

# Exercise of Getting Started

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## 1 Chapter 1: Foundations

### 1.1 The Role of Algorithms in Computing

I didn't make the exercise of this section because I didn't find them useful.

### 1.2 Getting Started

**Exercise 1.2-1):**

It could be an application like booking. When you search a hotel close to the airport, it gets involved algorithms as searching the hotels close to that airport and it should be searched in a short time period.

**Exercise 1.2-2):**

$$8n^2 < 64n \cdot \log_2 n \quad \rightarrow \quad n < 8 \cdot \log_2 n$$

Try values until this inequality is false. To  $n \lesssim 43$ , insertion sort runs faster than merge sort.

**Exercise 1.2-3):**

$$100n^2 < 2^n$$

Trying values, for  $n \lesssim 15$ ,  $2^n$  runs faster than  $100n^2$ .

**Exercise 1.2-4):**

*View photo of the exercise on the next page.*

	1 second	1 minute	1 hour	1 day	1 month	1 year	1 century
$\lg n$	$\infty$	$\infty$	$\infty$	$\infty$	$\infty$	$\infty$	$\infty$
$\sqrt{n}$	$10^{12}$	$3.6 \cdot 10^{15}$	$1.3 \cdot 10^{19}$	$7.47 \cdot 10^{21}$	$6.91 \cdot 10^{24}$	$9.95 \cdot 10^{26}$	$9.95 \cdot 10^{30}$
$n$	$10^6$	$6 \cdot 10^7$	$3.6 \cdot 10^9$	$8.64 \cdot 10^{10}$	$2.63 \cdot 10^{12}$	$3.16 \cdot 10^{13}$	$3.16 \cdot 10^{15}$
$n \lg n$	62746	$2.8 \cdot 10^6$	$1.33 \cdot 10^8$	$2.76 \cdot 10^9$	$7.29 \cdot 10^{10}$	$7.99 \cdot 10^{11}$	$6.87 \cdot 10^{13}$
$n^2$	1000	7746 (approx)	60000	293939	$1.62 \cdot 10^6$	$5.62 \cdot 10^6$	$5.61 \cdot 10^7$
$n^3$	100	391 (approx)	1532	4420	13803	31601	146679
$2^n$	20 (approx)	26 (approx)	32	36	41	44	51
$n!$	9	11	12	13	15	16	17

### Exercise 2.1-1):

Note: Resolved using the logic of C, C++, Java, etc. while iterating over an array on a for loop. Also the number that appears in **green**, is the number being checked. The number or numbers that appears in **red** are the numbers being moved.

i	Array
1)	[31, <b>41</b> , 59, 26, 41, 58]
2)	[31, 41, <b>59</b> , 26, 41, 58]
3)	[ <b>26</b> , <b>31</b> , <b>41</b> , <b>59</b> , 41, 58]
4)	[26, 31, 41, <b>41</b> , <b>59</b> , 58]
5)	[26, 31, 41, 41, <b>58</b> , <b>59</b> ]

### Exercise 2.1-2):

**Initialization:** The loop start getting the first number in the array. In spite of that, it has initialized to 0 the variable sum where the total sum will be stored. Due to that, the invariant holds the first number that will be added to sum.

**Maintenance:** On each iteration, the loop will hold only the index of the number that will be added, after add it, i will be incremented by 1, holding the next number (i + 1).

**Termination:** The loop will terminate when the 'n' elements of the array are added. In conclusion, sum it's equivalent of say that  $sum = \sum_{i=1}^n A[i]$ .

### Exercise 2.1-3):

click this link to see the resolution → [resolution](#)

### Exercise 2.1-4):

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#### Algorithm 1 Linear Search

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```

1: function LINEAR-SEARCH( $A, n, x$ )
2:   for  $i \leftarrow 1$  to  $n$  do
3:     if  $A[i] == x$  then return  $i$ 
4:   return NIL

```

---

**Initialization:** The loop start getting the first element of the array.

**Maintenance:** On each iteration, the loop takes the next element ( $i + 1$ ) and compare it with the value being search ( $x$ ). If it's found return  $i$ , else, continue searching that value.

**Termination:** When all values are read, if  $x$  wasn't found in the array, it returns NIL to indicate that no value was found on all the array.

**Exercise 2.1-5):**

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**Algorithm 2** ADD-BINARY-INTEGERS

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```
1: function ADD-BINARY-INTEGERS( $A, B, n$ )
2:   //Initialize array  $C$  with  $n$  values
3:    $carry \leftarrow 0$ 
4:   for  $i \leftarrow 1$  to  $n$  do
5:      $c \leftarrow A[i] + B[i]$ 
6:      $C[i] \leftarrow c \bmod 2$ 
7:      $carry \leftarrow c \div 2$  //Integer division

8:    $C[n] \leftarrow carry$ 
9:   return  $C$  //Return the array  $C$  with the values
```

---

**Initialization:** The loop starts with value of carry to 0, and getting the first bits of A and B.

**Maintenance:** On each iteration, the loop takes the next bits values of A and B. Add these values and calculate the value to insert into C and the carry that could exists.

**Termination:** All values were added and store, now  $C[0:n - 1]$  with the result of the sum. To reach the  $n$ -th value, adds the last carry value on the position  $n$ .

**Exercise 2.2-1):**

Like the book says,  $\Theta$  notation is like saying "roughly proportional to  $n^2$  (for example), when  $n$  is large." In this case, we remove constants, so the remaining expression is  $n^3 + n^2 + n + 3$ . The term with the highest exponent is  $n^3$ , so at any moment:  $n^3 \gg n^2 \gg n$ .

**Solution:**  $\Theta(n^3)$ .

**Exercise 2.2-2):**

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**Algorithm 3** SELECTION-SORT

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```
1: function SELECTION-SORT( $A, n$ )
2:   for  $i \leftarrow 1$  to  $n - 1$  do
3:      $ind\_small\_elm \leftarrow i$ 
4:     for  $j \leftarrow i + 1$  to  $n$  do
5:       if  $A[ind\_small\_elm] > A[j]$  then
6:          $ind\_small\_elm \leftarrow j$ 
7:     SWAP( $A[i], A[ind\_small\_elm]$ )
```

---

The invariant is that on each iteration of extern for, it only takes 1 by 1 element. In the inner for, also take all elements from  $i$  to  $n$ , and compare the value of the outer for against the inner for to take the smaller element.

When the algorithm arrives to the last element, all swaps occurred and the last element will be in the correct place.

The worst case happens when it must iterate on the outer for and also with all the elements from  $i$  to  $n$  in the inner for. So it's:  $\frac{n*(n-1)}{2}$ . That means that avoiding all constants values, the solution is:  $\Theta(n^2)$ .

The best case is not better because you have to check all values in the if, the only instruction that is avoided is the instruction inside the if because the if won't be evaluated to true. But that instruction is insignificant if  $n$  is too big.

**Exercise 2.2-3):**

Depends on the value where is storage, if the  $x$  value is storage at the first position it will take a constant value to search it. However, if the value is in the last element (worst case) it will spend  $constant * n$  time to find that value.

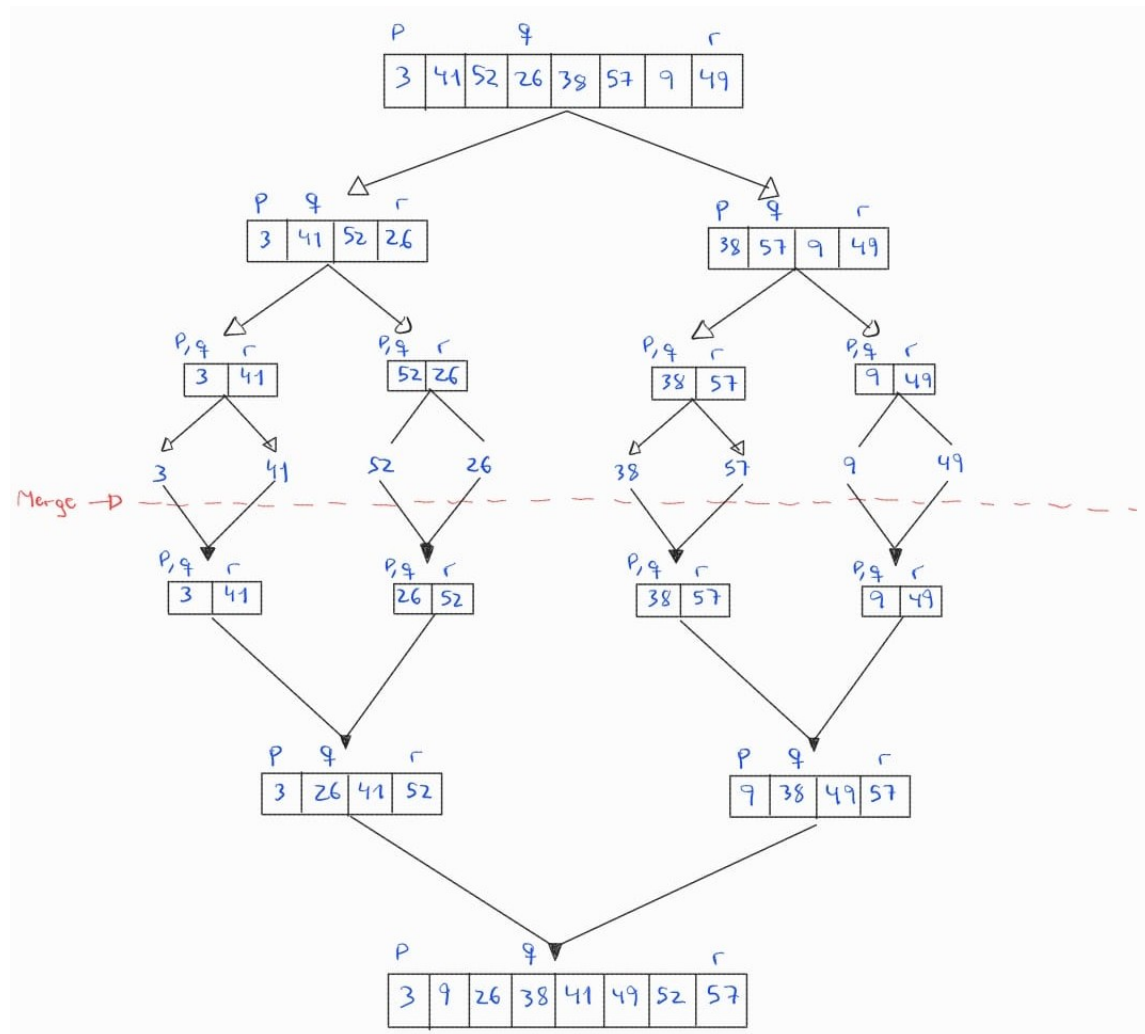
Average case is suposing that it's in the middle of the array. The average is  $\frac{n}{2} = n$  if  $n$  is too big.

Worst case as mentioned before is  $\Theta(n)$ .

**Exercise 2.2-3):**

The only thing you could do is a preprocessing step to check if it's already sorted or nearly to be sorted and then apply the algorithm who best fits when the best case was achieved.

**Exercise 2.3-1):**



**Exercise 2.3-2):**

The "**if**  $p \neq r$ " is not useful because  $p = 1$  and  $q > 1$ , so the if will be evaluated to true, and the return (the termination of recursion) will execute without doing any recursion step.

**Exercise 2.3-3):**

**Initialization:** The loop starts obtaining the first element to insert it in the sorted array.

**Maintenance:** On each iteration, the loop insert 1 element of the left or right array, then increment  $k$  by 1, to insert on the next iteration the next value 1 by 1. The values that will be inserted with the first loop in the best case is  $n - 1$  where  $n$  is the lenght of the subarray/array being sorted.

**Termination:** In one of the last 2 whiles, it will be inserted all remaining values (could be values in the left or right array) until reach the  $n$ th values in the sorted array.

**Exercise 2.3-4):**

$$n = 2$$

$$T(2) = 2$$

The solution given says that:

$$T(2) = 2 * \log_2 2 = 2 \cdot 1 = 2$$

Induction hypotesis:

$$T(k) = k \cdot \log_2 k$$

Where  $k$  is a power of 2. We want to demonstrate that  $n = 2k$ . Use recurrence to calculate  $T(2k)$ :

$$T(2k) = 2T(k) + 2k \rightarrow T(2k) = 2 \cdot (k \cdot \log_2 k) + 2k \rightarrow T(2k) = 2k \cdot (\log_2 k + 1) \rightarrow T(2k) = 2k \cdot \log_2 2k$$

As we mentiones before, replacing  $n = 2k$ , we conclude that the induction hypotesis is correct  $n \cdot \log_2 n$

**Exercise 2.3-5):**

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**Algorithm 4** INSERTION-SORT-RECURSIVE

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```

1: function INSERTION-SORT-RECURSIVE( $A, n$ )
2:   if  $n == 0$  then return
3:   INSERTION-SORT-RECURSIVE( $A, n - 1$ )
4:    $key \leftarrow A[n]$ 
5:    $i \leftarrow n - 1$ 
6:   while  $i \geq 0$  and  $A[i] > key$  do
7:      $A[i + 1] \leftarrow A[i]$ 
8:      $i \leftarrow i - 1$ 
9:    $A[i + 1] \leftarrow key$ 

```

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**Exercise 2.3-6):**

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**Algorithm 5** BINARY-SEARCH

---

```
1: function BINARYSEARCH( $A, x, l, n$ )
2:   if  $l > n$  then return
3:    $mid \leftarrow l + n/2$ 
4:   if  $A[mid] > x$  then
5:     BINARYSEARCH( $A, x, l, mid - 1$ )
6:   else if  $A[mid] < x$  then
7:     BINARYSEARCH( $A, x, mid + 1, r$ )
8:   else return  $mid$ 
```

---

**Exercise 2.3-7):**

You can't use binary search because while you are sorting most part of the time, it won't be that value in the sorted array. Maybe you should make a variation of binary search to find out in which direction has less difference between the number being search and then you should move all values 1 position to right and insert in the new position.

On worst case, imagine that the worst value is at the least position, you should move  $n$  items to the right  $+ n / 2$  that cost to search all the. So it's  $n \cdot \frac{n}{2} = \Theta(n^2)$

**Exercise 2.3-8):**

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**Algorithm 6** FIND-SUM-TWO-ELEMENTS

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```
1: function FINDSUMTWOELEMENTS( $S, n, x$ )
2:   MERGESORT( $S, 0, n - 1$ ) //  $\Theta(n * \log n)$ 
3:    $i \leftarrow 0$ 
4:    $j \leftarrow n - 1$ 
5:   while  $i < j$  do //  $\Theta(n)$ 
6:     if  $S[i] + S[j] = x$  then
7:       return  $i, j$ 
8:     else if  $S[i] + S[j] < x$  then
9:        $i \leftarrow i + 1$ 
10:    else
11:       $j \leftarrow j - 1$ 
12:  return No pair found
```

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Problems of page 45

**Exercise 2-1):**

a) The number of arrays to be sort are  $\frac{n}{k}$ , where  $n$  is the number of elements in the original array and  $k$  the number of elements to be sorted on *insertion sort*. Due to that, on the worst case it should be sorted  $\frac{n}{k} \cdot k^2 \rightarrow n \cdot k = \Theta(n \cdot k)$ .

b) The recursion will be called until reach  $\frac{n}{k}$  elements on a subarray. Hence it won't be called recursively until  $\log_2 n$  (when only 1 element is left). Due to that the number of recursions are delimited by  $\log_2 \frac{n}{k}$ . Finally in the worst case when only is left the first 2 subarrays, it will take  $n$  iterations to sort it. Due to that, we explain why it's true the expresion  $\Theta(n \cdot \log_2 \frac{n}{k})$ .

c)

$$\Theta\left(n \cdot k + n \cdot \log_2 \frac{n}{k}\right) = \Theta(n \cdot \log_2 n)$$

$$\begin{aligned}\Theta(n \cdot k) &= \Theta(n \cdot \log_2 n) \quad \rightarrow \quad k = \Theta(\log_2 n) \\ \Theta\left(n \cdot \log_2 \frac{n}{k}\right) &= \Theta(n \cdot \log_2 n) \quad // \text{Substituting } k = \Theta(\log_2 n) \\ \Theta\left(n \cdot \log_2 \frac{n}{\log_2 n}\right) &= \Theta(n \cdot \log_2 n) - \Theta(n \cdot \log_2 \log_2 n) \quad // \text{Dominant term is } \Theta(n \cdot \log_2 n)\end{aligned}$$

In conclusion, the biggest possible value which both variants of Merge Sort have the same result is for  $k = \Theta(\log_2 n)$ .

d) You should see in which value it's better use one algorithm or another to sort and combine the 2 algorithms. As we saw in the section c, this k value is calculated applying that formula.

**Exercise 2-2):**

a) Do you need to prove that on each iteration, of the inner for 1 element is being moved and it remains on all iterations. In addition to that, you must prove that on the extern for loop it's being incremented by 1.

b) **Initialization:** The loop starts taking the most right element on the array. So the invariant is that take 1 element at a time.

**Maintenance:** Loop takes on each iteration an element, compare with the left hand elemnt and if it's smaller than the left hand element, swap both elements. The loop invariant remains as Initialization because on each iteration only 1 element is being checked with another one. After that check, on the next iteration is taken the next left element.

**Termination:** When this for ends, there are a number of elements equals to  $i$  (extern for) that are sorted in the lowest positions of the array.

c) As I said before, on each time that the inner for loop ends, 1 value is sorted. Hence when the extern for loop ends, all values will be sorted on the right position and it's proved the inequality.

d) Both have the same worst-case running time ( $\Theta(n^2)$ ). But Insertion Sort is usually better on the averegage cases because it does less swaps and usually spends  $\Theta(n)$  on sort an array. On the other hand, Bubble Sort always spend  $\Theta(n^2)$  to sort the array.

**Exercise 2-3):**

a)  $\Theta(n)$  because it has to take all values of the array  $A$  and add it to  $x \cdot p$ .

b)

---

```

NAIVE-HORNER ( $A, x$ )
1   $y = 0$ 
2  for  $i = 1$  to  $A.length$ 
3       $m = 1$ 
4      for  $j = 1$  to  $i - 1$ 
5           $m = m \cdot x$ 
6       $y = y + A[i] \cdot m$ 

```

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Figure 1: Resolution extracted from <https://atekihcan.github.io/CLRS/02/P02-03/> I was lazy of do that hehehe.

c) For Maintenance:

$$\begin{aligned}
 y &= a_i + x \sum_{k=0}^{n-(i+1)} a_{k+i+1} x^k \\
 &= a_i x^0 + \sum_{k=0}^{n-i-1} a_{k+i+1} x^{k+1} \\
 &= a_i x^0 + \sum_{k=1}^{n-i} a_{k+i} x^k \\
 &= \sum_{k=0}^{n-i} a_{k+i} x^k.
 \end{aligned}$$

The loop terminates at  $i = -1$ :

$$= a_i x^0 + \sum_{k=0}^{n-i-1} a_{k+i+1} x^{k+1} = \sum_{k=0}^{n-i} a_{k+i} x^k.$$

**Exercise 2-4):**

a) Inversions are: (2, 1), (3, 1), (8, 6), (8, 1), (6, 1)

b) if the set is sorted in ascending order, it won't be 0 inversions in the set.

c) Both of them are  $\Theta(n^2)$  because you have to take 1 value from the most right position and compare if it's less than the  $i$  value (left one) on the array.

d)

---

**Algorithm 7** INVERSIONS

---

```

1: function INVERSIONS( $A, p, r$ )
2:   //On the else of the first while of Merge, add: Print( $L[i], R[j]$ )

```

---

## 1.3 Characterizing Running Times

**Exercise 3.1-1):**

We could do the same with saying that  $k$  is a multiple of 2. The left subarray has the biggest numbers, and the right one has the lowest numbers. If we want to move the biggest numbers to the right subarray, we should move  $n/2$  numbers and then another  $n/2$  to the left to move the lowest one at the beginning. Finally we have that we should move  $\frac{n}{2} \cdot \frac{n}{2} = \frac{n^2}{4} = \Omega(n^2)$

**Exercise 3.1-2):**

The external loop, executes in the worst case  $n - 1$  times. The inner loop, executes  $i + 1$  to  $n$  times. As mentioned before, the worst case is for  $i = 0$ , then it will be executed  $n - 1$  times. In conclusion, the worst case is  $(n - 1) \cdot (n - 1) = O(n^2)$ .

On the other hand, suppose that the array is divided in 2 subarrays, the left for the higher values and the right for the lower ones. Although, the external loop must iterate over all elements, so the better case is the same as the



worst ( $n - 1$ ). Then the inner loop is the same as the worst case. The only thing that executes  $n/2$  times is the instruction inside the if and the swap. These operations are constant operations. In conclusion, the lower bound of the asymptotic behaviour is  $(n - 1) \cdot (n - 1) = \Omega(n^2)$

$$O(n^2) = \Omega(n^2) = \Theta(n^2)$$

**Exercise 3.1-3):**

Consideramos un array  $A$  de tamaño  $n$ , dividido en tres partes:

- Primera parte: Las primeras  $\alpha n$  posiciones contienen los  $\alpha n$  valores más grandes.
- Segunda parte: Las siguientes  $(1 - 2\alpha)n$  posiciones son la parte media.
- Tercera parte: Las últimas  $\alpha n$  posiciones contienen los  $\alpha n$  valores más grandes después de ordenar.

El número total de movimientos es:

$$\text{Movimientos totales} = \alpha(1 - 2\alpha)n^2.$$

Para que el argumento tenga sentido, necesitamos que  $0 < \alpha < \frac{1}{2}$ .

Maximizamos la función:

$$f'(\alpha) = 1 - 4\alpha = 0 \quad \Rightarrow \quad \alpha = \frac{1}{4}.$$

El número total de movimientos es:

$$\frac{1}{4} \cdot \frac{1}{2}n^2 = \frac{1}{8}n^2.$$

Por lo tanto, el tiempo de ejecución en el peor caso es  $\Theta(n^2)$ .

**Exercise 3.2-1):**

$$0 \leq c_1g(n) \leq f(n) \leq c_2g(n) = \Theta$$

Prove that  $\max\{f(n), g(n)\} = O(f(n) + g(n)) \Rightarrow \max\{f(n), g(n)\} \leq c_2 \cdot (f(n) + g(n))$ .

If the max value is  $f(n)$ , then we have  $f(n) \leq c_2 \cdot (f(n) + g(n))$ . Also if the max value is  $f(n)$ , then we have  $g(n) \leq c_2 \cdot (f(n) + g(n))$  If  $c_2 = 1$ , and  $n \geq n_0$ , the result is  $\max\{f(n), g(n)\} = O(f(n) + g(n))$ .

Prove that  $\max\{f(n), g(n)\} = \Omega(f(n) + g(n)) \Rightarrow \max\{f(n), g(n)\} \geq c_1 \cdot (f(n) + g(n))$ .

If the max value is  $f(n)$ , then we have  $f(n) \geq c_1 \cdot (f(n) + g(n))$ . Also if the max value is  $f(n)$ , then we have  $g(n) \geq c_1 \cdot (f(n) + g(n))$  If  $c_1 = \frac{1}{2}$ , and  $n \geq n_0$ , the result is  $\max\{f(n), g(n)\} = \Omega(f(n) + g(n))$ .

**In conclusion:**  $\max\{f(n), g(n)\} = O(f(n) + g(n)) = \Omega(f(n) + g(n)) = \Theta(f(n) + g(n))$  for  $c_1 = \frac{1}{2}$  and  $c_2 = 1$ .

**Exercise 3.2-2):**

It's meaningless because de O notation defines asymptotically, the upper bound of  $f(n)$ . This not mean "Is at least  $O(n^2)$ " because it's only in the worst possible scenario. Although, we need to define the lower bound, for example the asymptotic lower bound is  $\Omega(n)$  that it's less than  $O(n^2)$ . Hence we can't say "At least" due to it could spend some value between  $O(n^2)$  on the worst case or  $\Omega(n)$  in the best cases.

**Exercise 3.2-3):**

With the properties of the powers, we have:

$$2^{n+1} = 2^n \cdot 2^1 = O(\max\{2^n, 2^1\}) = O(2^n)$$

The second one is wrong, because with the properties we can't remove the  $n$  there, so it should be  $O(2^{2n})$ .

**Exercise 3.2-5):**

$$\begin{aligned} 0 &\leq c_1 g(n) \leq g(n) \leq c_2 g(n) = \Theta(g(n)) \\ \Omega(g(n)) = c_1 g(n) &\leq g(n) \quad c_1 = \frac{1}{2} \text{ and } n \geq n_0 \\ O(g(n)) = c_2 g(n) &\geq g(n) \quad c_2 = 2 \text{ and } n \geq n_0 \end{aligned}$$

**Exercise 3.2-6):**

All the values of the time spent by the algorithm, will be on  $\Omega(g(n)) = g(n) = O(g(n))$  if  $\Theta(g(n))$ . Also we know that  $o(g(n)) > O(g(n))$  and  $\omega(g(n)) < \Omega(g(n))$ , so they won't have values in common.

**Exercise 3.2-7):**

$\Omega(g(n, m)) = \{f(n, m) : \text{if there exists a constant } c, n_0 \text{ and } m_0 \text{ such that } cg(n, m) \leq f(n, m) \text{ for all } n \geq n_0 \text{ or } m \geq m_0 \text{ and } c > 0\}$ .

$\Theta(g(n, m)) = \{f(n, m) \text{ if there exists a constant } c_1, c_2, n_0 \text{ and } m_0 \text{ such that } 0 < c_1 g(n, m) \leq f(n, m) \leq c_2 g(n, m) \text{ for all } n \geq n_0 \text{ or } m \geq m_0 \text{ and } c_1 > 0, c_2 > 0\}$ .

**Exercise 3.3-1):**

$f(n)$  is monotonically increasing because there is an  $f(m) \leq f(n)$ . For  $g(n)$  it's the same. Then we have:

$$f(m_1) \leq f(n_1) + g(m_2) \leq g(n_2) \Rightarrow f(m_1) + g(m_2) \leq f(n_1) + g(n_2)$$

Demonstrate  $f(g(n))$ :

$$f(g(m)) \leq f(g(n)) \quad m \leq n$$

Demonstrate  $f(n) \cdot g(n)$  are non negative for an  $n_1 > 0, n_2 > 0, m_1 < n_1 \text{ and } m_2 < n_2$

$$f(m_1) * g(m_2) \leq f(n_1) * g(n_2)$$

**Exercise 3.3-2):**

$$\begin{aligned} \lfloor \alpha n \rfloor &= \alpha n & \lceil (1 - \alpha)n \rceil &= (1 - \alpha)n \\ \alpha n + (1 - \alpha)n &= n(\alpha + 1 - \alpha) = n \end{aligned}$$

**Exercise 3.3-3):**

Applying the properties of exponentials, we have

$$(n + o(n))^k = n^k + o(n^k) \Rightarrow \Theta(\max\{n^k, n^k\}) = \Theta(n^k)$$

With the property of ceil and floor, we know  $\lceil n \rceil^k \leq n^k \leq \lfloor n \rfloor^k$ , the problem says  $\Theta(n^k) = n^k$

**Exercise 3.3-4):**

a) Equation  $a^{\log_b c} = c^{\log_b a}$

$$\begin{aligned} \log_b c &= x & \log_b a &= y \\ a^x &= (b^y)^x & \Rightarrow & a^{\log_b c} = b^{yx} \end{aligned}$$

Use the relation  $c = b^x$

$$\begin{aligned} c^y &= (b^x)^y & \Rightarrow & c^{\log_b a} = b^{xy} \\ a^{\log_b c} &= b^{yx} = c^{\log_b a} \end{aligned}$$

b) Demonstrate equations 3.26, 2.27 y 3.28.

3.26)

$$n! = \sqrt{2\pi n} * \left(\frac{n}{e}\right)^n + 1 \Rightarrow (2\pi n)^{\frac{1}{2}} * \left(\frac{n}{e}\right)^n + 1$$

Removing the constant values that are  $2, \pi, e, 1$ , the remaining values are:  $n^{\frac{1}{2}} \cdot n^n = o(n^n)$ .

3.27)

$$n! \approx \sqrt{2\pi n} \left(\frac{n}{e}\right)^n.$$

Prove  $n! = \omega(2^n)$ , that's mean:

$$\frac{n!}{2^n} \rightarrow \infty.$$

Dividiendo por  $2^n$ ,

$$\frac{n!}{2^n} \approx \sqrt{2\pi n} \left(\frac{n}{2e}\right)^n.$$

For a bigger value of  $n$ ,  $\frac{n}{2e} > 1$ , the term tends to infinity. We can conclude that

$$n! = \omega(2^n).$$

c)  $\log_2(\Theta(n)) = \Theta(\log_2 n)$

$$\log_2(c_1 \cdot n) \leq \log_2(f(n)) \leq \log_2(c_2 \cdot n) \Rightarrow \log_2 c_1 + \log_2 n \leq \log_2(f(n)) \leq \log_2 c_2 + \log_2 n.$$

$\log_2 c_1$  and  $\log_2 c_2$  are constants. Hence we have:  $\log_2(f(n)) = \Theta(\log_2 n) \Rightarrow \log_2(\Theta(n)) = \Theta(\log_2 n)$

### Exercise 3.3-5):

As we saw,  $\lceil \log_2 n \rceil! = \log_2 n!$  applying the formula 3.28, we have that  $\log_2 n = \Theta(n \log_2 n)$ . In conclusion, it's polinomially bounded.

$\lceil \log_2 \log_2 n \rceil! = \log_2 \log_2 n = \log_2 \Theta n * \log_2 n$  with that we can show that is **not** polinomally bounded.

### Exercise 3.3-6):

for the definition, we know  $\log_2^* n < 5$  (rarely will be upper to 5). If we suppose that takes the value of  $n = 2^{65536} = 10^{\frac{65536}{\log_2 10}} \approx 10^{19.728}$  The result of  $\log_2^* 10^{19.728} = 5$  for example, then we have  $\log_2 5 \approx 2.322$ .

On the other hand, for the same  $n$  value, we have  $\log_2 10^{19.728} \approx 65.535$  then looking the table, Applying the logarithm iteratively, we can see:

1.  $\log_2 65.535 \approx 6.02$ .
2.  $\log_2 6.02 \approx 1.37$
3.  $\log_2 1.37 \approx 0.45$

Because we could apply 3 times the iteration,  $\log_2^*(\log_2 n) = 3$ . **In conclusion**,  $\log_2^*(\log_2 n) > \log_2(\log_2^* n)$

### Exercise 3.3-7):

Substitute  $\phi = \frac{1+\sqrt{5}}{2}$  in  $x^2 = x + 1$ .

$$\left(\frac{1+\sqrt{5}}{2}\right)^2 = \frac{1+\sqrt{5}}{2} + 1 \Rightarrow \frac{3+\sqrt{5}}{2} = \frac{3+\sqrt{5}}{2}$$

With the  $\hat{\phi}$  is do the same procedure.

### Exercise 3.3-9):

supose  $\log_2 k = \log_2 n$ , then operating we have:

$$\frac{k * \log_2 n}{\log_2 n} = \Theta\left(\frac{n}{\log_2 n}\right) \Rightarrow k = \Theta\left(\frac{n}{\log_2 n}\right)$$

## 1.4 Divide and Conquer

### Exercise 4.1-1):

$T(n) = 8T(\lfloor \frac{n}{2} \rfloor) + \Theta(1)$ . As mentioned before, the ceil and floor doesn't matter on analyzing algorithms when  $n$  is too big. Due to that, the result is the same  $T(n) = \Theta(n^3)$ .

### Exercise 4.1-2):

The length of the matrix that you pass as a fourth parameter, now it should be  $k * n$ , for bigger values of  $n$  and  $k$ , is the same as says,  $T(n) = 8T(\frac{k*n}{2}) + \Theta(1)$ . Now the result is  $T(n) = \Theta(k * n^3)$ .

The second option is the same as the first one. In conclusion any of them is asymptotically faster than the other one, both of them have the same speed.

### Exercise 4.1-3):

Now is  $\Theta(n^2)$  the driving function because you need to combine the solutions. Then  $T(n) = 8T(\frac{n}{2}) * \Theta(n^2)$ . Applying the master theorem,  $n^{\log_2 8} = 3$ , case 1 applies again.  $f(n) = O(n^{3-\epsilon})$  for any positive  $\epsilon \leq 1$

### Exercise 4.1-4):

Exercise resolved in cpp on the file [MatrixAddRecursive.cpp](#) (click on that to go to the file).

The cost of that algorithm is  $T(n) = 4T(\frac{n}{2}) + \Theta(1)$ . The watershed function is:  $n^{\log_2 4} = n^2$ . We have that  $f(n) = O(n^{2-\epsilon})$  for a positive  $\epsilon \leq 2$ . So we are on the case 1, the solution is:  $T(n) = \Theta(n^2)$ .

The case we have:  $T(n) = 4T(\frac{n}{2}) + \Theta(n^2)$ . The watershed function is:  $n^{\log_2 4} = n^2 = f(n) = \Theta(n^2)$ . Applying case 2, the solution is:  $T(n) = \Theta(n^2 \log_2 n)$ .

### Exercise 4.2-1):

$$S_1 = 8 - 2 = 6$$

$$S_2 = 1 + 3 = 4$$

$$S_3 = 7 + 5 = 12$$

$$S_4 = 4 - 6 = -2$$

$$S_5 = 1 + 5 = 6$$

$$S_6 = 6 + 2 = 8$$

$$S_7 = 3 - 5 = -2$$

$$S_8 = 4 + 2 = 6$$

$$S_9 = 1 - 7 = -6$$

$$S_{10} = 6 + 8 = 14$$

The P values are:

$$P_1 = 1 * 6 = 6$$

$$P_2 = 4 * 2 = 8$$

$$P_3 = 12 * 6 = 72$$

$$P_4 = 5 * -2 = -10$$

$$P_5 = 6 * 8 = 48$$

$$P_6 = -2 * 6 = -12$$

$$P_7 = -6 * 14 = -84$$

The result of the matrix is:

$$C_{11} = 48 - 10 - 8 - 12 = 18$$

$$C_{12} = 6 + 8 = 12$$

$$C_{21} = 72 - 10 = 62$$

$$C_{22} = 48 + 6 - 72 + 84 = 66$$

$$C = \begin{bmatrix} 18 & 12 \\ 62 & 66 \end{bmatrix}$$

**Exercise 4.2-2):**

You can find the pseudocode on that website (it's not mine, it's from another one): <https://atekihcan.github.io/CLRS/04/E04.02-02/>.

I implemented it in C++ using the code of exercise 4.1-4 (adding the function to subtract matrices). You can find the result of that code clicking there: [StrassensAlgorithm.cpp](#).

**Exercise 4.2-3):**

The largest  $k$  should be 7 because it's the number of times that the algorithm is called recursively. Also we can prove that applying the case 1 of the master theorem to  $T(n) = aT\left(\frac{n}{2}\right) + \Theta(1)$  where  $a = k$  for the reasons explained at the beginning.

**Exercise 4.2-4):**

Strassen's algorithm is better than the naive way of multiplying matrices.

Then we know that the Strassen's algorithm spends  $\Theta(n^{\log_2 7}) = \Theta(n^{2.8})$ . Then applying the  $68 \times 68$  where  $n = 68$ , applying this method the amount of time required is  $68^{2.8} = 135215$ . For  $n = 70$ , the result is  $70^{2.8} = 146647$ . The last one is  $n = 72$  and the result is  $72^{2.8} = 158683$ . The Strassen's algorithm is a little bit inefficient than the Pan way to multiply this particular matrices.

**Exercise 4.2-6):**

It will be done using block matrices (join 2 different matrices in 1 matrix to operate). Then the solution will be  $M^2 \Rightarrow O((2n)^\alpha) = O(n^\alpha)$ .

**Exercise 4.7-2):**

To check that is polynomial-growth we need to prove  $\frac{f(n)}{n^c}$  for  $f(n) = n^2$ . We need to check if there exists such a constant  $c$  that:  $\frac{n^2}{n^c} = n^{2-c}$ . In that case for  $c = 3$  we have:  $\frac{n^2}{n^3} = n^{-1} = \frac{1}{n}$ . Since  $\frac{1}{n}$  is bounded for any  $n \geq 1$ ,  $f(n) = n^2$  satisfies the polynomial growth condition.

On the other hand we will apply the same argumentation. we need to check if there exists any  $c$  for  $\frac{2^n}{n^c}$ . We suppose the case of  $\lim_{n \rightarrow \infty} \frac{2^n}{n^c}$ . In that case  $2^n$  grows exponentially to  $\infty$  while  $n^c$  grows polynomially. Hence the exponentially is not bounded and  $2^n$  does not satisfy the polynomial-growth.

**Exercise 4.7-3):**

If  $n$  tends to  $\infty$ , the smallest possible value of  $f(n)$  will be 0, assuming it has a negative exponent. On the other hand, if  $f(n)$  is a polynomial function like  $n^2$ , all values will be well-defined because it satisfies the polynomial-growth condition.

**Exercise 4.7-4):**

As explained before  $2^n$  doesn't satisfy the polynomial-growth condition.

To prove  $f(\Theta(n)) = \Theta(f(n))$  we need a constant  $c$  that scales in the same asymptotic way. In that case:  $f(nc) = 2^{nc} = (2^n)^c = \Theta(f(n))$ . So this is a valid example.

**Exercise 4.7-5):**

- a)  $a_1 = a_2 = a_3 = 1$ ,  $b_1 = 2$ ,  $b_2 = 3$ ,  $b_4 = 6$ . We need to find a  $p$  value that  $(\frac{1}{2})^p + (\frac{1}{3})^p + (\frac{1}{6})^p = 1$ . For  $p = 0$ , the result is 3. for  $p = 1$ , the result is:  $p = 0.9999\dots$ . Then we know that  $0 < p < 1$ .  $f(x) = n \log_2 n$

$$\begin{aligned} T(n) &= \Theta \left( n^p \left( 1 + \int_1^n \frac{f(x)}{x^{p+1}} dx \right) \right) \\ &= \Theta \left( n^p \left( 1 + \int_1^n x^{-p} \log_2 x dx \right) \right) \\ &= 1 + \frac{n^{1-p} \log_2 n}{1-p} - \frac{n^{1-p}}{(1-p)^2} \end{aligned}$$

For  $p = 1$  we see the biggest order is  $T(n) = \Theta(n \log_2 n)$ .

## 1.5 Probabilistic Analysis and Randomized Algorithms

Note: Most exercises of this part weren't done because it wasn't my scope of understanding that book. Anyway, I just suck at learning it and I don't have too much free time to roll up my sleeves and learn that perfectly. Maybe in the future I will try this again.

**Exercise 5.1-1):**

You know who is better because best starts on 0, that is the leers rank that u can achieve. The biggest rank is bound at the upper with a maximum score of  $n$ . Betwen on that interval of scores you can index easly each worker by the score he got.

**Exercise 5.1-2):**

An imlementation could be multiply  $a$  for the value that was got by  $Random(0, 1)$  and then make another math operation with  $b$  for example to introduce aleatority and give as a result the number between  $a$  and  $b$ . That operations could be:  $a + \lfloor (Random(0, 1) \cdot (b - a + 1)) \rfloor$  That would give us a number between  $[0, b - a + 1]$  and then adding  $a$ , we take a value between  $[a, b]$ .

The expected running time is  $O(1)$ .

**Exercise 5.1-3):**

We see the 2 posible values that exists with  $p$  and  $1 - p$  are:

$$\begin{aligned} P(00) &= (1-p)(1-p), \\ P(01) &= (1-p)p, \\ P(10) &= p(1-p), \\ P(11) &= pp. \end{aligned}$$

01 and 10 happends with the same probability. If we have 01 we return 0. On the other hand if we have 10 return 1. If neither of that values, keep trying until get 1 of these values.

---

**Algorithm 8** Generación de bit imparcial a partir de BIASED-RANDOM

---

**procedure** UNBIASED-RANDOM

**while** true **do**

    first  $\leftarrow$  BIASED-RANDOM()

    second  $\leftarrow$  BIASED-RANDOM()

**if** first = 0 **and** second = 1 **then**

**return** 0

**else if** first = 1 **and** second = 0 **then**

**return** 1

---

Running time is  $\frac{2}{2p(1-p)} = \frac{1}{p(1-p)} = O\left(\frac{1}{p(1-p)}\right)$

**Exercise 5.2-1):**

First of all we will use the same indicator random variable as mentioned in the book few paragraphs before. The probability of being hired is  $\frac{1}{n}$  from 1 to  $n - 1$ . That's mean because it's presented in a random order, it could be someone before you that have better scores and he will be hired instead of you.

To hire exactly  $n$  times, its  $\frac{1}{n!}$  because there is  $n$  permutations where you hire everyone but only one of them is correct.

**Exercise 5.2-2):**

$\frac{(n-1)(n-2)!}{n!}$  There is  $n - 1$  positions to place the best candidate and also you have  $n - 2$  possibilities of place 2 person to hire them at the same time.

**Exercise 5.2-3):**

Let  $X = \sum_{i=1}^n X_i$ , where  $X_i$  is the value of the  $i$ -th die. We use indicator random variables  $I_i(k)$ , which take the value 1 if die  $i$  shows the value  $k$ , and 0 otherwise. Then we can write:

$$X_i = \sum_{k=1}^6 k \cdot I_i(k)$$

The expected value of  $X_i$  is:

$$E[X_i] = E\left[\sum_{k=1}^6 k \cdot I_i(k)\right] = \sum_{k=1}^6 k \cdot E[I_i(k)]$$

Since  $E[I_i(k)] = \frac{1}{6}$ , we get:

$$E[X_i] = \sum_{k=1}^6 k \cdot \frac{1}{6} = \frac{1}{6}(1 + 2 + 3 + 4 + 5 + 6) = 3.5$$

Now, the expected value of  $X$  is:

$$E[X] = E\left[\sum_{i=1}^n X_i\right] = \sum_{i=1}^n E[X_i] = n \cdot 3.5$$

**Exercise 5.2-5):**

$X_i = I_{\text{customer gets his own hat}}$ . Probability of customer  $i$  receives his own hat is  $E[X_i] = Pr I = \frac{1}{n}$ .

$$E[x_i] = E \left[ \sum_{i=1}^n X_i \right] = \sum_{i=1}^n E[X_i] = \sum_{i=1}^n \frac{1}{n} = \frac{n}{n} = 1$$

The number of costumers that receives his own hat is 1.

**Exercise 5.2-6):**

$X_{ij}$  = *Ian inversion was found*. Probability of the inversion  $ij$  to be found is  $E[X_{ij}] = PrI = \frac{1}{2}$ . Number of inversions is:

$$E[X_{ij}] = E \left[ \sum_{1 \leq i \leq j \leq n} X_{ij} \right] = \sum_{1 \leq i \leq j \leq n} E[X_{ij}] = \frac{1}{2} \binom{n}{2} = \frac{n(n-1)}{4}.$$

## 2 Sorting and Order Statics

### 2.1 Heapsort

**Exercise 6.1-1):**

The minimum number of elements is:  $2^h$  and the maximum is  $2^{h+1} - 1$

**Exercise 6.1-2):**

With the tree of the figure 6.1 for example the element of position 4 (whose value is 8) it's on height  $\lfloor \log_2 4 \rfloor = 2$ . And as the book explained before, That's the second level.

**Exercise 6.1-3):**

You have to keep in mind the property that for max-heap,  $A[parent] \geq A[child]$ . Following that, you achieve the tree like in figure 6.1.

**Exercise 6.1-4):**

In the most right position on the leafs.

**Exercise 6.1-5):**

Between the root or level 1 or 2.

**Exercise 6.1-6):**

If it's sorted in ascending order, yes, it's a min-heap.

**Exercise 6.1-7):**

No, The parent with value 15 has a child with value 16 and the condition of max-heap isn't satisfy.

**Exercise 6.1-8):**

We are going to suppose the same tree as figure 6.1. That tree has 10 elements. We know the leafs are 9, 3, 2, 4, 1 in this case, that's 5 leafs. In that case the number 9 are at the index 6, which is the same as say  $\frac{10}{2} + 1$  as the statement said. With the other numbers is the same as that.

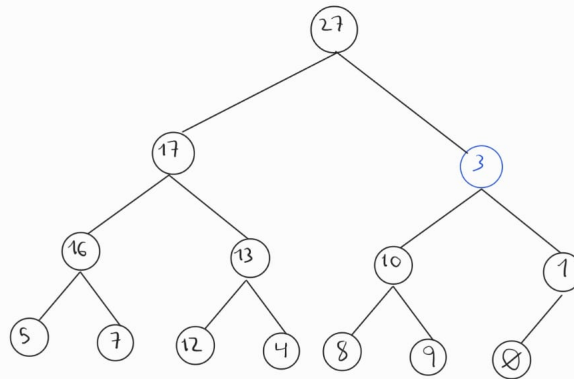
**Exercise 6.2-1):**

Done on the next page

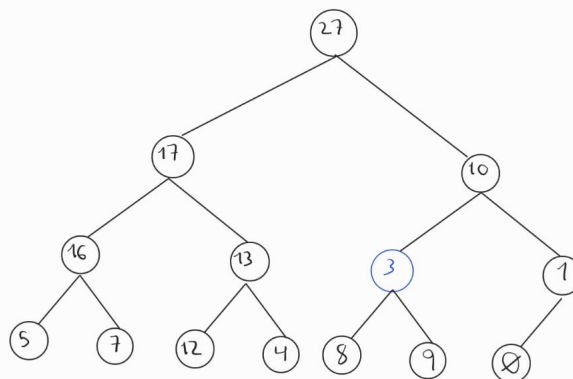


MaxHeapify(4,3)

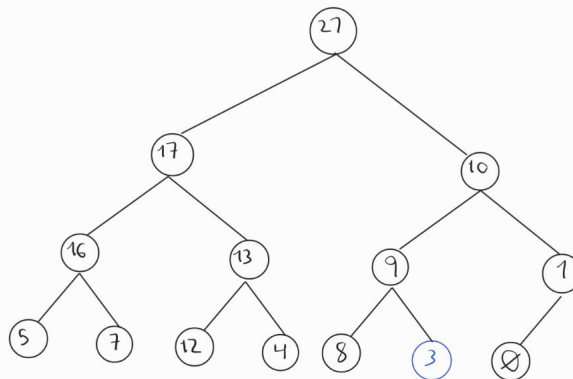
1)



2)



3)



### Exercise 6.2-2):

Suppose  $A_1$  and  $A_2$  are the children of the root. They are also the roots of another subtrees. We know they are balanced so one subtree can't have more nodes than the other subtree. If one tree has more than  $\frac{2n}{3}$  nodes, the other one must have  $\frac{n}{3}$  and that would violate the properties of the binary trees.

The smallest possible value is  $\alpha = \frac{2}{3}$ .

### Exercise 6.2-3):

The pseudocode used as reference is the one that appears on page 165. It would be the same but only changing the conditions of the first 2 if. Also we can change the variable name *largest* with *lowest*. The changes would be *if  $l \leq A.heap\_size$  and  $A[l] < A[i]$  then  $lowest = l$* , on the other if it would be *if  $r \leq A.heap\_size$  and  $A[r] < A[lowest]$  then  $lowest = r$* . The remaining lines of the pseudocode would be the same.

**Exercise 6.2-4):**

it won't continue making recursive calls, because that mean the subtree on the root has the biggest value posible following the definition of max-heap.

**Exercise 6.2-5):**

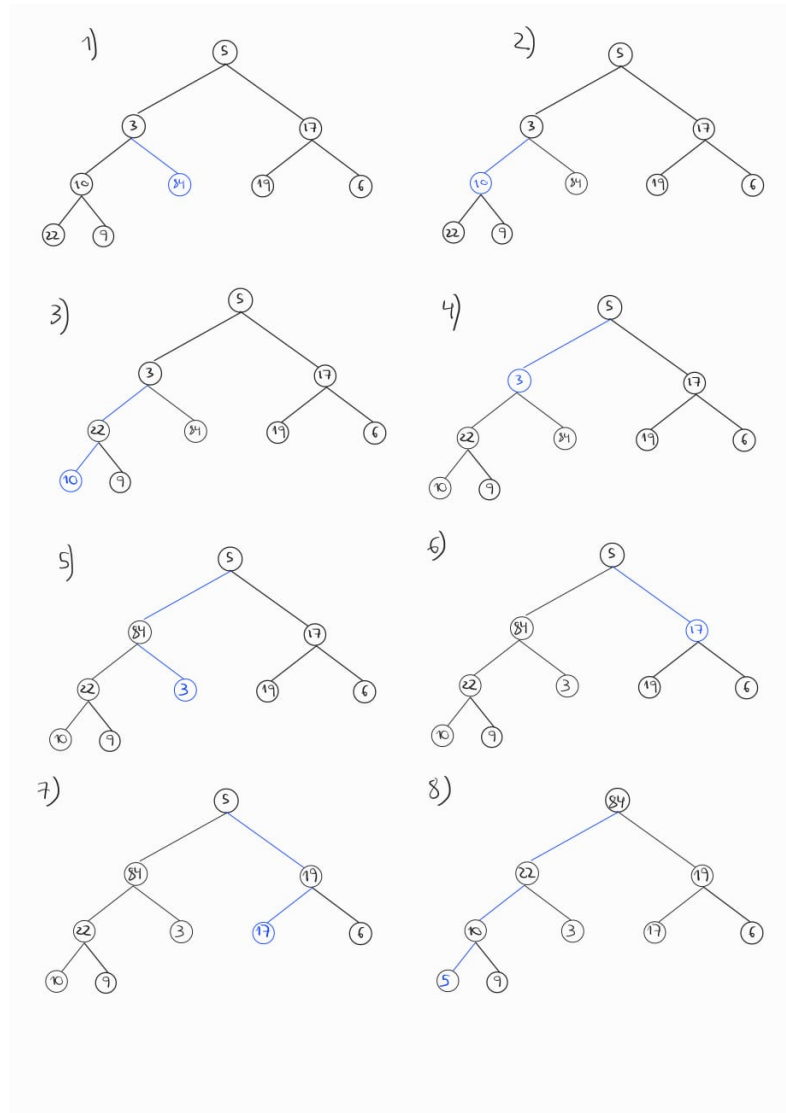
Anything because from  $A.\text{heap-size} / 2$  it's located all the leafs of the main tree. Due to that, any comparasions will be done.

**Exercise 6.2-6):**

Resolved on the file: [6.2-6.cpp](#)

**Exercise 6.2-7):**

Supose that you start from the root. Also supose that from the inmmediate children of the root, it will be called recursively. As we are going down until reach a leaf, also we know a tree has  $\log_2 n$  levels in that case it's the same as the amount of time the recursive call will be done. Due to that, the worst case is  $O(\log_2 n)$  as the sentence says.

**Exercise 6.3-1):**

**Exercise 6.3-2):**

$$\frac{n}{2^h} \geq \frac{1}{2} \Rightarrow n \geq \frac{1}{2} 2^h \Rightarrow \log_2 n \geq h$$

Because  $h$  is the height of the tree, and the height starts from 0, the result is:

$$0 \leq h \leq \lfloor \log_2 n \rfloor$$

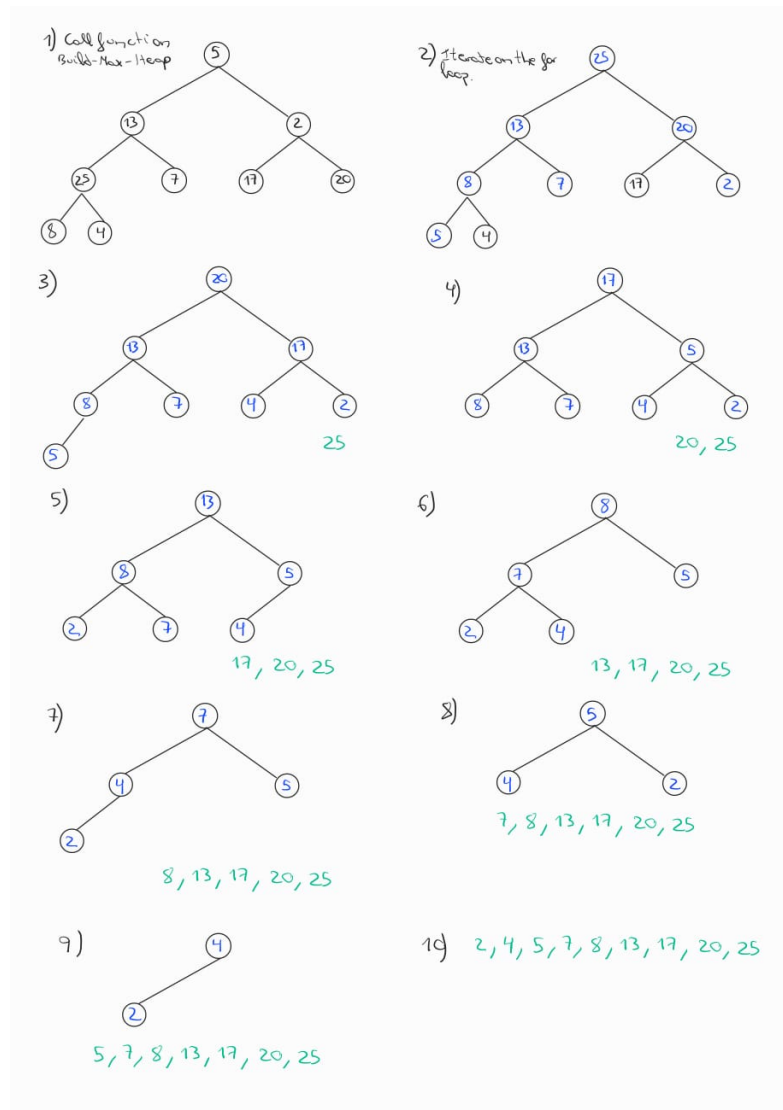
**Exercise 6.3-3):**

Doing from bottom-up you have guarantees that the left subtree is ordered. Hence on the fathers subtrees, when you order them you have guarantees that the child subtree is ordered. While on the other way we can't guarantee that.

**Exercise 6.3-4):**

We know that on each height on the tree, the numbers of elements got doubled. Also, the number of elements in the heap, is at least  $n$  and the total number of elements are  $2^h + 1$ . Due to that the result is what the sentence is asking about proof.

**Exercise 6.4-1):**



**Exercise 6.4-2):**

**Initialization:** At the start of the loop (before the first iteration), the subarray  $A[1 : n]$  is not sorted, but in the first iteration of the loop, the **MaxHeapify** function is executed over the entire array, ensuring that the array becomes a **max-heap**. Then, the largest element (at the root of the max-heap) is placed in its final position, that is, at the last position of the array, ensuring that the subarray  $A[1 : n]$  contains the smallest elements, while  $A[n]$  contains the largest element.

**Maintenance:** In each iteration of the loop, the following steps occur:

1. The subarray  $A[1 : i]$  is still a **max-heap** containing the  $i$  smallest elements of  $A[1 : n]$ .
2. Then, the element at the root (the largest one) is moved to position  $i$ . At this point, the subarray  $A[1 : i - 1]$  contains the  $i - 1$  smallest elements sorted (i.e., the largest ones).
3. The subarray  $A[i : n]$  now contains largest elements sorted.
4. The size of the heap is reduced by one (since the largest value has been placed in its correct position), and the **MaxHeapify** function is applied again to restore the heap property in the subarray  $A[1 : i - 1]$ .
5. This process repeats until the array is completely sorted.

**Termination:** The loop terminates when  $i$  reaches 1, that is, when the array is completely sorted. At the end of all iterations, the subarray  $A[1 : n]$  will be sorted in increasing order, and the max-heap property will have been maintained at all times.

**Exercise 6.4-3):**

It would be  $\Omega(n \log_2 n)$  because on the inner loop it will always remove the largest value, replace the root value with the less one, and then execute the function, it makes all time expend  $\Theta(n \log_2 n)$ .

**Exercise 6.4-4):**

Explained on the before exercise. Same logic as this.

**Exercise 6.4-5):**

It's the same explanation as the 2 before exercise. In this case the first function outside the loop could be in the average time, but the inner loop will be always  $\Theta(n \log_2 n)$ .

**Exercise 6.5-1):**

It just extract the element at the first position (because it's the biggest one). Then do the swap as HeapSort with the last element, to move at the first position the next biggest element.

**Exercise 6.5-2):**

Is added on the index with the value of `textitheap_size`, then when calling the function *Max\_heap\_increase\_key*, it will compare the value of the key with its parent keys, and will change the position if the parent key is less than the new key to be inserted. When that condition is not satisfied (or the new key reaches the root), it will end the procedure of insert because it will be inserted in the correct position.