rec.1 Sequences

The set of primitive recursive functions is remarkably robust. But we will be able to do even more once we have developed a adequate means of handling sequences. We will identify finite sequences of natural numbers with natural numbers in the following way: the sequence \( \langle a_0, a_1, a_2, \ldots, a_k \rangle \) corresponds to the number

\[
p_0^{a_0+1} \cdot p_1^{a_1+1} \cdot p_2^{a_2+1} \cdots p_k^{a_k+1}.
\]

We add one to the exponents to guarantee that, for example, the sequences \( \langle 2, 7, 3 \rangle \) and \( \langle 2, 7, 3, 0, 0 \rangle \) have distinct numeric codes. We can take both 0 and 1 to code the empty sequence; for concreteness, let \( \Lambda \) denote 0.

The reason that this coding of sequences works is the so-called Fundamental Theorem of Arithmetic: every natural number \( n \geq 2 \) can be written in one and only one way in the form

\[
n = p_0^{a_0} \cdot p_1^{a_1} \cdots p_k^{a_k}
\]

with \( a_k \geq 1 \). This guarantees that the mapping \( \langle a_0, \ldots, a_k \rangle = \langle a_0, \ldots, a_k \rangle \) is injective: different sequences are mapped to different numbers; to each number only at most one sequence corresponds.

We'll now show that the operations of determining the length of a sequence, determining its \( i \)th element, appending an element to a sequence, and concatenating two sequences, are all primitive recursive.

**Proposition rec.1.** The function \( \text{len}(s) \), which returns the length of the sequence \( s \), is primitive recursive.

**Proof.** Let \( R(i, s) \) be the relation defined by

\[
R(i, s) \text{ iff } p_i \mid s \land p_{i+1} \nmid s.
\]

\( R \) is clearly primitive recursive. Whenever \( s \) is the code of a non-empty sequence, i.e.,

\[
s = p_0^{a_0+1} \cdots p_k^{a_k+1},
\]

\( R(i, s) \) holds if \( p_i \) is the largest prime such that \( p_i \mid s \), i.e., \( i = k \). The length of \( s \) thus is \( i + 1 \) iff \( p_i \) is the largest prime that divides \( s \), so we can let

\[
\text{len}(s) = \begin{cases} 
0 & \text{if } s = 0 \text{ or } s = 1 \\
1 + \min \{ i < s \} R(i, s) & \text{otherwise}
\end{cases}
\]

We can use bounded minimization, since there is only one \( i \) that satisfies \( R(s, i) \) when \( s \) is a code of a sequence, and if \( i \) exists it is less than \( s \) itself.

**Proposition rec.2.** The function \( \text{append}(s, a) \), which returns the result of appending \( a \) to the sequence \( s \), is primitive recursive.
Proof. append can be defined by:

\[
\text{append}(s, a) = \begin{cases} 
2^{a+1} & \text{if } s = 0 \text{ or } s = 1 \\
sp\text{len}(s) & \text{otherwise.}
\end{cases}
\]

\[\square\]

**Proposition rec.3.** The function \(\text{element}(s, i)\), which returns the \(i\)th element of \(s\) (where the initial element is called the 0th), or 0 if \(i\) is greater than or equal to the length of \(s\), is primitive recursive.

**Proof.** Note that \(a\) is the \(i\)th element of \(s\) if \(p_i^{a+1}\) is the largest power of \(p_i\) that divides \(s\), i.e., \(p_i^{a+1} \mid s\) but \(p_i^{a+2} \not\mid s\). So:

\[
\text{element}(s, i) = \begin{cases} 
0 & \text{if } i \geq \text{len}(s) \\
\min a < s)(p_i^{a+2} \mid s) & \text{otherwise.}
\end{cases}
\]

\[\square\]

Instead of using the official names for the functions defined above, we introduce a more compact notation. We will use \((s)_i\) instead of \(\text{element}(s, i)\), and \(\langle s_0, \ldots, s_k \rangle\) to abbreviate

\[
\text{append}(\ldots \text{append}(\Lambda, s_0) \ldots, s_k).
\]

Note that if \(s\) has length \(k\), the elements of \(s\) are \((s)_0, \ldots, (s)_{k-1}\).

**Proposition rec.4.** The function \(\text{concat}(s, t)\), which concatenates two sequences, is primitive recursive.

**Proof.** We want a function \(\text{concat}\) with the property that

\[
\text{concat}((a_0, \ldots, a_k), (b_0, \ldots, b_l)) = (a_0, \ldots, a_k, b_0, \ldots, b_l).
\]

We’ll use a “helper” function \(\text{hconcat}(s, t, n)\) which concatenates the first \(n\) symbols of \(t\) to \(s\). This function can be defined by primitive recursion as follows:

\[
\text{hconcat}(s, t, 0) = s \\
\text{hconcat}(s, t, n + 1) = \text{append}(\text{hconcat}(s, t, n), (t)_n)
\]

Then we can define \(\text{concat}\) by

\[
\text{concat}(s, t) = \text{hconcat}(s, t, \text{len}(t)).
\]

\[\square\]

We will write \(s \triangleright t\) instead of \(\text{concat}(s, t)\).

It will be useful for us to be able to bound the numeric code of a sequence in terms of its length and its largest element. Suppose \(s\) is a sequence of length \(k\), each element of which is less than or equal to some number \(x\). Then \(s\) has at
most \( k \) prime factors, each at most \( p_{k-1} \), and each raised to at most \( x+1 \) in the prime factorization of \( s \). In other words, if we define

\[
\text{sequenceBound}(x, k) = p_{k-1}^{k(x+1)},
\]

then the numeric code of the sequence \( s \) described above is at most \( \text{sequenceBound}(x, k) \).

Having such a bound on sequences gives us a way of defining new functions using bounded search. For example, we can define \( \text{concat} \) using bounded search. All we need to do is write down a primitive recursive specification of the object (number of the concatenated sequence) we are looking for, and a bound on how far to look. The following works:

\[
\text{concat}(s, t) = (\min v < \text{sequenceBound}(s + t, \text{len}(s) + \text{len}(t)))
\]

\[
(\text{len}(v) = \text{len}(s) + \text{len}(t) \land \\
(\forall i < \text{len}(s)) \ (v)_i = (s)_i) \land \\
(\forall j < \text{len}(t)) \ (v)_{\text{len}(s)+j} = (t)_j)
\]

**Problem rec.1.** Show that there is a primitive recursive function \( \text{sconcat}(s) \) with the property that

\[
\text{sconcat}((s_0, \ldots, s_k)) = s_0 \ldots s_k.
\]

**Problem rec.2.** Show that there is a primitive recursive function \( \text{tail}(s) \) with the property that

\[
\text{tail}(\Lambda) = 0 \text{ and } \\
\text{tail}((s_0, \ldots, s_k)) = (s_1, \ldots, s_k).
\]

**Proposition rec.5.** The function \( \text{subseq}(s, i, n) \) which returns the subsequence of \( s \) of length \( n \) beginning at the \( i \)th element, is primitive recursive.

**Proof.** Exercise.

**Problem rec.3.** Prove Proposition rec.5.

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**Bibliography**