CSC236 Worksheet 6 Solution

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Question 1

- *Proof.* Assume that for all $k \in \mathbb{N}$, $R(3^k) = k3^k$.

  I need to prove $R \in \mathcal{O}(n \lg n)$ and $R \in \Omega(n \lg n)$.

  I will do so in parts.

  Part 1 (Proving $R \in \mathcal{O}(n \lg n)$):

  Define $n^* = 3^{\lceil \log_3 n \rceil}$. Then, we have,

  $$\lceil \log_3 n \rceil - 1 < \log_3 n \leq \lceil \log_3 n \rceil \Rightarrow n^*/3 < n \leq n^* \tag{1}$$

  I will also use the assumption (proved last week) that R is non-decreasing.

  Let $d = 6$. Then $d \in \mathbb{R}^+$. Let $B = 3$. Then $B \in \mathbb{N}^+$. Let n be an arbitrary natural number no smaller than B. Then,

$$
\begin{aligned}
R(n) &\leq R(n^*) && [\text{Since } n < n^*, \text{ and } R \text{ is non-decreasing}] & (2)\\
&= n^* \log_3 n^* && [\text{By assumption, and replacing } n^* \text{ for } 3^k] & (3)\\
&\leq 3n \log_3 3n && [\text{Since } n \leq n^* \Rightarrow 3n \leq 3n^*] & (4)\\
&\leq 3n(\log_3 n + 1) && & (5)\\
&\leq 3n(\log_3 n + \log_3 n) && [\text{Since } n \geq 3 \Rightarrow \log_3 n \geq 1] & (6)\\
&= 6n \log_3 n && & (7)\\
&\leq (6n \lg n)/\lg 3 && [\text{By change of basis to lg}] & (8)\\
&< 6n \lg n && & (9)\\
&= dn \lg n && [\text{Since } d = 6] & (10)
\end{aligned}
$$

So $R \in \mathcal{O}(n \lg n)$, since $\log_3 n$ differs from $\lg n$ by a constant factor.

Part 2 (Proving $R \in \Omega(n \lg n)$):

Define $n^* = 3^{\lceil \log_3 n \rceil}$. Then, we have,

$$\lceil \log_3 n \rceil - 1 < \log_3 n \leq \lceil \log_3 n \rceil \Rightarrow n^*/3 < n \leq n^* \tag{11}$$

I will also use the assumption (proved last week) that R is non-decreasing.

Let $d = 1/(6 \lg 3)$. Then $d \in \mathbb{R}^+$. Let $B = 9$. Then $B \in \mathbb{N}^+$. Let n be an arbitrary natural number no smaller than B. Then,

$$
\begin{aligned}
R(n) &\geq R(n^*/3) & &[\text{Since } n^*/3 < n, \text{ and } R \text{ is non-decreasing}] & (12)\\
&= (n^*/3) \cdot \log_3(n^*/3) & &[\text{By assumption, and replacing } n^* \text{ for } 3^k] & (13)\\
&\geq (n/3) \cdot \log_3(n/3) & &[\text{Since } n^* \leq n \Rightarrow n^*/3 \leq n/3] & (14)\\
&= (n/3) \cdot (\log_3 n - 1) & & & (15)\\
&\geq (n/3) \cdot (\log_3 n - (\log_3 n)/2) & &[\text{Since } n \geq 9 \Rightarrow (\log_3 n)/2 \geq 1] & (16)\\
&= (n/6) \cdot \log_3 n & & & (17)\\
&= (n/6) \cdot (\lg n / \lg 3) & & & (18)\\
&= (n/(6 \lg 3)) \cdot \lg n & & & (19)\\
&= dn \cdot \lg n & &[\text{Since } d = 1/(6 \lg 3)] & (20)
\end{aligned}
$$

So, $R \in \Omega(n \lg n)$.

$\square$

Correct Solution:

Assume that for all $k \in \mathbb{N}$, $R(3^k) = k3^k$.

I need to prove $R \in \mathcal{O}(n \lg n)$ and $R \in \Omega(n \lg n)$.

I will do so in parts.

Part 1 (Proving $R \in \mathcal{O}(n \lg n)$):

Define $n^* = 3^{\lceil \log_3 n \rceil}$. Then, we have,

$$\lceil \log_3 n \rceil - 1 < \log_3 n \leq \lceil \log_3 n \rceil \Rightarrow n^*/3 < n \leq n^* \tag{21}$$

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I will also use the assumption (proved last week) that R is non-decreasing.

Let $d = 6$. Then $d \in \mathbb{R}^+$. Let $B = 3$. Then $B \in \mathbb{N}^+$. Let n be an arbitrary natural number no smaller than B. Then,

$$
\begin{align}
R(n) &\leq R(n^*) && \text{[Since } n < n^*, \text{ and } R \text{ is non-decreasing]} & (22) \\
&= n^* \log_3 n^* && \text{[By assumption, and replacing } n^* \text{ for } 3^k] & (23) \\
&\leq 3n \log_3 3n && \text{[Since } n \leq n^* \Rightarrow 3n \leq 3n^*] & (24) \\
&= 3n(\log_3 n + 1) && & (25) \\
&\leq 3n(\log_3 n + \log_3 n) && \text{[Since } n \geq 3 \Rightarrow \log_3 n \geq 1] & (26) \\
&= 6n \log_3 n && & (27) \\
&= (6n \lg n)/\lg 3 && \text{[By change of basis to lg]} & (28) \\
&< 6n \lg n && & (29) \\
&= dn \lg n && \text{[Since } d = 6] & (30)
\end{align}
$$

So $R \in \mathcal{O}(n \lg n)$, since $\log_3 n$ differs from $\lg n$ by a constant factor.

Part 2 (Proving $R \in \Omega(n \lg n)$):

Define $n^* = 3^{\lceil \log_3 n \rceil}$. Then, we have,

$$\lceil \log_3 n \rceil - 1 < \log_3 n \leq \lceil \log_3 n \rceil \Rightarrow n^*/3 < n \leq n^* \tag{31}$$

I will also use the assumption (proved last week) that R is non-decreasing.

Let $d = 1/(6 \lg 3)$. Then $d \in \mathbb{R}^+$. Let $B = 9$. Then $B \in \mathbb{N}^+$. Let n be an arbitrary natural number no smaller than B. Then,

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$$R(n) \geq R(n^*/3) \qquad \text{[Since } n^*/3 < n, \text{ and } R \text{ is non-decreasing]} \tag{32}$$

$$= (n^*/3) \cdot \log_3(n^*/3) \qquad \text{[By assumption, and replacing } n^* \text{ for } 3^k\text{]} \tag{33}$$

$$\geq (n/3) \cdot \log_3(n/3) \qquad \text{[Since } n^* \leq n \Rightarrow n^*/3 \leq n/3\text{]} \tag{34}$$

$$= (n/3) \cdot (\log_3 n - 1) \tag{35}$$

$$\geq (n/3) \cdot (\log_3 n - (\log_3 n)/2) \qquad \text{[Since } n \geq 9 \Rightarrow (\log_3 n)/2 \geq 1\text{]} \tag{36}$$

$$= (n/6) \cdot \log_3 n \tag{37}$$

$$= (n/6) \cdot (\lg n / \lg 3) \tag{38}$$

$$= (n/(6 \lg 3)) \cdot \lg n \tag{39}$$

$$= dn \cdot \lg n \qquad \text{[Since } d = 1/(6 \lg 3)\text{]} \tag{40}$$

So, $R \in \Omega(n \lg n)$, since $\log_3 n$ differs from $\lg n$ by a constant factor.

Notes:

- Learned that if there is trouble going from $\log_3 n - 1$ to $dn \lg n$, a good approach is to increase the value of B.

- Noticed that professor used 'Let $d = $ _____. Then $d \in \mathbb{R}^+$' to define variable's value as well as its type.

- $g \in \Theta(f) : g \in \mathcal{O}(f) \wedge g \in \Omega(f)$

  or

  $g \in \Theta(f) : \exists c_1, c_2, n_1 \in \mathbb{R}^+, \forall n \in \mathbb{N}, n \geq n_1 \Rightarrow c_1 g(n) \leq f(n) \leq c_2 g(n)$, where $f, g : \mathbb{N} \to \mathbb{R}^{\geq 0}$

- $g \in \Omega(f) : \exists c, n_o \in \mathbb{R}^+, \forall n \in \mathbb{N}, n \geq n_0 \Rightarrow g(n) \geq cf(n)$, where $f, g : \mathbb{N} \to \mathbb{R}^{\geq 0}$

- $g \in \mathcal{O}(f) : \exists c, n_o \in \mathbb{R}^+, \forall n \in \mathbb{N}, n \geq n_0 \Rightarrow g(n) \leq cf(n)$, where $f, g : \mathbb{N} \to \mathbb{R}^{\geq 0}$

Question 2

- **Rough Work:**

Let $n \in \mathbb{N}$ and bits $b_0, \cdots, b_k \in \{0, 1\}$ be such that $n = \sum\limits_{i=0}^{i=k} 2^i b_i$. I will use identities:

$$\lfloor n/2 \rfloor = \sum_{i=1}^{i=k} 2^i b_i \tag{41}$$

$$b_0 = n \mod 2 \tag{42}$$

Define $P(n)$: "If n is a natural number, then *decimal_to_binary(n)*" terminates and returns binary string representing n with no leading zeros, except if n is 0.

I will use complete induction to prove $\forall n \in \mathbb{N}, P(n)$.

1. Inductive Step

   Let $n \in \mathbb{N}$. Assume $H(n) : \bigwedge\limits_{i=0}^{i=n-1} P(i)$. I will show $P(n)$ follows.

2. Base Case $(n < 2)$

   Let $n < 2$.

   Then, the if part of *decimal_to_binary(n)* executes, and the program terminates by outputing the input value.

   Since, binary rep of $n = 0$ is 0, and binary rep of $n = 1$ is 1, $P(n)$ follows in this step.

3. Case $(n \geq 2)$

Let $n \geq 2$.

Then, since $n \geq 2$, and $0 \leq n \% 2 \leq n//2 < n$, the induction hypothesis tells us $P(n//2)$ and $P(n \% 2)$ holds.

Then, since $n//2$ is $\lfloor n/2 \rfloor = \sum_{i=1}^{i=k} 2^i b_i$, and $n \% 2$ is $n \mod 2 = b_0$, we have

$$b_0 + \lfloor n/2 \rfloor = b_0 + \sum_{i=1}^{i=k} 2^i b_i \tag{43}$$

$$= 2^0 \cdot b_0 + \sum_{i=1}^{i=k} 2^i b_i \tag{44}$$

$$= \sum_{i=0}^{i=k} 2^i b_i \tag{45}$$

$$= n \tag{46}$$

Thus, $P(n)$ follows from $H(n)$ in this step.

Notes:

- **Correct:** A program is correct if it produces output on every acceptable input

- **Precondition** and **Postcondition** are assertions involving some of the variables of the program

    - **Precondition** states what must be true *before* program starts execution
    - **Postcondition** states what must be true when the program *ends*