Why Not to Use Binary Floating Point Datatypes in RDF

Jan Martin Keil and Merle Gänßinger
Heinz Nixdorf Chair for Distributed Information Systems, Institute for Computer Science, Friedrich Schiller University Jena, Jena, Germany
{jan-martin.keil,merle.gaenssinger}@uni-jena.de

Abstract. The XSD binary floating point datatypes are regularly used for precise numeric values in RDF. However, the use of these datatypes for knowledge representation can systematically impair the quality of data and, compared to the XSD decimal datatype, increases the probability of data processing producing false results. We argue why in most cases the XSD decimal datatype is better suited to represent numeric values in RDF. A survey of the actual usage of datatypes on the relevant subset of the September 2020 Web Data Commons dataset, containing 14,778,325,375 literals from real web data, substantiates the practical relevancy of the described problems: 29%-68% of binary floating point values are distorted due to the datatype.

Keywords: Data Quality · Datatypes · Floating Point Precision · Knowledge Graphs · Numerical Stability · RDF · XSD

1 Introduction

The Resource Description Framework (RDF) is the fundamental building block of knowledge graphs and the Semantic Web. In RDF, values are represented as literals. A literal consists of a lexical form, a datatype, and possibly a language tag. The use of XML Schema (XSD) built-in datatypes [1] is recommended by the RDF standard [2, Sec. 5.1]. For numeric values, this includes the primitive types float, double and decimal as well as all variations of integer\(^1\) which are derived from decimal.

The datatype decimal allows to represent numbers with arbitrary precision, whereas the datatypes float and double allow to represent binary floating point values of limited range and precision [1]. However, in practice, the binary floating point datatypes are regularly used for precise numeric values, although the datatype can not accurately represent these values. Even a popular ontology guideline [3] and a World Wide Web Consortium (W3C) working group note [4] use binary floating point datatypes for precise numeric values in examples.

In general, binary floating point numbers are meant to approximate decimal values in a fixed length binary representation to limit memory consumption and

\(^1\)integer, long, int, short, byte, nonNegativeInteger, positiveInteger, unsignedLong, unsignedInt, unsignedShort, unsignedByte, nonPositiveInteger, and negativeInteger
increase computation speed. In RDF, however, binary floating point numbers are defined to represent the exact value of the binary representation: Binary floating point values do not approximate typed decimals, as in programming languages, but typed decimals are abbreviations for exact binary floating point values. This causes ambiguity about the intended meaning of numeric values. We show that 29\%-68\% of the floating point values in real web data are distorted due to the datatype. With regard to the growing use of RDF for the representation of data, including research data, this ambiguity is concerning.

Further, the use of binary floating point datatypes for precise numeric values regularly causes rounding errors in the values actually represented, compared to typed values provided as decimals. Subsequently, error accumulation may significantly falsify the result of processing these values. Disasters, such as the Patriot Missile Failure, which resulted in 28 deaths, illustrate the potential impact of accumulated errors in real world applications [5]. The increasing relevance of knowledge graphs for real-world applications calls for general awareness of these issues in the Semantic Web community.

In this paper, we discuss advantages and disadvantages of the different numeric datatypes. We demonstrate the practical relevance of outlined problems with a survey of the actual usage of datatypes on the relevant subset of the September 2020 Web Data Commons dataset, containing 14,778,325,375 literals from real web data. We aim to raise awareness of the implications of datatype selection in RDF and to enable a more informed choice in the future. This work is structured as follows: In Section 2, we give an overview of relevant standards and related work, followed by a comparison of the properties of the binary floating point and decimal datatypes in Section 3. In Section 4, we discuss the implications of the datatype properties in different use cases. An approach for automatic problem detection is sketched in Section 5. In Section 6, we present a survey on the use of datatypes in the World Wide Web that demonstrates the practical relevance of the outlined problems. Finally, we indicate approaches for the general mitigation of the problems in Section 7.

2 Background

Each datatype in RDF consists of a lexical space, a value space, and a lexical-to-value mapping. This is compatible with datatypes in XSD [2].

The value space of a datatype is the set of values for that datatype [1,2].

The lexical space of a datatype is the prescribed set of strings, which the lexical mapping for that datatype maps to values of that datatype. The members of the lexical space are lexical representations (XSD) or lexical forms (RDF) of the values to which they are mapped [1,2].

The lexical mapping (XSD) or lexical-to-value mapping (RDF) for a datatype is a prescribed relation which maps from the lexical space of the datatype into its value space [1,2].
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RDF reuses many of the XSD datatypes [2]. For non-integer numbers, XSD provides the datatypes decimal, float and double. The XSD datatype **decimal** (xsd:decimal) represents a subset of the real numbers [1].

**Value space of xsd:decimal**: The set of numbers that can be obtained by dividing an integer by a non-negative power of ten: \(\frac{i}{10^n}\) with \(i \in \mathbb{Z}, n \in \mathbb{N}_0\), precision is not reflected [1].

**Lexical space of xsd:decimal**: The set of all decimal numbers with or without a decimal point [1].

**Lexical mapping of xsd:decimal**: Set \(i\) according to the decimal digits of the lexical representation and the leading sign, and set \(n\) according to the position of the period or 0, if the period is omitted. If the sign is omitted, “+” is assumed [1].

The XSD datatype **float** (xsd:float) is aligned with the IEEE 32-bit binary floating point datatype [6]\(^2\), the XSD datatype **double** (xsd:double) is aligned to the IEEE 64-bit binary floating point datatype [6]. Both represent subsets of the rational numbers. They only differ in their three defining constants [1].

**Value space of xsd:float (xsd:double)**: The set of the special values positiveZero, negativeZero, positiveInfinity, negativeInfinity, and notANumber and the numbers that can be obtained by multiplying an integer \(m\) whose absolute value is less than \(2^{24}\) (double: \(2^{53}\)) with a power of two whose exponent \(e\) is an integer between \(-149\) (double: \(-1074\)) and 104 (double: 971): \(m \cdot 2^e\) [1].

**Lexical space of xsd:float (xsd:double)**: The set of all decimal numbers with or without a decimal point, numbers in exponential notation, and the literals INF, +INF, -INF, and NaN [1].

**Lexical mapping of xsd:float (xsd:double)**: Set either the according numeric value (including rounding, if necessary), or the according special value. An implementation might choose between different rounding variants that satisfy the requirements of the IEEE specification.

Numbers with a fractional part of infinite length, like, for example, the rational number \(\frac{1}{3} = 0.3\) or the irrational number \(\sqrt{2} = 1.4142\ldots\), are not in the value space of xsd:float or xsd:double, as a number of finite length multiplied or divided by two is always a number of finite length again. Consequently, a finite decimal with sufficient precision can exactly represent every possible numeric value or lexical representation of an xsd:float or xsd:double, except of the special values positiveInfinity, negativeInfinity, and notANumber. In contrast, a finite binary floating point value can not exactly represent every possible decimal value.

Some serialization or query languages for RDF provide a shorthand syntax for numeric literals without explicit datatype specification. In Turtle, TriG and

\(^2\)As the XSD recommendation refers to IEEE 754-2008 version of the standard, we do not refer to the subsequent IEEE 754-2019 version.
SPARQL a number without fraction is an `xsd:integer`, a number with fraction is an `xsd:decimal`, and a number in exponential notation is an `xsd:double` [7,8,9]. In JSON-LD a number without fractions is an `xsd:integer` and a number with fraction is an `xsd:double`, to align with the common interpretation of numbers in JSON [10]. Other RDF languages, i.e. RDF/XML, N-Triples, N-Quads, and RDFa, do not provide a shorthand syntax for numeric literals [11,12,13,14]. Other languages for machine-readable annotation of HTML, which are regularly mapped to RDF, i.e. Microformats\(^3\), and Microdata\(^4\), do not incorporate explicit datatypes.

In addition to the core XSD datatypes, a W3C working group note introduces the `precisionDecimal` datatype [15]. It is aligned to the IEEE decimal floating-point datatypes [6] and represents a subset of real numbers. It retains precision and permits the special values `positiveZero`, `negativeZero`, `positiveInfinity`, `negativeInfinity`, and `notANumber`. Further, it supports exponential notation. The precision and exponent values of the `precisionDecimal` datatype are unbounded, but can be restricted in derived datatypes to comply with an actual IEEE decimal floating-point datatype. However, even though the RDF standard permits the use of `precisionDecimal`, it does not demand its support in compliant implementations [2]. Therefore, RDF frameworks can not be expected to always support `precisionDecimal`.

Another W3C working group note addresses the selection of proper numeric datatypes for different use cases. It identified three relevant use cases of numeric values: count, measurement, and constant. According to the note, the usually appropriate datatypes are (derived datatypes of) the integer datatype for counts, binary floating point datatypes for measurements, and the decimal datatype for constants [4].

The popular ontology schema.org\(^5\) defines alternative numeric datatypes `schema:Integer` and `schema:Float` and their super datatype `schema:Number`. A usage note restricts the lexical space of `schema:Number` to the digits 0 to 9 and at most one full stop. No further restrictions of the lexical or value space are made. `schema:Number` is directly in the range of 91 properties defined by schema.org and `schema:Integer` is directly in the range of 47 properties. `schema:Float` is not directly in the range of any property.

The digital representation or computation of numerical values can cause numerical problems: An `overflow error` occurs, if a represented value exceeds the maximum positive or negative value in the value space of a datatype. An `underflow error` occurs, if a represented value is smaller than the minimum positive or negative value different from zero in the value space of a datatype. A `rounding error` occurs, if a represented value is not in the value space of a datatype and is represented by a nearby value in the value space that is determined by a rounding scheme. A `cancellation` is caused by the subtraction of nearly equal values and eliminates leading accurate digits. This will expose rounding errors in the

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\(^3\)https://microformats.org

\(^4\)https://html.spec.whatwg.org/multipage/microdata.html

\(^5\)http://schema.org, current version 13.0
input values of the subtraction. *Error accumulation* is the insidious growth of errors due to the use of a numerically instable sequence of operations.

### 3 Properties of Binary Floating Point and Decimal Datatypes in RDF

Binary floating point and decimal datatypes in the context of RDF have individual properties, which make them more or less suitable for specific use cases:

- `xsd:float` and `xsd:double` permit the use of **positive and negative infinite values**. `xsd:decimal` supports neither positive nor negative infinite values.

- `xsd:float` and `xsd:double` permit the **exponential notation**. Especially in case of numbers with many leading or trailing zeros, this is more convenient and less error-prone to read or write for humans. `xsd:decimal` does not permit the exponential notation. There is no actual reason for this limitation. For example, Wikibase\(^6\) also accepts exponential notation for `xsd:double`.\(^7\) The *XML Schema Working Group* decided against allowing exponential notation for `xsd:decimal`, as the requirement to have a decimal datatype permitting exponential notation was already met by `precisionDecimal` [16], which, however, has been dropped in the later process of the standardization [17].

The value spaces of `xsd:float` and `xsd:double` only provide partial coverage of the lexical space. Therefore, the lexical mapping (3 in Figure 1) might require rounding to a possible binary representation and the actual value might slightly differ from the lexical representation. For example, `xsd:float` has no exact binary representation of 0.1 and, if using the default `roundTiesToEven`
rounding scheme [6], the lexical representation 0.1 of xsd:float actually maps to a slightly higher binary representation of 0.1000000149011612. Depending on the used RDF framework, it might be possible to preserve the exact value of the lexical representation by implementing a custom mapping to decimal (2 in Figure 1). However, this causes additional development effort and introduces non standard compliant behavior. The value space of xsd:decimal covers all values in the lexical space. Therefore, the lexical mapping (1 in Figure 1) always provides the exact numeric value described in the lexical representation without any rounding. All three datatypes, xsd:float, xsd:double, and xsd:decimal, do not cover the precision reflected by the lexical representation. The only discussed datatype that preserves precision is precisionDecimal.

The accuracy of calculations based on xsd:float or xsd:double literals (7 in Figure 1) is limited, as a properly implemented RDF framework will use binary floating point arithmetic by default. For example, this happens during the execution of SPARQL queries that include arithmetic functions or aggregations. Therefore, the calculations might be affected by various numeric problems, i.e. underflow errors, overflow errors, rounding errors, cancellation, and error accumulation. Calculations based on xsd:decimal literals (6 in Figure 1) will by default use a decimal arithmetic with arbitrary precision. Therefore, they might only be affected by rounding errors in case of (intermediate) results with a fractional part of infinite length, as well as accumulations of these rounding errors. This different behavior is demonstrated in Figure 2. Depending on the used RDF framework, it might be possible to cast between the datatypes (4 and 5 in Figure 1). However, a value cast from binary floating point to decimal (5 in Figure 1) is still affected by the rounding error of the floating point value caused by the lexical mapping and subsequent calculations (8 in Figure 1) will still result in approximate results only. In contrast, the results of calculations based on a value cast from decimal to floating point (4 in Figure 1) and based on an initial floating point value (3 in Figure 1) do not differ, if the same rounding method is used. The SPARQL query in Figure 2 and the according result provided by Wikibase6 demonstrates different numerical problems of the datatypes. Other SPARQL endpoints, i.e. Virtuoso 8.38 and Apache Fuseki 5.16.09, provide similar results.

4 Implications for the Choice of Numeric Datatypes

The traditional use case of RDF is the representation of knowledge. The XSD floating point datatypes provide two advantages for the knowledge representation compared to xsd:decimal: Firstly, the permitted representation of positive and negative infinite might be needed in some cases. Secondly, the exponential notation eases the representation of very large and very small values and reduces the risk of typing errors due to missing or additional zeros. This would not be an issue in case of proper user interface support. But popular tools, like,
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```sparql
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
SELECT ?datatype 
(xsd:decimal(STRDT("0.1", ?datatype)) AS ?rounded) 
(xsd:decimal(STRDT("1", ?datatype) / STRDT("3", ?datatype)) AS ?roundedInfinit) 
(xsd:decimal(STRDT("1.0000001", ?datatype) - STRDT("1.000000", ?datatype)) AS ?cancellation) 
(STRDT("1000000000000000000000000000000000000000", ?datatype) AS ?overflow) 
(STRDT("0.0000000000000000000000000000000001", ?datatype) AS ?underflow)
WHERE {VALUES ?datatype {xsd:float xsd:decimal}}
```

| datatype     | xsd:float       | xsd:decimal     |
|--------------|-----------------|-----------------|
| rounded      | 0.10000000149011612 | 0.1             |
| roundedInfinit| 0.3333333432674408 | 0.3333333333333333 |
| cancellation | 0.00000011920928955078125 | 0.0000001     |
| overflow     | Infinity        | 1000000000000000000000000000000000000000 |
| underflow    | 0.0             | 0.000000000000000000000000000000000001 |

Fig. 2. Top: A SPARQL query that demonstrates differing numerical problems of the datatypes float and decimal. Bottom: The corresponding query output (transformed), as on [http://query.wikidata.org](http://query.wikidata.org).

for example, WebProtégé and Protégé Desktop[^10], do not help the user here. Further, projects that manipulate their RDF documents under version control using SPARQL UPDATE queries, custom generation scripts and manual edits do not have such a user interface at all.

However, in most cases, knowledge concerned with numbers deals with exact decimal numbers or intervals of decimal values. Intervals are typically described with two exact decimal numbers, either with a minimum value and a maximum value (e.g. [0.05, 0.15]) or an value and a measurement uncertainty (e.g. 0.1±0.05) [18]. The binary floating point datatypes do not allow the accurate representation of exactly known or defined numbers in many cases. In addition, they entail the risk to fool data curators into believing that they stated the exact number, as the lexical representation on first sight appears to be exact. This becomes even more critical, if `xsd:double` was used unintentionally due to a shorthand syntax in Turtle, TrIG, SPARQL, or JSON-LD. This way, the use of binary floating point datatypes produces ambiguity in the data: The intended meaning could either be the actually represented number in the value space or the verbatim interpretation of the lexical representation. This ambiguity counteracts the basic ideas behind the Semantic Web and linked open data to ease understanding and reuse of data. Therefore, binary floating point datatypes are not suitable to fulfill the requirements for knowledge representation.

[^10]: [https://protege.stanford.edu/](https://protege.stanford.edu/)
In consequence, the knowledge can not be used for exact calculations without programming overhead. The possible small rounding errors of binary floating point input values might accumulate to significant errors in calculation results. Disasters, as the Patriot Missile Failure, illustrate the potential impact of accumulated errors in real world applications [5].

This contradicts a W3C working group note [4], stating that binary floating point datatypes are appropriate for measurements. It provided the following example representation of a measurement in the interval of 73.0 to 73.2:

```rdfs
_:w eg:value "73.1"^^xsd:float .
_:w eg:errorRange "0.1"^^xsd:float .
```

However, if using the default `roundTiesToEven` rounding scheme [6], this example actually represents a measurement in the interval 72.99999847263098388 to 73.19999847561121612, as 73.1 and 0.1 are not in the value space of `xsd:float`.11

In consequence, the actual represented error interval misses to cover all points between 73.19999847561121612 and 73.2. A common solution for this problem is the use of different rounding schemes for the calculation of the upper and lower bound of the interval (outward rounding) [19]. However, this is not provided in current RDF frameworks and causes additional programming effort. The example shows that also in case of measurements binary floating point datatypes have clear disadvantages compared to `xsd:decimal`.

Further, the use of binary floating point values in RDF restricts the selection of the used arithmetic for calculations, as it causes an implementation overhead for the application of decimal arithmetic with arbitrary precision. It must be mentioned that calculations using decimal arithmetic with arbitrary precision probably are significantly slower, compared to calculations using binary floating point arithmetic with limited precision. Hence, floating point calculations are better suited for many use cases. However, in certain cases they are not. Therefore, the selection of an arithmetic must be up to the application, not to the input data, as applications might widely vary regarding the required accuracy and the numerical conditioning of the underlying problem.

The same problem arises in use cases that involve the comparison of values, like ontology matching or ontology based data validation, because comparison values become blurred due to rounding. For example, if using the default `roundTiesToEven` rounding scheme, an upper bound of "0.1"^^`xsd:float` in a constraint still permits a value of 0.100000001. Thus, the use of binary floating point datatypes for knowledge representation can systematically impair the quality of data and increases the probability of data processing producing false results.

In other use cases, RDF might be used for the exchange of initially binary floating point values, as computational results or the output of analog-to-digital converters. If the data to exchange are binary floating point values, the original

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11Lexical mappings (`roundTiesToEven` rounding scheme): 73.1 → 73.0999984741211 and 0.1 → 0.1000000149011612, Interval calculations: 73.0999984741211 ± 0.1000000149011612
value can only contain values with an exact binary representation and corruption of data with rounding is impossible. Thus, the use of floating point datatypes for the exchange of computational results is reasonable.

5 Automatic Distortion Detection

The automatic detection of quality issues is key to an effective quality assurance. Therefore, RDF editors, like Protégé\textsuperscript{10}, or evaluation tools, like the OntOlogy Pitfall Scanner! [20], would ideally warn data curators, if the use of binary floating point datatypes would distort numeric values.

A simple test can be implemented by comparing the results of the default mapping to a binary floating point value (3 in Figure 1) followed by an cast to decimal (5 in Figure 1) and a custom mapping to a decimal value (2 in Figure 1). The SPARQL query in Figure 3 demonstrates the approach.

```sparql
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
SELECT
  (xsd:decimal(?defaultMapping) AS ?float)
  (?customMapping AS ?decimal)
  (xsd:decimal(?defaultMapping) != ?customMapping AS ?distorted)
WHERE {
  VALUES ?lexical {"10" "1" "0.1" "0.5"}
  BIND(STRDT(?lexical, xsd:float) AS ?defaultMapping)
  BIND(STRDT(?lexical, xsd:decimal) AS ?customMapping)
}
```

| float     | decimal | distorted |
|-----------|---------|-----------|
| 0.5       | 0.5     | false     |
| 0.10000000149011612 | 0.1     | true      |
| 1         | 1       | false     |
| 10        | 10      | false     |

Fig. 3. Top: A SPARQL query that demonstrates an approach to detect number distortion. Bottom: The corresponding query output, as on http://query.wikidata.org.

6 Datatype Usage Survey

To determine the practical relevance of the described problems, we conducted a survey of the actual usage of datatypes. The survey is based on the September 2020 edition\textsuperscript{12} of the Web Data Commons dataset [21]. The Web Data Commons dataset provides in several N-Quads files the embedded RDF data of 1.7e9 HTML

\textsuperscript{12}http://webdatacommons.org/structureddata/#results-2020-1
documents extracted from all 3.4e9 HTML documents contained in the September 2020 Common Crawl archive.\(^{13}\) The September 2020 Web Data Commons dataset is divided into data extracted from embedded JSON-LD, RDFa, Microdata, and several Microformats. We only considered data from embedded JSON-LD (7.7e8 URLs, 3.2e10 triples) and RDFa (4.1e8 URLs, 5.9e9 triples), as Microdata and Microformats do not incorporate explicit datatypes.

We created a Java program based on Apache Jena\(^9\) to stream and analyze the relevant parts of the Web Data Commons dataset. The dataset replicates malformed IRIs or literals as they appeared in the original source. To avoid parsing failures of whole files due to single malformed statements, each line was parsed independently. These failures were logged in a separate result table. The main reasons for failures were malformed IRIs and illegal character encodings. Transaction mechanisms were used to ensure the consistency of the resulting dataset in case of temporary failures of involved systems. Per source type, dataset file, property, and datatype we measured:

- **UnpreciseRepresentableInDouble**: The number of lexicals that are in the lexical space but not in the value space of xsd:double.
- **UnpreciseRepresentableInFloat**: The number of lexicals that are in the lexical space but not in the value space of xsd:float.
- **UsedAsDatatype**: The total number of literals with the datatype.
- **UsedAsPropertyRange**: The number of statements that specify the datatype as range of the property.
- **ValidDecimalNotation**: The number of lexicals that represent a number with decimal notation and whose lexical representation is thereby in the lexical space of xsd:decimal, xsd:float, and xsd:double.
- **ValidExponentialNotation**: The number of lexicals that represent a number with exponential notation and whose lexical representation is thereby in the lexical space of xsd:float, and xsd:double.
- **ValidInfOrNaNNotation**: The number of lexicals that equals either INF, +INF, -INF or NaN and whose lexical representation is thereby in the lexical space of xsd:float, and xsd:double.
- **ValidIntegerNotation**: The number of lexicals that represent an integer number and whose lexical representation is thereby in the lexical space of xsd:integer, xsd:decimal, xsd:float, and xsd:double.

Unfortunately, the lexical representation of xsd:double literals from embedded JSON-LD was normalized during the creation of the Web Data Commons dataset to always uses exponential notation with one integer digit and up to 16 fractional digits.\(^{14}\) This is a legal transformation according to the definition of xsd:double, as the represented value is preserved. However, this limits the use of the according Valid... and Unprecise... measures. At the same time, this

\(^{13}\)https://commoncrawl.org/2020/10/september-2020-crawl-archive-now-available/

\(^{14}\)https://github.com/jsonld-java/jsonld-java/blob/v0.13.1/core/src/main/java/com/github/jsonldjava/core/RDFDataset.java#L673
Why Not to Use Binary Floating Point Datatypes in RDF demonstrates, that the use of \texttt{xsd:float} or \texttt{xsd:double} might easily cause the loss of information reflected only in the lexical representation by legal transformations during the processing.

The resulting dataset consist of two CSV files containing the measurement results (5.4e7 lines, 0.6 GiB compressed, 11.0 GiB uncompressed) and the parsing failure log (4.5e7 lines, 0.5 GiB compressed, 9.7 GiB uncompressed). The analysis was conducted with python scripts. The tool [22], the resulting dataset [23], and the analysis scripts [24] are freely available for review and further use under permissive licenses.

For the analysis, we first applied some data cleaning: Some properties and datatypes where regularly denoted by IRIs in the http scheme as well as in the https scheme. To enable proper aggregation, the scheme of all IRIs in the dataset were unified to http. Further, the omission of namespace definitions in the source websites causes the occurrence of prefixed names instead of full IRIs. All prefixes in datatypes that occurred at least for one datatype more than 1000 times and whose namespace was obvious, have been replaced with the actual namespace. In the same way, all prefixes in properties that occurred at least for one property more than 1000 times and whose namespace was obvious, have been replaced with the actual namespace. We did not clean further kinds of typos, like, for example, missing or duplicated \\# or / after the namespace.

For the results presentation, we use the following prefixes to abbreviate IRIs:

\begin{verbatim}
dcterms: http://purl.org/dc/terms/
dv: http://rdf.data-vocabulary.org/
gr: http://purl.org/goodrelations/v1/
rev: http://purl.org/stuff/rev/
rdf: http://www.w3.org/1999/02/22-rdf-syntax-ns/
schema: http://schema.org/
use: http://search.yahoo.com/searchmonkey-datatype/use/
vcard: http://www.w3.org/2006/vcard/ns/
xsd: http://www.w3.org/2001/XMLSchema/
\end{verbatim}

Overall, we processed 14 778 325 375 literals from embedded JSON-LD and 4 674 734 966 literals from RDFa. Table 1 shows the number of occurrences of the most frequent datatypes. Table 2 shows the most frequently used properties that occurred with numerical datatypes from XSD or schema.org. Although the use of the schema.org numeric datatypes instead of XSD numeric datatypes is expected by the definition of many schema.org properties, including widely used properties, like, for example, \texttt{schema:position} or \texttt{schema:price}, we did find zero occurrences of schema.org numeric datatypes. In contrast, the usage of schema.org temporal datatypes \texttt{schema:Date} and \texttt{schema:DateTime} in JSON-LD exceeds the usage of XSD temporal datatypes by orders of magnitude. The most probable reason for this is the existence of shorthand syntaxes for XSD numeric datatypes. This emphasizes the importance of shorthand syntaxes for the choice of datatypes.

As shown in Table 1, the occurrences of \texttt{xsd:float} in RDFa and \texttt{xsd:double} in embedded JSON-LD surpass the occurrences of \texttt{xsd:decimal} by orders of
Table 1. The number of datatype occurrences in the Web Data Commons September 2020 dataset from RDFa and embedded JSON-LD sources in absolute numbers and relative to the total number of literals in the source type. Only the top 10, as well as selected further datatypes are shown.

| Datatype       | RDFa          | Embedded JSON-LD          |
|----------------|---------------|---------------------------|
| rdf:langString | 3179161585 (.68) | xsd:string 11277500571 (.76) |
| xsd:string     | 1305371136 (.28) | xsd:integer 2021243795 (.14) |
| xsd:dateTime   | 102987223 (.02)  | schema:Date 1313408439 (.09) |
| rdf:XMLLiteral | 62337177 (.01)  | xsd:double 101959406 (.01) |
| xsd:integer    | 21547053 (.00)  | xsd:boolean 26144338 (.00)  |
| xsd:float      | 1025753 (.00)   | schema:DateTime 25002464 (.00) |
| use:sku        | 729858 (.00)    | rdf:langString 12934431 (.00) |
| xsd:date       | 507454 (.00)    | xsd:float 90895 (.00)     |
| xsd:boolean    | 348334 (.00)    | xsd:dateTime 12260 (.00)  |
| schema:Date    | 246995 (.00)    | rdf:HTML 5785 (.00)      |
| xsd:decimal    | 8288 (.00)      | xsd:decimal 1 (.00)     |
| xsd:double     | 234 (.00)       | schema:Number 0 (.00)   |
| schema:Number  | 0 (.00)         | schema:Integer 0 (.00)  |
| schema:Integer | 0 (.00)         | schema:Float 0 (.00)    |
| schema:Float   | 0 (.00)         |                           |

Remarkably, we did find only one single occurrence\(^{15}\) of xsd:decimal among 14,778,325,375 literals from valid triples in embedded JSON-LD sources in the whole Web Data Commons September 2020 dataset. Table 3 shows properties that most frequently occurred with xsd:float in RDFa and with xsd:double in embedded JSON-LD. Based on these figures, at least 62% for xsd:float in RDFa and 54% for xsd:double in embedded JSON-LD represent (monetary) amounts, position numbers or single rating values, which are not initially binary floating point values. At least 33% for xsd:float in RDFa and 35% for xsd:double in embedded JSON-LD represent geolocation values, arbitrary quantity values or aggregated values, which might but do not need to origin from initially binary floating point values. rev:rating and schema:ratingValue cannot be assigned unambiguously to these categories. This shows, binary floating point numbers are regularly used for not initially binary floating point values.

As expected, because embedded RDF is not the proper place for vocabulary definitions, we found only few cases of property range definitions. They are limited to 54 unique property-datatype-pairs with two to 153 occurrences and for properties from only five different namespaces. This does not allow to draw further conclusions.

Table 4 shows the number of occurrences of different notations. Except of xsd:double in embedded JSON-LD, which is affected by normalization, exponential notation is only little used in the binary floating point datatypes. Special

\(^{15}\)https://web.archive.org/web/20200919100939/https://open.nrw/dataset/telefonverzeichnis-alphabetisch-oktober-2019-odp
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Table 2. The number of property occurrences with XSD or schema.org numerical datatypes in the Web Data Commons September 2020 dataset from RDFa and embedded JSON-LD sources in absolute numbers and relative to the total number of numeric literals in the source type. Only the top 10 are shown.

| Property                  | RDFa Occurrences (rel) | Embedded JSON-LD Occurrences (rel) |
|---------------------------|------------------------|------------------------------------|
| sioc:num_replies          | 21,391,187 (.95)       | 893,916,601 (.42)                  |
| gr:hasCurrencyValue       | 525,491 (.02)          | 448,636,253 (.21)                  |
| gr:hasMinValue            | 137,018 (.01)          | 446,308,779 (.21)                  |
| gr:amountOfThisGood       | 94,978 (.00)           | 71,045,655 (.03)                   |
| gr:hasMaxValue            | 52,772 (.00)           | 65,723,049 (.03)                   |
| vcard:latitude            | 49,428 (.00)           | 26,261,677 (.01)                   |
| vcard:longitude            | 49,428 (.00)           | 17,096,852 (.01)                   |
| gr:hasValue               | 25,800 (.00)           | 17,093,196 (.01)                   |
| dv:count                  | 24,672 (.00)           | 16,333,042 (.01)                   |
| dv:price                  | 23,936 (.00)           | 13,347,182 (.01)                   |

Table 3. The number of property occurrences with xsd:float in RDFa and with xsd:double in embedded JSON-LD in the Web Data Commons September 2020 dataset in absolute numbers and relative to the total number of literals with the same datatype in the same source type. Only the top 10 are shown.

| Property                  | RDFa Occurrences (rel) | Embedded JSON-LD Occurrences (rel) |
|---------------------------|------------------------|------------------------------------|
| gr:hasCurrencyValue       | 516,256 (.50)          | schema:price 49,740,982 (.49)      |
| gr:hasMinValue            | 134,954 (.13)          | schema:longitude 17,055,600 (.17)   |
| gr:amountOfThisGood       | 94,978 (.09)           | schema:latitude 17,053,362 (.17)    |
| gr:hasMaxValue            | 52,772 (.05)           | schema:ratingValue 9,928,412 (.10) |
| vcard:latitude            | 49,428 (.05)           | schema:lowPrice 2,240,110 (.02)     |
| vcard:longitude            | 49,428 (.05)           | schema:highPrice 1,840,080 (.02)    |
| gr:hasValue               | 25,800 (.03)           | schema:value 1,767,255 (.02)       |
| dv:price                  | 23,086 (.02)           | schema:worstRating 311,374 (.00)    |
| dv:average                | 21,038 (.02)           | schema:position 240,577 (.00)      |
| rev:rating                | 20,970 (.02)           | schema:minPrice 197,850 (.00)      |

values occurred only in even more rare cases. From that, we conclude, that the notation or needed special values are not the crucial consideration behind using binary floating point datatypes.

Table 5 shows the number of lexical representations that are not precisely representable in binary floating point datatypes. 33% of the represented xsd:float values in RDFa and 24% in embedded JSON-LD differ from lexical representations. In embedded JSON-LD the initial lexical representation of 69% of the xsd:double values must either have contained more than 17 significant digits or already been differing from the represented value. Referring to the most common properties used with xsd:double in embedded JSON-LD, shown in Table 3, the frequent occurrence of values with more than 17 significant digits is implausible. All together, this shows that 29%–68% of the values with binary floating point datatype in real web data are distorted due to the datatype.
### Table 4. The number of numeric notations occurrences in the lexical representation of literals per numeric datatype in the Web Data Commons September 2020 dataset in absolute numbers and relative to the total number of literals with the same datatype. The notation of `xsd:double` in embedded JSON-LD was normalized during the dataset generation.

| Datatype          | Notation                   | Integer | Decimal | Exponential | Inf / NaN |
|-------------------|----------------------------|---------|---------|-------------|-----------|
| `xsd:decimal`     |                            | 0 (.00) | 1 ( 1)  | 0 (.00)     | 0 (.0)    |
| `xsd:double`      |                            | 0 (.00) | 0 (.00) | 101.959.382 ( 1) | 24 (.0) |
| `xsd:float`       |                            | 35.951 (.40) | 24.837 (.27) | 4252 (.05) | 0 (.0)   |
| `xsd:integer`     |                            | 2.021.243.613 ( 1) | 0 (.00) | 0 (.00) | 0 (.0) |
| `xsd:long`        |                            | 36 ( 1) | 0 (.00) | 0 (.00) | 0 (.0) |

| Datatype          | Notation                   | Integer | Decimal | Exponential | Inf / NaN |
|-------------------|----------------------------|---------|---------|-------------|-----------|
| `xsd:decimal`     |                            | 89 (.01) | 7349 (.89) | 0 (.00) | 0 (.0) |
| `xsd:double`      |                            | 26 (.11) | 208 (.89) | 0 (.00) | 0 (.0) |
| `xsd:float`       |                            | 353.851 (.34) | 643.206 (.63) | 0 (.00) | 4 (.0) |
| `xsd:int`         |                            | 16.751 (.86) | 0 (.00) | 0 (.00) | 0 (.0) |
| `xsd:integer`     |                            | 21.507.446 ( 1) | 38 (.00) | 0 (.00) | 0 (.0) |
| `xsd:nonNegativeInteger` |                   | 585 ( 1) | 0 (.00) | 0 (.00) | 0 (.0) |
| `xsd:positiveInteger` |                       | 6 ( 1) | 0 (.00) | 0 (.00) | 0 (.0) |

### 7 Conclusion

Binary floating point numbers are meant to approximate decimal values to reduce memory consumption and increase computation speed. However, in RDF, decimals are used to approximate binary floating point numbers. This way, the use of binary floating point datatypes in RDF produces ambiguity in represented knowledge and restricts the choice of the arithmetic in standards compliant implementations. Its use can systematically impair the quality of data and falsify the results of data processing. This can cause serious impacts in real world applications.

A radical solution to remove ambiguity and restrictions on the choice of the arithmetic in standard compliant implementations, and that does not require to update existing data, would be the deprecation and replacement of `xsd:float` and `xsd:double` with an extended mandatory `xsd:decimal` datatype in RDF. The extended `xsd:decimal` datatype should additionally permit exponential notation and the special values `positiveInfinity`, `negativeInfinity`, and `notANumber`, to cover the whole lexical space and value space of `xsd:float` and `xsd:double`. It should also become the default datatype in the different serialization and query languages for numbers in decimal and exponential notation and be used for interpretation instead of the old deprecated datatypes, if these are used in existing data. One or several additional new datatypes with hexadecimal lexical representations should be used for the actual representation of binary floating point numbers.
Table 5. The number of lexical representation occurrences without exact representation in the value space of xsd:float and xsd:double per numeric datatype in the Web Data Commons September 2020 dataset in absolute numbers and relative to the total number of literals with the same datatype. The notation of xsd:double in embedded JSON-LD was normalized during the dataset generation.

| Datatype         | Embedded JSON-LD Unprecise In | RDFa Unprecise In |
|------------------|-------------------------------|-------------------|
| xsd:decimal      | 0 (.00)                       | 0 (.00)           |
|                  | 3087 (.37)                    | 3087 (.37)        |
| xsd:double       | 69,648,087 (.68)              | 69,646,819 (.68)  |
| xsd:float        | 21,750 (.24)                  | 21,750 (.24)      |
|                  | 339,583 (.33)                 | 338,676 (.33)     |
| xsd:int          | -                             | -                 |
|                  | 0 (.00)                       | 0 (.00)           |
| xsd:integer      | 7,564,635 (.00)               | 996 (.00)         |
| xsd:long         | 2 (.06)                       | 0 (.00)           |
| xsd:nonNegativeInteger | -                      | 136 (.23)         |
| xsd:positiveInteger | -                                | 0 (.00)           |

values. However, this radical solution would once make a decision for existing data in favor of the verbatim interpretation of the lexical representation.

A more cautious mitigation of the problem should tackle the disadvantages of xsd:decimal: It would be desirable to introduce in RDF mandatory support for (a) an exponential notation for the decimal datatype, and (b) a decimal datatype that supports infinite values, like precisionDecimal, to eliminate these disadvantages. Further, binary floating point datatypes should only be used for numeric values if (a) a representation of infinity is required, or (b) the original source provides binary floating point values. In general, xsd:decimal must become the first choice for the representation of numbers. Semantic Web teaching materials should clearly name the disadvantages of the binary floating point datatypes, shorthand syntaxes should in future prioritize the decimal datatype, and Semantic Web tools should hint to use xsd:decimal.

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References

1. W3C XML Schema Definition Language (XSD) 1.1 Part 2: Datatypes. W3C Recommendation. W3C, Apr. 5, 2012. url: http://www.w3.org/TR/2012/REC-xmlschema11-2-20120405/.

2. RDF 1.1 Concepts and Abstract Syntax. W3C Recommendation. W3C, Feb. 25, 2014. url: http://www.w3.org/TR/2014/REC-rdf11-concepts-20140225/.

3. Noy, N.F. and McGuinness, D.L.: Ontology Development 101: A Guide to Creating Your First Ontology. Tech. rep. KSL-01-05/SMI-2001-0880. Stanford Knowledge Systems Laboratory and Stanford Medical Informatics, Mar. 2001. url: http://www.ksl.stanford.edu/people/dlm/papers/ontology-tutorial-noy-mcguinness-abstract.html.

4. XML Schema Datatypes in RDF and OWL. W3C Working Group Note. W3C, Mar. 14, 2006. url: https://www.w3.org/TR/2006/NOTE-svbp-xsch-datatypes-20060314/.

5. Patriot Missile Defense: Software Problem Led to System Failure at Dhahran, Saudi Arabia. Tech. rep. GAO/IMTEC-92-26. General Accounting Office, Information Management and Technology Division, Feb. 4, 1992. 20 pp. url: https://www.gao.gov/products/IMTEC-92-26.

6. IEEE: IEEE 754-2008 Standard for Floating-Point Arithmetic. Standard 754. Aug. 29, 2008. 70 pp. doi: 10.1109/IEEESTD.2008.4610935.

7. Beckett, D., Berners-Lee, T., Prud’hommeaux, E., and Carothers, G.: RDF 1.1 Turtle: Terse RDF Triple Language. W3C Recommendation. W3C, Feb. 25, 2014. url: https://www.w3.org/TR/2014/REC-turtle-20140225/.

8. Bizer, C. and Cyganiak, R.: RDF 1.1 TriG: RDF Dataset Language. W3C Recommendation. W3C, Feb. 25, 2014. url: https://www.w3.org/TR/2014/REC-trig-20140225/.

9. SPARQL 1.1 Query Language. W3C Recommendation. W3C, Mar. 21, 2013. url: https://www.w3.org/TR/2013/REC-sparql11-query-20130321/.

10. Sporny, M., Longley, D., Kellogg, G., et al.: JSON-LD 1.1: A JSON-based Serialization for Linked Data. W3C Recommendation. W3C, July 16, 2020. url: https://www.w3.org/TR/2020/REC-jsonld-11-20200716/.

11. Gandon, F. and Schreiber, G., eds.: RDF 1.1 XML Syntax. W3C Recommendation. Feb. 25, 2014. url: https://www.w3.org/TR/2014/REC-rdf-syntax-grammar-20140225/.

12. Beckett, D.: RDF 1.1 N-Triples: A line-based syntax for an RDF graph. W3C Recommendation. W3C, Feb. 25, 2014. url: https://www.w3.org/TR/2014/REC-rdf-syntax-n-triples-20140225/.

13. RDF 1.1 N-Quads: A line-based syntax for RDF datasets. W3C Recommendation. W3C, Feb. 25, 2014. url: https://www.w3.org/TR/2014/REC-rdf-syntax-n-quadss-20140225/.

14. RDFa Core 1.1 - Third Edition: Syntax and processing rules for embedding RDF through attributes. W3C Recommendation. W3C, Mar. 17, 2015. url: https://www.w3.org/TR/2015/REC-rdfa-core-20150317/.

15. An XSD datatype for IEEE floating-point decimal. W3C Working Group Note. W3C, June 9, 2011. url: https://www.w3.org/TR/2011/NOTE-xsd-precisionDecimal-20110609/.

16. W3C XML Schema Working Group: RQ-28 Allow scientific notation for decimals (scientific-notn). Feb. 11, 2006. url: https://www.w3.org/2006/02/05-rq-28-allow-scientific-notation-for-decimals/.
17. W3C XML Schema Definition Language (XSD) 1.1 Part 2: Datatypes. W3C Candidate Recommendation. W3C, July 21, 2012. url: https://www.w3.org/TR/2011/CR-xmlschema11-2-20110721/.
18. International Vocabulary of Metrology. Basic and general concepts and associated terms. JCGM 200:2012 (JCGM 200:2008 with minor corrections). Joint Committee for Guides in Metrology, 2012.
19. Neumaier, A.: Introduction to Numerical Analysis. Cambridge University Press, Aug. 23, 2012. 366 pp.
20. Poveda-Villalón, M., Gómez-Pérez, A., and Suárez-Figueroa, M.C.: “OOPS! (Ontology Pitfall Scanner!): An On-line Tool for Ontology Evaluation”. In: International Journal on Semantic Web and Information Systems 10.2 (2014), pp. 7–34. doi: 10.4018/ijswis.2014040102.
21. Meusel, R., Petrovski, P., and Bizer, C.: “The WebDataCommons Microdata, RDFa and Microformat Dataset Series”. In: The Semantic Web - ISWC 2014 - 13th International Semantic Web Conference, Riva del Garda, Italy, October 19-23, 2014. Proceedings, Part I. Ed. by Mika, P., Tudorache, T., Bernstein, A., et al. Vol. 8796. Lecture Notes in Computer Science. Springer, 2014, pp. 277–292. doi: 10.1007/978-3-319-11964-9_18.
22. Gänßinger, M. and Keil, J.M.: RDF Property and Datatype Usage Scanner v1.0.0. 2021. doi: 10.5281/zenodo.6258887.
23. Keil, J.M. and Gänßinger, M.: Web Data Commons (December 2020) Property and Datatype Usage Dataset. 2022. doi: 10.5281/zenodo.6205111.
24. Keil, J.M.: Web Data Commons (December 2020) Property and Datatype Usage Analysis Scripts. 2022. doi: 10.5281/zenodo.6264286.