

Algorithms and Datastructures

Open Addressing, Priority Queue

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Algorithms and Datastructures, November 2017

Structure

Hashing

- Recapitulation

- Treatment of hash collisions

- Open Addressing

- Summary

Priority Queue

- Introduction

Hashing

Recapitulation

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- ▶ Then the random keys make sure that it is distributed evenly
- ▶ To find a good hash function for every key set universal hashing is needed
 - ▶ Then however, for a fixed set of keys not every hash function is suitable, but only some

Hashing

Recapitulation

Rehashing:

Hashing

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Rehashing:

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How to rehash?

- ▶ New hash table with a new random hash function

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How to rehash?

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 - ▶ Expensive but happens not often

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 - ▶ Therefore the average cost is low

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How to rehash?

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- ▶ Copy elements into the new table
 - ▶ Expensive but happens not often
 - ▶ Therefore the average cost is low
 - ▶ Look at **amortized analysis** in the next lecture

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Recapitulation

Treatment of hash collisions

Open Addressing

Summary

Priority Queue

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Linked List

Buckets as linked list:

Hashing

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Buckets as linked list:

- ▶ Each bucket is a linked list

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- ▶ Operations in $O(1)$ are possible if a suitable table size and hashfunction is selected

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- ▶ Worst case $O(n)$, e.g. table size of 1

Hashing

Linked List

Buckets as linked list:

- ▶ Each bucket is a linked list
- ▶ Colliding keys are inserted into the linked list of a bucket, either sorted or appended at the end



- ▶ Operations in $O(1)$ are possible if a suitable table size and hash function is selected
- ▶ Worst case $O(n)$, e.g. table size of 1
- ▶ Dynamic number of elements is possible

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Open Addressing

- ▶ For colliding keys we choose a new free entry

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Open Addressing

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- ▶ Static, fixed number of elements

Hashing

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

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Open Addressing

- ▶ For colliding keys we choose a new free entry
- ▶ Static, fixed number of elements
- ▶ 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

Hashing

Open Addressing

- ▶ For colliding keys we choose a new free entry
- ▶ Static, fixed number of elements
- ▶ The **probe sequence** determines for each key, in which sequence all hash table entries are searched for a free bucket
 - ▶ If an 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

Hashing

Open Addressing

Definitions:

Hashing

Open Addressing

Definitions:

$h(s)$ Hash function for key s

Hashing

Open Addressing

Definitions:

$h(s)$ Hash function for key s

$g(s, j)$ Probing function for key s with overflow positions
 $j \in \{0, \dots, m-1\}$ e.g. $g(s, j) = j$

Hashing

Open Addressing

Definitions:

$h(s)$ Hash function for key s

$g(s, j)$ Probing function for key s with overflow positions
 $j \in \{0, \dots, m-1\}$ e.g. $g(s, j) = j$

- The **probe sequence** is calculated by

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



Hashing

Open Addressing - 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)
```

Hashing

Open Addressing - 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
```

Hashing

Open Addressing - Linear Probing



Figure: Linear probe sequence

Hashing

Open Addressing - Linear Probing



Figure: Linear probe sequence

- Check the element with lower index: $g(s, j) := j$
⇒ Hash function: $h(s, j) = (h(s) - j) \bmod m$

Hashing

Open Addressing - Linear Probing



Figure: Linear probe sequence

- ▶ Check the element with lower index: $g(s, j) := j$
 \Rightarrow Hash function: $h(s, j) = (h(s) - j) \bmod m$
- ▶ This leads to the following probe sequence

$$h(s), h(s) - 1, h(s) - 2, \dots, \underbrace{0, m - 1}_{\text{clipping}}, m - 2, \dots, h(s) + 1$$

Hashing

Open Addressing - Linear Probing



Figure: Linear probe sequence

Hashing

Open Addressing - Linear Probing



Figure: Linear probe sequence

- Can result in primary clustering

Hashing

Open Addressing - Linear Probing



Figure: Linear probe sequence

- ▶ Can result in primary clustering
- ▶ Dealing with a hash collision will result in a higher probability of hash collisions in close entries

Hashing

Open Addressing - Linear Probing

Example:

Hashing

Open Addressing - Linear Probing

Example:

- Keys: {12, 53, 5, 15, 2, 19}

Hashing

Open Addressing - Linear Probing

Example:

- ▶ Keys: {12, 53, 5, 15, 2, 19}
- ▶ Hash function: $h(s, j) = (s \bmod 7 - j) \bmod 7$

Hashing

Open Addressing - Linear Probing

Example:

- ▶ Keys: {12, 53, 5, 15, 2, 19}
- ▶ Hash function: $h(s, j) = (s \bmod 7 - j) \bmod 7$
- ▶ t.insert (12, "A"), $h(12, 0) = 5$

0	1	2	3	4	5	6
					12, A	

Hashing

Open Addressing - Linear Probing

Example:

- ▶ Keys: {12, 53, 5, 15, 2, 19}
- ▶ Hash function: $h(s, j) = (s \bmod 7 - j) \bmod 7$
- ▶ t. insert (12, "A"), $h(12, 0) = 5$

0	1	2	3	4	5	6
					12, A	

- ▶ t. insert (53, "B"), $h(53, 0) = 4$

				53, B	12, A	
--	--	--	--	-------	-------	--

Figure: Probe/Insertion sequence on a hash map

Hashing

Open Addressing - Linear Probing

Example:

- ▶ Hash function: $h(s, j) = (s \bmod 7 - j) \bmod 7$

Hashing

Open Addressing - Linear Probing

Example:

- ▶ Hash function: $h(s, j) = (s \bmod 7 - j) \bmod 7$
- ▶ 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	

Hashing

Open Addressing - Linear Probing

Example:

- ▶ Hash function: $h(s, j) = (s \bmod 7 - j) \bmod 7$
- ▶ 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	

- ▶ t. insert (15, "D"), $h(15, 0) = 1$

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

Figure: Probe/Insertion sequence on a hash map

Hashing

Open Addressing - Linear Probing

Example:

- ▶ Hash function: $h(s, j) = (s \bmod 7 - j) \bmod 7$

Hashing

Open Addressing - Linear Probing

Example:

- ▶ Hash function: $h(s, j) = (s \bmod 7 - j) \bmod 7$
- ▶ t. insert (2, "E"), $h(2, 0) = 2$

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

Hashing

Open Addressing - Linear Probing

Example:

► Hash function: $h(s, j) = (s \bmod 7 - j) \bmod 7$

► t. insert (2, "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, "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	
-------	-------	------	------	-------	-------	--

Figure: Probe/Insertion sequence on a hash map

Hashing

Open Addressing - Squared Probing

Squared probing:

Hashing

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Squared probing:

- Motivation: Avoid local clustering

$$g(s, j) := (-1)^j \left\lceil \frac{j}{2} \right\rceil^2$$

Hashing

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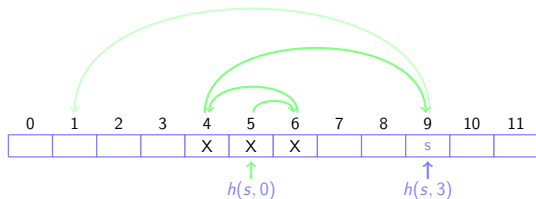


Figure: Squared probe sequence

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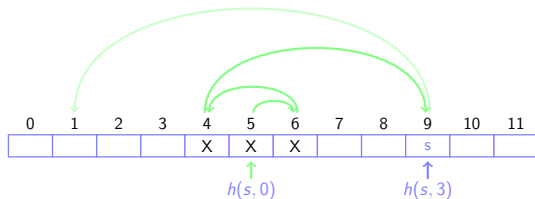


Figure: Squared probe sequence

- This leads to the following probe sequence

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

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Open Addressing - Squared Probing

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- If m is a prime number for which $m = 4 \cdot k + 3$ then the probe sequence is a permutation of the indices of the hash tables

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Squared probing:

$$g(s, j) := (-1)^j \left\lceil \frac{j}{2} \right\rceil^2$$

- ▶ If m is a prime number for which $m = 4 \cdot k + 3$ then the probe sequence is a permutation of the indices of the hash tables
- ▶ Alternatively: $h(s, j) := (h(s) - c_1 \cdot j + c_2 \cdot j^2) \bmod m$

Hashing

Open Addressing - Squared Probing

Squared probing:

$$g(s, j) := (-1)^j \left\lceil \frac{j}{2} \right\rceil^2$$

- ▶ If m is a prime number for which $m = 4 \cdot k + 3$ then the probe sequence is a permutation of the indices of the hash tables
- ▶ Alternatively: $h(s, j) := (h(s) - c_1 \cdot j + c_2 \cdot j^2) \bmod m$
- ▶ Problem of secondary clustering
No local clustering anymore, but keys with same hash value have similar probe sequence

Hashing

Open Addressing - Uniform Probing

Uniform Probing:

Hashing

Open Addressing - Uniform Probing

Uniform Probing:

- ▶ Motivation: So far uses function $g(s, j)$ only the step counter j for linear and squared probing
⇒ The probe sequence is independent of the key s

Hashing

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- ▶ Motivation: So far uses function $g(s, j)$ only the step counter j for linear and squared probing
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- ▶ Uniform probing computes the sequence $g(s, j)$ of permutations of all possible indices in dependency on key s

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- ▶ Motivation: So far uses function $g(s, j)$ only the step counter j for linear and squared probing
⇒ The probe sequence is independent of the key s
- ▶ Uniform probing computes the sequence $g(s, j)$ of permutations of all possible indices in dependency on key s
- ▶ **Advantage:** Prevents clustering because different keys with the same hash value do not produce the same probe sequence

Hashing

Open Addressing - Uniform Probing

Uniform Probing:

- ▶ Motivation: So far uses function $g(s, j)$ only the step counter j for linear and squared probing
⇒ The probe sequence is independent of the key s
- ▶ Uniform probing computes the sequence $g(s, j)$ of permutations of all possible indices in dependency on key s
- ▶ **Advantage:** Prevents clustering because different keys with the same hash value do not produce the same probe sequence
- ▶ **Disadvantage:** Hard to implement

Hashing

Double Hashing:

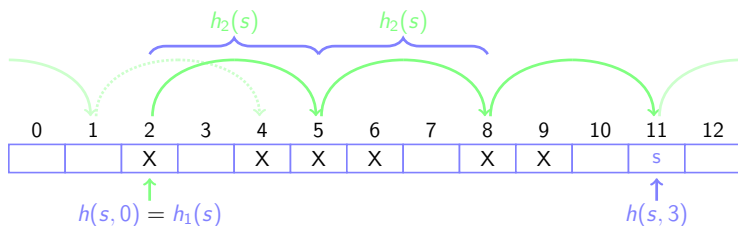


Figure: Double hashing probe sequence

Hashing

Open Addressing - Double Hashing

Double Hashing:



Figure: Double hashing probe sequence

- Motivation: Consider key s in probe sequence

Hashing

Open Addressing - Double Hashing

Double Hashing:



Figure: Double hashing probe sequence

- ▶ Motivation: Consider key s in probe sequence
- ▶ Use two independent hash functions $h_1(s)$, $h_2(s)$

Hashing

Open Addressing - Double Hashing

Double Hashing:



Figure: Double hashing probe sequence

- ▶ Motivation: Consider key s in probe sequence
- ▶ Use two independent hash functions $h_1(s)$, $h_2(s)$
- ▶ Hash function: $h(s, j) = (h_1(s) + j \cdot h_2(s)) \bmod m$

Hashing

Open Addressing - Double Hashing

Double Hashing:

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Open Addressing - Double Hashing

Double Hashing:

- ▶ Hash function: $h(s, j) = (h_1(s) + j \cdot h_2(s)) \bmod m$
- ▶ probe sequence:

$$h_1(s), h_1(s) + h_2(s), h_1(s) + 2 \cdot h_2(s), h_1(s) + 3 \cdot h_2(s), \dots$$

Hashing

Open Addressing - Double Hashing

Double Hashing:

- ▶ Hash function: $h(s, j) = (h_1(s) + j \cdot h_2(s)) \bmod m$
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Hashing

Open Addressing - Double Hashing

Double Hashing:

- ▶ Hash function: $h(s, j) = (h_1(s) + j \cdot h_2(s)) \bmod m$
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$$h_1(s), h_1(s) + h_2(s), h_1(s) + 2 \cdot h_2(s), h_1(s) + 3 \cdot h_2(s), \dots$$

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

Hashing

Open Addressing - Double Hashing - Example

Example:

Hashing

Open Addressing - Double Hashing - Example

Example:

$$h_1(s) = s \bmod 7$$

$$h_2(s) = (s \bmod 5) + 1$$

$$h(s, j) = h_1(s) + j \cdot h_2(s) \bmod 7$$

Hashing

Open Addressing - Double Hashing - Example

Example:

$$h_1(s) = s \bmod 7$$

$$h_2(s) = (s \bmod 5) + 1$$

$$h(s, j) = h_1(s) + j \cdot h_2(s) \bmod 7$$

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 $h_1(s) \neq h_2(s)$

Hashing

Open Addressing - Double Hashing - Optimization



Figure: Double hashing

Double hashing by Brent:

Hashing

Open Addressing - Double Hashing - Optimization



Figure: Double hashing

Double hashing by Brent:

- Motivation:

Because different keys have different probe sequences, the sequence of the insertions has impact on efficiency of a successful search

Hashing

Open Addressing - Double Hashing - Optimization



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Open Addressing - Double Hashing - Optimization

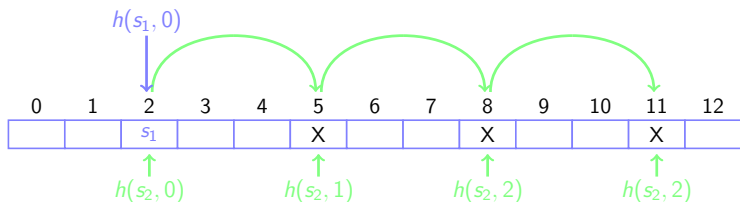


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Hashing

Open Addressing - Double Hashing - Optimization



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Hashing

Open Addressing - Double Hashing - Optimization



Figure: Double hashing

Example:

- ▶ The key s_1 is inserted at position $p_1 = h(s_1, 0)$

Hashing

Open Addressing - Double Hashing - Optimization



Figure: Double hashing

Example:

- ▶ The key s_1 is inserted at position $p_1 = h(s_1, 0)$
- ▶ The hash function for s_2 also results in $p_2 = h(s_2, 0) = p_1$

Hashing

Open Addressing - Double Hashing - Optimization



Figure: Double hashing

Example:

- ▶ The key s_1 is inserted at position $p_1 = h(s_1, 0)$
- ▶ The hash function for s_2 also results in $p_2 = h(s_2, 0) = p_1$
- ▶ The locations $h(s_2, j)$, $j \in \{1, \dots, n\}$ are also occupied

Hashing

Open Addressing - Double Hashing - Optimization



Figure: Double hashing

Example:

- ▶ The key s_1 is inserted at position $p_1 = h(s_1, 0)$
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Example:

- ▶ The key s_1 is inserted at position $p_1 = h(s_1, 0)$
- ▶ The hash function for s_2 also results in $p_2 = h(s_2, 0) = p_1$
- ▶ The locations $h(s_2, j)$, $j \in \{1, \dots, n\}$ are also occupied
- ▶ If we insert s_2 at position $h(s_2, n + 1)$ the search will be inefficient

Hashing

Open Addressing - Double Hashing - Optimization



Figure: Double hashing by Brent

Hashing

Open Addressing - Double Hashing - Optimization

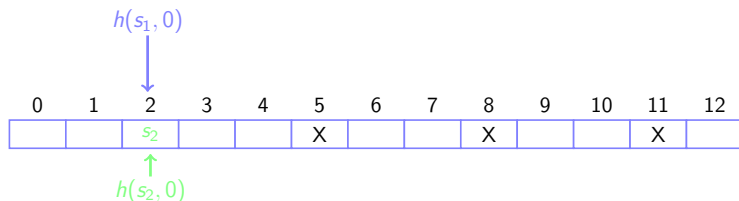


Figure: Double hashing by Brent

Hashing

Open Addressing - Double Hashing - Optimization



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Hashing

Open Addressing - Double Hashing - Optimization



Figure: Double hashing by Brent

- Reversed sequence of keys would have been better

Hashing

Open Addressing - Double Hashing - Optimization



Figure: Double hashing by Brent

- ▶ Reversed sequence of keys would have been better
- ▶ **Brents Idea:**

Hashing

Open Addressing - Double Hashing - Optimization



Figure: Double hashing by Brent

- ▶ Reversed sequence of keys would have been better
- ▶ **Brents Idea:**
 - ▶ Test if location $h(s_1, 1)$ is free

Hashing

Open Addressing - Double Hashing - Optimization



Figure: Double hashing by Brent

- ▶ 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 $h(s_2, 0)$

Hashing

Open Addressing - Ordered Hashing

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

Hashing

Open Addressing - Ordered Hashing

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

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

Hashing

Open Addressing - Robin-Hood Hashing

Motivation:

Hashing

Open Addressing - Robin-Hood Hashing

Motivation:

- ▶ Having similar length of probe sequences for all elements.
Total costs stay the same, but they are distributed evenly.
Results in approximately similar search times for all elements

Hashing

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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)

Hashing

Open Addressing - Robin-Hood Hashing

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Total costs stay the same, but they are distributed evenly.
Results in approximately similar search times for all elements

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

Hashing

Open Addressing - Robin-Hood Hashing

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

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

Hashing

Open Addressing - Implement Insert / Remove

Problem:

- ▶ The key s_1 is inserted at position p_1
- ▶ The key s_2 returns the same hash value, but is inserted at position p_2 because of the probing order
- ▶ If s_1 is removed, it is impossible to find s_2

Hashing

Open Addressing - Implement Insert / Remove

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Solution:

Hashing

Open Addressing - Implement Insert / Remove

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Solution:

- ▶ **Remove:** Elements are marked as removed, but not deleted

Hashing

Open Addressing - Implement Insert / Remove

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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
- ▶ If s_1 is removed, it is impossible to find s_2

Solution:

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

Structure

Hashing

- Recapitulation

- Treatment of hash collisions

- Open Addressing

- Summary

Priority Queue

- Introduction

Hashing

Open Addressing - Summary Collision Handling

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

Hashing

Open Addressing - Summary Collision Handling

Open hashing: (static, number of elements fixed)

Hashing

Open Addressing - Summary Collision Handling

Open hashing: (static, number of elements fixed)

- ▶ Uniform probing, double hashing:
 - ▶ Different probing orders for different keys
 - ▶ Avoids clustering of elements

Hashing

Open Addressing - Summary Collision Handling

Open hashing: (static, number of elements fixed)

- ▶ Uniform probing, double hashing:
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Improving efficiency: (Brent, Ordered Hashing)

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

Hashing

Open Addressing - Summary Hashing

Hashing:

Hashing

Open Addressing - Summary Hashing

Hashing:

- Efficient for dictionary operations:

Insert: $O(1) \dots O(n)$

Search: $O(1) \dots O(n)$

Remove: $O(1) \dots O(n)$

Hashing

Open Addressing - Summary Hashing

Hashing:

- ▶ Efficient for dictionary operations:
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Open Addressing - Summary Hashing

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 - Remove: $O(1) \dots O(n)$
- ▶ 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

Structure

Hashing

- Recapitulation

- Treatment of hash collisions

- Open Addressing

- Summary

Priority Queue

- Introduction

Priority Queue

Introduction

Definition:

Priority Queue

Introduction

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- ▶ A priority queue saves a set of elements

Priority Queue

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- ▶ A priority queue saves a set of elements
- ▶ Each element contains a key and a value like a map

Priority Queue

Introduction

Definition:

- ▶ A priority queue saves a set of elements
- ▶ Each element contains a key and a value like a map
- ▶ There is a total order (like \leq) defined on the keys

Priority Queue

Introduction

Definition:

Priority Queue

Introduction

Definition:

- ▶ The priority queue supports the following operations:

Priority Queue

Introduction

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- ▶ The priority queue supports the following operations:

`insert(key, value)`: Inserts a new element into the queue

Priority Queue

Introduction

Definition:

- ▶ The priority queue supports the following operations:

`insert(key, value):` Inserts a new element into the queue

`getMin():` Returns the element with the smallest key

`deleteMin():` Removes the element with the smallest key

Priority Queue

Introduction

Definition:

- ▶ The priority queue supports the following operations:

`insert(key, value):` Inserts a new element into the queue

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- ▶ Sometimes additional operations are defined:

Priority Queue

Introduction

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`changeKey(item, key):` Changes the key of the element

Priority Queue

Introduction

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- ▶ Sometimes additional operations are defined:

`changeKey(item, key):` Changes the key of the element

`remove(item):` Removes the element from the queue

Priority Queue

Introduction

Special features:

Priority Queue

Introduction

Special features:

- ▶ Multiple elements with the same key

Priority Queue

Introduction

Special features:

- ▶ Multiple elements with the same key
 - ▶ No problem and for many applications necessary
 - ▶ If there is more than one element with the smallest key
 - `getMin()`: Returns just one of the possible elements
 - `deleteMin()`: Deletes the element returned by `getMin`

Priority Queue

Introduction

Special features:

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- ▶ Argument of `changeKey` and `remove` operations

Priority Queue

Introduction

Special features:

- ▶ Multiple elements with the same key
 - ▶ No problem and for many applications necessary
 - ▶ If there is more than one element with the smallest key
 - `getMin()`: Returns just one of the possible elements
 - `deleteMin()`: Deletes the element returned by `getMin`
- ▶ Argument of `changeKey` and `remove` operations
 - ▶ There is no **quick-access** to a element in the queue
 - ▶ That's 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

```
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

Priority Queue

Application Example

Example 1:

Priority Queue

Application Example

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Priority Queue

Application Example

Example 1:

- ▶ Calculation of the sorted union of k sorted lists (multi-way merge or k -way merge)
- ▶ Runtime: N = length of resulting list

Priority Queue

Application Example

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- ▶ Calculation of the sorted union of k sorted lists (multi-way merge or k -way merge)
- ▶ Runtime: N = length of resulting list
 - ▶ Trivial: $\Theta(N \cdot k)$, minimum calculation $\Theta(k)$

Priority Queue

Application Example

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- ▶ Calculation of the sorted union of k sorted lists (multi-way merge or k -way merge)
- ▶ Runtime: N = length of resulting list
 - ▶ Trivial: $\Theta(N \cdot k)$, minimum calculation $\Theta(k)$
 - ▶ Priority queue: $\Theta(N \cdot \log k)$, minimum calculation $\Theta(\log k)$

Priority Queue

Application Example

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- ▶ Calculation of the sorted union of k sorted lists (multi-way merge or k -way merge)
- ▶ Runtime: N = length of resulting list
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 - ▶ Priority queue: $\Theta(N \cdot \log k)$, minimum calculation $\Theta(\log k)$

Example 2:

Priority Queue

Application Example

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- ▶ Calculation of the sorted union of k sorted lists (multi-way merge or k -way merge)
- ▶ Runtime: N = length of resulting list
 - ▶ Trivial: $\Theta(N \cdot k)$, minimum calculation $\Theta(k)$
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Example 2:

- ▶ For example Dijkstra's algorithm for computing the shortest path (\leftarrow following lecture)

Priority Queue

Application Example

Example 1:

- ▶ Calculation of the sorted union of k sorted lists (multi-way merge or k -way merge)
- ▶ Runtime: N = length of resulting list
 - ▶ Trivial: $\Theta(N \cdot k)$, minimum calculation $\Theta(k)$
 - ▶ Priority queue: $\Theta(N \cdot \log k)$, minimum calculation $\Theta(\log k)$

Example 2:

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

Priority Queue

Implementation

Idea:

Priority Queue

Implementation

Idea:

- ▶ Save elements as tuples in a binary heap

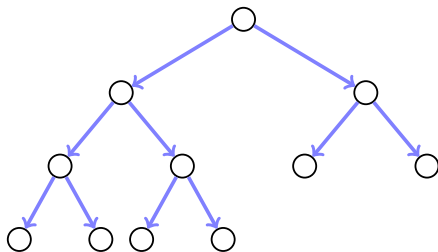


Figure: Heap with 11 nodes

Priority Queue

Implementation

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

Priority Queue

Implementation



Figure: Min heap stored in array

Storing a binary heap:

Priority Queue

Implementation

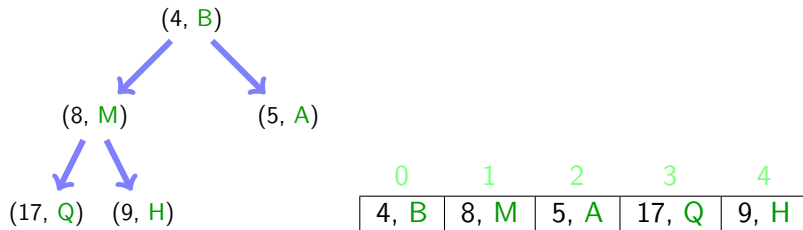


Figure: Min heap stored in array

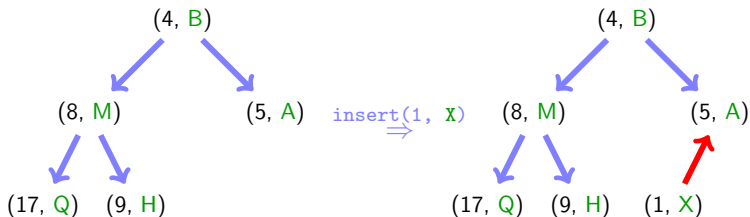
Storing a binary heap:

- ▶ 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 $\text{floor}((i - 1)/2)$

Priority Queue

Implementation - Insertion

Inserting an element: `insert(key, item)`



Priority Queue

Implementation - Insertion

Inserting an element: `insert(key, item)`

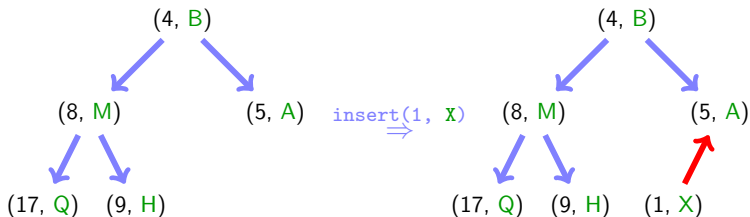


- Append the element at the end of the array

Priority Queue

Implementation - Insertion

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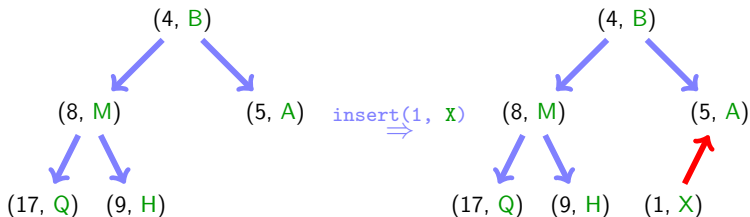


- ▶ Append the element at the end of the array
- ▶ The **heap condition** may be violated, but only at the last index

Priority Queue

Implementation - Insertion

Inserting an element: `insert(key, item)`



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

Priority Queue

Implementation

Returning the minimum: `getMin()`



Priority Queue

Implementation

Returning the minimum: `getMin()`



- Else return the first element

Priority Queue

Implementation

Returning the minimum: `getMin()`

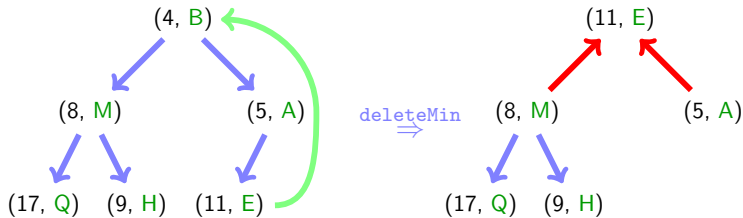


- ▶ Else return the first element
- ▶ If the heap is empty return `None`

Priority Queue

Implementation

Removing the minimum: `deleteMin()`



Priority Queue

Implementation

Removing the minimum: `deleteMin()`



- Deleting the element with the lowest key

Priority Queue

Implementation

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

Priority Queue

Implementation

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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Priority Queue

Implementation

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
- ▶ The **heap condition** may be violated, but only at the first index
- ▶ Repair **heap condition**

Priority Queue

Implementation

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

- ▶ The element (queue item) is given as argument
- ▶ Replace the key of the element
- ▶ The **heap condition** may be violated, but only at the element index and only in one direction (up / down)
- ▶ Repair **heap condition**



Priority Queue

Implementation

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



Priority Queue

Implementation

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



- The **heap condition** may be violated, but only at the element index and only in one direction (up / down)

Priority Queue

Implementation

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



- ▶ The **heap condition** may be violated, but only at the element index and only in one direction (up / down)
- ▶ Repair **heap condition**

Priority Queue

Implementation

Removing an element: `remove(item)`



Priority Queue

Implementation

Removing an element: `remove(item)`



- The element (queue item) is given as argument

Priority Queue

Implementation

Removing an element: `remove(item)`



- ▶ The element (queue item) is given as argument
- ▶ Replace the element with the last element and shrink the heap by one

Priority Queue

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Removing an element: `remove(item)`



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Priority Queue

Implementation

Removing an element: `remove(item)`



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- ▶ Replace the element with the last element and shrink the heap by one
- ▶ The **heap condition** may be violated, but only at the element index and only in one direction (up / down)
- ▶ Repair **heap condition**

Priority Queue

Implementation - Repairing the Heap

Repairing after modifying operations:

Priority Queue

Implementation - Repairing the Heap

Repairing after modifying operations:

- ▶ The heap condition can be violated after using `insert`, `deleteMin`, `changeKey`, `remove`, but only at one known position with index i

Priority Queue

Implementation - Repairing the Heap

Repairing after modifying operations:

- ▶ The heap condition can be violated after using `insert`, `deleteMin`, `changeKey`, `remove`, but only at one known position with index i
- ▶ Heap conditions can be violated in two directions:

Priority Queue

Implementation - Repairing the Heap

Repairing after modifying operations:

- ▶ The heap condition can be violated after using `insert`, `deleteMin`, `changeKey`, `remove`, but only at one known position with index i
- ▶ Heap conditions can be violated in two directions:
 - ▶ Downwards: The key at index i is not \leq than the value of its children

Priority Queue

Implementation - Repairing the Heap

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- ▶ The heap condition can be violated after using `insert`, `deleteMin`, `changeKey`, `remove`, but only at one known position with index i
- ▶ Heap conditions can be violated in two directions:
 - ▶ Downwards: The key at index i is not \leq than the value of its children
 - ▶ Upwards: The key at index i is not \geq than the value of its parent

Priority Queue

Implementation - Repairing the Heap

Repairing after modifying operations:

- ▶ The heap condition can be violated after using `insert`, `deleteMin`, `changeKey`, `remove`, but only at one known position with index i
- ▶ Heap conditions can be violated in two directions:
 - ▶ Downwards: The key at index i is not \leq than the value of its children
 - ▶ Upwards: The key at index i is not \geq than the value of its parent
- ▶ We need two repair methods: `repairHeapUp`, `repairHeapDown`

Priority Queue

Implementation - Repairing the Heap

`repairHeapDown:`

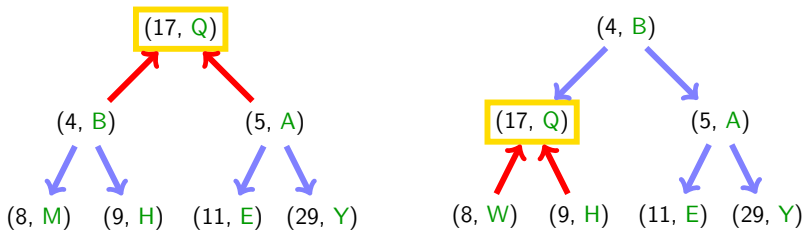


Figure: Repairing the heap downwards

Priority Queue

Implementation - Repairing the Heap

`repairHeapDown:`

- Sift the element until the **heap condition** is valid

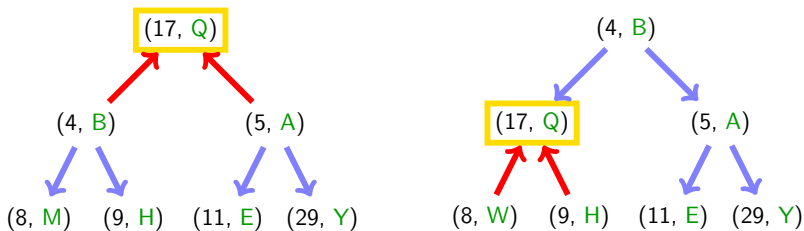


Figure: Repairing the heap downwards

Priority Queue

Implementation - Repairing the Heap

repairHeapDown:

- Sift the element until the **heap condition** is valid
 - Change node with child, which has the lower key of both children

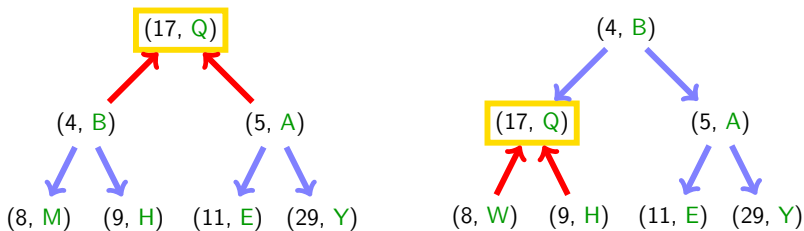


Figure: Repairing the heap downwards

Priority Queue

Implementation - Repairing the Heap

repairHeapDown:

- Sift the element until the **heap condition** is valid
 - Change node with child, which has the lower key of both children
 - If the **heap condition** is violated repeat for the child node



Figure: Repairing the heap downwards

Priority Queue

Implementation - Repairing the Heap

`repairHeapDown:`

- ▶ Sift the element until the **heap condition** is valid
 - ▶ Change node with child, which has the lower key of both children
 - ▶ If the **heap condition** is violated repeat for the child node



Figure: Repairing the heap downwards

Priority Queue

Implementation - Repairing the Heap

repairHeapUp:

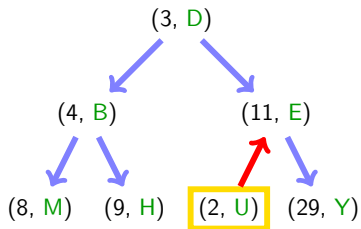


Figure: Repairing the heap upwards

Priority Queue

Implementation - Repairing the Heap

`repairHeapUp:`

- Change node with parent



Figure: Repairing the heap upwards

Priority Queue

Implementation - Repairing the Heap

`repairHeapUp:`

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



Figure: Repairing the heap upwards

Priority Queue

Implementation - Repairing the Heap

`repairHeapUp:`

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



Figure: Repairing the heap upwards

Priority Queue

Implementation - Priority Queue Item

Index of a priority queue item:

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

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

```
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
```

Priority Queue

Complexity

Summary lecture 1:

Priority Queue

Complexity

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- ▶ A full binary tree with n elements, has a depth of $O(\log n)$

Priority Queue

Complexity

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- ▶ The maximum distance from the root to a leaf can be $O(\log n)$ elements

Priority Queue

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- ▶ A full binary tree with n elements, has a depth of $O(\log n)$
- ▶ The maximum distance from the root to a leaf can be $O(\log n)$ elements
- ▶ Repairing the heap upwards and downwards:
We have only one path to traverse: $O(\log n)$

Priority Queue

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Runtime for methods

Priority Queue

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Runtime for methods

- ▶ `insert`, `deleteMin`, `changeKey`, `remove`:
We have to repair the heap: $O(\log n)$

Priority Queue

Complexity

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We have only one path to traverse: $O(\log n)$

Runtime for methods

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

Priority Queue

Complexity

Improvements (Fibonacci heaps):

Priority Queue

Complexity

Improvements (Fibonacci heaps):

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

Priority Queue

Complexity

Improvements (Fibonacci heaps):

- ▶ `getMin`, `insert` and `decreaseKey` in amortized time of $O(1)$
- ▶ `deleteMin` in amortized time $O(\log n)$

Priority Queue

Complexity

Improvements (Fibonacci heaps):

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Practical experience:

Priority Queue

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- ▶ 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`