



UNIVERSITÄT ZU KÖLN

Mathematisches Institut

BACHELORARBEIT

The Unum Number Format: Mathematical Foundations, Implementation and Comparison to IEEE 754 Floating-Point Numbers

Laslo Hunhold

Erstgutachterin:

Prof. Dr. Angela KUNOTH

Zweitgutachter:

Samuel LEWEKE

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1. Introduction

This thesis examines a modern concept for machine numbers based on interval arithmetic called ‘Unums’ and compares it to IEEE 754 floating-point arithmetic, evaluating possible uses of this format where floating-point numbers are inadequate. In the course of this examination, this thesis builds theoretical foundations for IEEE 754 floating-point numbers, interval arithmetic based on the projectively extended real numbers and Unums.

Machine Number Concepts Following the invention of machine floating-point numbers by Leonardo TORRES Y QUEVEDO in 1913 (see [Ran82, Section 3]) the format has evolved to be the standard used in numerical computations today. Over time though, different concepts and new approaches for representing numbers in a machine have emerged. One of these new concepts is the *infinity computer* developed by Yaroslav D. SERGEYEV, introducing *grossone* arithmetic for superfinite calculations. See [Ser15] for further reading.

Another concept are the *universal numbers* (‘Unums’) proposed by John L. GUSTAFSON. They were first introduced as a variable-length floating-point format with an uncertainty-bit as a superset of IEEE 754 floating-point numbers called ‘Unums 1.0’ (see [Gus15]). Reasoning about the complexity of machine implementations for and decimal calculation trade-offs with IEEE 754 floating-point numbers (see [Gus16b, Section 2]), GUSTAFSON presented a new format aiming to be easy to implement in the machine and provide a simple way to do decimal calculations with guaranteed error bounds (see [Gus16a] and [Gus16b]). He called the new format ‘Unums 2.0’. In the course of this thesis, we are referring to ‘Unums 2.0’ when talking about Unums.

Projectively Extended Real Numbers Besides the well-known and established concept of extending the real numbers with signed infinities $+\infty$ and $-\infty$, called the *affinely extended real numbers*, a different approach is to only use one unsigned symbol for infinity, denoted as ∞ in this thesis. This extension is called the *projectively extended real numbers* and we will prove that it is well-defined in terms of finite and infinite limits. It is in our interest to examine how much we lose and what we gain with this reduction, especially in regard to interval arithmetic.

Interval Arithmetic The concept behind interval arithmetic is to model quantities bounded by two values, thus in general being subsets rather than elements of the real numbers. Despite the fact that interval arithmetic in the machine can give definite bounds for a result, it is easy to find examples where it gives overly pessimistic results, for instance the dependency problem.

1. Introduction

This thesis will present a theory of interval arithmetic based on the projectively extended real numbers, picking up the idea of modelling degenerate intervals across the infinity point as well, allowing division by zero and showing many other useful properties.

Goal of this Thesis The goal of this thesis is to evaluate the Unum number format in a theoretical and practical context, make out advantages and see how reasonable it is to use Unums rather than the ubiquitous IEEE 754 floating-point format for certain tasks.

At the time of writing, all available implementations of the Unum arithmetic are using floating-point arithmetic at runtime instead of solely relying on lookup tables as GUSTAFSON proposes. The provided toolbox developed in the course of this thesis limits the use of floating-point arithmetic at runtime to the initialisation of input data. Thus it is a special point of interest to evaluate the format the way it was proposed and not in an artificial floating-point environment created by the currently available implementations.

Structure of this Thesis Following Chapter 2, which provides a formalisation of IEEE 754 floating-point numbers from the ground up solely based on the standard, deriving characteristics of the set of floating-point numbers and using numerical examples that show weaknesses of the format, Section 3.1 introduces the projectively extended real numbers and proves well-definedness of this extension after introducing a new concept of finite and infinite limits on it. Based on this foundation, Sections 3.2 and 3.3 construct a theory of interval arithmetic on top of the projectively extended real numbers, formalizing intuitive concepts of interval arithmetic.

Using the results obtained in Chapter 3, Chapter 4 embeds the Unums 2.0 number format proposed by John L. GUSTAFSON (see [Gus16a] and [Gus16b]) within this interval arithmetic, evaluating it both from a theoretical and practical perspective, providing a Unum 2.0 toolbox that was developed in the course of this thesis and giving numerical examples implemented in this toolbox.

2. IEEE 754 Floating-Point Arithmetic

Floating-point numbers have gone a long way since Konrad ZUSE's Z1 and Z3, which were among the first machines to implement floating-point numbers, back then obviously using a non-standardised format (see [Roj98, pp. 31, 40–48]). With more and more computers seeing the light of day in the decades following the pioneering days, the demand for a binary floating-point standard rose in the face of many different proprietary floating-point formats.

The Institute of Electrical and Electronics Engineers (IEEE) took on the task and formulated the ‘ANSI/IEEE 754-1985, Standard for Binary Floating-Point Arithmetic’ (see [IEE85]), published and adopted internationally in 1985 and revised in 2008 (see [IEE08]) with a few extensions, including decimal floating-point numbers (see [IEE08, Section 3.5]), which are not going to be presented here. This standardisation effort led to a homogenisation of floating-point formats across computer manufacturers, and this chapter will only deal with this standardised format and follow the concepts presented in the IEEE 754-2008 standard. All results in this chapter are solely derived from this standard.

2.1. Number Model

The idea behind floating-point numbers rests on the observation that given a base $b \in \mathbb{N}$ with $b \geq 2$ any $x \in \mathbb{R}$ can be represented by

$$\exists(s, e, d) \in \{0, 1\} \times \mathbb{Z} \times \{0, \dots, b-1\}^{\mathbb{N}_0} : x = (-1)^s \cdot b^e \cdot \sum_{i=0}^{\infty} d_i \cdot b^{-i}.$$

There exist multiple parametres (s, e, d) for a single x . For instance, $x = 6$ in the base $b = 10$ yields $(0, 0, \{6, 0, \dots\})$ and $(0, 1, \{0, 6, 0, \dots\})$ as two of many possible parametrisations.

Given the finite nature of the computer, the number of possible exponents e and digits d_i is limited. Within these bounds we can model a machine number \tilde{x} with exponent bounds $\underline{e}, \bar{e} \in \mathbb{Z}$, $\underline{e} \leq e \leq \bar{e}$ and a fixed number of digits $n_m \in \mathbb{N}$ and base $b = 2$ as

$$\tilde{x} = (-1)^s \cdot 2^e \cdot \sum_{i=0}^{n_m} d_i \cdot 2^{-i}.$$

Given binary is the native base the computer works with, we will assume $b = 2$ in this chapter. Despite being able to model finite floating-point numbers in the machine now, we still have problems with the lack of uniqueness. The IEEE 754 standard solves this by

2. IEEE 754 Floating-Point Arithmetic

reminding that the only difference between those multiple parametrisations for a given machine number $\tilde{x} \neq 0$ is that

$$\min \{i \in \{0, \dots, n_m\} \mid d_i = 0\}$$

is variable (see [IEE08, Section 3.4]). This means that we have a varying amount of 0's in the sequence $\{d_i\}_{i \in \{0, \dots, n_m\}}$ until we reach the first 1. One way to work around this redundancy is to use *normal* floating point numbers, which force $d_0 = 1$ (see [IEE08, Section 3.4]). The d_0 is not stored as it has always the same value. This results in the

Definition 2.1 (set of normal floating-point numbers). *Let $n_m \in \mathbb{N}$ and $\underline{e}, \bar{e} \in \mathbb{Z}$. The set of normal floating-point numbers is defined as*

$$\mathbb{M}_1(n_m, \underline{e}, \bar{e}) := \left\{ (-1)^s \cdot 2^e \cdot \left(1 + \sum_{i=1}^{n_m} d_i \cdot 2^{-i} \right) \mid s \in \{0, 1\} \wedge \underline{e} \leq e \leq \bar{e} \wedge d \in \{0, 1\}^{n_m} \right\}.$$

In addition to normal floating-point numbers, we can also define *subnormal* floating-point numbers, also known as *denormal* floating-point numbers, which force $d_0 = 0$ and $e = \underline{e}$ and are smaller in magnitude than the smallest (positive) normal floating-point number (see [IEE08, Section 3.4d]).

Definition 2.2 (set of subnormal floating-point numbers). *Let $n_m \in \mathbb{N}$ and $\underline{e} \in \mathbb{Z}$. The set of subnormal floating-point numbers is defined as*

$$\mathbb{M}_0(n_m, \underline{e}) := \left\{ (-1)^s \cdot 2^{\underline{e}} \cdot \left(0 + \sum_{i=1}^{n_m} d_i \cdot 2^{-i} \right) \mid s \in \{0, 1\} \wedge d \in \{0, 1\}^{n_m} \right\}.$$

The subnormal floating-point numbers allow us to express 0 with $d = 0$ and fill the so called ‘underflow gap’ between the smallest normal floating-point number and 0. With d and s variable, we use boundary values of the exponent to fit subnormal, normal and exception cases under one roof (see [IEE08, Section 3.4a-e]).

Definition 2.3 (set of floating-point numbers). *Let $n_m \in \mathbb{N}$, $\underline{e}, \bar{e} \in \mathbb{Z}$ and $d \in \{0, 1\}^{n_m}$. The set of floating point numbers is defined as*

$$\mathbb{M}(n_m, \underline{e} - 1, \bar{e} + 1) \ni: \tilde{x}(s, e, d) \begin{cases} \in \mathbb{M}_0(n_m, \underline{e}) & e = \underline{e} - 1 \\ \in \mathbb{M}_1(n_m, \underline{e}, \bar{e}) & \underline{e} \leq e \leq \bar{e} \\ = (-1)^s \cdot \infty & e = \bar{e} + 1 \wedge d = 0 \\ = \text{NaN} & e = \bar{e} + 1 \wedge d \neq 0. \end{cases}$$

In the interest of comparing different parametrisations for \mathbb{M} , we want to find expressions for the smallest positive non-zero subnormal, smallest positive normal and largest normal floating-point numbers.

Proposition 2.4 (smallest positive non-zero subnormal floating-point number). *Let $n_m \in \mathbb{N}$ and $\underline{e} \in \mathbb{Z}$. The smallest positive non-zero floating-point number is*

$$\min \left(\mathbb{M}_0(n_m, \underline{e}) \cap \mathbb{R}_{\neq 0}^+ \right) = 2^{\underline{e} - n_m}.$$

Proof. Let $0 \neq d \in \{0, 1\}^{n_m}$. It follows that

$$\min \left(\mathbb{M}_0(n_m, \underline{e}) \cap \mathbb{R}_{\neq 0}^+ \right) = \min \left((-1)^0 \cdot 2^{\underline{e}} \cdot \left[0 + \sum_{i=1}^{n_m} d_i \cdot 2^{-i} \right] \right) = 2^{\underline{e}} \cdot 2^{-n_m} = 2^{\underline{e}-n_m}. \quad \square$$

Proposition 2.5 (smallest positive normal floating-point number). *Let $n_m \in \mathbb{N}$ and $\underline{e}, \bar{e} \in \mathbb{Z}$. The smallest positive normal floating-point number is*

$$\min \left(\mathbb{M}_1(n_m, \underline{e}, \bar{e}) \cap \mathbb{R}_{\neq 0}^+ \right) = 2^{\underline{e}}.$$

Proof. Let $0 \neq d \in \{0, 1\}^{n_m}$ and $\underline{e} \leq e \leq \bar{e}$. It follows that

$$\min \left(\mathbb{M}_1(n_m, \underline{e}, \bar{e}) \cap \mathbb{R}_{\neq 0}^+ \right) = \min \left((-1)^0 \cdot 2^e \cdot \left[1 + \sum_{i=1}^{n_m} d_i \cdot 2^{-i} \right] \right) = 2^{\underline{e}}. \quad \square$$

Proposition 2.6 (largest normal floating-point number). *Let $n_m \in \mathbb{N}$ and $\underline{e}, \bar{e} \in \mathbb{Z}$. The largest normal floating-point number is*

$$\max \left(\mathbb{M}_1(n_m, \underline{e}, \bar{e}) \right) = 2^{\bar{e}} \cdot (2 - 2^{-n_m}).$$

Proof. Let $d \in \{0, 1\}^{n_m}$ and $\underline{e} \leq e \leq \bar{e}$. It follows with the finite geometric series that

$$\begin{aligned} \max \left(\mathbb{M}_1(n_m, \underline{e}, \bar{e}) \right) &= \max \left((-1)^s \cdot 2^e \cdot \left[1 + \sum_{i=1}^{n_m} d_i \cdot 2^{-i} \right] \right) \\ &= (-1)^0 \cdot 2^{\bar{e}} \cdot \left(1 + \sum_{i=1}^{n_m} 2^{-i} \right) \\ &= 2^{\bar{e}} \cdot \sum_{i=0}^{n_m} 2^{-i} \\ &= 2^{\bar{e}} \cdot \sum_{i=0}^{n_m} \left(\frac{1}{2} \right)^i \\ &= 2^{\bar{e}} \cdot \frac{1 - \left(\frac{1}{2} \right)^{n_m+1}}{1 - \frac{1}{2}} \\ &= 2^{\bar{e}} \cdot (2 - 2^{-n_m}) \end{aligned} \quad \square$$

Proposition 2.7 (number of NaN representations). *Let $n_m \in \mathbb{N}$ and $\underline{e}, \bar{e} \in \mathbb{Z}$. The number of NaN representations is*

$$|\text{NaN}|(n_m) := \left| \left\{ \tilde{x}(s, e, d) \in \mathbb{M}(n_m, \underline{e} - 1, \bar{e} + 1) \mid \tilde{x} = \text{NaN} \right\} \right| = 2^{n_m+1} - 2.$$

Proof. Let $0 \neq d \in \{0, 1\}^{n_m}$. It follows from Definition 2.3 that

$$\tilde{x}(s, e, d) = \text{NaN} \quad \Leftrightarrow \quad e = \bar{e} + 1 \wedge d \neq 0.$$

This means that there are $2^{n_m} - 1$ possible choices for d , yielding with the arbitrary $s \in \{0, 1\}$ that

$$|\text{NaN}|(n_m) = 2 \cdot (2^{n_m} - 1) = 2^{n_m+1} - 2. \quad \square$$

2.2. Memory Structure

It is in our interest to map $\mathbb{M}(n_m, \underline{e} - 1, \bar{e} + 1)$ into a memory region, more specifically a bit array. The format defined by the IEEE 754-2008 standard is shown in Figure 2.1, where n_e stands for the number of bits in the exponent, n_m for the bits in the mantissa and the leading single bit is reserved for the sign bit.



Figure 2.1.: IEEE 754 Floating-point memory layout; see [IEE08, Figure 3.1].

Handling the exponent just as an unsigned integer would not allow the use of negative exponents. To solve this, the so called *exponent bias* was introduced in the IEEE 754 standard, which is the value $2^{n_e-1} - 1$ subtracted from the unsigned value of the exponent (see [IEE08, Section 3.4b]) and should not be confused with the *two's complement*, the usual way to express signed integers in a machine. Looking at the exponent values, the exponent bias results in

$$\underline{e} - 1 = -2^{n_e-1} + 1 \leq e \leq 2^{n_e} - 2^{n_e-1} = \bar{e} + 1$$

and thus

$$(\underline{e}, \bar{e}) = (-2^{n_e-1} + 2, 2^{n_e} - 2^{n_e-1} - 1) = (-2^{n_e-1} + 2, 2^{n_e-1} - 1).$$

This can be formally expressed as the

Definition 2.8 (exponent bias). *Let $n_e \in \mathbb{N}$. The exponent bias is defined as*

$$\begin{aligned} \underline{e}(n_e) &:= -2^{n_e-1} + 2 \\ \bar{e}(n_e) &:= 2^{n_e-1} - 1. \end{aligned}$$

With the exponent bias representation, we know how many exponent values can be assumed. Because of that it is now possible to determine the

Proposition 2.9 (number of normal floating-point numbers). *Let $n_m, n_e \in \mathbb{N}$. The number of normal floating-point numbers is*

$$|\mathbb{M}_1(n_m, \underline{e}(n_e), \bar{e}(n_e))| = 2^{1+n_e+n_m} - 2^{n_m+2}.$$

Proof. According to Definition 2.1 there are

$$\bar{e}(n_e) - \underline{e}(n_e) + 1 = 2^{n_e-1} - 1 + 2^{n_e-1} - 2 + 1 = 2^{n_e} - 2$$

different exponents for $\mathbb{M}_1(n_m, \underline{e}(n_e), \bar{e}(n_e))$. Given $d \in \{0, 1\}^{n_m}$ and $s \in \{0, 1\}$ are arbitrary it follows that

$$|\mathbb{M}_1(n_m, \underline{e}(n_e), \bar{e}(n_e))| = 2 \cdot 2^{n_m} \cdot (2^{n_e} - 2) = 2^{1+n_e+n_m} - 2^{n_m+2}. \quad \square$$

Proposition 2.10 (number of subnormal floating-point numbers). *Let $n_m, n_e \in \mathbb{N}$. The number of subnormal floating-point numbers is*

$$|\mathbb{M}_0(n_m, \underline{e}(n_e))| = 2^{n_m+1}.$$

Proof. According to Definition 2.2 it follows with arbitrary $d \in \{0, 1\}^{n_m}$ and $s \in \{0, 1\}$ that

$$|\mathbb{M}_0(n_m, \underline{e}(n_e))| = 2 \cdot 2^{n_m} = 2^{n_m+1}. \quad \square$$

Proposition 2.11 (number of floating-point numbers). *Let $n_m, n_e \in \mathbb{N}$. The number of floating point numbers is*

$$|\mathbb{M}(n_m, \underline{e}(n_e) + 1, \bar{e}(n_e) - 1)| = 2^{1+n_e+n_m}.$$

Proof. We define

$$|\infty| := \left| \left\{ \tilde{x}(s, e, d) \in \mathbb{M}(n_m, \underline{e} - 1, \bar{e} + 1) \mid \tilde{x} = \pm\infty \right\} \right| = 2$$

and conclude from Definition 2.3 that

$$\begin{aligned} |\mathbb{M}(n_m, \underline{e}(n_e) + 1, \bar{e}(n_e) - 1)| &= |\mathbb{M}_0(n_m, \underline{e}(n_e))| + |\mathbb{M}_1(n_m, \underline{e}(n_e), \bar{e}(n_e))| + |\infty| + |\text{NaN}| \\ &= 2^{n_m+1} + 2^{1+n_e+n_m} - 2^{n_m+2} + 2 + 2^{n_m+1} - 2 \\ &= 2^{1+n_e+n_m} + 2^{n_m+1} + 2^{n_m+1} - 2 \cdot 2^{n_m+1} \\ &= 2^{1+n_e+n_m}. \end{aligned}$$

□

Excluding the extended precisions above 64 bit, the IEEE 754 standard defines three storage sizes for floating-point numbers (see [IEE08, Section 3.6]), parametrised by n_m and n_e , as can be seen in Table 2.1. Half precision floating-point numbers (binary16) were introduced in IEEE 754-2008 and are just meant to be a storage format and not used for arithmetic operations given the low dynamic range.

2.3. Rounding

Given $\mathbb{M}(n_m, \underline{e} - 1, \bar{e} + 1)$ is a finite set, we need a way to map arbitrary real values into it if we want floating-point numbers to be a useful model of the real numbers. The IEEE 754 standard solves this with *rounding*, an operation mapping real values to preferably close floating-point numbers based on a set of rules (see [IEE08, Section 4.3]). Given the different requirements depending on the task at hand, the IEEE 754 standard defines five rounding rules. Two based on rounding to the nearest value (see [IEE08, Section 4.3.1]) and three based on a directed approach (see [IEE08, Section 4.3.2]).

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precision	half (binary16)	single (binary32)	double (binary64)
storage size (bit)	16	32	64
n_e (bit)	5	8	11
n_m (bit)	10	23	52
exponent bias	15	127	1023
\underline{e}	-14	-126	-1022
\bar{e}	15	127	1023
$\min(\mathbb{M}_0 \cap \mathbb{R}_{\neq 0}^+)$	$\approx 5.96 \cdot 10^{-8}$	$\approx 1.40 \cdot 10^{-45}$	$\approx 4.94 \cdot 10^{-324}$
$\min(\mathbb{M}_1 \cap \mathbb{R}_{\neq 0}^+)$	$\approx 6.10 \cdot 10^{-5}$	$\approx 1.18 \cdot 10^{-38}$	$\approx 2.23 \cdot 10^{-308}$
$\max(\mathbb{M}_1)$	$\approx 6.55 \cdot 10^4$	$\approx 3.40 \cdot 10^{38}$	$\approx 1.80 \cdot 10^{308}$
$ \mathbb{M}_0 $	$\approx 2.04 \cdot 10^3$	$\approx 1.68 \cdot 10^7$	$\approx 9.01 \cdot 10^{15}$
$ \mathbb{M}_1 $	$\approx 6.14 \cdot 10^4$	$\approx 4.26 \cdot 10^9$	$\approx 1.84 \cdot 10^{19}$
$ \text{NaN} $	$\approx 2.05 \cdot 10^3$	$\approx 1.68 \cdot 10^7$	$\approx 9.01 \cdot 10^{15}$
$ \mathbb{M} $	$\approx 6.55 \cdot 10^4$	$\approx 4.29 \cdot 10^9$	$\approx 1.84 \cdot 10^{19}$
$ \text{NaN} / \mathbb{M} $ (%)	≈ 3.12	≈ 0.39	≈ 0.05

Table 2.1.: IEEE 754-2008 binary floating-point numbers up to 64 bit with their characterizing properties.

2.3.1. Nearest

The most intuitive approach is to just round to the nearest floating-point number. In case of a tie though, there has to be a rule in place to make a decision possible. Two rules proposed by the IEEE 754 standard are *tiing to even* (also known as *Banker's rounding*) and *tiing away from zero*. Only the first mode is presented here, which is also the default rounding mode (see [IEE08, Section 4.3.3]).

This part of the standard is often misunderstood, resulting in many publications not presenting nearest and tie to even rounding as the standard rounding operation but nearest and tie away from zero rounding, which is not correct but easy to overlook.

Definition 2.12 (nearest and tie to even rounding). *Let $n_m \in \mathbb{N}$, $\underline{e}, \bar{e} \in \mathbb{Z}$ and $x \in \mathbb{R}$ with $(s, e, d) \in \{0, 1\} \times \mathbb{Z} \times \{0, 1\}^{\mathbb{N}_0}$ satisfying*

$$x = (-1)^s \cdot 2^e \cdot \sum_{i=0}^{\infty} (d_i \cdot 2^{-i}).$$

The nearest and tie to even rounding reduction

$$\text{rd}_{\mathcal{E}}: \mathbb{R} \rightarrow \mathbb{M}(n_m, \underline{e} - 1, \bar{e} + 1)$$

is defined for

$$\begin{aligned}\underline{x} &:= (-1)^s \cdot 2^e \cdot \sum_{i=0}^{n_m} (d_i \cdot 2^{-i}) \\ \bar{x} &:= (-1)^s \cdot 2^e \cdot \left[\sum_{i=0}^{n_m} (d_i \cdot 2^{-i}) + 1 \cdot 2^{-n_m} \right]\end{aligned}$$

as

$$x \mapsto \begin{cases} (-1)^s \cdot \infty & |x| \geq \max(\mathbb{M}_1) - (2^{\bar{e}} \cdot 2^{-n_m}) = 2^{\bar{e}} \cdot (2 - 2^{-(n_m-1)}) \\ \bar{x} & |x - \bar{x}| < |x - \underline{x}| \vee [|x - \bar{x}| = |x - \underline{x}| \wedge d_{n_m} = 1] \\ \underline{x} & |x - \bar{x}| > |x - \underline{x}| \vee [|x - \bar{x}| = |x - \underline{x}| \wedge d_{n_m} = 0]. \end{cases}$$

What this means is that if two nearest machine numbers \underline{x} and \bar{x} are equally close to x , the last mantissa bit d_{n_m} of \underline{x} decides whether x is rounded to \underline{x} or \bar{x} . For $d_{n_m} = 0$ we know that \underline{x} is even and for $d_{n_m} = 1$ it follows from the definition that \bar{x} is even.

Tying to even may seem like an arbitrary and complicated approach to rounding, but its stochastic properties make it very useful to avoid biased rounding-effects in only one direction. Given for a set of rounding-operations the number of even and odd ties, if they appear, will be roughly the same with the number of rounding-operations approaching infinity, it results in a balanced behaviour of up- and downrounding in tie-cases.

2.3.2. Directed

Another way to round numbers is a directed rounding approach to a given orientation. The three modes have three distinct orientations: Rounding *toward zero*, *upward* and *downward*. The first mode is not presented here.

Definition 2.13 (upward rounding). *Let $n_m \in \mathbb{N}$, $\underline{e}, \bar{e} \in \mathbb{Z}$ and $x \in \mathbb{R}$ with $(s, e, d) \in \{0, 1\} \times \mathbb{Z} \times \{0, 1\}^{\mathbb{N}_0}$ satisfying*

$$x = (-1)^s \cdot 2^e \cdot \sum_{i=0}^{\infty} (d_i \cdot 2^{-i}).$$

The upward rounding reduction

$$\text{rd}_{\uparrow}: \mathbb{R} \rightarrow \mathbb{M}(n_m, \underline{e} - 1, \bar{e} + 1)$$

is defined for \underline{x}, \bar{x} as in Definition 2.12 as

$$x \mapsto \begin{cases} \underline{x} & x < 0 \\ \begin{cases} \underline{x} & \forall i > n_m : d_i = 0 \\ \bar{x} & \exists i > n_m : d_i = 1 \end{cases} & x \geq 0. \end{cases}$$

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Definition 2.14 (downward rounding). Let $n_m \in \mathbb{N}$, $e, \bar{e} \in \mathbb{Z}$ and $x \in \mathbb{R}$ with $(s, e, d) \in \{0, 1\} \times \mathbb{Z} \times \{0, 1\}^{\mathbb{N}_0}$ satisfying

$$x = (-1)^s \cdot 2^e \cdot \sum_{i=0}^{\infty} (d_i \cdot 2^{-i}).$$

The downward rounding reduction

$$\text{rd}_\downarrow : \mathbb{R} \rightarrow \mathbb{M}(n_m, \underline{e} - 1, \bar{e} + 1)$$

is defined for \underline{x}, \bar{x} as in Definition 2.12 as

$$x \mapsto \begin{cases} \underline{x} & \forall i > n_m : d_i = 0 \\ \bar{x} & \exists i > n_m : d_i = 1 \\ \underline{x} & x \geq 0. \end{cases}$$

The directed rounding modes are important for interval-arithmetic where it is important not to round down the upper bound or round up the lower bound of an interval. This way it is always guaranteed that for $a, b \in \mathbb{R}$ and $a \leq b$

$$[a, b] \subseteq [\text{rd}_\downarrow(a), \text{rd}_\uparrow(b)] \quad (2.1)$$

is satisfied. The bounds may grow faster than by using a to-nearest rounding mode, but it is guaranteed that the solution lies inbetween them.

2.4. Problems

As with any numerical system, we can find problems exhibiting its weaknesses. In this context we examine three different kinds of problems. Using the results obtained here it will allow us to evaluate if and how good the Unum arithmetic solves these problems respectively.

2.4.1. The Silent Spike

This example has been taken from [Kah06, §7] and simplified. Consider the function $f: \mathbb{R} \rightarrow \mathbb{R}$ defined as

$$f(x) := \ln(|3 \cdot (1 - x) + 1|). \quad (2.2)$$

It is easy to see that we hit a spike where

$$\begin{aligned} & |3 \cdot (1 - x) + 1| = 0 \\ \Leftrightarrow & 3 \cdot (1 - x) + 1 = 0 \\ \Leftrightarrow & 3 - 3 \cdot x + 1 = 0 \\ \Leftrightarrow & x = \frac{4}{3}. \end{aligned}$$

More specifically,

$$\lim_{x \downarrow \frac{4}{3}} (f(x)) = \lim_{x \uparrow \frac{4}{3}} (f(x)) = -\infty.$$

Implementing this problem using IEEE 754 floating-point numbers (see listing B.1.1), we might expect to receive a very small number or even negative infinity in an environment of $\frac{4}{3}$. However, this is not the case.

Instead, as you can see in Figure 2.2, the program claims that $f(\frac{4}{3}) \approx -36.044$ is the minimum in direct vicinity of $\frac{4}{3}$, completely hiding the fact that f is singular in $\frac{4}{3}$. The reason why the floating-point implementation hides the singularity is not that the

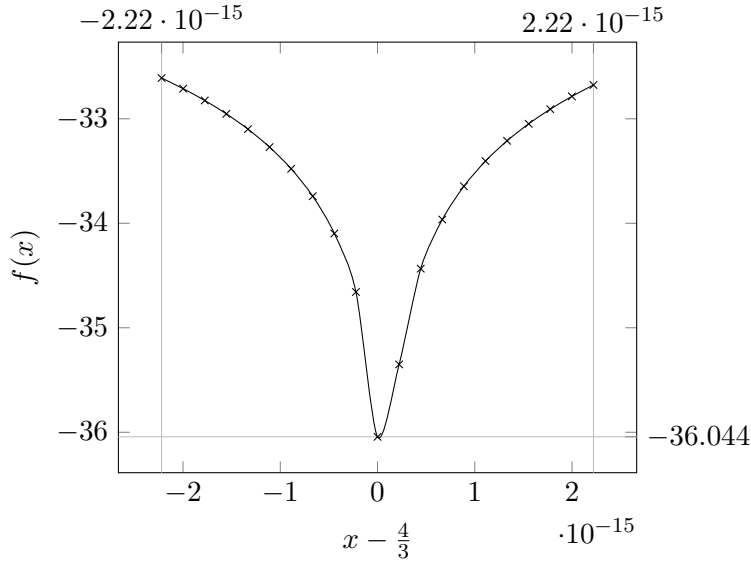


Figure 2.2.: Interpolated evaluations (demarked by crosses) of f (see (2.2)) in the neighbourhood of $\frac{4}{3}$ for all possible double floating-point numbers in $\left[\frac{4}{3} - 2.22 \cdot 10^{-15}, \frac{4}{3} + 2.22 \cdot 10^{-15}\right]$ (see listing B.1.1).

logarithm implementation is faulty, but because the value passed to the logarithm is off in the first place. It is easy to see the singular point $\frac{4}{3}$ cannot be exactly represented in the machine. This effect is increased with rounding errors occurring during the evaluation (see Listing B.1.1) of

$$\left| \text{rd}_{\mathcal{E}} \left\{ \text{rd}_{\mathcal{E}} \left[\text{rd}_{\mathcal{E}}(3) \cdot \text{rd}_{\mathcal{E}} \left(\text{rd}_{\mathcal{E}}(1) - \text{rd}_{\mathcal{E}} \left(\frac{4}{3} \right) \right) \right] + \text{rd}_{\mathcal{E}}(1) \right\} \right| \approx 2.2204 \cdot 10^{-16}.$$

In magnitude, this is relatively close to zero, but given

$$\ln(2.2204 \cdot 10^{-16}) \approx -36.0437$$

we not only see the significance of the rounding error, but also the reason why the floating-point implementation claims that -36.044 is the minimum of f in direct vicinity of $\frac{4}{3}$.

2. IEEE 754 Floating-Point Arithmetic

This result indicates that there are simple examples where floating-point numbers fail for piecewise continuous functions with singularities. Not being able to spot singularities for a given function might have drastic consequences, for example ‘hiding’ destructive frequencies in resonance curves for the oscillation of bridge stay cables, which are, for instance, derived in [PdCMBL96].

2.4.2. Devil’s Sequence

This example has been taken from [MBdD⁺10, Chapter 1.3.2]. Consider the recurrent series $\{u_n\}_{n \in \mathbb{N}_0}$ defined as

$$u_n := \begin{cases} 2 & n = 0 \\ -4 & n = 1 \\ 111 - \frac{1130}{u_{n-1}} + \frac{3000}{u_{n-1} \cdot u_{n-2}} & n \geq 2 \end{cases} \quad (2.3)$$

and determine the possible limits of this series, if they exist. For this purpose, we assume convergence with $u := u_n = u_{n-1} = u_{n-2}$ and obtain the characteristic polynomial relation

$$\begin{aligned} u &= 111 - \frac{1130}{u} + \frac{3000}{u^2} \\ \Leftrightarrow u^3 &= 111 \cdot u^2 - 1130 \cdot u + 3000 \\ \Leftrightarrow 0 &= u^3 - 111 \cdot u^2 + 1130 \cdot u - 3000 \end{aligned}$$

with solutions 5, 6 and 100. As further described in [Kah06, §5] for a similar recurrence, we obtain the general solution with $\alpha, \beta, \gamma \in \mathbb{R}$ under the condition $|\alpha| + |\beta| + |\gamma| \neq 0$

$$u_n = \frac{\alpha \cdot 100^{n+1} + \beta \cdot 6^{n+1} + \gamma \cdot 5^{n+1}}{\alpha \cdot 100^n + \beta \cdot 6^n + \gamma \cdot 5^n}. \quad (2.4)$$

For $u_0 = 2$ and $u_1 = -4$ we obtain $\alpha = 0$ and $\gamma = -\frac{3}{4} \cdot \beta \neq 0$, resulting in

$$\begin{aligned} u_n &= \frac{6^{n+1} - \frac{3}{4} \cdot 5^{n+1}}{6^n - \frac{3}{4} \cdot 5^n} \\ &= \frac{6^{n+1} - \frac{3}{4} \cdot \left(\frac{5}{6} \cdot 6\right)^{n+1}}{6^n - \frac{3}{4} \cdot \left(\frac{5}{6} \cdot 6\right)^n} \\ &= \frac{6^{n+1}}{6^n} \cdot \frac{1 - \frac{3}{4} \cdot \left(\frac{5}{6}\right)^{n+1}}{1 - \frac{3}{4} \cdot \left(\frac{5}{6}\right)^n} \\ &= 6 \cdot \frac{1 - \frac{3}{4} \cdot \left(\frac{5}{6}\right)^{n+1}}{1 - \frac{3}{4} \cdot \left(\frac{5}{6}\right)^n}. \end{aligned}$$

It follows that

$$\lim_{n \rightarrow \infty} (u_n) = 6.$$

If we take a look at the floating-point implementation (see listing B.1.2) of this problem, we can observe a rather peculiar behaviour: Figure 2.3 shows that the IEEE 754-based solver behaves completely opposite from what one might expect. Using the closed form

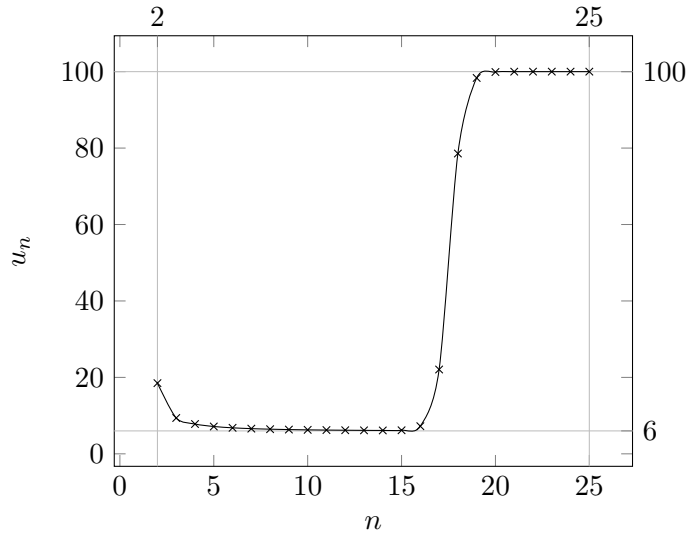


Figure 2.3.: Interpolated double floating-point evaluations (demarked by crosses) of the devil's sequence u_n (see (2.3)) for $n \in \{2, \dots, 25\}$ (see listing B.1.2).

(2.4) we have shown that the recurrence (2.3) converges to 6. However, even though the floating-point solver comes quite close to 6 up until $n = 15$, it unexpectedly converges to 100 in subsequent iterations. The reason for that is found within consecutive rounding errors of u_n , which skew the results so far that the parameter α of the closed form (2.4) becomes non-zero.

The carefully chosen starting values $u_0 = 2$ and $u_1 = -4$ deliberately make α disappear in (2.4), which shows how even little rounding errors can give completely wrong results for such a pathologic example.

2.4.3. The Chaotic Bank Society

This example has been taken from [MBdD⁺10, Chapter 1.3.2]. Consider the recurrent series $\{a_n\}_{n \in \mathbb{N}_0}$ defined for $a_0 \in \mathbb{R}$ as

$$a_n := \begin{cases} a_0 & n = 0 \\ a_{n-1} \cdot n - 1 & n \geq 1 \end{cases} \quad (2.5)$$

with the task being to determine u_{25} for $a_0 = e - 1$.

2. IEEE 754 Floating-Point Arithmetic

The name of this example can be derived by thinking of the series as an imaginary offer by a bank to start with a deposit of $e - 1$ currency units and in each year for 25 years, multiply it by the current running year number and subtract one currency unit as banking charges.

For a theoretical answer, we first want to find a closed form of u_n . We observe the pattern

$$\begin{aligned}
 a_0 &= a_0 &&= 0! \cdot (a_0) \\
 a_1 &= a_0 \cdot 1 - 1 &&= 1! \cdot \left(a_0 - \frac{1}{1!}\right) \\
 a_2 &= (a_0 \cdot 1 - 1) \cdot 2 - 1 &&= 2! \cdot \left(a_0 - \frac{1}{1!} - \frac{1}{2!}\right) \\
 a_3 &= [(a_0 \cdot 1 - 1) \cdot 2 - 1] \cdot 3 - 1 &&= 3! \cdot \left(a_0 - \frac{1}{1!} - \frac{1}{2!} - \frac{1}{3!}\right).
 \end{aligned}$$

This leads us to the

Proposition 2.15 (closed form of a_n). *The closed form of the recurrent series (2.5) is*

$$a_n = n! \cdot \left(a_0 - \sum_{k=1}^n \frac{1}{k!}\right)$$

Proof. We prove the statement by induction over $n \in \mathbb{N}_0$.

- a) $a_0 = a_0 = 0! \cdot a_0$.
- b) Assume $a_n = n! \cdot \left(a_0 - \sum_{k=1}^n \frac{1}{k!}\right)$ holds true for an arbitrary but fixed $n \in \mathbb{N}$.
- c) Show $n \mapsto n + 1$.

$$\begin{aligned}
 a_{n+1} &= a_n \cdot (n + 1) - 1 \\
 &\stackrel{b)}{=} n! \cdot \left(a_0 - \sum_{k=1}^n \frac{1}{k!}\right) \cdot (n + 1) - 1 \\
 &= (n + 1)! \cdot \left(a_0 - \sum_{k=1}^n \frac{1}{k!} - \frac{1}{(n + 1)!}\right) \\
 &= (n + 1)! \cdot \left(a_0 - \sum_{k=1}^{n+1} \frac{1}{k!}\right) \quad \square
 \end{aligned}$$

Using the closed form of a_n and the definition of EULER's number, we get for a

disturbed $a_0 = (e - 1) + \delta$ with $\delta \in \mathbb{R}$

$$\begin{aligned}
 a_n &= n! \cdot \left((e - 1) + \delta - \sum_{k=1}^n \frac{1}{k!} \right) \\
 &= n! \cdot \left(\delta + e - 1 - \sum_{k=1}^n \frac{1}{k!} \right) \\
 &= n! \cdot \left(\delta + \sum_{k=0}^{+\infty} \frac{1}{k!} - \sum_{k=0}^n \frac{1}{k!} \right) \\
 &= n! \cdot \left(\delta + \sum_{k=n+1}^{+\infty} \frac{1}{k!} \right) \\
 &= n! \cdot \delta + \sum_{k=n+1}^{+\infty} \frac{n!}{k!}.
 \end{aligned}$$

It follows that

$$\lim_{n \rightarrow +\infty} (a_n) = \begin{cases} -\infty & \delta < 0 \\ 0 & \delta = 0 \\ +\infty & \delta > 0 \end{cases}$$

and, thus, we can assume $a_{25} \in (0, e - 1)$ for an undisturbed $a_0 = e - 1$. In regard to the banking context this means that this offer would not be favourable for any investor.

A sloppy but quicker approach to get an answer to the problem is to write a program based on IEEE 754 floating-point numbers to calculate the account balance a_{25} (see listing B.1.3). However, the answer it gives is $a_{25} = 1201807247.410449$, suggesting a profitable offer by the bank, which it clearly is not. The reason for this erratic behaviour is that

$$\text{rd}_{\mathcal{E}}(1.718281828459045235) > e - 1,$$

resulting in $\delta > 0$ and a_n going towards positive infinity.

This example shows how rounding errors in floating-point arithmetic can lead to false predictions and ultimately decisions, indicating the need for guaranteed solution bounds. As elaborated in Subsection 2.3.1, the nearest and tie to even rounding reduction has some advantages, but in cases like this can skew the result undesiredly and unexpectedly due to the inhomogenous behaviour of rounding. Because of that, using another constant expression for a value close to $e - 1$ might result in the answer going towards negative infinity.

3. Interval Arithmetic

The foundation for modern interval arithmetic was set by Ramon E. MOORE in 1967 (see [Moo67]) as a means for automatic error analysis in algorithms. Since then, the usage of interval arithmetic beyond stability analysis was limited to some applications (see [MKŠ⁺06], [Moo79] and [MKC09]), which is also indicated by the fact that the first IEEE standard for interval arithmetic, IEEE 1788-2015, was published in 2015 (see [IEE15]). The standard is based on the ubiquitous *affinely extended real numbers*

$$\overline{\mathbb{R}} := \mathbb{R} \cup \{+\infty\} \cup \{-\infty\},$$

which this chapter will not make use of. Instead, the basis will be the *projectively extended real numbers*

$$\mathbb{R}^* := \mathbb{R} \cup \{\infty\}.$$

The motivation for this chapter is to find out how much we lose when only having one symbol for infinity, and more importantly, what we gain in this process, ultimately proving well-definedness of \mathbb{R}^* . Based on the findings, it is in our interest to construct an interval arithmetic on top of \mathbb{R}^* , which we can later use to formalise the Unum arithmetic.

3.1. Projectively Extended Real Numbers

With respect to simple reciprocation and negation of numbers, the projectively extended real numbers come to mind. Topologically speaking, this is the Alexandroff compactification of \mathbb{R} with the point $\infty \notin \mathbb{R}$ (see [Kow14, Section 25.4] for further reading).

As one can see in Figure 3.1, the geometric projection of \mathbb{R} and infinity ∞ onto a circle, and thinking of reciprocation and negation as horizontal and vertical reflections on this circle respectively, is the ideal model in this context, presenting an intuitive approach to arithmetic operations on sets of real numbers.

Just like we can not definitely give the number 0 a sign and just by convention denote it as a positive number, there is no reason for its reciprocal ∞ to have a sign. As intuitive as this approach is, rigorous results and a formal definition are necessary to build a solid foundation for interval arithmetic on the projectively extended real numbers. In the course of the following chapter we are going to define finite and infinite limits on the projectively extended real numbers and show well-definedness of this extension in terms of infinite limits. The formal definition of \mathbb{R}^* is according to [Rei82].

Definition 3.1 (projectively extended real numbers). *The projectively extended real numbers are defined as*

$$\mathbb{R}^* := \mathbb{R} \cup \{\infty\}.$$

3. Interval Arithmetic

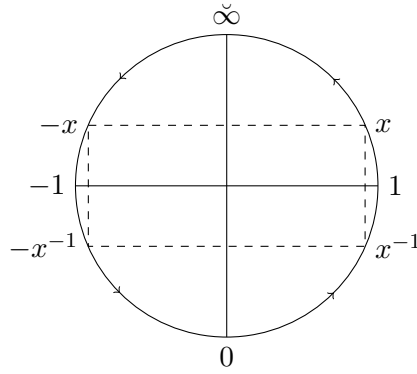


Figure 3.1.: Schema of \mathbb{R}^* with the counter-clockwise orientation indicated by arrows (see Definition 3.1).

The arithmetic operations $+$ and \cdot are partially extended for $a, b \in \mathbb{R}$ with $b \neq 0$ to

$$-(\infty) := \infty \quad (3.1a)$$

$$a + \infty = \infty + a := \infty \quad (3.1b)$$

$$b \cdot \infty = \infty \cdot b := \infty \quad (3.1c)$$

$$a/\infty := 0 \quad (3.1d)$$

$$b/0 := \infty. \quad (3.1e)$$

Left undefined are $\infty + \infty$, $\infty \cdot \infty$, $0 \cdot \infty$, $0/0$, ∞/∞ and $\infty/0$.

For more information on indeterminate forms on extensions of the real numbers see [TF95].

To be able to show well-definedness of the extension of the arithmetic operations in \mathbb{R}^* in terms of infinite limits, we first have to introduce the concept of ∞ -infinite limits on \mathbb{R}^* .

3.1.1. Finite and Infinite Limits

Since we can not use two signed symbols for infinity, namely $\pm\infty$, directed limits can be specified with the direction of approach to ∞ , from above or below, indicated by vertical arrows. In this regard, ascension is interpreted in regard to the natural order of \mathbb{R} , from smallest to largest number. Approaching ∞ from below corresponds to a limit toward $+\infty$ on \mathbb{R} , approaching ∞ from above corresponds to a limit toward $-\infty$ on \mathbb{R} .

There is no sacrifice in only having one symbol for infinity up to this point, given $+\infty$ and $-\infty$ can only be approached from one direction in standard analysis. Having one symbol that can be approached from two directions fills the gap seamlessly for finite limits.

3.1. Projectively Extended Real Numbers

Definition 3.2 ($\check{\infty}$ -finite limit). *Let $f: \mathbb{R} \rightarrow \mathbb{R}$. The $\check{\infty}$ -finite limit of f for x approaching $\check{\infty}$ is defined for $\ell \in \mathbb{R}$ as*

$$\begin{aligned} \lim_{x \downarrow \check{\infty}} (f(x)) = \ell & \quad :\Leftrightarrow \quad \forall \varepsilon > 0 : \exists c \in \mathbb{R} : \forall x \in \mathbb{R} : x < c : |f(x) - \ell| < \varepsilon \\ \lim_{x \uparrow \check{\infty}} (f(x)) = \ell & \quad :\Leftrightarrow \quad \forall \varepsilon > 0 : \exists c \in \mathbb{R} : \forall x \in \mathbb{R} : x > c : |f(x) - \ell| < \varepsilon \\ \lim_{x \rightarrow \check{\infty}} (f(x)) = \ell & \quad :\Leftrightarrow \quad \lim_{x \downarrow \check{\infty}} (f(x)) = \ell \wedge \lim_{x \uparrow \check{\infty}} (f(x)) = \ell. \end{aligned}$$

Remark 3.3 (standard-finite limit relationship). *Let $f: \mathbb{R} \rightarrow \mathbb{R}$ and $\ell \in \mathbb{R}$. One can convert between standard-finite limits and $\check{\infty}$ -finite limits using the relations*

$$\begin{aligned} \lim_{x \downarrow \check{\infty}} (f(x)) = \ell & \quad \Leftrightarrow \quad \lim_{x \rightarrow -\infty} (f(x)) = \ell \\ \lim_{x \uparrow \check{\infty}} (f(x)) = \ell & \quad \Leftrightarrow \quad \lim_{x \rightarrow +\infty} (f(x)) = \ell. \end{aligned}$$

Besides finite limits, we also need a way to express when a function diverges. In this regard, having only one infinity-symbol induces some losses, as only the absolute values of the functions can be evaluated. However, it still holds that if a function diverges in standard-infinite limits it also diverges in $\check{\infty}$ -infinite limits.

Definition 3.4 ($\check{\infty}$ -infinite limit). *Let $f: \mathbb{R} \rightarrow \mathbb{R}$. The $\check{\infty}$ -infinite limit of f for $x \in \mathbb{R}$ approaching $a \in \mathbb{R}$ is defined as*

$$\begin{aligned} \lim_{x \downarrow a} (f(x)) = \check{\infty} & \quad :\Leftrightarrow \quad \forall \varepsilon > 0 : \exists \delta > 0 : 0 < x - a < \delta \Rightarrow |f(x)| > \varepsilon \\ \lim_{x \uparrow a} (f(x)) = \check{\infty} & \quad :\Leftrightarrow \quad \forall \varepsilon > 0 : \exists \delta > 0 : 0 < a - x < \delta \Rightarrow |f(x)| > \varepsilon \\ \lim_{x \rightarrow a} (f(x)) = \check{\infty} & \quad :\Leftrightarrow \quad \lim_{x \downarrow a} (f(x)) = \check{\infty} \wedge \lim_{x \uparrow a} (f(x)) = \check{\infty}, \end{aligned}$$

and for $x \in \mathbb{R}$ approaching $\check{\infty}$ as

$$\begin{aligned} \lim_{x \downarrow \check{\infty}} (f(x)) = \check{\infty} & \quad :\Leftrightarrow \quad \forall \varepsilon > 0 : \exists c \in \mathbb{R} : \forall x \in \mathbb{R} : x < c : |f(x)| > \varepsilon \\ \lim_{x \uparrow \check{\infty}} (f(x)) = \check{\infty} & \quad :\Leftrightarrow \quad \forall \varepsilon > 0 : \exists c \in \mathbb{R} : \forall x \in \mathbb{R} : x > c : |f(x)| > \varepsilon \\ \lim_{x \rightarrow \check{\infty}} (f(x)) = \check{\infty} & \quad :\Leftrightarrow \quad \lim_{x \downarrow \check{\infty}} (f(x)) = \check{\infty} \wedge \lim_{x \uparrow \check{\infty}} (f(x)) = \check{\infty}. \end{aligned}$$

Remark 3.5 (standard-infinite limit relationship). *Let $f: \mathbb{R} \rightarrow \mathbb{R}$ and $a \in \mathbb{R}$. One can convert between standard-infinite limits and $\check{\infty}$ -infinite limits using the relations*

$$\begin{aligned} \lim_{x \downarrow a} (f(x)) = \check{\infty} & \quad \Leftarrow \quad \lim_{x \downarrow a} (f(x)) = \pm\infty \\ \lim_{x \uparrow a} (f(x)) = \check{\infty} & \quad \Leftarrow \quad \lim_{x \uparrow a} (f(x)) = \pm\infty \\ \lim_{x \downarrow \check{\infty}} (f(x)) = \check{\infty} & \quad \Leftarrow \quad \lim_{x \rightarrow -\infty} (f(x)) = \pm\infty \\ \lim_{x \uparrow \check{\infty}} (f(x)) = \check{\infty} & \quad \Leftarrow \quad \lim_{x \rightarrow +\infty} (f(x)) = \pm\infty. \end{aligned}$$

3. Interval Arithmetic

3.1.2. Well-Definedness

We can now use our definitions of ∞ -finite and ∞ -infinite limits to show that \mathbb{R}^* with the extensions given in Definition 3.1 is well-defined in terms of infinite limits.

Theorem 3.6 (well-definedness of \mathbb{R}^*). *\mathbb{R}^* is well-defined in terms of infinite limits.*

Proof. Let $f_\infty, f_a, f_b, f_0: \mathbb{R} \rightarrow \mathbb{R}$, $a, b \in \mathbb{R}$ and $b \neq 0$. Without loss of generality we assume that ∞ is approached from below and specify

$$\lim_{x \uparrow \infty} (f_\infty(x)) = \infty \quad (3.2a)$$

$$\lim_{x \uparrow \infty} (f_a(x)) = a \quad (3.2b)$$

$$\lim_{x \uparrow \infty} (f_b(x)) = b \quad (3.2c)$$

$$\lim_{x \uparrow \infty} (f_0(x)) = 0. \quad (3.2d)$$

To show well-definedness, we go through each axiom given in Definition 3.1.

Let $\tilde{\varepsilon} > 0$.

(3.1a) By Definition 3.4 we know that

$$\lim_{x \uparrow \infty} (f_\infty(x)) = \infty \quad \Leftrightarrow \quad \lim_{x \uparrow \infty} (-f_\infty(x)) = \infty$$

and, thus, $-(\infty) = \infty$ is well-defined.

(3.1b) To show that $a + \infty = \infty + a = \infty$ is well-defined we have to show that

$$\lim_{x \uparrow \infty} (f_a(x) + f_\infty(x)) = \lim_{x \uparrow \infty} (f_\infty(x) + f_a(x)) = \infty. \quad (3.3)$$

Following from precondition (3.2b), Definition 3.4 and $\tilde{\varepsilon} > 0$ we know that

$$\exists c_{2,a} \in \mathbb{R} : \forall x > c_{2,a} : |f_a(x) - a| < \tilde{\varepsilon}.$$

It follows for $x > c_{2,a}$ using the reverse triangle inequality that

$$\begin{aligned} \tilde{\varepsilon} &> |f_a(x) - a| \geq ||f_a(x)| - |a|| \geq |f_a(x)| - |a| \\ \Rightarrow |f_a(x)| &< \tilde{\varepsilon} + |a|. \end{aligned} \quad (3.4)$$

Following from precondition (3.2a), Definition 3.4 and $2 \cdot \tilde{\varepsilon} + |a| > 0$ we also know that

$$\exists c_{2,\infty} \in \mathbb{R} : \forall x > c_{2,\infty} : |f_\infty(x)| > 2 \cdot \tilde{\varepsilon} + |a|. \quad (3.5)$$

Let $x > \tilde{c}_2 := \max\{c_{2,a}, c_{2,\infty}\}$ to satisfy both (3.4) and (3.5). It follows using the reverse triangle inequality that

$$\begin{aligned} |f_\infty(x)| &> 2 \cdot \tilde{\varepsilon} + |a| = \tilde{\varepsilon} + (\tilde{\varepsilon} + |a|) > \tilde{\varepsilon} + |f_a(x)| \\ \Rightarrow \tilde{\varepsilon} &< |f_\infty(x)| - |f_a(x)| = |f_\infty(x)| - |-f_a(x)| \leq |f_\infty(x) - (-f_a(x))| \\ \Rightarrow |f_a(x) + f_\infty(x)| &= |f_\infty(x) + f_a(x)| > \tilde{\varepsilon}, \end{aligned}$$

which by Definition 3.4 is equivalent to (3.3) and was to be shown.

3.1. Projectively Extended Real Numbers

(3.1c) To show that $b \cdot \infty = \infty \cdot b = \infty$ is well-defined we have to show that

$$\lim_{x \uparrow \infty} (f_b(x) \cdot f_\infty(x)) = \lim_{x \uparrow \infty} (f_\infty(x) \cdot f_b(x)) = \infty. \quad (3.6)$$

Following from precondition (3.2c), Definition 3.4 and $\frac{|b|}{2} > 0$ we know

$$\exists c_{3,b} \in \mathbb{R} : \forall x > c_{3,b} : |f_b(x) - b| < \frac{|b|}{2}.$$

It follows for $x > c_{3,b}$ using the triangle and reverse triangle inequalities that

$$\begin{aligned} |f_b(x) - b| &< \frac{|b|}{2} = \frac{|0 - b|}{2} \leq \frac{|0 - f_b(x)| + |f_b(x) - b|}{2} \\ \Rightarrow \frac{|f_b(x) - b|}{2} &< \frac{|f_b(x)|}{2} \\ \Leftrightarrow |f_b(x)| > |f_b(x) - b| &= |b - f_b(x)| \geq ||b| - |f_b(x)|| \geq |b| - |f_b(x)| \\ \Rightarrow |f_b(x)| > \frac{|b|}{2}. \end{aligned} \quad (3.7)$$

Following from precondition (3.2a), Definition 3.4 and $\frac{2 \cdot \tilde{\varepsilon}}{|b|} > 0$ we also know that

$$\exists c_{3,\infty} \in \mathbb{R} : \forall x > c_{3,\infty} : |f_\infty(x)| > \frac{2 \cdot \tilde{\varepsilon}}{|b|}. \quad (3.8)$$

Let $x > \tilde{c}_3 := \max\{c_{3,b}, c_{3,\infty}\}$ to satisfy both (3.7) and (3.8). It follows that

$$\begin{aligned} |f_\infty(x)| &> \frac{2 \cdot \tilde{\varepsilon}}{|b|} > \frac{\tilde{\varepsilon}}{|f_b(x)|} \\ \Rightarrow |f_b(x)| \cdot |f_\infty(x)| &> \tilde{\varepsilon} \\ \Leftrightarrow |f_b(x) \cdot f_\infty(x)| &= |f_\infty(x) \cdot f_b(x)| > \tilde{\varepsilon}, \end{aligned}$$

which by Definition 3.4 is equivalent to (3.6) and was to be shown.

(3.1d) To show that $a/\infty = 0$ is well-defined we have to show that

$$\lim_{x \uparrow \infty} \left(\frac{f_a(x)}{f_\infty(x)} \right) = 0. \quad (3.9)$$

Following from precondition (3.2a), Definition 3.4 and $\frac{\tilde{\varepsilon} + |a|}{\tilde{\varepsilon}} > 0$ we know

$$\exists c_{4,\infty} \in \mathbb{R} : \forall x > c_{4,\infty} : |f_\infty(x)| > \frac{\tilde{\varepsilon} + |a|}{\tilde{\varepsilon}}. \quad (3.10)$$

Let $x > \tilde{c}_4 := \max\{c_{2,a}, c_{4,\infty}\}$ to satisfy both (3.4) and (3.10). It follows that

$$\begin{aligned} |f_a(x)| &< \tilde{\varepsilon} + |a| = \tilde{\varepsilon} \cdot \frac{\tilde{\varepsilon} + |a|}{\tilde{\varepsilon}} < \tilde{\varepsilon} \cdot |f_\infty(x)| \\ \Rightarrow \frac{|f_a(x)|}{|f_\infty(x)|} &< \tilde{\varepsilon} \\ \Leftrightarrow \left| \frac{f_a(x)}{f_\infty(x)} - 0 \right| &< \tilde{\varepsilon}, \end{aligned}$$

which by Definition 3.2 is equivalent to (3.9) and was to be shown.

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(3.1e) To show that $b/0 = \infty$ is well-defined we have to show that

$$\lim_{x \uparrow \infty} \left(\frac{f_b(x)}{f_0(x)} \right) = \infty. \quad (3.11)$$

Following from precondition (3.2a), Definition 3.4 and $\frac{|b|}{2 \cdot \tilde{\varepsilon}} > 0$ we know

$$\exists c_{5,0} \in \mathbb{R} : \forall x > c_{5,0} : |f_0(x)| < \frac{|b|}{2 \cdot \tilde{\varepsilon}} \quad (3.12)$$

Let $x > \tilde{c}_5 := \max\{c_{3,b}, c_{5,0}\}$ to satisfy both (3.7) and (3.12). It follows that

$$\begin{aligned} |f_b(x)| &> \frac{|b|}{2} = \tilde{\varepsilon} \cdot \frac{|b|}{2 \cdot \tilde{\varepsilon}} > \tilde{\varepsilon} \cdot |f_0(x)| \\ \Rightarrow |f_b(x)| &> \tilde{\varepsilon} \cdot |f_0(x)| \\ \Leftrightarrow \frac{|f_b(x)|}{|f_0(x)|} &> \tilde{\varepsilon} \\ \Leftrightarrow \left| \frac{f_b(x)}{f_0(x)} \right| &> \tilde{\varepsilon}, \end{aligned}$$

which by Definition 3.2 is equivalent to (3.11) and was to be shown. \square

3.2. Open Intervals

With well-definedness of \mathbb{R}^* shown we have built a solid foundation for \mathbb{R}^* -interval arithmetic. Given \mathbb{R}^* is not an ordered set, we have to introduce a new definition for intervals that seamlessly extend to ∞ . Our goal is to define operations on open intervals and singletons and to use them to model arbitrary subsets of \mathbb{R}^* .

To allow degenerate intervals across ∞ , the convention proposed in [Rei82, pp. 88-89] is to give \mathbb{R}^* a counter-clockwise orientation (see Figure 3.1) and define for $\underline{a}, \bar{a} \in \mathbb{R}$ and $\underline{a} < \bar{a}$ the degenerate interval (\bar{a}, \underline{a}) by tracing all elements from \bar{a} to \underline{a} . It is in our interest to formalise this intuitive but informal approach. To denote degenerate intervals, we first need to define the

Definition 3.7 (disjoint union). *Let A be a set and $\{A_i\}_{i \in I}$ a family of sets over an index set I with $A_i \subseteq A$. A is the disjoint union of $\{A_i\}_{i \in I}$, denoted by*

$$A = \bigsqcup_{i \in I} A_i,$$

if and only if

$$\forall i, j \in I : i \neq j : A_i \cap A_j = \emptyset \quad (3.13)$$

and

$$A = \bigcup_{i \in I} A_i. \quad (3.14)$$

Definition 3.8 (open \mathbb{R}^* -interval). Let $\underline{a}, \bar{a} \in \mathbb{R}^*$. An open \mathbb{R}^* -interval between \underline{a} and \bar{a} is defined as

$$\mathbb{R}^* \supset (\underline{a}, \bar{a}) := \begin{cases} \mathbb{R} & \underline{a} = \bar{a} = \check{\infty} \\ \{x \in \mathbb{R} \mid x < \bar{a}\} & \underline{a} = \check{\infty} \\ \{x \in \mathbb{R} \mid x > \underline{a}\} & \bar{a} = \check{\infty} \\ \{x \in \mathbb{R} \mid \underline{a} < x < \bar{a}\} & \underline{a} \leq \bar{a} \\ (\bar{a}, \check{\infty}) \sqcup \{\check{\infty}\} \sqcup (\check{\infty}, \underline{a}) & \underline{a} > \bar{a} \end{cases}$$

In the interest of defining operations on open \mathbb{R}^* -intervals, we introduce the

Definition 3.9 (set of open \mathbb{R}^* -intervals). The set of open \mathbb{R}^* -intervals is defined as

$$\mathbb{I} := \{(\underline{a}, \bar{a}) \mid \underline{a}, \bar{a} \in \mathbb{R}^*\}. \quad (3.15)$$

with the operations $\oplus: \mathbb{I} \times \mathbb{I} \rightarrow \mathbb{I}$ defined as

$$((\underline{a}, \bar{a}), (\underline{b}, \bar{b})) \mapsto \begin{cases} \begin{cases} \emptyset & \underline{a} \in \mathbb{R} \\ \emptyset & \underline{b}, \bar{b} \in \mathbb{R} \wedge \underline{b} \geq \bar{b} \\ \mathbb{R} & \text{else} \end{cases} & \underline{a} = \bar{a} & (3.16a) \\ (\underline{b}, \bar{b}) \oplus (\underline{a}, \bar{a}) & \underline{b} = \bar{b} & (3.16b) \\ (\check{\infty}, \bar{a} + \bar{b}) & \underline{a} = \underline{b} = \check{\infty} & (3.16c) \\ (\underline{a} + \underline{b}, \check{\infty}) & \bar{a} = \bar{b} = \check{\infty} & (3.16d) \\ \mathbb{R} & \underline{a} = \bar{b} = \check{\infty} & (3.16e) \\ (\underline{b}, \bar{b}) \oplus (\underline{a}, \bar{a}) & \bar{a} = \underline{b} = \check{\infty} & (3.16f) \\ \begin{cases} \emptyset & \underline{b} > \bar{b} \\ (\check{\infty}, \bar{a} + \bar{b}) & \text{else} \end{cases} & \underline{a} = \check{\infty} & (3.16g) \\ \begin{cases} \emptyset & \underline{b} > \bar{b} \\ (\underline{a} + \underline{b}, \check{\infty}) & \text{else} \end{cases} & \bar{a} = \check{\infty} & (3.16h) \\ (\underline{b}, \bar{b}) \oplus (\underline{a}, \bar{a}) & \underline{b} = \check{\infty} & (3.16i) \\ (\underline{b}, \bar{b}) \oplus (\underline{a}, \bar{a}) & \bar{b} = \check{\infty} & (3.16j) \\ \begin{cases} \emptyset & \underline{a} > \bar{a} \wedge \underline{b} > \bar{b} \\ (\underline{a} + \underline{b}, \bar{a} + \bar{b}) & \text{else} \end{cases} & \text{else} & (3.16k) \end{cases}$$

and, using $\underline{A} := \{\underline{a} \cdot \underline{b}, \underline{a} \cdot \bar{b}\}$, $\bar{A} := \{\bar{a} \cdot \underline{b}, \bar{a} \cdot \bar{b}\}$ and $A := \underline{A} \cup \bar{A}$ for $\underline{a}, \bar{a}, \underline{b}, \bar{b} \in \mathbb{R}$, $\otimes: \mathbb{I} \times \mathbb{I} \rightarrow \mathbb{I}$

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defined as

$$\begin{aligned}
 ((a, \bar{a}), (\underline{b}, \bar{b})) \mapsto & \begin{cases} \emptyset & \underline{a} \in \mathbb{R} \\ \emptyset & \underline{b}, \bar{b} \in \mathbb{R} \wedge \underline{b} \geq \bar{b} \\ \mathbb{R} & \text{else} \end{cases} & \underline{a} = \bar{a} & (3.17a) \\
 & (\underline{b}, \bar{b}) \otimes (a, \bar{a}) & \underline{b} = \bar{b} & (3.17b) \\
 & \begin{cases} (\bar{a} \cdot \bar{b}, \check{\infty}) & \bar{a} \leq 0 \wedge \bar{b} \leq 0 \\ \mathbb{R} & \text{else} \end{cases} & \underline{a} = \underline{b} = \check{\infty} & (3.17c) \\
 & \begin{cases} (a \cdot \underline{b}, \check{\infty}) & a \geq 0 \wedge \underline{b} \geq 0 \\ \mathbb{R} & \text{else} \end{cases} & \bar{a} = \bar{b} = \check{\infty} & (3.17d) \\
 & \begin{cases} (\check{\infty}, \bar{a} \cdot \underline{b}) & \bar{a} \leq 0 \wedge \underline{b} \geq 0 \\ \mathbb{R} & \text{else} \end{cases} & \underline{a} = \bar{b} = \check{\infty} & (3.17e) \\
 & (\underline{b}, \bar{b}) \otimes (a, \bar{a}) & \bar{a} = \underline{b} = \check{\infty} & (3.17f) \\
 & \begin{cases} \mathbb{R} & \underline{b} > \bar{b} \\ (\check{\infty}, \max(\bar{A})) & \underline{b} \geq 0 \\ (\min(\bar{A}), \check{\infty}) & \bar{b} \leq 0 \\ \mathbb{R} & \text{else} \end{cases} & \underline{a} = \check{\infty} & (3.17g) \\
 & \begin{cases} \mathbb{R} & \underline{b} > \bar{b} \\ (\min(\underline{A}), \check{\infty}) & \underline{b} \geq 0 \\ (\check{\infty}, \max(\underline{A})) & \bar{b} \leq 0 \\ \mathbb{R} & \text{else} \end{cases} & \bar{a} = \check{\infty} & (3.17h) \\
 & (\underline{b}, \bar{b}) \otimes (a, \bar{a}) & \underline{b} = \check{\infty} & (3.17i) \\
 & (\underline{b}, \bar{b}) \otimes (a, \bar{a}) & \bar{b} = \check{\infty} & (3.17j) \\
 & \emptyset & \underline{a} > \bar{a} \wedge \underline{b} > \bar{b} & (3.17k) \\
 & \begin{cases} (\max(\underline{A}), \min(\bar{A})) & \text{sgn}(\underline{b}) = \text{sgn}(\bar{b}) \\ \emptyset & \text{else} \end{cases} & \underline{a} > \bar{a} & (3.17l) \\
 & (\underline{b}, \bar{b}) \otimes (a, \bar{a}) & \underline{b} > \bar{b} & (3.17m) \\
 & \emptyset & \underline{a} = \bar{a} \vee \underline{b} = \bar{b} & (3.17n) \\
 & (\min(A), \max(A)) & \text{else} & (3.17o)
 \end{aligned}
 \end{aligned}$$

Remark 3.10 (role of empty set in definition). *The use of the empty set in Definition 3.9 denotes cases where undefined behaviour occurs.*

Theorem 3.11 (well-definedness of \mathbb{I}). *\mathbb{I} is well-defined in terms of set theory.*

Proof. One can see that the operations \oplus and \otimes satisfy closedness with regard to \mathbb{I} . Symmetry is also satisfied given the explicit transposed forms (3.16b), (3.16f), (3.16i) and (3.16j) for \oplus and (3.17b), (3.17f), (3.17i), (3.17j) and (3.17m) for \otimes .

Well-definedness in terms of set theory is based on the condition that for given $A, B \in \mathbb{I}$ the two operations \oplus and \otimes must satisfy

$$A \oplus B = \{a + b \mid a \in A \wedge b \in B\}$$

and

$$A \otimes B = \{a \cdot b \mid a \in A \wedge b \in B\}$$

respectively, except for cases where undefined behaviour occurs. It follows from the conditions that if either $A = \emptyset$ or $B = \emptyset$ the resulting set is also empty (see (3.16a) and (3.17a)).

Let $a, b \in \mathbb{I}$ and $\underline{a}, \bar{a}, \underline{b}, \bar{b} \in \mathbb{R}$.

(3.16a) This case either corresponds to

$$\emptyset \oplus b,$$

yielding the empty set, or

$$\mathbb{R} \oplus b,$$

yielding \mathbb{R} , unless b is degenerate, given it contains ∞ and $\mathbb{R}^* \notin \mathbb{I}$ is undefined, or empty, yielding the empty set.

(3.16c) This case corresponds to

$$(\infty, \bar{a}) \oplus (\infty, \bar{b})$$

and yields, using Definition 3.8,

$$\{x \in \mathbb{R} \mid x < \bar{a}\} \oplus \{x \in \mathbb{R} \mid x < \bar{b}\} = \{x \in \mathbb{R} \mid x < \bar{a} + \bar{b}\} = (\infty, \bar{a} + \bar{b}).$$

(3.16d) This case corresponds to

$$(\underline{a}, \infty) \oplus (\bar{a}, \infty)$$

and yields, using Definition 3.8,

$$\{x \in \mathbb{R} \mid x > \underline{a}\} \oplus \{x \in \mathbb{R} \mid x > \bar{a}\} = \{x \in \mathbb{R} \mid x > \underline{a} + \bar{a}\} = (\underline{a} + \bar{a}, \infty).$$

(3.16e) This case corresponds to

$$(\infty, \bar{a}) \oplus (\underline{b}, \infty)$$

and yields, using Definition 3.8,

$$\{x \in \mathbb{R} \mid x < \bar{a}\} \oplus \{x \in \mathbb{R} \mid x > \underline{b}\} = \mathbb{R}.$$

(3.16g) This case corresponds to

$$(\infty, \bar{a}) \oplus (\underline{b}, \bar{b})$$

and yields, using Definition 3.8, if (\underline{b}, \bar{b}) is degenerate

$$\{x \in \mathbb{R} \mid x < \bar{a}\} \oplus ((\bar{b}, \infty) \sqcup \{\infty\} \sqcup (\infty, \underline{b})) = \mathbb{R}^*$$

and, thus, the empty set as $\mathbb{R}^* \notin \mathbb{I}$ is undefined, or else

$$\{x \in \mathbb{R} \mid x < \bar{a}\} \oplus \{x \in \mathbb{R} \mid \underline{b} < x < \bar{b}\} = \{x \in \mathbb{R} \mid x < \bar{a} + \bar{b}\} = (\infty, \bar{a} + \bar{b}).$$

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(3.16h) This case corresponds to

$$(\underline{a}, \check{\infty}) \oplus (\underline{b}, \bar{b})$$

and yields, using Definition 3.8, if (\underline{b}, \bar{b}) is degenerate

$$\{x \in \mathbb{R} \mid x > \underline{a}\} \oplus ((\bar{b}, \check{\infty}) \sqcup \{\check{\infty}\} \sqcup (\check{\infty}, \underline{b})) = \mathbb{R}^*$$

and, thus, the empty set as $\mathbb{R}^* \notin \mathbb{I}$ is undefined, or else

$$\{x \in \mathbb{R} \mid x > \underline{a}\} \oplus \{x \in \mathbb{R} \mid \underline{b} < x < \bar{b}\} = \{x \in \mathbb{R} \mid x > \underline{a} + \underline{b}\} = (\underline{a} + \underline{b}, \check{\infty}).$$

(3.16k) This case corresponds to

$$(\underline{a}, \bar{a}) \oplus (\underline{b}, \bar{b})$$

and yields, using Definition 3.8, if both (\underline{a}, \bar{a}) and (\underline{b}, \bar{b}) are degenerate

$$((\bar{a}, \check{\infty}) \sqcup \{\check{\infty}\} \sqcup (\check{\infty}, \underline{a})) \oplus ((\bar{b}, \check{\infty}) \sqcup \{\check{\infty}\} \sqcup (\check{\infty}, \underline{b}))$$

the empty set, as $\check{\infty} + \check{\infty}$ is undefined. If, without loss of generality, only (\underline{a}, \bar{a}) is degenerate, it yields

$$((\underline{a}, \check{\infty}) \sqcup \{\check{\infty}\} \sqcup (\check{\infty}, \bar{a})) \oplus (\underline{b}, \bar{b}) = (\underline{a} + \underline{b}, \check{\infty}) \sqcup \{\check{\infty}\} \sqcup (\check{\infty}, \bar{a} + \bar{b}) = (\bar{a} + \bar{b}, \bar{a} + \bar{b}).$$

If neither (\underline{a}, \bar{a}) nor (\underline{b}, \bar{b}) are degenerate, it yields

$$\{x \in \mathbb{R} \mid \underline{a} < x < \bar{a}\} \oplus \{x \in \mathbb{R} \mid \underline{b} < x < \bar{b}\} = \{x \in \mathbb{R} \mid \underline{a} + \underline{b} < x < \bar{a} + \bar{b}\} = (\underline{a} + \underline{b}, \bar{a} + \bar{b}).$$

The cases (3.17a), (3.17c), (3.17d), (3.17e), (3.17g), (3.17h), (3.17k), (3.17l), (3.17n) and (3.17o) for \otimes are shown analogously. \square

Given the complexity of open interval arithmetic alone, it becomes clear why open intervals have been studied independently up to this point. We will now expand \mathbb{I} with singletons and introduce the concept of \mathbb{R}^* -Flakes.

3.3. Flakes

To model subsets of \mathbb{R}^* , one easily finds that open intervals alone are not sufficient to model even simple sets. Using singletons to expand \mathbb{I} can present new possibilities. Before we introduce the central concept of this chapter, we first need to formalise the definition of singletons in \mathbb{R}^* .

Definition 3.12 (set of singletons). *Let S be a set. The set of S -singletons is defined as*

$$\S(S) := \{\{x\} : x \in S\}.$$

Now we proceed to define the expansion of \mathbb{I} with \mathbb{R}^* -singletons as the

Definition 3.13 (set of \mathbb{R}^* -Flakes). *Let $a, b \in \mathbb{F}$. The set of \mathbb{R}^* -Flakes is defined as*

$$\mathbb{F} := \mathbb{I} \sqcup \mathfrak{S}(\mathbb{R}^*).$$

To simplify notation, set the correspondences for $\underline{a}, \bar{a}, \tilde{a}, \underline{b}, \bar{b}, \tilde{b} \in \mathbb{R}^*$

$$\begin{aligned} a \in \mathbb{I} &\leftrightarrow a = (\underline{a}, \bar{a}) \\ a \in \mathfrak{S}(\mathbb{R}^*) &\leftrightarrow a = \{\tilde{a}\} \\ b \in \mathbb{I} &\leftrightarrow b = (\underline{b}, \bar{b}) \\ b \in \mathfrak{S}(\mathbb{R}^*) &\leftrightarrow b = \{\tilde{b}\} \end{aligned}$$

and use them to define the operations $\boxplus: \mathbb{F} \times \mathbb{F} \rightarrow \mathbb{F}$ defined as

$$(a, b) \mapsto \begin{cases} a \oplus b & a, b \in \mathbb{I} & (3.18a) \\ \begin{cases} \emptyset & \tilde{a} = \tilde{b} = \infty \\ \{\tilde{a} + \tilde{b}\} & \text{else} \end{cases} & a, b \in \mathfrak{S}(\mathbb{R}^*) & (3.18b) \\ \begin{cases} \begin{cases} \emptyset & \underline{b} \geq \bar{b} \\ \{\infty\} & \text{else} \end{cases} & \tilde{a} = \infty \\ \emptyset & \underline{b} = \bar{b} \\ (\tilde{a} + \underline{b}, \tilde{a} + \bar{b}) & \text{else} \end{cases} & a \in \mathfrak{S}(\mathbb{R}^*) \wedge b \in \mathbb{I} & (3.18c) \\ b \boxplus a & a \in \mathbb{I} \wedge b \in \mathfrak{S}(\mathbb{R}^*) & (3.18d) \end{cases}$$

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and, using $A = \{\tilde{a} \cdot \underline{b}, \tilde{a} \cdot \bar{b}\}$ for $\tilde{a}, \underline{b}, \bar{b} \in \mathbb{R}$, $\boxtimes: \mathbb{F} \times \mathbb{F} \rightarrow \mathbb{F}$ defined as

$$(a, b) \mapsto \left\{ \begin{array}{ll} a \otimes b & a, b \in \mathbb{I} \quad (3.19a) \\ \left\{ \begin{array}{ll} \emptyset & \tilde{a} = \infty \wedge \bar{b} \in \{0, \infty\} \\ \emptyset & \tilde{a} \in \{0, \infty\} \wedge \bar{b} = \infty \\ \{\tilde{a} \cdot \bar{b}\} & \text{else} \end{array} \right. & a, b \in \mathbb{S}(\mathbb{R}^*) \quad (3.19b) \\ \left\{ \begin{array}{ll} \left\{ \begin{array}{ll} \{\infty\} & \bar{b} < 0 \\ \emptyset & \text{else} \end{array} \right. & \underline{b} = \infty \\ \left\{ \begin{array}{ll} \{\infty\} & \bar{b} > 0 \\ \emptyset & \text{else} \end{array} \right. & \bar{b} = \infty \\ \emptyset & \underline{b} > \bar{b} \\ \{\infty\} & \text{sgn}(\underline{b}) = \text{sgn}(\bar{b}) \\ \emptyset & \text{else} \end{array} \right. & \tilde{a} = \infty \\ \left\{ \begin{array}{ll} (\infty, \tilde{a} \cdot \bar{b}) & \tilde{a} > 0 \\ (\tilde{a} \cdot \bar{b}, \infty) & \tilde{a} < 0 \\ \emptyset & \text{else} \end{array} \right. & \underline{b} = \infty \\ \left\{ \begin{array}{ll} (\tilde{a} \cdot \underline{b}, \infty) & \tilde{a} > 0 \\ (\infty, \tilde{a} \cdot \underline{b}) & \tilde{a} < 0 \\ \emptyset & \text{else} \end{array} \right. & \bar{b} = \infty \\ (\max(A), \min(A)) & \underline{b} > \bar{b} \\ \emptyset & \underline{b} = \bar{b} \\ (\min(A), \max(A)) & \text{else} \end{array} \right. & a \in \mathbb{S}(\mathbb{R}^*) \wedge b \in \mathbb{I} \quad (3.19c) \\ b \boxtimes a & a \in \mathbb{I} \wedge b \in \mathbb{S}(\mathbb{R}^*) \quad (3.19d) \end{array} \right.$$

The inverse element of $a \in \mathbb{F}$ for \boxplus is defined as

$$-a := \left\{ \begin{array}{ll} \{-\tilde{a}\} & a \in \mathbb{S}(\mathbb{R}^*) \\ \emptyset & a = \emptyset \\ \{-\bar{a}, -\underline{a}\} & \text{else} \end{array} \right. \quad a \in \mathbb{I}$$

and the inverse element of $a \in \mathbb{F}$ for \boxtimes is defined as

$$/a := \left\{ \begin{array}{ll} \{\tilde{a}^{-1}\} & a \in \mathbb{S}(\mathbb{R}^*) \\ \emptyset & a = \emptyset \\ \{\bar{a}^{-1}, \underline{a}^{-1}\} & \text{else} \end{array} \right. \quad a \in \mathbb{I}.$$

While this definition is definitely complex, we can see that going step by step and first defining operations on open \mathbb{R}^* -intervals alone makes it easier to prove well-definedness of those operations as a whole. It shall be noted here that \mathbb{R}^* -Flakes allow us to model closed and open sets on \mathbb{R}^* easily.

Theorem 3.14 (well-definedness of \mathbb{F}). \mathbb{F} is well-defined in terms of set theory.

Proof. One can see that the operations \boxplus and \boxtimes satisfy closedness with regard to \mathbb{F} . Symmetry is also satisfied given the explicit transposed forms (3.18d) for \boxplus and (3.19d) for \boxtimes and the fact that we have shown in Theorem 3.11 that \oplus and \otimes are symmetric.

Well-definedness in terms of set theory is based on the condition that for given $A, B \in \mathbb{F}$ the two operations \boxplus and \boxtimes must satisfy

$$A \boxplus B = \{a + b \mid a \in A \wedge b \in B\}$$

and

$$A \boxtimes B = \{a \cdot b \mid a \in A \wedge b \in B\}$$

respectively, except for cases where undefined behaviour occurs.

Let $a, b \in \mathbb{F}$ as in Definition 3.13.

(3.18a) We have shown in Proposition 3.11 that \boxplus is well-defined in terms of set theory.

(3.18b) This case corresponds to

$$\{\tilde{a}\} \boxplus \{\tilde{b}\}$$

and yields

$$\{\tilde{a} + \tilde{b}\}$$

unless $\tilde{a} = \tilde{b} = \infty$, which is undefined, where the empty set is returned.

(3.18c) This case corresponds to

$$\{\tilde{a}\} + (\underline{b}, \bar{b})$$

and yields $\{\infty\}$ if $\tilde{a} = \infty$ and b is not degenerate or empty, which yields the empty set. If $\tilde{a} \in \mathbb{R}$, it yields

$$(\tilde{a} + \underline{b}, \tilde{a} + \bar{b}),$$

for degenerate and non-degenerate b , unless b is empty, which yields the empty set.

The cases (3.19a), (3.19b) and (3.19c) for \boxtimes are shown analogously.

What remains to be shown is that the inverse elements are well-defined. One can see that the inverse elements are all closed under \mathbb{F} and map \emptyset to \emptyset . We now have to show that the operation of an element in \mathbb{F} with its respective inverse element results in a set containing the respective neutral elements of \mathbb{R}^* except where undefined behaviour occurs.

For \boxplus with ‘-’ and \boxtimes and ‘/’ we observe for singletons

$$\begin{aligned} \{\tilde{a}\} \boxplus -\{\tilde{a}\} &= \{\tilde{a}\} \boxplus \{-\tilde{a}\} = \{\tilde{a} - \tilde{a}\} = \{0\} \ni 0 \\ \{\tilde{a}\} \boxtimes / \{\tilde{a}\} &= \{\tilde{a}\} \boxtimes \{\tilde{a}^{-1}\} = \begin{cases} \emptyset & \tilde{a} = \infty \\ \{1\} \ni 1 & \text{else.} \end{cases} \end{aligned}$$

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Analogously, we observe for open \mathbb{R}^* -intervals with $(\underline{a}, \bar{a}) \neq \emptyset$

$$\begin{aligned} (\underline{a}, \bar{a}) \boxplus -(\underline{a}, \bar{a}) &= (\underline{a}, \bar{a}) \boxplus (-\bar{a}, -\underline{a}) = \begin{cases} \mathbb{R} \ni 0 & \underline{a} = \check{\infty} \vee \bar{a} = \check{\infty} \\ \emptyset & \underline{a} > \bar{a} \\ (\underline{a} - \bar{a}, \bar{a} - \underline{a}) \ni 0 & \text{else} \end{cases} \\ (\underline{a}, \bar{a}) \boxtimes /(\underline{a}, \bar{a}) &= (\underline{a}, \bar{a}) \boxtimes (\bar{a}^{-1}, \underline{a}^{-1}) = \begin{cases} \mathbb{R} \ni 1 & \underline{a} = \check{\infty} \vee \bar{a} = \check{\infty} \\ \emptyset & \underline{a} > \bar{a} \\ (\frac{\underline{a}}{\bar{a}}, \frac{\bar{a}}{\underline{a}}) \ni 1 & \text{else.} \end{cases} \end{aligned}$$

It follows the well-definedness of the inverse elements. \square

Now that we have shown well-definedness of \mathbb{F} , we can proceed with showing some useful properties that allow easier generalisations on Flakes. One of them is the

Definition 3.15 (\mathbb{R}^* -Flake evaluation of strictly increasing functions). *Let $f: \mathbb{R} \rightarrow \mathbb{R}$ be strictly increasing. The \mathbb{R}^* -Flake evaluation of f*

$$f_{\mathbb{F}}: \mathbb{F} \rightarrow \mathbb{F}$$

is defined with the notation $f(\check{\infty}) := \check{\infty}$ as

$$a \mapsto \begin{cases} \{f(\bar{a})\} & a = \{\bar{a}\} \in \mathcal{S}(\mathbb{R}^*) \\ (f(\underline{a}), f(\bar{a})) & a = (\underline{a}, \bar{a}) \in \mathbb{I}. \end{cases}$$

Proposition 3.16 (well-definedness of $\bullet_{\mathbb{F}}$). *The \mathbb{R}^* -Flake evaluation of strictly increasing functions is well-defined in terms of set theory.*

Proof. Let $f: \mathbb{R} \rightarrow \mathbb{R}$ be strictly increasing. We can see that $f_{\mathbb{F}}$ is closed in \mathbb{F} and maps \emptyset to \emptyset . For singletons well-definedness follows immediately, as it just corresponds to the singleton of the single function evaluation of f . In this context, $f(\check{\infty}) = \check{\infty}$, treating $\check{\infty}$ as an invariant object, is also consistent with the axioms of Definition 3.1, as

$$\lim_{x \uparrow \check{\infty}} (f(x)) = \lim_{x \downarrow \check{\infty}} (f(x)) = \check{\infty}.$$

For non-degenerate non-empty open \mathbb{R}^* -intervals the bounds grow accordingly, as

$$\forall \underline{a}, \bar{a} \in \mathbb{R}: \quad \underline{a} < \bar{a} \quad \Leftrightarrow \quad f(\underline{a}) < f(\bar{a}).$$

This also implies the well-definedness of the degenerate case, as for $\underline{a}, \bar{a} \in \mathbb{R}$ and $\underline{a} > \bar{a}$ it holds that

$$\begin{aligned} f_{\mathbb{F}}((\underline{a}, \bar{a})) &= f_{\mathbb{F}}((\bar{a}, \check{\infty})) \sqcup f_{\mathbb{F}}(\{\check{\infty}\}) \sqcup f_{\mathbb{F}}((\check{\infty}, \underline{a})) \\ &= (f_{\mathbb{F}}(\bar{a}), \check{\infty}) \sqcup \{\check{\infty}\} \sqcup (\check{\infty}, f_{\mathbb{F}}(\underline{a})) \\ &= (f_{\mathbb{F}}(\underline{a}), f_{\mathbb{F}}(\bar{a})). \end{aligned} \quad \square$$

Definition 3.17 (\mathbb{R}^* Flake evaluation of strictly decreasing functions). *Let $f: \mathbb{R} \rightarrow \mathbb{R}$ be strictly decreasing. The \mathbb{R}^* Flake evaluation of f*

$$f_{\mathbb{F}}: \mathbb{F} \rightarrow \mathbb{F}$$

is defined as

$$a \mapsto -((-f)_{\mathbb{F}}(a)).$$

With these results we have shown in general that we can evaluate strictly monotonic functions on \mathbb{R}^* -Flakes, for instance \exp or \ln confined to $\mathbb{R}_{\neq 0}^+$, which will be used later. We require strictly monotonic functions, as a constant function $f(x) = c \in \mathbb{R}$, that is monotonic but not strictly monotonic, would yield

$$f_{\mathbb{F}}((1, 2)) = (f(1), f(2)) = (c, c) = \emptyset,$$

which is not well-defined in terms of set theory.

Using the results obtained in this Chapter, we can now examine a discrete set of Unums as a subset of \mathbb{F} . This especially allows us to use those now well-defined operations and identify them on the set of Unums, provided we choose it properly.

4. Unum Arithmetic

This Chapter will construct the Unum arithmetic based on the results in Chapter 3 and the publications [Gus16a] and [Gus16b] by GUSTAFSON. We start off by examining the

Definition 4.1 (set of Unums). *Let*

$$P = \{p_1, \dots, p_n \mid \forall i < j : p_i < p_j\} \subset (1, \infty),$$

$p_0 := 1$ and $p_{n+1} := \infty$. *The set of Unums on the lattice P is defined as*

$$\begin{aligned} \mathbb{F} \supset \mathbb{U}(P) := & \bigsqcup_{i=1}^n [\{p_i\} \sqcup / \{p_i\} \sqcup - \{p_i\} \sqcup - / \{p_i\}] \sqcup \\ & \bigsqcup_{i=0}^n [\{(p_i, p_{i+1})\} \sqcup / (p_i, p_{i+1}) \sqcup \{-(p_i, p_{i+1})\} \sqcup \{- / (p_i, p_{i+1})\}] \sqcup \\ & \{1\} \sqcup \{-1\} \sqcup \{0\} \sqcup \{\infty\} \end{aligned}$$

Remark 4.2. *By Definition 4.1, \mathbb{U} is closed under inversion with regard to \boxplus and \boxtimes .*

In regard to \mathbb{F} , Remark 4.2 underlines the fact that this choice for \mathbb{U} , generated by a set of lattice points between $(1, \infty)$, is in fact a good one. We will now proceed to derive some elemental properties of \mathbb{U} and prepare it to define operations on it.

Proposition 4.3 (cardinality of \mathbb{U}). *Let P as in Definition 4.1. The number of Unums is*

$$|\mathbb{U}| = 8 \cdot (|P| + 1).$$

Proof. Each quadrant of \mathbb{R}^* is filled with $|P|$ lattice points and $|P| + 1$ intervals. Added to this are the 4 fixed points $1, -1, 0, \infty$. It follows from Definition 4.1 of $|\mathbb{U}|$ as a disjoint union of finite sets that

$$|\mathbb{U}| = 4 \cdot |P| + 4 \cdot (|P| + 1) + 4 = 4 \cdot (2 \cdot |P| + 2) = 8 \cdot (|P| + 1). \quad \square$$

Before we proceed with constructing operations on the set of Unums, we first have to define the

Definition 4.4 (power set). *Let S be a set. The power set of S is defined as*

$$\mathcal{P}(S) := \{s \subseteq S\}.$$

To use the results we have derived for \mathbb{F} , we need to find a way to ‘blur’ \mathbb{R}^* -Flakes into sets of Unums. For this purpose, we define the

4. Unum Arithmetic

Definition 4.5 (blur operator). *Let P as in Definition 4.1. The blur operator*

$$\text{bl}: \mathbb{F} \rightarrow \mathcal{P}(\mathbb{U}(P))$$

is defined as

$$f \mapsto \{u \in \mathbb{U} : f \subseteq u\}.$$

We are now able to embed \mathbb{R}^* -Flakes into subsets of \mathbb{U} , which allows us to define operations on \mathbb{U} by identifying them with operations on \mathbb{F} using the bl-operator.

Remark 4.6 (dependent sets and dependency problem). *It is not within the scope of this thesis to elaborate on the theory of dependent sets, and there are multiple ways to approach it. To give a simple example, evaluating for $A = (-1, 1) \in \mathbb{I}$*

$$A - A$$

is expected to yield $\{0\}$, but using interval arithmetic, the expression just decays to

$$(-1, 1) - (-1, 1) = (-1, 1) + (-1, 1) = (-2, 2),$$

effectively doubling the width of the interval. This is known as the dependency problem.

It is in our interest to find an approach to limit this problem. As follows, we will denote two dependent sets S_1 and S_2 with $S_1 \sim S_2$, and with regard to the example given above, it holds that $A \sim A$.

To approach the dependency problem, we only evaluate pairwise operations for dependent sets. The underlying idea is that if a given value is present in the first set within a Unum, the dependency guarantees it will also only be within this Unum in the second set. We identify operations on \mathbb{F} with operations on \mathbb{U} by defining the

Definition 4.7 (dual Unum operation). *Let $\star: \mathbb{F} \times \mathbb{F} \rightarrow \mathbb{F}$ be an operation on \mathbb{F} and P as in Definition 4.1. The dual Unum operation*

$$\langle \star \rangle: \mathcal{P}(\mathbb{U}(P)) \times \mathcal{P}(\mathbb{U}(P)) \rightarrow \mathcal{P}(\mathbb{U}(P))$$

is defined as

$$(U, V) \mapsto \bigcup_{u \in U} \bigcup_{v \in V} \begin{cases} \emptyset & U \sim V \wedge u \neq v \\ \mathbb{R}^* & u \star v = \emptyset \\ \text{bl}(u \star v) & \text{else.} \end{cases}$$

Remark 4.8 (NaN for Unum operations). *As one can see in Definition 4.7, when an \mathbb{R}^* -Flake operation \star yields the empty set, indicating an empty set or that undefined behaviour was witnessed, the Unum arithmetic proposed by GUSTAFSON in [Gus16b, Table 2] mandates that the respective dual Unum operation yields \mathbb{R}^* .*

This is not the ideal behaviour, as we carefully defined \boxplus and \boxtimes to give the empty set if one operand is the empty set, $-\emptyset = \emptyset$ and $/\emptyset = \emptyset$. This behaviour is useful, as just like NaN for floating-point numbers, which, once it occurs, is carried through the entire stream of floating-point calculations, the empty set plays this special role in the Unum context.

In the interest of staying compatible with the Unum format proposed by GUSTAFSON, this weak spot in the proposal was implemented in the Unum toolbox anyway.

Definition 4.9. (Unum evaluation of strictly increasing functions) Let $f: \mathbb{R} \rightarrow \mathbb{R}$ be strictly increasing. The Unum evaluation of f

$$\langle f_{\mathbb{F}} \rangle: \mathcal{P}(\mathbb{U}(P)) \rightarrow \mathcal{P}(\mathbb{U}(P))$$

is defined as

$$U \mapsto \bigcup_{u \in U} \text{bl}(f_{\mathbb{F}}(u)).$$

Definition 4.10 (Unum evaluation of strictly decreasing functions). Let $f: \mathbb{R} \rightarrow \mathbb{R}$ be strictly decreasing. The Unum evaluation of f

$$\langle f_{\mathbb{F}} \rangle: \mathcal{P}(\mathbb{U}(P)) \rightarrow \mathcal{P}(\mathbb{U}(P))$$

is defined as

$$U \mapsto \bigcup_{u \in U} \text{bl}(-((-f)_{\mathbb{F}}(u))).$$

4.1. Lattice Selection

Until now, we have worked with arbitrary P . This set of lattice points is the only parametrisation for \mathbb{U} , so we want to investigate what the ideal construction of P is.

4.1.1. Linear Lattice

The simplest approach is a linear distribution of p lattice points up to a maximum value $m \in (1, \infty)$.

Definition 4.11 (linear Unum lattice). Let $p \in \mathbb{N}$ and $m \in (1, \infty)$. The linear Unum lattice with p lattice points and maximum m is defined as

$$P_L(p, m) := \left\{ p_i := 1 + i \cdot \frac{m-1}{p} \mid i \in \{1, \dots, p\} \right\}.$$

Proposition 4.12 (well-definedness of the linear Unum lattice). Let $p \in \mathbb{N}$ and $m \in (1, \infty)$. $P_L(p, m)$ is well-defined in terms of Definition 4.1.

Proof. The desired properties $|P_L(p, m)| = p$ and $\max(P_L(p, m)) = m$ follow from Definition 4.11. We show that

$$\forall i > j : p_i > p_j.$$

This is given because $m - 1 > 0$ and

$$p_i - p_j = (i - j) \cdot \frac{m-1}{p} > 0.$$

The proof is finished by showing that $p_i \in (1, \infty)$. It suffices to prove that $p_1, p_p \in (1, \infty)$, as $\forall i > j : p_i > p_j$ and the boundary points dictate the behaviour of the interior points.

$$p_1 = 1 + \frac{m-1}{p} \in (1, \infty)$$

$$p_p = 1 + m - 1 = m \in (1, \infty) \quad \square$$

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The problem with a linear Unum lattice is the lack of dynamic range. Just like with floating-point numbers, we want a dense distribution of lattice points around 1 and a lighter distribution the further we move away from 1. As we can deduce from this observation, a desired quality of the Unum lattice could be, for instance, an exponential distribution.

4.1.2. Exponential Lattice

Definition 4.13 (exponential Unum lattice). *Let $p \in \mathbb{N}$ and $m \in (1, \infty)$. The exponential Unum lattice with p lattice points and maximum m is defined as*

$$P_E(p, m) := \left\{ p_i := \exp\left(i \cdot \frac{\ln(m)}{p}\right) \mid i \in \{1, \dots, p\} \right\}.$$

Proposition 4.14 (well-definedness of the exponential Unum lattice). *Let $p \in \mathbb{N}$ and $m \in (1, \infty)$. $P_E(p, m)$ is well-defined in terms of Definition 4.1.*

Proof. The desired properties $|P_E(p, m)| = p$ and $\max(P_E(p, m)) = m$ follow from Definition 4.13. We show that

$$\forall i > j : p_i > p_j.$$

This is given because \exp is strictly monotonically increasing and

$$p_i - p_j = \exp\left(i \cdot \frac{\ln(m)}{p}\right) - \exp\left(j \cdot \frac{\ln(m)}{p}\right) > 0.$$

The proof is finished by showing that $p_i \in (1, \infty)$.

$$p_i = \exp\left(i \cdot \frac{\ln(m)}{p}\right) > \exp(0) = 1 \quad \square$$

The problem of an exponential Unum lattice is that the lattice points may have an ideal distribution, but fall onto rather inaccessible points. For such a number system to work, it has to contain a decent amount of integers, which is not the case here.

4.1.3. Decade Lattice

A different approach is to specify the number of desired significant decimal digits of each lattice point and fill the set by scaling with multiples of 10. For example, specifying 1 significant digit yields

$$P = \{2, 3, \dots, 9, 10, 20, 30, \dots, 90, 100, 200, 300, \dots\}.$$

We define this formally, using the remainder of the EUCLIDEAN division of a by b , denoted by $a \bmod b$ for $a \in \mathbb{N}_0$ and $b \in \mathbb{N}$, as the

Definition 4.15 (decade Unum lattice). *Let $p \in \mathbb{N}_0$ and $s \in \mathbb{N}$. The decade Unum lattice with p lattice points and s significant digits is defined as*

$$P_D(p, s) := \left\{ p_i := \left[1 + 10^{-(s-1)} \cdot (i \bmod (10^s - 10^{s-1})) \right] \cdot 10^{\left\lfloor \frac{i}{10^s - 10^{s-1}} \right\rfloor} \mid i \in \{1, \dots, p\} \right\}.$$

Proposition 4.16 (well-definedness of the decade Unum lattice). *Let $p \in \mathbb{N}_0$ and $s \in \mathbb{N}$. $P_D(p, s)$ is well-defined in terms of Definition 4.1.*

Proof. The desired property $|P_E(p, m)| = p$ follows from Definition 4.15. We show that

$$\forall i, j \in \{1, \dots, p\} : i > j : p_i > p_j.$$

This is trivial for $p = 1$. For $p > 1$ and $i \in \{1, \dots, p-1\}$ we note that for $m \in \mathbb{N}$ it holds that

$$\begin{aligned} (i+1) \bmod m = 0 &\Rightarrow \left\{ \begin{array}{l} i \bmod m = m-1 \\ \exists n \in \mathbb{N}_0 : (i+1) = n \cdot m \end{array} \right\} \\ &\Rightarrow \left\{ \begin{array}{l} \lfloor \frac{i+1}{m} \rfloor = \lfloor n \rfloor = n \\ \lfloor \frac{i}{m} \rfloor = n-1 \end{array} \right\} \\ &\Rightarrow \lfloor \frac{i+1}{m} \rfloor = \lfloor \frac{i}{m} \rfloor + 1 \end{aligned}$$

and obtain

$$\begin{aligned} p_{i+1} - p_i &= \left[1 + 10^{-(s-1)} \cdot \left((i+1) \bmod (10^s - 10^{s-1}) \right) \right] \cdot 10^{\lfloor \frac{i+1}{10^s - 10^{s-1}} \rfloor} - \\ &\quad \left[1 + 10^{-(s-1)} \cdot \left(i \bmod (10^s - 10^{s-1}) \right) \right] \cdot 10^{\lfloor \frac{i}{10^s - 10^{s-1}} \rfloor} \\ &\geq \left[1 + 10^{-(s-1)} \cdot 0 \right] \cdot 10^{\lfloor \frac{i}{10^s - 10^{s-1}} \rfloor + 1} - \\ &\quad \left[1 + 10^{-(s-1)} \cdot (10^s - 10^{s-1} - 1) \right] \cdot 10^{\lfloor \frac{i}{10^s - 10^{s-1}} \rfloor} \\ &= \left[10 - 1 - 10^{-(s-1)+s} + 10^{-(s-1)+s-1} + 10^{-(s-1)} \right] \cdot 10^{\lfloor \frac{i}{10^s - 10^{s-1}} \rfloor} \\ &= 10^{-(s-1)} \cdot 10^{\lfloor \frac{i}{10^s - 10^{s-1}} \rfloor} \\ &> 0. \end{aligned}$$

The proof is finished by showing that $p_i \in (1, \infty)$.

$$\begin{aligned} p_i &= \left[1 + 10^{-(s-1)} \cdot \left(i \bmod (10^s - 10^{s-1}) \right) \right] \cdot 10^{\lfloor \frac{i}{10^s - 10^{s-1}} \rfloor} \\ &\geq 1 + 10^{-(s-1)} \cdot \left(i \bmod (10^s - 10^{s-1}) \right) \\ &> 1 \end{aligned} \quad \square$$

Proposition 4.17 (maximum of the decade Unum lattice). *Let $p \in \mathbb{N}_0$ and $s \in \mathbb{N}$. The maximum of the decade Unum lattice is*

$$\max \{P_D(p, s)\} = \left(1 + 10^{-(s-1)} \cdot \left[p \bmod (10^s - 10^{s-1}) \right] \right) \cdot 10^{\lfloor \frac{p}{10^s - 10^{s-1}} \rfloor}.$$

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Proof. As shown in the proof of Proposition 4.16, $\forall i > j : p_i > p_j$ and thus

$$\max \{P_D(p, s)\} = p_p = \left(1 + 10^{-(s-1)} \cdot \left[p \bmod \left(10^s - 10^{s-1}\right)\right]\right) \cdot 10^{\left\lfloor \frac{p}{10^s - 10^{s-1}} \right\rfloor}. \quad \square$$

Comparing the resulting distribution to an exponential curve fitted to the boundary-points, as shown in Figure 4.1, one can see that a nearly exponential distribution has been achieved. As we can see, the decade Unum lattice is a good compromise between a linear and an exponential Unum lattice.

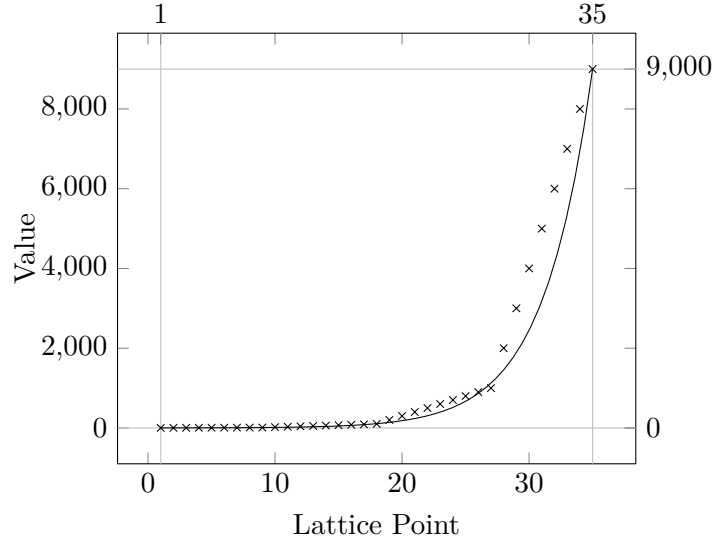


Figure 4.1.: $P_D(35, 1)$ (demarcated by crosses) in comparison with an exponential curve fitted to the endpoints $(0, 0)$ and $(35, \max(P_D(35, 1)))$.

4.2. Machine Implementation

The goal of a machine implementation for Unums is to find a model for $\mathcal{P}(\mathbb{U}(P))$ on a specially chosen lattice P . This means the ability to model subsets of \mathbb{R}^* using multiple Unums, including degenerate intervals.

4.2.1. Unum Enumeration

We start off with the definition of the

Definition 4.18 (ascension operator). *Let $(S, <)$ be a finite strictly ordered set. The ascension operator*

$$\text{asc}: S \times \{1, \dots, |S|\} \rightarrow S$$

is defined for

$$s_i \in \{s_i \mid i \in \{1, \dots, |S|\} \wedge s_1 < \dots < s_{|S|}\} = S$$

as

$$(S, n) \mapsto s_n$$

Using the ascension operator, we enumerate the elements in $\mathbb{U}(P)$ with P as in Definition 4.1, taking note that $\mathbb{U}(P) \cap \mathcal{P}((0, 1))$, $\mathbb{U}(P) \cap \mathcal{P}((1, \infty))$, $\mathbb{U}(P) \cap \mathcal{P}((\infty, -1))$ and $\mathbb{U}(P) \cap \mathcal{P}((-1, 0))$ are finite strictly ordered sets. In other words, we define a mapping from $\{0, \dots, |\mathbb{U}(P)| - 1\}$, which is $\{0, \dots, 8 \cdot (|P| + 1) - 1\}$ according to Proposition 4.3, into $\mathbb{U}(P)$, called the

Definition 4.19 (Unum enumeration). *Let P as in Definition 4.1. The Unum enumeration*

$$u: \{0, \dots, |\mathbb{U}(P)| - 1\} \rightarrow \mathbb{U}(P)$$

is defined as

$$n \mapsto \begin{cases} \{0\} & n = 0 \cdot (|P| + 1) \\ \text{asc}(\mathbb{U}(P) \cap \mathcal{P}((0, 1)), n - 0 \cdot (|P| + 1)) & 0 \cdot (|P| + 1) < n < 2 \cdot (|P| + 1) \\ \{1\} & n = 2 \cdot (|P| + 1) \\ \text{asc}(\mathbb{U}(P) \cap \mathcal{P}((1, \infty)), n - 2 \cdot (|P| + 1)) & 2 \cdot (|P| + 1) < n < 4 \cdot (|P| + 1) \\ \{\infty\} & n = 4 \cdot (|P| + 1) \\ \text{asc}(\mathbb{U}(P) \cap \mathcal{P}((\infty, -1)), n - 4 \cdot (|P| + 1)) & 4 \cdot (|P| + 1) < n < 6 \cdot (|P| + 1) \\ \{-1\} & n = 6 \cdot (|P| + 1) \\ \text{asc}(\mathbb{U}(P) \cap \mathcal{P}((-1, 0)), n - 6 \cdot (|P| + 1)) & 6 \cdot (|P| + 1) < n < 8 \cdot (|P| + 1). \end{cases}$$

Remark 4.20 (enumeration of infinity). *For arbitrary $\mathbb{U}(P)$ with P as in Definition 4.1 it follows that*

$$u\left(\frac{|\mathbb{U}(P)|}{2}\right) = \{\infty\}.$$

To describe the enumeration intuitively, we cut the \mathbb{R}^* -circle at 0 and trace all Unums from 0 to 0 in a counter-clockwise direction. In the machine the Unum enumeration mapping can be realised using unsigned integers. One can deduce that for a given number of *Unum bits* $n_b \in \mathbb{N}$ an unsigned n_b -bit integer can represent 2^{n_b} values, namely 0 through $2^{n_b} - 1$.

Even though in theory the size of $|P|$ can be arbitrary, as it is the case for the provided toolbox, one must respect the fundamental data-types in a machine, resulting in the limitation $n_b \in \{8, 16, 32, 64, \dots\}$ in the interest of not wasting any bit patterns in the process. It follows that we are interested in finding out the required lattice size for a given n_b .

Proposition 4.21 (lattice size depending on Unum bits). *Let $n_b \in \mathbb{N}$, $n_b > 2$ and P as in Definition 4.1. Given n_b Unum bits it follows that*

$$|P| = 2^{n_b-3} - 1.$$

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Proof. With n_b Unum bits it follows that $|\mathbb{U}(P)| = 2^{n_b}$. According to Proposition 4.3 we know that $|\mathbb{U}(P)| = 8 \cdot (|P| + 1)$ and thus

$$2^{n_b} = 8 \cdot (|P| + 1) = 2^3 \cdot (|P| + 1) \quad \Leftrightarrow \quad |P| = 2^{n_b-3} - 1 \quad \square$$

According to the results obtained in Section 4.1, we will only take decade lattices into account. We are led to the

Definition 4.22 (set of machine Unums). *Let $n_b \in \mathbb{N}$, $n_b > 2$ and $n_s \in \mathbb{N}$. The set of machine Unums with n_b bits and n_s significant digits is defined as*

$$\mathbb{U}_M(n_b, n_s) := \mathbb{U}(P_D(2^{n_b-3} - 1, n_s)).$$

Having found an expression for machine Unums, it is now possible to represent arbitrary elements of $\mathcal{P}(\mathbb{U}_M(n_b, n_s))$ in the machine to model sets of real numbers.

4.2.2. Operations on Sets of Real Numbers

Unums alone are not very useful for arithmetic purposes, given the nature of dual Unum operations (see Definition 4.7), which we want to illustrate with the following example.

Example 4.23. *Let $P = \{2, 3.5, 5, 6\}$, which satisfies Definition 4.1. We see that $(1, 2), \{3.5\} \in \mathbb{U}(P)$, but*

$$\text{bl}((1, 2) \boxplus \{3.5\}) = \text{bl}((4.5, 5.5)) = \{(3.5, 5), \{5\}, (5, 6)\} \notin \mathbb{U}(P).$$

The basic datatype, thus, has to be an element of $\mathcal{P}(\mathbb{U}_M(n_b, n_s))$. Given this set is finite with $2^{(|\mathbb{U}_M(n_b, n_s)|)} = 2^{2^{n_b}}$ elements, a bit string of length 2^{n_b} can represent all elements of $\mathcal{P}(\mathbb{U}_M(n_b, n_s))$. We call this bit string a ‘SORN’ for ‘set of real numbers’.

Operations on SORNs are carried out in the machine by having lookup tables (LUTs) for $\text{bl}(u(i) \star u(j))$, where $\star \in \{\boxplus, \boxtimes\}$ is an \mathbb{R}^* -Flake-operation evaluated for arbitrary Unum-indices $i, j \in \{0, \dots, 2^{n_b} - 1\}$. Given \boxplus and \boxtimes are associative, limiting the lookup table to $i \leq j$ is sufficient, resulting in a triangular array for each operation.

The results $\text{bl}(u(i) \star u(j))$, being connected subsets of $\mathbb{U}_M(n_b, n_s)$, can be expressed as an oriented range $[u(m), u(n)]$ with $m, n \in \{0, \dots, 2^{n_b} - 1\}$ and $m \leq n$, containing all Unums between $u(m)$ and $u(n)$. This can be stored in the machine as indices $\{m, n\}$ each taking up n_b bit of storage. Thus, each table entry takes up $2 \cdot n_b$ bit of storage.

Proposition 4.24 (size of LUTs). *The Unum LUTs for \boxplus and \boxtimes take up $n_b \cdot 2^{n_b+1} \cdot (2^{n_b} + 1)$ bit.*

Proof. With 2^{n_b} rows, we know that each LUT has $\sum_{i=1}^{2^{n_b}} i$ entries. Using the Gauß summation formula and the facts that each entry takes up $2 \cdot n_b$ bit and we have two operations and, thus, two LUTs, the total storage size is

$$2 \cdot (2 \cdot n_b) \cdot \left(\sum_{i=1}^{2^{n_b}} i \right) \text{ bit} = 4 \cdot n_b \cdot \left(\frac{2^{n_b} \cdot (2^{n_b} + 1)}{2} \right) \text{ bit} = n_b \cdot 2^{n_b+1} \cdot (2^{n_b} + 1) \text{ bit.} \quad \square$$

With the lookup tables constructed, operations on SORNs are analogous to dual Unum operations (see Definition 4.7), with the only difference that the set union for the bit strings is realised with a bitwise OR.

4.2.3. Unum Toolbox

To examine the numerical properties of Unums, there needs to be a toolbox to see how this concept works out inside the machine. The reason why a new toolbox was developed in the course of this thesis is that all other toolboxes available at the time of writing are not using LUTs to do calculations. Instead, they emulate Unum-arithmetic with floating-point numbers that are mapped to a given lattice.

To give an answer to the question if Unums could in theory replace floating-point numbers for some applications, it is necessary to avoid floating-point arithmetic at runtime as much as possible. A possible future machine implementing Unums in hardware would also be constrained to LUTs and would not be able to use floating-point numbers in the process and at the same time leverage the energy and complexity savings projected by GUSTAFSON in [Gus16b].

The Unum toolbox programmed in the course of this thesis and used to examine the numerical behaviour of Unums in Section 4.3 is split up in two parts. The first part is the environment generator `gen` (see Listing B.2.1), generating the LUTs in `table.c`, based on type definitions in `table.h` (see Listing B.2.2) and the environment parameters in `config.mk` (see Listing B.2.4), and the lattice-specific toolbox-header `unum.h`. The choice of lattice points can be arbitrary and it is relatively simple to extend the generator, but because of the results obtained in Section 4.1 only the generating function for a decade Unum lattice is implemented (see `gendeclattice()` in Listing B.2.1).

The second part is the toolbox itself (see Listing B.2.3), working with the previously generated `table.c` and `unum.h`, but being lattice-agnostic in general. The fundamental data type for operations is `SORN` defined in `unum.h`, corresponding to the `SORN`-concept constructed earlier. Just as proposed by GUSTAFSON in [Gus16b, Section 3.2], the `SORN` is a bit array on which operations are carried out as proposed and close to how it would happen in a native machine implementation.

The provided toolbox functions (see `unum.h` and Listing B.2.3) are of both arithmetic and set theoretical nature. The arithmetic functions corresponding to addition and subtraction are `uadd()` and `usub()`. Addition in this context means the dual Unum operation $\langle \boxplus \rangle$ using the addition LUT `addtable` in `table.c`. Subtraction is achieved by negating the second argument on a per-Unum basis and performing an addition, preserving set-dependencies if present. Analogously, there are `umul()` and `udiv()` for multiplication and division using $\langle \boxtimes \rangle$ and the multiplication LUT `multable` in `table.c`. The arithmetic functions `uneg()` and `uinv()` negate and invert a `SORN` respectively on a per-Unum basis corresponding to the \mathbb{R}^* -Flake negation ‘ $-$ ’ and inversion ‘ $/$ ’. The function `uabs()` corresponds to a Unum modulus function and the `uog()` function is an implementation of the `ln` function on Unums using the LUT `logtable`.

`SORN` operations and modifications are generalised in the functions `_sornop()` and `_sornmod()` in Listing B.2.3 respectively. They are the foundation for almost all arithmetic functions of this toolbox. Dependent sets are detected by comparing the two pointers to the operands passed to the arithmetic functions. If they are equal, the sets are dependent.

The set theoretical functions are `uemp()` and `uset()` for emptying and setting `SORN`s,

4. Unum Arithmetic

`ucut()` and `uuni()` for cutting and taking the union of two SORNs and `uequ()` and `usup()` to check if two SORNs are equal and if one SORN is the superset of another.

The input and output functions play a special role in this toolbox. `uint()` is the only function using floating point numbers to add a closed interval to a SORN and `uout()` prints a SORN in a human-readable format to standard output.

When using the Unum toolbox, only the components `unum.h` and the static library `libunum.a` are relevant and need to be present when compiling programs using the Unum toolbox (see Section B.3). All functions are reentrant and, thus, thread-safe.

4.3. Revisiting Floating-Point-Problems

Using the toolbox presented in Subsection 4.2.3, we implement the IEEE 754 floating-point problems studied in Section 2.4 and examine their behaviour within the Unum arithmetic. For all examples in this section the environment was set to $(n_b, n_s) = (12, 2)$.

4.3.1. The Silent Spike

We can express the spike function (2.2) within the Unum arithmetic, using a LUT-based natural logarithm

$$\text{LN}: \mathcal{P}(\mathbb{U}(P)) \rightarrow \mathcal{P}(\mathbb{U}(P))$$

defined as

$$U \mapsto \begin{cases} \langle \ln_{\mathbb{F}} \rangle(U) & U \cap \mathcal{P}((-\infty, 0]) = \emptyset \\ \emptyset & \text{else} \end{cases}$$

(see `uilog()` in Listing B.2.3) and an elementary Unum modulus function $|\cdot|$ (see `uabs()` in Listing B.2.3), as

$$F(X) := \text{LN}(|\text{bl}(\{3\}) \boxtimes (\text{bl}(\{1\}) \boxplus -X) \boxplus \text{bl}(\{1\})|). \quad (4.1)$$

As we have previously evaluated f in an environment of all floating-point numbers of the singularity at $\frac{4}{3}$ (see Figure 2.2), we evaluate F in an environment of all Unums of the singularity $\text{bl}(\frac{4}{3})$ using the Unum toolbox (see Listing B.3.4). The behaviour is exhibited in Figure 4.2 and it can be observed that the spike is not hidden any more as was the case with the floating-point implementation.

This shows that Unums can effectively be used to quickly evaluate guaranteed bounds for a given function and observe singular behaviour without taking the risk of missing it. The bounds are guaranteed as the foundation for the Unum arithmetic are the well-defined operations on \mathbb{R}^* -Flakes (see Definition 3.13 and Theorem 3.14).

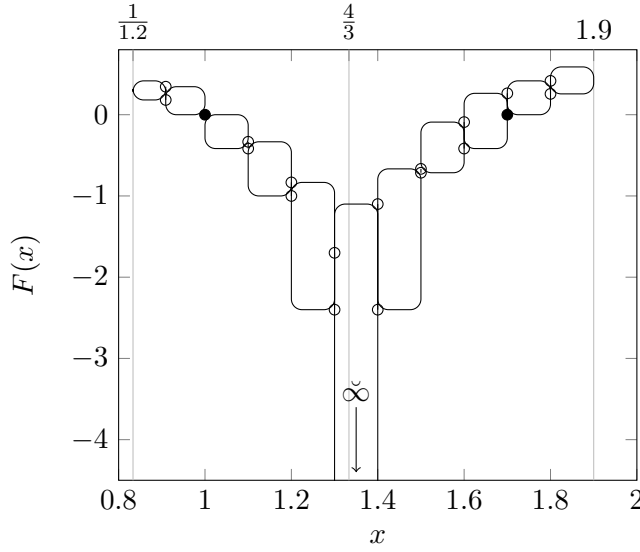


Figure 4.2.: Evaluation of the Unum spike function F (see (4.1)) on all Unums in $[\frac{1}{1.2}, 1.9]$ with $(n_b, n_s) = (12, 2)$ (o/• demarks open/closed interval endpoints); see Listing B.3.4.

4.3.2. Devil's Sequence

The devil's sequence is translated into Unum arithmetic by transforming (2.3) into the equivalent SORN-sequence

$$U_n := \begin{cases} \text{bl}(\{2\}) & n = 0 \\ \text{bl}(\{-4\}) & n = 1 \\ \text{bl}(\{111\}) \boxplus -\text{bl}(\{1130\}) \boxtimes /U_{n-1} \boxplus \text{bl}(\{3000\}) \boxtimes / (U_{n-1} \boxtimes U_{n-2}) & n \geq 2. \end{cases}$$

Running the Unum toolbox implementation (see Listing B.3.2) of this problem, we obtain

$$U_{25} = \mathbb{R}^*.$$

This indicates the instability of the problem posed. Even though the information loss is great, this result can at least be a warning to investigate the numerical behaviour of the given sequence.

4.3.3. The Chaotic Bank Society

Taking a look at the chaotic bank society problem, we determine the equivalent SORN-sequence to (2.5) as

$$A_n := \begin{cases} A_0 & n = 0 \\ A_{n-1} \boxtimes \text{bl}(\{n\}) \boxplus -\text{bl}(\{1\}) & n \geq 1. \end{cases}$$

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Again, running the Unum toolbox implementation (see Listing B.3.3), we obtain for $A_0 = \text{bl}(\{e - 1\}) = (1.7, 1.8)$

$$A_{25} = \mathbb{R}^*.$$

This is consistent with the theoretical results we obtained, given we can find an $\varepsilon > 0$ such that A_0 contains $e - 1 + \delta$ with $\delta \in (-\varepsilon, \varepsilon)$, as $e - 1 \notin P_D(2^{n_b-3} - 1, n_d)$.

We observe that, even though the results do not lie about the solution, the information loss is great.

Concluding, introducing Unums as a number format allowing you to neglect stability analysis has turned out to be a false promise. We can also not sustain the notion that naïvely implementing algorithms in Unums abolishes the need for a break condition. Besides complete information loss, sticking- and creeping-effects elaborated in Subsection 4.4.2 additionally make it difficult to think of proper ways to do that.

4.4. Discussion

With the theoretical formulation of Unums and practical results, it is now time to discuss the format taking into account the results obtained in the previous chapters.

4.4.1. Comparison to IEEE 754 Floating-Point Numbers

It is of central interest to see how the Unums hold up to the previously introduced IEEE 754 floating-point numbers. To illustrate the behaviour of the machine Unums, different parameters of the systems are laid out in Table 4.1.

n_b (bit)	8	16	32	64
n_s	1	3	7	15
$ P_D $	$= 3.10 \cdot 10^{+1}$	$\approx 8.19 \cdot 10^{+3}$	$\approx 5.37 \cdot 10^{+8}$	$\approx 2.31 \cdot 10^{+18}$
$ \mathbb{U}_M $	$= 2.56 \cdot 10^{+2}$	$\approx 6.55 \cdot 10^{+4}$	$\approx 4.29 \cdot 10^{+9}$	$\approx 1.84 \cdot 10^{+19}$
$\max(P_D)$	$= 5.00 \cdot 10^{+3}$	$= 1.91 \cdot 10^{+9}$	$\approx 6.87 \cdot 10^{+59}$	$\approx 1.43 \cdot 10^{+2562}$
$\max(P_D)^{-1}$	$= 2.00 \cdot 10^{-4}$	$\approx 5.24 \cdot 10^{-10}$	$\approx 1.45 \cdot 10^{-60}$	$\approx 6.99 \cdot 10^{-2563}$
Size of LUTs	≈ 132 kB	≈ 17 GB	$\approx 1.48 \cdot 10^{20}$ B	$\approx 5.44 \cdot 10^{39}$ B

Table 4.1.: Machine Unums properties for $n_b \in \{8, 16, 32, 64\}$ and n_s selected to match IEEE 754 significant decimal digits ($= \lfloor \log_{10}(2^{n_m+1}) \rfloor$) for each storage size.

Comparing Table 4.1 to Table 2.1, we note that for the same number of storage bits, the dynamic range, the ratio of the largest and smallest representable numbers, of Unums is orders of magnitude larger than that of IEEE 754 floating-point numbers. For example, with a storage size of 16 bit, the dynamic range of IEEE 754 floating-point numbers is

$$\frac{\max(\mathbb{M}_1)}{\min(\mathbb{M}_0 \cap \mathbb{R}_{\neq 0}^+)} \approx \frac{6.55 \cdot 10^{+4}}{5.96 \cdot 10^{-8}} \approx 1.10 \cdot 10^{12}.$$

For Unums, we obtain

$$\frac{\max(P_D)}{\max(P_D)^{-1}} \approx \frac{1.91 \cdot 10^{+9}}{5.24 \cdot 10^{-10}} \approx 3.65 \cdot 10^{18}$$

respectively, which is an increase of roughly 6 orders of magnitude. The reason for this significant difference is the fact that no bit patterns are wasted for NaN-representations in the Unum number format.

On the other hand, one can see that any values for n_b beyond roughly 12 bit (corresponding to a LUT size of ≈ 50 MB) is not feasible given the huge size of the LUTs. It shows that we can only really reason about machine Unum environments with $n_b \in \{3, \dots, 12\}$.

4.4.2. Sticking and Creeping

Working with the Unum toolbox, two effects seem to influence iterative calculations substantially. A fitting description would be to call them *sticking-* and *creeping-effects* respectively. They can be observed, for instance, when evaluating infinite series within the Unum arithmetic, and this example will be examined here.

Example 4.25 (EULER's number). *Determining EULER's number in the Unum arithmetic can be done by defining a SORN-series E_n satisfying*

$$\text{bl}(\{e\}) \in \lim_{n \rightarrow \infty} (E_n),$$

where

$$E_n := \left\langle \bigoplus_{k=0}^n \left[\bigoplus_{\ell=0}^k \text{bl}(\{\ell\}) \right] \right\rangle, \quad (4.2)$$

which corresponds to the partial sums of the infinite series representation of e as

$$e = \sum_{k=0}^{\infty} \frac{1}{k!},$$

Using the Unum toolbox (see Listing B.3.1), the partial sums of this problem are visualised in Figure 4.3. The first 21 iterates are depicted and illustrate a pathological behaviour.

Starting from $n = 3$, the lower bound of the solution set is stuck at the value 2.6. One can also observe that the upper bound is growing linearly on each iteration. It creeps away from e and reduces the quality of the solution with each step.

The cause of these sticking- and creeping-effects is the fact that we add infinitesimally small values to the SORN on each iteration. The lower bound gets stuck because the value added is smaller than the length of the lowest interval, hitting a blind spot of the blur function. The upper bound creeps away because even though we add an infinitesimally small value, it expands to at least the next following Unum value.

4. Unum Arithmetic

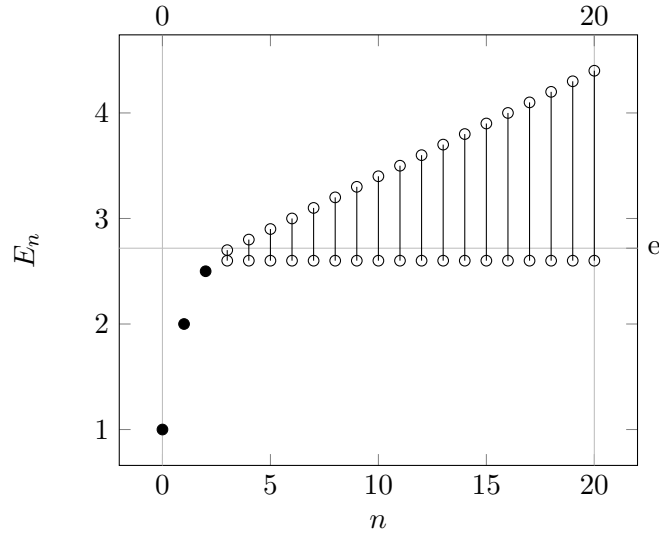


Figure 4.3.: Evaluation of the Unum EULER partial sums (4.2) for iterations $n \in \{0, \dots, 20\}$ with $(n_b, n_s) = (12, 2)$ (\circ/\bullet demarks open/closed interval endpoints); see Listing B.3.1.

This problem makes it impossible to work with Unums to examine infinite series or sequences and iterative problems in general. Even though Unums do not lie about the solution, the quality of it is decreased on each iteration, as we could already see in Subsections 4.3.2 and 4.3.3. There is also no chance of formulating a break condition for the given algorithm because of this behaviour. We observe comparable problems for finding break conditions for infinite series that do not converge quickly using floating-point numbers, so we can generally think of it as an unsolved problem following from the finite nature of the machine.

4.4.3. Lattice Switching

A strong theoretical advantage is that one could evaluate an expression on a set of Unums with a coarse lattice first and then refine the lattice as soon as the set of possible solutions shrinks. It is questionable how this could be possible within the machine. One may find ways to reduce the size of the lookup tables, but assuming multiple different lattice-precisions including all LUTs would take up massive amounts of space on a microchip. Additionally, there needs to be a theory on how existing SORNs are translated between the different lattices, which might require its own set of LUTs for each transition, greatly increasing complexity.

If the solution space is only observed within small bounds, considerable amounts of memory are wasted for set representations beyond the bounds using a naïve SORN representation. The SORNs may be needed for intermediate values of a calculation, which could easily expand beyond the bounds of the solution space, but not for the final

results.

This problem can be approached using a run-length encoding for SORNs comparable to how LUTs were implemented (see Subsection 4.2.2), but this would make SORN operations in general less efficient unless the operations take place directly on top of Unum enumeration indices.

4.4.4. Complexity

Despite the efforts to simplify arithmetic operations and overhead by creating lookup tables and working on bit strings in a simple manner, the cost of this simplification weighs heavily. The contradiction lies within the fact that to at least reduce the detrimental effects of sticking and creeping it is necessary to increase the number of Unum bits n_b . However, this is only possible up to a certain point until the LUTs become too large. In this context, dealing with strictly monotonic functions like \ln in the Unum context requires LUTs for each of them as well (see Subsection 4.3.1).

It is questionable how useful the Unum arithmetic is within the tight bounds set by these limiting factors. However, it should be taken into account that there are possible uses for Unums on very coarse grids, for instance inverse kinematics. GUSTAFSON also identifies the problem (see [Gus16b, Section 6]) and notes that this problem could indicate that Unums are ‘ [...] primarily practical for low-accuracy but high-validity applications, thereby complementing float arithmetic instead of replacing it. ’ [Gus16b, Section 6.2]

5. Summary and Outlook

In the course of this thesis we started off with the construction of a mathematical description of IEEE 754 floating-point numbers, compared the properties of different binary storage formats and studied examples which uncover inherent weaknesses of this arithmetic.

Following from these observations, we constructed the projectively extended real numbers based on a small set of axioms. After introducing a definition of finite and infinite limits on the projectively extended real numbers, we showed their well-definedness in terms of these limits. Based on this foundation, we developed the Flake arithmetic and proved well-definedness in terms of set theory.

This effort led us to the mathematical foundation of Unums, which as proposed approaches the interval arithmetic dependency problem in a new way and is meant to be easy to implement in the machine. We presented different types of Unum lattices, evaluated the requirements for hardware implementations and studied the numerical behaviour in a Unum toolbox, which was developed in the course of this thesis. Using these results, we were able to draw the conclusion that Unums may not be a number format allowing naïve computations, but exhibited promising results in low-precision but high-validity applications.

The author expected to find drawbacks of this nature for the Unum number format, as any numerical system exhibits its strength only within certain conditions, making it easy to find examples where it fails. In this context, it was observed that IEEE 754 floating-point numbers and Unums complement each other. Given the nature of Unum arithmetic, it may be on the one hand difficult to do stability analysis due to the complexity of the arithmetic rules, but on the other hand the guaranteed bounds of the result do not cover up when an algorithm is not fit for this environment and indicate the need to approach the problem using a different numerical approach.

At the point of writing, the revised Unum format was approached with neither a mathematical foundation nor formalisation. The available toolboxes were only emulating Unums using floating-point arithmetic, hiding numerous drawbacks with regard to the complexity of lookup tables. The results obtained in this thesis make it possible to reason about Unums in the bounds that will also be present when it comes to implementing Unums in hardware and not only in software.

In general it is questionable if the approach of using lookup tables is really the best way to go, despite the possible advantage of simplifying calculations. It is questionable if it is really worth it to throw the entire IEEE 754 floating-point infrastructure overboard and have two exclusive numerical systems.

The `bl` operator presented in this thesis corresponds to the rounding operation for floating-point numbers to a certain extent. A topic for further research could be to

5. Summary and Outlook

introduce closed \mathbb{R}^* -intervals for $a, b \in \mathbb{R}^*$ with

$$[a, b] := \{a\} \sqcup (a, b) \sqcup \{b\} \subset \mathbb{F}.$$

Operations on \mathbb{R}^* -Flakes were shown to be well-defined and, thus, it is possible to extend Flake operations $\star \in \{\boxplus, \boxtimes\}$ to automatically well-defined operations \diamond on closed intervals with

$$\begin{aligned} [a, b] \diamond [c, d] := & \{a\} \star \{c\} \cup \{a\} \star (c, d) \cup \{a\} \star \{d\} \cup \\ & (a, b) \star \{c\} \cup (a, b) \star (c, d) \cup (a, b) \star \{d\} \cup \\ & \{b\} \star \{c\} \cup \{b\} \star (c, d) \cup \{b\} \star \{d\} \end{aligned}$$

and simplify it accordingly. Discretisation is achieved by using floating-point numbers for the interval bounds and directed rounding for guaranteed bounds, as elaborated in (2.1).

Unums present the need to have lookup tables for every operation and nearly every elementary function to be feasible, which is a huge complexity problem. This is the reason why using floats instead of lookup tables to achieve this makes sense, because we studied the behaviour of strictly monotonic functions on Flakes in this thesis and can directly use strictly monotonic floating-point functions for Flake arithmetic instead of lookup tables. In the end, this could combine the accuracy of floating point numbers and the certainty of interval arithmetic. The difference between this and ordinary interval arithmetic using floating-point number bounds (see [IEE15]) is the use of the projectively extended real numbers instead of the affinely extended real numbers, making it possible to model degenerate intervals and divide by zero, and the knowledge of the results obtained in this thesis to approach the dependency problem. It comes at the cost of a total order relation and only offers a partial order, which can be assumed to be a smaller problem than it seems.

In the end, it all boils down to the question if using two 32 bit IEEE 754 floating-point numbers to model such a closed interval is better than using a single 64 bit IEEE 754 floating-point number for a diverse set of algorithms. The strategy of finding a solution by going from a coarse to a fine grid for Unums could be easily realised with floating-point bounded closed intervals and also prove to be useful for certain applications.

Reaching a point where the dynamic range of high-bit floating-point numbers is exceeding the range of numbers of usable magnitude only to compensate rounding errors to a certain extent, we might find interval arithmetic on the projectively extended real numbers to be a good future direction for improving the results of the very calculations we are doing every day.

A. Notation Directory

A.1. Section 2: IEEE 754 Floating-Point Arithmetic

n_m	number of mantissa-digits (\equiv mantissa-bits in base-2)
n_e	number of exponent-bits
$\mathbb{M}_0(n_m, \underline{e})$	set of subnormal floating-point numbers; see Definition 2.2
$\mathbb{M}_1(n_m, \underline{e}, \bar{e})$	set of normal floating-point numbers; see Definition 2.1
$\mathbb{M}(n_m, \underline{e} - 1, \bar{e} + 1)$	set of floating-point numbers; see Definition 2.3
$ \text{NaN} (n_m)$	number of NaN representations; see Proposition 2.7
$\underline{e}(n_e), \bar{e}(n_e)$	exponent bias; see Definition 2.8
$\text{rd}_{\mathcal{E}}$	nearest and tie to even rounding; see Definition 2.12
rd_{\uparrow}	upward rounding; see Definition 2.13
rd_{\downarrow}	downward rounding; see Definition 2.14

A.2. Section 3: Interval Arithmetic

\mathbb{R}^*	projectively extended real numbers; see Definition 3.1
∞	infinity symbol of \mathbb{R}^* ; see Definition 3.1
\sqcup	disjoint union; see Definition 3.7
(\underline{a}, \bar{a})	open \mathbb{R}^* -interval between \underline{a} and \bar{a} ; see Definition 3.8
\mathbb{I}	set of open \mathbb{R}^* -intervals; see Definition 3.9
\oplus	addition operator on \mathbb{I} ; see Definition 3.9
\otimes	multiplication operator on \mathbb{I} ; see Definition 3.9
$\S(S)$	set of S-singletons; see Definition 3.12
\mathbb{F}	set of \mathbb{R}^* -Flakes; see Definition 3.13
\boxplus	addition operator on \mathbb{F} ; see Definition 3.13
\boxtimes	multiplication operator on \mathbb{F} ; see Definition 3.13
$f_{\mathbb{F}}$	\mathbb{R}^* -Flake evaluation of the strictly monotonic function f ; see Definitions 3.15 and 3.17

A.3. Section 4: Unum Arithmetic

A. Notation Directory

$\mathbb{U}(P)$	set of Unums on the lattice P ; see Definition 4.1
$\mathcal{P}(S)$	powerset of S ; see Definition 4.4
bl	blur operator; see Definition 4.5
$\langle \star \rangle$	dual Unum operation; see Definition 4.7
$\langle f_{\mathbb{F}} \rangle$	Unum evaluation of the strictly monotonic function f ; see Definitions 4.9 and 4.10
$P_L(p, n)$	linear Unum lattice; see Definition 4.11
$P_E(p, m)$	exponential Unum lattice; see Definition 4.13
$P_D(p, s)$	decade Unum lattice; see Definition 4.15
asc	ascension operator; see Definition 4.18
$u(n)$	n th Unum in the Unum enumeration; see Definition 4.19
n_b	number of Unum bits
n_d	number of significant digits
$\mathbb{U}_M(n_b, n_s)$	set of machine Unums; see Definition 4.22

B. Code Listings

B.1. IEEE 754 Floating-Point Problems

B.1.1. spike.c

```
1 #include <float.h>
2 #include <math.h>
3 #include <stdio.h>
4
5 #define LEN(x) (sizeof (x) / sizeof *(x))
6 #define NUMPOINTS (10)
7 #define POLE (4.0/3.0)
8
9 int
10 main(void)
11 {
12     double x[NUMPOINTS * 2 + 1][2];
13     int i;
14
15     /* fill POINT environment */
16     x[NUMPOINTS][0] = POLE;
17     for (i = NUMPOINTS - 1; i >= 0; i--) {
18         x[i][0] = nextafter(x[i + 1][0], -INFINITY);
19     }
20     for (i = NUMPOINTS + 1; i < NUMPOINTS * 2 + 1; i++) {
21         x[i][0] = nextafter(x[i - 1][0], +INFINITY);
22     }
23
24     /* calculate values of |3*(1-x)+1| in the POINT environment */
25     for (i = 0; i < NUMPOINTS * 2 + 1; i++) {
26         x[i][1] = fabs(3 * (1 - x[i][0]) + 1);
27         printf("x-%.2f=%.20e|3*(1-x)+1|=%.20f\n", POLE,
28             x[i][0]-POLE, x[i][1]);
29     }
30
31     putchar('\n');
32
33     /* calculate values of f(x) in the POINT environment */
```

B. Code Listings

```
34     for (i = 0; i < NUMPOINTS * 2 + 1; i++) {
35         x[i][1] = log(fabs(3 * (1 - x[i][0]) + 1));
36         printf("x-%.2f=%.20e_f(x)=%.20f\n", POLE,
37             x[i][0]-POLE, x[i][1]);
38     }
39
40     return 0;
41 }
```

B.1.2. devil.c

```
1  #include <stdio.h>
2
3  int
4  main(void)
5  {
6      double a, b, tmp;
7      int i;
8
9      a = 2;
10     b = -4;
11
12     for (i = 2; i < 26; i++) {
13         tmp = 111 - 1130 / b + 3000 / (b * a);
14         a = b;
15         b = tmp;
16         printf("u_%.2d_=%f\n", i, b);
17     }
18
19     return 0;
20 }
```

B.1.3. bank.c

```
1  #include <float.h>
2  #include <math.h>
3  #include <stdio.h>
4
5  const int years = 25;
6
7  int
8  main(void)
```

```

9  {
10     double a;
11     int n;
12
13     a = 1.718281828459045235;
14
15     for (n = 1; n <= years; n++) {
16         a = a * n - 1;
17     }
18
19     printf("u_%d=%f\n", years, a);
20
21     return 0;
22 }

```

B.1.4. Makefile

```

1  PROBLEMS = devil bank
2  LMPROBLEMS = spike
3
4  all: $(PROBLEMS) $(LMPROBLEMS)
5
6  $(LMPROBLEMS): LDFLAGS = -lm
7
8  %: %.c
9     cc $^ -o $@ $(LDFLAGS)
10
11 clean:
12     rm -f $(PROBLEMS) $(LMPROBLEMS)

```

B.2. Unum Toolbox

B.2.1. gen.c

```

1  #include <fenv.h>
2  #include <float.h>
3  #include <math.h>
4  #include <stdint.h>
5  #include <stdio.h>
6  #include <stdlib.h>
7  #include <string.h>
8
9  #undef LEN

```

B. Code Listings

```
10 #define LEN(x) sizeof(x) / sizeof(*x)
11 #undef UCLAMP
12 #define UCLAMP(i, off) (((off < 0) && (i) < -off) ? \
13     numunums - ((-off - (i)) % numunums) : \
14     ((off > 0) && (i) + off > numunums - 1) ? \
15     ((i) + off % numunums) % numunums : (i) + off)) \
16     % numunums)
17 #undef MIN
18 #define MIN(x,y) ((x) < (y) ? (x) : (y))
19 #undef MAX
20 #define MAX(x,y) ((x) > (y) ? (x) : (y))
21
22 struct _unum {
23     double val;
24     char *name;
25 };
26
27 struct _unumrange {
28     size_t low;
29     size_t upp;
30 };
31
32 struct _latticep {
33     char *name;
34     double val;
35 };
36
37 static void
38 printunums(struct _unum *unum, size_t numunums)
39 {
40     size_t i;
41
42     fputs("\nstruct _unum[]=\n", stdout);
43
44     for (i = 0; i < numunums; i++) {
45         if (isnan(unum[i].val) && !unum[i].name) {
46             printf("\t{ NAN, NULL },\n");
47         } else if (isinf(unum[i].val)) {
48             printf("\t{ INFINITY, \"%s\" },\n",
49                 unum[i].name);
50         } else {
51             printf("\t{ %f, \"%s\" },\n", unum[i].val,
52                 unum[i].name);
53         }
54     }
55 }
```

```

54     }
55
56     fputs("};\n", stdout);
57 }
58
59 size_t
60 blur(double val, struct _unum *unum, size_t numunums)
61 {
62     size_t i;
63
64     /* infinity is infinity */
65     if (isinf(val)) {
66         return numunums / 2;
67     }
68
69     for (i = 0; i < numunums; i++) {
70         /* equality within relative epsilon */
71         if (isfinite(unum[i].val) && fabs(unum[i].val - val) <=
72             DBL_EPSILON * MAX(fabs(unum[i].val), fabs(val))) {
73             return i;
74         }
75
76         /* in range */
77         if (isnan(unum[i].val) &&
78             val < unum[UCLAMP(i, +1)].val &&
79             val > unum[UCLAMP(i, -1)].val) {
80             return i;
81         }
82     }
83
84     /* negative or positive range outshot */
85     return (val < 0) ? (numunums / 2 + 1) : (val > 0) ?
86         (numunums / 2 - 1) : 0;
87 }
88
89 void
90 add(size_t a, size_t b, struct _unumrange *res,
91     struct _unum *unum, size_t numunums)
92 {
93     double av, bv, aupp, alow, bupp, blow;
94
95     av = unum[a].val;
96     bv = unum[b].val;
97

```

B. Code Listings

```
98     if (isnan(av) && isnan(bv)) {
99         /*
100          * a interval, b interval
101          */
102         aupp = unum[UCLAMP(a, +1)].val;
103         alow = unum[UCLAMP(a, -1)].val;
104         bupp = unum[UCLAMP(b, +1)].val;
105         blow = unum[UCLAMP(b, -1)].val;
106
107         if ((isinf(alow) && isinf(aupp)) ||
108             (isinf(blow) && isinf(bupp))) {
109             /* all real numbers */
110             res->low = numunums / 2 + 1;
111             res->upp = numunums / 2 - 1;
112             return;
113         } else if (isinf(alow) && isinf(blow)) {
114             /* (iffy, aupp + bupp) */
115             res->low = numunums / 2 + 1;
116             fesetround(FE_UPWARD);
117             res->upp = blur(aupp + bupp, unum,
118                             numunums);
119         } else if (isinf(aupp) && isinf(bupp)) {
120             /* (alow + blow, iffy) */
121             fesetround(FE_DOWNWARD);
122             res->low = blur(alow + blow, unum, numunums);
123             res->upp = numunums / 2 + 1;
124         } else {
125             /* (alow + blow, aupp + bupp) */
126             fesetround(FE_DOWNWARD);
127             res->low = blur(alow + blow, unum, numunums);
128             fesetround(FE_UPWARD);
129             res->upp = blur(aupp + bupp, unum, numunums);
130         }
131     } else if (!isnan(av) && !isnan(bv)) {
132         /*
133          * a point, b point
134          */
135         if (isinf(av) && isinf(bv)) {
136             /* all extended real numbers */
137             res->low = 0;
138             res->upp = numunums - 1;
139             return;
140         } else {
141             fesetround(FE_DOWNWARD);
```

```

142         res->low = blur(av + bv, unum, numunums);
143         fesetround(FE_UPWARD);
144         res->upp = blur(av + bv, unum, numunums);
145     }
146 } else if (!isnan(av) && isnan(bv)) {
147     /*
148      * a point, b interval
149      */
150     bupp = unum[UCLAMP(b, +1)].val;
151     blow = unum[UCLAMP(b, -1)].val;
152
153     if (isinf(av)) {
154         /* all extended real numbers */
155         res->low = 0;
156         res->upp = numunums - 1;
157         return;
158     } else {
159         fesetround(FE_DOWNWARD);
160         res->low = blur(av + blow, unum, numunums);
161         fesetround(FE_UPWARD);
162         res->upp = blur(av + bupp, unum, numunums);
163     }
164 } else if (!isnan(bv) && isnan(av)) {
165     /*
166      * a interval, b point
167      */
168     add(b, a, res, unum, numunums);
169     return;
170 }
171
172 if (isnan(av) || isnan(bv)) {
173     /* we had an open interval in our calculation
174      * and need to check if res->upp or res->low
175      * are a point. If this is the case, we have
176      * to round it down to respect the openness
177      * of the real interval */
178     if (!isnan(unum[res->low].val)) {
179         res->low = UCLAMP(res->low, +1);
180     }
181     if (!isnan(unum[res->upp].val)) {
182         res->upp = UCLAMP(res->upp, -1);
183     }
184 }
185 }

```

B. Code Listings

```
186
187 void
188 mul(size_t a, size_t b, struct _unumrange *res,
189     struct _unum *unum, size_t numunums)
190 {
191     double av, bv, aupp, allow, bupp, blow;
192
193     av = unum[a].val;
194     bv = unum[b].val;
195
196     if (isnan(av) && isnan(bv)) {
197         /*
198          * a interval, b interval
199          */
200         aupp = unum[UCLAMP(a, +1)].val;
201         allow = unum[UCLAMP(a, -1)].val;
202         bupp = unum[UCLAMP(b, +1)].val;
203         blow = unum[UCLAMP(b, -1)].val;
204
205         if ((isinf(allow) && isinf(aupp)) ||
206             (isinf(blow) && isinf(bupp))) {
207             /* all real numbers */
208             res->low = numunums / 2 + 1;
209             res->upp = numunums / 2 - 1;
210             return;
211         } else if (isinf(allow) && isinf(blow)) {
212             if (aupp <= 0 && bupp <= 0) {
213                 /* (aupp * bupp, iffy) */
214                 fesetround(FE_DOWNWARD);
215                 res->low = blur(aupp * bupp,
216                               unum, numunums);
217                 res->upp = numunums / 2 - 1;
218             } else {
219                 /* all real numbers */
220                 res->low = numunums / 2 + 1;
221                 res->upp = numunums / 2 - 1;
222                 return;
223             }
224         } else if (isinf(aupp) && isinf(bupp)) {
225             if (allow >= 0 && blow >= 0) {
226                 /* (allow * blow, iffy) */
227                 fesetround(FE_DOWNWARD);
228                 res->low = blur(allow * blow,
229                               unum, numunums);
```



```

230         res->upp = numunums / 2 - 1;
231     } else {
232         /* all real numbers */
233         res->low = numunums / 2 + 1;
234         res->upp = numunums / 2 - 1;
235         return;
236     }
237 } else if (isinf(alow) && isinf(bupp)) {
238     if (aupp <= 0 && blow >= 0) {
239         /* (iffy, aupp * blow) */
240         res->low = numunums / 2 + 1;
241         fesetround(FE_UPWARD);
242         res->upp = blur(aupp * blow,
243                        unum, numunums);
244     } else {
245         /* all real numbers */
246         res->low = numunums / 2 + 1;
247         res->upp = numunums / 2 - 1;
248         return;
249     }
250 } else if (isinf(aupp) && isinf(blow)) {
251     mul(b, a, res, unum, numunums);
252     return;
253 } else if (isinf(alow)) {
254     if (blow >= 0) {
255         /* (iffy, MAX(aupp * blow,
256                    *      aupp * bupp) */
257         res->low = numunums / 2 + 1;
258         fesetround(FE_UPWARD);
259         res->upp = blur(MAX(aupp * blow,
260                           aupp * bupp),
261                        unum, numunums);
262     } else if (bupp <= 0) {
263         /* (MIN(aupp * blow, aupp * bupp),
264            *      iffy) */
265         fesetround(FE_DOWNWARD);
266         res->low = blur(MIN(aupp * blow,
267                           aupp * bupp),
268                        unum, numunums);
269         res->upp = numunums / 2 - 1;
270     } else {
271         /* all real numbers */
272         res->low = numunums / 2 + 1;
273         res->upp = numunums / 2 - 1;

```

B. Code Listings

```
274         return;
275     }
276 } else if (isinf(aupp)) {
277     if (blow >= 0) {
278         /* (MIN(alow * blow, aupp * bupp),
279          *  iffy) */
280         fesetround(FE_DOWNWARD);
281         res->low = blur(MIN(alow * blow,
282                          alow * bupp),
283                       unum, numunums);
284         res->upp = numunums / 2 - 1;
285     } else if (bupp <= 0) {
286         /* (iffy, MAX(alow * blow,
287          *             alow * bupp) */
288         res->low = numunums / 2 + 1;
289         fesetround(FE_UPWARD);
290         res->upp = blur(MAX(alow * blow,
291                          alow * bupp),
292                       unum, numunums);
293     } else {
294         /* all real numbers */
295         res->low = numunums / 2 + 1;
296         res->upp = numunums / 2 - 1;
297         return;
298     }
299 } else if (isinf(blow) || isinf(bupp)) {
300     mul(b, a, res, unum, numunums);
301 } else {
302     /* (MIN(C), MAX(C)) */
303     fesetround(FE_DOWNWARD);
304     res->low = blur(MIN(MIN(alow * blow,
305                          alow * bupp),
306                      MIN(aupp * blow,
307                          aupp * bupp)),
308                   unum, numunums);
309     fesetround(FE_UPWARD);
310     res->upp = blur(MAX(MAX(alow * blow,
311                          alow * bupp),
312                      MAX(aupp * blow,
313                          aupp * bupp)),
314                   unum, numunums);
315 }
316 } else if (!isnan(av) && !isnan(bv)) {
317     /*
```

```

318     * a point, b point
319     */
320     if ((isinf(av) && (fabs(bv) <= DBL_EPSILON *
321         fabs(bv) || isinf(bv))) ||
322         (isinf(bv) && (fabs(av) <= DBL_EPSILON *
323         fabs(av) || isinf(av)))) {
324         /* all extended real numbers */
325         res->low = 0;
326         res->upp = numunums - 1;
327         return;
328     } else {
329         fesetround(FE_DOWNWARD);
330         res->low = blur(av * bv, unum, numunums);
331         fesetround(FE_UPWARD);
332         res->upp = blur(av * bv, unum, numunums);
333     }
334 } else if (!isnan(av) && isnan(bv)) {
335     /*
336     * a point, b interval
337     */
338     bupp = unum[UCLAMP(b, +1)].val;
339     blow = unum[UCLAMP(b, -1)].val;
340
341     if (isinf(av)) {
342         if (isinf(blow)) {
343             if (bupp < 0) {
344                 /* infinity */
345                 res->low = numunums / 2;
346                 res->upp = numunums / 2;
347                 return;
348             } else {
349                 /* all extended real
350                 * numbers */
351                 res->low = 0;
352                 res->upp = numunums - 1;
353                 return;
354             }
355         } else if (isinf(bupp)) {
356             if (blow > 0) {
357                 /* infinity */
358                 res->low = numunums / 2;
359                 res->upp = numunums / 2;
360                 return;
361             } else {

```

B. Code Listings

```
362                                     /* all extended real
363                                     * numbers */
364                                     res->low = 0;
365                                     res->upp = numunums - 1;
366                                     return;
367                                     }
368     } else if ((blow < 0) == (bupp < 0)) {
369         /* infinity */
370         res->low = numunums / 2;
371         res->upp = numunums / 2;
372         return;
373     } else {
374         /* all extended real numbers */
375         res->low = 0;
376         res->upp = numunums - 1;
377         return;
378     }
379 } else {
380     /* (MIN(av * blow, av * bupp),
381        * MAX(av * blow, av * bupp)) */
382     fesetround(FE_DOWNWARD);
383     res->low = blur(MIN(av * blow,
384                       av * bupp),
385                   unum, numunums);
386     fesetround(FE_UPWARD);
387     res->upp = blur(MAX(av * blow,
388                       av * bupp),
389                   unum, numunums);
390 }
391 } else if (isnan(av) && !isnan(bv)) {
392     /*
393     * a interval, b point
394     */
395     mul(b, a, res, unum, numunums);
396     return;
397 }
398
399 if (isnan(av) || isnan(bv)) {
400     /* we had an open interval in our calculation
401     * and need to check if res->upp or res->low
402     * are a point. If this is the case, we have
403     * to round it down to respect the openness
404     * of the real interval */
405     if (!isnan(unum[res->low].val)) {
```

```

406         res->low = UCLAMP(res->low, +1);
407     }
408     if (!isnan(unum[res->upp].val)) {
409         res->upp = UCLAMP(res->upp, -1);
410     }
411 }
412 }
413
414 static void
415 gentable(char *name, void (*f)(size_t, size_t, struct _unumrange *,
416     struct _unum *, size_t), struct _unum *unum, size_t numunums)
417 {
418     struct _unumrange res;
419     size_t s, z;
420
421     printf("\nstruct _unumrange _%stable[] _=_{\n", name);
422
423     for (z = 0; z < numunums; z++) {
424         putc('\t', stdout);
425
426         for (s = 0; s <= z; s++) {
427             f(s, z, &res, unum, numunums);
428             printf("%s{_%zd,_%zd},", s ? "_" : "",
429                 res.low, res.upp);
430         }
431
432         fputs("\n", stdout);
433     }
434
435     fputs("};\n", stdout);
436 }
437
438 void
439 ulog(size_t u, struct _unumrange *res, struct _unum *unum,
440     size_t numunums)
441 {
442     double uv, ulow, uupp;
443
444     uv = unum[u].val;
445
446     if (isnan(uv)) {
447         ulow = unum[UCLAMP(u, -1)].val;
448         uupp = unum[UCLAMP(u, +1)].val;
449     }

```

B. Code Listings

```
450         res->low = blur(log(ulow), unum, numunums);
451         res->upp = blur(log(uupp), unum, numunums);
452     } else {
453         res->low = res->upp = blur(log(uv), unum, numunums);
454     }
455 }
456
457 static void
458 genfunctable(char *name, void (*f)(size_t, struct _unumrange *,
459     struct _unum *, size_t), struct _unum *unum, size_t numunums)
460 {
461     struct _unumrange res;
462     size_t u;
463
464     printf("\nstruct _unumrange %stable[] = {\n", name);
465
466     for (u = 0; u <= numunums / 2; u++) {
467         f(u, &res, unum, numunums);
468         printf("\t{ %zd, %zd },\n", res.low, res.upp);
469     }
470
471     fputs("};\n", stdout);
472 }
473
474 static void
475 genunums(struct _latticep *lattice, size_t latticesize,
476     struct _unum *unum, size_t numunums)
477 {
478     size_t off;
479     ssize_t i;
480
481     off = 0;
482
483     /* 0 */
484     unum[off].val = 0.0;
485     unum[off].name = "0";
486     off++;
487     unum[off].val = NAN;
488     unum[off].name = NULL;
489     off++;
490
491     /* (0,1) */
492     for (i = latticesize - 1; i >= 0; i--, off++) {
493         unum[off].val = 1 / lattice[i].val;
```

```

494         if (lattice[i].name[0] == '/') {
495             unum[off].name = lattice[i].name + 1;
496         } else {
497             /* add '/' prefix */
498             if (!(unum[off].name =
499                 malloc(strlen(lattice[i].name) + 2))) {
500                 fprintf(stderr, "out_of_memory\n");
501                 exit(1);
502             }
503             strcpy(unum[off].name + 1, lattice[i].name);
504             unum[off].name[0] = '/';
505         }
506         off++;
507         unum[off].val = NAN;
508         unum[off].name = NULL;
509     }
510
511     /* 1 */
512     unum[off].val = 1.0;
513     unum[off].name = "1";
514     off++;
515     unum[off].val = NAN;
516     unum[off].name = NULL;
517     off++;
518
519     /* (1, INF) */
520     for (i = 0; i < latticesize; i++, off++) {
521         unum[off].val = lattice[i].val;
522         unum[off].name = lattice[i].name;
523         off++;
524         unum[off].val = NAN;
525         unum[off].name = NULL;
526     }
527
528     /* INF */
529     unum[off].val = INFINITY;
530     unum[off].name = "\u221E";
531     off++;
532     unum[off].val = NAN;
533     unum[off].name = NULL;
534     off++;
535
536     /* (INF, -1) */
537     for (i = latticesize - 1; i >= 0; i--, off++) {

```

B. Code Listings

```
538         unum[off].val = -lattice[i].val;
539         if (!(unum[off].name =
540             malloc(strlen(lattice[i].name) + 2))) {
541             fprintf(stderr, "out_of_memory\n");
542             exit(1);
543         }
544         strcpy(unum[off].name + 1, lattice[i].name);
545         unum[off].name[0] = '-';
546         off++;
547         unum[off].val = NAN;
548         unum[off].name = NULL;
549     }
550
551     /* -1 */
552     unum[off].val = -1.0;
553     unum[off].name = "-1";
554     off++;
555     unum[off].val = NAN;
556     unum[off].name = NULL;
557     off++;
558
559     /* (-1, 0) */
560     for (i = 0; i < latticesize; i++, off++) {
561         unum[off].val = - 1 / lattice[i].val;
562         if (lattice[i].name[0] == '/') {
563             if (!(unum[off].name =
564                 strdup(lattice[i].name))) {
565                 fprintf(stderr, "out_of_memory\n");
566                 exit(1);
567             }
568             unum[off].name[0] = '-';
569         } else {
570             /* add '-/' prefix */
571             if (!(unum[off].name =
572                 malloc(strlen(lattice[i].name) + 3))) {
573                 fprintf(stderr, "out_of_memory\n");
574                 exit(1);
575             }
576             strcpy(unum[off].name + 2, lattice[i].name);
577             unum[off].name[0] = '-';
578             unum[off].name[1] = '/';
579         }
580         off++;
581         unum[off].val = NAN;
```



```

582         unum[off].name = NULL;
583     }
584 }
585
586 void
587 gendeclattice(struct _latticep **lattice, size_t *latticesize,
588             double maximum, int sigdigs)
589 {
590     size_t i, maxlen;
591     double c1, c2, curmax;
592     char *fmt = "%. *f";
593
594     /*
595      * Check prerequisites
596      */
597     if (sigdigs == 0) {
598         fprintf(stderr, "invalid_number_of_"
599                 "significant_digits\n");
600     }
601     if ((*latticesize == 0) == isinf(maximum)) {
602         fprintf(stderr, "gendeclattice: accepting_"
603                 "only_one_parameter_besides_number_of_"
604                 "significant_digits\n");
605         exit(1);
606     }
607
608     c1 = pow(10, sigdigs) - pow(10, sigdigs - 1);
609     c2 = pow(10, -(sigdigs - 1));
610
611     if (*latticesize == 0) {
612         /* calculate lattice size until maximum is
613          * contained */
614         for (curmax = 0; curmax < maximum; (*latticesize)++) {
615             curmax = (1 + c2 *
616                     (*latticesize % (size_t)c1)) *
617                     pow(10, floor(*latticesize / c1));
618         }
619     } else { /* isinf(maximum) */
620         /* calculate maximum */
621         maximum = (1 + c2 *
622                 (*latticesize % (size_t)c1)) *
623                 pow(10, floor(*latticesize / c1));
624     }
625

```

B. Code Listings

```
626     /*
627     * Generate lattice
628     */
629     if (!(*lattice = malloc(sizeof(struct _latticep) *
630                             *latticesize))) {
631         fprintf(stderr, "out_of_memory\n");
632         exit(1);
633     }
634     maxlen = snprintf(NULL, 0, fmt, sigdigs - 1, maximum) + 1;
635     for (i = 0; i < *latticesize; i++) {
636         (*lattice)[i].val = (1 + c2 *
637                             ((i + 1) % (size_t)c1)) *
638                             pow(10, floor((i + 1) / c1));
639         if (!((*lattice)[i].name = malloc(maxlen))) {
640             fprintf(stderr, "out_of_memory\n");
641             exit(1);
642         }
643         snprintf((*lattice)[i].name, maxlen, fmt,
644                 sigdigs - 1, (*lattice)[i].val);
645     }
646 }
647
648 int
649 main(void)
650 {
651     struct _unum *unum;
652     struct _latticep *lattice;
653     size_t latticebits, latticesize, numunums;
654     ssize_t i;
655     int bits;
656
657     /* Generate lattice */
658     latticesize = (1 << (UBITS - 3)) - 1;
659     gendeclattice(&lattice, &latticesize, INFINITY, DIGITS);
660
661     /*
662     * Print unum.h includes
663     */
664     fprintf(stderr, "#include<math.h>\n#include<stddef.h>\n"
665                 "#include<stdint.h>\n\n");
666
667     /*
668     * Determine number of effective bits used
669     */
```

```

670 struct {
671     int bits;
672     char *type;
673 } types[] = {
674     { 8, "uint8_t" },
675     { 16, "uint16_t" },
676     { 32, "uint32_t" },
677     { 64, "uint64_t" },
678 };
679
680 numunums = 8 * (latticesize + 1);
681 for (bits = 1; bits <= types[LEN(types) - 1].bits; bits++) {
682     if (numunums == (1 << bits))
683         break;
684 }
685 if (bits > types[LEN(types) - 1].bits) {
686     fprintf(stderr, "invalid_number_of_lattice
687         "points\n");
688     return 1;
689 }
690
691 /*
692  * Determine type needed to store the unum
693  */
694 for (i = 0; i < LEN(types); i++) {
695     if (types[i].bits >= bits)
696         break;
697 }
698 if (i == LEN(types)) {
699     fprintf(stderr, "cannot_fit_bits_into_system"
700         "types\n");
701     return 1;
702 }
703
704 /*
705  * Print list of preliminary unum.h definitions
706  */
707 fprintf(stderr, "typedef_s_unum;\n#define_ULEN_%d\n"
708     "#define_NUMUNUMS_%zd\n", types[i].type, bits,
709     numunums);
710
711 fprintf(stderr, "#define_UCLAMP(i,off)_((((off<0)&&(i)<"
712     "-off)?\\\n\tNUMUNUMS_((-off-(i))_%%_NUMUNUMS):"
713     "\\n\t((off>0)&&(i)+_off>_NUMUNUMS-1)?\\\n\t"

```

B. Code Listings

```

714         ((i) + off % NUMUNUMS) % NUMUNUMS : (i) + off) % NUMUNUMS) \n\n");
715
716
717     fprintf(stderr, "typedef struct {\n\tuint8_t data[%d];\n} SORN;\n",
718             (1 << bits) / 8);
719
720     fprintf(stderr, "\nvoid uadd(SORN*, SORN*);\n"
721             "void usub(SORN*, SORN*);\n"
722             "void umul(SORN*, SORN*);\n"
723             "void udiv(SORN*, SORN*);\n"
724             "void uneg(SORN*);\n"
725             "void uinv(SORN*);\n"
726             "void uabs(SORN*);\n\n"
727             "void ulog(SORN*);\n\n"
728             "void uemp(SORN*);\n"
729             "void uset(SORN*, SORN*);\n"
730             "void ucut(SORN*, SORN*);\n"
731             "void uuni(SORN*, SORN*);\n"
732             "int uequ(SORN*, SORN*);\n"
733             "int usup(SORN*, SORN*);\n\n"
734             "void uint(SORN*, double, double);\n"
735             "void uout(SORN*);\n");
736
737     /*
738      * Generate unums
739      */
740     if (!(unum = malloc(sizeof(struct _unum) * numunums))) {
741         fprintf(stderr, "out of memory\n");
742         return 1;
743     }
744     genunums(lattice, latticesize, unum, numunums);
745
746     /*
747      * Print table.c includes
748      */
749     printf("#include \"table.h\"\n");
750
751     /*
752      * Print list of unums
753      */
754     printunums(unum, numunums);
755
756     /*
757      * Generate and print tables

```

```

758     */
759     gentable("add", add, unum, numunums);
760     gentable("mul", mul, unum, numunums);
761
762     /*
763     * Generate function tables
764     */
765     genfunctable("log", ulog, unum, numunums);
766
767     return 0;
768 }

```

B.2.2. table.h

```

1  #include "unum.h"
2
3  struct _unumrange {
4      unum a;
5      unum b;
6  };
7
8  struct _unum {
9      double val;
10     char *name;
11 };
12
13 extern struct _unum unums[];
14 extern struct _unumrange addtable[];
15 extern struct _unumrange multable[];
16 extern struct _unumrange logtable[];

```

B.2.3. unum.c

```

1  #include <float.h>
2  #include <math.h>
3  #include <stdio.h>
4
5  #include "table.h"
6
7  #undef MAX
8  #define MAX(x,y) ((x) > (y) ? (x) : (y))
9

```

B. Code Listings

```
10 static size_t
11 blur(double val)
12 {
13     size_t i;
14
15     /* infinity is infinity */
16     if (isinf(val)) {
17         return NUMUNUMS / 2;
18     }
19
20     for (i = 0; i < NUMUNUMS; i++) {
21         /* equality within relative epsilon */
22         if (isfinite(unums[i].val) && fabs(unums[i].val - val) <=
23             DBL_EPSILON * MAX(fabs(unums[i].val), fabs(val))) {
24             return i;
25         }
26
27         /* in range */
28         if (isnan(unums[i].val) &&
29             val < unums[UCLAMP(i, +1)].val &&
30             val > unums[UCLAMP(i, -1)].val) {
31             return i;
32         }
33     }
34
35     /* negative or positive range outshot */
36     return (val < 0) ? (NUMUNUMS / 2 + 1) : (val > 0) ?
37         (NUMUNUMS / 2 - 1) : 0;
38 }
39
40 static void
41 _sornaddrange(SORN *s, unum lower, unum upper)
42 {
43     unum u;
44     size_t i, j;
45     int first;
46
47     for (first = 1, u = lower; u != UCLAMP(upper, +1) ||
48         (first && lower == UCLAMP(upper, +1));
49         u = UCLAMP(u, +1)) {
50         first = 0;
51         i = u / (sizeof(*s->data) * 8);
52         j = u % (sizeof(*s->data) * 8);
53
```

```

54         s->data[i] |= (1 << (sizeof(*s->data) * 8 - 1 - j));
55     }
56 }
57
58 static unum
59 _unumnegate(unum u)
60 {
61     return UCLAMP(NUMUNUMS, -u);
62 }
63
64 static unum
65 _unuminvert(unum u)
66 {
67     return _unumnegate(UCLAMP(u, +(NUMUNUMS / 2)));
68 }
69
70 static unum
71 _unumabs(unum u)
72 {
73     return (u > NUMUNUMS / 2) ? _unumnegate(u) : u;
74 }
75
76 static void
77 _sornop(SORN *a, SORN *b, struct _unumrange table[],
78         unum (*mod)(unum))
79 {
80     unum u, v, low, upp;
81     size_t i, j, m, n;
82     static SORN res;
83
84     /* empty result SORN */
85     for (i = 0; i < sizeof(res.data); i++) {
86         res.data[i] = 0;
87     }
88
89     for (i = 0; i < sizeof(a->data); i++) {
90         for (j = 0; j < sizeof(*a->data) * 8; j++) {
91             if (!(a->data[i] & (1 << (sizeof(*a->data) * 8 -
92                                     1 - j)))) {
93                 continue;
94             }
95             /* unum u = (so * i + j) is in the first set */
96             u = sizeof(*a->data) * 8 * i + j;
97             for (m = 0; m < sizeof(b->data); m++) {

```

B. Code Listings

```
98     for (n = 0; n < sizeof(*b->data) * 8;
99         n++) {
100         if (!(b->data[m] & (1 <<
101             (sizeof(*b->data) * 8 - 1 -
102             n)))) {
103             continue;
104         }
105         /* unum v = (so * m + n) is in
106            * the second set */
107         v = sizeof(*b->data) * 8 * m + n;
108
109         /*
110            * compare struct pointers to
111            * identify dependent arguments
112            * and in this case only do
113            * pairwise operations
114            */
115         if (a == b && u != v)
116             continue;
117
118         /* apply an optional modifier
119            * after the dependency check */
120         if (mod) {
121             v = mod(v);
122         }
123
124         /* get bounds from table;
125            * according to gauß 1 + 2 + 3
126            * ... + n = (n * (n + 1)) / 2,
127            * used to traverse triangle
128            * array */
129         if (u <= v) {
130             low = table[((size_t)v *
131                 (v + 1)) /
132                 2 + u].a;
133             upp = table[((size_t)v *
134                 (v + 1)) /
135                 2 + u].b;
136         } else {
137             low = table[((size_t)u *
138                 (u + 1)) /
139                 2 + v].a;
140             upp = table[((size_t)u *
141                 (u + 1)) /
```



```

142                                     2 + v].b;
143
144                                     }
145                                     _sornaddrange(&res, low, upp);
146                                     }
147                                 }
148                            }
149                    }
150
151                /* write result to first operand */
152                for (i = 0; i < sizeof(a->data); i++) {
153                    a->data[i] = res.data[i];
154                }
155        }
156
157    static void
158    _sornmod(SORN *s, unum (mod)(unum))
159    {
160        SORN res;
161        unum u;
162        size_t i, j, k, l;
163
164        for (i = 0; i < sizeof(res.data); i++) {
165            res.data[i] = 0;
166        }
167
168        for (i = 0; i < sizeof(s->data); i++) {
169            for (j = 0; j < sizeof(*s->data) * 8; j++) {
170                if (!(s->data[i] & (1 <<
171                    (sizeof(*s->data) * 8 - 1 - j)))) {
172                    continue;
173                }
174                /* unum u = (so * i + j) is in the set */
175                u = sizeof(*s->data) * 8 * i + j;
176                u = mod(u);
177
178                k = u / (sizeof(*s->data) * 8);
179                l = u % (sizeof(*s->data) * 8);
180                res.data[k] |= (1 << (sizeof(*res.data) *
181                    8 - 1 - l));
182            }
183        }
184
185        /* write result to operand */

```

B. Code Listings

```
186         for (i = 0; i < sizeof(s->data); i++) {
187             s->data[i] = res.data[i];
188         }
189     }
190
191     void
192     uadd(SORN *a, SORN *b)
193     {
194         _sornop(a, b, addtable, NULL);
195     }
196
197     void
198     usub(SORN *a, SORN *b)
199     {
200         _sornop(a, b, addtable, _unumnegate);
201     }
202
203     void
204     umul(SORN *a, SORN *b)
205     {
206         _sornop(a, b, multable, NULL);
207     }
208
209     void
210     udiv(SORN *a, SORN *b)
211     {
212         _sornop(a, b, multable, _unuminvert);
213     }
214
215     void
216     uneg(SORN *s)
217     {
218         _sornmod(s, _unumnegate);
219     }
220
221     void
222     uinv(SORN *s)
223     {
224         _sornmod(s, _unuminvert);
225     }
226
227     void
228     uabs(SORN *s)
229     {
```

```

230     _sornmod(s, _unumabs);
231 }
232
233 void
234 ulog(SORN *s)
235 {
236     unum u;
237     size_t i, j;
238     static SORN res;
239
240     /* empty result SORN */
241     for (i = 0; i < sizeof(res.data); i++) {
242         res.data[i] = 0;
243     }
244
245     for (i = 0; i < sizeof(s->data); i++) {
246         for (j = 0; j < sizeof(*s->data) * 8; j++) {
247             if (!(s->data[i] & (1 << (sizeof(*s->data) * 8 -
248                                     1 - j)))) {
249                 continue;
250             }
251             /* unum u = (so * i + j) is in the set */
252             u = sizeof(*s->data) * 8 * i + j;
253
254             /* is SORN negative? not defined */
255             if (u > NUMUNUMS / 2) {
256                 _sornaddrange(&res, 0, NUMUNUMS - 1);
257                 goto done;
258             }
259
260             /* read the table and apply ranges */
261             _sornaddrange(&res, logtable[u].a,
262                           logtable[u].b);
263         }
264     }
265 done:
266     /* write result to operand */
267     for (i = 0; i < sizeof(s->data); i++) {
268         s->data[i] = res.data[i];
269     }
270 }
271
272 void
273 uemp(SORN *s)

```

B. Code Listings

```
274 {
275     size_t i;
276
277     for (i = 0; i < sizeof(s->data); i++) {
278         s->data[i] = 0;
279     }
280 }
281
282 void
283 uset(SORN *a, SORN *b)
284 {
285     size_t i;
286
287     for (i = 0; i < sizeof(a->data); i++) {
288         a->data[i] = b->data[i];
289     }
290 }
291
292 void
293 ucut(SORN *a, SORN *b)
294 {
295     size_t i;
296
297     for (i = 0; i < sizeof(a->data); i++) {
298         a->data[i] = a->data[i] & b->data[i];
299     }
300 }
301
302 void
303 uuni(SORN *a, SORN *b)
304 {
305     size_t i;
306
307     for (i = 0; i < sizeof(a->data); i++) {
308         a->data[i] = a->data[i] | b->data[i];
309     }
310 }
311
312 int
313 uequ(SORN *a, SORN *b)
314 {
315     size_t i;
316
317     for (i = 0; i < sizeof(a->data); i++) {
```

```

318         if (a->data[i] != b->data[i]) {
319             return 0;
320         }
321     }
322
323     return 1;
324 }
325
326 int
327 usup(SORN *a, SORN *b)
328 {
329     ucut(a, b);
330
331     return uequ(a, b);
332 }
333
334 void
335 uint(SORN *s, double lower, double upper)
336 {
337     _sornaddrange(s, blur(lower), blur(upper));
338 }
339
340 void
341 uout(SORN *s)
342 {
343     unum loopstart, u;
344     size_t i, j;
345     int active, insorn, loop2run;
346
347     loop2run = 0;
348     for (active = 0, i = sizeof(s->data) / 2; i < sizeof(s->data);
349         i++) {
350 loop1start:
351         for (j = 0; j < sizeof(*s->data) * 8; j++) {
352             u = sizeof(*s->data) * 8 * i + j;
353             insorn = s->data[i] & (1 << (sizeof(*s->data) *
354                 8 - 1 - j));
355             if (!active && insorn) {
356                 /* print the opening of a closed
357                  * subset */
358                 active = 1;
359                 if (unums[u].name) {
360                     printf("[%s,", unums[u].name);
361                 } else {

```

B. Code Listings

```
362             printf("(%s", unums[UCLAMP(u,
363                 -1)].name);
364         }
365     } else if (active && !insorn) {
366         /* print the closing of a closed
367         * subset */
368         active = 0;
369         if (unums[UCLAMP(u, -1)].name) {
370             printf("%s]_", unums[UCLAMP(u,
371                 -1)].name);
372         } else {
373             printf("%s]_", unums[u].name);
374         }
375     }
376 }
377 if (loop2run) {
378     goto loop2end;
379 }
380 }
381
382 loop2run = 1;
383 for (i = 0; i < sizeof(s->data) / 2; i++) {
384     goto loop1start;
385 loop2end:
386     ;
387 }
388
389 if (active) {
390     printf("\u221E");
391 }
392 }
```

B.2.4. config.mk

```
1  UBITS = 12
2  DIGITS = 2
```

B.2.5. Makefile

```
1  include config.mk
2
3  all: libunum.a
```

```

4
5 libunum.a: table.o unum.o
6     ar rcs libunum.a table.o unum.o
7
8 unum.o: unum.c
9     cc -c unum.c -lm
10
11 table.o: table.c
12     cc -c table.c
13
14 table.c: gen
15     ./gen 2> unum.h 1> table.c
16
17 gen: gen.c config.mk
18     cc -o gen -DUBITS=${UBITS} -DDIGITS=${DIGITS} gen.c -lm
19
20 %: %.c libunum.a
21     cc $^ -o $@
22
23 clean:
24     rm -f gen table.c unum.h table.o unum.o libunum.a

```

B.3. Unum Problems

These programs expect `libunum.a` and `unum.h` in the current directory at compile time. It is recommended to create symbolic links to the toolbox directory given both are generated dynamically there and thus subject to change.

The environment parameters for the decade lattice are set in `config.mk` (see Listing B.2.4).

B.3.1. euler.c

```

1 #include <stdio.h>
2
3 #include "unum.h"
4
5 void
6 factorial(SORN *s, int f)
7 {
8     SORN tmp;
9     int i;
10
11     uemp(s);

```

B. Code Listings

```
12     uint(s, 1, 1);
13
14     for (i = f; i > 1; i--) {
15         uemp(&tmp);
16         uint(&tmp, i, i);
17         umul(s, &tmp);
18     }
19 }
20
21 int
22 main(void)
23 {
24     SORN e, tmp;
25     int i;
26
27     uemp(&e);
28     uint(&e, 1, 1);
29     uout(&e);
30     putchar('\n');
31
32     for (i = 1; i <= 20; i++) {
33         factorial(&tmp, i);
34         uinv(&tmp);
35         uadd(&e, &tmp);
36         uout(&e);
37         putchar('\n');
38     }
39
40     return 0;
41 }
```

B.3.2. devil.c

```
1 #include <stdio.h>
2
3 #include "unum.h"
4
5 int
6 main(void)
7 {
8     SORN a, b, c, tmp1, tmp2, tmp3;
9     int n;
10 }
```



```

11     uemp(&a);
12     uemp(&b);
13     uemp(&c);
14
15     uint(&a, 2, 2);
16     uint(&b, -4, -4);
17
18     for (n = 2; n <= 25; n++) {
19         if (n > 2) {
20             uset(&a, &b);
21             uset(&b, &c);
22         }
23
24         uemp(&tmp1);
25         uint(&tmp1, 111, 111);
26
27         uemp(&tmp2);
28         uint(&tmp2, 1130, 1130);
29         udiv(&tmp2, &b);
30         usub(&tmp1, &tmp2);
31
32         uemp(&tmp2);
33         uint(&tmp2, 3000, 3000);
34         uset(&tmp3, &b);
35         umul(&tmp3, &a);
36
37         udiv(&tmp2, &tmp3);
38         uadd(&tmp1, &tmp2);
39
40         uset(&c, &tmp1);
41
42         printf("U_%d_=", n);
43         uout(&c);
44         putchar('\n');
45     }
46
47     return 0;
48 }

```

B.3.3. bank.c

```

1 #include <math.h>
2 #include <stdio.h>

```

B. Code Listings

```
3
4 #include "unum.h"
5
6 int
7 main(void)
8 {
9     SORN a, tmp;
10    int y;
11
12    uemp(&a);
13    uint(&a, M_E - 1, M_E - 1);
14
15    for (y = 1; y <= 25; y++) {
16        uemp(&tmp);
17        uint(&tmp, y, y);
18        umul(&a, &tmp);
19
20        uemp(&tmp);
21        uint(&tmp, 1, 1);
22        usub(&a, &tmp);
23
24        printf("year_%2d:", y);
25        uout(&a);
26        putchar('\n');
27    }
28
29    return 0;
30 }
```

B.3.4. spike.c

```
1 #include <stdio.h>
2
3 #include "unum.h"
4
5 #define NUMPOINTS (10)
6 #define POLE (4.0/3.0)
7
8 int
9 main(void)
10 {
11     SORN res, tmp;
12     size_t i, j;
```

```

13     unum pole, u;
14
15     /* get the unum containing the POLE */
16     uemp(&res);
17     uint(&res, POLE, POLE);
18     for (i = 0; i < sizeof(res.data); i++) {
19         if (res.data[i]) {
20             for (j = 0; j < sizeof(res.data[i]) * 8; j++) {
21                 if ((1 << (8 - j - 1)) & res.data[i]) {
22                     break;
23                 }
24             }
25             pole = 8 * i + j;
26             break;
27         }
28     }
29
30     for (u = UCLAMP(pole, -NUMPOINTS); u <= UCLAMP(pole,
31         +NUMPOINTS); u++) {
32         /* fill res just with the single u */
33         uemp(&res);
34         res.data[u / 8] = 1 << (8 - (u % 8) - 1);
35         uout(&res);
36         printf("_|->_");
37
38         /* calculate F(res) */
39         uneg(&res);
40
41         uemp(&tmp);
42         uint(&tmp, 1, 1);
43         uadd(&res, &tmp);
44
45         uemp(&tmp);
46         uint(&tmp, 3, 3);
47         umul(&res, &tmp);
48
49         uemp(&tmp);
50         uint(&tmp, 1, 1);
51         uadd(&res, &tmp);
52
53         uabs(&res);
54         ulog(&res);
55         uout(&res);
56         putchar('\n');

```

B. Code Listings

```
57     }  
58  
59     return 0;  
60 }
```

B.3.5. Makefile

```
1 PROBLEMS = euler devil bank spike  
2  
3 all: $(PROBLEMS)  
4  
5 %: %.c  
6     cc -o $@ $^ libunum.a  
7  
8 clean:  
9     rm -rf $(PROBLEMS)
```

B.4. License

This ISC license applies to all code listings in Chapter B.

```
1 Copyright © 2016, Laslo Hunhold  
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```

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Eigenständigkeitserklärung

Hiermit bestätige ich, daß ich die vorliegende Arbeit selbstständig verfaßt und keine anderen als die angegebenen Hilfsmittel verwendet habe.

Die Stellen der Arbeit, die dem Wortlaut oder dem Sinn nach anderen Werken entnommen sind, wurden unter Angabe der Quelle kenntlich gemacht.

Laslo Hunhold