

CSE 548: Analysis of Algorithms

**Lectures 13, 14, 15 & 16
(Binomial Heaps)**

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Mergeable Heap Operations

MAKE-HEAP(x): return a new heap containing only element x

INSERT(H, x): insert element x into heap H

MINIMUM(H): return a pointer to an element in H containing the smallest key

EXTRACT-MIN(H): delete an element with the smallest key from H and return a pointer to that element

UNION(H_1, H_2): return a new heap containing all elements of heaps H_1 and H_2 , and destroy the input heaps

More mergeable heap operations:

DECREASE-KEY(H, x, k): change the key of element x of heap H to k assuming $k \leq$ the current key of x

DELETE(H, x): delete element x from heap H

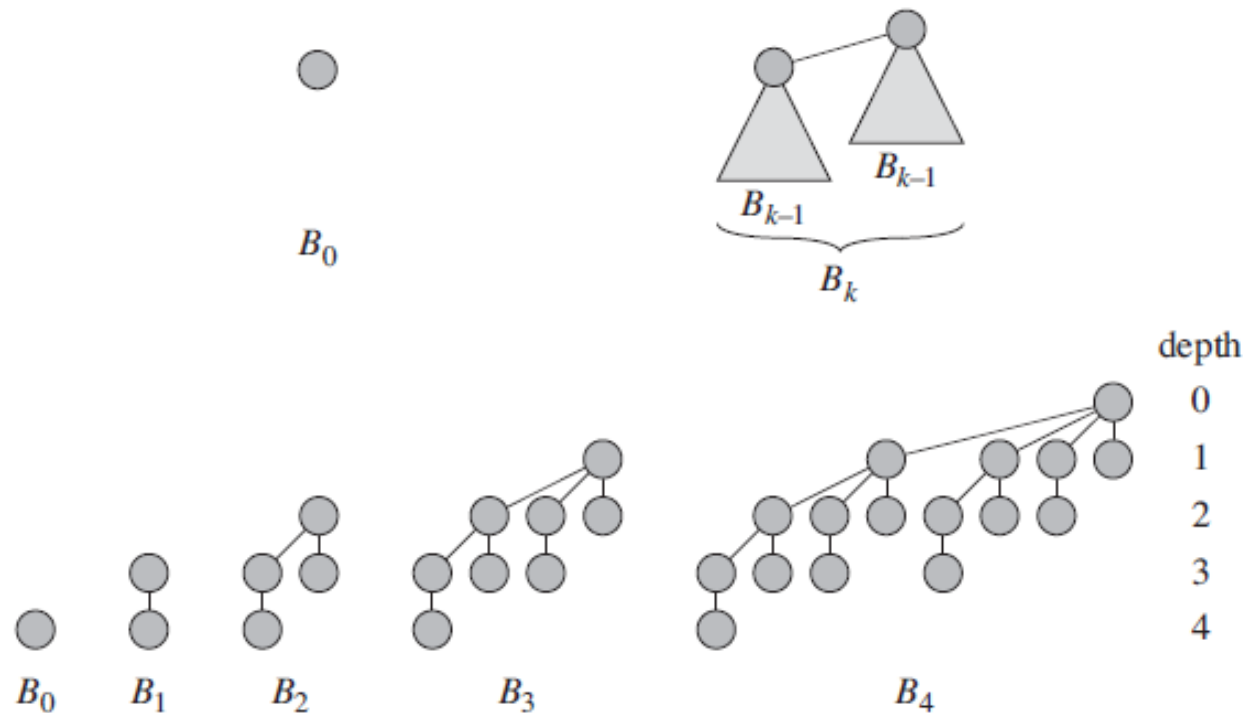
Mergeable Heap Operations

Heap Operation	Binary Heap (worst-case)	Binomial Heap (amortized)
MAKE-HEAP	$\Theta(1)$	$\Theta(1)$
INSERT	$O(\log n)$	$\Theta(1)$
MINIMUM	$\Theta(1)$	$\Theta(1)$
EXTRACT-MIN	$O(\log n)$	$O(\log n)$
UNION	$\Theta(n)$	$\Theta(1)$
DECREASE-KEY	$O(\log n)$	—
DELETE	$O(\log n)$	—

Binomial Trees

A binomial tree B_k is an ordered tree defined recursively as follows.

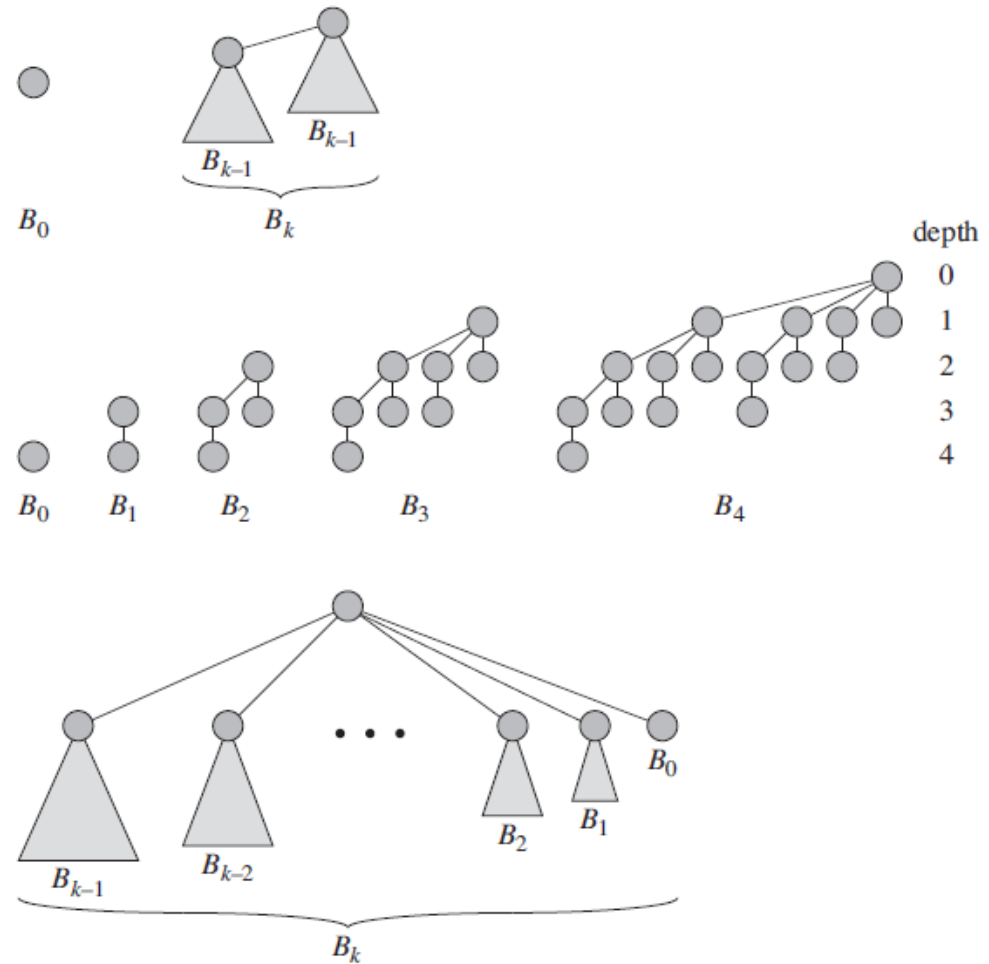
- B_0 consists of a single node
- For $k > 0$, B_k consists of two B_{k-1} 's that are linked together so that the root of one is the left child of the root of the other



Binomial Trees

Some useful properties of B_k are as follows.

1. it has exactly 2^k nodes
2. its height is k
3. there are exactly $\binom{k}{i}$ nodes at depth $i = 0, 1, 2, \dots, k$
4. the root has degree k
5. if the children of the root are numbered from left to right by $k - 1, k - 2, \dots, 0$, then child i is the root of a B_i

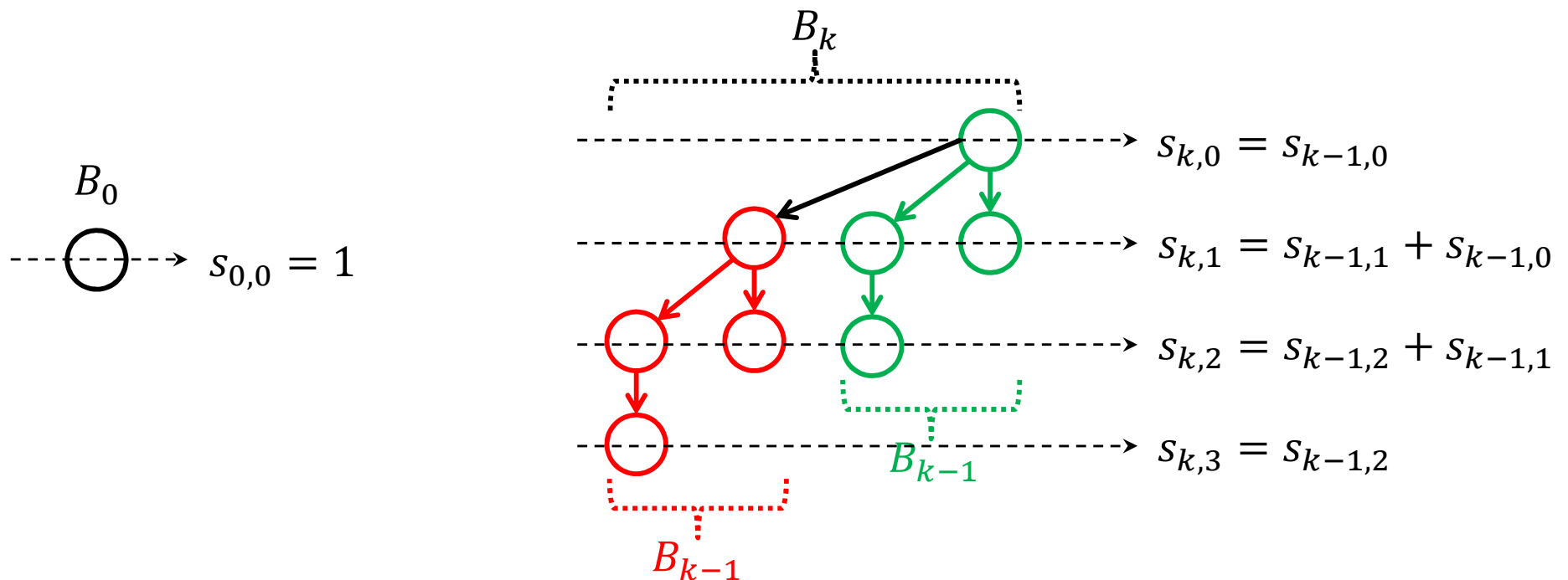


Binomial Trees

Prove: B_k has exactly $\binom{k}{i}$ nodes at depth $i = 0, 1, 2, \dots, k$.

Proof: Suppose B_k has $s_{k,i}$ nodes at depth i .

$$s_{k,i} = \begin{cases} 0 & \text{if } i < 0 \text{ or } i > k, \\ 1 & \text{if } i = k = 0, \\ s_{k-1,i} + s_{k-1,i-1} & \text{otherwise.} \end{cases}$$



Binomial Trees

$$s_{k,i} = \begin{cases} 0 & \text{if } i < 0 \text{ or } i > k, \\ 1 & \text{if } i = k = 0, \\ s_{k-1,i} + s_{k-1,i-1} & \text{otherwise.} \end{cases}$$

$$\Rightarrow s_{k,i} = [k \geq i \geq 0](s_{k-1,i} + s_{k-1,i-1} + [i = k = 0])$$

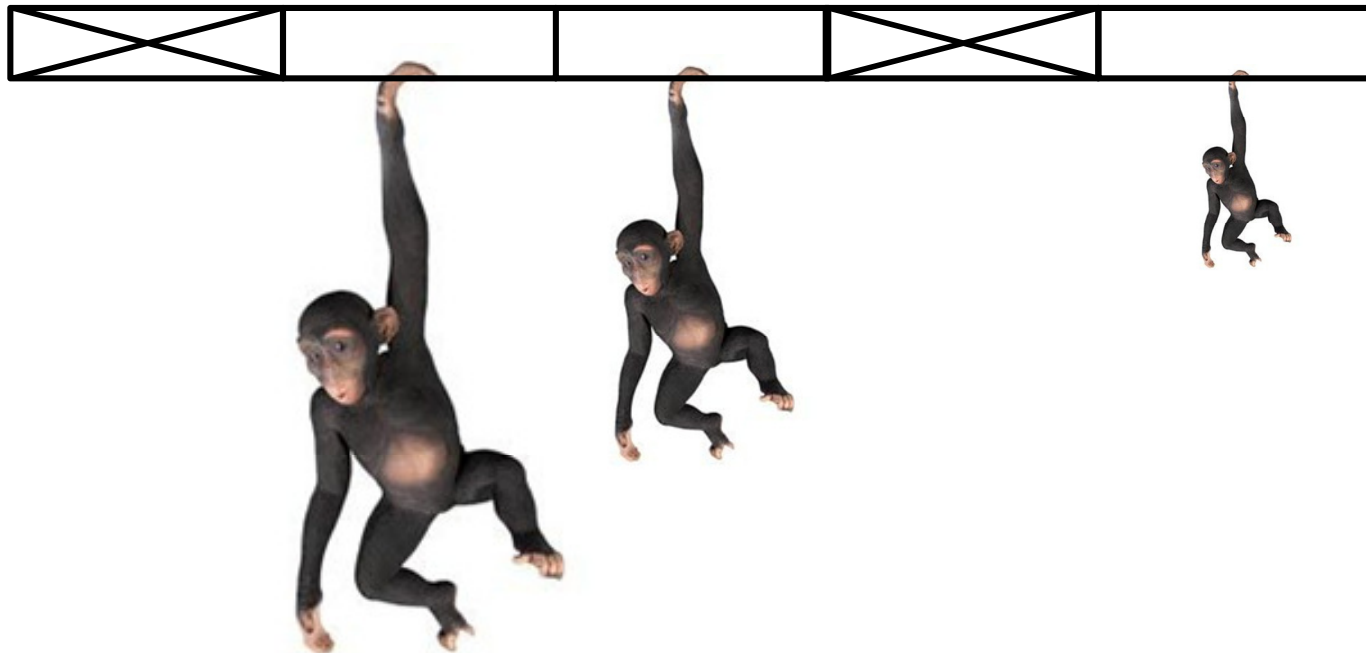
Generating function: $S_k(z) = s_{k,0} + s_{k,1}z + s_{k,2}z^2 + \dots + s_{k,k}z^k$

$$\begin{aligned} S_{k \geq 0}(z) &= \sum_{i=0}^k s_{k,i}z^i = \sum_{i=0}^k s_{k-1,i}z^i + \sum_{i=0}^k s_{k-1,i-1}z^i + [k=0] \sum_{i=0}^k [i=0]z^i \\ &= \sum_{i=0}^{k-1} s_{k-1,i}z^i + z \sum_{i=0}^{k-1} s_{k-1,i}z^i + [k=0] \\ &= S_{k-1}(z) + zS_{k-1}(z) + [k=0] = (1+z)S_{k-1}(z) + [k=0] \\ \Rightarrow S_k(z) &= \begin{cases} 1 & \text{if } k=0, \\ (1+z)S_{k-1}(z) & \text{otherwise.} \end{cases} \\ &= (1+z)^k \end{aligned}$$

Equating the coefficient of z^i from both sides: $s_{k,i} = \binom{k}{i}$

Binomial Heaps

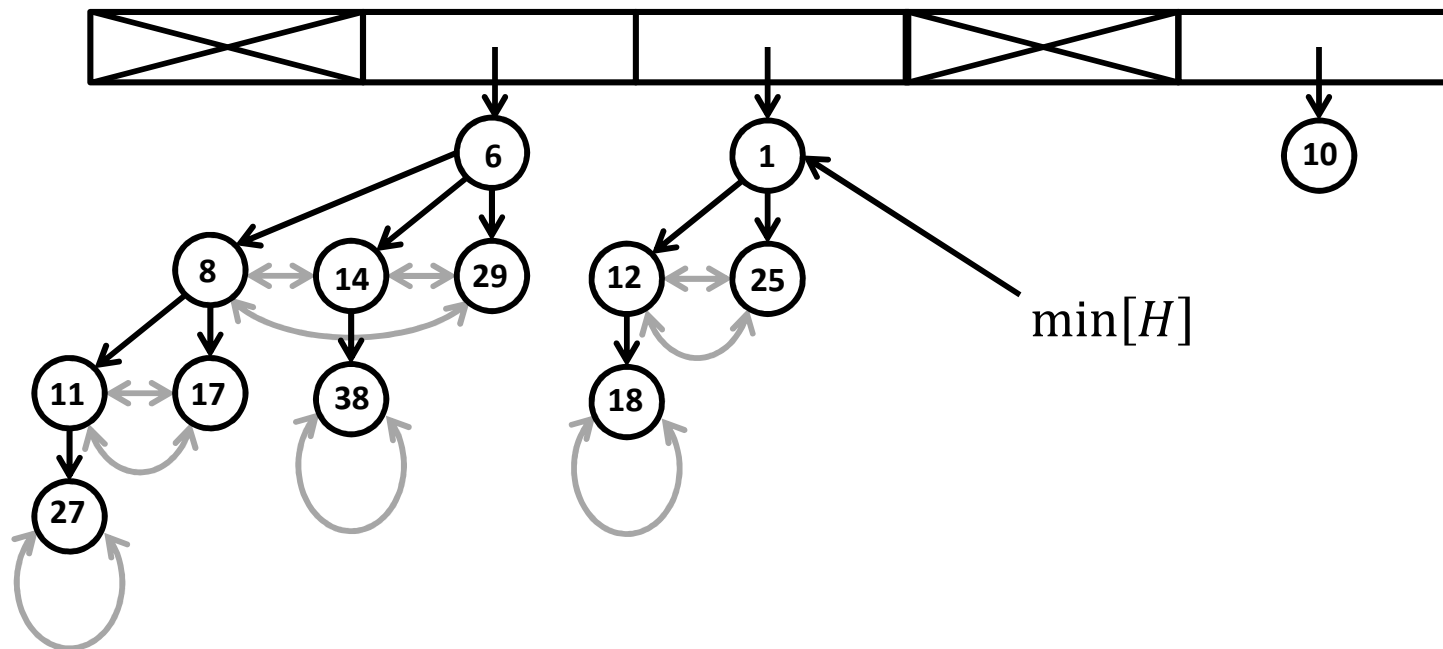
A *binomial heap* H is a set of binomial trees that satisfies the following properties:



Binomial Heaps

A *binomial heap* H is a set of binomial trees that satisfies the following properties:

1. each node has a key
2. each binomial tree in H obeys the min-heap property
3. for any integer $k \geq 0$, there is at most one binomial tree in H whose root node has degree k



Rank of Binomial Trees

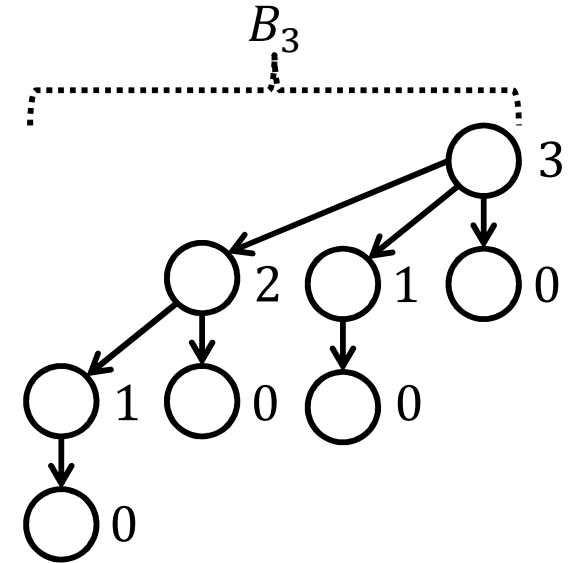
The *rank* of a binomial tree node x , denoted $rank(x)$, is the number of children of x .

The figure on the right shows the rank of each node in B_3 .

Observe that $rank(\text{root}(B_k)) = k$.

Rank of a binomial tree is the rank of its root. Hence,

$$rank(B_k) = rank(\text{root}(B_k)) = k$$

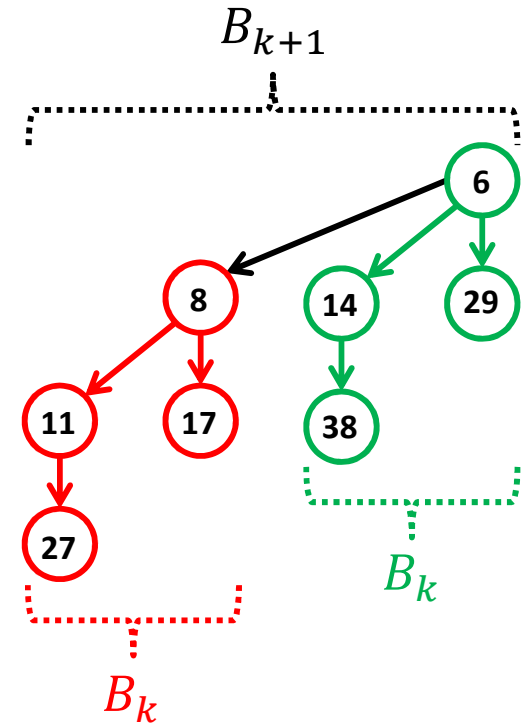


A Basic Operation: Linking Two Binomial Trees

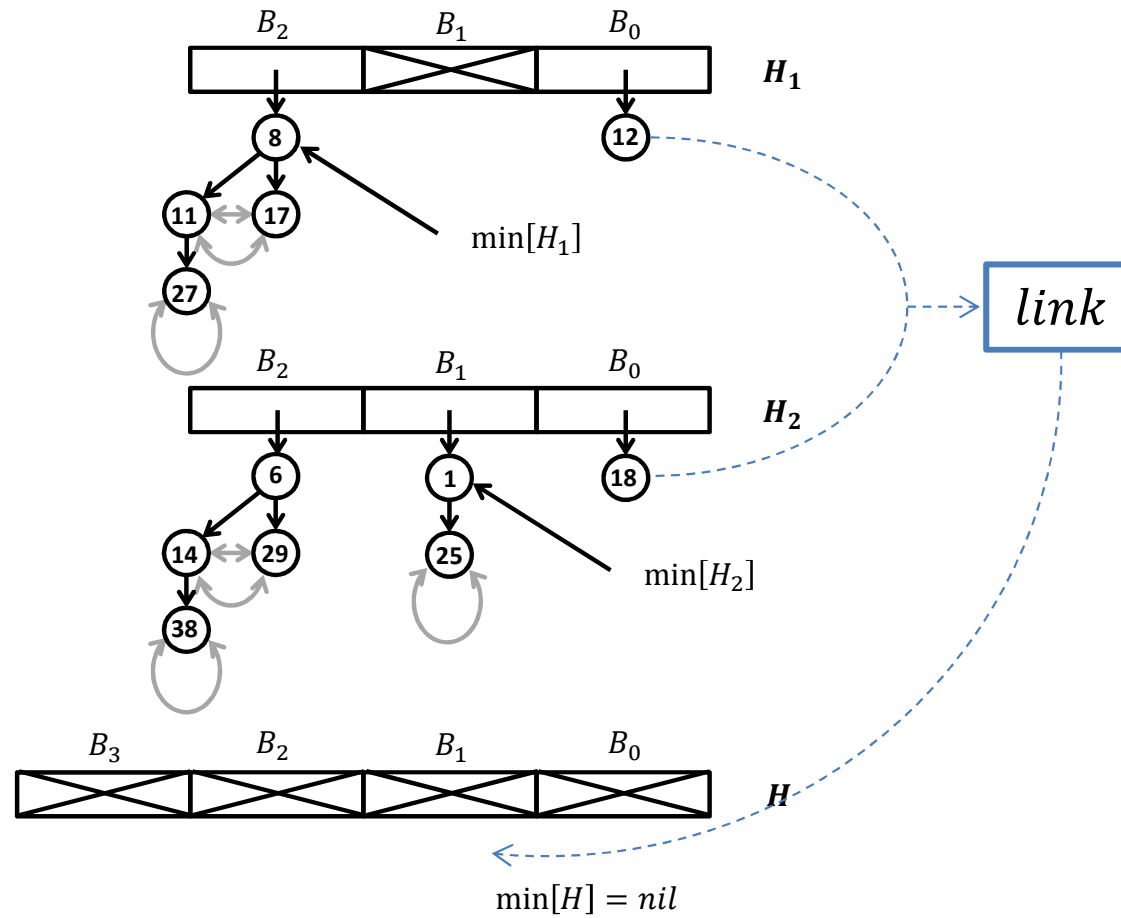
Given *two binomial trees of the same rank*, say, two B_k 's, we link them in constant time by making the root of one tree the left child of the root of the other, and thus producing a B_{k+1} .

If the trees are part of a binomial min-heap, we always make the root with the smaller key the parent, and the one with the larger key the child.

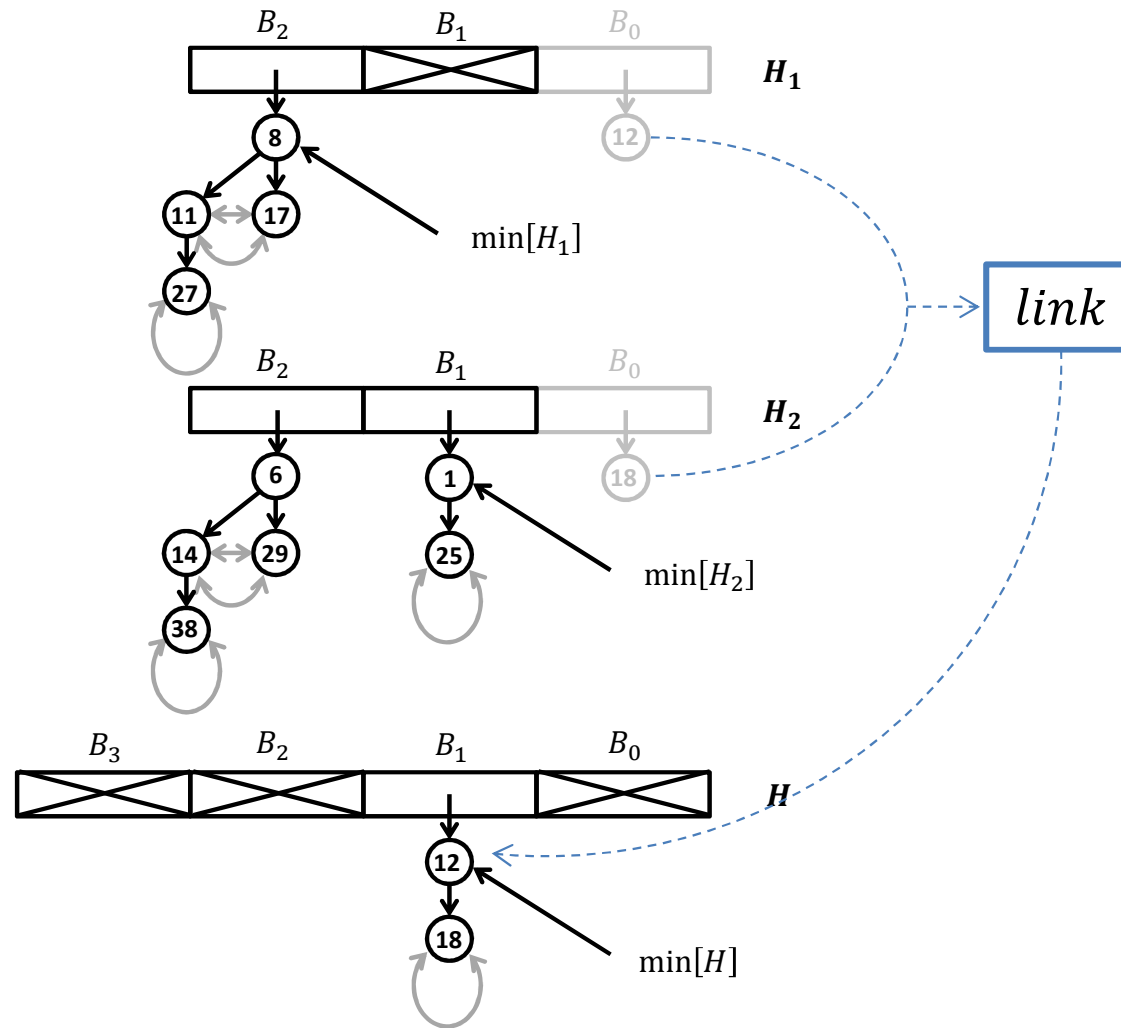
Ties are broken arbitrarily.



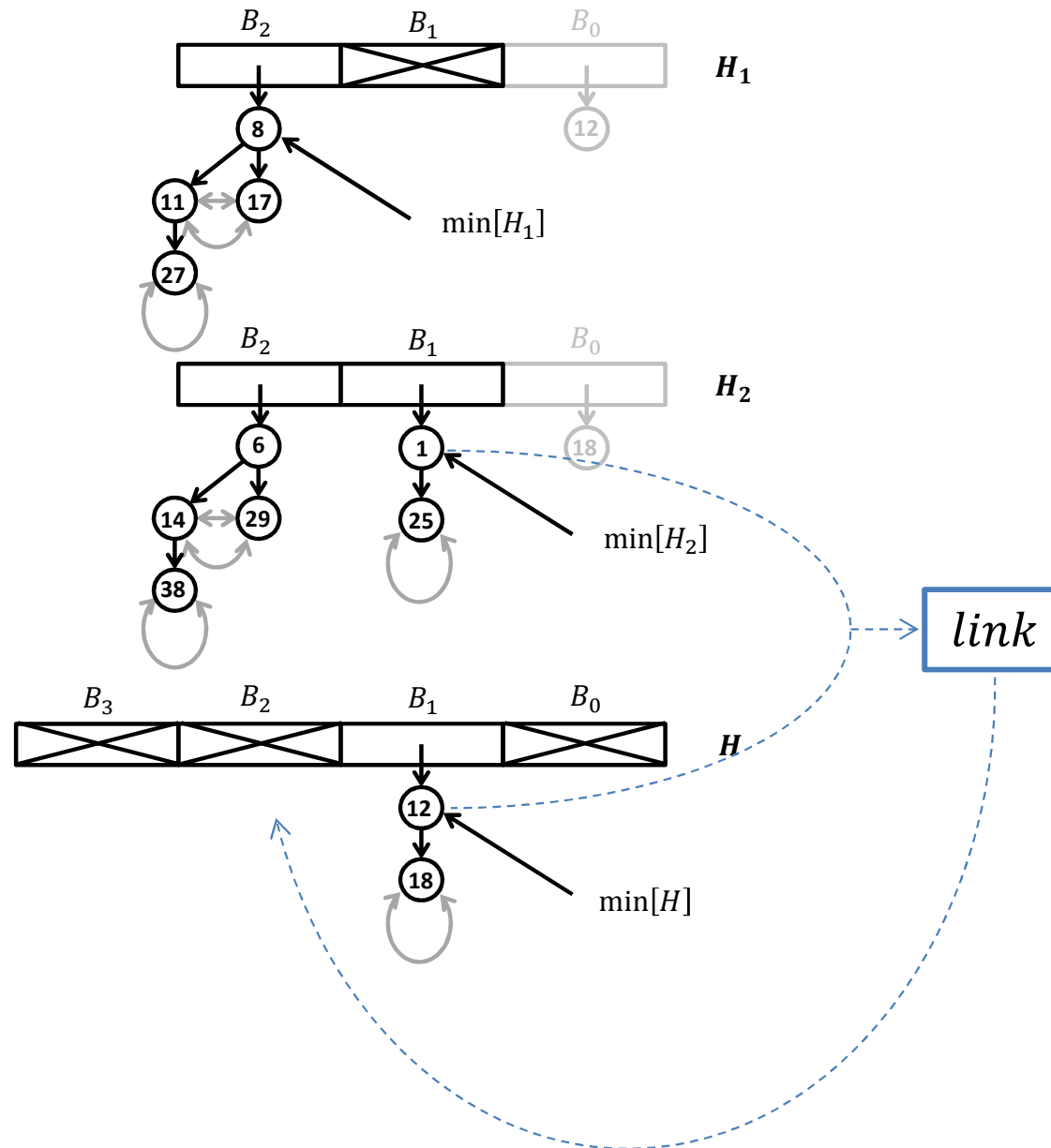
Binomial Heap Operations: UNION(H_1, H_2)



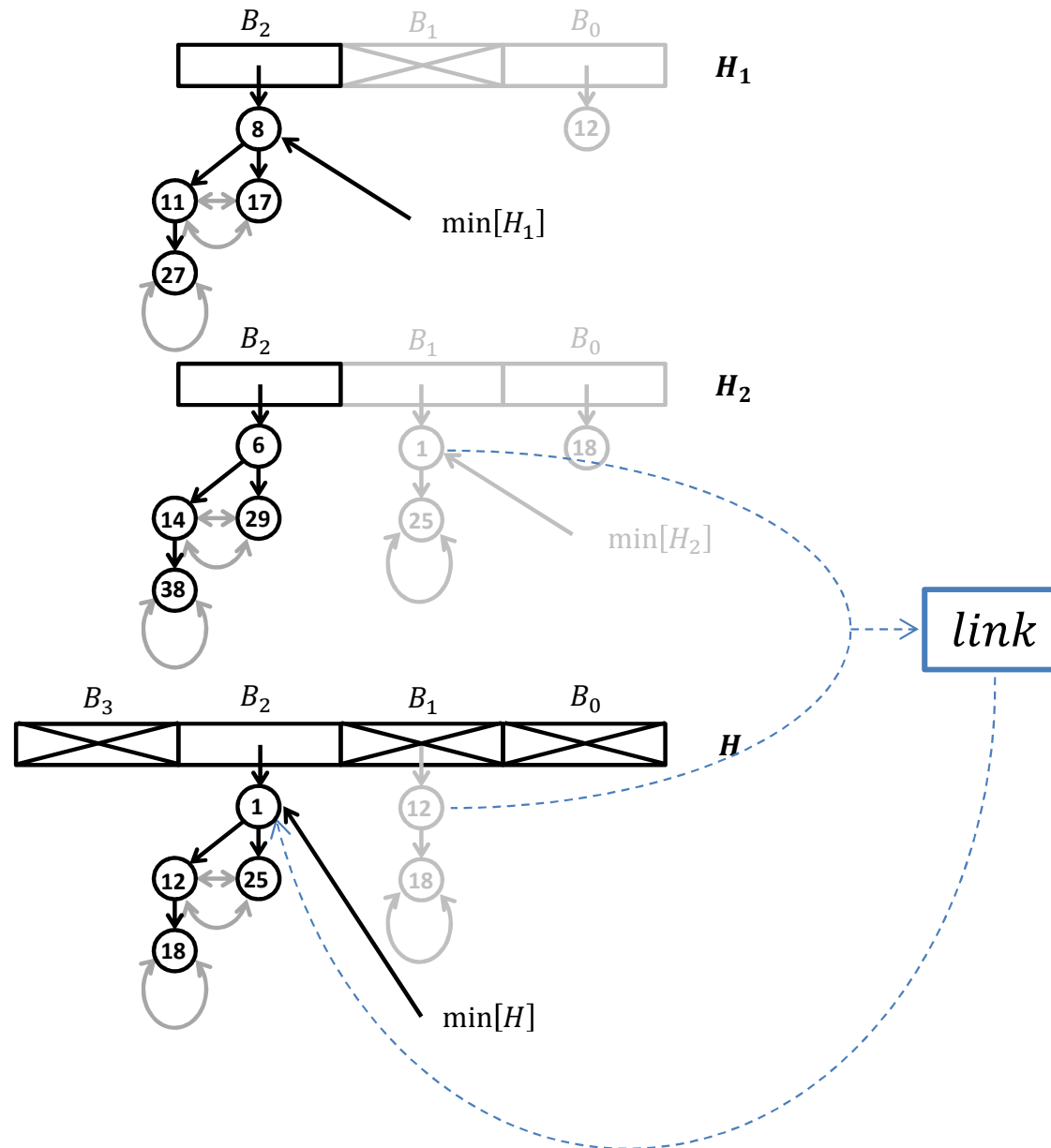
Binomial Heap Operations: UNION(H_1, H_2)



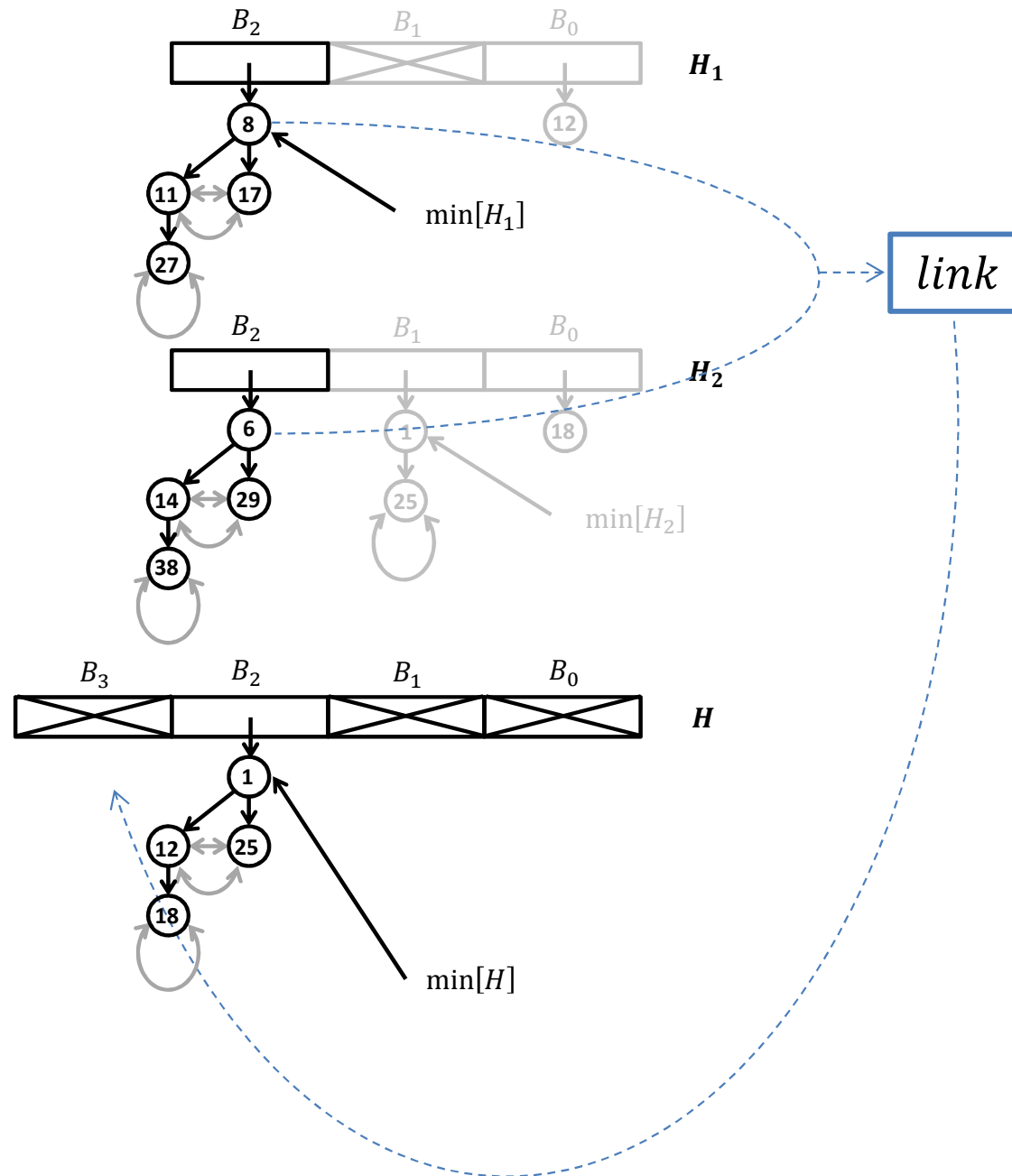
Binomial Heap Operations: UNION(H_1, H_2)



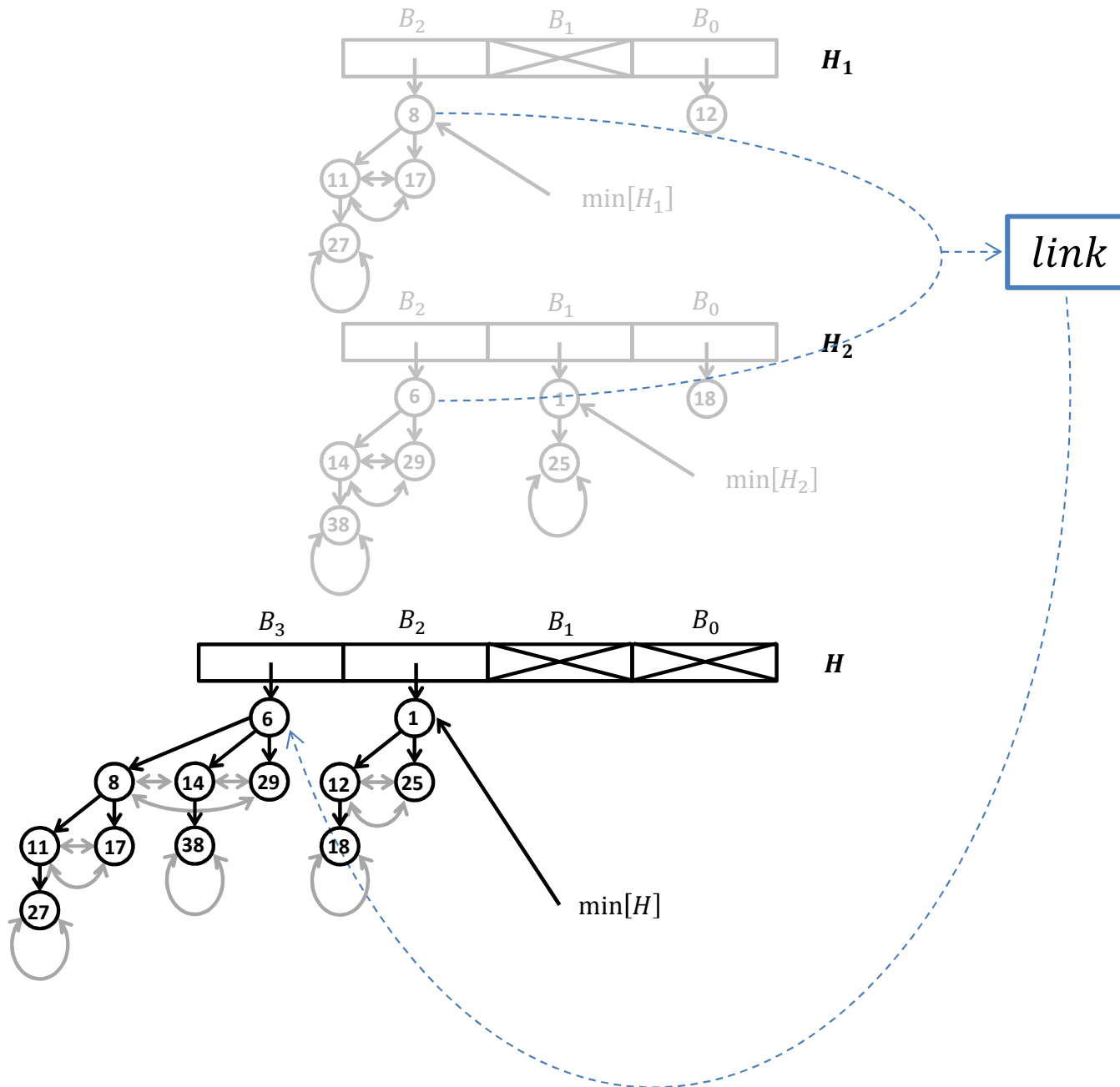
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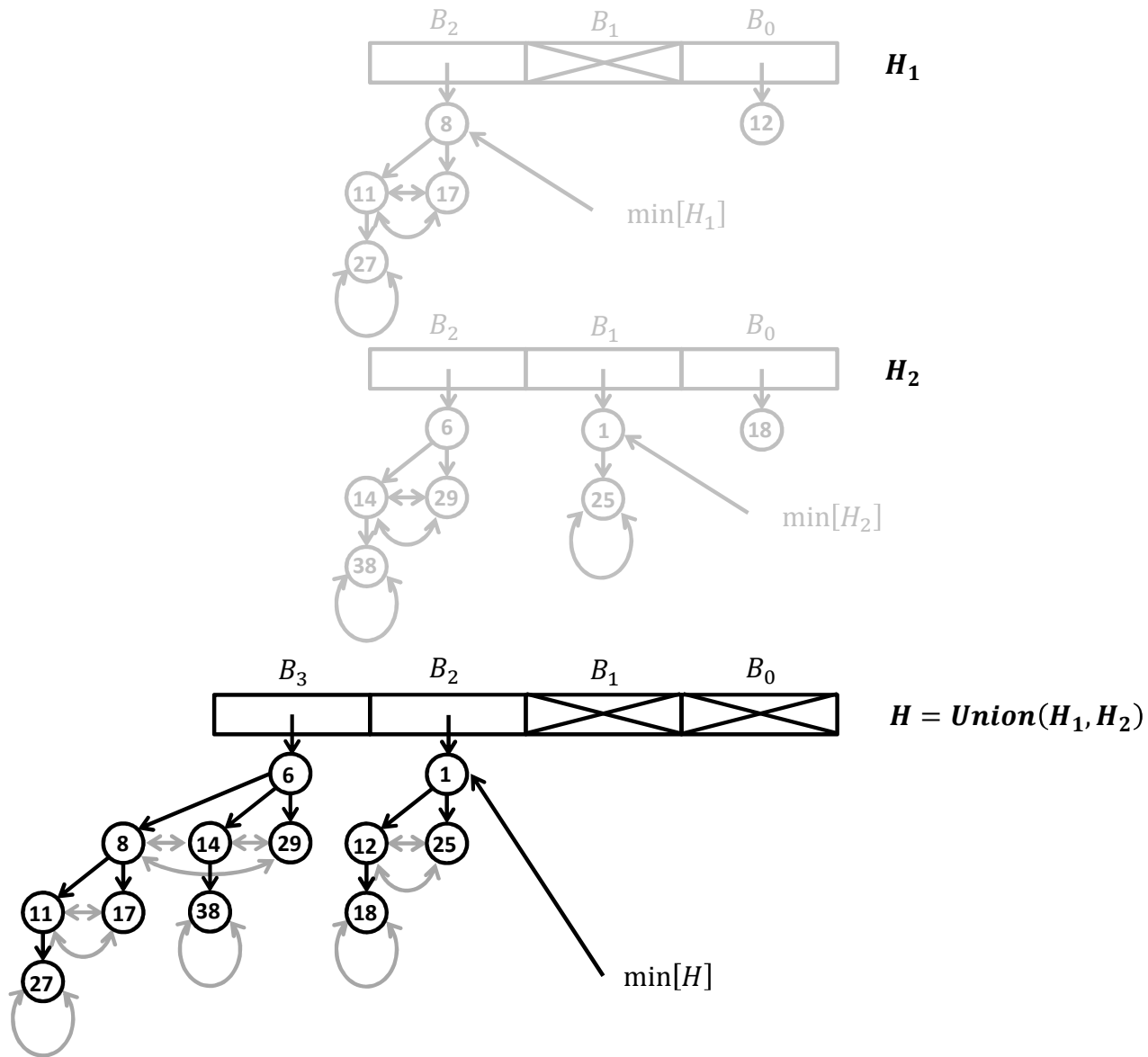
Binomial Heap Operations: UNION(H_1, H_2)



Binomial Heap Operations: UNION(H_1, H_2)



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Binomial Heap Operations: UNION(H_1, H_2)

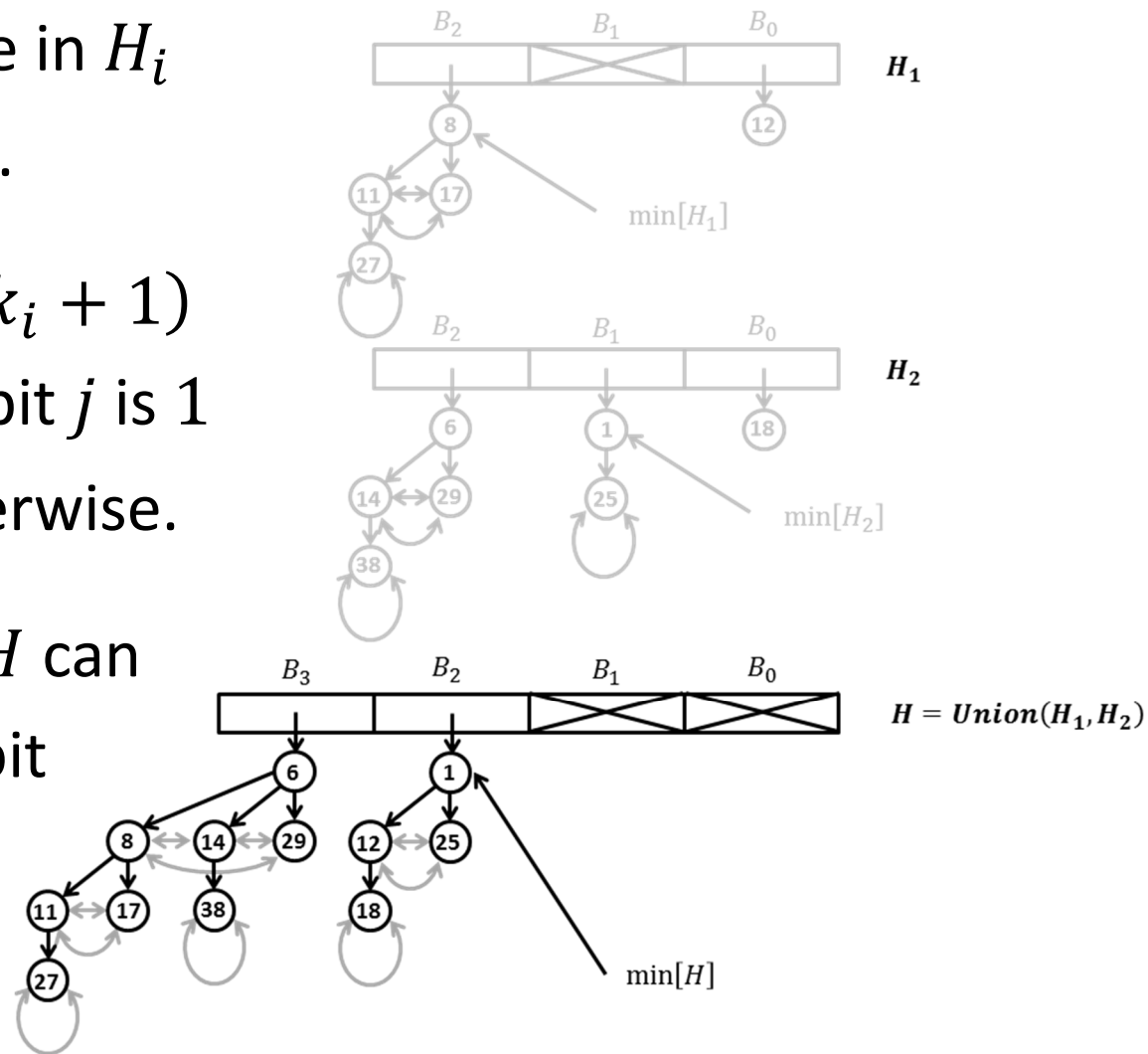
UNION(H_1, H_2) works in exactly the same way as binary addition.

Let n_i be the number of nodes in H_i ($i = 1, 2$).

Then the largest binomial tree in H_i is a B_{k_i} , where $k_i = \lfloor \log_2 n_i \rfloor$.

Thus H_i can be treated as a $(k_i + 1)$ bit binary number x_i , where bit j is 1 if H_i contains a B_j , and 0 otherwise.

If $H = \text{Union}(H_1, H_2)$, then H can be viewed as a $k = \lfloor \log_2 n \rfloor$ bit binary number $x = x_1 + x_2$, where $n = n_1 + n_2$.



Binomial Heap Operations: UNION(H_1, H_2)

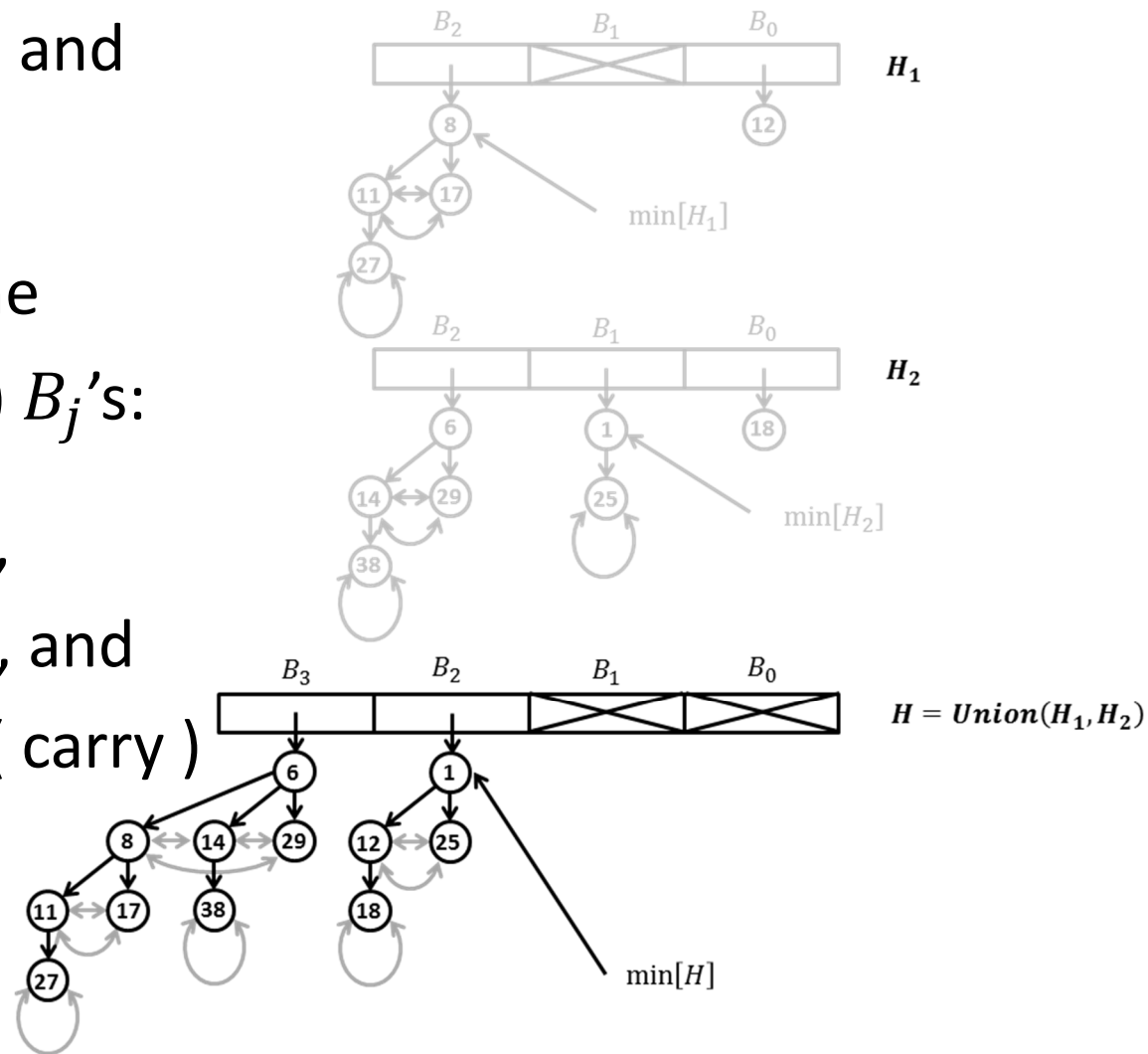
UNION(H_1, H_2) works in exactly the same way as binary addition.

Initially, H does not contain any binomial trees.

Melding starts from B_0 (LSB) and continues up to B_k (MSB).

At each location $j \in [0, k]$, one encounters at most three (3) B_j 's:

- at most 1 from H_1 (input),
- at most 1 from H_2 (input), and
- if $j > 0$, at most 1 from H (carry)

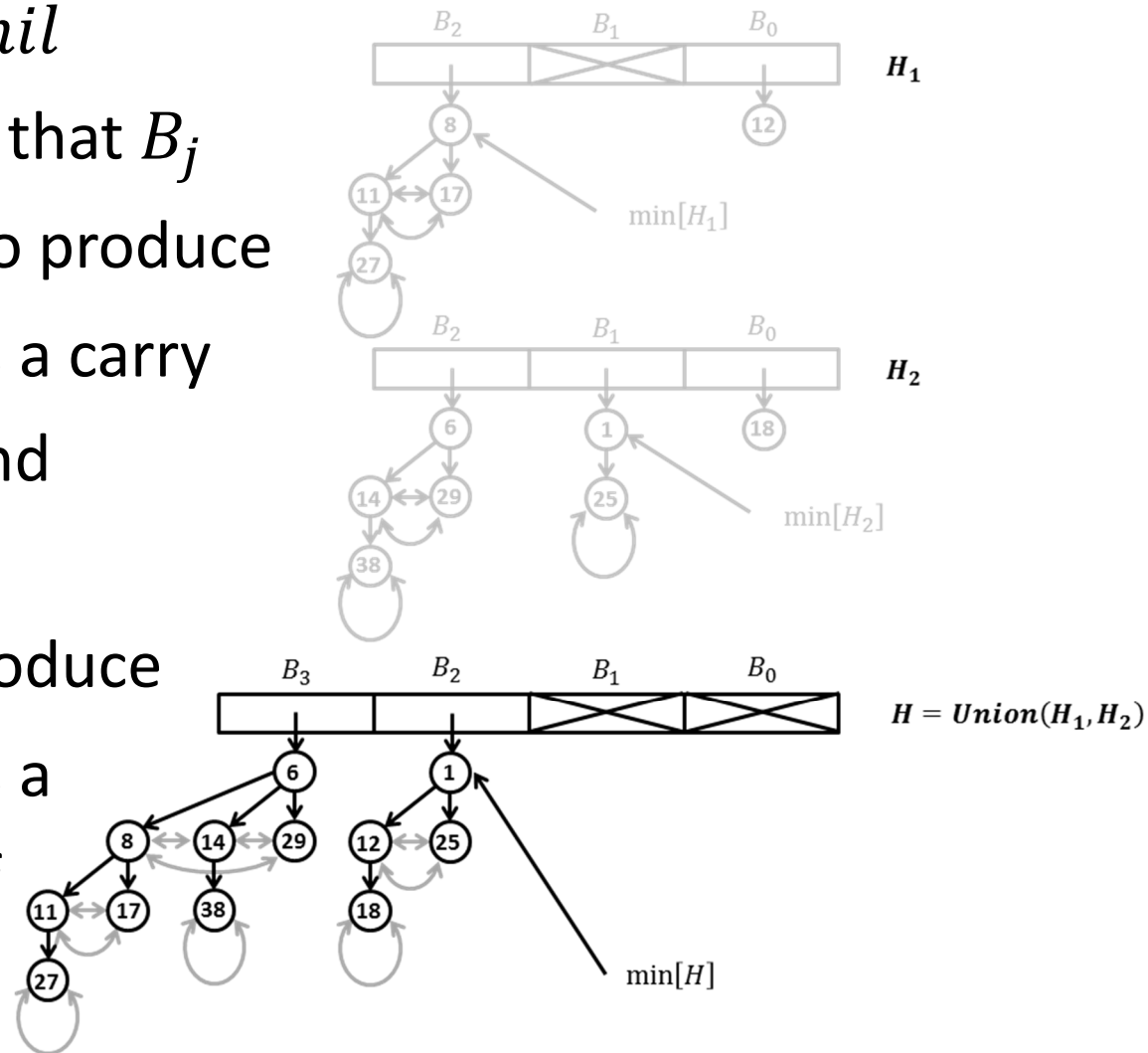


Binomial Heap Operations: UNION(H_1, H_2)

UNION(H_1, H_2) works in exactly the same way as binary addition.

When the number of B_j 's at location $j \in [0, k]$ is:

- 0: location j of H is set to *nil*
- 1: location j of H points to that B_j
- 2: the two B_j 's are linked to produce a B_{j+1} which is stored as a carry at location $j + 1$ of H , and location j is set to *nil*
- 3: two B_j 's are linked to produce a B_{j+1} which is stored as a carry at location $j + 1$ of H , and the 3rd B_j is stored at location j



Binomial Heap Operations: UNION(H_1, H_2)

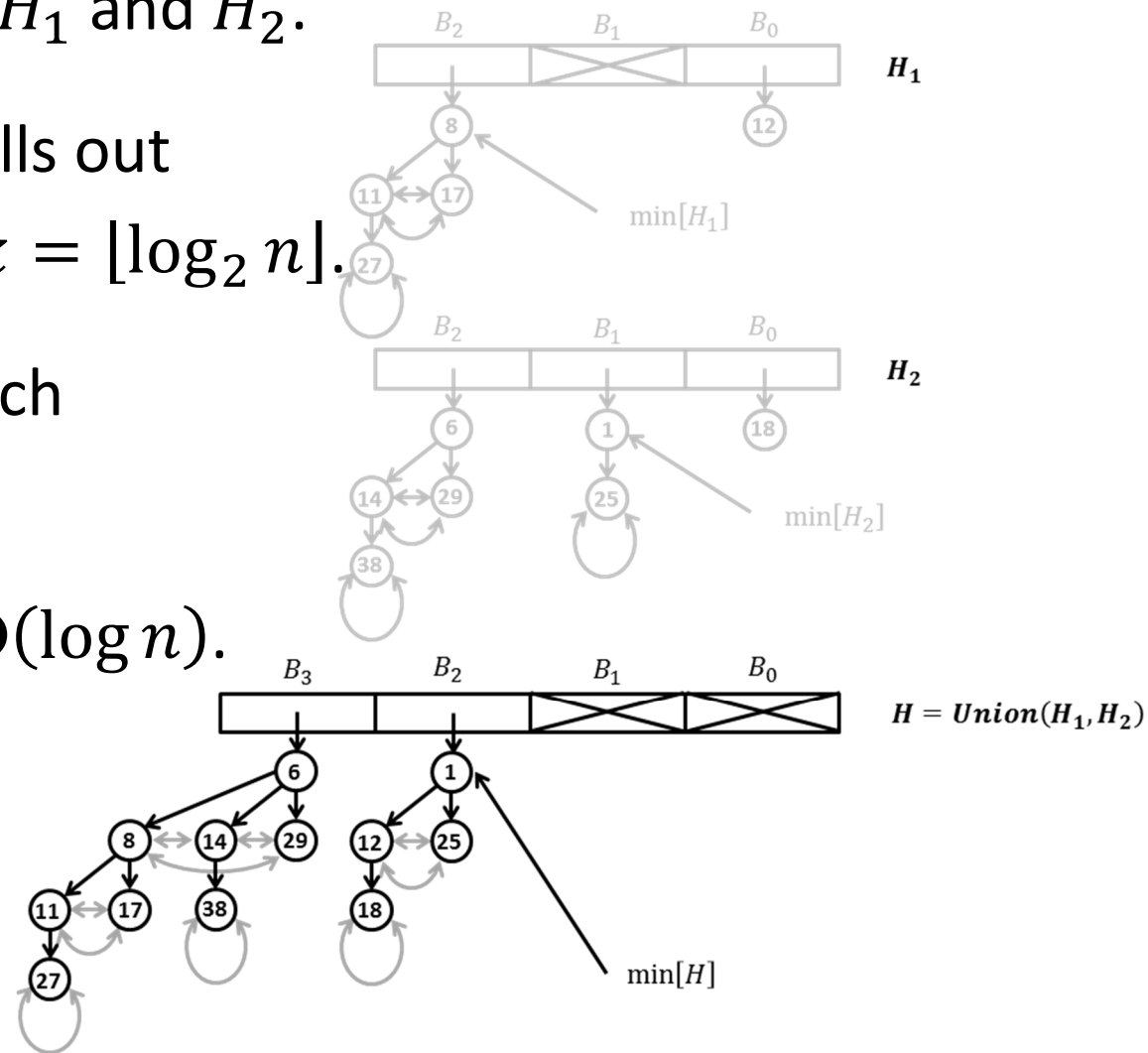
UNION(H_1, H_2) works in exactly the same way as binary addition.

Worst case cost of UNION(H_1, H_2) is clearly $\Theta(\log n)$, where n is the total number of nodes in H_1 and H_2 .

Observe that this operation fills out $k + 1$ locations of H , where $k = \lfloor \log_2 n \rfloor$.

It does only $\Theta(1)$ work for each location.

Hence, total cost is $\Theta(k) = \Theta(\log n)$.



Binomial Heap Operations: UNION(H_1, H_2)

One can improve the performance of UNION(H_1, H_2) as follows.

W.l.o.g., suppose H_2 is at least as large as H_1 , i.e., $n_2 \geq n_1$.

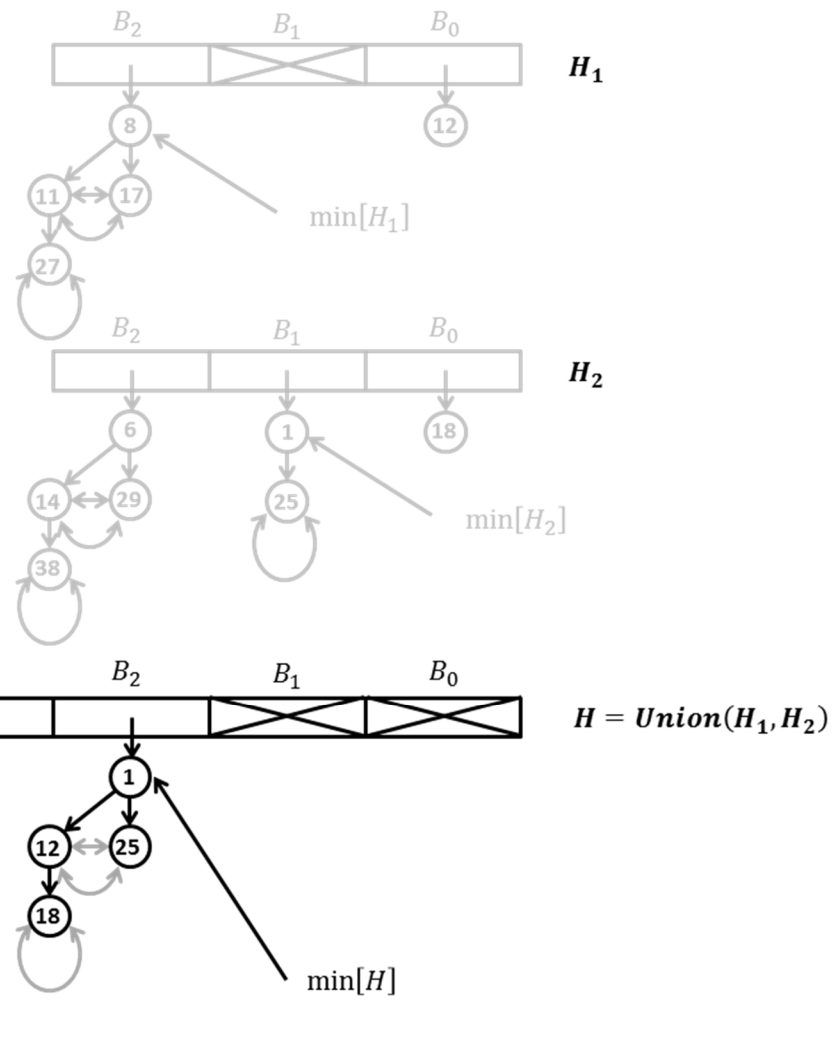
We also assume that H_2 has enough space to store at least up to B_k , where, $k = \lfloor \log_2(n_1 + n_2) \rfloor$.

Then instead of melding H_1 and H_2 to a new heap H , we can meld them in-place at H_2 .

After melding till B_{k_1} , we stop once the carry stops propagating.

The cost is $\Omega(k_1)$, but $O(k_2)$.

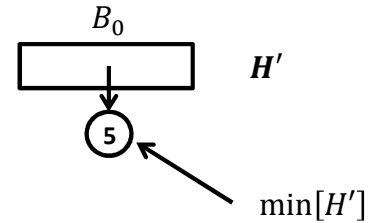
Worst-case cost is still $O(k) = O(\log n)$.



Binomial Heap Operations: INSERT(H, x)

Step 1: $H' \leftarrow \text{MAKE-HEAP}(x)$

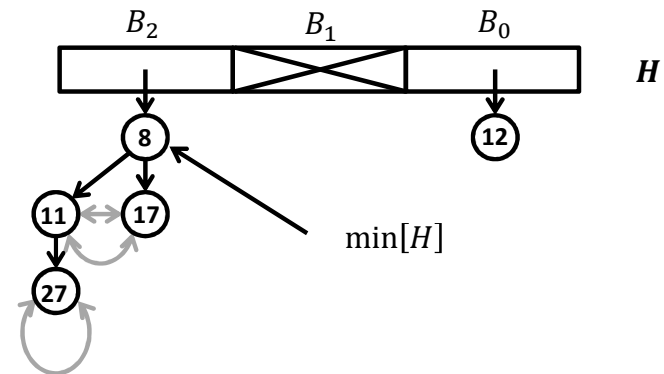
Takes $\Theta(1)$ time.



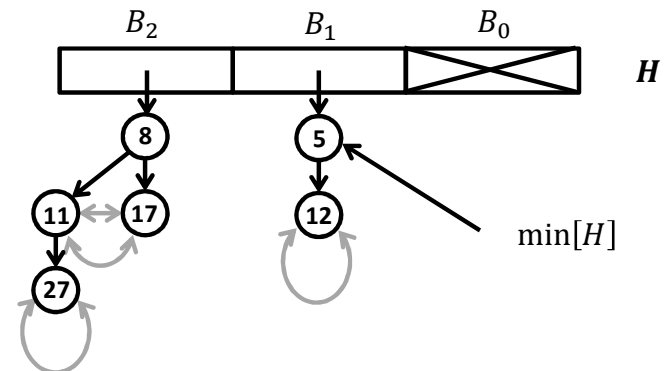
Step 2: $H \leftarrow \text{UNION}(H, H')$
(in-place at H)

Takes $O(\log n)$ time, where

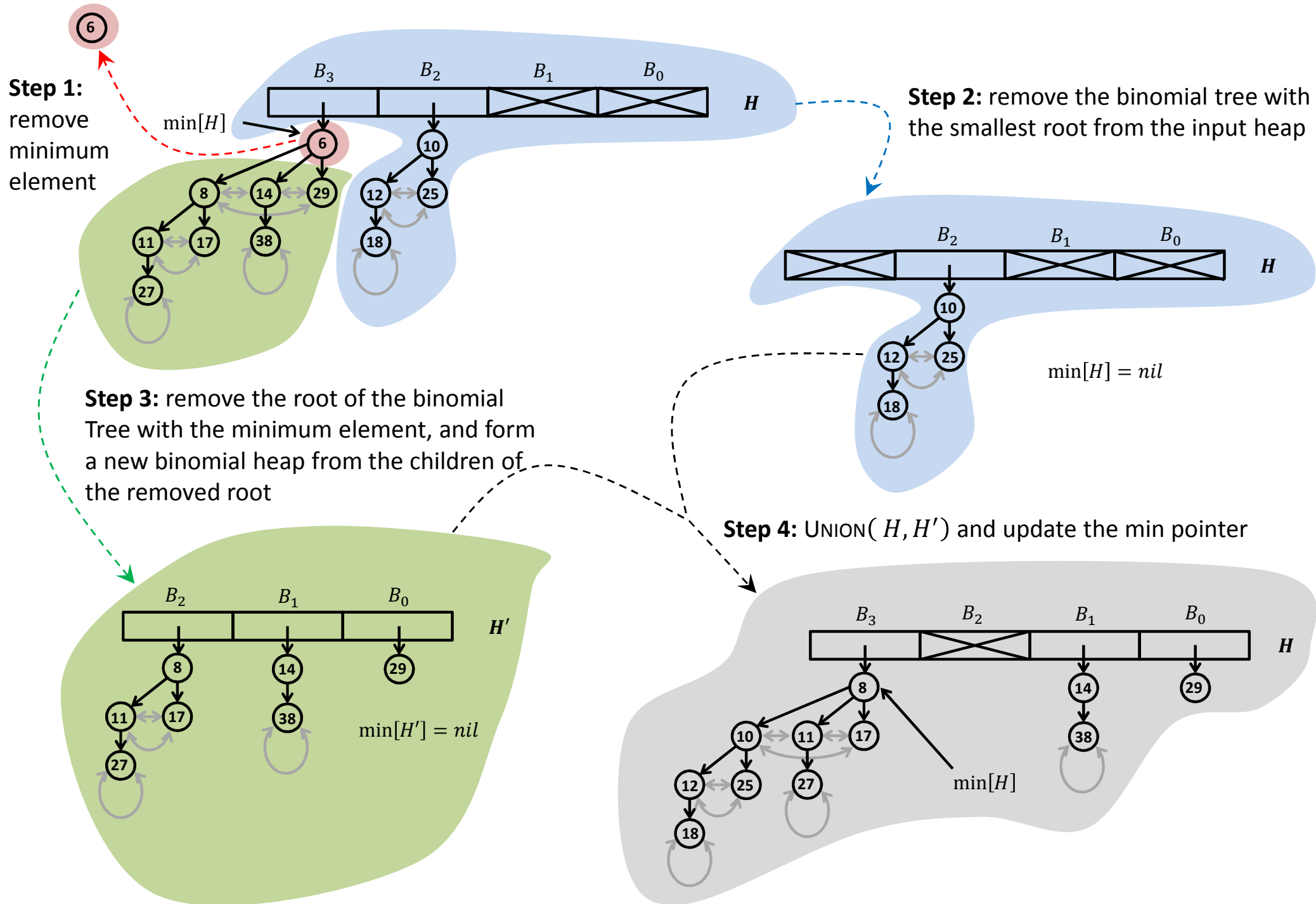
n is the number of nodes in H .



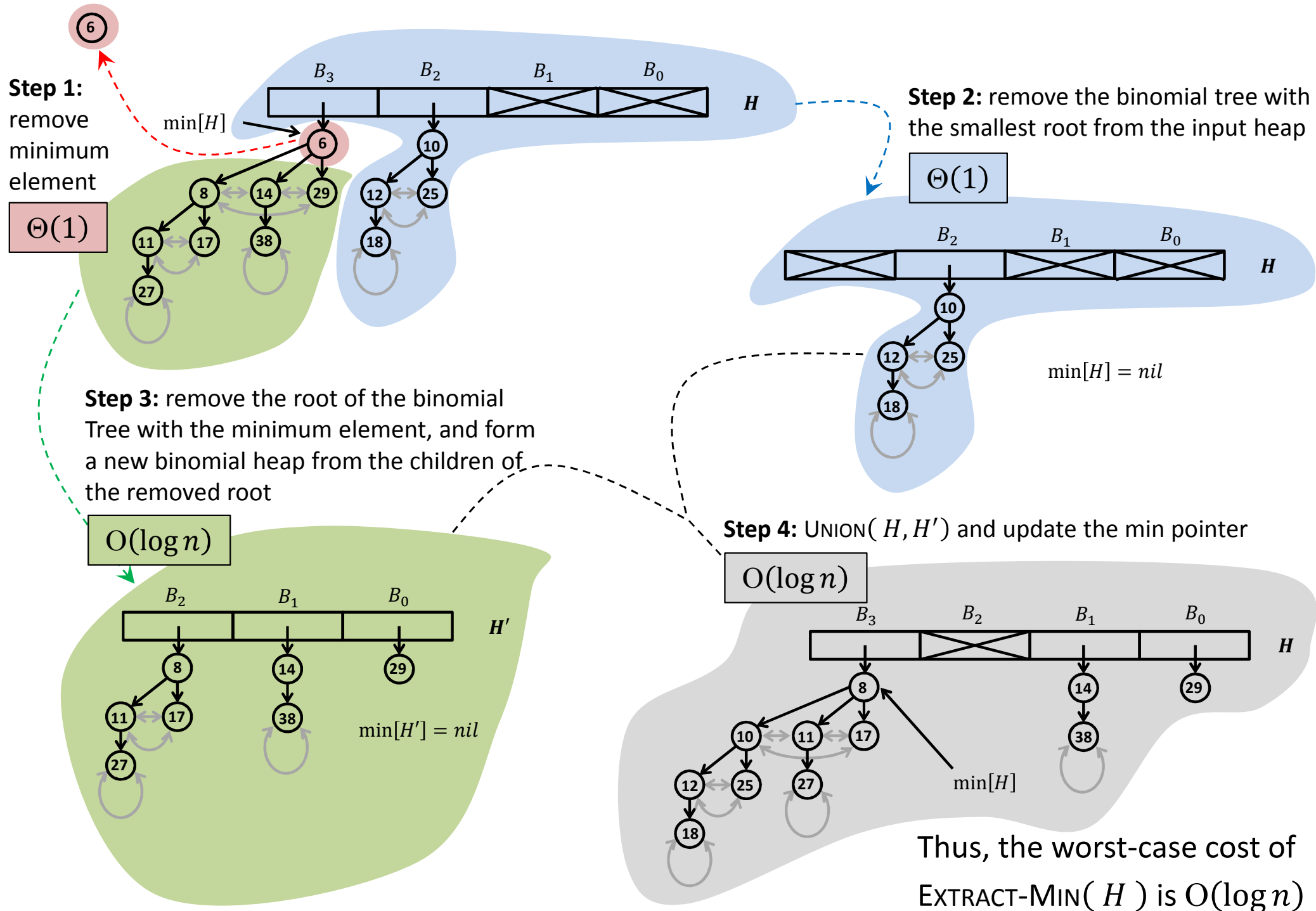
Thus the worst-case cost of $\text{INSERT}(H, x)$ is $O(\log n)$, where n is the number of items already in the heap.



Binomial Heap Operations: $\text{EXTRACT-MIN}(H)$



Binomial Heap Operations: **EXTRACT-MIN(H)**



Binomial Heap Operations

Heap Operation	Worst-case
MAKE-HEAP	$\Theta(1)$
INSERT	$O(\log n)$
MINIMUM	$\Theta(1)$
EXTRACT-MIN	$O(\log n)$
UNION	$O(\log n)$

Amortized Analysis (Accounting Method)

We maintain a credit account for every tree in the heap, and always maintain the following invariant:

$$\bigwedge_{B_j \in H} \text{credit}(B_j) = 1$$

MAKE-HEAP(x):

actual cost, $c_i = 1$ (for creating the singleton heap)

extra charge, $\delta_i = 1$ (for storing in the credit account
of the new tree)

amortized cost, $\hat{c}_i = c_i + \delta_i = 2 = \Theta(1)$

Amortized Analysis (Accounting Method)

We maintain a credit account for every tree in the heap, and always maintain the following invariant:

$$\bigwedge_{B_j \in H} \text{credit}(B_j) = 1$$

LINK($B_k^{(1)}$, $B_k^{(2)}$):

actual cost, $c_i = 1$ (for linking the two trees)

We use $\text{credit}(B_k^{(1)})$ pay for this actual work.

Let B_{k+1} be the newly created tree. We restore the credit invariant

by transferring $\text{credit}(B_k^{(2)})$ to $\text{credit}(B_{k+1})$.

Hence, amortized cost, $\hat{c}_i = c_i + \delta_i = 1 - 1 = 0$

Amortized Analysis (Accounting Method)

We maintain a credit account for every tree in the heap, and always maintain the following invariant:

$$\bigwedge_{B_j \in H} \text{credit}(B_j) = 1$$

INSERT(H, x):

Amortized cost of MAKE-HEAP(x) is = 2

Then UNION(H, H') is simply a sequence of free LINK operations with only a constant amount of additional work that do not create any new trees. Thus the credit invariant is maintained, and the amortized cost of this step is = 1.

Hence, amortized cost of INSERT, $\hat{c}_i = 2 + 1 = 3 = \Theta(1)$

Amortized Analysis (Accounting Method)

We maintain a credit account for every tree in the heap, and always maintain the following invariant:

$$\bigwedge_{B_j \in H} \text{credit}(B_j) = 1$$

UNION(H_1, H_2):

UNION(H_1, H_2) includes a sequence of free LINK operations that maintain the credit invariant.

But it also includes $O(\log n)$ other operations that are not free (e.g., consider melding a heap with $n = 2^k$ elements with one containing $n - 1$ elements). These operations do not create new trees (and so do not violate the credit invariant), and each cost $\Theta(1)$.

Hence, amortized cost of UNION, $\hat{c}_i = O(\log n)$

Amortized Analysis (Accounting Method)

We maintain a credit account for every tree in the heap, and always maintain the following invariant:

$$\bigwedge_{B_j \in H} \text{credit}(B_j) = 1$$

EXTRACT-MIN(H):

Steps 1 & 2: The $\Theta(1)$ actual cost is paid for by the credit released by the deleted tree.

Step 3: Exposes $O(\log n)$ new trees, and we charge 1 unit of extra credit for storing in the credit account of each such tree.

Step 4: Performs a UNION that has $O(\log n)$ amortized cost.

Hence, amortized cost of EXTRACT-MIN, $\hat{c}_i = O(\log n)$

Amortized Analysis (Potential Method)

Potential Function,

$$\Phi(D_i) = c \times (\text{\#trees in the data structure after the } i\text{-th operation}),$$

where c is a constant.

Clearly, $\Phi(D_0) = 0$ (no trees in the data structure initially)

and for all $i > 0$, $\Phi(D_i) \geq 0$ (#trees cannot be negative)

MAKE-HEAP(x):

actual cost, $c_i = 1$ (for creating the singleton heap)

potential change, $\Delta_i = \Phi(D_i) - \Phi(D_{i-1}) = c$

(as #trees increases by 1)

amortized cost, $\hat{c}_i = c_i + \Delta_i = 1 + c = \Theta(1)$

Amortized Analysis (Potential Method)

Potential Function,

$$\Phi(D_i) = c \times (\text{\#trees in the data structure after the } i\text{-th operation}),$$

where c is a constant.

INSERT(H, x):

The number of trees increases by 1 initially.

Then the operation scans $k > 0$ (say) locations of the array of tree pointers. Observe that we use tree linking $(k - 1)$ times each of which reduces the number of trees by 1.

$$\text{actual cost, } c_i = 1 + k$$

$$\begin{aligned} \text{potential change, } \Delta_i &= \Phi(D_i) - \Phi(D_{i-1}) = c(1 - (k - 1)) \\ &= c - c(k - 1) \end{aligned}$$

$$\text{amortized cost, } \hat{c}_i = c_i + \Delta_i = 2 + c - (c - 1)(k - 1)$$

$$\text{For } c \geq 1, \text{ we have, } \hat{c}_i \leq 2 + c = \Theta(1)$$

Amortized Analysis (Potential Method)

Potential Function,

$$\Phi(D_i) = c \times (\text{\#trees in the data structure after the } i\text{-th operation}),$$

where c is a constant.

UNION(H_1, H_2):

Suppose the operation scans $k > 0$ locations of the array of tree pointers, and uses the link operation l times. Observe that $k > l \geq 0$. Each link reduces the number of trees by 1.

actual cost, $c_i = k$

potential change, $\Delta_i = \Phi(D_i) - \Phi(D_{i-1}) = -c \times l$

amortized cost, $\hat{c}_i = c_i + \Delta_i = k - c \times l$

Since $k = O(\log n)$ and $l = O(\log n)$, we have,

$\hat{c}_i = O(\log n)$ for any c .

Amortized Analysis (Potential Method)

Potential Function,

$$\Phi(D_i) = c \times (\text{\#trees in the data structure after the } i\text{-th operation}),$$

where c is a constant.

EXTRACT-MIN(H):

Let in Step 1: r = rank of the tree with the smallest key

and in Step 4: k = #locations of pointer array scanned during UNION

l = #link operations during UNION

t = #trees in the heap after the UNION

$$\begin{aligned} \text{Then actual cost, } c_i &= 1 \text{ (step 1)} + 1 \text{ (step 2)} + r \text{ (step 3)} \\ &+ k \text{ (step 4: union)} + t \text{ (step 4: update } \mathit{min} \text{ ptr)} \\ &= 2 + k + t + r \end{aligned}$$

Amortized Analysis (Potential Method)

Potential Function,

$$\Phi(D_i) = c \times (\text{\#trees in the data structure after the } i\text{-th operation}),$$

where c is a constant.

EXTRACT-MIN(H):

Let in Step 1: $r =$ rank of the tree with the smallest key

and in Step 4: $k =$ #locations of pointer array scanned during UNION

$l =$ #link operations during UNION

$t =$ #trees in the heap after the UNION

potential change, $\Delta_i = \Phi(D_i) - \Phi(D_{i-1})$

$= c \times (r - 1)$ (removing *min* element in step 1
removes 1 tree but creates r new ones)

$-c \times l$ (linkings in step 4
reduces #trees by l)

Amortized Analysis (Potential Method)

Potential Function,

$$\Phi(D_i) = c \times (\text{\#trees in the data structure after the } i\text{-th operation}),$$

where c is a constant.

EXTRACT-MIN(H):

Let in Step 1: $r =$ rank of the tree with the smallest key

and in Step 4: $k =$ #locations of pointer array scanned during UNION

$l =$ #link operations during UNION

$t =$ #trees in the heap after the UNION

actual cost, $c_i = 2 + k + t + r$

potential change, $\Delta_i = \Phi(D_i) - \Phi(D_{i-1}) = c \times (r - l - 1)$

Then amortized cost, $\hat{c}_i = c_i + \Delta_i = 2 + k + t + r + c \times (r - l - 1)$

Since $k = O(\log n)$, $l = O(\log n)$, $t = O(\log n)$ & $r = O(\log n)$,

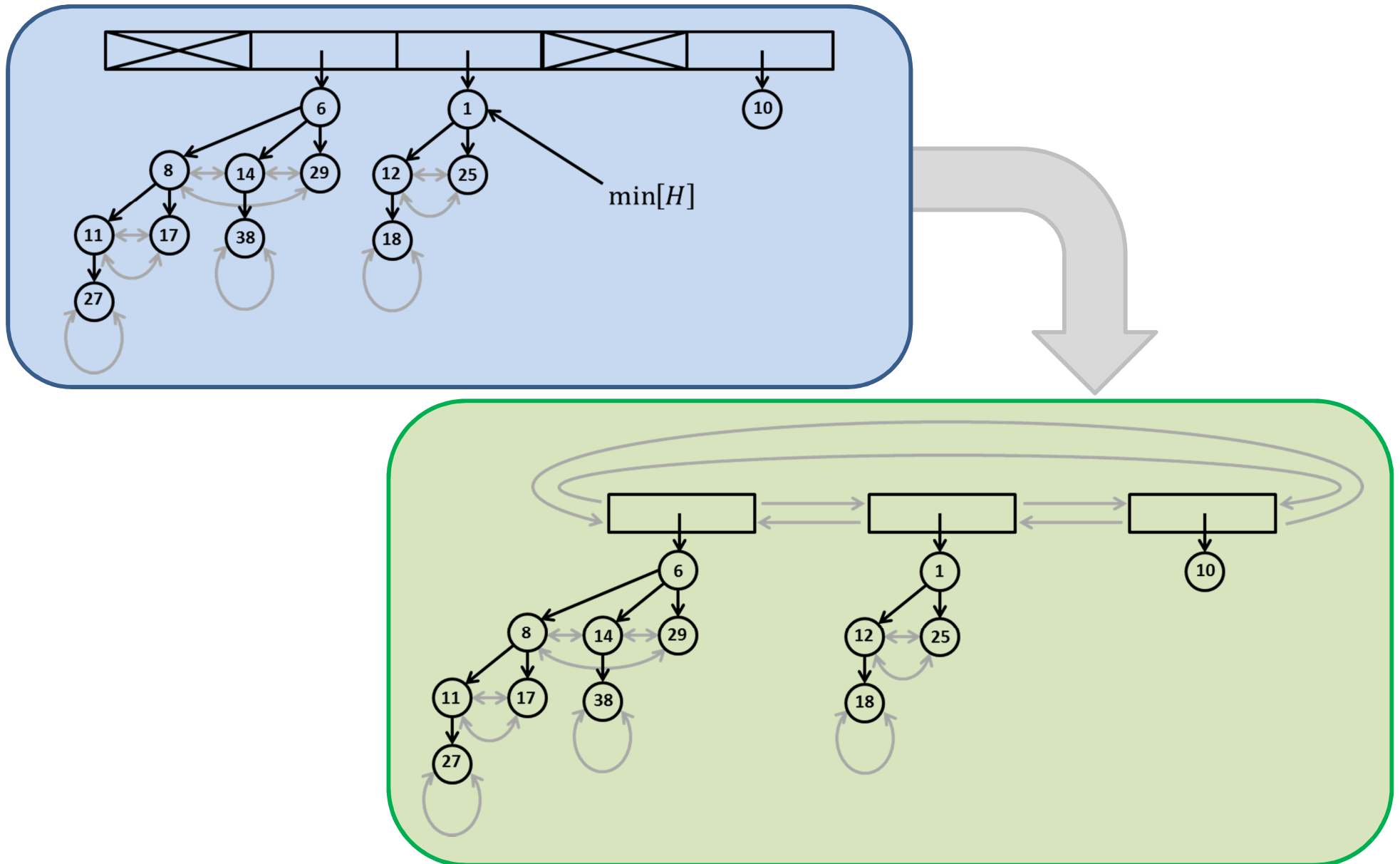
we have, $\hat{c}_i = O(\log n)$ for any c .

Binomial Heap Operations

Heap Operation	Worst-case	Amortized
MAKE-HEAP	$\Theta(1)$	$\Theta(1)$
INSERT	$O(\log n)$	$\Theta(1)$
MINIMUM	$\Theta(1)$	$\Theta(1)$
EXTRACT-MIN	$O(\log n)$	$O(\log n)$
UNION	$O(\log n)$	$O(\log n)$

Binomial Heaps with Lazy Union

We maintain pointers to the trees in a doubly linked circular list (instead of an array), but do not maintain a *min* pointer.



Binomial Heap Operations with Lazy Union

We maintain the following invariant:

$$\bigwedge_{B_j \in H} \text{credit}(B_j) = 2$$

MAKE-HEAP(x): Create a singleton heap as before. Hence, amortized cost = $\Theta(1)$.

LINK($B_k^{(1)}, B_k^{(2)}$): The two input trees have 4 units of saved credits of which 1 unit will be used to pay for the actual cost of linking, and 2 units will be saved as credit for the newly created tree. So, linking is still free, and it has 1 unused credit that can be used to pay for additional work if necessary.

UNION(H_1, H_2): Simply concatenate the two root lists into one, and update the min pointer. Clearly, amortized cost = $\Theta(1)$.

INSERT(H, x): This is MAKE-HEAP followed by a UNION. Hence, amortized cost = $\Theta(1)$.

Binomial Heap Operations with Lazy Union

We maintain the following invariant:

$$\bigwedge_{B_j \in H} \text{credit}(B_j) = 2$$

EXTRACT-MIN(H): Unlike in the array version, in this case we may have several trees of the same rank.

We create an array of length $\lfloor \log_2 n \rfloor + 1$ with each location containing a *nil* pointer. We use this array to transform the linked list version to array version.

We go through the list of trees of H , inserting them one by one into the array, and linking and carrying if necessary so that finally we have at most one tree of each rank. We also create a min pointer.

We now perform EXTRACT-MIN as in the array case.

Finally, we collect the nonempty trees from the array into a doubly linked list, and return.

Binomial Heap Operations with Lazy Union

We maintain the following invariant:

$$\bigwedge_{B_j \in H} \text{credit}(B_j) = 2$$

EXTRACT-MIN(H): We only need to show that converting from linked list version to array version takes $O(\log n)$ amortized time.

Suppose we start with t trees, and perform l links. So, we spend $O(t + l)$ time overall.

As each link decreases the number of trees by 1, after l links we end up with $t - l$ trees. Since at that point we have at most one tree of each rank, we have $t - l \leq \lfloor \log_2 n \rfloor + 1$.

Thus $t + l = 2l + (t - l) = O(l + \log n)$.

The $O(l)$ part can be paid for by the l extra credits from l links.

We only charge the $O(\log n)$ part to EXTRACT-MIN.

Binomial Heap Operations with Lazy Union

We use exactly the same potential function as in the previous version,

$$\Phi(D_i) = c \times (\text{\#trees in the data structure after the } i\text{-th operation}),$$

where c is a constant.

As before, clearly, $\Phi(D_0) = 0$

and for all $i > 0$, $\Phi(D_i) \geq 0$

MAKE-HEAP(x):

actual cost, $c_i = 1$ (for creating the singleton heap)

potential change, $\Delta_i = \Phi(D_i) - \Phi(D_{i-1}) = c$

(as #trees increases by 1)

amortized cost, $\hat{c}_i = c_i + \Delta_i = 1 + c = \Theta(1)$

Binomial Heap Operations with Lazy Union

We use exactly the same potential function as in the previous version,

$$\Phi(D_i) = c \times (\text{\#trees in the data structure after the } i\text{-th operation}),$$

where c is a constant.

UNION(H_1, H_2):

actual cost, $c_i = 1$ (for merging the two doubly linked lists)

potential change, $\Delta_i = \Phi(D_i) - \Phi(D_{i-1}) = 0$

(no new tree is created or destroyed)

amortized cost, $\hat{c}_i = c_i + \Delta_i = 1 = \Theta(1)$

Binomial Heap Operations with Lazy Union

We use exactly the same potential function as in the previous version,

$$\Phi(D_i) = c \times (\text{\#trees in the data structure after the } i\text{-th operation}),$$

where c is a constant.

INSERT(H, x):

Constant amount of work is done by MAKE-HEAP and UNION, and MAKE-HEAP creates a new tree.

$$\text{actual cost, } c_i = 1 + 1 = 2$$

$$\text{potential change, } \Delta_i = \Phi(D_i) - \Phi(D_{i-1}) = c$$

$$\text{amortized cost, } \hat{c}_i = c_i + \Delta_i = 2 + c = \Theta(1)$$

Binomial Heap Operations with Lazy Union

We use exactly the same potential function as in the previous version,

$$\Phi(D_i) = c \times (\text{\#trees in the data structure after the } i\text{-th operation}),$$

where c is a constant.

EXTRACT-MIN(H):

Cost of creating the array of pointers is $\lfloor \log_2 n \rfloor + 1$.

Suppose we start with t trees in the doubly linked list, and perform l link operations during the conversion from linked list to array version.

So we perform $t + l$ work, and end up with $t - l$ trees.

Cost of converting to the linked list version is $t - l$.

actual cost, $c_i = \lfloor \log_2 n \rfloor + 1 + (t + l) + (t - l) = 2t + \lfloor \log_2 n \rfloor + 1$

potential change, $\Delta_i = \Phi(D_i) - \Phi(D_{i-1}) = -c \times l$

Binomial Heap Operations with Lazy Union

We use exactly the same potential function as in the previous version,

$$\Phi(D_i) = c \times (\text{\#trees in the data structure after the } i\text{-th operation}),$$

where c is a constant.

EXTRACT-MIN(H):

$$\text{actual cost, } c_i = \lfloor \log_2 n \rfloor + 1 + (t + l) + (t - l) = 2t + \lfloor \log_2 n \rfloor + 1$$

$$\text{potential change, } \Delta_i = \Phi(D_i) - \Phi(D_{i-1}) = -c \times l$$

$$\text{amortized cost, } \hat{c}_i = c_i + \Delta_i = 2(t - l) + \lfloor \log_2 n \rfloor + 1 - (c - 2) \times l$$

But $t - l \leq \lfloor \log_2 n \rfloor + 1$ (as we have at most one tree of each rank)

$$\begin{aligned} \text{So, } \hat{c}_i &\leq 3\lfloor \log_2 n \rfloor + 3 - (c - 2) \times l \\ &\leq 3\lfloor \log_2 n \rfloor + 3 \quad (\text{assuming } c \geq 2) \\ &= O(\log n) \end{aligned}$$

Binomial Heap Operations

Heap Operation	Worst-case	Amortized (Eager Union)	Amortized (Lazy Union)
MAKE-HEAP	$\Theta(1)$	$\Theta(1)$	$\Theta(1)$
INSERT	$O(\log n)$	$\Theta(1)$	$\Theta(1)$
MINIMUM	$\Theta(1)$	$\Theta(1)$	$\Theta(1)$
EXTRACT-MIN	$O(\log n)$	$O(\log n)$	$O(\log n)$
UNION	$O(\log n)$	$O(\log n)$	$\Theta(1)$