Abstract

This article provides a formalization of the W3C Draft Core SHACL Semantics specification using Z notation. This formalization exercise has identified a number of quality issues in the draft. It has also established that the recursive definitions in the draft are well-founded. Further formal validation of the draft will require the use of an executable specification technology.

1 Introduction

The W3C RDF Data Shapes Working Group [3] is developing SHACL, a new language for describing constraints on RDF graphs. A semantics for Core SHACL has been proposed [2], hereafter referred to as the semantics draft. The proposed semantics includes an abstract syntax, inference rules, and a definition of typing which allows for certain kinds of recursion. The semantics draft uses precise mathematical language, but is informal in the sense that it is not written in a formal specification language and therefore cannot benefit from tools such as type-checkers.

This document provides a formal translation of the semantics draft into Z Notation [6]. The \LaTeX{} source for this article has been type-checked using the fuzz type-checker [7] and is available in the GitHub repository [4] agryman/z-core-shacl-semantics.

Our motive for formalizing and type-checking the semantics draft is to help to improve its quality and the ultimate design of SHACL.

1.1 Organization of this Article

The remainder of this article is organized as follows.

- Section 2 formalizes some basic RDF concepts.
- Section 3 translates the abstract syntax of SHACL into Z notation.
- Section 4 formalizes the evaluation semantics of SHACL.
• Section 5 formalizes the declarative semantics of shape expression schemas.
• Section 6 summarizes the quality issues found in the draft.
• Section 7 concludes with some remarks about the benefits of the formalization exercise and possible next steps.

## 2 Basic RDF Concepts

This section formalizes some basic RDF concepts. We reuse some formal definitions given in [5], modifying the identifiers to match those used in the semantics draft.

### 2.1 TERM

Let \( \text{TERM} \) be the set of all RDF terms.

\[ \text{TERM} \]

### 2.2 Iri, Blank, and Lit

The set of all RDF terms is partitioned into IRIs, blank nodes, and literals.

\[
\begin{align*}
\text{Iri, Blank, Lit} & : P \text{ TERM} \\
\langle \text{Iri, Blank, Lit} \rangle & \text{ partition TERM}
\end{align*}
\]

### 2.3 IRI

The semantics draft introduces the term \( \text{Iri} \), but it uses the term \( \text{IRI} \) in the definitions of the abstract syntax. We treat \( \text{IRI} \) as a synonym for \( \text{Iri} \).

\( \text{IRI} \equiv \text{Iri} \)

### 2.4 Triple

An RDF triple is an ordered triple of RDF terms referred to as the subject, predicate, and object.

\[
\text{Triple} \equiv \{ s, p, o : \text{TERM} \mid s \notin \text{Lit} \land p \in \text{IRI} \}
\]

- The subject is not a literal.
- The predicate is an IRI.
subject, predicate, and object

It is convenient to define generic functions that select the first, second, or third component of a Cartesian product of three sets.

\[
\begin{align*}
\text{fst}[X, Y, Z] &= (\lambda x : X; y : Y; z : Z \bullet x) \\
\text{snd}[X, Y, Z] &= (\lambda x : X; y : Y; z : Z \bullet y) \\
\text{trd}[X, Y, Z] &= (\lambda x : X; y : Y; z : Z \bullet z)
\end{align*}
\]

The subject, predicate, and object of an RDF triple are the terms that appear in the corresponding positions.

\[
\begin{align*}
\text{subject} &= (\lambda t : \text{Triple} \bullet \text{fst}(t)) \\
\text{predicate} &= (\lambda t : \text{Triple} \bullet \text{snd}(t)) \\
\text{object} &= (\lambda t : \text{Triple} \bullet \text{trd}(t))
\end{align*}
\]

Graph

An RDF graph is a finite set of RDF triples.

\[
\text{Graph} \equiv \text{F Triple}
\]

subjects, predicates, and objects

The subjects, predicates, and objects of a graph are the sets of RDF terms that appear in the corresponding positions of its triples.

\[
\begin{align*}
\text{subjects} &= (\lambda g : \text{Graph} \bullet \{ t : g \bullet \text{subject}(t) \} ) \\
\text{predicates} &= (\lambda g : \text{Graph} \bullet \{ t : g \bullet \text{predicate}(t) \} ) \\
\text{objects} &= (\lambda g : \text{Graph} \bullet \{ t : g \bullet \text{object}(t) \} )
\end{align*}
\]

nodes

The nodes of an RDF are its subjects and objects.

\[
\text{nodes} \equiv (\lambda g : \text{Graph} \bullet \text{subjects}(g) \cup \text{objects}(g))
\]

PointedGraph

A pointed graph is a graph and a distinguished node in the graph. The distinguished node is variously referred to as the start, base, or focus node of the pointed graph, depending on the context.

\[
\text{PointedGraph} \equiv \{ g : \text{Graph}; n : \text{TERM} \mid n \in \text{nodes}(g) \} \]
3 Abstract Syntax

This section contains a translation of the abstract syntax of SHACL into Z. The semantics draft defines the abstract syntax using an informal Extended Backus-Naur Form (EBNF).

The approach used here is to interpret each term or expression that appears in the abstract syntax as a mathematical set that is isomorphic to the set of abstract syntax tree fragments denoted by the corresponding term or expression. Care has been taken to preserve the exact spelling and case of each abstract syntax term so that there is a direct correspondence between the abstract syntax and Z. For example, the term Schema is interpreted as the set Schema.

We give a Z definition for each abstract syntax term that appears on the left-hand side of the EBNF definition operator (::=). The order in which these terms appear in the semantics draft has been preserved in this document. If a Z term has a corresponding EBNF rule, we include it here for easy reference. Refer to [2] for the complete definition of the abstract syntax.

A sequence of two or more abstract syntax terms is interpreted as the Cartesian product of the corresponding sets, i.e. A B is interpreted as $A \times B$.

The abstract syntax Kleene star (*) and plus (+) operators are interpreted as sequence (seq) and non-empty sequence (seq1) operators on the corresponding sets, i.e. $A^+$ is interpreted as $\text{seq}_1 A$.

The abstract syntax optional operator (?) is interpreted as taking the union of the set of singletons and the empty set of the corresponding set using the generic function $\text{OPTIONAL}$ (defined below), i.e. $A?$ is interpreted as $\text{OPTIONAL}[A]$.

Abstract syntax terms that are defined as alternations (I) of two or more expressions are translated into either free types or unions of sets. A side effect of this process is that constructors may be required for each branch of the alternation. In some cases the name of the constructors can be derived from a corresponding element of the abstract syntax. For example, in ShapeDefinition, open and close are mapped to the constructors open and close. In the cases where there is no convenient element of the abstract syntax, we mint new constructor names.

We also introduce new Z identifiers when an element of the abstract syntax does not map to a valid alphanumeric Z identifier. For example the the shape label negation operator (!) is mapped to negate.

3.1 OPTIONAL

An optional value is represented by a singleton set, if the value is present, or the empty set, if the value is absent.

$$\text{OPTIONAL}[X] == \{ v : X \bullet \{v\} \} \cup \{\emptyset\}$$

3.2 Schema

Schema ::= Rule+
A schema is a sequence of one or more rules.

\[ \text{Schema} == \text{seq}_1 \text{Rule} \]

### 3.3 Rule

\[ \text{Rule} ::= \text{ShapeLabel \ ShapeDefinition \ ExtensionCondition}^* \]

A rule consists of a shape label, a shape definition, and a sequence of zero or more extension conditions.

\[ \text{Rule} == \text{ShapeLabel} \times \text{ShapeDefinition} \times \text{seq ExtensionCondition} \]

It is convenient to introduce functions that select the components of a rule.

\[ \text{shapeLabel} == (\lambda r : \text{Rule} \cdot \text{fst}(r)) \]
\[ \text{shapeDef} == (\lambda r : \text{Rule} \cdot \text{snd}(r)) \]
\[ \text{extConds} == (\lambda r : \text{Rule} \cdot \text{trd}(r)) \]

### 3.4 ShapeLabel

\[ \text{ShapeLabel} ::= \text{an identifier} \]

A shape label is an identifier drawn from some given set.

\[ [\text{ShapeLabel}] \]

### 3.5 ShapeDefinition

\[ \text{ShapeDefinition} ::= \text{ClosedShape} | \text{OpenShape} \]

A shape definition is either a closed shape or an open shape.

\[ \text{ShapeDefinition} ::= \]
\[ \text{close} \{ \text{ShapeExpr} \} | \text{open} \{ \text{OPTIONAL}[\text{InclPropSet}] \times \text{ShapeExpr} \} \]

Note that abstract syntax terms that are defined using alternation are naturally represented as free types in Z Notation.

- \text{close} is the constructor for closed shapes. A closed shape consists of a shape expression.
- \text{open} is the constructor for open shapes. An open shape consists of an optional included properties set and a shape expression.

Given a shape definition \( d \), let \( \text{shapeExpr}(d) \) be its shape expression.

\[ \text{shapeExpr} : \text{ShapeDefinition} \rightarrow \text{ShapeExpr} \]

\[ \forall x : \text{ShapeExpr} \cdot \]
\[ \text{shapeExpr}(\text{close}(x)) = x \]
\[ \forall o : \text{OPTIONAL}[\text{InclPropSet}] ; x : \text{ShapeExpr} \cdot \]
\[ \text{shapeExpr}(\text{open}(o, x)) = x \]

5
3.6  ClosedShape
ClosedShape ::= 'close' ShapeExpr

The set of closed shapes is the range of the close shape definition constructor.

\[ \text{ClosedShape} = \text{ran \ close} \]

3.7  OpenShape
OpenShape ::= 'open' InclPropSet? ShapeExpr

The set of open shapes is the range of the open shape definition constructor.

\[ \text{OpenShape} = \text{ran \ open} \]

3.8  InclPropSet
InclPropSet ::= PropertiesSet

An included properties set is a properties set.

\[ \text{InclPropSet} = \text{PropertiesSet} \]

Note that there seems little motivation to introduce the term InclPropSet since it is identical to PropertiesSet.

3.9  PropertiesSet
PropertiesSet ::= set of IRI

A properties set is a set of IRIs.

\[ \text{PropertiesSet} = \{ \text{IRI} \} \]

3.10  ShapeExpr
ShapeExpr ::= EmptyShape
| TripleConstraint Cardinality
| InverseTripleConstraint Cardinality
| NegatedTripleConstraint
| NegatedInverseTripleConstraint
| SomeOfShape
| OneOfShape
| GroupShape
| RepetitionShape
A shape expression defines constraints on RDF graphs.

\[
\text{ShapeExpr} ::= \\
\text{emptyshape} | \\
\text{triple} \langle \text{DirectedTripleConstraint} \times \text{Cardinality} \rangle | \\
\text{someOf} \langle \text{seq}_1 \text{ShapeExpr} \rangle | \\
\text{oneOf} \langle \text{seq}_1 \text{ShapeExpr} \rangle | \\
\text{group} \langle \text{seq}_1 \text{ShapeExpr} \rangle | \\
\text{repetition} \langle \text{ShapeExpr} \times \text{Cardinality} \rangle
\]

- \text{emptyshape} is the empty shape expression.
- \text{triple} is the constructor for triple constraint shape expressions. A triple constraint shape expression consists of a directed triple constraint and a cardinality.
- \text{someOf} is the constructor for some-of shape expressions. A some-of shape expression consists of a sequence of one or more shape expressions.
- \text{oneOf} is the constructor for one-of shape expressions. A one-of shape expression consists of a sequence of one or more shape expressions.
- \text{group} is the constructor for grouping shape expressions. A grouping shape expression consists of a sequence of one or more shape expressions.
- \text{repetition} is the constructor for repetition shape expressions. A repetition shape expression consists of a shape expression and a cardinality.

### 3.11 EmptyShape

\[
\text{EmptyShape} ::= \text{'}emptyshape\text{'}
\]

The set of empty shape expressions is the singleton set that contains the empty shape.

\[
\text{EmptyShape} == \{ \text{emptyshape} \}
\]

### 3.12 DirectedPredicate

A directed predicate is an IRI with a direction that indicates its usage in a triple. \textit{nop} indicates the normal direction, namely the predicate relates the subject node to the object node. \textit{inv} indicates the inverse direction, namely the predicate relates the object node to the subject node.

\[
\text{DirectedPredicate} ::= \\
\text{nop}\langle \text{IRI} \rangle | \\
\text{inv}\langle \text{IRI} \rangle
\]

The semantics draft uses the notation \( ^p \) for \( \text{inv}(p) \).
Let $\text{predDF}(dp)$ denote the predicate of a directed predicate $dp$.

$\text{predDP} : \text{DirectedPredicate} \rightarrow \text{IRI}$

$\forall p : \text{IRI} \bullet \text{predDP}(\text{nop}(p)) = \text{predDP}(\text{inv}(p)) = p$

### 3.13 DirectedTripleConstraint

A directed triple constraint consists of a directed predicate and a constraint. The constraint is a value or shape constraint on the object of a triple if the direction is normal, or a shape constraint on the subject of a triple if the direction is inverted.

$$\text{DirectedTripleConstraint} ==$

$$\{ \, dp : \text{DirectedPredicate}; \, C : \text{Constraint} \mid$

$$\text{dp} \in \text{ran inv} \Rightarrow C \in \text{ShapeConstr} \, \}$$

The semantics draft uses the notation $\, p:\! :C$ for $(\text{nop}(p), C)$ and $\, \neg p:\! :C$ for $(\text{inv}(p), C)$.

Let $\text{predDTC}(dtc)$ denote the predicate of the directed triple constraint $dtc$.

$\text{predDTC} : \text{DirectedTripleConstraint} \rightarrow \text{IRI}$

$\forall dp : \text{DirectedPredicate}; \, C : \text{Constraint} \mid$

$\, (dp, C) \in \text{DirectedTripleConstraint} \bullet$

$\text{predDTC}(dp, C) = \text{predDP}(dp)$

Let $\text{constrDTC}(dtc)$ denote the constraint of the directed triple constraint $dtc$.

$\text{constrDTC} : \text{DirectedTripleConstraint} \rightarrow \text{Constraint}$

$\forall dp : \text{DirectedPredicate}; \, C : \text{Constraint} \mid$

$\, (dp, C) \in \text{DirectedTripleConstraint} \bullet$

$\text{constrDTC}(dp, C) = C$

### 3.14 TripleConstraint

$\text{TripleConstraint} ::= \text{IRI \ ValueConstr | IRI \ ShapeConstr}$

A triple constraint places conditions on triples whose subject is a given focus node and whose predicate is a given IRI.

$$\text{TripleConstraint} : P \text{ DirectedTripleConstraint}$$

$$\text{TripleConstraint} =$$

$$\{ \, p : \text{IRI}; \, C : \text{Constraint} \bullet (\text{nop}(p), C) \, \}$$
3.15 \textit{InverseTripleConstraint}

\textit{InverseTripleConstraint} ::= \texttt{}``\texttt{I} IRI \textit{ShapeConstr}

An inverse triple constraint places conditions on triples whose object is a given focus node and whose predicate is a given IRI.

\[
\text{InverseTripleConstraint} = P \text{ DirectedTripleConstraint} = \{ p : IRI; C : \textit{ShapeConstr} \bullet (\text{inv}(p), C) \}
\]

3.16 \textit{Constraint}

A constraint is a condition on the object node of a triple for normal predicates or the subject node of a triple for inverse predicates.

\[
\textit{Constraint} ::= \textit{valueSet} \cup \textit{datatype} \cup \textit{kind} \cup \textit{or} \cup \textit{and} \cup \textit{nor} \cup \textit{nand}
\]

- \textit{valueSet} is the constructor for value set value constraints. A value set value constraint consists of a set of literals and IRIs.
- \textit{datatype} is the constructor for literal datatype value constraints. A literal datatype value constraint consists of a literal datatype and an optional XML Schema facet.
- \textit{kind} is the constructor for node kind value constraints. A node kind value constraint consists of a specification for a subset of RDF terms.
- \textit{or} is the constructor for disjunction shape constraints. A node must satisfy at least one of the shapes.
- \textit{and} is the constructor for conjunction shape constraints. A node must satisfy all of the shapes.
- \textit{nor} is the constructor for negated disjunction shape constraints. A node must not satisfy any of the shapes.
- \textit{nand} is the constructor for negated conjunction shape constraints. A node must not satisfy all of the shapes.
3.17 \textit{Cardinality}

\texttt{Cardinality ::= \textquoteleft [\textquoteleft MinCardinality \textquoteleft ;\textquoteleft MaxCardinality \textquoteleft \textquoteright ]\textquoteright}

Cardinality defines a range for the number of elements in a set.

\textit{Cardinality} ::= MinCardinality \times MaxCardinality

- A cardinality consists of a minimum cardinality and a maximum cardinality.

3.18 \textit{MinCardinality}

\texttt{MinCardinality ::= a natural number}

Minimum cardinality is the minimum number of elements required to be in a set.

\textit{MinCardinality} ::= \mathbb{N}

3.19 \textit{MaxCardinality}

\texttt{MaxCardinality ::= a natural number | 'unbound'}

Maximum cardinality is the maximum number of elements required to be in a set.

\textit{MaxCardinality} ::= maxCard(\mathbb{N}) | unbound

- \textit{maxCard} is the constructor for finite maximum cardinalities. A finite maximum cardinality is a natural number. Note that a maximum cardinality of 0 means that the set must be empty.
- \textit{unbound} indicates that the maximum number of elements in a set is unbounded.

3.20 \textit{inBounds}

A natural number \(k\) is said to be in bounds of a cardinality when \(k\) is between the minimum and maximum limits of the cardinality.

\texttt{inBounds : \mathbb{N} \leftrightarrow Cardinality}

\(\forall k, n : \mathbb{N} \bullet\)

\(k \text{ inBounds} (n, \text{unbound}) \leftrightarrow n \leq k\)

\(\forall k, n, m : \mathbb{N} \bullet\)

\(k \text{ inBounds} (n, \text{maxCard}(m)) \leftrightarrow n \leq k \leq m\)
3.21 Notation

Let a be an IRI, let C be a value or shape constraint, let n and m be non-negative integers. The semantics draft uses the notation listed in Table 1 for some shape expressions.

| Notation       | Meaning                                                                                      |
|----------------|--------------------------------------------------------------------------------------------|
| a::C[n;m]      | triple(nop(a, C), (n, maxCard(m)))                                                          |
| ^a::C[n;m]     | triple(inv(a, C), (n, maxCard(m)))                                                          |
| a::C           | a::C[1;1]                                                                                  |
| ^a::C          | ^a::C[1;1]                                                                                 |
| !a::C          | a::C[0;0]                                                                                  |
| !^a::C         | ^a::C[0;0]                                                                                 |

Table 1: Meaning of shape expression notation

- If the cardinality is [1;1] it may be omitted.
- The negated shape expressions are semantically equivalent to the corresponding non-negated shape expressions with cardinality [0;0].

3.22 none, one

It is convenient to define some common cardinalities.

none == (0, maxCard(0))

one == (1, maxCard(1))

- A cardinality of none = [0;0] is used to indicate a negated triple or inverse triple constraint.
- A cardinality of one = [1;1] is the default cardinality of a triple or inverse triple constraint when no cardinality is explicitly given in the notations a::C and ^a::C.

3.23 NegatedTripleConstraint

NegatedTripleConstraint ::= ‘!’ TripleConstraint

A negated triple constraint shape expression is a triple constraint shape expression that has a cardinality of none.

NegatedTripleConstraint ==
{ tc : TripleConstraint • triple(tc, none) }
3.24  \textit{NegatedInverseTripleConstraint} \\
\textit{NegatedInverseTripleConstraint} ::= '!' \textit{InverseTripleConstraint} \\

A negated inverse triple constraint shape expression is an inverse triple constraint shape expression that has a cardinality of \textit{none}. \\
\textit{NegatedInverseTripleConstraint} == \{ itc : \textit{InverseTripleConstraint} \bullet \text{triple}(itc, none) \}

3.25  \textit{ValueConstr} \\
\textit{ValueConstr} ::= \textit{ValueSet} \mid \textit{LiteralDatatype} \textit{XSFacet}? \mid \textit{NodeKind} \\

A value constraint places conditions on the object nodes of triples for normal predicates and on the subject nodes of triples for inverse predicates. \\
\textit{ValueConstr} == \text{ran valueSet} \cup \text{ran datatype} \cup \text{ran kind}

3.26  \textit{ValueSet} \\
\textit{ValueSet} ::= \text{set of literals and IRI} \\

The set of value set value constraints is the range of the \textit{valueSet} constructor. \\
\textit{ValueSet} == \text{ran valueSet}

3.27  \textit{LiteralDatatype} \\
\textit{LiteralDatatype} ::= \text{an RDF literal datatype} \\

A literal datatype is an IRI that identifies a set of literal RDF terms. We assume that this subset of IRIs is given. \\
\quad | \textit{LiteralDatatype} : \textbf{P IRI} \\

We also assume that we are given an interpretation of each literal datatype as a set of literals. \\
\quad | \text{literalsOfDatatype} : \textit{LiteralDatatype} \rightarrow \textbf{P Lit}

3.28  \textit{NodeKind} \\
\textit{NodeKind} ::= 'iri' \mid 'blank' \mid 'literal' \mid 'nonliteral' \\

A node kind identifies a subset of RDF terms. \\
\textit{NodeKind} ::= \text{iri} \mid \text{blank} \mid \text{literal} \mid \text{nonliteral} \\
\quad \bullet \text{iri} identifies the set of IRIs.
• blank identifies the set of blank nodes.
• literal identifies the set of literals.
• nonliteral identifies the complement of the set of literals, i.e. the union of IRIs and blank nodes.

Each node kind corresponds to a set of RDF terms.

$$termsOfKind : \text{NodeKind} \rightarrow \mathcal{P} \text{TERM}$$

- $$termsOfKind(iri) = \text{IRI}$$
- $$termsOfKind(blank) = \text{Blank}$$
- $$termsOfKind(literal) = \text{Lit}$$
- $$termsOfKind(nonliteral) = \text{TERM} \setminus \text{Lit}$$

3.29 XSFacet

XSFacet ::= an XSD restriction

An XML Schema facet places restrictions on literals. We assume this is a given set.

[XSFacet]

We also assume that we are given an interpretation of facets as sets of literals.

$$\forall d : \text{LiteralDatatype}; f : \text{XSFacet} \bullet$$

$$\text{literalsOfFacet}(d,f) \subseteq \text{literalsOfDatatype}(d)$$

- The literals that correspond to a facet of a datatype are a subset of the literals that correspond to the datatype.

3.30 ShapeConstr

ShapeConstr ::= ('!'? DisjShapeConstr | ConjShapeConstraint

A shape constraint requires that a node satisfy logical combinations of one or more other shapes which are identified by their shape labels.

$$\text{ShapeConstr} \equiv \text{ran or} \cup \text{ran and} \cup \text{ran nor} \cup \text{ran nand}$$

3.31 DisjShapeConstr

DisjShapeConstr ::= ShapeLabel ('or' ShapeLabel)*

The set of all disjunctive shape constraints is the range of the or constructor.

$$\text{DisjShapeConstr} \equiv \text{ran or}$$
3.32  *ConjShapeConstraint*

\[
\text{ConjShapeConstraint} ::= \text{ShapeLabel} \ ('and' \ \text{ShapeLabel})\star \\
\]

The set of all conjunctive shape constraints is the range of the *and* constructor.

\[
\text{ConjShapeConstraint} == \text{ran} \ and \\
\]

3.33  *SomeOfShape*

\[
\text{SomeOfShape} ::= \text{ShapeExpr} \ ('|' \ \text{ShapeExpr})\star \\
\]

The set of some-of shape expressions is the range of *someOf*.

\[
\text{SomeOfShape} == \text{ran} \ someOf \\
\]

3.34  *OneOfShape*

\[
\text{OneOfShape} ::= \text{ShapeExpr} \ ('@' \ \text{ShapeExpr})\star \\
\]

The set of one-of shape expressions is the range of *oneOf*.

\[
\text{OneOfShape} == \text{ran} \ oneOf \\
\]

3.35  *GroupShape*

\[
\text{GroupShape} ::= \text{ShapeExpr} \ (',' \ \text{ShapeExpr})\star \\
\]

The set of grouping shape expressions is the range of *group*.

\[
\text{GroupShape} == \text{ran} \ group \\
\]

3.36  *RepetitionShape*

\[
\text{RepetitionShape} ::= \text{ShapeExpr} \ \text{Cardinality} \\
\]

The set of repetition shape expressions is the range of *repetition*.

\[
\text{RepetitionShape} == \text{ran} \ repetition \\
\]

3.37  *ExtensionCondition*

\[
\text{ExtensionCondition} ::= \text{ExtLangName} \ \text{ExtDefinition} \\
\]

An extension condition is the definition of a constraint written in an extension language.

\[
\text{ExtensionCondition} == \text{ExtLangName} \times \text{ExtDefinition} \\
\]
3.38  \textit{ExtLangName}

\textit{ExtLangName ::= an identifier}

An extension language name is an identifier for an extension language, such
as JavaScript. We assume this is a given set.

\text{[ExtLangName]}

3.39  \textit{ExtDefinition}

\textit{ExtDefinition ::= a string}

An extension definition is a program written in some extension language
that implements a constraint check. We assume this is a given set.

\text{[ExtDefinition]}

An extension condition represents a function that takes as input a pointed
graph, and returns as output a boolean with the value \textit{true} if the constraint
is violated and \textit{false} is satisfied. We assume we are given a mapping that
associates each extension condition with the set of pointed graphs that violate
it.

\text{violatedBy : ExtensionCondition} \rightarrow \text{P PointedGraph}

3.40  \textit{ShapeLabel Definitions}

Given a schema \(S\), let \(\text{defs}(S)\) be the set of all shape labels defined in \(S\).

\text{defs} == (\lambda S : \text{Schema} \cdot
\text{\{ } r : \text{ran} S \cdot \text{shapeLabel}(r) \text{\}})

Each rule in a schema must be identified by a unique shape label.

\text{SchemaUL} == \{ S : \text{Schema} \mid \#S = \#(\text{defs}(S)) \}

• In a schema with unique rule labels there are as many rules as labels.

3.41  \textit{rule}

Given a schema \(S\) with unique rule labels, and a label \(T\) defined in \(S\), let
\(\text{rule}(T, S)\) be the corresponding rule.

\text{rule : ShapeLabel} \times \text{SchemaUL} \leftrightarrow \text{Rule}

\text{dom rule} = \{ T : \text{ShapeLabel} ; S : \text{SchemaUL} \mid T \in \text{defs}(S) \}

\forall S : \text{SchemaUL} \cdot
\forall r : \text{ran}(S) \cdot
\text{let } T == \text{shapeLabel}(r) \cdot
\text{rule}(T, S) = r
3.42 ShapeLabel References

Given a schema $S$, let $\text{refs}(S)$ be the set of shape labels referenced in $S$.

$$\text{refs} == (\lambda S : \text{Schema} \cdot \bigcup \{r : \text{ran } S \cdot \text{refsRule}(r)\})$$

- The set of references in a schema is the union of the sets of references in its rules.

Given a rule $r$, let $\text{refsRule}(r)$ be the set of shape labels referenced in $r$.

$$\text{refsRule} == (\lambda r : \text{Rule} \cdot \text{refsShapeDefinition}(\text{shapeDef}(r)))$$

- The set of references in a rule is the set of references in its shape definition.

Given a shape definition $d$, let $\text{refsShapeDefinition}(d)$ be the set of shape labels referenced in $d$.

$$\forall d : \text{ShapeDefinition} \cdot \text{refsShapeDefinition}(d) = \text{refsShapeExpr}(\text{shapeExpr}(d))$$

- The set of references in a shape definition is the set of references in its shape expression.

Given a shape expression $x$, let $\text{refsShapeExpr}(x)$ be the set of shape labels referenced in $x$.

$$\forall x : \text{ShapeExpr} \cdot \text{refsShapeExpr}(\text{repetition}(x, c)) = \text{refsShapeExpr}(x)$$

- The empty shape expression references no labels.

- A directed triple constraint shape expression references the labels referenced in the directed triple constraint.
• A some-of or one-of or group shape expression references the union of the labels referenced in each component shape expression.

• A repetition shape expression references the labels referenced in its unrepeated shape expression.

Given a directed triple constraint \( \text{dtc} \), let \( \text{refsDirectedTripleConstraint}(\text{dtc}) \) be the set of shape labels referenced in \( \text{dtc} \).

\[
\text{refsDirectedTripleConstraint} : \text{DirectedTripleConstraint} \rightarrow \text{F ShapeLabel}
\]

\[
\forall a : \text{IRI}; C : \text{ValueConstr} \bullet
\quad \text{refsDirectedTripleConstraint}((\text{nop}(a), C)) = \emptyset
\]

\[
\forall a : \text{IRI}; C : \text{ShapeConstr} \bullet
\quad \text{refsDirectedTripleConstraint}((\text{nop}(a), C)) = \text{refsShapeConstr}(C)
\]

\[
\forall a : \text{IRI}; C : \text{ValueConstr} \bullet
\quad \text{refsDirectedTripleConstraint}((\text{inv}(a), C)) = \text{refsShapeConstr}(C)
\]

• A value triple constraint references no labels.

• A shape triple constraint references the labels in its shape constraint.

Given a shape constraint \( C \), let \( \text{refsShapeConstr}(C) \) be the set of shape labels referenced in \( C \).

\[
\text{refsShapeConstr} : \text{ShapeConstr} \rightarrow \text{F ShapeLabel}
\]

\[
\forall ls : \text{seq}(\text{ShapeLabel}) \bullet
\quad \text{refsShapeConstr}(\text{or}(ls)) = \text{ran} \( ls \)
\]

\[
\forall ls : \text{seq}(\text{ShapeLabel}) \bullet
\quad \text{refsShapeConstr}(\text{and}(ls)) = \text{ran} \( ls \)
\]

\[
\forall ls : \text{seq}(\text{ShapeLabel}) \bullet
\quad \text{refsShapeConstr}(\text{nor}(ls)) = \text{ran} \( ls \)
\]

\[
\forall ls : \text{seq}(\text{ShapeLabel}) \bullet
\quad \text{refsShapeConstr}(\text{nand}(ls)) = \text{ran} \( ls \)
\]

• A shape constraint references the range of its sequence of shape labels.

Every shape label referenced in a schema must be defined in the schema.

\[
\text{SchemaRD} == \{ s : \text{Schema} \mid \text{refs}(s) \subseteq \text{defs}(s) \}
\]

A schema is well-formed if its rules have unique labels and all referenced shape labels are defined.

\[
\text{SchemaWF} == \text{SchemaUL} \cap \text{SchemaRD}
\]

### 4 Evaluation

This section defines the interpretation of shapes as constraints on RDF graphs. All functions that are defined in the semantics draft are given formal definitions here. We assume that from this point on whenever the semantics draft refers to schemas they are well-formed.
4.1 shapes
Given a well-formed schema \( S \), let \( \text{shapes}(S) \) be the set of shape labels that appear in \( S \).

\[
\text{shapes} == (\lambda S : \text{SchemaWF} \bullet \text{defs}(S))
\]

4.2 expr
Given a shape label \( T \) and a well-formed schema \( S \), let \( \text{expr}(T, S) \) be the shape expression in the rule with label \( T \) in \( S \).

\[
\text{expr} : \text{ShapeLabel} \times \text{SchemaWF} \rightarrow \text{ShapeExpr}
\]

\[
\text{dom } \text{expr} = \{ T : \text{ShapeLabel}; S : \text{SchemaWF} \mid T \in \text{shapes}(S) \}
\]

\[
\forall T : \text{ShapeLabel}; S : \text{SchemaWF} \mid T \in \text{shapes}(S) \bullet
\]

\[
\text{let } r == \text{rule}(T, S) \bullet
\]

\[
\text{expr}(T, S) = \text{shapeExpr} (\text{shapeDef}(r))
\]

- The shape expression for a shape label \( T \) is the shape expression in the shape definition of the rule \( r \) that has shape label \( T \).

4.3 incl
Given a shape label \( T \) defined in a well-formed schema \( S \), let \( \text{incl}(T, S) \) be the, possibly empty, set of included properties.

\[
\text{incl} : \text{ShapeLabel} \times \text{SchemaWF} \rightarrow \text{InclPropSet}
\]

\[
\text{dom } \text{incl} = \{ T : \text{ShapeLabel}; S : \text{SchemaWF} \mid T \in \text{shapes}(S) \}
\]

\[
\forall T : \text{ShapeLabel}; S : \text{SchemaWF} \mid T \in \text{shapes}(S) \bullet
\]

\[
\exists r : \text{ran } S \mid T = \text{shapeLabel}(r) \bullet
\]

\[
\text{incl}(T, S) = \text{inclShapeDefinition} (\text{shapeDef}(r))
\]

- The included properties set for a shape label \( T \) is the included properties set in the shape definition of the rule \( r \) that has shape label \( T \).

Given a shape definition \( d \), let \( \text{inclShapeDefinition}(d) \) be its included properties set.

\[
\text{inclShapeDefinition} : \text{ShapeDefinition} \rightarrow \text{InclPropSet}
\]

\[
\forall x : \text{ShapeExpr} \bullet
\]

\[
\text{inclShapeDefinition}(\text{close}(x)) =
\]

\[
\text{inclShapeDefinition}(\text{open}(\{\emptyset\}, x))
\]

\[
= \emptyset
\]

\[
\forall \text{ips} : \text{InclPropSet}; x : \text{ShapeExpr} \bullet
\]

\[
\text{inclShapeDefinition}(\text{open}(\{\text{ips}\}, x)) = \text{ips}
\]
• The included property set of a closed shape definition or an open definition with no included property set is the empty set.

• The included property set of an open shape definition with an included property set is that included property set.

4.4 properties

Given a shape expression $x$, let $\text{properties}(x)$ be the set of properties that appear in some triple constraint in $x$.

\[
\begin{align*}
\text{properties} &: \text{ShapeExpr} \rightarrow \text{PropertiesSet} \\
\text{properties}(\text{emptyshape}) &= \emptyset \\
\forall tc : \text{TripleConstraint}; \ c : \text{Cardinality} \quad &\text{properties}(\text{triple}(tc, c)) = \text{propertiesTripleConstraint}(tc) \\
\forall itc : \text{InverseTripleConstraint}; \ c : \text{Cardinality} \quad &\text{properties}(\text{triple}(itc, c)) = \emptyset \\
\forall xs : \text{seq}_1 \text{ShapeExpr} \quad &\text{properties}(\text{someOf}(xs)) = \text{properties}(\text{oneOf}(xs)) = \text{properties}(\text{group}(xs)) = \bigcup\{ x : \text{ran} \, xs \quad \text{properties}(x) \} \\
\forall x : \text{ShapeExpr}; \ c : \text{Cardinality} \quad &\text{properties}(\text{repetition}(x, c)) = \text{properties}(x)
\end{align*}
\]

• An empty shape expression has no properties.

• The properties of a triple constraint shape expression are the properties of its triple constraint.

• Inverse triple constraint shape expressions have no properties.

• The properties of a some-of, one-of, or grouping shape expression are the union of the properties of their component shape expressions.

• The properties of a repetition shape expression are the properties of the shape expression being repeated.

Given a triple constraint $tc$, let $\text{propertiesTripleConstraint}(tc)$ be its set of properties.

\[
\begin{align*}
\text{propertiesTripleConstraint} &: \text{TripleConstraint} \rightarrow \text{PropertiesSet} \\
\forall a : \text{IRI}; \ C : \text{Constraint} \quad &\text{propertiesTripleConstraint}((\text{nop}(a), C)) = \{ a \}
\end{align*}
\]
• The properties of a triple constraint is the singleton set that contains its IRI.

4.5 invproperties

Given a shape expression $x$, let $\text{invproperties}(x)$ be the set of properties that appear in some inverse triple constraint in $x$.

$$
\text{invproperties : ShapeExpr} \rightarrow \text{PropertiesSet}
$$

$\text{invproperties}(\text{emptyshape}) = \emptyset$

$\forall tc : \text{TripleConstraint}; c : \text{Cardinality}$

$\text{invproperties}(\text{triple}(tc, c)) = \emptyset$

$\forall itc : \text{InverseTripleConstraint}; c : \text{Cardinality}$

$\text{invproperties}(\text{triple}(itc, c)) = \text{invpropertiesInverseTripleConstraint}(itc)$

$\forall xs : \text{seq}, \text{ShapeExpr}$

$\text{invproperties}(\text{someOf}(xs)) = \text{invproperties}(\text{oneOf}(xs)) = \text{invproperties}(\text{group}(xs)) = \bigcup \{ x : \text{ran } xs \land \text{invproperties}(x) \}$

$\forall x : \text{ShapeExpr}; c : \text{Cardinality}$

$\text{invproperties}(\text{repetition}(x, c)) = \text{invproperties}(x)$

• An empty shape expression has no inverse properties.

• A triple constraint shape expression has no inverse properties.

• The inverse properties of an inverse triple constraint shape expression are the inverse properties in its inverse triple constraint.

• The inverse properties of a some-of, one-of, or grouping shape expression is the union of the inverse properties of their component shape expressions.

• The inverse properties of a repetition shape expression are the inverse properties of the shape expression being repeated.

Given an inverse triple constraint $itc$, let $\text{invpropertiesInverseTripleConstraint}(itc)$ be its set of inverse properties.

$$
\text{invpropertiesInverseTripleConstraint : InverseTripleConstraint} \rightarrow \text{PropertiesSet}
$$

$\forall a : \text{IRI}; C : \text{Shape Constr}$

$\text{invpropertiesInverseTripleConstraint}((\text{inv}(a), C)) = \{ a \}$

• The inverse properties of an inverse triple constraint is the singleton set that contains its IRI.
4.6  *dep_graph*

4.6.1  *DiGraph*

A directed graph consists of a set of nodes and a set of directed edges that connect the nodes.

\[
\text{\texttt{DiGraph}}[X] \\
\text{nodes} : \text{P} X \\
\text{edges} : X \leftrightarrow X \\
\text{edges} \in \text{nodes} \leftrightarrow \text{nodes}
\]

- Each edge connects a pair of nodes in the graph.

4.6.2  *DepGraph*

Given a well-formed schema \( S \), let the shapes dependency graph be the directed graph whose nodes are the shape labels in \( S \) and whose edges connect label \( T_1 \) to label \( T_2 \) when the shape expression that defines \( T_1 \) refers to \( T_2 \).

\[
\text{\texttt{DepGraph}} \\
\text{\texttt{S}} : \text{SchemaWF} \\
\text{\texttt{DiGraph}}[\text{ShapeLabel}] \\
\text{nodes} = \text{shapes}(S) \\
\text{edges} = \{ T_1, T_2 : \text{nodes} \mid T_2 \in \text{refsShapeExpr(expr(T1,S))} \}\}
\]

- The nodes are the shapes of the schema.
- There is an edge from \( T_1 \) to \( T_2 \) when the definition of \( T_1 \) refers to \( T_2 \).

4.6.3  *dep_graph*

Let \( \text{dep_graph}(S) \) be the dependency graph of \( S \).

\[
\text{\texttt{dep_graph}} : \text{SchemaWF} \rightarrow \text{DiGraph}[\text{ShapeLabel}] \\
\text{\texttt{dep_graph}} = \{ \text{DepGraph} \bullet S \mapsto \theta \text{DiGraph} \}
\]

4.7  *dep_subgraph*

4.7.1  *reachable*

Given a directed graph \( g \) and a node \( T \) in \( g \), a node \( U \) is reachable from \( T \) if there is a directed path of one or more edges that connects \( T \) to \( U \).
### 4.7.2 DepSubgraph

Given a well-formed schema $S$ and a shape label $T$ in $S$, the shapes dependency graph is the subgraph induced by the nodes that are reachable from $T$.

\[
\text{DepSubgraph} \\
S : \text{SchemaWF} \\
T : \text{ShapeLabel} \\
\text{DiGraph}[\text{ShapeLabel}] \\
T \in \text{shapes}(S) \\
\text{let } g == \text{dep_graph}(S) \bullet \\
\text{nodes} = \text{reachable}(g, T) \land \\
\text{edges} = g.\text{edges} \cap (\text{nodes} \times \text{nodes})
\]

- The nodes of the subgraph consist of all the nodes reachable from $T$.
- The edges of the subgraph consist of all edges of the graph whose nodes are in the subgraph.

Note that the above formal definition of the dependency subgraph is a literal translation of the text in the semantics draft. In particular, this literal translation does not explicitly include the label $T$ as a node. Therefore $T$ will not be in the subgraph unless it is in a directed cycle of edges.

### 4.7.3 dep_subgraph

Let $\text{dep_subgraph}(T, S)$ be the dependency subgraph of $T$ in $S$.

\[
\text{dep_subgraph} : \text{ShapeLabel} \times \text{SchemaWF} \rightarrow \text{DiGraph}[\text{ShapeLabel}] \\
\text{dep_subgraph} = \{ \text{DepSubgraph} \bullet (T, S) \mapsto \theta \text{DiGraph} \}
\]

### 4.8 negshapes

The definition of $\text{negshapes}$ makes use of several auxiliary definitions. In the following we assume that $S$ is a well-formed schema and that $T$ is a shape label in $S$. 
Let $\text{inNeg}(S)$ be the set of labels that appear in some negated shape constraint.

$$\text{inNeg} : \text{SchemaWF} \rightarrow \mathcal{F} \text{ShapeLabel}$$

$$\forall S : \text{SchemaWF} \bullet$$

$$\text{inNeg}(S) = \bigcup \{ T : \text{shapes}(S) \bullet \text{inNegExpr}(\text{expr}(T, S)) \}$$

Given a shape expression $x$, let $\text{inNegExpr}(x)$ be the set of labels that appear in some negated shape constraint in $x$.

$$\text{inNegExpr} : \text{ShapeExpr} \rightarrow \mathcal{F} \text{ShapeLabel}$$

$$\text{inNegExpr}(\text{emptyshape}) = \emptyset$$

$$\forall tc : \text{TripleConstraint}; c : \text{Cardinality} \bullet$$

$$\text{inNegExpr}((\text{triple}(tc, c))) = \text{inNegTripleConstraint}(tc)$$

$$\forall itc : \text{InverseTripleConstraint}; c : \text{Cardinality} \bullet$$

$$\text{inNegExpr}((\text{triple}(itc, c))) = \text{inNegInverseTripleConstraint}(itc)$$

$$\forall xs : \text{seq}_1 \text{ShapeExpr} \bullet$$

$$\text{inNegExpr}(\text{someOf}(xs)) = \text{inNegExpr}(\text{oneOf}(xs)) = \text{inNegExpr}(\text{group}(xs)) = \bigcup \{ x : \text{ran} \cdot \text{inNegExpr}(x) \}$$

$$\forall x : \text{ShapeExpr}; c : \text{Cardinality} \bullet$$

$$\text{inNegExpr}(\text{repetition}(x, c)) = \text{inNegExpr}(x)$$

Given a triple constraint $tc$, let $\text{inNegTripleConstraint}(tc)$ be the set of labels that appear in some negated shape constraint in $tc$.

$$\text{inNegTripleConstraint} : \text{TripleConstraint} \rightarrow \mathcal{F} \text{ShapeLabel}$$

$$\forall a : \text{IRI}; C : \text{ValueConstr} \bullet$$

$$\text{inNegTripleConstraint}((\text{nop}(a), C)) = \emptyset$$

$$\forall a : \text{IRI}; C : \text{ShapeConstr} \bullet$$

$$\text{inNegTripleConstraint}((\text{nop}(a), C)) = \text{inNegShapeConstr}(C)$$

Given an inverse triple constraint $itc$, let $\text{inNegInverseTripleConstraint}(itc)$ be the set of labels that appear in some negated shape constraint in $itc$.

$$\text{inNegInverseTripleConstraint} : \text{InverseTripleConstraint} \rightarrow \mathcal{F} \text{ShapeLabel}$$

$$\forall a : \text{IRI}; C : \text{ShapeConstr} \bullet$$

$$\text{inNegInverseTripleConstraint}((\text{inv}(a), C)) = \text{inNegShapeConstr}(C)$$
Given a shape constraint $C$, let $\text{inNegShapeConstr}(C)$ be the set of labels that appear in $C$ when it is negated, or the empty set otherwise.

\[
\text{inNegShapeConstr} : \text{ShapeConstr} \rightarrow \mathcal{F} \text{ ShapeLabel}
\]

\[
\forall Ts : \text{seq1 ShapeLabel} \bullet
\text{inNegShapeConstr}(\text{or}(Ts)) = \bigcup \{ T : \text{shapes}(\text{or}(Ts)) \}
\]

\[
\forall Ts : \text{seq1 ShapeLabel} \bullet
\text{inNegShapeConstr}(\text{and}(Ts)) = \bigcap \{ T : \text{shapes}(\text{and}(Ts)) \}
\]

\[
\forall Ts : \text{seq1 ShapeLabel} \bullet
\text{inNegShapeConstr}(\text{nor}(Ts)) = \bigcap \{ T : \text{shapes}(\text{nor}(Ts)) \}
\]

\[
\forall Ts : \text{seq1 ShapeLabel} \bullet
\text{inNegShapeConstr}(\text{nand}(Ts)) = \bigcap \{ T : \text{shapes}(\text{nand}(Ts)) \}
\]

4.8.2 underOneOf

Let $\text{underOneOf}(S)$ be the set of labels that appear in some triple constraint or inverse triple constraint under a one-of constraint in $S$.

\[
\text{underOneOf} : \text{SchemaWF} \rightarrow \mathcal{F} \text{ ShapeLabel}
\]

\[
\forall S : \text{SchemaWF} \bullet
\text{underOneOf}(S) = \bigcup \{ T : \text{shapes}(S) \bullet \text{underOneOfExpr} \text{expr}(T, S) \}
\]

Given a shape expression $x$, let $\text{underOneOfExpr}(x)$ be the set of labels that appear in some triple constraint or inverse triple constraint under a one-of constraint in $x$.

\[
\text{underOneOfExpr} : \text{ShapeExpr} \rightarrow \mathcal{F} \text{ ShapeLabel}
\]

\[
\forall x : \text{ShapeExpr} \bullet
\text{underOneOfExpr}(x) = \begin{cases} \text{refsShapeExpr}(x) & \text{if } x \in \text{ran someOf} \\ \emptyset & \text{else} \end{cases}
\]

4.8.3 inTripleConstr

Let $\text{inTripleConstr}(S)$ be the set of labels $T$ such that there is a shape label $T1$ and a triple constraint $p::C$ or an inverse shape triple constraint $^{^p}::C$ in $\text{expr}(T1, S)$, and $T$ appears in $C$.

Note that this definition looks wrong since it does not involve negation of shapes. Nevertheless, a literal translation is given here. The only difference between $\text{inTripleConstr}(S)$ and $\text{refs}(S)$ seems to be that the cardinality on the triple and inverse triple constraints is $\{1, 1\}$ since it is not explicitly included in the notations $p::C$ and $^{^p}::C$. 

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\( \text{inTripleConstr} : \text{SchemaWF} \rightarrow \wp \text{ShapeLabel} \)

\[ \forall S : \text{SchemaWF} \bullet \\
\text{inTripleConstr}(S) = \\
\bigcup \{ T1 : \text{shapes}(S) \bullet \text{inTripleConstrExpr}(\text{expr}(T1, S)) \} \]

Given a shape expression \( x \), let \( \text{inTripleConstrExpr}(x) \) be the set of labels \( T \) such that \( x \) contains a triple constraint \( p::\mathcal{C} \) or an inverse shape triple constraint \( \neg p::\mathcal{C} \) and \( T \) appears in \( x \).

\( \text{inTripleConstrExpr} : \text{ShapeExpr} \rightarrow \wp \text{ShapeLabel} \)

\[ \forall \text{dtc} : \text{DirectedTripleConstraint}; c : \text{Cardinality} \bullet \\
\text{inTripleConstrExpr}(\text{triple}(\text{dtc}, c)) = \\
\quad \begin{cases} 
\text{refsDirectedTripleConstraint}(\text{dtc}) & \text{if } c = \text{one} \\
\emptyset & \text{else}
\end{cases} \\
\forall \text{xs} : \text{seq}_1 \text{ShapeExpr} \bullet \\
\text{inTripleConstrExpr}(\text{someOf}(\text{xs})) = \\
\text{inTripleConstrExpr}(\text{oneOf}(\text{xs})) = \\
\text{inTripleConstrExpr}(\text{group}(\text{xs})) = \\
\bigcup \{ x : \text{ran} \text{xs} \bullet \text{inTripleConstrExpr}(x) \} \\
\forall x : \text{ShapeExpr}; c : \text{Cardinality} \bullet \\
\text{inTripleConstrExpr}(\text{repetition}(x, c)) = \text{inTripleConstrExpr}(x) \]

### 4.8.4 negshapes

The semantics draft makes the following statement.

Intuitively, \( \text{negshapes}(S) \) is the set of shapes labels for which one needs to check whether some nodes in a graph do not satisfy these shapes, in order to validate the graph against the schema \( S \).

Let \( \text{negshapes}(S) \) be the set of negated shape labels that appear in \( S \).

\( \text{negshapes} : \text{SchemaWF} \rightarrow \wp \text{ShapeLabel} \)

\[ \forall S : \text{SchemaWF} \bullet \\
\text{negshapes}(S) = \text{inNeg}(S) \cup \text{underOneOf}(S) \cup \text{inTripleConstr}(S) \]

- A negated shape label is a shape label that appears in a negated shape constraint, or in a triple or inverse triple constraint under a one-of shape expression, or in a triple or inverse triple constraint that has cardinality \([1,1]\).

Note that, as remarked above, the definition of \( \text{inTripleConstr} \) seems wrong.
4.9 ShapeVerdict

The semantics draft defines the notation $\neg T$ for shape labels $T$ to indicate that $T$ is negated. The semantics of a schema involves assigning sets of shape labels and negated shape labels to the nodes of a graph, which indicates which shapes must be satisfied or violated at each node.

A shape verdict indicates if a shape must be satisfied or violated. An asserted label must be satisfied. A negated label must be violated.

$$ShapeVerdict ::= assert\langle\text{ShapeLabel}\rangle | negate\langle\text{ShapeLabel}\rangle$$

The notation $\neg T$ corresponds to $\text{negate}(T)$.

4.10 allowed

Given a value constraint $V$, let $\text{allowed}(V)$ be the set of all allowed values defined by $V$.

$$\text{allowed} : \text{ValueConstr} \rightarrow \mathcal{P}(\text{Lit} \cup \text{IRI})$$

$\forall vs : \mathcal{P}(\text{Lit} \cup \text{IRI}) \bullet \text{allowed}(\text{valueSet}(vs)) = vs$

$\forall dt : \text{LiteralDatatype} \bullet \text{allowed}(\text{datatype}(dt, \emptyset)) = \text{literalsOfDatatype}(dt)$

$\forall dt : \text{LiteralDatatype}; f : \text{XSFacet} \bullet \text{allowed}(\text{datatype}(dt, \{f\})) = \text{literalsOfFacet}(dt, f)$

$\forall k : \text{NodeKind} \bullet \text{allowed}(\text{kind}(k)) = \text{termsOfKind}(k)$

4.10.1 DAG

A directed, acyclic graph is a directed graph in which no node is reachable from itself.

$$\text{DAG}[X]$$

$$\text{DiGraph}[X]$$

let $g == \emptyset\text{DiGraph}$ •

$\forall T : \text{nodes} \bullet T \notin \text{reachable}(g, T)$

4.11 ReplaceShape

The semantics draft introduces the notation $S_{ri}$ for a reduced schema where $S$ is a schema, $r$ is a rule-of-one node in a proof tree, and $i$ corresponds to a premise of $r$. The reduced schema is constructed by replacing a shape with one
in which the corresponding one-of component is eliminated. This replacement operation is described here. The full definition of $S_{ri}$ is given below following the definition of proof trees.

Given a schema $S$, a shape label $T$ defined in $S$, and a shape expression $Expr'$, the schema $replaceShape(S, T, Expr')$ is the schema $S'$ that is the same as $S$ except that $expr(T, S') = Expr'$.

| ReplaceShape |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| $S, S': SchemaWD$ | $T: ShapeLabel$ | $Expr': ShapeExpr$ | $l: N_1$ | $d, d': ShapeDefinition$ |
| $ecs: seq ExtensionCondition$ | $l \in \text{dom} S$ | $S(l) = (T, d, ecs)$ | $\forall o: \text{OPTIONAL}[\text{InclPropSet}]; Expr: ShapeExpr | $d = \text{open}(o, Expr) \bullet d' = \text{open}(o, Expr')$ |
| $\forall Expr: ShapeExpr | $d = \text{close}(Expr) \bullet d' = \text{close}(Expr')$ |
| $S' = S \oplus \{ l \mapsto (T, d', ecs) \}$ |

| replaceShape |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| $SchemaWF \times ShapeLabel \times ShapeExpr \rightarrow SchemaWF$ | $replaceShape = \{ \text{ReplaceShape } \bullet (S, T, Expr') \mapsto S' \}$ |

### 4.12 SchemaWD

Given a well-formed schema $S$, it is said to be well-defined if for each negated label $T$ in $\text{negshapes}(T)$, the dependency subgraph $\text{dep_subgraph}(T, S)$ is a directed, acyclic graph.

$$SchemaWD = = \{ S: SchemaWF | \forall T: \text{negshapes}(S) \bullet dep_{\text{subgraph}}(T, S) \in \text{DAG}[\text{ShapeLabel}] \}$$

The semantics of shape expression schemas is sound only for well-defined schemas. Only well-defined schemas will be considered from this point forward.
5 Declarative semantics of shape expression schemas

Recall that negated triple and inverse triple shape expressions are represented by the corresponding non-negated expressions with cardinality $none = [0;0]$.

5.1 LabelledTriple

A labelled triple is either an incoming or outgoing edge in an RDF graph.

\[
LabelledTriple ::= \\
out(Triple) | inc(Triple)
\]

Sometimes labelled triples are referred to simply as triples.

5.2 matches

A labelled triple matches a directed triple constraint when they have the same direction and predicate.

\[
\text{matches} : \text{LabelledTriple} \leftrightarrow \text{DirectedTripleConstraint} \\
\text{matches} = \text{matches\_out} \cup \text{matches\_inc}
\]

5.2.1 matches\_out

matches\_out matches outgoing triples to triple constraints.

\[
\text{matches\_out} == \\
\{ s, p, o : \text{TERM}; C : \text{Constraint} | \\
(s, p, o) \in \text{Triple} \bullet \\
out(s, p, o) \mapsto (\text{nop}(p), C) \}
\]

Note that this definition ignores any value constraints defined in $C$. The absence of restrictions imposed by value constraints makes matching weaker than it could be. This may be an error in the semantics draft.

The semantics drafts contains the following text.

The following definition introduces the notion of satisfiability of a shape constraint by a set of triples. Such satisfiability is going to be used for checking that the neighbourhood of a node satisfies locally the constraints defined by a shape expression, without taking into account whether the shapes required by the triple constraints and inverse triple constraints are satisfied.

Read literally, only shape constraints should be ignored, so unless value constraints are handled elsewhere, the semantics draft has an error in the definition of matches.
5.2.2 *matches\_inc*

*matches\_inc* matches incoming triples to inverse triple constraints.

\[
\text{matches\_inc} = \{ s, p, o : \text{TERM}; C : \text{ShapeConstr} \mid \\
(s, p, o) \in \text{Triple} \bullet \\
\text{inc}(s, p, o) \mapsto (\text{inv}(p), C) \}
\]

5.3 *satisfies*

A set of labelled triples *Neigh* is said to satisfy a shape expression *Expr* if the constraints, other than shape constraints, defined in *Expr* are satisfied.

Note that the definition of *matches* ignores both value and shape constraints.

\[
satisfies : \text{F LabelledTriple} \leftrightarrow \text{ShapeExpr}
\]

This relation is defined recursively by inference rules for each type of shape expression.

\[
satisfies = \\
\text{rule\_empty} \cup \\
\text{rule\_triple\_constraint} \cup \\
\text{rule\_inverse\_triple\_constraint} \cup \\
\text{rule\_some\_of} \cup \\
\text{rule\_one\_of} \cup \\
\text{rule\_group} \cup \\
\text{rule\_repeat}
\]

5.3.1 *InfRule*

An inference rule defines a relation between a set of labelled triples and a shape expression. It is convenient to define a base schema for the inference rules.

\[
\begin{array}{l}
\text{InfRule} \\
\text{Neigh : F LabelledTriple} \\
\text{Expr : ShapeExpr}
\end{array}
\]

5.3.2 *rule\_empty*

An empty set of triples satisfies the empty shape expression.

\[
\begin{array}{l}
\text{RuleEmpty} \\
\text{InfRule} \\
\text{Expr = emptyshape} \\
\text{Neigh = \emptyset}
\end{array}
\]
5.3.3 rule_triple_constraint

A set of triples satisfies a triple constraint shape expression when each triple matches the constraint and the total number of constraints is within the bounds of the cardinality.

\[
\text{RuleTripleConstraint}\\
\begin{align*}
\text{InfRule} \\
&k : \mathbb{N} \\
&p : \text{IRI} \\
&C : \text{Constraint} \\
&c : \text{Cardinality} \\
\text{Expr} = \text{triple}((\text{nop}(p), C), c) \\
&k = \#\text{Neigh} \\
&k \text{ inBounds } c \\
&\forall t : \text{Neigh} :: t \text{ matches } (\text{nop}(p), C)
\end{align*}
\]

5.3.4 rule_inverse_triple_constraint

A set of triples satisfies an inverse triple constraint shape expression when each triple matches the constraint and the total number of constraints is within the bounds of the cardinality.

\[
\text{RuleInverseTripleConstraint}\\
\begin{align*}
\text{InfRule} \\
&k : \mathbb{N} \\
&p : \text{IRI} \\
&C : \text{Constraint} \\
&c : \text{Cardinality} \\
\text{Expr} = \text{triple}((\text{inv}(p), C), c) \\
&k = \#\text{Neigh} \\
&k \text{ inBounds } c \\
&\forall t : \text{Neigh} :: t \text{ matches } (\text{inv}(p), C)
\end{align*}
\]
5.3.5 rule\_some\_of

A set of triples satisfies a some-of shape expression when the set of triples satisfies one of the component shape expressions.

\[
\text{RuleSomeOf } \begin{array}{c}
\text{InfRule} \\
\text{Exprs} : \text{seq}\_1 \text{ShapeExpr} \\
i : \mathbb{N}
\end{array}
\begin{array}{c}
\text{Expr} = \text{someOf}(\text{Exprs}) \\
i \in \text{dom} \text{Exprs} \\
\text{Neigh satisfies} \text{Exprs}(i)
\end{array}
\]

\[
\text{rule\_some\_of} : \text{F LabelledTriple} \leftrightarrow \text{ShapeExpr}
\]
\[
\text{rule\_some\_of} = \\
\{ \text{RuleSomeOf } \bullet \text{Neigh} \mapsto \text{Expr} \}
\]

5.3.6 rule\_one\_of

A set of triples satisfies a one-of shape expression when the set of triples satisfies one of the component shape expressions.

\[
\text{RuleOneOf } \begin{array}{c}
\text{InfRule} \\
\text{Exprs} : \text{seq}\_1 \text{ShapeExpr} \\
i : \mathbb{N}
\end{array}
\begin{array}{c}
\text{Expr} = \text{oneOf}(\text{Exprs}) \\
i \in \text{dom} \text{Exprs} \\
\text{Neigh satisfies} \text{Exprs}(i)
\end{array}
\]

\[
\text{rule\_one\_of} : \text{F LabelledTriple} \leftrightarrow \text{ShapeExpr}
\]
\[
\text{rule\_one\_of} = \\
\{ \text{RuleOneOf } \bullet \text{Neigh} \mapsto \text{Expr} \}
\]

The semantics draft contains the following text.

Note that the conditions for some-of and one-of shapes are identical. The distinction between both will be made by taking into account also the non-local, shape constraints.
5.3.7  **rule_group**

A set of triples satisfies a group shape expression when the set of triples can be partitioned into a sequence of subsets whose length is the same as the sequence of component shape expressions, and each subset satisfies the corresponding component shape expression.

```
RuleGroup
InfRule
Neighs : seq₁(\(F\) LabelledTriple)
Exprs : seq₁ ShapeExpr

Expr = group(Exprs)
Neighs partition Neigh
\#Neighs = \#Exprs
\forall j : \text{dom Neigh} \quad \text{Neighs}(j) \text{ satisfies } Exprs(j)
```

```text
rule_group : \(F\) LabelledTriple \(\leftrightarrow\) ShapeExpr
rule_group =
    \{ RuleGroup \(\bullet\) Neigh \(\mapsto\) Expr \}
```

5.3.8  **rule_repeat**

A set of triples satisfies a repetition shape expression when the set of triples can be partitioned into a sequence of subsets whose length is in the bounds of the cardinality, and each subset satisfies the component shape expression of the repetition shape expression.

```
RuleRepeat
InfRule
Expr₁ : ShapeExpr
Neighs : seq₁(\(F\) LabelledTriple)
k : \(\mathbb{N}\)
c : Cardinality

Expr = repetition(Expr₁, c)
k = \#Neighs
k inBounds c
Neighs partition Neigh
\forall j : \text{dom Neigh} \quad \text{Neighs}(j) \text{ satisfies } Expr₁
```
5.4 Proof Trees

The preceding definition of satisfies is based on the existence of certain characteristics of the set of triples. For example, a set of triples satisfies one of a sequence of shape expressions when it satisfies exactly one of them, but the satisfies relation forgets the actual shape expression that the set of triples satisfies. We can remember this type of information in a proof tree.

5.4.1 RuleTree

A rule tree is a tree of inference rules and optional child rule trees. Child rule trees occur in cases where the inference rule depends on other inference rules.

\[
\text{RuleTree ::= } \text{ruleEmpty} \mid \text{ruleTripleConstraint} \mid \text{ruleInverseTripleConstraint} \mid \text{ruleSomeOf} \times \text{RuleTree} \mid \text{ruleOneOf} \times \text{RuleTree} \mid \text{ruleGroup} \times \text{seq}_1 \text{RuleTree} \mid \text{ruleRepeat} \times \text{seq}_1 \text{RuleTree}
\]

5.4.2 baseRule

Each node in a rule tree contains an inference rule and, therefore, a base inference rule.
baseRule : RuleTree → InfRule

∀ RuleEmpty •
  let rule == ∅ RuleEmpty;
  base == ∅ InfRule •
  baseRule(ruleEmpty(rule)) = base

∀ RuleTripleConstraint •
  let rule == ∅ RuleTripleConstraint;
  base == ∅ InfRule •
  baseRule(ruleTripleConstraint(rule)) = base

∀ RuleInverseTripleConstraint •
  let rule == ∅ RuleInverseTripleConstraint;
  base == ∅ InfRule •
  baseRule(ruleInverseTripleConstraint(rule)) = base

∀ RuleSomeOf; tree : RuleTree •
  let rule == ∅ RuleSomeOf;
  base == ∅ InfRule •
  baseRule(ruleSomeOf(rule, tree)) = base

∀ RuleOneOf; tree : RuleTree •
  let rule == ∅ RuleOneOf;
  base == ∅ InfRule •
  baseRule(ruleOneOf(rule, tree)) = base

∀ RuleGroup; trees : seq₁ RuleTree •
  let rule == ∅ RuleGroup;
  base == ∅ InfRule •
  baseRule(ruleGroup(rule, trees)) = base

∀ RuleRepeat; trees : seq₁ RuleTree •
  let rule == ∅ RuleRepeat;
  base == ∅ InfRule •
  baseRule(ruleRepeat(rule, trees)) = base

5.4.3 baseNeigh

Each node in a rule tree has a base set of labelled triples.

baseNeigh : RuleTree → ✓ LabelledTriple

∀ tree : RuleTree •
  baseNeigh(tree) = (baseRule(tree)).Neigh

5.4.4 baseExpr

Each node in a rule tree has a base shape expression.
5.4.5 ProofTree

A proof tree is a rule tree in which the child trees prove subgoals of their parent nodes.

\begin{align*}
\text{ProofTree} : & \mathcal{P} \text{RuleTree} \\
\text{The definition of proof tree is recursive so it is given by a set of constraints, one for each type of node.}
\end{align*}

Any rule tree whose root node contains an empty shape expression is a proof tree since it has no subgoals.

ran \text{ruleEmpty} \subset \text{ProofTree}

Any rule tree whose root node node contains a triple constraint shape expression is a proof tree since it has no subgoals.

ran \text{ruleTripleConstraint} \subset \text{ProofTree}

Any rule tree whose root node node contains an inverse triple constraint shape expression is a proof tree since it has no subgoals.

ran \text{ruleInverseTripleConstraint} \subset \text{ProofTree}

A rule tree whose root node contains a some-of shape expression is a proof tree if and only if its child rule tree correspond to the distinguished shape expression at index \( i \) and it is a proof tree.

\begin{align*}
\forall \text{RuleSomeOf}; \text{tree} : & \text{RuleTree} \bullet \\
\text{ruleSomeOf}((\theta \text{RuleSomeOf}, \text{tree}) \in \text{ProofTree} \iff \\
& \text{baseNeigh}(\text{tree}) = \text{Neigh} \land \\
& \text{baseExpr}(\text{tree}) = \text{Exprs}(i) \land \\
& \text{tree} \in \text{ProofTree}
\end{align*}

A rule tree whose root node contains a one-of shape expression is a proof tree if and only if its child rule tree correspond to the distinguished shape expression at index \( i \) and it is a proof tree.

\begin{align*}
\forall \text{RuleOneOf}; \text{tree} : & \text{RuleTree} \bullet \\
\text{ruleOneOf}((\theta \text{RuleOneOf}, \text{tree}) \in \text{ProofTree} \iff \\
& \text{baseNeigh}(\text{tree}) = \text{Neigh} \land \\
& \text{baseExpr}(\text{tree}) = \text{Exprs}(i) \land \\
& \text{tree} \in \text{ProofTree}
\end{align*}
A rule tree whose root node contains a group shape expression is a proof tree if and only if its sequence of child rule trees correspond to its sequence of component neighbourhood and shape expressions and each child rule tree is a proof tree.

\[ ∀ \text{RuleGroup}; \text{trees} : \text{seq}_1 \text{RuleTree} \bullet \]
\[ \text{ruleGroup}(θ \text{RuleGroup}, \text{trees}) ∈ \text{ProofTree} ⇔ \]
\[ #\text{Exprs} = #\text{trees} ∧ \]
\[ (∀ i : \text{dom trees} \bullet \]
\[ \text{baseNeigh}(\text{trees}(i)) = \text{Neighs}(i) ∧ \]
\[ \text{baseExpr}(\text{trees}(i)) = \text{Exprs}(i) ∧ \]
\[ \text{trees}(i) ∈ \text{ProofTree} \]

A rule tree whose root node contains a repetition shape expression is a proof tree if and only if its sequence of child rule trees correspond to its sequence of component neighbourhoods and each child rule tree is a proof tree.

\[ ∀ \text{RuleRepeat}; \text{trees} : \text{seq}_1 \text{RuleTree} \bullet \]
\[ \text{ruleRepeat}(θ \text{RuleRepeat}, \text{trees}) ∈ \text{ProofTree} ⇔ \]
\[ #\text{Neighs} = #\text{trees} ∧ \]
\[ (∀ i : \text{dom trees} \bullet \]
\[ \text{baseNeigh}(\text{trees}(i)) = \text{Neighs}(i) ∧ \]
\[ \text{baseExpr}(\text{trees}(i)) = \text{Expr1} ∧ \]
\[ \text{trees}(i) ∈ \text{ProofTree} \]

We have the following relation between proof trees and the satisfies relation.

\[ ⊢ \text{satisfies} = \{ \text{tree} : \text{ProofTree} \bullet \text{baseNeigh}(\text{tree}) → \text{baseExpr}(\text{tree}) \} \]

### 5.5 Reduced Schema for rule-one-of

As mentioned above, inference rules and proof trees treat rule-one-of exactly the same as rule-some-of. The difference between these rules appears when considering valid typings, which are described in detail later.

Let \( t \) be a valid typing of graph \( G \) under schema \( S \). Let \( n \) be a node in \( G \) and let \( T \) be a shape label in \( t(n) \). Let \( \text{Expr} = \text{expr}(T, S) \) be the shape expression for \( T \). Let \( \text{tree} \) be a proof tree that the neighbourhood of \( n \) satisfies \( \text{Expr} \). Let \( r \) be a node of the proof tree that contains an application of rule-one-of and let \( i \) be the index of the component expression used in the application of the rule. The intention of the one-of shape expression is that the triples match exactly one of the component expressions. Therefore, if the matched shape expression is removed from the one-of expression then there must not be any valid typings of \( G \) under the reduced schema \( S_{ri} \).

Note that a one-of shape expression may have one or more components. The number of components is denoted by \( k \) in the inference rule. However, if it contains exactly one component then there no further semantic conditions
that must hold and there is no corresponding reduced schema. Therefore, the
definition of the reduced schema only applies to the case where the number of
components is greater than one, i.e. \( k > 1 \).

Rule trees are ordered trees. A child tree can be specified by giving its index
among all the children. The maximum index of a child depends on the type of
rule. For leaf trees, the maximum child index is 0.

\[
\text{maxChild} : \text{RuleTree} \rightarrow \mathbb{N}
\]

\[
\forall \text{tree} : \text{ran ruleEmpty} \bullet \text{maxChild(tree)} = 0
\]

\[
\forall \text{tree} : \text{ran ruleTripleConstraint} \bullet \text{maxChild(tree)} = 0
\]

\[
\forall \text{tree} : \text{ran ruleInverseTripleConstraint} \bullet \text{maxChild(tree)} = 0
\]

\[
\forall \text{tree} : \text{ran ruleSomeOf} \bullet \text{maxChild(tree)} = 1
\]

\[
\forall \text{tree} : \text{ran ruleOneOf} \bullet \text{maxChild(tree)} = 1
\]

\[
\forall r : \text{RuleGroup}; \text{trees} : \text{seq}_1 \text{RuleTree} \bullet
\text{maxChild(\text{ruleGroup}(r, \text{trees}))} = \#\text{trees}
\]

\[
\forall r : \text{RuleRepeat}; \text{trees} : \text{seq}_1 \text{RuleTree} \bullet
\text{maxChild(\text{ruleRepeat}(r, \text{trees}))} = \#\text{trees}
\]

Given a tree \( \text{tree} \) and a valid child index \( j \), the child tree at the index is \( \text{childAt}(\text{tree}, j) \).

\[
\text{childAt} : \text{RuleTree} \times \mathbb{N}_1 \leftrightarrow \text{RuleTree}
\]

\[
\text{dom} \text{childAt} =
\{ \text{tree} : \text{RuleTree}; \text{ci} : \mathbb{N}_1 \mid \text{ci} \leq \text{maxChild(tree)} \}
\]

\[
\forall r : \text{RuleSomeOf}; \text{tree} : \text{RuleTree} \bullet
\text{childAt(\text{ruleSomeOf}(r, \text{tree}), 1)} = \text{tree}
\]

\[
\forall r : \text{RuleOneOf}; \text{tree} : \text{RuleTree} \bullet
\text{childAt(\text{ruleOneOf}(r, \text{tree}), 1)} = \text{tree}
\]

\[
\forall r : \text{RuleGroup}; \text{trees} : \text{seq}_1 \text{RuleTree} \bullet
\text{let} \text{tree} == \text{ruleGroup}(r, \text{trees}) \bullet
\forall \text{ci} : 1 .. \text{maxChild(tree)} \bullet
\text{childAt(tree, ci)} = \text{trees(ci)}
\]

\[
\forall r : \text{RuleRepeat}; \text{trees} : \text{seq}_1 \text{RuleTree} \bullet
\text{let} \text{tree} == \text{ruleRepeat}(r, \text{trees}) \bullet
\forall \text{ci} : 1 .. \text{maxChild(tree)} \bullet
\text{childAt(tree, ci)} = \text{trees(ci)}
\]

The location of a node within a rule tree can be specified by giving a sequence
of positive integers that specify the index of each child tree. The root of the
tree is specified by the empty sequence. Such a sequence of integers is referred
to as a rule path. Given a rule tree \( \text{tree} \), the set of all of its rule paths is \( \text{rulePaths}(\text{tree}) \).

\[
\text{rulePaths} : \text{RuleTree} \to \forall (\text{seq}\ N_1)
\]

\[
\forall \text{tree} : \text{RuleTree} \mid \text{maxChild} (\text{tree}) = 0 \bullet \\
\text{rulePaths} (\text{tree}) = \{\langle \rangle\}
\]

\[
\forall \text{tree} : \text{RuleTree} \mid \text{maxChild} (\text{tree}) > 0 \bullet \\
\text{rulePaths} (\text{tree}) = \\
\bigcup \{ \text{ci} : 1 \ldots \text{maxChild} (\text{tree}) \bullet \\
\{ \text{path} : \text{rulePaths} (\text{childAt} (\text{tree}, \text{ci})) \bullet (\text{ci}) \sim \text{path} \} \}
\]

Given a rule tree \( \text{tree} \) and a rule path \( \text{path} \), the tree node specified by the path is \( \text{treeAt}(\text{tree}, \text{path}) \).

\[
\text{treeAt} : \text{RuleTree} \times \text{seq}\ N_1 \to \text{RuleTree}
\]

\[
\text{dom} \text{treeAt} = \\
\{ \text{tree} : \text{RuleTree}; \text{path} : \text{seq}\ N_1 \mid \text{path} \in \text{rulePaths}(\text{tree}) \}
\]

\[
\forall \text{tree} : \text{RuleTree} \bullet \text{treeAt}(\text{tree}, \langle \rangle) = \text{tree}
\]

\[
\forall \text{tree} : \text{RuleTree}; \text{ci} : N_1; \text{path} : \text{seq}\ N_1 \mid \\
(\text{ci}) \sim \text{path} \in \text{rulePaths}(\text{tree}) \bullet \\
\text{treeAt}(\text{tree}, (\text{ci}) \sim \text{path}) = \text{treeAt}(\text{childAt}(\text{tree}, \text{ci}), \text{path})
\]

Given a one-of shape expression \( \text{Expr} \) that has more than one component, and an index \( i \) of one component, \( \text{elimExpr}(\text{Expr}, i) \) is the reduced expression in which component \( i \) is eliminated.

\[
\text{expr} : \text{ShapeExpr} \times \text{ShapeExpr}
\]

\[
\text{exprL}, \text{exprR} : \text{seq}\ 1 \text{ShapeExpr}
\]

\[
i : N
\]

\[
\text{expr} = \text{oneOf}(\text{exprs})
\]

\[
\# \text{exprs} > 1
\]

\[
i \in \text{dom} \text{exprs}
\]

\[
\text{exprs} = \text{exprsL} \sim (\text{exprs}(i)) \sim \text{exprsR}
\]

\[
\text{expr'} = \text{oneOf}(\text{exprsL} \sim \text{exprsR})
\]

Given a proof tree \( \text{tree} \) with the shape expression \( \text{Expr} \) as its base, and a path \( \text{path} \) to some application \( r \) of rule-one-of in \( \text{tree} \) in which the rule-of expression has more than one component,
The path is a valid rule path in the proof tree.

- The tree at the path is an application of rule-one-of.
- There are more than one components in the one-of shape expression.

\(reduceExpr(\text{tree}, \text{path})\) is the reduced base shape expression with the corresponding one-of expression in \(\text{Expr}\) replaced by the reduced one-of expression.

- The domain of this function requires that the path be a valid rule path in the proof tree.
- In the case of an empty path, the tree must be a one-of tree and the branch taken is eliminated.
- When the path is not empty, this function is defined recursively by additional constraints which follow. There are four possible cases in which the proof tree has children. These cases correspond to applications of rule-some-of, rule-one-of, rule-group, and rule-repeat. Each case is defined by a schema below.
\textbf{ReduceSomeOf}

\textbf{RuleOneOfApplication}
\textbf{RuleSomeOf}
child : ProofTree
tail : seq \mathbb{N}_1
ExprsL, ExprsR : seq ShapeExpr
Expr' : ShapeExpr

\(\text{tree} = \text{ruleSomeOf}(\theta\text{RuleSomeOf}, \text{child})\)

\(\text{path} = \langle 1 \rangle \setminus \text{tail}\)

\(\text{Exprs} = \text{ExprsL} \setminus \langle \text{Exprs}(i) \rangle \setminus \text{ExprsR}\)

\(\text{Expr}' = \text{someOf}(\text{ExprsL} \setminus \langle \text{reduceExpr}(\text{child}, \text{tail}) \rangle \setminus \text{ExprsL})\)

\(\forall \text{ReduceSomeOf} \bullet \)
\(\text{reduceExpr}(\text{tree}, \text{path}) = \text{Expr}'\)

\textbf{ReduceOneOf}

\textbf{RuleOneOfApplication}
\textbf{RuleOneOf}
child : ProofTree
tail : seq \mathbb{N}_1
ExprsL, ExprsR : seq ShapeExpr
Expr' : ShapeExpr

\(\text{tree} = \text{ruleOneOf}(\theta\text{RuleOneOf}, \text{child})\)

\(\text{path} = \langle 1 \rangle \setminus \text{tail}\)

\(\text{Exprs} = \text{ExprsL} \setminus \langle \text{Exprs}(i) \rangle \setminus \text{ExprsR}\)

\(\text{Expr}' = \text{oneOf}(\text{ExprsL} \setminus \langle \text{reduceExpr}(\text{child}, \text{tail}) \rangle \setminus \text{ExprsL})\)

\(\forall \text{ReduceOneOf} \bullet \)
\(\text{reduceExpr}(\text{tree}, \text{path}) = \text{Expr}'\)
\[ \text{ReduceGroup} \]
\begin{align*}
\text{RuleOneOfApplication} \\
\text{RuleGroup} \\
\text{children} : \text{seq}_1 \text{ ProofTree} \\
\text{ci} : \text{N}_1 \\
\text{tail} : \text{seq}_1 \text{N}_1 \\
\text{ExprsL}, \text{ExprsR} : \text{seq} \text{ShapeExpr} \\
\text{Expr} : \text{ShapeExpr} \\
\end{align*}

\[ \text{Expr}' : \text{ShapeExpr} \]

\[ \text{tree} = \text{ruleGroup}(\emptyset \text{RuleGroup}, \text{children}) \]
\[ \text{path} = \langle \text{ci} \rangle \sim \text{tail} \]
\[ \text{Exprs} = \text{ExprsL} \sim \langle \text{Exprs}(\text{ci}) \rangle \sim \text{ExprsR} \]
\[ \text{Expr}' = \text{group}([\text{ExprsL} \sim \langle \text{reduceExpr(\text{children}(\text{ci}), \text{tail})} \rangle] \sim \text{ExprsL}) \]

\[ \forall \text{ReduceGroup} \bullet \]
\[ \text{reduceExpr(\text{tree}, \text{path}) = \text{Expr}'} \]

\[ \text{ReduceRepeat} \]
\begin{align*}
\text{RuleOneOfApplication} \\
\text{RuleRepeat} \\
\text{children} : \text{seq}_1 \text{ ProofTree} \\
\text{ci} : \text{N}_1 \\
\text{tail} : \text{seq}_1 \text{N}_1 \\
\text{Expr} : \text{ShapeExpr} \\
\end{align*}

\[ \text{Expr} : \text{ShapeExpr} \]

\[ \text{tree} = \text{ruleRepeat}(\emptyset \text{RuleRepeat}, \text{children}) \]
\[ \text{path} = \langle \text{ci} \rangle \sim \text{tail} \]
\[ \text{Expr}' = \text{repetition(\text{reduceExpr(\text{children}(\text{ci}), \text{tail}), c})} \]

\[ \forall \text{ReduceRepeat} \bullet \]
\[ \text{reduceExpr(\text{tree}, \text{path}) = \text{Expr}'} \]

- Something looks wrong here because if a repetition expression has a one-of expression as a child then there is no way to associate the reduced one-of expression with just the path taken in the proof tree since all the children of a repetition expression share the same shape expression. However, a rule-repeat node in the proof tree has many children and there is no requirement that all children would use the same branch of the one-of expression. To make progress, I’ll assume that all children of the repeat will eliminate the same branch of the one-of. I will report this to the mailing list later, along with the observation that the reduction should only one done when a one-of expression has more than one component.
5.6 Witness Mappings

Given a set of labelled triples $\text{Neigh}$, a shape expression $\text{Expr}$ and a proof tree $\text{tree}$ that proves $\text{Neigh}$ satisfies $\text{Expr}$, each labelled triple $\text{triple}$ appears in a unique leaf node of the proof tree whose rule matches $\text{triple}$ with a directed triple constraint $\text{dtc}$. This association of $\text{triple}$ with $\text{dtc}$ is called a witness mapping, $\text{wm(triple)} = \text{dtc}$.

5.7 Witness Mapping

$\text{WitnessMapping} == \text{LabelledTriple} \leftrightarrow \text{DirectedTripleConstraint}$

5.7.1 witness

$\text{witness : ProofTree } \rightarrow \text{WitnessMapping}$

\[
\forall r : \text{RuleEmpty} \bullet \\
\quad \text{let } tree == \text{ruleEmpty}(r) \bullet \\
\quad \text{witness(tree)} = \emptyset
\]

\[
\forall r : \text{RuleTripleConstraint}; \text{dtc} : \text{DirectedTripleConstraint}; c : \text{Cardinality} \mid \\
\text{r.Expr} = \text{triple}(\text{dtc}, c) \bullet \\
\quad \text{let } tree == \text{ruleTripleConstraint}(r) \bullet \\
\quad \text{witness(tree)} = \text{baseNeigh(tree)} \times \{\text{dtc}\}
\]

\[
\forall r : \text{RuleInverseTripleConstraint}; \text{dtc} : \text{DirectedTripleConstraint}; c : \text{Cardinality} \mid \\
\text{r.Expr} = \text{triple}(\text{dtc}, c) \bullet \\
\quad \text{let } tree == \text{ruleInverseTripleConstraint}(r) \bullet \\
\quad \text{witness(tree)} = \text{baseNeigh(tree)} \times \{\text{dtc}\}
\]

\[
\forall r : \text{RuleSomeOf}; \text{subtree} : \text{ProofTree} \bullet \\
\quad \text{let } tree == \text{ruleSomeOf}(r, \text{subtree}) \bullet \\
\quad \text{tree} \in \text{ProofTree} \Rightarrow \\
\quad \text{witness(tree)} = \text{witness(subtree)}
\]

\[
\forall r : \text{RuleOneOf}; \text{subtree} : \text{ProofTree} \bullet \\
\quad \text{let } tree == \text{ruleOneOf}(r, \text{subtree}) \bullet \\
\quad \text{tree} \in \text{ProofTree} \Rightarrow \\
\quad \text{witness(tree)} = \text{witness(subtree)}
\]

\[
\forall r : \text{RuleGroup}; \text{subtrees} : \text{seq1 ProofTree} \bullet \\
\quad \text{let } tree == \text{ruleGroup}(r, \text{subtrees}) \bullet \\
\quad \text{tree} \in \text{ProofTree} \Rightarrow \\
\quad \text{witness(tree)} = \bigcup \{ \text{subtree} : \text{ran subtrees} \bullet \text{witness(subtree)} \}
\]

\[
\forall r : \text{RuleRepeat}; \text{subtrees} : \text{seq1 ProofTree} \bullet \\
\quad \text{let } tree == \text{ruleRepeat}(r, \text{subtrees}) \bullet \\
\quad \text{tree} \in \text{ProofTree} \Rightarrow \\
\quad \text{witness(tree)} = \bigcup \{ \text{subtree} : \text{ran subtrees} \bullet \text{witness(subtree)} \}
\]
5.8 \textit{outNeigh}

The outgoing neighbourhood of a node \( n \) in an RDF graph \( G \) is the set of outgoing labelled triples that correspond to triples in \( G \) with subject \( n \).

\[
\text{outNeigh} : \text{Graph} \times \text{TERM} \rightarrow \mathbb{F} \text{LabelledTriple}
\]
\[
\forall G : \text{Graph}; \; n : \text{TERM} \bullet
outNeigh(G, n) = \{ \; p, o : \text{TERM} \mid (n, p, o) \in G \bullet out(n, p, o) \}\]

5.9 \textit{incNeigh}

The ingoing neighbourhood of a node \( n \) in an RDF graph \( G \) is the set of ingoing labelled triples that correspond to triples in \( G \) with object \( n \).

\[
\text{incNeigh} : \text{Graph} \times \text{TERM} \rightarrow \mathbb{F} \text{LabelledTriple}
\]
\[
\forall G : \text{Graph}; \; n : \text{TERM} \bullet
incNeigh(G, n) = \{ \; p, s : \text{TERM} \mid (s, p, n) \in G \bullet inc(n, p, s) \}\]

5.10 \textit{Typing}

Given a schema \( S \) and a graph \( G \), a typing \( t \) is a map that associates to each node \( n \) of \( G \) a, possibly empty, set \( t(n) \) of shape labels and negated shape labels such that if \( T \) is a negated shape label then either \( T \) or \( !T \) is in \( t(n) \). Here I infer that \( T \) and \( !T \) are mutually exclusive.

A typing map associates a finite, possibly empty, set of shape verdicts to nodes.

\[
\text{Typing} = = \text{TERM} \rightarrow \mathbb{F} \text{ShapeVerdict}
\]
• The typing associates a set of shape verdicts to each node in the graph.

• If a node is required to satisfy \( T \) then \( T \) must be a shape label of the schema.

• If a node is required to violate \( T \) then \( T \) must be a negated shape label of the schema.

• If \( T \) is a negated shape label of the schema then each node must be required to either satisfy or violate it.

• No node must be required to both satisfy and violate the same shape.

\[
\begin{align*}
typings : & Graph \times SchemaWD \rightarrow \mathcal{P} \text{Typing} \\
\forall G : Graph; S : SchemaWD \bullet \\
typings(G, S) &= \{ m :TypingMap \mid m.G = G \land m.S = S \bullet m.t \}
\end{align*}
\]

5.11 TypingSatisfies

Given a typing \( t \), a node \( u \), and a shape constraint \( C \), the typing satisfies the constraint at the node if the boolean conditions implied by the shape constraint hold.

\[
\begin{align*}
\text{TypingSatisfies} & \\
\text{TypingMap} & \\
u : & TERM \\
C : & ShapeConstr \\
Ts : & seq1 \text{ShapeLabel} \\
u \in & nodes(G) \\
C = & \text{and}(Ts) \Rightarrow \\
(\forall T : \text{ran } Ts \bullet \text{assert}(T) \in t(u)) \\
C = & \text{or}(Ts) \Rightarrow \\
(\exists T : \text{ran } Ts \bullet \text{assert}(T) \in t(u)) \\
C = & \text{nand}(Ts) \Rightarrow \\
(\exists T : \text{ran } Ts \bullet \text{negate}(T) \in t(u)) \\
C = & \text{nor}(Ts) \Rightarrow \\
(\forall T : \text{ran } Ts \bullet \text{negate}(T) \in t(u))
\end{align*}
\]

• The node is in the graph.

• The node is required to satisfy every shape in an and shape constraint.

• The node is required to satisfy some shape in an or shape constraint.

• The node is required to violate some shape in a nand shape constraint.
• The node is required to violate every shape in a nor shape constraint.

\[
\text{typingSatisfies} : \text{Typing} \times \TERM \leftrightarrow \text{ShapeConstr}
\]

\[
\text{typingSatisfies} = \{ \text{TypingSatisfies} \bullet (t, u) \mapsto C \}
\]

5.12 Matching

Given a node \( n \) in graph \( G \), a typing \( t \), and a directed triple constraint \( X \), let \( \text{Matching}(G, n, t, X) \) be the set of triples in the graph with focus node \( n \) that match \( X \) under \( t \).

\[
\text{MatchingTriples} \\
\text{TypingMap} \\
n, p : \TERM \\
X : \text{DirectedTripleConstraint} \\
C : \text{Constraint} \\
triples : \Term \text{LabelledTriple}
\]

\[
C \in \text{ValueConstr} \land X = (\text{nop}(p), C) \Rightarrow \\
\text{triples} = \{ u : \TERM \mid (n, p, u) \in G \land \\
u \in \text{allowed}(C) \bullet \text{out}(n, p, u) \}
\]

\[
C \in \text{ShapeConstr} \land X = (\text{nop}(p), C) \Rightarrow \\
\text{triples} = \{ u : \TERM \mid (n, p, u) \in G \land \\
(t, u) \text{typingSatisfies} C \bullet \text{out}(n, p, u) \}
\]

\[
C \in \text{ShapeConstr} \land X = (\text{inv}(p), C) \Rightarrow \\
\text{triples} = \{ u : \TERM \mid (u, p, n) \in G \land \\
(t, u) \text{typingSatisfies} C \bullet \text{inc}(u, p, n) \}
\]

• An outgoing triple matches a value constraint if its object is an allowed value.

• An outgoing triple matches a shape constraint if the typing of its object satisfies the constraint.

• An incoming triple matches a shape constraint if the typing of its subject satisfies the constraint.

\[
\text{Matching} : \text{Graph} \times \TERM \times \text{Typing} \times \text{DirectedTripleConstraint} \rightarrow \\
\Term \text{LabelledTriple}
\]

\[
\text{Matching} = \{ \text{MatchingTriples} \bullet (G, n, t, X) \mapsto \text{triples} \}
\]
5.13 validTypings

The definition of what it means for a graph to satisfy a shape schema is given in terms of the existence of a valid typing. Given a graph $G$ and a schema $S$, a valid typing of $G$ by $S$ is a typing that satisfies certain additional conditions at each node $n$ in $G$.

$\forall G : Graph; S : SchemaWD \bullet$

validTypings $(G, S) \subseteq typings(G, S)$

5.13.1 ValidTypingNodeLabel

The definition of a valid typing is given in terms of a series of conditions that must hold at each node and for each shape verdict at that node. It is convenient to introduce the following base schema for conditions.

$validTypings(\mathbf{G} \times \mathbf{SchemaWD} \rightarrow \mathbf{Typing})$

5.13.2 tripleConstraints

Given a shape expression $Expr$ let $tripleConstraints(Expr)$ be the set of all triple or inverse triple constraints contained in it.
tripleConstraints : ShapeExpr → F DirectedTripleConstraint

tripleConstraints(emptyshape) = ∅

∀ dtc : DirectedTripleConstraint; c : Cardinality •
tripleConstraints(triple(dtc, c)) = {dtc}

∀ Exprs : seq1 ShapeExpr •
tripleConstraints(someOf(Exprs)) =
tripleConstraints(oneOf(Exprs)) =
tripleConstraints(group(Exprs)) =
∪{ Expr : ran Exprs • tripleConstraints(Expr) }

∀ Expr : ShapeExpr; c : Cardinality •
tripleConstraints(repetition(Expr, c)) = tripleConstraints(Expr)

5.13.3 NegatedShapeLabel

The semantics draft states:

for all negated shape label !T, if !T ∈ t(n), then t1 is not a valid typing, where t1 is the typing that agrees with t everywhere, except for T ∈ t1(n)

NegatedShapeLabel

ValidTypingNodeLabel

negate(T) ∈ t(n)

• The shape T is negated at node n.

5.13.4 AssertShape

AssertShape

NegatedShapeLabel

t1 : Typing

t1 = t ⊕ {n → (t(n) \ {negate(T)}) \ {assert(T)]]}

• The typing t1 is the same as t except that at node n the shape label T is asserted instead of negated.

In a valid typing if any node has a negated shape, then the related typing with this shape asserted is invalid.

∀ AssertShape •
t1 ∉ validTypings(G, S)

Although this condition on t(n) is recursive in terms of the definition of validTypings, it is well-founded since t1(n) has one fewer negated shapes than t(n). Therefore it remains to define the meaning of validTypings for typings that contain no negated shapes.

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5.13.5 assertShape

Given a typing $t$, node $n$, and shape label $T$ such that $\text{negate}(T) \in t(n)$, define $\text{assertShape}(t, n, T)$ to be the typing $t_1$ that is the same as $t$ except that $\text{assert}(T) \in t_1(n)$.

\[
\text{assertShape} : \text{Typing} \times \text{TERM} \times \text{ShapeLabel} \rightarrow \text{Typing}
\]

\[
\text{assertShape} = \left\{ \text{AssertShape} \bullet \ (t, n, T) \mapsto t_1 \right\}
\]

5.13.6 AssertedShapeLabel

The semantics draft defines the meaning of valid typings $t$ by imposing several conditions that must hold for all nodes $n$ and all asserted shape labels $\text{assert}(T) \in t(n)$.

\[
\begin{array}{c}
\text{AssertedShapeLabel} \\
\text{ValidTypingNodeLabel} \\
\text{assert}(T) \in t(n)
\end{array}
\]

- The shape label $T$ is asserted at node $n$.

The semantics draft states that the following conditions must hold for all valid typings $t$ and all nodes $n$ such that $T$ is asserted at $n$:

- for all shape label $T$, if $T \in t(n)$, then there exist three mutually disjoint sets $\text{Matching}$, $\text{OpenProp}$, $\text{Rest}$ such that

  1. $\text{out}(G, n) \cup \text{inc}(G, n) = \text{Matching} \cup \text{OpenProp} \cup \text{Rest}$, and
  2. $\text{Rest} = \text{Rest}_{\text{out}} \cup \text{Rest}_{\text{inc}}$, where
     - $\text{Rest}_{\text{out}} = \{(\text{out}, n, p, u) \in \text{out}(G, n) \mid p \notin \text{properties}(\text{expr}(T, S))\}$, and
     - $\text{Rest}_{\text{inc}} = \{(\text{inc}, u, p, n) \in \text{inc}(G, n) \mid p \notin \text{invproperties}(\text{expr}(T, S))\}$, and
  3. $\text{Matching}$ is the union of the sets $\text{Matching}(n, t, X)$ for all triple constraint or inverse triple constraint $X$ that appears in $\text{expr}(T, S)$, and
  4. if $T$ is a closed shape, then $\text{Rest}_{\text{out}} = \emptyset$ and $\text{OpenProp} = \emptyset$
  5. if $T$ is an open shape, then $\text{OpenProp} \subseteq \{(\text{out}, n, p, u) \in \text{out}(G, n) \mid p \in \text{incl}(T, S)\}$
  6. there exists a proof tree with corresponding witness mapping $\text{wm}$ for the fact that $\text{Matching}$ satisfies $\text{expr}(T, S)$, and s.t.
for all outgoing triple \((\text{out}, n, p, u)\), it holds \((\text{out}, n, p, u) \in \text{Matching}(n, t, \text{wm}((\text{out}, n, p, u)))\), and moreover if \(\text{wm}((\text{out}, n, p, u))\) is a shape triple constraint, then there is no value triple constraint \(p::C\) in \(\text{expr}(T, S)\) s.t. \((\text{out}, n, p, u) \in \text{Matching}(n, t, p :: C)\), and

- for all incoming triple \((\text{inc}, u, p, n) \in G\), it holds \((\text{inc}, u, p, n) \in \text{Matching}(u, t, \text{wm}((\text{inc}, u, p, n)))\), and

- for all node \(r\) that corresponds to an application of rule one-of in the proof tree, there does not exist a valid typing \(t1\) of \(G\) by \(S\), s.t. \(T \in t1(n)\), and

7. for all extension condition \((\text{lang}, \text{cond})\), associated with the type \(T\), \(f_{\text{lang}}(G, n, \text{cond})\) returns true or undefined.

5.13.7 \text{MatchingOpenRest}

for all shape label \(T\), if \(T \in t(n)\), then there exist three mutually disjoint sets \(\text{Matching}, \text{OpenProp}, \text{Rest}\)

\[
\text{MatchingOpenRest}
\]

\[
\text{AssertedShapeLabel}
\]

\[
\text{MatchingNeigh}, \text{OpenProp}, \text{Rest} : \forall \text{LabelledTriple}
\]

\[
\text{disjoint} \langle \text{MatchingNeigh}, \text{OpenProp}, \text{Rest} \rangle
\]

- There are three mutually disjoint sets of labelled triples.

- Note that the name \text{MatchingNeigh} is used to avoid conflict with the previously defined \text{Matching} function.

\[
\forall \text{AssertedShapeLabel} \bullet
\exists \text{MatchingNeigh}, \text{OpenProp}, \text{Rest} : \forall \text{LabelledTriple} \bullet
\text{MatchingOpenRest}
\]

5.13.8 \text{PartitionNeigh}

\(\text{out}(G, n) \cup \text{inc}(G, n) = \text{Matching} \cup \text{OpenProp} \cup \text{Rest}\)

\[
\text{PartitionNeigh}
\]

\[
\text{MatchingOpenRest}
\]

\[
(\text{MatchingNeigh}, \text{OpenProp}, \text{Rest}) \text{ partition}
\]

\[
\text{outNeigh}(G, n) \cup \text{incNeigh}(G, n)
\]

\[
\forall \text{AssertedShapeLabel} \bullet
\exists \text{MatchingNeigh}, \text{OpenProp}, \text{Rest} : \forall \text{LabelledTriple} \bullet
\text{PartitionNeigh}
\]

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5.13.9 \textit{RestDef}

\[\text{Rest} = \text{Rest}_\text{out} \cup \text{Rest}_\text{inc}, \text{ where}\]

- \[\text{Rest}_\text{out} = \{(\text{out}, n, p, u) \in \text{out}(G, n) | p \notin \text{properties}(\text{expr}(T, S))\},\]
  and
- \[\text{Rest}_\text{inc} = \{(\text{inc}, u, p, n) \in \text{inc}(G, n) | p \notin \text{invproperties}(\text{expr}(T, S))\},\]
  and

\text{RestDef} \quad \text{MatchingOpenRest} \quad \text{Rest}_\text{out}, \text{Rest}_\text{inc} : \text{F LabelledTriple}

\[\text{Rest} = \text{Rest}_\text{out} \cup \text{Rest}_\text{inc}\]

\[\text{Rest}_\text{out} = \{p, u : \text{TERM} | \]
\[\text{out}(n, p, u) \in \text{outNeigh}(G, n) \land \]
\[p \notin \text{properties}(\text{expr}(T, S)) \bullet \]
\[\text{out}(n, p, u)\}\]

\[\text{Rest}_\text{inc} = \{p, u : \text{TERM} | \]
\[\text{inc}(u, p, n) \in \text{incNeigh}(G, n) \land \]
\[p \notin \text{invproperties}(\text{expr}(T, S)) \bullet \]
\[\text{inc}(u, p, n)\}\]

\(\forall \text{MatchingOpenRest} \bullet \]
\(\exists_1 \text{Rest}_\text{out}, \text{Rest}_\text{inc} : \text{F LabelledTriple} \bullet \]
\text{RestDef}

5.13.10 \textit{MatchingDef}

\textit{Matching} is the union of the sets \textit{Matching}(n, t, X) for all triple constraint or inverse triple constraint \(X\) that appears in \textit{expr}(T, S)

\text{MatchingDef} \quad \text{MatchingOpenRest}

\text{MatchingNeigh} = \]
\(\bigcup\{X : Xs \bullet \text{Matching}(G, n, t, X)\}\)

\(\forall \text{MatchingOpenRest} \bullet \]
\text{MatchingDef}

50
5.13.11  \textit{ClosedShapes}

if \( T \) is a closed shape, then \( \text{Rest}_{\text{out}} = \emptyset \) and \( \text{OpenProp} = \emptyset \)

\[
\begin{array}{c}
\text{ClosedShapes} \\
\text{RestDef}
\end{array}
\]

\[
def T \in \text{ran close} \Rightarrow \\
\text{Rest}_{\text{out}} = \emptyset \land \\
\text{OpenProp} = \emptyset
\]

\( \forall \text{RestDef} \bullet \\
\text{ClosedShapes} \)

5.13.12  \textit{OpenShapes}

if \( T \) is an open shape, then

\( \text{OpenProp} \subseteq \{(\text{out}, n, p, u) \in \text{out}(G, n) \mid p \in \text{incl}(T, S)\} \)

\[
\begin{array}{c}
\text{OpenShapes} \\
\text{MatchingOpenRest}
\end{array}
\]

\[
def T \in \text{ran open} \Rightarrow \\
\text{OpenProp} \subseteq \\
\{ p, u : \text{TERM} \mid \\
\text{out}(n, p, u) \in \text{outNeigh}(G, n) \land \\
p \in \text{incl}(T, S) \bullet \\
\text{out}(n, p, u) \}
\]

\( \forall \text{MatchingOpenRest} \bullet \\
\text{OpenShapes} \)

5.13.13  \textit{ProofWitness}

there exists a proof tree with corresponding witness mapping \( \text{wm} \)
for the fact that \( \text{Matching} \) satisfies \( \text{expr}(T, S) \), and s.t.

- for all outgoing triple \( (\text{out}, n, p, u) \), it holds \( (\text{out}, n, p, u) \in \text{Matching}(n, t, \text{wm}((\text{out}, n, p, u))) \), and moreover if \( \text{wm}((\text{out}, n, p, u)) \)
is a shape triple constraint, then there is no value triple constraint \( p::C \) in \( \text{expr}(T, S) \) s.t. \( (\text{out}, n, p, u) \in \text{Matching}(n, t, p :: C) \), and

- for all incoming triple \( (\text{inc}, u, p, n) \in G \), it holds \( (\text{inc}, u, p, n) \in \text{Matching}(n, t, \text{wm}((\text{inc}, u, p, n))) \), and

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• for all node \( r \) that corresponds to an application of rule-one-of in the proof tree, there does not exist a valid typing \( t_1 \) of \( G \) by \( S_{ri} \) s.t. \( T \in t_1(n) \), and

\[
\begin{align*}
\mathbf{ProofWitness} \\
\mathbf{MatchingDef} \\
\text{tree} : \text{ProofTree} \\
\text{wm} : \text{WitnessMapping} \\
\text{baseNeigh}(\text{tree}) = \text{MatchingNeigh} \\
\text{baseExpr}(\text{tree}) = \text{Expr} \\
\text{wm} = \text{witness}(\text{tree})
\end{align*}
\]

\[\forall \text{MatchingDef} \quad \exists \text{tree} : \text{ProofTree}; \text{wm} : \text{WitnessMapping} \quad \text{ProofWitness}\]

5.13.14 OutgoingTriples

for all outgoing triple \((\text{out}, n, p, u)\), it holds

\[(\text{out}, n, p, u) \in \text{Matching}(n, t, \text{wm}(\text{out}, n, p, u))\],

and moreover if \(\text{wm}(\text{out}, n, p, u)\) is a shape triple constraint, then there is no value triple constraint \(p::C\) in \(\text{expr}(T, S)\) s.t.

\[(\text{out}, n, p, u) \in \text{Matching}(n, t, p :: C)\]

\[
\begin{align*}
\mathbf{OutgoingTriples} \quad \mathbf{ProofWitness} \\
\forall \text{triple} : \text{outNeigh}(G, n); p, u : \text{TERM} | \\
\text{triple} = \text{out}(n, p, u) \quad \bullet \\
\text{let} \ X == \text{wm}(\text{triple}) \quad \bullet \\
\text{triple} \in \text{Matching}(G, n, t, X) \land \\
(\text{constrDTC}(X) \in \text{ShapeConstr} \Rightarrow \\
\neg (\exists C : \text{ValueConstr} \mid (\text{nop}(p), C) \in Xs \quad \bullet \\
\text{triple} \in \text{Matching}(G, n, t, (\text{nop}(p), C)\)))
\end{align*}
\]

\[\forall \text{ProofWitness} \quad \bullet \quad \text{OutgoingTriples}\]

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5.13.15  \textit{IncomingTriples}

for all incoming triple $(\text{inc}, u, p, n) \in G$, it holds

$$(\text{inc}, u, p, n) \in \text{Matching}(n, t, \text{wm}((\text{inc}, u, p, n)))$$

\hspace{1cm} \text{IncomingTriples} \hspace{1cm} \text{ProofWitness}

$\forall \text{triple} : \text{incNeigh}(G, n) \bullet$
\hspace{1cm} \text{let } X == \text{wm(triple)} \bullet$
\hspace{1cm} triple \in \text{Matching}(G, n, t, X) \hspace{1cm} \text{ProofWitness} \hspace{1cm} \text{IncomingTriples}$

5.13.16  \textit{OneOfNodes}

for all node $r$ that corresponds to an application of rule-one-of in the proof tree, there does not exist a valid typing $t1$ of $G$ by $S_r$ s.t. $T \in t1(n)$

Let \textit{OneOfNodes} describe the situation where we are given a graph $G$, a schema $S$, a typing $t$ of $G$ under $S$, a node $n$ in $G$, a shape label $T$ in $t(n)$, a proof tree $\text{tree}$ for the triples $\text{MatchNeigh}$ and the expression $\text{Expr} = expr(T, S)$ and an application of rule-one-of $r$ in the proof tree.

\hspace{1cm} \text{OneOfNodes} \hspace{1cm} \text{ProofWitness}

\hspace{1cm} \text{RuleOneOfApplication}

\hspace{1cm} \text{Expr}_{\text{ri}} : \text{ShapeExpr}$

\hspace{1cm} \text{S}_{\text{ri}} : \text{SchemaWD}$

\hspace{1cm} \text{Expr}_{\text{ri}} = \text{reduceExpr}(\text{tree}, \text{path})$

\hspace{1cm} \text{S}_{\text{ri}} = \text{replaceShape}(S, T, \text{Expr}_{\text{ri}})$

Whenever rule-one-of is applied in the proof tree, there must not be any valid typings $t1$ for the reduced schema $S_{\text{ri}}$ in which the selected component of the one-of shape expression is eliminated.

$\forall \text{OneOfNodes} \bullet$
\hspace{1cm} $\neg (\exists t1 : \text{validTypings}(G, S_{\text{ri}}) \bullet$
\hspace{1cm} $\text{assert}(T) \in t1(n))$
5.13.17  *ExtensionConditions*

for all extension condition \((\text{lang}, \text{cond})\), associated with the type \(T\),
\(f_{\text{lang}}(G, n, \text{cond})\) returns true or undefined

The semantics of an extension condition is given by a language oracle function that evaluates the extension condition \(\text{cond}\) on a pointed graph \((G, n)\) and returns a code indicating whether the pointed graph satisfies the extension condition, or if an error condition holds, or if the extension condition is undefined.

\[
f : \text{ExtLangName} \times \text{Graph} \times \text{TERM} \times \text{ExtDefinition} \rightarrow \text{ReturnCode}
\]

\[
\forall G : \text{Graph}; n : \text{TERM} \mid (G, n) \in \text{PointedGraph} \bullet \\
\forall \text{lang} : \text{ExtLangName}; \text{cond} : \text{ExtDefinition} \bullet \\
\text{let } \text{returnCode} == f(\text{lang}, G, n, \text{cond}) \bullet \\
\text{returnCode} = \text{trueRC} \Rightarrow (G, n) \notin \text{violatedBy}(\text{lang}, \text{cond}) \land \\
\text{returnCode} = \text{falseRC} \Rightarrow (G, n) \in \text{violatedBy}(\text{lang}, \text{cond})
\]

• If the oracle returns true then the pointed graph satisfies the extension condition.
• If the oracle returns false then the pointed graph violates the extension condition.

Let the return codes for the language oracles be \(\text{ReturnCode}\).

\[
\text{ReturnCode} ::= \text{trueRC} | \text{falseRC} | \text{errorRC} | \text{undefinedRC}
\]

• true means the extension condition is satisfied.
• false means the extension condition is violated.
• error means an error occurred.
• undefined means the extension condition is undefined.

\[
\begin{align*}
\text{ExtensionConditions} \\
\text{MatchingOpenRest} \\
\text{lang} : \text{ExtLangName} \\
\text{cond} : \text{ExtDefinition} \\
\text{let } \text{ecs} == \text{extConds}(\text{rule}T) \bullet \\
(\text{lang}, \text{cond}) \in \text{ran} \text{ecs}
\end{align*}
\]

• \((\text{lang}, \text{cond})\) is an extension condition for \(T\).

\[
\forall \text{ExtensionConditions} \bullet \\
f(\text{lang}, G, n, \text{cond}) \in \{\text{trueRC}, \text{undefinedRC}\}
\]
6 Issues

Some areas of the semantics draft have multiple interpretations or appear to be wrong and therefore require further clarification. These areas are discussed below.

6.1 \texttt{dep-subgraph}(T,S)

In the definition of \texttt{dep-subgraph}(T,S), is the shape T considered to be reachable from itself?

6.2 \texttt{negshapes}(S)

In the definition of \texttt{negshapes}(S), the third bullet states:

\begin{quote}
there is a shape label T1 and a shape triple constraint \texttt{p:C}, or an inverse shape triple constraints \texttt{^p:C} in expr(T1, S), and T appears in C.
\end{quote}

This statement looks wrong because it omits mention of negation. If there is no negation involved, why would T be in \texttt{negshapes}(S)?

Does this definition only select directed triple constraints that have cardinality [1,1] because that is the default? If not then \texttt{negshapes}(S) is the set of all labels that are referenced in any shape definition (\texttt{refs}(S)), which seems wrong.

6.3 Triple matches constraint

The definition of matching \texttt{p:C} and \texttt{^p:C} omits consideration of C. The explanation is as follows.

The following definition introduces the notion of satisfiability of a shape constraint by a set of triples. Such satisfiability is going to be used for checking that the neighborhood of a node satisfies locally the constraints defined by a shape expression, without taking into account whether the shapes required by the triple constraints and inverse triple constraints are satisfied.

This statement implies that only shape constraints should be ignored here. However, the definition ignores the value set constraints too. This looks wrong.

6.4 rule-triple-constraint

Add the condition that all the outgoing triples must be distinct.
6.5 rule-inverse-triple-constraint
Add the condition that all the incoming triples must be distinct.

6.6 rule-group
Add the condition that $i$ and $j$ must be different.

6.7 rule-repeat
Add the condition that $i$ and $j$ must be different.

6.8 Reduced Schema for rule-one-of
This is an edge case. It only makes sense to reduce the schema if there are more than one components. Applying rule-one-of to a sequence of one shape is equivalent to requiring that shape. Add this condition to the definition.

6.9 Reduced Schema for rule-one-of under a repetition expression
Something looks wrong here because if a repetition expression has a one-of expression as a child then there is no way to associate the reduced one-of expression with just the path taken in the proof tree since all the children of a repetition expression share the same shape expression. However, a rule-repeat node in the proof tree has many children and there is no requirement that all children would use the same branch of the one-of expression.

7 Conclusion
The exercise of formalizing the semantics draft has resulted in a considerable expansion in the size of the document. The result has been the identification of a number of quality issues. This exercise has also established that the recursive definitions in the semantics draft are well-founded. However, it is not clear that these definitions produce results that agree with our intuition, or that they can be computed efficiently.

One possible way to further validate the semantics draft is to translate it into an executable formal specification system such as Coq [1] and test it on a set of examples, including both typical documents and corner cases.

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