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Valid Time RDF

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by

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Abstract

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The Semantic Web aims at building a foundation of semantic-based data models and languages for not only manipulating data and knowledge, but also supporting decision making by machines. Naturally, time-varying data and knowledge are required in Semantic Web applications to incorporate time and further reason about it. However, the original specifications of Resource Description Framework (RDF) and Web Ontology Language (OWL) do not include constructs for handling time-varying data and knowledge. For simplicity, RDF model is confined to binary predicates, hence some form of reification is needed to represent higher-arity predicates. To this date, there are many proposals extending RDF and OWL for handling temporal data and knowledge. They all focus on the valid time. Some of these proposals stay within the standards whereas others add new constructs to RDF and its query language, SPARQL. We first study these models in a comparative framework and develop a taxonomy for classifying them. On this basis, we propose a new temporal data model, Valid Time RDF, or VTRDF, that incorporates valid time explicitly into RDF. We define valid time resources as the building blocks of VTRDF. Our approach treats all resources in VTRDF uniformly, which is significant in that the need of RDF reification is eliminated. In particular, using VTRDF to handle temporal data and knowledge requires no additional triples or objects. We formally define valid time triples and graphs, which are subject to the Temporal Triple Integrity, and the formal semantics for the layered sets of VTRDF vocabularies. To query VTRDF triple databases, we design a query language, VT-SPARQL, that extends the standard SPARQL to handle valid time resources, time intervals, and temporal reasoning. We have also shown that space

and time complexity of VTRDF, and the time complexity of the evaluating VT-SPARQL queries.

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Chapter 1

Introduction

1.1 Knowledge Representation and the Semantic Web

In the past decades, *Knowledge Representation* has been an emerging research subject. Its development was, among others, one of the by-products of research and practices in Artificial Intelligent (AI). The goal of AI applications is to take the role of human experts to support decision making. The Semantic Web is one of the fields that has been moving the frontier of knowledge management. For the scope of this thesis, we consider that knowledge is essentially declarative. However, this does not deny the importance of other types of knowledge, such as the procedural knowledge. Declarative knowledge is manifested by simple facts or assertions about the world, such as a simple fact, *John is a student*. Humans can easily store, process, and use this fact or a collection of facts. Nevertheless, for machines to use and manage a fact like this, it needs to be formulated, which usually requires the use of mathematical artifacts.

Recent research in knowledge representation has brought fruitful achievements. Many knowledge representation formalisms are available, such as Propositional Logic, First Order Logic, Production Rule, Semantic Network, Frame, Description Logic, Ontology, Resource Description Framework (RDF), and Web Ontology Language (OWL). While some of these evolved from the

intuition that *logic* is unambiguous in terms of capturing facts about the world, others originated from needs of developing legacy expert systems, or moved towards the object-oriented paradigm.

The Semantic Web was proposed by Tim Berners-Lee [12] and later advocated by the World Wide Web Consortium (W3C). It is based on the vision of machine understandable web infrastructure and contents. The term *web resource* is used to designate all kinds of web contents. Web resources are mostly consumed by human users. The Semantic Web provides additional metadata specifications, so that all identifiable resources can be annotated with metadata. The metadata layer yields the core of a semantic-based data model that facilitates description of every identifiable resource by named properties. As a result, web resources can be consumed by both human and machines.

The efforts led by W3C helped popularize ontology, knowledge representation and reasoning for machine processing. In Computer Science, ontology is a model of concepts and relationships among them. In this respect, an ontology is the conceptualization used to help programs, machines and humans use and share knowledge [29]. An ontological approach encodes knowledge about the world in terms of concepts, classes, instances and relationships. Its specification is materialized by using some ontology framework, such as RDF or its variants. The objective of using ontology is to create formal vocabularies, terminologies and semantic structures for using and exchanging knowledge about a domain of interest. Moreover, an inference engine, such as Pellet [56], FaCT++ [70], etc., can be used to derive knowledge that can be logically inferred from an ontology specification.

1.2 Motivation

Temporality is a common aspect of data models of all kinds. It is exhibited by contents that change over time where both the old and new contents are critical. Among many approaches to model temporal data and knowledge, one can choose to incorporate *Time* into a model as an explicit part of the model or language. Alternatively, *Time* can also be realized implicitly by capturing temporal

order of different temporal states. That is, when the state changes over time, an updated version is generated and timestamped. The original one becomes the previous version. This leads to a notion of *versioning* which suffers from the rapid proliferation of state objects.

There is a long history of research in temporal databases as extensions of various data models, mainly of the relational data model, and temporal extension of SQL. In fact, major database packages today include temporal support. Similarly, there are extensive research efforts underway for incorporating temporality into the Semantic Web data model, namely RDF and its variants. However, this is a challenging issue since RDF is hard-wired as triples. Handling temporality in RDF requires reification although semantically sound reification has a high overhead. To this date, there has not been a W3C recommended approach for modeling and querying temporal data and knowledge in RDF.

In the literature, most of the proposals for temporal data models of the Semantic Web incorporate time into the model explicitly, instead of versioning. These proposals are mainly based on RDF reification [30, 19], 4D fluents [73, 6, 49], Named Graphs [18], or N-ary Relations [53] etc. As we have indicated above, reification has a high overhead, and it is not practical for handling a large volume of data sets. Therefore, it is imperative to develop a practical temporal model for handling temporal data and knowledge in RDF.

Two attributes of time are usually considered in a temporal data model: valid time (VT) and transaction time (TT). Valid Time is the validity period of a fact, whereas Transaction Time records the time when that fact is registered in the database. To the best of our knowledge, the transaction time has not been extensively considered in the literature.

This thesis therefore focuses on modeling binary relations that have the necessity of adding an additional dimension with the standard RDF model which confines to binary relations or predicates. We select the valid time as the additional dimension, which provides the foundation of data models that concern time-varying properties or values, and their changes. Adding a time dimension to RDF is very challenging because RDF is a binary-relation-only model, and there is no triple

level identification within.

Our contributions in this thesis include:

- We have conducted an up-to-date comprehensive survey of temporal data models of the Semantic Web, which updates existing survey papers of temporal data models of the Semantic Web, such as [24].

- We adopt a comparative framework in evaluating the surveyed temporal models. The result provides a useful guideline for the researchers and practitioners of the Semantic Web in managing temporal data and knowledge.

- We have developed a taxonomy for classifying temporal data models of the Semantic Web. The taxonomy is based on the concept of reification which manifests itself as *Explicit Reification* and *Implicit Reification*. In the *Implicit Reification* case, we have identified three subgroups: (1) Instantiating-Identifying Concept/Relationship, (2) Relationship Entity Conversion, and (3) Named Graphs.

- A new temporal data model, Valid Time RDF, or VTRDF, is proposed. Valid time resources are defined as the building blocks of VTRDF. In comparison to the standard RDF where *static* resources are used, every resource and relationship in VTRDF are inherently equipped with their valid time, which provides means of preserving complete temporal semantics and more practical temporal reasoning.

- We complete VTRDF by providing formal definitions of its syntax, pre-defined vocabularies, semantics, temporal triple integrity, and entailment patterns.

- A query language, VT-SPARQL, is defined for VTRDF. VT-SPARQL extends the standard SPARQL to handle the representation and manipulation of valid time resources, time intervals, and temporal reasoning by Allen's temporal predicates [4]. We have decided on supporting two query forms in VT-SPARQL: SELECT and CONSTRUCT queries, which

provide practical data retrieval means and characterize the distinctive feature of VTRDF and VT-SPARQL.

- We have also shown that the complexity aspects of VTRDF, including storage, entailment, and query evaluation, resemble the complexity aspects of the standard RDF.

This thesis is organized as follows: chapter 2 introduces the background of Knowledge Representation formalisms and the Semantic Web. Specifically, we focus on RDF with its formal definitions given in Appendix A. Chapter 3 provides the foundation for our proposed VTRDF by surveying temporal extensions to RDF from the literatures. Chapter 4 explains our modeling approach and proposes the Valid Time RDF. Definitions of the proposed VTRDF are given, with running examples that characterize how valid time vocabularies, triples and graphs are used. VTRDF and VTRDF Schema vocabularies, their formal semantics, and entailment patterns are also defined in Chapter 4. Chapter 5 continues the development of a query language, VT-SPARQL, and provides ways to query VTRDF triple databases. Chapter 6 analyzes the complexity of VTRDF, including space and the evaluation of VT-SPARQL queries. We conclude this thesis with observations and future works in Chapter 7.

Chapter 2

Background

2.1 Knowledge Representation

From Merriam-Webster online Dictionary [2], *Knowledge* is defined as follows:

> *The fact or condition of knowing something with familiarity gained through experience or association.*

Based on this definition, *Knowledge Representation* is a subject that aims at formally expressing the condition of knowing something. Attempts have been made to categorize knowledge. If our concern is the nature of knowledge, we have the declarative or procedural knowledge. Declarative knowledge is manifested by simple facts or assertions about the world, such as *John enrolled in the Semantic Web course*. Humans can easily store, process, and use a fact or a collection of facts. However, for machines to use and manage a fact like this, it needs to be formulated or modeled, which usually requires the use of mathematical artifacts. In comparison, procedural knowledge usually contains a set of ordered processes that are necessary to achieve a specific goal. For instance, to model the knowledge of *how to ride a bike* requires descriptions of a sequence of facts which are typically declarative.

A knowledge-based system is a computer system that reasons over a knowledge base to solve problems [78]. For instance, expert systems are knowledge-based and designed to solve complex problems by reasoning over the knowledge base which is mainly represented as IF-THEN rules [77]. Typically, a knowledge-based system contains two main components: the knowledge base and an inference engine which provides the reasoning capability. The knowledge base may contain simple facts, rules, or cases, whereas the inference engine utilizes logical deductions or other reasoning operations to derive the implicit knowledge from the knowledge base. Although the functionalities of the knowledge base and the inference engine differ, they are closely related, as Bench-Capon argues in his book [10]:

> *The syntactic structure of an effective representation must directly mirror the inferential structure of the knowledge it encodes.*

The above argument hints that the structure and syntax of the chosen knowledge representation formalism should be rich enough and include primitives that enable the explicit encoding of the inferential structure of a body of knowledge.

While requirements of devising a knowledge representation formalism vary among domains and applications, in general the expressive power, clarity, uniformity, and computational tractability of the formalism all need to be considered in designing or selecting a knowledge representation formalism [10]. When it comes to design an AI application program, there are essential things that we want the application to know about, such as facts, or processes that cause these facts to happen, etc. Moreover, relationships among facts or objects are also indispensable information. The main task of knowledge representation is therefore to model these facts, relationships, and other components by using a formalism that is processable by both humans and machines.

The most intuitive knowledge representation is by the natural language, as almost any simple or complex facts, and relationships or rules associated with them can be expressed in a natural language. While it is simple to utilize, there is little uniformity in structures of natural language

constructs. More importantly, defining the formal semantics for a natural language is complex and ends up with unsatisfactory computational tractability in most cases.

In the rest of this section, we briefly introduce fundamental knowledge representation formalisms that are relevant to the scope of this thesis.

2.1.1 Classical Logic

Classical logic was developed as a knowledge representation formalism long before the emergence of the computer era. It evolved from the need of formalizing the mathematics of declarative knowledge. In a classical logic language, such as Propositional Logic, simple facts are represented by logical expressions defined over variables that assume binary values, true or false. As an algebra, Propositional logic models the reasoning of the truth value of well-formed logical expressions. A logical expression may contain propositional variables and logical operators, such as *AND* ($\wedge$), *OR* ($\vee$), and *NOT* ($\neg$). Complex facts are formed by joining simple ones with logical operators. Furthermore, using the propositional logic benefits from available automatic *Boolean Satisfiability (SAT)* solvers [76], which decide whether a truth assignment exists for a given logical expression.

First-Order Logic (FOL), or Predicate Logic, was first proposed by John McCarthy [47]. FOL extends Propositional Logic by adding predicates and quantifiers to provide more expressive power. Predicates are functions that describe properties of objects or variables. Universal quantifiers are abbreviations for individual objects that can be otherwise enumerated without quantifiers. In comparison, existential quantifiers are used to posit unknown individual objects who carry some facts and characteristics.

Reasoning and inference in classical logic languages generally amount to verifying logical consequences out of the facts explicitly modeled by logical expressions.

2.1.2 Production Rule

In procedural programming, a *selection* structure of IF-THEN implements a decision process for a given goal by a set of conditions and actions that help to realize the goal [10]. Production rule systems resemble such a *selection* construct. A production rule system typically has two components. First, it contains a list of conditions to be evaluated based on the input given to it. Secondly, there a list of actions to be performed accordingly if the conditions have been satisfied. The execution cycle of a production rule system is shown in Figure 2.1, which contains the following modules:

1. A working memory records the input, and the status of rule execution.

2. A production memory contains rules governing the execution of the rule system. Rules are generally in the form of *IF conditions THEN actions*.

3. A rule interpreter, or the inference engine, selects applicable rules from the production memory that match the contents of the working memory. Once the rules have been selected, it performs the associated actions.

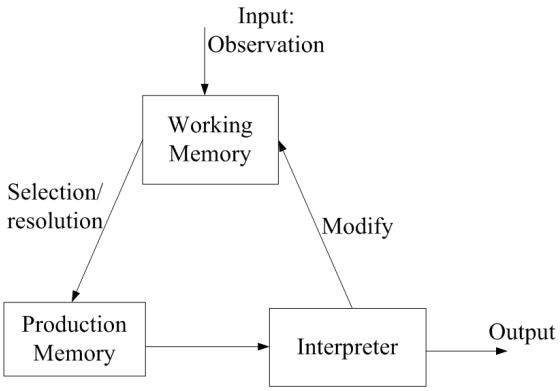


Figure 2.1: Production System Execution Cycle

One of the advantages of using a production rule system is that such a system is more flexible in handling incomplete and uncertain data and knowledge. On the other hand, the disadvantages of using production rule systems include: (1) blurred relationships between rules, (2) inefficient

rule searching strategy, especially in large pool of rules, and (3) inability to learn and evolve intelligently.

2.1.3 Semantic Network

The origin of the Semantic Network lied in *Aristotle's associationism and reductionism*, and later became an attempt to describe the meaning of words and to give descriptions by associating symbols in a given network. A semantic network is a graphical representation of information and knowledge by interconnecting nodes and links. Nodes represent units of information, such as concepts, predicates, properties, frames, features, and constraints. The links resemble inference dependencies between nodes. An inference dependency provides semantic information, such as a *is_a* or *subClassOf* link, that describes the relationship between a pair of linked nodes. As a result, class hierarchical and inheritance can be represented in semantic networks. Furthermore, practices suggest that information and knowledge relevant to a specific node are typically clustered. This resembles how human memory works in associating objects, and also enhances computational effectiveness [10]. Figure 2.2 shows an example of a semantic network. It represents that John is an instance of the class *STUDENT*, while *Semantic Web* is an instance of the class *COURSE*. John, as a student, enrolled in the course, *Semantic Web*.

Benefits of using the Semantic Network as a knowledge representation formalism include: first, it provides efficient storage as technology and high-performance algorithms exist for network-based data storage and manipulation. Secondly, inferencing about information and knowledge in a semantic network reduces to traversing the network for which optimized algorithms also exist. In addition, a semantic network can be transformed to an equivalent FOL representation, which benefits from automatic Boolean Satisfiability Solvers [76] as means of logical deduction. A few limitations of the Semantic Network exit, such as unable to express multiple inheritance cases, disjunction, negation and quantification.

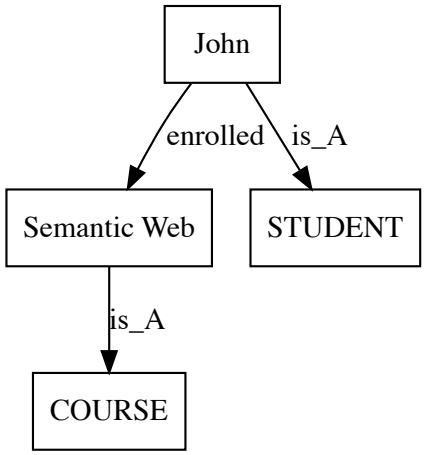


Figure 2.2: A Semantic Network Example

2.1.4 Frame

In 1975, Marvin Minsky proposed the theory of *frames* as a way to arrange knowledge. A frame is presented as record-like data structure, which gathers all relevant information in one place for handling situations. In other words, a frame contains descriptions of concepts and knowledge about an entity, and its associations to other frames if any. Figure 2.3 shows a single frame of a student instance identified by John. In this frame, Name, ID, LivedIn, enrolled, Admission Record, and

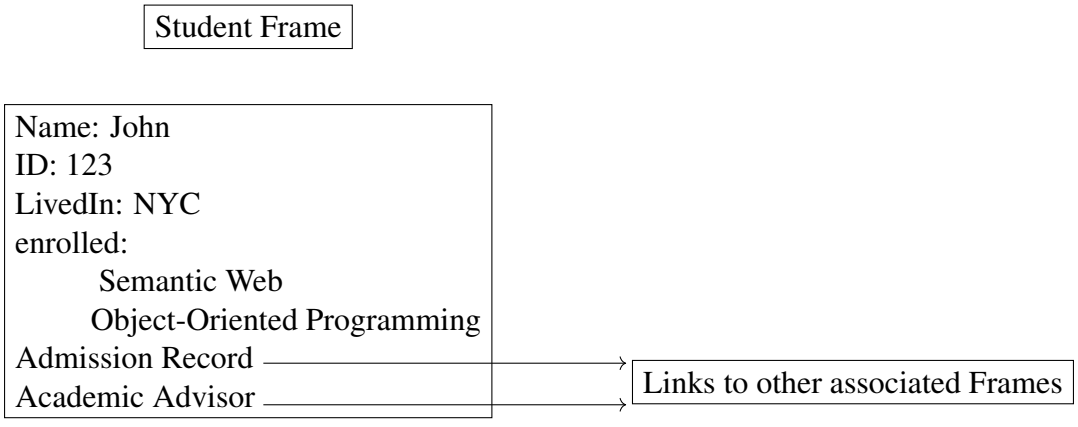


Figure 2.3: An Example of a Student Frame

Academic Advisor are *slots* which are filled with values or links to other associated frames. For instance, the a value, John, fills the Name slot, and the Admission Record slot is associated to other frames.

There are a few limitations of representing knowledge in Frames. First, Frames are a general methodology rather than a specific knowledge representation formalism. To an extremity, frames can be used in an arbitrary manner, or ad hoc that lacks formal semantics. For instance, a frame for a student and a frame for a person can have no common part, which is abnormal to most object-oriented modeling approaches. Secondly, because of its ad hoc nature, there is no reasoning and inference mechanism that can be justified.

2.1.5 Description Logic

Description Logic (DL) is closely related to Frames and Semantic Networks introduced in section 2.1.3 and 2.1.4 respectively. DL overcomes limitations of Frames and Semantic Networks to provide complete formal semantics and inference mechanisms. DL is based on Predicate Logic with selective constructs that bear necessary expressive power for practical modeling purposes, and still preserves good computational tractability.

In DL, facts are represented by descriptions, which contain properties or constraints individuals need to satisfy in order to remain members or participants of the facts. A knowledge representation system based on DL typically consists of two components: TBox and ABox. The TBox, or terminology box, contains general knowledge in the form of concepts and roles about the knowledge domain modeled. Concepts can be atomic or complex ones. An atomic concept is represented by an unary predicate or logical expressions that contain only one free variable. A complex concept is formed by atomic concepts with concept constructors, such as intersection or conjunction. As an example, a concept, Woman is defined by the intersection of two atomic concepts, *Person* and *Female*, and written as Woman $\equiv$ Person $\sqcap$ Female. Roles are binary predicates or logical expressions with two free variables. They can also be atomic or complex. For instance, *hasChild*

is a complex role described by the union of two atomic roles, *hasSon* and *hasDaughter*. In comparison, an ABox contains assertional knowledge that is specific to individuals of the knowledge domain modeled. Individuals are named constants, such as *John*. Assertional knowledge is subject to change under different circumstances while the knowledge in TBox is not.

There are many language variants of Description Logic, and each provides different constructs for levels of expressive power in exchange of computational tractability. The more expressive power a DL language has, the less computational tractability it has. The Attribute Language, or AL, is the minimal logic that contains a set of practically usable vocabulary. AL allows descriptions of atomic concepts, atomic roles, atomic negation, value restrictions, and limited existential quantification. It can be further extended by adding new constructs to enable more expressive power. Table 2.1 shows symbolic names of possible extensions to AL logic. The name of a new logic is formed from the string $\mathcal{AL}[\mathcal{U}][\mathcal{E}][\mathcal{N}][\mathcal{C}]$. For instance, the logic $\mathcal{ALC}$ is the AL logic extended with the negation of an arbitrary concept. $\mathcal{ALC}$ is also called $\mathcal{S}$ due to its relationship to propositional modal logic $\mathcal{S}4_m$ [39, 61]. Further extending the logic ($\mathcal{S}$) to include role hierarchy ($\mathcal{H}$), nominals ($\mathcal{O}$), inverse roles ($\mathcal{I}$), number restrictions ($\mathcal{N}$), and concrete domains results the logic $\mathcal{SHOIN}$(D) on which OWL-DL is based. OWL-Lite, OWL-DL, and OWL-Full [50] are three variants of the Web Ontology Language, OWL, with increasing expressive power and computational overhead.

Name	**Syntax**	**Note**
$\mathcal{U}$	$C \sqcup D$	Union of Two Concepts
$\mathcal{E}$	$\exists R.C$	Full Existential Quantification
$\mathcal{N}$	$\geq nR$ $\leq nR$	Number Restriction
$\mathcal{C}$	$\neg C$	Negation of an Arbitrary Concepts

Table 2.1: Extensions to AL logic

The main inference task over concept and role expressions in DL is *subsumption*. Given two concepts C and D, if the concept described by D is more general than another denoted by C, D

subsums C and write $C \subseteq D$. Other inference tasks in DL include satisfiability, instance checking, equivalence checking, and the retrieval of a set of individuals that satisfy a concept description.

2.2 The Semantic Web

The Semantic Web is a collaborative project envisioned by Tim Berners-Lee [12], the inventor of the World Wide Web. It aims at achieving a linked-data medium for machine-processable information exchange on the World Wide Web. The Semantic Web provides additional metadata specification, so web contents or resources can be annotated with metadata and also linked. The Semantic Web technologies enable users to create vocabularies and data stores, use and represent data and knowledge, and reason about meanings of data and knowledge. The linked-data is facilitated by technologies such as Resource Description Framework (RDF), SPARQL, Web Ontology Language (OWL), etc.

The efforts on the development of the Semantic Web technologies led by W3C have popularized ontology, knowledge representation, and reasoning for machine processing. Ontology is the study or concern about what kinds of things exist, what entities or things there are in the universe. In Computer Science, ontology is a model of concepts and relationships among them. The most popular definition of ontology cited is due to Gruber. Gruber [29] defined an ontology as the specification of conceptualizations used to help programs and human share knowledge. Such a conceptualization relies on the knowledge about the world in terms of entities and relationships, which are similar to the Entity-Relationship data model used in relational database modeling. Main components in an ontology are concepts, relations, instances, and axioms, briefly described as follows:

- Concepts are considered invariants. That is, things do not change in reality. A concept represents a set of entities, or a class, and may have properties, such as subclass or superclass. Furthermore, a concept is either a primitive concept or a defined concept. A primitive

concept is fundamental and reflects necessary conditions for being a member of that concept, whereas a defined concept is derived by joining primitive concepts and reflects both necessary and sufficient conditions for being a member of that derived concept.

- Relations describe the relationships between concepts or properties of concepts.
- Instances are existing things represented by a concept via membership. For instance, John as an individual is an instance of the concept *Student*.
- Axioms are rules to constrain properties or memberships of classes or instances.

The World Wide Web Consortium (W3C) has established a set of recommended standards for representing data and knowledge in ways that machines can process. Resource Description Framework (RDF), Web Ontology Language (OWL), and XML based languages have been developed. Specifically, they support concept descriptions of data and knowledge in different styles of syntax, notations, and serialization formats. For RDF, we present its formal definitions in Appendix A and how it is used in the following section in this chapter. Web Ontology Language (OWL) is based on Description Logic and provides more expressive power than RDF does. For the scope of this research, we will skip discussions of OWL.

2.3 RDF Basics

Resource Description Framework (RDF) [21] is a graph-based data model. Its basic form is a triple: (subject, predicate, object) that asserts a named property for a subject. For instance, (John, enrolled, SW) is a triple that asserts that John enrolled in a course SW, or the Semantic Web. Each component in a triple is a RDF resource identified by International Resource Identifier (IRI) [21] that conforms to RFC3987 [22], or a local existential variable for a *blank node*. The predicate logically relates a subject resource to an object resource. A subject and an object of a RDF triple

are visualized as vertices while a predicate is visualized as an edge. A set of logically related RDF triples constitutes a RDF graph.

RDF is formed by layered sets of pre-defined vocabularies, such as RDF vocabulary or RDF Schema vocabulary. These vocabularies provide different levels of expressive power. RDF vocabulary, or rdfV, includes a typing predicate and a superclass of all RDF properties. RDF Schema [16], or RDFS, further extends RDF, as a semantic extension, to allow descriptions of classes, their relationships, and properties, which can be arranged in a hierarchy of classes or properties. In addition, certain types of inferencing, such as class membership and subclass hierarchy, are supported in RDF Schema by stating the classes to which the subject and the object of a property must belong.

The formal semantics of the Semantic Web layered stack is defined accordingly for each semantic extension. Model-theoretic semantics is used to define an interpretation model for each semantic extension. Defining an interpretation model also characterizes an entailment regime. For instance, two entailment patterns are defined for rdfV, while thirteen patterns are defined for RDF Schema [36]. RDF entailment and inference definitions can be found in Appendix A.

SPARQL Protocol and RDF Query Language (SPARQL) [58] and its newer version SPARQL1.1 [32] are the main query language for RDF and RDFS triple databases. From now on when we say SPARQL, it refers to its latest version SPARQL 1.1. SPARQL has a similar syntax form to SQL, but it is specifically tailored for graphs. SPARQL provides graph pattern specifications and a SELECT construct, among others, to retrieve matched graph segments from a RDF graph. Definitions and query examples of SPARQL is detailed in Appendix A.

In the remainder of this chapter, we focus on RDF namespace, notations, and a running example for illustrating how RDF and RDFS are used. Moreover, RDF reification will be discussed as it is an important aspect that serves as a foundation for our survey of temporal data models of the Semantic Web that will be presented in Chapter 3. For RDF, its formal model definitions, semantics, entailment patterns, and the query language, SPARQL are given in Appendix A.

As a starting example, consider the facts given in Table 2.2: John enrolled in the Semantic Web course, or SW, and he lived in NYC.

Name	enrolled	livedIn
John	SW	NYC

Table 2.2: Person Relation

A transformation of Table 2.2 allows us to identify John, SW, and NYC as resources, and further model these facts as two RDF triples: (John, enrolled, SW) and (John, livedIn, NYC). These two triples are presented as a RDF graph shown in Figure 2.4.

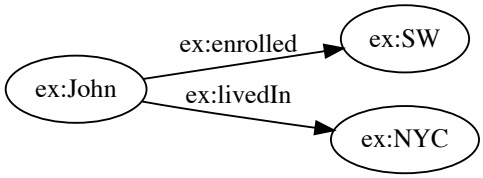


Figure 2.4: Person Relation Transformed to a RDF Graph

2.4 RDF Namespace and Notation

To encode a RDF graph, W3C recommends serializing it into a verbose XML or a compact syntax, such as Notation 3 (N3) [11], Turtle [9], or N-Triples [8], etc. These three variations of syntax are closely related in that N3 is the superset of Turtle and N-Triples. That is: N-Triples $\subset$ Turtle $\subset$ N3. In this thesis, graph-based representations of examples are used for illustrating the standard RDF model, and our proposed Valid Time RDF, which will be defined in Chapter 4. For a RDF graph presentation, such as the graph in Figure 2.4, an oval denotes a RDF resource or a literal as a subject or an object. A directed link represents a predicate. When a literal value is used, it

is double quoted and annotated with a data type or a language tag. The RDF graph illustrated in Figure 2.4 will be used as the RDF running example to illustrate aspects of RDF in the remainder of this chapter and also in Appendix A, which provides detailed definitions of RDF vocabularies, their semantics, and inference patterns.

When necessary, we also use the line-based Turtle syntax of [9] for presenting RDF triples and graphs. A triple written in Turtle syntax has the form shown in Figure 2.5. The angled bracket pair in each resource encloses a full IRI. When a prefix is appropriately declared, a full IRI may be shortened by carrying the prefix and without the angled brackets.

```
<subject> <predicate> <object>.
```

Figure 2.5: Line-based Turtle Syntax [9]

For instance, Figure 2.6 shows the serialization of the RDF graph of Figure 2.4 in Turtle syntax [9], and Figure 2.7 shows the same example in RDF/XML serialization.

```
PREFIX ex: <http://example.org/RDF-SW#>.


ex:John  ex:enrolled  ex:SW.
ex:John  ex:livedIn  ex:NYC.
```

Figure 2.6: RDF Running Example in Turtle Syntax

The namespace and prefix taken from [1, 20], shown in Figure 2.8, will be used as common notations in all RDF modeling and query examples in this chapter and Appendix A, unless otherwise specified.

The prefix rdf: and rdfs: refer to the namespace of RDF vocabulary and RDF schema respectively. Our running example is under a base ontology identified by http://example.org/RDF-SW. We use ex: as its prefix. In the standard RDF model, an IRI may contain a fragment identifier, separated by the symbol # [21], that denotes an additional part of the primary resource. For instance,

```
<?xml version="1.0"?>
<rdf:RDF xmlns="http://example.org/RDF-SW#"
xml:base="http://example.org/RDF-SW"
xmlns:RDF-SW="http://example.org/RDF-SW#"
xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
xmlns:owl="http://www.w3.org/2002/07/owl#"
xmlns:xml="http://www.w3.org/XML/1998/namespace"
xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#">
<owl:Ontology rdf:about="http://example.org/RDF-SW"/>
<owl:ObjectProperty rdf:about="http://example.org/RDF-SW#enrolled"/>
<owl:ObjectProperty rdf:about="http://example.org/RDF-SW#livedIn"/>
<owl:NamedIndividual rdf:about="http://example.org/RDF-SW#John">
<enrolled rdf:resource="http://example.org/RDF-SW#SW"/>
<livedIn rdf:resource="http://example.org/RDF-SW#NYC"/>
</owl:NamedIndividual>
<owl:NamedIndividual rdf:about="http://example.org/RDF-SW#NYC"/>
<owl:NamedIndividual rdf:about="http://example.org/RDF-SW#SW"/>
</rdf:RDF>

<!-- Generated by the OWL API (version 4.2.8.20170104-2310)
https://github.com/owlcs/owlapi -->
```

Figure 2.7: RDF Running Example in RDF/XML

```
@PREFIX xsd: <http://www.w3.org/2001/XMLSchema#> .
@PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#> .
@PREFIX owl: <http://www.w3.org/2002/07/owl#> .
@PREFIX  ex:   <http://example.org/RDF-SW#> .
```

Figure 2.8: Prefix for RDF Examples

http://example.org/RDF-SW#John contains a fragment identifier ‘John’that is under the primary resource denoted by http://example.org/RDF-SW.

We have prepared formal definitions of RDF syntax, semantics, entailment patterns, and SPARQL query examples in Appendix A for reference.

2.5 RDF Reification

The verb *reify* originates from *res* in Latin, meaning to *thingify* or to convert into a concrete thing. It is commonly used in different disciplines. For instance, in First Order Logic, reification generally

refers to the use of terms to express concepts that are normally represented using predicates [27]. In other words, it allows making an assertion about a predicate. RDF is confined to binary predicates; hence reification is needed to represent higher-arity predicates. A RDF triple makes an assertion about a subject and an object. We can consider it as an atomic statement. When we want to make another assertion about an atomic statement, we need a new construct in RDF. That is reification. A reification process starts by making a given statement bind to a new identifiable *resource* (i.e., an identifier is used to represent the statement) which acts as a proxy for the statement. The proxy then can further be used to assert properties on behalf of the statement.

Consider the facts given in Table 2.3. John enrolled in the Semantic Web course when he lived in NYC, and a time interval is associated with facts about John. Clearly, this statement asserts several facts and can not be expressed in one RDF triple. For instance, a binary predicate *enrolled*(John, SW) represents part of this fact. If the predicate *enrolled* is reified, it becomes a new term that can be used consequently as a component in other assertions. We explain the two forms of reification by an example.

Name	enrolled	livedIn	hasDate
John	SW	NYC	2/1/2016-5/31/2016

Table 2.3: Person Relation with Temporal Information

There are two types of reification in RDF: implicit reification and explicit reification. We illustrate both forms of reification by using the facts given in Person relation of Table 2.3, which represents a person whose name is John. For simplicity, we also use the term *John* as an identifier. This individual enrolled in SW, lived in NYC, and had a validity interval 2/1/2016-5/31/2016. *Person*(John, SW, NYC, 2/1/2016-5/31/2016) is a 4-ary predicate that represents the relation given in Person table. Obviously, RDF can not represent it directly, so it needs to be broken into several triples by using reification. Implicit reification allows defining binary predicates shown in Figure 2.9. Obviously, implicit reification breaks any n-ary relationships into several binary relationships.

This is similar to representing a n-ary relationship in Entity Relationship Data models into corresponding binary relationships.

```
enrolled(John, SW)
livedIn(John, NYC)
hasDate(John, 2/1/2016-5/31/2016)
```

Figure 2.9: Binary Predicates for Person Relation

All of these predicates can directly be represented in RDF. *enrolled* and *livedIN* predicates are clear; however the last predicate *hasDate*(John, 2/1/2016-5/31/2016) asserts that John has a date 2/1/2016-5/31/2016. It is not clear whether it is for *enrolled* or *livedIn*, or both, or something else. Resolving this ambiguity requires explicit reification that is also provided in RDF, which are the vocabularies: rdf:Statement, rdf:subject, rdf:predicate, and rdf:object defined in Appendix A.2. Considering that the date value 2/1/2016-5/31/2016 actually applies to John's enrollment in SW, this fact is reified as given in Figure 2.10.

In explicit RDF reification process, a triple is instantiated as a new resource that belongs to the class *rdf:Statement*. According to RDF specification, the new resource required in reification can be written as a blank node or identified by an IRI. In the latter case, such an IRI does not represent any concrete realization of a triple or resource. The original triple can then be associated with additional properties as if it is a standard resource. Figure 2.10 depicts the reification of a simple triple (ex:John, ex:enrolled, ex:SW). First a new identifier ex:stmt1 is defined . This identifier represents the triple, (ex:John, ex:enrolled, ex:SW), which is further augmented by meta properties. Hence, components of the original triple become objects of special meta properties, including *rdf:subject, rdf:predicate and rdf:object*. The new resource *ex:stmt1* can be described by additional properties, such as the occurring time (2/1/2016 to 5/31/2016), place, certainty or provenance.

According to RDF specification, *'the reification of a triple does not entail the triple, and is not entailed by it'* [36]. However, from the reification in Figure 2.10, there is an entailment pattern

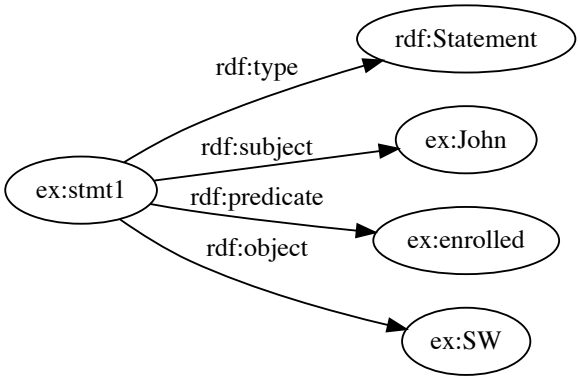


Figure 2.10: RDF Reification of (ex:John, ex:enrolled, ex:SW)

to infer the original triple of (John, enrolled, SW). Since RDF specification does not constrain the semantics of standard reification, it is the user's decision to accept the entailment pattern or not.

Moreover, reification also suffers from the proliferation of extra objects and triples that are needed for representing higher order relations. That is, to reify (John, enrolled, SW), four additional triples are needed before additional facts can be added. As a result, the graph size increases. And even worse, the reified graph makes queries more difficult to write as we will see it in an example later.

For the user's convenience, two presentations of RDF graphs are commonly used in the literature. Figure 2.11(a) includes the original triple instead of converting the predicate *:enrolled* to an object. In contrast, Figure 2.11(b) uses a node connecting to an edge instead of another node. This treatment is a violation of the general definition of graphs, and common graph-based operations can not be applied directly.

As we shall see in the next chapter, proposals of temporal extensions to RDF reported in the literatures mostly use RDF reification explicitly or implicitly.

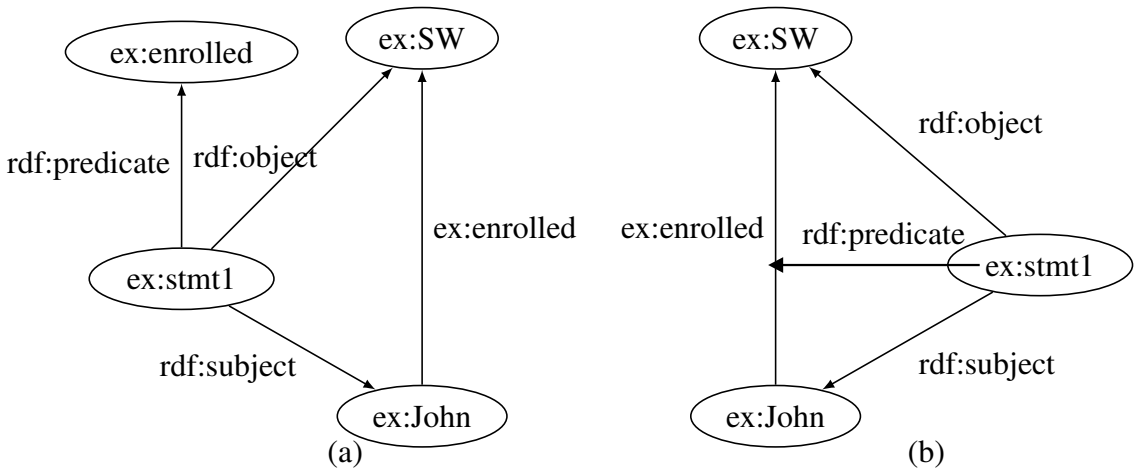


Figure 2.11: Two Common Graph Representations of RDF Reification for (ex:John, ex:enrolled, ex:SW)

Chapter 3

Survey of Temporal Extensions to RDF

3.1 The Running Example and Namespace

In this chapter, we survey temporal data models of the Semantic Web reported in the literature. This survey is also based on our previous study in [72]. We examine the characteristics of each temporal model and develop a taxonomy to categorize them into two groups: explicit reification-based and implicit reification-based. Explicit reification-based temporal models involve the use of standard RDF reification. In comparison, temporal models in *implicit reification* group employ some mechanism to identify a concept, a triple, a relationship or a graph. This group is further categorized into three subgroups: (1) Instantiating-Identifying Concept/Relationship, (2) Relationship Entity Conversion, and (3) Named Graphs.

For each model, we consider core model components, extensions to RDF/RDFS vocabularies, SPARQL query support and special features, if any.

Running Example and Query The data in Table 2.3 is used for illustrating each temporal model. A simple RDF triple, (John, enrolled, SW), asserts the fact about an individual *Student* John and his enrollment in a Semantic Web course between 2/1/2016 and 5/31/2016. The predicate *enrolled* re-

lates a *Student* instance to a *Class* instance (i.e., as domain and range respectively). Furthermore, a semi-closed interval [2/1/2016, 5/31/2016) needs to be associated with this triple. John may enroll in other courses over time. Hence, it is conceivable to have another triple: (John, enrolled, OOP) making another assertion about his enrollment in other time, such as [8/31/2016, 12/22/2016).

The query *"retrieve the valid time when John enrolled in the Semantic Web course"* will also be used as a running query to illustrate how a query is expressed in each temporal model and its version of SPARQL [32].

Namespace and Prefixes The prefixes and namespace defined in section 2.4 remain in use as a common notation for all examples unless otherwise specified. Additional prefixes are needed, and we combine them as follows:

```
@PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>.
@PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>.
@PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>.
@PREFIX owl: <http://www.w3.org/2002/07/owl#>.
@PREFIX owlTime: <http://www.w3.org/2006/time#>.
@PREFIX  :   <http://example.org/Temporal-SW#>.
```

The base ontology of the running example for the survey has a Namespace– http://example.org/Temporal-SW#, and we use : (colon) as its prefix.

3.2 Time Domain

W3C recommended OWL-Time ontology [37] as a standard for definitions of temporal entities: instant and interval, and properties, such as before, after or equals for instants or intervals. Some

of the proposed temporal models use OWL-Time ontology, whereas others include their own definition of time, such as using natural numbers. For the scope of this thesis, time domain is defined as follows and will be used in this survey and also in our proposed VTRDF in Chapter 4.

Time is naturally contiguous. However, for the sake of representation, it is usually modeled as a discrete sequence of instants. For instance, Figure 3.1 shows a set of consecutive equally-distant points in a time line. The sequence 0, 1, 2, 3, 4, ..., represent discrete time points. 0, now, and ∞ are interpreted as follows:

- 0 is the lower bound of the time axis whose interpretation is open for user's needs of data modeling.
- *now* is a special constant that represents the current time. Its value will change as time advances.
- ∞ is a constant that represents the upper bound of the time axis.

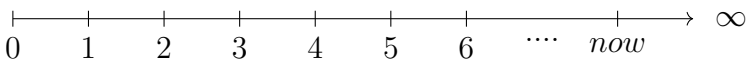


Figure 3.1: Time Axis

We consider time domain, $T = \{0, 1, 2, 3, ..., ...now, ..., \infty\}$ as the set of time points with a linear order less-than ($<$). For the sake of simplicity, we would use the standard U.S. calendar days as the unit of time points represented in the format of month/day/year. The granularity of the chosen time representation may create an ambiguity in terms of the time zone. In such a case, we assume our locality as the time zone, GMT-4 unless otherwise specified. For instance, $1/10/1995$ is a time point in T under the zone of GMT-4.

Furthermore, contiguous time points are combined into intervals for a compact representation. The set of time intervals, T_I, is defined over the time points of T. That is: $T_I \subset T \times T$. The definition of time intervals and their properties are given as follows:

- Let $[l, u)$ be a time interval that contains a finite set of consecutive time points between l and u. l is the beginning time point or lower bound of the interval. u is the end time point or upper bound. The set of time intervals, T_I, is:

$$T_I = \{[l, u) | l \in T \wedge u \in T \wedge l < u\} \tag{3.2.1}$$

  In this case, each interval $[l, u)$ is closed at the beginning and open at the end. A time interval may be closed at both ends, such as $[l, u]$. In the remainder of the paper, we may use an identifier i and an explicit representation $[l, u)$ interchangeably to reference an interval.

- Two disjoint intervals $[l, u)$ and $[l', u')$ share no common time points, or $[l, u) \cap [l', u') = \emptyset$. Otherwise, they overlap or $[l, u) \cap [l', u') \neq \emptyset$.

- Two intervals $[l_1, u_1)$ and $[l_2, u_2)$ are adjacent if $l_2 = u_1$ or $l_1 = u_2$.

- Set theoretic operations, such as union, intersection, and difference can be defined on intervals. Nevertheless, intervals are not closed under set theoretic operations.

- When the closure property is required, *temporal elements* [26] can be used in place of intervals. A temporal element is a finite union of disjoint and non-adjacent intervals. For instance, the set $\{[1/10/1985, 1/10/2005), [2/1/2016, 5/31/2016)\}$ is a temporal element. A set of temporal elements are closed under set theoretic operations.

3.3 Explicit Reification Based Temporal Models

One of the early and formal extensions of RDF to handle temporality is Temporal RDF [30]. Later enhancements are introduced to this extension, such as [19, 41, 59]. In the following, we review Temporal RDF and its enhanced versions.

Temporal RDF In Temporal RDF [30], each triple is timestamped with a time instant or an interval. Timestamping is achieved by using standard RDF definitions and an internal time domain that includes temporal property specifications, such as *temporal, instant, interval, initial* and *final*. A Temporal RDF triple is in the form of (s, p, o)[T] and visualized as a temporal RDF graph given in Figure 3.2. ":stmt1" and ":temporal#1" are ground nodes that substitute blank nodes, which are used as subjects in the original work for reification.

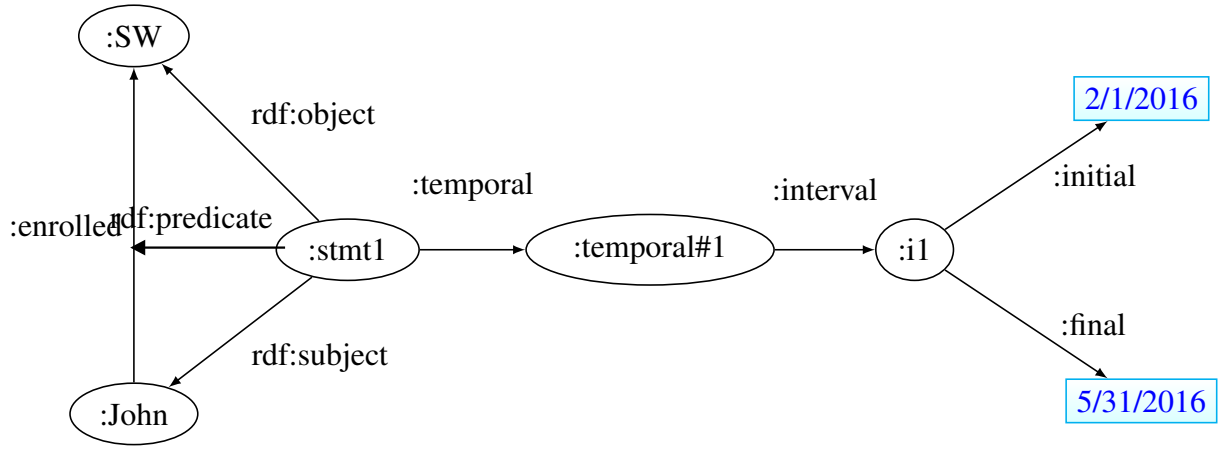


Figure 3.2: Temporal RDF

In Figure 3.2, the triple (John, enrolled, SW) is reified by *:stmt1* of rdf:Statement class. *:stmt1*, is further associated with a temporal entity :temporal#1 and then an interval :i1. :i1 is the valid time interval of the triple which has its begin and finish time instants "2/1/2016" and "5/31/2016" respectively, whereas natural numbers are used as time instants in the original work. This temporal fact is therefore represented by seven RDF triples in the case of time interval and by six triples in the case of time instant.

The semantics of a Temporal RDF graph [30] is provided in terms of non-temporal RDF and RDFS graphs. Temporal entailment is defined based on the closure of temporal and non-temporal graphs. Specifically, a temporal graph $G1$ entails G_2, denoted by $G_1 \models G_2$, if and only temporal closure of G_1 entails G_2. Furthermore, a deductive inference rule system for Temporal RDF graphs

is outlined. Temporal rules are defined to equate an interval and a instant version of temporal graphs.

A query language proposed for Temporal RDF graphs is provided in SQWRL-like [54] rule form. The running example query can be expressed conceptually as follows:

```
(:X, :interval, ?Y), (?Y, :initial, ?ti), (?Y, :final, ?tf)
<-- (:John, :enrolled, :SW):[?ti, ?tf].
```

Rewriting the above working query in SPARQL results in the following:

```
SELECT ?Y ?ti ?tf
WHERE { :John  :enrolled  :SW.
?X  rdf:type  rdf:Statement.
?X  rdf:subject  :John.
?X  rdf:predicate  :enrolled.
?X  rdf:object  :SW.
?X  :interval  ?Y.
?Y  :initial  ?ti.
?Y  :final  ?tf.
}
```

In this query, presence of the original triple (John, enrolled, SW) is assumed. Nevertheless, the query result preserves it even if this assumption is dropped. Query processing and semantics are also defined as a temporal tableau similar to a language presented in [31]. The complexity of query processing of the rule-like form above is briefly explained. Moreover, the authors conclude that the additional time dimension in their proposal does not add to the complexity of query answering. In other words, Temporal RDF model is still NP complete in query processing.

Enhanced Temporal RDF The temporal RDF model [30] is enhanced by allowing anonymous timestamp [19]. A temporal triple is represented in a similar form, (s, p, o):[X] where X is an anonymous timestamp, i.e., unknown time. *General temporal graphs* are defined as temporal graphs with known or anonymous timestamps. The *t-ground* general temporal graph is defined as one that does not contain anonymous timestamps.

The semantics of general temporal graphs is given similar to Temporal RDF semantics developed in [30] and it includes an additional slice closure of general temporal graphs. Slice closure of a general temporal graph is computed by a non-temporal closure of snapshot graphs for each time point. The complexity of evaluating entailment for general Temporal RDF graphs is shown to be NP-complete. Query language for the general Temporal RDF is similar to the example shown above for Temporal RDF.

C-Temporal Graph Temporal RDF model [30] is further extended to include temporal constraints and reasoning [41]. A C-Temporal Graph is a pair $C = (G, \Sigma)$, where G is a graph with temporal triples, and Σ is a set of temporal constraints over time intervals of G. *Temporal blanks* are introduced, and time variables in Temporal RDF [30] are allowed. This treatment is the same as the anonymous timestamp [19]. As an example, a student went to high school at an unknown time T1, and later he went to college at some other unknown time, T2. These facts are represented as two Temporal RDF triples with the timestamp T1 and T2 as time variables respectively. To preserve a proper temporal order, a constraint, T2 $>$ T1, is enforced in the model. Entailment of a C-Temporal graph can be reduced to finding mappings to the closed version of temporal slice closure defined in [19]. Additionally, query processing for C-Temporal graphs also reduces to matching the query pattern and the closed graphs.

tRDF for Indeterminate Triples The tRDF model [59] is based on the Temporal RDF proposed earlier in [30, 19]. tRDF particularly supports another type of *anonymous timestamp* in indeter-

minate triples. A *determinate triple* (s, p, o)[T] represents a relationship p between s and o that holds at every time point in the time interval T. In contrast, an *indeterminate triple* (s, p:[n:T], o) represents that the relationship holds at most n distinct time points in T. A tRDF graph includes indeterminate temporal triples. In addition, the concept of normalizing a tRDF graph is defined in order to preserve good properties of the tRDF model. Normalizing tRDF employs the notion of *value-equivalent-tuples* from temporal databases [42]. Two tRDF triples are value-equivalent if their non-temporal parts are identical. As an example, suppose John actually enrolled in Semantic Web class twice: (John, enrolled, SW)[T1] and (John, enrolled, SW)[T2]. Instead of storing two value-equivalent triples, *coalescence* is applied to merge overlapping or connecting intervals into a single cumulative interval, i.e., $T1 \bigcup T2$. The consolidated interval can then be used as the timestamp of a single representative triple (John, enrolled, SW)$\{T1 \bigcup T2\}$. As a result, a normalized tRDF graph G entails each one of the coalesced tRDF graphs.

Indexing structure, tGRIN, is proposed to improve the performance of tRDF triple storage in query evaluation. A tGRIN index is a balanced tree structure that stores *close* graph vertices together in the same index node. The closeness of two resources x and y is determined by a distance metric that combines general graph distance, $d_G(x, y)$, and temporal graph distance, $d_T(x, y)$, by a *k-norm* function, $[d_G(x, y)^k + d_T(x, y)^k]^{1/k}$ [59]. Experiments show that tGRIN is a better match for tRDF queries than the use of standard B-tree used in traditional relational databases.

The formal semantics and querying tRDF are based on equivalent models developed in Temporal RDF [30, 19]. Additional semantic conditions are also needed to interpret indeterminate triples and queries.

Generalized RDF Annotation In [79], a generalized framework for representing and reasoning annotated RDFS is proposed. This model is based on the works of annotated RDF [71] and its query language, AnQL [44]. Annotated RDFS is based on the logic programming, and has an abstract form of triples: (s,p,o)[T]. The annotation domain could be temporal, fuzzy, their com-

bination, or others. It is defined as an algebraic structure: $D = \{L, \preceq, \bigwedge, \vee, \otimes \Rightarrow, \bot, \top\}$ where elements in L are annotation terms. For instance, L=[0,1] is for a fuzzy domain while L=[T] id for a temporal domain. The top$\top$, bottom$\bot$, order $\preceq$, meet operator $\wedge$, join operator $\vee$ and t-norm $\otimes$ are used for constructing the annotation domain and its inference patterns. The t-norm $\otimes$ is used to model the conjunction of information. For instance, from (a, rdfs:subClassOf, b):I and (b, rdfs:subClassOf, c):I', infer (a, rdfs:subClassOf, c):I $\otimes$ I'. For the temporal case, $\otimes$ is overloaded to represent the intersection of time intervals. Multiple annotation domains may be combined using the generalized framework. A complex domain D can be constructed from individual annotation domains: $D = D_1 \times D_2 \times .... \times D_n = \{L, \preceq, \otimes, \bot, \top\}$. The model is also augmented by a set of inference rules for annotated RDFS.

RDF$\star$ Hartig proposed extensions of the RDF model and SPARQL to represent statement-level metadata [33]. The RDF$\star$ model allows nested triples. That is, a triple can be embedded as a subject or an object in another triple. Figure 3.3 depicts the running example. The original triple, (John, enrolled, SW), is nested in an abstract object. To accommodate its nested structure, RDF$\star$ requires syntactic and semantic extensions of RDF model. Nevertheless, RDF$\star$ graphs can be transformed to standard RDF graphs by a set of special functions provided in [33]. They are blank node assignment function, reification function and unfold function. A transformed RDF$\star$ graph is an explicitly reified standard RDF graph and would be similar to the example in Figure 2.10. In addition, Turtle$\star$ and SPARQL$\star$ are proposed as extensions of standard Turtle and SPARQL notations respectively. The running query can be written in SPARQL$\star$ as follows. Double bracket pairs show a nested triple:

```
SELECT ?t1 ?t2
WHERE { <<:john  :enrolled  :sw>>   :hasVT  ?i1.
        ?i1  :hasBeginning  ?t1.
        ?i1  :hasEnd        ?t2.}
```

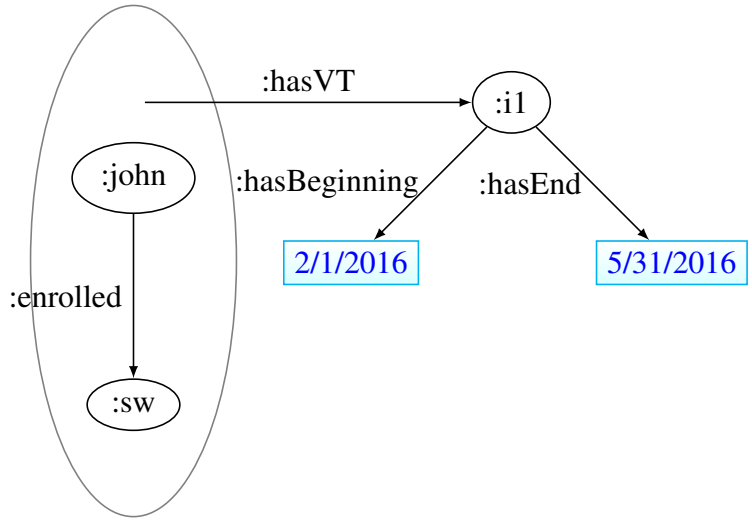


Figure 3.3: RDF⋆

YAGO 2 The original YAGO Knowledge Base [65] is constructed automatically from articles on Wikipedia. Each simple article on Wikipedia belongs to a article category, and mainly contains a lead section, a content body, appendices and bottom notes [3]. An article becomes an entity in YAGO. Article categories on Wikipedia provide the *typing information* for it. Th typing information is linked to the taxonomy of WordNet [38]. In YAGO, each fact is represented by a triple, (s, p, o). Each fact is also reified, so a triple identifier is assigned. This effectively results a quintuple: (id, s, p, o).

YAGO2 is the new version of YAGO. YAGO2 employs an extensible extraction architecture that is based on declarative rules, whereas YAGO's extraction rules are hard-wired to the source code [38]. In addition, YAGO2 incorporate both *temporal* and *spatial* dimensions to the knowledge base. For the temporal dimension, *yagoDate* is the main data type that denotes time points in days. A time interval can be represented by two time points with a pair of relations, such as *occursSince* and *OccursUntil* [38]. *Entity time* and *Fact time* to denotes its existence in time, and the event period respectively. The running example can be represented similarly to Temporal RDF of Figure 3.2

3.4 Implicit Reification Based Temporal Models

In general, implicit reification based models use different types of abstraction for handling reification. They do not employ reification vocabularies of RDF specifications. Two subcategories follow.

3.4.1 Instantiating-Identifying Concept/Relationship (IIR)

In IIR models, a concept or relationship is reified and further temporalized. Either such relationship is abstracted as a new object, or a concept is viewed as four dimensional and instantiated to have temporal extents. *Singleton Property* converts each relationship to be universally unique. *4D fluents* use concepts that view each resource as a perdurant. Fluents represent properties that change over time.

Singleton Property Nguyen et al. propose the concept of singleton property for representing and querying meta knowledge in [52]. This approach recognizes each RDF triple as an unique relationship and introduces multiple contextual instances to it as needed. Given a relationship between two objects under a context, a singleton property is introduced to denote the relationship instance with a specific context, such as temporality, provenance, etc. In other words, a singleton property is an instance of a given relationship used to assert the context property values. Figure 3.4 shows the running example in singleton property approach.

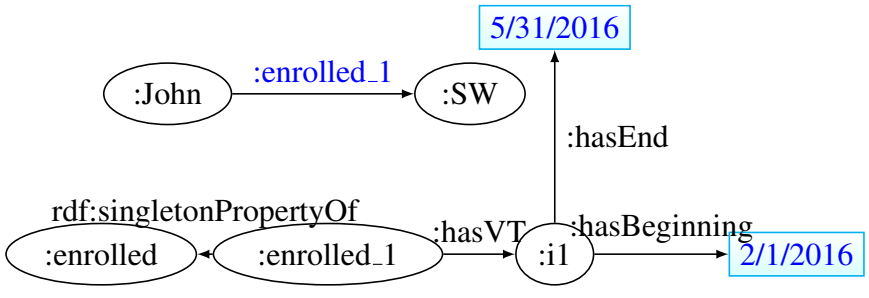


Figure 3.4: Singleton Property

The unique property :enrolled_1 in Figure 3.4 is an instantiation of the generic *:enrolled* by the predicate, *rdf:singletonPropertyOf*. It is then used for asserting the relationship between John and the class SW. The temporal context is therefore asserted by (:enrolled_1, :hasVT, :i1).

The formal semantics of the singleton property is derived from the standard RDF and RDFS semantics with the additional semantics extension for the vocabulary *rdf:singletonPropertyOf*. The singleton property gives rises to three cases of query patterns: data, metadata and mixed patterns which SPARQL supports. The running example query belongs to the metadata pattern and can be written in SPARQL as follows:

```
SELECT ?ti ?tf
WHERE { ?p  rdf:singletonPropertyOf  :enrolled.
:john ?p  :sw.
?p :hasVT  ?i1.
?i1  :hasBeginning  ?ti.
?i1  :hasEnd  ?tf.
}
```

4D Fluents Welty et al. proposed 4D Fluents model for representing time-varying relationships in OWL [73]. This model employs *4D view* and *Fluent*. Haynes introduced *four dimensional view* or *perdurantist view* into Computer Science in his seminal work [35]. *Perdurantism* is a philosophical theory of persistence and identity [34], and it is closely related to *four dimensionalism*. In the *four dimensional view*, an object that persists through time has distinct temporal parts at every time instant through its existence in time. Furthermore, each persisting object can be considered a *four dimensional spacetime worm* that stretches across space-time. Slicing the worm at a specific time interval or instant of the time dimension yields a temporal part. A Temporal part is also called a *time slice* in other literature [49]. The slicing produces *entity-at-a-time*. In contrast, *three dimensional view* considers that an object is wholly present or endures through its existence in time.

Therefore there are no temporal parts.

Fluent is a component of *Situational Calculus* which is a logical language for representing change. McCarthy first introduced *Situational Calculus* [46, 48]. It concerns situations, actions and fluents in a dynamic domain. *Actions* make the domain change from one situation to another. Fluents are situation-dependent functions for describing the effects of actions.

In 4D Fluents model, *fluents* are properties that change over time [73]. These properties are special cases in that both the domain and range of them are temporal parts of the corresponding entities. *TemporalPart* is the main class for converting regular entities to 4D spacetime worm ones. OWL-Time ontology of [37] is used as time domain in 4D Fluents model. Particularly, a class *TimeInterval* derived from the equivalent class of OWL-Time is used for all temporal terms.

Several object and fluents properties are listed in Table 3.1. Figure 3.5 represents running example in 4D Fluents model.

Object Property	Domain	Range
:fluentProperty	:TemporalPart	:TemporalPart
:temporalExtent	:TemporalPart	:TimeInterval
:temporalPartOf	:TemporalPart	complementOf(:TimeInterval)

Table 3.1: Object Property of 4D Fluents Ontology

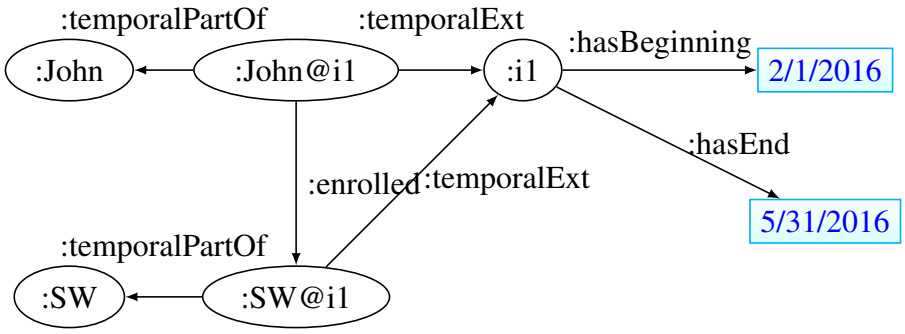


Figure 3.5: 4D Fluents

In Figure 3.5, individuals :John and :SW are two *4D entities*. Each entity has temporal parts, :John@i1 and :SW@i1 respectively. The property *:enrolled* is transformed to a fluent whose do-

main and range are both *temporal parts*. Each temporal part is associated with a specific temporal extent , i.e., time interval, that denotes its valid time. One fluent property requires two extra objects, i.e., temporal parts, and two properties, in contrast to reification, that uses one extra object and four properties as illustrated in Figure 2.10. Moreover, the 4D fluents model has advantages. Particularly, OWL inverse operator and cardinality constraints are available and standard OWL reasoners can be used for inferencing.

The 4D Fluents model is within standard RDF and OWL-DL. Its semantics is defined based on OWL-DL semantics. Consequently, there is no need to extend RDF or OWL. The running example query can be written in SPARQL 4D Fluents model:

```
SELECT ?ti  ?tf
WHERE {?ts1  :temporalPartOf  :John.
?ts2  :temporalPartOf  :SW.
?ts1  :enrolled  ?ts2.
?ts1  :temporalExt  ?i.
?ts2  :temporalExt  ?i.
?i    :hasBeginning  ?ti.
?i    :hasEnd  ?tf.
}
```

Since the 4D Fluents model imports OWL-Time [37], :i1 in Figure 3.5 is an OWL-Time interval, while ?ti and ?tf in the above query are two OWL-Time instants.

Extended 4D Fluents Batsakis et al. extended 4D Fluents model to incorporate qualitative temporal relations that have unknown temporal information [6, 7]. Such a relation is considered an object property between time intervals. The model employs OWL-Time [37] and Allen's temporal relations [4], such as before, meets and overlaps, etc. Consider the running example and additionally the triple that John enrolled in another class OOP in a later semester. However, the actual

enrollment time was unknown. In Figure 3.6, time interval *:i2* denotes the valid time of John's OOP enrollment and its relationship to *:i1* is captured by the object property *before*. Semantics of the extended 4D Fluents model is based on the original 4D Fluents model, with the additional temporal semantics needed for qualitative temporal relations.

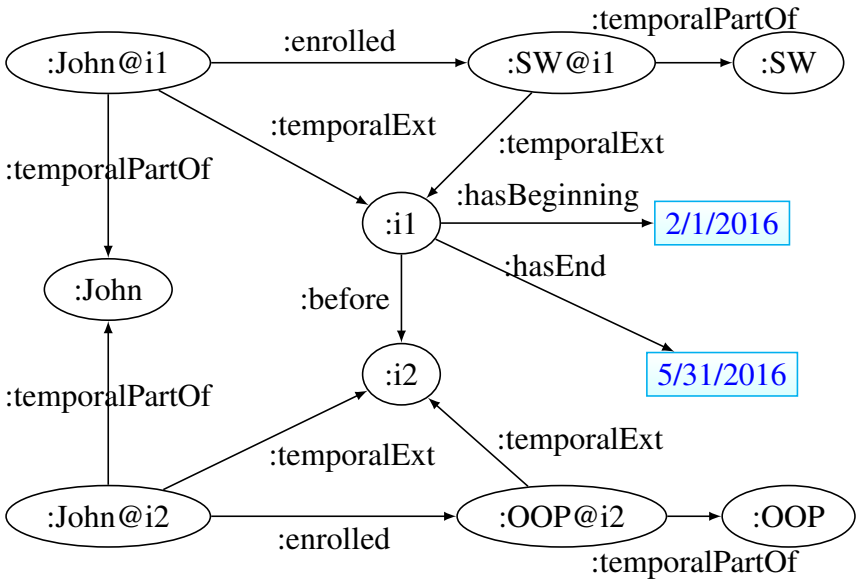


Figure 3.6: Extended 4D Fluents

TOQL [5] is the SQL-like query language for Extended 4D Fluents model. To accommodate querying qualitative temporal relations, additionally query constructs, such as "AT" clause and Allen temporal operators [4], such as before, after, meets, etc., are included in TOQL.

Temporal Web Ontology Language- tOWL Fransincar et al. proposed an extension of the OWL-DL language, called tOWL [49], for representing time and changes in an ontology. tOWL uses a subset of OWL-DL whose foundation is the logic $\mathcal{SHIN}(D)$. This logic is sufficiently expressive and is decidable for a sound and complete reasoning algorithm [45]. The time domain of tOWL handles both instants and intervals that are modeled by rational numbers and a set of partial order relations over them. As a result, an actual time instant, an interval or Allen's temporal

relations [4] are all converted to rational number-based equivalent instants or relations. For modeling changing values, tOWL employs the 4D Fluents model, i.e., perdurantist's view [73]. tOWL is conceptualized as a layered approach. The foundation layer is OWL-DL and the extended concrete domain is the second layer. Time representation is at the third layer, which is defined by the concrete domain.

Figure 3.7 gives the running example in tOWL. Note that tOWL requires separate intervals for :John and :SW. Therefore, a restriction on the equivalence of towl:interval1 and towl:interval2 is enforced by a relation *towl:equal* in Figure 3.7 which is one more triple used compared to 4D Fluents model in [73].

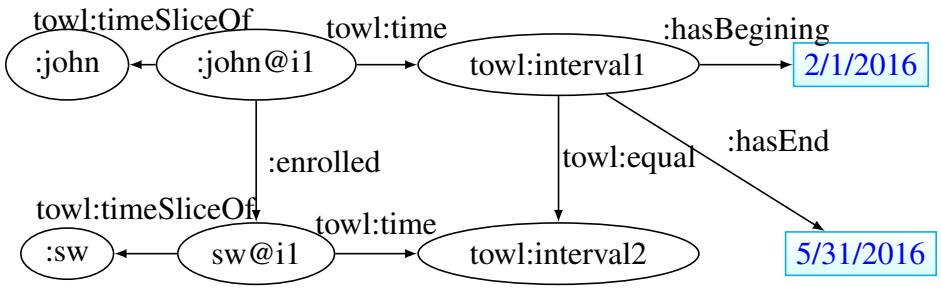


Figure 3.7: tOWL

In tOWL, the time domain is based on rational numbers and relations over them. This approach makes tOWL more expressive in representing complex temporal relations. For instance, in Figure 3.7, a temporal constraint *towl:interval1 equates towl:interval2* can be expressed with the equality of endpoints of the two intervals. Additionally, tOWL reduces the proliferation of objects by differentiating types of fluents as FluentObjectProperty and FluentDatatypeProperty. For a FluentDatatypeProperty, which relates a time slice to a typed value, three triples can be saved due to that the time slice is not needed for a typed value.

3.4.2 Relationship to Entity Conversion (REC)

In REC models, a relationship is transformed to a *composite entity*. The transformed entity comes in two forms: a new entity that implicitly reifies the original triple, or an abstract object that becomes a term for further use. As an example of REC models, N-ary relations provide a main modeling concept: a triple is *objectified* as a new entity and can further be associated to properties, such as time.

N-ary Relations In principle, the N-ary relation is a generalization of reification. For each N-ary relation, a new class with an instance is introduced for it as if the relation is objectified. Further property assertions can be made with respect to the newly introduced instance. Figure 3.8 gives the running example in N-ary relations.

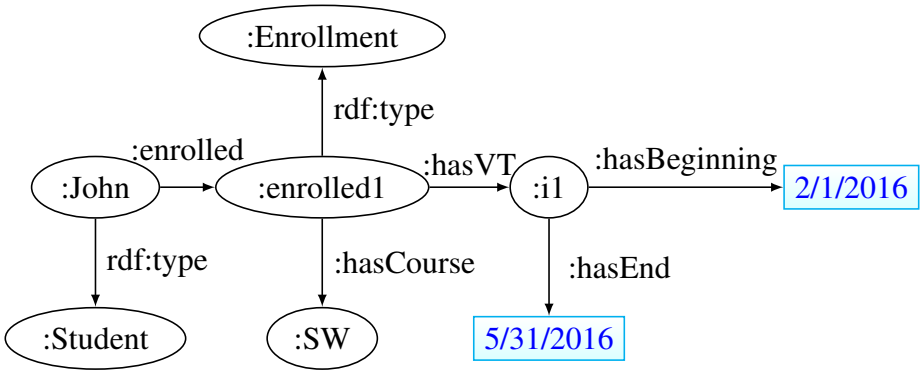


Figure 3.8: N-ary Relation

The resource *:enrolled1* in Figure 3.8 is introduced as a new instance encapsulating both the course name value, SW, and its valid time interval through two properties, *:hasCourse* and *:hasVT*. The relation (:John, :enrolled, :SW) is converted to an entity class *:Enrollment*. The property *:enrolled* is overloaded, so its range becomes the newly introduced class *:Enrollment*. Adding time to the original triple, i.e., (John, enrolled, SW), requires three more triples.

N-ary relation approach does not require extension to RDF, RDFS or OWL vocabularies. It simply converts relationships to entities that encapsulate properties. The semantics for N-ary re-

lation approach is based on RDF and RDFS semantics. In Figure 3.8, the new object :enrolled1 may also be represented by a blank node. A blank node does not have any meaning, but acts like a wrapper for grouping related objects.

The running example query in SPARQL is as follows:

```
SELECT ?ti  ?tf
WHERE {
:John  :enrolled  ?e.
?e  rdf:type :Enrollment.
?e  :hasCourse  :SW.
?e  :hasVT  ?i.
?i :hasBeginning ?ti.
?i :hasFinish ?tf.
}
```

While N-ary relation approach can be applied to OWL, it would incur overheads. For instance, multiple inverse properties are needed for a N-ary relation. Moreover, the use of cardinality restrictions becomes limiting on some roles that depend on the class of some other roles [53].

FrameBase FrameBase [60] integrates FrameNet [25] and WordNet [43] for constructing an extensible RDFS schema. FrameNet originated from *Frame Semantics* [25]. Frame Semantics assumes that people understand the meaning of words by evoking semantic frames, and relate words to meanings. FrameNet is a large lexical database that contains semantic frames for describing meanings of natural language words. It also provides example sentences annotated with frames and frame elements to demonstrate the use of words in the frame. Each distinct semantic frame contains *lexical units* and *frame elements*. Lexical units are the *keywords* used to evoke the frame, while frame elements are the roles that describe properties of the frame.

WordNet [43] is another well known lexical database for English that provides meanings of words. Each type of words , such as nouns, verbs, adjectives etc. is organized to form a *synset*, or a synonym set. Each set represents a lexical concept [43]. WordNet contains about 117,000 synsets, and each may be linked to others. The major relation is *hyperonymy*,or *is_A* relation, and *meronymy*, or *part-whole*. These relations, among other components, form a lexical network of words and concepts.

The main representation model used in FrameBase is similar to the model of N-ary relations discussed above and in Figure 3.8. A primary entity is created to form a semantic frame for the N-ary relation. The frame's properties can be asserted in a sense of *semantic role* [28, 53]. A mapping between FrameNet and WordNet is created to form the basis lexical units and relations for FrameBase's schema.The mapping is further transformed by the *schema induction* and *automatic reification-dereification mechanism* to yield a light weight yet broad covering frames [60].

Valid-Time Temporal Model O'Connor et al. propose a valid-time temporal model and a SWRL-based [40] query mechanism for manipulating temporal knowledge in OWL ontologies [55]. The model introduces a new class, *temporalFact*, and uses N-ary relations. The running example is represented in Figure 3.9. The graph in Figure 3.9 is similar to N-ary relations in Figure 3.8. However, there are differences on the class hierarchy. In the valid-time temporal model, any existing OWL class can have temporal aspects as long as it subclasses *temporal:Fact*, which is the super class of all temporal facts. This avoids significant ontology rewriting in converting an ontology to a temporal version.

The temporal expressivity of this model is further enhanced by using SWRL [40] to construct temporal rules. A set of temporal operators that includes Allen's operators [4] is implemented as library-like *built-ins* for SWRL rules. With the temporal ontology and temporal built-in operators, complex temporal rules can be constructed.

Querying the temporal ontology is done by SQWRL [54]. All SWRL built-ins [40] are included

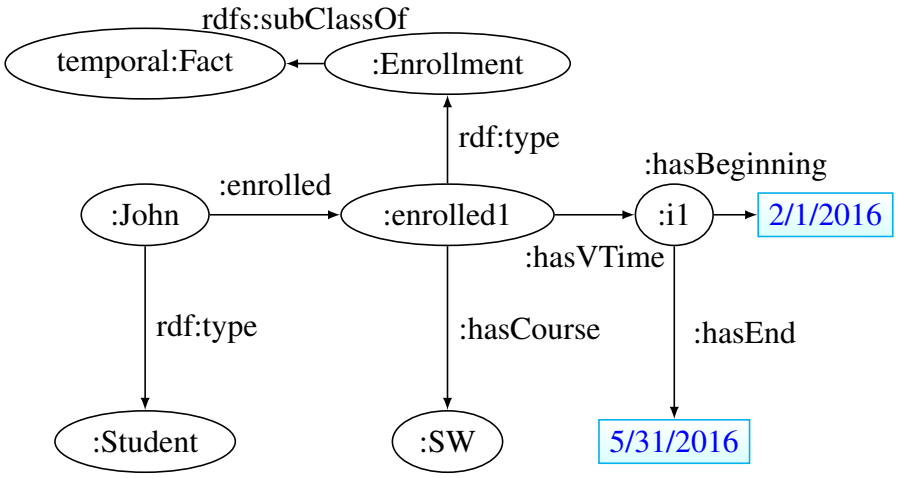


Figure 3.9: Valid-Time OWL

for SQWRL, so complex temporal queries can be formed. These include queries that require complex closure, negation, or complex aggregation and grouping. The running example query is adapted to show temporal operator usefulness in this model. The following SQWRL query retrieves all resources who took the course :SW before 2016. The symbol $\wedge$ denotes logical *and*.

```
Student(?s) ∧ :enrolled(?s, ?e) ∧
:hasCourse(?e, :sw) ∧
temporal:hasValidTime(?e, ?vt) ∧
temporal.before(?vt, "2016")
--> sqwrl:SELECT(?s)
```

The above query can be transformed to a standard but lengthy SPARQL query. However, there are very limited temporal operator supports in SPARQL. If done so, the temporal order, such as *temporal:before*, may need to be fulfilled by using literal value comparisons. This model is designed to be implemented at the users' level. There is no formal extension to RDF, RDFS or OWL model and vocabularies. However, the additional semantics for Allen's temporal operator [4] and the built-in SWRL rules need to be added.

3.4.3 Named Graphs

The term Named graph was first introduced in [18]. Named Graphs extend RDF model to provide a mechanism for identifying grouped RDF triples. A named graph, denoted by (u_1, G_1) where G_1 is a standard RDF graph that is named by an IRI u_i [18]. W3C has adopted Named Graphs model in SPARQL query language [58, 32]. With the Named Graph model, the running example is represented in Figure 3.10.

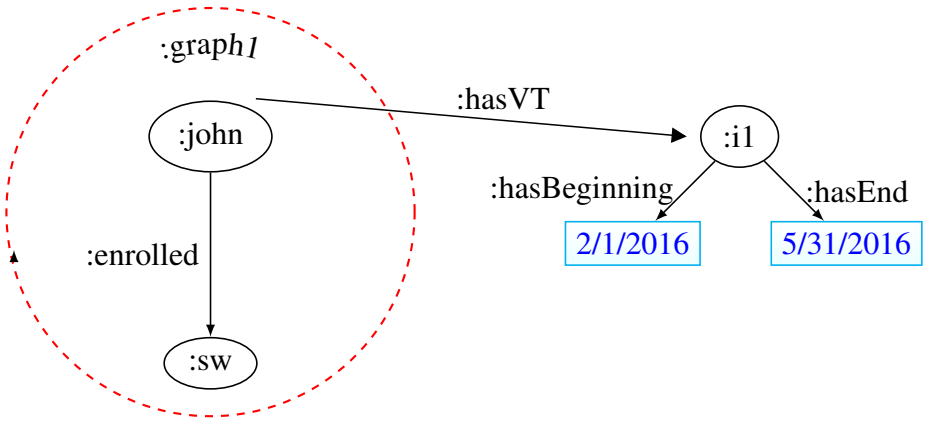


Figure 3.10: Named Graph

In Figure 3.10, :graph1 indicates a graph for which additional properties can be asserted. W3C adopted a line-based N-Quads as concrete syntax for RDF 1.1 Datasets [17]. The format is a quad: <subject, predicate, object, GraphName>. For querying Named Graphs, TriQL[14], RDFQ [64] and SPARQL are available. The running example query can be written in SPARQL as follows:

```
SELECT ?ti  ?tf
FROM :graph1
WHERE {:graph1  :hasVT  ?i.
?i1  :hasBeginning  ?ti.
?i1  :hasEnd  ?tf.
:John  :enrolled  :SW.}
```

Named Graphs model is a general purpose *triple grouping*. In the above query, it is assumed that all triples share the same temporal extent are grouped in the same graph. The *FROM* clause indicates the source graph. In an extreme case that each triple requires a different time reference, a significant amount of named graphs is needed. When triples may need multiple metadata annotation, using Named Graphs model becomes complex.

τSPARQL Temporal Queries Tappolet et al. propose a temporal RDF query approach τSPARQL [67]. τSPARQL is defined as a shorthand format for querying such a temporal ontology. In this model, OWL-Time ontology [37] is used as the time domain which defines time instants and intervals. The target temporal RDF model is designed using Named Graphs. Each graph is identified by exactly one time interval. Triples with the same temporal extent are grouped to the same graph. In other words, the *name* of a graph is the time interval. The grouping also introduces complexity to the model in that the indexing structure would have a significant impact on query retrieval time.

τSPARQL is based on SPARQL, and recognizes a *quadruple* form, such as ([ti, tf], s, p, o), as the main query pattern. The interval [ti, tf] is to be checked against *names* of graphs. The triple s, p, o are handled as a SPARQL query pattern. As a result, a τSPARQL query can be mapped to a standard SPARQL 1.1 one. The running example query can be written in τSPARQL as follows:

```
SELECT ?ti ?tf
WHERE {
[?ti, ?tf]  :John  :enrolled  :SW.
}
```

Assuming that the working example is represented as in Figure 3.10, mapping the above query to standard SPARQL results the following:

```
SELECT ?ti ?tf
WHERE {
```

```
GRAPH :graph1 {:John  :enrolled  :SW.}
:graph1  :hasBeginning  ?ti.
:graph1  :hasEnd  ?tf.
}
```

RDF+ RDF+ model [62] uses named graphs and triple-level identifiers. Named graphs are used in place of RDF reification. Triple identifiers allow explicit annotation of meta knowledge. RDF+ model has two type of statements: literal and meta knowledge statement. A RDF+ literal statement is a quintuple form (g, s, p, o, θ) where g is the graph's IRI, s,p,o are standard RDF triple components, and θ is a statement identifier. Based on the triple identifier in the RDF+ literal statement, the RDF+ meta knowledge statement can be formed as (θ, π, ω). θ is the literal statement identifier, π is the meta knowledge property and ω is the range value of π. The set K of RDF+ literal statements and the set M of RDF+ meta knowledge statements constitute a RDF+ theory, (K, M) [62].

Bidirectional mappings between RDF and RDF+ are also defined in [62]. Our running example is mapped to the RDF+ model and results the following RDF+ literal statements and meta knowledge statement. Please note that we also adapt the N-triple-like syntax for representing a quintuple in the example. In addition, time intervals are assumed available although the original work uses time instants.

```
# K <--RDF+ literal statements
<:graph1> <:John> <:enrolled> <:SW> <:stmtID1>.
<:graph2> <:graph1> <:timestamp>
<[2/1/2016, 5/31/2016)>   <:stmtID2>.

# M<--RDF+ meta knowledge statement
<:graph3> <:stmtID1> <:timestamp>
```

```
"[2/1/2016, 5/31/2016)".
```

In the above mapping, :graph1 and stmtID1 both identify the original triple. :graph2 and :stmtID2 refer to the meta knowledge for :graph1. The statement in :graph2 is further stored as the associated meta knowledge in order to be compatible with standard RDF semantics. The formal semantics for RDF+ is provided by *'Meta Knowledge Interpretation and Model'* [62] that combines a standard interpretation I_s for statements in K, and a Π- interpretation for meta knowledge statements in M. An extension to SPARQL is also proposed. The running example query can be written as follows:

```
SELECT ?x
WITH META :graph3
FROM NAMED :graph1
FROM NAMED :graph2
WHERE { GRAPH ?g { ?x  :enrolled  :SW }
```

The above extended SPARQL utilizes additional constructs: (1) an optional *WITH META* clause specifying the graphs which contains the associated meta knowledge, and (2) the *FROM NAMED* clause that specifies the target graph for quadruple pattern matching [62]. The query evaluation system binds the variable ?x to the matched values based on the specified quadruple pattern. It further outputs values for all meta knowledge associated with the pattern, such as the following:

```
?x                timestamp
---------------------------------
:John          [2/1/2016, 5/31/2016)
```

3.5 Discussion

We have constructed a taxonomy depicted in Figure 3.11 for classifying the proposed temporal extensions to RDF and OWL. Table 3.2 is a concise summary of various characteristics. For summarizing and comparing them, we use the following characteristics: (1) RDF, RDFS or OWL extension of these proposals, (2) additional objects required, (3) number of triples needed, (4) formal semantics specified or not, (5) Time Domain, (6) Instant or Interval used, and (7) query language. For completeness, our proposed Valid Time RDF, or VTRDF, is also included in Table 3.2 and the taxonomy in Figure 3.11 for comparison. VTRDF will be introduced in Chapter 4.

Taxonomy The temporal models for the Semantic Web surveyed in this paper use either explicit or implicit reification. In explicit reification, RDF reification vocabulary or its equivalent is used, whereas in implicit reification, some form of identification for a triple is introduced.

Temporal RDF [30, 19] and its variants [41, 59] are based on explicit RDF reification. RDF$\star$ introduces nested triples and needs an extension to RDF/S specifications. However, nested triples in a RDF$\star$ graph can be unnested to an explicitly reified RDF graph. Yago2 [38] reifies each fact and assigns an idenfier to it to form a quintuple. In contrast, all the other temporal models handle reification implicitly by using different forms of transformation on a triple, relationship or graph. Such a transformation does not rely on RDF/S reification vocabularies. The type of transformation differentiates these RDF models: (1)Instantiating-Identifying Concept/Relationship , (2) Relationship Entity Conversion and (3) Named Graphs.

There are two temporal models in Instantiating-Identifying Concept/Relationship models. 4D Fluents [73, 6, 7] introduces *temporal part* for an entity changing over time. Each temporal part corresponds to a distinguishable timestamp. A fluent property associates two temporal parts. On the other hand, Singleton Property [52] ensures every relationship to be universally unique. As a result, an ordinary relationship, such as *enrolled*, becomes a *relationship type*. Each of its instances, such as enrolled#1 in Figure 3.4, is used for an unique property assertion.

N-ary relations, FrameBase and OWL Temporal Model are examples of Relationship Entity Conversion models. N-ary relations [53] convert each relationship to an entity. FrameBase forms a semantic frame for each N-ary relation. Frame properties are asserted as semantic roles [28, 53]. OWL Temporal Model [55] is also based on N-ary relations. Lastly, Named Graphs are in RDF and RDFS specifications. A set of RDF/S triples can be identified with an IRI, that is, the graph name. Thus, graph level identification becomes available. As a result, additional properties for the graph can be associated through the graph's IRI.

RDF, RDFS, OWL Extension and Compliance The majority of models extend RDF/S to gain temporal expressiveness. For instance, Temporal RDF [30, 19] and its variants [41, 59] introduce a set of temporal vocabularies to use explicit reification. The model provides a coverage of formal semantics of temporal graphs, query language prototype and complexity analysis. Similarly, 4D Fluents [73, 6, 7], N-ary relations [53] and Named Graphs [18] can all be implemented by RDF, RDFS and OWL vocabularies. These models benefit from available ontology tools, such as reasoners.

On the other hand, there are models that require formal extensions to RDF and RDFS specifications. For instance, Singleton Property [52] introduces *rdf:singletonPropertyOf* for instantiating a Singleton Property from its generic property type. Every Singleton Property is made universally unique. RDF$\star$ adopts *nested triples* to transform a triple to an entity. Nested triples informally allow *triple level identification* that is not available in RDF/S or OWL. As a result, RDF$\star$ requires syntactic and semantic extensions to RDF/S and OWL specifications. Similarly, Annotated RDFS [79] and RDF+ [62] require extensions to both RDF/S syntax and semantics. tOWL [49] extends OWL-DL to cover concrete domain for representing both time instants and intervals. Furthermore, it also incorporates Allen's temporal relations [4] to increase the model's temporal expressivity.

Additional Objects and Triples When additional objects are required for a temporal model, they may cause quicker storage depletion or make writing standard queries more complex. The proliferation of objects is common in reification-based modeling approaches. In Temporal RDF model [30, 19], eight triples: four for reification and four for temporal assertions, are required to associate a time interval to an ordinary triple. 4D Fluents [73, 6, 7] use seven triples to cover temporal parts of an entity. Singleton Property [52] requires fewer triples (five triples). Named-Graphs [18] require only five temporal assertions, two triples for time instants, three for intervals. Since RDF+ has a form of quintuple [62] that can be mapped to standard RDF triples via explicit RDF reification, it requires at least eight triples.

Semantics Typically, a temporal model extending RDF/S or OWL requires additional semantics, so temporal entailment can be defined. For instance, Temporal RDF [30, 19] specifies a temporal entailment semantics by using RDF and RDFS graphs. Additionally, this semantics extended to Enhanced Temporal RDF [41] and tRDF for Indeterminate Triples [59] with added temporal entailment scenarios, i.e., anonymous timestamp and indeterminate triples respectively.

In contrast, formal extensions to RDF/S or OWL semantics are introduced by extended vocabularies in other models. For instance, Annotated RDF [79] extends RDFS semantics by defining an algebraic structure for annotation domain, and also provides a deductive system. Singleton Property [52] requires RDF/S semantics extension to cover its *SingletonPropertyOf* interpretation. tOWL [49] requires a semantic extension for the translations between rational numbers, $\mathbb{Q}$, and XML datetime data types. τSPARQL [67] relies on Named Graphs where the identifier of a graph is a timestamp instead of an IRI. RDF+ [62] introduces additional semantics for its RDF+ literal and meta knowledge statement.

Time Domain OWL-Time ontology includes class *TemporalEntity* [37] which is made-up of *Instants* and *Intervals*. Some of the temporal models use OWL-Time as their time domain. 4D

fluents [73], extended 4D fluents [6, 7] and τSPARQL [67] all employ OWL-Time. The rest of the models do not use OWL-Time. They typically define a time domain or a time ontology of their own. For instance, the time domain in Temporal RDF [30, 19] is defined based on natural numbers. tOWL [49] uses the set of rational numbers, and provides a mapping to actual XML datetime type. Nevertheless, there are models that do not explicitly adopt a time domain specification. Instead, the time definition is left to applications.

Querying SPARQL [32, 58] and SQWRL [54] or their extended forms are are used in querying temporal RDF data. SQWRL is for querying an OWL-based ontology. Temporal RDF [30, 19] provide a query language sketch in rule-like form. An equivalent SPARQL query can be written directly, as it is based on RDF reification. Extensions to SPARQL syntax and semantics are needed for Singleton Property [52], RDF$\star$ [33], enhanced Temporal RDF [41, 59], RDF+ [62], τSPARQL [67], annotated RDF [79] and Extended 4D Fluents [6]. In general, such extension needs to accommodate additional patterns of syntax and query specifications. For instance, SPARQL$\star$ requires additional notation for nested triple while RDF+ adds *With Meta* and *From Named* constructs for querying its meta knowledge statements. A dedicated query language TOQL [5] is proposed for Extended 4D Fluents [6]. AnQL [44] is the query language tailored for Annotated RDFS [79]. SPARQL 1.1 directly supports Named Graphs, so there is no need for a new query language for Named Graphs [18].

Figure 3.11: Taxonomy of Temporal RDF Models [72]

Table 3.2: Temporal Model Comparison [72]

Approach	**RDF/S Ext.**	**Add. Object**	**# of Triples**	**Semantics**	**Time Domain**	**Inst/Interval**	**Query**
Temporal RDF, Enh. YAGO2	N	Y	8 quadruple	RDF/S and Temporal Graph closure	Model Def.	Both	SWRL Prototype
c-Temporal Graph tRDF	N	Y	8	RDF/S, Temporal Graph closure for indeterminate	Model Def.	Both	Algorithm
RDF $\star$	Y	Y	7	RDF/S	Model Def.	Interval	SPARQL$\star$
Annotated RDF	Y	Y	N/A[1]	annotated logic and Inference rules	Model Def.	Both	Algorithm
4D Fluents and Ext.	N	Y	7	OWL	OWL-Time	Interval	SPARQL
tOWL	Y	Y	8	OWL-DL	Concrete Domain	Both	SPARQL
Singleton Property	Y	Y	5	RDF/S ext.	Instant	SPARQL	SPARQL
VT-OWL	N	Y	8	OWL	User	User	SPARQL
N-ary, FrameBase	N	Y	7	OWL	User	User	SPARQL
Named Graphs	N	Y	3	RDF/S	User	User	SPARQL
τ SPARQL	N	Y	3	RDF/S	OWL-Time	Both	τ SPARQL
RDF+	Y	Y	Quintuple	RDF+	Model Def.	Both	Ext. SPARQL
VTRDF[2]	Y	N	3	VTRDF	Model Def.	Interval	VT-SPARQL

[1] The annotated RDF framework does not discuss its model implementation.

[2] VTRDF is our proposed Temporal Model and will be introduced in Chapter 4.

Chapter 4

Valid Time RDF

4.1 Modeling Approach

Hayes introduced the *four dimensional view* (4D view), also known as *perdurantist view*, into Computer Science in his seminal work [35]. *Perdurantism* is a philosophical theory of persistence and identity [34]. It is closely related to *four dimensionalism*. In *4D view*, an object that persists through time has distinct temporal parts at every time instant during its existence in time. Each persisting object is considered a four dimensional *spacetime worm* that stretches across the space-time domain. Slicing the spacetime worm at a specific time instant or interval results a temporal part or time slice which manifests itself as *entity-at-a-time*.

In contrast, the *three dimensional view* (3D view), also known as *endurantist view*, considers an object wholly present during its existence in time. There are no temporal parts. In the literature [63], Sider defended four-dimensionalism based on object identity and part-hood. The arguments mostly concern whether the identity of the same object remains through times.

Consider that an entity John persists through time. Two time instants characterize his existence in time: birth and death dates. John was born on January 10, 1995 and is still alive. An interval, $[1/10/1995, now]$, represents his *existence time* or *valid time*. The interval $[1/10/1995, now]$ is

closed at both ends. Its lower bound is a standard calendar date in the format of month/day/year or mm/dd/yyyy, and its upper bound, *now*, is a special time instant for the current time. In comparison, entities, such as music, paintings, and scientific theories, may exist indefinitely from its inception [38]. Their existence time typically has an upper boundary denoted by an infinite instant ∞. For instance, the valid time of Moore's law [74] is $[4/19/1965, \infty]$. In general, every entity naturally comes with an *existence time* which can be represented by a timestamp, such as time points or intervals.

On the other hand, a fact *John attended PS101* describes a binary relationship denoted by the verb *attend*, between John and PS101. Among many other modeling approaches , the fact can be represented in a predicate form: attend(John, PS101). This relationship naturally comes with a factual time interval, such as [9/1/2008, 6/25/2013), that denotes its validity in time. Adding this additional time parameter to the relationship results a ternary one, such as attendTemporal(John, PS101, [9/1/2008, 6/25/2013)) where *attendTemporal* is the 3-ary predicate name. Alternatively, a second order relationship, or nested relationship, also suits the same modeling case, such as attendTemporalNested(attend(John, PS101), [9/1/2008, 6/25/2013)) where *attendTemporalNested* is a 2-ary predicate name. Nevertheless, neither can be represented directly in RDF which requires binary relationships fundamentally.

From the above observation, we know that every entity or relationship naturally comes with a valid timestamp. As a result, a binary relationship actually incurs three timestamps: the valid time of the relationship and two participating entities. To fully preserve the temporal aspect of the binary relationship, all three timestamps shall be incorporated into the model. This is a modeling problem similar to the case of defining N-ary or high order relations in the Semantic Web [53].

With the John's example mentioned above and the 4D view interpretation, we found that it is actually that the temporal part of John was associated with the temporal part that corresponded to the same time period when PS101 had John as an elementary school student. This is due to that in the 4D view, entities spread through time instead of ranging over time. 'Entities *spreading*

through time'means that they only exist for some period of time, whereas 'entities ranging over time'reflects that they are wholly present. Although John is the main entity, the identity of John in [9/1/2008, 6/25/2013) is conceptually distinguishable from that of John in [9/1/2013, 6/25/2015).

In this thesis, we adopt a modeling approach that employs ideas from the 4D view and originated from the study in [66], and propose the Valid Time RDF, or VTRDF in short. VTRDF is based on *temporal resource* and *temporal relationship* or *temporal fact*. A temporal resource is a RDF-compliance resource equipped with a timestamp to denote its existence in time. Each temporal resource is a coalesce of all its temporal parts. In other words, a temporal resource is wholly present during its existence in time. Temporal parts are derived by slicing or projecting a temporal resource on to the time dimension. A temporal relationship is formed between either temporal parts or temporal resources provided that the participating or parts or resources coexist in time. A temporal relationship is a factual assertion that relates qualified temporal resources.

We base the VTRDF model on the standard RDF model and its model semantics. A standard RDF triple (s, p, o) contains elements that are all resources: $s, p, o \in \mathbb{R}$, and $\mathbb{R}$ is an infinite set of resources. We introduce $\mathbb{VTR}$, an infinite set of valid time resources, as the building block for VTRDF triples and VTRDF graphs. A valid time resource is a resource with its existence time or valid time. In VTRDF, we consider a valid time resource as a collection of all its temporal parts. Assertions can be made with respect to both the collection and any individual temporal part. A temporal resource is a master resource, whereas all its temporal parts are member resources. Projections from the master resource to its temporal parts are possible via projection functions. The temporal aspects of the resources can use valid time, transaction time, or bitemporal. In this research, we focus on the valid time. Hence, we would use valid time resources and temporal resources interchangeably as appropriate.

4.2 Notations, Namespace, and Time Domain

In the remainder of this chapter, we will define VTRDF and present examples. As introduced in section 2.4, we still use the graph-based representation for illustrating VTRDF examples. For instance, in Figure 4.1, an oval denotes a temporal resource as a subject or object, and a literal as an object. A directed link represents a predicate. When a literal value is used, it is double quoted and annotated with a data type or a language tag. When necessary, we also use the line-based Turtle syntax [9] to serialize VTRDF triples and graphs.

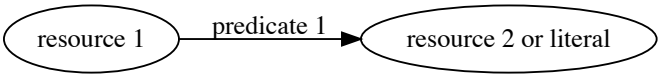


Figure 4.1: Graph Notation for VTRDF

The prefix rdf:, rdfs:, and xsd: have been defined in section 2.4, and their uses remain in VTRDF. Besides, we introduce new namespace, summarize as follows:

```
@PREFIX vtrdf:   <http://example.org/vtrdf-syntax#>
@PREFIX vtrdfs:  <http://example.org/vtrdf-schema#>
@PREFIX xsd:     <http://www.w3.org/2001/XMLSchema#>
@PREFIX :        <http://example.org/temporal-SW#>
```

The customized prefix vtrdf: and vtrdfs: refer to the namespace of VTRDF vocabulary and VTRDF Schema vocabulary respectively. Well use a base ontology for the running example, explained in the next section, to illustrate syntax and semantics of the VTRDF model. It assumes the Namespace http://example.org/temporal-SW, and we use : (colon) as its prefix.

While the symbol # is used to denote an additional part of the primary resource in the standard RDF model, VTRDF requires a second fragment identifier to accommodate the valid time dimension. The symbol • is used as a delimiter that separates the first fragment identifier from the valid

time. For instance, the IRI http://example.org/temporal-SW#John•[1/10/1995–now] denotes the complete valid time resource which embeds a valid time interval.

For the time domain, we follow the definitions given in section 3.2. Main terms for the time domain are summarized as follows:

- T is the set of time points with a linear order less-than ($<$). For simplicity, we use the standard U.S. calendar dates as the unit of time points in the format of month/day/year, such as 1/10/1995.
- T_I is the set of time intervals defined over T, as follows:

$$T_I = \{[l, u) | l \in T \wedge u \in T \wedge l < u\} \tag{4.2.1}$$

- 0 is the lower bound of the time axis whose interpretation is open for user's need of data modeling.
- *now* is a special constant that represents the current time. Its value will change as time advances.
- ∞ is a constant that represents the upper bound of the time axis.
- $[0, \infty]$ is a special interval used to represent the maximal interval.

4.3 Running Example

We follow the same relation given in Table 2.3 which considers a 4-ary relation: Person(John, SW, NYC, [2/1/2016, 5/31/2016]). Recall that it represents an individual person whose name is John. For simplicity, we also use the term John as an identifier. John enrolled in the Semantic Web course (SW), lived in New York City (NYC), and had a valid time [2/1/2016, 5/31/2016). To represent the

relation using the standard RDF, it needs to be decomposed to several triples through reification. Implicit reification analyzed in Section 3.4 allows transforming the facts of Table 2.3 to a RDF graph in Figure 4.2. The triple (John, hasDate, [2/1/2016, 5/31/2016)) asserts that John has a date [2/1/2016, 5/31/2016). Suppose that the interval [2/1/2016, 5/31/2016) actually applies to John's enrollment in SW. Adding this interval to the triple (John, enrolled, SW) results in a quadruple: (John, enrolled, SW, [2/1/2016, 5/31/2016)) which is not directly representable in standard RDF. This example addresses the modeling problem that we focus on.

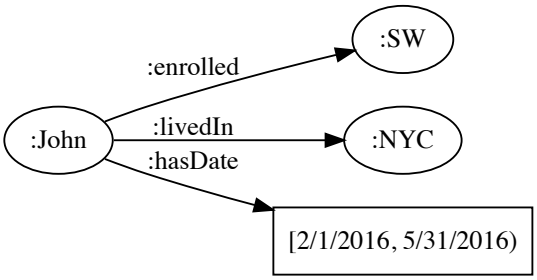


Figure 4.2: Person Relation of Table 2.3 Transformed to a RDF Graph

The Valid Time RDF, or VTRDF, is proposed to tackle the mentioned modeling problem. Figure 4.3 illustrates a VTRDF graph that combines the RDF graph in Figure 4.2, the temporal information provided in the column, hasDate, of Table 2.3, and additional valid time information of all entities. The distinctive feature of the VTRDF is that every standard RDF resource becomes a temporal resource with its valid time embedded.

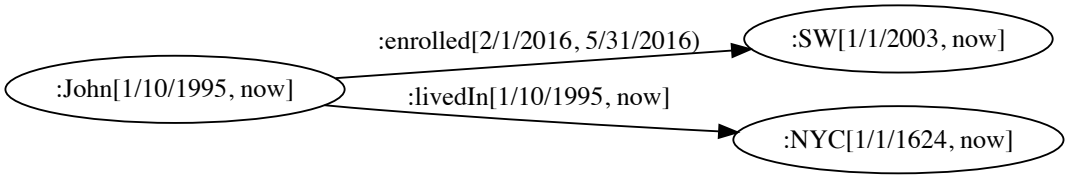


Figure 4.3: VTRDF Graph for the Running Example

4.4 Valid Time RDF

We propose the Valid Time RDF, or VTRDF, for modeling temporal data and knowledge with RDF. In our model, all resources are *temporal resources* or, specifically, *valid time resources* as we focus on the valid time. For instance, in Figure 4.3, the subject :John[1/10/1995, now] denotes both the underlying resource *:John* and his *valid time* which corresponds to his birthday and living to date. The object :SW [1/1/2003, now] denotes the Semantic Web course *:SW* and its *valid time* which is assumed $[1/1/2003, now]$. The predicate :enrolled[2/1/2016, 5/31/2016) establishes a valid time relationship between John and the course SW, and characterizes the *temporal triple integrity*. A valid time relationship references existing pair of resources whose valid time overlaps. The validity time interval of the relationship is bounded by the intersection of the valid time of participating resources. Similarly, John has been living in NYC since he was born, which is annotated by the valid time [1/10/1995, now]. The object :NYC[1/1/1624, now] represents the city and its valid time on which New York City was founded [75].

4.5 VTRDF Triple and Graph Definitions

VTRDF is a RDF-compliant model with all standard resources temporalized by their valid time. The following definitions provide the foundation for VTRDF model and its semantics. In the

remainder of this chapter, we use VTRDF graph instances in the examples.

Definition 4.5.1. Valid Time Resource

Let $\mathbb{R}$ be an infinite set of standard RDF resources, T_I be the set of intervals and $VTR = \mathbb{R} \times T_I$ be their Cartesian product. A valid time resource $r^t \in VTR$ is a resource with a timestamp that denotes its validity in time. A valid time resource is formed by the concatenation of a standard resource $r \in \mathbb{R}$ and $i \in T_I$ to integrate both its resource and valid time parts, i.e. $r \bullet i$ where $\bullet$ is a delimiter. The valid time resource is a special case in considering other attributes of time, such as transaction time or bitemporal. In the case of transaction time, a transaction time resource is the concatenation of a standard resource and its transaction time that denotes when it is recorded or created in the database.

Definition 4.5.2. Valid Time Internationalized Resource Identifier

A valid time Internationalized Resource Identifier (IRI) is used to denote a valid time resource uniquely. It consists of two parts. The first denotes a resource, and the second denotes its valid time. The resource part employs the IRI specification used in standard RDF, which may contain a fragment identifier as specified in section 4.2. The valid time is added as the second fragment identifier by a delimiter •, while the first fragment identifier starts with the delimiter #. The following is a valid time IRI resource that denotes a resource John whose valid time is [1/10/1995, now]:

http://example.org/temporal-SW#John•[01-10-1995–now]

In the remainder of this thesis, we sometimes abuse this notation and do not include the second delimiter, in representing temporal resources.

Definition 4.5.3. Valid Time Literal

Let L be an infinite set of standard literals, $[0, \infty]$ the maximal interval, and $VTL = L \times [0, \infty]$ be the Cartesian product. A valid time literal $l^t \in VTL$ represents a literal that is always valid in time. That is, all literals assume a default maximal interval $[0, \infty]$ unless otherwise specified.

Definition 4.5.4. Valid Time Data Type

Let D be an infinite set of standard data types, $[0, \infty]$ the maximal interval, and $VTD = D \times [0, \infty]$ be the Cartesian product. A valid time data type $d^t \in VTD$ is a data type recognized in the standard RDF with a default maximal interval $[0, \infty]$. In other words, all valid time data types are always valid in time. Valid time data types are used to annotate valid time literals. For instance, "1"^^ xsd:integer$[0, \infty]$ denotes an integer 1 by the XML Schema integer type. A special data type vtrdf:langString$[0, \infty]$ can also be used to denote a language-tagged string value. For instance, "Neuva York City"@sp$[0, \infty]$ is a valid time literal "New York City" in a Spanish language tag.

Definition 4.5.5. Lexical-to-Value Mapping Function $VTL2V$

$VTL2V$ is a partial mapping from the lexical space of valid time literals to the value space $\mathcal{V}$. A valid time literal l^t with a valid time data type d^t denote the mapped value obtained from the value space. That is, $VTL2V(l^t, d^t) = v$ where $v \in \mathcal{V}$.

Definition 4.5.6. Valid Time Property

Let P be the set of any properties, including those defined in RDF and RDFS vocabularies [16], T_I be the set of intervals, and $VTP = P \times T_I$ be the Cartesian product of them. A valid time property $p^t \in VTP$ is any property that is valid during a specified interval $i \in T_I$.

Definition 4.5.7. Valid Time Blank Node

Let B be an infinite set of blank nodes, T_I be the set of intervals, and $VTB = B \times T_I$ be the Cartesian product. A valid time blank node $b^t \in VTB$ denotes the existence of a resource whose valid time may or may not be known. For simplicity, every valid time blank node in the VTRDF model assumes a default maximal valid interval $[0, \infty]$ unless otherwise specified. A valid time blank node is usually identified by a local identifier.

Definition 4.5.8. Valid Time Resource Projection Function

A valid time resource projection function, $f_k : VTR \rightarrow [\mathbb{R}|T_I|T|VTR]$, $k = \{res, vt, vt_s, vt_e, i\}$, takes a valid time resource $r^t \in VTR$ and projects to either the resource dimension (subscripted res), the valid time dimension (subscripted vt) which is further categorized to vt_s and vt_e for the beginning and end of the interval, or a slice of the resource r^t at the interval i (parameterized (r^t, i)). Given a valid time resource $r^t = r[l, u) \in VTR$, the projection function characterizes the following cases.

- Resource Projection

$$\Pi_{res} r^t = r \tag{4.5.1}$$

- Valid Time Projection

$$\Pi_{vt} r^t = [l, u) \tag{4.5.2}$$

$$\Pi_{vt_s} r^t = l \tag{4.5.3}$$

$$\Pi_{vt_e} r^t = u \tag{4.5.4}$$

- Resource Slice Projection given an interval i

$$\Pi(i, r^t) = r_1^t \text{ where } \Pi_{res} r_1^t = \Pi_{res} r^t \text{ and } \Pi_{vt} r_1 = i \cap \Pi_{vt} r^t \tag{4.5.5}$$

In addition, we overload the projection function to accommodate operations for valid time blank nodes. As a blank node is not given a valid time IRI, its *resource* part is undefined. Its resource projection therefore results a locally-scoped identifier which has been assigned. In other words,

given a valid time blank node b^t, we have:

$$\Pi_{res} b^t = \text{locally-scopped identifier} \tag{4.5.6}$$

$$\Pi_{vt} b^t = [l, u) \tag{4.5.7}$$

In the case of the slice projection function, we also call the resulting resource a slice of the original valid time resource. Furthermore, a shortcut dot notation (.) is also used in place of the algebraic forms, such as $r^t.res = \Pi_{res} r^t$.

As an example, given a valid time resource r^t= :John[1/10/1995, now] and $i = [2/1/2016, 5/31/2016)$, we have the following:

$$\Pi_{res} r^t = \text{:John} \tag{4.5.8}$$

$$\Pi_{vt} r^t = [1/10/1995, now] \tag{4.5.9}$$

$$\Pi_{vt_s} r^t = 1/10/1995 \tag{4.5.10}$$

$$\Pi_{vt_e} r^t = now \tag{4.5.11}$$

$$\Pi(r^t, i) = \text{:John[2/1/2016, 5/31/2016)} \tag{4.5.12}$$

Definition 4.5.9. Valid Time RDF Triple

Let s^t, p^t, o^t be VTRDF resources defined as follows. They represent the subject, the predicate, and the object respectively.

- $s^t \in VTR \cup VTB$
- $p^t \in VTP$
- $o^t \in VTR \cup VTB \cup VTL$

A Valid Time RDF triple (s^t, p^t, o^t) satisfies the temporal constraint, called *Temporal Triple Integrity* , as follows:

$$\Pi_{vt}(p^t) \subseteq \Pi_{vt}(s^t) \cap \Pi_{vt}(o^t) \; where \; \Pi_{vt}(s^t) \cap \Pi_{vt}(o^t) \neq \emptyset. \tag{4.5.13}$$

The integrity constraint enforces that the valid time of the property or predicate $p^t \in VTP$ is bounded by the interval that is formed by the common valid time of s^t and o^t. In other words, the temporal triple integrity requires that a valid time relationship can only be established between two existing resources with non-disjoint valid time.

Definition 4.5.10. Predicate Defining Time (PDT) and Resource Modeling Time (RMT)

Any valid time resource $r^t \in VTR$ takes one of the Predicate Defining Time (PDT) or Resource Modeling Time (PMT) based on its use in VTRDF triples.

- Predicate Defining Time (PDT):

  r^t takes PDT when it is used in a VTRDF triple as a predicate to define the time of a relationship. In this case, PDT corresponds to the interval during which the relationship is valid.

- Resource Modeling Time (RMT):

  r^t takes RMT when it is used in a VTRDF triple as a subject or an object that eventually involves in a relationship. RMT is the time that we want to store about the facts into the database. Given r^t for each subject or object, it always has a unique RMT as its valid time.

Definition 4.5.11. VTRDF Graph

A VTRDF graph G^t is a set of VTRDF triples defined as follows :

$$\begin{aligned} G^t = \{(s^t, p^t, o^t) | s^t \in (VTR \cup VTB) \wedge p^t \in VTP \wedge o^t \in (VTR \cup VTL \cup VTB) \wedge \\ (p^t.vt \subseteq s^t.vt \cap o^t.vt) \wedge \\ (s^t.vt \cap o^t.vt \neq \emptyset) \wedge \\ \neg\exists((x^t, y^t, z^t)((s^t.res = x^t.res \wedge p^t.res = y^t.res \wedge o^t.res = z^t.res \wedge \\ (s^t.vt \cap x^t.vt \neq \emptyset \vee s^t.vt_e = x^t.vt_s) \wedge \\ (p^t.vt \cap y^t.vt \neq \emptyset \vee p^t.vt_e = y^t.vt_s) \wedge \\ (o^t.vt \cap z^t.vt \neq \emptyset \vee o^t.vt_e = z^t.vt_s)) \vee \\ \neg\exists(x^t, y^t, z^t)(s^t.res = z^t.res \wedge s^t.vt \cap z^t.vt \neq \emptyset) \vee \\ \neg\exists(x^t, y^t, z^t)(o^t.res = x^t.res \wedge o^t.vt \cap x^t.vt \neq \emptyset)\} \end{aligned} \tag{4.5.14}$$

Definition 4.5.12. Valid Timeslice Operator

Given a VTRDF graph G^t and an interval $i = [l, u)$, the valid time slice operator, $\mathbb{T}\$$, returns a temporal subgraph of G^t at i, defined as follows:

$$\mathbb{T}\$(G_1^t, i) : G_1^t \rightarrow G_2^t \tag{4.5.15}$$

$$\begin{aligned} G_2^t = \{(s_1^t, p_1^t, o_1^t) | (s^t, p^t, o^t) \in G_1^t \wedge s_1^t.res = s^t.res \wedge p_1^t.res = p^t.res \wedge o_1^t.res = o^t.res \wedge \\ i_1 = (i \cap s^t.vt \cap p^t.vt \cap o^t.vt) \wedge i_1 \neq \emptyset \wedge s_1^t.vt = i_1 \wedge p_1^t.vt = i_1 \wedge o_1^t.vt = i_1\} \end{aligned} \tag{4.5.16}$$

$\mathbb{T}\$$ takes a VTRDF graph G_1^t and an interval i as arguments. The resource slice projection

function of the Definition 4.5.8 is then applied to component resources of triples in G_1^t. Hence, this operation creates a new VTRDF graph, G_2^t, from G_1^t provided i overlaps with the valid time of subjects, predicates, and objects appear in G_1^t. Otherwise, $\mathbb{TS}$ returns an empty set. Please note that a legal VTRDF triple satisfies the temporal triple integrity specified Definition 4.5.9. Hence, the condition $(i \cap s^t.vt \cap p^t.vt \cap o^t.vt)$ in Expression 4.5.16 can be reduced to $(i \cap p^t.vt)$.

Suppose that G_1^t denotes the running example shown in Figure 4.3, Figure 4.4 shows a VTRDF graph G_2^t derived from the graph G_1^t by applying the $\mathbb{TS}$ operation to G_1^t at $[2/1/2016, 5/31/2016)$.

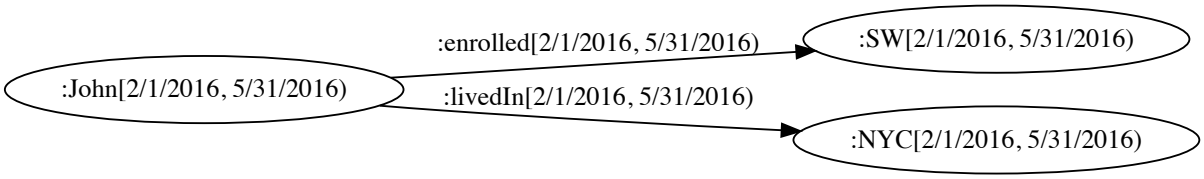


Figure 4.4: VTRDF Graph for the Running Example Sliced at the Interval $[2/1/2016, 5/31/2016)$

Definition 4.5.13. VTRDF Subgraph

A VTRDF graph H^t is a subgraph of another VTRDF graph G^t if H^t includes some of the VTRDF triples in G^t. For instance, the VTRDF graph in Figure 4.5 is a subgraph of the graph in Figure 4.3.

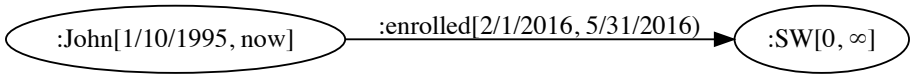


Figure 4.5: A VTRDF Subgraph of the Running Example in Figure 4.3

Additionally, a valid timeslice of a VTRDF graph G^t is a *temporal subgraph* of it. That is, the

graph in Figure 4.4 is a temporal subgraph of the graph in Figure 4.3.

Definition 4.5.14. VTRDF Underlying Triple

Given a VTRDF triple $e = (s^t, p^t, o^t)$, its underlying triple $u(e)$ is defined as:

$$u(e) = (\Pi_{res} s^t, \Pi_{res} p^t, \Pi_{res} o^t) \tag{4.5.17}$$

Definition 4.5.15. VTRDF Underlying Graph

Given a VTRDF graph G^t, its underlying graph $u(G^t)$ is defined as:

$$u(G^t) = \{(u(e)|e \in G^t\} \text{ where e is a VTRDF triple} \tag{4.5.18}$$

$u(G^t)$ becomes a standard RDF graph. Duplicate triples are eliminated. If two or more triples agree on the subject or object, they are combined to one triple. As an example, the underlying graph of the VTRDF graph in Figure 4.3 is shown in Figure 4.6.

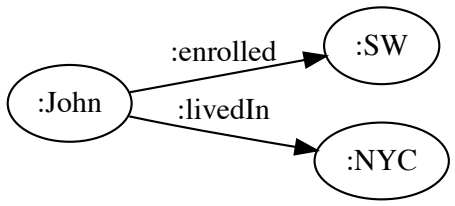


Figure 4.6: A VTRDF Underlying Graph of the Running Example in Figure 4.3

Definition 4.5.16. VTRDF Graph Vocabulary

Given a VTRDF graph G^t and the set of valid time resources VTR appear in G^t, the vocabulary $voc(G^t)$ is the set of valid time IRIs that appear in G^t excluding valid time literals.

Definition 4.5.17. Ground VTRDF Graph

A ground VTRDF graph is a VTRDF graph that does not contain any valid time blank nodes.

Definition 4.5.18. VTRDF Mapping Function

A mapping function, $M^t : (VTR \cup VTB \cup VTL) \rightarrow (VTR \cup VTB \cup VTL)$, maps a valid time resource, a valid time literal, or a valid time blank node to a valid time resource, a valid time literal, or another valid time blank node. M^t is defined to map elements of one VTRDF graph to another. Four mapping cases at the resource level are defined for two given VTRDF graphs G_1^t and G_2^t as follows:

- $M^t(r_1^t) = r_2^t$ where $r_1^t \in G_1^t$, $r_2^t \in G_2^t$, $r_1.res = r_2.res$, and $r_1.vt = r_2.vt$.
- $M^t(l_1^t) = l_2^t$ where $l_1^t \in G_1^t$, $l_2^t \in G_2^t$, $l_1.res = l_2.res$, and $l_1.vt = l_2.vt$.
- $M^t(b^t) = r^t$ where $b^t \in G_1^t$, $b^t.vt = [0, \infty]$, $r^t \in G_2^t$ and $r^t.vt \subseteq b^t.vt$.
- $M^t(b_1^t) = b_2^t$ where $b_1^t \in G_1^t$, and $b_2^t \in G_2^t$.

In addition, M^t can be overloaded to map a VTRDF graph. Given a VTRDF graph G^t, $M^t(G^t)$ maps to a set of all $(M^t(s^t), M^t(p^t), M^t(o^t)$ where $(s^t, p^t, o^t) \in G^t$.

4.6 VTRDF Vocabulary (vtrdfV)

VTRDF is formulated as layers and RDF-compliant. VTRDF triples and graphs are constructed and manipulated as they are in the standard RDF model. Basic VTRDF triple assertions are at the base layer which is augmented by VTRDF vocabularies, and further by VTRDF schema vocabularies. VTRDF provides ontological modeling primitives to define terminology vocabularies and use them for asserting facts while incorporating valid time herein.

Figure 4.7 shows the serialization for the running example of Figure 4.3 in Turtle syntax [9]. As discussed in section 4.4, each component in a VTRDF triple denotes a standard RDF resource and its valid time altogether. The main advantage of using VTRDF is self-explanatory. We are able to capture the fact that John, who is identified as a standard RDF resource, was born on 1/10/1995

and now is alive. In addition, NYC and SW both exist permanently since their inception. *enroll* and *liveIn* are both valid time properties that relate two valid time resources and satisfy *Temporal Triple Integrity* of Definition 4.5.9. By checking the following two expressions (4.6.1) and (4.6.2), we assure that the triples in Figure 4.7 are valid VTRDF triples.

```
PREFIX  :  http://example.org/temporal-SW#>
:John[1/10/1995,now] :enrolled[2/1/2016,5/31/2016) :SW[1/1/2003, now].
:John[1/10/1995,now] :liveIn[1/10/1995,now] :NYC[1/1/1624, now].
```

Figure 4.7: Running Example in Turtle Syntax

$$[2/1/2016, 5/31/2016) \subseteq [1/10/1995, now] \cap [1/1/2003, now] \tag{4.6.1}$$

$$[1/10/1995, now] \subseteq [1/10/1995, now] \cap [1/1/1624, now] \tag{4.6.2}$$

A set of vocabularies, called VTRDF vocabulary, or vtrdfV, is defined below. vtrdfV augments the VTRDF model with more expressive power.

- vtrdf:type[l, u) is a valid time property that has different temporal references depending on how it is used. The *type* property holds valid during [l, u) as a *predicate defining time* given in section 4.5.10. vtrdf:type[l, u) can also be used in the subject or object position. In this case, [l, u) corresponds to *resource modeling time* given in Definition 4.5.10.

- vtrdf:Property[l, u) is the valid time class of all valid time properties with a coalesced valid time,[l, u), from all of its instances. As the class denotes a generic class in time, we may assign the maximal interval $[0, \infty]$ as its valid time. Otherwise [l, u) is used.

- vtrdf:Statement[l, u) is the valid time class of all VTRDF statements. The class denotes a generic concept in time, and we may assign the maximal interval $[0, \infty]$ as its valid time. Otherwise [l, u) is used.

- vtrdf:subject[l_1, u_1), vtrdf:predicate[l_2, u_2) and vtrdf:object[l_3, u_3) are valid time properties used to assert the subject, predicate and the object of a VTRDF statement respectively. They are intended to be used in the reification.

By using VTRDF vocabularies, additional knowledge about the running example of Figure 4.3 can be expressed. Figure 4.8 shows a graph that contains three fresh facts: John is a student in [2/1/2016, 5/31/2016), NYC is a city that was founded in 1624, and SW is a course established on 1/1/2003. City and Course are likewise having the valid time that reflects their lifespan.

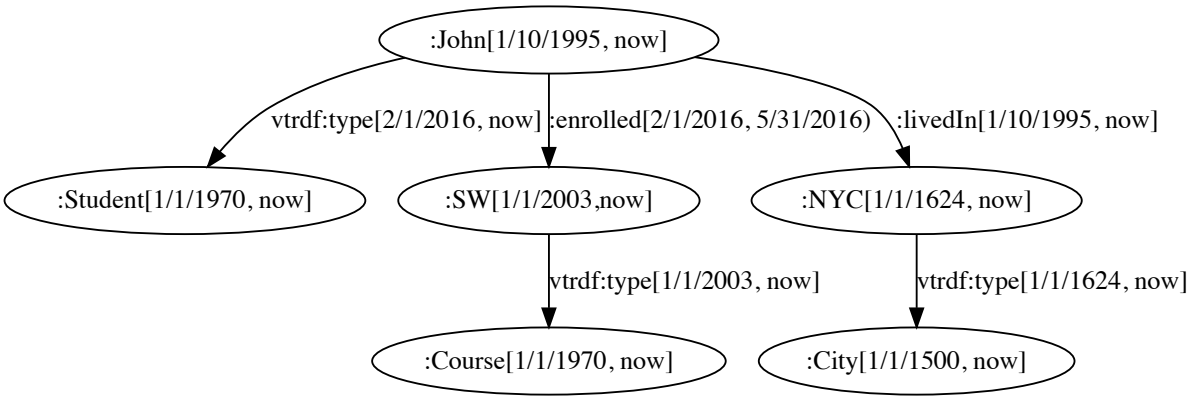


Figure 4.8: Running Example with Additional Facts in VTRDF Vocabulary (vtrdfV)

Each valid time triple in Figure 4.8 satisfies the temporal triple integrity in the Definition 4.5.9. In addition, special temporal constraints could be imposed depending on the modeling needs. For instance, the graph in Figure 4.9 is a subgraph of Figure 4.8. Suppose a constraint that the property *enrolled* is applicable to John only when he is a student has to be imposed. That is, the valid time of the enrolled property should be the subset of the valid time of the type property for student. In the VTRDF model, such a constraint can be enforced as a special temporal constraint.

In addition, a set of axioms, shown in Figure 4.10, follows from the above definitions of vtrdfV. Each axiom satisfies the temporal triple integrity in Definition 4.5.9: $[l_2, u_2) \subseteq [l_1, u_1) \cap [l_3, u_3)$.

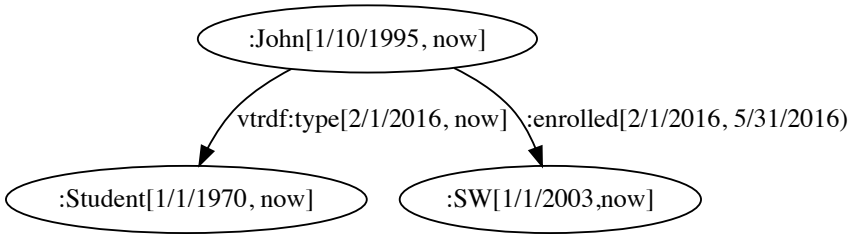


Figure 4.9: A Subgraph of Figure 4.8

```
PREFIX  vtrdf:   <http://example.org/vtrdf-syntax#>


vtrdf:type[l1,u1) vtrdf:type[l2,u2) vtrdf:Property[l3,u3).
vtrdf:subject[l1,u1) vtrdf:type[l2,u2) vtrdf:Property[l3,u3).
vtrdf:predicate[l1,u1) vtrdf:type[l2,u2) vtrdf:Property[l3,u3).
vtrdf:object[l1,u1) vtrdf:type[l2,u2) vtrdf:Property[l3,u3).
```

Figure 4.10: Axioms of VTRDF Vocabulary (vtrdfV)

4.7 VTRDF Schema Vocabulary (vtrdfsV)

VTRDF Schema Vocabulary, or vtrdfsV, augments VTRDF to provide more semantic constructs, including valid time classes and their properties.

Definition 4.7.1. Valid Time Class

Let C be an infinite set of standard classes, T_I be the set of intervals, and $VTC = C \times T_I$ be the Cartesian product. A valid time class $c^t \in VTC$ is a class whose valid time is the union of the valid time of all its member resources. Practically, a maximal interval $[0, \infty]$ is assigned to every valid time class unless otherwise specified.

Valid time classes in VTRDF schema denote generic concepts, therefore they are all assigned the maximal interval as their valid time. In addition, valid time properties are used to define relationships between valid time resources, and they take predicate defining time as their valid time. vtrdfsV is defined as follows:

- Valid Time Classes:
  - vtrdfs:Resource[l, u) is the superclass of all valid time resources.
  - vtrdfs:Literal[l, u) is the class of all valid time literals.
  - vtrdfs:Class[l, u) is the class of all valid time classes.
- Valid Time Properties:
  - vtrdfs:domain[l, u) defines the domain of a valid time property. It can also be used to define itself.
  - vtrdfs:range[l, u) defines the range of a valid time property. It can also be used to define itself.
  - vtrdfs:subClassOf[l, u) defines the valid time class hierarchy.
  - vtrdfs:subPropertyOf[l, u) defines the valid time property hierarchy.

A set of axioms in Figure 4.11, written in Turtle syntax [9], follows from the above definitions of valid time classes and properties. The temporal triple integrity specified in the Definition 4.5.9 applies to all axioms.

By using the valid time classes, class properties, and the set of VTRDFS axioms, inference can be made. Entailed knowledge can be explicitly added. For instance, the type range axiom in Figure 4.11 allows us to infer that the resources :Student[$1/1/1970, now$], :Course[$1/1/1970, now$] and :City[$1/1/1500, now$] are all range values of specific type assertions. Therefore they are valid time

```
PREFIX  vtrdf:   <http://example.org/vtrdf-syntax#>
PREFIX  vtrdfs:  <http://example.org/vtrdf-schema#>

vtrdfs:Class[l1,u1) vtrdfs:subClassOf[l2,u2) vtrdfs:Resource[l3,u3).
vtrdfs:Property[l1,u1) vtrdfs:subClassOf[l2,u2) vtrdfs:Resource[l3,u3).
vtrdfs:Literal[l1,u1) vtrdfs:subClassOf[l2,u2) vtrdfs:Resource[l3,u3).
vtrdf:type[l1,u1) vtrdfs:domain[l2,u2) vtrdfs:Resource[l3,u3).
vtrdf:type[l1,u1) vtrdfs:range[l2,u2) vtrdfs:Class[l3,u3).
vtrdfs:domain[l1,u1) vtrdfs:domain[l2,u2) vtrdf:Property[l3,u3).
vtrdfs:domain[l1,u1) vtrdfs:range[l2,u2) vtrdfs:Class[l3,u3).
vtrdfs:range[l1,u1) vtrdfs:domain[l2,u2) vtrdf:Property[l3,u3).
vtrdfs:range[l1,u1) vtrdfs:range[l2,u2) vtrdfs:Class[l3,u3).
vtrdfs:subClassOf[l1,u1) vtrdfs:domain[l2,u2) vtrdfs:Class[l3,u3).
vtrdfs:subClassOf[l1,u1) vtrdfs:range[l2,u2) vtrdfs:Class[l3,u3).
vtrdfs:subPropertyOf[l1,u1) vtrdfs:domain[l2,u2) vtrdf:Property[l3,u3).
vtrdfs:subPropertyOf[l1,u1) vtrdfs:range[l2,u2) vtrdf:Property[l3,u3).
```

Figure 4.11: Axioms of VTRDF Schema Vocabulary (vtrdfsV)

classes. The inferred triples are shown in Figure 4.12 and we are adding them to the graph of Figure 4.8. Figure 4.13 shows the updated graph. Please note that the definitions of the inference and entailment will be discussed in the section 4.8.

```
:Student[1/1/1970, now] vtrdf:type[1/1/1970, now] vtrdfs:Class[1/1/1970, now].
:Course[1/1/1970, now] vtrdf:type[1/1/1970, now] vtrdfs:Class[1/1/1970, now].
:City[1/1/1500, now] vtrdf:type[1/1/1970, now] vtrdfs:Class[1/1/1970, now].
```

Figure 4.12: Inferred Triples Based on the Range Axiom in Figure 4.11

Furthermore, properties about :enrolled[2/1/2016, 5/31/2016) and :livedIn[1/10/1995, now] can be asserted by using vtrdfs:domain[l_1, u_1) and vtrdfs:range[l_2, u_2). In this way, they are defined as terminology vocabularies which are used to assert facts. Figure 4.14 shows the complete knowledge base, written in Turtle syntax [9], of the running example originally illustrated in Figure

4.3.

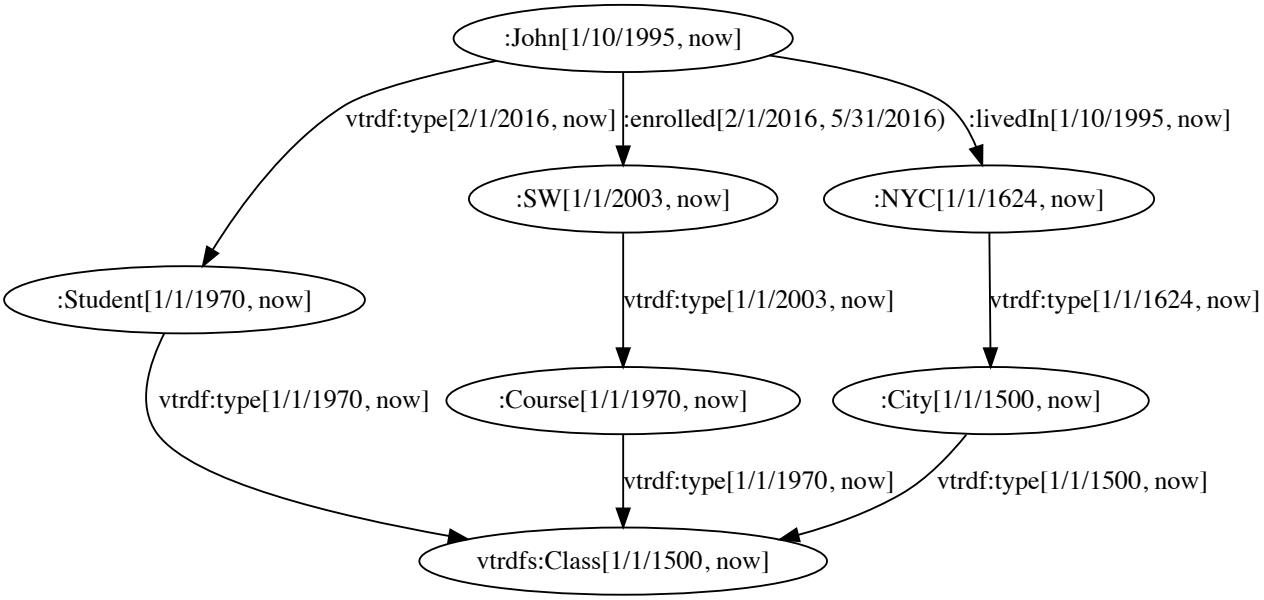


Figure 4.13: Running Example with Additional Facts in VTRDF Schema Vocabulary (vtrdfsV)

```
:enrolled[2/1/2016, 5/31/2016) vtrdfs:domain[2/1/2016, 5/31/2016)
:Student[1/1/1970, now].
:enrolled[2/1/2016, 5/31/2016) vtrdfs:range[2/1/2016, 5/31/2016)
:Course[1/1/1970, now].
:livedIn[1/10/1995, now] vtrdfs:domain[1/10/1995, now] :Student[1/1/1970, now].
:livedIn[1/10/1995, now]  vtrdfs:range[1/10/1995, now] :City[1/1/1500, now].
:SW[1/1/2003, now]  vtrdf:type[1/1/2003, now]  :Course[1/1/1970, now].
:Student[1/1/1970, now] vtrdf:type[1/1/1970, now] vtrdfs:Class[1/1/1500, now].
:Course[1/1/1970, now] vtrdf:type[1/1/1970, now] vtrdfs:Class[1/1/1500, now].
:City[1/1/1500, now] vtrdf:type[1/1/1500, now] vtrdfs:Class[1/1/1500, now].
:John[1/10/1995, now] vtrdf:type[2/1/2016, now] :Student[1/1/1970, now].
:John[1/10/1995, now] :enrolled[2/1/2016, 5/31/2016) :SW[1/1/2003, now].
:John[1/10/1995, now] :livedIn[1/10/1995, now]  :NYC[1/1/1624, now].
```

Figure 4.14: Complete Knowledge Base of the Original Running Example with Additional Facts in Turtle Syntax

4.8 VTRDF Semantics and Entailment

Now the focus turns to the formal semantics of the VTRDF model. The standard RDF 1.1 [36] employs the model-theoretic semantics which introduces *interpretation models* and semantic conditions for its layered vocabularies of RDF and RDFS. In VTRDF, we characterize the model semantics in four groups of vocabularies, and define formal semantics accordingly for each group. In each group, an interpretation model is defined based on interpretation domain and a set of semantic conditions for its vocabularies. These groups of vocabularies are:

1. Simple Vocabulary (V^t)

   V^t refers to vocabularies without valid time data types D^t, vtrdfV, or vtrdfsV. That is, $V^t \cap (vtrdfV) \cap (vtrdfsV) = \emptyset$.

2. Simple Vocabulary with Valid Time Data Types (V^t-D^t)

   V^t-D^t includes the simple vocabulary V^t and the Valid Time data type D^t.

3. VTRDF Vocabulary with Data Types D^t (vtrdfV-D^t)

   vtrdfV-D^t includes the simple vocabulary V^t, the valid time data type D^t and vtrdfV defined in section 4.6.

4. VTRDF and VTRDFS Vocabularies with Data Type D^t (vtrdfsV-D^t)

   vtrdfsV-D^t includes the above mentioned vocabularies and vtrdfsV defined in section 4.7, mainly including: vtrdfs:Class$[0, \infty]$, vtrdfs:subClassOf$[l, u)$, vtrdfs:SubPropertyOf$[l, u)$, vtrdfs:domain$[l, u)$, and vtrdfs:range$[l, u)$.

As we shall see later, defining an interpretation model also identifies a certain set of entailment patterns. Entailment, introduced in section A.4 for the standard RDF model, is also known as the logical consequence. For the standard RDF model, there is no temporal aspect nor valid time is considered. In comparison, the entailment for the proposed VTRDF model characterizes the temporal entailment.

Definition 4.8.1. Temporal Entailment

Given ground VTRDF graphs G_1^t, G_2^t, G_1^t temporally entails G_2^t, denoted by $G_1^t \models_t G_2^t$, if and only if there exists a mapping function that maps G_2^t to any timeslice of G_1^t.

4.8.1 Simple Interpretation

Given a simple vocabulary, V^t, the simple interpretation I^t is defined as the following components:

- A set VTR of valid time resources as the domain of I^t.
- A set VTP of valid time properties in I^t.
- A mapping $\mathbb{IXT}^t$ from VTP to $VTR \times VTR$.
- A mapping $\mathbb{IS}^t$ from valid time IRI to $VTR \cup\ VTP$.
- A partial mapping $\mathbb{IL}^t$ from valid time literals to VTR.

$\mathbb{IXT}^t$ maps any valid time property VTP to $VTR \times VTR$ which is the set of all (r_1^t, r_2^t) where $r_1^t \in VTR$ and $r_1^t \in VTR$, and satisfies $r_1^t.vt \cap r_2^t.vt \neq \emptyset$. That is, each valid time property can only be mapped to a pair of ordered valid time resources that have overlapping valid time intervals. This is the temporal triple integrity given in Definition 4.5.9.

Given a VTRDF triple (s_i^t, p_i^t, o_i^t), $I^t((s_i^t, p_i^t, o_i^t))$ is true or satisfiable if all of the following conditions hold:

- $s_i^t \in V^t$, $p_i^t \in V^t$, $o_i^t \in V^t$
- $\mathbb{IS}^t(p_i^t) \in VTP$
- $(\mathbb{IS}^t(s_i^t), \mathbb{IS}^t(o_i^t))\ \in \mathbb{IXT}^t(\mathbb{IS}^t(p_i^t))$
- $p_i^t.vt \subseteq s_i^t.vt \cap o_i^t.vt$

Given a VTRDF graph, G^t, $I^t(G^t)$ is true or satisfiable if for every triple $(s_i^t, p_i^t, o_i^t) \in G^t$, $I^t((s_i^t, p_i^t, o_i^t))$ is true, otherwise $I^t(G^t)$ is false or unsatisfiable. We say that I^t is a model for G^t and write $I^t \models_t G^t$.

4.8.2 Simple Entailment

Given two VTRDF graphs G_1^t and G_2^t, a simple entailment pattern can be identified as the subgraph relationship. If G_2^t is a subgraph of G_1^t, G_1^t entails G_2^t. For instance, the VTRDF graph, G_1^t, in Figure 4.13 entails the graph, G_2^t, in Figure 4.8 beacuse G_2^t contains a subset of triples in G_1^t.

4.8.3 Simple-D^t Interpretation

Given the vocabulary V^t-D^t, the simple-D^t interpretation, I^t, is defined as the following conditions:

- Any VTRDF graph that contains ill-typed valid time literals is false or unsatisfiable.
- For a valid time literal, l^t, together with a valid time data type, d^t, where $l^t \in VTL$ and $d^t \in VTD$, represented as $l^t \wedge\wedge d^t$, its value is defined as:

$$IL^t(l^t \wedge\wedge d^t) = VTL2V(I^t(d^t), l^t) \tag{4.8.1}$$

4.8.4 Simple-D^t Entailment

Given two VTRDF triples e_1 and e_2 that contain valid time literals: l_1^t and l_2^t, and data types: d_1^t, d_1^t respectively. e_1 simple-D^t entails e_2 if and only if $VTL2V(l_1^t, I^t(d_1^t)) = VTL2V(l_2^t, I^t(d_2^t))$.

4.8.5 VTRDF Interpretation

Given vtrdfV given in section 4.6, a VTRDF interpretation I^t is a simple-D^t interpretation and satisfies the additional semantic conditions as follows:

1. For a valid time property $p^t \in VTP$:
   - $(p^t, I^t(\text{vtrdf:Property}[0,\infty])) \in \mathbb{IXT}^t(I^t(\text{vtrdf:type}[l,u))$
   - $[l,u) \subseteq p^t.vt \cap [0,\infty]$
2. For a valid time literal l^t and a valid time data type d^t, $(l^t, I^t(d^t))$ is in $\mathbb{IXT}^t(I^t(\text{vtrdf:type}[l,u)))$ if and only if l^t is in the value space of $I^t(d^t)$.
3. The set of VTRDF axiomatic triples given in Figure 4.6 needs to be satisfied.

4.8.6 VTRDF Entailment

The first semantic condition given above leads to the following entailment pattern:
Given a VTRDF graph G^t and any VTRDF triple $(s^t, p^t, o^t) \in G^t$:

$$G^t \models_t (p^t, \text{vtrdf:type}[l,u), \text{vtrdf:Property}[0,\infty]) \text{ where } [l,u) = p^t.vt \tag{4.8.2}$$

For instance, the following graph,

```
:John[1/10/1995, now] :enrolled[2/1/2016, 5/31/2016) :SW[1/1/2003, now].
```

entails

```
:enrolled[2/1/2016,5/31/2016) vtrdf:type[2/1/2016,5/31/2016)
vtrdf:Property[0,∞].
```

4.8.7 VTRDFS Interpretation

The semantics of valid time classes and class properties requires an additional component for mapping the set of valid time classes, VTC, given in Definition 4.7.1. A mapping function $\mathbb{VTCIXT}^t$ maps VTC to a subset of VTR. A VTRDFS interpretation I^t recognizing D^t is defined as the following semantic conditions:

1. For a valid time class $c^t \in VTC$, its mapping $\mathbb{VTCIXT}^t(c^t)$ is a collections of resources r^t that are of the same kinds, and defined as $\{r^t|(r^t, c^t) \in \mathbb{IXT}^t(I^t(\text{vtrdf:type}[l, u)))\}$ and $[l, u) \subseteq r^t.vt \cap c^t.vt$.

2. $\mathbb{VTCIXT}^t(I^t(\text{vtrdfs:Resource}[0, \infty]))=VTR$. This states that the mapping of the superclass of all valid time resources is the domain of the interpretation I^t.

3. If $(r_1^t, r_2^t) \in \mathbb{IXT}^t(I^t(\text{vtrdfs:domain}[l, u)))$, $[l, u) \subseteq r_1^t.vt \cap r_2^t.vt$, $(x^t, y^t) \in \mathbb{IXT}^t(r_1^t)$, and $r_1^t.vt \subseteq x^t.vt \cap y^t.vt$, then $x^t \in \mathbb{VTCIXT}^t(r_2^t)$ and $y^t.vt \subseteq r_2^t.vt$.

4. If $(r_1^t, r_2^t) \in \mathbb{IXT}^t(I^t(\text{vtrdfs:range}[l, u)))$, $[l, u) \subseteq r_1^t.vt \cap r_2^t.vt$, $(x^t, y^t) \in \mathbb{IXT}^t(r_1^t)$, and $r_1^t.vt \subseteq x^t.vt \cap y^t.vt$, then $y^t \in \mathbb{VTCIXT}^t(r_2^t)$ and $y^t.vt \subseteq r_2^t.vt$.

5. $\mathbb{IXT}^t(I^t(\text{vtrdfs:subPropertyOf}[l, u)))$ is transitive on VTP.

6. If $(p_1^t, p_2^t) \in \mathbb{IXT}^t(I^t(\text{vtrdfs:subPropertyOf}[l, u)))$ and $[l, u) \subseteq p_1^t.vt \cap p_2^t.vt$, then $p_1^t, p_2^t \in VTP^t$, $\mathbb{IXT}^t(p_1^t) \subseteq \mathbb{IXT}^t(p_2^t)$ and $p_1^t.vt \subseteq p_2^t.vt$.

7. $\mathbb{IXT}^t(I^t(\text{vtrdfs:subClassOf}[l, u)))$ is transitive on VTC.

8. If $c^t \in VTC$, then
   (c^t, $I^t(\text{vtrdfs:Resource}[0, \infty])) \in \mathbb{IXT}^t(I^t(\text{vtrdfs:subClassOf}[l, u)))$ and $[l, u] \subseteq [0, \infty) \cap c^t.vt$.

9. If $(c_1^t, c_2^t) \in \mathbb{IXT}^t(I^t(\text{vtrdfs:subClassOf}[l, u)))$ and $[l, u) \subseteq c_1^t.vt \cap c_2^t.vt$, then $c_1^t \in VTC$, $c_2^t \in VTC$, $\mathbb{VTCIXT}^t(c_1^t) \subseteq \mathbb{VTCIXT}^t(c_2^t)$, and $c_1^t.vt \subseteq c_2^t.vt$.

10. The combined set of VTRDF and VTRDF schema axioms from Figure 4.10 and Figure 4.11 needs to be satisfied, as follows in Figure 4.15. The temporal triple integrity specified in the Definition 4.5.9 applies to all axioms: $[l_2, u_2) \subseteq [l_1, u_1) \cap [l_3, u_3)$.

vtrdf:type$[l_1, u_2)$ vtrdf:type$[l_2, u_2)$ vtrdf:Property$[l_3, u_3)$.
vtrdf:subject$[l_1, u_1)$ vtrdf:type$[l_2, u_2)$ vtrdf:Property$[l_3, u_3)$.
vtrdf:predicate$[l_1, u_1)$ vtrdf:type$[l_2, u_2)$ vtrdf:Property$[l_3, u_3)$.
vtrdf:object$[l_1, u_1)$ vtrdf:type$[l_2, u_2)$ vtrdf:Property$[l_3, u_3)$.
vtrdfs:Class$[l_1, u_1)$ vtrdfs:subClassOf$[l_2, u_2)$ vtrdfs:Resource$[l_3, u_3)$.
vtrdfs:Property$[l_1, u_1)$ vtrdfs:subClassOf$[l_2, u_2)$
vtrdfs:Resource$[l_3, u_3)$.
vtrdfs:Literal$[l_1, u_1)$ vtrdfs:subClassOf$[l_2, u_2)$
vtrdfs:Resource$[l_3, u_3)$.
vtrdf:type$[l_1, u_1)$ vtrdfs:domain$[l_2, u_2)$ vtrdfs:Resource$[l_3, u_3)$.
vtrdf:type$[l_1, u_1)$ vtrdfs:range$[l_2, u_2)$ vtrdfs:Class$[l_3, u_3)$.
vtrdfs:domain$[l_1, u_1)$ vtrdfs:domain$[l_2, u_2)$ vtrdf:Property$[l_3, u_3)$.
vtrdfs:domain$[l_1, u_1)$ vtrdfs:range$[l_2, u_2)$ vtrdfs:Class$[l_3, u_3)$.
vtrdfs:range$[l_1, u_1)$ vtrdfs:domain$[l_2, u_2)$ vtrdf:Property$[l_3, u_3)$.
vtrdfs:range$[l_1, u_1)$ vtrdfs:range$[l_2, u_2)$ vtrdfs:Class$[l_3, u_3)$.
vtrdfs:subClassOf$[l_1, u_1)$ vtrdfs:domain$[l_2, u_2)$ vtrdfs:Class$[l_3, u_3)$.
vtrdfs:subClassOf$[l_1, u_1)$ vtrdfs:range$[l_2, u_2)$ vtrdfs:Class$[l_3, u_3)$.
vtrdfs:subPropertyOf$[l_1, u_1)$ vtrdfs:domain$[l_2, u_2)$
vtrdf:Property$[l_3, u_3)$.
vtrdfs:subPropertyOf$[l_1, u_1)$ vtrdfs:range$[l_2, u_2)$
vtrdf:Property$[l_3, u_3)$.

Figure 4.15: Combined Set of Axioms of VTRDF and VTRDF Schema Vocabulary

4.8.8 VTRDFS Entailment

VTRDF schema entailment patterns are defined based on the semantic conditions discussed in the previous section.

1.
$$\frac{(p[0,\infty], vtrdfs:domain[0,\infty], c[0,\infty]), \quad (s^t, p[l,u), o^t)}{(s^t, vtrdf:type[l,u), c[0,\infty])} \tag{4.8.3}$$

2.
$$\frac{(p[0,\infty], vtrdfs:range[0,\infty], c[0,\infty]), (s^t, p[l,u), o[m,n))}{(o[m,n), vtrdf:type[m,n), c[0,\infty])} \tag{4.8.4}$$

3.
$$\frac{(p_1^t, vtrdfs:subPropertyOf[0,\infty], p_2^t), (p_2^t, vtrdfs:subPropertyOf[0,\infty], p_3^t)}{(p_1^t, vtrdfs:subPropertyOf[0,\infty], p_3^t)} \tag{4.8.5}$$

4.
$$\frac{(p[0,\infty], vtrdfs:subPropertyOf[0,\infty], q[0,\infty]), (s^t, p[l,u), o^t)}{(s^t, q[l,u), o^t)} \tag{4.8.6}$$

5.
$$\frac{(c_1^t, vtrdfs:subClassOf[0,\infty], c_2^t), (c_2^t, vtrdfs:subClassOf[0,\infty], c_3^t)}{(c_1^t, vtrdfs:subClassOf[0,\infty], c_3^t)} \tag{4.8.7}$$

6.
$$\frac{(c_1^t, vtrdfs:subClassOf[0,\infty], c_2^t), (x^t, vtrdf:type[l,u), c_1^t)}{(x^t, vtrdf:type[l,u), c_2^t)} \tag{4.8.8}$$

Chapter 5

VT-SPARQL Query Language

5.1 VT-SPARQL Query Language

We design a query language, called Valid Time SPARQL, or VT-SPARQL, for querying VTRDF triple databases. The query language, SPARQL [32, 58], for the standard RDF is introduced in Appendix A.5. In comparison, our VTRDF differs from the standard RDF in a few ways. Hence, in designing a query language for VTRDF, additional requirements are considered, as follows:

1. The query language for VTRDF is based on SPARQL and RDF-compliant.

2. All resources in VTRDF are valid time resources. The representation of valid time resources, time intervals, and time instant are available. Particularly, the dot notation given in Definition 4.5.8 is allowed in all parts of a VT-SPARQL query statement.

3. Valid time variables in VT-SPARQL correspond to the standard variables in SPARQL. In VT-SPARQL, a valid time variable matches to a valid time resource.

4. Comparisons of valid time resources, their resource part, or valid time part are available.

5. Allen's temporal predicates [4] are incorporated for comparing time intervals.

6. Temporal Triple Integrity given in Definition 4.5.9 needs to be implicitly satisfied when VTRDF triple or graph patterns are specified in a query statement.

VT-SPARQL is derived from the standard SPARQL [32, 58] and employs VTRDF triple and graph patterns, which will be defined later in this section. Two query forms are considered in VT-SPARQL: SELECT and CONSTRUCT queries. A VT-SPARQL query statement is formed by using the grammar shown in Figure 5.1.

```
[PREFIX Prefix1:  IRIOfPrefix1]
[PREFIX ...]
{SELECT ValidTimeResourceList | CONSTRUCT {ValidTimeTripleList}}
[FROM IRIOfDefaultGraph]
[FROM NAMED IRIOfNamedGraphList]
WHERE
{ValidTimeTriplePatternList
[FILTER (Expressions)]
}
[ORDER BY orderComparatorList]
```

Figure 5.1: The Grammar of VT-SPARQL

1. PREFIX declaration

   A VT-SPARQL query starts with an optional PREFIX declaration, which is used to substitute any full valid time IRIs throughout the query. A PREFIX declaration is composed of the prefix and its IRI. In the grammar shown in Figure 5.1, *Prefix1:* stands for *IRIOdPrefix1*, which is a full valid time IRI. More than one prefix declaration can be specified. In such a case, each prefix declaration is separated by a line break.

2. SELECT and CONSTRUCT clause

   These two clauses are the choice of two query forms considered in VT-SPARQL. A SELECT query retrieves resources from the VTRDF triple database. Its SELECT clause defines the query output by itemizing variable bindings as a list of valid time resources which correspond

to the term *ValidTimeResourceList* in the grammar shown in Figure 5.1. Each valid time resource in the list is separated by space if more than one valid time resource is used. The actual output is subject to a VTRDF triple or graph pattern match specified in the WHERE clause, which will also be defined later in this section. Furthermore, the output can be manipulated by applying valid time resource projection functions given in Definition 4.5.8. As a result, the output can be either valid time resources, standard RDF resources or valid timestamps, depending on projection functions used.

In comparison, a CONSTRUCT query outputs a single VTRDF graph. Its CONSTRUCT clause defines a VTRDF graph template by a list of valid time triples, which correspond to the term *ValidTimeTripleList* represented in the grammar shown in Figure 5.1. A VTRDF graph template is composed of at least one VTRDF triple. If more than one triple is needed, each is delimited by a period (.). The actual output is subject to a VTRDF triple or graph pattern match specified in the WHERE clause, which will also be defined in this section.

3. FROM and FROM NAMED clauses

   Both FROM and FROM NAMED clauses are optional. The FROM clause contains a valid time IRI of a default VTRDF graph to be used for matching triple or graph patterns, which correspond to the term *IRIOfDefaultGraph* represented in Figure 5.1. The FROM NAMED clause contains a set of valid time IRIs of named graphs to be used for matching VTRDF triple or graph patterns. More than one named graphs can be specified, and each named graph's IRI should be separated by space.

4. WHERE clause

   The WHERE clause is mandatory for a VT-SPARQL query. At least one triple pattern is required in the WHERE clause. A VTRDF triple pattern is the same as a VTRDF triple in the form of $s^t\ p^t\ o^t$, with possibly some or all of the components being a valid time variable. A valid time variable starts with a question mark (?) followed by the name of the variable.

It is used in place of any position of subject, predicate or object to bind to any valid time resource in the VTRDF triple database. For instance, given the VTRDF graph in Figure 4.14 and a triple pattern, ?s :enrolled[2/1/2016, 5/31/2016) :SW[1/1/2003, now], the valid time variable ?s binds to the resource :John[1/15/1995, now]. Furthermore, the triple pattern implicitly satisfies the Temporal Triple Integrity given in Definition 4.5.9. For the sake of conciseness, we do not allow explicit specifications of valid time resources, i.e., an interval together with a resource name, in the WHERE clause. We only allow valid time variables to match valid time resources. However, the reference to the component of a valid time variable is allowed in parts of the WHERE clause.

5. FILTER clause

   A filter clause is optional within the *WHERE* clause. It introduces conditions for restricting output solutions that make the specified conditions true. When more than one filter condition is used, the logical *and* (&&) connects conditions to form a compound condition. Please note that logical *or* connector is not considered in VT-SPARQL. Filter conditions can be formed for the following types of variable bindings or values:

   (a) Literal values by regular expressions

   A regular expression, or regex, is used in the standard SPARQL [58, 32] for comparing literals. In VT-SPARQL, each regular expression takes two arguments, as follows:

$$regex(text, pattern) \tag{5.1.1}$$

   The first argument *text* is the bound literal value that can be either an actual literal or a reference to the resource part of a valid time variable by the dot notation. The *pattern* represents a simple literal to be compared with the text. The regex expression returns true if the *text* matches or contains the *pattern*, otherwise it returns false.

(b) Numerical values by arithmetic expressions

Arithmetic expressions are available in the standard SPARQL. In VT-SPARQL, arithmetic expressions are also allowed to filter numerical variable bindings via mathematical comparisons that use greater than ($>$), greater than equal to ($>=$), less than ($<$), less than equal to ($<=$), equal to ($=$), and not equal to ($\neq$).

(c) Standard Resource by SameResource expressions

For comparing the resource parts of valid time resources, we introduce *same resource expression*, or SameResource, into VT-SPARQL. A SameResource expression takes two arguments, as follows:

$$SameResource(res1, res2) \tag{5.1.2}$$

The expression checks whether two non-temporal resources, res1 and res2, are equivalent and returns true if they are. Otherwise, false is returned. res1 and res2 are references to the reaource parts of some valid time variables or valid time resources by the dot notation.

(d) Time intervals by temporal predicate

In order to compare time intervals, we introduce Allen's temporal predicates [4] into VT-SPARQL. Specifically, Allen's temporal predicates can be used to form conditions in the FILTER clause. These predicates defines thirteen possible relationships between two time intervals shown in Table 5.1. Each predicate takes two time intervals as arguments and returns true if the two intervals satisfy the specified condition. For instance, given two intervals: i=[2/1/2016, 5/31/2016) and j=[1/1/2017, now), the predicate Before(i, j) is true while Overlaps(i, j) is false. In VT-SPARQL, either a time interval literal, or a bound valid time variable that has been projected to its valid time part can appear as arguments of the temporal predicates shown in Table 5.1.

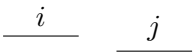
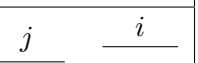
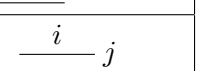
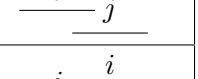
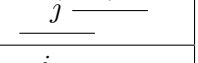
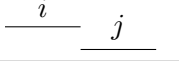
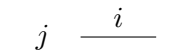
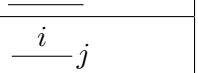
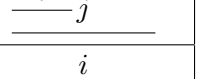
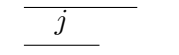
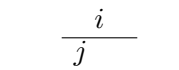
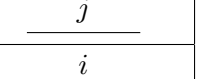
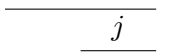
Predicate	Illustration
Before(i, j)	
After (i, j)	
Overlaps(i, j)	
OverlappedBy(i, j)	
Meets(i, j)	
MetBy(i, j)	
Starts(i, j)	
StartedBy(i, j)	
Finishes(i, j)	
FinishedBy(i, j)	
During(i, j)	
Contains(i, j)	
Equals(i, j)	

Table 5.1: Allen's Temporal Relations [4]

6. ORDER BY clause

   ORDER BY clause is used to modify the order of the output based on the specified order comparator list. Each order comparator is composed of a bound valid time variable and an optional order modifier. The order modifier is either ascending, indicated by ASC( ), or descending, indicated DESC(). For instance, suppose ?student is a valid time variable, ORDER By DESC(?student) modifies the output sequence to a descending alphabetic order based on the valid time IRI of bound values of ?student.

5.2 VT-SPARQL Examples

Now we give VT-SPARQL query examples based the VTRDF triple database shown in Figure 5.2.

```
# VTRDFGraph: http://example.org/temporal-SW/VTSPARQLDefaultGraph
:SW[1/1/2003, now]  vtrdf:type[1/1/2003, now]  :Course[1/1/1970, now].
:SW[1/1/2003, now]  :CourseName[1/1/2003, now]
"The Semantic Web"^^ xsd:string[0, ∞].
:SW[1/1/2003, now]  :requiredTextbook[2/1/2016, 5/31/2016)
:book1[1/1/2014, now].
:book1[1/1/2014, now]  :title[1/1/2014, now]
"Introduction to Semantic Web Technology"^^xsd:string[0,∞].
:book1[1/1/2014, now]  :listPrice[2/1/2016, 5/31/2016)
"149"^^ xsd:integer[0, ∞].
:Student[1/1/1970, now] vtrdf:type[1/1/1970, now]
vtrdfs:Class[1/1/1500, now].
:undergraduateStudent[1/1/1970, now]  vtrdf:type[1/1/1970, now]
vtrdfs:Class[1/1/1500, now].
:graduateStudent[1/1/1970, now]  vtrdf:type[1/1/1970, now]
vtrdfs:Class[1/1/1500, now].
:Course[1/1/1970, now] vtrdf:type[1/1/1970, now]
 vtrdfs:Class[1/1/1500, now].
:City[1/1/1500, now] vtrdf:type[1/1/1500, now]
 vtrdfs:Class[1/1/1500, now].
:John[1/10/1995, now] vtrdf:type[2/1/2016, now]
:graduateStudent[1/1/1970, now].
:John[1/10/1995, now] :enrolled[2/1/2016, 5/31/2016)
:SW[1/1/2003, now].
:John[1/10/1995, now] :enrolled[2/1/2016, 5/31/2016)
:OOP[1/1/2003, now].
:John[1/10/1995, now] :enrolled[2/1/2018, 5/31/2018)
:DBMS[1/1/1970, now].
:John[1/10/1995, now] :livedIn[1/10/1995, now]  :NYC[1/1/1624, now].
:Alex[3/15/1996, now] :type[2/1/2018, now]
:undergraduateStudent[1/1/1970, now].
:Alex[3/15/1996, now] :enrolled[2/1/2018, 5/31/2018]
:DBMS[1/1/1970, now].
```

Figure 5.2: The VTRDF Triple Database for VT-SPARQL Query Examples

The database is taken from Figure 4.14 along with more triples added for demonstrating each clause and language component defined in the previous seciton. We also reference the database in Figure 5.2 by the graph name, G^t, whose valid time IRI is:
http://example.org/temporal-SW/VTSPARQLDefaultGraph.
For each query example, it is presented in two parts unless otherwise specified: the query statement and the output. While the query statement is written in Turtle [9], the output is presented in a tabular format to avoid using verbose expressions. When necessary, the output can also be presented by graphs.

1. Find all triples about John as a subject. Output valid time resources.

```
PREFIX :  <http://example.org/temporal-SW#>.
SELECT :John[1/10/1995, now] ?predicate ?object
FROM <http://example.org/temporal-SW/VTSPARQLDefaultGraph>
WHERE
{
:John[1/10/1995, now] ?predicate ?object
}
```

:John	predicate	object
:John[1/10/1995, now]	vtrdf:type[2/1/2016, now]	:graduateStudent[1/1/1970, now]
:John[1/10/1995, now]	:enrolled[2/1/2016, 5/31/2016)	:SW[1/1/2003, now]
:John[1/10/1995, now]	:enrolled[2/1/2016, 5/31/2016)	:OOP[1/1/2003, now]
:John[1/10/1995, now]	:enrolled[2/1/2018, 5/31/2018)	:DBMS[1/1/1970, now]
:John[1/10/1995, now]	:livedIn[1/10/1995, now]	:NYC[1/1/1624, now]

Table 5.2: Output of Query 1: Find all triples about John as a subject

2. Find courses in which John enrolled in [2/1/2016, 5/31/2016). Output valid time resources.

```
PREFIX :  <http://example.org/temporal-SW#>.
SELECT ?object
FROM <http://example.org/temporal-SW/VTSPARQLDefaultGraph>
WHERE
{
:John[1/10/1995, now] :enrolled[2/1/2016, 5/31/2016) ?object.
}
```

object
:SW[1/1/2016, now]
:OOP[1/1/2016, now]

Table 5.3: Output of Query 2: Find courses in which John enrolled in [2/1/2016, 5/31/2016)

3. Find the course names in which John enrolled in [2/1/2016, 5/31/2016). Output the literals of course names.

```
PREFIX :  <http://example.org/temporal-SW#>.
SELECT ?name.res
FROM <http://example.org/temporal-SW/VTSPARQLDefaultGraph>
WHERE
{
:John[1/10/1995, now] :enrolled[2/1/2016, 5/31/2016) ?course.
?course :CourseName[2/1/2016, 5/31/2016) ?name.
}
```

In Query 3, a VTRDF graph pattern is introduced in the WHERE clause. To make sense of this query, it is required that the valid time of the two predicates :enrolled and :CourseName equals.

name.res
”The Semantic Web”

Table 5.4: Output of Query 3: Find the course names in which John enrolled in [2/1/2016, 5/31/2016)

That is, both the enrolled courses and their course names should be valid during the same time interval. As a consequence, in evaluating the query, for all triples (s^t, p^t, o^t) in the VTRDF triple database, the property :CourseName[2/1/2016, 5/31/2016) matches any p^t if and only if :CourseName[2/1/2016, 5/31/2016) is a resource slice of p^t. That is, applying the resource slice projection function defined in Definition 4.5.8 with the interval [2/1/2016, 5/31/2016) to p^t should yield :CourseName[2/1/2016, 5/31/2016).

4. Find course names that contain the literal ”Semantic”. Output the literals of course names.

```
PREFIX :  <http://example.org/temporal-SW#>.
SELECT ?name.res
FROM <http://example.org/temporal-SW/VTSPARQLDefaultGraph>
WHERE
{
?subject :CourseName[1/1/2003, now] ?name.
FILTER regex(?name.res, "^Semantic")
}
```

name.res
”The Semantic Web”

Table 5.5: Output of Query 4: Find course names that contain the literal ”Semantic”

Query 4 retrieves the course names that contain the literal ”Semantic”. Note that the symbol $\wedge$ in the *pattern* argument indicates that both an exact and approximate matches are accepted.

The regex in the filter clause evaluates the bound $?name.res$ against the specified pattern and returns a boolean.

5. Find books that have a list price higher than 100 dollars. Output the literals of book names.

```
PREFIX :  <http://example.org/temporal-SW#>.
SELECT ?bookName.res
FROM <http://example.org/temporal-SW/VTSPARQLDefaultGraph>
WHERE
{
?book ?predicate1 ?bookName.
?book ?predicate2 ?price.
FILTER (?price.res > 100 &&
SameResource(?predicate1.res, :title) &&
SameResource(?predicate2.res, :listPrice) &&
Equals(?book.vt, ?predicate1.vt) &&
Equals(?book.vt, ?predicate2.vt))
}
```

bookName.res
”Introduction to Semantic Web Technology”

Table 5.6: Output of Query 5: Find books that have a list price higher than 100 dollars

In Query 5, the graph pattern is matched as follows: for all triples (s^t, p^t, o^t) in the VTRDF triple database, ?predicate1 matches p^t if and only if ?predicate1 is a resource slice of :title[1/1/2014, now]. Similarly, ?predicate2 matches p^t if and only if ?predicate2 is a resource slice of :listPrice[2/1/2016, 5/31/2016).

6. Find the city where John lived when he enrolled in the course SW in [2/1/2016, 5/31/2016). Output the valid time resources.

```
PREFIX :  <http://example.org/temporal-SW#>.
SELECT ?city
FROM <http://example.org/temporal-SW/VTSPARQLDefaultGraph>
WHERE
{:John[1/10/1995,now] :enrolled[2/1/2016, 5/31/2016) :SW[1/1/2003, now].
:John[1/10/1995,now] ?predicate ?object.
FILTER (SameResource(?predicate.res, :livedIn) &&
Contains(?predicate.vt, [2/1/2016, 5/31/2016)))
}
```

city
:NYC[1/1/1624, now]

Table 5.7: Output of Query 6: Find the city where John lived when he enrolled in the course SW in [2/1/2016, 5/31/2016)

7. Find students who enrolled in th course SW and the course Object-Oriented Programming (OOP) at the same time. Output the valid time resources.

```
PREFIX :  <http://example.org/temporal-SW#>.
SELECT ?student
FROM <http://example.org/temporal-SW/VTSPARQLDefaultGraph>
WHERE
{
?student ?e1 :SW[1/1/2003, now].
?student ?e2 :OOP[1/1/1990, now].
FILTER (SameResource(?e1.res, ?e2.res) &&
SameResource(?e1.res, :enrolled) &&
Equals(?e1.vt, ?e2.vt))
}
```

student
:John[1/10/1995, now]

Table 5.8: Output of Query 7: Find students who enrolled in th course SW and the course Object-Oriented Programming (OOP) at the same time

8. Find courses that have both undergraduate and graduate students enrolled. Output the valid time resources.

```
PREFIX :  <http://example.org/temporal-SW#>.
SELECT ?course
FROM <http://example.org/temporal-SW/VTSPARQLDefaultGraph>
WHERE
{
?student1 ?type1 graduateStudent[1/1/1970, now].
?student1 ?e1 ?course.
?student2 ?type2 undergraduateStudent[1/1/1970, now].
?student2 ?e2 ?course.
FILTER (SameResource(?type1.res, rdf:type) &&
SameResource(?type2.res, rdf:type) &&
Contains(?type1.vt, ?e1.vt) &&
Contains(?type2.vt, ?e2.vt) &&
SameResource(?e1.res, :enrolled) &&
SameResource(?e2.res, :enrolled) &&
Equals(?e1.vt, ?e2.vt))
}
```

course
:DBMS[1/1/1970, now]

Table 5.9: Output of Query 8: Find courses that have both undergraduate and graduate students enrolled

9. Construct a VTRDF graph that contains the property *resident of* for John, Output the VTRDF graph.

```
PREFIX :  <http://example.org/temporal-SW#>.
CONSTRUCT {:John[1/10/1995, now] ?predicate ?city.}
FROM <http://example.org/temporal-SW/VTSPARQLDefaultGraph>
WHERE
{
 :John[1/10/1995, now] :livedIn[1/10/1995, now] ?city.
 FILTER ( SameResource(?predicate.res, :residentOf) &&
 Equals(?predicate.vt, [1/10/1995, now])
}
```

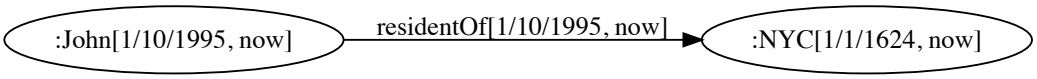


Figure 5.3: Output of Query 9: Construct a VTRDF graph that contains the property *resident of* for John, Output the VTRDF graph

10. Find courses in which John enrolled in the year of 2016. Output the course resource and the time of enrollment separately. Order by the course resource in ascending order.

```
PREFIX :  <http://example.org/temporal-SW#>.
SELECT ?course.res ?enroll.vt
FROM <http://example.org/temporal-SW/VTSPARQLDefaultGraph>
WHERE
{
:John[1/10/1995, now] ?enroll ?course.
FILTER (SameResource(?enroll.res, :enrolled) &&
Contains([1/1/2016, 12/31/2016), ?enroll.vt) &&
)
ORDER BY ASC(?course.res)
}
```

course.res	enroll.vt
:OOP	[2/1/2016, 5/31/2016)
:SW	[2/1/2016, 5/31/2016)

Table 5.10: Output of Query 10: Find courses in which John enrolled in the year of 2016

Chapter 6

Complexity of VTRDF

Definitions of VTRDF, how it is used, formal semantics, and VT-SPARQL queries have been presented in Chapter 4 and 5. While the implementation of VTRDF triple store is beyond the scope of this thesis, we want to analyze the computational property of VTRDF, particularly the space and time complexity. In this chapter, we would discuss the complexity of VTRDF by considering native and non-native storage approaches adopted from the complexity analysis of the standard RDF covered in Appendix A.7. Space requirement, insertion, deletion, update, and retrieval operations, and the evaluation of VT-SPARQL queries are considered.

In Chapter 3, we have provided a comparison of temporal data models of the Semantic Web in Table 3.2. We also include VTRDF in the table for comparison. Particularly, the number of triples needed and the need of additional objects are our main concern. As VTRDF treats all resources uniformly, no additional object is needed for modeling temporal data and knowledge herein, and the number of triples remains the same. To encode a valid time resource, we have extended the standard IRI to the valid time IRI. Each character of a valid time IRI may occupy one to four bytes, plus sixteen bytes for the time interval (i.e., eight bytes for the lower bound instant and eight bytes for the upper bound instant). A length ℓ valid time IRI occupies $(\ell + 16)$ bytes to $(4\ell + 16)$ bytes.

We analyze the non-native approach first. Consider a VTRDF triple store containing n triples

and a graph pattern GP where there are m triple patterns in a VT-SPARQL query. Also consider that we use a relational DBMS. The VTRDFDB would require $3n\ell + 48n$ bytes to $12n\ell + 48n$ bytes. Therefore the space complexity is still $\mathcal{O}(1)$. Naturally, the VTRDFDB is mapped to a relational DBMS. Table 6.1 shows the result of converting the VTRDF triple database for VT-SPARQL queries shown in Figure 5.2 to a six-column table in a relational DBMS.

s.res	**s.vt**	**p.res**	**p.vt**	**o.res**	**o.vt**
:SW	[1/1/2003, now]	vtrdf:type	[1/1/2003, now]	:Course	[1/1/1970, now]
:SW	[1/1/2003, now]	:CourseName	[1/1/2003, now]	"The Semantic Web"∧∧ xsd:string	[0, ∞]
...	...	...	...	...	
...	...	...	...	...	
:John	[1/10/1995, now]	:enrolled	[2/1/2016, 5/31/2016)	:SW	[1/1/2003, now]
:John	[1/10/1995, now]	:enrolled	[2/1/2016, 5/31/2016)	:OOP	[1/1/2003, now]
...	...	...	...	...	

Table 6.1: Mapping from a VTRDF Triple Database of Figure 5.2 to a Six-Column Relational Database

In the above table, The column s.res, p.res, and o.res correspond to triples in the standard RDF, which requires $3n\ell$ to $12n\ell$ bytes, as analyzed in Appendix A.7. The column s.vt, p.vt, and o.vt are the addition, and they contribute $48n$ bytes. Even though the result is larger than the standard RDF case, its space complexity is still $\mathcal{O}(1)$.

For insertion, deletion, and update operations, they are of the same complexity as in the relational database, which is $\mathcal{O}(1)$. For retrieval or search operations, among others, there are two possibilities: sequential search and index search. We also assume that there is a preprocessor for converting VTRDF queries to the standard RDF queries. Therefore, the efficiency of the sequential search would be $\mathcal{O}(n)$, and the index search is $\mathcal{O}(\log n)$. Clearly, the processing of VTRDF retrieval is more complex since a more complex data structure is used for representing valid time resources. However, their effect on the processing time is still limited.

As we have indicated that there is a preprocessor that converts VTRDF to RDF, all clauses of VT-SPARQL defined in Chapter 5 directly apply to SPARQL, except a few changes, as follows:

- A valid time variable in VT-SPARQL is converted to a resource variable in SPARQL. Moreover, it is allowed to refer to the components of a valid time variable, i.e., the resource part and the valid time part.

- In regular or arithmetic expressions, references to the resource part and the valid time part of valid time resources or valid time variables are allowed.

- SameResource in VT-SPARQL expressions are converted to regular expressions in SPARQL, which compare literal values.

- Temporal predicates in VT-SPARQL can be directly converted to arithmetic expressions in SPARQL.

The preprocessor would use these rules to convert a VT-SPARQL query to an equivalent SPARQL query, which is then evaluated against the temporal triple store.

On this basis, we adopt the complexity analysis in [57], which showed that evaluating SPARQL queries can be solved in time $\mathcal{O}(mn)$, where m is the number of triple patterns and n is the number of triples in the triple database, for a graph pattern formed by using only AND and FILTER operators. This case is the same as our VT-SPARQL query evaluation based on the analysis of correspondence between VT-SPARQL and SPARQL. That is, evaluating VT-SPARQL queries can also be solved in time $\mathcal{O}(mn)$. Furthermore, it is also shown in [57] that if the UNION and OPTION operator are allowed in the graph pattern expressions, the query evaluation becomes NP-complete and PSPACE-complete.

Even though the complexity of VTRDF entailment is beyond the scope of this thesis, we have a few observations. As we have indicated that VTRDF is RDF-compliant, the complexity of VTRDF entailment may resemble the case of the entailment in the standard RDF. That is, both VTRDF and VTRDFS entailments are NP-Complete. As a hint for further analysis, we observe that in Temporal RDF [30, 19] that we have surveyed, which incorporated one timestamp into a RDF

triple and used RDF reification, it has been proved that the temporal entailment for temporal RDF graphs is NP-complete. This outcome the remains the same as the case in the standard RDF analyzed in Appendix A.7. In other words, the time dimension does not increase the complexity of non-temporal entailment.

Chapter 7

Conclusions and Future Works

This thesis focuses on modeling binary relations that have the necessity of adding an additional temporal dimension with the standard RDF, which is a binary-relation-only model. There are extensive research efforts underway for incorporating temporality into RDF and its variants. For temporal data models, two attributes of time are usually considered: valid time and transaction time. As the majority of temporal models reported focus on the valid-time aspect of temporality, we select valid time as the additional dimension. We therefore investigate proposals of temporal models of the Semantic Web in the literature. These models mainly extend RDF, RDFS, or OWL to represent temporal data by either Explicit Reification or Implicit Reification, which are the basis of a taxonomy, shown in Figure 3.11, that we have developed to classify them. While Explicit Reification is a method included in the RDF standard, Implicit Reification aims at generating identity by which additional data can be specified in RDF. We expect that the taxonomy would be a base for a better understanding of temporal extensions to RDF. Additionally, we have summarized key characteristics of these models and provided them in Table 3.2. The summary in Table 3.2 would be useful for the researchers and practitioners of the Semantic Web. We envision that RDF, RDFS or OWL compliant temporal models can be handled and implemented directly, and available tools, such as triple stores and reasoners can also be used. However, representing temporal data and

knowledge definitely requires additional triples. The proliferation of triples causes performance, maintenance and storage issues. A feasible solution would be to reduce the number of additional triples to a minimum for representing temporal data. Also, this would make writing queries more intuitive and less complex.

On this basis, we adopt a modeling approach motivated by the 4D view to address the issues we have observed in the survey. Most proposals we investigated in Chapter 3 concern only one timestamp for a given RDF triple. However, we believe that three timestamps should be incorporated for fully representing temporal knowledge in order to preserve the complete temporal aspect of a RDF triple. Every resource naturally comes with a valid timestamp that denotes its existence in time. When two resources coexist in time and form a binary relationship, a *factual* time is settled. This is the timestamp that most of the proposals surveyed in Chapter 3 focus on. Altogether, we observe that three timestamps are necessary for a binary relationship. To materialize the idea, we come up with the *valid time resource*, and propose Valid Time RDF, or VTRDF. VTRDF takes the valid time resource as its first-class citizen. A valid time resource is a RDF-compliant resource equipped with a valid time that denotes its existence in time. Our approach treats all resources in VTRDF uniformly, which is significant in that the need of RDF reification is eliminated. In particular, using VTRDF to handle temporal data and knowledge requires no additional triples or objects.

To formally represent valid time resources, and construct VTRDF triples and graphs, we extend the standard IRI to Valid Time IRI, which separates the second fragment identifier by a delimiter (•) in addition to the first fragment identifier delimited by # of the standard IRI. For time representation, we employ interval-based timestamps defined in section 4.2, whose unit of time points is the standard U.S. calendar days in the format of month/day/year. Furthermore, literals, data types, blank nodes of the standard RDF are all *temporalized* to their valid time variants. Operations for valid time resources are carried out by a family of projection functions, which project valid time resources to various dimensions, such as the resource dimension and the valid time dimension.

For convenience, we allow the dot notation (.) to denote a projection to a given dimension. For instance, $v^t.res$ denotes a non-temporal resource part of the valid time resource v^t.

A VTRDF triple is defined over qualifying valid time resources. Each VTRDF triple is required to satisfy the *Temporal Triple Integrity* given in Definition 4.5.9. For compactness, we confine a VTRDF graph to strict temporal constraints given in Definition 4.5.11. On top of simple use of VTRDF, we define layered sets of VTRDF vocabulary and VTRDF Schema vocabulary, which are the temporal variants of their counterparts in the standard RDF. These new vocabularies are under the customized namespace prefixed by vtrdf: and vtrdfs: respectively. The formal semantics of VTRDF is given by the model-theoretic semantics, which uses interpretation models and semantic conditions for evaluating VTRDF triples and graphs. We also identify useful entailment patterns for both VTRDF and VTRDF Schema vocabularies.

For querying VTRDF triple databases, we design a query language, Valid Time SPARQL (VT-SPARQL). As VTRDF differs from the standard RDF, additional requirements are considered in designing VT-SPARQL. For instance, the representation of valid time resources, time intervals, and instants are available. Valid time variables are used in VT-SPARQL in correspondence to the standard variables in SPARQL. Specifically a valid time variable matches to a valid time resource. Two query forms are considered in VT-SPARQL: SELECT and CONSTRUCT queries. For FILTER conditions used within the WHERE clause, we incorporate Allen's temporal predicates [4] for comparing time intervals explicitly. Either a time interval literal, or a bound valid time variable that has been projected to its valid time part can appear as arguments of the temporal predicates. We have also provided a set of examples in VT-SPARQL. These examples demonstrate the use of built-in constructs of VT-SPARQL with an example triple database that originated from the running example given in Figure 4.3.

In the complexity analysis of VTRDF, we have shown that storing VTRDF triples in a relational database requires $3n\ell + 48n$ bytes to $12n\ell + 48n$ bytes where n is the number of triples in the VTRDF triple database. Even though the space requirement is higher, its space complexity

is still $\mathcal{O}(1)$. Furthermore, there is no additional object needed for modeling temporal data and knowledge, and the number of triples remains the same. For insertion, deletion, and update operations, they are of the same time complexity as in the relational database, which is $\mathcal{O}(1)$. For retrieval or search operations, the efficiency of the sequential search would be $\mathcal{O}(n)$, and the index search is $\mathcal{O}(\log n)$. The processing of VTRDF retrieval is more complex since a more complex data structure is needed for representing valid time resources. However, their effect on the processing time is still limited.

We assume a non-native implementation of VTRDF triple database and also a preprocessor. The complexity of evaluating VT-SPARQL queries therefore resembles the complexity of evaluating SPARQL queries based on their corresponding constructs and changes discussed in chapter 6. Evaluating SPARQL queries can be solved in time $\mathcal{O}(mn)$, where m is the number of triple patterns and n is the number of triples in the triple database, for the graph pattern formed by using only AND and FILTER operators. Furthermore, it is also shown in [57] that if the UNION and OPTION operator are allowed in the graph pattern expressions, the query evaluation becomes NP-complete and PSPACE-complete.

There are several directions that we can further investigate. The majority of temporal models focuses on the valid time aspect of temporality. However, being able to incorporate other temporal dimensions, such as transaction time or bitemporal, would allow richer implementation in temporal semantics of the Semantic Web applications. A top-level time ontology that provides enough temporal expressive power, and facilitates more powerful temporal reasoning would be highly desirable too.

In this thesis, we do not address the impact of valid time blank nodes on the semantics of VTRDF graphs. Valid time blank nodes are used to denote existential resources without specifying their valid time IRIs, and the semantics requires definitions of closure properties of VTRDF graphs. This extension will allow more VTRDF modeling cases that involve anonymous resources or timestamps.

For VT-SPARQL, we only allow valid time variables and require matching to valid time resources exclusively. We can further open up more query scenarios by allowing two additional types of variables: standard resource variables and time interval variables. A standard resource variable would be used in place of the resource part of a valid time resource. It is to bind to a standard resource provided that their valid time strictly matches. A time interval variable, represented by two instant variables, which are the beginning and end instants, would be used in place of the valid time part of a valid time resource. In this way, we will be able to represent an arbitrary valid time resource by concatenating an arbitrary atemporal resource with a valid timestamp.

Lastly, regarding the implementation, we are looking at available tools and packages, shown in Table B1 of Appendix B, that are open to customization of our VTRDF triple database and VT-SPARQL query language. For instance, Protege [51] has been a popular ontology editor and knowledge management system develop by Stanford Center for Biomedical Informatics Research. The Valid-Time Temporal Model of [55] surveyed in section 3.4.1 has also contributed a Protege Plugin and SWRLTab to work with SWRL rules and SQWRL queries. Extending Protege to have the capability of VTRDF could be a worthwhile effort.

Appendices

A.1 RDF Definitions

The following definitions provide foundations of RDF model and its semantics.

Definition A.1.1. RDF Resource

A RDF resource, r, is any object that can be identified universally. A RDF resource is denoted by an IRI, or a local identified for a blank node. We designate $\mathcal{R}$ as an infinite set of standard RDF resources.

Definition A.1.2. International Resource Identifier (IRI)

International Resource Identifier, or IRI [23], is an internet protocol standard that is based on Uniform Resource Identifier, or URI. IRI allows more characters to be used compared to URI. In the RDF model, an IRI identifies a resource. For instance, a resource John is identified by an IRI, http://example.org/RDF-SW#John. The symbol # separates the main name space from the fragment identifier.

Definition A.1.3. RDF Literal

A RDF literal, l, is used for denoting a concrete value, such as a string, a date, or an integer. A literal is also a constant and will not change its value. A RDF literal contains either two or three components [21]:

- A lexical form in an unicode string.
- A data type IRI.
- An optional language tag identified by the IRI, http://www.w3.org/1999/02/22-rdf-syntax-ns#langString.

For instance, "1"^^xsd:integer denotes an integer 10 by the XML Schema integer type. We designate $\mathcal{L}$ as a set of all RDF literals.

Definition A.1.4. RDF Data Type

A RDF data type, d, is used with a RDF literal to represent a concrete value. A data type is denoted by one or more IRIs and consists of:

- A non-empty set of unicode strings as the lexical space $\mathcal{L}(d)$.
- A non-empty value space $\mathcal{V}(d)$.
- A lexical-to-value mapping $L2V$: $\mathcal{L}(d) \rightarrow \mathcal{V}(d)$.

Definition A.1.5. Lexical to Value Mapping function (L2V)

L2V is a partial mapping from the lexical space of RDF literals to the value space $\mathcal{V}$. For a RDF literal l annotated with a data type d, its value is obtained from the value space by L2V. That is: $L2V(l, d) = v$ where $v \in \mathcal{V}$. The $L2V$ mapping can be one-to-one or many-to-one. As an example for the later case, XML schema data type *xsd:boolean* [13] has the type specification as follows:

- $\mathcal{L}(d) = \{"0", "1", "T", "F"\}$
- $\mathcal{V}(d) = \{true, flase\}$
- $L2V : \{"T" \rightarrow true, "F" \rightarrow false, "1" \rightarrow true, "0" \rightarrow false\}$

Definition A.1.6. RDF Property

Let $\mathcal{P}$ be the set of any properties. A RDF property $p \in \mathcal{P}$ is any binary relation that relates two logically compatible RDF resources. $\mathcal{P}$ include properties that belong to RDF and RDFS vocabularies, which will be defined in section A.2 and section A.3 respectively.

Definition A.1.7. RDF Blank Node

Let $\mathcal{B}$ be a set of blank node, a RDF blank node $b \in \mathcal{B}$ denotes the existence of a RDF resource whose IRI is not yet known. b is typically assigned a local identifier which has an effective scope limited to a local RDF triple database.

Definition A.1.8. RDF Triple

A RDF triple is in the form of (s, p, o) where s, p, o are RDF resources defined as follows. They represent the subject, predicate, and object respectively.

- $s \in \mathcal{R} \cup \mathcal{B}$
- $p \in \mathcal{P}$
- $o \in \mathcal{R} \cup \mathcal{B} \cup \mathcal{L}$

Definition A.1.9. RDF Graph

A RDF graph, G, is a set of RDF triples defined as follows:

$$G = \{(s, p, o) | s \in (\mathcal{R} \cup \mathcal{B}) \wedge p \in \mathcal{P} \wedge o \in (\mathcal{R} \cup \mathcal{B} \cup \mathcal{L})\} \tag{A.1.1}$$

Definition A.1.10. Subgraph

A RDF graph H is a subgraph of another RDF graph$G$ if H includes some of the RDF triples in G. For instance, the RDF graph in Figure A1 is a subgraph of the graph in Figure 2.4. A proper subgraph is a proper subset of the RDF triples in the graph.

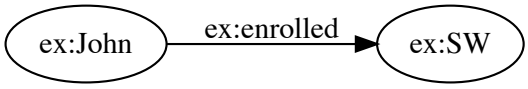


Figure A1: A RDF Subgraph of the Running Example in Figure 2.4

Definition A.1.11. RDF Graph Vocabulary

Given a RDF graph G and the set of RDF resources $\mathcal{R}$ appear in G, the vocabulary $voc(G)$ is the set of valid IRIs that appear in G excluding RDF literals.

Definition A.1.12. Ground RDF Triple and Graph

A ground RDF triple is a RDF triple that does not contain any blank nodes. A ground RDF graph is therefore a RDF graph that contains only ground RDF triples.

Definition A.1.13. RDF Mapping Function

A mapping function, $M : (R \cup B \cup L) \rightarrow (R \cup B \cup L)$, maps a RDF resource, a RDF literal, or a RDF blank node to a RDF resource, a RDF literal, or another RDF blank node. M is defined to map elements of one RDF graph to another. Four mapping cases at the resource level are defined for two given RDF graphs G_1^t and G_2^t as follows:

- $M(r_1) = r_2$ where $r_1 \in G_1$, $r_2 \in G_2$, and $r_1 = r_2$.
- $M(l_1) = l_2$ where $l_1 \in G_1$, $l_2 \in G_2$, and $l_1 = l_2$.
- $M(b) = r$ where $b \in G_1$, and $r \in G_2$.
- $M(b_1) = b_2$ where $b_1 \in G_1$, and $b_2 \in G_2$.

In addition, M can be overloaded to map a RDF graph. Given a RDF graph G, $M(G)$ maps to a set of all $(M(s), M(p), M(o)$ where $(s, p, o) \in G$.

A.2 RDF Vocabulary (rdfV)

The RDF model provides ontological modeling primitives to define terminology vocabularies and use them for asserting facts. The following set of vocabularies, called RDF vocabulary, or rdfV, provides more expressive power so that we can model more knowledge for the running example in Figure 2.4. l

- rdf:Property is the superclass of all properties.

- rdf:type is a RDF property to represent *instance of* relationship between an instance and a class.
- rdf:Statement is the superclass of all RDF statements.
- rdf:subject, rdf:predicate and rdf:object are RDF properties used to assert the subject, predicate and the object of a RDF statement respectively. They are intended to be used in the reification. The definition of RDF reification and its implication have been discussed in the next section.

By using rdfV, additional knowledge about the running example of Figure 2.4 can be expressed. Figure A2 shows a RDF graph that contains three fresh facts: John is a student, NYC is a city, and SW is a course.

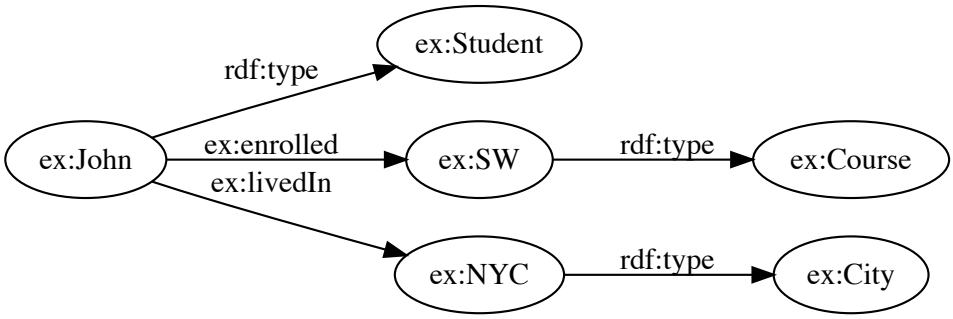


Figure A2: Running Example with Additional Facts in RDF Vocabulary (rdfV)

In addition, a set of axioms, shown in Figure A3, follows from the above definitions of vocabularies.

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>.


rdf:type  rdf:type  rdf:Property.
rdf:subject  rdf:type  rdf:Property.
rdf:predicate  rdf:type  rdf:Property.
rdf:object  rdf:type  rdf:Property.
```

Figure A3: Axioms of RDF Vocabulary (rdfV)

A.3 RDF Schema Vocabulary (rdfsV)

RDF schema, or RDFS, extends RDF vocabulary (rdfV) to allow descriptions of classes, class taxonomies, and class properties. For RDF properties, their domain and range can also be defined.

Definition A.3.1. RDF Class

A RDF class c is any set of similar resources. Each member is an instance of the class and defined by using rdf:type assertions. Class hierarchy can also be defined by a subclass relationship. We designate $\mathcal{C}$ as the set of all RDF classes.

RDFS vocabularies are characterized as follows:

- RDF Classes:
  - rdfs:Resource is the superclass of all RDF resources.
  - rdfs:Literal is the class of all RDF literals.
  - rdfs:Class is the the class of all RDF classes.
- RDF Properties:
  - rdfs:domain defines the domain of a property. It is also used to define itself.

- rdfs:range defines the range of a property. It is also used to define itself.
- rdfs:subClassOf defines the class hierarchy.
- rdfs:subPropertyOf defines the property hierarchy.

A set of axioms in Figure A4, written in Turtle syntax [9], follows from the above definitions of the RDF classes and properties.

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>.
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>.

rdfs:Class  rdfs:subClassOf  rdfs:Resource.
rdfs:Property  rdfs:subClassOf  rdfs:Resource.
rdfs:Literal  rdfs:subClassOf  rdfs:Resource.
rdf:type  rdfs:domain  rdfs:Resource.
rdf:type  rdfs:range  rdfs:Class.
rdfs:domain  rdfs:domain  vtrdf:Property.
rdfs:domain  rdfs:range  rdfs:Class.
rdfs:range  rdfs:domain  vtrdf:Property.
rdfs:range  rdfs:range  rdfs:Class.
rdfs:subClassOf  rdfs:domain  rdfs:Class.
rdfs:subClassOf  rdfs:range  rdfs:Class.
rdfs:subPropertyOf  rdfs:domain vtrdf:Property.
rdfs:subPropertyOf  rdfs:range  vtrdf:Property.
```

Figure A4: Axioms of RDF Schema Vocabulary (rdfsV)

By using the RDFS classes, class properties and the set of RDFS axioms, inference can be made. Entailed knowledge can be explicitly added. For instance, the type range axiom in Figure A4 allows us to infer that the resources ex:Student, ex:Course and ex:City are all range values of type assertions. Therefore they are RDF classes. The inferred triples are shown in Figure A5 and we are adding them to the graph of Figure A2 and end up with the updated graph shown in Figure A6. Please note that the definitions of the inference and entailment will be discussed in the section A.4.

```
ex:Student  rdf:type  rdfs:Class.
ex:Course rdf:type  rdfs:Class.
ex:City rdf:type  rdfs:Class.
```

Figure A5: Inferred Triples Based on the Range Axiom in Figure A4

Furthermore, properties about ex:enrolled and ex:livedIn can be asserted by using rdfs:domain and rdfs:range. In this way, they are defined as terminology vocabularies which are used to assert facts. Figure A7 shows the complete knowledge base, written in Turtle syntax [9], of the running example originally described in Figure A2 and Figure A6.

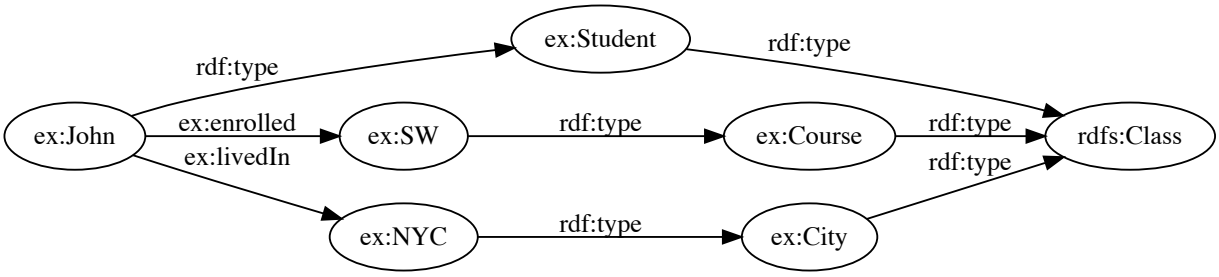


Figure A6: Running Example with Additional Facts in RDF Schema Vocabulary (rdfsV)

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>.
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>.
PREFIX ex: <http://example.org/RDF-SW#>.

ex:enrolled  rdfs:domain  ex:Student.
ex:enrolled  rdfs:range  ex:Course.
ex:livedIn  rdfs:domain ex:Student.
ex:livedIn  rdfs:range  ex:City.
ex:SW  rdf:type  ex:Course.
ex:Student  rdf:type  rdfs:Class.
ex:Course  rdf:type  rdfs:Class.
ex:City  rdf:type  rdfs:Class.
ex:John  rdf:type  ex:Student.
ex:John  ex:enrolled  ex:SW.
ex:John  ex:livedIn  ex:NYC.
```

Figure A7: Complete Knowledge Base of the Running Example with Additional Facts in Turtle Syntax

A.4 RDF Semantics and Entailment

The RDF model employs model-theoretic semantics to define its formal semantics [36]. A RDF triple or a RDF graph asserts facts about the world. The world is so situated that makes these assertions true. In order to evaluate the truth of a RDF triple or a RDF graph, an interpretation model is needed to specify the semantic conditions about the situated world. An interpretation model is basically a functional structure that defines how IRIs or literals should be mapped to the domain of the interpretation.

RDF is formed by layered sets of pre-defined vocabularies. In fact, the base layer hosts *simple vocabulary* that essentially allows any vocabularies except pre-defined ones. On top of it, data types are allowed, and further to RDF vocabulary, or rdfV and RDFS vocabulary or rdfsV. These layers of vocabularies give increasing expressive power for the RDF model.

In what follows we will characterize RDF model semantics by four groups of vocabularies, and define formal semantics for each respectively. In each group, an interpretation model is defined based on the interpretation domain and a set of semantic conditions for its pre-defined vocabularies. These groups of vocabularies are:

- Simple Vocabulary (V)

  V refers to any vocabularies excluding any data type D, rdfV, or rdfsV.

- Simple Vocabulary with Data Type (V-D)

  V-D includes the simple vocabulary V and data type D.

- RDF Vocabulary with Data Type D (rdfV-D)

  rdfv-D includes the simple vocabulary, data type D, and rdfV defined in section A.2.

- RDFS Vocabulary with Data Type D (rdfsV-D)

  rdfsV-D includes the above mentioned vocabularies and rdfsV defined in section A.3, mainly including: rdfs:Class, rdfs:subClassOf, rdfs:subPropertyOf, rdfs:domain, and rdfs:range.

An interpretation model is composed of a domain, mapping functions, and semantic conditions. Given a RDF graph, E, if there is an interpretation model I that makes E true, we say that I satisfies E and write $I(E) = \text{true}$. Otherwise E is unsatisfiable. Furthermore, defining an interpretation model also identifies a certain set of entailment patterns. Entailment, also known as the logical consequence, describes a satisfaction relationship between statements of logical formulas if one statement logically follows from one or more statements. Suppose a formula ψ logically follows from a formula ϕ. We say that ϕ entails ψ and write:

$$\phi \models \psi \tag{A.4.1}$$

The expression (A.4.1) reflects that there exists an interpretation model or truth assignment that satisfies ϕ also satisfies ψ. If we consider a RDF graph as a logical formula, the entailment regime should work similarly for RDF triples and graphs. As we shall see later, for a given vocabulary, we identify a set of entailment patterns which are on the other hand a set of inference rules. Inference rules are useful in that given a RDF graph, implicit triples can potentially be derived by applying appropriate inference rules. In other words, additional knowledge can be inferred and added to the original RDF graph .

A.4.1 Simple Interpretation

Given a simple vocabulary V, the simple interpretation I is defined as the following components:

- A set $\mathcal{R}$ of resources as the domain of I.
- A set $\mathcal{P}$ of RDF properties in I.
- A mapping $\mathbb{IXT}$ from $\mathcal{P}$ to $\mathcal{R} \times \mathcal{R}$.
- A mapping $\mathbb{IS}$ from IRI to $\mathcal{R} \cup \mathcal{P}$.

- A partial mapping $\mathbb{IL}$ from $\mathcal{L}$ to $\mathcal{R}$.

Given a ground RDF triple (s, p, o), $I((s, p, o))$ is true or satisfiable if all of the following conditions hold:

- $s, p, o \in V$
- $\mathbb{IS}(p) \in \mathcal{P}$
- $< \mathbb{IS}(s), \mathbb{IS}(o) > \in \mathbb{IXT}(\mathbb{IS}(p))$

Otherwise, $I((s, p, o))$ is false. Given a set of triples S, $I(S)$ is true or satisfiable if for every triple $(s, p, o) \in S$, $I((s, p, o))$ is true, otherwise $I(S)$ is false or unsatisfiable. We say that I is a model for S and write $I \models S$.

A.4.2 Simple Entailment

Given two RDF graphs G_1 and G_2, a simple entailment pattern can be identified as the subgraph relationship, which follows the *interpolation lemma* in the RDF specification [36], as follows:

G simply entails a graph E if and only if a subgraph of G is an instance of E (A.4.2)

As a result, if G_2 is a subgraph of G_1, G_1 entails G_2, or $G_1 \models G_2$. For instance, the RDF graph, G_1, in Figure A6 entails the graph, G_2, in Figure A2 because G_2 contains a subset of triples in G_1.

A.4.3 Simple-D Interpretation

On top of the simple interpretation, a simple-D interpretation satisfies additional semantic conditions with a set of IRIs that identifies RDF data types, denoted by D. Given the vocabulary V-D, the simple-D interpretation, I, is defined as the following conditions:

- Any RDF graph that contains ill-typed literals is false or unsatisfiable.

- For a RDF literal, l, together with a data type, d, where $l \in \mathcal{L}$ and $d \in \mathcal{D}$, represented as $l \wedge\wedge d$, its value is defined as:

$$\mathbb{IL}(l \wedge\wedge d) = L2V(I(d), l) \tag{A.4.3}$$

A.4.4 Simple-D Entailment

Given two RDF triples e_1 and e_2 that contain RDF literals l_1 and l_2, and data types: d_1, d_1 respectively, as follows:

$$\begin{aligned} e_1 &= (s, p, l_1^{\wedge\wedge} d_1) \\ e_2 &= (s, p, l_2^{\wedge\wedge} d_2) \end{aligned} \tag{A.4.4}$$

e_1 entails e_2 if and only if $L2V(l_1, I(d_1)) = L2V(l_2, I(d_2))$.

The simple-D entailment pattern holds if both literals l_1 and l_2 map to the same value under the lexical-to-value map of the data type in D, regardless of their surface representations. For instance, the entailment in expression A.4.5 holds as the two typed literals, "25.0"$\wedge\wedge$xsd:decimal and "25"$\wedge\wedge$xsd:decimal map to the same value of xsd:integer in D.

(ex:book1, ex:listPrice, "25.0"$^{\wedge\wedge}$xsd:decimal) $\models$ (ex:book1, ex:listPrice, "25"$^{\wedge\wedge}$ xsd:decimal) (A.4.5)

A.4.5 RDF Interpretation

Given rdfV given in section A.2, a RDF interpretation I is a simple-D interpretation and satisfies the additional semantic conditions as follows:

1. For a RDF property $p \in \mathcal{P}$, $(p, I(\text{rdf:Property})) \in \mathbb{IXT}(I(\text{rdf:type})$.

2. For a RDF literal l and a RDF data type d, $(l, I(d))$ is in $\mathbb{IXT}(I(\text{rdf:type})$ if and only if l is in the value space of $I(d)$.

3. The set of RDF axiomatic triples given in Figure A3 needs to be satisfied.

A.4.6 RDF Entailment

The first semantic condition given above leads to the following entailment pattern:
Given a RDF graph G and a RDF triple $(s, p, o) \in G$:

$$G \models (p, \text{rdf:type}, \text{rdf:Property}) \tag{A.4.6}$$

For instance, the following triple,

```
ex:John ex:enrolled ex:SW
```

entails

```
:enrolled rdf:type rdf:Property.
```

A.4.7 RDFS Interpretation

For the RDFS vocabulary, an additional component for mapping the set of RDFS classes, $\mathcal{C}$, of Definition A.3.1 is needed. A mapping function $\mathbb{CIXT}$ maps $\mathcal{C}$ to a subset of $\mathcal{R}$. A RDFS interpretation I recognizing $\mathcal{D}$ is defined as the following semantic conditions:

1. For a RDF class $c \in \mathcal{C}$, its mapping $\mathbb{CIXT}(c)$ is a collection of resources r that are of the same kind, and defined as:

$$c = \{r | (r, t) \in IXT(I(rdf : type))\} \tag{A.4.7}$$

2. $\mathbb{CIXT}(I(\text{rdfs:Resource}))=\mathcal{R}$. This states that the mapping of the superclass of all RDF resources is the domain of the interpretation I.

3. If $(r_1, r_2) \in \mathbb{IXT}(I(\text{rdfs:domain}))$ and $(x, y) \in \mathbb{IXT}(r_1)$, then $x \in \mathbb{CIXT}(r_2)$.

4. If $(r_1, r_2) \in \mathbb{IXT}(I(\text{rdfs:range}))$ and $(x, y) \in \mathbb{IXT}(r_1)$, then $y \in \mathbb{CIXT}(r_2)$.

5. $\mathbb{IXT}(I(\text{rdfs:subPropertyOf}))$ is transitive on $\mathcal{P}$.

6. If $(r_1, r_2) \in \mathbb{IXT}(I(\text{rdfs:subPropertyOf}))$, then $r_1 \in \mathcal{P}$, $r_2 \in \mathcal{P}$, and $\mathbb{IXT}(r_1) \subseteq \mathbb{IXT}(r_2)$.

7. If $c \in \mathcal{C}$, then $(x, I(\text{rdfs:Resource})) \in \mathbb{IXT}(I(\text{rdfs:subClassOf}))$.

8. $\mathbb{IXT}(I(\text{rdfs:subClassOf}))$ is transitive on $\mathcal{C}$.

9. If $(c_1, c_2) \in \mathbb{IXT}(I(\text{rdfs:subClassOf}))$, then $c_1 \in \mathcal{C}$, $c_2 \in \mathcal{C}$, and $\mathbb{CIXT}(c_1) \subseteq \mathbb{CIXT}(c_2)$.

10. The combined set of RDF and RDF schema axioms from Figure A4 and Figure A3 needs to be satisfied, as follows in Figure A8.

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#> .

rdf:type  rdf:type  rdf:Property.
rdf:subject  rdf:type  rdf:Property.
rdf:predicate  rdf:type  rdf:Property.
rdf:object  rdf:type  rdf:Property.
rdfs:Class  rdfs:subClassOf  rdfs:Resource.
rdfs:Property  rdfs:subClassOf  rdfs:Resource.
rdfs:Literal  rdfs:subClassOf  rdfs:Resource.
rdf:type  rdfs:domain  rdfs:Resource.
rdf:type  rdfs:range  rdfs:Class.
rdfs:domain  rdfs:domain  vtrdf:Property.
rdfs:domain  rdfs:range  rdfs:Class.
rdfs:range  rdfs:domain  vtrdf:Property.
rdfs:range  rdfs:range  rdfs:Class.
rdfs:subClassOf  rdfs:domain  rdfs:Class.
rdfs:subClassOf  rdfs:range  rdfs:Class.
rdfs:subPropertyOf  rdfs:domain vtrdf:Property.
rdfs:subPropertyOf  rdfs:range  vtrdf:Property.
```

Figure A8: Combined Set of Axioms of RDF and RDF Schema Vocabulary

A.4.8 RDFS Entailment

RDF schema entailment patterns are defined based on the RDFS interpretation model and semantic conditions discussed in section A.4.7.

1.
$$\frac{(p, \text{rdfs:domain}, c), \quad (s, p, o)}{(s, \text{rdf:type}, c)} \tag{A.4.8}$$

2.
$$\frac{(p, \text{rdfs:range}, c), (s, p, o)}{(o, \text{rdf:type}, c)} \tag{A.4.9}$$

3.
$$\frac{(p_1, \text{rdfs:subPropertyOf}, p_2), (p_2, \text{vtrdfs:subPropertyOf}, p_3)}{(p_1, \text{rdfs:subPropertyOf}, p_3)} \tag{A.4.10}$$

4.
$$\frac{(p, \text{rdfs:subPropertyOf}, q), (s, p, o)}{(s, q, o)} \tag{A.4.11}$$

5.
$$\frac{(c_1, \text{rdfs:subClassOf}, c_2), (c_2, \text{rdfs:subClassOf}, c_3)}{(c_1, \text{rdfs:subClassOf}, c_3)} \tag{A.4.12}$$

6.
$$\frac{(c_1, \text{rdfs:subClassOf}, c_2), (x, \text{rdf:type}, c_1)}{(x, \text{rdf:type}, c_2)} \tag{A.4.13}$$

A.5 SPARQL Query Language

SPARQL Protocol and RDF Query Language (SPARQL) [58, 32] is the main query language for RDF and RDFS. SPARQL supports four main query forms, among others: SELECT, CONSTRUCT, ASK, and DESCRIBE. For the scope of this research, we only consider the SELECT

and CONSTRUCT queries. A SPARQL SELECT or CONSTRUCT query is formed by using the grammar shown in Figure A9.

```
[PREFIX Prefix1:  IRIOfPrefix1]
[PREFIX ...]
{SELECT RDFResourceList | CONSTRUCT {RDFTripleList}}
[FROM IRIOfDefaultGraph]
[FROM NAMED IRIOfNamedGraphList]
WHERE
{RDFTriplePatternList
[FILTER (Expressions)]
}
[ORDER BY {ASC(orderComparatorList) | DESC(orderComparatorList)}]
```

Figure A9: The Grammar of SPARQL

1. PREFIX declaration

   A SPARQL query starts with an optional PREFIX declaration for substituting any full valid time IRIs throughout the query. A PREFIX declaration is composed of the prefix itself and the full IRI that it stands for. In Figure A9, the term *Prefix1:* stands for *IRIOdPrefix1*, which is a full IRI. When more than one prefix declaration is needed, each prefix declaration is separated by a line break. For instance, Figure A10 shows three prefixes: ex:, rdf:, and rdfs:.

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX  ex:   <http://example.org/RDF-SW#>
```

Figure A10: PREFIX Declaration in a SPARQL Query Statement

2. SELECT or CONSTRUCT clause

   A SELECT query retrieves resources from the RDF triple database. The SELECT clause defines the query output by itemizing a list of variable bindings or RDF resources, which correspond to the term *RDFResourceList* in Figure A9. Each variable or RDF resource in the list is separated by space if more than one is used. For instance, the SELECT clause

Figure A11 contains one RDF resource and two resource variables for the output. Moreover, the actual output is subject to matches against the RDF triple or graph patterns specified in the WHERE clause, which will also be defined in this section.

```
SELECT ex:John ?predicate ?object
```

Figure A11: A SELECT Clause in a SPARQL Query Statement

In comparison, a CONSTRUCT query outputs a single RDF graph. The CONSTRUCT clause defines a RDF graph template by a list of standard RDF triples, which correspond to the term *RDFTripleList* represented in Figure A9. A RDF graph template is composed of at least one RDF triple, and each triple is composed of RDF resources or resource variables. If more than one triple is used, each is delimited by a period (.). For instance, the CONSTRUCT clause in Figure A12 defines a RDF graph template to form a RDF graph with a fresh predicate, *isA*, in place of rdf:type defined in section A.2. Moreover, the actual output is subject to matches against the RDF triple or graph patterns specified in the WHERE clause, which will also be defined in this section.

```
CONSTRUCT {?subject ex:isA ?object.}
```

Figure A12: A CONSTRUCT Clause in a SPARQL Query Statement

3. FROM and FROM NAMED clauses

   Both FROM and FROM NAMED clauses are optional. The FROM clause contains a standard IRI of a default RDF graph to be used for matching triple or graph patterns, which correspond to the term *IRIOfDefaultGraph* represented in Figure A9. For instance, the FROM clause in Figure A13 specifies the IRI, http://example.org/RDF-SW/SPARQLDefaultGraph, of the default RDF graph for the query. The FROM NAMED clause contains a set of standard IRIs of named graphs to be used for matching RDF triple or graph patterns. More than

one named graphs can be specified, and the IRI of each named graph should be separated by space.

```
FROM <http://example.org/RDF-SW/SPARQLDefaultGraph>
```

Figure A13: A FROM Clause in a SPARQL Query Statement

4. WHERE clause

   The WHERE clause is mandatory for a SPARQL query. At least one triple pattern is required in the WHERE clause. A RDF triple pattern is the same as a RDF triple in the form of $s\ p\ o$, with possibly some or all of the components being a resource variable. Each component is separated by a space. A resource variable starts with a question mark (?) followed by the name of the variable. It is used in place of any position of subject, predicate or object to bind to any RDF resource in the RDF triple database. For instance, given the RDF graph in Figure 2.4 and a triple pattern, ?s :enrolled :SW, the resource variable, ?s, binds to the resource :John.

5. FILTER clause

   A filter clause is optional within the WHERE clause. It introduces conditions for restricting output solutions that make the specified conditions true. When more than one filter condition is used, the logical *and* (&&) connects individual conditions. Please note that for the purpose of this search, we do not consider logical *or* connector in SPARQL. The conditions can be formed for the following types of variable bindings or values:

   (a) Literal values by regular expressions

   A regular expression, or regex, is used for comparing literals. Each regular expression takes two arguments, as follows:

$$regex(text, pattern) \tag{A.5.1}$$

The first argument *text* is the bound literal value that can be either an actual literal or a resource variable bound to a literal in the RDF triple database. The *pattern* represents a literal to be compared with the text. The expression returns true if the *text* matches or contains the *pattern* exactly, otherwise it returns false. For instance, the FILTER clause in Figure A14 use regex to compare a resource variable, ?text, with a pattern, "The Semantic Web". The regex returns true if ?text binds to "The Semantic Web" exactly in the RDF triple database. When approximate match is needed, the pattern is affixed with the symbol $\wedge$. For instance, a bound text "The Semantic Web" would match the pattern "$\wedge$Semantic".

```
FILTER regex(?text, "The Semantic Web")
```

Figure A14: A FILTER Clause with regex in a SPARQL Query Statement

(b) Numerical values by arithmetic expressions

In SPARQL, arithmetic expressions are used to filter numerical variable bindings via mathematical comparisons that use greater than ($>$), greater than equal to ($>=$), less than ($<$), less than equal to ($<=$), equal to ($=$), and not equal to ($\neq$). The FILTER clause in Figure A15 uses a *greater than* comparison to restrict the RDF resource variable, ?price.

```
FILTER (?price >100)
```

Figure A15: A FILTER Clause with an Arithmetic Expression for a SPARQL Query Statement

(c) ORDER BY clause

ORDER BY clause is used to modify the order of the output based on the specified order comparator list. Each order comparator is composed of a bound resource variable and an optional order modifier. The order modifier is either ascending, indicated by ASC(), or descending, indicated DESC(). For instance, in Figure A16, ORDER By

DESC(?student) modifies the resource variable, ?student so the output sequence will appear in a descending order based on the IRI of bound values of ?student.

```
SELECT ?student
WHERE
{       ?student ex:enroll ?course      }
ORDER BY DESC(?student)
```

Figure A16: An ORDER BY Modifier in a SPARQL Query Statement

A.6 SPARQL Examples

Now we give SPARQL query examples based on the RDF triple database shown in Figure A17. The database is taken from Figure A7 along with more triples added for demonstrating each clause and language component defined in this section. We also reference the database in Figure A17 by the graph name, H, whose valid time IRI is: http://example.org/RDF-SW/SPARQLDefaultGraph. For each query example, it is presented in two parts: the query statement and the output, unless otherwise specified. While the query statement is written in Turtle [9], the output is presented in a tabular format to avoid using verbose expressions, such as using XML serializations. When necessary, the output can also be presented by RDF graphs.

```
# RDFGraph:  http://example.org/RDF-SW/SPARQLDefaultGraph
ex:SW  rdfex:type  ex:Course.
ex:SW  ex:CourseName
"The Semantic Web"^^ xsd:string.
ex:SW  ex:requiredTextbook  ex:book1.
ex:book1  ex:title
"Introduction to Semantic Web Technology"^^xsd:string.
ex:book1  ex:listPrice  "149"^^ xsd:integer.
ex:OOP  rdf:type  ex:Course.
ex:OOP  ex:CourseName  "Object-Oriented Programming"^^ xsd:string.
ex:OOP  ex:requiredTextbook  ex:book2.
ex:book2  ex:title  "Thinking in C++"^^xsd:string.
ex:book2  ex:listPrice  "99"^^ xsd:integer.
ex:Student  rdf:type  rdfs:Class.
ex:undergraduateStudent  rdf:type  rdfs:Class.
ex:graduateStudent  rdf:type  rdfs:Class.
ex:Course  rdf:type  rdfs:Class.
:City  rdf:type  rdfs:Class.
ex:John  rdf:type  ex:graduateStudent.
ex:John  ex:enrolled  ex:SW.
ex:John  ex:enrolled  ex:OOP.
ex:John  ex:enrolled  ex:DBMS.
ex:John  ex:livedIn    ex:NYC.
ex:Alex  rdf:type  ex:undergraduateStudent.
ex:Alex  ex:enrolled  ex:DBMS.
```

Figure A17: The RDF Triple Database for SPARQL Query Examples

1. Find all triples about John as a subject.

```
PREFIX ex:  <http://example.org/RDF-SW#>
SELECT ex:John ?predicate ?object
FROM <http://example.org/RDF-SW/SPARQLDefaultGraph>
WHERE
{
ex:John ?predicate ?object
}
```

:John	predicate	object
ex:John	rdf:type	ex:graduateStudent
ex:John	ex:enrolled	ex:SW
ex:John	ex:enrolled	ex:OOP
ex:John	ex:enrolled	ex:DBMS
ex:John	ex:livedIn	ex:NYC

Table A1: Output of SPARQL Query 1: Find all triples about John as a subject

2. Find courses in which John enrolled.

```
PREFIX ex:  <http://example.org/RDF-SW#>
SELECT ?course
FROM <http://example.org/RDF-SW/SPARQLDefaultGraph>
WHERE
{
ex:John ex:enrolled ?course
}
```

course
ex:SW
ex:OOP

Table A2: Output of SPARQL Query 2: Find courses in which John enrolled

3. Find the course names in which John enrolled.

```
PREFIX ex:  <http://example.org/RDF-SW#>
SELECT ?name
FROM <http://example.org/RDF-SW/SPARQLDefaultGraph>
WHERE
{
ex:John ex:enrolled ?course.
?course ex:CourseName  ?name.
}
```

name
”The Semantic Web”
”Object-Oriented Programming”

Table A3: Output of SPARQL Query 3: Find the course names in which John enrolled

4. Find course names that contain the literal ”Semantic”.

```
PREFIX ex:  <http://example.org/RDF-SW#>
SELECT ?name
FROM <http://example.org/RDF-SW/SPARQLDefaultGraph>
WHERE
{
?subject ex:CourseName ?name.
FILTER regex(?name, "^Semantic")
}
```

name
”The Semantic Web”

Table A4: Output of SPARQL Query 4: Find course names that contain the literal ”Semantic”

5. Find books that have a list price higher than 100 dollars. Output the literals of book names.

```
PREFIX ex:  <http://example.org/RDF-SW#>.
SELECT ?bookName
FROM <http://example.org/RDF-SW/SPARQLDefaultGraph>
WHERE
{
?book ex:title  ?bookName.
?book ex:listPrice ?price.
FILTER (?price > 100)
}
```

name
”The Semantic Web”

Table A5: Output of SPARQL Query 5: Find books that have a list price higher than 100 dollars

6. Find students who enrolled in both the course SW and the course Object-Oriented Programming (OOP).

```
PREFIX ex:  <http://example.org/RDF-SW#>
SELECT ?student
FROM <http://example.org/RDF-SW/SPARQLDefaultGraph>
WHERE
{
?student ex:enroll ex:SW.
?student ex:enroll ex:OOP.
}
```

student
ex:John

Table A6: Output of SPARQL Query 6: Find students who enrolled in both the course SW and the course Object-Oriented Programming (OOP)

7. Find courses that have both undergraduate and graduate students enrolled.

```
PREFIX ex:  <http://example.org/RDF-SW#>
SELECT ?course
FROM <http://example.org/RDF-SW/SPARQLDefaultGraph>
WHERE
{
?student1 rdf:type ex:graduateStudent.
?student1 ex:enrolled ?course.
?student2 rdf:type ex:undergraduateStudent.
?student2 ex:enrolled ?course.
}
```

student
ex:DBMS

Table A7: Output of SPARQL Query 7: Find courses that have both undergraduate and graduate students enrolled

8. Construct a RDF graph that contains a new property *residentOf* whose IRI is:

   http://example.org/RDF-SW#residentOf.

```
PREFIX ex:  <http://example.org/RDF-SW#>
CONSTRUCT {ex:John ex:residentOf ?city.}
FROM <http://example.org/RDF-SW/SPARQLDefaultGraph>
WHERE
{ex:John ex:livedIn ?city.}
```

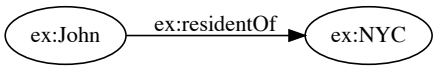


Figure A18: Output of SPARQL Query 8: Construct a RDF graph that contains a new property *residentOf* whose IRI is: http://example.org/Temporal-SW#residentOf

A.7 Complexity of RDF

In this section, we discuss its complexity of RDF with respect to space, insertion, deletion, update, and retrieval queries in SPARQL.

As we have indicated in section 2.4, encoding RDF triples and graphs are achieved by text-based serializations, such as XML and Turtle [9], which are all Unicode strings. On this basis, a *RDF Triple Store* could utilize a storage scheme to assure the performance of database-like operations, such as retrieval, insertion, update, and deletion of triples, RDF/RDFS entailment, and SPARQL query execution. In fact, only IRIs, local existential variables, or literals are needed in storing RDF triples and processing SPARQL queries. An IRI is a Unicode string that conforms to RFC 3987 [22]. Each character of an IRI may occupy one to four bytes, depending on the encoding scheme and the allowable character set employed by the storage system. A length ℓ of an IRI occupies at most 4ℓ bytes. Hence, the space requirement for one RDF triple is bounded by 12ℓ bytes (i.e., 4ℓ bytes for each of the subject, predicate, and object). A RDF triple store containing n triples would require $3n\ell$ to $12n\ell$ bytes. Therefore the space complexity is $\mathcal{O}(1)$.

In [15], a taxonomy of the RDF implementation identifies two main approaches: non-native implementation and native implementation. The non-native implementation mostly stores RDF triples and graphs in a Database Management System (DBMS) by converting RDF schema to a target database schema, such as the relational model. In comparison, the native implementation does not use any existing DBMS, but implement its own storage and indexing solutions.

Consider a non-native storage approach, a RDF triple database, or RDFDB, which contains n triples, and a graph pattern GP where there are m triple patterns. Also consider that we use a relational database, the RDFDB is mapped to a three-column table stored in a relational DBMS. For instance, the triple store shown in Figure A17 is mapped to the three-column table shown in Table A8. Clearly, its space complexity is $\mathcal{O}(1)$ it requires $3n\ell$ to $12n\ell$ bytes.

For insertion, deletion, and update operations, they are of the same in time efficiency as in the

Subject	Predicate	Object
:SW	rdf:type	:Course
:SW	:CourseName	”The Semantic Web”∧∧xsd:string
...	...	...
...	...	...
:John	:enrolled	:SW
:John	:enrolled	:OOP
...	...	...

Table A8: Mapping from a RDF Triple Database of Figure A17 to a Three-Column Relational Database

relational database, which is the $\mathcal{O}(1)$. For retrieval or search operations, among others, we may consider two possibilities: sequential search and index search. The efficiency of the sequential search would be $\mathcal{O}(n)$, and the index search is $\mathcal{O}(\log n)$.

The complexity of evaluating SPARQL queries has been proved $\mathcal{O}(mn)$ [57] where n is the number of triples and m is the number of triple patterns in a graph pattern, for the graph pattern constructed by using only AND and FILTER operators. Furthermore, if the UNION operator is allowed in the graph pattern expressions, the evaluation is NP-complete and PSPACE-complete. For query evaluation, we can follow the previous two cases, native and non-native approaches. In the non-native implementation, storing RDF graphs in a relational database benefits from query optimization available in a relational DBMS. In the case of the native storage approach, the data structure may be more efficient since there is no overhead needed for the relational DBMS. Probably its space efficiency is comparable to the non-native case, if not better. However, the main drawback is that the whole system needs to be implemented from scratch, which is expensive and time consuming.

In the previous sections, four levels of RDF entailments: simple, simple-D, RDF, and RDFS entailments, are discussed. The complexity of these entailments are well known, and have been proved NP-Complete via the equivalence with *Graph Homomorphism* [31], a reduction to a *Clique* problem [69], or a *graph coloring* problem [68]. A polynomial case is possible when the target

graph of the entailment problem is a ground RDF graph [69]. The proof of entailment is beyond the scope of this thesis.

B.1 Summary of RDF and RDFS Tools and Packages

Category \ Tool	Protege	Jena	Sesame	SWIProlog	AllegroGraph	ClioPartria	BigData	Oracle	Semantic Turkey	RDFLib	RDFSharp
Development	Y				Y				Y		
Parser	Y	Y	Y								
API	Y	Y	Y								Y
TripleStore	Y		Y		Y	Y	Y	Y		Y	
Reasoner	Y	Y	Y		Y	Y	Y	Y			
RDFS Reasoner		Y	Y		Y		Y				
Rule Reasoner		Y				Y					
Visualizer	Y								Y		
Programming		Y	Y	Y	Y	Y				Y	Y

Table B1: Summary of RDF and RDFS Tools

- Protege: free, an open source ontology editor and knowledge management system.
- Jena: free and open source Java framework for building Semantic Web and Linked Data applications.
- Sesame: open-source framework for querying and analyzing RDF data with Java API.
- SWIProlog: open source implementation of the programming language Prolog–interfacing to RDF/RDFS.
- AllegroGraph: closed source triplestore; currently in use in Open source projects, commercial projects and Department of Defense projects.
- BigData: standards-based, high-performance, scalable, open-source graph database, written entirely in Java.
- Oracle: open, standards-based, scalable, secure, reliable and performant RDF management platform
- Semantic Turkey: free, extensible, open source Knowledge Management and Acquisition tool, written in Java and deployed as a Firefox extension
- RDFLib: Python library for working with RDF, a simple yet powerful language for representing information
- RDFSharp: lightweight C# framework designed to ease the creation of .NET applications based on the RDF model

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