Algorithms and Datastructures
Open Addressing, Priority Queue

Albert-Ludwigs-Universität Freiburg

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Bioinformatics Group / Department of Computer Science
Algorithms and Datastructures, November 2017

Structure

Hashing
Recapitulation
Treatment of hash collisions
Open Addressing
Summary

Priority Queue
Introduction

Hashing:

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    - Then however, for a fixed set of keys not every hash function is suitable, but only some

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    - Look at amortized analysis in the next lecture

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Buckets as linked list:

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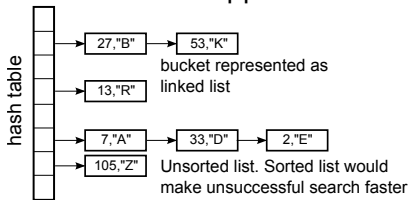
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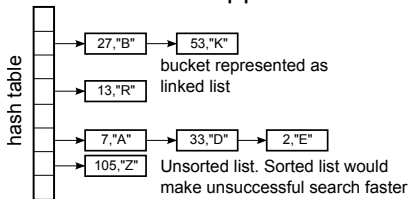
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- Worst case $O(n)$, e.g. tablesize of 1
- Dynamic number of elements is possible

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Open Addressing

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- The **probe sequence** determines for each key, in which sequence all hash table entries are searched for a free bucket
    - If a entry is already occupied, then iteratively the following entry can be checked. If a free entry is found the element is inserted
    - If element is not found at the corresponding table entry, even if the entry is occupied, then probing has to be performed until the element or a free entry have been found

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      $j \in \{0, \dots, m-1\}$ e.g. $g(s,j)=j$
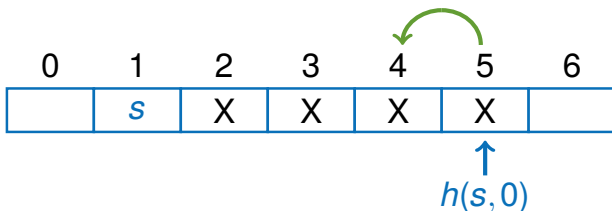
Definitions:

$h(s)$ Hash function for key *s*

$g(s,j)$ Probing function for key *s* with overflow positions

$j \in \{0, \ldots, m-1\}$ e.g. g(s,j)=j

- The **probe sequence** is calculated by

$$h(s,j) = (h(s) - g(s,j)) \mod m \in \{0, \ldots, m-1\}$$

```python
def insert(s, value):
    j = 0

    while t[(h(s) - g(s, j)) mod m] \
            is not None:
        j += 1

    t[(h(s) - g(s, j)) mod m] \
        = (s, value)
```

```python
def lookup(s):
    j = 0

    while t[(h(s) - g(s, j)) mod m] \
            is not None:

        if t[(h(s) - g(s, j)) mod m][0] == s:
            return t[(h(s) - g(s, j)) mod m]

        j += 1

    return None
```
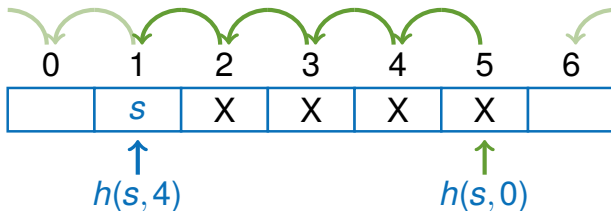
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- This leads to the following probe sequence

$$h(s), h(s) - 1, h(s) - 2, \ldots, \underbrace{0, m-1}_{\text{clipping}}, m-2, \ldots, h(s) + 1$$
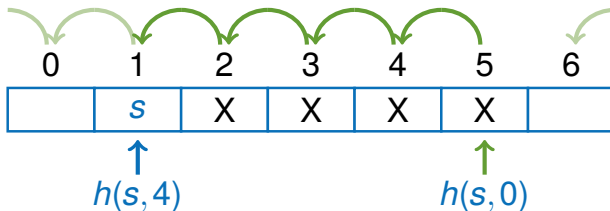
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- Can result in primary clustering
- Dealing with a hash collision will result in a higher probability of hash collisions in close entries

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0	1	2	3	4	5	6
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- t . insert (53, "B"), $h(53, 0) = 4$

				53, B	12, A	

Figure: Probe/Insertion sequence on a hash map

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- t . insert (5, "C"), $h(5,0) = 5$, $h(5,1) = 4$, $h(5,2) = 3$

0	1	2	3	4	5	6
			5, C	53, B	12, A	

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- t . insert $(15, \text{"D"})$, $h(15,0) = 1$

	15, D		5, C	53, B	12, A	

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- t . insert $(2, \text{"E"})$, $h(2,0) = 2$

0	1	2	3	4	5	6
	15, D	2, E	5, C	53, B	12, A	

- t . insert $(19, \text{"F"})$, $h(19,0) = 5$, $h(19,1) = 4$,
  $h(19,2) = 3$, $h(19,3) = 2$, $h(19,4) = 1$, $h(19,5) = 0$

19, F	15, D	2, E	5, C	53, B	12, A	

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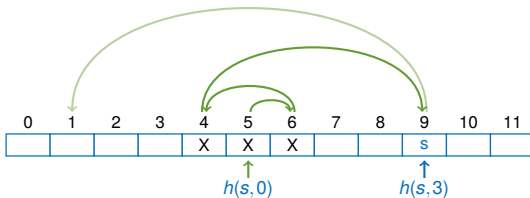
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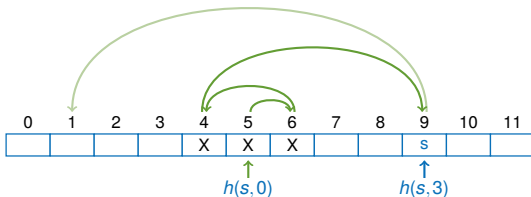
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$h(s), \; h(s) + 1, \; h(s) - 1, \; h(s) + 4, \; h(s) - 4, \; h(s) + 9, \; h(s) - 9, \; \ldots$

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- Alternatively: $h(s,j) := (h(s) - c_1 \cdot j + c_2 \cdot j^2) \mod m$
- Problem of secondary clustering
  No local clustering anymore, but keys with same hash value have similar probe sequence

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- **Disadvantage:** Hard to implement

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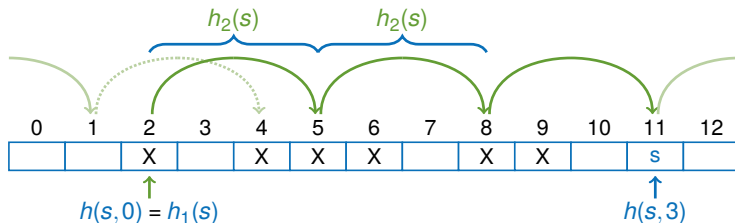
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- Works well in practical use
- This method is an approximation of uniform probing

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$$h_2(s) = (s \mod 5) + 1$$
$$h(s,j) = h_1(s) + j \cdot h_2(s) \mod 7$$

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Table: Comparing both hash functions

s	10	19	31	22	14	16
$h_1(s)$	3	5	3	1	0	2
$h_2(s)$	1	5	2	3	5	2

- The efficiency of double hashing is dependent on
  $h_1(s) \neq h_2(s)$

$h(s_1, 0)$

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Double hashing by Brent:

Hashing
Open Addressing - Double Hashing - Optimization

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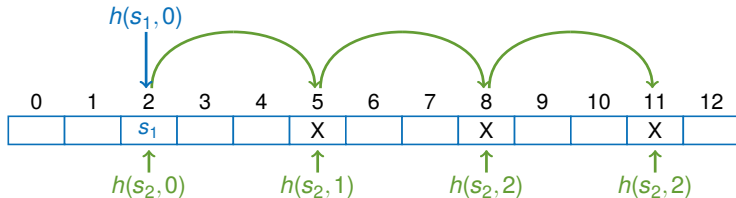 the sequence of the insertions has impact on efficiency of
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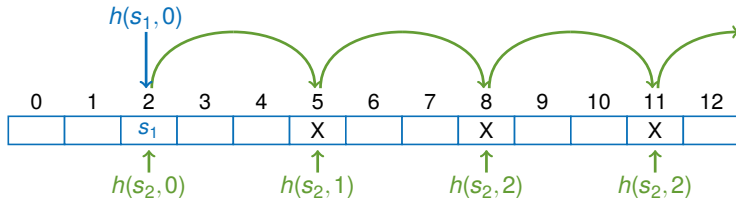
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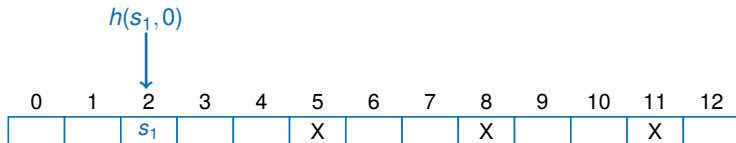 the sequence of the insertions has impact on efficiency of
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$h(s_1, 0)$

0	1	2	3	4	5	6	7	8	9	10	11	12
		s_1			X			X			X	

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Hashing

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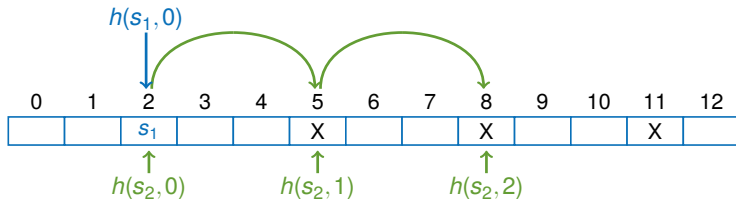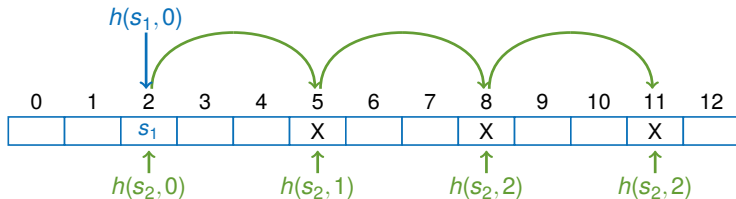- The locations $h(s_2, j)$, $j \in \{1, \ldots, n\}$ are also occupied

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- The locations $h(s_2, j)$, $j \in \{1, \ldots, n\}$ are also occupied
- If we insert s_2 at position $h(s_2, n + 1)$ the search will be inefficient

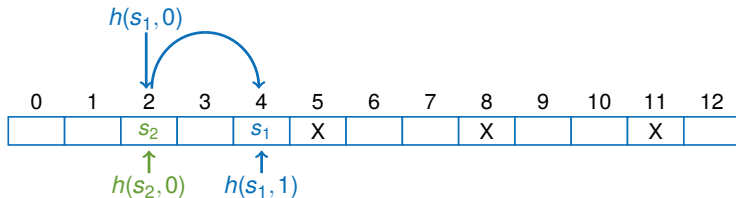Figure: Double hashing by Brent

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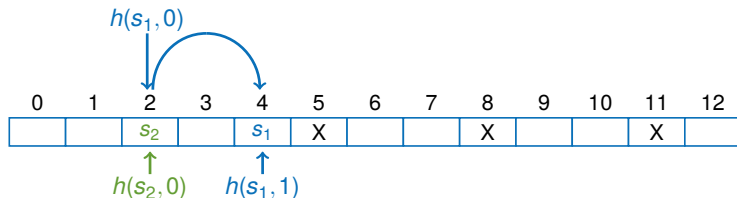- Reversed sequence of keys would have been better

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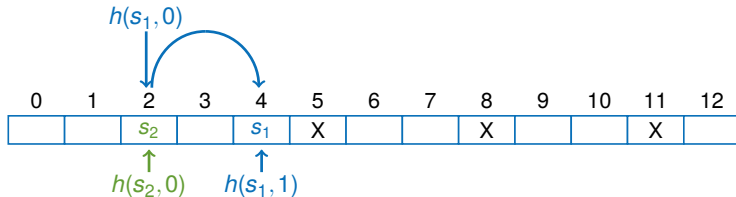 - Test if location $h(s_1, 1)$ is free

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- Reversed sequence of keys would have been better
- **Brents Idea:**
    - Test if location $h(s_1, 1)$ is free
    - If yes, move s_1 from $h(s_1, 0)$ to $h(s_1, 1)$ and insert s_2 at $h(s_2, 0)$

Idea:

- Motivation: Colliding elements are inserted in the hashtable sorted.
- Therefore, in case of an unsuccessful search of elements in combination with linear probing or double hashing, aborting is earlier possible because single probing steps have a fixed length

Implementation:

- Compare both keys if a collision occurs
- Insert the smaller key at p_1
- Search a position based on the diversion order for the bigger key

Example:

- The key 12 is saved at position $p_1 = h(12, 0)$
- We insert the key 5 into the hash map
- We assume $h(5, 0)$ results in location p_1
- Because $5 < 12$ we insert the key 5 at position p_1
- For the key 12 we iterate through the sequence

$$h(12, 1), h(12, 2), h(12, 3), \ldots$$

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- If two keys s_1, s_2 collide ($p_1 = h(s_1, j_1) = h(s_2, j_2)$) we compare the length of the sequence (j_1 or j_2)

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Implementation:

- If two keys s_1, s_2 collide ($p_1 = h(s_1, j_1) = h(s_2, j_2)$) we compare the length of the sequence (j_1 or j_2)
- The key with the bigger search sequence is inserted at p_1 The other key is assigned a new location based on the sequence

Example:

- The key 12 is saved at position $p_1 = h(12, 7)$
- We insert the key 5 into the hash map
- We assume $h(5, 0)$ results in location p_1
- Because $j_1 < j_2$ ($0 < 7$) the key 12 stays at position p_1
- For the key 5 we iterate through the sequence

$$h(5, 1), h(5, 2), h(5, 3), \ldots$$

Problem:

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- The key s_2 returns the same hash value, but is inserted at position p_2 because of the probing order
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Solution:

- **Remove:** Elements are marked as removed, but not deleted
- **Inserting:** Elements marked as removed will we overwritten

Structure

Bucket as linked list: (dynamic, number of elements variable)

- Save colliding elements as linked list

Open hashing: (static, number of elements fixed)

- Determine a probe sequence, permutation of all hash values
- Linear, quadratic probing:
    - Easy to implement
    - Raise the probability of collisions because probing order does not depend on the key

Open hashing: (static, number of elements fixed)

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Improving efficiency: (Brent, Ordered Hashing)

- Improve search efficiency by sorting colliding insertions
    - Abortion of unsuccessfull search
    - Search sequence length balancing

Hashing:

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- Efficient fo dictionary operations:
    Insert: $O(1) \ldots O(n)$
    Search: $O(1) \ldots O(n)$
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Hashing
Open Addressing - Summary Hashing

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- Direct access of all elements in a hash table
- Using a hash function to find the position (hash value) in the hash table
- Hash function, size of the hash table and strategy to avoid hash collisions influence the efficiency of the datastructure

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Priority Queue
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- Argument of changeKey and remove operations
    - There is no **quick-access** to a element in the queue
    - Thats why insert and getMin return a reference (handle, accessor object)
    - changeKey and remove take this reference as argument
    - Therefore each element has to store its current position in the heap.

Priority Queue
Python

```python
from queue import PriorityQueue

q = PriorityQueue()

e1 = (5, "A") # element with priority 5
q.put(e1); # insert element e1

# remove and return the lowest item
e2 = q.get()
```

Priority Queue
Application Example

Example 1:

- Calculation of the sorted union of *k* sorted lists
  (multi-way merge or *k*-way merge)

L_1 :

3	5	8	12	...

L_3 :

1	10	11	24	...

L_2 :

4	5	6	7	...

$\Rightarrow R$:

1	3	4	5	5	6	7	8	10	...
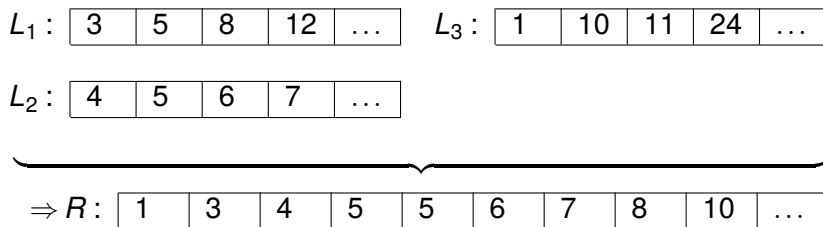
Figure: 3-way merge

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Priority Queue
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Priority Queue
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Priority Queue
Application Example

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Example 2:

- For example Dijkstra's algorithm for computing the shortest path ($\leftarrow$ following lecture)
- Among other applications it can be used for sorting

Idea:

Idea:

- Save elements as tuples in a binary heap
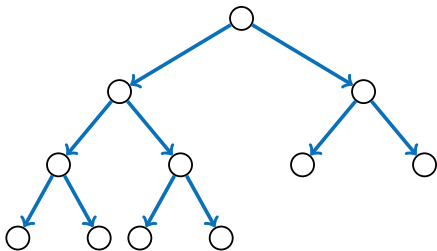
Figure: Heap with 11 nodes

Idea:

- Save elements as tuples in a binary heap
- Summary from lecture 1 (*HeapSort*):
  - Nearly complete binary tree
  - Heap condition:
    The key of each node $\leq$ the keys of the children

Figure: Heap with 11 nodes
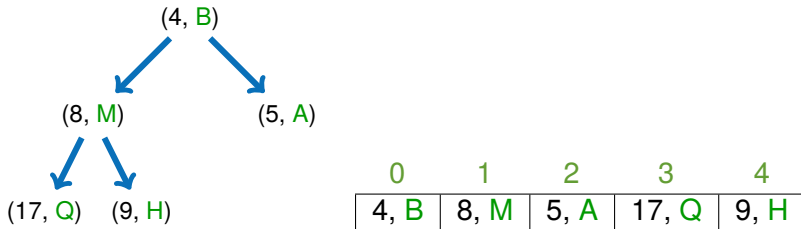
Priority Queue
Implementation

Figure: Min heap stored in array
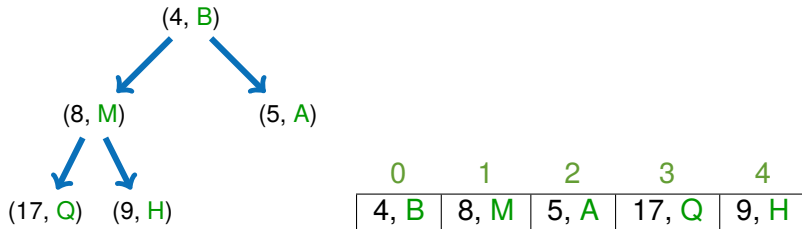
Figure: Min heap stored in array

Storing a binary heap:

Figure: Min heap stored in array

Storing a binary heap:

- Number nodes from top to bottom and left to right starting with 0 and store entries in array
- Children of node i are the nodes $2i + 1$ and $2i + 2$
- Parent node of node i is $\text{floor}((i - 1)/2)$

Inserting an element: `insert(key, item)`
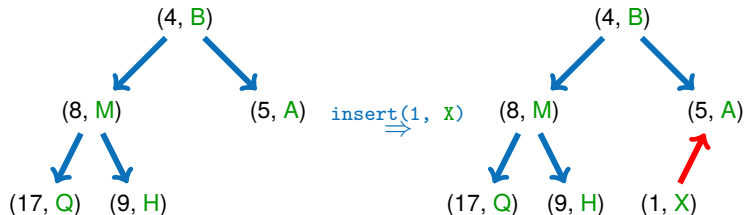
Inserting an element: `insert(key, item)`
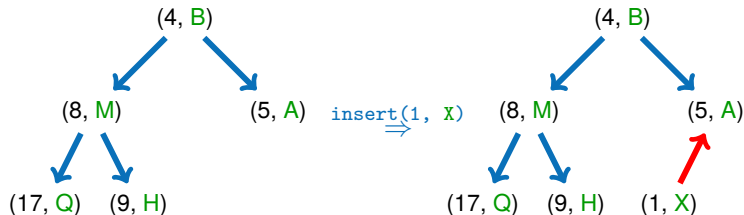
- Append the element at the end of the array

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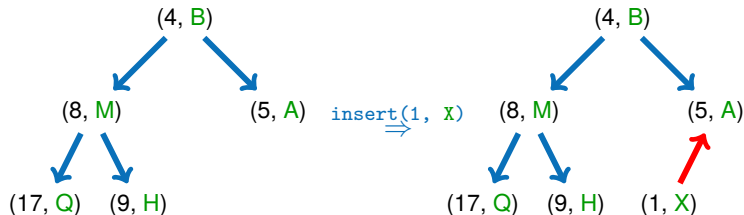
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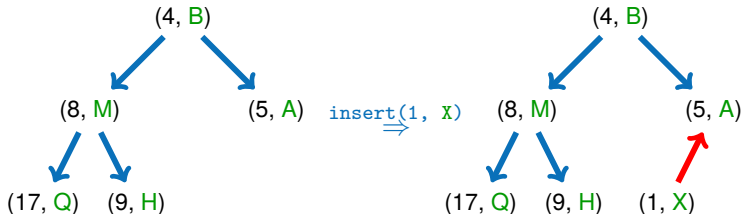
- Append the element at the end of the array
- The heap condition may be violated, but only at the last index
- Repair heap condition ⇒ We will see later how to do this

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Returning the minimum: `getMin()`

(4, B)
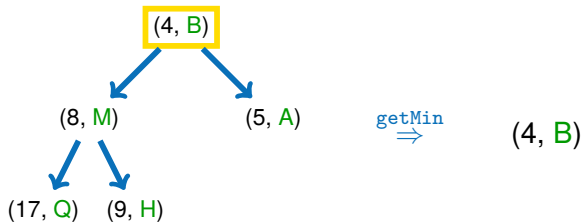
$\stackrel{\texttt{getMin}}{\Rightarrow}$ (4, B)

Returning the minimum: `getMin()`

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Returning the minimum: getMin()
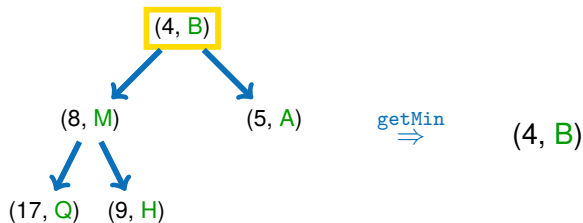
- Else return the first element
- If the heap is empty return None

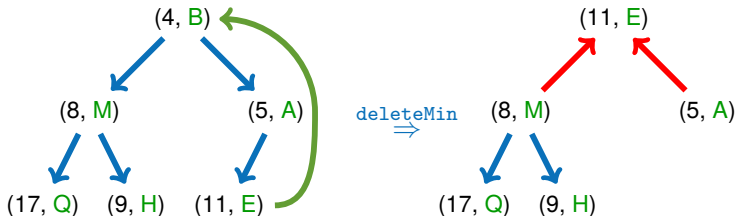**Removing the minimum:** `deleteMin()`
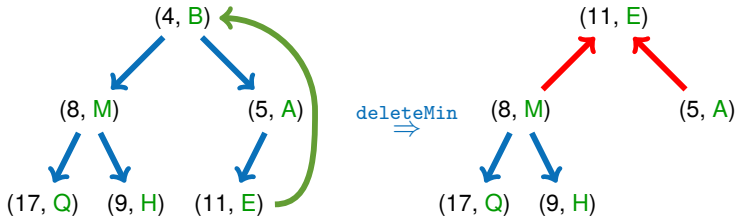
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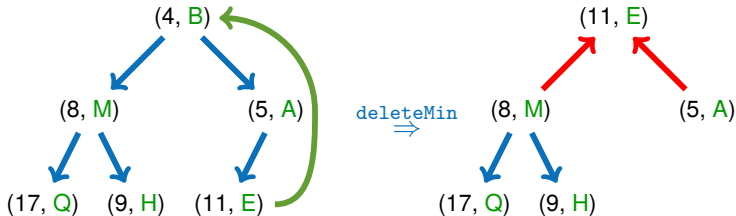
- Deleting the element with the lowest key
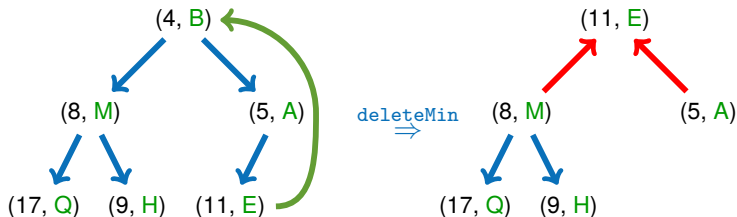
Removing the minimum: `deleteMin()`

- Deleting the element with the lowest key
- Swap the last element with the first element and shrink the heap by one

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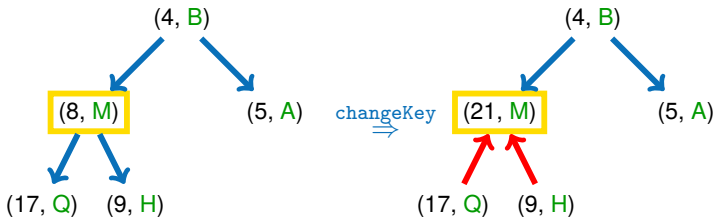
Changing the key (priority): `changeKey(item, key)`

- The element (queue item) is given as argument
- Replace the key of the element
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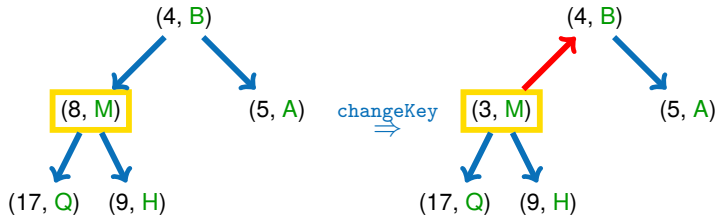
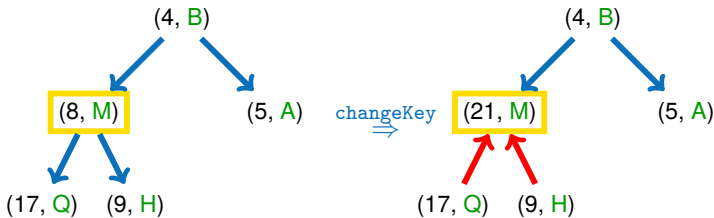**Changing the key (priority):** `changeKey(item, key)`

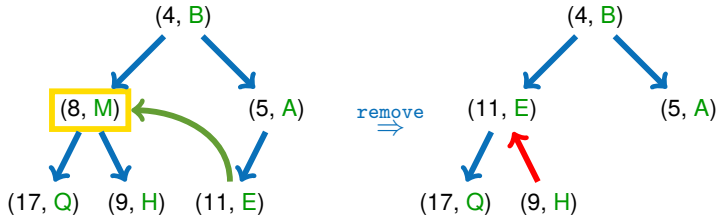**Changing the key (priority):** `changeKey(item, key)`

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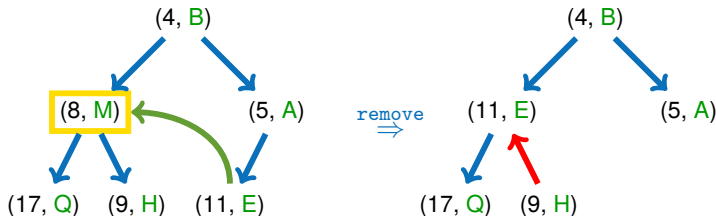
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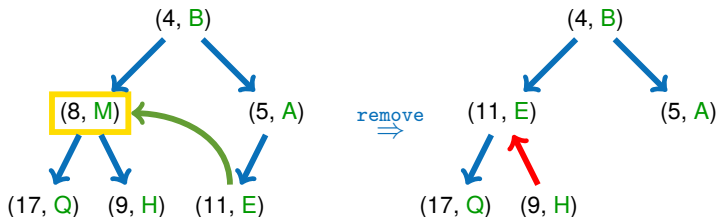## Removing an element: `remove(item)`

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Priority Queue
Implementation - Reparing the Heap

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Priority Queue
Implementation - Reparing the Heap

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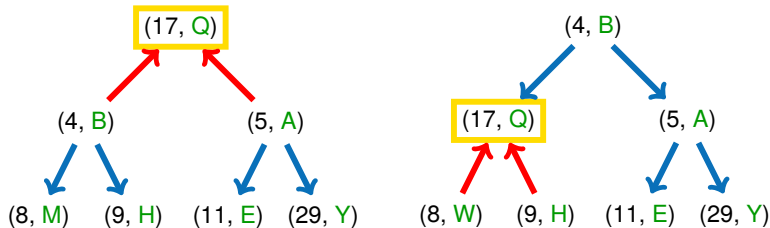- We need two repair methods: `repairHeapUp`, `repairHeapDown`

`repairHeapDown:`

Figure: Repairing the heap downwards

`repairHeapDown:`
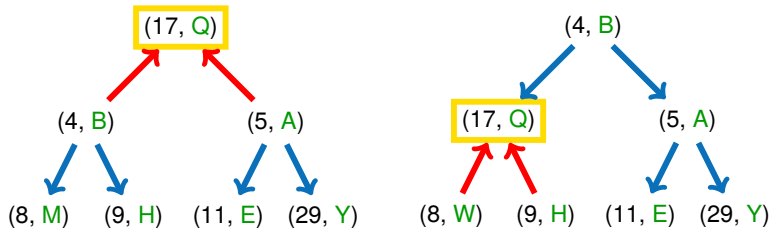- Sift the element until the heap condition is valid

Figure: Repairing the heap downwards

`repairHeapDown:`
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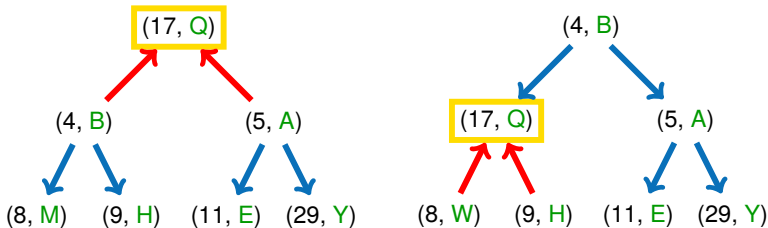

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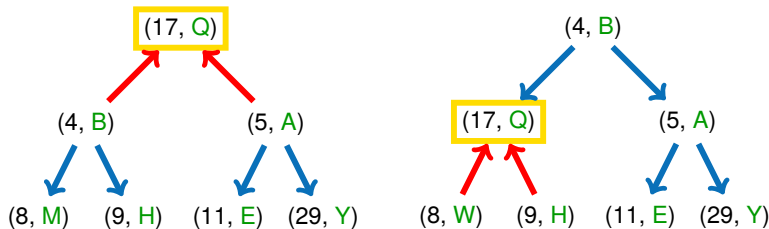 - If the heap condition is violated repeat for the child node
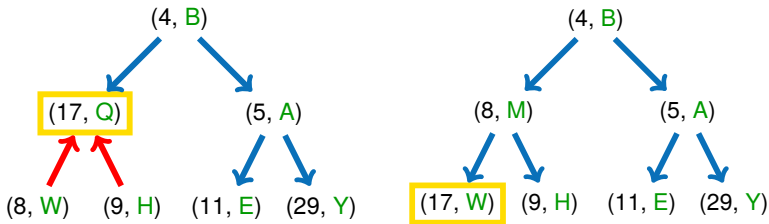
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`repairHeapUp:`

Figure: Repairing the heap upwards

`repairHeapUp:`

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Figure: Repairing the heap upwards

repairHeapUp:

- Change node with parent
- If the heap condition is violated repeat for parent node
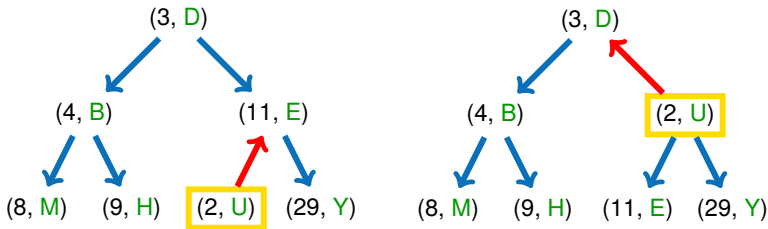

Figure: Repairing the heap upwards

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Figure: Repairing the heap upwards

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Priority Queue
Implementation - Priority Queue Item

Index of a priority queue item:

- Attention: For `changeKey` and `remove` the item has to "know" where it is located in the heap
- Remember for `repairHeapUp` and `repairHeapDown`: Update the index if moving an heap element

Priority Queue
Implementation - Priority Queue Item - Python

```python
class PriorityQueueItem:

    """Provides a handle for a queue item.

    This handle can be used to remove or
    update the queue item.
    """

    def __init__(self, key, value, index):
        self.key = key
        self.value = value
        self.index = index
```

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Priority Queue
Complexity

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Priority Queue
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Runtime for methods

- `insert`, `deleteMin`, `changeKey`, `remove`: We have to repair the heap: $O(\log n)$
- `getMin`: Return the element at index 0: $O(1)$

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- getMin, insert and decreaseKey in amortized time of $O(1)$

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Practical experience:

- The binary heap is simpler: Costs for managing the structure are low
- If the number of elements is relatively small so the difference is negligible
- Example:
  - For $n = 2^{10} \approx 1,000$ is the the depth $\log_2 n$ only 10
  - For $n = 2^{20} \approx 1,000,000$ is the depth $\log_2 n$ only 20

Further Literature

- **General**

  [CRL01] Thomas H. Cormen, Ronald L. Rivest, and
          Charles E. Leiserson.
          Introduction to Algorithms.
          MIT Press, Cambridge, Mass, 2001.

  [MS08] Kurt Mehlhorn and Peter Sanders.
          Algorithms and data structures, 2008.
          https://people.mpi-inf.mpg.de/~mehlhorn/
          ftp/Mehlhorn-Sanders-Toolbox.pdf.

Further Literature

- **Priority Queue - Implementations / API**

  [Cpp] C++ - priority_queue
        http:
        //www.sgi.com/tech/stl/priority_queue.html

  [Jav] Java - PriorityQueue
        https://docs.oracle.com/javase/7/docs/api/
        java/util/PriorityQueue.html

  [Pyt] Python - PriorityQueue
        https://docs.python.org/3/library/queue.
        html#queue.PriorityQueue