

Problem Set 4 Solution

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Question 1

- a. **Statement:** $\forall f, g : \mathbb{N} \rightarrow \mathbb{R}^+, b \in \mathbb{R}^+, (g(n) \in \Theta(f(n))) \wedge (n_0 \in \mathbb{N}, n \geq n_0 \Rightarrow f(n) \geq b \wedge g(n) \geq b) \wedge (b > 1) \Rightarrow \log_b(g(n)) \in \Theta(\log_b(f(n)))$

Statement Expanded: $\forall f, g : \mathbb{N} \rightarrow \mathbb{R}^+, b \in \mathbb{R}^+, \left(\exists c_1, c_2, n_0 \in \mathbb{R}^+, \forall n \in \mathbb{N}, n \geq n_0 \Rightarrow c_1 \cdot g(n) \leq f(n) \leq c_2 \cdot g(n) \right) \wedge \left(\exists n_1 \in \mathbb{N}, n \geq n_1 \Rightarrow f(n) \geq b \wedge g(n) \geq b \right) \wedge (b > 1) \Rightarrow \left(\exists d_1, d_2, n_2 \in \mathbb{R}^+, \forall n \in \mathbb{N}, n \geq n_2 \Rightarrow d_1 \cdot \log_b(g(n)) \leq \log_b(f(n)) \leq d_2 \cdot \log_b(g(n)) \right)$

Proof. Let $f, g : \mathbb{N} \rightarrow \mathbb{R}^+$, and $b \in \mathbb{R}^+$. Assume $c_1 = 1$, $c_2 = b$, and $n_0 = 1$, and $n \in \mathbb{N}$ such that $n \geq n_0$ and $c_1 \cdot g(n) \leq f(n) \leq c_2 \cdot g(n)$. Assume $f(n)$ and $g(n)$ are eventually $\geq b$. Assume $b > 1$. Let $d_1 = 1$, $d_2 = 2$, and $n_2 = n_0$. Assume $n \geq n_2$.

We need to show $d_1 \cdot \log_b g(n) \leq \log_b f(n) \leq d_2 \cdot \log_b g(n)$.

We will do so in two parts. One for $(d_1 \cdot \log_b g(n) \leq \log_b f(n))$ and the other for $(\log_b f(n) \leq d_2 \cdot \log_b g(n))$.

Part 1 $(d_1 \cdot \log_b g(n) \leq \log_b f(n))$:

The assumption tell us

$$c_1 \cdot g(n) \leq f(n) \tag{1}$$

Then, it follows from the fact $\forall x, y \in \mathbb{R}^+, x \geq y \Leftrightarrow \log x \geq \log y$

$$\log(c_1 \cdot g(n)) \leq \log(f(n)) \tag{2}$$

Then, using the fact $b > 1$, we can calculate

$$\frac{\log(c_1 \cdot g(n))}{\log b} \leq \frac{\log(f(n))}{\log b} \quad (3)$$

$$\frac{\log(c_1) + \log(g(n))}{\log b} \leq \frac{\log(f(n))}{\log b} \quad (4)$$

Then,

$$\frac{\log(g(n))}{\log b} \leq \frac{\log(f(n))}{\log b} \quad (5)$$

by the fact $c_1 = 1$ and $\log c_1 = 0$.

Then, since $\frac{\log f(x)}{\log b} = \log_b f(x)$,

$$\log_b(g(n)) \leq \log_b(f(n)) \quad (6)$$

Then, because we know $d_1 = 1$, we can conclude

$$\log_b(g(n)) \leq d_1 \cdot \log_b(f(n)) \quad (7)$$

Part 2 ($\log_b f(n) \leq d_2 \cdot \log_b g(n)$):

The assumption tells us

$$f(n) \leq c_2 \cdot g(n) \quad (8)$$

Then, it follows from the fact $\forall x, y \in \mathbb{R}^+, x \geq y \Leftrightarrow \log x \geq \log y$

$$\log(f(n)) \leq \log(c_2 \cdot g(n)) \quad (9)$$

Then, using the fact $b > 1$, we can calculate

$$\frac{\log(f(n))}{\log b} \leq \frac{\log(c_2 \cdot g(n))}{\log b} \quad (10)$$

$$\frac{\log(f(n))}{\log b} \leq \frac{\log(c_2) + \log(g(n))}{\log b} \quad (11)$$

Then, since $c_2 = b$,

$$\frac{\log(f(n))}{\log b} \leq \frac{\log(b) + \log(g(n))}{\log b} \quad (12)$$

Then, using the fact $g(n)$ is eventually $\geq b$, we can write

$$\frac{\log(f(n))}{\log b} \leq \frac{\log(g(n)) + \log(g(n))}{\log b} \quad (13)$$

$$\frac{\log(f(n))}{\log b} \leq \frac{2 \cdot \log(g(n))}{\log b} \quad (14)$$

Then, since $\frac{\log f(x)}{\log b} = \log_b f(x)$,

$$\log_b(f(n)) \leq 2 \cdot \log_b(g(n)) \quad (15)$$

Then, because we know $d_2 = 2$, we can conclude

$$\log_b(f(n)) \leq d_2 \cdot \log_b(g(n)) \quad (16)$$

□

Notes:

- $\forall x, y \in \mathbb{R}^+, x \geq y \Leftrightarrow \log x \geq \log y$
- $\exists c_1, c_2, n_0 \in \mathbb{R}^+, \forall n \in \mathbb{N}, n \geq n_0 \Rightarrow c_1 \cdot g(n) \leq f(n) \leq c_2 \cdot g(n)$
- **Definition of Eventually:** $\exists n_0 \in \mathbb{N}, n \geq n_0 \Rightarrow P$, where $P : \mathbb{N} \rightarrow \{\text{True}, \text{False}\}$

b. *Proof.* Let $k \in \mathbb{N}$.

First, we will analyze the cost of loop 2 over iteration of loop 1.

The code tells us loop 2 starts at $j_k = 1$ with j_k increasing by a factor of 3 per iteration until $j_k \geq i$.

Using these facts, we can calculate that the terminating condition occurs when

$$3^k \geq i \tag{1}$$

$$k \geq \log_3 i \tag{2}$$

Because we know the number of iterations is the smallest value of k satisfying the above inequality, we can conclude loop 2 has

$$\lceil \log_3 i \rceil \tag{3}$$

iterations.

Next, we need to determine the total number of iterations of loop 2 over all iterations of loop 1.

The code tells us loop 1 starts at $i = 1$ and ends at $i = n$ with each i increasing by 1 per iteration.

Using these facts, we can conclude loop 2 has total of

$$\lceil \log_3 1 \rceil + \lceil \log_3 2 \rceil + \cdots + \lceil \log_3 n \rceil = \sum_{i=1}^n \lceil \log_3 i \rceil \tag{4}$$

iterations. □

c. After scratching head and looking at solution many times, I realized that there are many things I do not yet understand, and it's the best to write what I have and learn from the solution. Here is my best attempt :).

Proof. Let $n \in \mathbb{N}$.

The previous answer tells us the exact cost of the algorithm is

$$\sum_{i=1}^n \lceil \log_3 i \rceil \quad (1)$$

Then, it follows by changing the variable i to $i' = \log_3 i$ we can write

$$\sum_{i'=0}^{\lceil \log_3 n \rceil} i' \quad (2)$$

Then, because we know $\sum_{i=0}^n i = \frac{n(n+1)}{2}$, we can conclude

$$\sum_{i'=0}^{\lceil \log_3 n \rceil} i' = \frac{(\lceil \log_3 n \rceil)(\lceil \log_3 n \rceil + 1)}{2} \quad (3)$$

$$= \frac{\lceil \log_3 n \rceil^2 + \lceil \log_3 n \rceil}{2} \quad (4)$$

Then, we can conclude the runtime of the algorithm is $\Theta(\log_3^2 n)$. □

Correct Solution:

We need to determine Θ of the algorithm.

We will prove that the Θ of the algorithm is $\Theta(n \log n)$.

The answer to previous question tells us the total exact cost of the algorithm is

$$\sum_{i=1}^n \lceil \log_3 i \rceil \quad (5)$$

Then, by using fact 1 $\forall x \in \mathbb{R}, x \leq \lceil x \rceil \leq x + 1$, we can calculate

$$\sum_{i=1}^n \log_3 i \leq \sum_{i=1}^n \lceil \log_3 i \rceil \leq \sum_{i=1}^n (\log_3 i + 1) \quad (6)$$

$$\sum_{i=1}^n \log_3 i \leq \sum_{i=1}^n \lceil \log_3 i \rceil \leq \left(\sum_{i=1}^n \log_3 i + \sum_{i=1}^n 1 \right) \quad (7)$$

$$\sum_{i=1}^n \log_3 i \leq \sum_{i=1}^n \lceil \log_3 i \rceil \leq \sum_{i=1}^n \log_3 i + n \quad (8)$$

Then,

$$\log_3 \left(\prod_{i=1}^n i \right) \leq \sum_{i=1}^n \lceil \log_3 i \rceil \leq \log_3 \left(\prod_{i=1}^n i \right) + n \quad (9)$$

$$\log_3(n!) \leq \sum_{i=1}^n \lceil \log_3 i \rceil \leq \log_3(n!) + n \quad (10)$$

by the fact $\forall a, b \in \mathbb{R}^+, \log(a) + \log(b) = \log(ab)$.

Then,

$$\frac{\ln n!}{\ln 3} \leq \sum_{i=1}^n \lceil \log_3 i \rceil \leq \frac{\ln(n!)}{\ln 3} + n \quad (11)$$

by changing the base to e using the formula $\log_3 n! = \frac{\log_e n!}{\log_e 3} = \frac{\ln n!}{\ln 3}$.

Now, the fact 2 tells us $n! \in \Theta(e^{n \ln n - n + \frac{1}{2} \ln n})$.

Because we know from fact 3 that $n \ln n - n + \frac{1}{2} \ln n$ is eventually ≥ 1 , we can conclude $e^{n \ln n - n + \frac{1}{2} \ln n}$ is eventually $\geq e$.

Since $n!$ is also eventually $\geq e$, by using solution to problem 1.a with $g(n) = n!$ and $f(n) = e^{n \ln n - n + \frac{1}{2} \ln n}$ and $b = e$, we can write

$$\ln(n!) \in \Theta(\ln(e^{n \ln n - n + \frac{1}{2} \ln n})) \quad (12)$$

$$\ln(n!) \in \Theta(n \ln n - n + \frac{1}{2} \ln n) \quad (13)$$

Then,

$$\ln(n!) \in \Theta(n \ln n) \quad (14)$$

by the fact $n \ln n - n + \frac{1}{2} \ln n \in \Theta(n \ln n)$.

So, since the algorithm runs at least $\frac{\ln n!}{\ln 3}$, we can conclude it has asymptotic lower bound of $\Omega(n \ln n)$, and since the algorithm runs at most $\frac{\ln n!}{\ln 3} + n$, we can conclude it has upper bound running time of $\mathcal{O}(n \ln n)$.

Since the value of Ω and \mathcal{O} are the same, we can conclude the algorithm has running time of $\Theta(n \ln n)$ or $\Theta(n \log n)$.

Notes:

- In a main flow of proof, when there is a huge interruption like showing $\ln(n!) \in \Theta(n \ln n)$, how can a sentence be started to tell the audience we are working on another major idea?
- When an interruption in proof has been occurred for another major part of a proof, how can a sentence be started to combine parts together?
- How can a sentence be written to say condition x_1 , x_2 , and x_3 are satisfied, so a statement y can be used to an equation or an idea?

Question 2

a. We need to evaluate tight asymptotic upper bound.

We will prove that the tight asymptotic upper bound of the algorithm is $\mathcal{O}(n^2)$.

First, we need to analyze the number of iterations of loop 2 per iteration of loop 1.

The code tells us loop 2 starts at $j = 0$ and ends at most $j = i - 1$ with j increasing by 1 per iteration.

Then, using these facts, we can conclude loop 2 has at most

$$\left\lceil \frac{i - 1 - 0 + 1}{1} \right\rceil = i \quad (1)$$

iterations.

Next, we need to determine the total number of iterations of loop 2 over all iterations of loop 1.

The code tells us that loop 1 starts at $i = n$ and ends at most $i = 0$ with i decreasing by 1 per iteration.

Because we know each iteration of loop 1 takes i iterations by loop 2, using these facts, we can conclude the total number of iterations of loop 2 is at most

$$n + (n - 1) + (n - 2) + \cdots + 0 = \sum_{i=1}^n \quad (2)$$

$$= \frac{n(n + 1)}{2} \quad (3)$$

iterations, or $\mathcal{O}(n^2)$.

Correct Solution:

We need to evaluate tight asymptotic upper bound.

We will prove that the tight asymptotic upper bound of the algorithm is $\mathcal{O}(n^2)$.

First, we need to analyze the cost of loop 2.

The code tells us loop 2 starts at $j = 0$ and ends at most $j = i - 1$ with j increasing by 1 per iteration.

Then, since each iteration of loop 2 takes a constant step (1 step), using these facts, we can conclude the cost of loop 2 is at most

$$1 \cdot (i - 1 - 0 + 1) = i \quad (1)$$

steps.

Next, we need to determine cost of loop 1.

The code tells us that loop 1 starts at $i = n$ and ends at most $i = 0$ with i decreasing by 1 per iteration.

Because we know each iteration of loop 1 takes $i + 1$ steps (where i is from loop 2 and 1 from line 8), using these facts, we can conclude the total cost of loop 1 is at most

$$(n + 1) + n + (n - 1) + (n - 2) + \cdots + 1 = \sum_{i=0}^n (i + 1) \quad (2)$$

$$= \sum_{i=0}^n i + \sum_{i=0}^n 1 \quad (3)$$

$$= \sum_{i=0}^n i + (n + 1) \quad (4)$$

$$= \frac{n(n + 1)}{2} + (n + 1) \quad (5)$$

$$= \frac{(n + 1)(n + 2)}{2} \quad (6)$$

steps.

Finally, adding the cost of line 6, we can conclude the algorithm has total cost of $\frac{(n+1)(n+2)}{2} + 1$ steps, which is $\mathcal{O}(n^2)$.

Notes:

- Noticed professor writes proof that gets to a point (i.e. ... where each iteration takes $i + 1$ **steps**), and provides more detailed explanation in brackets (i.e. ... where each iteration takes $i + 1$ steps (**Adding the cost of loop 2 and 1 step for other constant time operations**)).
- Noticed professor uses 'finally' when proof has reached the final step that leads to its conclusion.

b. Let $n, k \in \mathbb{N}$, and $list = [0, 0, \dots, 0, 1, 0, \dots, 0]$ where 1 is at $\lceil \frac{n}{2} \rceil$ position.

We will prove that the tight asymptotic lower bound running time of this algorithm is $\Omega(n^2)$.

First, we need to evaluate the cost of loop 2.

The code tells us loop 2 starts at $j_k = 0$, and j_k will increase by 1 until $j_k \geq \lceil \frac{n}{2} \rceil + 1$ (where $+1$ is because of loop 2 stopping at $j_k = \lceil \frac{n}{2} \rceil$ by the if condition on line 10).

Using the fact $j_k = k + 1$, we can calculate that loop 2 stops when

$$k + 1 \geq \lceil \frac{n}{2} \rceil + 1 \quad (1)$$

$$k \geq \lceil \frac{n}{2} \rceil \quad (2)$$

Since we are looking for the smallest value of k (because the smallest value of k translates to number of iterations), we can conclude the loop has

$$\lceil \frac{n}{2} \rceil \quad (3)$$

iterations.

Since each iteration takes a constant time (1 step), the cost of loop 2 is

$$\lceil \frac{n}{2} \rceil \cdot 1 = \lceil \frac{n}{2} \rceil \quad (4)$$

steps.

Next, we need to evaluate the cost of loop 1.

The code tell us loop 1 will start at $i_k = n$, and i_k will decrease by 1 per iteration until $i_k \leq \lceil \frac{n}{2} \rceil$.

Using the fact $i_k = k - 1$, we can write loop 1 stops when

$$k - 1 \leq \lceil \frac{n}{2} \rceil \quad (5)$$

$$k \leq \lceil \frac{n}{2} \rceil + 1 \quad (6)$$

Since we are looking for the largest value of k (because the largest value of k translates to number of iterations), we can conclude loop 1 has

$$\lceil \frac{n}{2} \rceil + 1 \quad (7)$$

iterations.

Since each costs $\lceil \frac{n}{2} \rceil + 1$ steps, we can conclude loop 1 has cost of

$$\left(\left\lceil \frac{n}{2} \right\rceil + 1\right) \left(\left\lceil \frac{n}{2} \right\rceil + 1\right) = \left\lceil \frac{n}{2} \right\rceil^2 + 2 \cdot \left\lceil \frac{n}{2} \right\rceil + 1 \quad (8)$$

steps.

Finally, by adding the cost of line 6 (1 step), the total running time of this algorithm is

$$\left\lceil \frac{n}{2} \right\rceil^2 + 2 \cdot \left\lceil \frac{n}{2} \right\rceil + 2 \quad (9)$$

steps, which is $\Omega(n^2)$

Correct Solution:

Let $n, k \in \mathbb{N}$, and $list = [0, 0, \dots, 0, 1, 0, \dots, 0]$ where 1 is at $\lceil \frac{n}{2} \rceil$ position.

We will prove that the tight asymptotic lower bound running time of this algorithm is $\Omega(n^2)$.

First, we need to evaluate the cost of loop 2.

The code tells us loop 2 starts at $j_k = 0$, and j_k will increase by 1 until $j_k \geq \lceil \frac{n}{2} \rceil + 1$ (where +1 is because of loop 2 stopping at $j_k = \lceil \frac{n}{2} \rceil$ by the if condition on line 10).

Using the fact $j_k = k$, we can calculate that loop 2 stops when

$$k \geq \left\lceil \frac{n}{2} \right\rceil + 1 \quad (1)$$

Since we are looking for the smallest value of k (because the smallest value of k translates to number of iterations), we can conclude the loop has

$$\left\lceil \frac{n}{2} \right\rceil + 1 \quad (2)$$

iterations.

Since each iteration takes a constant time (1 step), the cost of loop 2 is

$$\left(\left\lceil \frac{n}{2} \right\rceil + 1\right) \cdot 1 = \left\lceil \frac{n}{2} \right\rceil + 1 \quad (3)$$

steps.

Next, we need to evaluate the cost of loop 1.

The code tell us loop 1 will start at $i_k = n$, and i_k will decrease by 1 per iteration until $i_k \leq \left\lceil \frac{n}{2} \right\rceil$.

Using the fact $i_k = n - k$, we can write loop 1 stops when

$$n - k \leq \left\lceil \frac{n}{2} \right\rceil \quad (4)$$

$$-k \leq \left\lceil \frac{n}{2} \right\rceil - n \quad (5)$$

$$k \geq n - \left\lceil \frac{n}{2} \right\rceil \quad (6)$$

Since we are looking for the largest value of k (because the largest value of k translates to number of iterations), we can conclude loop 1 has

$$n - \left\lceil \frac{n}{2} \right\rceil \quad (7)$$

iterations.

Since each iteration costs $\left\lceil \frac{n}{2} \right\rceil + 2$ steps (where $\left\lceil \frac{n}{2} \right\rceil + 1$ is the cost of loop 2 and $+1$ is the cost of line 14), we can conclude loop 1 has cost of

$$\left(\left\lceil \frac{n}{2} \right\rceil + 2\right) \left(n - \left\lceil \frac{n}{2} \right\rceil\right) \quad (8)$$

steps.

Finally, since the loop takes $\lceil \frac{n}{2} \rceil + 1$ extra steps (where $\lceil \frac{n}{2} \rceil$ is the cost of traveling from $j = 0$ until $j = \lceil \frac{n}{2} \rceil$ and $+1$ is the cost of line 14) before coming to a full stop, the total running time is at least

$$\left(\left\lceil \frac{n}{2} \right\rceil + 2\right) \left(n - \left\lceil \frac{n}{2} \right\rceil\right) + \left\lceil \frac{n}{2} \right\rceil + 1 \quad (9)$$

steps, which is $\Omega(n^2)$

Notes:

- Noticed there is no room for errors. (most of mark deductions are from not being careful with the analysis).
- Realized I need to take time to verify and re-verify steps using examples at a very fine level (i.e at this step this happens ... at this step this happens) until conclusion.
- Noticed professor uses $i_k = n - k$ when going backward starting from n . And for the inequality, $i_k \leq$ is used as opposed to the normal $i_k \geq$.

c. *Proof.* Let $k, n \in \mathbb{N}$.

We will prove the statement using proof by cases.

Case 1: When all elements in $nums$ are even

Let $nums = [a_1, a_2, \dots, a_n]$ where a_1, \dots, a_n are even numbers.

We want to prove the best-case lower bound running time of this algorithm is $\Omega(n)$.

First, we need to analyze the cost of loop 2.

Given the iteration count k , the code tells us, the loop starts at $j_k = 0$ and increases by 1 per iteration, and so we know $j_k = k$.

Because we know loop 2 runs until $j_k \geq i$, we can conclude loop 2 stops when

$$k \geq i \quad (1)$$

Since we are looking for the smallest value of k (because it represents the number of iterations), we can conclude loop 2 has i iterations.

Because we know each iteration of loop 2 costs a constant time (1 step), we can conclude loop 2 has cost of at least

$$k \cdot 1 = k \tag{2}$$

steps.

Now, we need to evaluate the cost of loop 1.

The code tells us loop 1 starts at $i = n$ and ends at $i = n$ due to the truthy condition of line 14.

Using these facts, we can conclude loop 1 has

$$\lceil n - n + 1 \rceil = 1 \tag{3}$$

iteration.

Because we know each iteration of loop 1 costs $i + 2$ steps (where i is from the cost of loop 2, and $+2$ are from the cost of line 8 and line 16), we can conclude loop 1 has cost of at least

$$(i + 2) \cdot 1 = i + 2 \tag{4}$$

steps.

Finally, because we know $i = n$, the total running time is at least $n + 2$, which is $\Omega(n)$.

Case 2: When one or more elements in *nums* are odd

Let $nums = [1, a_2, a_3, \dots, a_{n-1}]$ where a_2, a_3, \dots, a_{n-1} are even numbers.

We will prove the algorithm has best-case lower bound running time of $\Omega(n)$.

First, we need to evaluate the cost of loop 2.

The code tells us loop 2 starts at $j = 0$ and ends at $j = 0$ due to the truthy condition of line 10.

Using these facts, we can calculate loop 2 has 1 iteration.

Because we know loop 2 takes constant time (1 step) per iteration, we can conclude loop 2 has cost of 1 step.

Next, we need to evaluate the cost of loop 1.

The code tells us that loop 1 starts at $i = n$, and i increases by 1 until $i_k \leq -1$, where k represents the iteration count of loop 1.

Because we know $i_k = n - k$, we can conclude the loop stops when

$$n - k \leq -1 \quad (5)$$

$$k \geq n + 1 \quad (6)$$

Since we are looking for the smallest value of k (because it represents the number of iterations), we can conclude loop 1 has

$$n + 1 \quad (7)$$

Since each iteration of loop 1 takes 2 steps (where 1 is the cost of loop 2 and the other 1 is the cost of line 8), we can conclude that loop 1 has cost of at least

$$2 \cdot (n + 1) \quad (8)$$

steps.

Finally, adding the cost of line 8, we can conclude the algorithm has running time of at least $2(n + 1) + 1$ steps, which is $\Omega(n)$. \square

Attempt 2:

Let $k, n \in \mathbb{N}$.

We will prove this statement using proof by cases.

Case 1: When all elements in $nums$ are even

Let $nums = [a_1, a_2, \dots, a_n]$ where a_1, \dots, a_n are even numbers.

We want to prove the best-case lower bound running time of this algorithm is $\Omega(n)$.

First, we need to analyze the cost of loop 2.

Given the iteration count k , the code tells us, the loop starts at $j_k = 0$ and increases by 1 per iteration, and so we know $j_k = k$.

Because we know loop 2 runs until $j_k \geq i$, we can conclude loop 2 stops when

$$k \geq i \tag{1}$$

Since we are looking for the smallest value of k (because it represents the number of iterations), we can conclude loop 2 has i iterations.

Because we know each iteration of loop 2 costs a constant time (1 step), we can conclude loop 2 has cost of at least

$$k \cdot 1 = k \tag{2}$$

steps.

Now, we need to evaluate the cost of loop 1.

The code tells us loop 1 starts at $i = n$ and ends at $i = n$ due to the truthy condition of line 14.

Using these facts, we can conclude loop 1 has

$$\lceil n - n + 1 \rceil = 1 \tag{3}$$

iteration.

Because we know each iteration of loop 1 costs $i + 2$ steps (where i is from the cost of loop 2, and +2 are from the cost of line 8 and line 16), we can conclude loop 1 has cost of at least

$$(i + 2) \cdot 1 = i + 2 \tag{4}$$

steps.

Finally, because we know $i = n$, the total running time is at least $n + 2$, which is $\Omega(n)$.

Case 2: When one or more elements in $nums$ are odd

In this case, let m be the index of first odd number in $nums$.

We need to prove this algorithm has best-case lower bound running time of $\Omega(n)$.

First, we need to evaluate the cost of loop 2.

Given loop 2 iteration count k , the code tells us loop 2 starts at $j = 0$, and j increases by 1 until $j_k \geq m + 1$.

Since we know $j_k = k$, using these facts, we can calculate loop 2 terminates when

$$k \geq m + 1 \tag{5}$$

Since we are looking for the smallest value of k (because it represents the number of iterations), we can conclude loop 2 has

$$m + 1 \tag{6}$$

iterations.

Next, we need to evaluate the cost of loop 1.

Given loop 1 iteration count k , The code tells us that loop 1 starts at $i = n$, and i decreases by 1 until $i_k \leq m - 1$.

Since we know $i_k = n - k$, using these facts, we can calculate loop 1 stops when

$$n - k \leq m - 1 \tag{7}$$

$$k \geq n - m + 1 \tag{8}$$

Since we are looking for the smallest value of k (because it represents the number of iterations), we can conclude loop 1 has

$$n - m + 1 \tag{9}$$

iterations.

Because we know that for the first $n - k$ iterations, each iteration of loop 1 costs $m + 2$ steps (where $m + 1$ is the cost of loop 2 and $+1$ is the cost of line 8), and last iteration of loop 1 costs another $m + 2$ (where m is the cost of loop 2 and $+2$ are the cost of line 8 and 15), we can conclude loop 1 has cost of

$$(n - m + 1)(m + 2) \tag{10}$$

steps.

Next, adding the cost of line 6, we can conclude the algorithm has total cost of at least

$$(n - m + 1)(m + 2) + 1 \tag{11}$$

steps.

Finally, we need to show this algorithm has runtime of $\Omega(n)$.

Using the total cost of algorithm, we can calculate

$$(n - m + 1)(m + 2) + 1 = (n - m)(m + 2) + (m + 2) + 1 \tag{12}$$

$$> (n - m)(m + 2) + (m + 2) \tag{13}$$

$$= (n - m)m + 2(n - m) + (m + 2) \tag{14}$$

$$> (n - m)m + (n - m) + m \tag{15}$$

$$= (n - m)m + n \tag{16}$$

Because we know $n - m \geq 0$ and $m \geq 0$, we can conclude that

$$(n - m + 1)(m + 2) + 1 > n \quad (17)$$

and the algorithm has best case lower bound running time of $\Omega(n)$.

Notes:

- The solution in problem 2.b adds constant time operations into total cost where as the solution to this problem doesn't... Is there a rule behind when and when not they can be included?
- Noticed professor reduces the exact cost to n by separating it from the rest of the terms

$$(n - m + 1)(m + 2) > (n - m)m + n$$

- Realized the best-case lower bound running time doesn't use input family like worst-case lower bound running time

Question 3

a. *Proof.* Let $n \in \mathbb{N}$ and lst be a list with all negative numbers.

Then, the code tells us line 9-12 will run for all elements in the list.

Because we know i increases by a factor of 2 per iteration, we can conclude that at k^{th} iteration, i has value of $i_k = 2^k$.

Because we know loop terminates when $i_k \geq n$, we can conclude this is true when

$$2^k \geq n \quad (1)$$

$$k \geq \log n \quad (2)$$

Since we are looking for the smallest value of k (since it represents the number of iterations), we can conclude loop has

$$\lceil \log n \rceil \quad (3)$$

iterations.

Since each iteration of while loop takes a constant time (1 step), we can conclude the loop has cost of

$$\lceil \log n \rceil \quad (4)$$

steps.

Finally, since lines 2 to 4 have cost of 1 each, by adding to the costs together, we can conclude the algorithm has total running time of $\lceil \log n \rceil + 3$, which is $\Theta(\log n)$. \square

Correct Solution:

Let $n, k \in \mathbb{N}$ and lst be a list with all negative numbers.

In this case, the loop follows this pattern

- **iteration 1** - else condition executes and j increases by a factor of 2
- **iteration 2** - if condition executes and i increases by a factor of 2, and moves to where j is
- **iteration 3** - else condition executes again and j increases by a factor of 2
- **iteration 4** - if condition executes again and i increases by a factor of 2 and moves to where j is.
- and this pattern repeats until the end of while loop.

Now, we need to determine the total number of iterations in while loop.

Because we know i increases by a factor of 2 per execution of **if $lst[i] \geq 0$: condition**, we can conclude that at k^{th} execution of **if $lst[i] \geq 0$: condition**, i has value of $i_k = 2^k$.

Because we know loop terminates when $i_k \geq n$, we can conclude this is true when

$$2^k \geq n \quad (1)$$

$$k \geq \log n \quad (2)$$

Since we are looking for the smallest value of k (since it represents the number of executions caused by the **if $lst[i] \geq 0$: condition**), we can conclude loop has

$$\lceil \log n \rceil \tag{3}$$

executions due to the **if** `lst[i] >= 0`: condition.

Because we know every execution of **if** `lst[i] >= 0`: condition in an iteration, is followed by the execution of **else**: condition in previous iteration, we can conclude while loop has total of

$$2 \cdot \lceil \log n \rceil \tag{4}$$

executions, or iterations.

Since each iteration of while loop takes a constant time (1 step), we can conclude the while loop has cost of

$$2 \cdot \lceil \log n \rceil \tag{5}$$

steps.

Finally, adding cost of 1 for the constant time operations on line 2-4, we can conclude the algorithm has total running time of $2 \cdot \lceil \log n \rceil + 1$ steps, which is $\Theta(\log n)$.

Notes:

- Noticed professor bundles up time of constant operations (i.e. line 2-4) to 1, and same for the ones within while loop.
 - Noticed professor introduces k in body as ' k^{th} execution of the if/else branch', and he doesn't introduce the variable in header.
 - Noticed professor uses the word 'execution' to focus on the number of iterations caused by the if condition.
 - Noticed professor lays out the pattern in while loop before moving onto proof.
- b. *Proof.* Let $n \in \mathbb{N}$, and `lst` be a list of integers where `lst[0]` to `lst[$\frac{n}{2}$]` have value 0, and `lst[$\frac{n}{2} + 1$]` to `lst[n - 1]` have value -1.

In this case, the loop follows this pattern:

- When $j = 1$, if branch performs $\frac{n}{2} + 1$ executions, stops at $i = \frac{n}{2} + 1$

- else branch performs, and value of j doubles, and i resets to 0
- When $j = 2$, if branch performs $\frac{n}{4} + 1$ executions, stops at $i = \frac{n}{2} + 2$
- else branch performs, and value of j doubles, and i resets to 0
- When $j = 4$, if branch performs $\frac{n}{8} + 1$ executions, stops at $i = \frac{n}{2} + 4$
- else branch performs, and value of j doubles, and i resets to 0
- When $j = 8$, if branch performs $\frac{n}{16} + 1$ executions, stops at $i = \frac{n}{2} + 8$
- This pattern repeats until k^{th} execution of else branch of statements has value of j half the size of n .
- Loop terminates one iteration after i reaches the end of array.

Now, we will prove this statement in two parts: one for determining the number of executions of else branch of statements in while loop, and another for determining the runtime of whole algorithm.

Part 1: Determining the number of executions of else branch:

We need to prove the else branch executes $\Omega(\log n)$ times.

The pattern tells us while loop depends on j , and j increases by a factor of 2 per execution of else branch until $j_{k+1} \geq n$.

Because we know at k^{th} execution of else branch has j with value of $j_k = 2^k$, using these facts, we can calculate

$$2^{k+1} \geq n \tag{1}$$

$$k + 1 \geq \log n \tag{2}$$

$$k \geq \log n - 1 \tag{3}$$

So we know the else branch executes at least $\log n - 1$ times, which is $\Omega(\log n)$.

Part 2: Determining running time of algorithm:

We need to prove this algorithm has running time of $\Theta(n)$.

First, we need to determine number of executions of if branch in while loop.

The pattern tells us at k^{th} execution of else branch of statements in while loop, $\frac{n}{2^{k+1}} + 1$ many executions of if branch of statements are performed.

Since loop performs $\log n - 1$ many executions of the else branch of statements, we can conclude

$$\sum_{k=1}^{\log n - 2} \left(\frac{n}{2^{k+1}} + 1 \right) \quad (4)$$

many executions of the if branch are performed.

Then, since we know $\log n \in \mathbb{N}$ due to n being in factors of 2, using the fact $\forall n \in \mathbb{N}, \forall r \in \mathbb{R}, \sum_{i=0}^{n-1} r^i = \frac{1-r^n}{1-r}$, we can calculate that

$$\sum_{k=1}^{\log n - 2} \left(\frac{n}{2^{k+1}} + 1 \right) = \sum_{k=1}^{\log n - 2} \frac{n}{2^{k+1}} + \sum_{k=1}^{\log n - 2} 1 \quad (5)$$

$$= \frac{n}{2} \cdot \sum_{k=1}^{\log n - 2} \frac{1}{2^k} + \sum_{k=1}^{\log n - 2} 1 \quad (6)$$

$$= \frac{n}{2} \cdot \sum_{k=1}^{\log n - 2} \frac{1}{2^k} + (\log n - 2) \quad (7)$$

$$= \frac{n}{2} \cdot \left(\frac{1 - \frac{2}{2^{\log n}}}{1 - \frac{1}{2}} \right) + (\log n - 2) \quad (8)$$

$$= n \cdot \left(1 - \frac{2}{n} \right) + (\log n - 2) \quad (9)$$

$$= n - 2 + \log n - 2 \quad (10)$$

$$= n + \log n - 4 \quad (11)$$

Now, adding the cost of the number of executions of else statements and the extra iteration taken to verify loop's terminating condition, we can conclude while loop has total of

$$n + \log n - 4 + (\log n - 1) + 1 = n + 2 \log n - 4 \quad (12)$$

executions or iterations.

Since each execution takes a constant time (1 step), we can conclude while loop has cost of

$$1 \cdot (n + 2 \log n - 4) = (n + 2 \log n - 4) \quad (13)$$

steps.

Finally, adding constant time operations on line 2 to 4 (1 step), the algorithm has running time of

$$n + 2 \log n - 3 \quad (14)$$

which is $\Theta(n)$.

□

Notes:

- I analyzed the example $[0, 0, -1, -1]$. This is what I found.
 - **iteration 1:** if brach of statement executes and i increases by a 1 ($i = 1, j = 1$)
 - **iteration 2:** if brach of statement executes and i increases by a 1 ($i = 2, j = 1$)
 - **iteration 3:** if brach of statement executes and i increases by a 1 ($i = 3, j = 1$)
 - **iteration 4:** else brach of statement executes, causing $\text{lst}[i] = \text{abs}(\text{lst}[i])$, $i = 0$, and j to increase by twice of its size ($i = 0, j = 2$)

The following is how the list looks after update

$$[0, 0, 1, -1]$$

- **iteration 5:** if brach of statement executes and i increases by a 2 ($i = 2, j = 2$)
- **iteration 6:** if brach of statement executes and i increases by a 2 ($i = 4, j = 2$)
- **iteration 7:** Loop terminates,

Here's what I found about j

- Loop terminates when $k + 1^{\text{th}}$ execution of else statement is greater than or equal to n .

Here's what I found about i

- When $j = 1$, loop performs $\frac{n}{2} + 1$ executions, stops at $\frac{n}{2} + 1$
- When $j = 2$, loop performs $\frac{n}{4} + 1$ executions, stops at $\frac{n}{2} + 2$
- loop terminates 1 after

- Number of execution of if branch of statements depend on the number of execution of else branch of statements

$$\text{num of exec. of if statements} = \sum_{k=0}^{\text{num of exec. of else}} \left(\frac{n}{2^k + 1} + 1 \right) \quad (15)$$

- I analyzed the example $[0, 0, 0, 0, -1, -1, -1, -1]$. This is what I found.

- **iteration 1:** if brach of statement executes and i increases by a 1 ($i = 1, j = 1$)
- **iteration 2:** if brach of statement executes and i increases by a 1 ($i = 2, j = 1$)
- **iteration 3:** if brach of statement executes and i increases by a 1 ($i = 3, j = 1$)
- **iteration 4:** if brach of statement executes and i increases by a 1 ($i = 4, j = 1$)
- **iteration 5:** else brach of statement executes, causing $\text{lst}[i] = \text{abs}(\text{lst}[i])$, $i = 0$, and j to increase by twice of its size ($i = 0, j = 2$)

The following is how the list looks after update

$$[0, 0, 0, 0, 1, -1, -1, -1]$$

- **iteration 6:** if brach of statement executes and i increases by a 2 ($i = 2, j = 2$)
- **iteration 7:** if brach of statement executes and i increases by a 2 ($i = 4, j = 2$)
- **iteration 8:** if brach of statement executes and i increases by a 2 ($i = 6, j = 2$)
- **iteration 9:** else brach of statement executes, causing $\text{lst}[i] = \text{abs}(\text{lst}[i])$, $i = 0$, and j to increase by twice of its size ($i = 0, j = 4$)

The following is how the list looks after update

$$[0, 0, 0, 0, 1, -1, 1, -1]$$

- **iteration 10:** if brach of statement executes and i increases by a 4 ($i = 4, j = 4$)
- **iteration 11:** if brach of statement executes and i increases by a 4 ($i = 8, j = 4$)
- **iteration 12:** Loop terminates,

Here's what I found about j

- Loop terminates when $k + 1^{\text{th}}$ execution of else statement is greater than or equal to n .

Here's what I found about i

- When $j = 1$, loop performs $\frac{n}{2} + 1$ iterations, stops at $\frac{n}{2} + 1$

- When $j = 2$, loop performs $\frac{n}{4} + 1$ iterations, stops at $\frac{n}{2} + 2$
- When $j = 4$, loop performs $\frac{n}{8} + 1$ iterations, stops at $\frac{n}{2} + 4$
- Loop terminates 1 after
- Number of execution of if branch of statements depend on the number of execution of else branch of statements

$$\text{num of exec. of if statements} = \sum_{k=0}^{\text{num of exec. of else}} \left(\frac{n}{2^k + 1} + 1 \right) \quad (16)$$

- I analyzed the example $[0, 0, 0, 0, 0, 0, 0, 0, -1, -1, -1, -1, -1, -1, -1, -1]$. This is what I found.

- **iteration 1:** if brach of statement executes and i increases by a 1 ($i = 1, j = 1$)
- **iteration 2:** if brach of statement executes and i increases by a 1 ($i = 2, j = 1$)
- **iteration 3:** if brach of statement executes and i increases by a 1 ($i = 3, j = 1$)
- **iteration 4:** if brach of statement executes and i increases by a 1 ($i = 4, j = 1$)
- **iteration 5:** if brach of statement executes and i increases by a 1 ($i = 5, j = 1$)
- **iteration 6:** if brach of statement executes and i increases by a 1 ($i = 6, j = 1$)
- **iteration 7:** if brach of statement executes and i increases by a 1 ($i = 7, j = 1$)
- **iteration 8:** if brach of statement executes and i increases by a 1 ($i = 8, j = 1$)
- **iteration 9:** if brach of statement executes and i increases by a 1 ($i = 9, j = 1$)
- **iteration 10:** else branch of statement executes, causing $\text{lst}[i] = \text{abs}(\text{lst}[i])$, $i = 0$, and j to increase by twice of its size ($i = 0, j = 2$)

The following is how the list looks after update

$$[0, 0, 0, 0, 0, 0, 0, 0, 1, -1, -1, -1, -1, -1, -1, -1]$$

- **iteration 11:** if brach of statement executes and i increases by a 2 ($i = 2, j = 2$)
- **iteration 12:** if brach of statement executes and i increases by a 2 ($i = 4, j = 2$)
- **iteration 13:** if brach of statement executes and i increases by a 2 ($i = 6, j = 2$)
- **iteration 14:** if brach of statement executes and i increases by a 2 ($i = 8, j = 2$)
- **iteration 15:** if brach of statement executes and i increases by a 2 ($i = 10, j = 2$)
- **iteration 16:** else branch of statement executes, causing $\text{lst}[i] = \text{abs}(\text{lst}[i])$, $i = 0$, and j to increase by twice of its size ($i = 0, j = 4$)

The following is how the list looks after update

$$[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, -1, -1, -1, -1, -1, -1]$$

- **iteration 17:** if brach of statement executes and i increases by a 4 ($i = 4, j = 4$)
- **iteration 18:** if brach of statement executes and i increases by a 4 ($i = 8, j = 4$)
- **iteration 19:** if brach of statement executes and i increases by a 4 ($i = 12, j = 4$)
- **iteration 20:** else branch of statement executes, causing $\mathbf{lst}[i] = \mathbf{abs}(\mathbf{lst}[i])$, $i = 0$, and j to increase by twice of its size ($i = 0, j = 8$)

The following is how the list looks after update

[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, -1, 1, -1, -1, -1]

- **iteration 21:** if brach of statement executes and i increases by a 8 ($i = 8, j = 8$)
- **iteration 22:** if brach of statement executes and i increases by a 8 ($i = 16, j = 8$)
- **iteration 23:** Loop terminates.

Here's what I found about j

- * Loop terminates when $k + 1^{th}$ execution of else statement is greater than or equal to n .

Here's what I found about i

- * When $j = 1$, if branch performs $\frac{n}{2} + 1$ executions, stops at $\frac{n}{2} + 1$
- * When $j = 2$, if branch performs $\frac{n}{4} + 1$ executions, stops at $\frac{n}{2} + 2$
- * When $j = 4$, if branch performs $\frac{n}{8} + 1$ executions, stops at $\frac{n}{2} + 4$
- * When $j = 8$, if branch performs $\frac{n}{16} + 1$ executions, stops at $\frac{n}{2} + 8$
- * Loop terminates 1 after
- * Number of execution of if branch of statements depend on the number of execution of else branch of statements

$$\text{num of exec. of if statements} = \sum_{k=0}^{\text{num of exec. of else}} \left(\frac{n}{2^k + 1} + 1 \right) \quad (17)$$

Question 4