

### 3 Formal definition of Elm

First, we define some notations:

- $\mathbb{N}$  is the set of the natural numbers starting from 1.
- $\mathbb{N}_0$  is the set of the natural numbers starting from 0.
- $\mathbb{N}_a^b := \{i \in \mathbb{N}_0 \mid a \leq i \wedge i \leq b\}$  is the set of the natural numbers between  $a$  and  $b$ .
- We will use “.” to separate a quantifier from a statement:  $\forall a.F$  and  $\exists a.F$ , where  $a$  is a variable and  $F$  is a formula.
- Function types will be written as  $a_1 \rightarrow \dots \rightarrow a_n \rightarrow b$  instead of  $a_1 \times \dots \times a_n \rightarrow b$ , thus an  $n$ -ary function is represented as a unary function whose result is a  $(n-1)$ -ary function. This concept is called “currying”.
- We allow the use of lambda notation for functions, i.e.  $\lambda x.T$  denotes the function  $f$  defined by the equation  $f(x) = T$  where  $T$  is a term.

#### 3.1 Hindley-Milner Type System

For functional languages considered in this thesis we will use a Hindley-Milner type system [DM82]. The main idea is to have a type system that implies an order among the types. The ordering will then allow us to infer the type of any expression. In the following, we give a formal definition of this type system.

##### 3.1.1 Notion of Types

We will first introduce types, afterwards we will define how types relate to sets by explicitly defining the values of types as finite sets. Types are split in *mono types* and *poly types*. Mono types can contain so called *type variables* that can then be bound by a quantifier within a poly type. Note that quantifiers can only occur in the outermost position, thus poly types are more general types than mono types.

##### Definition 3.1: Mono types, poly types, types

We define

$T$  is a *mono type*  $:\Leftrightarrow T$  is a type variable

$\vee T$  is a type application

$\vee T$  is an algebraic type

$\vee T$  is a product type

$\vee T$  is a function type

$T$  is a *poly type*  $:\Leftrightarrow T = \forall a.T'$

where  $T'$  is a mono type or poly type and  $a$  is a symbol

$T$  is a *type*  $:\Leftrightarrow T$  is a mono type  $\vee T$  is a poly type.

by using the following predicates:

$T$  is a *type variable*  $:\Leftrightarrow T$  is a symbol.

$T$  is a *type application*  $:\Leftrightarrow T$  is of form  $C\ T_1 \dots T_n$

where  $n \in \mathbb{N}$ ,  $C$  is a symbol and the  $T_i$  are mono types for all  $i \in \mathbb{N}_1^n$ .

$T$  is a *algebraic type*  $:\Leftrightarrow T$  is of form  $\mu C.C_1\ T_{1,1} \dots T_{1,k(1)} \mid \dots \mid C_n\ T_{n,1} \dots T_{n,k(n)}$

such that  $\exists i \in \mathbb{N}.\forall j \in \mathbb{N}_1^{k(i)}.T_{i,j} \neq C$

where  $n \in \mathbb{N}$ ,  $k \in \mathbb{N}_1^n \rightarrow \mathbb{N}_0$ ,  $C$  is a symbol and  $T_{i,k(j)}$

is a mono type or  $C$  for all  $i \in \mathbb{N}_1^n$  and  $j \in \mathbb{N}_1^{k(i)}$ .

$T$  is a *product type*  $:\Leftrightarrow T$  is of form  $\{l_1 : T_1, \dots, l_n : T_n\}$

where  $n \in \mathbb{N}_0$  and  $l_i$  are symbols and  $T_i$  are mono types for all  $i \in \mathbb{N}_1^n$ .

$T$  is a *function type*  $:\Leftrightarrow T$  is of form  $T_1 \rightarrow T_2$

where  $T_1$  and  $T_2$  are mono types.

Note that the quantifier  $\mu C$  is called a *recursive quantifier*. By using the symbol  $C$  we can describe a recursive structure in a non recursive way. That said we need to ensure that every algebraic type has a non-recursive case (called a base case). That's why we require  $\exists i \in \mathbb{N}.\forall j \in \mathbb{N}_1^{k(i)}.T_{i,j} \neq C$ .

### Axiom 3.1

We consider the types  $T_i$  for  $i \in \mathbb{N}$  in a product type as unordered, i.e.,

$$\{a : T_1, b : T_2, \dots\} = \{b : T_2, a : T_1, \dots\}$$

for all symbols  $a, b, \dots$  and mono types  $T_1, T_2, \dots$

### Example 3.1

The symbol `Char` is a type variable. The expression `Sequence Char` is a type application. These expressions can be thought of as types whose implementation is unknown. The interpretation of a type variable or a type application depends on its context.

### Example 3.2

$Bool = \mu\_ . True \mid False$  is an algebraic type.

Note that we use the symbol `_` to specify a symbol that is only used once in the definition. Multiple occurrences of `_` would be seen as multiple different symbols. We call `_` a *wild card*.

### Example 3.3

$List = \forall a. \mu C. Empty \mid Cons\ a\ C$  is a poly type whose body  $\mu C. Empty \mid Cons\ a\ C$  is an algebraic type.

### Example 3.4

The empty product type  $\{\}$  is a mono type.

#### Definition 3.2: Sort, Terminal

Let  $n \in \mathbb{N}$ ,  $k_j \in \mathbb{N}$ ,  $T_{i,j}$  be a mono type,  $C, C_i$  be symbols,  $t_j : T_{i,j}$  for all  $j \in \mathbb{N}_1^n$ ,  $i \in \mathbb{N}_1^n$  and  $T = \mu C. C_1\ T_{1,1} \dots T_{1,k_1} \mid \dots \mid C_n\ T_{n,1} \dots T_{n,k_n}$  be a algebraic type.

We call

- $C_i$  a *terminal* of  $T$  and
- $C_i\ T_{i,1} \dots T_{i,k_i}$  a *sort* of  $T$  for all instantiation of all type-variables in  $T_{i,j}$  by mono types that do not contain type variables.

### Example 3.5

The natural numbers and the integers can be defined as algebraic types using the peano axioms [Pea89]:

- 1 is a natural number.
- Every natural number has a successor.

These axioms can be used for the definition of the type application.

$$Nat ::= \mu C. 1 \mid Succ\ C$$

For integers, we can use the property that they contain 0 as well as all positive and negative numbers.

$$Int ::= \mu_. 0 \mid Pos\ Nat \mid Neg\ Nat$$

In this case numbers like 1,  $Succ\ 1$  for  $Nat$  or  $Neg\ (Succ\ 1)$  for  $Int$  are sorts, whereas 1 and  $Succ$  for  $Nat$  and  $Neg, Pos$  and 0 for  $Int$  are terminals.

#### Definition 3.3: Label

Let  $n \in \mathbb{N}$ . Let  $T_i$  be a type,  $l_i$  be a unique symbol for all  $i \in \mathbb{N}_1^n$ .

We say  $l_i$  is a *label* of the product type  $\{l_1 : T_1, \dots, l_n : T_n\}$  for all  $i \in \mathbb{N}_1^n$ .

We define

$$T_1 \times \cdots \times T_n := \{1 : T_1, \dots, n : T_n\}$$

as the *ordered product type* with  $n$  components.

The most general example of a product type is a record. Tuples can be represented as ordered product types.

#### Definition 3.4: Bound, Free, Set of free variables

Let  $n \in \mathbb{N}_0$ ,  $a$  be a type variable,  $T$  be a type,  $C$  be a symbol,  $k \in \mathbb{N}_1^n \rightarrow \mathbb{N}_0$ ,  $T_i$  be a type,  $T_{i,k(j)}$  be a type or a symbol and  $C_i$  be a symbol for all  $i \in \mathbb{N}_1^n$  and  $j \in \mathbb{N}_1^n$ .

We say

- $a$  is *free* in  $T : \Leftrightarrow a \in \text{free}(T)$
- $a$  is *bound* in  $T : \Leftrightarrow a \notin \text{free}(T)$  and  $a$  occurs in  $T$ .

where

$$\begin{aligned} \text{free}(a) &:= \{a\} \\ \text{free}(C \ T_1 \ \dots \ T_n) &:= \bigcup_{i \in \mathbb{N}_1^n} \text{free}(T_i) \\ \text{free} \left( \begin{array}{c} \mu C. \\ C_1 \ T_{1,1} \ \dots \ T_{1,k(1)} \\ \vdots \\ C_n \ T_{n,1} \ \dots \ T_{n,k(n)} \end{array} \right) &:= \bigcup_{i \in \mathbb{N}_0^n} \bigcup_{j \in \mathbb{N}_0^{k_i}} \begin{cases} \emptyset & \text{if } T_{i,j} = C \\ \text{free}(T_{i,j}) & \text{else} \end{cases} \\ \text{free}(\{ \_ : T_1, \dots, \_ : T_n \}) &:= \bigcup_{i \in \mathbb{N}_1^n} \text{free}(T_i) \\ \text{free}(T_1 \rightarrow T_2) &:= \text{free}(T_1) \cup \text{free}(T_2) \\ \text{free}(\forall a. T) &:= \text{free}(T) \setminus \{a\} \end{aligned}$$

#### Definition 3.5: Partial function

Let  $T_1$  and  $T_2$  be sets and  $f \subseteq T_1 \times T_2$ .

We say  $f$  is a *partial function* (Notation:  $f : T_1 \rightharpoonup T_2$ ) :  $\Leftrightarrow$

$$\forall x \in T_1, y \in T_2. (x, y_1) \in f \wedge (x, y_2) \in f \Rightarrow y_1 = y_2.$$

#### Definition 3.6: Sets of Types

We define

- $\mathcal{V} := \{a \mid a \text{ is a symbol}\}$  as the set of all type variables (symbols).
- $\mathcal{T} := \{T \mid T \text{ is a type}\}$  as the set of all types.

A type can be substituted by replacing a bound type variable with a mono type:

**Definition 3.7: Type substitution**

Let  $n \in \mathbb{N}$ ,  $\Theta : \mathcal{V} \rightarrow \mathcal{T}$ ,  $a \in \mathcal{V}$ . Let  $T, T_1, T_2, k \in \mathbb{N}_1^n \rightarrow \mathbb{N}_0$  and  $T_{i,k(j)} \in \mathcal{T}$  for all  $i \in \mathbb{N}_1^n$  and  $j \in \mathbb{N}_1^n$ .

We define the substitute of a type  $[\cdot]_\Theta : \mathcal{T} \rightarrow \mathcal{T}$  as

$$\begin{aligned}
 [a]_\Theta &:= \begin{cases} S & \text{if } (a, S) \in \Theta \\ a & \text{else} \end{cases} \\
 \left[ \begin{array}{c} \mu C. \\ C_1 T_{1,1} \dots T_{1,k(1)} \\ \vdots \\ C_n T_{n,1} \dots T_{n,k(n)} \end{array} \right]_\Theta &:= \begin{array}{c} \mu C. \\ C_1 [T_{1,1}]_{\Theta \setminus \{C, \_ \}} \dots [T_{1,k(1)}]_{\Theta \setminus \{C, \_ \}} \\ \vdots \\ C_n [T_{n,1}]_{\Theta \setminus \{C, \_ \}} \dots [T_{n,k(n)}]_{\Theta \setminus \{C, \_ \}} \end{array} \\
 [\{l_1 : T_1, \dots, l_n : T_n\}]_\Theta &:= \{l_1 : [T_1]_\Theta, \dots, l_n : [T_n]_\Theta\} \\
 [T_1 \rightarrow T_2]_\Theta &:= [T_1]_\Theta \rightarrow [T_2]_\Theta \\
 [\forall b. T]_\Theta &:= \begin{cases} [T]_\Theta & \text{if } \exists (b, \_) \in \Theta \\ \forall b. [T]_\Theta & \text{else.} \end{cases}
 \end{aligned}$$

$\Theta$  is called the set of substitutions.

The type substitution gives rise to a partial order  $\sqsubseteq$ :

**Definition 3.8: Type Order**

Let  $n, m \in \mathbb{N}$ ,  $T_1, T_2 \in \mathcal{T}$ ,  $a_i$  for all  $i \in \mathbb{N}_0^n$  and  $b_i \in \mathcal{V}$  for all  $i \in \mathbb{N}_0^m$ .

We define the partial order  $\sqsubseteq$  on poly types as

$$\begin{aligned}
 \forall a_1 \dots \forall a_n. T_1 \sqsubseteq \forall b_1 \dots \forall b_m. T_2 &: \Leftrightarrow \exists \Theta = \{(a_i, S_i) \mid i \in \mathbb{N}_1^n \wedge a_i \in \mathcal{V} \wedge S_i \in \mathcal{T}\}. \\
 T_2 &= [T_1]_\Theta \wedge \forall i \in \mathbb{N}_0^m. b_i \notin \text{free}(\forall a_1 \dots \forall a_n. T_1)
 \end{aligned}$$

From a given type  $T_1$  we can construct a more specialized type  $T_2$  such that  $T_1 \sqsubseteq T_2$  by the following steps

1. First replace all bounded variables  $a_i$  with types  $S_i$ .
2. Next rebound any new variables  $b_i$  that were previously not free.

**Example 3.6**

$\forall a. a$  is the smallest type in the type system. The partial order forms a tree structure with  $\forall a. a$  at the root and different branches for  $\forall a. C a$ ,  $\forall a. \forall b. a \rightarrow b$  and so on. The leaves of the tree are all possible mono types.

### 3.1.2 Interpretation of Types

Before we interpret a type, we will first introduce a set of labelled elements as a record.

#### Definition 3.9: Record

Let  $n$  in  $\mathbb{N}$ ,  $l_i$  be a symbol,  $t_i$  arbitrary for all  $i$  in  $\mathbb{N}_1^n$ .

—  
We define

$$\begin{aligned} & \{l_1 = t_1, \dots, l_n = t_n\} : \{l_1, \dots, l_n\} \rightarrow \{t_1, \dots, t_n\} \\ & \{l_1 = t_1, \dots, l_n = t_n\}(l) := t \text{ such that } \exists i \in \mathbb{N}_1^n. l = l_i \wedge t = t_i \end{aligned}$$

Note that values of an ordered product type are equivalent to tuples:

$$\forall i \in \mathbb{N}_1^n. \{l_1 = t_1, \dots, l_n = t_n\}(i) = (t_1, \dots, t_n).i$$

Thus, we will use the notation of tuples for values of an ordered product type.

#### Definition 3.10: Application Constructor

Let  $n \in \mathbb{N}_0$ . Let  $T$  be a mono type. Let  $\{a_1, \dots, a_n\} := \text{free}(T)$ .

—  
We call the function

$$\begin{aligned} & (\forall a_1 \dots a_n. T) : \underbrace{\mathcal{T} \rightarrow \dots \rightarrow \mathcal{T}}_{n \text{ times}} \rightarrow \mathcal{T} \\ & (\forall a_1 \dots a_n. T)(T_1, \dots, T_n) := [\forall a_1 \dots a_n. T]_{\{(a_1, T_1), \dots, (a_n, T_n)\}}. \end{aligned}$$

the *application constructor* of  $T$ .

We define  $\mathcal{C} = \{f \mid f \text{ is an application constructor}\}$  as the set of all application constructors.

#### Definition 3.11: Context

$\Gamma : \mathcal{V} \rightarrow \mathcal{C}$  is called a *context*.

Note that mono types with no free variables are considered to be application constructors with no arguments.

#### Definition 3.12: Values

Let  $\mathcal{S}$  the class of all finite sets,  $n \in \mathbb{N}$ ,  $\Theta : \mathcal{V} \rightarrow \mathcal{T}$ ,  $a \in \mathcal{V}$ ,  $T, T_1, T_2, S \in \mathcal{T}$ ,  $k \in \mathbb{N}_1^n \rightarrow \mathbb{N}_0$  and  $T_{i,k(j)} \in \mathcal{T}$  for all  $i \in \mathbb{N}_1^n$  and  $j \in \mathbb{N}_1^{k(i)}$ . Let  $\Gamma$  be a context.

We define

$$\begin{aligned}
& \text{values}_\Gamma : \mathcal{V} \rightarrow \mathcal{S} \\
& \text{values}_\Gamma(a) := \text{values}_\Gamma(\Gamma(a)) \\
& \text{values}_\Gamma(C \ T_1 \ \dots \ T_n) := \text{values}_\Gamma(\Gamma(C)(T_1, \dots, T_n)) \\
& \text{values}_\Gamma \left( \begin{array}{c} \mu C. \\ | C_1 \ T_{1,1} \ \dots \ T_{1,k(1)} \\ | \dots \\ | C_n \ T_{n,1} \ \dots \ T_{n,k(n)} \end{array} \right) := \bigcup_{i \in \mathbb{N}_0} \text{rvalues}_\Gamma \left( i, \begin{array}{c} \mu C. \\ | C_1 \ T_{1,1} \ \dots \ T_{1,k(1)} \\ | \dots \\ | C_n \ T_{n,1} \ \dots \ T_{n,k(n)} \end{array} \right) \\
& \text{values}_\Gamma(\{l_1 : T_1, \dots, l_n : T_n\}) := \\
& \quad \{ \{l_1 = t_1, \dots, l_n = t_n\} \mid \forall i \in \mathbb{N}_1^n. t_i \in \text{values}_\Gamma(T_i) \} \\
& \text{values}_\Gamma(T_1 \rightarrow T_2) := \{ f \mid f : \text{values}_\Gamma(T_1) \rightarrow \text{values}_\Gamma(T_2) \} \\
& \text{values}_\Gamma(\forall a. T) := \lambda b. \text{values}_{\{(a,b)\} \cup \Gamma}(T) \text{ where the symbol } b \text{ does} \\
& \quad \text{not occur in } T.
\end{aligned}$$

using the following helper function.

Let  $l \in \mathbb{N}, T := \mu C. | C_1 \ T_{1,1} \ \dots \ T_{1,k(1)} | \dots | C_n \ T_{n,1} \ \dots \ T_{n,k(n)}$ . We define:

$$\begin{aligned}
& \text{rvalues}_\Gamma(0, T) := \left\{ C_i \ v_1 \ \dots \ v_n \ \middle| \begin{array}{l} i \in \mathbb{N}_1^n \\ \wedge \forall j \in \mathbb{N}_1^{k(i)}. T_{i,j} \neq C \wedge v_j \in \text{values}_\Gamma(T_{i,j}) \end{array} \right\} \\
& \text{rvalues}_\Gamma(l+1, T) := \left\{ C_i \ v_1 \ \dots \ v_n \ \middle| \begin{array}{l} i \in \mathbb{N}_1^n \\ \wedge \forall j \in \mathbb{N}_1^{k(i)}. v_j \in \begin{cases} \text{rvalues}_\Gamma(l, T) & \text{if } T_{i,j} = C \\ \text{values}_\Gamma(T_{i,j}) & \text{else} \end{cases} \end{array} \right\}
\end{aligned}$$

The base case of this recursive function is in  $\text{rvalues}_\Gamma(0, T)$  for a given  $T$ .

### Theorem 3.1: rvalue is nested

Let  $n \in \mathbb{N}_0$ . Let  $T := \mu C. | C_1 \ T_{1,1} \ \dots \ T_{1,k(1)} | \dots | C_n \ T_{n,1} \ \dots \ T_{n,k(n)}$ . Let  $\Gamma$  be a context.

We then have:

$$\bigcup_{i \in \mathbb{N}_0^n} \text{rvalues}_\Gamma(i, T) = \text{rvalues}_\Gamma(n, T)$$

*Proof.* It should be clear that  $\bigcup_{i \in \mathbb{N}_0^n} \text{rvalues}_\Gamma(i, T) \supseteq \text{rvalues}_\Gamma(n, T)$ . This follows directly from the definition of the union. In order to show  $\bigcup_{i \in \mathbb{N}_0^n} \text{rvalues}_\Gamma(i, T) \subseteq \text{rvalues}_\Gamma(n, T)$ , it is sufficient to prove by induction over  $n$  that

$$\forall n \in \mathbb{N}_0. \text{rvalues}_\Gamma(n, T) \subseteq \text{rvalues}_\Gamma(n+1, T).$$

**Base case:** We will show  $\text{rvalues}_\Gamma(0, T) \subseteq \text{rvalues}_\Gamma(1, T)$ .

$$\begin{aligned}
& \text{rvalues}_\Gamma(1, T) \\
&= \left\{ C_i v_1 \dots v_n \mid \begin{array}{l} i \in \mathbb{N}_1^n \\ \wedge \forall j \in \mathbb{N}_1^{k(i)}. v_j \in \begin{cases} \text{rvalues}_\Gamma(0, T) & \text{if } T_{i,j} = C \\ \text{values}_\Gamma(T_{i,j}) & \text{else} \end{cases} \end{array} \right\} \\
&\supseteq \left\{ C_i v_1 \dots v_n \mid \begin{array}{l} i \in \mathbb{N}_1^n \\ \wedge \forall j \in \mathbb{N}_1^{k(i)}. T_{i,j} \neq C \wedge v_j \in \text{values}_\Gamma(T_{i,j}) \end{array} \right\} \\
&= \text{rvalues}_\Gamma(0, T).
\end{aligned}$$

**Inductive step:** Assuming  $\text{rvalues}_\Gamma(n, T) \subseteq \text{rvalues}_\Gamma(n+1, T)$ , we will prove

$$\text{rvalues}_\Gamma(n+1, T) \subseteq \text{rvalues}_\Gamma(n+2, T).$$

$$\begin{aligned}
& \text{rvalues}_\Gamma(n+2, T) \\
&= \left\{ C_i v_1 \dots v_n \mid \begin{array}{l} i \in \mathbb{N}_1^n \\ \wedge \forall j \in \mathbb{N}_1^{k(i)}. v_j \in \begin{cases} \text{rvalues}_\Gamma(n+1, T) & \text{if } T_{i,j} = C \\ \text{values}_\Gamma(T_{i,j}) & \text{else} \end{cases} \end{array} \right\} \\
&\supseteq \left\{ C_i v_1 \dots v_n \mid \begin{array}{l} i \in \mathbb{N}_1^n \\ \wedge \forall j \in \mathbb{N}_1^{k(i)}. v_j \in \begin{cases} \text{rvalues}_\Gamma(n, T) & \text{if } T_{i,j} = C \\ \text{values}_\Gamma(T_{i,j}) & \text{else} \end{cases} \end{array} \right\} \\
&= \text{rvalues}_\Gamma(n+1, T)
\end{aligned}$$

□

As an example we can now prove that the values of  $Nat$  from example 3.5 are isomorphic to the natural numbers.

### Theorem 3.2

Let the algebraic type  $Nat$  defined as  $Nat := \mu C.1 | Succ\ C$ .

Then we have:

$$\text{values}(Nat) \cong \mathbb{N}$$

*Proof.* Let  $\Gamma$  be a context.

First we will introduce a new notation in order to simplify the proof: For any  $n \in \mathbb{N}_0$  We define  $Succ^n 1 := \underbrace{Succ \dots Succ}_{n \text{ times}} 1$ . Note that  $Succ^0 1 = 1$ .

Next we show by induction over  $n \in \mathbb{N}_0$  that

$$\text{rvalues}_\Gamma(n, \mu C.1 | Succ\ C) = \{Succ^i 1 \mid i \in \mathbb{N}_0^n\}.$$

**Base case:**  $\text{rvalues}_\Gamma(0, \mu C.1 | Succ\ C) = \{1\} = \{Succ^0 1\}$ . This is true.

**Inductive step:**

Assuming  $\text{rvalues}_\Gamma(n, \mu C.1 | Succ\ C) = \{Succ^i 1 \mid i \in \mathbb{N}_0^n\}$ , we will prove  $\text{rvalues}_\Gamma(n+1, \mu C.1 | Succ\ C) = \{Succ^i 1 \mid i \in \mathbb{N}_0^{n+1}\}$ .



$$\begin{aligned}
& \text{rvalues}_\Gamma(n+1, \mu C.1 | \text{Succ } C) \\
&= \left\{ C_i v_1 \dots v_n \left| \begin{array}{l} i \in \mathbb{N}_1^n \\ \wedge \forall j \in \mathbb{N}_1^{k(i)}. v_j \in \begin{cases} \text{rvalues}_\Gamma(n, T) & \text{if } T_{i,j} = C \\ \text{values}_\Gamma(T_{i,j}) & \text{else} \end{cases} \end{array} \right. \right\} \\
&= \left\{ C_i v_1 \dots v_n \left| \begin{array}{l} i \in \mathbb{N}_1^n \\ \wedge \forall j \in \mathbb{N}_1^{k(i)}. v_j \in \begin{cases} \{\text{Succ}^k 1 | k \in \mathbb{N}_0^n\} & \text{if } T_{i,j} = C \\ \text{values}_\Gamma(T_{i,j}) & \text{else} \end{cases} \end{array} \right. \right\} \\
&= \{1\} \cup \{\text{Succ}^i v | v \in \{\text{Succ}^i 1 | i \in \mathbb{N}_0^n\}\} \\
&= \{\text{Succ}^i 1 | i \in \mathbb{N}_0^{n+1}\}
\end{aligned}$$

Finally, we will be proving

$$\text{values}(\mu C.1 | \text{Succ } C) = \{\text{Succ}^n 1 | n \in \mathbb{N}_0\}.$$

" $\subseteq$ ": Let  $x \in \text{values}(\mu C.1 | \text{Succ } C) = \bigcup_{i \in \mathbb{N}_0} \text{rvalues}_\Gamma(i, \mu C.1 | \text{Succ } C)$ .

$$\begin{aligned}
x &\in \bigcup_{i \in \mathbb{N}_0} \text{rvalues}_\Gamma(i, \mu C.1 | \text{Succ } C) \\
&\Rightarrow \exists i \in \mathbb{N}_0. x \in \text{rvalues}_\Gamma(i, \mu C.1 | \text{Succ } C) = \{\text{Succ}^k 1 | k \in \mathbb{N}_0^i\} \\
&\Rightarrow \exists i \in \mathbb{N}_0. \exists k \in \mathbb{N}_0^i. x = \text{Succ}^k 1 \\
&\Rightarrow x \in \{\text{Succ}^n 1 | n \in \mathbb{N}_0\}
\end{aligned}$$

" $\supseteq$ ": Let  $x \in \{\text{Succ}^n 1 | n \in \mathbb{N}_0\}$ . Then there exists  $k \in \mathbb{N}_0$  such that  $x = \text{Succ}^k 1$ . We know that

$$\text{Succ}^k 1 \in \{\text{Succ}^i 1 | i \in \mathbb{N}_0^k\} = \text{rvalues}_\Gamma(k, \mu C.1 | \text{Succ } C) \subseteq \{\text{Succ}^n 1 | n \in \mathbb{N}_0\}.$$

Therefore  $x = \text{Succ}^k 1 \in \{\text{Succ}^n 1 | n \in \mathbb{N}_0\}$ .

In conclusion, we have now shown that  $\text{values}(\text{Nat}) = \{\text{Succ}^n 1 | n \in \mathbb{N}_0\}$ . Using the bijection

$$\begin{aligned}
f &: \{\text{Succ}^n 1 | n \in \mathbb{N}_0\} \rightarrow \mathbb{N} \\
f(\text{Succ}^n 1) &= n + 1 \\
f^{-1}(n) &= \text{Succ}^{n-1} 1
\end{aligned}$$

we see that  $\{\text{Succ}^n 1 | n \in \mathbb{N}_0\} \cong \mathbb{N}$ . □

## References

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