

## Problem Set 1

**Both theory and programming questions** are due **Thursday, September 15 at 11:59PM**. Please download the .zip archive for this problem set, and refer to the `README.txt` file for instructions on preparing your solutions. Remember, your goal is to communicate. Full credit will be given only to a correct solution which is described clearly. Convoluted and obtuse descriptions might receive low marks, even when they are correct. Also, aim for concise solutions, as it will save you time spent on write-ups, and also help you conceptualize the key idea of the problem.

We will provide the solutions to the problem set 10 hours after the problem set is due, which you will use to find any errors in the proof that you submitted. You will need to submit a critique of your solutions by **Tuesday, September 20th, 11:59PM**. Your grade will be based on both your solutions and your critique of the solutions.

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**Collaborators:** By myself

### Problem 1-1. [15 points] Asymptotic Practice

For each group of functions, sort the functions in increasing order of asymptotic (big-O) complexity:

**(a) [5 points] Group 1:**

$$\begin{aligned}f_1(n) &= n^{0.999999} \log n \\f_2(n) &= 10000000n \\f_3(n) &= 1.000001^n \\f_4(n) &= n^2\end{aligned}$$

**Your Solution:**  $f_1(n), f_2(n), f_4(n), f_3(n)$

For  $f_1(n) = n^{0.999999} \log n$ , since  $\log n = O(n^c)$ , we can treat constant  $c$  as  $0.000001$ , therefore  $f_1(n) = n^{0.999999} \log n = n^{0.999999} \times n^{0.000001} = n = O(n)$ .

$$f_2(n) = 10000000n = O(n).$$

$$f_3(n) = 1.000001^n = O(2^n)$$

$$f_4(n) = n^2 = O(n^2)$$

Consequently, the increasing order of asymptotic complexity is  $f_1(n), f_2(n), f_4(n), f_3(n)$ .

**(b) [5 points] Group 2:**

$$\begin{aligned}f_1(n) &= 2^{1000000} \\f_2(n) &= 2^{1000000n} \\f_3(n) &= \binom{n}{2} \\f_4(n) &= n\sqrt{n}\end{aligned}$$

**Your Solution:**  $f_1(n), f_4(n), f_3(n), f_2(n)$

$$f_1(n) = 2^{2^{1000000}} = O(1)$$

$$f_2(n) = 2^{100000n} = O(c2^n) = O(2^n)$$

$$f_3(n) = \binom{n}{2} = \frac{n!}{2! \times (n-2)!} = \frac{n(n-1)}{2} = O(n^2)$$

$$f_4(n) = n\sqrt{n} = O(n^{\frac{3}{2}})$$

Therefore, the increasing order of asymptotic complexity is  $f_1(n), f_4(n), f_3(n), f_2(n)$ .

(c) [5 points] **Group 3:**

$$\begin{aligned} f_1(n) &= n^{\sqrt{n}} \\ f_2(n) &= 2^n \\ f_3(n) &= n^{10} \cdot 2^{n/2} \\ f_4(n) &= \sum_{i=1}^n (i+1) \end{aligned}$$

**Your Solution:**  $f_4(n), f_1(n), f_3(n), f_2(n)$

$$f_1(n) = n^{\sqrt{n}} = (2^{\log_2 n})^{\sqrt{n}} = O(2^{\sqrt{n} \log_2 n})$$

$$f_2(n) = 2^n = O(2^n)$$

$$f_3(n) = n^{10} \cdot 2^{n/2} = O(n^{10} \cdot 2^n) = 2^{10 \log_2 n} \cdot 2^{n/2} = O(2^{n/2 + \log_2 n})$$

$$f_4(n) = \sum_{i=1}^n (i+1) = \frac{(2 + (n+1))n}{2} \text{ (summation of arithmetic sequence)} = O(n^2)$$

Due to the equation  $(2)^{cg(x)} = (2^c)^{g(x)}$ , where  $c$  is a constant and  $g(x)$  is a function of  $x$ , which signifies that  $f_3(n) = O(\sqrt{2}^{n+2 \log_2 n})$  so  $f_3(n) = O(f_2(n))$  but  $f_2(n) \neq O(f_3(n))$  (special trick) Therefore, the increasing order of asymptotic complexity is  $f_4(n), f_1(n), f_3(n), f_2(n)$ .

### Problem 1-2. [15 points] Recurrence Relation Resolution

For each of the following recurrence relations, pick the correct asymptotic runtime:

(a) [5 points] Select the correct asymptotic complexity of an algorithm with runtime  $T(n, n)$  where

$$\begin{aligned} T(x, c) &= \Theta(x) && \text{for } c \leq 2, \\ T(c, y) &= \Theta(y) && \text{for } c \leq 2, \text{ and} \\ T(x, y) &= \Theta(x + y) + T(x/2, y/2). \end{aligned}$$

1.  $\Theta(\log n)$ .

2.  $\Theta(n)$ .
3.  $\Theta(n \log n)$ .
4.  $\Theta(n \log^2 n)$ .
5.  $\Theta(n^2)$ .
6.  $\Theta(2^n)$ .

**Your Solution: 2**

$$T(n, n) = \Theta(n + n) + T(n/2, n/2) = \Theta(2n) + \Theta(n) + \Theta(n/2) + \dots + \Theta(1)$$

(sum of geometric sequence)  $= 2n(1 - 0.5^n)/0.5 = 4n - n \cdot 2^{(2-n)} = \Theta(n)$

- (b) [5 points] Select the correct asymptotic complexity of an algorithm with runtime  $T(n, n)$  where

$$\begin{aligned} T(x, c) &= \Theta(x) && \text{for } c \leq 2, \\ T(c, y) &= \Theta(y) && \text{for } c \leq 2, \text{ and} \\ T(x, y) &= \Theta(x) + T(x, y/2). \end{aligned}$$

1.  $\Theta(\log n)$ .
2.  $\Theta(n)$ .
3.  $\Theta(n \log n)$ .
4.  $\Theta(n \log^2 n)$ .
5.  $\Theta(n^2)$ .
6.  $\Theta(2^n)$ .

**Your Solution: 3**

$$T(n, n) = \Theta(n) + T(n, n/2) = \Theta(n) + \Theta(n) + \dots + \Theta(n) \text{ (with } \log(n) \text{ occurrences of } \Theta(n) \text{ in the sum.)} = \log n \cdot \Theta(n) = \Theta(n \log n)$$

- (c) [5 points] Select the correct asymptotic complexity of an algorithm with runtime  $T(n, n)$  where

$$\begin{aligned} T(x, c) &= \Theta(x) && \text{for } c \leq 2, \\ T(x, y) &= \Theta(x) + S(x, y/2), \\ S(c, y) &= \Theta(y) && \text{for } c \leq 2, \text{ and} \\ S(x, y) &= \Theta(y) + T(x/2, y). \end{aligned}$$

1.  $\Theta(\log n)$ .
2.  $\Theta(n)$ .
3.  $\Theta(n \log n)$ .
4.  $\Theta(n \log^2 n)$ .

5.  $\Theta(n^2)$ .

6.  $\Theta(2^n)$ .

**Your Solution:** 2

$T(n, n) = \Theta(n) + S(n, n/2) = \Theta(n) + \Theta(n) + T(n/2, n/2)$ , it is similar to the problem (a). From the experience of problem (a).  $T(n, n) = \Theta(n) + \Theta(n) + T(n/2, n/2) = \Theta(n)$ .

## Peak-Finding

In Lecture 1, you saw the peak-finding problem. As a reminder, a *peak* in a matrix is a location with the property that its four neighbors (north, south, east, and west) have value less than or equal to the value of the peak. We have posted Python code for solving this problem to the website in a file called `ps1.zip`. In the file `algorithms.py`, there are four different algorithms which have been written to solve the peak-finding problem, only some of which are correct. Your goal is to figure out which of these algorithms are correct and which are efficient.

### Problem 1-3. [16 points] Peak-Finding Correctness

(a) [4 points] Is `algorithm1` correct?

1. Yes.
2. No.

**Your Solution:** Yes.

(b) [4 points] Is `algorithm2` correct?

1. Yes.
2. No.

**Your Solution:** Yes.

(c) [4 points] Is `algorithm3` correct?

1. Yes.
2. No.

**Your Solution:** No.

(d) [4 points] Is `algorithm4` correct?

1. Yes.
2. No.

**Your Solution:** Yes.

**Problem 1-4.** [16 points] **Peak-Finding Efficiency**

(a) [4 points] What is the worst-case runtime of `algorithm1` on a problem of size  $n \times n$ ?

1.  $\Theta(\log n)$ .
2.  $\Theta(n)$ .
3.  $\Theta(n \log n)$ .
4.  $\Theta(n \log^2 n)$ .
5.  $\Theta(n^2)$ .
6.  $\Theta(2^n)$ .

**Your Solution:**  $\Theta(n \log n)$

In `algorithm1`, the first step is to find the maximum in the middle column of the problem with  $n \times n$  elements, which would take  $\Theta(n)$ . Second, determine whether the neighbors of the maximum is larger than maximum. If so, divide problem into subproblem with dimension  $n \times 2/n$  and repeat the first step until you find a peak.

Consequently, the run time of `algorithm1` can be written as  $T(n, n) = \Theta(n) + T(n, n/2) = \Theta(n \log n)$ , which we have discussed in Problem 1-2 (b). Therefore the worst-case runtime of `algorithm1` is  $\Theta(n \log n)$ .

(b) [4 points] What is the worst-case runtime of `algorithm2` on a problem of size  $n \times n$ ?

1.  $\Theta(\log n)$ .
2.  $\Theta(n)$ .
3.  $\Theta(n \log n)$ .
4.  $\Theta(n \log^2 n)$ .
5.  $\Theta(n^2)$ .
6.  $\Theta(2^n)$ .

**Your Solution:**  $\Theta(n^2)$

For `algorithm2`, it utilizes greedy strategy to approach a peak step by step. Each step costs  $\Theta(1)$  runtime. The worst-case need to check all the elements in the problem. Therefore the worst-case runtime of `algorithm1` is  $\Theta(n^2)$ .

(c) [4 points] What is the worst-case runtime of `algorithm3` on a problem of size  $n \times n$ ?

1.  $\Theta(\log n)$ .
2.  $\Theta(n)$ .

3.  $\Theta(n \log n)$ .
4.  $\Theta(n \log^2 n)$ .
5.  $\Theta(n^2)$ .
6.  $\Theta(2^n)$ .

**Your Solution:**  $\Theta(n)$

In algorithm3, the first step is to find the maximum in the middle column and row of the problem with  $n \times n$  elements, which would take  $\Theta(2n)$ . Second, determine whether the neighbors of the maximum is larger than maximum. If so, divide problem into subproblem with dimension  $2/n \times 2/n$  and repeat the first step until you find a peak.

This algorithm is not correct in this problem. However, the worst-case runtime can be presented as  $T(n, n) = \Theta(2n) + T(2/n, 2/n)$ , which we have discussed in Problem 1-2 (a). The worst-case runtime of algorithm3 is  $\Theta(n)$ .

**(d) [4 points]** What is the worst-case runtime of algorithm4 on a problem of size  $n \times n$ ?

1.  $\Theta(\log n)$ .
2.  $\Theta(n)$ .
3.  $\Theta(n \log n)$ .
4.  $\Theta(n \log^2 n)$ .
5.  $\Theta(n^2)$ .
6.  $\Theta(2^n)$ .

**Your Solution:**  $\Theta(n)$

In algorithm1, the first step is to find the maximum in the middle column of the problem with  $n \times n$  elements, which would take  $\Theta(n)$ . Second, determine whether the neighbors of the maximum is larger than maximum. If so, divide problem into subproblem with dimension  $n \times 2/n$ . Back to first step and, however, find the maximum in the middle row of the subproblem then determine whether the neighbors of the maximum is larger than maximum. Do the above instructions recursively until we find a peak.

Consequently, the run time of algorithm1 can be written as  $T(n, n) = \Theta(n) + S(n, n/2)$ , and  $S(n, n) = \Theta(n) + T(n/2, n)$ , which we have discussed in Problem 1-2 (c). Therefore the worst-case runtime of algorithm4  $T(n, n)$  is  $\Theta(n)$ .

### Problem 1-5. [19 points] Peak-Finding Proof

Please modify the proof below to construct a proof of correctness for the *most efficient correct algorithm* among algorithm2, algorithm3, and algorithm4.

The following is the proof of correctness for `algorithm1`, which was sketched in Lecture 1.

We wish to show that `algorithm1` will always return a peak, as long as the problem is not empty. To that end, we wish to prove the following two statements:

**1. If the peak problem is not empty, then `algorithm1` will always return a location.** Say that we start with a problem of size  $m \times n$ . The recursive subproblem examined by `algorithm1` will have dimensions  $m \times \lfloor n/2 \rfloor$  or  $m \times (n - \lfloor n/2 \rfloor - 1)$ . Therefore, the number of columns in the problem strictly decreases with each recursive call as long as  $n > 0$ . So `algorithm1` either returns a location at some point, or eventually examines a subproblem with a non-positive number of columns. The only way for the number of columns to become strictly negative, according to the formulas that determine the size of the subproblem, is to have  $n = 0$  at some point. So if `algorithm1` doesn't return a location, it must eventually examine an empty subproblem.

We wish to show that there is no way that this can occur. Assume, to the contrary, that `algorithm1` does examine an empty subproblem. Just prior to this, it must examine a subproblem of size  $m \times 1$  or  $m \times 2$ . If the problem is of size  $m \times 1$ , then calculating the maximum of the central column is equivalent to calculating the maximum of the entire problem. Hence, the maximum that the algorithm finds must be a peak, and it will halt and return the location. If the problem has dimensions  $m \times 2$ , then there are two possibilities: either the maximum of the central column is a peak (in which case the algorithm will halt and return the location), or it has a strictly better neighbor in the other column (in which case the algorithm will recurse on the non-empty subproblem with dimensions  $m \times 1$ , thus reducing to the previous case). So `algorithm1` can never recurse into an empty subproblem, and therefore `algorithm1` must eventually return a location.

**2. If `algorithm1` returns a location, it will be a peak in the original problem.** If `algorithm1` returns a location  $(r_1, c_1)$ , then that location must have the best value in column  $c_1$ , and must have been a peak within some recursive subproblem. Assume, for the sake of contradiction, that  $(r_1, c_1)$  is not also a peak within the original problem. Then as the location  $(r_1, c_1)$  is passed up the chain of recursive calls, it must eventually reach a level where it stops being a peak. At that level, the location  $(r_1, c_1)$  must be adjacent to the dividing column  $c_2$  (where  $|c_1 - c_2| = 1$ ), and the values must satisfy the inequality  $val(r_1, c_1) < val(r_1, c_2)$ .

Let  $(r_2, c_2)$  be the location of the maximum value found by `algorithm1` in the dividing column. As a result, it must be that  $val(r_1, c_2) \leq val(r_2, c_2)$ . Because the algorithm chose to recurse on the half containing  $(r_1, c_1)$ , we know that  $val(r_2, c_2) < val(r_2, c_1)$ . Hence, we have the following chain of inequalities:

$$val(r_1, c_1) < val(r_1, c_2) \leq val(r_2, c_2) < val(r_2, c_1)$$

But in order for `algorithm1` to return  $(r_1, c_1)$  as a peak, the value at  $(r_1, c_1)$  must have been the greatest in its column, making  $val(r_1, c_1) \geq val(r_2, c_1)$ . Hence, we have a contradiction.

**Your Solution:**

For algorithm3, it goes wrong because in the algorithm, it will return the result if it finds a maximum in the middle column and row in the subproblem, and check the neighbors to ensure they are all smaller than the maximum in the subproblem. This instruction may lost the comparison between the maximum and the neighbor outside the subproblem, which result in the incorrect result in some cases.

To fix this instruction, we can compare the the maximum with the best point we have ever seen after checking the neighbors around maximum. If the maximum is smaller than the best point, do the recursion until the maximum is equal to the best point.

**Problem 1-6. [19 points] Peak-Finding Counterexamples**

For each incorrect algorithm, upload a Python file giving a counterexample (i.e. a matrix for which the algorithm returns a location that is not a peak).

**Your Solution:**

Counterexamples for algorithm3

```
problemMatrix = [
    [0, 0, 0, 0, 0, 0, 0],
    [0, 0, 0, 0, 0, 0, 0],
    [0, 0, 0, 0, 0, 0, 0],
    [0, 3, 0, 0, 0, 1, 0],
    [0, 2, 0, 0, 0, 0, 0],
    [0, 0, 0, 0, 0, 0, 0],
    [0, 0, 6, 5, 0, 0, 0]
]

problemMatrix = [
    [ 4,  5,  6,  7,  8,  7,  6,  5,  4,  3,  2],
    [ 5,  6,  7,  8,  9,  8,  7,  6,  5,  4,  3],
    [ 6,  7,  8,  9, 10, 11,  8,  7,  6,  5,  4],
    [ 7,  8,  9, 10,  9, 10,  9,  8,  7,  6,  5],
    [ 8,  9, 10, 11, 13, 11, 10,  9,  8,  7,  6],
    [ 7,  8,  9, 10, 12, 10,  9,  8,  7,  6,  5],
    [ 6,  7,  8,  9, 10,  9,  8,  7,  6,  5,  4],
    [ 5,  6,  7,  8,  9,  8,  7,  6,  5,  4,  3],
    [ 4,  5,  6,  7,  8,  7,  6,  5,  4,  3,  2],
    [ 3,  4,  5,  6,  7,  6,  5,  4,  3,  2,  1],
    [ 2,  3,  4,  5,  6,  5,  4,  3,  2,  1,  0]
]
```



