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Q1.A solution

According to the text, $f(i)$ is the depth of the first i characters of the string s. And $f(j)$ is the depth of the first j characters of the string s.

As $f(i) = f(j)$, $d(S_{\leq i}) = d(S_{\leq j})$, which means that

$$\#a(S_{\leq i}) - \#b(S_{\leq i}) = \#a(S_{\leq j}) - \#b(S_{\leq j})$$

.

By simplifying this equation, we get $\#a(S_{\leq j}) - \#a(S_{\leq i}) - (\#b(S_{\leq j}) - \#b(S_{\leq i})) = 0$.

It can be seen that $\#a(S_{\leq j}) - \#a(S_{\leq i})$ is the number of a in the string constructed by index $i+1$ to j in string s, $\#b(S_{\leq j}) - \#b(S_{\leq i})$ is the number of b in the string constructed by index $i+1$ to j in string s.

So, $s_{i+1}s_{i+2}\ldots s_j$ is a weakly balanced string.

Q1.B solution

Define the set of strings that meet any of the three conditions in the problem as $P \subseteq \sum^*$, and define the set of all balanced strings as $F \subseteq \sum^*$. We are going to prove $P \subseteq F$ first.

The (i) case is $s = \epsilon$. It is obvious that d(t)=0 and $\#_a(s) >= \#_b(s)$ since $\#_a(s) = \#_b(s) = 0$.

So, (i) is proved. Empty string is balanced.

In case (ii), as $x, y \in F$ and they are non-empty, by definition, we have $d(xy) = d(x) + d(y)$. As $d(x) = d(y) = 0$, $d(xy) = 0$. So $s = xy$ is also weakly balanced. Because x is a balanced string, any prefix substring p1 of the first part of $s = xy$ satisfies $\#_a(p1) >= \#_b(p1)$. Any prefix substring t of y satisfy $\#_a(t) >= \#_b(t)$. $s = xy$ means adding the same number of a and b before y, then any prefix substring p2 of the second part of $s = xy$ still satisfy $\#_a(p2) >= \#_b(p2)$.

So, (ii) is proved.

In case (iii), assume $s_1 = a$, $s_2 = b$. By definition, $d(s_1) = 1$, $d(s_2) = -1$. Since we also have $d(xy) = d(x) + d(y)$, we can get $d(axb) = d(s_1) + d(x) + d(s_2) = 1 + d(x) - 1$. As x is a balanced string, $d(x) = 0$. So, $d(axb) = 0$, $s = axb$ is also weakly balanced. As x is a balanced string, any prefix substring p of x satisfies $\#_a(p) >= \#_b(p)$. Add one a means that $\#_a(t) >= \#_b(t)$ still right for any prefix substring t of string ax. As for the total string $s = axb$, $\#_a(s) = \#_b(s)$.

So, (iii) is proved. So, $P \subseteq F$ has been proved.

Now, we are going to prove that $F \subseteq P$.

Suppose there is a string $s \in F$ and the length of s is n, which means that s is a balanced string. We first classify according to whether the string is empty.

case (1): s is an empty string. in that case, $s \in P$.

case (2): s is a non-empty string. According to the definition of balanced string, we can know that "s must start with a", because any prefix substring p of s satisfies

$\#_a(p) >= \#_b(p)$, we can consider the prefix substring with only one letter. At the same time, "s must end with b", because for the (n-1) letter prefix substring, it satisfies $\#_a(p) >= \#_b(p)$, and $\#_a(s) = \#_b(s)$. As s is balanced with $\#_a(s) = \#_b(s)$, "the string between the first 'a' and the last 'b' is a weakly balanced string".

So balanced string s can be expressed as aqb with weakly balanced string q. if q is empty, it is obvious that $s = aqb \in P$. So we then assume that q is a non-empty string. On the premise of case 2, we next classify s according to whether the string q is balanced.

case(2.1): q is a balanced string. In this case, $s = aqb \in P$ as it satisfies the requirements of (iii).

case(2.2): q is a weakly balanced string and q is not a balanced string.

- q is not a balanced string ==> $\exists p$, a prefix substring of q, we have that $\#_a(p) < \#_b(p)$.(1)
- aqb is a balanced string ==> for any prefix substring p of aq, we have that $\#_a(p) >= \#_b(p)$.(2)

From (1) and (2), we can conclude that:

- For any prefix substring h of string q, it must satisfying $\#_a(h) >= \#_b(h) - 1$.(3)
- q has at least one prefix substring m, which satisfies $\#_a(m) + 1 = \#_b(m)$. (4)
- For any prefix substring t of string m, it must satisfying $\#_a(t) + 1 >= \#_b(t)$. (5)

Using (4), We just find and cut the prefix substring m, and split the q into string m and string n. Now, if we can prove that am and nb are both non-empty balanced strings like what (ii) says, then we can prove that in case(2.2), $q \in P$.

First of all, it is obvious that because of $\#_a(m) + 1 = \#_b(m)$, $\#_a(n) - 1 = \#_b(n)$, am and nb are both weakly balanced strings.

For am, using (5), when you add one "a" before m, we can conclude that "for any prefix substring t of string am, they must satisfying $\#_a(t) >= \#_b(t)$", so am is balanced string.

For nb, suppose $\#_a(m) = x$, then $\#_b(m) = (x + 1)$, using (3), when you delete m before $q = mn$, we can conclude that "for any prefix substring h of string q, there is a corresponding prefix substring c of string n, which must satisfying $\#_a(c) = \#_a(h) - x >= \#_b(h) - x - 1 = \#_b(c)$".

Thus, am and nb are both non-empty balanced strings. In case (2.2), $q \in P$. Because in case(1), case(2.1), case(2.2), we can derive that $q \in P$, we prove that $F \subseteq P$. Thus, $F = P$ and we have proved that if a string is balanced, it is either belongs to (i)(ii)(iii) in the question.

Q1.C solution

Let $f(i) = d(s_{\leq i})$. If $f(i) = f(j)$ with $i < j$, then $s_i s_{i+1} ... s_j$ is a weakly balanced string, which is proved in 1.A. It suggests that everytime the value of $f(i)$ repeats, we can cut in the corresponding position to get weakly balanced substring. If there are m - 1 repetitive values of $f(i)$ for a certain value of i, then we can cut m - 1 times, and get m substrings.

Then we use contradiction to prove question C.Suppose there exists a balanced string $s_c \in \{a, b\}^*$ of length n such that it doesn't satisfy condition (i) and (ii). For formally,

- The maximum depth of s_c is $< \sqrt{n}$ and

• s_c can't be broken into m non-empty substrings $s_c = t_1|t_2|..|t_m$ such that $t_2, t_3, ...t_{m-1}$ are weakly balanced strings and $m \geq \sqrt{n} - 1$

To let s_c fail to satisfy condition (ii), we try to find minimum possible value of m. This situation happens when there are minimum repetitive values of $f(i)$ for a given i. By definition of $f(i)$ we can get the following formula for $f(i)$ with $i \geq 1$:

$$f(i) = \begin{cases} f(i-1)+1, & s_i \text{ is a,} \\ f(i-1)-1, & s_i \text{ is b} \end{cases}$$

As we can see in the formula, alternating as and bs increase the number of repetitive values of $f(i)$. So the situation happens in the case of least number of alternating as and bs, i.e. all as first and then b,like $aaaa...bbbb..aaaa..bbbb$. As maximum depth of s_c is $< \sqrt{n}$, the minimum number of $aaaa..bbbb..$ is $\frac{n}{2\sqrt{n}} - 1 = \frac{\sqrt{n}}{2} - 1$. The minimum number of repetitive values of $f(i)$ is $(\frac{\sqrt{n}}{2} - 1) * 2 = \sqrt{n} - 2$ and minimum possible value of m is $\sqrt{n} - 1$, which means such s_c doesn't exist. So any balanced string much satisfy condition either (i) or (ii).

Q2 solution

We use induction to solve this problem.

Base case: Let n = 2. There are only two people in the world and if there's only one tribe with 2 people, no lambs are sacrificed. If there are two tribes each with 1 person, then one tribe will lose and one lamb is sacrificed. In both cases. The number of lambs sacrificed is smaller than $nlog_2n = 2$

Let n = 3, Then then number of lambs sacrificed can be 0 or 1, both of which is smaller than $3log_23$.

Inductive hypothesis: For any $n > 1$, at most $nlog_2n$ lambs got sacrificed.

Induction step: Let W be a world of n people, Assume inductive hypothesis holds for all worlds with number of people greater than 2 and less than n.

Then in the world with n-1 people, we have number of lambs sacrificed $\leq (n-1)log_2(n-1)$. By adding one more person, this world will have n people. If the tribe this new-added person is in wins all the fight, then the number of lambs sacrificed doesn't change. If the the tribe this new-added person is in loses, there will be one more lamb sacrificed. In this case, we have

$$\begin{aligned} Number\ of\ lambs\ sacrificed\ in\ world\ W &\leq (n-1)log_2(n-1) + 1 \\ &= nlog_2(n-1) + 1 - log_2(n-1) \\ &\leq nlog_2(n-1) \\ &< nlog_2(n) \end{aligned}$$

In both cases, the number of lambs sacrificed in world W is less than $nlog_2(n)$

So during this process, at most $nlog_2n$ lambs got sacrificed.

Q3.A solution

Intuition: Assume that $\exists t \in Z$ and $\exists C \in R$,for any n $\in Z$ satisfying $n <= t$ and $n >= 4$, we can get $T(n) <= Cnlogn$. Now, we are attempting to prove that for $n = t + 1$, $T(n) <= Cnlogn$.

- since $n >= 4$, $[n/4] < n <= t$, $[3n/4] < n <= t$,

$$\begin{aligned} T(n) &= 2n + T([n/4]) + T([3n/4]) \\ &<= 2n + \frac{Cn}{4}\log\frac{n}{4} + \frac{3Cn}{4}\log\frac{3n}{4} \\ &= 2n + \frac{Cn}{4}(\log n - \log 4) + \frac{3Cn}{4}(\log n + \log\frac{3}{4}) \\ &= 2n + Cn\log n + \frac{3Cn\log 3}{4} - Cn\log 4 \end{aligned}$$

- In order to let $T(n) <= Cnlogn$,

$$\begin{aligned} &2n + \frac{3Cn\log 3}{4} - Cn\log 4 < 0 \\ &2 + \frac{3C\log 3}{4} - C\log 4 < 0 \\ &C > \frac{2}{\log 4 - \frac{3}{4}\log 3} \approx 8.189 \end{aligned}$$

Formal answer: Let $C = 9$ and set a constant b satisfying $b >= 1$. We assume that $T(n) <= 9nlogn + b$.

- **base case:** For $n = 1$ and $n = 2$, it is obvious that $T(1) = 1 <= b$ and $T(2) = 1 <= 18log2 + b$.
- **Induction hypothesis:** Let $k > 0$ be an arbitary integer, assume that $T(n) <= 9nlogn + b$ for any integer n satisfying $n <= k$.
- **Induction Step:** Now, if we prove that $T(n) <= 9nlogn + b$ holds for n=k+1, then we can conclude that $T(n) <= 9nlogn + b$.

case 1($k <= 8$): $T(n) = 1$ for n satisfying $n = k + 1 <= 9$. Let $f(n) = 9nlogn + b$. Because $f'(n) = 9 + 9logn > 0$ for $n >= 1$, f(n) is an increasing function. We can prove that $T(n) <= f(1) <= f(n) = 9nlogn + b$.

case 2($k >= 9$): $T(n) = 2n + T([n/4]) + T([3n/4])$ for n satisfying $n = k + 1 >= 10$. since $n = k + 1 >= 10$, we could know that $[n/4] < n <= k$ and $[3n/4] < n <= k$. Thus,

$$\begin{aligned} T(n) &= 2n + T([n/4]) + T([3n/4]) \\ &<= 2n + \frac{9n}{4}\log\frac{n}{4} + \frac{27n}{4}\log\frac{3n}{4} + 2b \\ &= 2n + \frac{9n}{4}(\log n - \log 4) + \frac{27n}{4}(\log n + \log\frac{3}{4}) + 2b \\ &= 2n + 9n\log n + \frac{27n\log 3}{4} - 9n\log 4 + 2b \\ &= -0.1980n + 9nlogn + 2b \end{aligned}$$

In order to let $T(n) <= 9nlogn + b$, we can get $b <= 0.1980n$. Since b is any constant that satisfying $b >= 1$ and $n = k + 1 >= 10$, we can simply let $b = 1$.

$$T(n) = -0.1980n + 9nlogn + 2 <= 9nlogn + 0.02 <= 9nlogn + 1 = 9nlogn + b$$

Now, we can conclude that $T(n) <= 9nlogn + 1$ for all natural number n. According to the definition, we prove that $T(n) = O(nlogn)$ for nutural number n . Finally, we consider the case where n is a negative integer or 0. Obviously, $T(n) = 1$, so $T(n) = O(1)$ for negative integer or 0. Overall, $T(n) = O(nlogn)$ for all integer n.

Q3.B solution Intuition: Assume that $\exists t \in Z$ and $\exists C \in R$,for any n $\in Z$ satisfying $n <= t$ and $n >= 1$, we can get $T(n) <= Cn$. Now, we are attempting to prove that for $n = t + 1$, $T(n) <= Cn$.

- since $n >= 1$, $[n/4] <= n <= t$, $[n/6] <= n <= t$, $[n/7] <= n <= t$

$$\begin{aligned} T(n) &= n + T([n/2]) + T([n/6]) + T([n/7]) \\ &<= n + \frac{Cn}{2} + \frac{Cn}{6} + \frac{Cn}{7} \end{aligned}$$

- In order to let $T(n) <= Cn$,

$$\begin{aligned} &n + \frac{Cn}{2} + \frac{Cn}{6} + \frac{Cn}{7} <= Cn \\ &n <= \frac{4Cn}{21} \\ &C >= \frac{21}{4}, (n >= 1) \end{aligned}$$

Formal answer: Let $C = 10$. We assume that $T(n) <= f(n) = 10n$.

- **base case:** For $n = 1$ and $n = 2$, it is obvious that $T(1) = 1 <= 10 = f(1)$ and $T(2) = 1 <= 20 = f(2)$.
- **Induction hypothesis:** Let $k > 0$ be an arbitary integer, assume that $T(n) <= 10n$ for any integer n satisfying $n <= k$.
- **Induction Step:** Now, if we prove that $T(n) <= 10n$ holds for n=k+1, then we can conclude that $T(n) <= 10n$.

case 1($k <= 22$): $T(n) = 1$ for n satisfying $n = k + 1 <= 23$. Let $f(n) = 10n$. Because $f'(n) = 10 > 0$ for $n >= 1$, f(n) is an increasing function. We can prove that $T(n) <= f(1) <= f(n) = 10n$.

case 2($k >= 23$): $T(n) = n + T([n/4]) + T([n/6]) + T([n/7])$ for n satisfying $n = k+1 >= 24$. since $n = k+1 >= 24$, we could know that $[n/4] < n <= k$, $[n/6] <= n <= t$ and $[n/7] <= n <= t$. Thus,

$$\begin{aligned} T(n) &= n + T([n/4]) + T([n/6]) + T([n/7]) \\ &<= n + \frac{10n}{4} + \frac{10n}{6} + \frac{10n}{7} \\ &= \frac{277}{42}n \\ &\approx 6.5952n <= 10n \end{aligned}$$

Now, we can conclude that $T(n) <= 10n$ for all integer n. According to the definition, we prove that $T(n) = O(n)$. Finally, we consider the case where n is a negative integer or 0. Obviously, $T(n) = 1$, so $T(n) = O(1)$ for negative integer or 0. Overall, $T(n) = O(n)$ for all integer n.