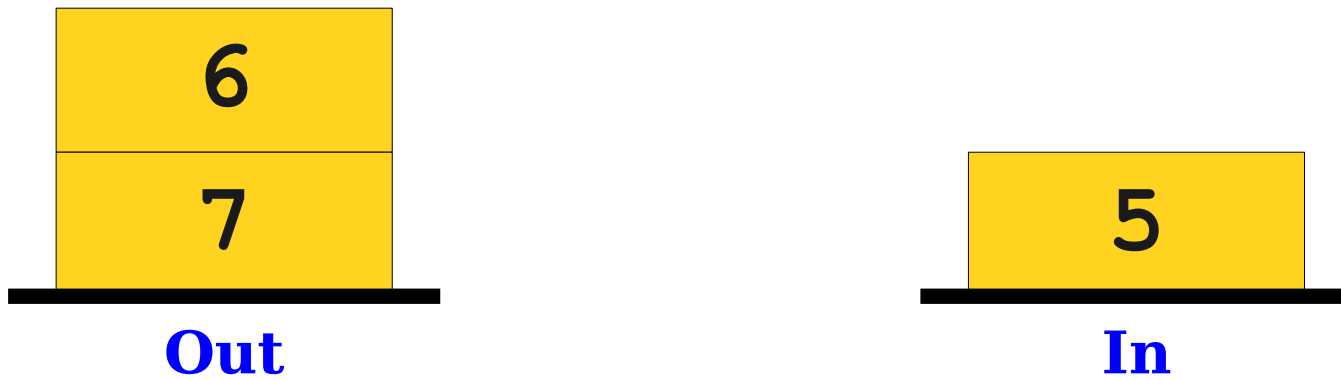
6

7  
**Out**

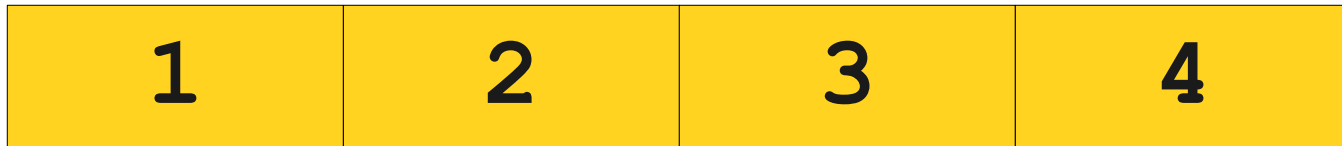
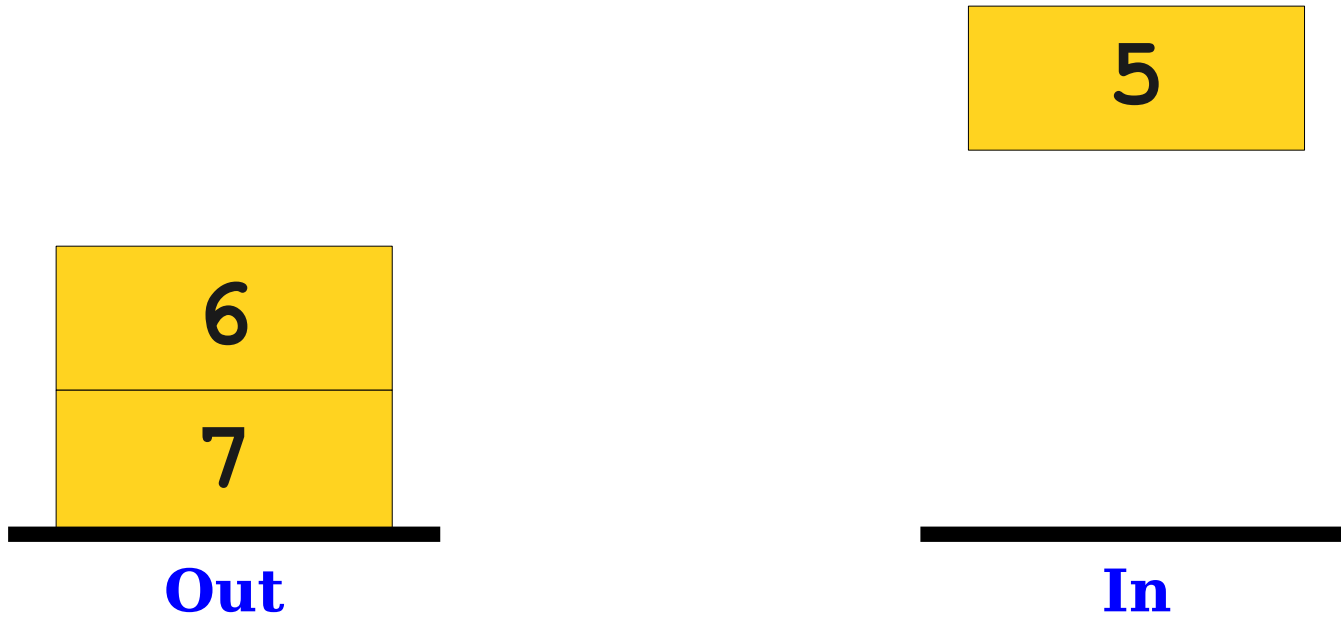
5  
**In**

1 2 3 4

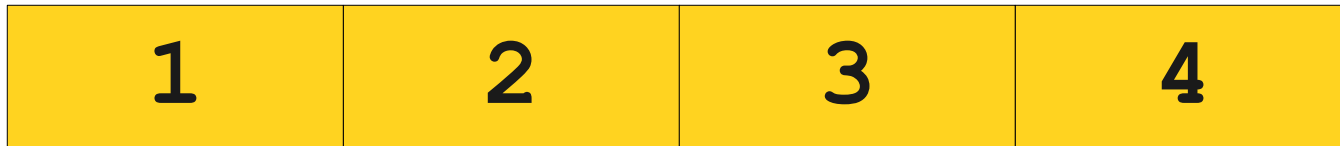
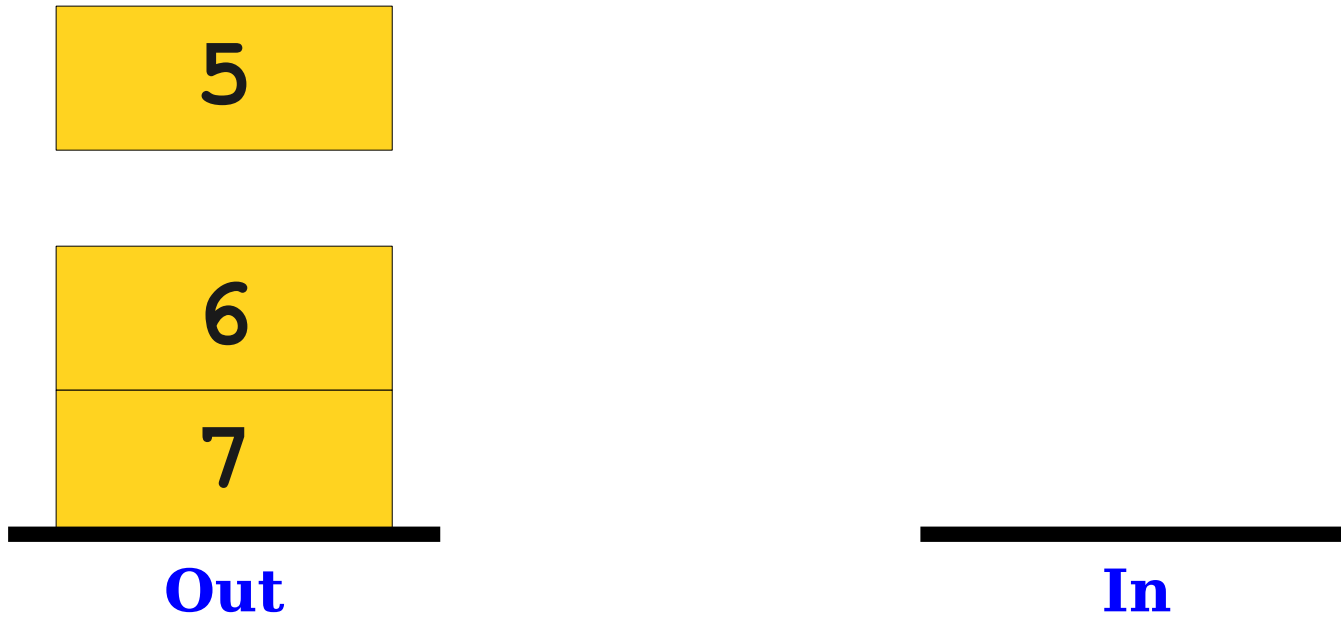
# The Two-Stack Queue



# The Two-Stack Queue

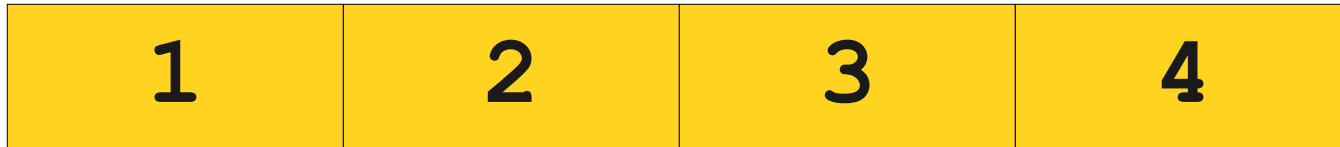
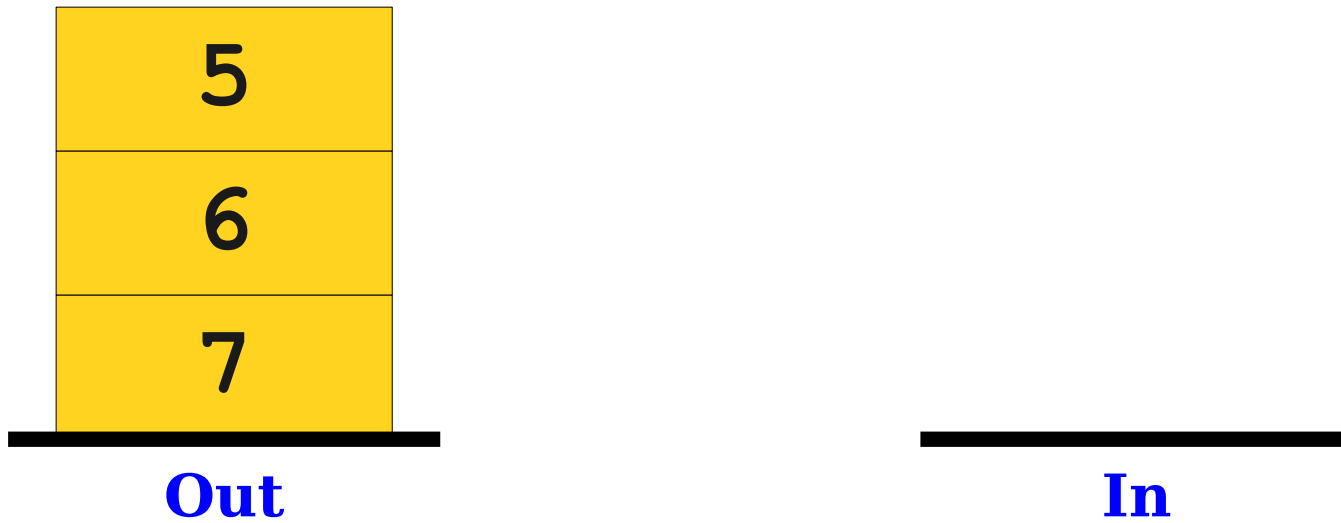


# The Two-Stack Queue

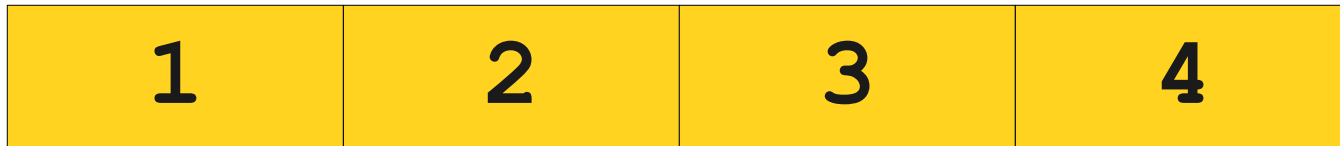
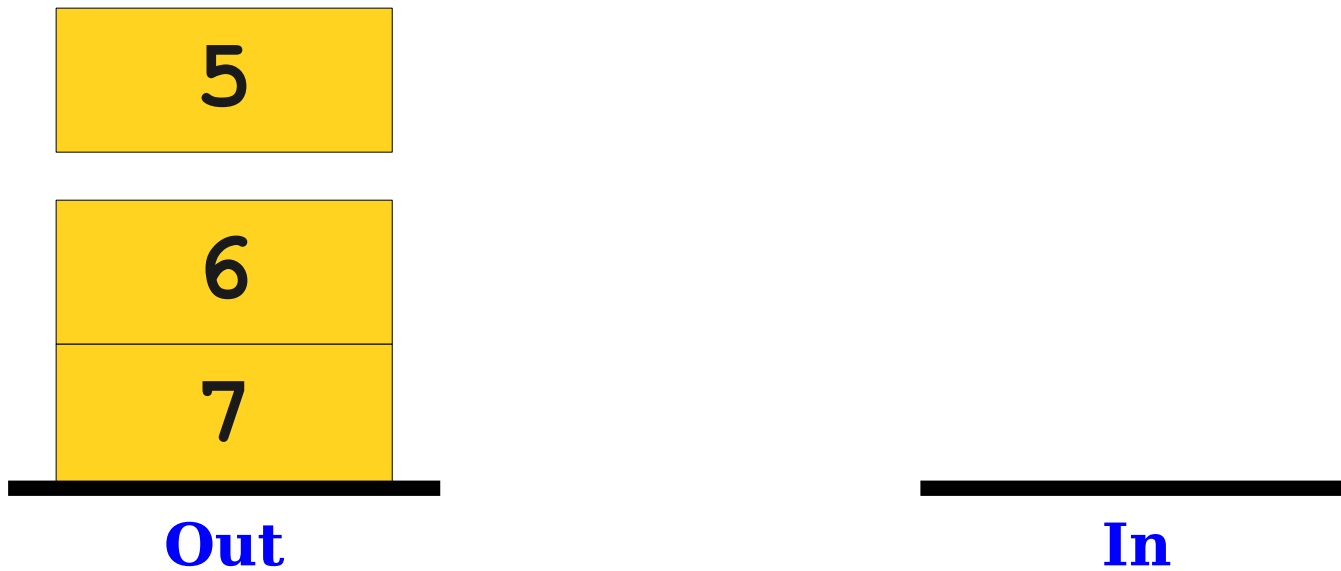




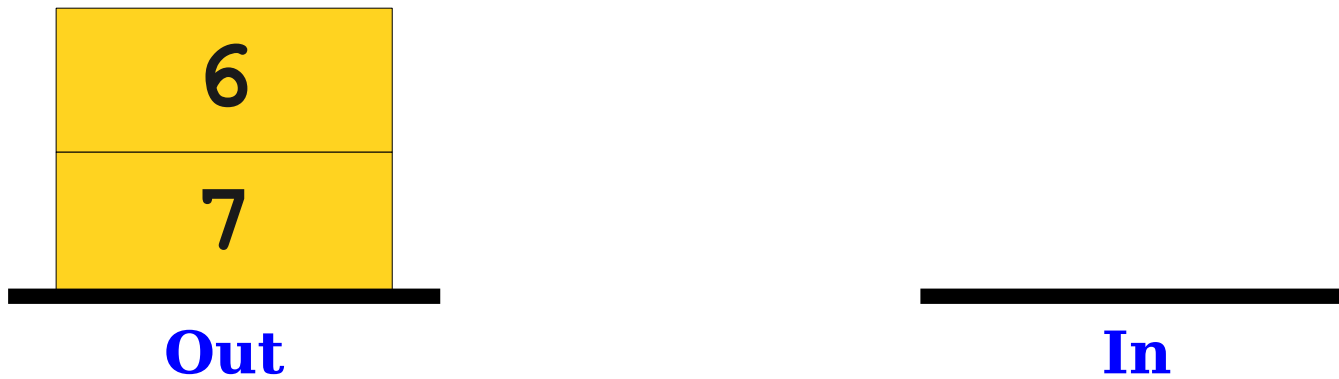
# The Two-Stack Queue



# The Two-Stack Queue



# The Two-Stack Queue



# The Two-Stack Queue

- Maintain two stacks, an **In** stack and an **Out** stack.
- To enqueue an element, push it onto the **In** stack.
- To dequeue an element:
  - If the **Out** stack is empty, pop everything off the **In** stack and push it onto the **Out** stack.
  - Pop the **Out** stack and return its value.

# An Aggregate Analysis

- **Claim:** Cost of a sequence of  $n$  intermixed enqueues and dequeues is  $O(n)$ .
- **Proof:**
  - Every value is pushed onto a stack at most twice: once for *in*, once for *out*.
  - Every value is popped off of a stack at most twice: once for *in*, once for *out*.
  - Each push/pop takes time  $O(1)$ .
  - Net runtime:  **$O(n)$** .

# The Banker's Method

- Let's analyze this data structure using the banker's method.
- Some observations:
- All enqueues take worst-case time  $O(1)$ .
- Each dequeue can be split into a “light” or “heavy” dequeue.
  - In a “light” dequeue, the **out** stack is nonempty. Worst-case time is  $O(1)$ .
  - In a “heavy” dequeue, the **out** stack is empty. Worst-case time is  $O(n)$ .

# The Two-Stack Queue



**Out**

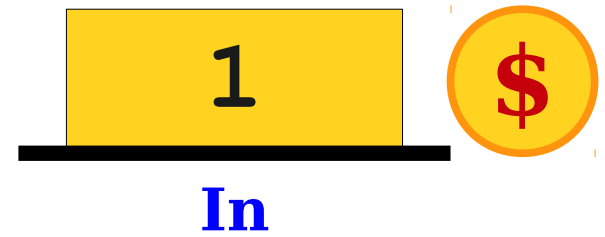


**In**

# The Two-Stack Queue

**Out**

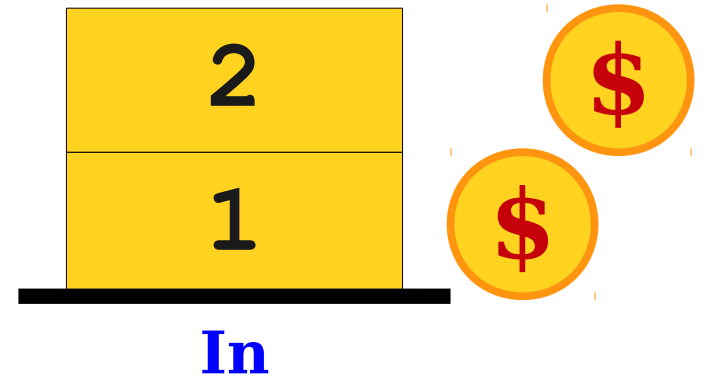
**1**  
**In**





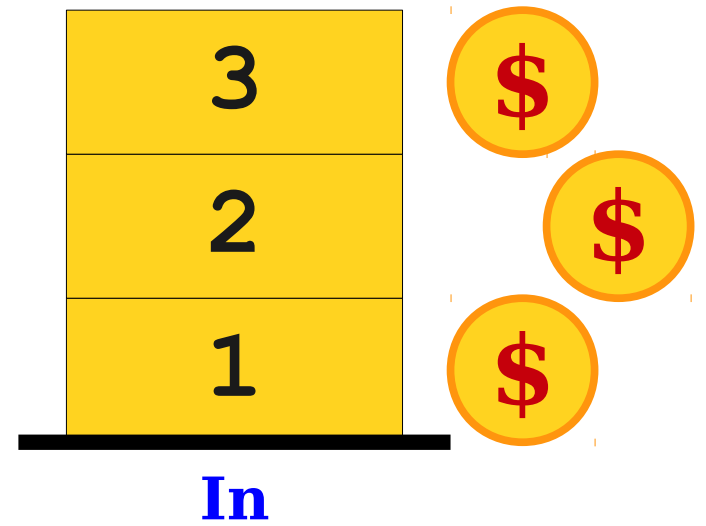
# The Two-Stack Queue

**Out**

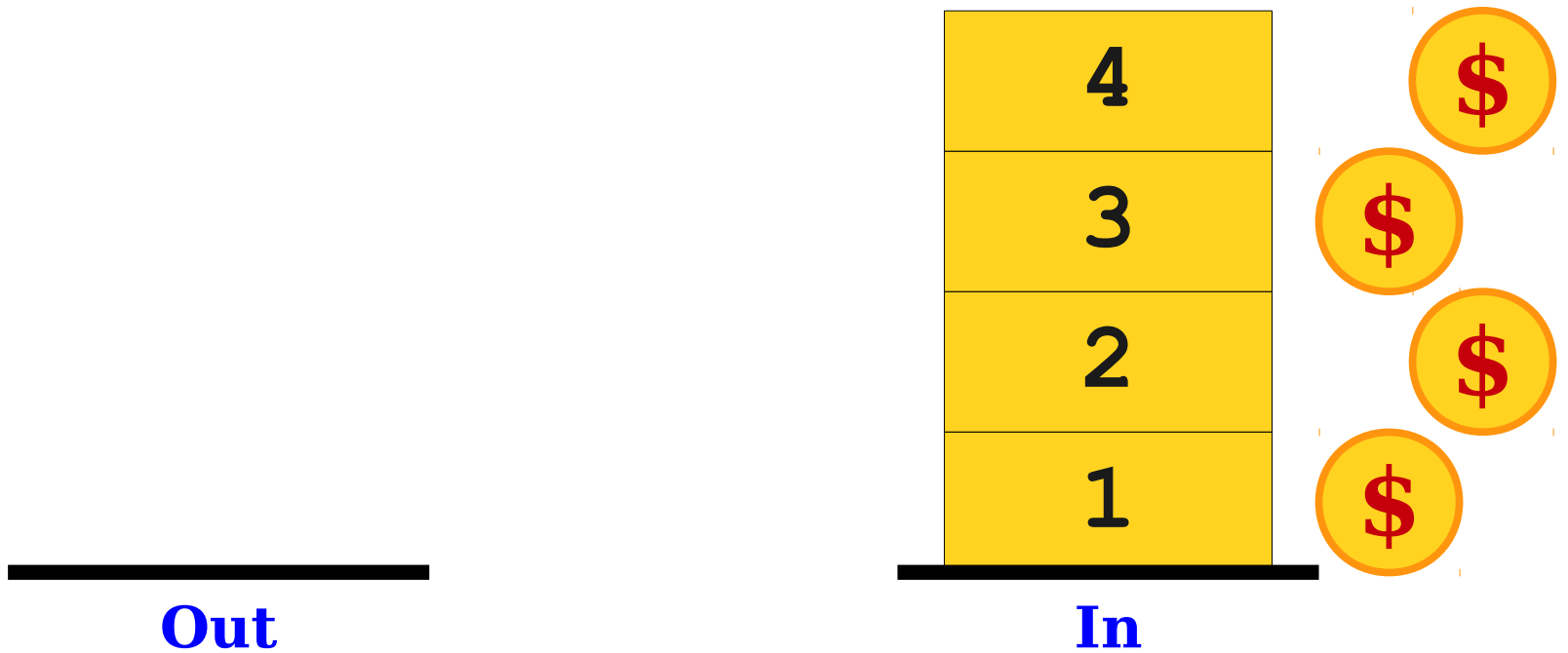


# The Two-Stack Queue

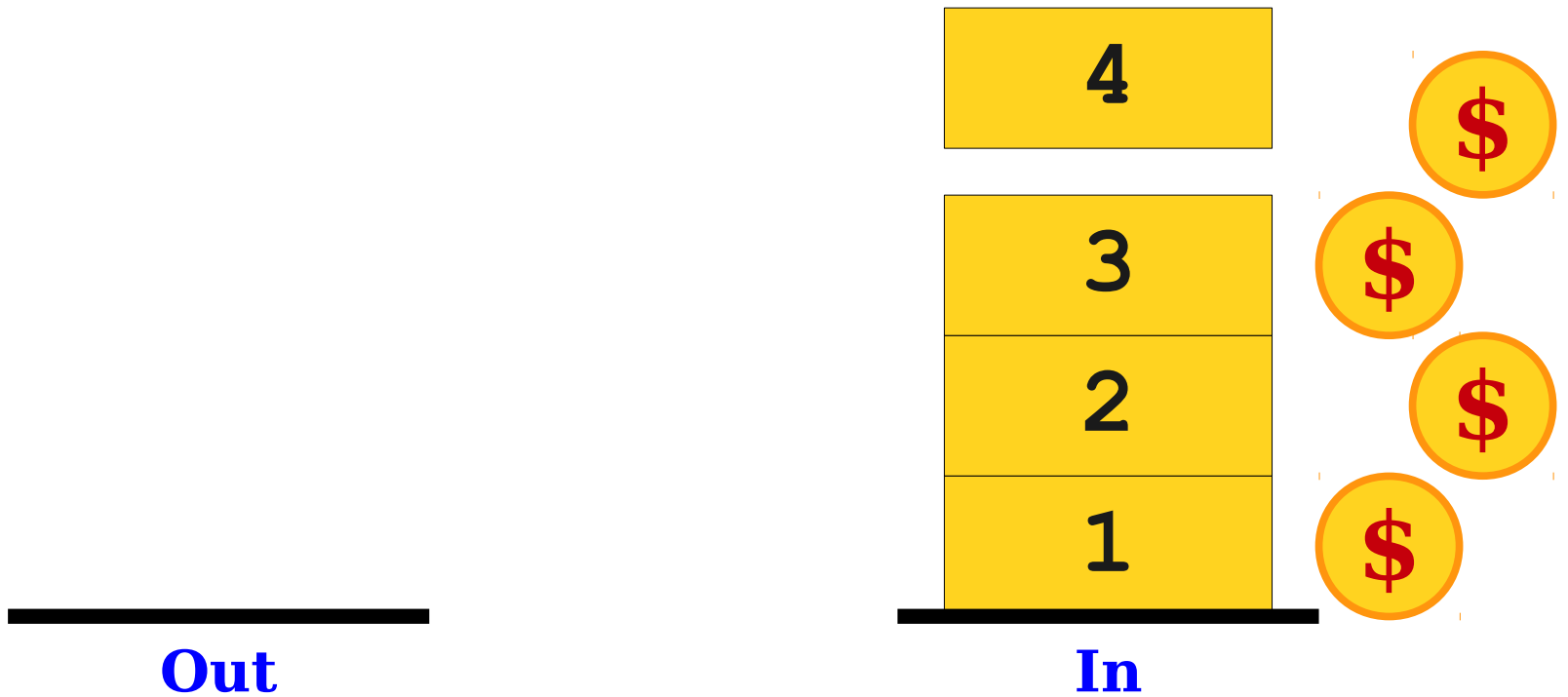
**Out**



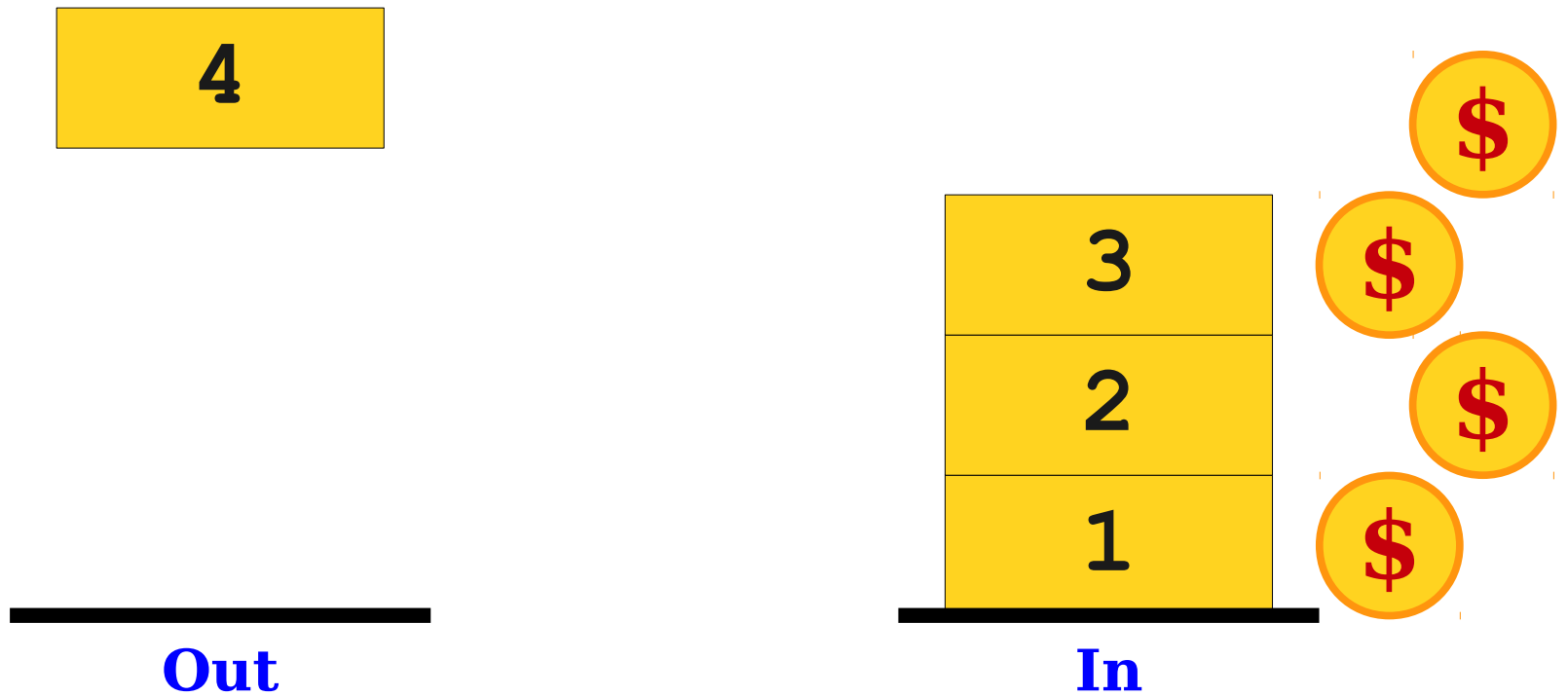
# The Two-Stack Queue



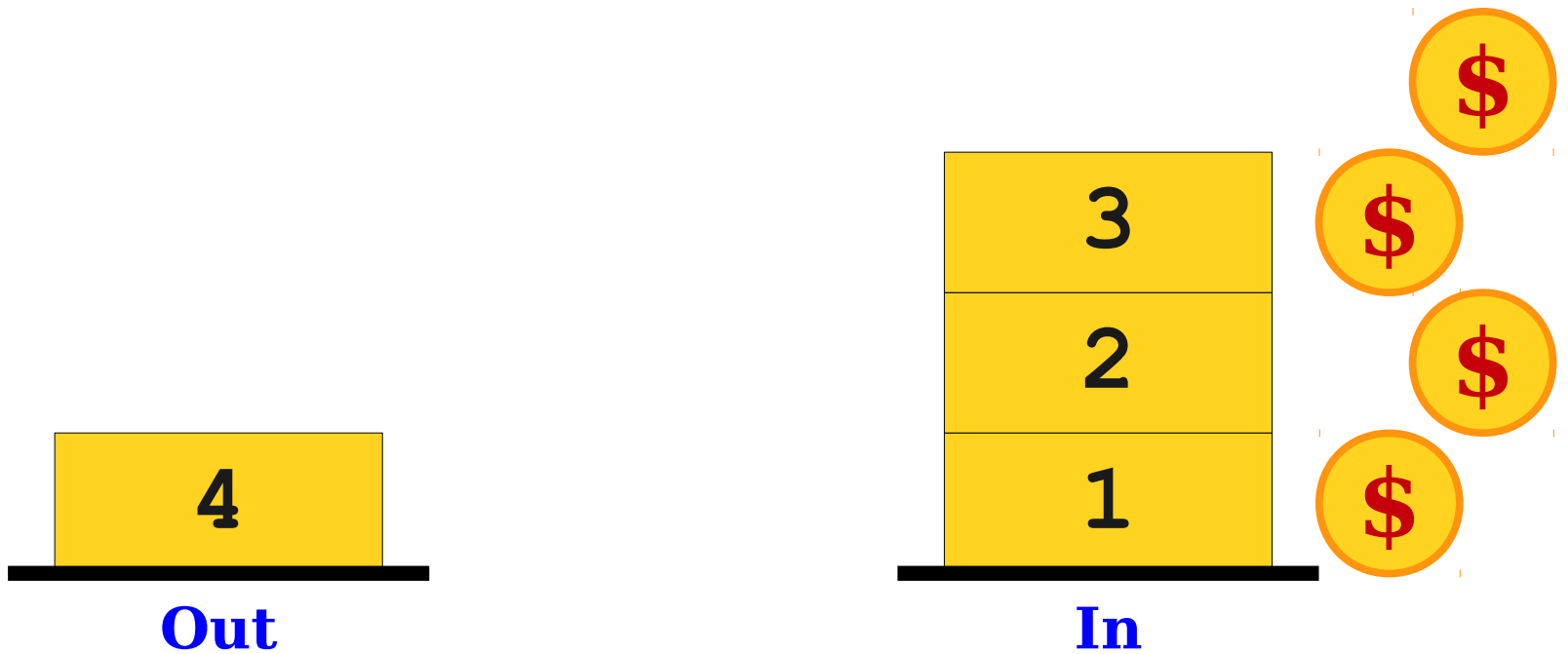
# The Two-Stack Queue



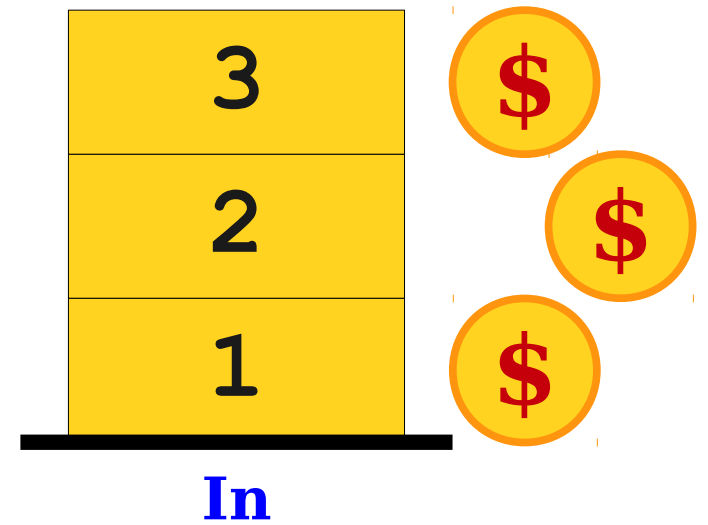
# The Two-Stack Queue



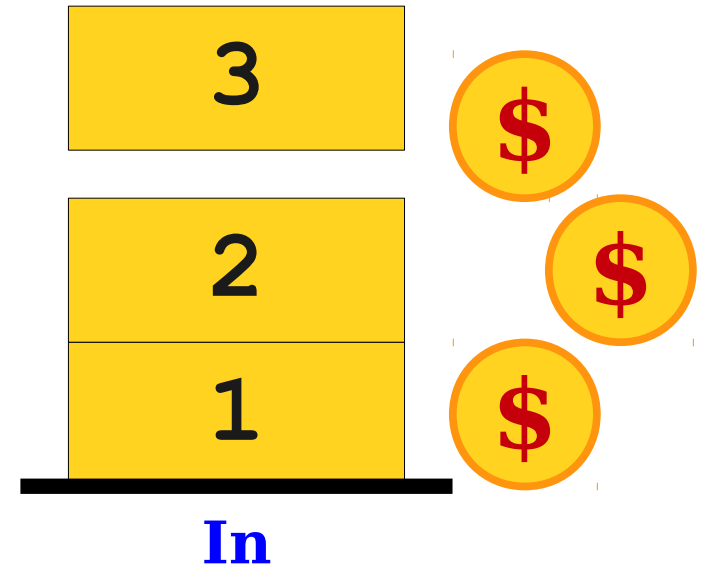
# The Two-Stack Queue



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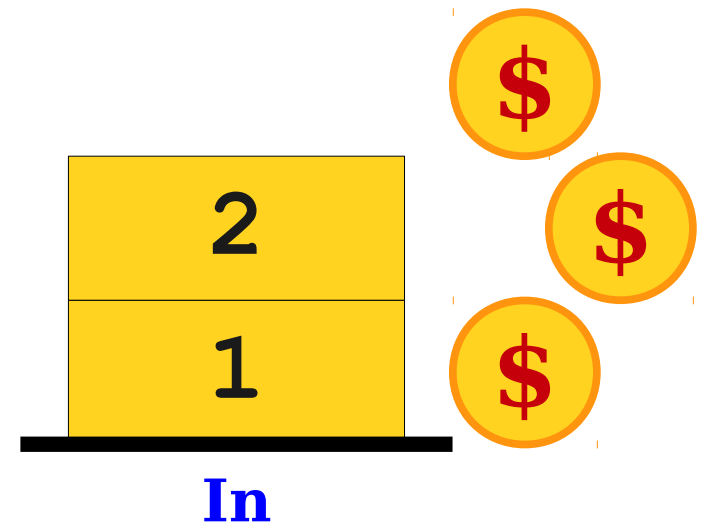
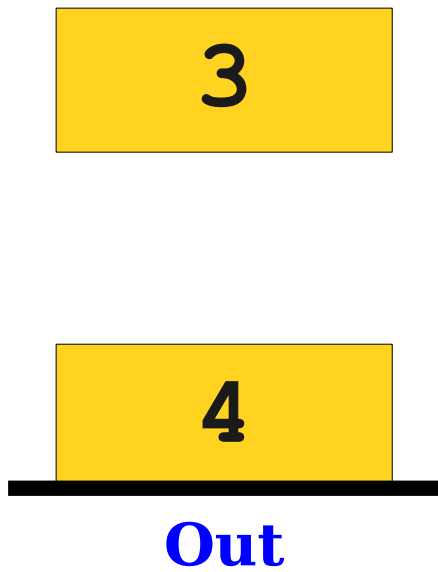


# The Two-Stack Queue

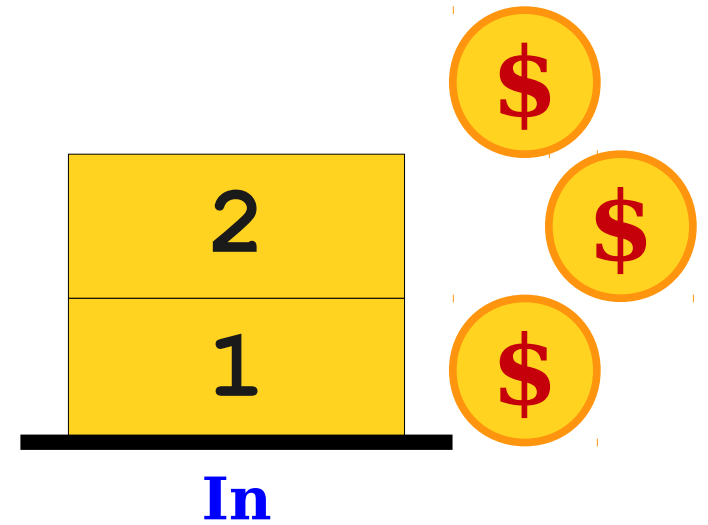
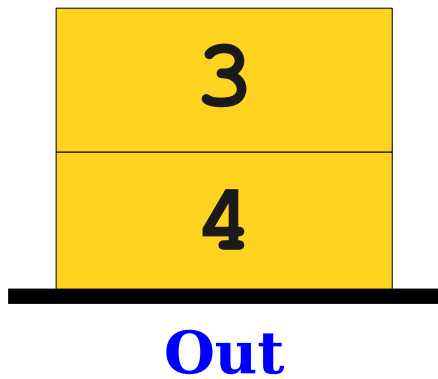




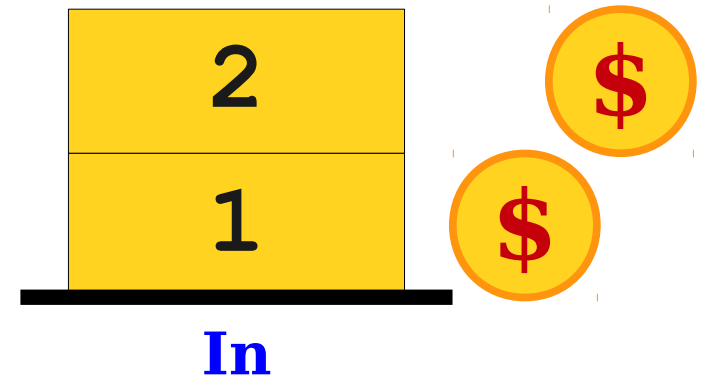
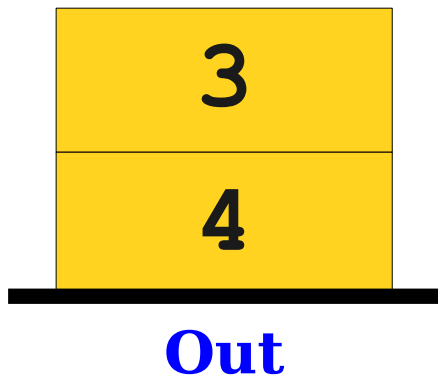
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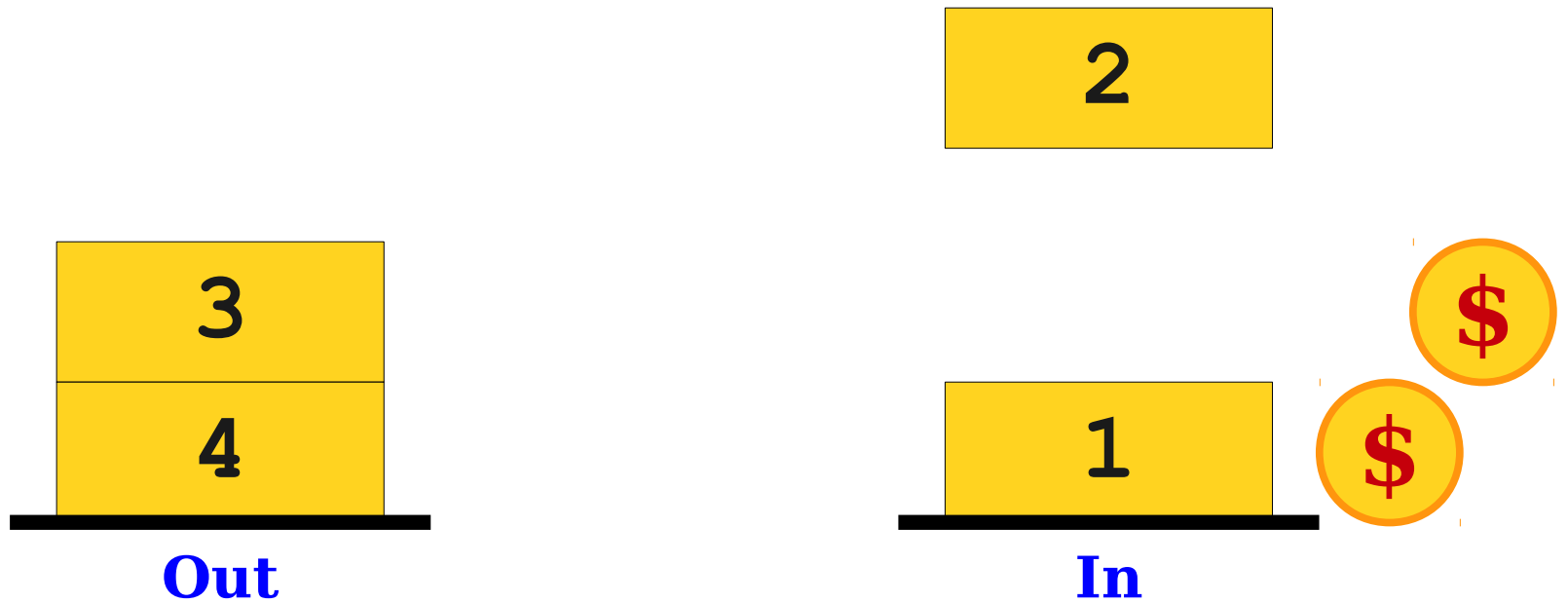
# The Two-Stack Queue



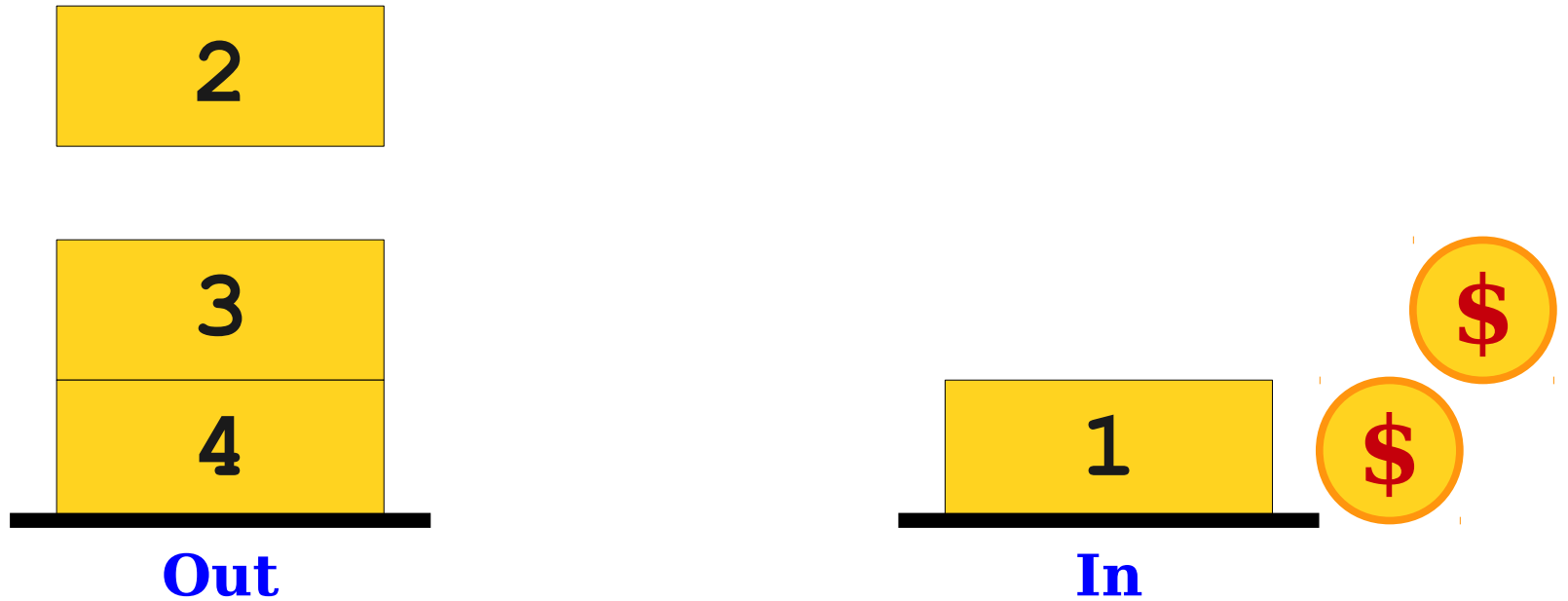
# The Two-Stack Queue



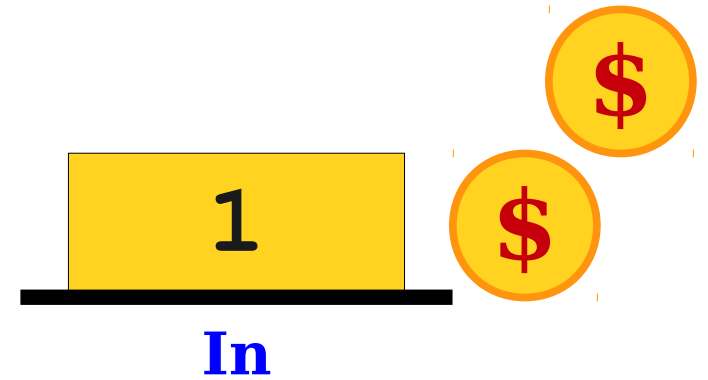
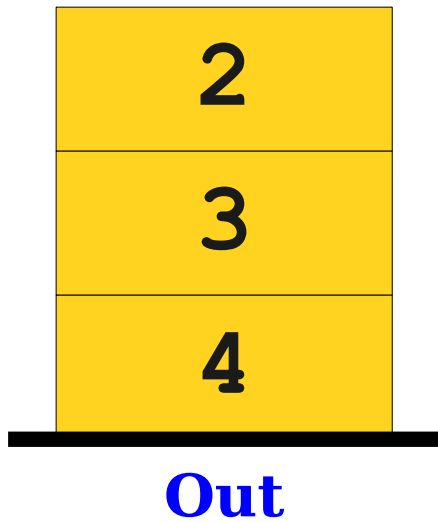
# The Two-Stack Queue



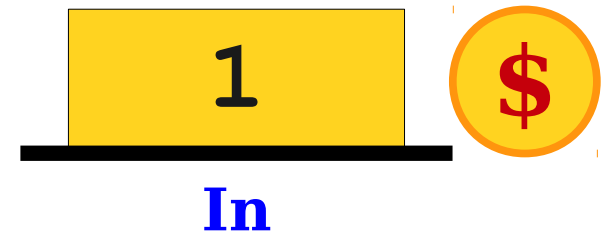
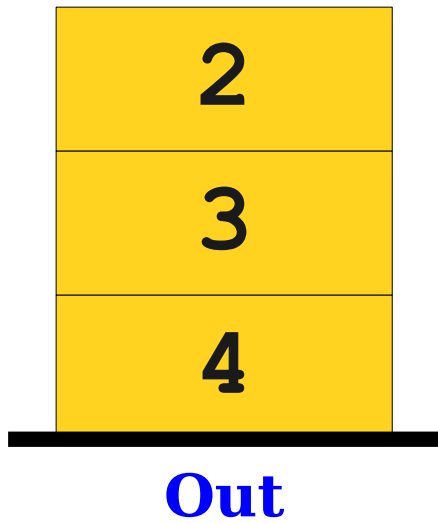
# The Two-Stack Queue



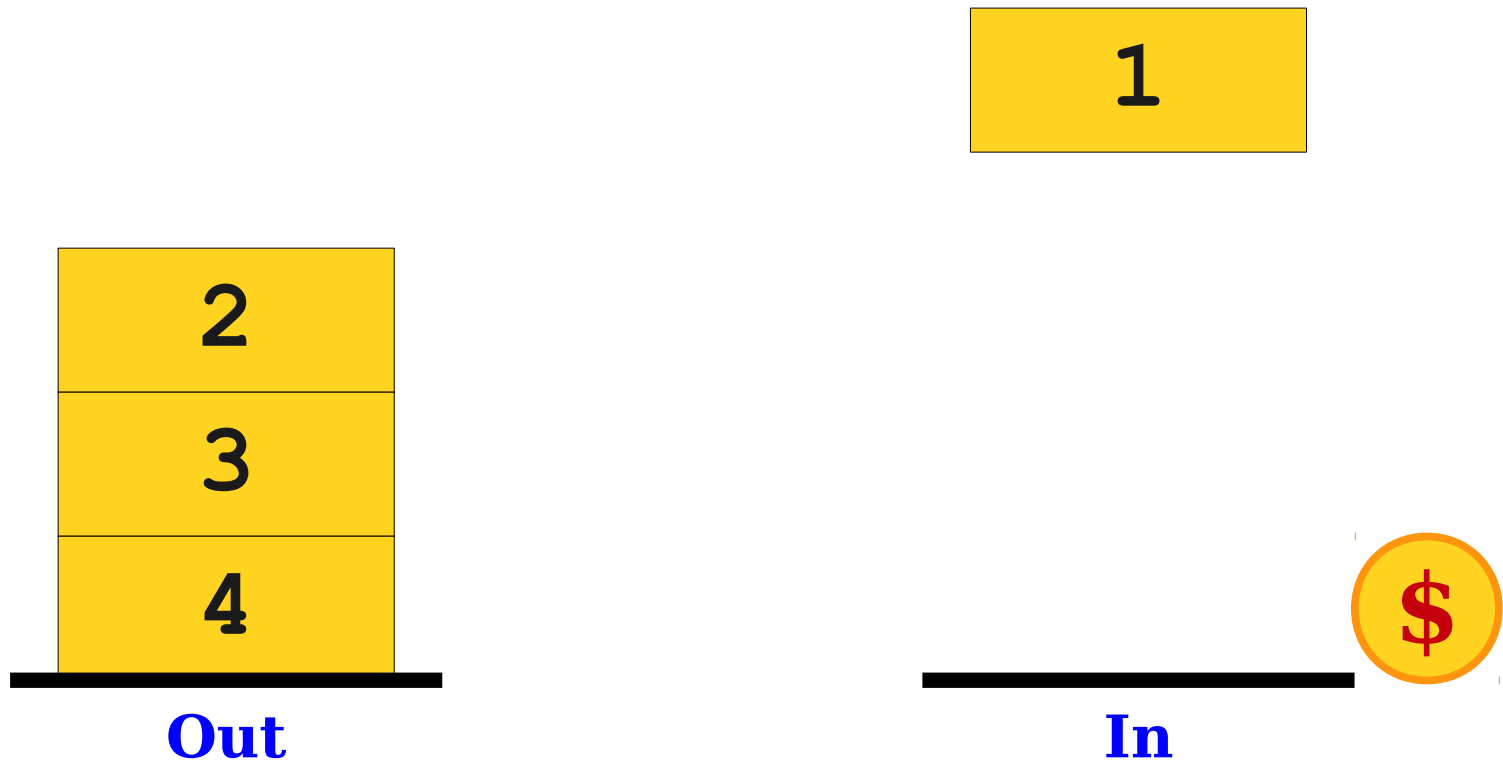
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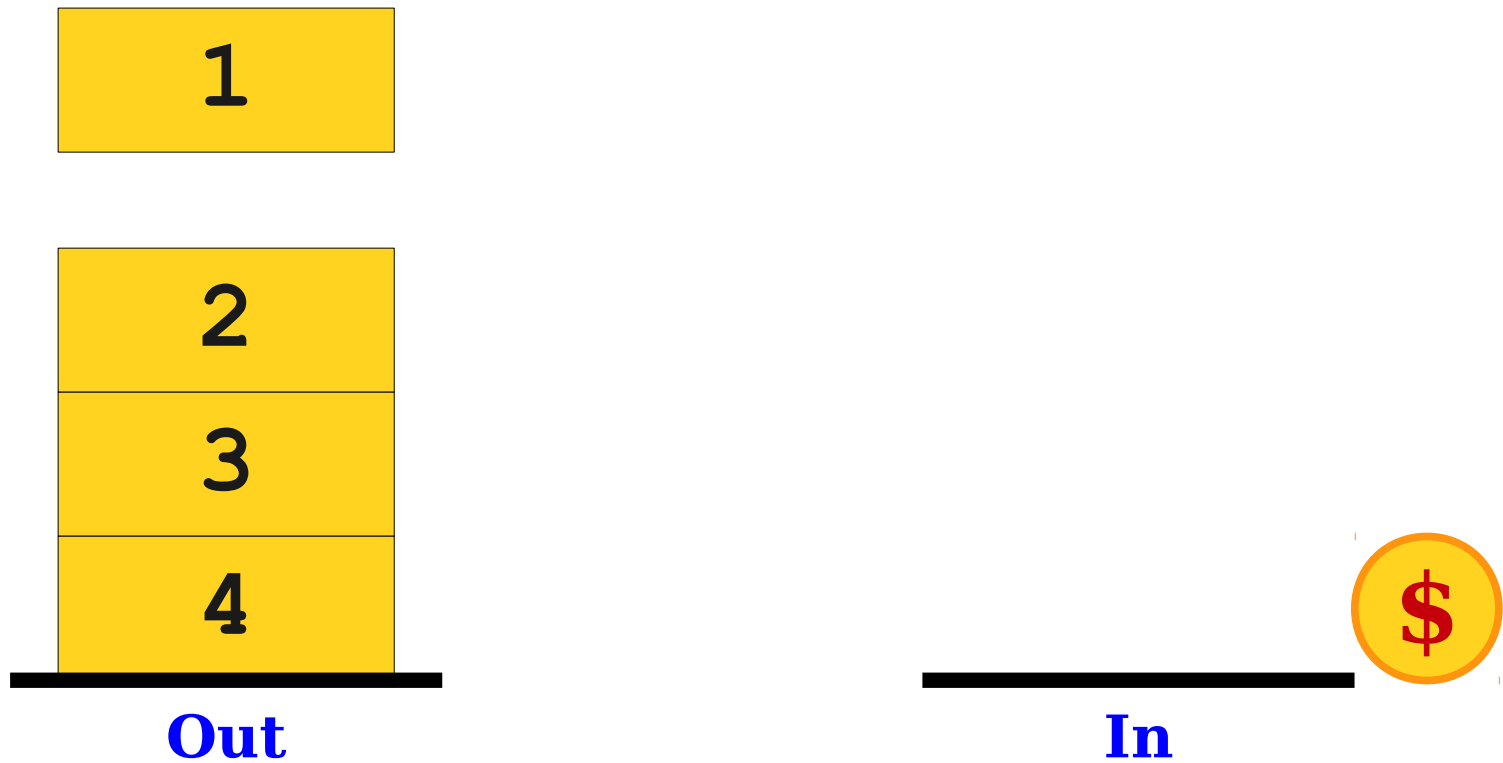


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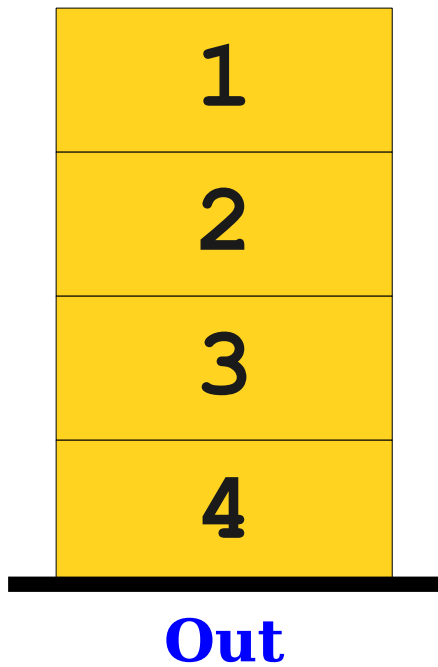




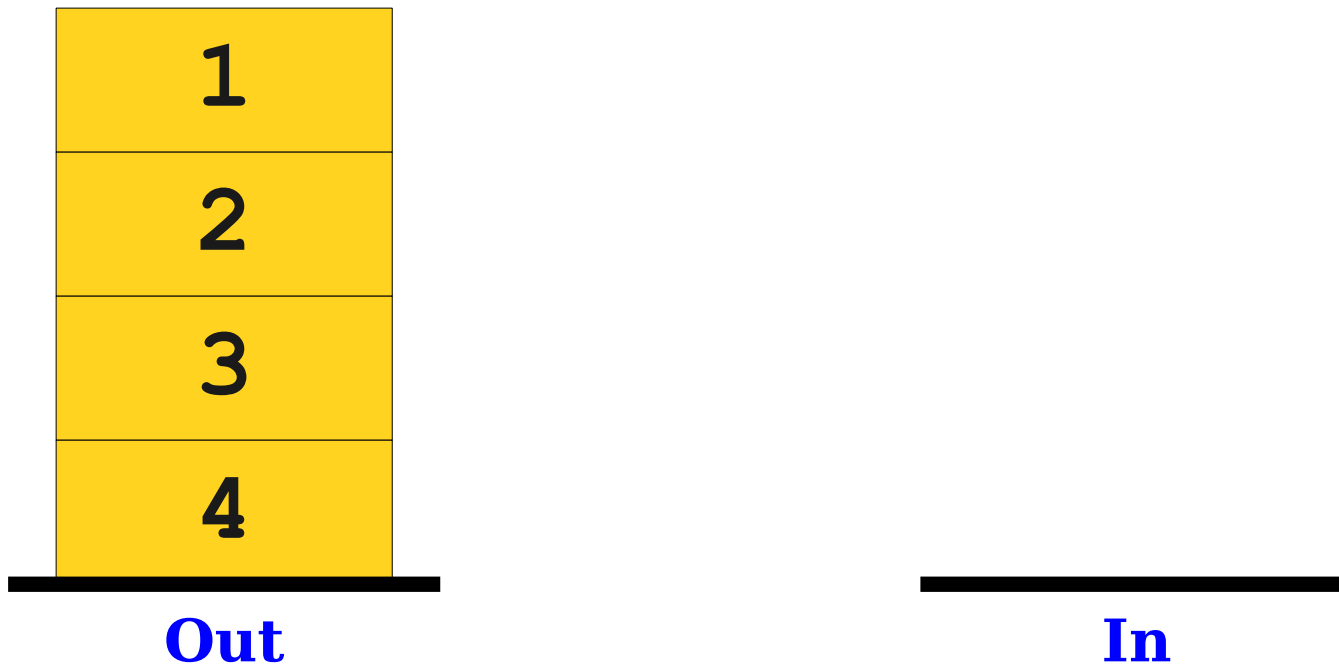
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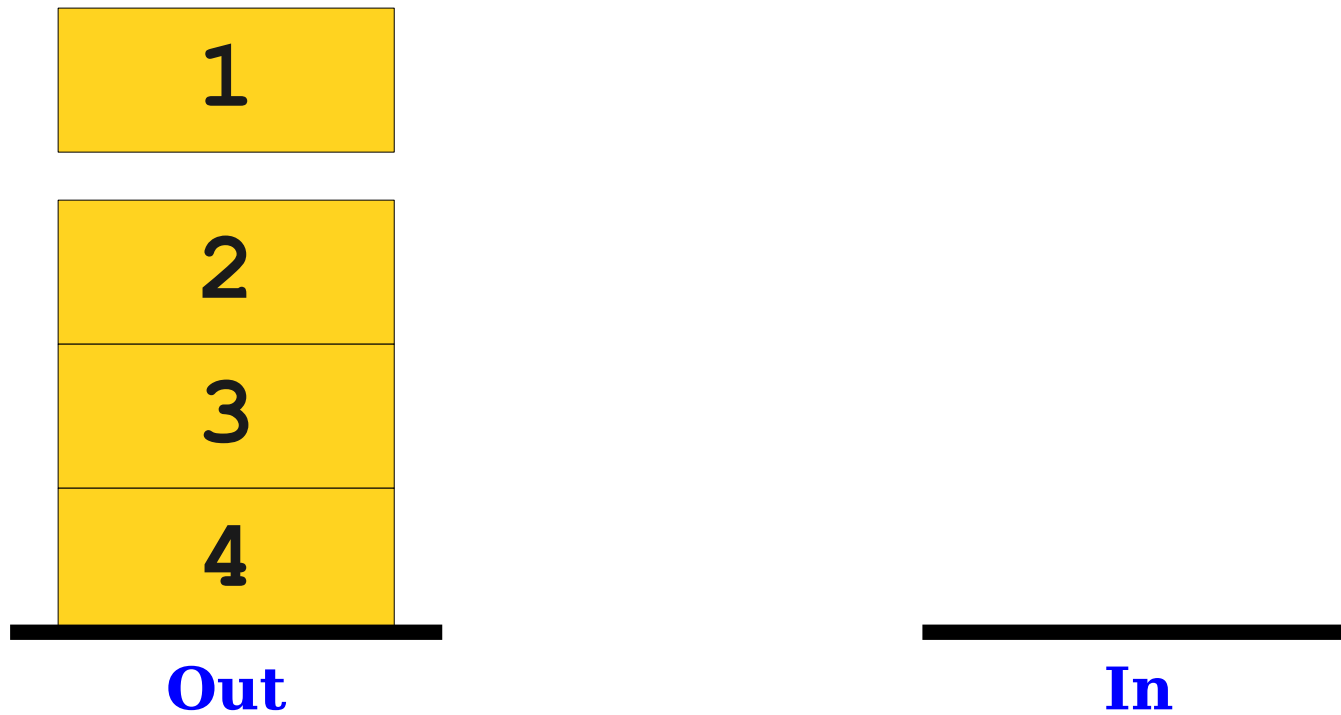
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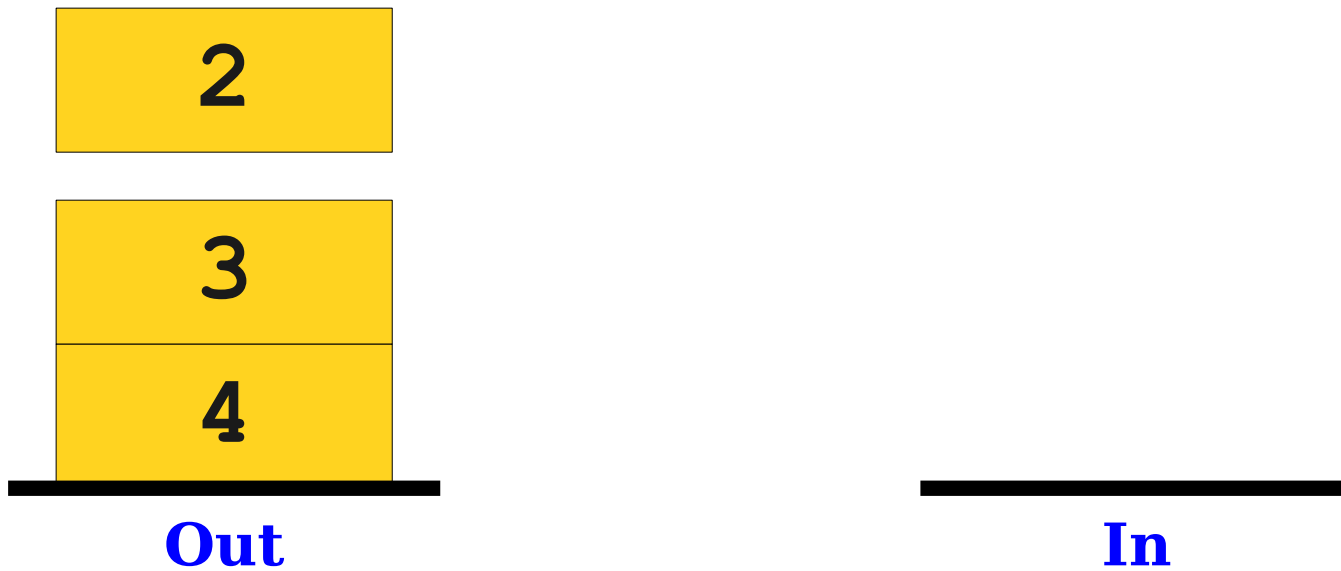
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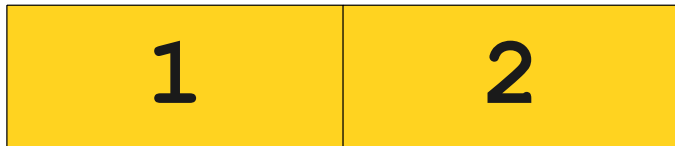
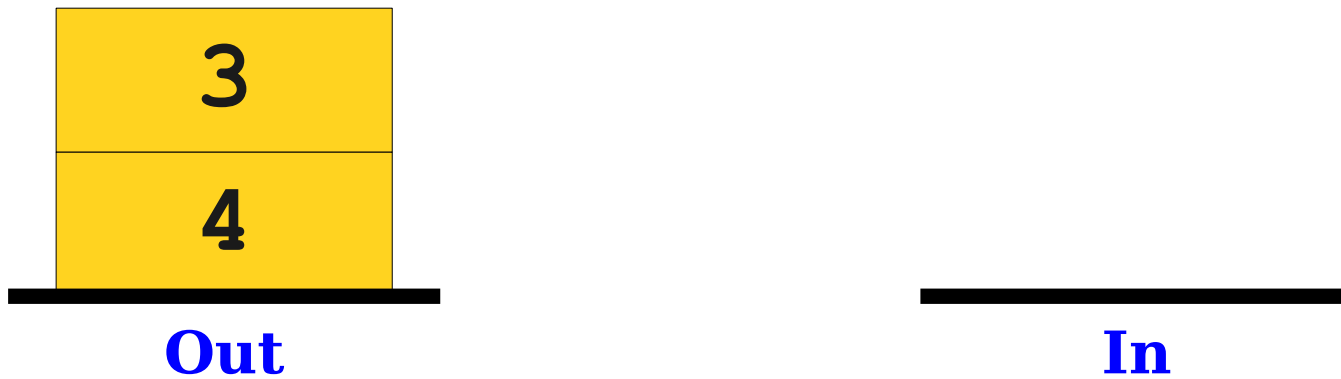
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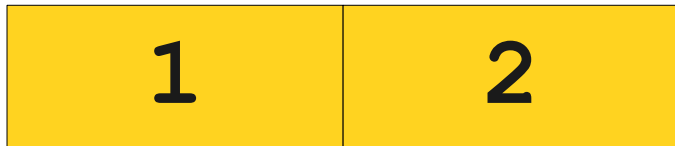
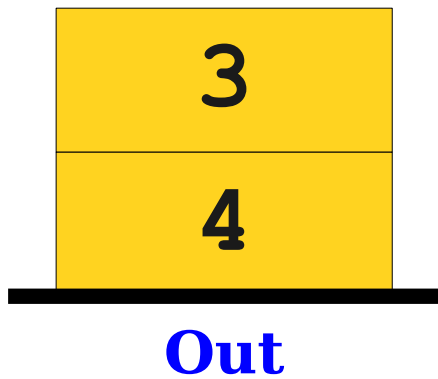
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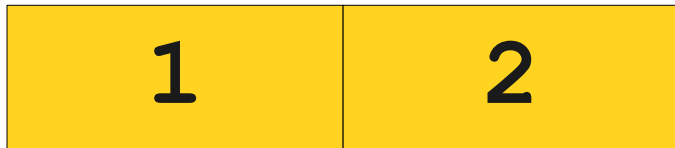
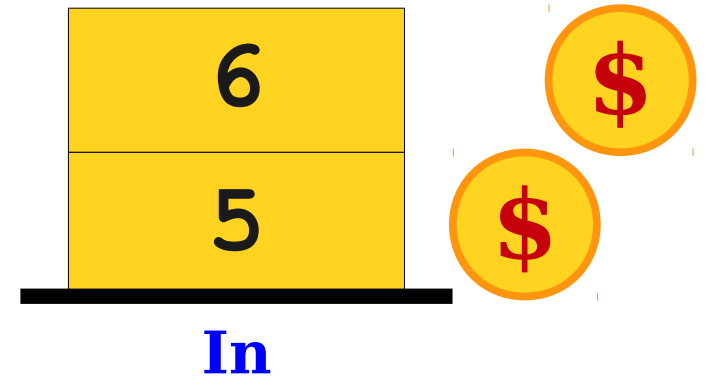
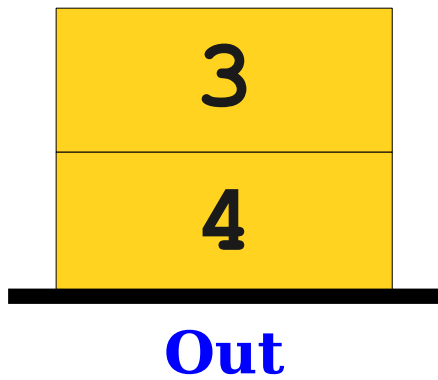


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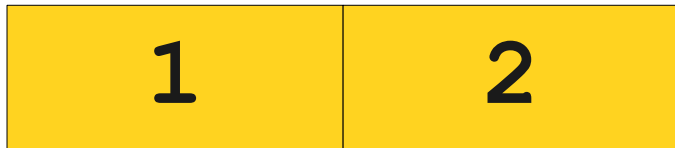
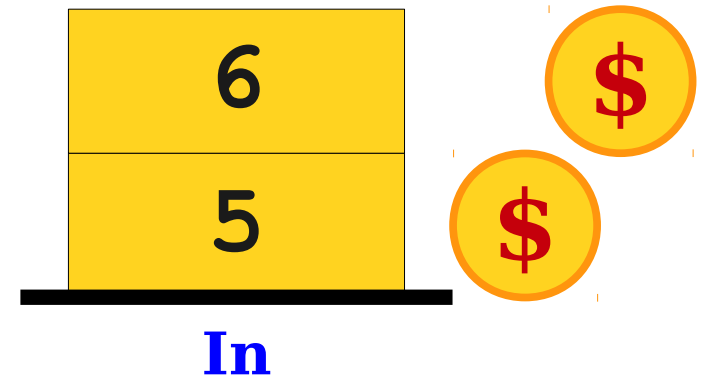
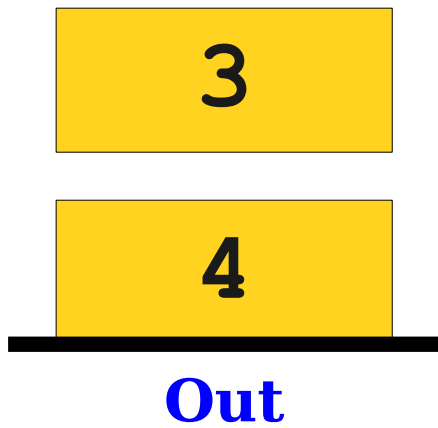




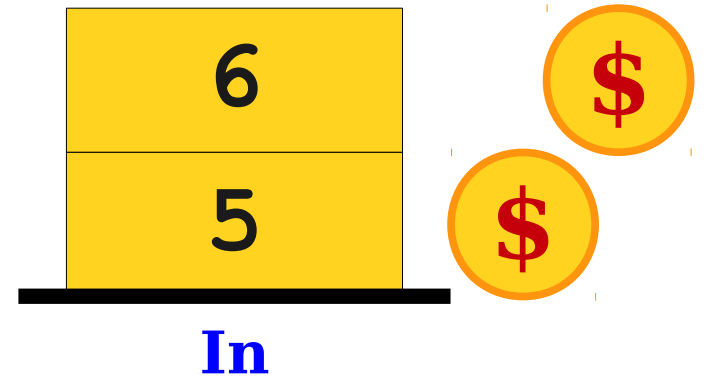
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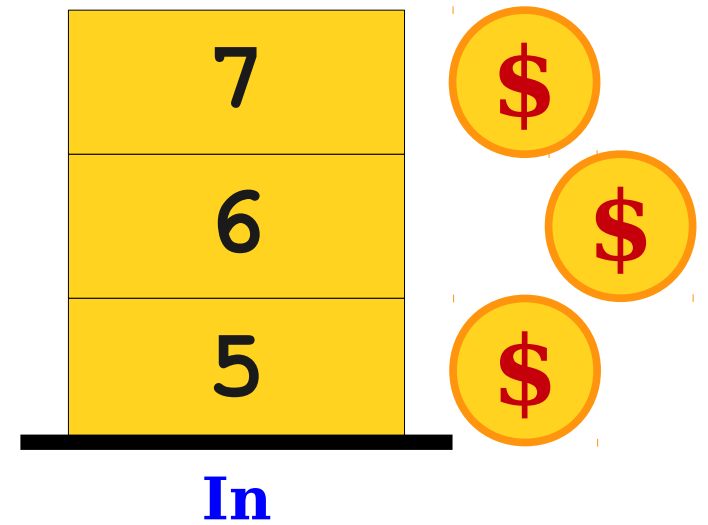
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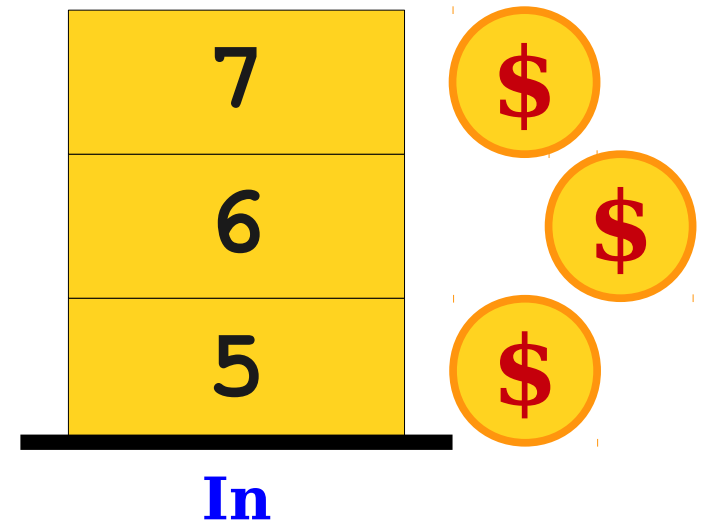
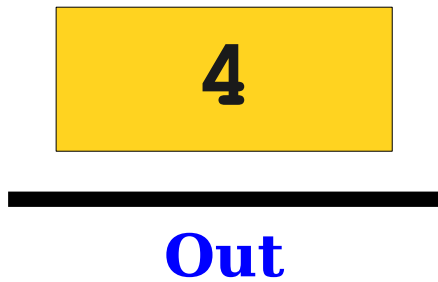
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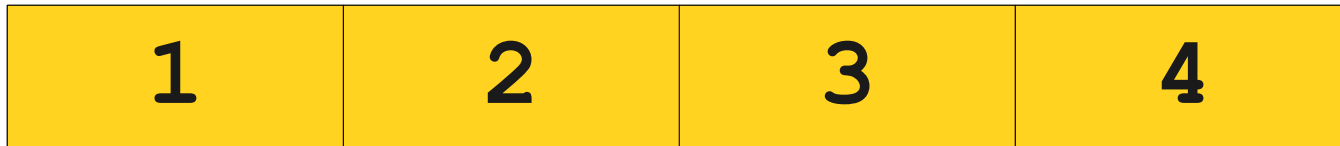
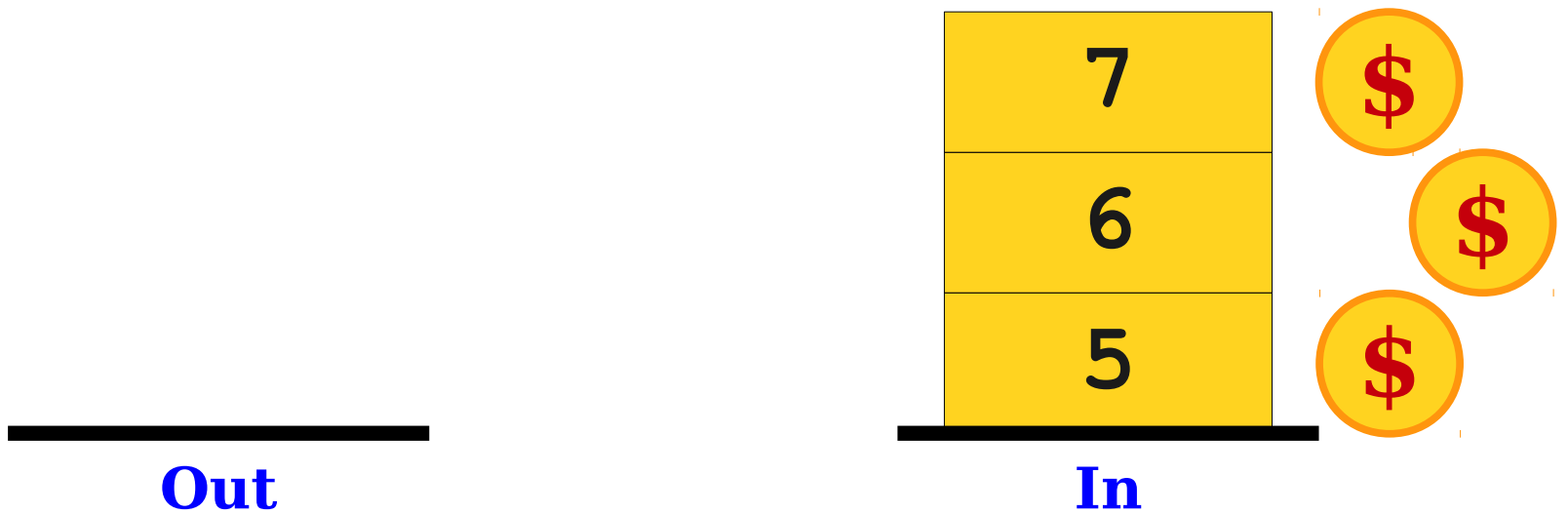
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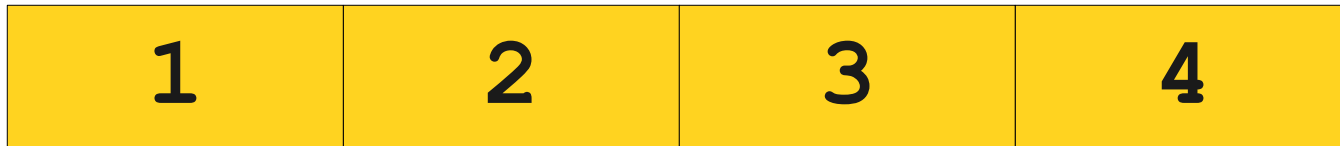
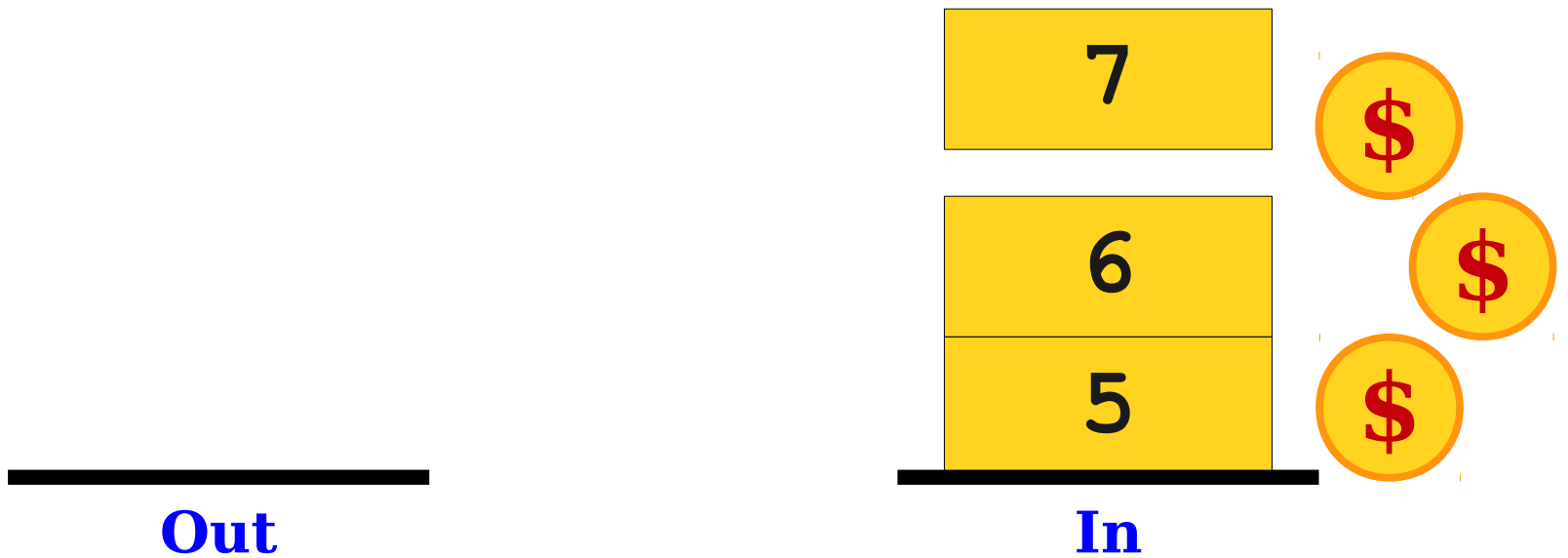
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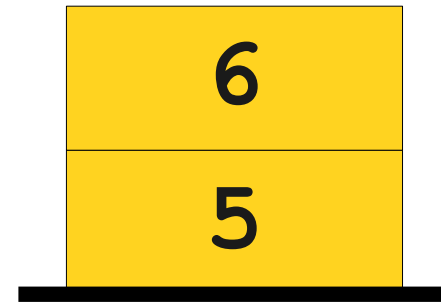
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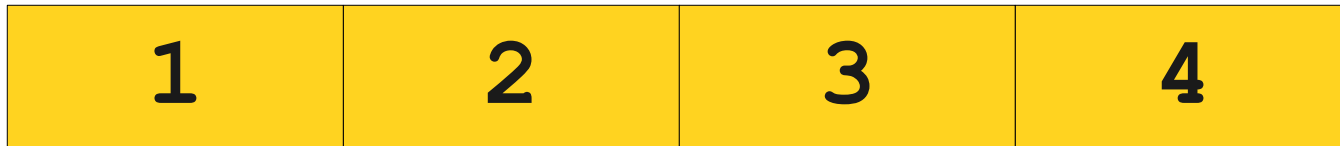
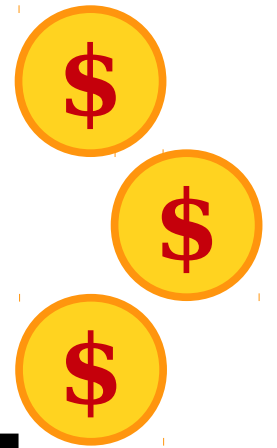
# The Two-Stack Queue



**Out**

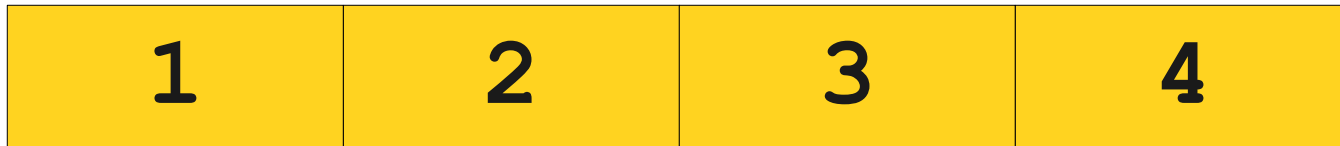
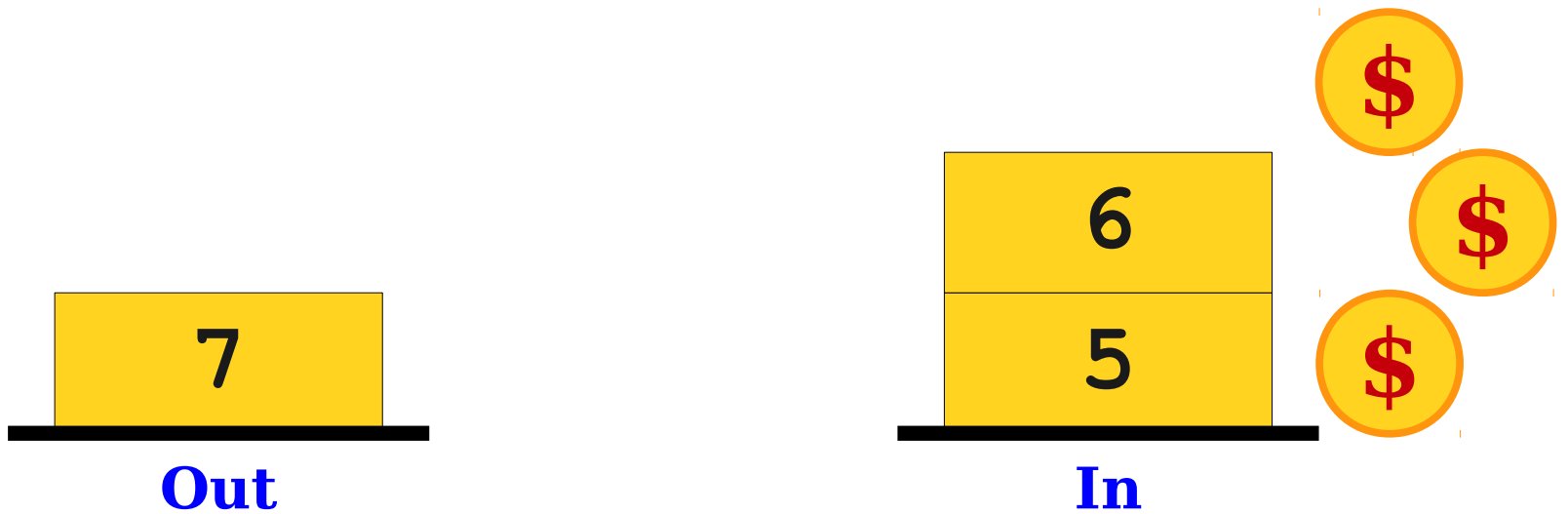


**In**

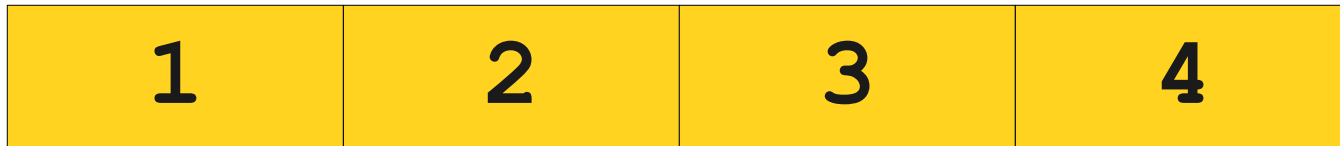
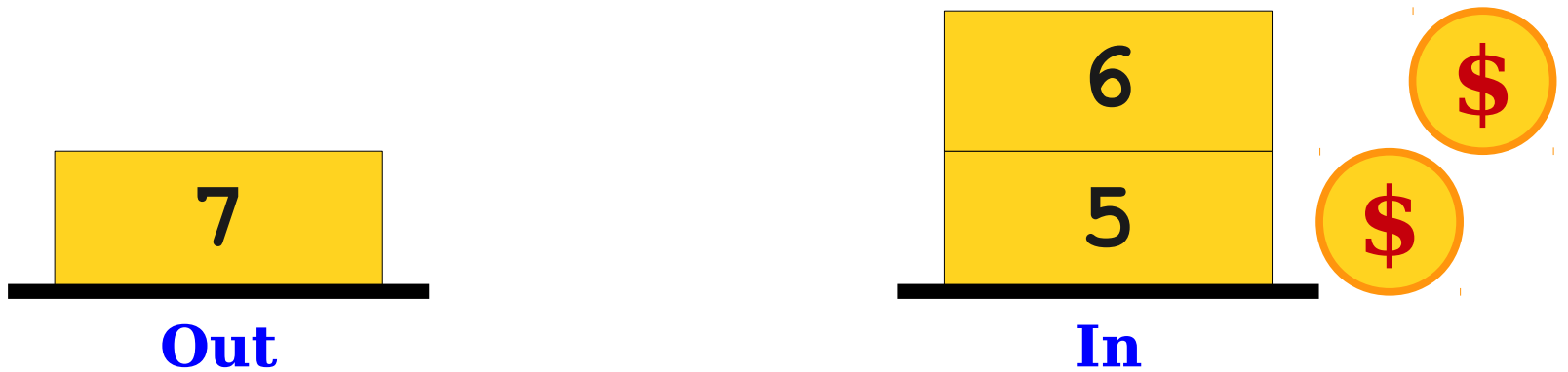




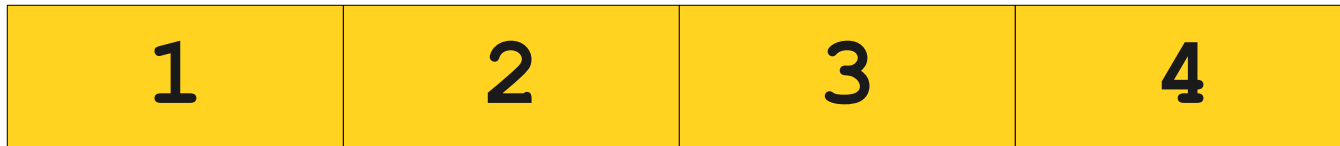
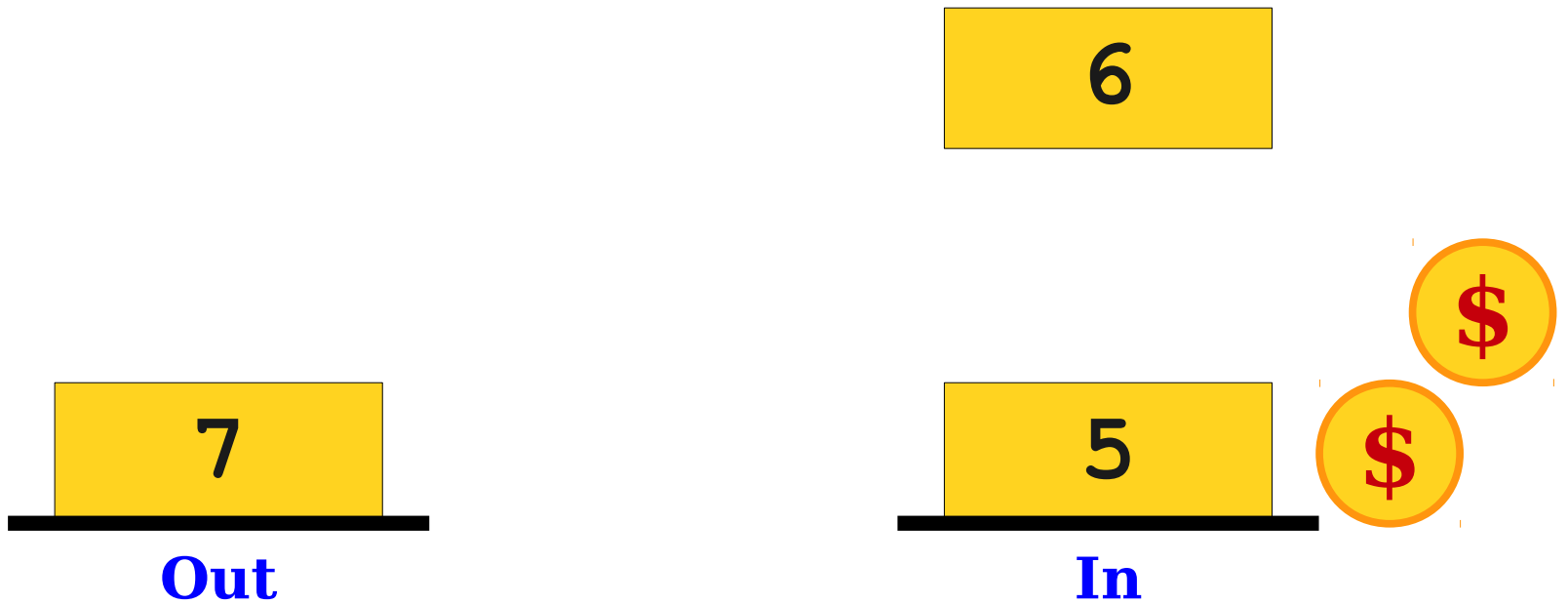
# The Two-Stack Queue



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# The Two-Stack Queue




# The Two-Stack Queue

6

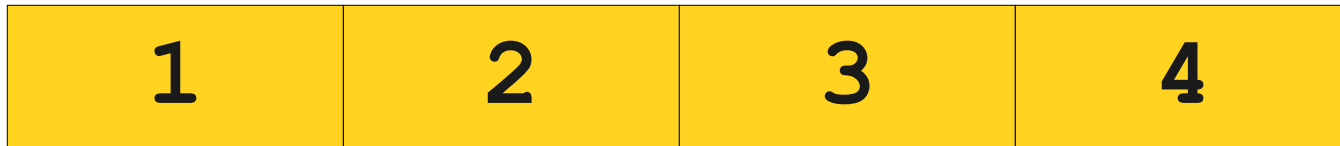
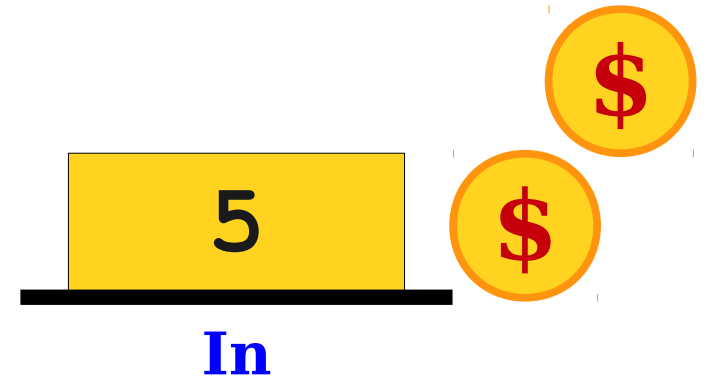
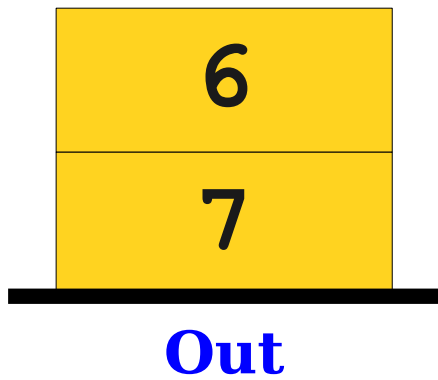
7  
**Out**

5  
**In**

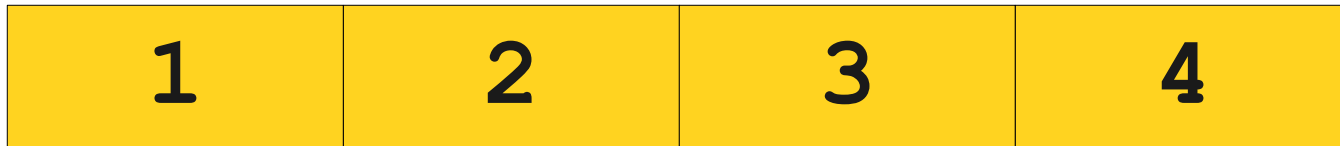
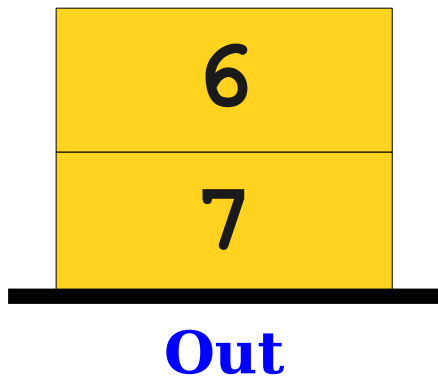


1 2 3 4

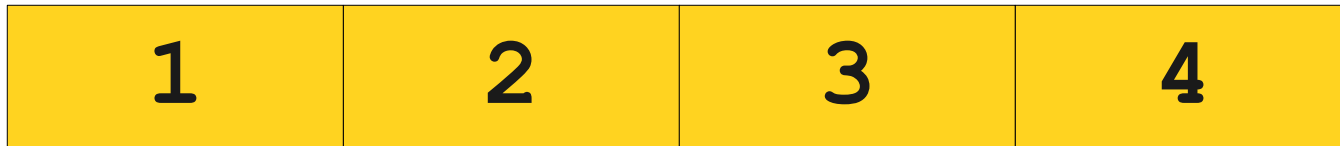
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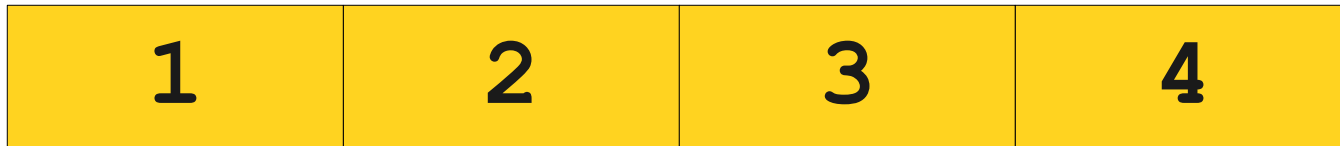
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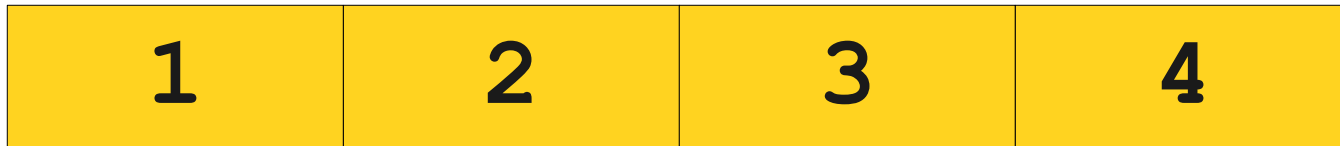
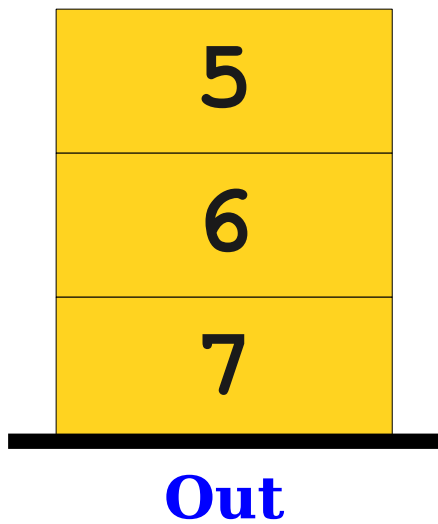


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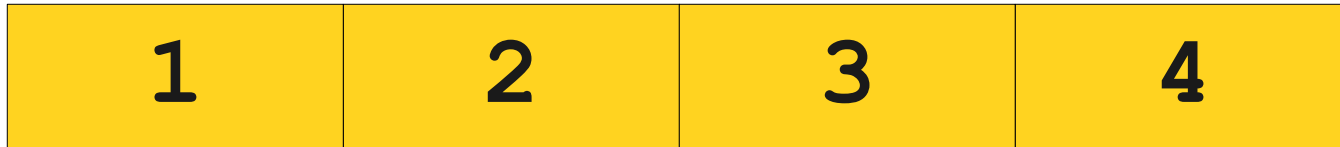
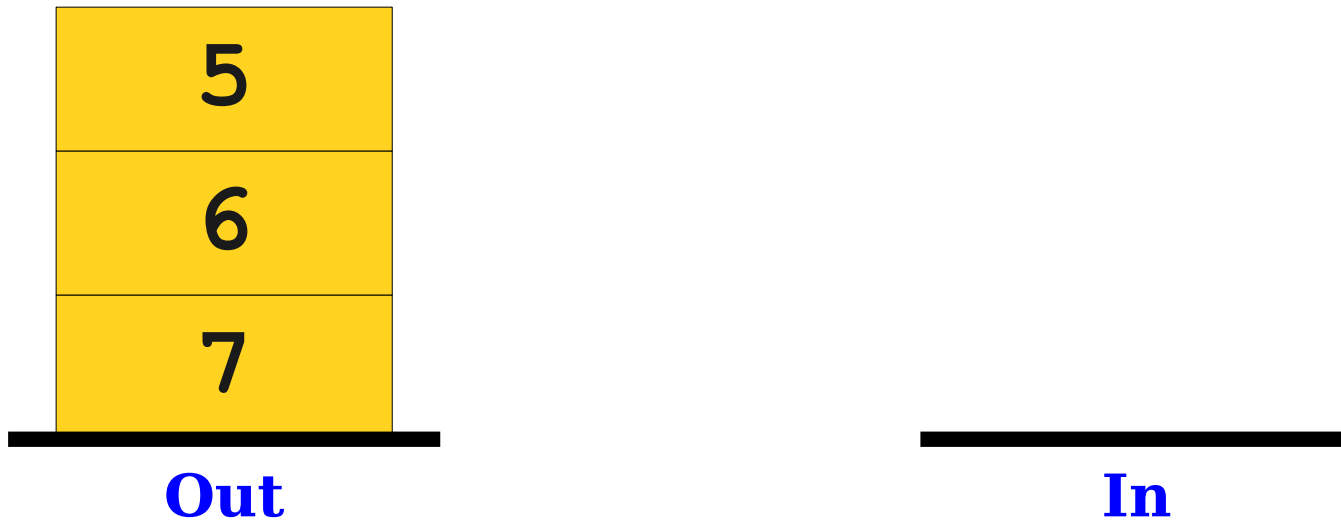




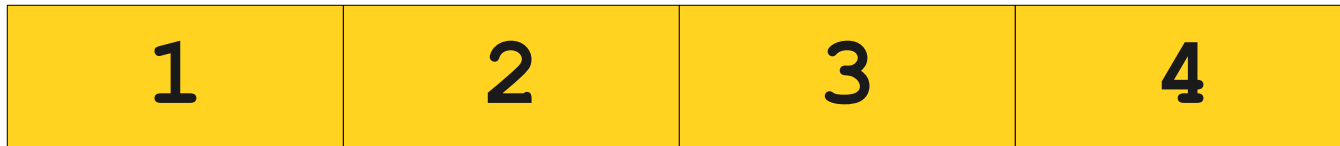
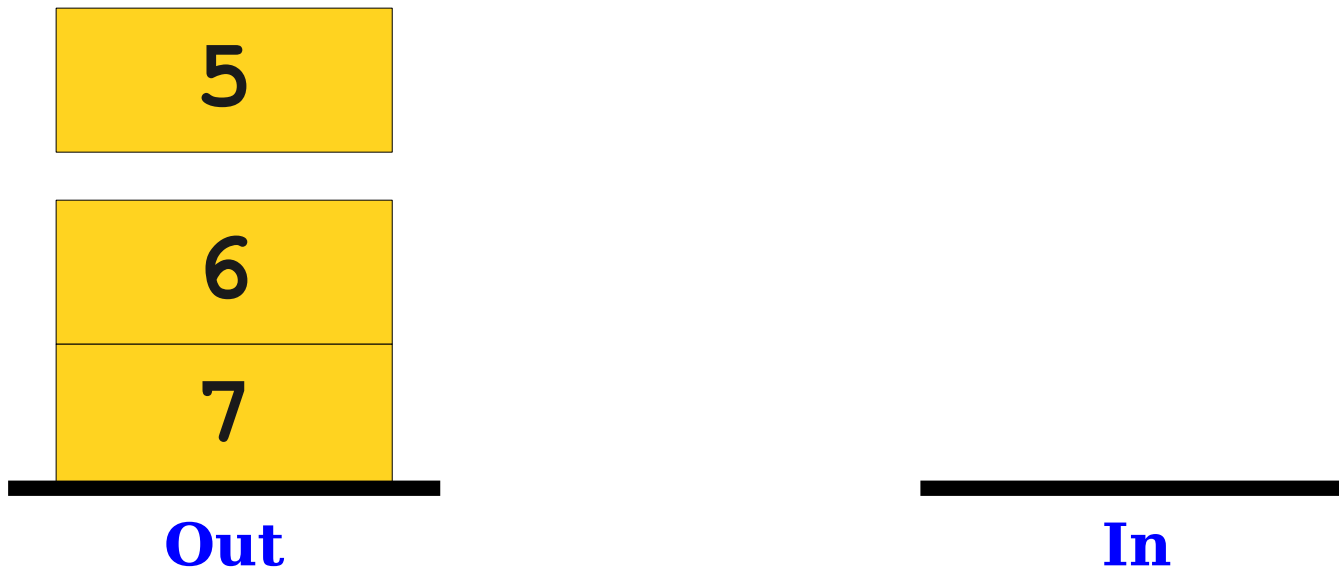
# The Two-Stack Queue



# The Two-Stack Queue



# The Two-Stack Queue



# The Two-Stack Queue



# The Banker's Method

- Enqueue:
  - $O(1)$  work, plus one credit added.
  - Amortized cost:  **$O(1)$** .
- “Light” dequeue:
  - $O(1)$  work, plus no change in credits.
  - Amortized cost:  **$O(1)$** .
- “Heavy” dequeue:
  - $\Theta(k)$  work, where  $k$  is the number of entries that started in the “in” stack.
  - $k$  credits spent.
  - By choosing the amount of work in a credit appropriately, amortized cost is  **$O(1)$** .

# The Potential Method

- Define  $\Phi(D)$  to be the height of the **in** stack.
- Enqueue:
  - Does  $O(1)$  work and increases  $\Phi$  by one.
  - Amortized cost:  **$O(1)$** .
- “Light” dequeue:
  - Does  $O(1)$  work and leaves  $\Phi$  unchanged.
  - Amortized cost:  **$O(1)$** .
- “Heavy” dequeue:
  - Does  $\Theta(k)$  work, where  $k$  is the number of entries moved from the “in” stack.
  - $\Delta\Phi = -k$ .
  - By choosing the amount of work stored in each unit of potential correctly, amortized cost becomes  **$O(1)$** .

Another Examples: **2-3-4 Trees**

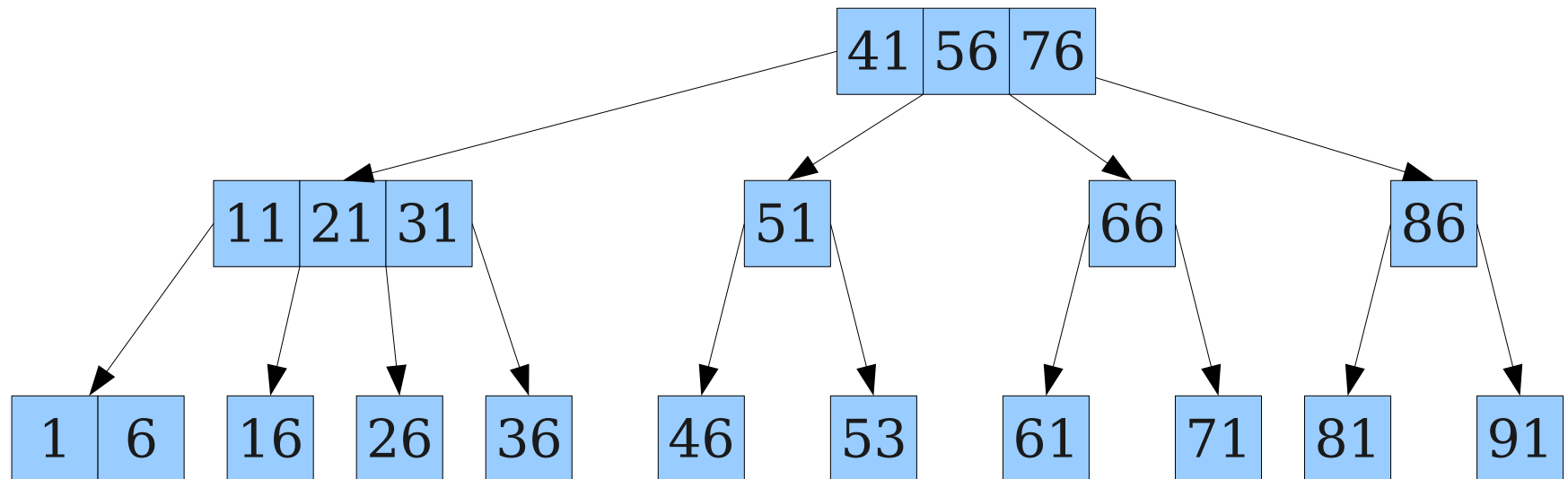
# 2-3-4 Trees

- Inserting or deleting values from a 2-3-4 trees takes time  $O(\log n)$ .
- Why is that?
  - Some amount of work finding the insertion or deletion point, which is  $\Theta(\log n)$ .
  - Some amount of work “fixing up” the tree by doing insertions or deletions.
- How much is that second amount?



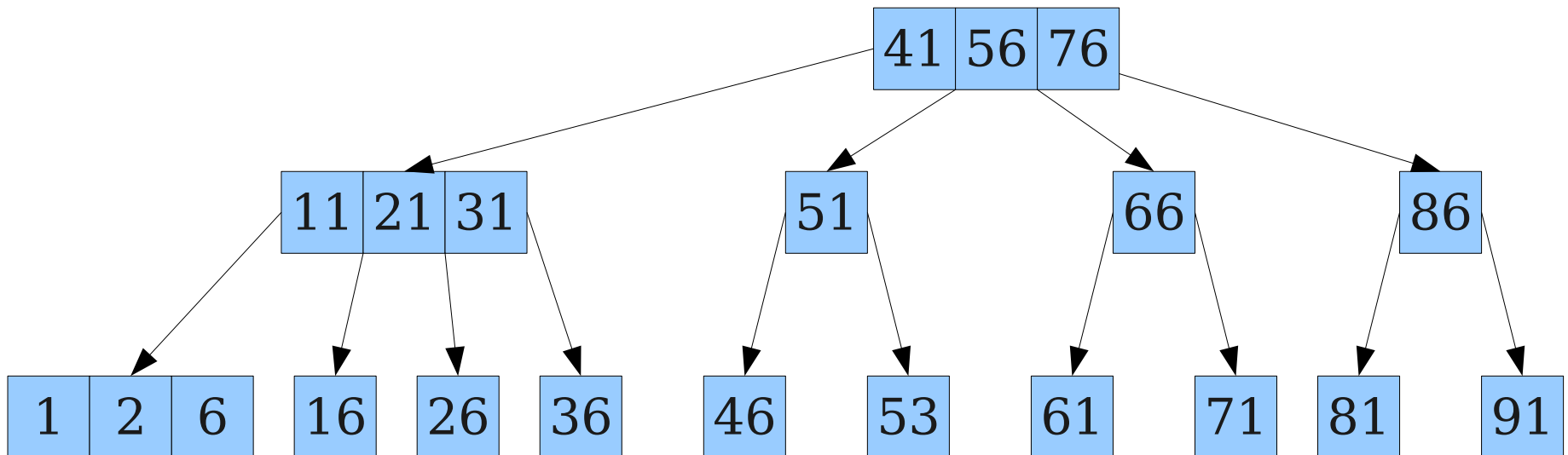
# 2-3-4 Tree Insertions

- Most insertions into 2-3-4 trees require no fixup – we just insert an extra key into a leaf.
- Some insertions require some fixup to split nodes and propagate upward.



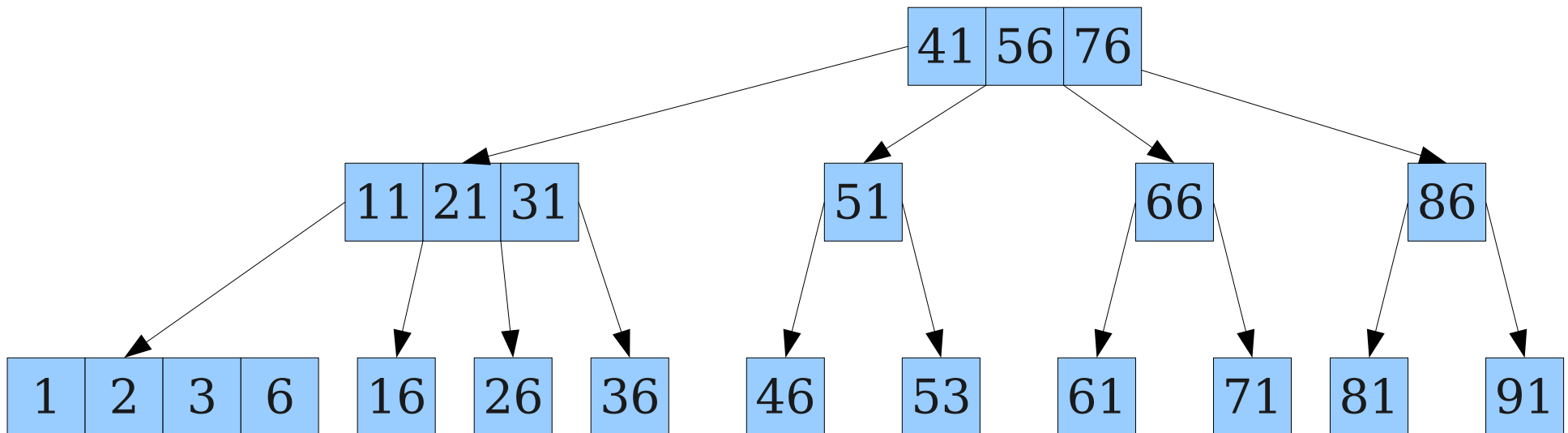
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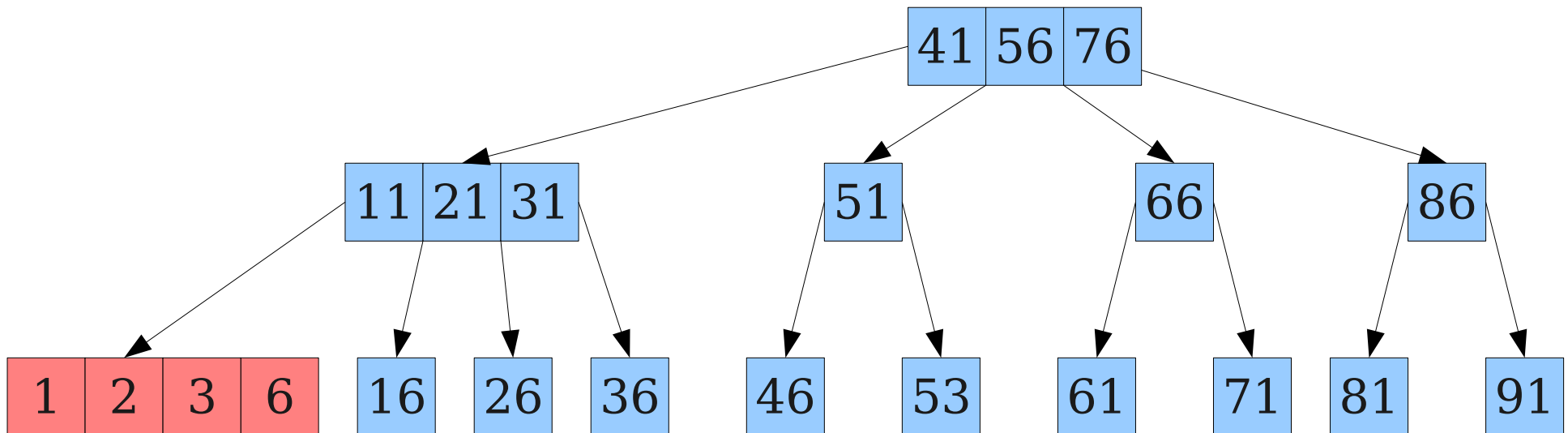
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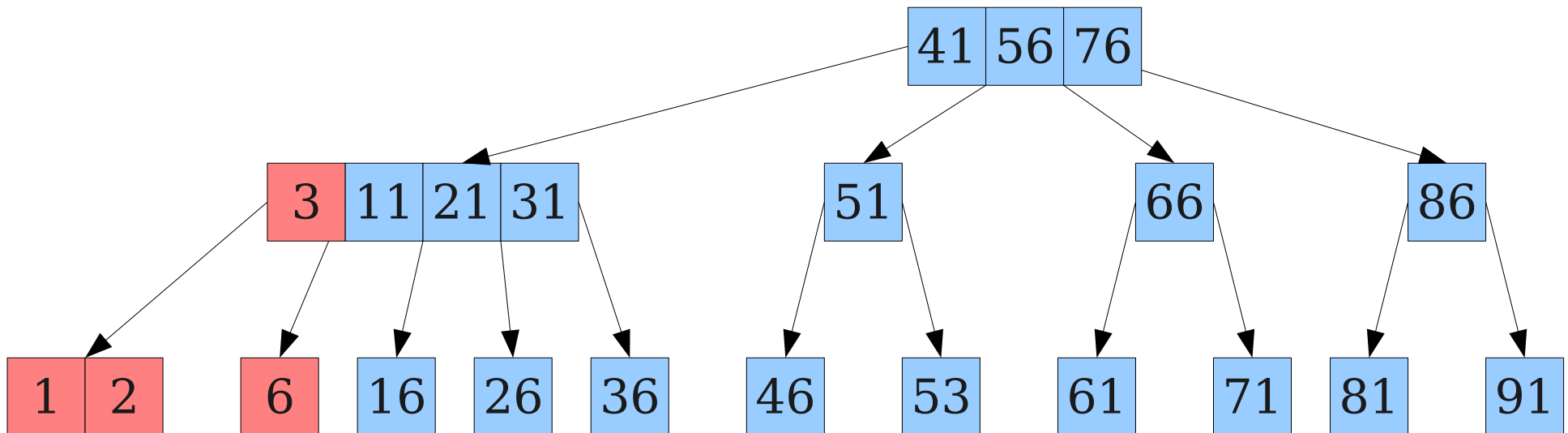
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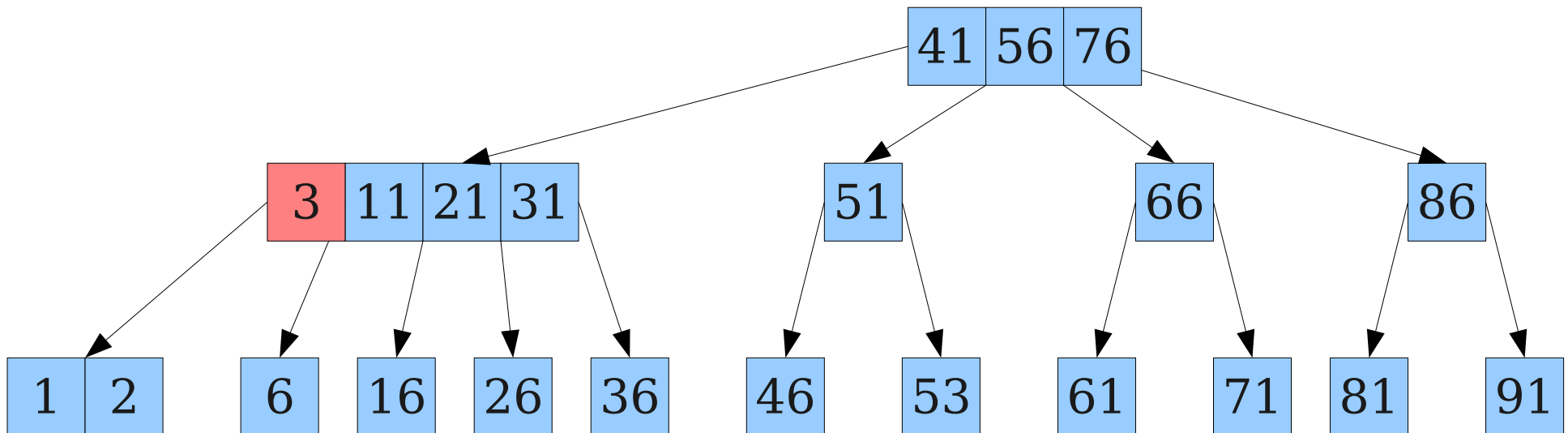
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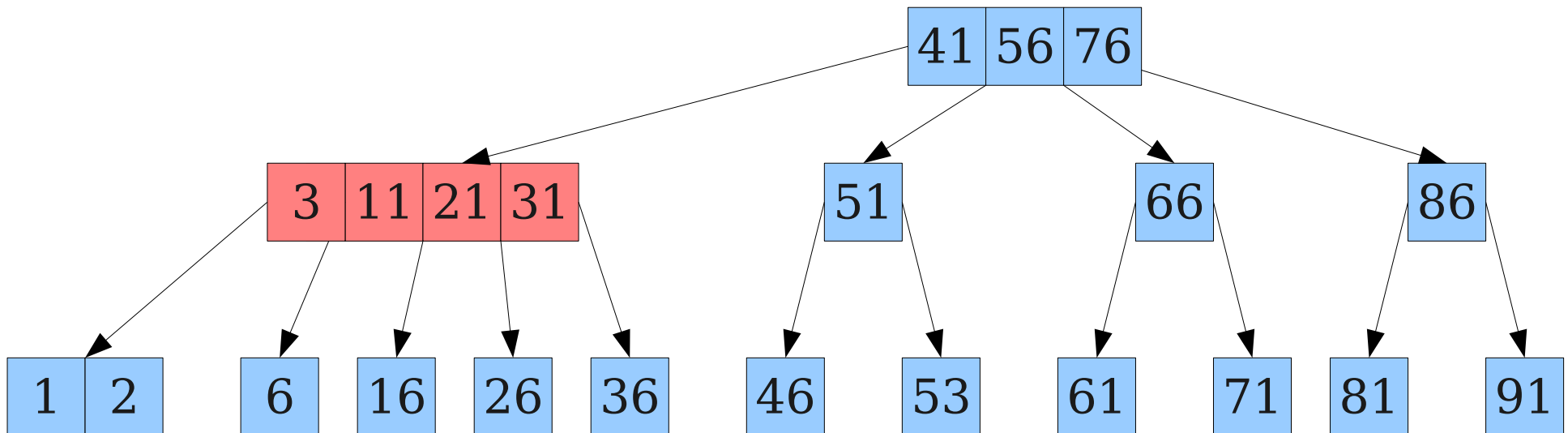
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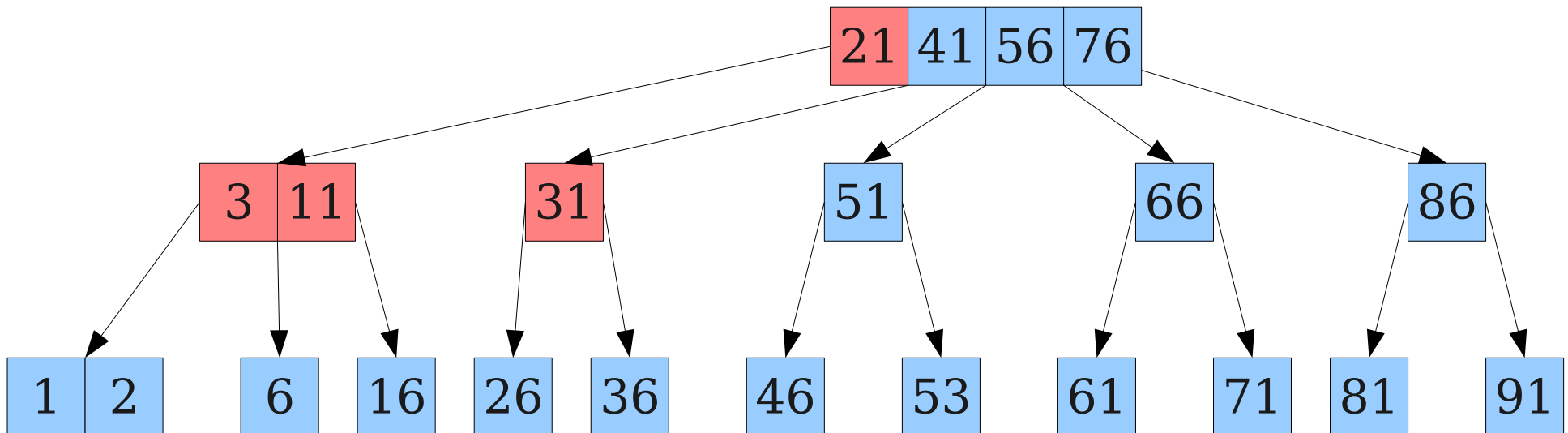
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# 2-3-4 Tree Insertions

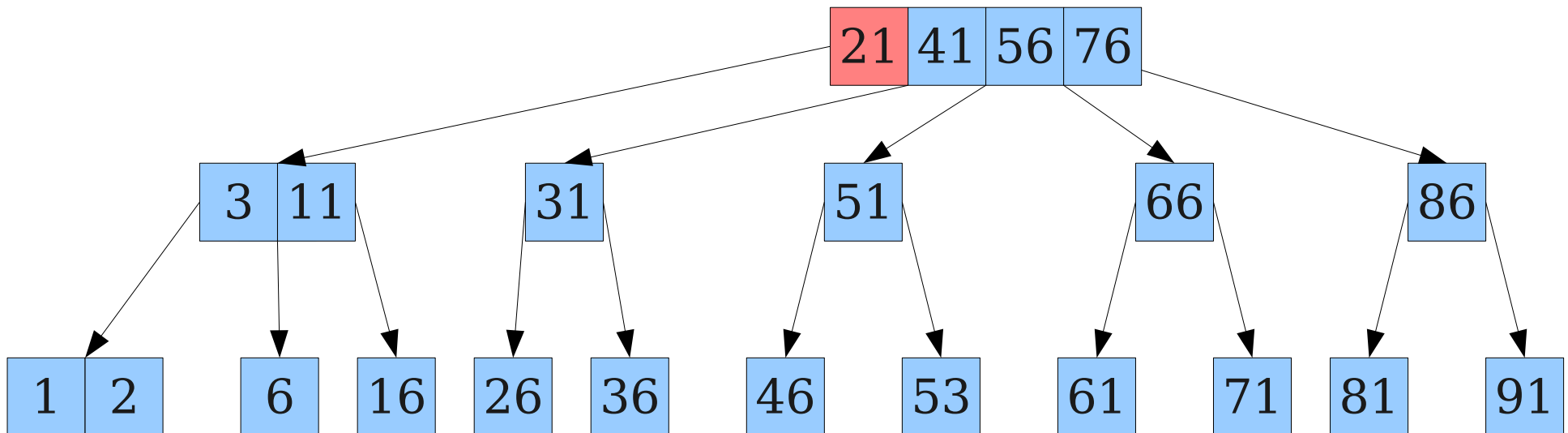
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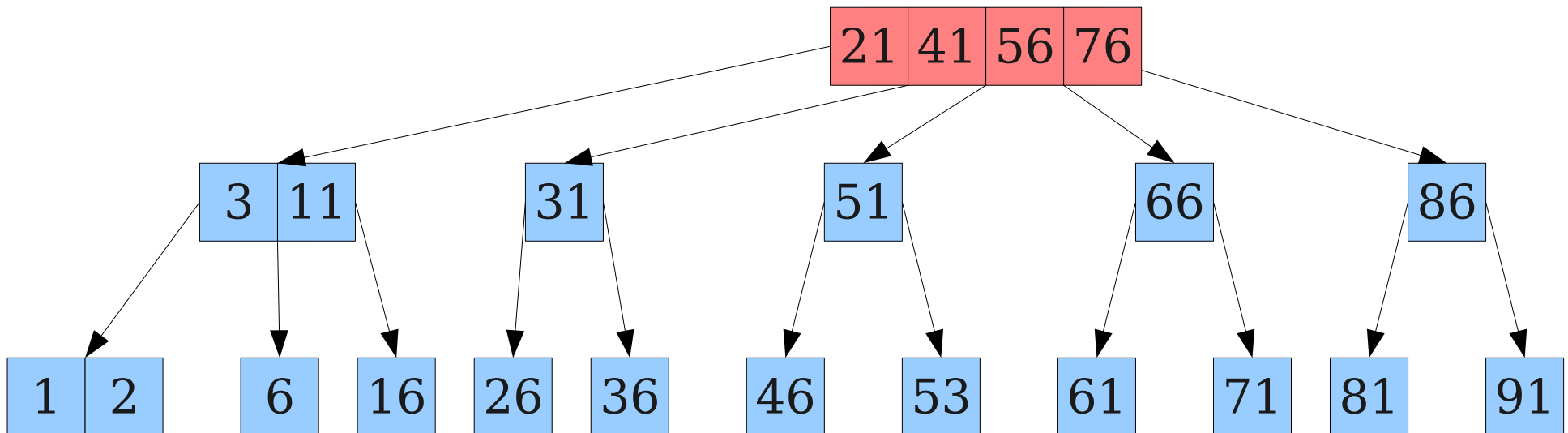
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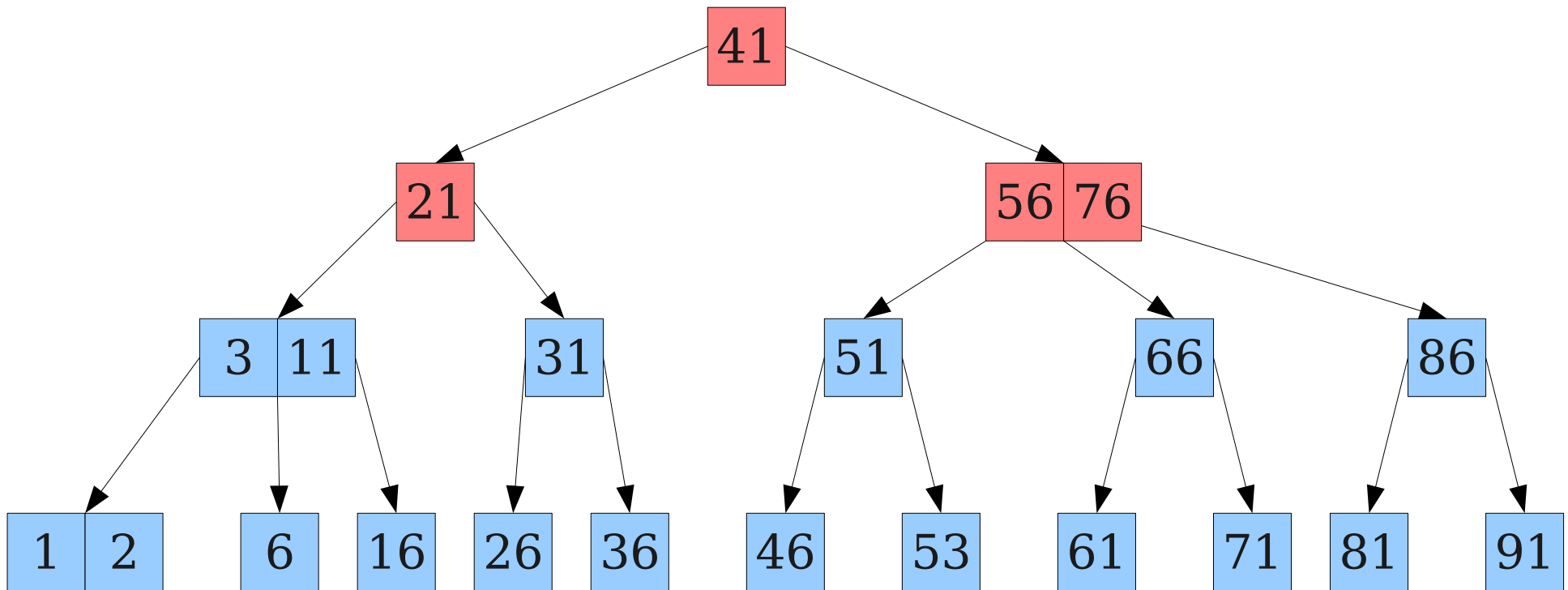
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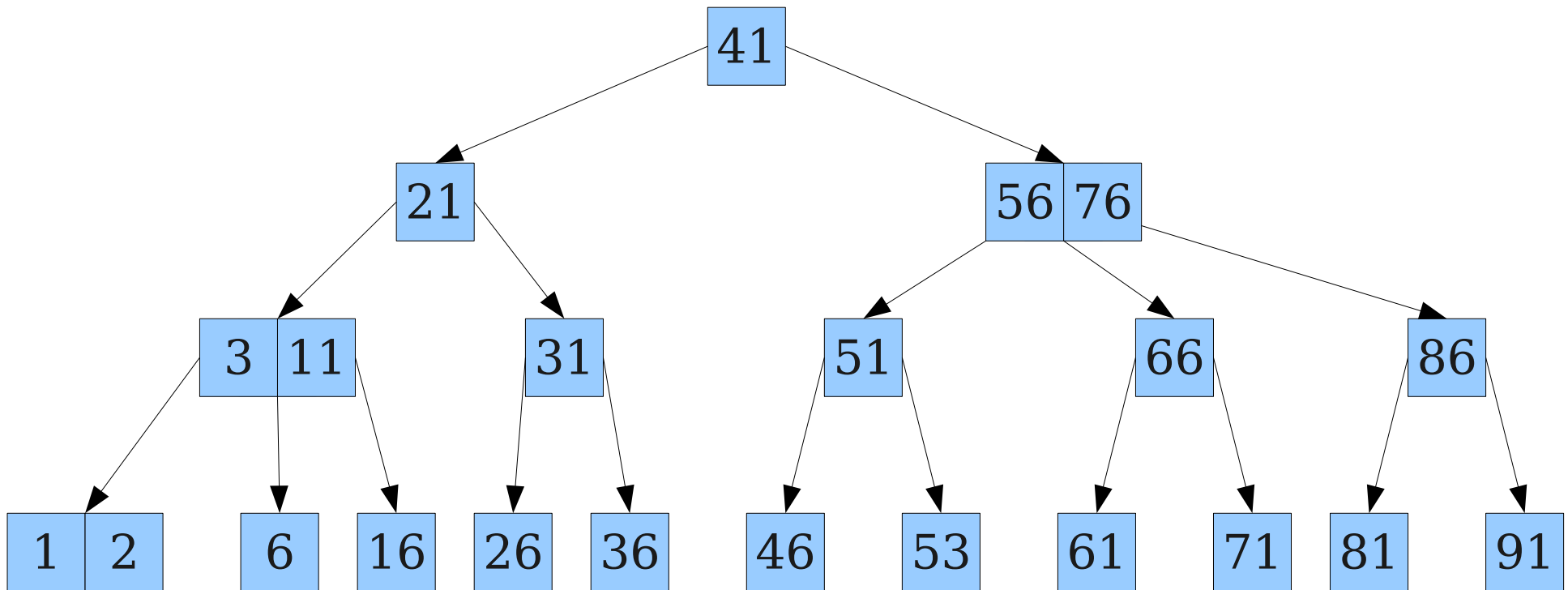
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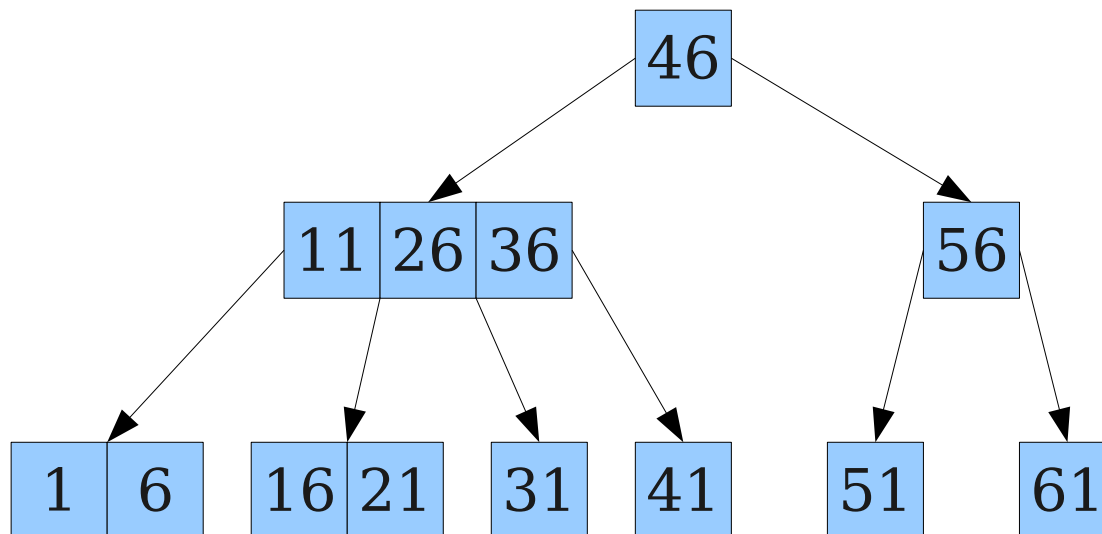
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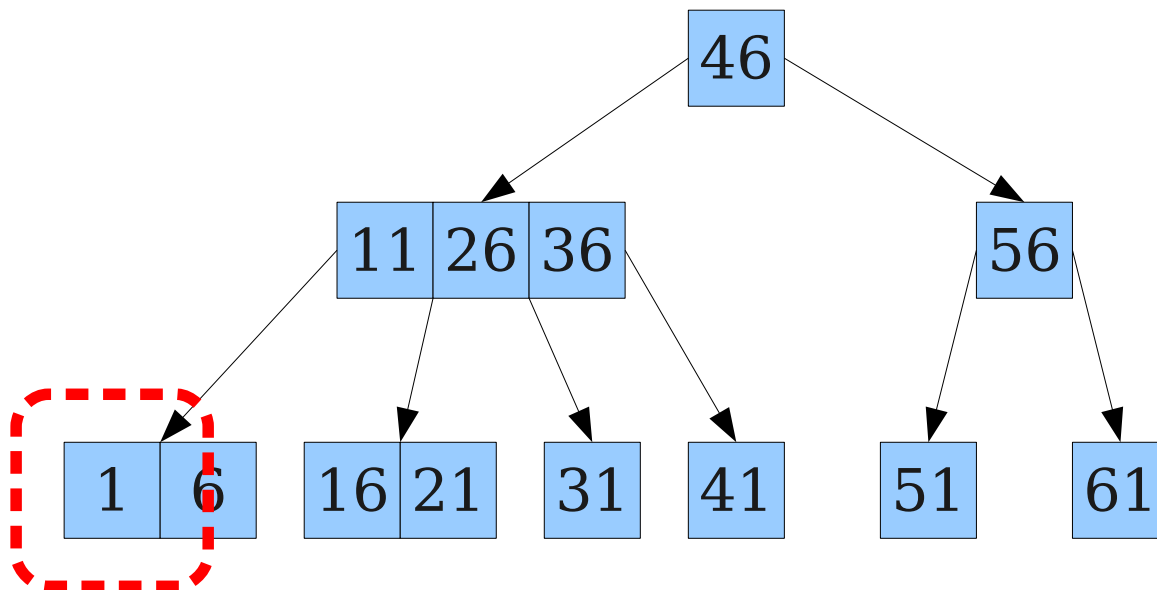
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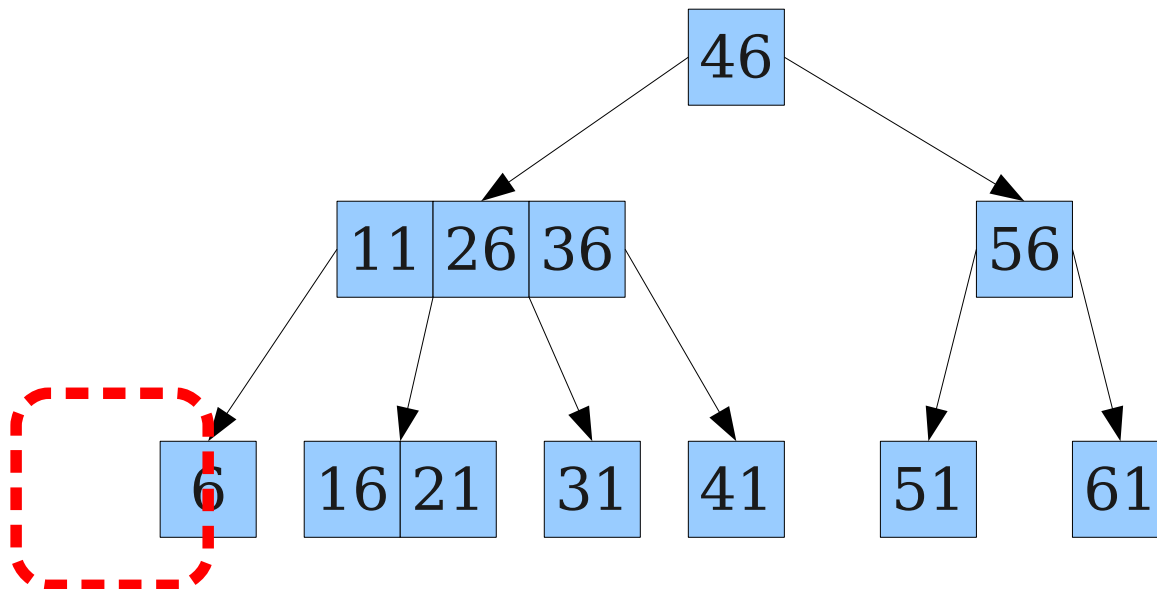
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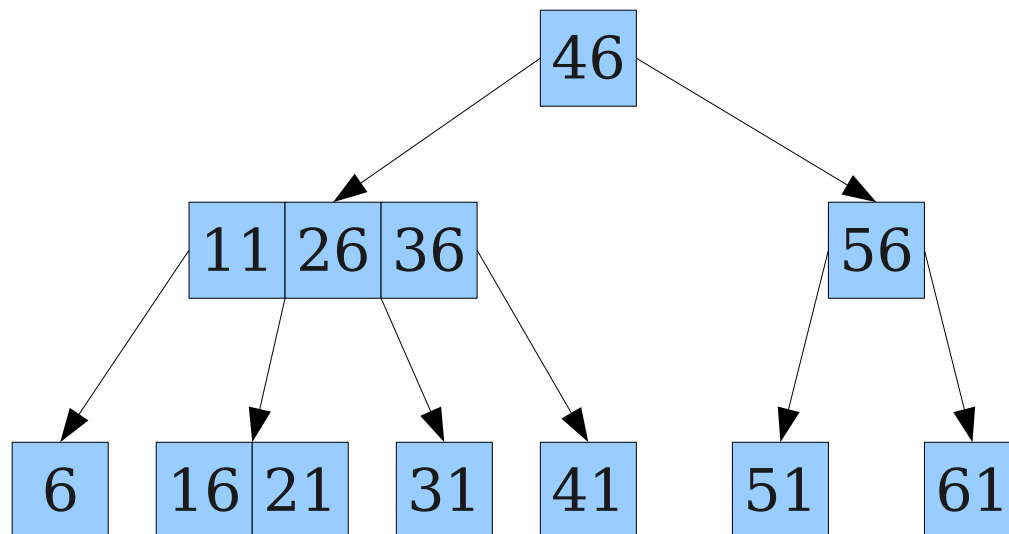
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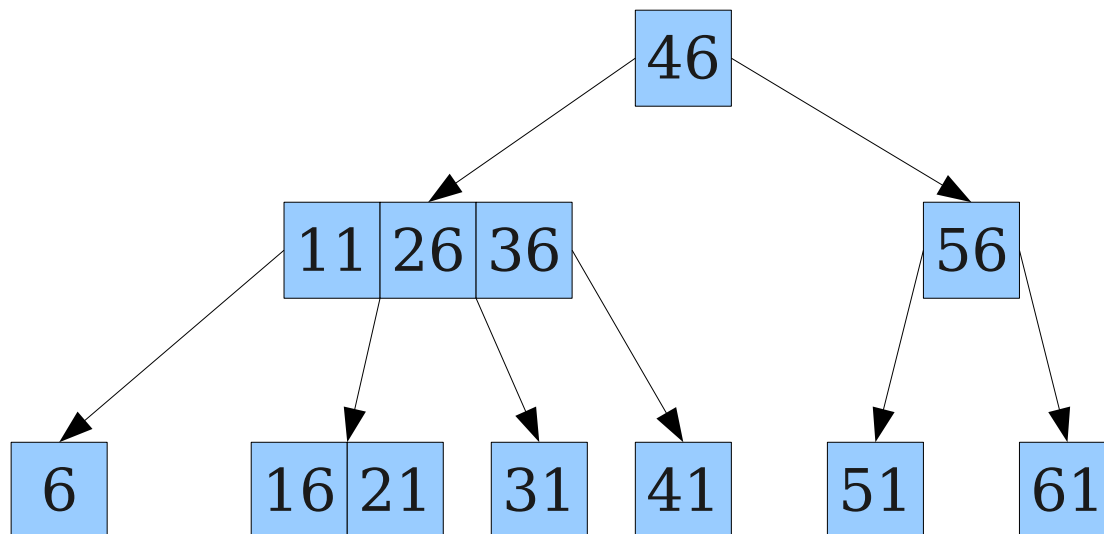
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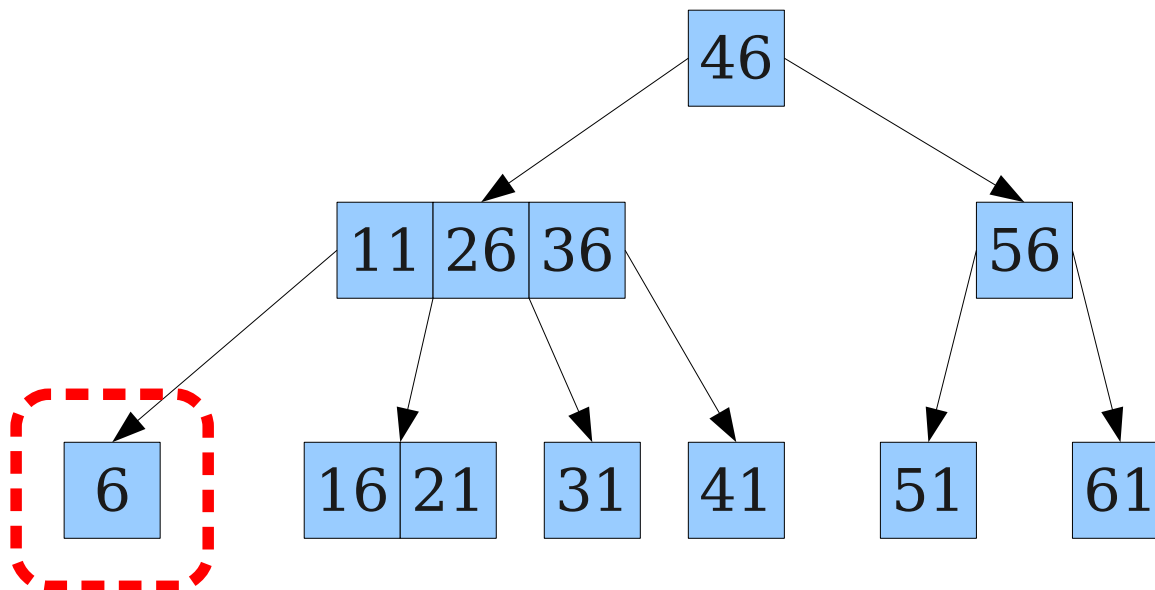
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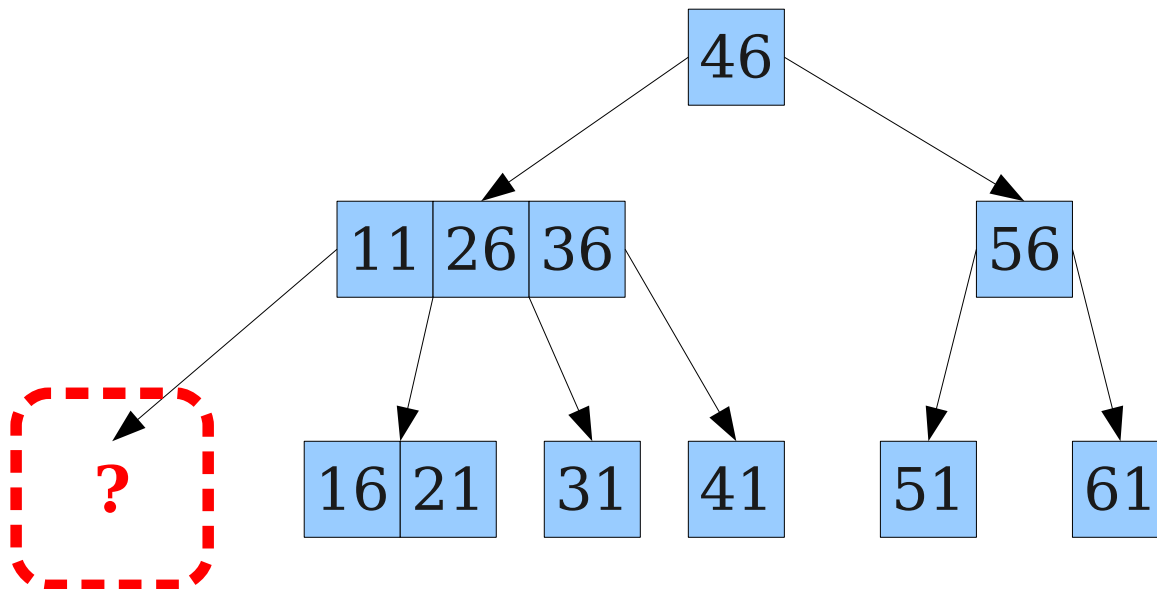
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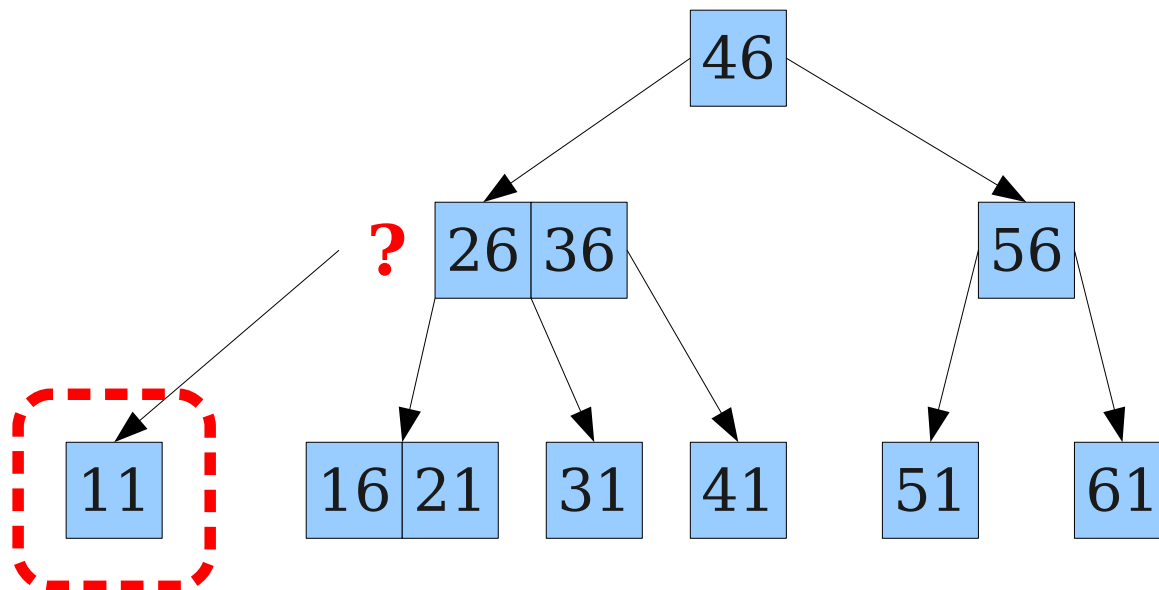
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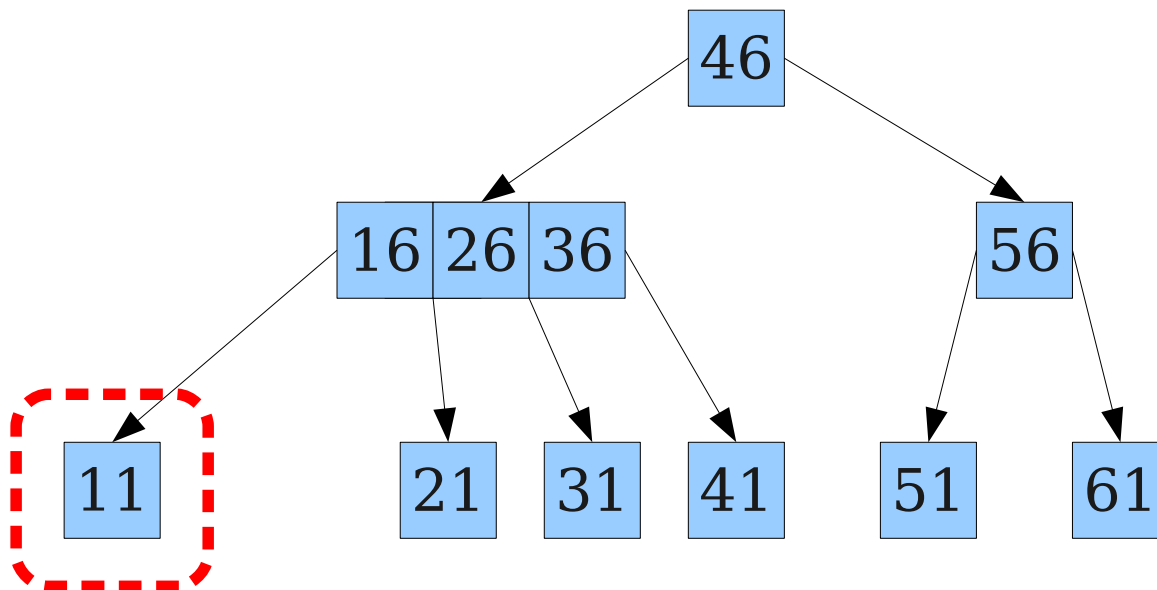
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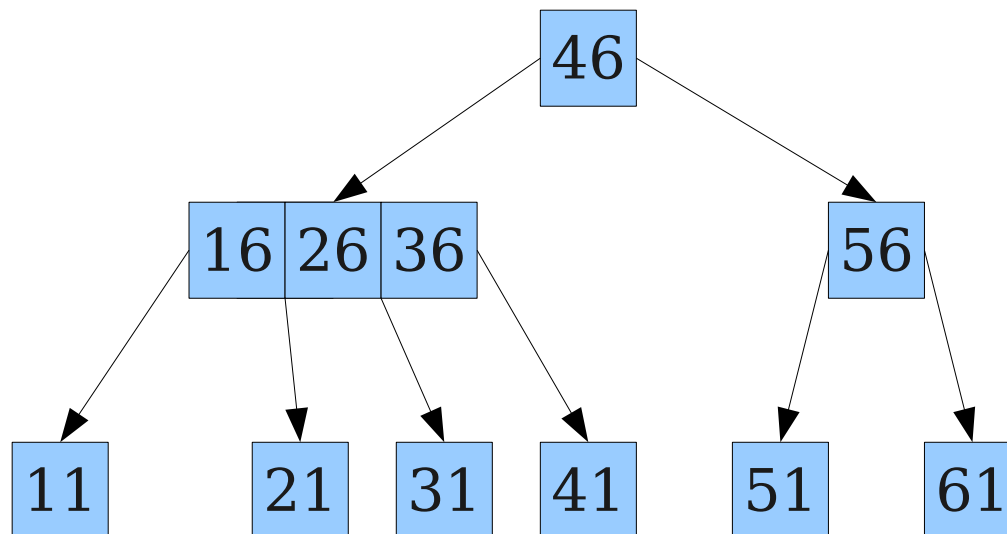
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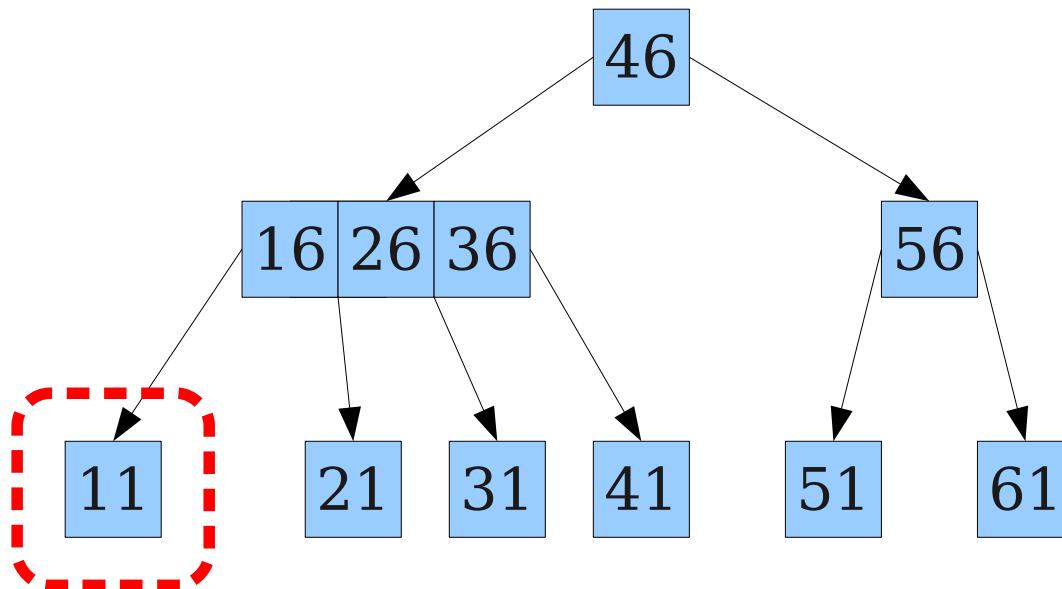
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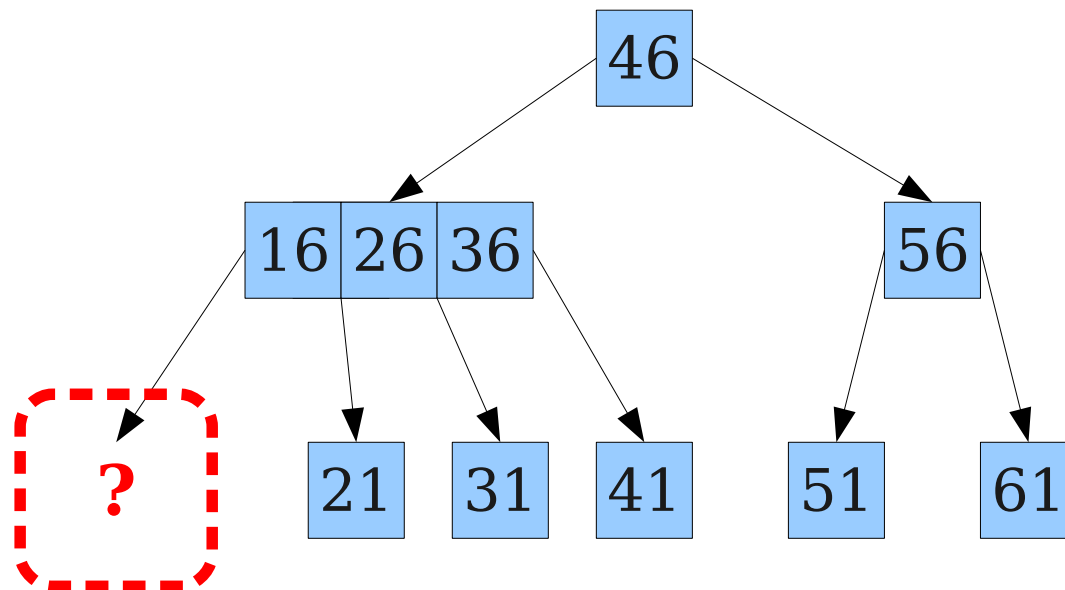
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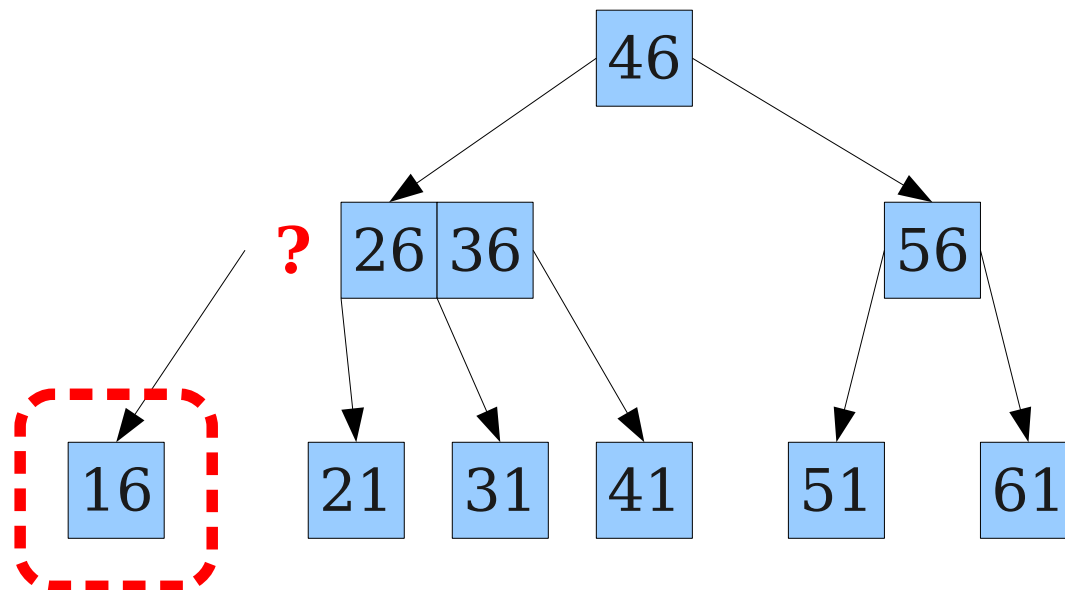
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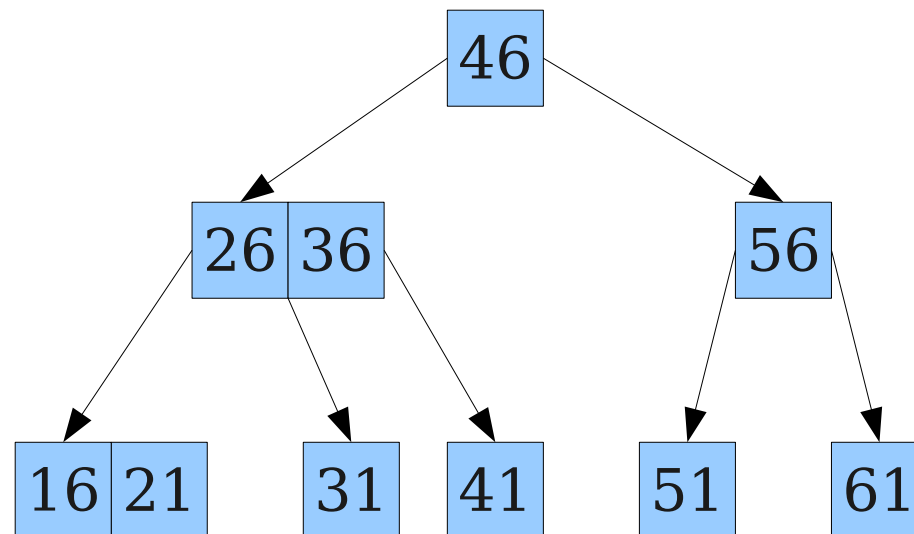
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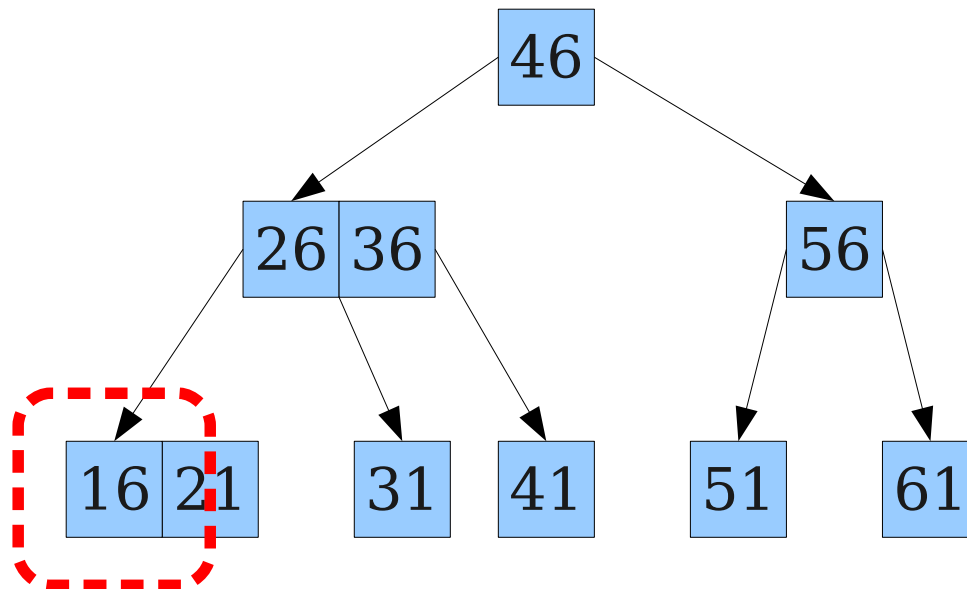
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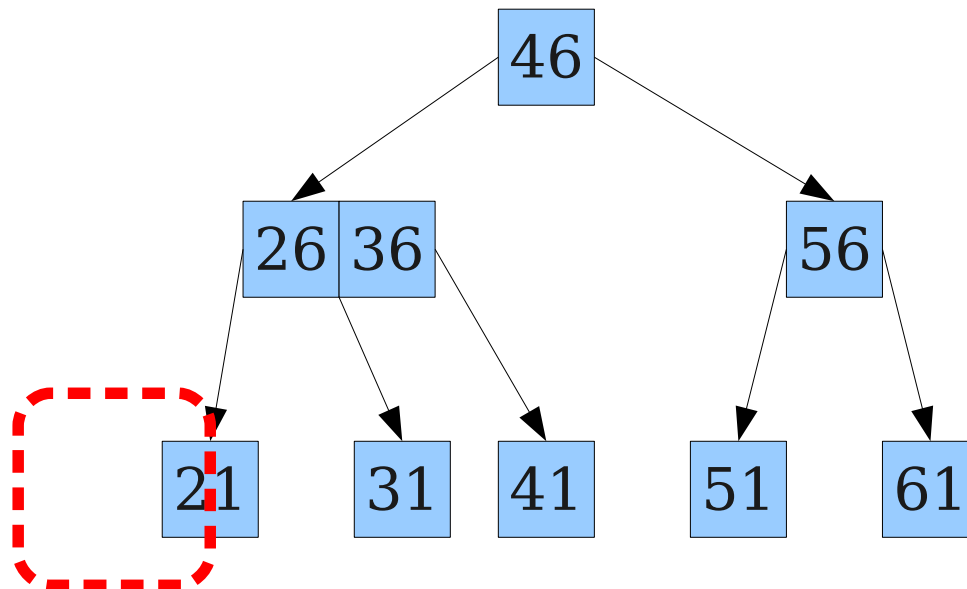
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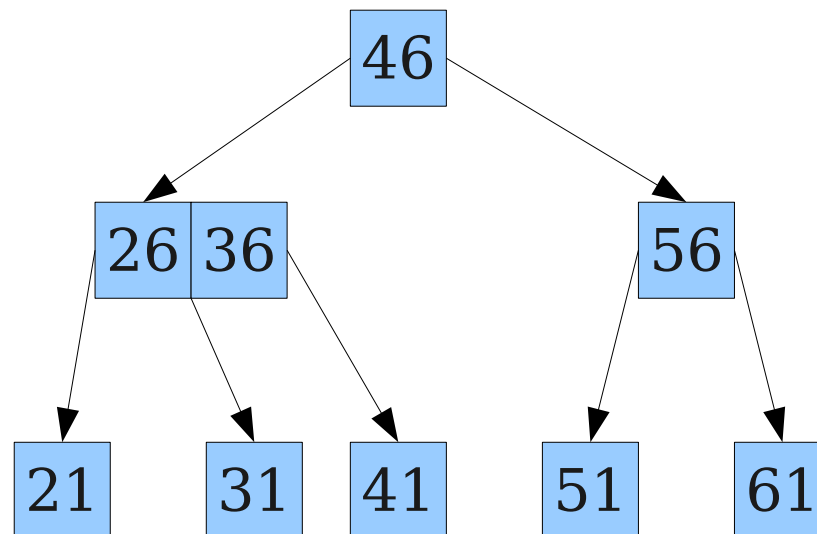
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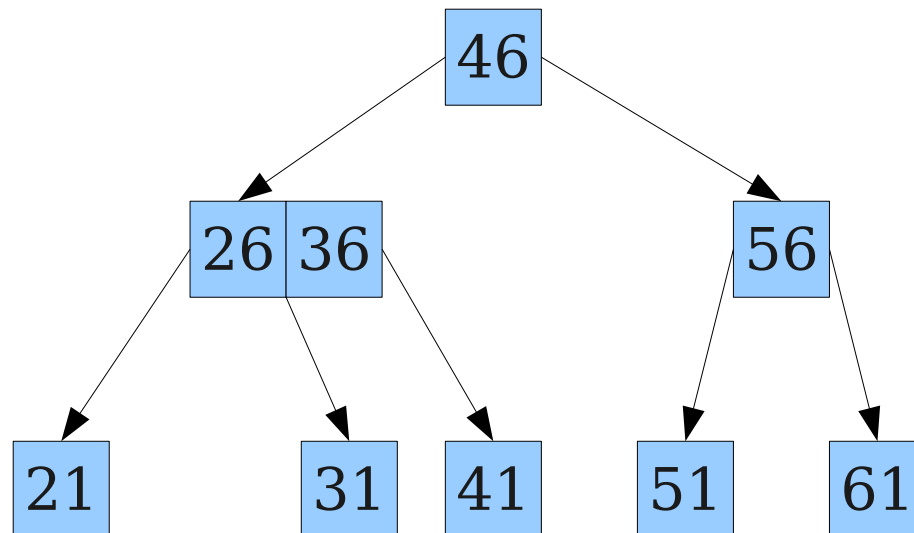
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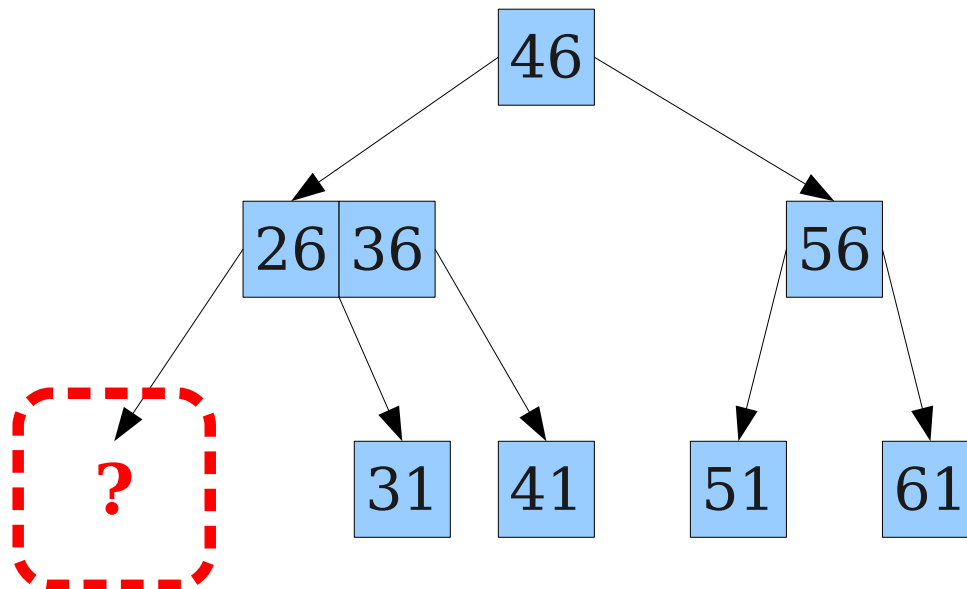
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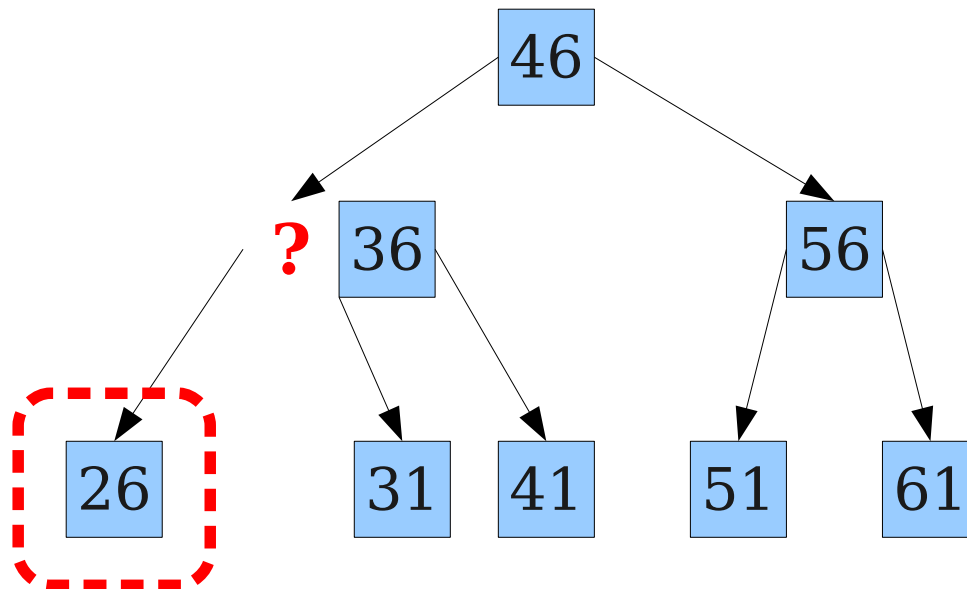
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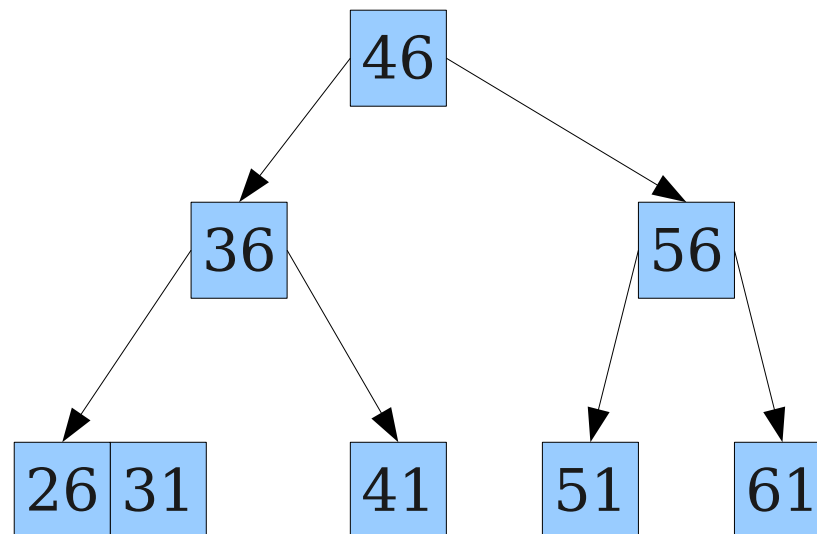
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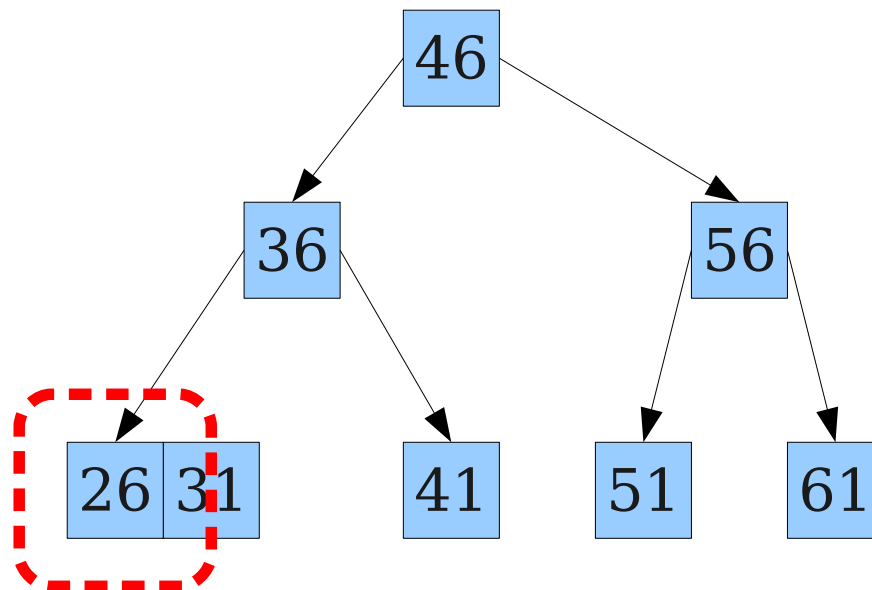
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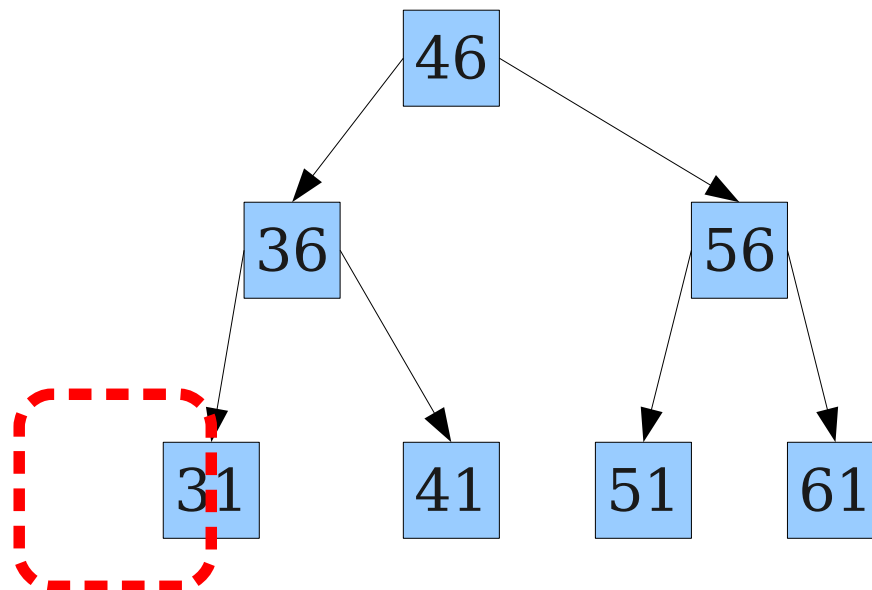
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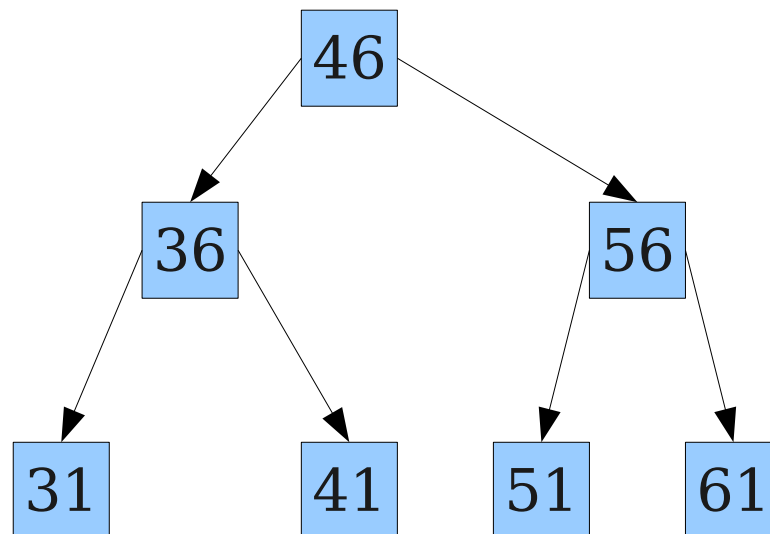
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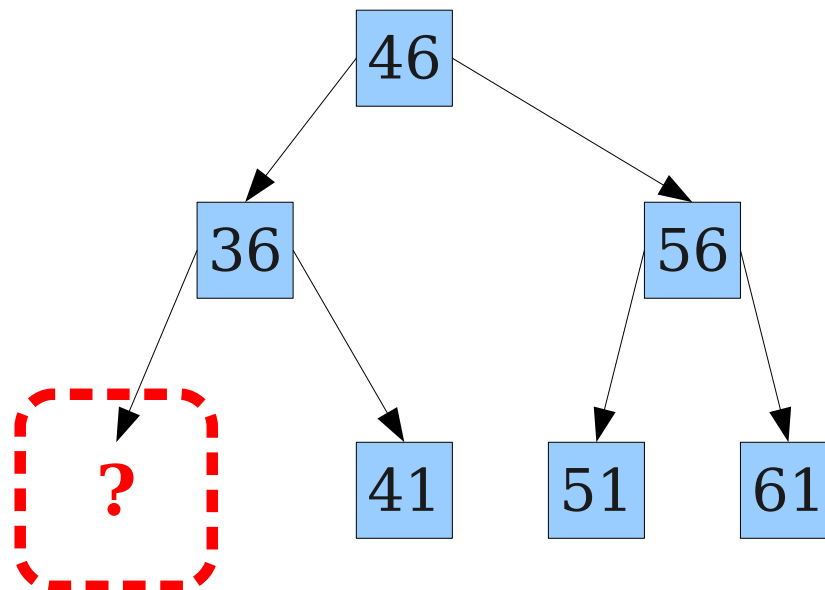
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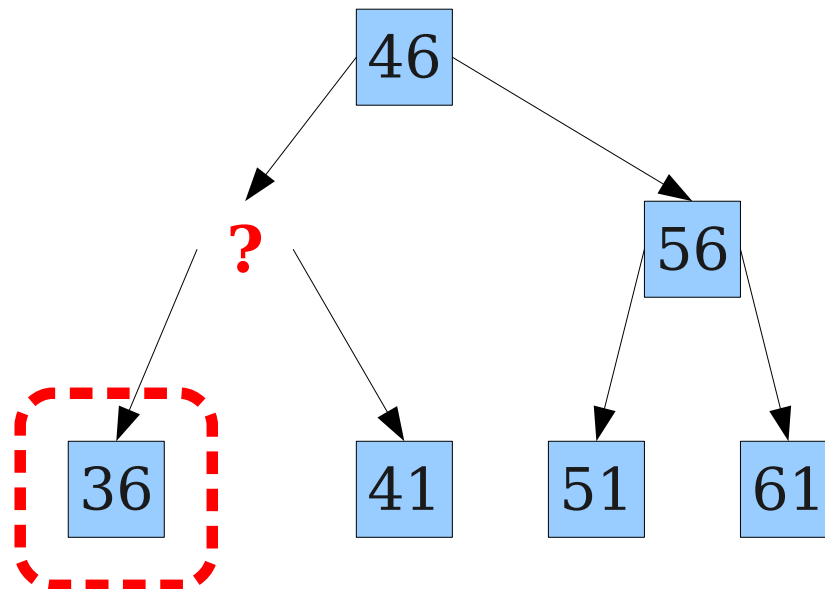
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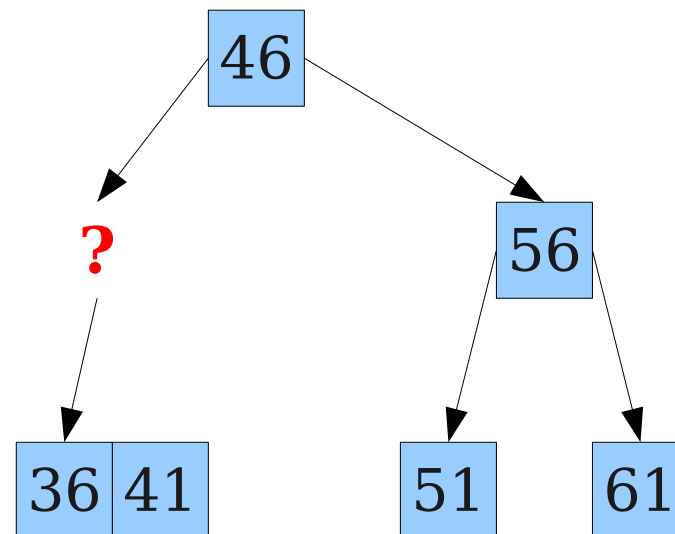
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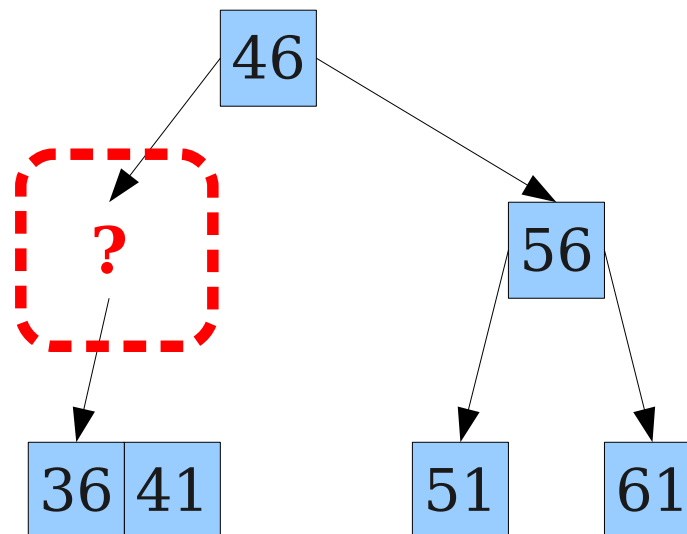
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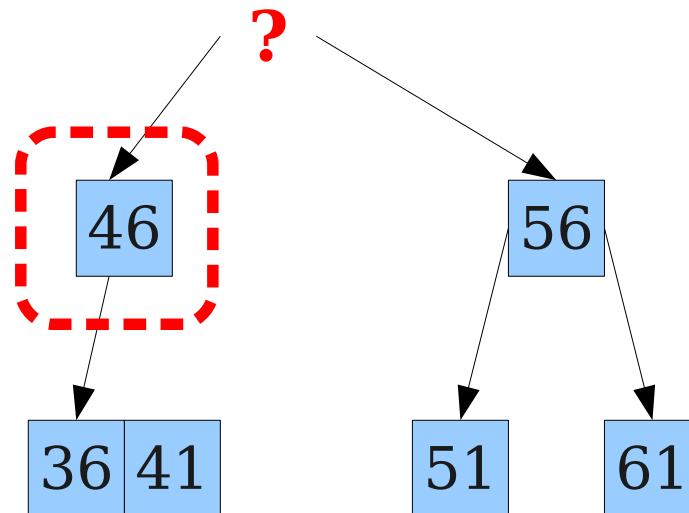
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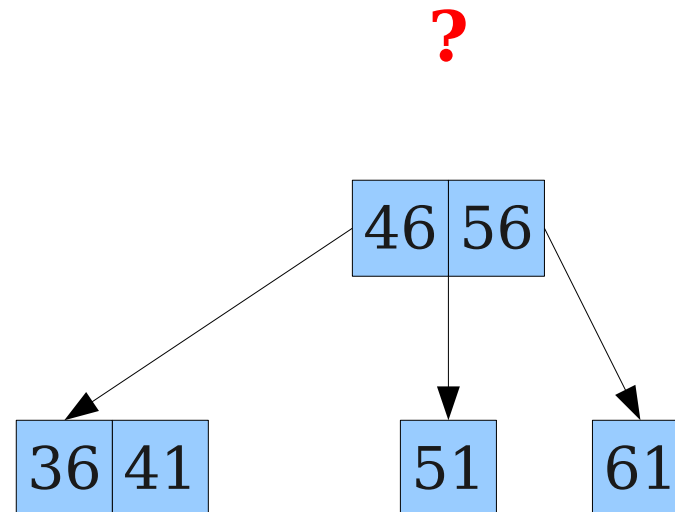
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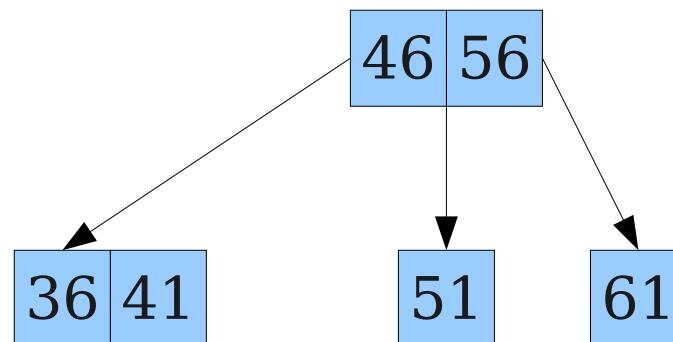
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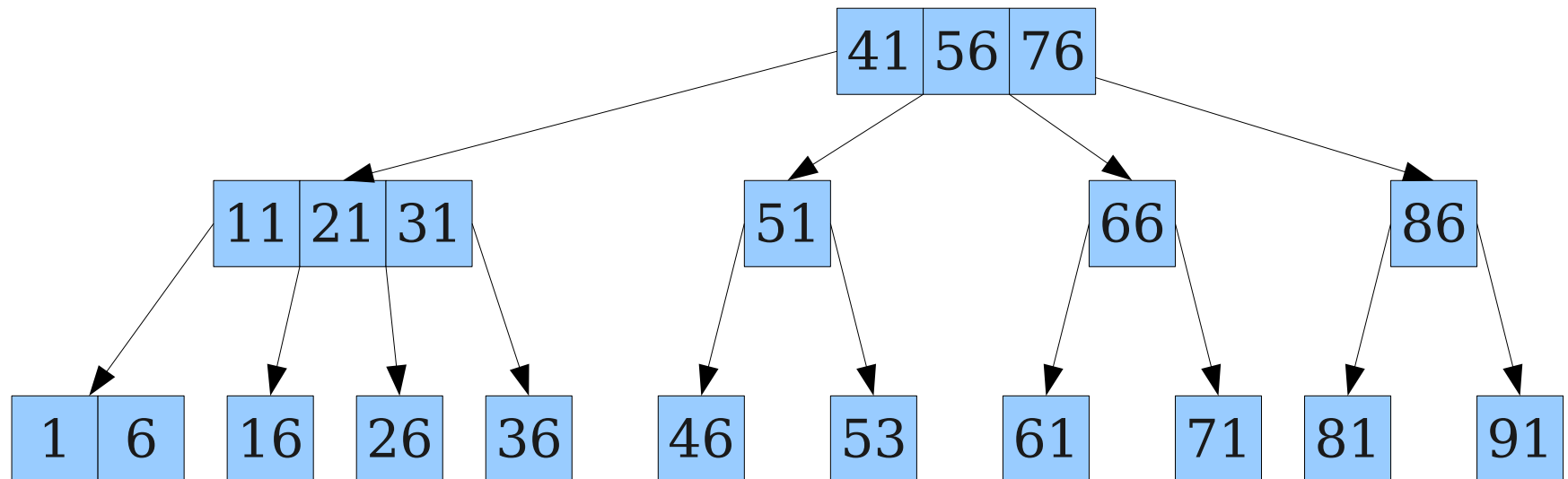


# 2-3-4 Tree Fixup

- **Claim:** The fixup work on 2-3-4 trees is amortized  $O(1)$ .
- We'll prove this in three steps:
  - First, we'll prove that in any sequence of  $m$  insertions, the amortized fixup work is  $O(1)$ .
  - Next, we'll prove that in any sequence of  $m$  deletions, the amortized fixup work is  $O(1)$ .
  - Finally, we'll show that in any sequence of insertions and deletions, the amortized fixup work is  $O(1)$ .

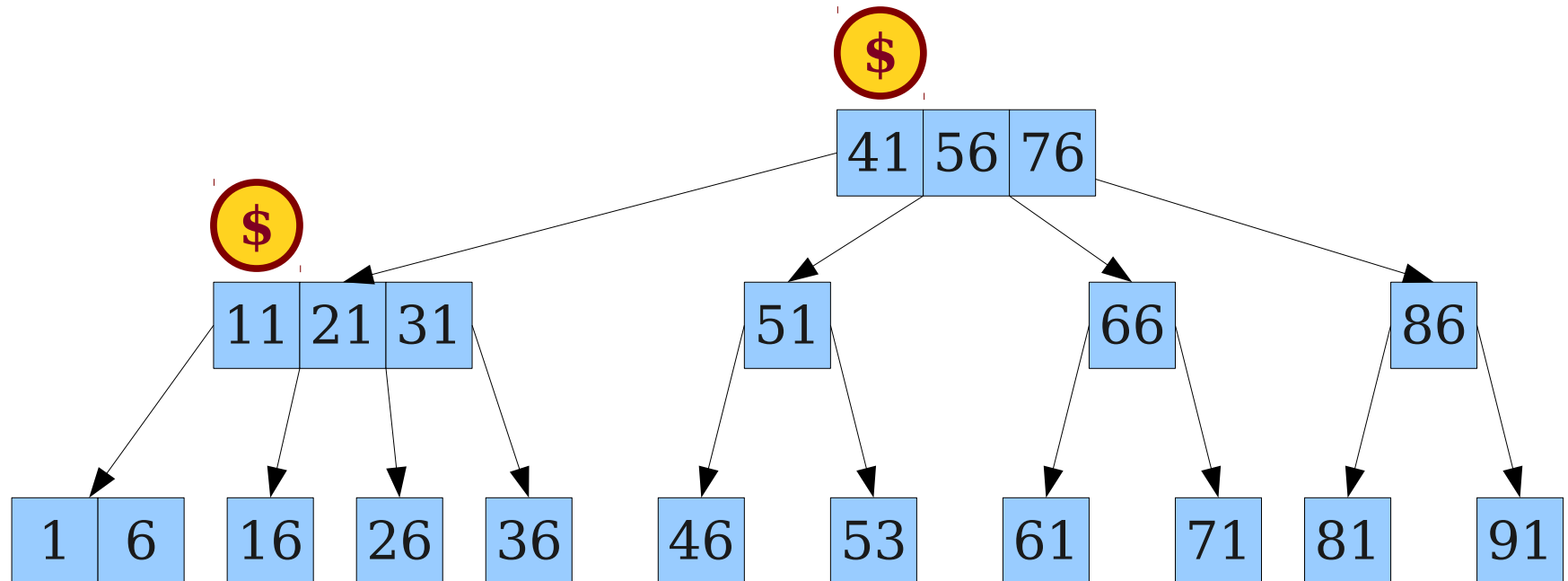
# 2-3-4 Tree Insertions

- Suppose we only insert and never delete.
- The fixup work for an insertion is proportional to the number of 4-nodes that get split.
- **Idea:** Place a credit on each 4-node to pay for future splits.



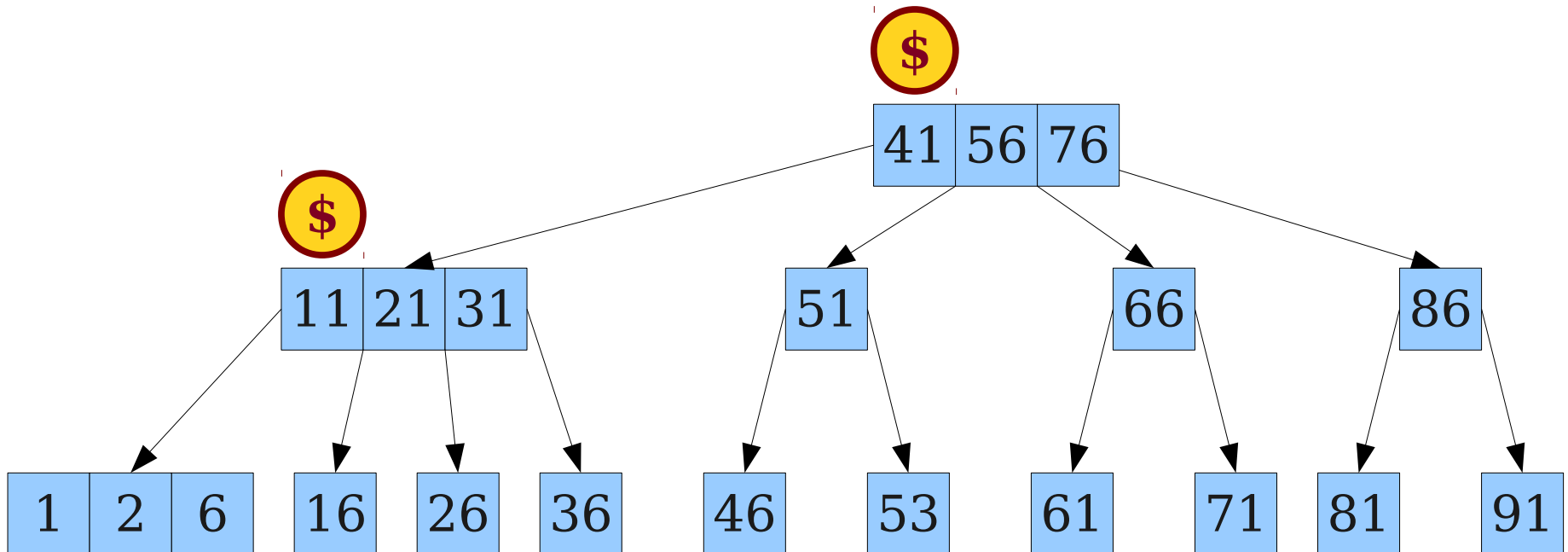
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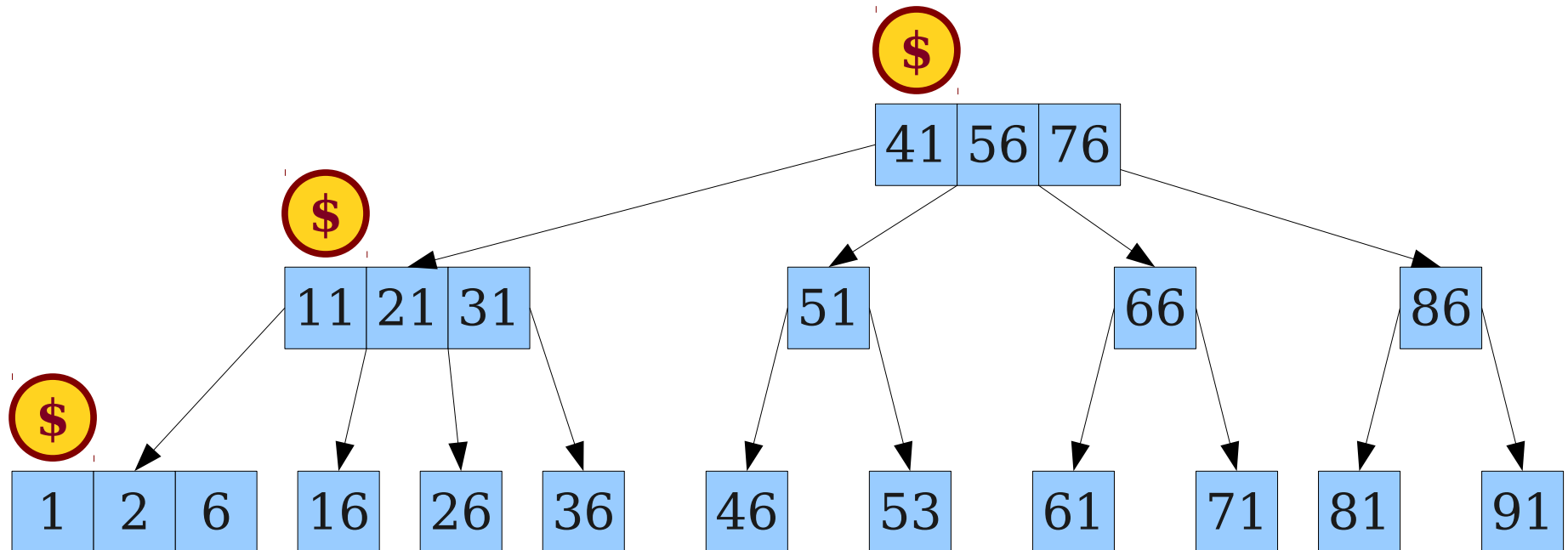
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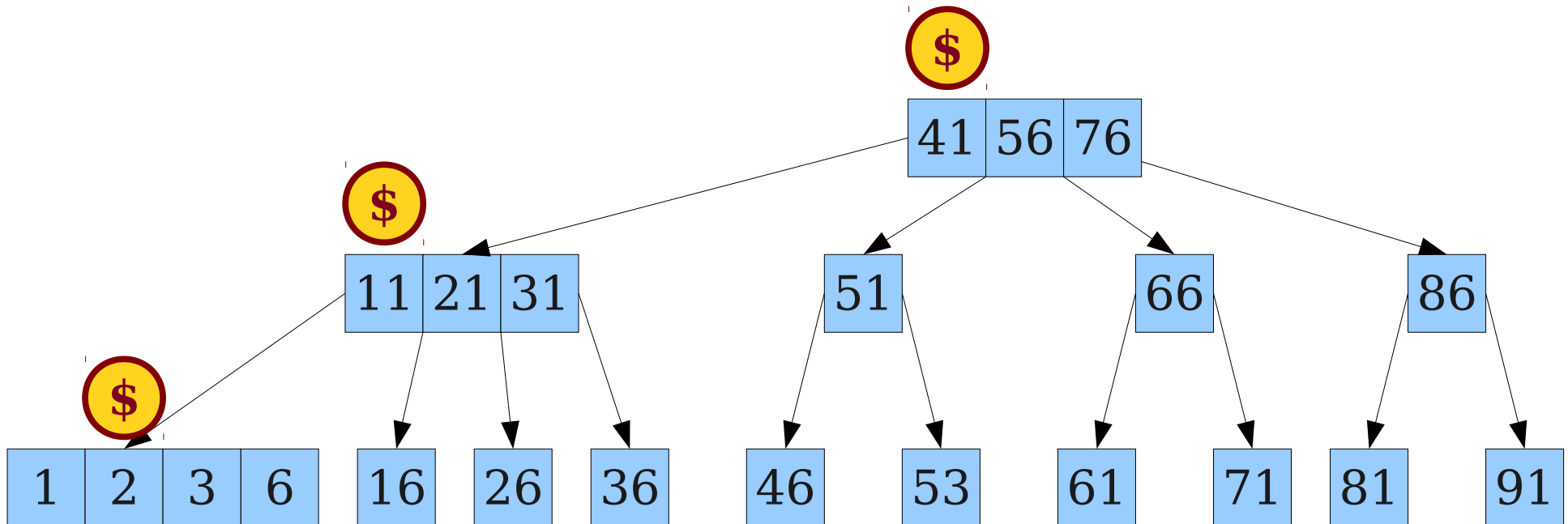
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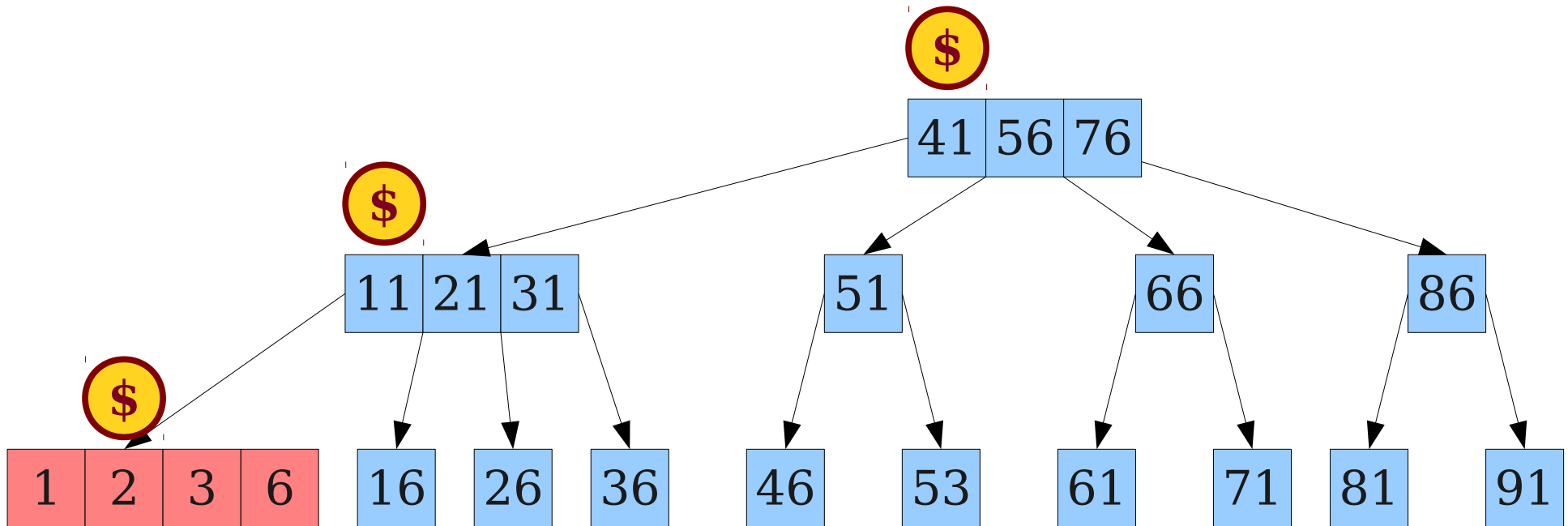
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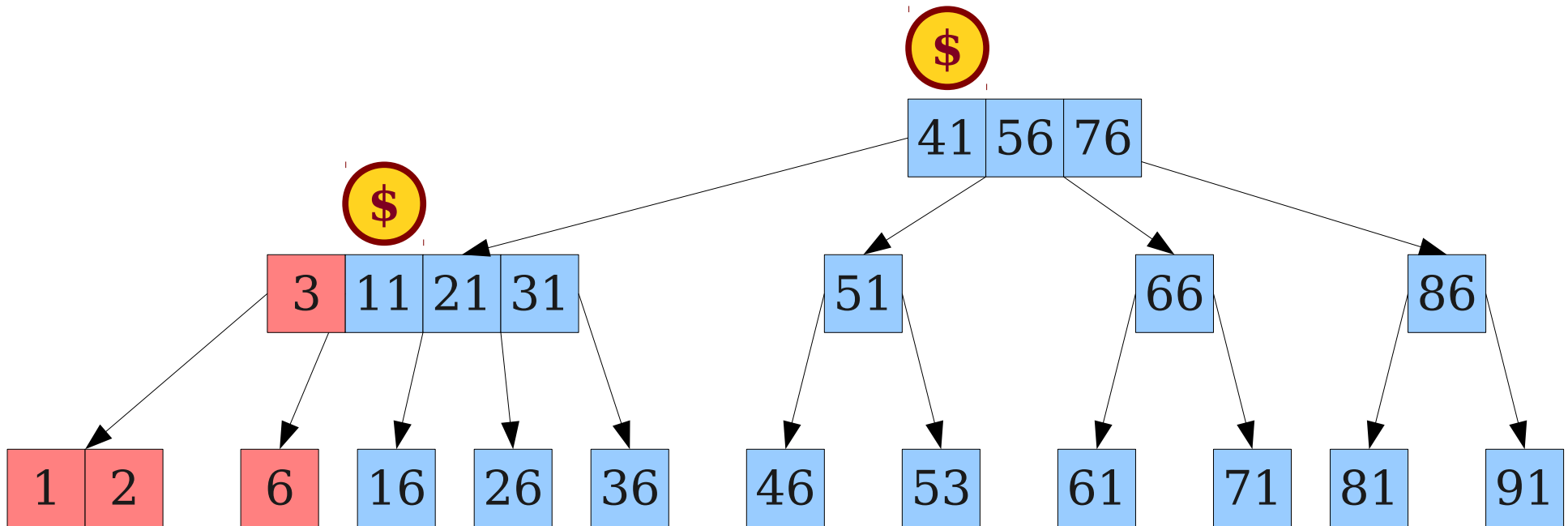
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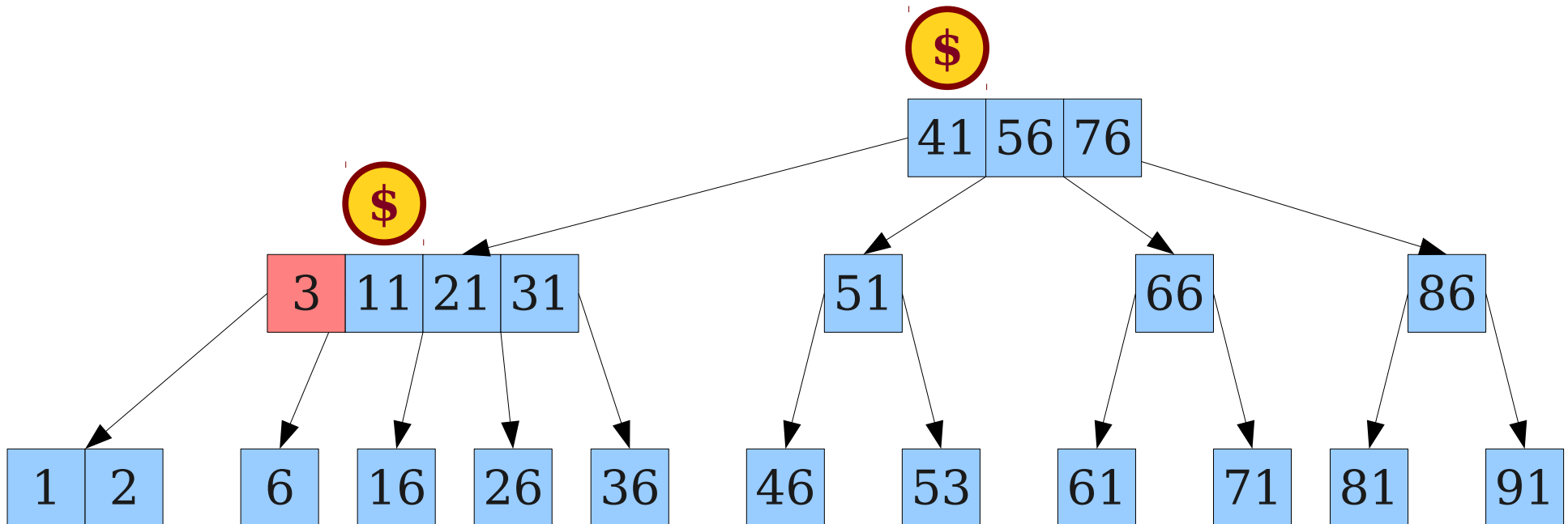
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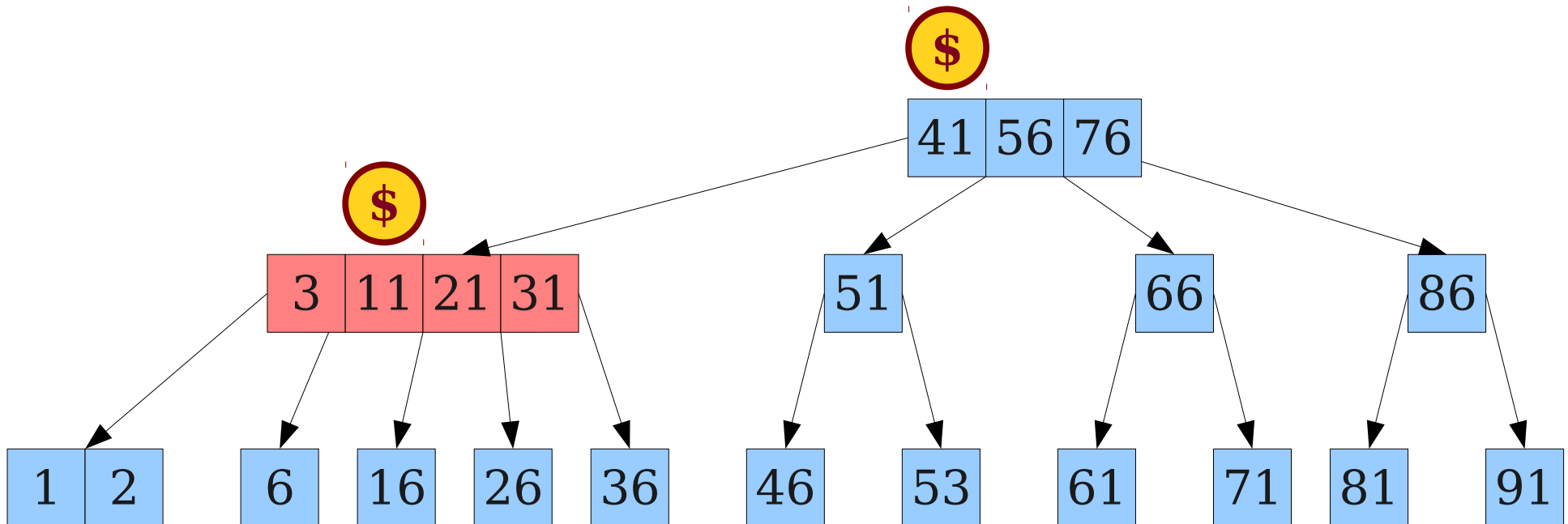
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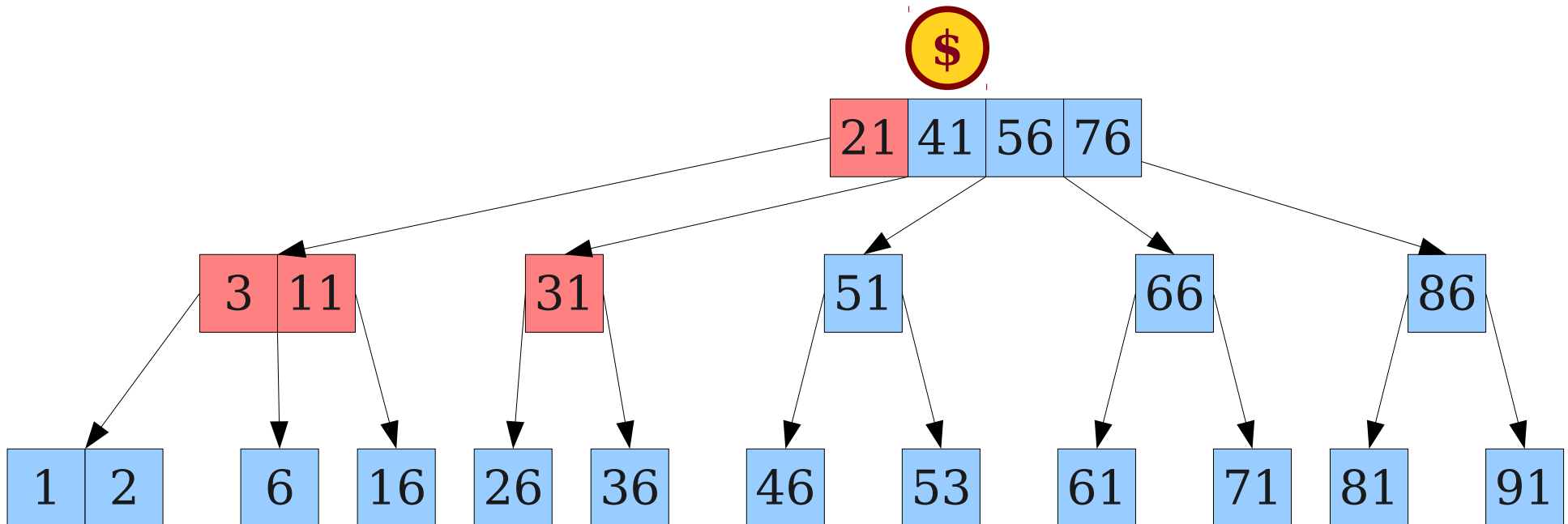
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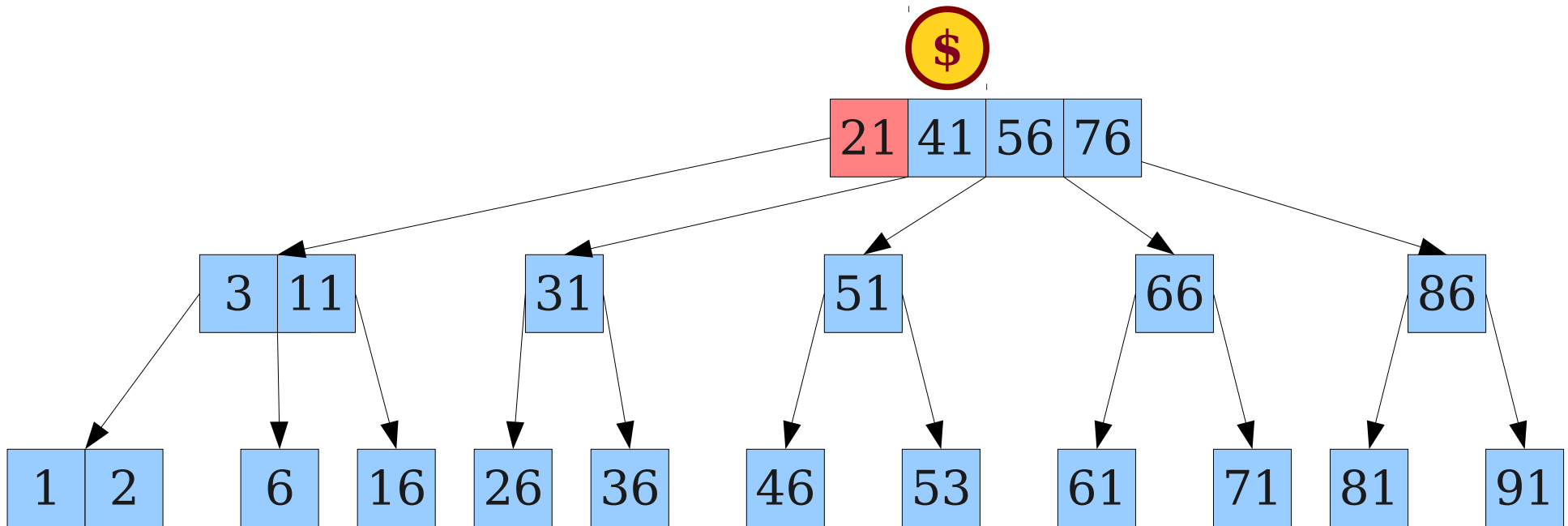
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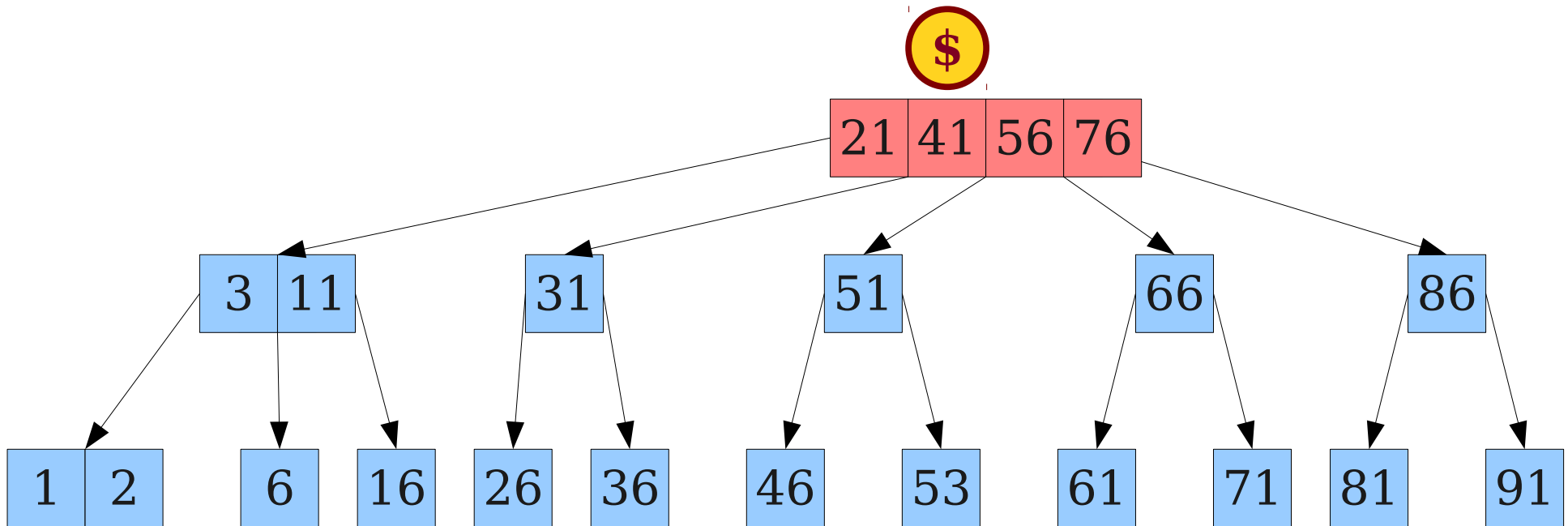
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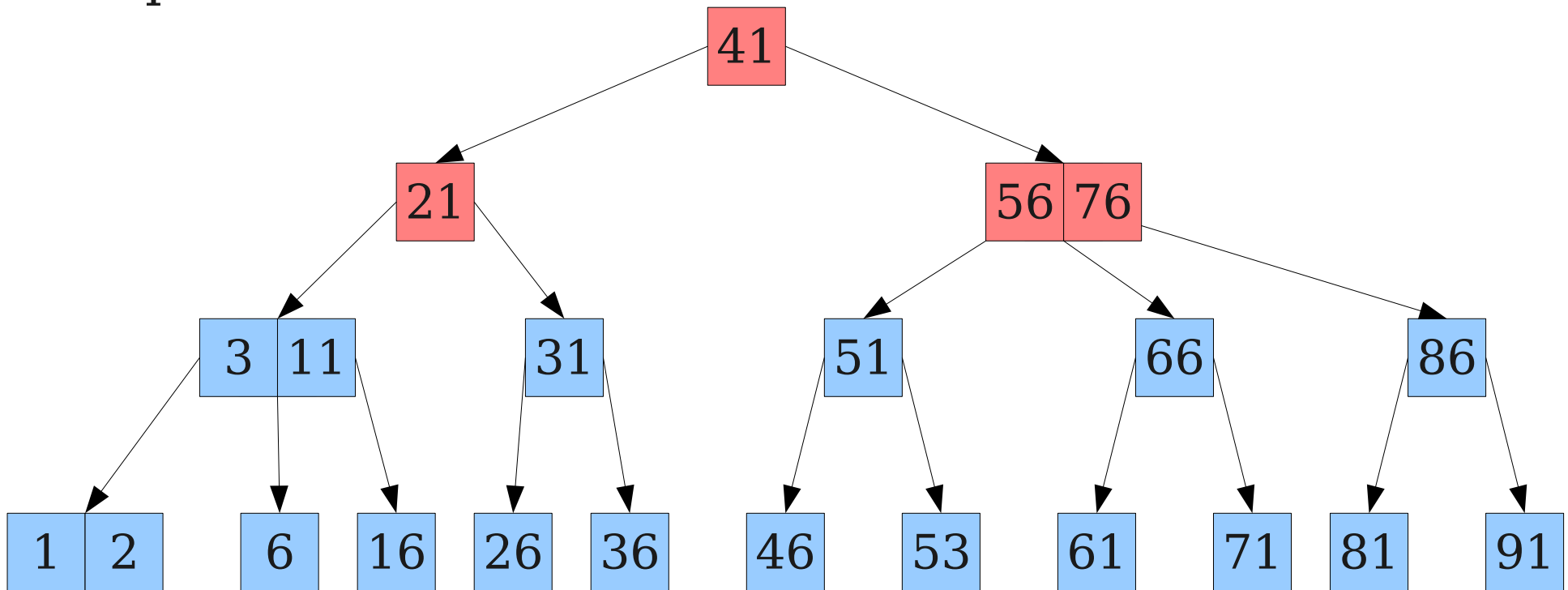
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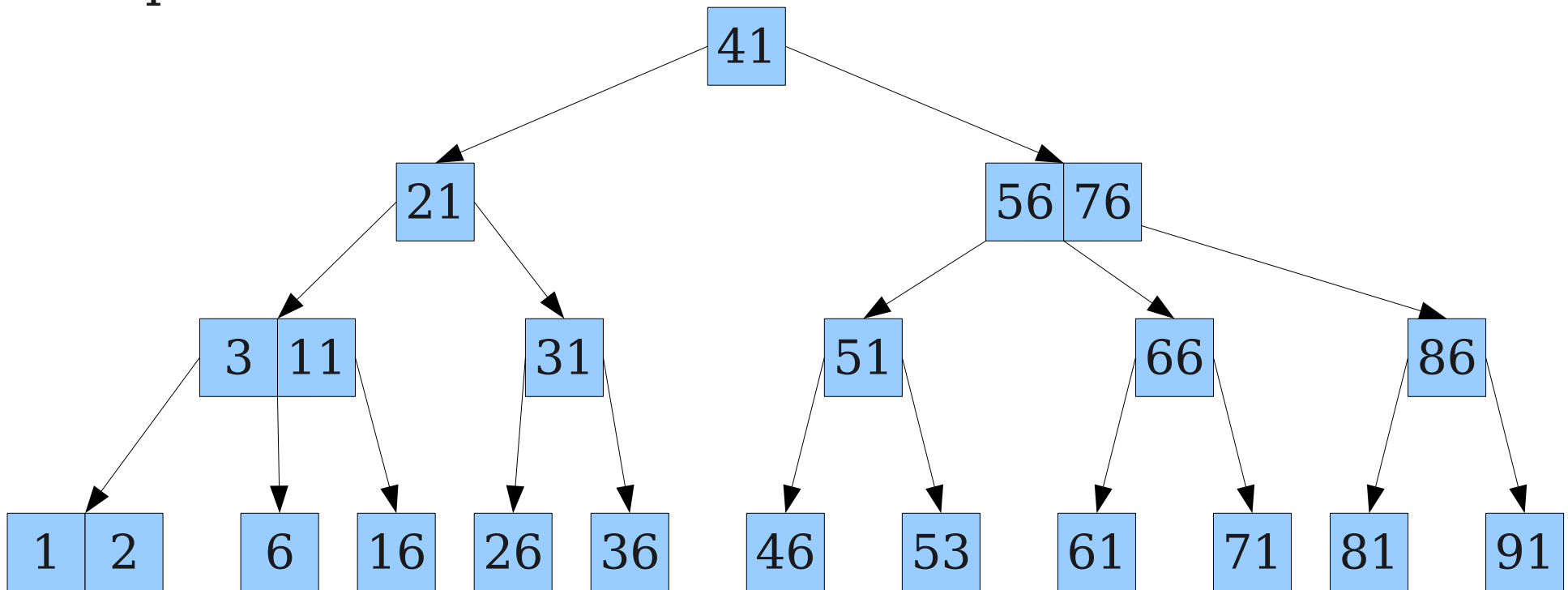
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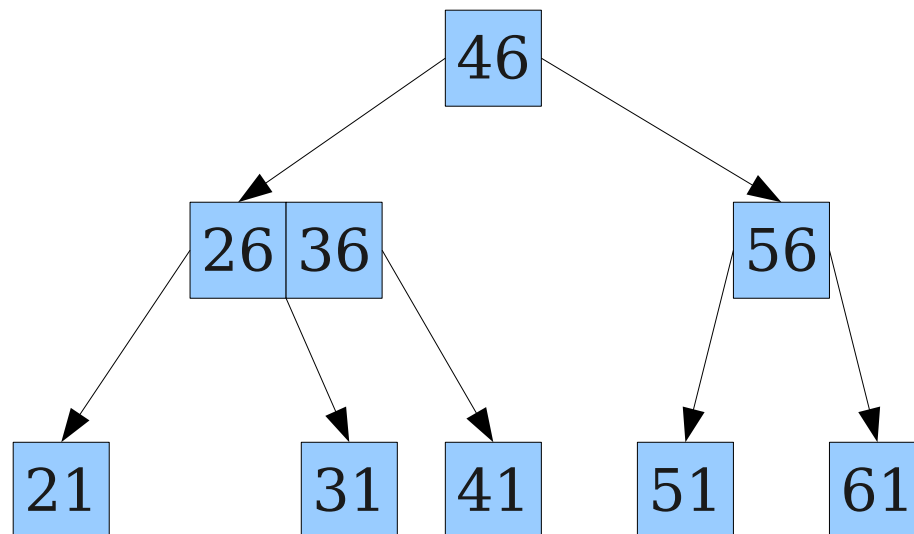


# 2-3-4 Tree Insertions

- Using the banker's method, we get that pure insertions have  $O(1)$  amortized fixup work.
- Could also do this using the potential method.
  - Define  $\Phi$  to be the number of 4-nodes.
  - Each “light” insertion might introduce a new 4-node, requiring amortized  $O(1)$  work.
  - Each “heavy” insertion splits  $k$  4-nodes and decreases the potential by  $k$  for  $O(1)$  amortized work.

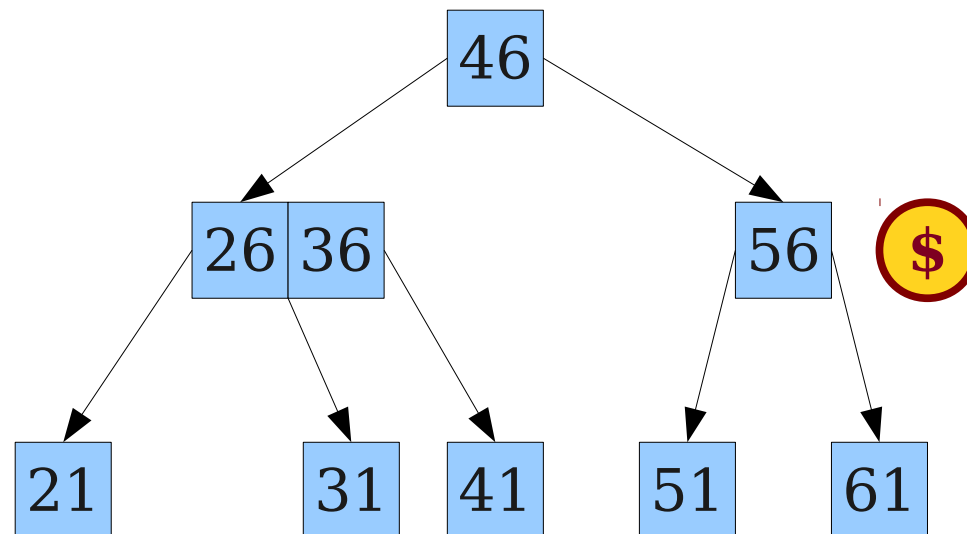
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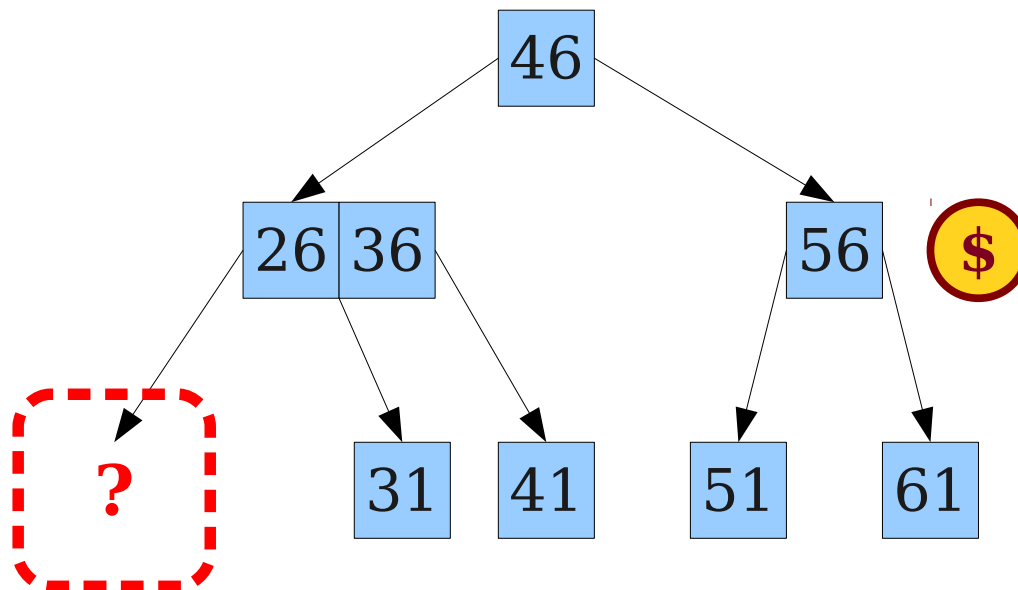
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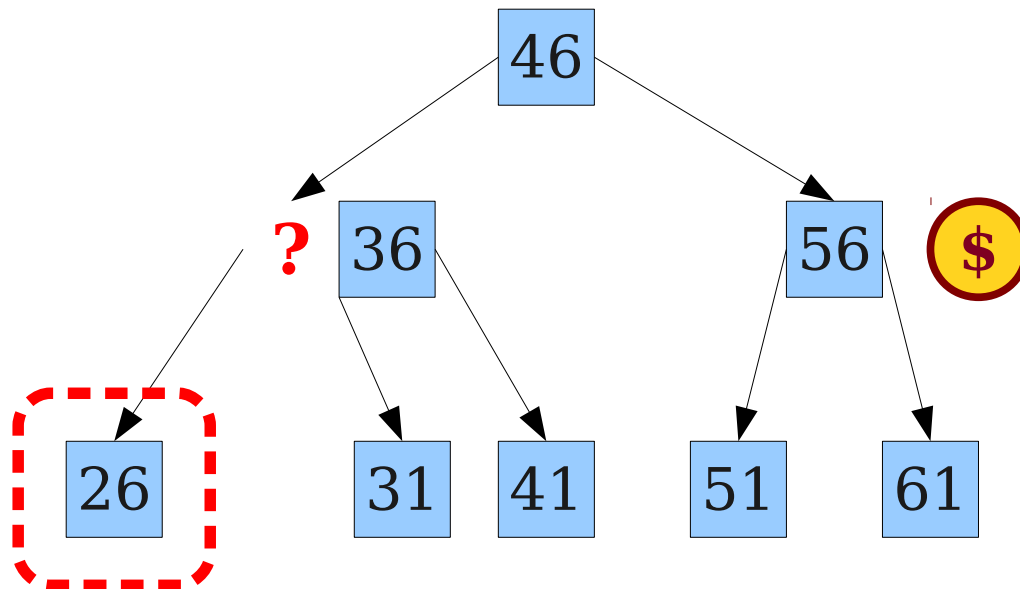
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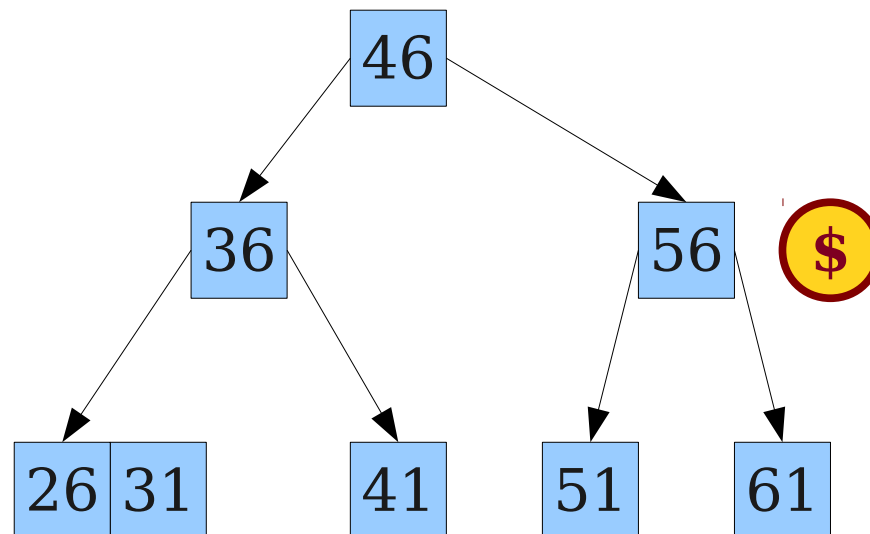
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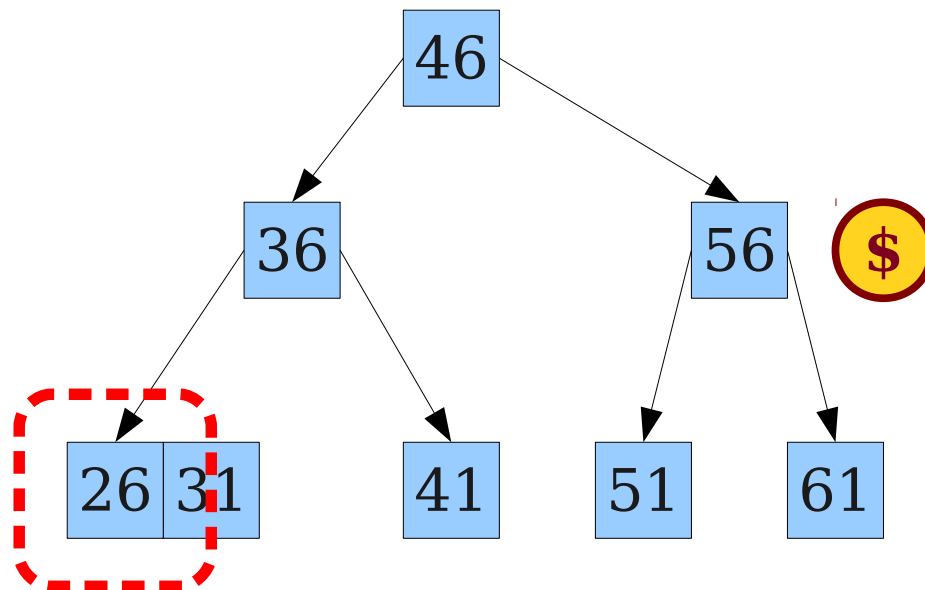
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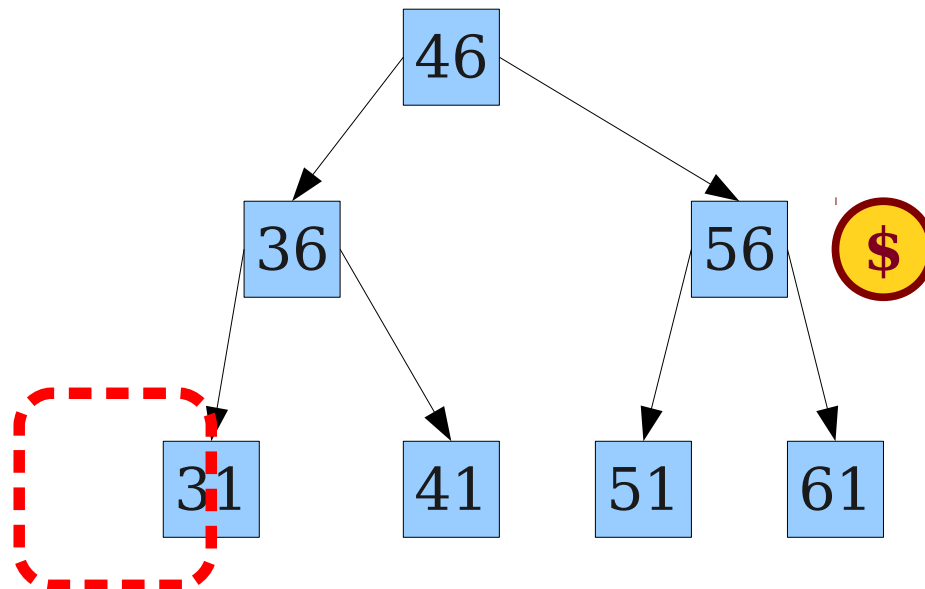
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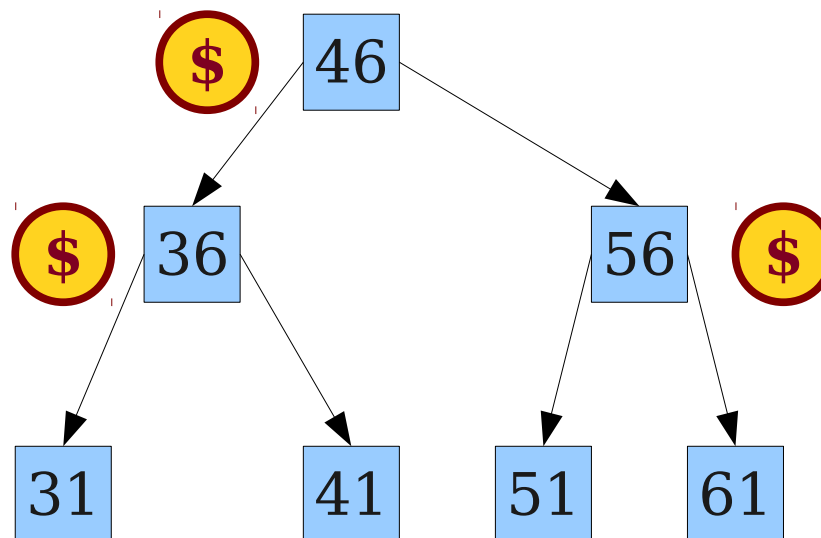
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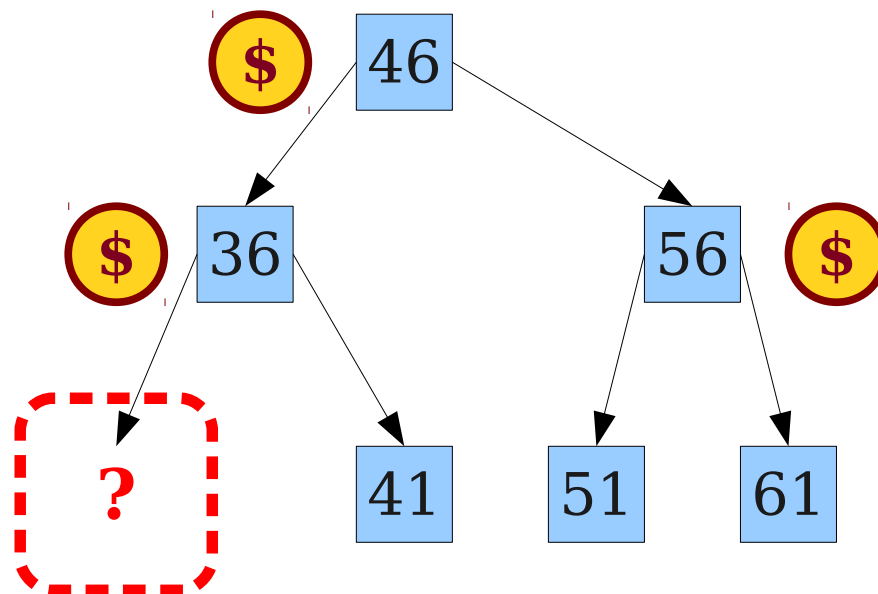
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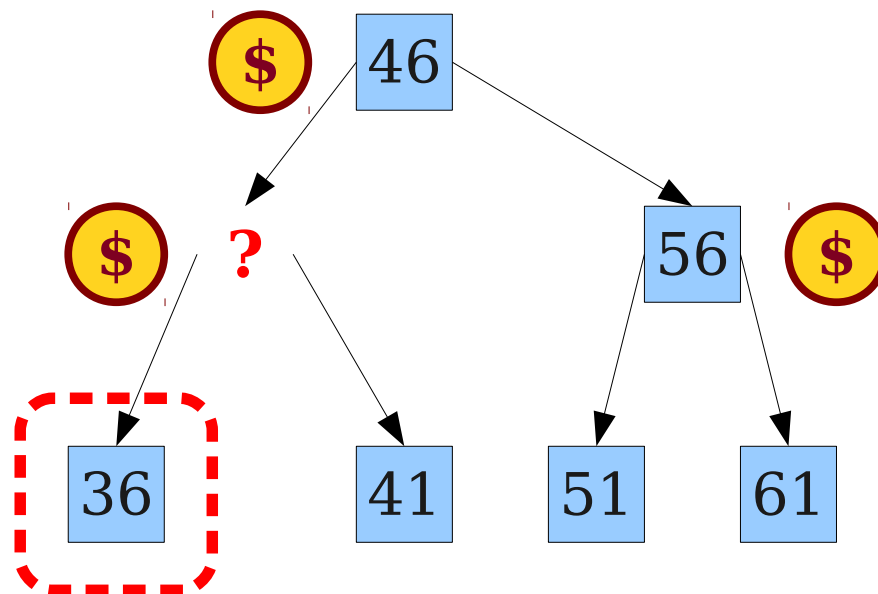
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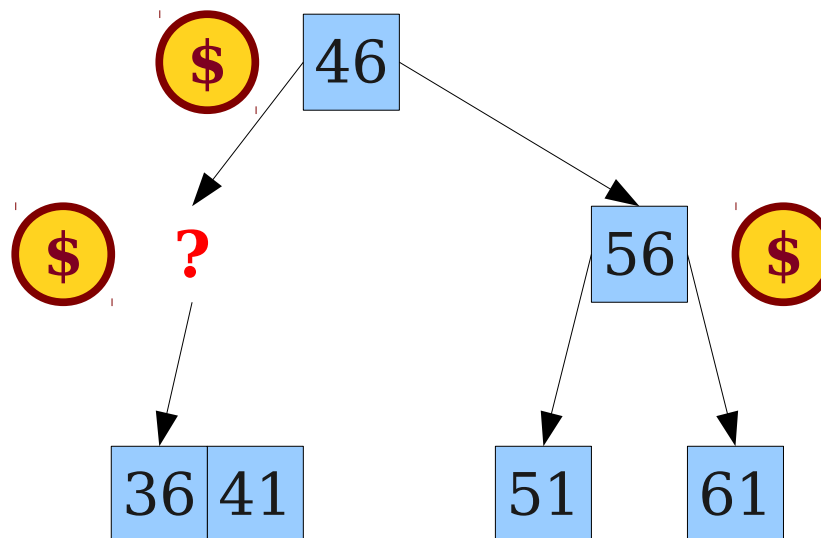
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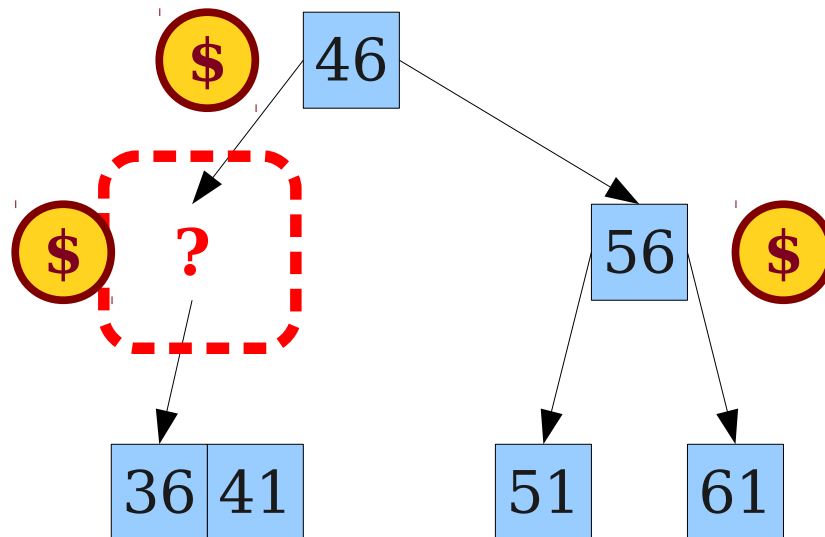
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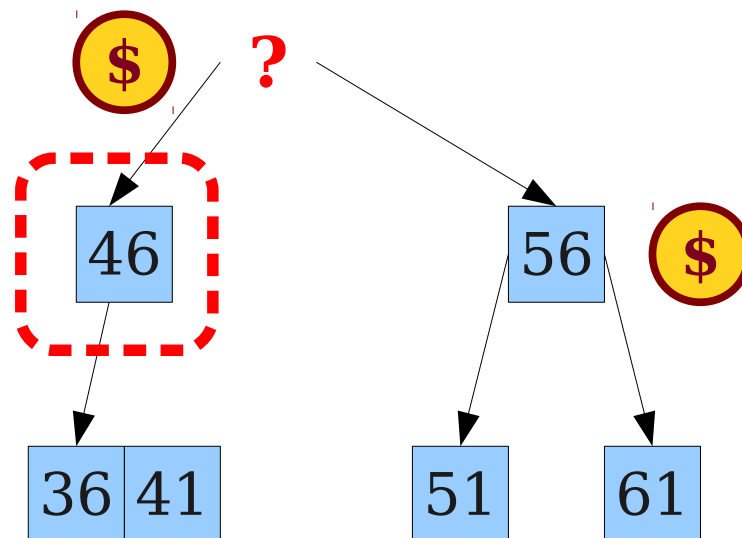
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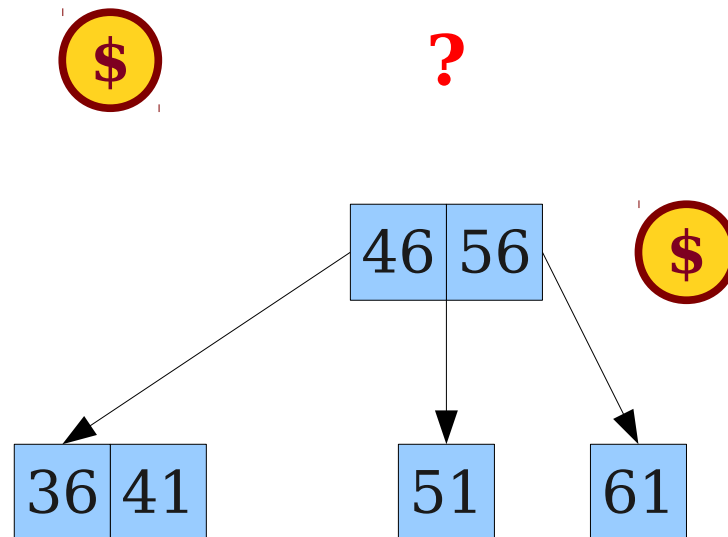
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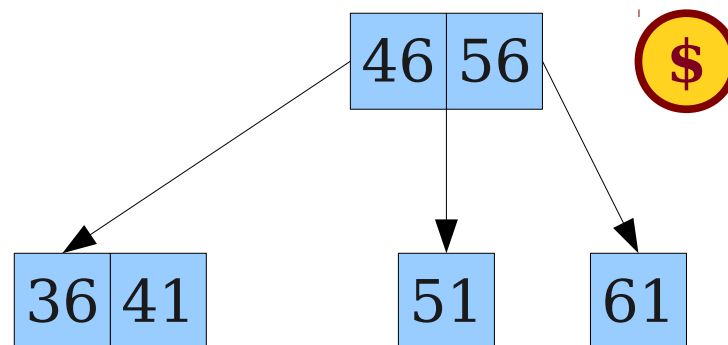
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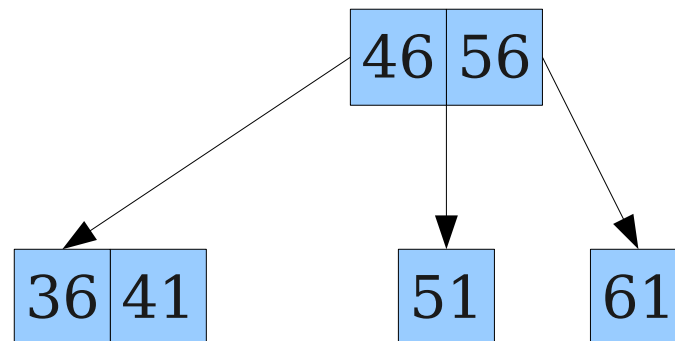
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# 2-3-4 Tree Deletions

- Using the banker's method, we get that pure deletions have  $O(1)$  amortized fixup work.
- Could also do this using the potential method.
  - Define  $\Phi$  to be the number of 2-nodes with two 2-node children (call these “tiny triangles.”)
  - Each “light” deletion might introduce two tiny triangles: one at the node where the deletion ended and one right above it. Amortized time is  $O(1)$ .
  - Each “heavy” deletion combines  $k$  tiny triangles and decreases the potential by at least  $k$ . Amortized time is  $O(1)$ .

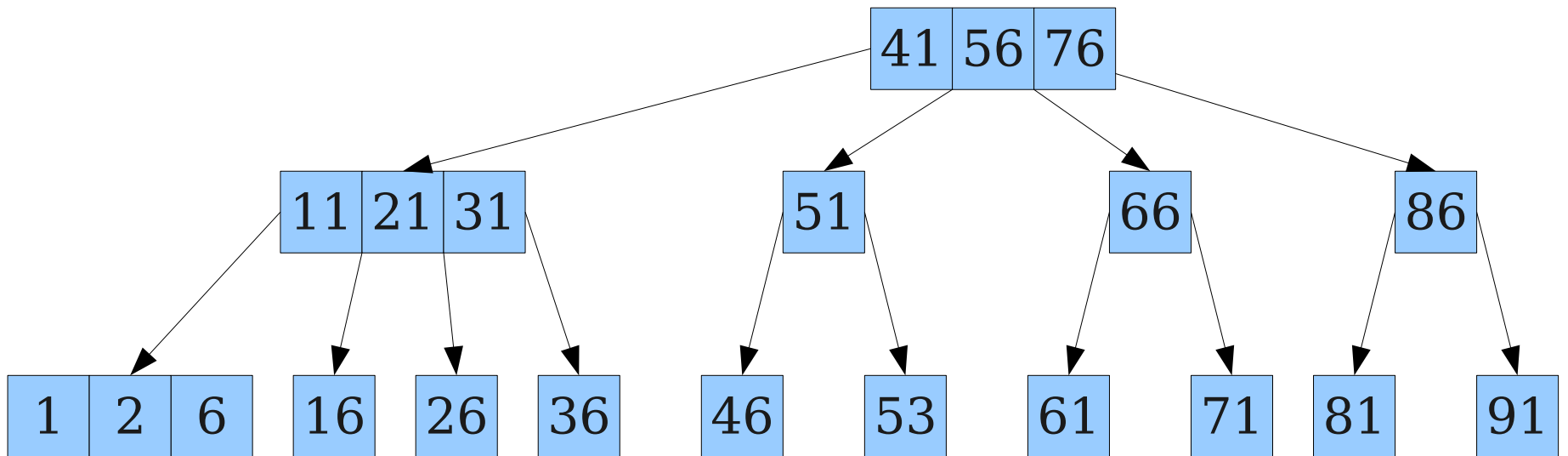
# Combining the Two

- We've shown that pure insertions and pure deletions require  $O(1)$  amortized fixup time.
- What about interleaved insertions and deletions?
- Initial idea: Use a potential function that's the sum of the two previous potential functions.
- $\Phi$  is the number of 4-nodes plus the number of tiny triangles.

$$\Phi = \# \left( \begin{array}{|c|c|c|} \hline \square & \square & \square \\ \hline \end{array} \right) + \# \left( \begin{array}{c} \square \\ \swarrow \quad \searrow \\ \square \quad \square \end{array} \right)$$

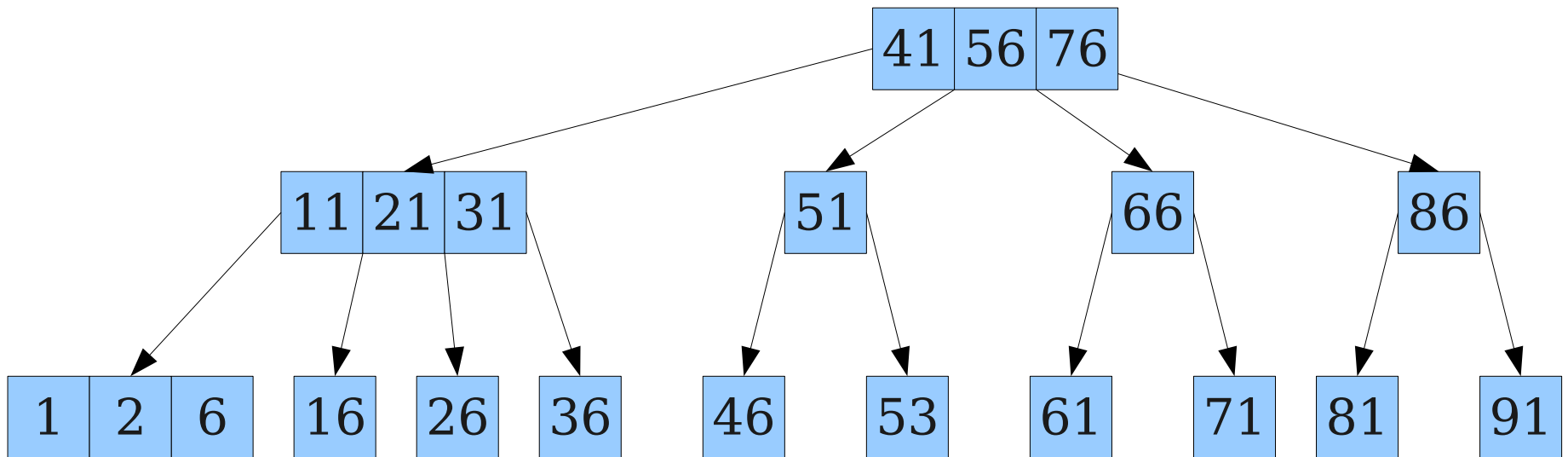
# A Problem

$$\Phi = \#(\text{array of 3 boxes}) + \#(\text{tree with 3 nodes})$$



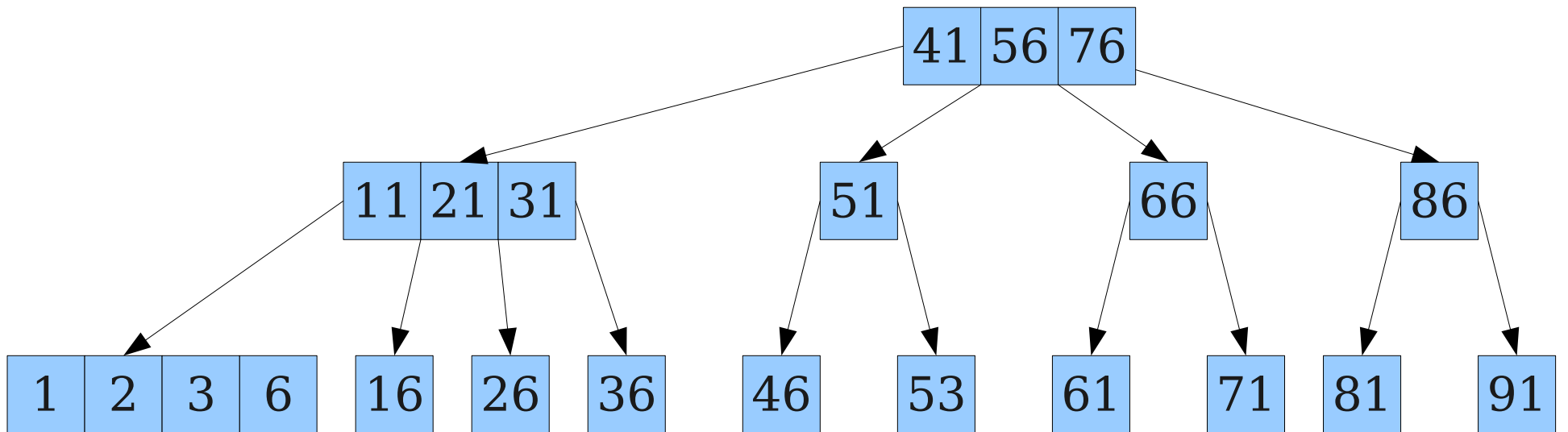
# A Problem

$$\Phi = \#(\text{array of 3 boxes}) + \#(\text{tree with 3 nodes})$$
$$= 6$$



# A Problem

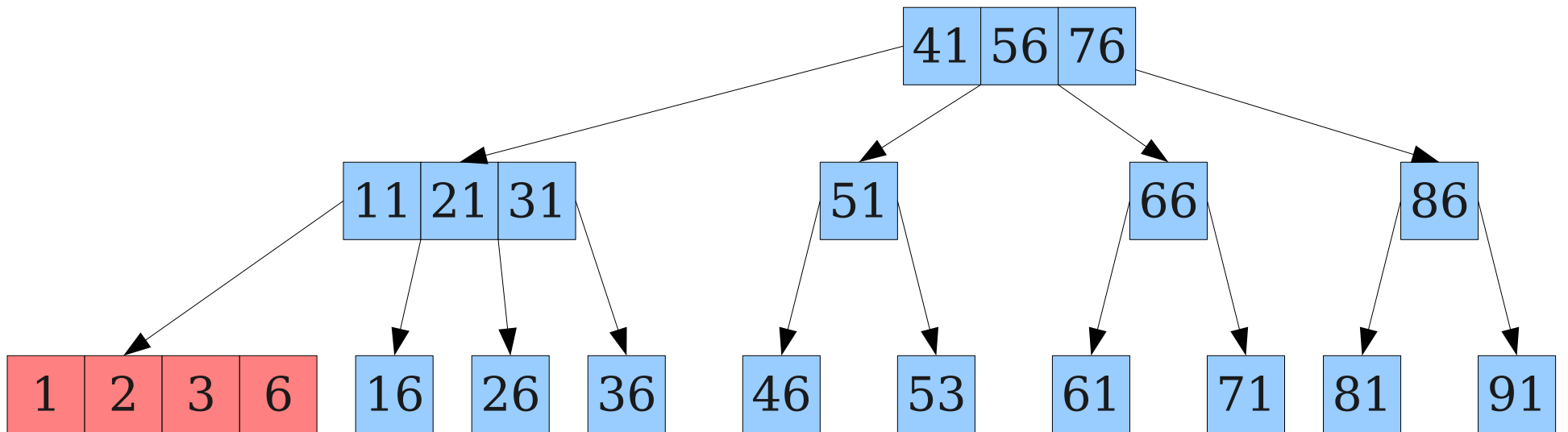
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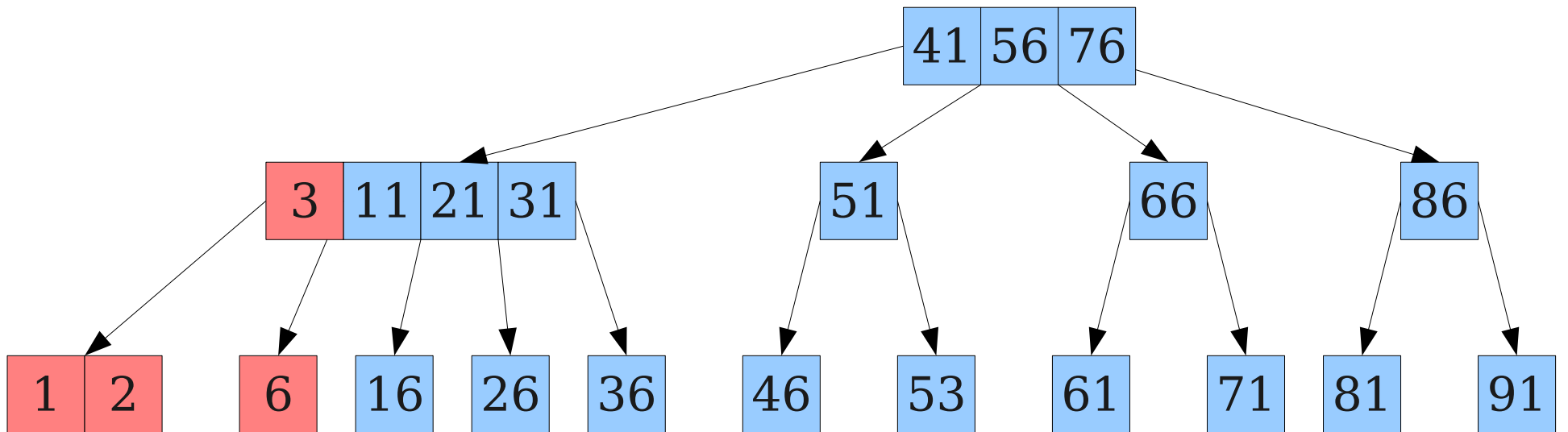
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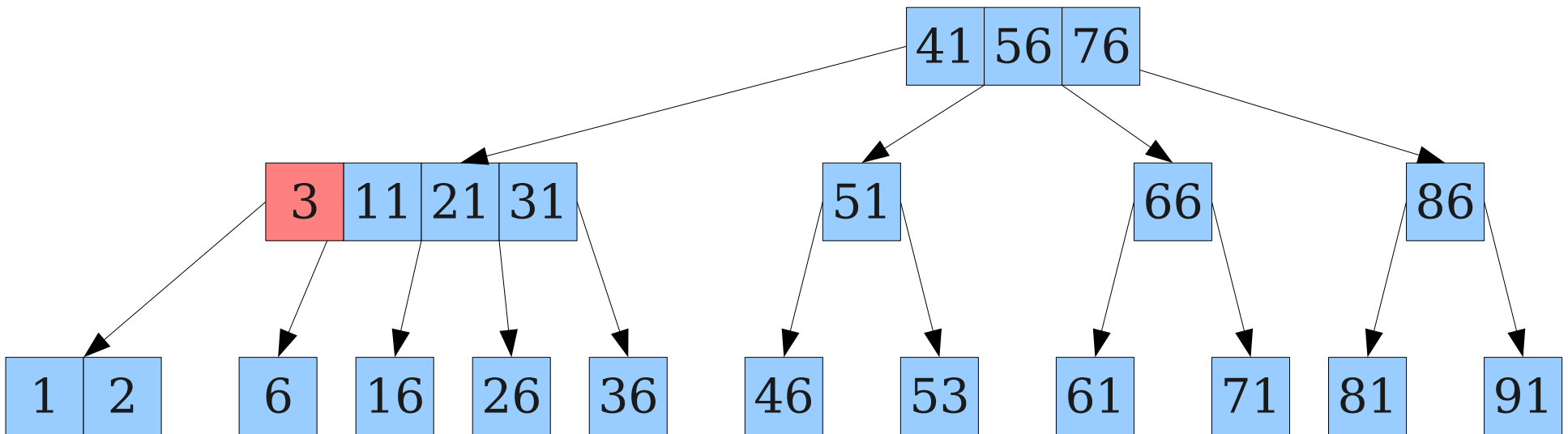
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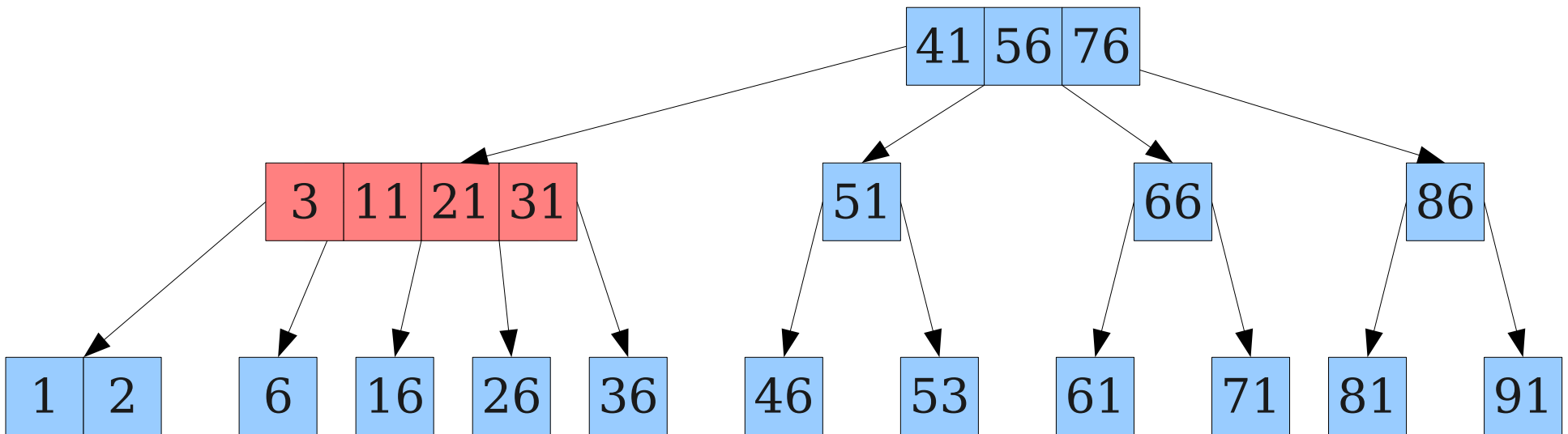
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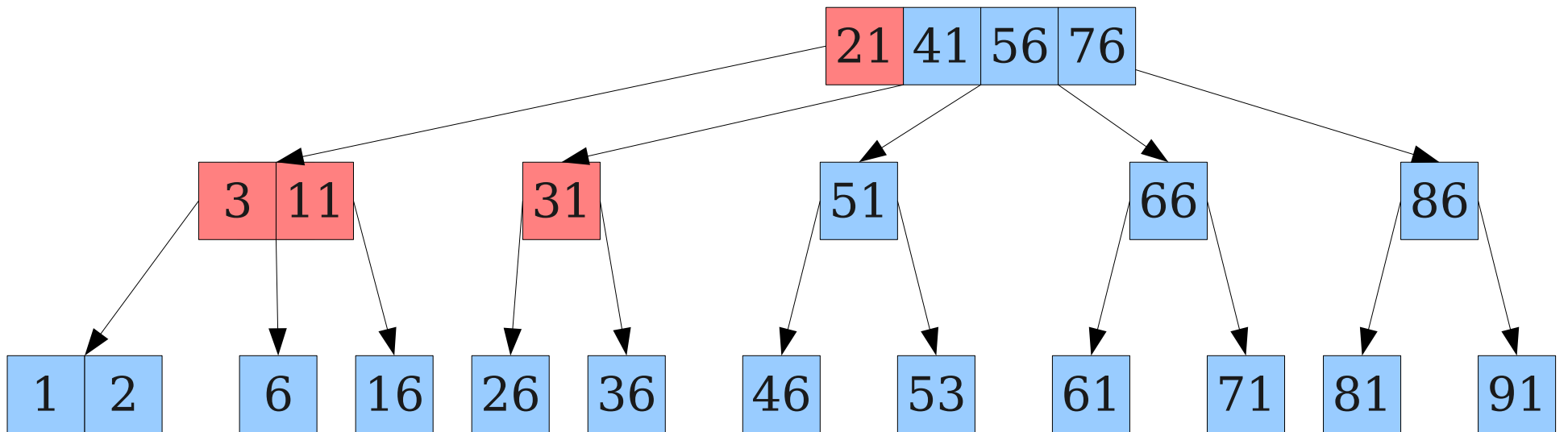
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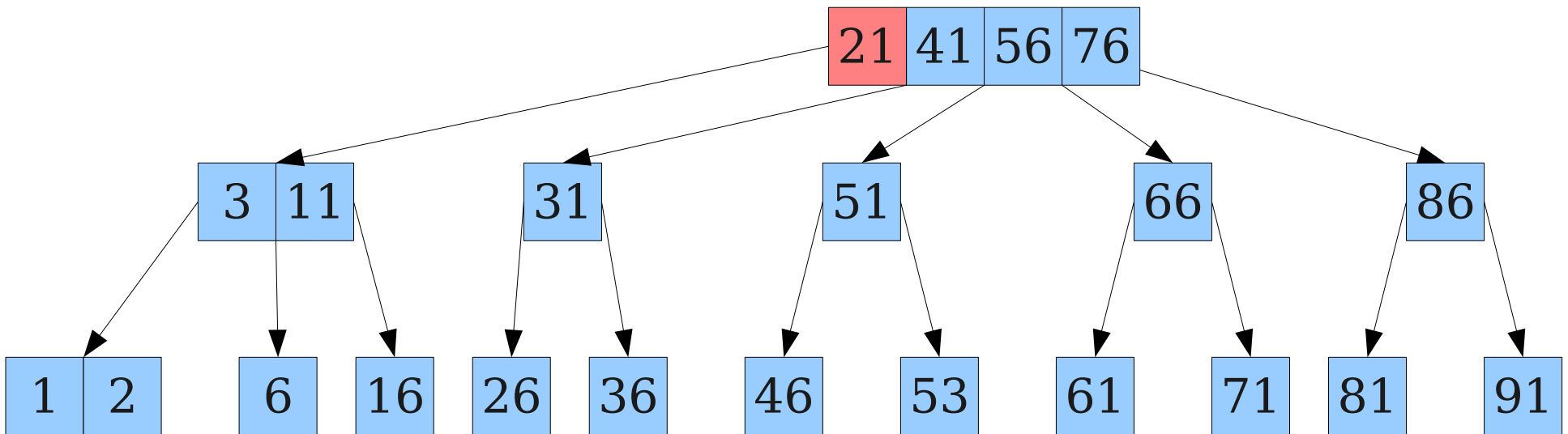
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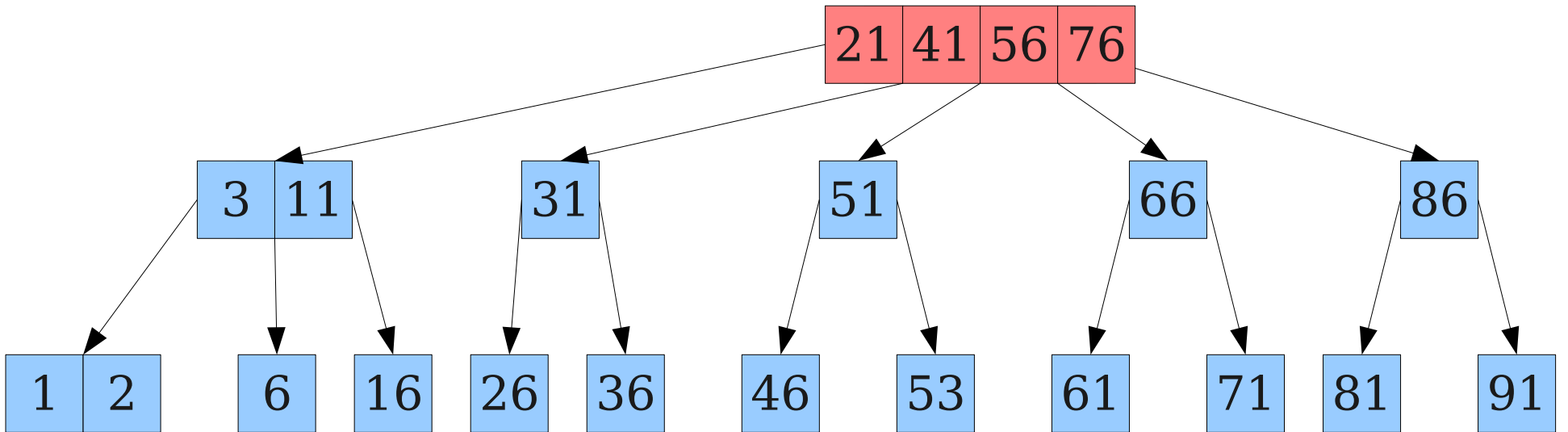
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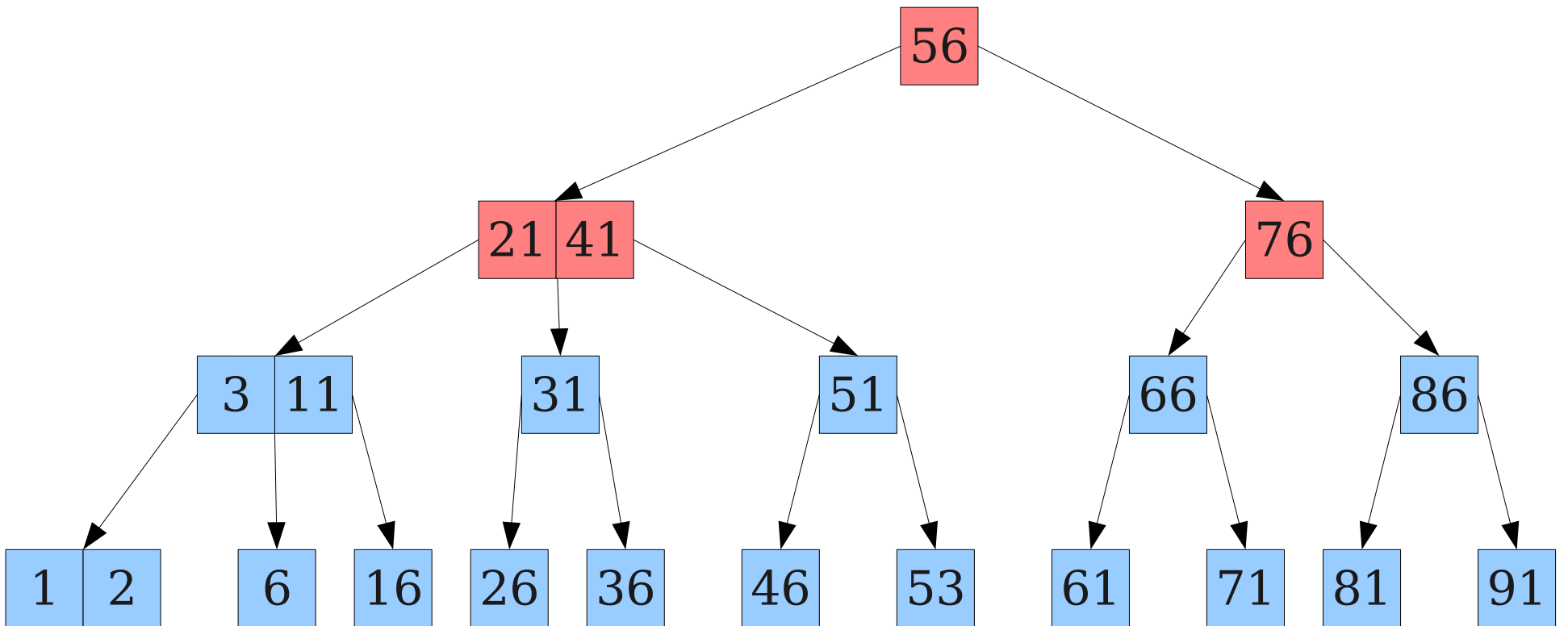
# A Problem

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# A Problem

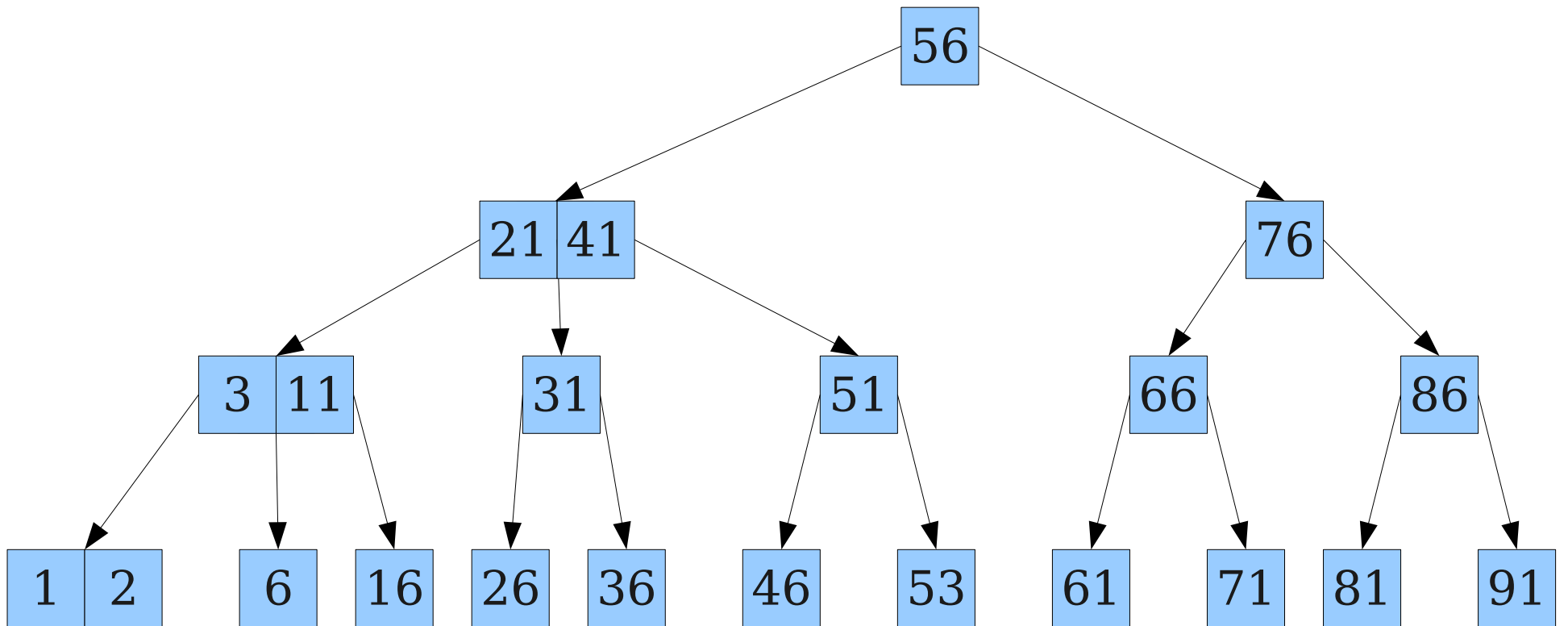
$$\Phi = \#(\text{array of 3 boxes}) + \#(\text{tree with 3 nodes})$$





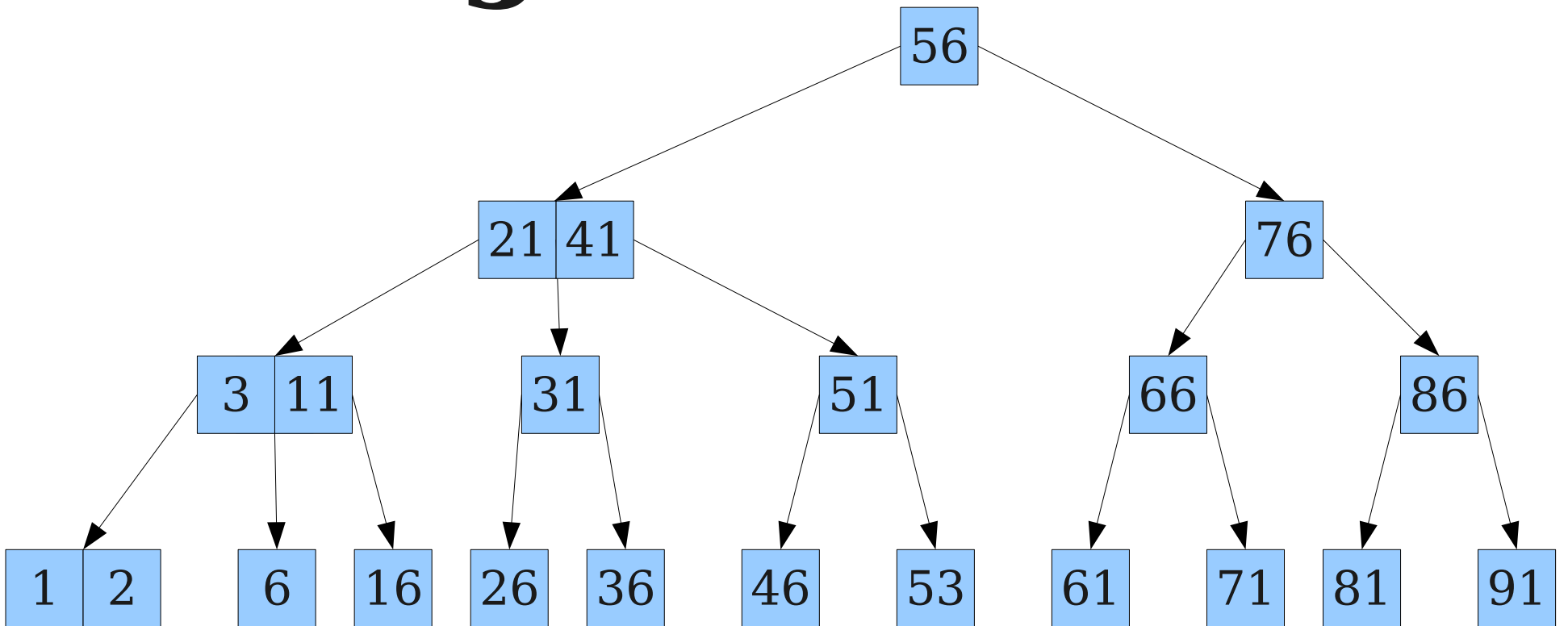
# A Problem

$$\Phi = \#(\text{array of 3 boxes}) + \#(\text{tree structure})$$



# A Problem

$$\Phi = \#(\text{□□□}) + \#(\text{□} \begin{array}{l} \swarrow \searrow \\ \text{□} \quad \text{□} \end{array})$$
$$= 5$$



# A Problem

- When doing a “heavy” insertion that splits multiple 4-nodes, the resulting nodes might produce new “tiny triangles.”
- Net result: The potential only drops by one even in a long chain of splits.
- Amortized cost of the operation works out to  $\Theta(\log n)$ , not  $O(1)$  as we hoped.

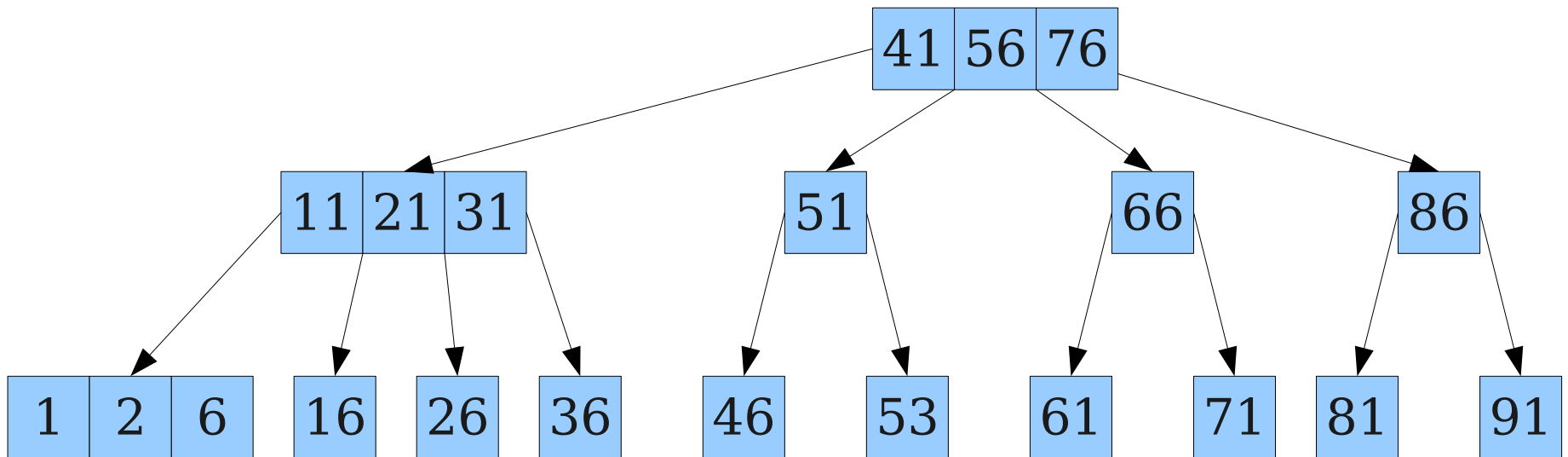
# The Solution

- 4-nodes are troublesome for two separate reasons:
  - They cause chained splits in an insertion.
  - After an insertion, they might split and produce a tiny triangle.
- **Idea:** Have each 4-node pay for the work to split itself and to propagate up a deletion one layer.

$$\Phi = 2 \#(\text{□□□}) + \#(\text{□} \begin{array}{l} \swarrow \searrow \\ \text{□} \quad \text{□} \end{array})$$

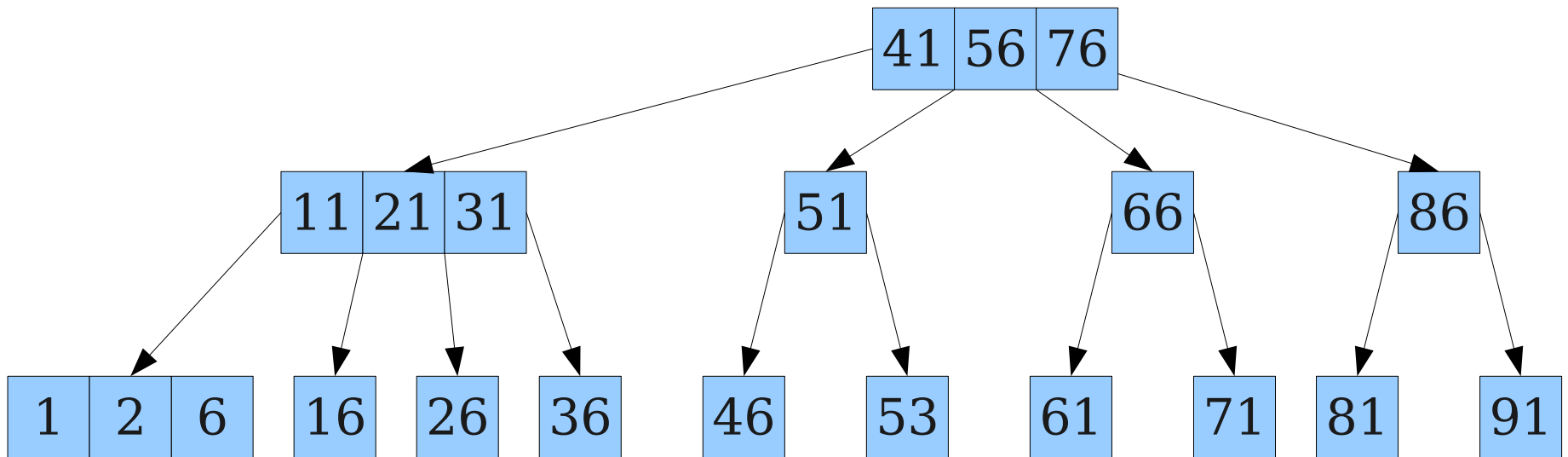
# A Problem

$$\Phi = 2\#(\text{□□□}) + \#(\begin{array}{c} \square \\ \swarrow \quad \searrow \\ \square \quad \square \end{array})$$



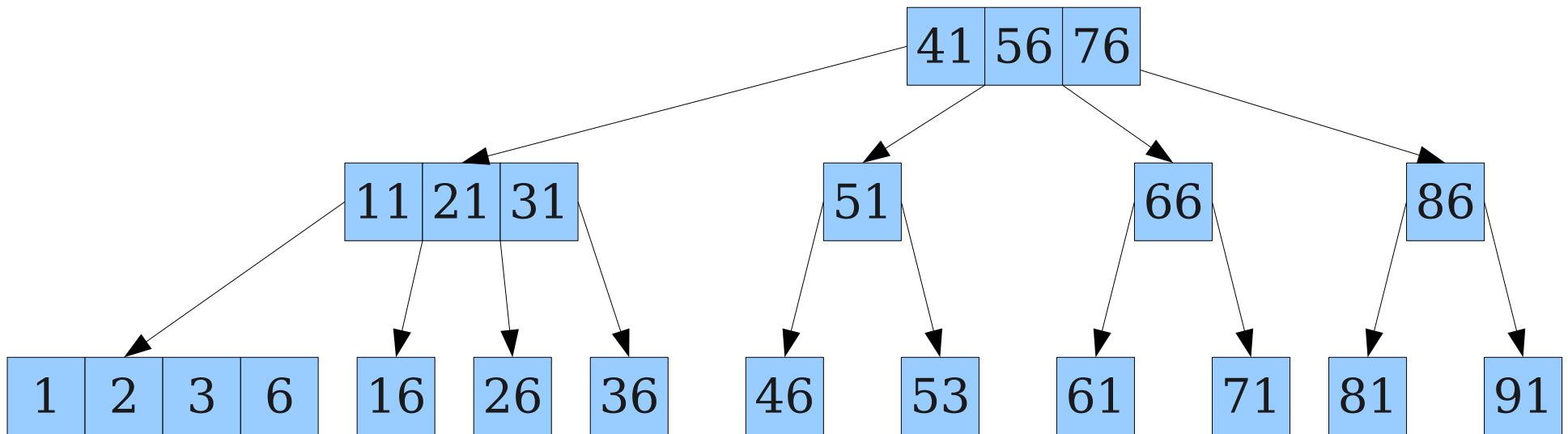
# A Problem

$$\Phi = 2\#(\text{□□□}) + \#(\text{□} \begin{array}{l} \swarrow \searrow \\ \text{□} \quad \text{□} \end{array})$$
$$= 9$$



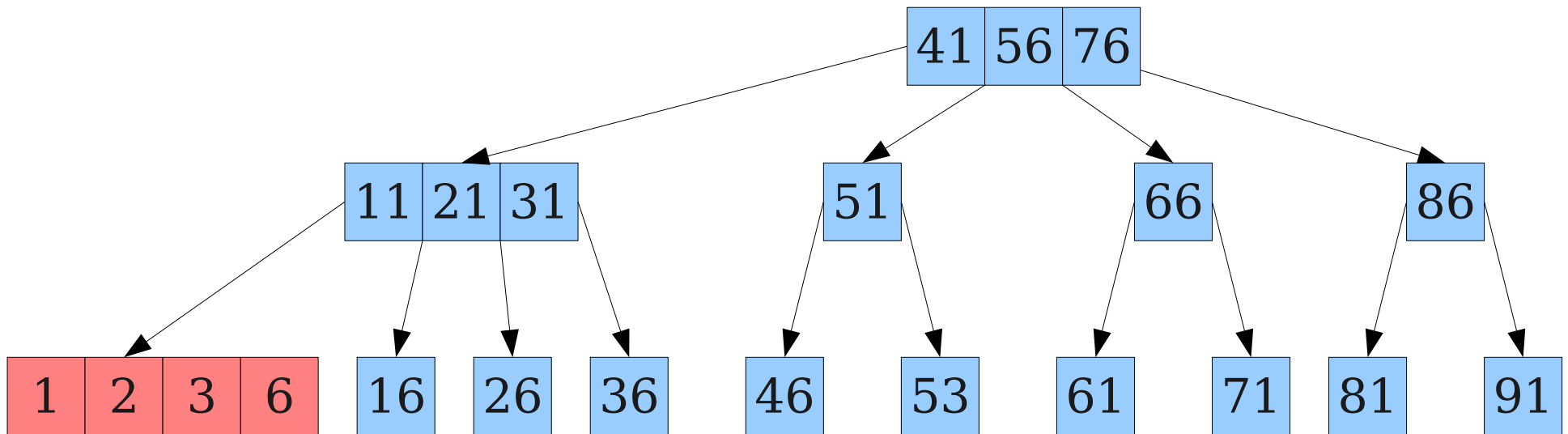
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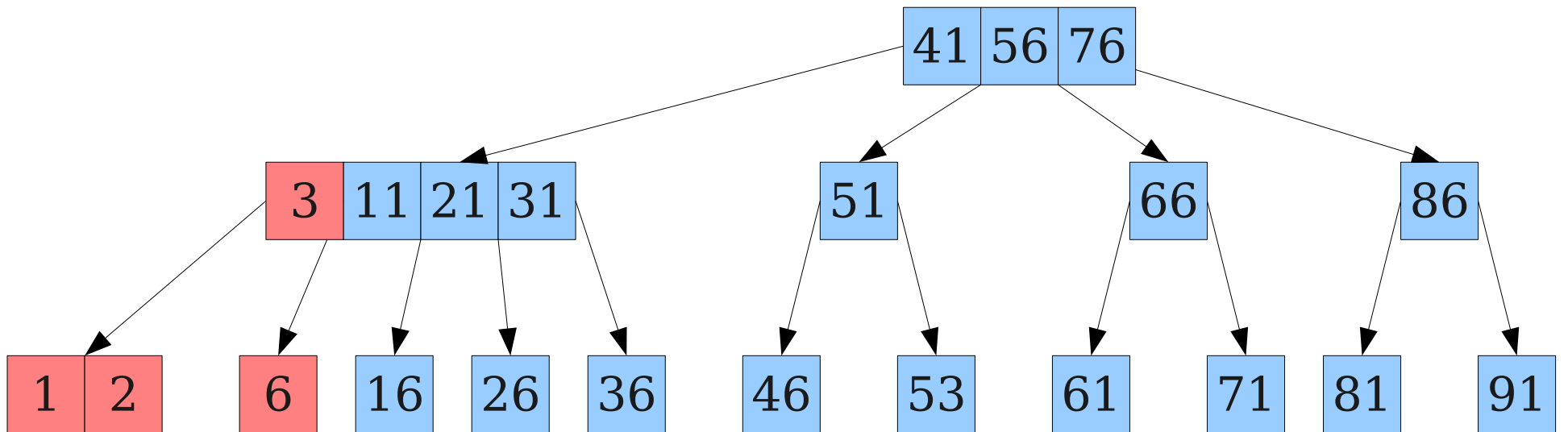
$$\Phi = 2\#(\text{□□□}) + \#(\text{□} \begin{array}{l} \swarrow \searrow \\ \text{□} \quad \text{□} \end{array})$$





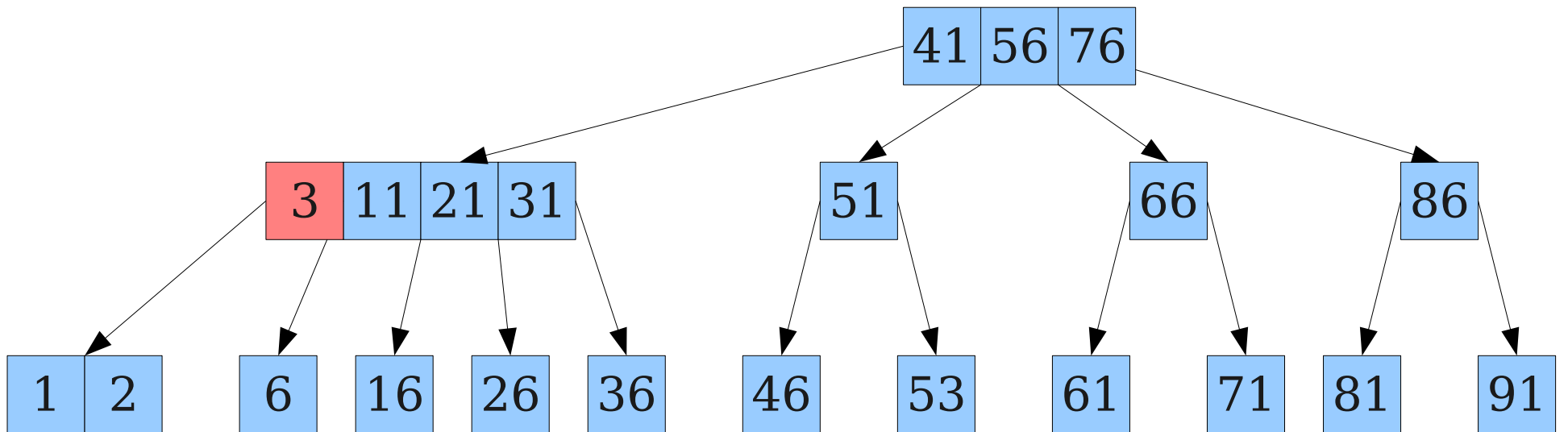
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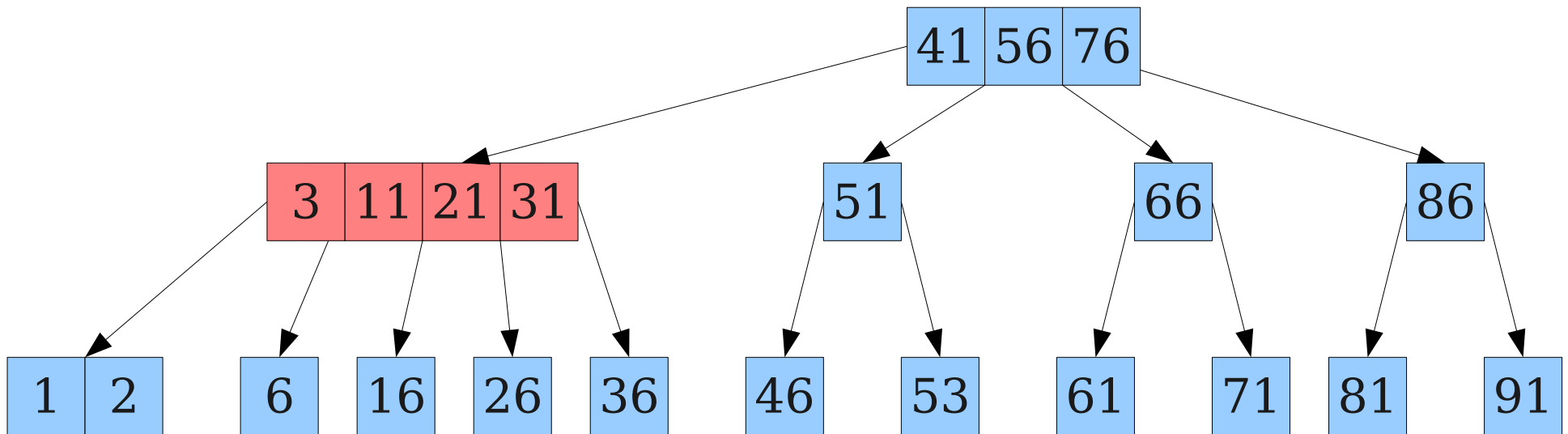
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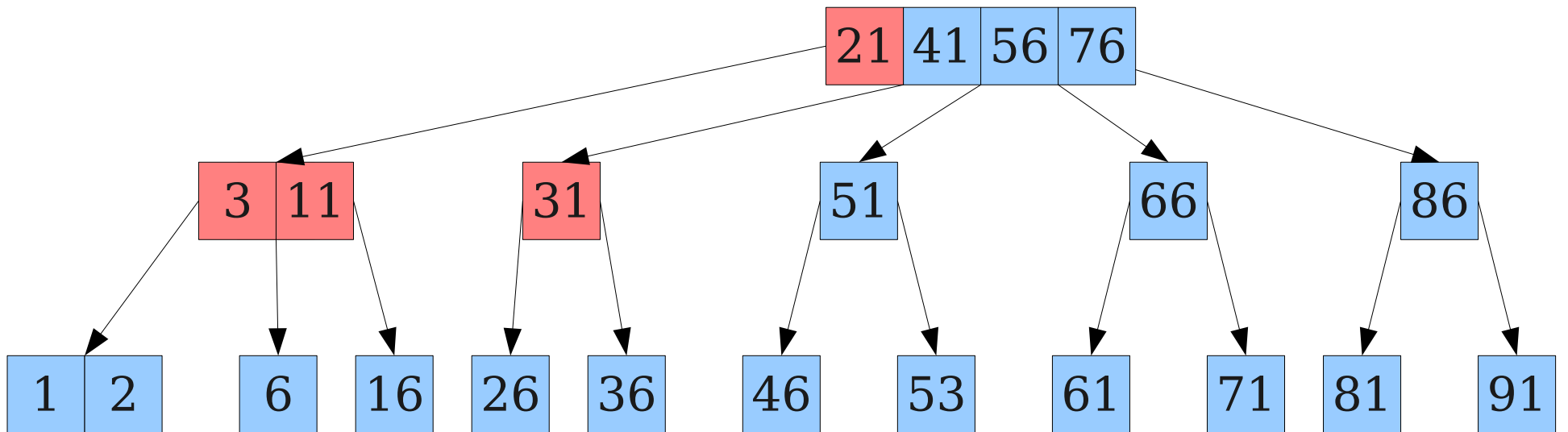
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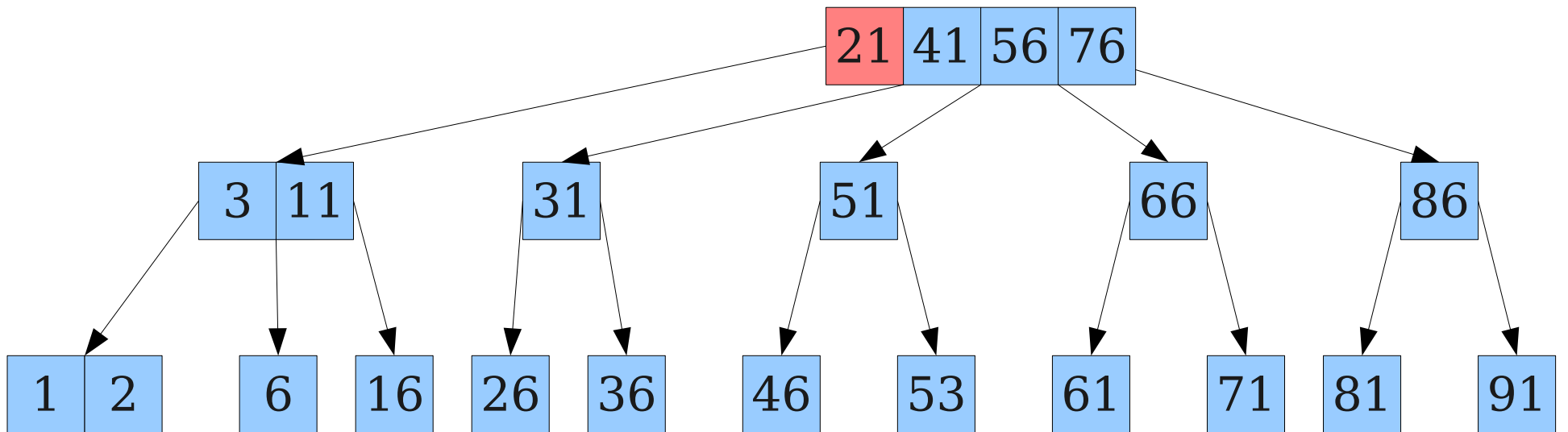
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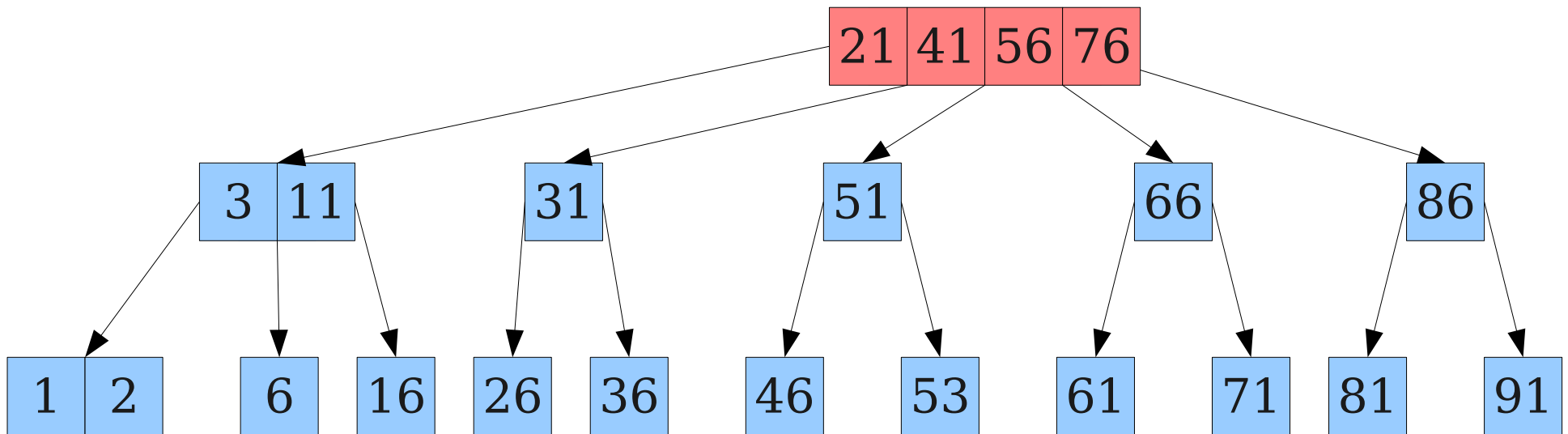
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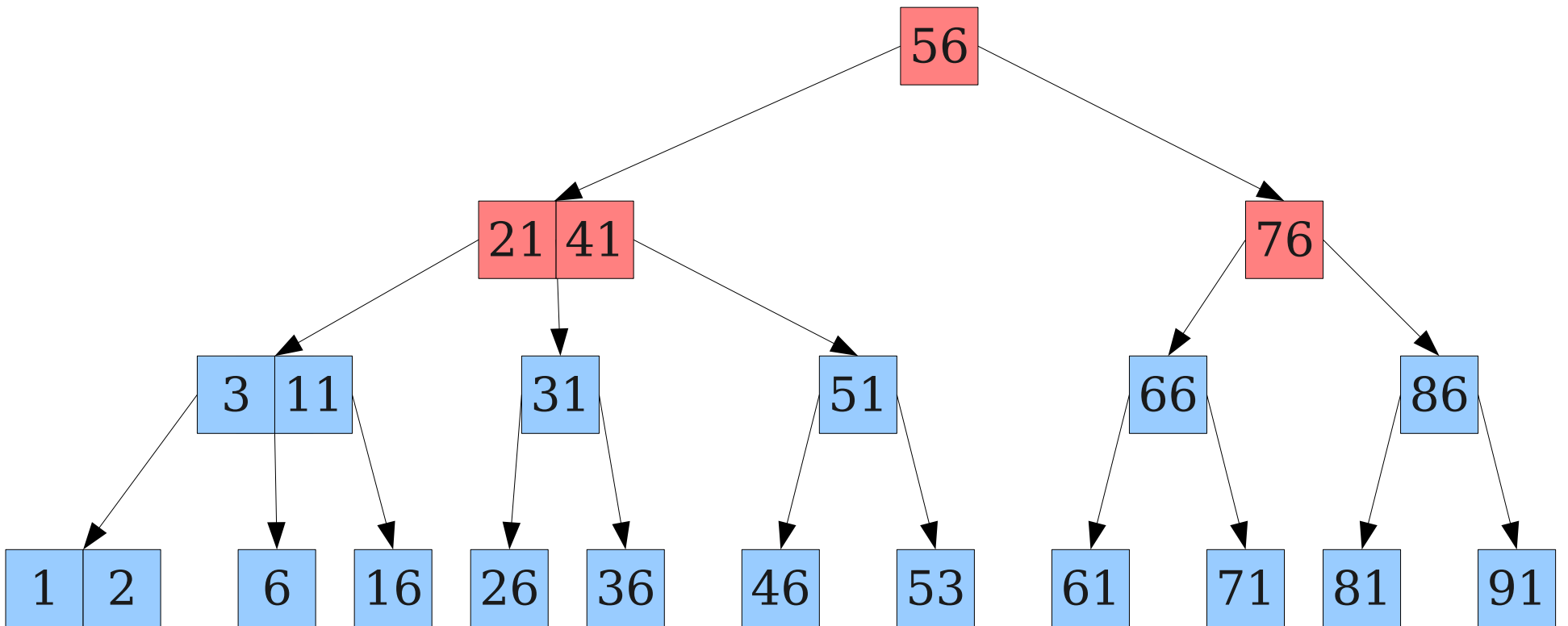
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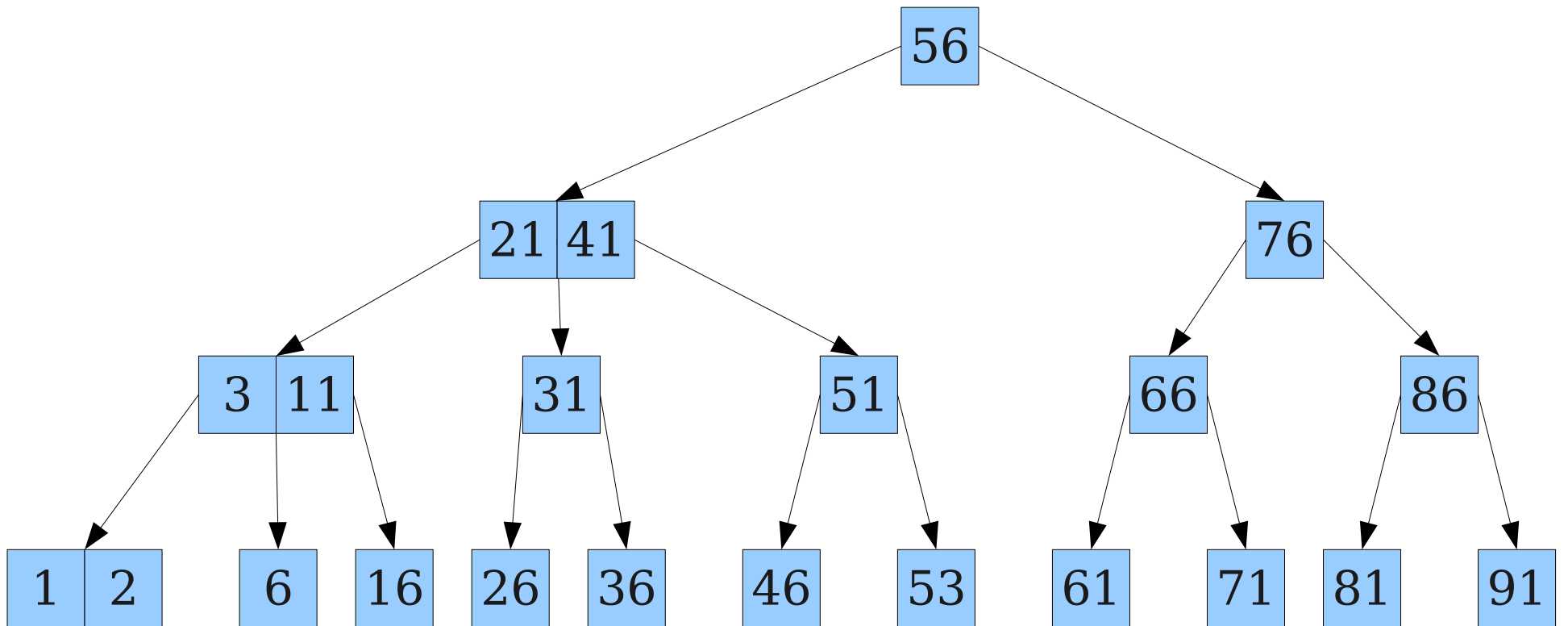
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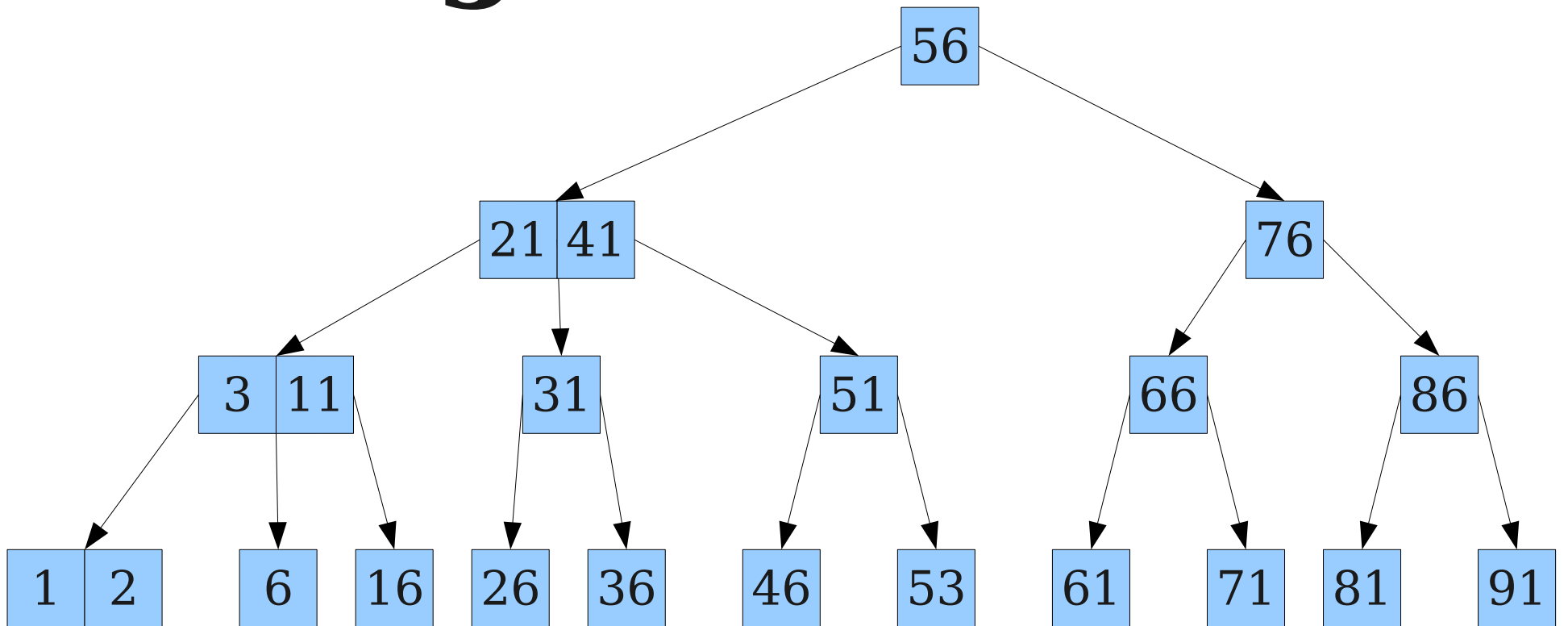
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# A Problem

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$$= 5$$



# The Solution

- This new potential function ensures that if an insertion chains up  $k$  levels, the potential drop is at least  $k$  (and possibly up to  $2k$ ).
- Therefore, the amortized fixup work for an insertion is  $O(1)$ .
- Using the same argument as before, deletions require amortized  $O(1)$  fixups.

# Why This Matters

- Via the isometry, red/black trees have  $O(1)$  amortized fixup per insertion or deletion.
- In practice, this makes red/black trees much faster than other balanced trees on insertions and deletions, even though other balanced trees can be better balanced.

# Next Time

- **Binomial Heaps**
  - A simple and versatile heap data structure.
- **Fibonacci Heaps, Part One**
  - A specialized data structure for graph algorithms.