

From Partial Recursive to λ -Definable Functions

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Abstract. Adapting the presentation by Sørensen en Urzyczyn in [1] to the definitions used in the lecture, we show that partial recursive functions are λ -definable.

1 Primitive recursive and partial recursive functions

We start with the definition of primitive recursive functions on the natural numbers $\mathbb{N} := \{0, 1, 2, \dots\}$ including 0.

Definition 1. The class \mathcal{PR} of *primitive recursive functions* with values in \mathbb{N} is the smallest class \mathcal{C} of functions contained in $\{h \mid h : \mathbb{N}^n \rightarrow \mathbb{N}, n \in \mathbb{N}\}$ that contains the *base functions*:

- $\mathcal{O} : \mathbb{N}^0 = \{\emptyset\} \rightarrow \mathbb{N}, \emptyset \mapsto 0$ (0-ary constant-0 function);
- $\text{Succ} : \mathbb{N} \rightarrow \mathbb{N}, x \mapsto x + 1$ (successor function);
- $\pi_i^n : \mathbb{N}^n \rightarrow \mathbb{N}, \vec{x} = \langle x_1, \dots, x_n \rangle \mapsto x_i$ (projection function).

and is closed under the operations composition and primitive recursion:

- *Composition*: if $f : \mathbb{N}^k \rightarrow \mathbb{N}$, and $g_i : \mathbb{N}^n \rightarrow \mathbb{N}$ are in \mathcal{C} , then so is $h = f \circ (g_1 \times \dots \times g_k) : \mathbb{N}^n \rightarrow \mathbb{N}$ defined by

$$h(\vec{x}) = f(g_1(\vec{x}), \dots, g_k(\vec{x})).$$

- *Primitive recursion*: if $f : \mathbb{N}^n \rightarrow \mathbb{N}$, $g : \mathbb{N}^{n+2} \rightarrow \mathbb{N}$ are in \mathcal{C} then so is $h = \text{pr}(f; g) : \mathbb{N}^{n+1} \rightarrow \mathbb{N}$ defined by:

$$\begin{aligned} h(\vec{x}, 0) &= f(\vec{x}) \\ h(\vec{x}, y+1) &= g(\vec{x}, h(\vec{x}, y), y). \end{aligned}$$

A function belonging to \mathcal{PR} is called *primitive recursive*.

Next, we give the definition of the classes of partial recursive, and of total recursive, functions. For a partial function¹ $f : \mathbb{N}^n \rightharpoonup \mathbb{N}$, and for $\vec{x} = \langle x_1, \dots, x_n \rangle \in \mathbb{N}^n$ we write $f(\vec{x})\downarrow$ if $f(\vec{x})$ is defined, and $f(\vec{x})\uparrow$ if $f(\vec{x})$ is undefined.

¹ Note that possible partiality of f is indicated by using the harpoon symbol “ \rightharpoonup ” instead of the symbol “ \rightarrow ” in the expression $f : \mathbb{N}^n \rightharpoonup \mathbb{N}$.

Definition 2. The class \mathcal{P} of *partial recursive functions*² with values in \mathbb{N} is the smallest class \mathcal{C} of partial functions contained in $\{h \mid h : \mathbb{N}^n \rightarrow \mathbb{N}, n \in \mathbb{N}\}$ that contains the base functions (see Definition 1), and is closed under the operations of composition and primitive recursion (see Definition 1) as well as of unbounded minimisation (μ -recursion):

- *Unbounded minimisation:* if $g : \mathbb{N}^{n+1} \rightarrow \mathbb{N}$ is in \mathcal{C} , then so is $\mu(g)$ defined by:

$$\begin{aligned} \mu(g) : \mathbb{N}^n &\rightarrow \mathbb{N} \\ \vec{x} &\mapsto \mu z. [g(\vec{x}, z) = 0] := \\ &\begin{cases} z & \dots g(\vec{x}, z) = 0 \wedge \forall y (0 \leq y < g(z) \rightarrow (g(\vec{x}, y) \downarrow \neq 0)) \\ \uparrow & \dots \neg \exists y (g(\vec{x}, y) = 0 \wedge \forall z (0 \leq z < y \rightarrow (g(\vec{x}, z) \downarrow))) \end{cases} \end{aligned}$$

We denote by \mathcal{R} the class of functions that consists of all partial functions in \mathcal{P} that are total, that is, of all functions in \mathcal{P} that are defined for all $n \in \mathbb{N}$.

Functions in \mathcal{P} are called *partial recursive*, and functions in \mathcal{R} are called *(total) recursive*.

The Kleene Normal Form Theorem below (due to Stephen Cole Kleene) states that every partial recursive function can be factorised into the composition of a primitive recursive function with the unbounded minimisation of a (second) primitive recursive function.

Theorem 3 (Kleene’s Normal Form Theorem). *For every partial recursive function $h : \mathbb{N}^n \rightarrow \mathbb{N}$ there exist primitive recursive functions $f : \mathbb{N} \rightarrow \mathbb{N}$ and $g : \mathbb{N}^{n+1} \rightarrow \mathbb{N}$ such that:*

$$\begin{aligned} h(x_1, \dots, x_n) &= (f \circ \mu(g))(x_1, \dots, x_n) . \\ &= f(\mu(g)(x_1, \dots, x_n)) \end{aligned}$$

2 λ -definable functions

In order to ‘code’ natural numbers in λ -calculus as pure λ -terms, on which λ -terms that mimic functions on natural numbers are then able to operate (by application of λ -terms), we define the ‘Church numerals’ (due to Alonzo Church).

Definition 4. For every $n \in \mathbb{N}$, the *Church numeral* $\ulcorner n \urcorner$ for n is defined by:

$$\begin{aligned} \ulcorner n \urcorner &:= \lambda f x. f^n x \\ &= \lambda f x. f(\underbrace{f(\dots(f x) \dots)}_n) . \end{aligned}$$

Example 5. We find: $\ulcorner 0 \urcorner = \lambda f x. x$, $\ulcorner 1 \urcorner = \lambda f x. f x$, $\ulcorner 2 \urcorner = \lambda f x. f(f x)$.

² As mentioned in the lecture, “recursive, partial functions” would be a more adequate name.

Based on Church numerals we now give the definition of definability in λ -calculus of total, and of partial, functions on natural numbers.

Definition 6. (i) Let $f : \mathbb{N}^n \rightarrow \mathbb{N}$ be total. A λ -term M_f *represents* f if for all $m_1, \dots, m_n \in \mathbb{N}$:

$$M_f \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner \rightarrow_\beta \ulcorner f(m_1, \dots, m_n) \urcorner.$$

f is called *λ -definable* if there exists a λ -term that represents f .

(ii) Let $f : \mathbb{N}^n \rightharpoonup \mathbb{N}$ be a partial function. A λ -term M_f *represents* f if for all $m_1, \dots, m_n \in \mathbb{N}$:

$$f(m_1, \dots, m_n) \downarrow \implies M_f \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner \rightarrow_\beta \ulcorner f(m_1, \dots, m_n) \urcorner,$$

$$f(m_1, \dots, m_n) \uparrow \implies M_f \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner \text{ has no normal form.}$$

f is called *λ -definable* if there exists a λ -term that represents f .

Example 7. We give a few examples of λ -terms representing operations on natural numbers:

- *successor*: $M_{\text{Succ}} := \lambda n f x. f(n f x)$
- *addition*: $M_+ := \lambda m n f x. m f(n f x)$
- *multiplication*: $M_\times := \lambda m n f x. m(n f)x$
- *exponentiation*: $M_E := \lambda m n f x. m n f x$
- *unary constant zero function*: $M_{C_0^1} = \lambda m. \ulcorner 0 \urcorner$
- *projection function*: $M_{\pi_i^n} = \lambda m_1 \dots m_n. m_i$

For recognising that M_{Succ} indeed represents the successor function, we find that for all $n \in \mathbb{N}$ the following \rightarrow_β -rewrite sequence:

$$\begin{aligned} M_{\text{Succ}} \ulcorner n \urcorner &= (\lambda n f x. f(n f x)) \ulcorner n \urcorner \\ &\rightarrow_\beta \lambda f x. f(\ulcorner n \urcorner f x) \\ &= \lambda f x. f((\lambda f x. f^n x) f x) \\ &\rightarrow_\beta \lambda f x. f((\lambda x. f^n x) x) \\ &\rightarrow_\beta \lambda f x. f(f^n x) \\ &= \lambda f x. f^{n+1} x \\ &= \ulcorner n + 1 \urcorner. \end{aligned} \tag{1}$$

3 Primitive recursive functions are λ -definable

In this section we verify that all primitive recursive functions are λ -definable.

For use in the proofs below, we start by defining how pairs of λ -terms can be coded as λ -terms.

Definition 8. For all λ -terms M, N we define the λ -term *pair* $\langle M, N \rangle$ representing M and N by:

$$\langle M, N \rangle := \lambda x. xMN$$

and the *unpairing projections* ρ_1 and ρ_2 by:

$$\begin{aligned}\rho_1 &:= \lambda p. p(\lambda xy. x) \\ \rho_2 &:= \lambda p. p(\lambda xy. y)\end{aligned}$$

Based on this definition, the following proposition is easy to check.

Proposition 9. *For all λ -terms M_1, M_2 and $i = 1, 2$ it holds:*

$$\rho_i(\langle M_1, M_2 \rangle) \rightarrow_\beta M_i.$$

Having assembled some essential tools, we can now formulate, and then prove, the statement on λ -definability of the primitive recursive functions.

Theorem 10. *Every primitive recursive function is λ -definable.*

Proof. We show the theorem by proving that the class of primitive recursive functions is contained in the class of λ -definable total functions.

First we have to show that the class of λ -definable functions contains the base functions of Definition 1:

- ▷ The 0-ary function \mathcal{O} can be represented by $\ulcorner 0 \urcorner$, the Church numeral for 0.
- ▷ The successor function **Succ** can be represented by the λ -term $M_{\text{Succ}} := \lambda nfx. f(nfx)$, as we saw above in (1).
- ▷ Every projection function $\pi_i^n : \mathbb{N}^n \rightarrow \mathbb{N}$, can be represented by the λ -term $M_{\pi_i^n} = \lambda m_1 \dots m_n. m_i$, as is straightforward to check.

Second, we have to show that the class of λ -definable total functions is closed under composition. For this we let $f : \mathbb{N}^k \rightarrow \mathbb{N}$, and $g_i : \mathbb{N}^n \rightarrow \mathbb{N}$, for all $i \in \{1, \dots, k\}$, be arbitrary λ -definable functions. We have to show that $h = f \circ (g_1 \times \dots \times g_k) : \mathbb{N}^n \rightarrow \mathbb{N}$ is λ -definable as well. Suppose that f and g_1, \dots, g_k are represented by the λ -terms $M_f, M_{g_1}, \dots, M_{g_k}$, respectively. Then it is easy to check that the λ -term:

$$M_h := \lambda x_1 \dots x_n. M_f(M_{g_1}x_1 \dots x_n) \dots (M_{g_k}x_1 \dots x_n)$$

represents h .

Finally, we have to establish that the class of λ -definable total functions is closed under primitive recursion. For this, let $f : \mathbb{N}^n \rightarrow \mathbb{N}$ and $g : \mathbb{N}^{n+2} \rightarrow \mathbb{N}$ be arbitrary λ -definable (total) functions. Suppose that f and g are represented by λ -terms M_f, M_g , respectively. We have to show that the function $h := \text{pr}(f; g) : \mathbb{N}^{n+1} \rightarrow \mathbb{N}$ defined by:

$$\begin{aligned}h(\vec{x}, 0) &= f(\vec{x}) \\ h(\vec{x}, y+1) &= g(\vec{x}, h(\vec{x}, y), y)\end{aligned}$$

is λ -definable as well.

In order to establish this, we let:

$$\begin{aligned}\text{Init} &:= \langle \ulcorner 0 \urcorner, M_f x_1 \dots x_n \rangle \\ \text{Step} &:= \lambda p. \langle M_{\text{Succ}}(\rho_1(p)), M_g x_1 \dots x_n (\rho_2(p))(\rho_1(p)) \rangle\end{aligned}$$

and will show that the λ -term M_h defined by:

$$M_h := \lambda x_1 \dots x_n x. \rho_2((x \text{ Step Init}))$$

represents h .

Let $m_1, \dots, m_n \in \mathbb{N}$ be arbitrary.

For establishing that, M_h faithfully represents applications $h(m_1, \dots, m_n, 0)$ for all tuples $\langle m_1, \dots, m_n, 0 \rangle \in \mathbb{N}^{n+1}$ for which the base case of the definition of h by primitive recursion applies, we find the rewrite sequence:

$$\begin{aligned}M_h \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner \ulcorner 0 \urcorner &\rightarrow_{\beta} \rho_2(\ulcorner 0 \urcorner (\text{Step}[x_1 := \ulcorner m_1 \urcorner, \dots, x_n := \ulcorner m_n \urcorner \urcorner] (\text{Init}[x_1 := \ulcorner m_1 \urcorner, \dots, x_n := \ulcorner m_n \urcorner \urcorner])) \\ &= \rho_2(\ulcorner 0 \urcorner (\text{Step}[x_1 := \ulcorner m_1 \urcorner, \dots, x_n := \ulcorner m_n \urcorner \urcorner] \langle \ulcorner 0 \urcorner, M_f \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner \urcorner \rangle) \\ &= \rho_2((\lambda f x. x) (\text{Step}[x_1 := \ulcorner m_1 \urcorner, \dots, x_n := \ulcorner m_n \urcorner \urcorner] \langle \ulcorner 0 \urcorner, M_f \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner \urcorner \rangle) \\ &\rightarrow_{\beta} \rho_2((\lambda x. x) \langle \ulcorner 0 \urcorner, M_f \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner \urcorner \rangle) \\ &\rightarrow_{\beta} \rho_2(\langle \ulcorner 0 \urcorner, M_f \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner \urcorner \rangle) \\ &\rightarrow_{\beta} M_f \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner \\ &\rightarrow_{\beta} \ulcorner f(m_1, \dots, m_n) \urcorner \\ &= \ulcorner h(m_1, \dots, m_n, 0) \urcorner\end{aligned}$$

For establishing that M_h faithfully represents applications $h(m_1, \dots, m_n, 1)$ for all tuples $\langle m_1, \dots, m_n, 1 \rangle \in \mathbb{N}^{n+1}$, we find the rewrite sequence:

$$\begin{aligned}M_h \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner \ulcorner 1 \urcorner &\rightarrow_{\beta} \rho_2(\ulcorner 1 \urcorner \text{Step}[x_1 := \ulcorner m_1 \urcorner, \dots, x_n := \ulcorner m_n \urcorner \urcorner] \text{Init}[x_1 := \ulcorner m_1 \urcorner, \dots, x_n := \ulcorner m_n \urcorner \urcorner]) \\ &= \rho_2(\ulcorner 1 \urcorner (\lambda p. \langle M_{\text{Succ}}(\rho_1(p)), M_g \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner (\rho_2(p))(\rho_1(p)) \rangle) \langle \ulcorner 0 \urcorner, M_f \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner \urcorner \rangle) \\ &= \rho_2((\lambda f x. f x) (\lambda p. \langle \dots, \dots \rangle) \langle \ulcorner 0 \urcorner, M_f \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner \urcorner \rangle) \\ &\rightarrow_{\beta} \rho_2((\lambda p. \langle \dots, \dots \rangle) \langle \ulcorner 0 \urcorner, M_f \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner \urcorner \rangle) \\ &\rightarrow_{\beta} \rho_2((\lambda p. \langle \dots, \dots \rangle) \langle \ulcorner 0 \urcorner, \underbrace{\ulcorner f(m_1, \dots, m_n) \urcorner}_{= \ulcorner h(m_1, \dots, m_n, 0) \urcorner} \rangle) \\ &= \rho_2((\lambda p. \langle M_{\text{Succ}}(\rho_1(p)), M_g \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner (\rho_2(p))(\rho_1(p)) \rangle) \langle \ulcorner 0 \urcorner, \ulcorner h(m_1, \dots, m_n, 0) \urcorner \rangle) \\ &\rightarrow_{\beta} \rho_2(\langle \dots, M_g \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner (\rho_2(\langle \ulcorner 0 \urcorner, \ulcorner h(m_1, \dots, m_n, 0) \urcorner \rangle))(\rho_1(\langle \ulcorner 0 \urcorner, \ulcorner h(m_1, \dots, m_n, 0) \urcorner \rangle))) \rangle) \\ &\rightarrow_{\beta} M_g \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner (\rho_2(\langle \ulcorner 0 \urcorner, \ulcorner h(m_1, \dots, m_n, 0) \urcorner \rangle))(\rho_1(\langle \ulcorner 0 \urcorner, \ulcorner h(m_1, \dots, m_n, 0) \urcorner \rangle))) \\ &\rightarrow_{\beta} M_g \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner \ulcorner h(m_1, \dots, m_n, 0) \urcorner \urcorner \ulcorner 0 \urcorner \urcorner \\ &\rightarrow_{\beta} \ulcorner g(m_1, \dots, m_n, h(m_1, \dots, m_n, 0), 0) \urcorner \\ &\rightarrow_{\beta} \ulcorner h(m_1, \dots, m_n, 1) \urcorner\end{aligned}$$

For tuples $\langle m_1, \dots, m_n, k \rangle \in \mathbb{N}^{n+1}$ with $k > 1$ the argument is similar, making use of rewrite sequences:

$$\begin{aligned}
& \ulcorner k \urcorner \text{Step}[x_1 := \ulcorner m_1 \urcorner, \dots, x_n := \ulcorner m_n \urcorner] \text{Init}[x_1 := \ulcorner m_1 \urcorner, \dots, x_n := \ulcorner m_n \urcorner] \\
&= \ulcorner k \urcorner (\lambda p. \langle M_{\text{Succ}}(\rho_1(p)), M_g \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner (\rho_2(p)) (\rho_1(p)) \rangle) \langle \ulcorner 0 \urcorner, M_f \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner \rangle \\
&= (\lambda f x. f^k x) (\dots) \langle \dots, \dots \rangle \\
&\rightarrow_\beta \langle \ulcorner k \urcorner, \ulcorner h(m_1, \dots, m_n, k) \urcorner \rangle,
\end{aligned}$$

the existence of which can be shown by an easy induction on k , to obtain, for all $k \in \mathbb{N}$, $k \geq 1$, rewrite sequences:

$$\begin{aligned}
& M_h \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner \ulcorner k \urcorner \\
&\rightarrow_\beta \ulcorner k \urcorner \text{Step}[x_1 := \ulcorner m_1 \urcorner, \dots, x_n := \ulcorner m_n \urcorner] \text{Init}[x_1 := \ulcorner m_1 \urcorner, \dots, x_n := \ulcorner m_n \urcorner] \\
&= (\lambda f x. f^k x) \text{Step}[x_1 := \ulcorner m_1 \urcorner, \dots, x_n := \ulcorner m_n \urcorner] \text{Init}[x_1 := \ulcorner m_1 \urcorner, \dots, x_n := \ulcorner m_n \urcorner] \\
&\rightarrow_\beta \langle k, \ulcorner h(m_1, \dots, m_n, k) \urcorner \rangle.
\end{aligned}$$

In this way we establish that M_h represents h .

Having established that the class of primitive recursive functions is contained in the class of λ -definable total functions, we have shown the theorem. \square

4 Partial recursive functions are λ -definable

In this section we prove that all partial recursive functions are λ -definable.

For use in the proof below, we define codings of the Boolean truth values, a test function for equality with zero, and the if-then-else construct in λ -calculus.

Definition 11. For representing the Boolean truth values “true” and “false” we define λ -terms **true** and **false**, and for representing a predicate that tests on λ -terms for being equal to the Church numeral $\ulcorner 0 \urcorner$ we define the λ -term **zero?** as follows:

$$\mathbf{true} := \lambda xy. x \quad \mathbf{false} := \lambda xy. y \quad \mathbf{zero?} := \lambda x. x(\lambda y. \mathbf{false}) \mathbf{true}$$

Furthermore we define, for all λ -terms P , Q , and R , the λ -term **if P then Q else R** as follows:

$$\mathbf{if } P \mathbf{ then } Q \mathbf{ else } R := PQR$$

Proposition 12. For all λ -terms Q and R , and for all $n \in \mathbb{N}$ it holds:

$$\begin{aligned}
& \mathbf{if } \mathbf{true} \mathbf{ then } Q \mathbf{ else } R \rightarrow_\beta Q \\
& \mathbf{if } \mathbf{false} \mathbf{ then } Q \mathbf{ else } R \rightarrow_\beta R \\
& \mathbf{zero?} \ulcorner 0 \urcorner \rightarrow_\beta \mathbf{true} \\
& \mathbf{zero?} \ulcorner n + 1 \urcorner \rightarrow_\beta \mathbf{false}
\end{aligned}$$

Proof. These properties are easy to verify by using β -reduction.

We now set out to proving λ -definability for all partial recursive functions.

Theorem 13. *Every partial recursive function is λ -definable.*

Proof. Let $h : \mathbb{N}^{n+1} \rightarrow \mathbb{N}$ be an arbitrary partial recursive function. Then by Theorem 3, Kleene's normal form theorem, there exist $g : \mathbb{N}^{n+1} \rightarrow \mathbb{N}$ and $f : \mathbb{N} \rightarrow \mathbb{N}$ such that:

$$h(\vec{x}) = f \circ \mu(g)(\vec{x}) = f(\mu z. [g(\vec{x}, z) = 0]) .$$

Let M_f and M_g be λ -terms representing f and g , respectively. Let:

$$W := \lambda y. \mathbf{if} \ (\mathbf{zero?} \ M_g x_1 \dots x_n y) \ \mathbf{then} \ (\lambda w. M_f y) \ \mathbf{else} \ (\lambda w. w(M_{\text{Succ}} y)w) .$$

We will show that the following λ -term M_h represents h :

$$M_h := \lambda x_1 \dots x_n. W \ulcorner 0 \urcorner W .$$

For this we first observe:

$$M_h \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner \twoheadrightarrow_{\beta} W' \ulcorner 0 \urcorner W' \tag{2}$$

for $W' := W[x_1 := \ulcorner m_1 \urcorner] \dots [x_n := \ulcorner m_n \urcorner]$.

Furthermore, for $\vec{m} = \langle m_1, \dots, m_n \rangle \in \mathbb{N}^n$ and $l \in \mathbb{N}$ such that $g(\vec{m}, l) = 0$ we find the rewrite sequence:

$$\begin{aligned} W' \ulcorner l \urcorner W' &\rightarrow_{\beta} (\mathbf{zero?} \ \underbrace{M_g \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner \ulcorner l \urcorner}_{\twoheadrightarrow_{\beta} \ulcorner g(m_1, \dots, m_n, l) \urcorner = \ulcorner 0 \urcorner}}) (\lambda w. M_f \ulcorner l \urcorner) (\lambda w. w(M_{\text{Succ}} \ulcorner l \urcorner) w) W' \\ &\twoheadrightarrow_{\beta} \mathbf{true} \\ &\twoheadrightarrow_{\beta} \mathbf{true} (\lambda w. M_f \ulcorner l \urcorner) (\lambda w. w(M_{\text{Succ}} \ulcorner l \urcorner) w) W' \\ &\twoheadrightarrow_{\beta} (\lambda w. M_f \ulcorner l \urcorner) W' \\ &\twoheadrightarrow_{\beta} M_f \ulcorner l \urcorner \\ &\twoheadrightarrow_{\beta} \ulcorner f(l) \urcorner . \end{aligned} \tag{3}$$

For $\vec{m} = \langle m_1, \dots, m_n \rangle \in \mathbb{N}^n$ and $l \in \mathbb{N}$ such that $g(\vec{m}, l) \neq 0$, we find:

$$\begin{aligned} W' \ulcorner l \urcorner W' &\rightarrow_{\beta} (\mathbf{zero?} \ \underbrace{M_g \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner \ulcorner l \urcorner}_{\twoheadrightarrow_{\beta} \ulcorner g(m_1, \dots, m_n, l) \urcorner \neq \ulcorner 0 \urcorner}}) (\lambda w. M_f \ulcorner l \urcorner) (\lambda w. w(M_{\text{Succ}} \ulcorner l \urcorner) w) W' \\ &\twoheadrightarrow_{\beta} \mathbf{false} \\ &\twoheadrightarrow_{\beta} \mathbf{false} (\lambda w. M_f \ulcorner l \urcorner) (\lambda w. w(M_{\text{Succ}} \ulcorner l \urcorner) w) W' \\ &\twoheadrightarrow_{\beta} (\lambda w. w(M_{\text{Succ}} \ulcorner l \urcorner) w) W' \\ &\twoheadrightarrow_{\beta} W' \ulcorner l \urcorner + 1 \urcorner W' . \end{aligned} \tag{4}$$

Let now $m_1, \dots, m_n \in \mathbb{N}$ be arbitrary.

Suppose that $h(m_1, \dots, m_n) \downarrow$. Then it follows that $\mu(g)(m_1, \dots, m_n) \downarrow$, and hence there exists $m \in \mathbb{N}$ such that $g(m_1, \dots, m_n, m) = 0$ and such that $g(m_1, \dots, m_n, l) \downarrow \neq 0$ for all $l \in \mathbb{N}$ with $l < m$. Then by (2) and by repeated application of the statement corresponding to (4) followed by a single application of the statement corresponding to (3), we obtain:

$$\begin{aligned} M_h \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner &\rightarrow_{\beta} W' \ulcorner 0 \urcorner W' \rightarrow_{\beta} W' \ulcorner 1 \urcorner W' \rightarrow_{\beta} \dots \rightarrow_{\beta} W' \ulcorner m \urcorner W' \\ &\rightarrow_{\beta} \ulcorner f(m) \urcorner = \ulcorner f(\mu(g)(m_1, \dots, m_n)) \urcorner \\ &= \ulcorner h(m_1, \dots, m_n) \urcorner. \end{aligned}$$

Suppose now that $h(m_1, \dots, m_n) \uparrow$. Then it follows that $\mu(g)(m_1, \dots, m_n) \uparrow$, and hence for all $m \in \mathbb{N}$ it holds that $g(m_1, \dots, m_n, m) \neq 0$. Then it follows by (2) and by repeated application of the statement connected to (4) that there is the following infinite rewrite sequence:

$$\begin{aligned} M_h \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner &\rightarrow_{\beta} W' \ulcorner 0 \urcorner W' \rightarrow_{\beta} W' \ulcorner 1 \urcorner W' \rightarrow_{\beta} \dots \\ &\rightarrow_{\beta} W' \ulcorner n \urcorner W' \rightarrow_{\beta} W' \ulcorner n + 1 \urcorner W' \rightarrow_{\beta} \dots \end{aligned}$$

Since this rewrite sequence is a maximal left-most rewrite sequence, and since maximal left-most rewrite sequences in λ -calculus are known to be normalizing (that is, they always lead to a normal form whenever there exists one), it follows that $M_h \ulcorner m_1 \urcorner \dots \ulcorner m_n \urcorner$ has no normal form.

By what we showed in particular in the last two paragraphs, we have established that M_h indeed represents h . \square

References

1. Morten Heine Sørensen and Paweł Urzyczyn. *Lectures on the Curry–Howard Isomorphism*. Elsevier, 2006.