

# ELEMENTS OF PROGRAMMING SOLUTIONS

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## 1. FOUNDATIONS

### 1.1. Categories of Ideas: Entity, Species, Genus.

### 1.2. Values.

**Lemma 1.1.** *If a value type is uniquely represented, equality implies representational equality.*

*Solution.* Suppose a value type  $T$  is uniquely represented. Denote by  $v, v' : T$  as equal values of  $T$ . By unique representation,  $v, v'$  each correspond uniquely to the abstract entities  $E, E'$ , and by equality of values, these entities must also be equal. Hence the data  $D, D'$  for  $v, v'$  are identical, and so  $v, v'$  are representationally equal.  $\square$

**Lemma 1.2.** *If a value type is not ambiguous, representational equality implies equality.*

*Solution.* Suppose a value type  $T$  is not ambiguous. Denote by  $v, v' : T$  as representationally equal values of  $T$ . As  $T$  is not ambiguous,  $v, v'$  must each have at most one interpretation, and by representational equality, the data  $D, D'$  for the values are identical. Hence the values  $v, v'$  must represent the same abstract entity  $E$ , and so they are equal.  $\square$

### 1.3. Objects.

### 1.4. Procedures.

### 1.5. Regular Types.

**Lemma 1.3.** *A well-formed object is partially formed.*

*Solution.* Suppose  $a$  is an object that is well-formed. Let  $S(a)$  be the state of  $a$ , which by definition is a value  $v : T$  of some value type  $T$ . By well-formedness of  $a$ ,  $S(a)$  is also well-formed as a value, i.e. WLOG, we may reduce to the case where  $T$  is `double` as an object type for  $a$ . Let  $b$  be another object of type `double`. Certainly  $a$  may be assigned to  $b$  without modifying the state  $S(b)$  of  $b$ , and  $a$  may be destroyed as well. Therefore  $a$  is partially formed.  $\square$

### 1.6. Regular Procedures.

**Exercise 1.1.** *Extend the notion of regularity to input/output objects of a procedure, that is, to objects that are modified as well as read.*

*Solution.* A procedure is *regular* if and only if the input objects  $a_0, \dots, a_r$ , when replaced by equal objects  $b_0, \dots, b_r$ , i.e. for each  $i \in \{0, \dots, r\}$ , the states  $S(a_i) = S(b_i)$  are equivalent for the objects  $a_i, b_i$  of type  $T_i$ , yield equivalent output objects  $c_i = d_i$  (where equality of objects means equivalence of the corresponding states). There is a natural equivalence for input/output objects in the following way: an input/output object  $s$  is equivalent to  $t$ , i.e.  $s \equiv t$ , if there is a regular procedure  $F$  for which  $t$  is the output object of the input  $s$  under  $F$ , or symmetrically if  $s$  is the output object of the input  $t$  under  $F$ .  $\square$

**Exercise 1.2.** *Assuming that `int` is a 32-bit two's complement type, determine the exact definition and result space.*

*Solution.* Supposing `int` is 32-bit two's complement, i.e. `int` is signed, the exact definition space would consist of the closed interval  $I := [-46340, 46340]$  and the result space would consist of the set  $\{x * x | x : \text{int}, x \in I\}$ , i.e.  $\{1, 4, 9, \dots, 46340 * 46340\}$ .  $\square$

## 2. TRANSFORMATIONS AND THEIR ORBITS

### 2.1. Transformations.

**Lemma 2.1.** `euclidean_norm(x, y, z) = euclidean_norm(euclidean_norm(x, y), z)`

*Solution.* `euclidean_norm(x, y, z)` is a ternary operation with the signature

$$\text{euclidean\_norm} :: T \times T \times T \rightarrow T$$

where  $T$  is well-formed as an object type, i.e.  $T$  is either an integral or floating point type. After currying, the signature becomes

$$\text{euclidean\_norm} :: T \rightarrow T \rightarrow T \rightarrow T$$

which clearly associates to

$$\text{euclidean\_norm} :: T \rightarrow (T \rightarrow T \rightarrow T)$$

Now, one can un-curry the parenthesized to obtain

$$\text{euclidean\_norm} :: T \rightarrow (T \times T \rightarrow T)$$

Where, now, the parenthesized is simply the binary operation `euclidean_norm(x, y)`, which may be taken as a partial application of the function `euclidean_norm(x, y, z)` to the arguments  $x, y$ , upon which one can then apply the third argument  $z$  to obtain the Euclidean norm of all three. So it is possible to "build" a ternary operation from a binary operation.  $\square$