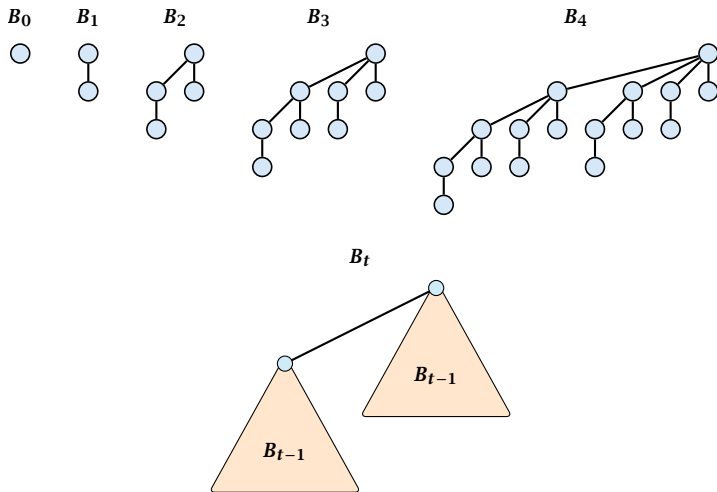


8.2 Binomial Heaps

<i>Operation</i>	<i>Binary Heap</i>	<i>BST</i>	<i>Binomial Heap</i>	<i>Fibonacci Heap*</i>
build	n	$n \log n$	$n \log n$	n
minimum	1	$\log n$	$\log n$	1
is-empty	1	1	1	1
insert	$\log n$	$\log n$	$\log n$	1
delete	$\log n^{**}$	$\log n$	$\log n$	$\log n$
delete-min	$\log n$	$\log n$	$\log n$	$\log n$
decrease-key	$\log n$	$\log n$	$\log n$	1
merge	n	$n \log n$	$\log n$	1

Binomial Trees



Binomial Trees

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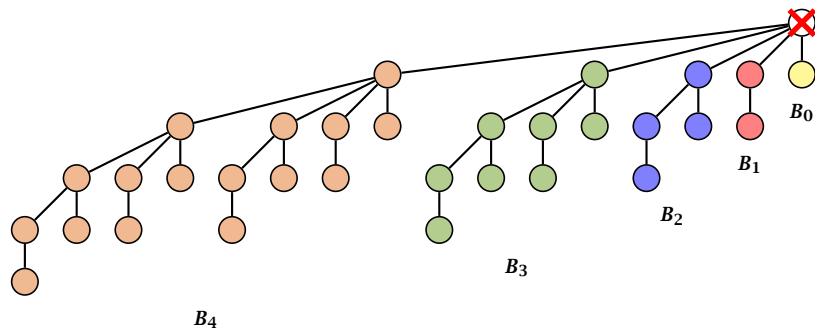
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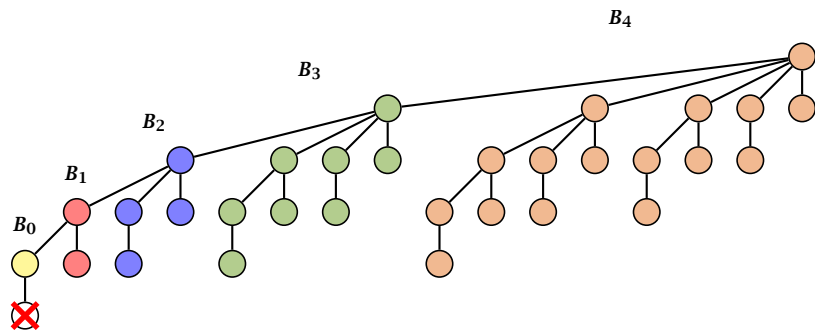
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- ▶ The root of B_k has degree k .
- ▶ B_k has $\binom{k}{\ell}$ nodes on level ℓ .
- ▶ Deleting the root of B_k gives trees B_0, B_1, \dots, B_{k-1} .

Binomial Trees



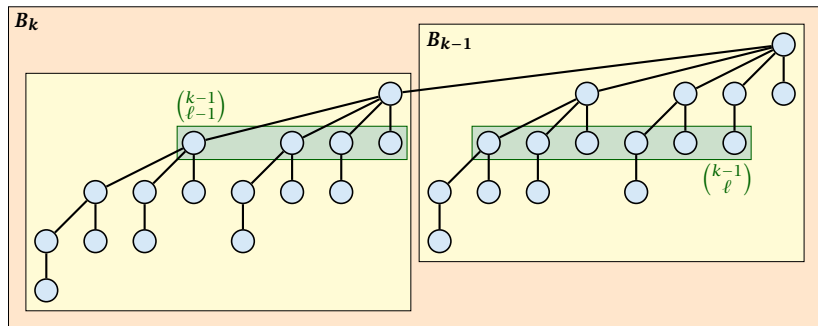
Deleting the root of B_5 leaves sub-trees B_4 , B_3 , B_2 , B_1 , and B_0 .

Binomial Trees



Deleting the leaf furthest from the root (in B_5) leaves a path that connects the roots of sub-trees B_4 , B_3 , B_2 , B_1 , and B_0 .

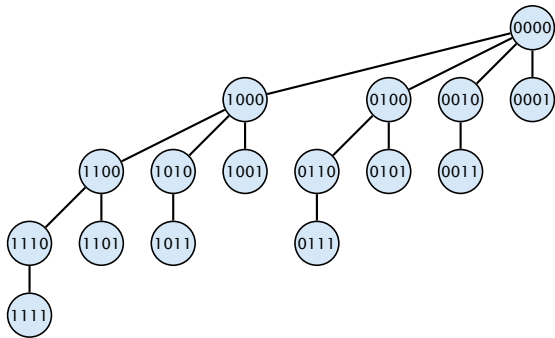
Binomial Trees



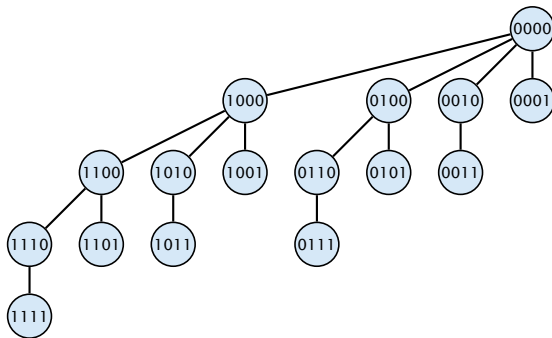
The number of nodes on level ℓ in tree B_k is therefore

$$\binom{k-1}{\ell-1} + \binom{k-1}{\ell} = \binom{k}{\ell}$$

Binomial Trees

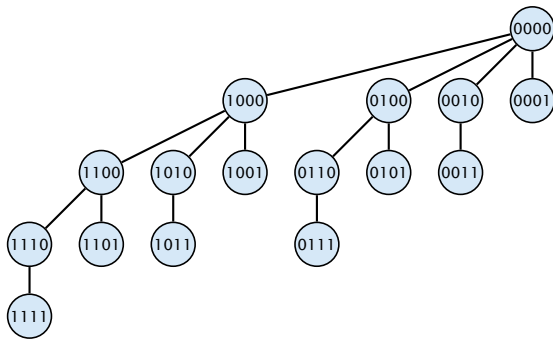


Binomial Trees



The binomial tree B_k is a sub-graph of the hypercube H_k .

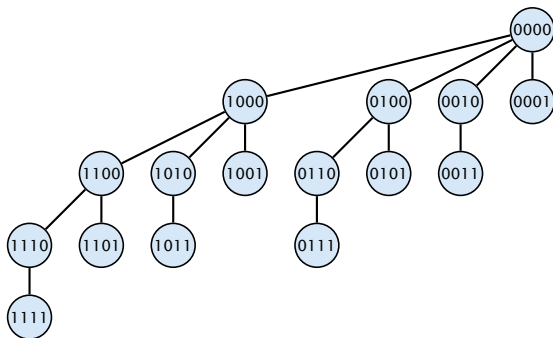
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The parent of a node with label b_k, \dots, b_1 is obtained by setting the least significant 1-bit to 0.

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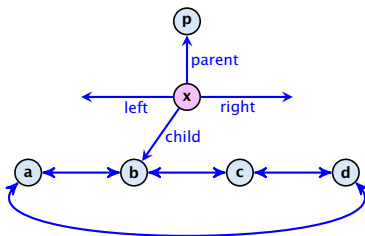
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The ℓ -th level contains nodes that have ℓ 1's in their label.

8.2 Binomial Heaps

How do we implement trees with non-constant degree?

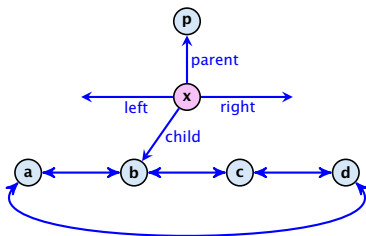
- ▶ The children of a node are arranged in a **circular linked list**.



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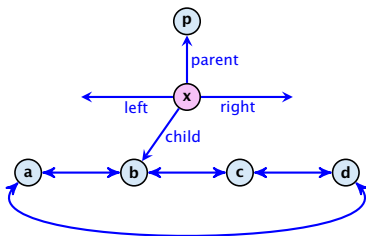
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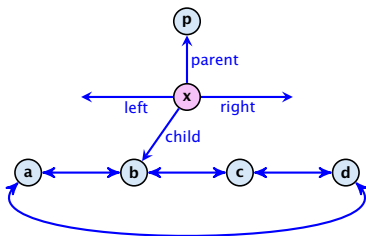
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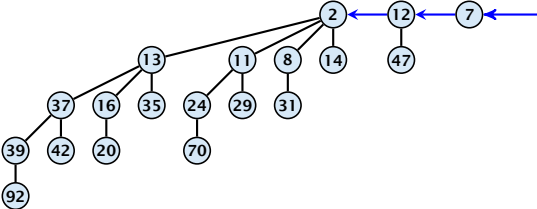
- ▶ The children of a node are arranged in a **circular linked list**.
- ▶ A child-pointer points to an arbitrary node within the list.
- ▶ A parent-pointer points to the parent node.
- ▶ Pointers $x.left$ and $x.right$ point to the left and right sibling of x (if x does not have siblings then $x.left = x.right = x$).



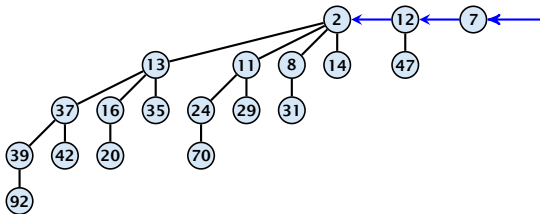
8.2 Binomial Heaps

- ▶ Given a pointer to a node x we can splice out the sub-tree rooted at x in constant time.
- ▶ We can add a child-tree T to a node x in constant time if we are given a pointer to x and a pointer to the root of T .

Binomial Heap

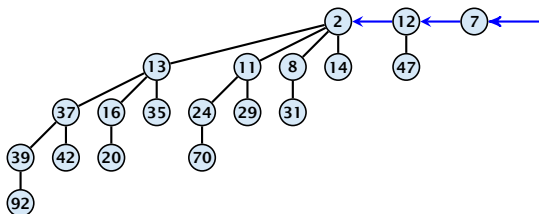


Binomial Heap



In a binomial heap the keys are arranged in a collection of binomial trees.

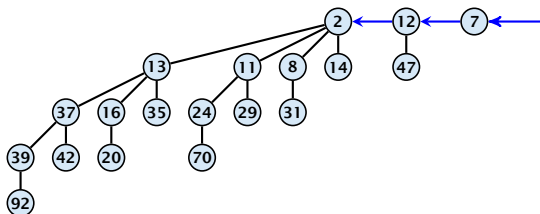
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There is at most one tree for every dimension/order. For example the above heap contains trees B_0 , B_1 , and B_4 .

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Let $B_{k_1}, B_{k_2}, B_{k_3}, k_i < k_{i+1}$ denote the binomial trees in the collection and recall that every tree may be contained at most once.

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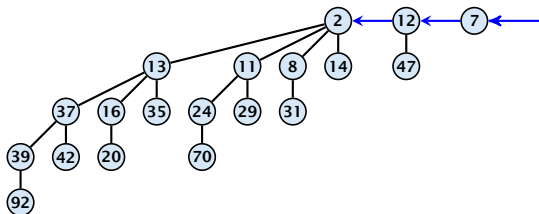
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Then $n = \sum_i 2^{k_i}$ must hold. But since the k_i are all distinct this means that the k_i define the non-zero bit-positions in the binary representation of n .

Binomial Heap

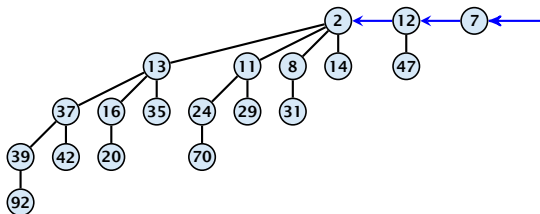
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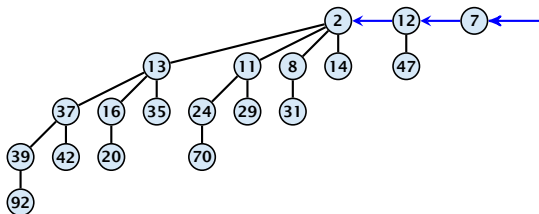
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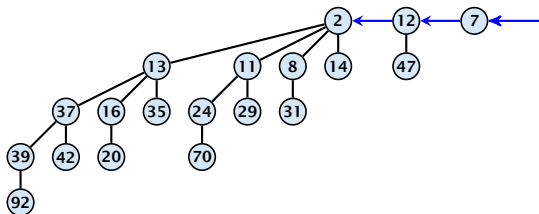
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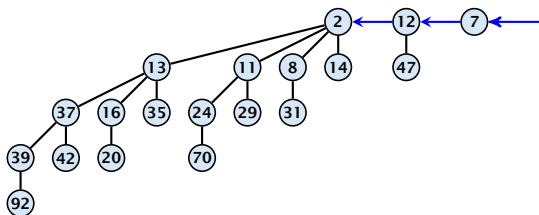
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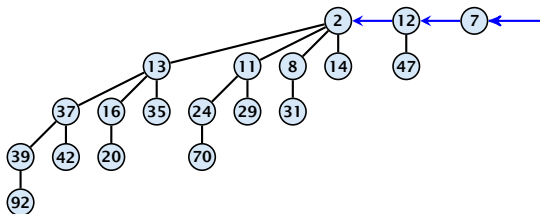
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Binomial Heap

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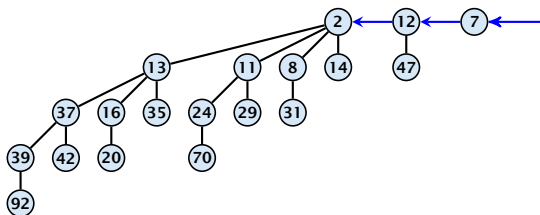
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- ▶ The minimum must be contained in one of the roots.
- ▶ The height of the largest tree is at most $\lfloor \log n \rfloor$.
- ▶ The trees are stored in a single-linked list; ordered by dimension/size.



Binomial Heap: Merge

The merge-operation is instrumental for binomial heaps.

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Otherwise, we cannot do this because the merged heap is not allowed to contain two trees of the same order.

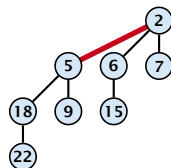
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Merging two trees of the same size: Add the tree with larger root-value as a child to the other tree.



Binomial Heap: Merge

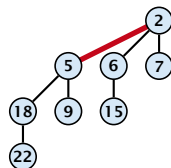
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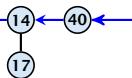
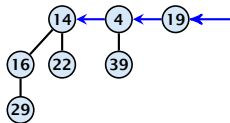
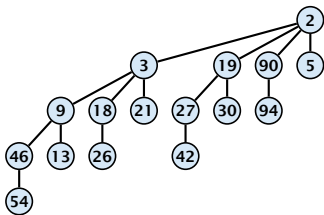
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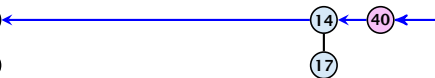
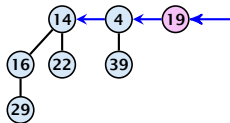
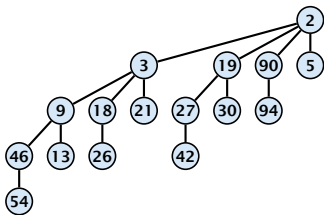
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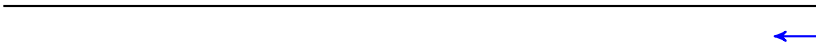
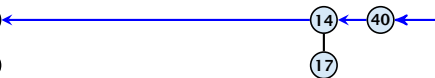
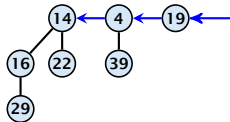
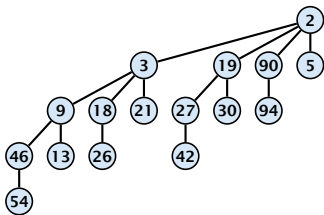
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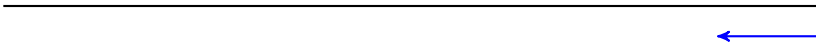
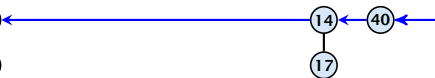
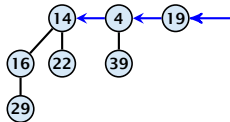
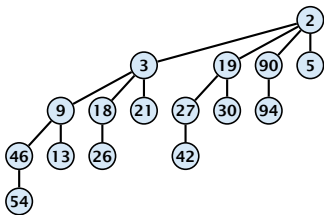
For more trees the technique is analogous to binary addition.

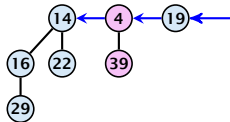
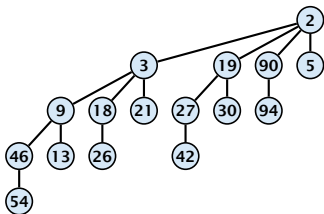


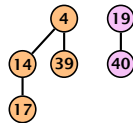
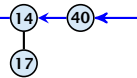
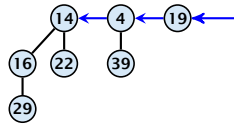
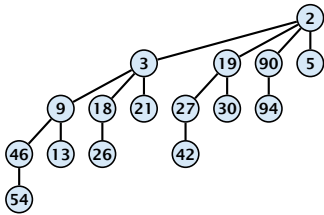


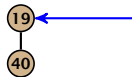
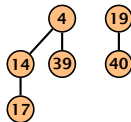
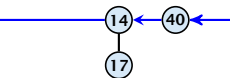
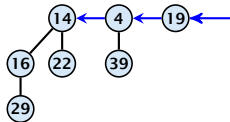
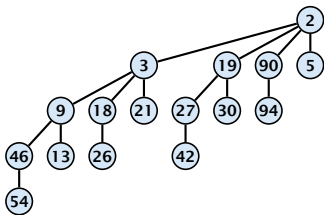


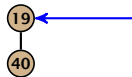
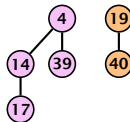
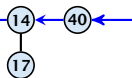
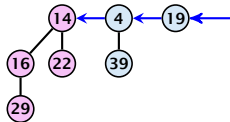
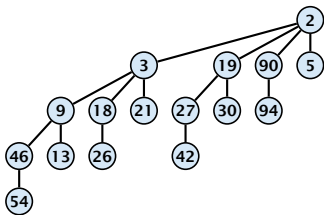


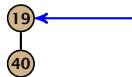
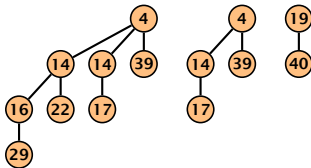
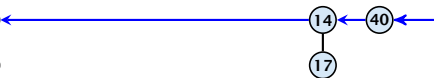
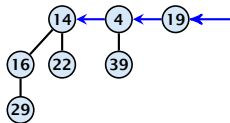
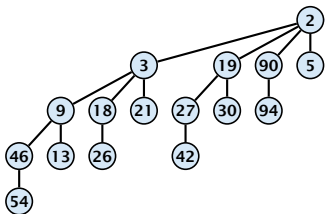


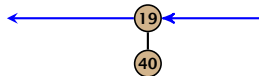
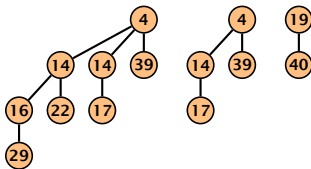
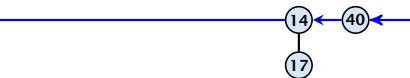
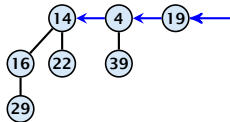
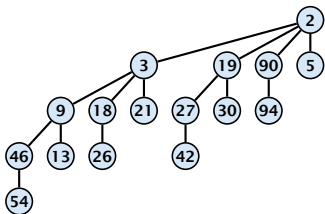


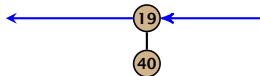
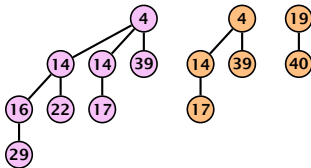
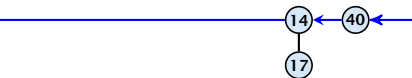
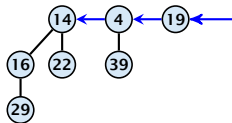
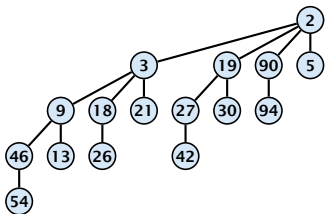




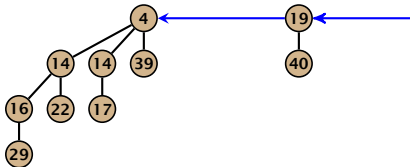
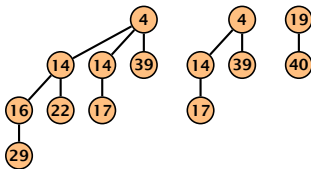
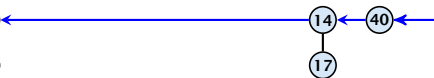
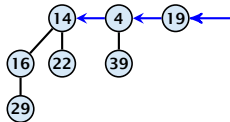
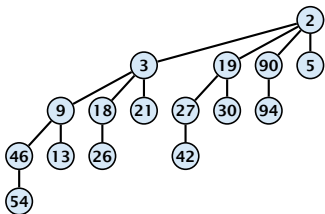




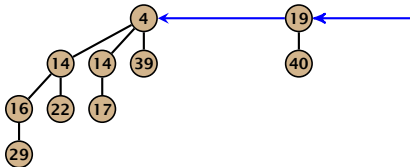
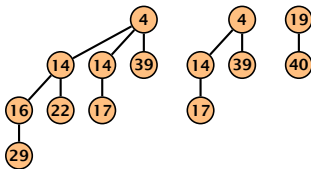
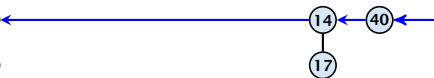
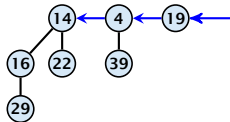
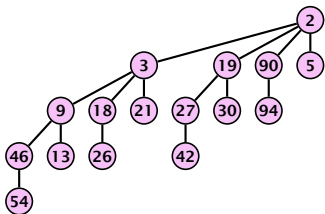


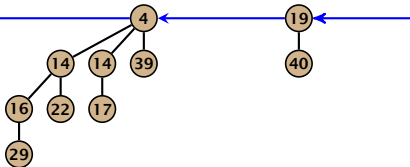
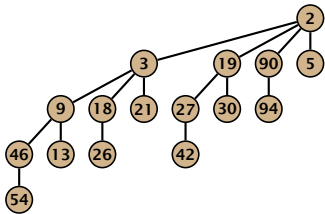
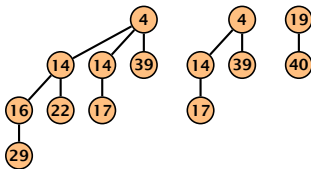
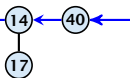
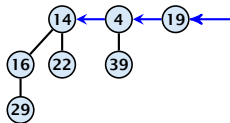
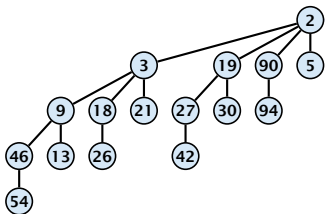


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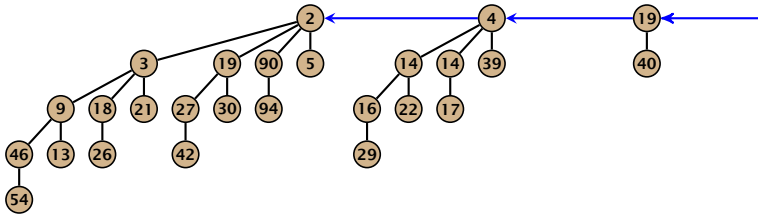
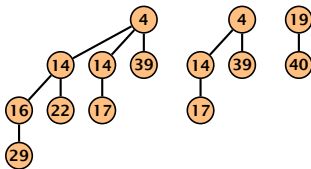
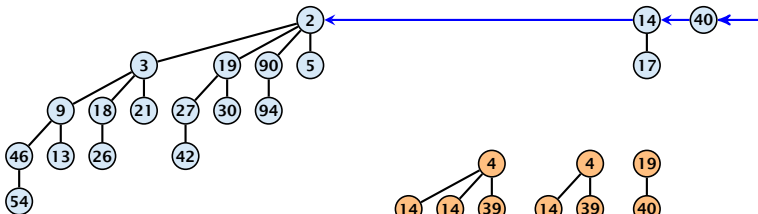


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8.2 Binomial Heaps

S_1 . merge(S_2):

- ▶ Analogous to binary addition.

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All other operations can be reduced to `merge()`.

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8.2 Binomial Heaps

S. minimum():

- ▶ Find the minimum key-value among all roots.
- ▶ Time: $\mathcal{O}(\log n)$.

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- ▶ Remove the corresponding tree T_{\min} from the heap.
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- ▶ Compute $S.\text{merge}(S')$.
- ▶ Time: $\mathcal{O}(\log n)$.

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***S.* decrease-key(handle *h*):**

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- ▶ Decrease the key of the element pointed to by h .
- ▶ Bubble the element up in the tree until the heap property is fulfilled.
- ▶ Time: $\mathcal{O}(\log n)$ since the trees have height $\mathcal{O}(\log n)$.

8.2 Binomial Heaps

***S.* delete(handle *h*):**

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S . delete(handle h):

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- ▶ Execute S . delete-min().

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- ▶ Execute S . decrease-key($h, -\infty$).
- ▶ Execute S . delete-min().
- ▶ Time: $\mathcal{O}(\log n)$.