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Algorithms and Datastructures
Winter Term 2024
Sample Solution Exercise Sheet 13

Due: Wednesday, Febuary 12th, 2pm

Exercise 1: (Binary) Heaps and Heapsort *(12 Bonus Points)*

(a) Implement a *binary heap* using the *array implementation* from the lecture. The heap should support the following functions: `create`, `insert` (eines key-value pairs), `get_min` and `delete_min`. You may use the template *heap.py*. *(5 Points)*

Hint: To implement `delete_min` efficiently one overwrites the root with the last element of the heap and then deletes the last element. Afterwards one has to repair the min-heap property.

(b) Implement the heapsort algorithm by using your implementation from the previous task.[1] Explain the $O(n \log n)$ runtime of heapsort.

Argue why there can't be a heap implementation where `insert`, `get_min` and `delete_min` have all constant runtime. *(3 Points)*

(c) In this task we consider *ternary* heaps. They are similar to binary heaps with the difference that each parent node may have 3 children. We also have that the underlying tree is filled up with nodes from 'top to bottom' and 'left to right'.

Give the minimal and maximal number of nodes of a ternary heap of depth d. *(1 Point)*

Assume we use an array implementation for ternary heaps[2], starting with index 1 (not 0). Let i be the index of a node v that is neither the root nor a leaf. What are the indices of v's parent and its three children? *(3 Points)*

Sample Solution

(a) See `heap.py`

(b) Heaport inserts n elements into the heap. In a second loop, alternating `get_min` and `delete_min` empties the heap and retrieving the smallest element at any time. The runtimes of `insert` and `delete_min` are logarithmic in the number of elements while `get_min` is constant:

$$\sum_{i=1}^{n} \underbrace{O(\log n)}_{\text{insert}} + \sum_{i=1}^{n} \left(\underbrace{O(1)}_{\text{get}} + \underbrace{O(\log n)}_{\textit{delete}} \right) = O(n \log n)$$

Why these 3 operations can not be constant: Assume all of them would be constant, then heapsort would sort an array of n arbitrary numbers in time $O(n)$. This is a contradiction to the fact that any comparison-based sorting algorithm takes at least $\Omega(n \log n)$ time.

[1] If you did not solve the previous task, you may use `heapq`. In `heapq`, `heappush` equals the `insert` and `heappop` the `delete-min` operation from the lecture. `heappush` and `heappop` can be applied on Python-lists (for more detail see here).

[2] Similar to the array implementation of binary heaps on slide 26 in lecture 9.

(c) **Min**: Tee is complete up depth $d-1$ but contains just 1 node in depth d:

$$1+\sum_{i=0}^{d-1} 3^i = 1 + \frac{3^d - 1}{3-1} = \frac{3^d + 1}{2}$$

Max: Tee is complete up depth d:

$$\sum_{i=0}^{d} 3^i = \frac{3^{d+1} - 1}{3-1} = \frac{3^{d+1} - 1}{2}$$

Index left child: $3 \cdot i - 1$
Index middle child: $3 \cdot i$
Index right child: $3 \cdot i + 1$
Index parent: $\left\lfloor \frac{i+1}{3} \right\rfloor$

Exercise 2: Hashing *(8 Bonus Points)*

(a) Let $h(s, j) := h_1(s) - 2j \bmod m$ and $h_1(x) := x + 2 \bmod m$. Insert the keys 51, 13, 21, 30, 23, 72 (in the given order) into a hash table of size $m = 7$ by using the hash function h and *linear probing* for collision resolution. (The following table should show the final state after inserting all keys.) *(1 Point)*

0	1	2	3	4	5	6

(b) Assume we would like to insert the sequence of numbers from part a) in a table of size $m = 7$ by using *quadratic probing.* Which of the following hash functions would be the better choice? Explain your answer.

- $h_1(x, i) := x + 6i + 2i^2 \bmod m$
- $h_2(x, i) := x + i + 4i^2 \bmod m$

Insert the keys by using the better hash function into the following table. *(2 Points)*

0	1	2	3	4	5	6

(c) Let $h(s, j) := h_1(s) + j \cdot h_2(s) \bmod m$ with $h_1(x) = x \bmod m$ and $h_2(x) = 1 + \big(x \bmod (m - 1)\big)$. Insert the keys 28, 59, 47, 13, 39, 69, 12 in a hash table of size $m = 11$ by using *double-hashing* for collision resolution. *(2 Points)*

0	1	2	3	4	5	6	7	8	9	10

(d) Given the hash functions $h_1(x) := x + 2 \bmod m$ and $h_2(x) := 3x \bmod m$ with $m = 7$, find three pairwise distinct keys $u, v, w \in \mathbb{N}$ such that $h_1(u) = h_1(v) = h_1(w) \neq h_2(u) = h_2(v) = h_2(w)$. Insert u and v into the following table by using *Cuckoo Hashing.*

0	1	2	3	4	5	6

If we also insert w, we obtain a cycle. To avoid this, we apply a rehash by increasing the table's size to $m' = 11$ and use two new hash functions h'_1 and h'_2. Give two distinct functions h'_1 and h'_2 of the form $(ax \bmod m')$ with $a \not\equiv 0$ such that u, v and w can be inserted into the new table (i.e., that no cycle is created). *(3 Points)*

Sample Solution

(a)

30	13	21	72	51	23	
0	1	2	3	4	5	6

(b) h_2 ist not suitable, since there is no free array position for 23:

$$h_2(51,0) = 2$$
$$h_2(13,0) = 6$$
$$h_2(21,0) = 0$$
$$h_2(30,6) = 5$$
$$h_2(23,0) = 2$$
$$h_2(23,1) = 0$$
$$h_2(23,2) = 6$$
$$h_2(23,3) = 6$$
$$h_2(23,4) = 0$$
$$h_2(23,5) = 2$$
$$h_2(23,6) = 5$$

Table filled with h_2:

21	23	51	30		72	13
0	1	2	3	4	5	6

(c)

	69	13	47	59	39	28	12			
0	1	2	3	4	5	6	7	8	9	10

(d) We choose $u := 2$, $v := 9$ and $w := 16$. Thus, we have $h_1(u) = h_1(v) = h_1(w) = 4 \neq 6 = h_2(w) = h_2(v) = h_2(u)$.

				v		u
0	1	2	3	4	5	6

As new functions we can choose for instance $h_1'(x) = x \bmod 11$ and $h_2'(x) = 2x \bmod 11$.