

# **Design and Analysis of Algorithm**

## **Advanced Data Structure (Binomial Heap)**

**LECTURE 29-32**

# Overview

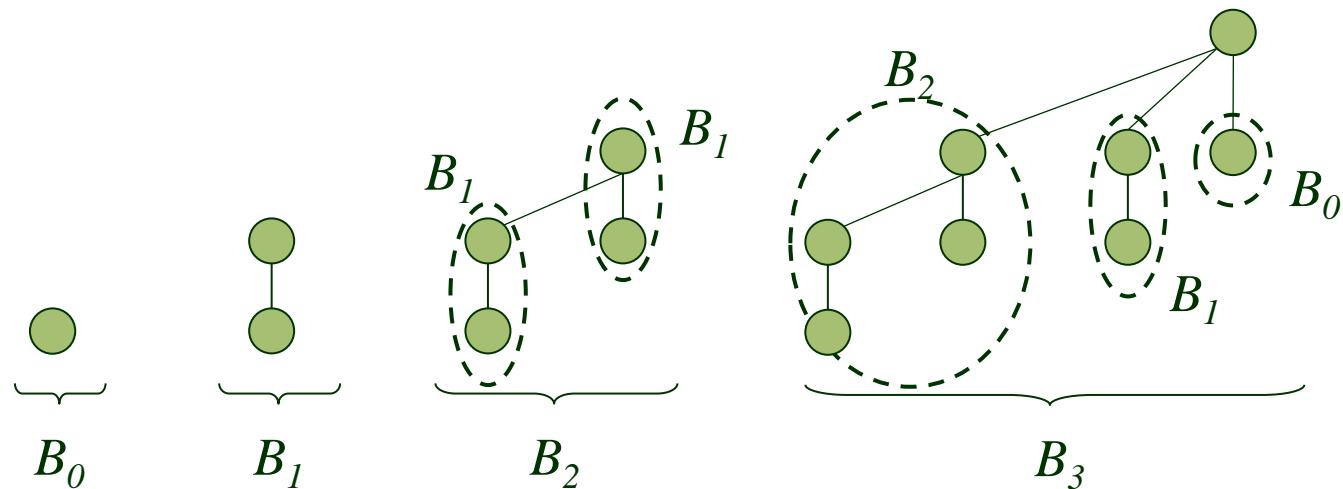
- This section presents a data structure known as **“Mergeable Heaps”**, which supports the following seven operations.
  - MAKE-BINOMIAL-HEAP
  - BINOMIAL-HEAP-INSERT
  - BINOMIAL-HEAP-MINIMUM
  - BINOMIAL-HEAP-EXTRACT-MIN
  - BINOMIAL-HEAP-UNION
  - BINOMIAL-HEAP DECREASE-KEY
  - BINOMIAL-HEAP-DELETE

# Binomial Heap

- Binomial heap was introduced in 1978 by Jean Vuillemin. He is a professor in mathematics and computer science.
- The other name of Binomial Heap is **Mergeable heaps**.
- A binomial heap is a collection of binomial trees.
  - Lets learn **What is Binomial Tree?**

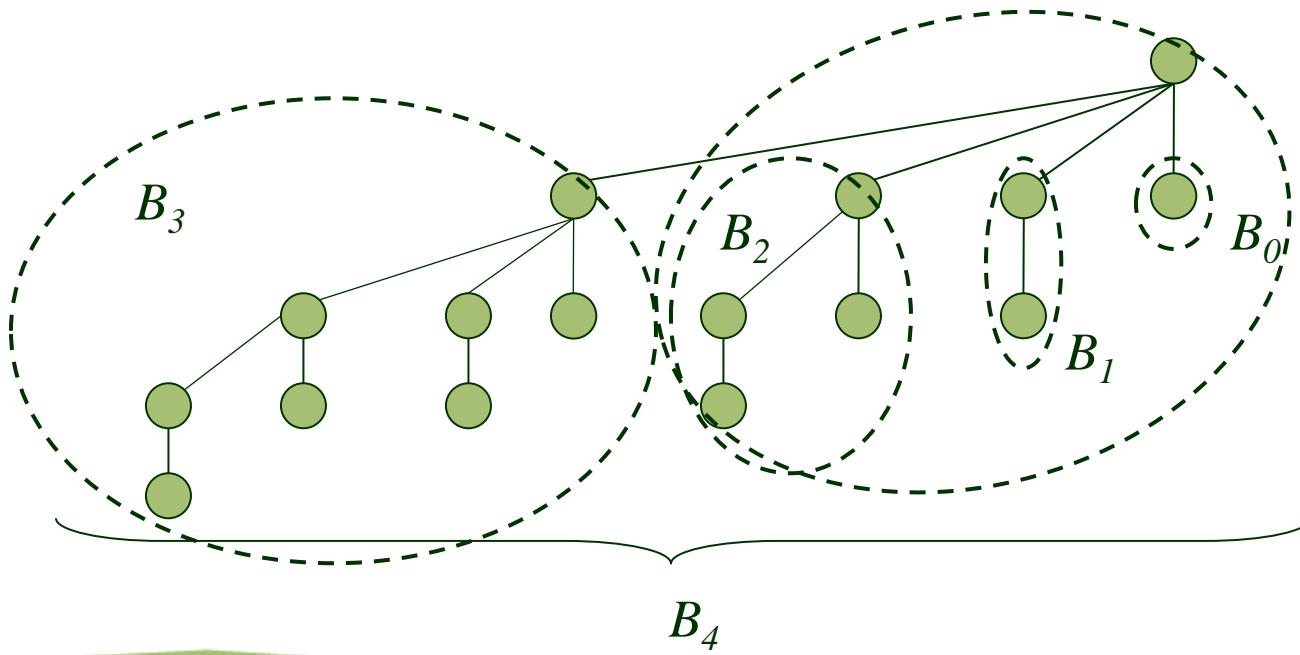
# Binomial Tree

- Binomial tree  $B_k$  is an ordered tree defined recursively.
- The binomial tree  $B_0$  has one node.
- The binomial tree  $B_k$  consists of two binomial trees  $B_{k-1}$  and they are connected such that the root of one tree is the leftmost child of the other.



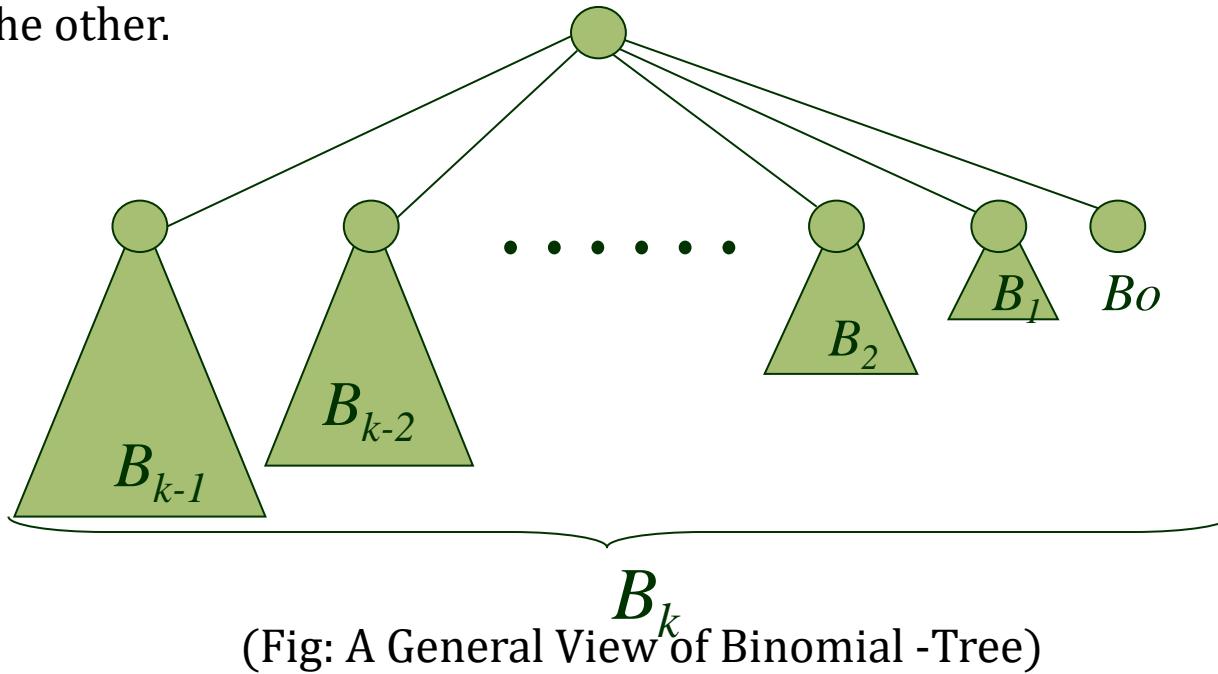
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# Binomial Tree (Property)

A Binomial tree satisfy the following properties:

- $B_k$  has  $2^k$  nodes
- $B_k$  has height  $k$
- There are exactly  $\binom{k}{i}$  combination of nodes at depth  $i$  for  $i=0, 1, 2, \dots, k$ .

For Example:

Lets check in  $B_4$  and depth 2(*i.e.*  $k = 4$  and  $i = 2$ )

$$\binom{k}{i} = \frac{k!}{i!(k-i)!} = \binom{4}{2} = \frac{4!}{2! (4-2)!} = \frac{4 \times 3 \times 2 \times 1}{2 \times 1 \times 2 \times 1} = 6$$

Hence 6 numbers of nodes are available in depth 2 of  $B_4$

- The root has degree  $k$  which is greater than other node in the tree. Each of the root's child is the root of a subtree  $B_i$ .

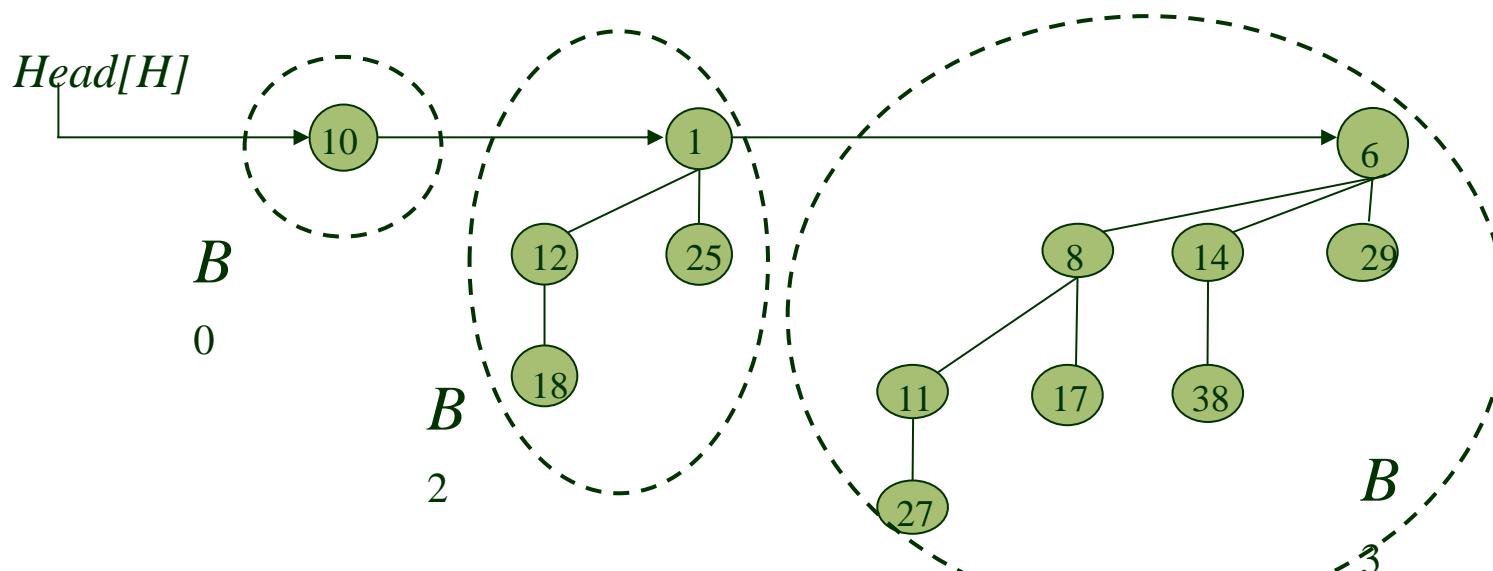
# Binomial Heap (Property)

A Binomial Heap  $H$  is a set of binomial trees that satisfies the following properties:

- P1. Each binomial tree in  $H$  obeys the **min heap property**.  
*(i.e. key of a node is greater or equal to the key of its parent. Hence the root has the smallest key in the tree).*
- P2. For any non negative integer  $k$ , there is at most one binomial tree whose root has degree  $k$ .  
*(e.g. it implies that an  $n$  node Binomial heap  $H$  consists of at most  $\lceil \log n \rceil + 1$  binomial Tree. (Fig. is available in next page))*
- P3. The binomial trees in the binomial heap are arranged in increasing order of degree.

# Binomial Heap (Property)

- Example:



Here  $n=13$

So  $\lfloor \log n \rfloor + 1 = \lfloor \log 13 \rfloor + 1 = 3 + 1 = 4$  (So at most 4)

The Above Figure of Binomial Heap consists of  $B_0$ ,  $B_2$  and  $B_3$

# Binomial Heap (Representation)

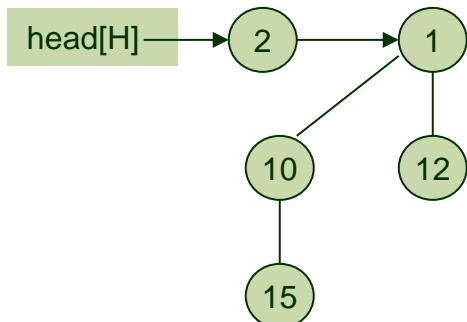
- Each binomial tree within a binomial heap is stored in the left-child, right-sibling representation
- Each node  $x$  contains POINTERS
  - $p[x] \rightarrow parent$  to its parent
  - $key[x] \rightarrow key$  to its key value
  - $child[x] \rightarrow child$  to its leftmost child
  - $sibling[x] \rightarrow sibling$  to its immediately right sibling
  - $degree[x] \rightarrow degree$  to its degree value (i.e. denotes the number of children of  $x$ )

# Binomial Heap (Representation)

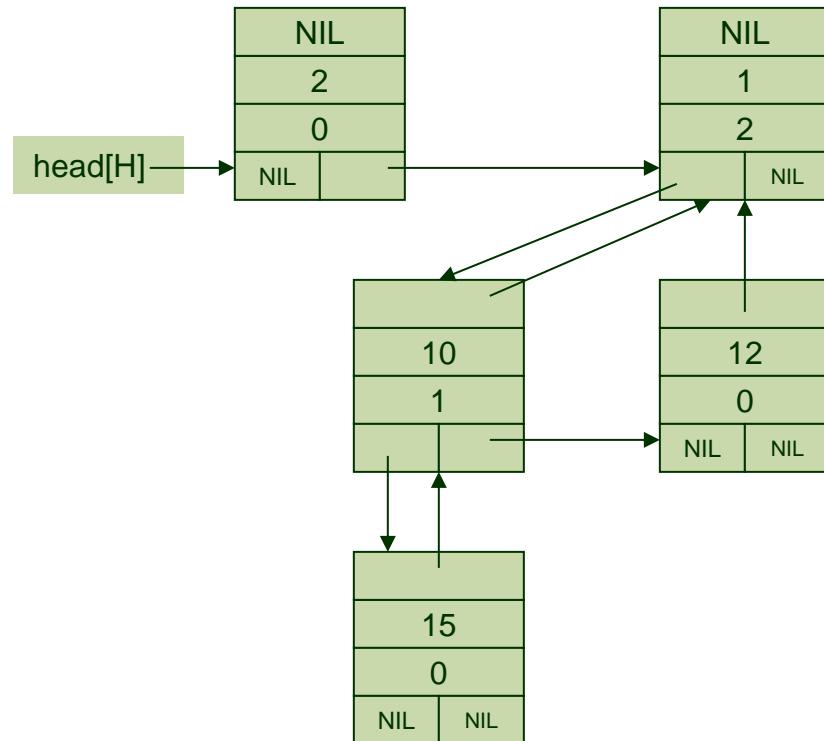
a)

p	
key	
degree	
child	sibling

b)



c)



# **Binomial Heap (Operations)**

Binomial Heap support the following five operations:

1. **MAKE-HEAP()** creates and returns a new heap containing no elements.
2. **MINIMUM(H)** returns a pointer to the node in heap H whose key is minimum.
3. **UNION(H1, H2)** creates and returns a new heap that contains all the nodes of heaps H1 and H2. Heaps H1 and H2 are "destroyed" by this operation.
4. **EXTRACT-MIN(H)** deletes the node from heap H whose key is minimum, returning a pointer to the node.

# **Binomial Heap (Operations)**

5. **INSERT(H, x)** inserts node x, whose key field has already been filled in, into heap H.
6. **DECREASE-KEY(H, x, k)** assigns to node x within heap H the new key value k, which is assumed to be no greater than its current key value.[1]
7. **DELETE(H, x)** deletes node x from heap H

# **Binomial Heap (Operations\_1)**

1. **MAKE-HEAP()** : creates and returns a new heap containing no elements.

To make an empty binomial heap, the MAKE-BINOMIAL-HEAP procedure simply allocates and returns an object H , where head[H ] = NIL.

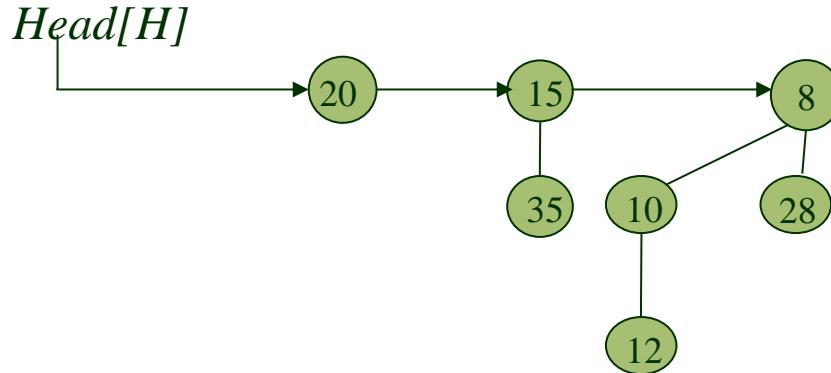
The running time is  $\Theta(1)$ .

# **Binomial Heap (Operations\_2)**

**2. MINIMUM(H) :** Since the binomial heap is a min-heap-order, the minimum key of each binomial tree must be at the root. This operation checks all the roots to find the minimum key.

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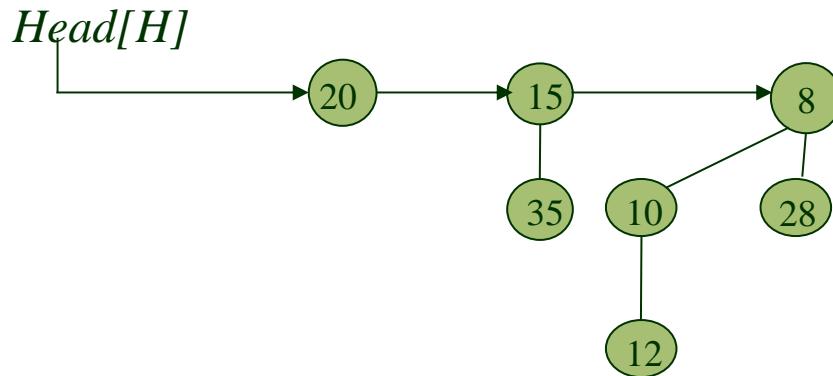
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Pseudocode: This implementation assumes that there are no keys with value  $\infty$ .

BINOMIAL-HEAP-MINIMUM(H)

```
1  y ← NIL
2  x ← head[H]
3  min ←  $\infty$ 
4  while x ≠ NIL
5      do if key[x] < min
           then min ← key[x]
6      y ← x
7      x ← sibling[x]
8
9  return y
```



# Binomial Heap (Operations\_2)

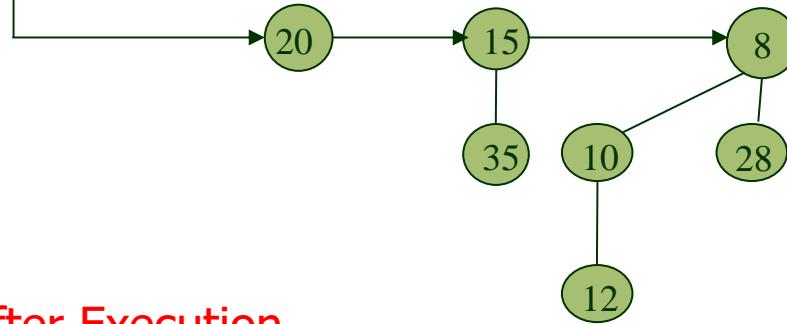
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9  return y
```

*Head[H]*



After Execution  
Return y=8

# Binomial Heap (Operations\_2)

Since binomial heap is Heap-ordered and the minimum key must reside in a ROOT node. The **BINOMIAL-HEAP-MINIMUM(H)** checks all roots in  $O(lgn)$ . Because,

*Number of Roots in Binomial Heap is at least  $\lfloor \log n \rfloor + 1$  ( property 2)*

Hence *RUNNING-TIME =  $O(lgn)$*

# Binomial Heap (Operations\_3)

## 3. UNION(H1, H2)

This operation consists of the following steps

- Merge two binomial heaps H1 and H2. The resulting heap has the roots in increasing order of degree
- For each tree in the binomial heap H, if it has the same order with another tree, link the two trees together such that the resulting tree obeys min-heap-order.

For this there is an requirement of 3 pointers into the root list

$x$  = points to the root currently being examined

$\text{prev-}x$  = points to the root PRECEDING  $x$  on the root list  
    **sibling** [ $\text{prev-}x$ ] =  $x$

$\text{next-}x$  = points to the root FOLLOWING  $x$  on the root list  
    **sibling** [ $x$ ] =  $\text{next-}x$

# Binomial Heap (Operations\_3)

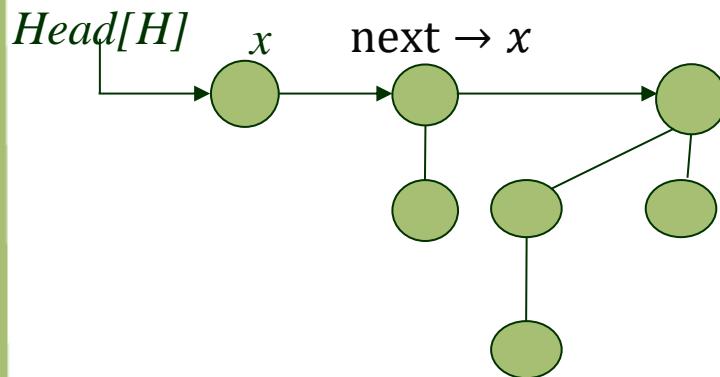
This operation perform by the help of 4(four) number of cases.

**Case 1:** *if* ( $\text{degree}[x] \neq \text{degree}[\text{next} \rightarrow x]$ )

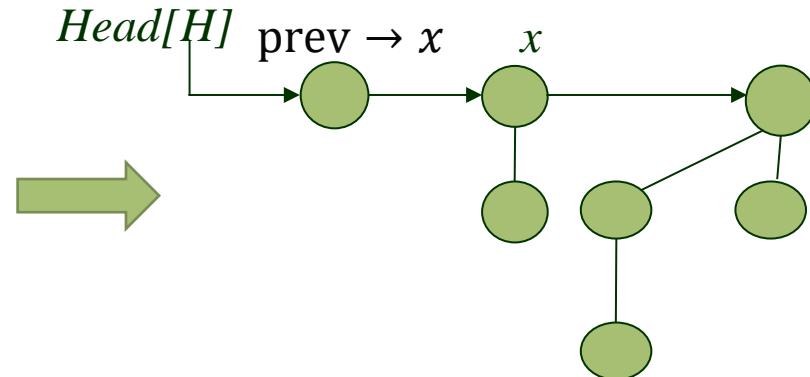
$\text{prev} \rightarrow x = x$

$x = \text{next} \rightarrow x$

Example:



Before Case 1



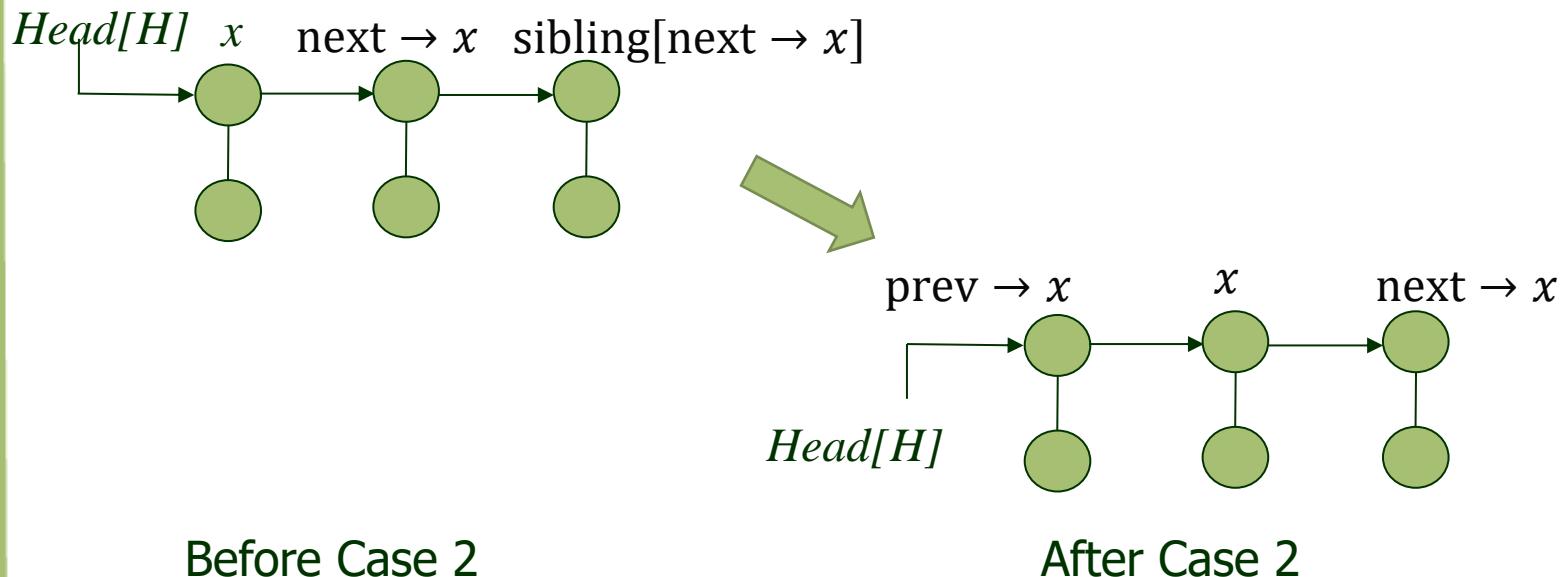
After Case 1

# Binomial Heap (Operations\_3)

This operation perform by the help of 4(four) number of cases.

Case 2: *if* ( $\text{degree}[x] = \text{degree}[\text{next} \rightarrow x] = \text{degree}[\text{sibling}[\text{next} \rightarrow x]]$ )  
    prev  $\rightarrow x = x$   
    x= $\text{next} \rightarrow x$

Example:

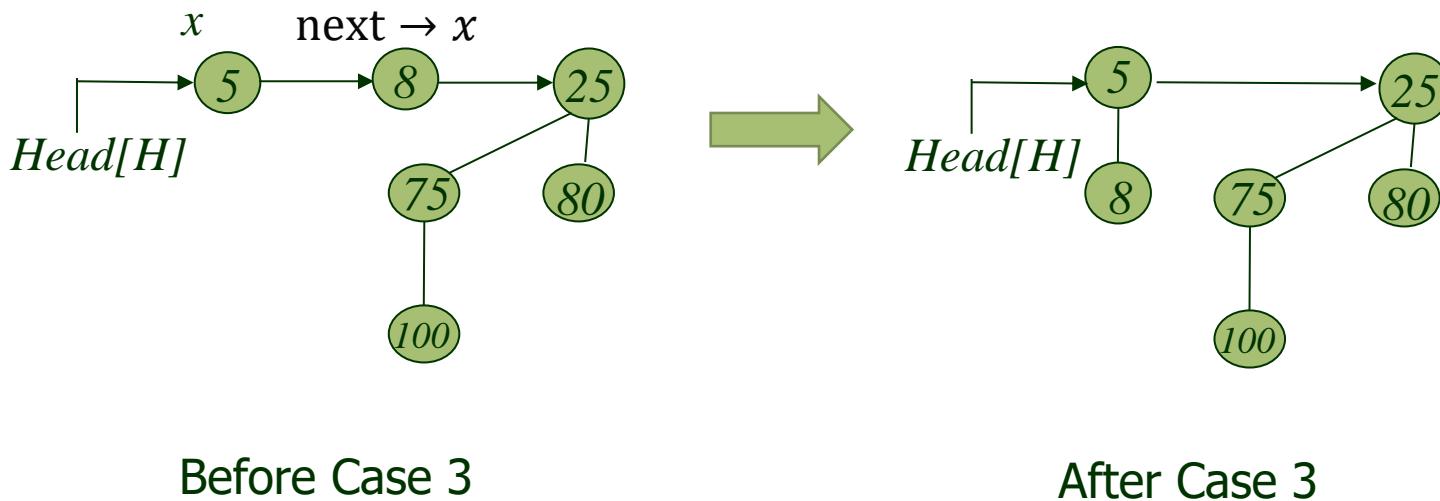


# Binomial Heap (Operations\_3)

This operation perform by the help of 4(four) number of cases.

**Case 3:** *if* ( $\text{degree}[x] = \text{degree}[\text{next} \rightarrow x]$ ) and ( $\text{key}[x] \leq \text{key}[\text{next}]$ )  
     $\text{sibling}[x]=\text{sibling}[\text{next} \rightarrow x]$   
    Binomial Link( $\text{next} \rightarrow x, x$ )

Example:



# Binomial Heap (Operations\_3)

This operation perform by the help of 4(four) number of cases.

Case 4: *if* ( $degree[x] = degree[next \rightarrow x]$ ) and ( $key[x] \geq key[next]$ )

*if*( $prev \rightarrow x == \text{Null}$ )

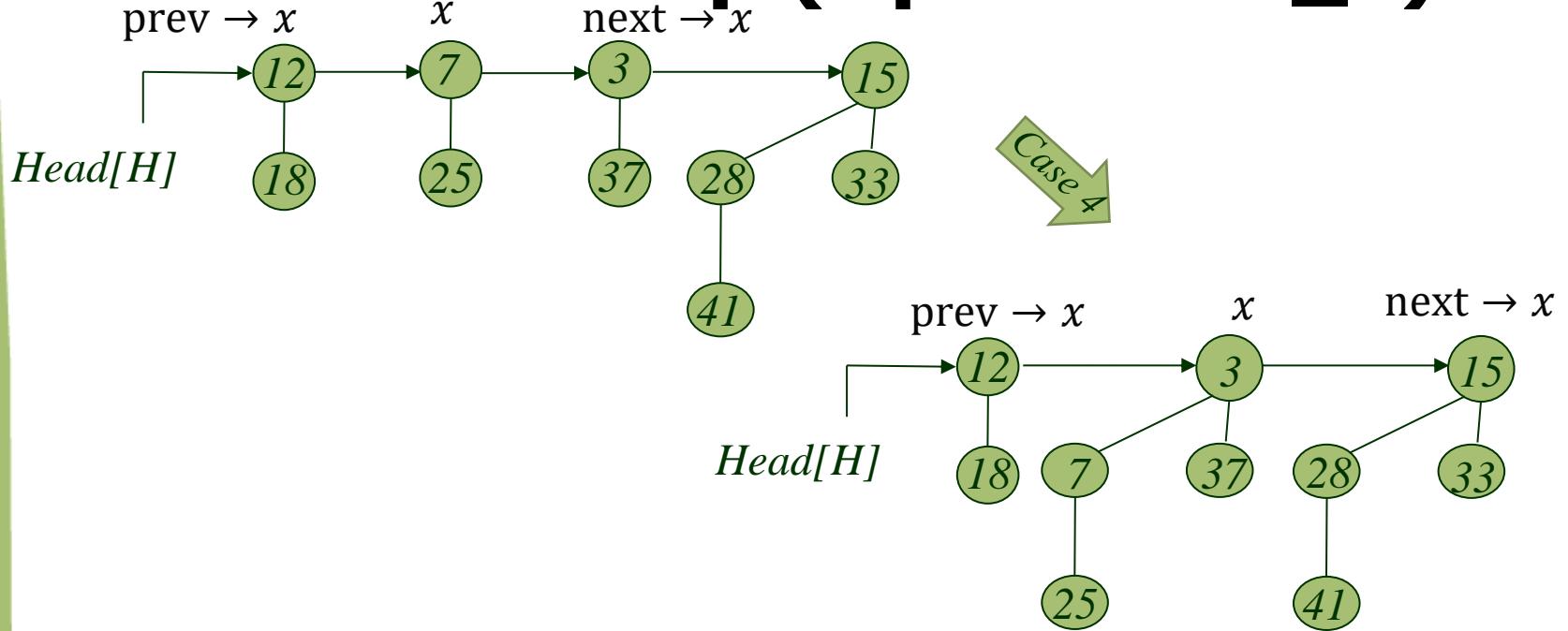
$\text{Head}[H] = next \rightarrow x$

*else*

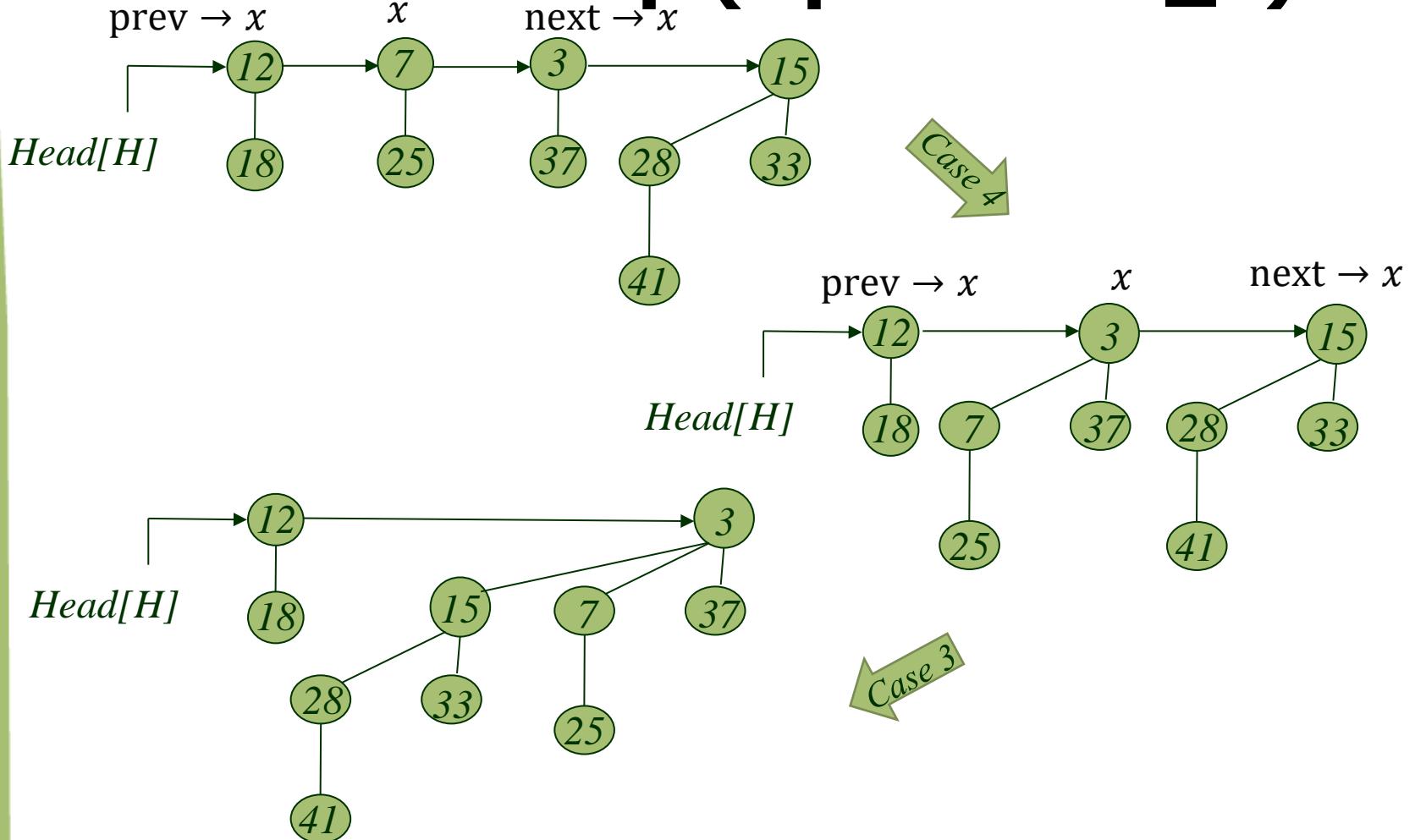
$\text{sibling}[prev \rightarrow x] = next \rightarrow x$

    Binomial Link( $x, next \rightarrow x$ )

# Binomial Heap (Operations\_3)



# Binomial Heap (Operations\_3)



# **Binomial Heap (Operations\_3)**

BINOMIAL-LINK(y, z)

1  $p[y] = z$

2  $sibling[y] = child[z]$

3  $child[z] = y$

4  $degree[z] = degree[z] + 1$

# Binomial Heap (Operations\_3)

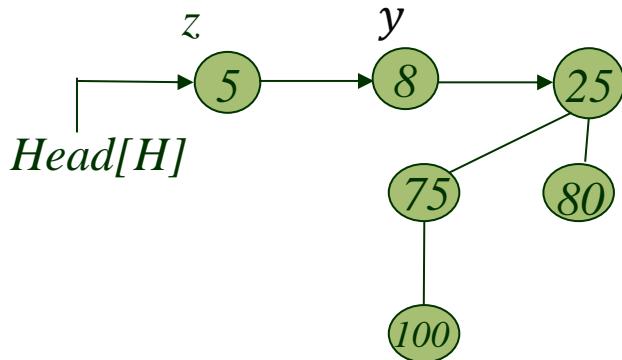
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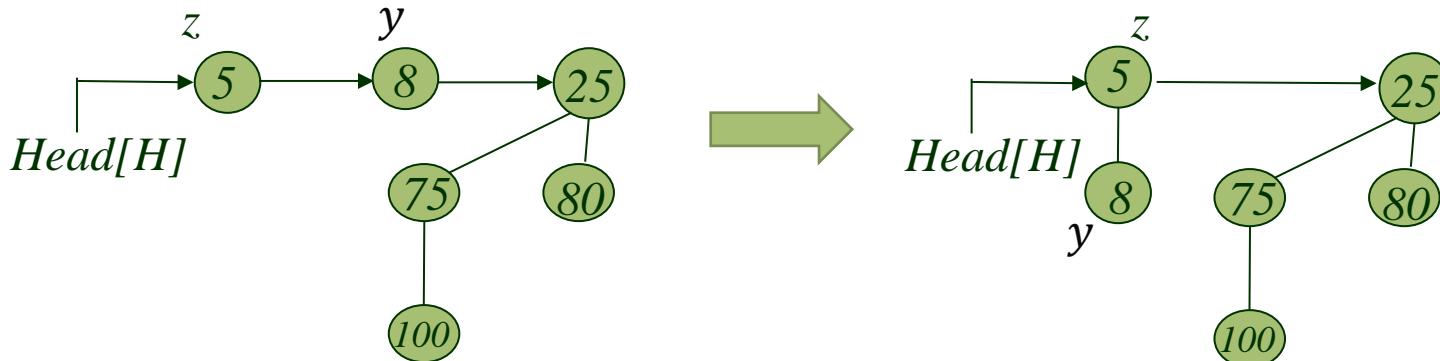
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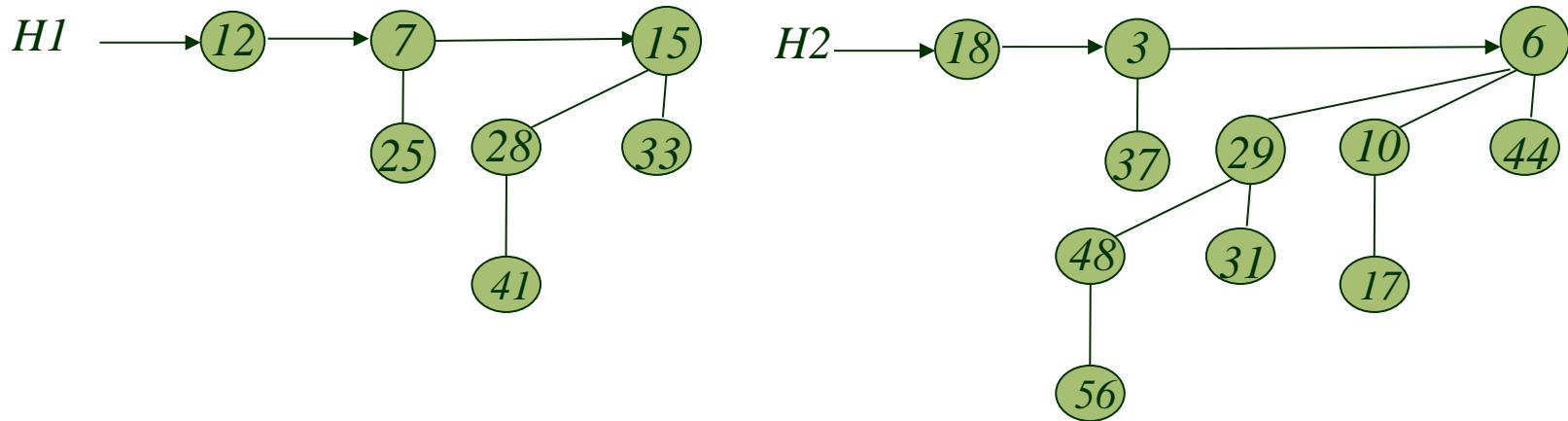
3  $\text{ child}[z] = y$

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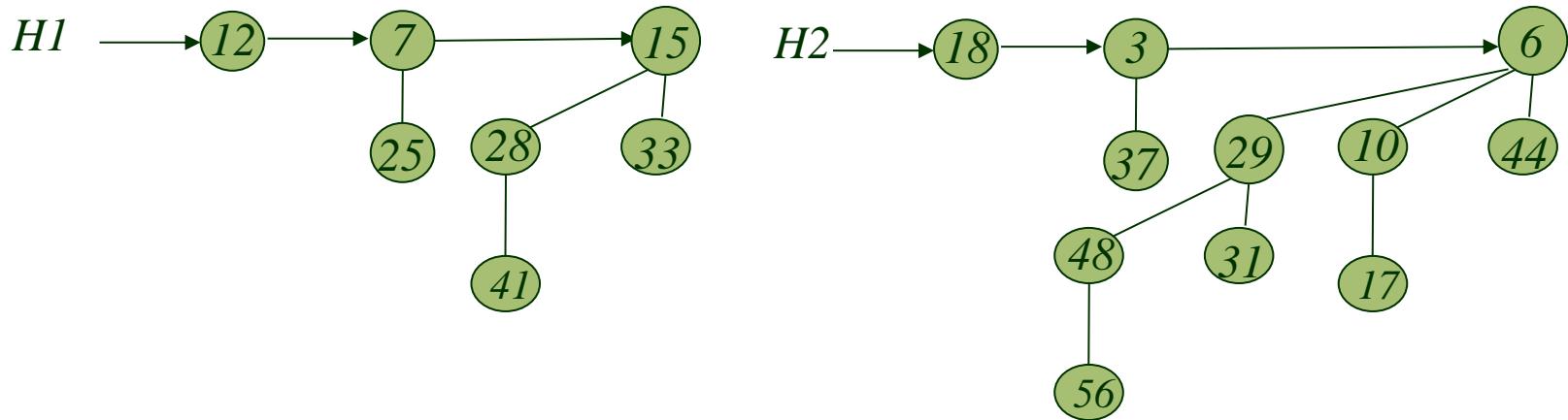
# Binomial Heap (Operations\_3)

Example 1: Merge the following two Binomial heap H1 and H2.



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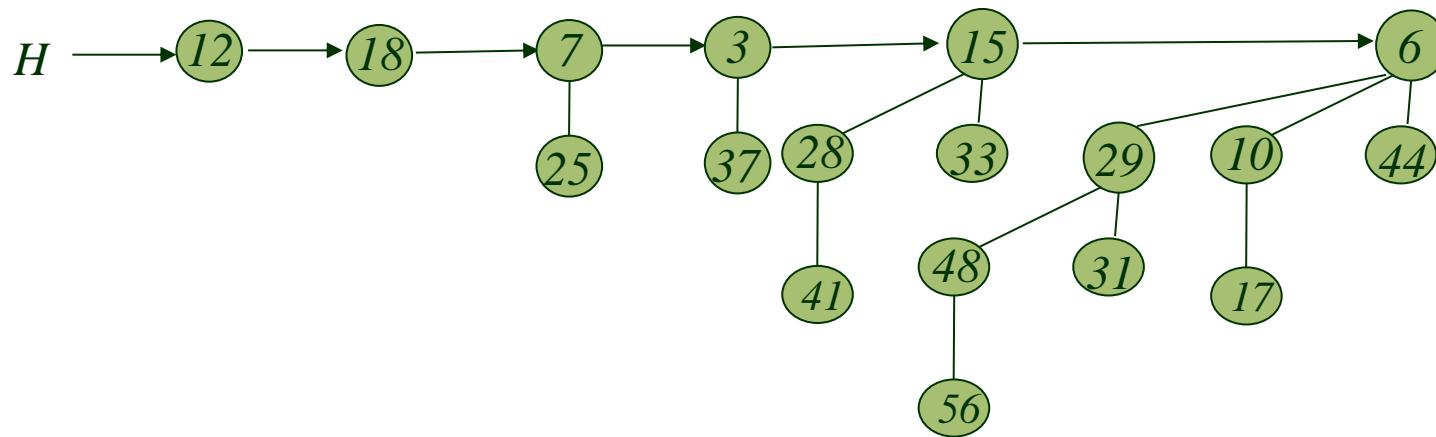
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After Merging.....

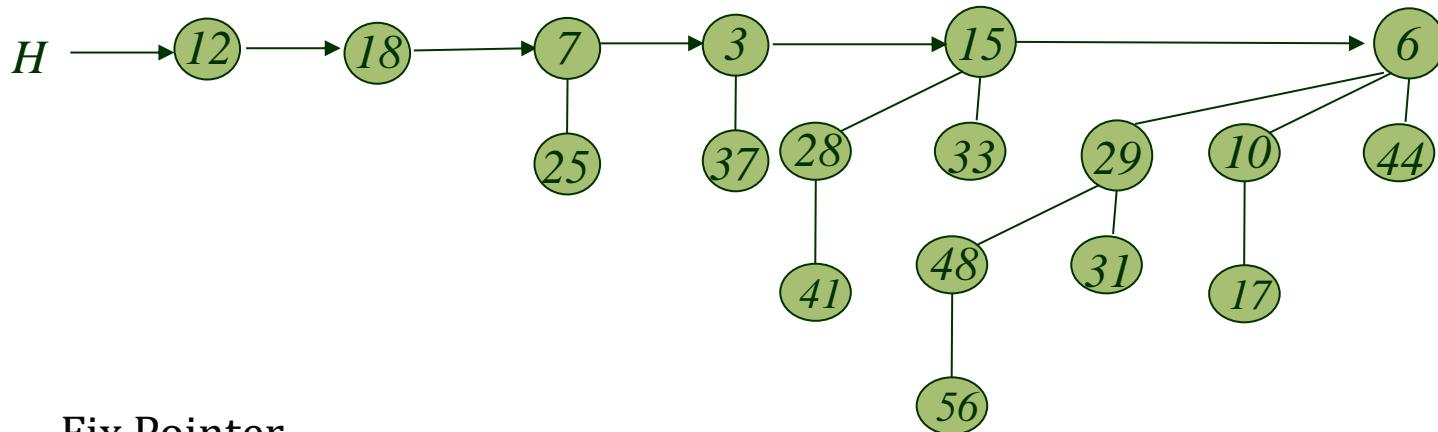
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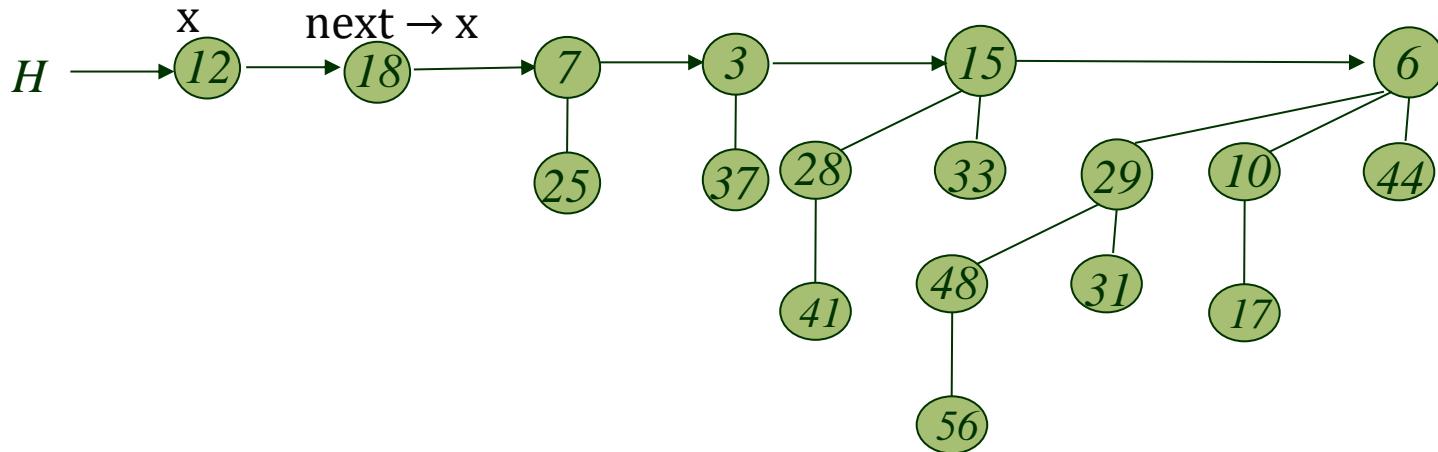
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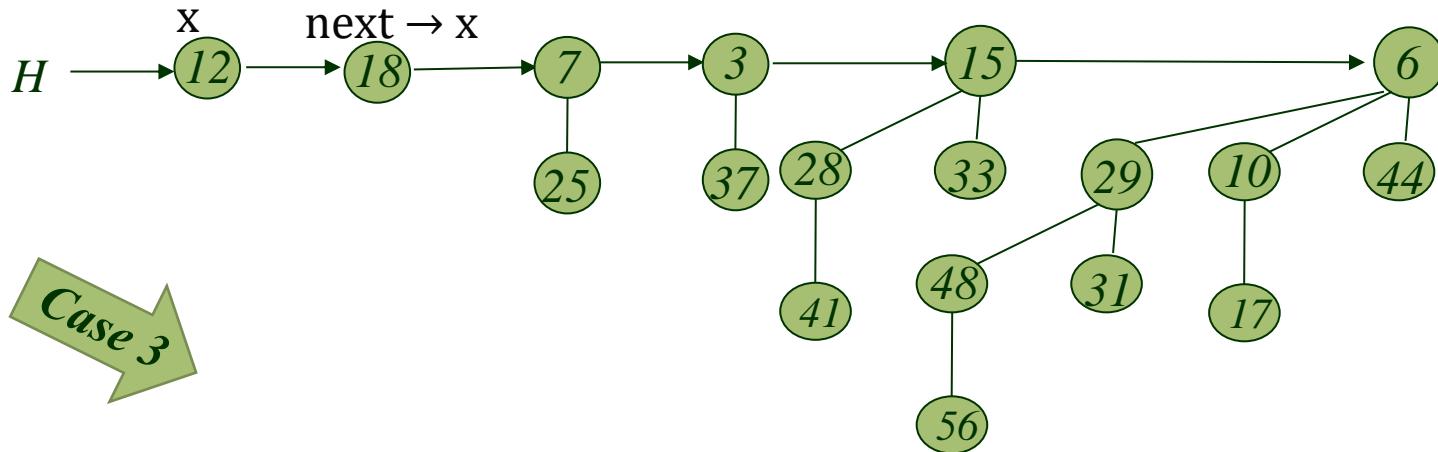
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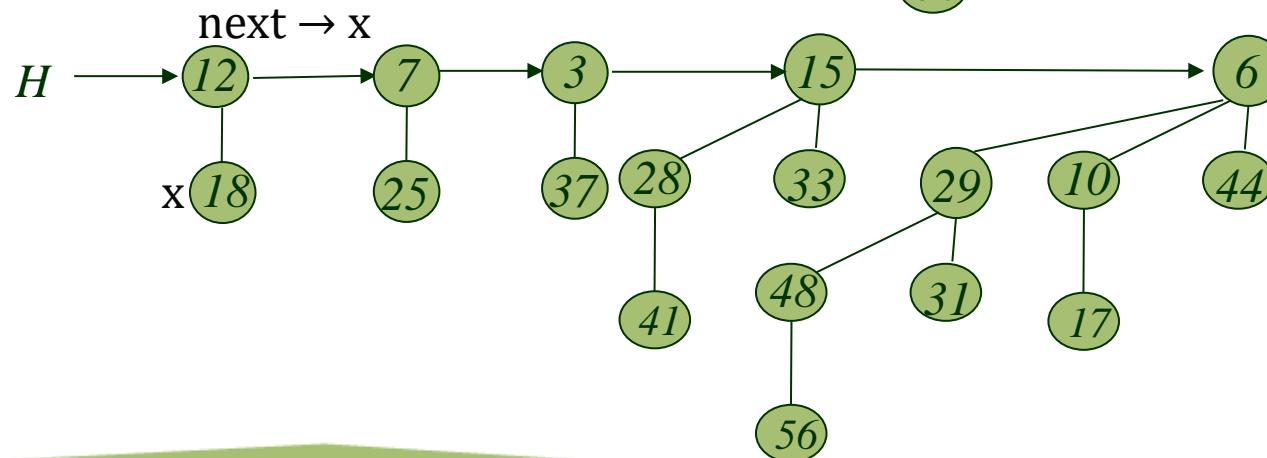
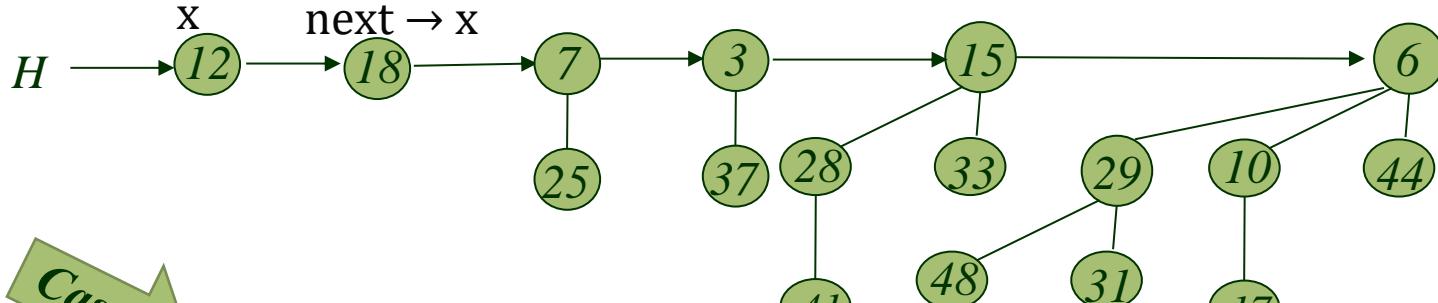
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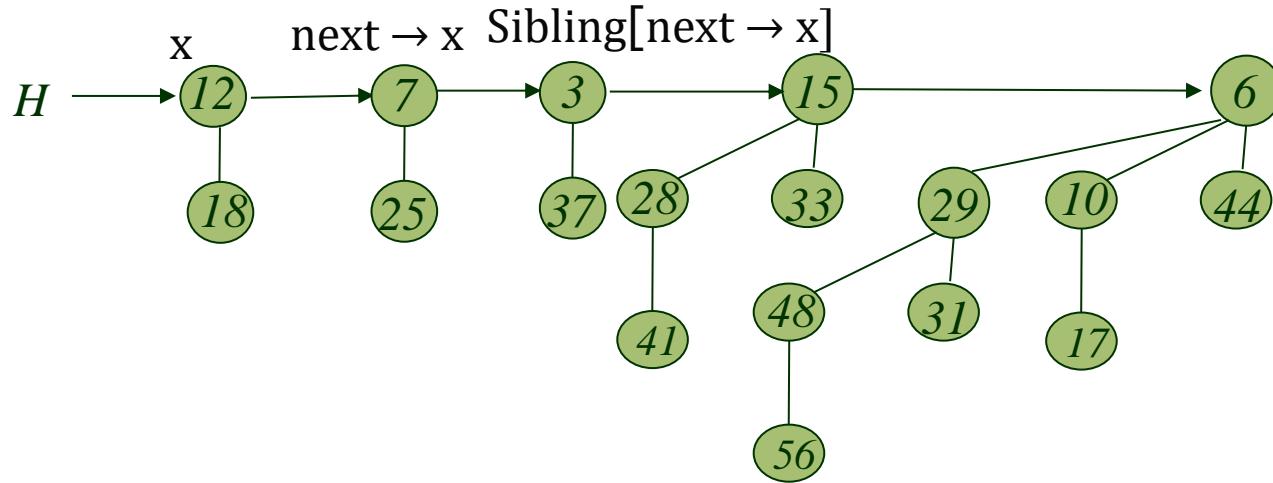
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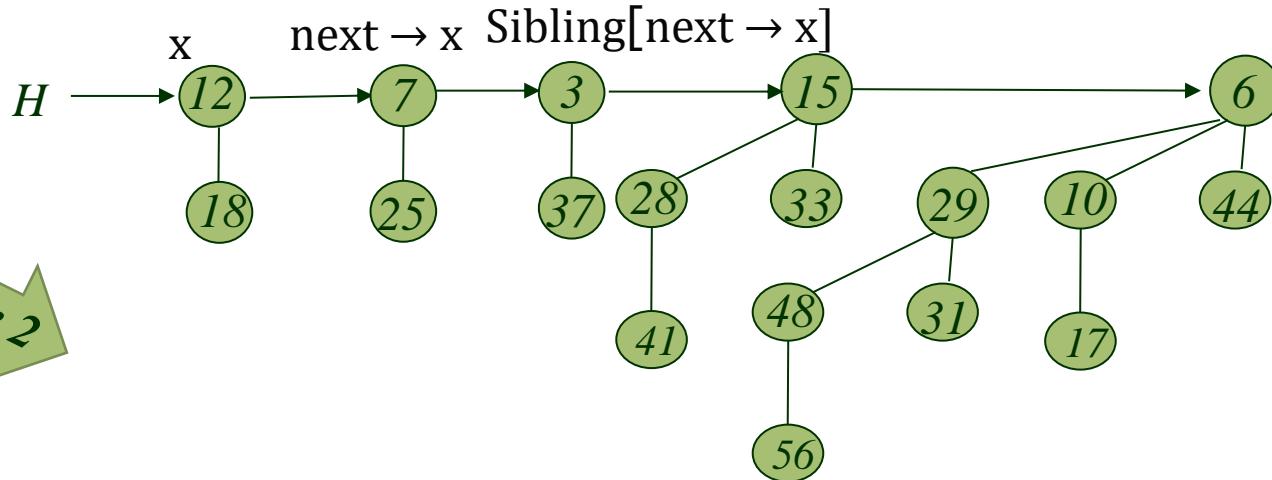
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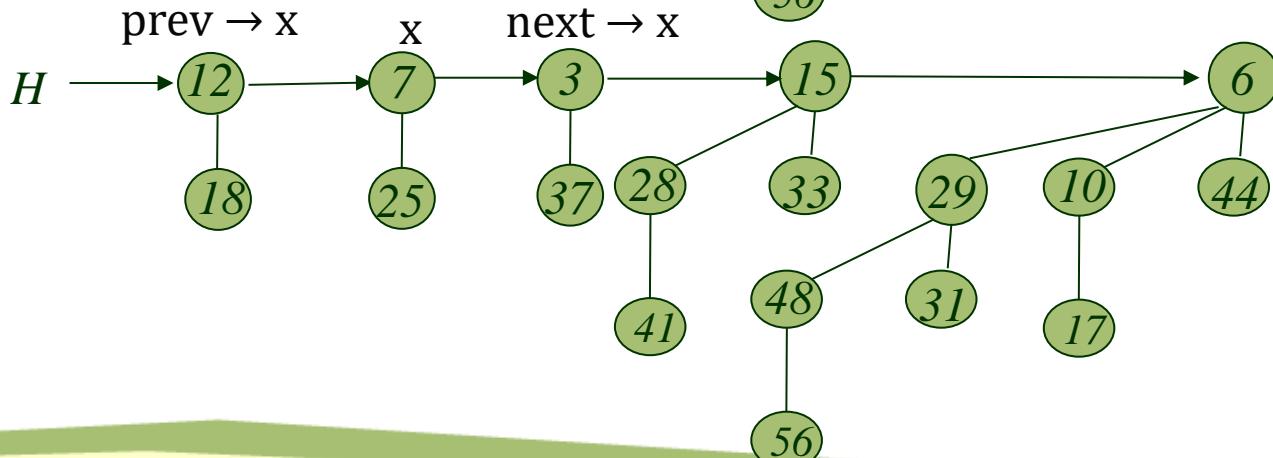
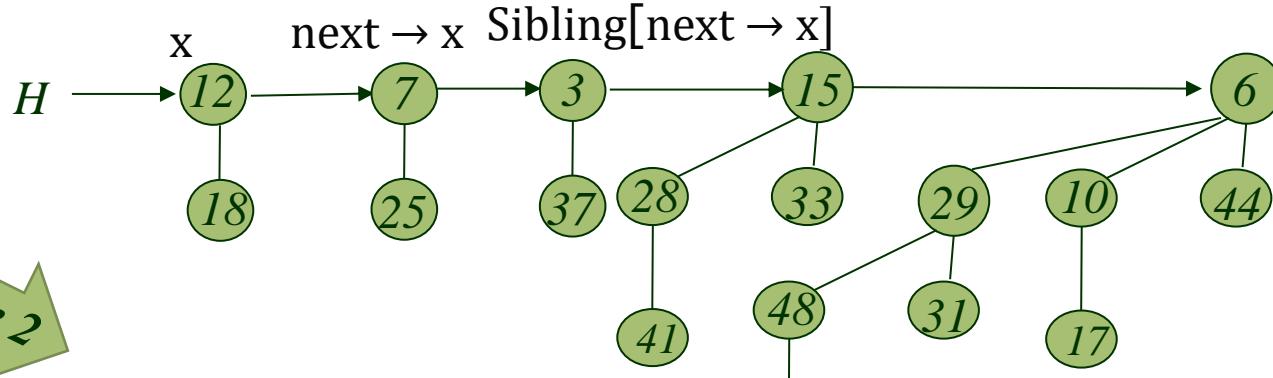
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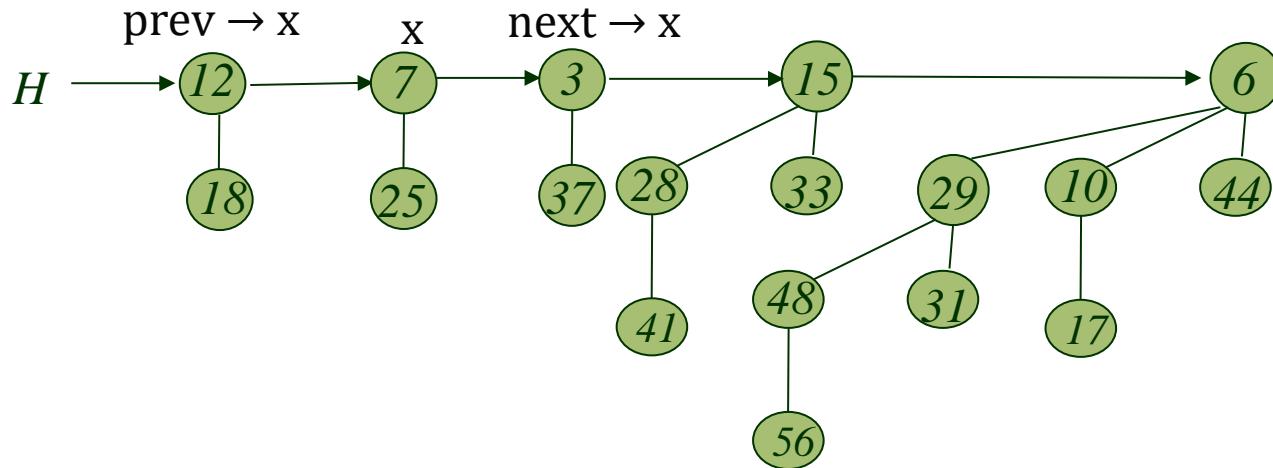
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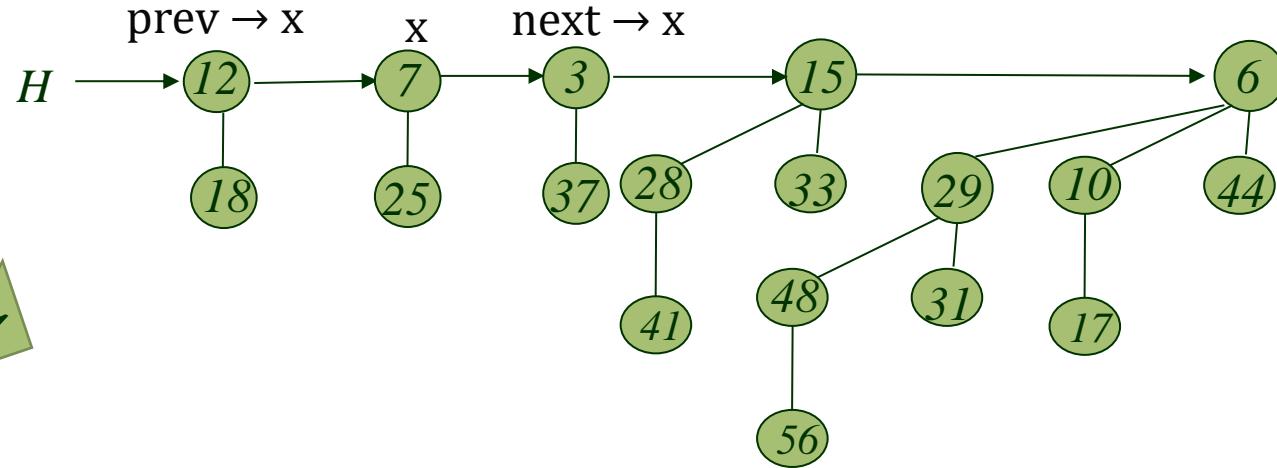
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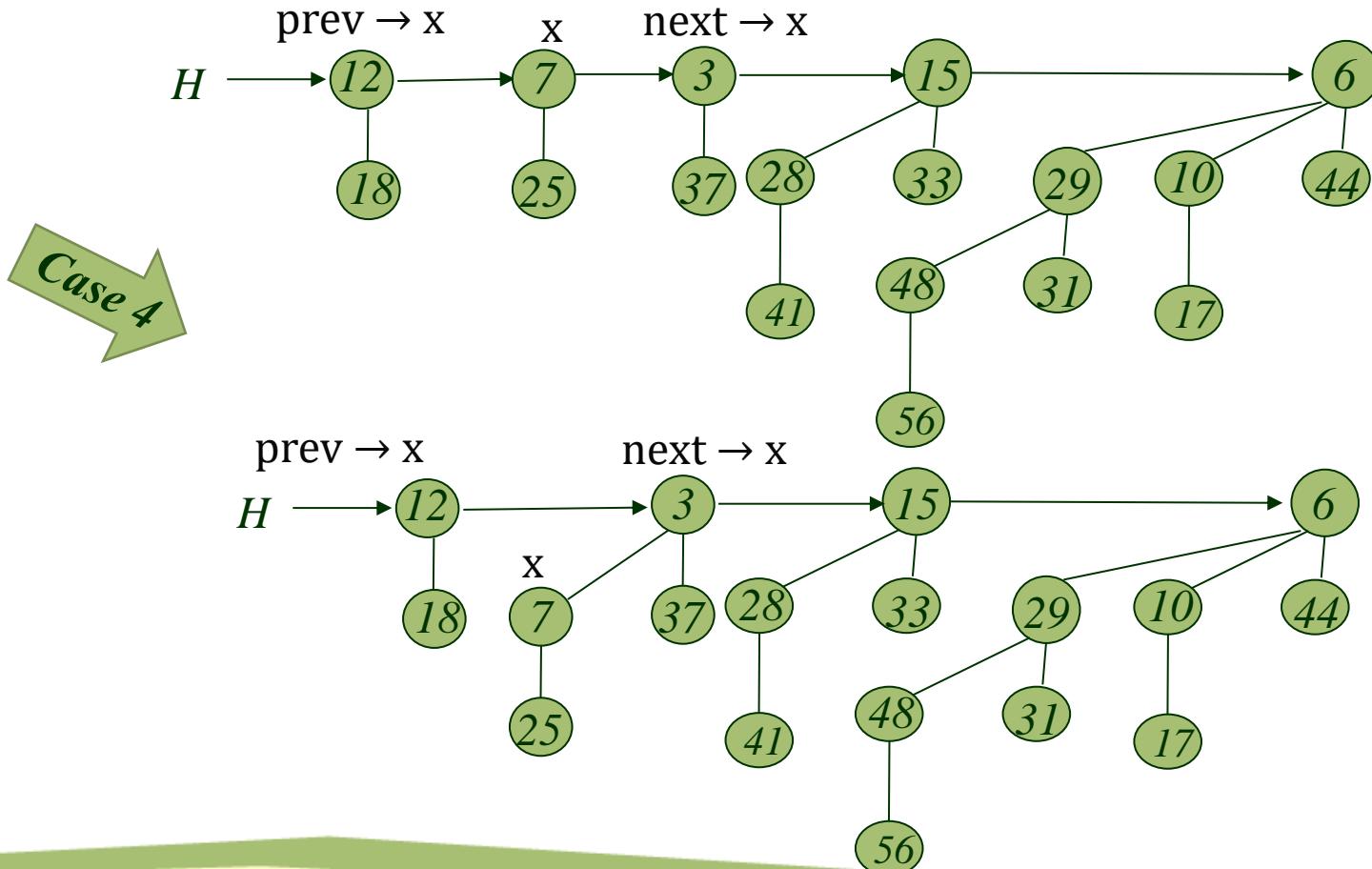
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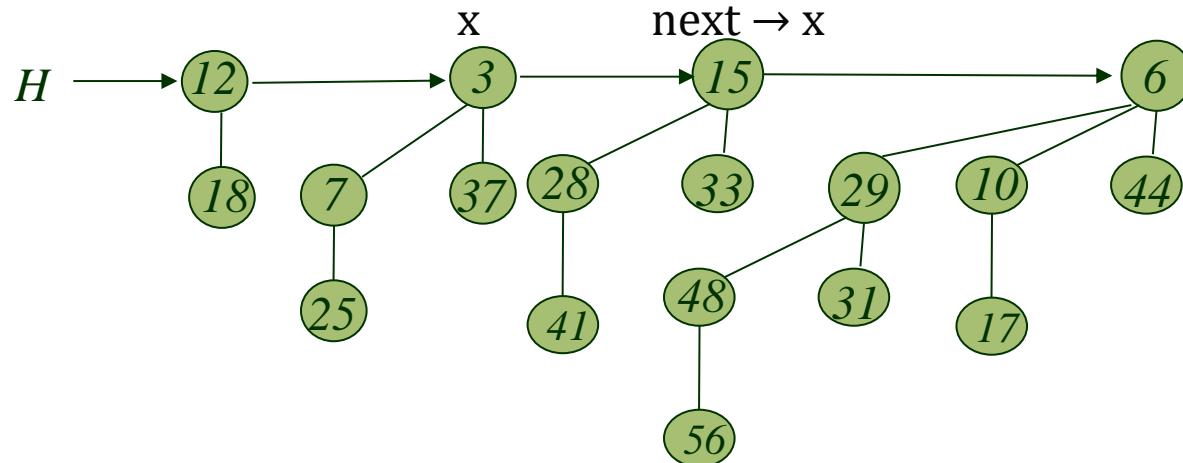
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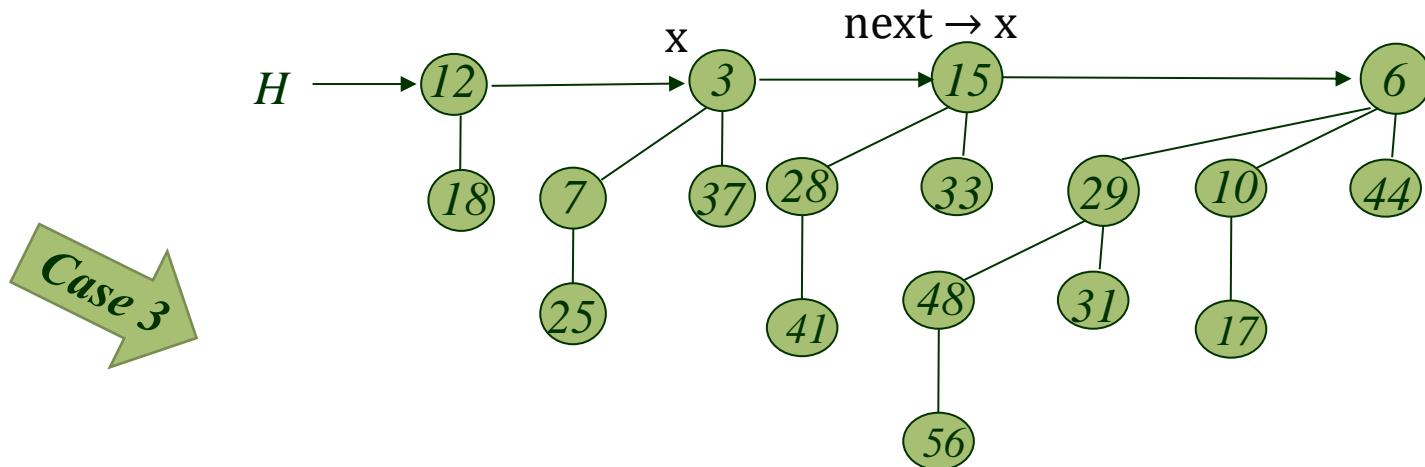
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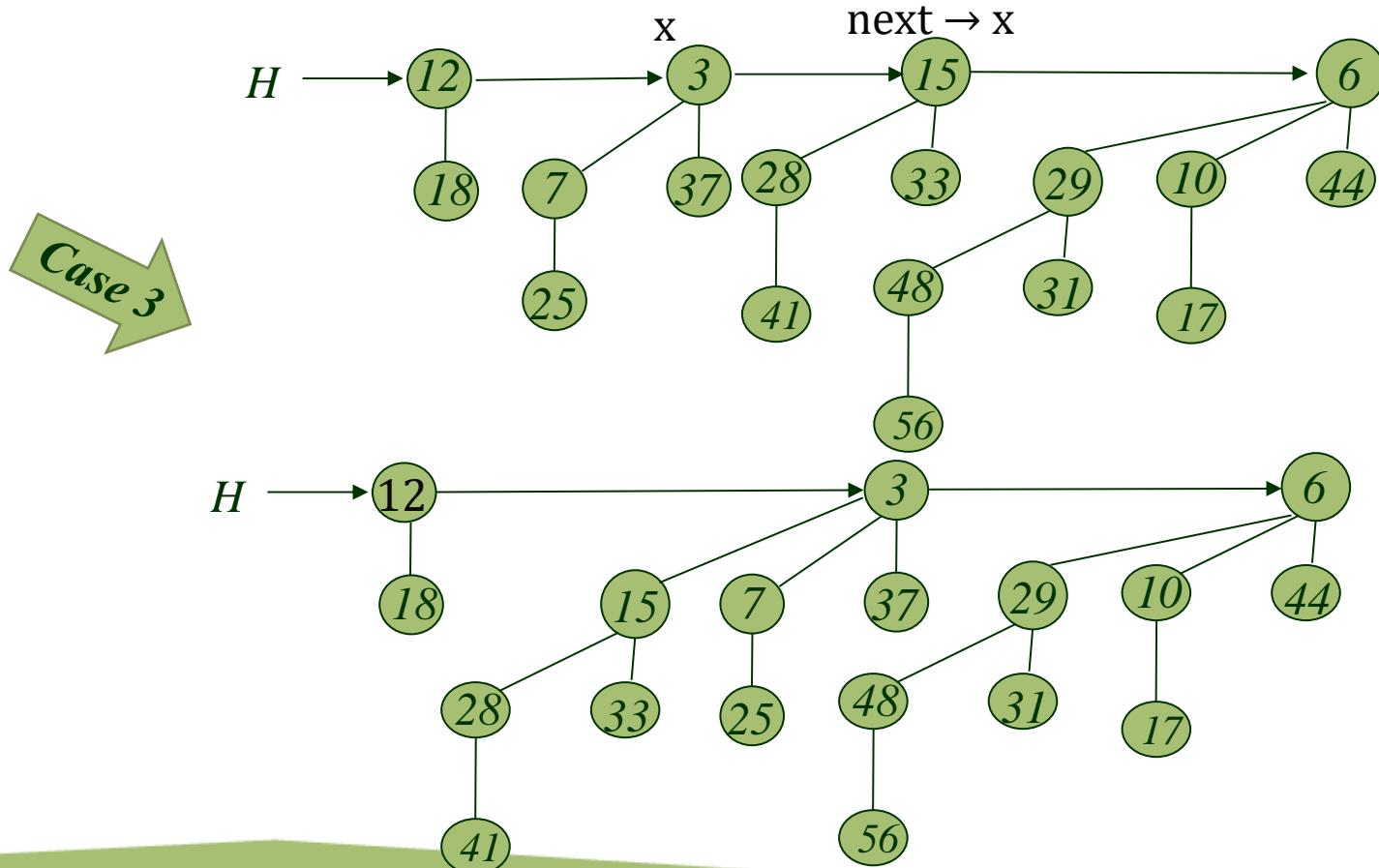
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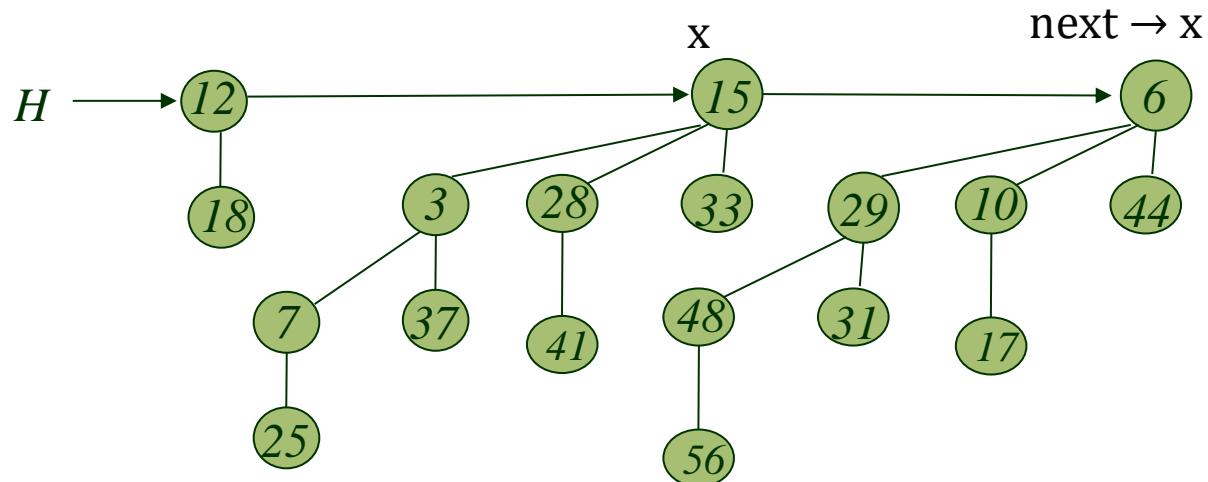
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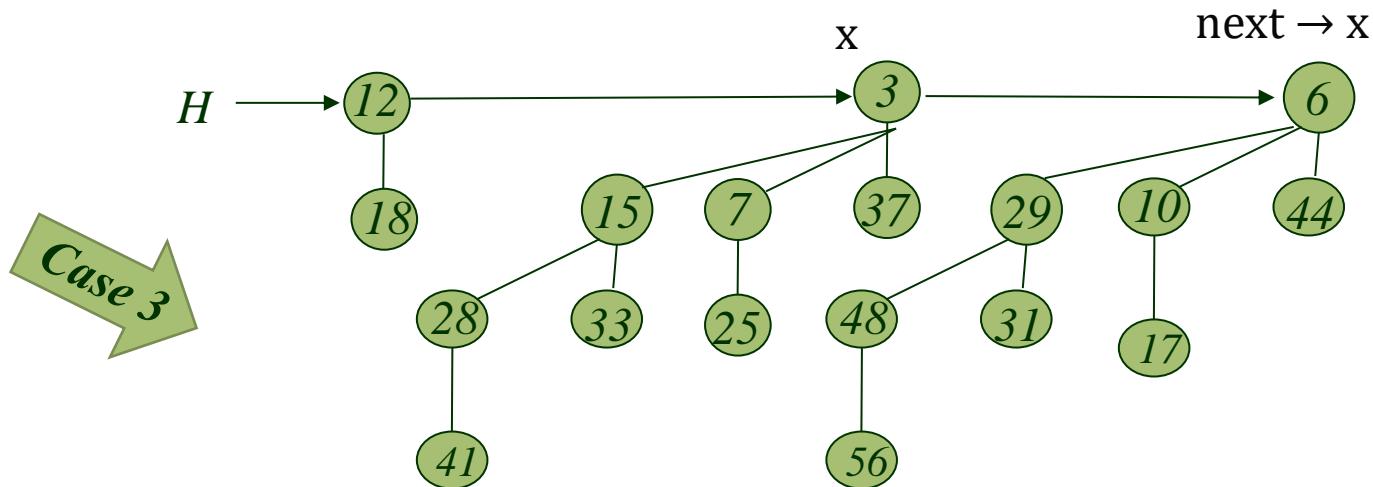
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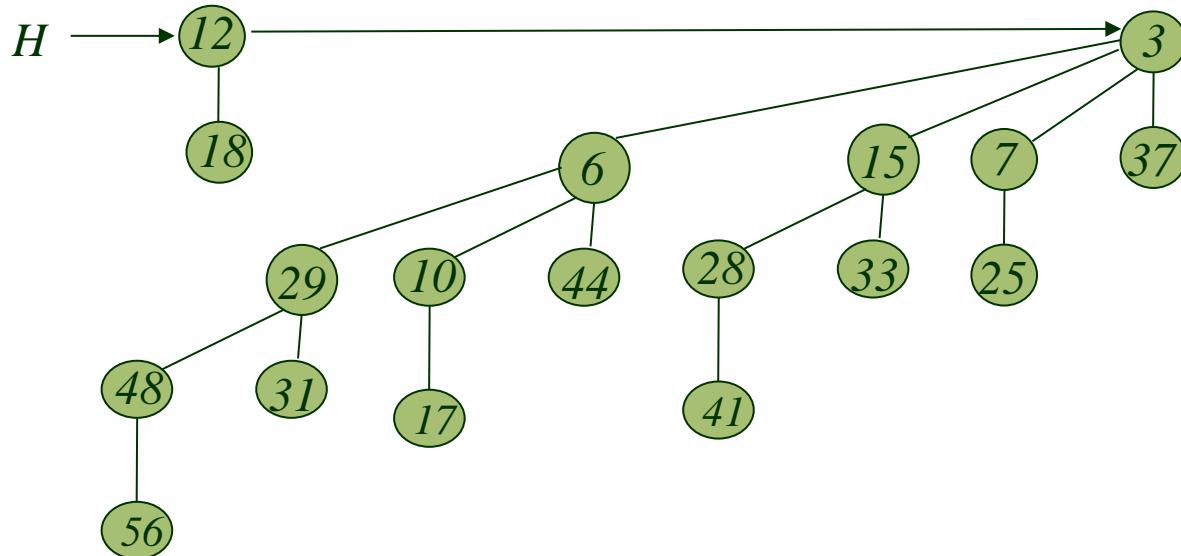
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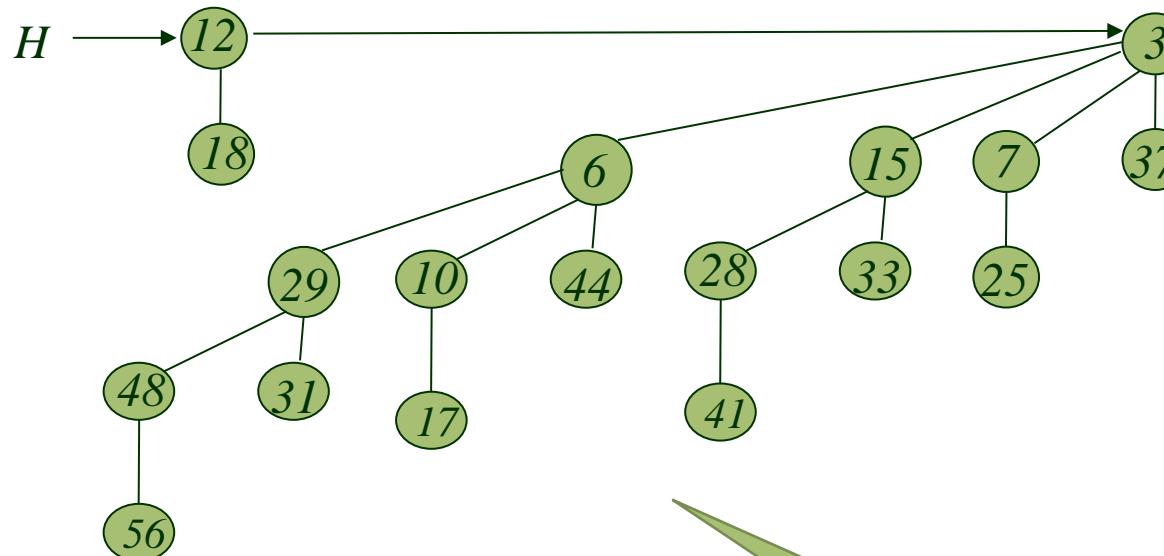
# Binomial Heap (Operations\_3)

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# Binomial Heap (Operations\_3)

Example 1: Merge the following two Binomial heap H1 and H2.



Final  
Binomial  
Heap Tree

# Binomial Heap (Operations\_3)

BINOMIAL-HEAP-UNION(H1, H2)

- 1 H = MAKE-BINOMIAL-HEAP()
- 2 head[H] = BINOMIAL-HEAP-MERGE(H1, H2)
- 3 free the objects H1 and H2 but not the lists they point to
- 4 if head[H] = NIL
- 5     then return H
- 6 prev-x  $\leftarrow$  NIL
- 7 x  $\leftarrow$  head[H]
- 8 next-x  $\leftarrow$  sibling[x]

# Binomial Heap (Operations\_3)

```

9   while next-x ≠ NIL
10    do if (degree[x] ≠ degree[next-x]) or
11       ( sibling[next-x] ≠ NIL and degree[sibling[next-x]] = degree[x] )
12       then prev-x ← x                                ▷ Cases 1 and 2
13       x ← next-x                                  ▷ Cases 1 and 2
14     else if key[x] ≤ key[next-x]
15       then sibling[x] ← sibling[next-x]           ▷ Case 3
16       BINOMIAL-LINK(next-x, x)                   ▷ Case 3
17     else if prev-x = NIL                         ▷ Case 4
18       then head[H] ← next-x                     ▷ Case 4
19       else sibling[prev-x] ← next-x             ▷ Case 4
20       BINOMIAL-LINK(x, next-x)                 ▷ Case 4
21       x ← next-x                               ▷ Case 4
22   next-x ← sibling[x]
23 return H

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# Binomial Heap (Operations\_3)

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19       BINOMIAL-LINK(x, next-x)                  ▷ Case 4
20       x ← next-x                               ▷ Case 4
21   next-x ← sibling[x]
22 return H
```

# Binomial Heap (Operations\_3)

Analysis of BINOMIAL-HEAP-UNION( $H_1, H_2$ )

The running time of BINOMIAL-HEAP-UNION is  $O(\lg n)$ , where  $n$  is the total number of nodes in binomial heaps  $H_1$  and  $H_2$ .

We can see this as follows.

- Let  $H_1$  contain  $n_1$  nodes and  $H_2$  contain  $n_2$  nodes,  
Hence,  $n = n_1 + n_2$ .
- Then  $H_1$  contains at most  $\lfloor \lg n_1 \rfloor + 1$  roots.
- and  $H_2$  contains at most  $\lfloor \lg n_2 \rfloor + 1$  roots,
- Hence  $H$  contains at most  $\lfloor \lg n_1 \rfloor + \lfloor \lg n_2 \rfloor + 2 \leq 2\lfloor \lg n \rfloor + 2 = O(\lg n)$  roots immediately after the call of BINOMIAL-HEAP-MERGE.
- The time required to perform BINOMIAL-HEAP-MERGE is thus  $O(\lg n)$ .

# Binomial Heap (Operations\_3)

Analysis of BINOMIAL-HEAP-UNION( $H_1, H_2$ )

- Each iteration of the while loop takes  $O(1)$  time, and there are at most  $\lfloor \lg n_1 \rfloor + \lfloor \lg n_2 \rfloor + 2$  iterations.  
(because each iteration either advances the pointers one position down the root list of  $H$  or removes a root from the root list. )
- Hence the total time required to execute BINOMIAL-HEAP-UNION is  $O(\lg n)$ .

# Binomial Heap (Operations\_4)

## 4. EXTRACT-MIN(H)

The following procedure extracts the node with the minimum key from binomial heap H and returns a pointer to the extracted node.

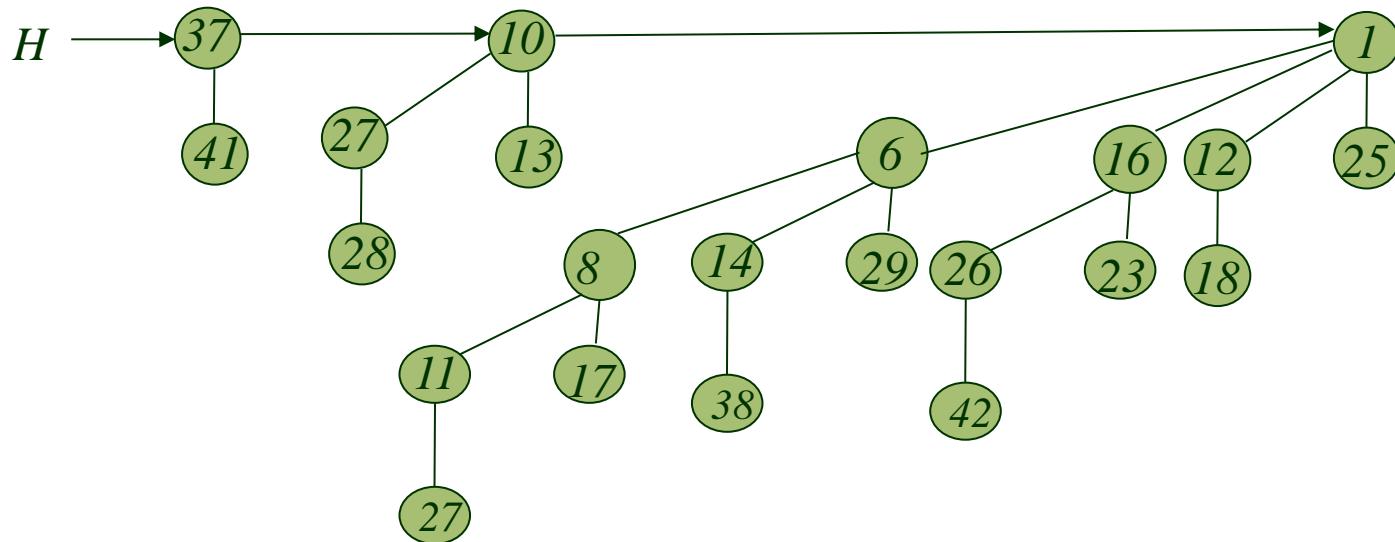
### BINOMIAL-HEAP-EXTRACT-MIN(H)

- 1 find the root x with the minimum key in the root list of H,  
and remove x from the root list of H
- 2  $H' \leftarrow$  call MAKE-BINOMIAL-HEAP()
- 3 reverse the order of the linked list of x's children, and set  
 $\text{head}[H']$  to point to the head of the resulting list
- 4  $H \leftarrow$  call BINOMIAL-HEAP-UNION(H, H')
- 5 return x

# Binomial Heap (Operations\_4)

**Example:**

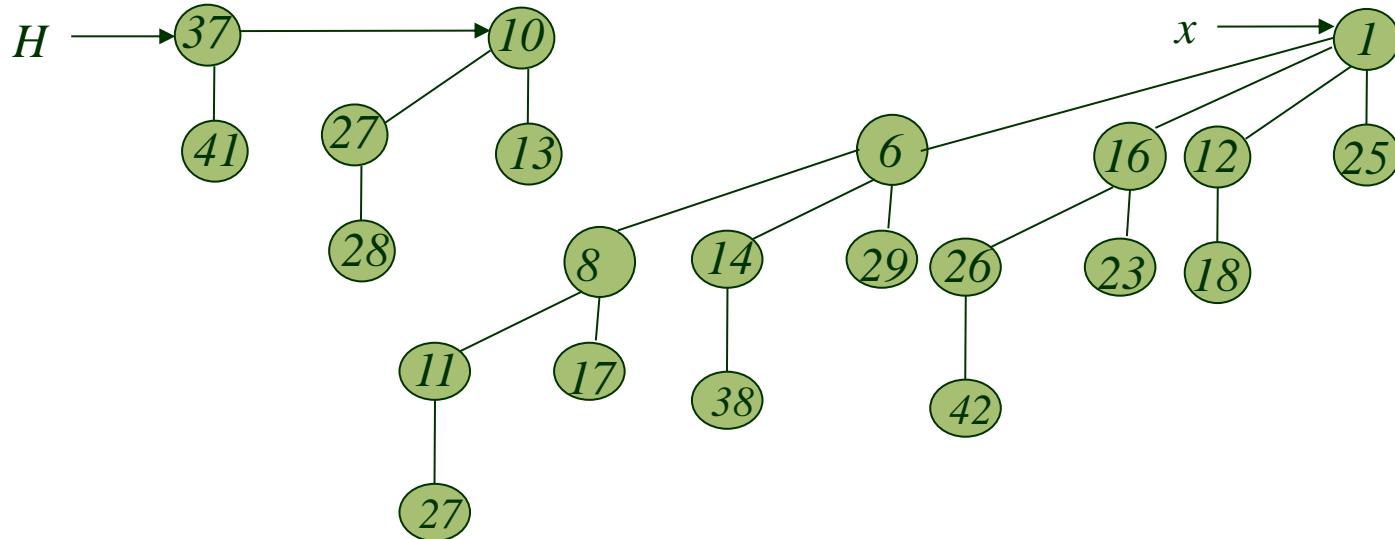
Extract the node with minimum key from following Binomial Heap.



# Binomial Heap (Operations\_4)

Example:

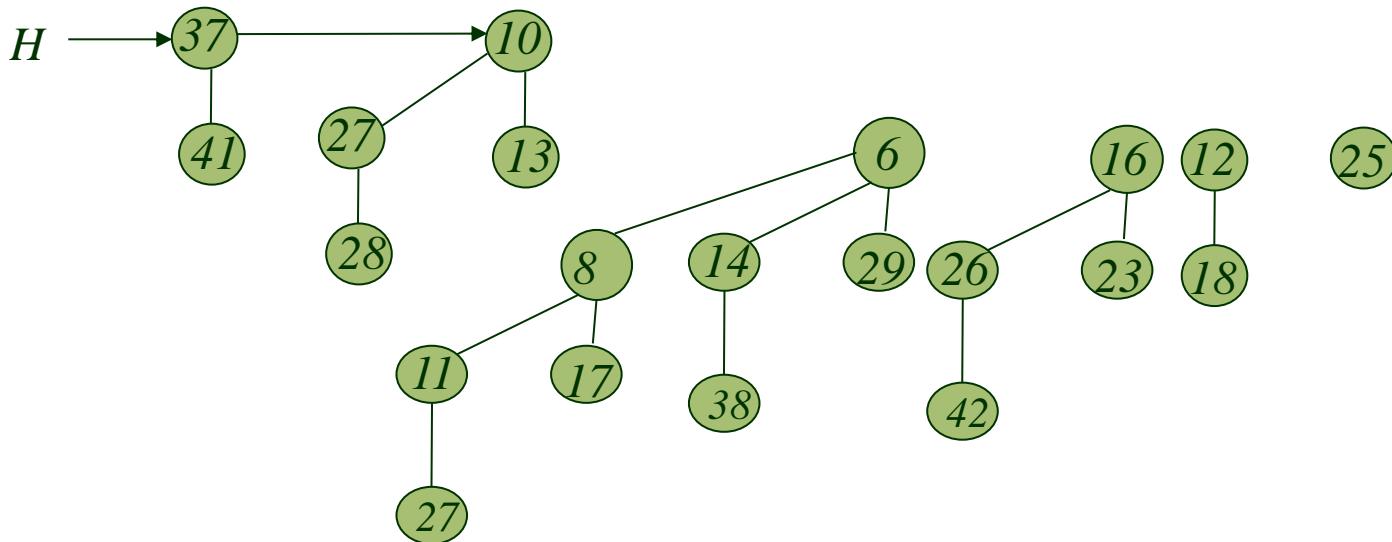
Hear minimum is 1(i.e. x), so remove it



# Binomial Heap (Operations\_4)

Example:

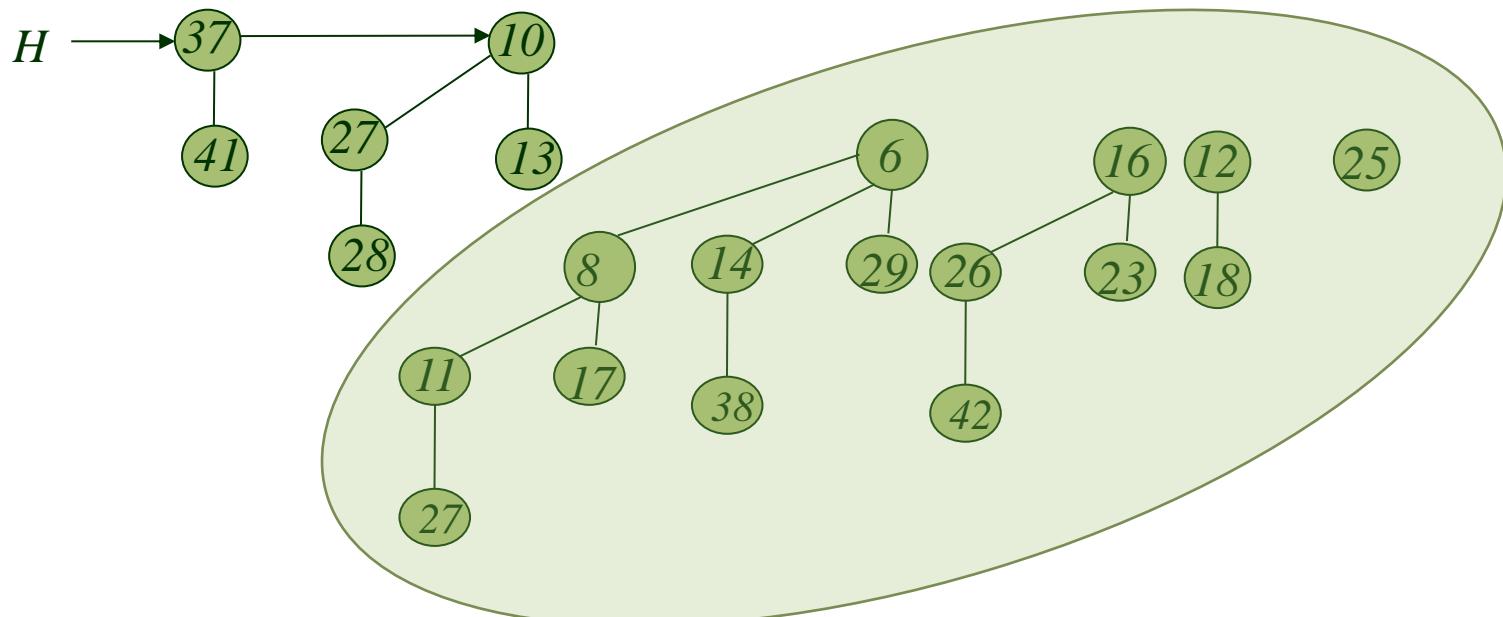
Hear minimum is 1(i.e. x), so remove it



# Binomial Heap (Operations\_4)

Example:

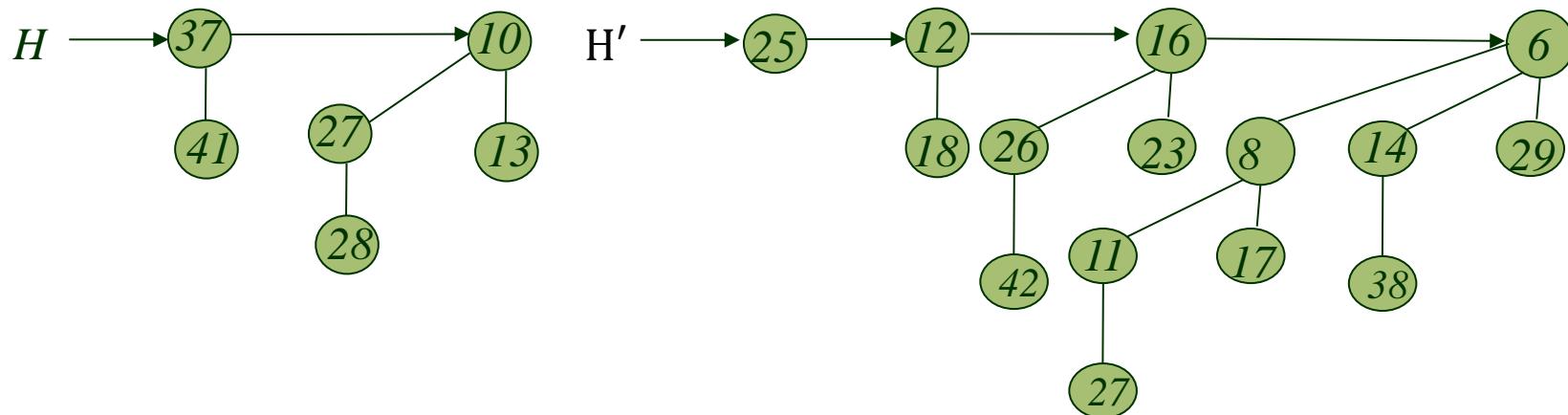
Here minimum is 1(i.e. x), so remove it



# Binomial Heap (Operations\_4)

Example:

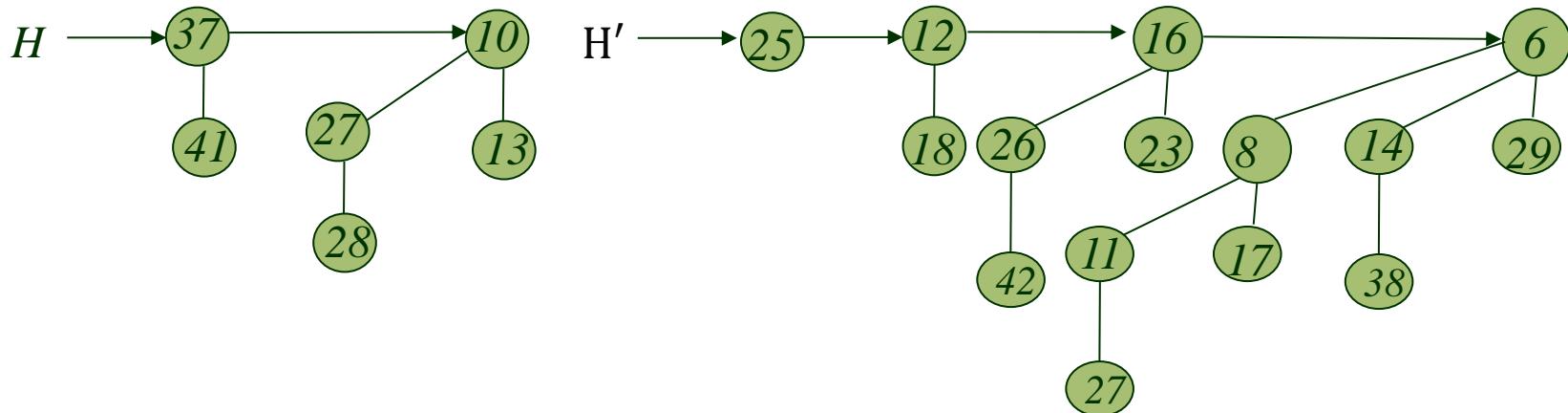
After remove x reverse the order of the list and put it in H'



# Binomial Heap (Operations\_4)

Example:

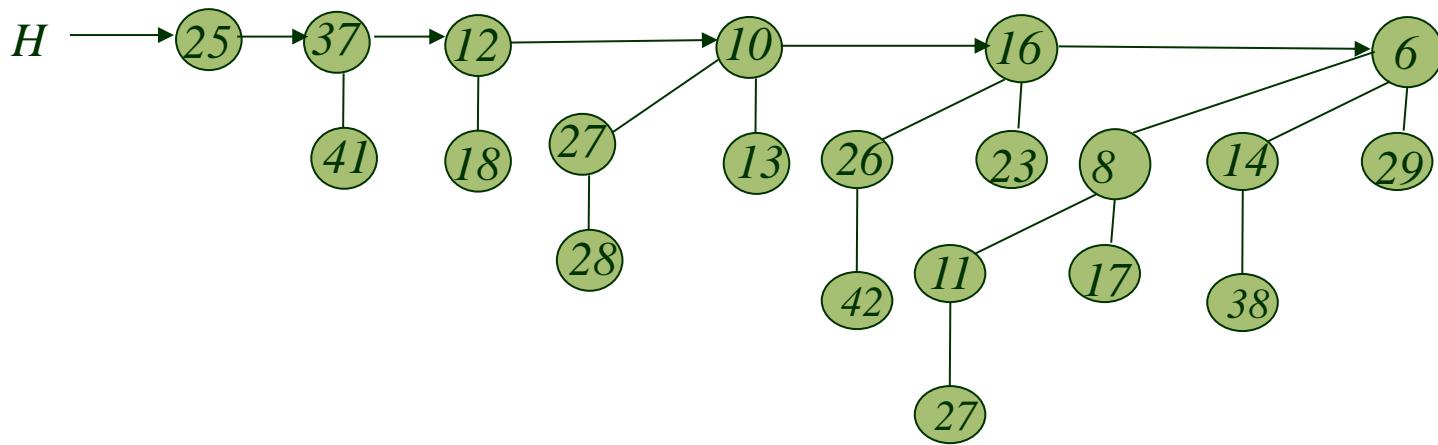
Apply BINOMIAL-HEAP-UNION( $H$ ,  $H'$ ) on the following two Binomial Heap



# Binomial Heap (Operations\_4)

Example:

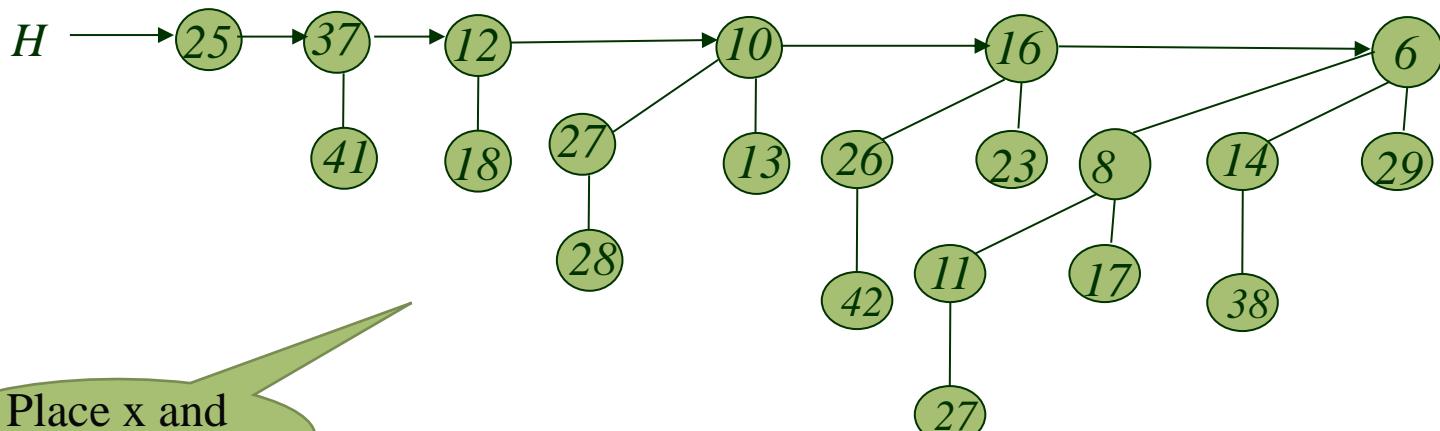
After merging of two binomial heap H and H'



# Binomial Heap (Operations\_4)

Example:

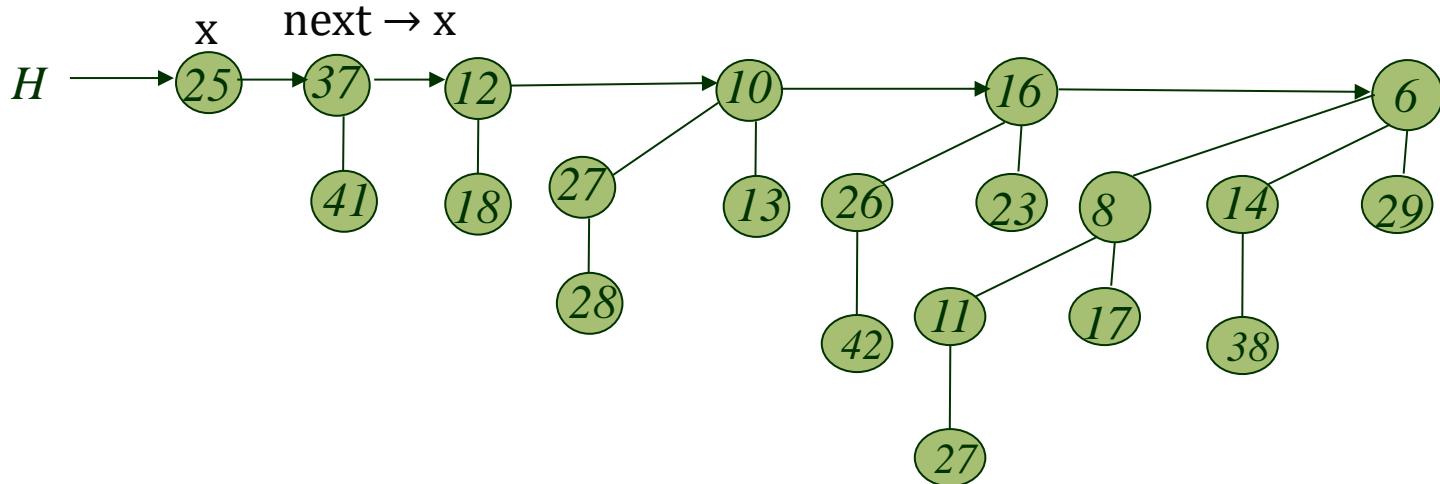
After merging of two binomial heap H and H'



# Binomial Heap (Operations\_4)

Example:

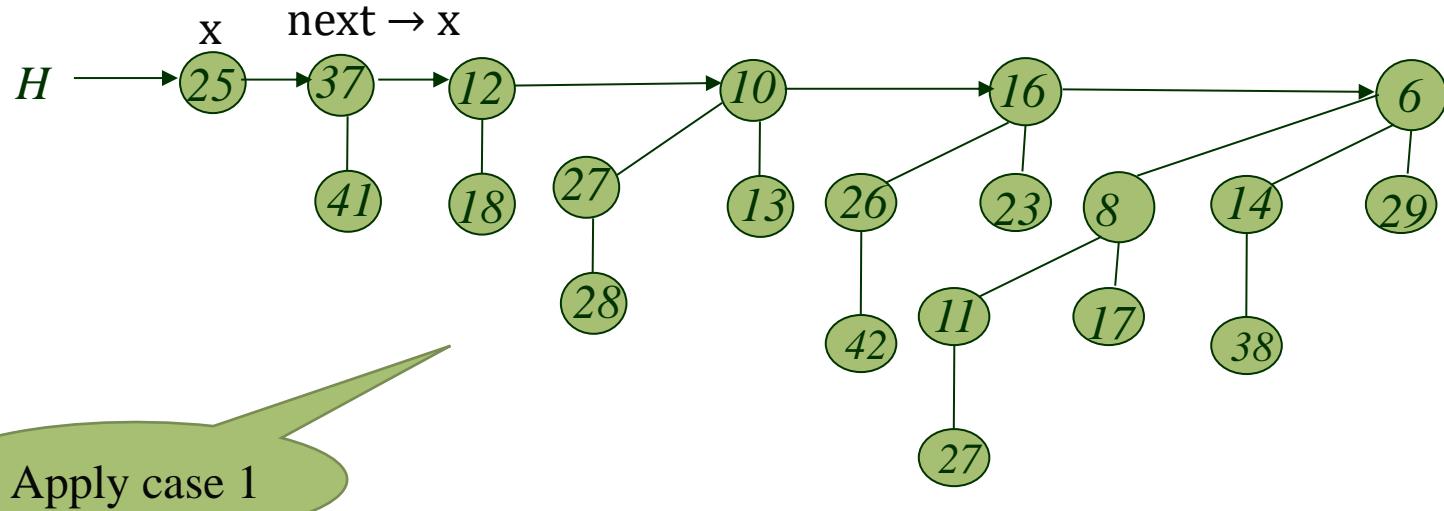
After placing x and next → x



# Binomial Heap (Operations\_4)

Example:

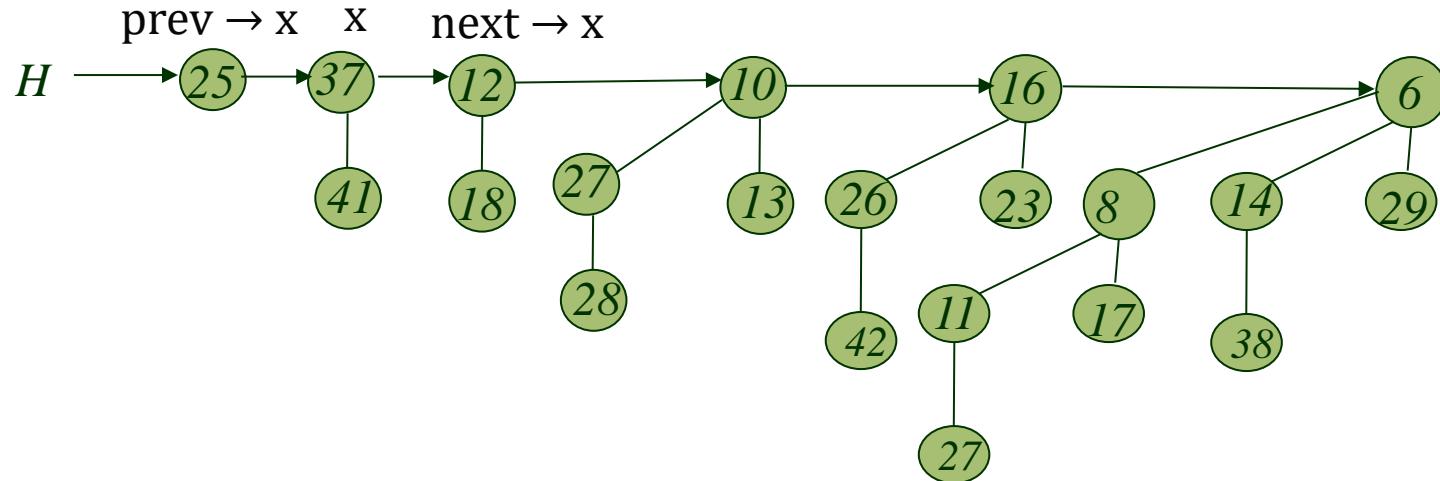
After placing x and next → x



# Binomial Heap (Operations\_4)

Example:

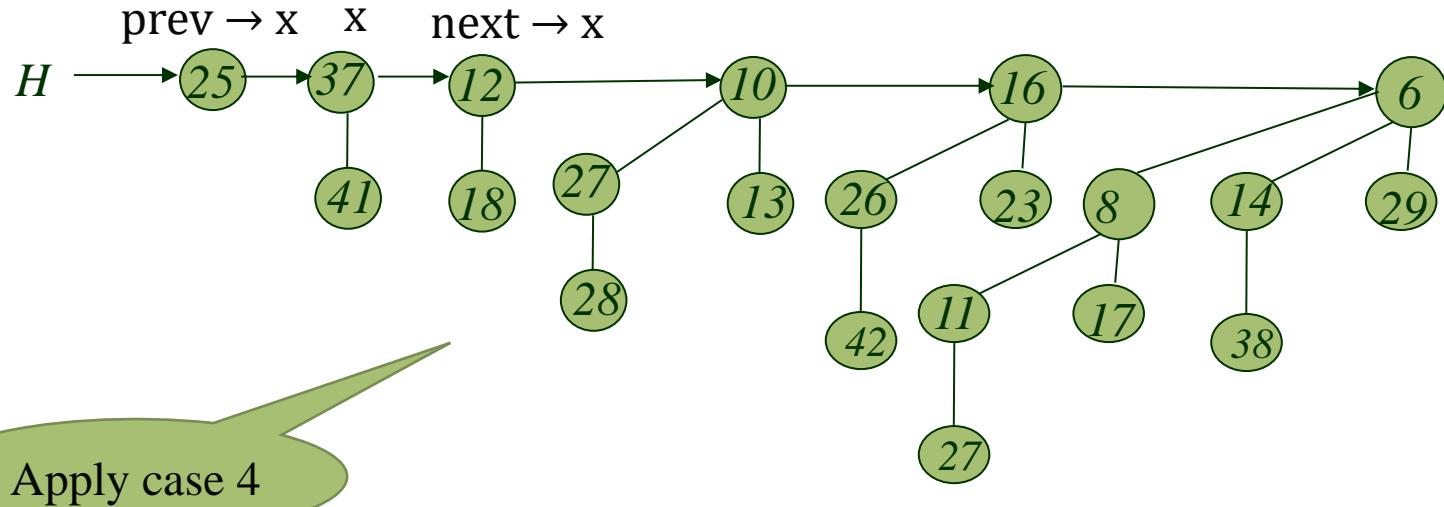
After applying case 1



# Binomial Heap (Operations\_4)

Example:

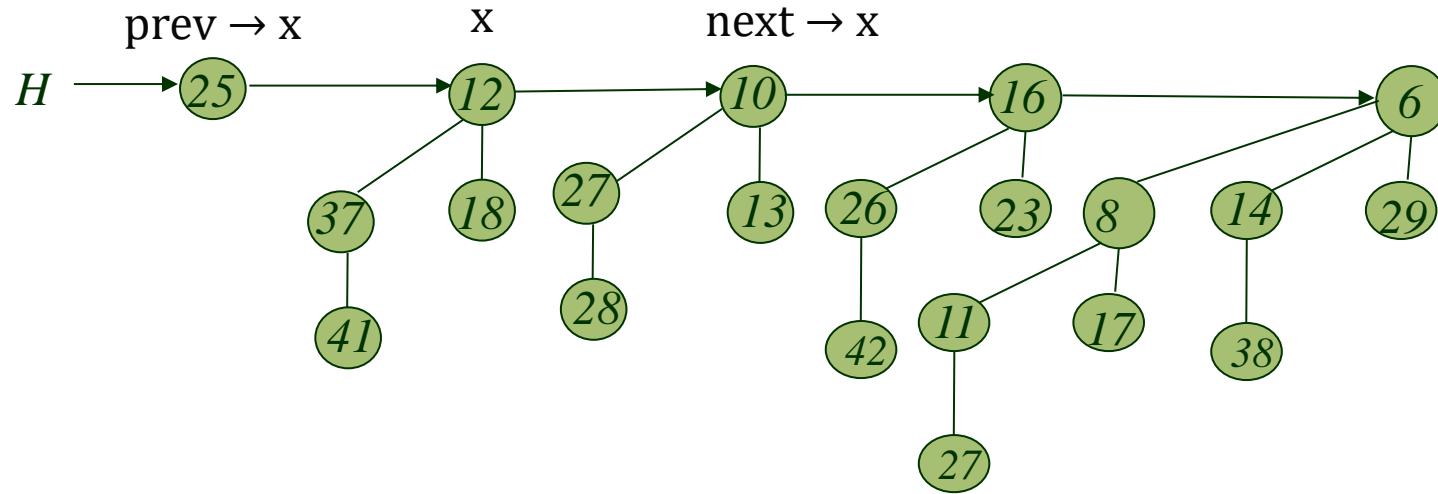
After applying case 1



# Binomial Heap (Operations\_4)

Example:

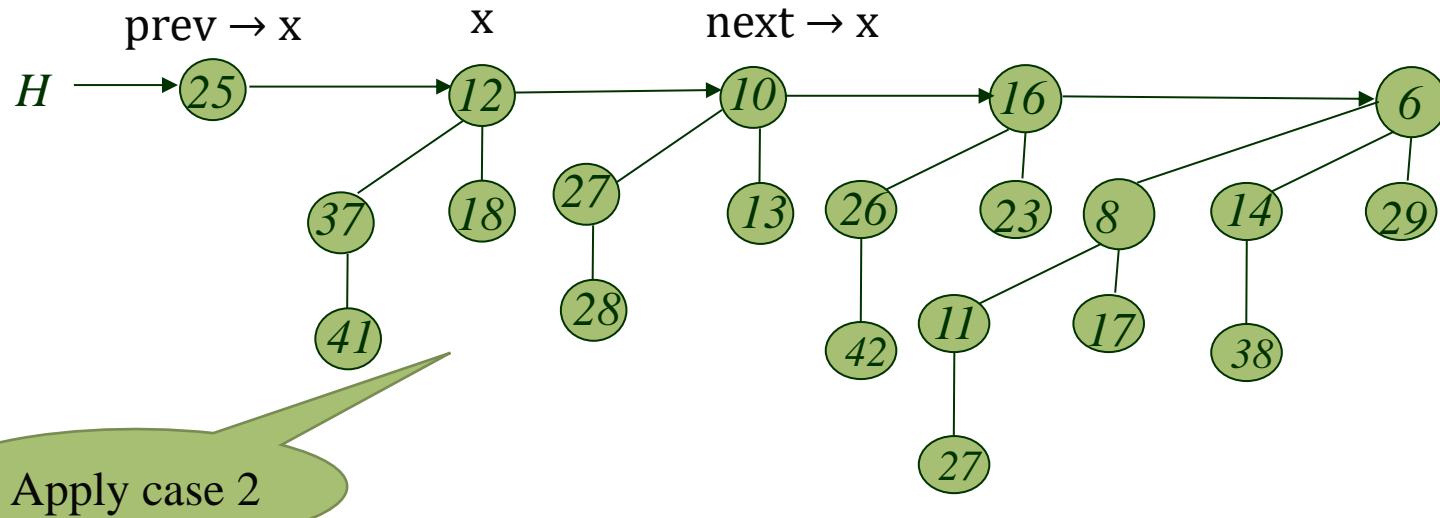
After applying case 4



# Binomial Heap (Operations\_4)

Example:

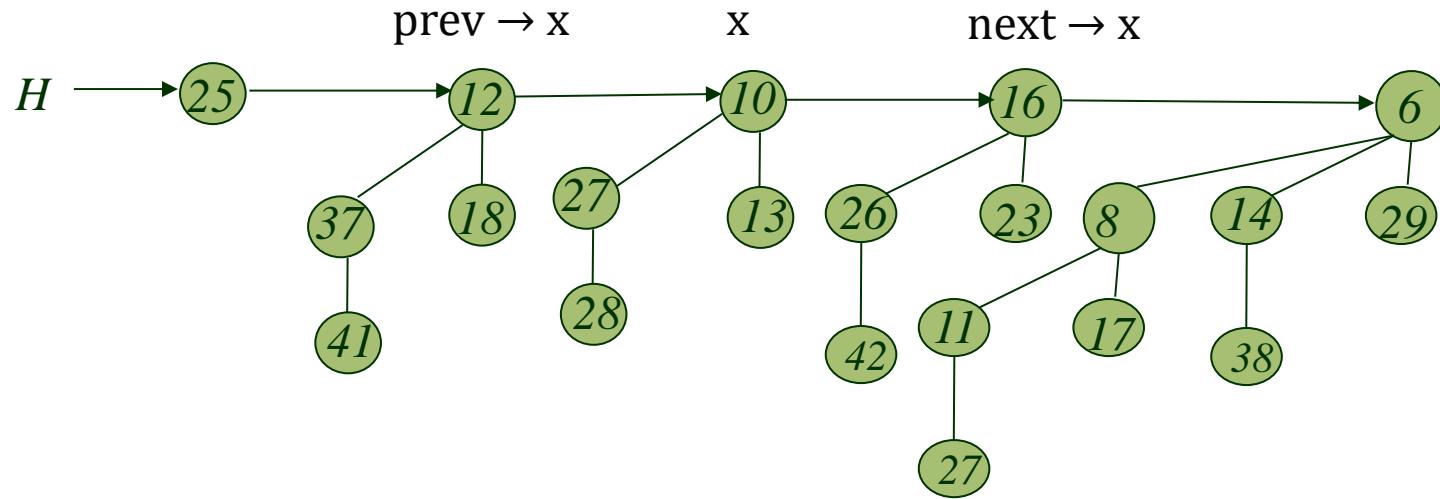
After applying case 4



# Binomial Heap (Operations\_4)

Example:

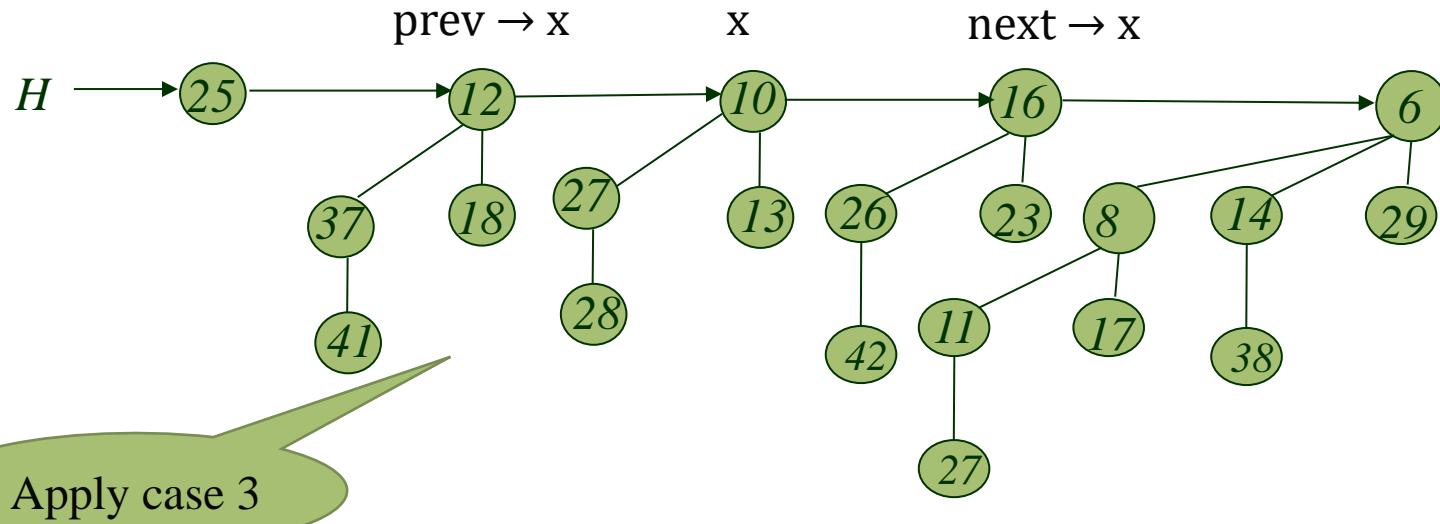
After applying case 2



# Binomial Heap (Operations\_4)

Example:

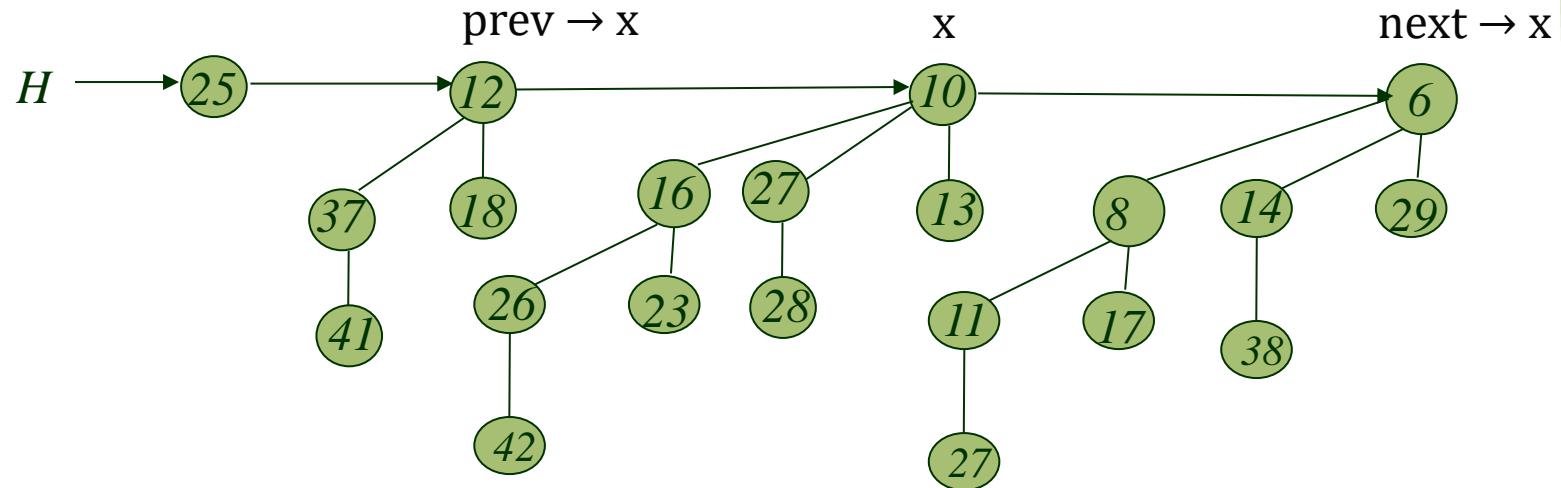
After applying case 2



# Binomial Heap (Operations\_4)

Example:

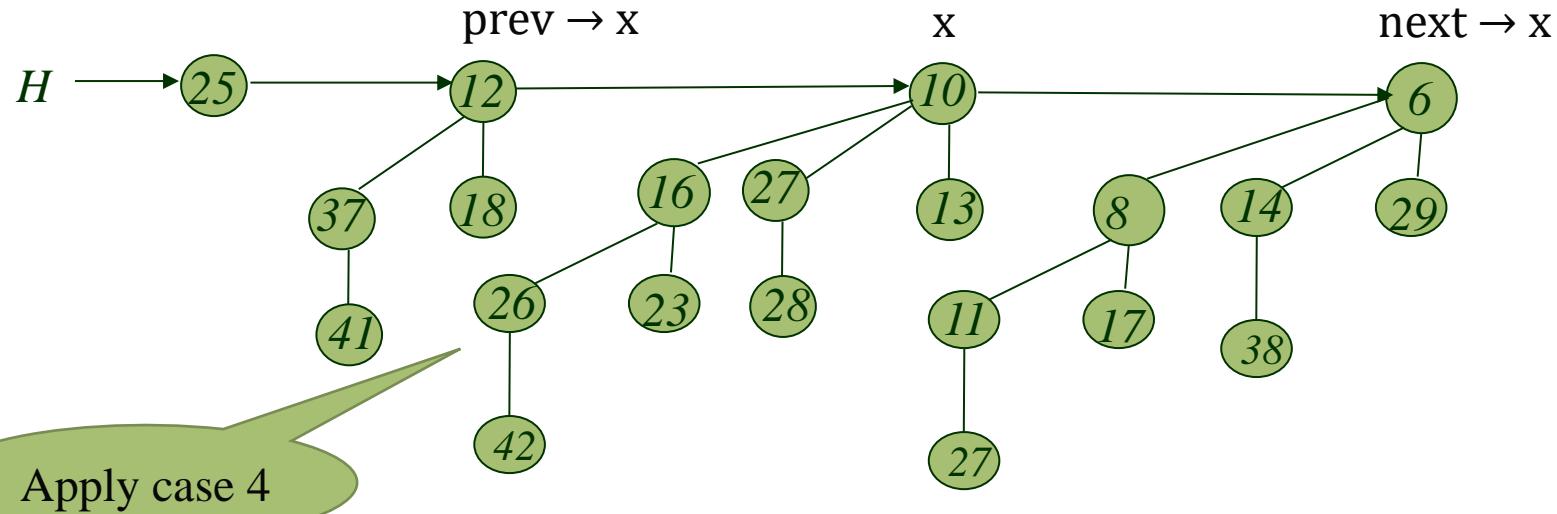
After applying case 3



# Binomial Heap (Operations\_4)

Example:

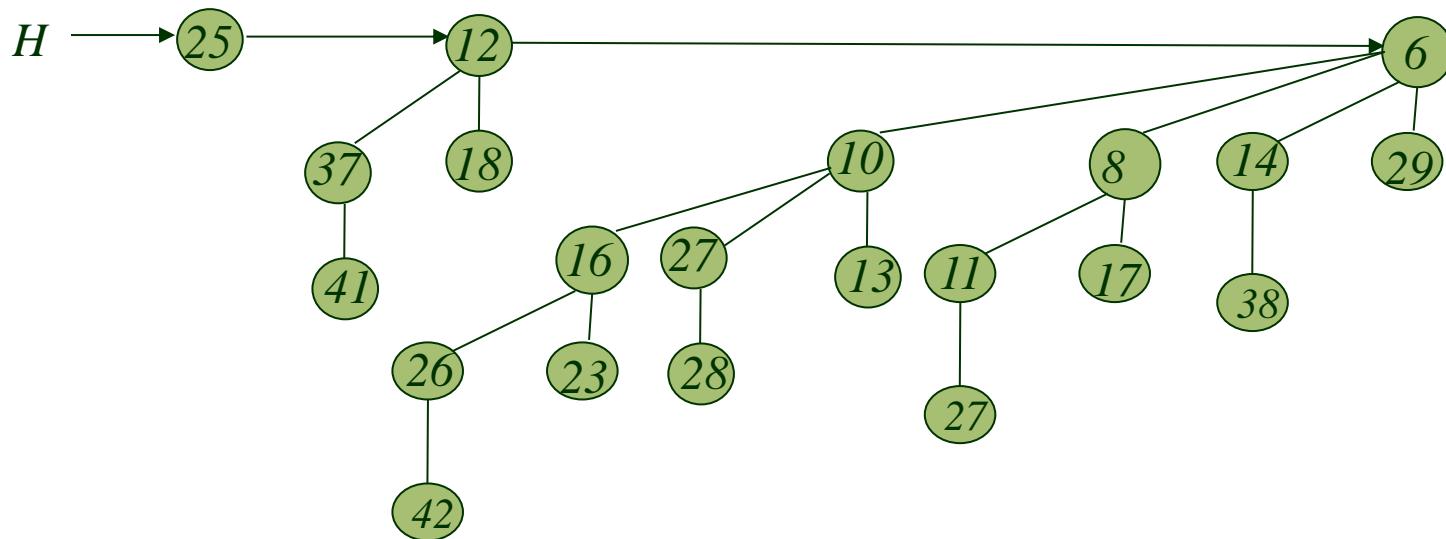
After applying case 3



# Binomial Heap (Operations\_4)

Example:

After applying case 4



# **Binomial Heap (Operations\_5)**

## **5. INSERT (H, x)**

The BINOMIAL-HEAP-INSERT procedure inserts node x into binomial heap H , assuming that x has already been allocated and key[x] has already been filled in.

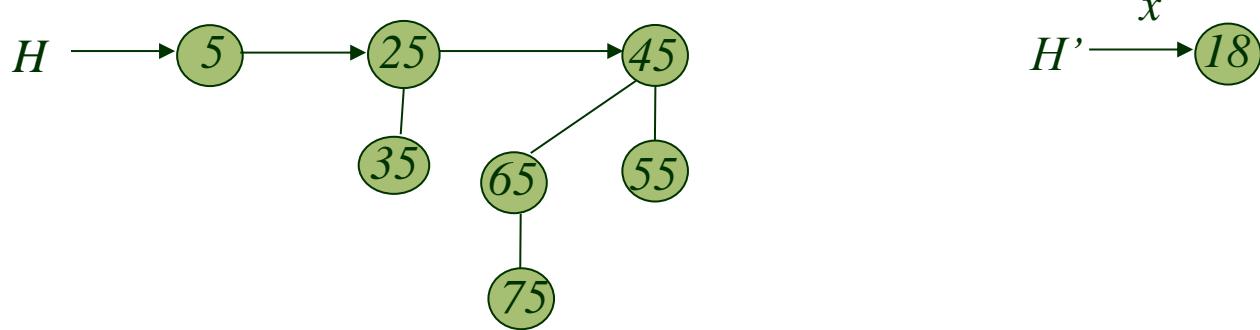
BINOMIAL-HEAP-INSERT(H, x)

- 1  $H' \leftarrow$  call MAKE-BINOMIAL-HEAP()
- 2  $p[x] \leftarrow$  NIL
- 3  $child[x] \leftarrow$  NIL
- 4  $sibling[x] \leftarrow$  NIL
- 5  $degree[x] \leftarrow 0$
- 6  $head[H'] \leftarrow x$
- 7  $H \leftarrow$  call BINOMIAL-HEAP-UNION(H, H')

# Binomial Heap (Operations\_5)

Example:

inserts node x into binomial heap H



# Binomial Heap (Operations\_5)

Example:

inserts node x into binomial heap H

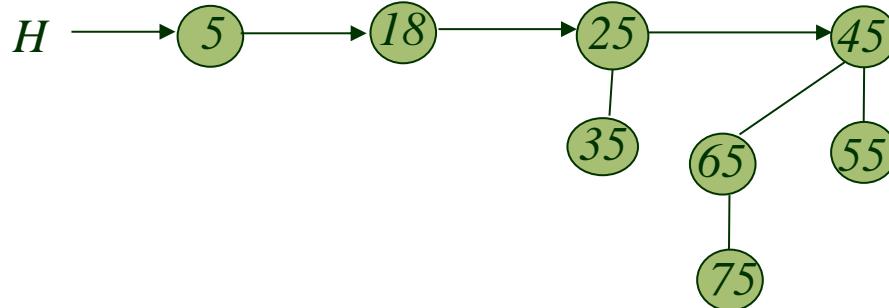


Apply Merge

# Binomial Heap (Operations\_5)

Example:

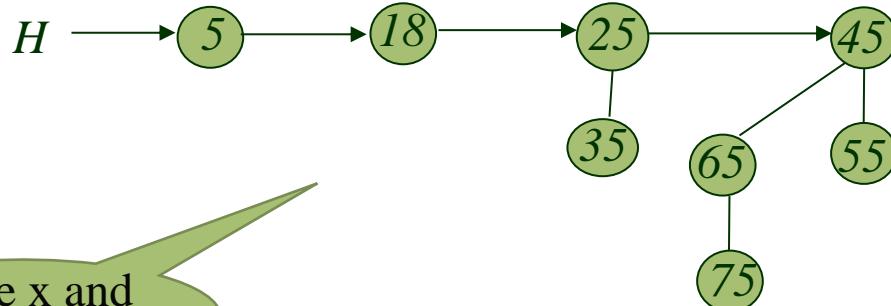
After Merging



# Binomial Heap (Operations\_5)

Example:

After Merging

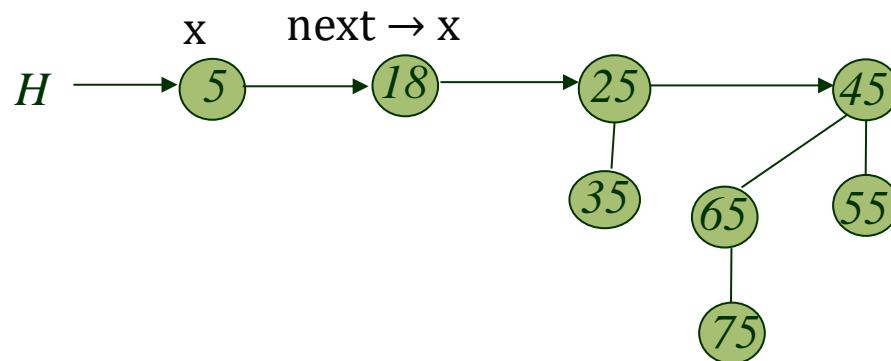


Place x and  
next → x

# Binomial Heap (Operations\_5)

Example:

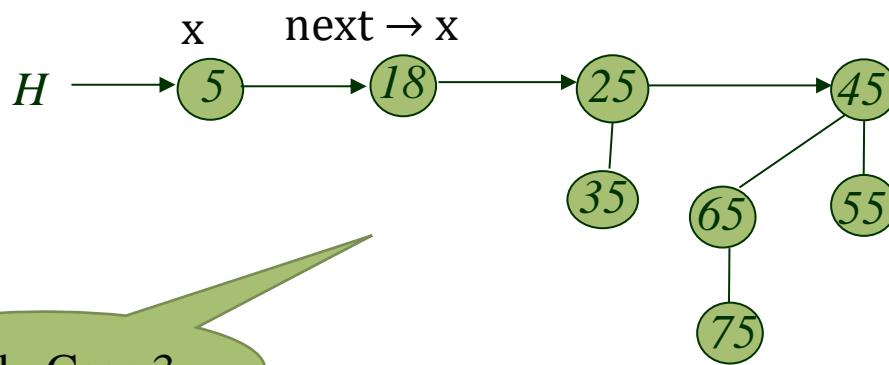
After placing x and next → x



# Binomial Heap (Operations\_5)

Example:

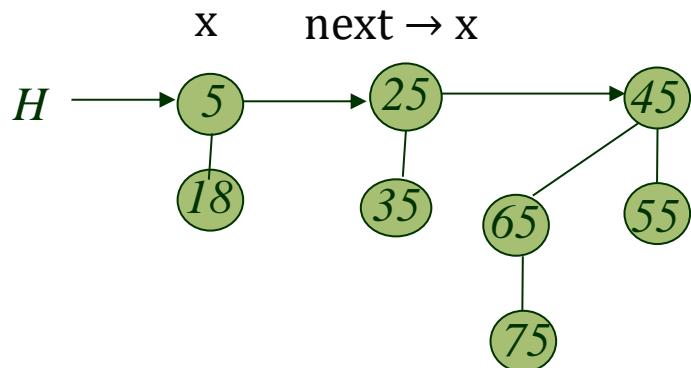
After placing x and next → x



# Binomial Heap (Operations\_5)

Example:

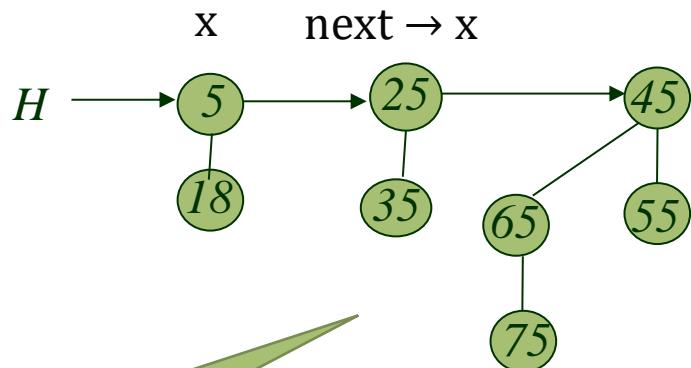
After applying case 3



# Binomial Heap (Operations\_5)

Example:

After applying case 3

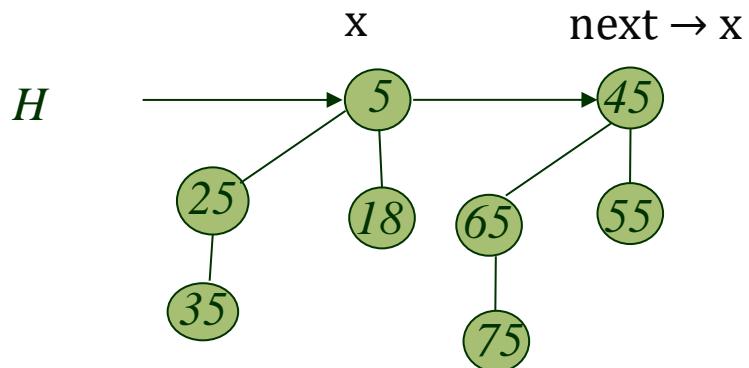


Apply Case 3

# Binomial Heap (Operations\_5)

Example:

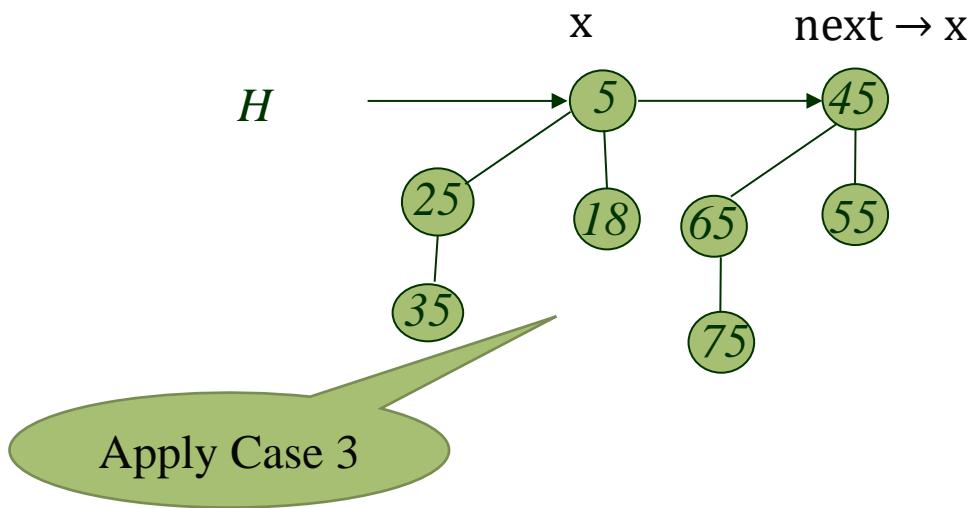
After applying case 3



# Binomial Heap (Operations\_5)

Example:

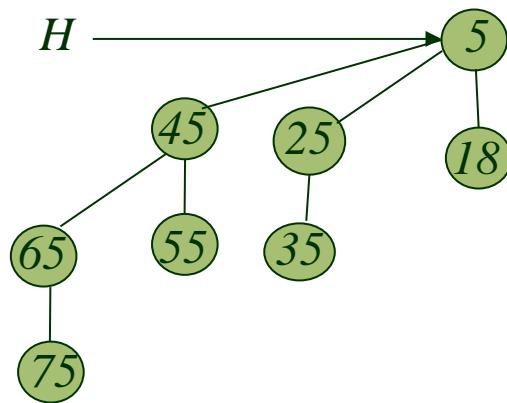
After applying case 3



# Binomial Heap (Operations\_5)

Example:

After applying case 3



# Binomial Heap (Operations\_6)

## 6. DECREASE KEY (H, x, k)

The DECREASE KEY procedure decreases the key of a node x in a binomial heap H to a new value k. It signals an error if k is greater than x's current key.

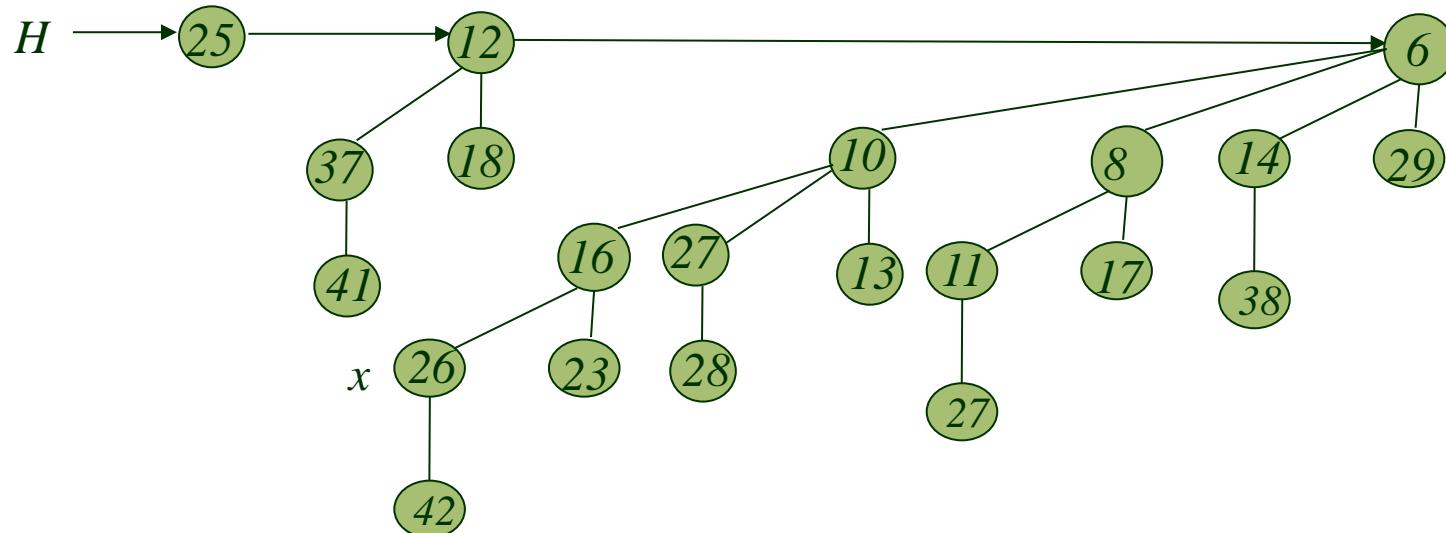
BINOMIAL-HEAP-DECREASE-KEY(H, x, k)

- 1    if  $k > \text{key}[x]$
- 2                then error "new key is greater than current key"
- 3     $\text{key}[x] \leftarrow k$
- 4     $y \leftarrow x$
- 5     $z \leftarrow p[y]$
- 6    while  $z \neq \text{NIL}$  and  $\text{key}[y] < \text{key}[z]$
- 7                do exchange  $\text{key}[y] \leftrightarrow \text{key}[z]$ 
  - 8                      ▶ If y and z have satellite fields, exchange them, too.
- 9                 $y \leftarrow z$
- 10                $z \leftarrow p[y]$

# Binomial Heap (Operations\_6)

Example:

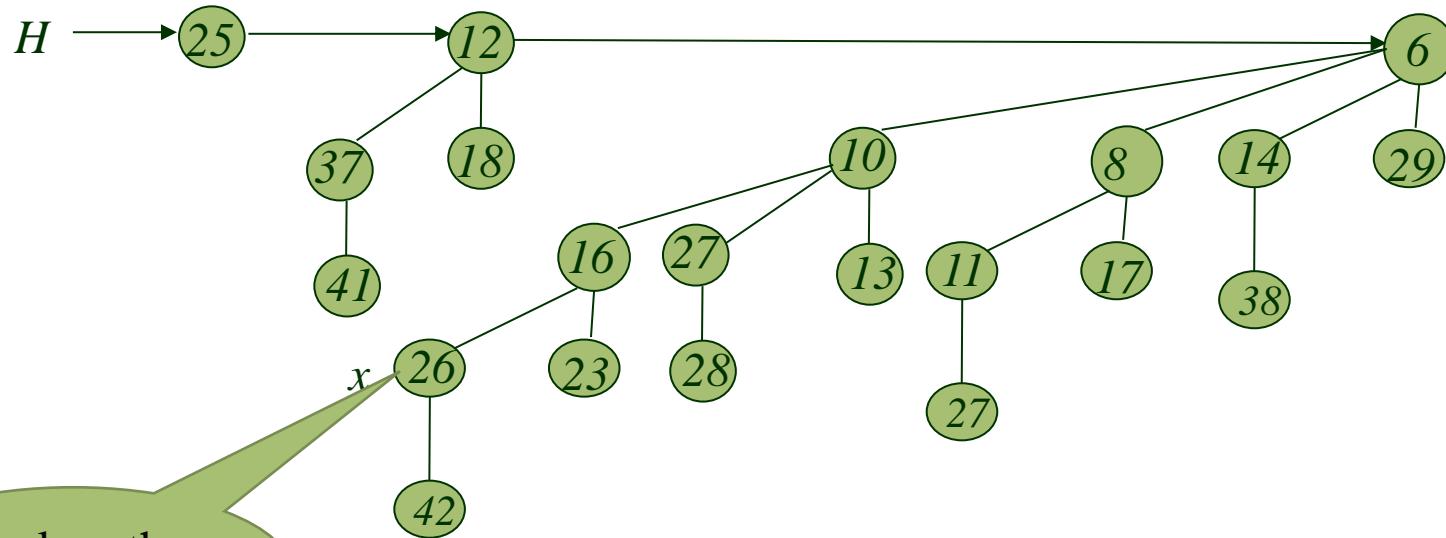
Decreases the key of a node  $x$  (i.e. 26) in a binomial heap  $H$  to a new value  $k$  (i.e. 7).



# Binomial Heap (Operations\_6)

Example:

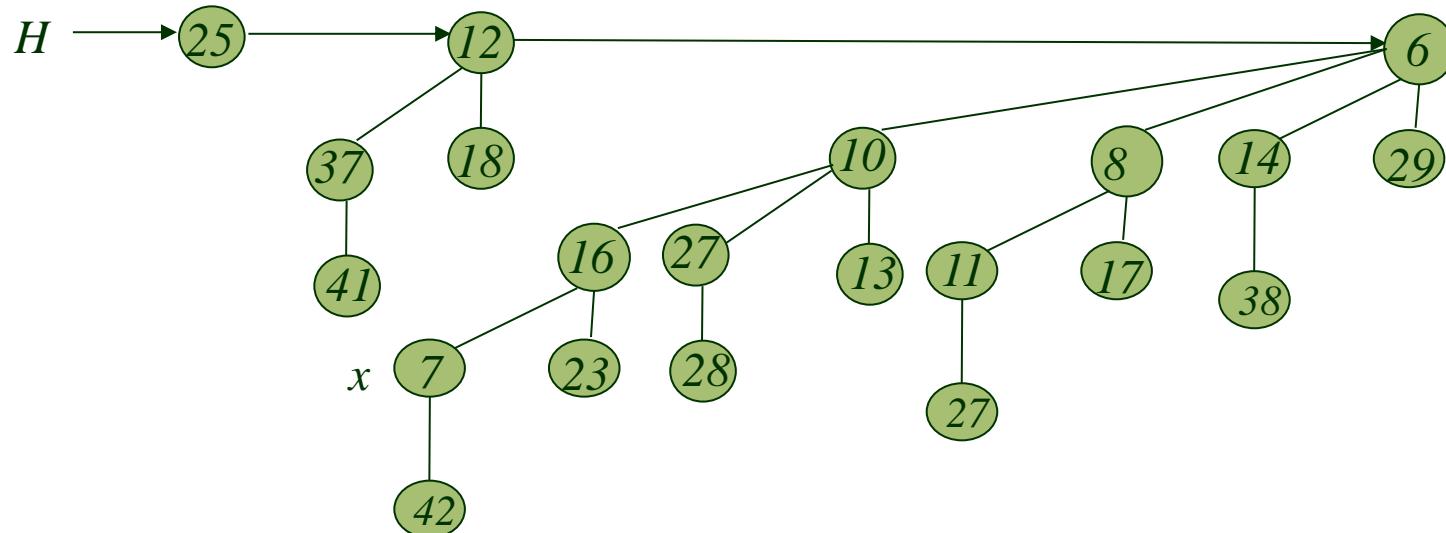
Decreases the key of a node  $x$  (i.e. 26) in a binomial heap  $H$  to a new value  $k$  (i.e. 7).



# Binomial Heap (Operations\_6)

Example:

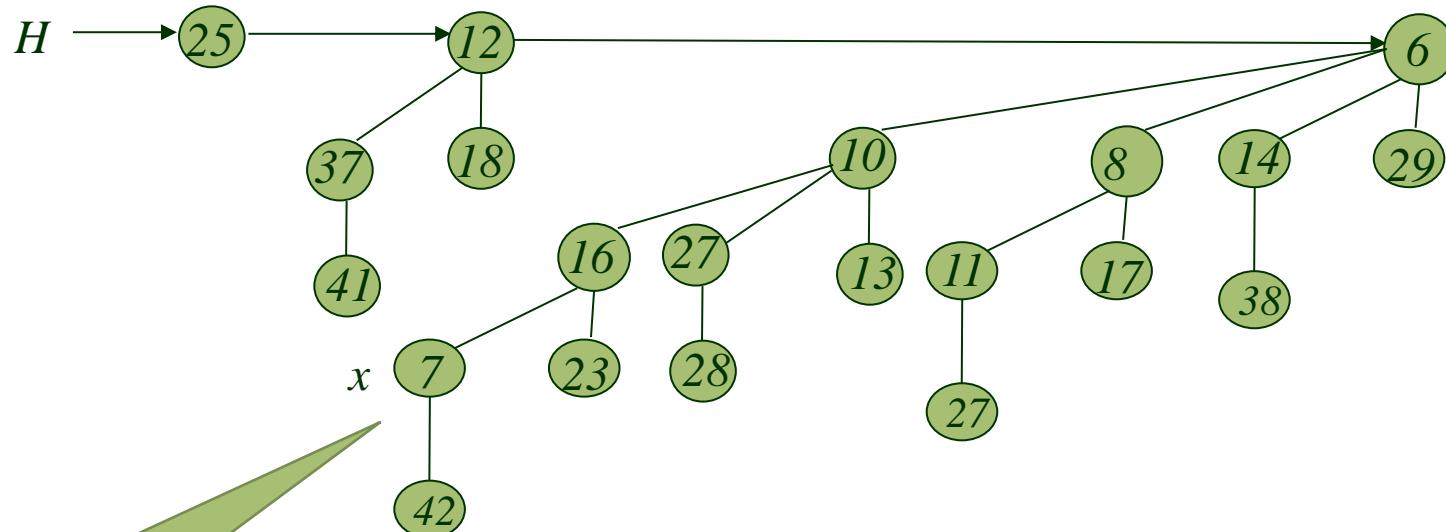
Decreases the key of a node  $x$  (i.e. 26) in a binomial heap  $H$  to a new value  $k$  (i.e. 7).



# Binomial Heap (Operations\_6)

Example:

Decreases the key of a node  $x$  (i.e. 26) in a binomial heap  $H$  to a new value  $k$  (i.e. 7).

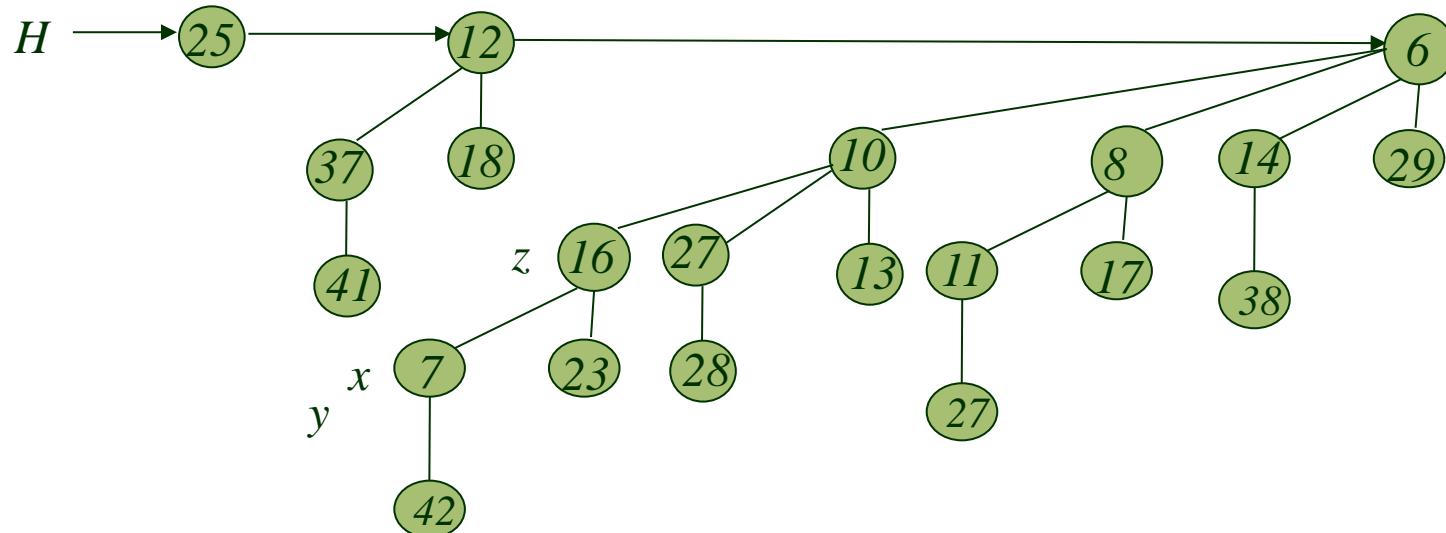


Set the pointer  
y and z

# Binomial Heap (Operations\_6)

Example:

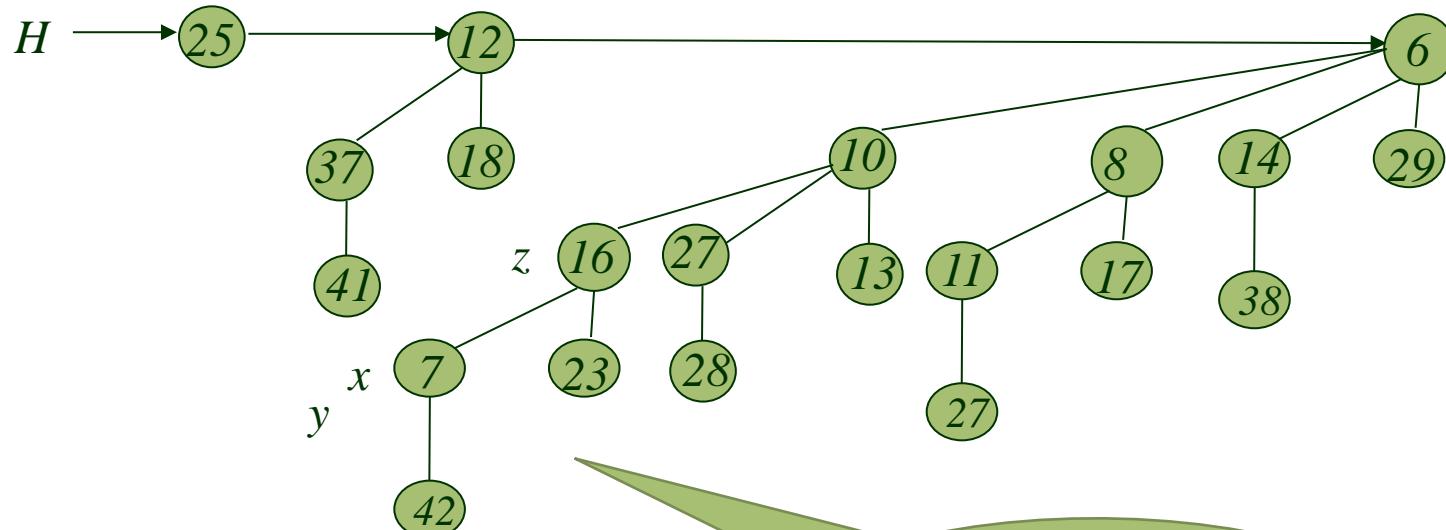
Decreases the key of a node  $x$  (i.e. 26) in a binomial heap  $H$  to a new value  $k$  (i.e. 7).



# Binomial Heap (Operations\_6)

Example:

Decreases the key of a node x (i.e. 26) in a binomial heap H to a new value k (i.e. 7).

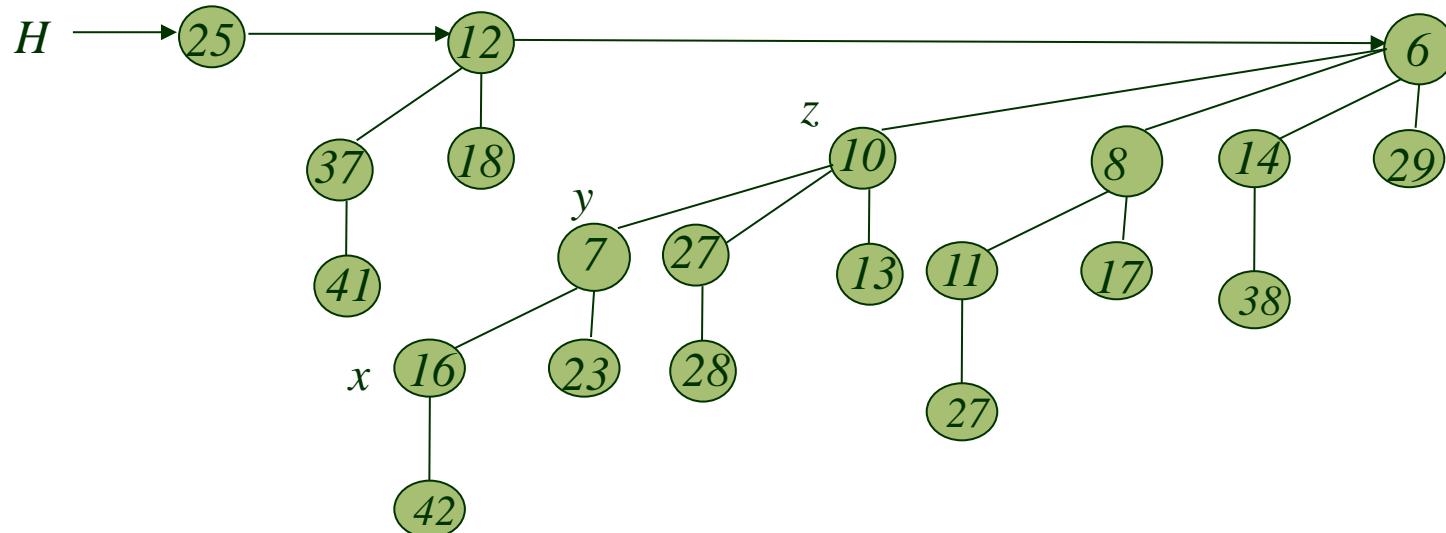


Exchange key[y] with  
key[z] and change the  
position of y and z

# Binomial Heap (Operations\_6)

Example:

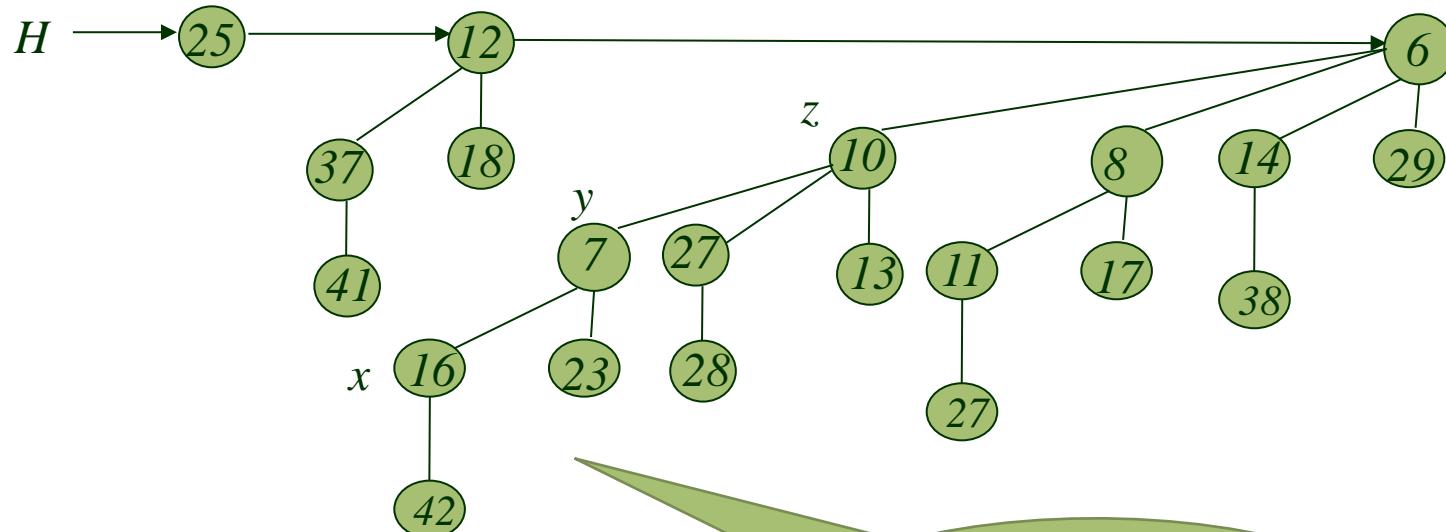
Decreases the key of a node  $x$  (i.e. 26) in a binomial heap  $H$  to a new value  $k$  (i.e. 7).



# Binomial Heap (Operations\_6)

Example:

Decreases the key of a node x (i.e. 26) in a binomial heap H to a new value k (i.e. 7).

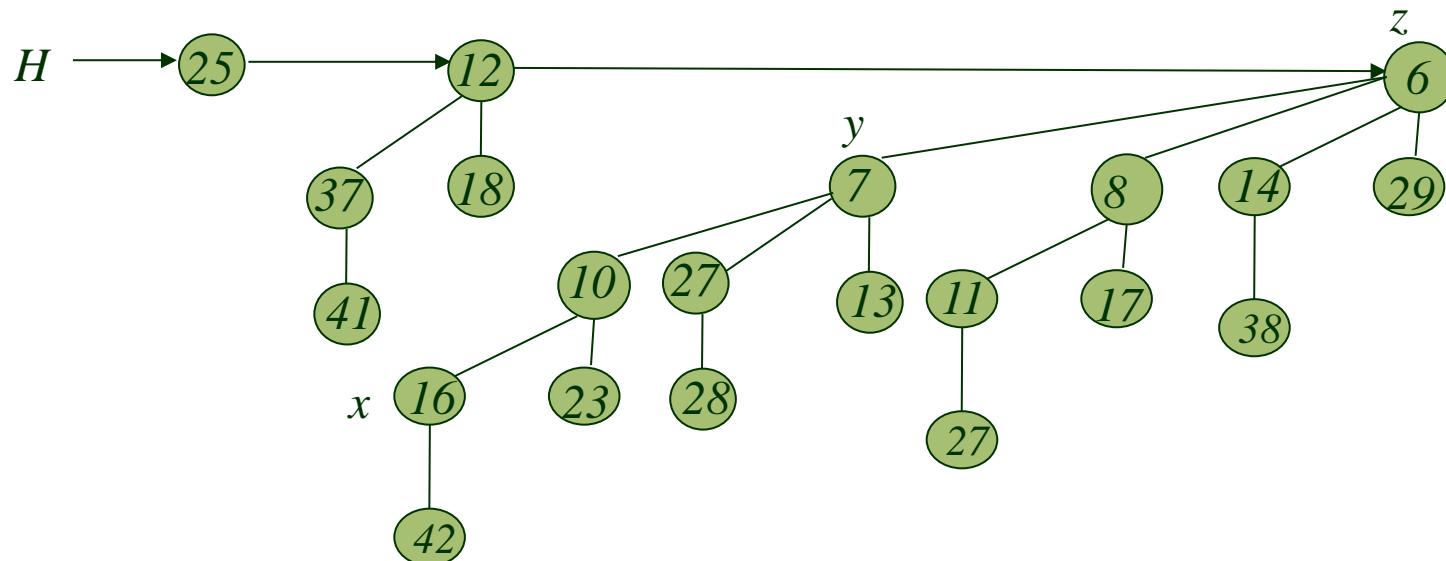


Exchange key[y] with  
key[z] and change the  
position of y and z

# Binomial Heap (Operations\_6)

Example:

Decreases the key of a node  $x$  (i.e. 26) in a binomial heap  $H$  to a new value  $k$  (i.e. 7).



# **Binomial Heap (Operations\_7)**

## **7. DELETE(H, x)**

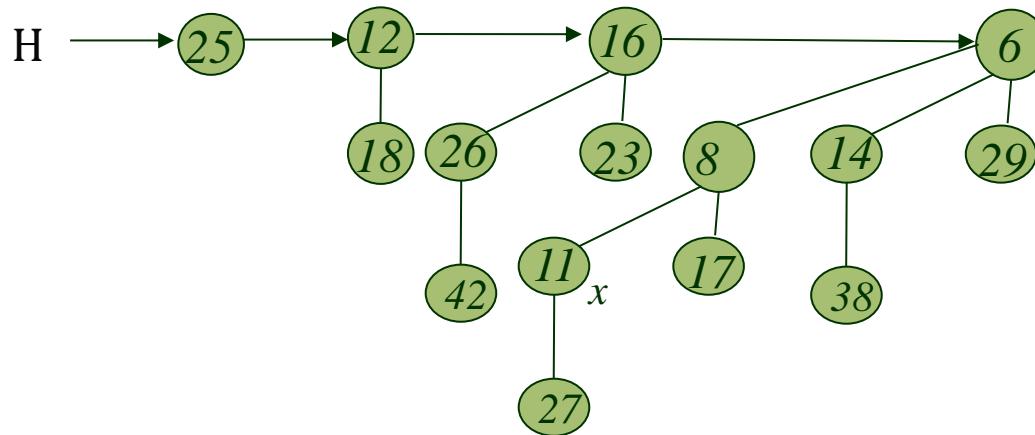
The delete procedure delete the key x with an assumption that no node currently in the binomial heap has a key of  $-\infty$ .

**BINOMIAL-HEAP-DELETE(H, x)**

- 1 **BINOMIAL-HEAP-DECREASE-KEY(H, x,  $-\infty$ )**
- 2 **BINOMIAL-HEAP-EXTRACT-MIN(H)**

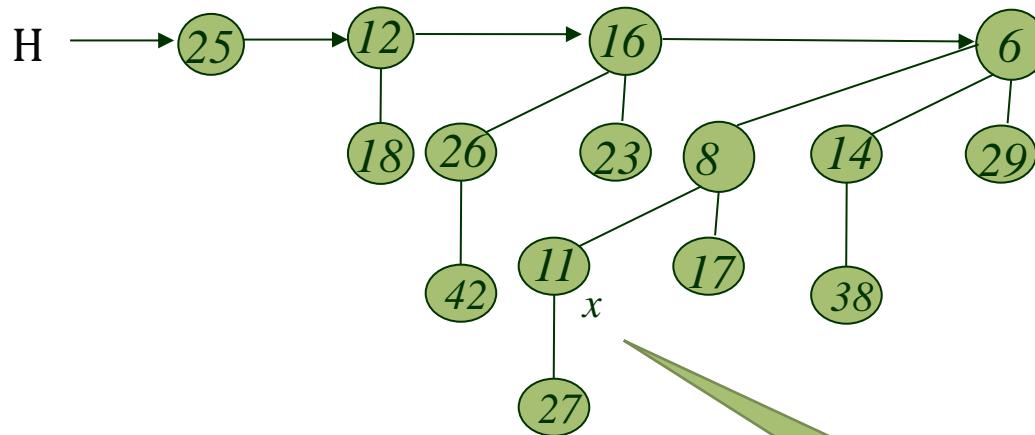
# Binomial Heap (Operations\_7)

**Example:** Delete the key  $x$  with an assumption that no node currently in the binomial heap has a key of  $-\infty$ .



# Binomial Heap (Operations\_7)

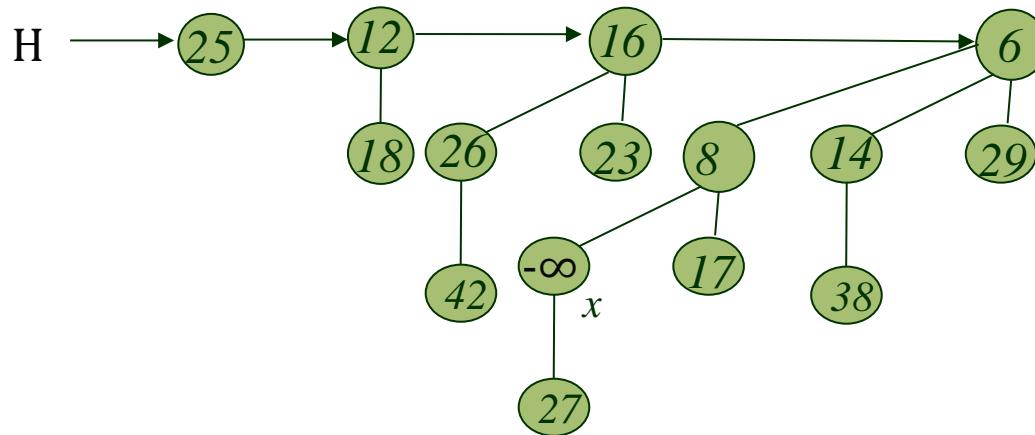
**Example:** Delete the key  $x$  with an assumption that no node currently in the binomial heap has a key of  $-\infty$  (i.e.  $k$ ).



Replace the  
key[x] with k

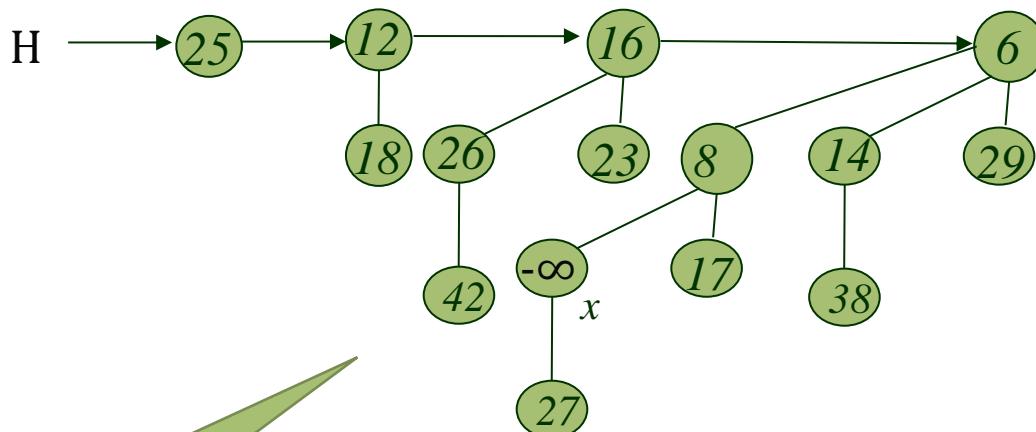
# Binomial Heap (Operations\_7)

**Example:** Delete the key  $x$  with an assumption that no node currently in the binomial heap has a key of  $-\infty$  (i.e.  $k$ ).



# Binomial Heap (Operations\_7)

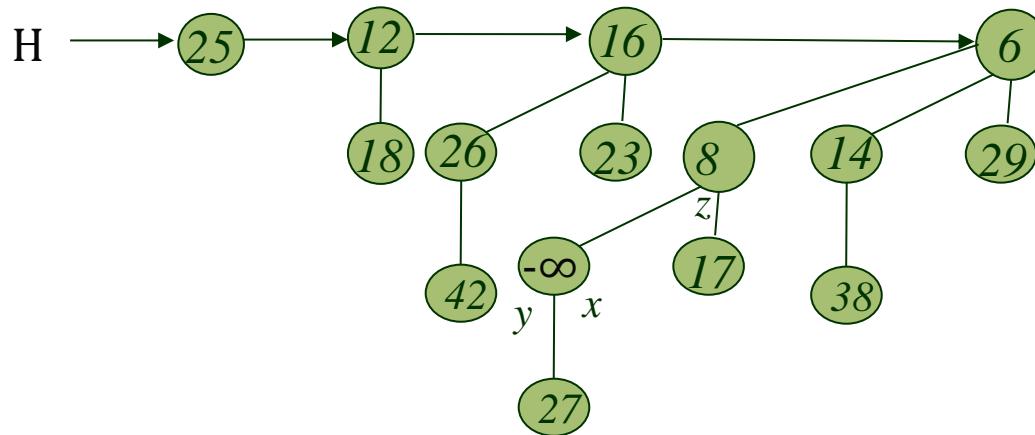
**Example:** Delete the key  $x$  with an assumption that no node currently in the binomial heap has a key of  $-\infty$  (i.e.  $k$ ).



Set the pointer  
y and z

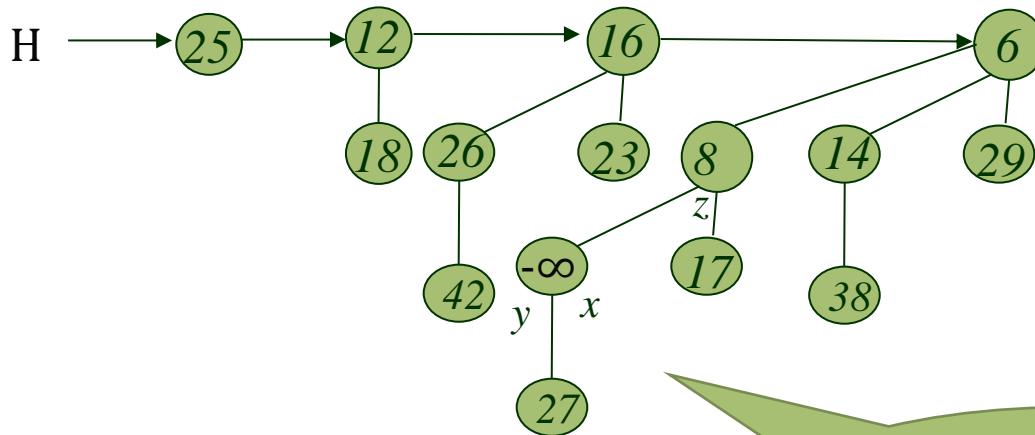
# Binomial Heap (Operations\_7)

**Example:** Delete the key  $x$  with an assumption that no node currently in the binomial heap has a key of  $-\infty$  (i.e.  $k$ ).



# Binomial Heap (Operations\_7)

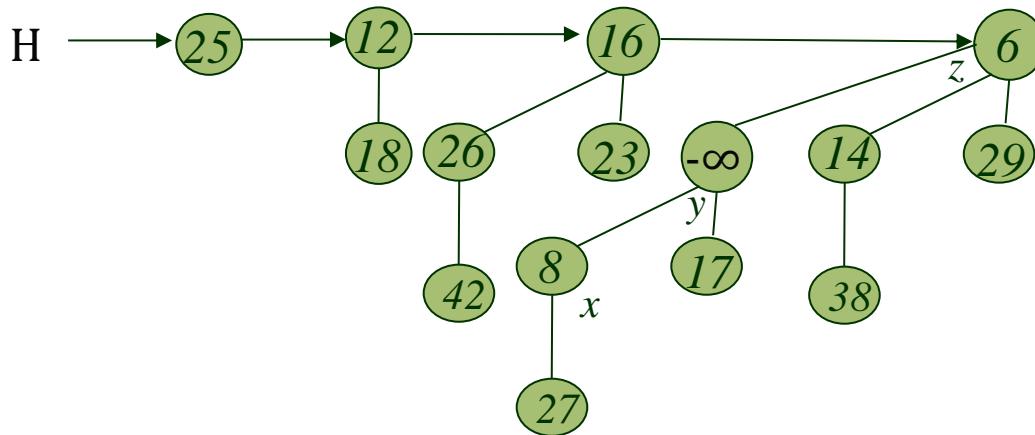
**Example:** Delete the key  $x$  with an assumption that no node currently in the binomial heap has a key of  $-\infty$  (i.e.  $k$ ).



Exchange key[y] with  
key[z] and change the  
position of y and z

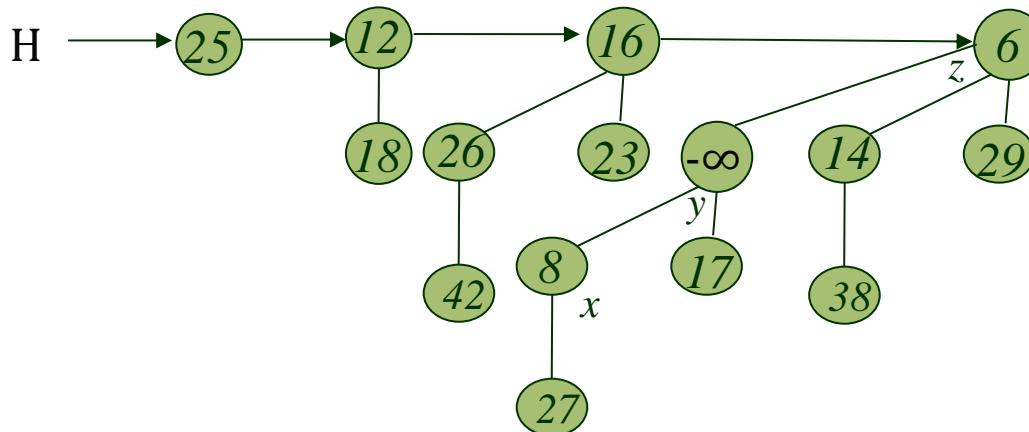
# Binomial Heap (Operations\_7)

**Example:** Delete the key  $x$  with an assumption that no node currently in the binomial heap has a key of  $-\infty$  (i.e.  $k$ ).



# Binomial Heap (Operations\_7)

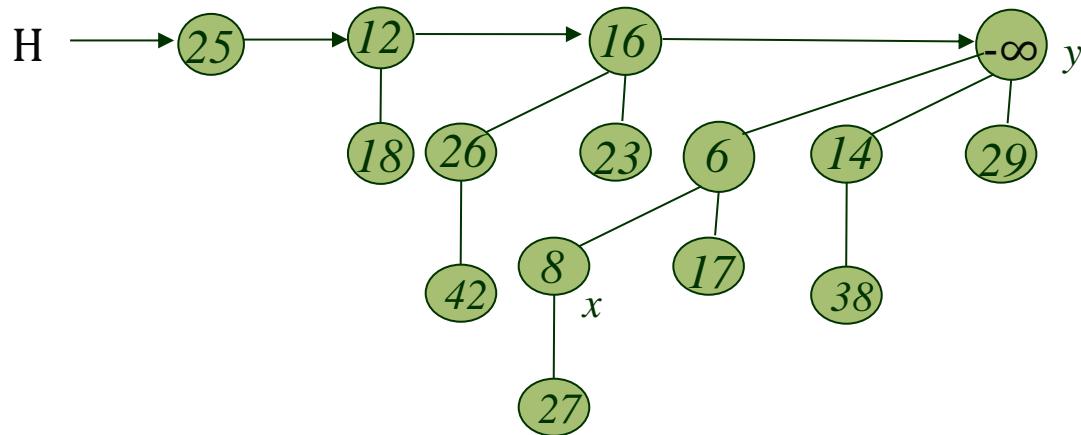
**Example:** Delete the key x with an assumption that no node currently in the binomial heap has a key of  $-\infty$  (i.e. k).



Exchange  
key[y] with  
key[z] and  
change the  
position of y  
and z

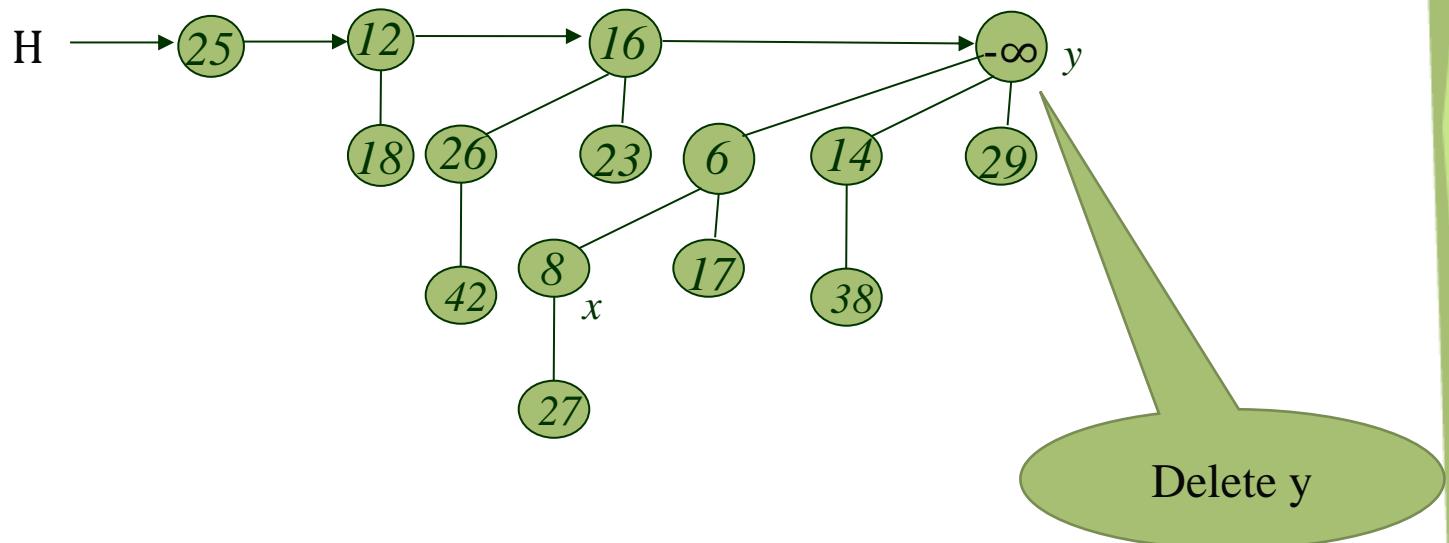
# Binomial Heap (Operations\_7)

**Example:** Delete the key  $x$  with an assumption that no node currently in the binomial heap has a key of  $-\infty$  (i.e.  $k$ ).



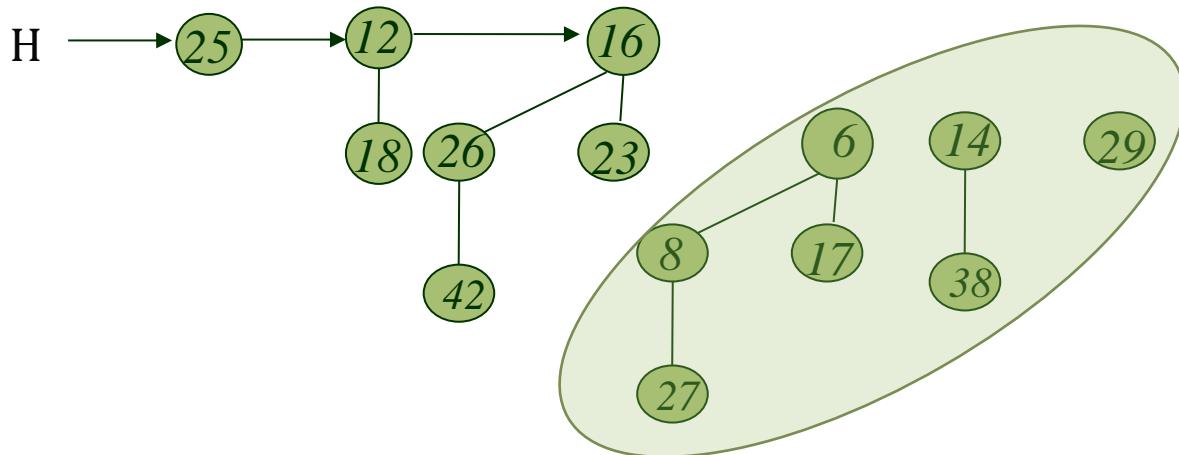
# Binomial Heap (Operations\_7)

**Example:** Delete the key  $x$  with an assumption that no node currently in the binomial heap has a key of  $-\infty$  (i.e.  $k$ ).



# Binomial Heap (Operations\_7)

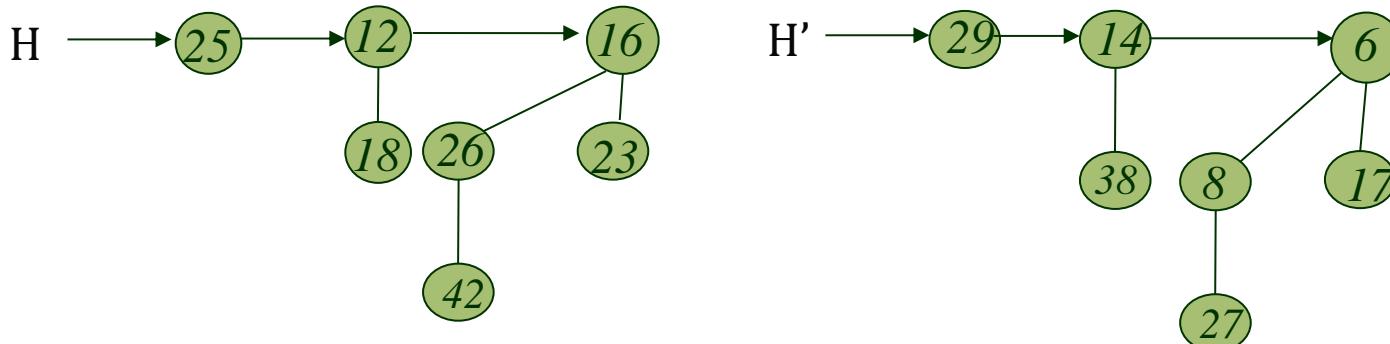
**Example:** Delete the key x with an assumption that no node currently in the binomial heap has a key of  $-\infty$  (i.e. k).



After remove x reverse the order of the list and put it in  $H'$

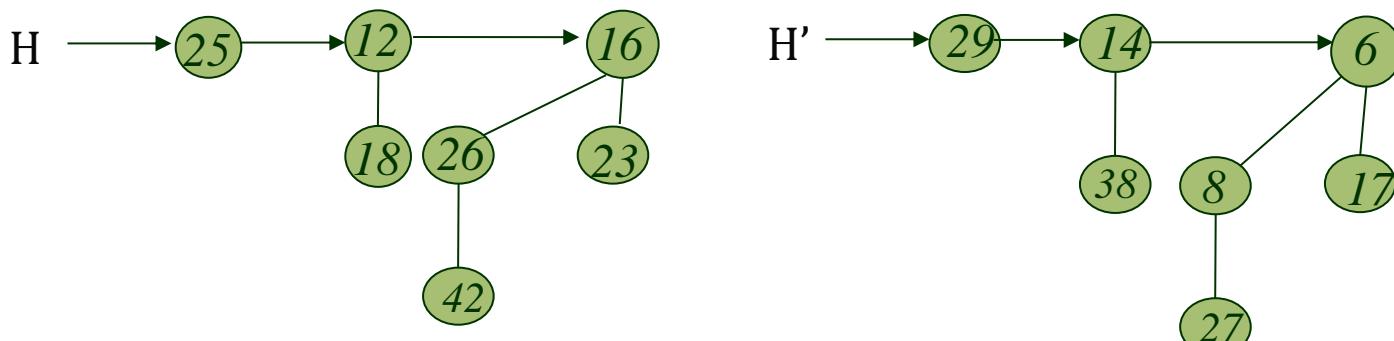
# Binomial Heap (Operations\_7)

**Example:** Delete the key x with an assumption that no node currently in the binomial heap has a key of  $-\infty$  (i.e. k).



# Binomial Heap (Operations\_7)

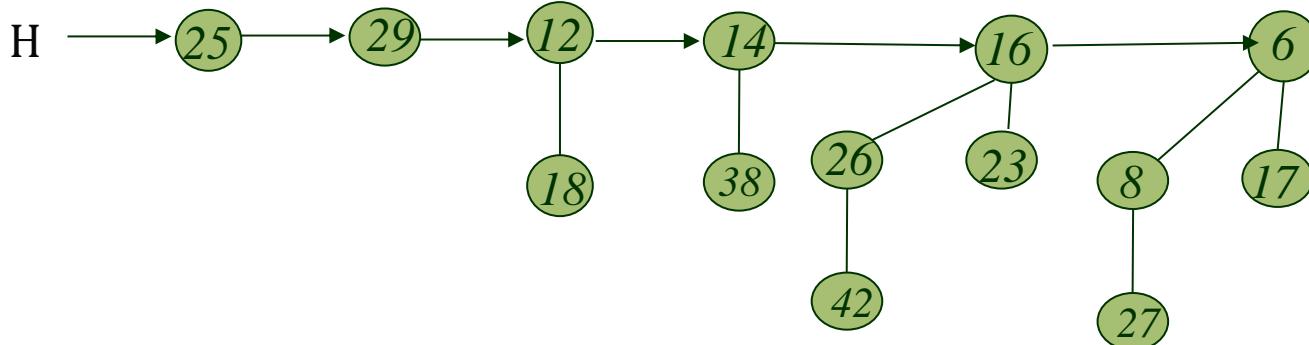
**Example:** Delete the key x with an assumption that no node currently in the binomial heap has a key of  $-\infty$  (i.e. k).



Merge two Binomial  
Heap Tree

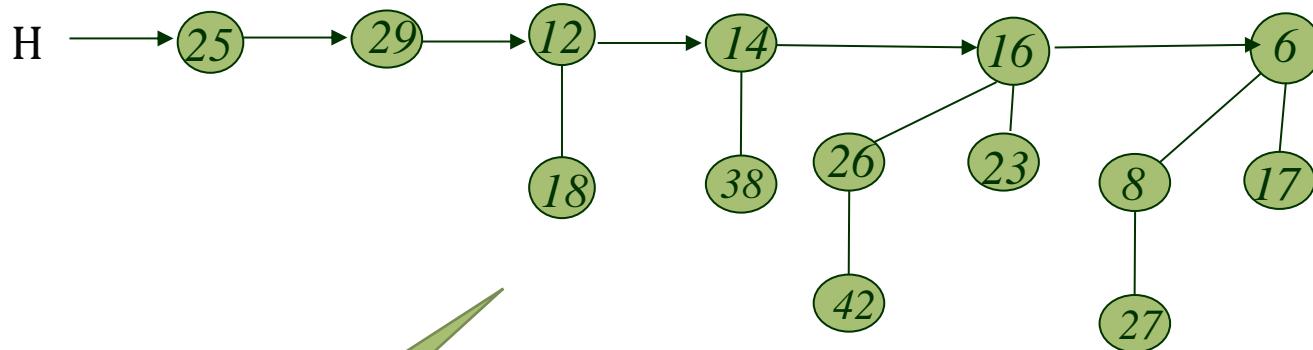
# Binomial Heap (Operations\_7)

**Example:** Delete the key x with an assumption that no node currently in the binomial heap has a key of  $-\infty$  (i.e. k).



# Binomial Heap (Operations\_7)

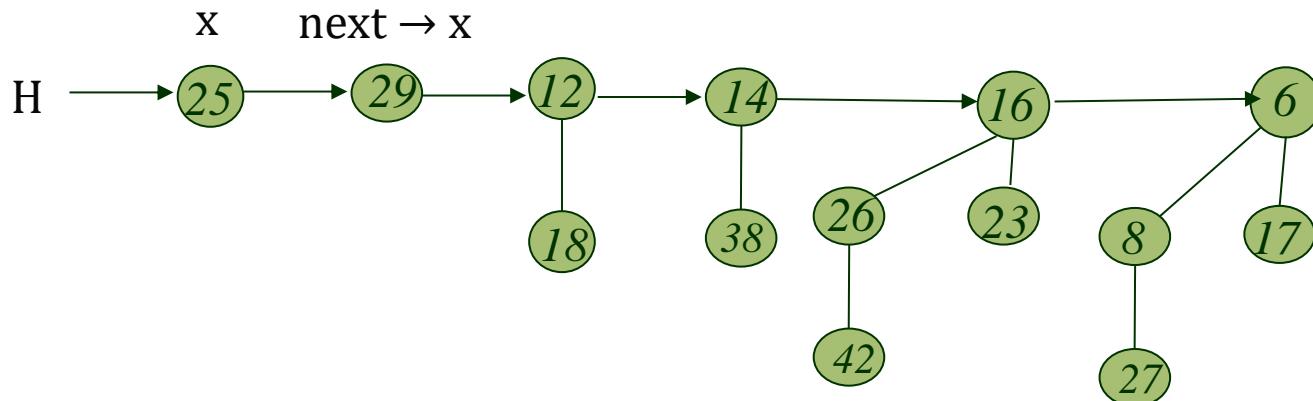
**Example:** Delete the key x with an assumption that no node currently in the binomial heap has a key of  $-\infty$  (i.e. k).



Place x and  
next → x

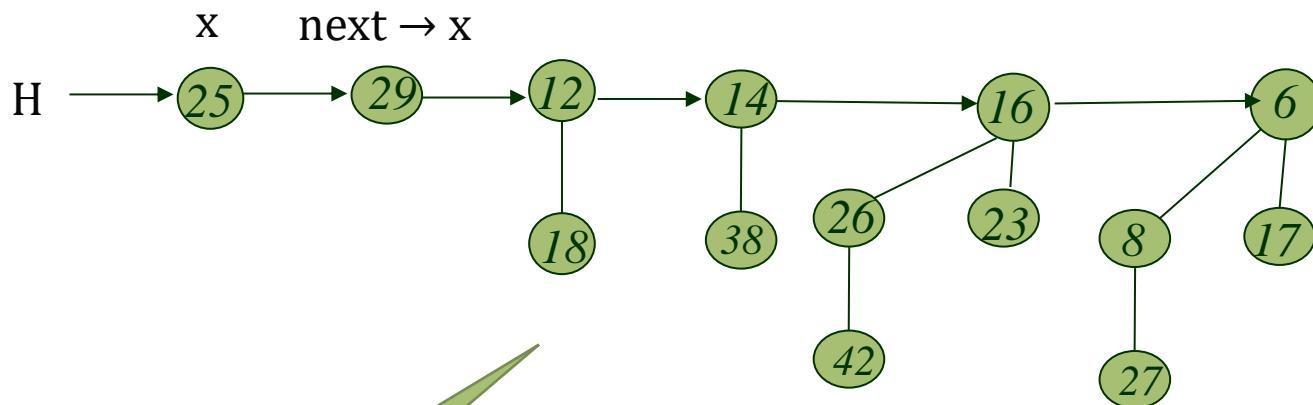
# Binomial Heap (Operations\_7)

**Example:** Delete the key x with an assumption that no node currently in the binomial heap has a key of  $-\infty$  (i.e. k).



# Binomial Heap (Operations\_7)

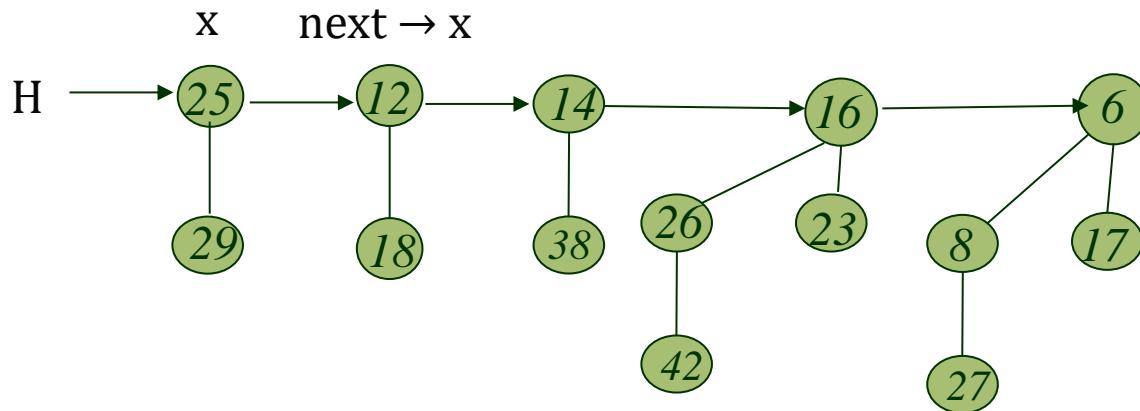
**Example:** Delete the key x with an assumption that no node currently in the binomial heap has a key of  $-\infty$  (i.e. k).



Apply case 3

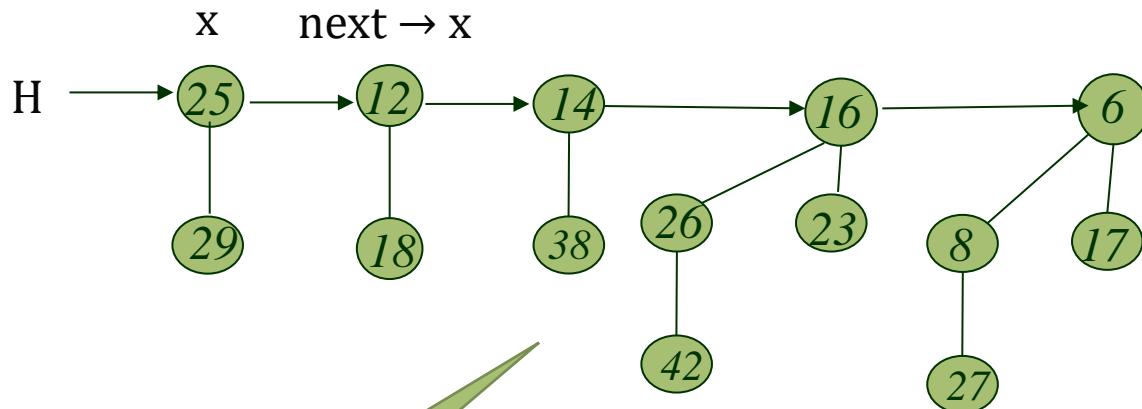
# Binomial Heap (Operations\_7)

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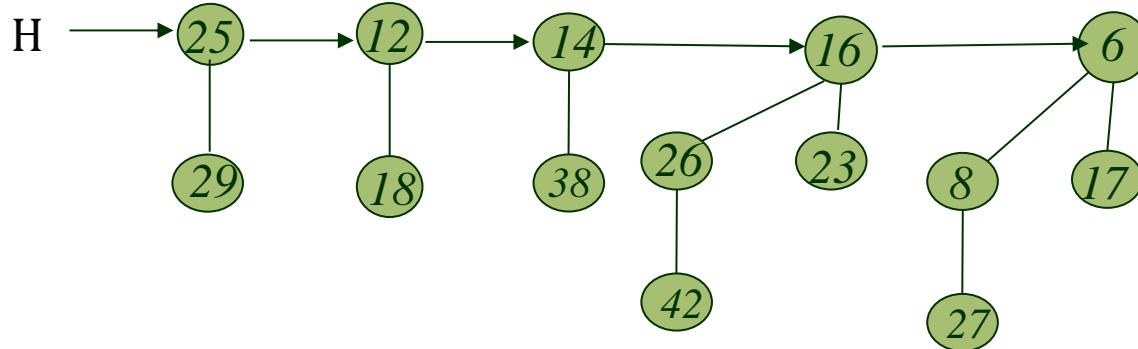


Apply case 2

# Binomial Heap (Operations\_7)

**Example:** Delete the key x with an assumption that no node currently in the binomial heap has a key of  $-\infty$  (i.e. k).

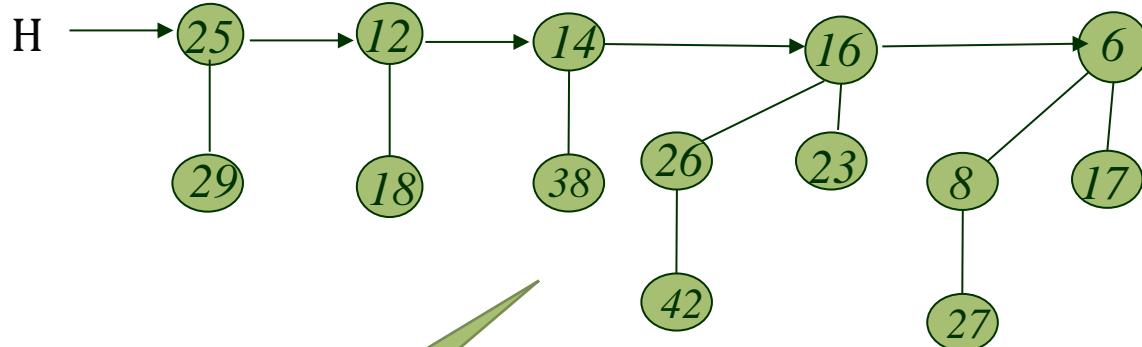
prev → x    x    next → x



# Binomial Heap (Operations\_7)

**Example:** Delete the key x with an assumption that no node currently in the binomial heap has a key of  $-\infty$  (i.e. k).

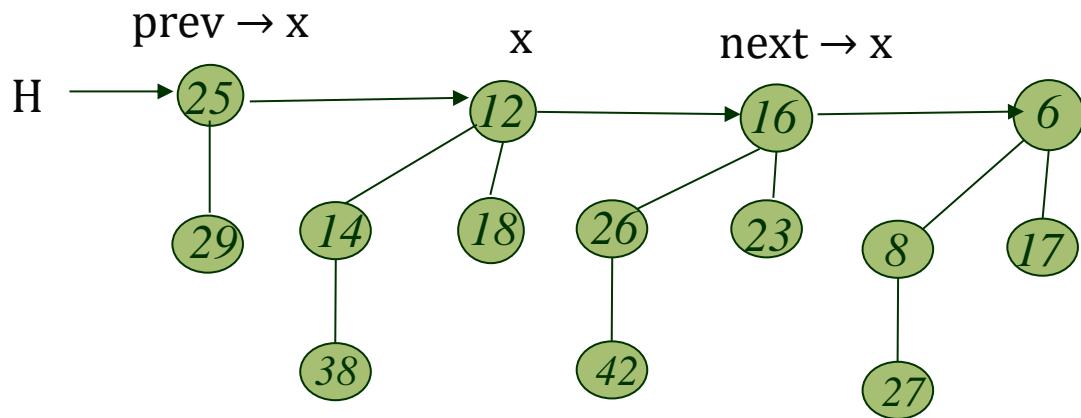
prev → x    x    next → x



Apply case 3

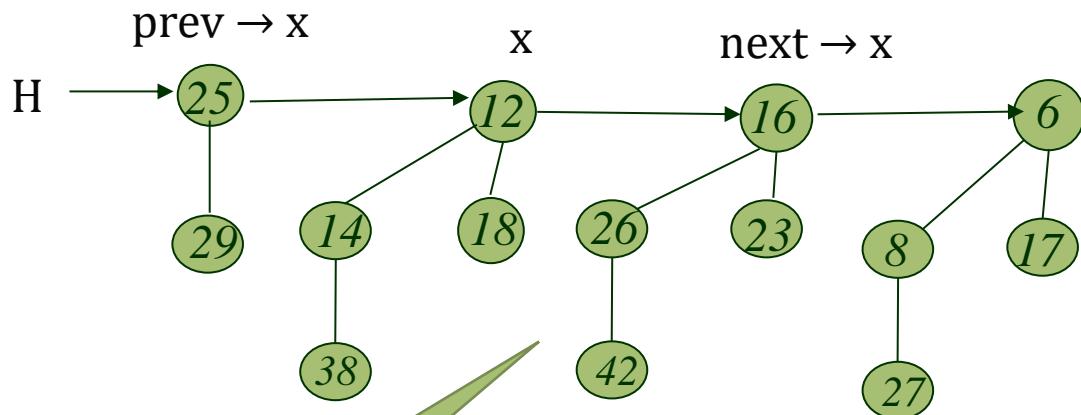
# Binomial Heap (Operations\_7)

**Example:** Delete the key  $x$  with an assumption that no node currently in the binomial heap has a key of  $-\infty$  (i.e.  $k$ ).



# Binomial Heap (Operations\_7)

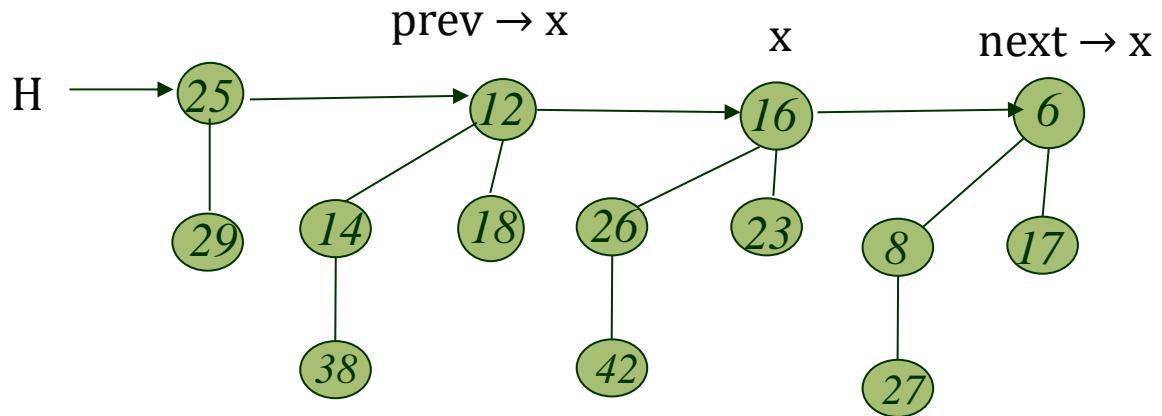
**Example:** Delete the key  $x$  with an assumption that no node currently in the binomial heap has a key of  $-\infty$  (i.e.  $k$ ).



Apply case 2

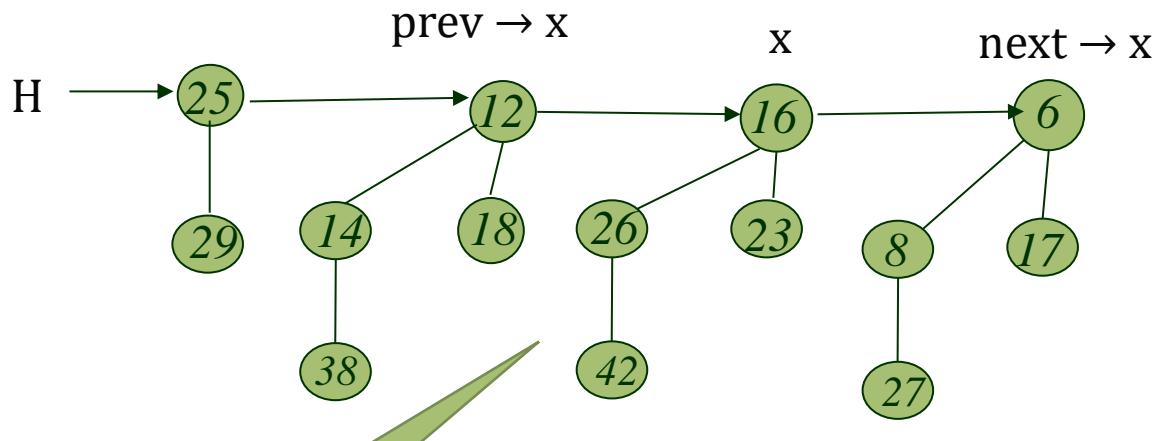
# Binomial Heap (Operations\_7)

**Example:** Delete the key x with an assumption that no node currently in the binomial heap has a key of  $-\infty$  (i.e. k).



# Binomial Heap (Operations\_7)

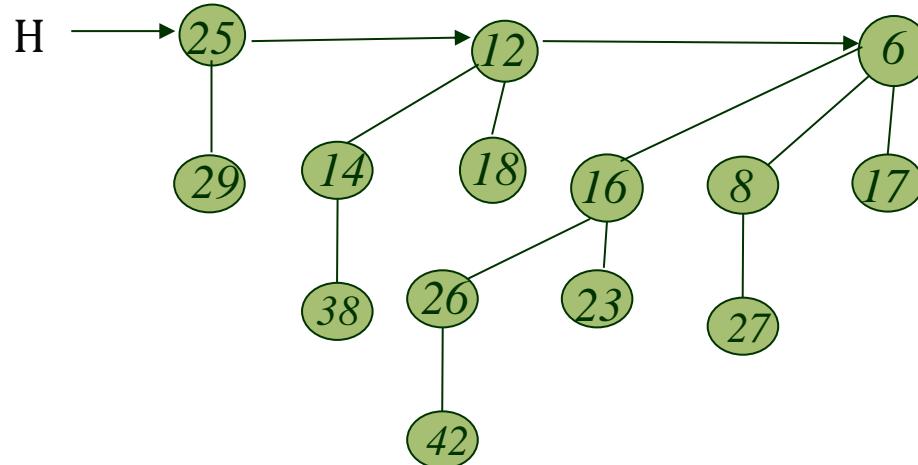
**Example:** Delete the key  $x$  with an assumption that no node currently in the binomial heap has a key of  $-\infty$  (i.e.  $k$ ).



Apply case 4

# Binomial Heap (Operations\_7)

**Example:** Delete the key x with an assumption that no node currently in the binomial heap has a key of  $-\infty$  (i.e. k).



# Binomial Heap

The running time of binomial Heap w.r.t Binary Heap is given below

Procedure	Binary heap (worst-case)	Binomial heap (worst-case)
INSERT	$\Theta(\lg n)$	$O(\lg n)$
MINIMUM	$\Theta(1)$	$O(\lg n)$
EXTRACT-MIN	$\Theta(\lg n)$	$\Theta(\lg n)$
UNION	$\Theta(n)$	$O(\lg n)$
DECREASEKEY	$\Theta(\lg n)$	$\Theta(\lg n)$
DELETE	$\Theta(\lg n)$	$\Theta(\lg n)$

Thank U