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IEEE Standard for Interval Arithmetic

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IEEE Standard for Interval Arithmetic

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of the
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Abstract: This standard specifies basic interval arithmetic (IA) operations selecting and following one of the commonly used mathematical interval models. This standard supports the IEEE 754™ floating-point formats of practical use in interval computations. Exception conditions are defined, and standard handling of these conditions is specified. Consistency with the interval model is tempered with practical considerations based on input from representatives of vendors, developers and maintainers of existing systems.

The standard provides a layer between the hardware and the programming language levels. It does not mandate that any operations be implemented in hardware. It does not define any realization of the basic operations as functions in a programming language.

Keywords: arithmetic, computing, decoration, enclosure, hull, IEEE 1788™, interval, operation, verified

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Van Snyder
Josep Vehi
Julio Villalba-Moreno
G. William Walster
Yan Wang
Lee Winter
Pierre-Alain Yvars
Sergei Zhilin
Mohamed Zidan
Dan Zuras

The working group wishes to record with regret the loss of two members. Antony Popov of Sofia University, Bulgaria, died suddenly in 2012 at the young age of 49. Walter Krämer, of the Bergische Universität Wuppertal, Germany, died in October 2014 at the age of 62. Despite illness, Walter had remained an active participant until June 2014.

The following members of the individual balloting committee voted on this guide. Balloters may have voted for approval, disapproval, or abstention.

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Keith Chow
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Introduction

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This introduction explains some of the alternative interpretations, and sometimes competing objectives, that influenced the design of this standard. Implementers should study it for a fuller understanding of the design choices made in this standard among these interpretations and objectives. For more information on interval computations, including history, applications and software, see[a] e.g. [B1, B14] and the references therein, and also the interval computations web site [B5].

Mathematical context

Interval computation is a collaboration between human programmer and machine infrastructure which, correctly done, produces mathematically proven numerical results about continuous problems—for instance, rigorous bounds on the global minimum of a function or the solution of a differential equation. It is part of the discipline of "constructive real analysis." In the long term, the results of such computations might become sufficiently trusted to be accepted as contributing to legal decisions. The machine infrastructure acts as a body of theorems on which the correctness of an interval algorithm relies, so it must be made as reliable as is practical. In its logical chain are many links—hardware, underlying floating-point system, etc.—over which this standard has no control. The standard aims to strengthen one specific link, by defining interval objects and operations that are theoretically well-founded and practical to implement.

This document uses the standard notation $[a, b]$ for "the interval between numbers a and b," with various detailed meanings depending on the underlying theory. The "classical" interval arithmetic (IA) of R.A. Moore [B8] uses only bounded, closed, nonempty intervals in the real numbers $\mathbb{R}$—that is, $[a, b] = \{\, x \in \mathbb{R} \mid a \le x \le b \,\}$ where $a, b \in \mathbb{R}$ with $a \le b$. So, for instance, division by an interval containing 0 is not defined in it. It was agreed early on that this standard should strictly extend classical IA in virtue of allowing an interval to be unbounded or empty.

Beyond this, various extensions of classical IA were considered. One choice that distinguishes between theories is: Are arithmetic operations purely algebraic, or do they involve topology? An example of the latter is containment set (cset) theory [B13], which extends functions over the reals to functions over the extended reals, e.g., $\sin(+\infty)$ is the set of all possible limits of $\sin x$ as $x \to +\infty$, which is $[-1, 1]$. The complications of this were deemed to outweigh the advantages, and it was agreed that operations should be purely algebraic.

Another choice is: Is an interval a set—a subset of the number line—or is it something different? The most widely used forms of IA are *set-based* and define an interval to be a set of real numbers [B10]. They have established software to find validated solutions of linear and nonlinear algebraic equations, optimization problems, differential equations, etc.

However, *Kaucher* IA and the nearly equivalent *modal* IA have significant applications. In the former, an interval is formally a pair (a, b) of real numbers, which for $a \le b$ is "proper" and identified with the normal interval $\{\, x \in \mathbb{R} \mid a \le x \le b \,\}$, and for $a > b$ is "improper." In the latter, an interval is a pair (X, Q), where X is a normal interval and Q is a quantifier, either $\exists$ or $\forall$. At the time of writing, it finds commercial use in the graphics rendering industry. Both forms are referred to as Kaucher IA henceforth.

In view of their significance, it was decided to support both set-based and Kaucher IA. Because of their different mathematical bases, this led to the concept of *flavors* (see Clause 7). A flavor is a version of IA that extends classical IA in a precisely defined sense, such that when only classical intervals and restricted operations are used (avoiding, e.g., division by an interval containing zero), all flavors produce the same results at the mathematical level and also—up to roundoff—in finite precision.

Currently, the standard includes only the set-based flavor. Among other possible flavors are Kaucher/modal intervals; containment-sets; and the interval system of Siegfried Rump [B15], which handles the relation between floating-point numbers and intervals, including overflow, in an elegant way, as well as being able to support open and half-open intervals. All of these extend classical IA in the defined sense.

[a] The numbers in brackets correspond to those of the bibliography in Annex A.

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Clause 1 through Clause 9 contain a common set of definitions and requirements that apply to all flavors. Clause 10 through Clause 14 contain the set-based flavor, in which:

– Intervals are subsets of the set $\mathbb{R}$ of real numbers. At the mathematical level (Level 1 in the structure defined in Clause 5) they are precisely all topologically closed and connected subsets of $\mathbb{R}$. The finite-precision level (Level 2) uses the notion of an interval type, which is a finite set of Level 1 intervals.

– The interval version of an elementary function such as $\sin x$ is essentially the natural extension to sets of the corresponding pointwise function on real numbers.

Fuzzy sets, like intervals, are a way to handle uncertain knowledge, and the two topics are related. However, to consider this relation was beyond the scope of this project.

Specification levels

The floating-point standard IEEE Std 754™-2008 describes itself as layered into four Specification Levels. To manage complexity, the present standard uses a corresponding structure. It deals mainly with Level 1, of mathematical *interval theory*, and Level 2, the finite set of *interval datums* in terms of which finite-precision interval computation is defined. It has some concern with Level 3, of *representations* of intervals as data structures; and with Level 4, of interchange *encoding* in *bit strings*.

There is another important player: the programming language. It was a recognized omission of the first (1985) version of IEEE Std 754-2008 that it specified individual operations but not how they should be used in expressions. Optimizing compilers have, since well before that standard, used clever transformations so that it is impossible to know the precisions used and the roundings performed while evaluating an expression, or whether the compiler has even "optimized away" $(1.0 + x) - 1.0$ to become simply x. The 2008 revision specifies this by placing requirements on how operations should be used in expressions, though as of this writing, few programming languages have adopted that.

The lack of any restrictions is also a problem for intervals. Thus the standard makes requirements and recommendations on language implementations, thereby defining the notion of a standard-conforming implementation of intervals within a language.

The language does not constitute a fifth level in some linear sequence; from the user's viewpoint, most current languages sit above datum level 2, alongside theory level 1, as a practical means to implement interval algorithms by manipulating Level 2 entities (though most languages have influence on Levels 3 and 4 also). This standard extends them to provide an instantiation of Level 2 entities.

The Fundamental Theorem

Moore's [B8] Fundamental Theorem of Interval Arithmetic (FTIA) is central to interval computation. Roughly, it says as follows. Let f be an *explicit arithmetic expression*—that is, it is built from finitely many elementary functions (arithmetic operations) such as $+, -, \times, \div, \sin, \exp, \ldots$, with no non-arithmetic operations such as intersection, so that it defines a real function $f(x_1, \ldots, x_n)$. Then evaluating f "in interval mode" over any interval input box $(\boldsymbol{x}_1, \ldots, \boldsymbol{x}_n)$ is guaranteed to enclose (i.e., give a set that contains) the range of f over those inputs. Typically there are sub-cases, where extra conditions lead to stronger conclusions such as f being continuous on the input box.

A version of the FTIA holds in all variants of interval theory, but with varying hypotheses and conclusions. In the context of this standard, an expression should be evaluated entirely in one flavor, and inferences made strictly from that flavor's FTIA; otherwise, a user might believe an FTIA holds in a case where it does not, with possibly serious effects in applications. As stated, the FTIA is about the mathematical level. Moore's achievements were to see that "outward rounding" makes the FTIA hold also in finite precision and to follow through the consequences. An advantage of the level structure used by the standard is that the mapping between Levels 1 and 2 defines a framework where it is easily proved that

Each flavor's finite-precision FTIA holds in any conforming implementation.

Generally, during program execution it can only be decided *after* evaluating an expression whether the conditions for any sub-case of the FTIA hold. The purpose of each flavor's *decoration system* is to make such decisions computable, see 6.4 and Clause 7.

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For the set-based flavor, see [B12] for background on its decoration system, 6.4 for a statement of its FTIA, and Annex B for a statement and proof of its FTDIA.

Operations

There are several interpretations of *evaluation outside an operation's domain* and *operations as relations rather than functions*. This includes classical alternative meanings of division by an interval containing zero, or square root of an interval containing negative values. To illustrate the different interpretations, consider $\boldsymbol{y} = \sqrt{\boldsymbol{x}}$ where $\boldsymbol{x} = [-1, 4]$.

a) In *optimization*, when computing lower bounds on the objective function, it is generally appropriate to return the result $\boldsymbol{y} = [0, 2]$, and ignore the fact that $\sqrt{\cdot}$ has been applied to negative elements of $\boldsymbol{x}$.

b) In applications (such as solving differential equations) where one must check whether the hypotheses of a *fixed point theorem* are satisfied:

   1) one might need to be sure that the function is defined and continuous on the input and, hence, report an illegal argument when, as in the above case, this fails; or

   2) one might need the result $\boldsymbol{y} = [0, 2]$, but must flag the fact that $\sqrt{\cdot}$ has been evaluated at points where it is undefined or not continuous.

c) In *constraint propagation*, the equation is often to be interpreted as: find an interval enclosing all y such that $y^2 = x$ for some $x \in [-1, 4]$. In this case the answer is $[-2, 2]$.

The standard provides means to meet these diverse needs, while aiming to preserve clarity and efficiency. A language might achieve this by binding one of the above three interpretations—usually some variant of b)—to its built-in operations, and providing the others as library procedures.

In the context of flavors, a key idea is that of *common operation instances*: those elementary interval calculations that at the mathematical level are required to give the same result in all flavors. For example $[1, 2]/[3, 4] = [1/4, 2/3]$ is common, while division by an interval containing zero is not common.

Decorations

Many interval algorithms are only valid if certain mathematical conditions are satisfied: for instance, one might need to know that a function f, defined by an expression, is everywhere continuous on a box in $\mathbb{R}^n$ defined by n input intervals $\boldsymbol{x}_1, \ldots, \boldsymbol{x}_n$. The IEEE 754 use of global flags to record events such as division by zero was considered inadequate in an era of massively parallel processing. In this standard, such events are recorded locally by *decorations*.

A *decorated interval* is an ordinary interval tagged with a few bits that encode the decoration. A small number of decorations is provided, designed for efficient propagation of such property information. For instance, if evaluation outputs an interval $\boldsymbol{y}$ with the `dac` decoration, then f is *d*efined *a*nd *c*ontinuous on its input box, with range contained in $\boldsymbol{y}$. This allows a rigorous check, for instance, that the conditions for applying a fixed-point theorem hold. Depending on need, a programmer may use bare (undecorated) intervals, or decorated intervals, or (if provided) the optional *compressed* decorated interval arithmetic that offers less decoration capability in exchange for faster execution.

The Basic standard

To make the standard more accessible and speed up production of implementations, a subset of the set-based standard called the Basic Standard for Interval Arithmetic (BSIA) has been written. It includes just one finite-precision interval type—intervals whose endpoints are IEEE 754 `binary64` numbers—and those operations that in the editors' view are most commonly used. A minimal implementation of the BSIA is not a conforming implementation of the full standard since some required operations of the latter are omitted or provided in a restricted form. However a program that runs using such an implementation should run, and give identical output within roundoff, using an implementation of the full standard. At the time of writing a project is underway to issue the BSIA as a separate IEEE standard.

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IEEE Standard for Interval Arithmetic

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PART 1

General Requirements

1. Overview

1.1 Scope

This standard specifies basic interval arithmetic (IA) operations selecting and following one of the commonly used mathematical interval models. This standard supports the IEEE 754™ floating-point formats of practical use in interval computations. Exception conditions are defined, and standard handling of these conditions is specified. Consistency with the interval model is tempered with practical considerations based on input from representatives of vendors, developers and maintainers of existing systems.

The standard provides a layer between the hardware and the programming language levels. It does not mandate that any operations be implemented in hardware. It does not define any realization of the basic operations as functions in a programming language.

1.2 Purpose

The aim of the standard is to improve the availability of reliable computing in modern hardware and software environments by defining the basic building blocks needed for performing interval arithmetic. There are presently many systems for interval arithmetic in use; lack of a standard inhibits development, portability, and ability to verify correctness of codes.

1.3 Inclusions

This standard specifies

– Types for interval data based on underlying numeric formats, with a special class of type derived from IEEE 754 floating-point formats.

– Constructors for intervals from numeric and character sequence data.

– Addition, subtraction, multiplication, division, fused multiply add, square root; other interval-valued operations for intervals.

– Midpoint, radius and other numeric functions of intervals.

– Interval comparison relations and other boolean functions of intervals.

– Elementary interval functions of intervals.

– Conversions between different interval types.

– Conversions between interval types and external representations as text strings.

– Interval-related exceptional conditions and their handling.

1.4 Exclusions

This standard does not specify

– Which numeric formats supported by the underlying system shall have an associated interval type.

– How (for implementations supporting IEEE 754 arithmetic) operations act on the IEEE 754 status flags.

– How an implementation represents intervals at the level of programming language data types or bit patterns.

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