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Lambda Calculus
Winter Term 2023/24
Exercise Sheet 3

Exercise 1 (Fixed-point Combinator)

a) In the last tutorial, we came up with an encoding for lists together with the functions nil, cons, null, hd, and tl. Use a fixed-point combinator to compute the length of a list in this encoding.

b) In the last homework, we encoded lists with the fold encoding, i.e. a list $[x, y, z]$ is represented as $\lambda c\, n.\ c\, x\, (c\, y\, (c\, z\, n))$. Define a length function for lists in this encoding.

Exercise 2 (β-reduction on de Bruijn Preserves Substitution)

We consider an alternative representation of λ-terms that is due to de Bruijn. In this representation, λ-terms are defined according to the following grammar:

$$d ::= i \in \mathbb{N}_0 \mid d_1\ d_2 \mid \lambda\ d$$

a) Convert the terms $\lambda x\ y.\ x$ and $\lambda x\ y\ z.\ x\ z\ (y\ z)$ into terms according to de Bruijn.

b) Convert the term $\lambda\ ((\lambda\ (1\ (\lambda\ 1)))\ (\lambda\ (2\ 1)))$ into our usual representation.

c) Define substitution and β-reduction on de Bruijn terms.

d) Now restate Lemma 1.2.5 for de Bruijn terms and prove it:

$$s \to_\beta s' \implies s[u/x] \to_\beta s'[u/x]$$

Homework 3 (Multiplication)

Define multiplication using fix and prove its correctness. You can assume that you are given a predecessor function pred such that:

- pred $\underline{0} \rightarrow_\beta^* \underline{0}$
- pred $(\mathsf{succ}\ n) \rightarrow_\beta^* n$

Homework 4 (Efficient Substitution on de Bruijn)

We define a new lifting operator $- \uparrow_{-}^{-}$:

$$
\begin{aligned}
i \uparrow_l^n &= \begin{cases} i, \text{ if } i < l \\ i + n, \text{ if } i \geq l \end{cases} \\
(d_1\ d_2) \uparrow_l^n &= d_1 \uparrow_l^n\ \ d_2 \uparrow_l^n \\
(\lambda\ d) \uparrow_l^n &= \lambda\ d \uparrow_{l+1}^n
\end{aligned}
$$

Use $- \uparrow_{-}^{-}$ to define a more efficient version of substitution for de Bruijn terms that only applies lifting in the case that a variable is actually replaced by a term. Prove that $t[s/0]$ yields the same result for both, your new version and the version from the tutorial. *Hint*: Find a suitable generalization first.

Homework 5 (Expanding Lets)

We have a language with `let`-expressions, i.e.:

$$t ::= v \mid t\ t \mid \texttt{let}\ v = t\ \texttt{in}\ t$$

Write a program which expands all `let`-expressions. The `let`-semantics are:

$$(\texttt{let}\ v = t_1\ \texttt{in}\ t_2) = (\lambda v.\ t_2)\ t_1$$

You can find a Haskell template for this exercise here.