The following problems ask you to prove some "obvious" claims about recursively-defined string functions. In each case, we want a self-contained, step-by-step induction proof that builds on formal definitions and prior reults, *not* on intuition. In particular, your proofs must refer to the formal recursive definitions of string length and string concatenation:

$$|w| := \begin{cases} 0 & \text{if } w = \varepsilon \\ 1 + |x| & \text{if } w = ax \text{ for some symbol } a \text{ and some string } x \end{cases}$$

$$w \bullet z := \begin{cases} z & \text{if } w = \varepsilon \\ a \cdot (x \bullet z) & \text{if } w = ax \text{ for some symbol } a \text{ and some string } x \end{cases}$$

You may freely use the following results, which were proved in the lecture notes:

Lemma 1: $w \bullet \varepsilon = w$ for all strings w.

Lemma 2: $|w \bullet x| = |w| + |x|$ for all strings w and x.

Lemma 3: $(w \bullet x) \bullet y = w \bullet (x \bullet y)$ for all strings w, x, and y.

The ***reversal*** $\boldsymbol{w^R}$ of a string w is defined recursively as follows:

$$w^R := \begin{cases} \varepsilon & \text{if } w = \varepsilon \\ x^R \bullet a & \text{if } w = ax \text{ for some symbol } a \text{ and some string } x \end{cases}$$

For example, $\texttt{STRESSED}^R = \texttt{DESSERTS}$ and $\texttt{WTF374}^R = \texttt{473FTW}$.

1. Prove that $|w^R| = |w|$ for every string w.

Solution (induction on w):

Let w be an arbitrary string.

Assume for any string x where $|x| < |w|$ that $|x^R| = |x|$.

There are two cases to consider.

- If $w = \varepsilon$, then

$$\begin{aligned} |w^R| &= |\varepsilon| && \text{by definition of } {}^R \\ &= |w| && \text{by definition of } |\cdot| \end{aligned}$$

- Otherwise, $w = ax$ for some symbol a and some string x. In that case, we have

$$\begin{aligned} |w^R| &= |x^R \bullet a| && \text{by definition of } w^R \\ &= |x^R| + |a| && \text{by Lemma 2} \\ &= |x^R| + 1 && \text{by definition of } |\cdot| \text{ (twice)} \\ &= |x| + 1 && \text{by the induction hypothesis} = |w| \quad \text{by definition of } |\cdot| \end{aligned}$$

In both cases, we conclude that $|w^R| = |w|$. ■

2. Prove that $(w \bullet z)^R = z^R \bullet w^R$ for all strings w and z.

Solution (induction on w):

Let w and z be arbitrary strings.

Assume for any string x where $|x| < |w|$ that $(x \bullet z)^R = x^R \bullet z^R$.

There are two cases to consider:

- If $w = \varepsilon$, then
$$\begin{aligned}(w \bullet z)^R &= z^R && \text{by definition of } \bullet\\ &= z^R \bullet \varepsilon && \text{by Lemma 1}\\ &= z^R \bullet w^R && \text{by definition of } {}^R\end{aligned}$$
- Otherwise, $w = ax$ for some symbol a and some string x.
$$\begin{aligned}(w \bullet z)^R &= (a \cdot (x \bullet z))^R && \text{by definition of } \bullet\\ &= (x \bullet z)^R \bullet a && \text{by definition of } {}^R\\ &= (z^R \bullet x^R) \bullet a && \text{by the induction hypothesis, because } |x| < |w|\\ &= z^R \bullet (x^R \bullet a) && \text{by Lemma 3}\\ &= z^R \bullet w^R && \text{by definition of } {}^R\end{aligned}$$

In both cases, we conclude that $(w \bullet z)^R = z^R \bullet w^R$. ■

> But how did I know that the induction hypothesis needs to change the first string w, but not the second string z? I wrote down the inductive argument first, and then noticed that in the proof for $w \bullet z$, we needed the inductive hypothesis on $x \bullet z$. Same string z, but w changed to x. Alternatively, in light of Lemma 2, I could have inducted on the **sum** of the string lengths with the inductive hypothesis "Assume for all strings x and y such that $|x| + |y| < |w| + |z|$ that $(x \bullet y)^R = x^R \bullet y^R$."

3. Prove that $(w^R)^R = w$ for every string w.

Solution (induction on w):

Let w be an arbitrary string.

Assume for any string x where $|x| < |w|$ that $(x^R)^R = x$.

There are two cases to consider.

- If $w = \varepsilon$, then $(w^R)^R = \varepsilon^R = \varepsilon$ by definition.
- Otherwise, $w = ax$ for some symbol a and some string x.
$$\begin{aligned}(w^R)^R &= (x^R \bullet a)^R && \text{by definition of } {}^R\\ &= a^R \bullet (x^R)^R && \text{by problem 2}\\ &= a \bullet (x^R)^R && \text{by definition of } {}^R\\ &= a \cdot (x^R)^R && \text{by definition of } \bullet\\ &= a \cdot x && \text{by the induction hypothesis}\\ &= w && \text{by assumption}\end{aligned}$$

In both cases, we conclude that $(w^R)^R = w$. ■

To think about later: Let $\#(a,w)$ denote the number of times symbol a appears in string w. For example, $\#(\texttt{X},\texttt{WTF374}) = 0$ and $\#(\texttt{0},\texttt{0000101010010100}) = 12$.

4. Give a formal recursive definition of $\#(a,w)$.

   Solution:

$$\#(a,w) = \begin{cases} 0 & \text{if } w = \varepsilon \\ 1 + \#(a,x) & \text{if } w = ax \text{ for some string } x \\ \#(a,x) & \text{if } w = bx \text{ for some symbol } b \neq a \text{ and some string } x \end{cases}$$

■

5. Prove that $\#(a, w \bullet z) = \#(a,w) + \#(a,z)$ for all symbols a and all strings w and z.

   Solution (induction on w):

   Let a be an arbitrary symbol, and let w and z be arbitrary strings.

   Assume for any string x such that $|x| < |w|$ that $\#(a, x \bullet z) = \#(a,x) + \#(a,z)$.

   There are three cases to consider.

   - If $w = \varepsilon$, then

$$\begin{aligned} \#(a, w \bullet x) &= \#(a,x) && \text{by definition of } \bullet \\ &= \#(a,w) + \#(a,x) && \text{by definition of } \# \end{aligned}$$

   - If $w = ax$ for some string x, then

$$\begin{aligned} \#(a, w \bullet z) &= \#(a, ax \bullet z) && \text{by definition of } \bullet \\ &= \#(a, a \cdot (x \bullet z)) && \text{by definition of } \bullet \\ &= 1 + \#(a, x \bullet z) && \text{by definition of } \# \\ &= 1 + \#(a,x) + \#(a,z) && \text{by the induction hypothesis} \\ &= \#(a,ax) + \#(a,z) && \text{by definition of } \# \\ &= \#(a,w) + \#(a,z) && \text{because } w = ax \end{aligned}$$

   - If $w = bx$ for some symbol $b \neq a$ and some string x, then

$$\begin{aligned} \#(a, w \bullet z) &= \#(a, b \cdot (x \bullet z)) && \text{by definition of } \bullet \\ &= \#(a, x \bullet z) && \text{by definition of } \# \\ &= \#(a,x) + \#(a,z) && \text{by the induction hypothesis} \\ &= \#(a,bx) + \#(a,z) && \text{by definition of } \# \\ &= \#(a,w) + \#(a,z) && \text{because } w = bx \end{aligned}$$

   In every case, we conclude that $\#(a, w \bullet z) = \#(a,w) + \#(a,z)$. ■

6. Prove that $\#(a, w^R) = \#(a, w)$ for all symbols a and all strings w.

Solution (induction on w): Let a be an arbitrary symbol, and let w be an arbitrary string. Assume for any string x such that $|x| < |w|$ that $\#(a, x^R) = \#(a, x)$.
There are three cases to consider.

- If $w = \varepsilon$, then $w^R = \varepsilon = w$ by definition, so $\#(a, w^R) = \#(a, w)$.
- If $w = ax$ for some string x, then

$$\begin{aligned}
\#(a, w^R) &= \#(a, x^R \bullet a) && \text{by definition of } {}^R \\
&= \#(a, x^R) + \#(a, a) && \text{by problem 5} \\
&= \#(a, x^R) + 1 && \text{by definition of } \# \\
&= \#(a, x) + 1 && \text{by the induction hypothesis} \\
&= \#(a, w) && \text{by definition of } \#
\end{aligned}$$

- If $w = bx$ for some symbol $b \neq a$ and some string x, then

$$\begin{aligned}
\#(a, w^R) &= \#(a, x^R \bullet b) && \text{by definition of } {}^R \\
&= \#(a, x^R) + \#(a, b) && \text{by problem 5} \\
&= \#(a, x^R) && \text{by definition of } \# \\
&= \#(a, x) && \text{by the induction hypothesis} \\
&= \#(a, w) && \text{by definition of } \#
\end{aligned}$$

In every case, we conclude that $\#(a, w^R) = \#(a, w)$. ■