Solution to Problem 14

Problem. Sketch an example of a Turing machine for implementing primitive recursion (i.e., a for-loop), the way we did it in class, on the example of the following simple for-loop

```
sum = a;
for(int i = 1; i <= b; i++)
  {sum = sum + a;}
```

No details are required, but any details will give you extra credit.

Solution. In mathematical terms, the above for-loop takes the following form:

$$sum(a, 0) = a;$$

$$sum(a, m + 1) = sum(a, m) + a.$$

After we rename the function *sum* into h and the parameter a into n_1, we get the standard form:

$$h(n_1, 0) = n_1;$$

$$h(n_1, m + 1) = h(n_1, m) + n_1.$$

In this standard form, we have $f(n_1) = n_1$, i.e., $f = \pi_1^1$, and $g(n_1, m, h) = h+n_1$, i.e., $g = add(\pi_3^3, \pi_1^3)$.

Let us follow the general scheme for computing primitive recursion. Suppose that we have Turing machines computing the functions $f(n_1) = n_1$ and $g(n_1, m, h) = h + n_1$. Let us show how to build a Turing machine that compute the desired function $h = PR(f, g)$. We start with the state

$\underline{-}$	n_1	$-$	x	$-$	$\ldots$

start

and we want to end up in the state

$\underline{-}$	$h(n_1, x)$	$-$	$\ldots$

halt

This can be done as follows. First, we copy x, add 0, then copy the number n_1, and move the head into the cell right before the second copy of n_1:

$-$	n_1	$-$	x	$-$	x	$-$	0	$\underline{-}$	n_1	$-$	$\ldots$

Then, we apply the Turing machine f. Since a Turing machine never goes beyond the cell where it starts, it will compute the value

$$h(n_1, 0) = f(n_1) = n_1,$$

so we will have the following state of the tape:

$$\begin{array}{|c|c|c|c|c|c|c|c|c|c|c|c}\hline - & n_1 & - & x & - & x & - & 0 & \underline{-} & h(n_1,0) & - & \ldots \\ \hline\end{array}$$

Now, we copy n_1 and 0 before h, and get

$$\begin{array}{|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c}\hline - & n_1 & - & x & - & x & - & 0 & \underline{-} & n_1 & - & 0 & - & h(n_1,0) & - & \ldots \\ \hline\end{array}$$

Then, we apply the Turing machine for computing the function g, and get $h(n_1, 1) = g(n_1, 0, h, 0))$. So, the tape has the form:

$$\begin{array}{|c|c|c|c|c|c|c|c|c|c|c|c}\hline - & n_1 & - & x & - & x & - & 0 & \underline{-} & h(n_1,1) & - & \ldots \\ \hline\end{array}$$

After that, we decrease the second copy of x by 1, increase 0 by 1, and get the following:

$$\begin{array}{|c|c|c|c|c|c|c|c|c|c|c|c}\hline - & n_1 & - & x & - & x-1 & - & 1 & \underline{-} & h(n_1,1) & - & \ldots \\ \hline\end{array}$$

and we repeat a similar procedure.

In general, for each $m \le x$, we get the following state of the tape:

$$\begin{array}{|c|c|c|c|c|c|c|c|c|c|c|c}\hline - & n_1 & - & x & - & x-m & - & m & \underline{-} & h(n_1,m) & - & \ldots \\ \hline\end{array}$$

Then, we copy n_1 and m before h, and get

$$\begin{array}{|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c}\hline - & n_1 & - & x & - & x-m & - & m & \underline{-} & n_1 & - & m & - & h(n_1,m) & - & \ldots \\ \hline\end{array}$$

Now, we apply the Turing machine for computing the function g, and get

$$h(n_1, m+1) = h(n_1, m, h(n_1, m)).$$

So, the tape has the form:

$$\begin{array}{|c|c|c|c|c|c|c|c|c|c|c|c}\hline - & n_1 & - & x & - & x-m & - & m & \underline{-} & h(n_1,m+1) & - & \ldots \\ \hline\end{array}$$

Then, we check whether $x - m = 0$. If $x - m > 0$, we decrease $x - m$ by 1, increase m by 1, and get the following:

$-$	n_1	$-$	x	$-$	$x-(m+1)$	$-$	$m+1$	$\underline{-}$	$h(n_1, m+1)$	$-$	$\dots$

and we repeat a similar procedure.

Once we get $x - m = 0$ i.e., $m = x$, the state of the tape takes the form

$-$	n_1	$-$	x	$-$	0	$-$	x	$\underline{-}$	$h(n_1, x)$	$-$	$\dots$

Here, we have $k + 4 = 5$ numbers:

- the number n_1, and
- four numbers x, 0, x, and $h(n_1, x)$.

The desired value $h(n_1, x)$ is 5-th out of 5, so we can get it by applying the Turing machine computing the corresponding projection π_5^5:

$\underline{-}$	$h(n_1, x)$	$-$	$\dots$	halt

This is exactly what we wanted.

In this construction, we use composition, adding 1, subtracting 1, copying, and projection. We know how to do all this on a Turing machine, so indeed we can thus build a Turing machine for computing the function $PR(f, g)$.