A Practical Guide to Building OWL Ontologies Using Protégé 5.5 and Plugins

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A Practical Guide to Building OWL Ontologies

Using Protégé 5.5 and Plugins

Edition 3.0

8 April 2021

Michael DeBellis

This is a revised version of the Protégé 4 Tutorial version 1.3 by Matthew Horridge. Previous versions of the tutorial were developed by Holger Knublauch , Alan Rector , Robert Stevens, Chris Wroe, Simon Jupp, Georgina Moulton, Nick Drummond, and Sebastian Brandt.

Chapters 3-5 are based on the original tutorial. I have updated the tutorial to be consistent with Protégé 5. I have also made some changes to address some of the most common issues I've seen new users grapple with, to remove some of the dated information about older frame-based versions of Protégé, and various miscellaneous changes. Chapters 6-11 are new. I have added new sections for technologies such as SWRL, SPARQL and SHACL as well as some details on concepts such as IRIs and namespaces.

Note: this document may get updates frequently. It is a good idea to check my blog at: https://www.michaeldebellis.com/post/new-protege-pizza-tutorial to make sure you have the latest version.

If you have questions or comments feel free to contact me at mdebellissf@gmail.com

Contents

Chapter 1 Introduction

This introduces Protégé 5 for creating OWL ontologies as well as various plugins. If you have questions specific to this tutorial, please feel free to email me directly: mdebellissf@gmail.com However, if you have general questions about Protégé, OWL, or plugins you should subscribe to and send an email to the User Support for Protégé and Web Protégé email list. This list has many people (including me) who monitor it and can contribute their knowledge to help you understand how to get the most out of this technology. To subscribe to the list, go to: https://protege.stanford.edu/support.php and click on the first orange Subscribe button. That will enable you to subscribe to the list and give you the email to send questions to.

This chapter covers licensing and describes conventions used in the tutorial. Chapter 2 covers the requirements for the tutorial and describes the Protégé user interface. Chapter 3 gives a brief overview of the OWL ontology language. Chapter 4 focuses on building an OWL ontology with classes and object properties. Chapter 4 also describes using a Description Logic Reasoner to check the consistency of the ontology and automatically compute the ontology class hierarchy.

Chapter 5 describes data properties. Chapter 6 describes design patterns and shows one design pattern: adding an order to an enumerated class. Chapter 7 describes the various concepts related to the name of an OWL entity.

Chapter 8 introduces an extended version of the Pizza tutorial developed in chapters 1-7. This ontology has a small number of instances and property values already created which can be used to illustrate the tools in the later chapters for writing rules, doing queries, and defining constraints.

Chapter 9 describes two tools for doing queries: Description Logic queries and SPARQL queries. Chapter 10 introduces the Semantic Web Rule Language (SWRL) and walks you through creating SWRL and SQWRL rules. Chapter 11 introduces the Shapes Constraint Language (SHACL) and discusses the difference between defining logical axioms in Description Logic and data integrity constraints in SHACL. Chapter 12 has some concluding thoughts and opinions and Chapter 13 provides a bibliography.

1.1 Licensing
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https://creativecommons.org/licenses/by-sa/4.0/legalcode

1.2 Conventions
Class, property, rule, and individual names are written in `Consolas` font `like this`. The term used for any such construct in Protégé and in this document is an *Entity*. Individuals and classes can also be referred to as objects.

Names for user interface tabs, views, menu selections, buttons, and text entry are highlighted like this.

Any time you see highlighted text such as File>Preferences or OK or PizzaTopping it refers to something that you should or optionally could view or enter into the user interface. If you ever aren't sure what to do to accomplish some task look for the highlighted text. Often, as with `PizzaTopping` the text you enter into a field in the Protégé UI will be the name of a class, property, etc. In those cases, where the

name is meant to be entered into a field it will only be highlighted rather than highlighted and printed in `Consolas` font.

Menu options are shown with the name of the top-level menu, followed by a > followed by the next level down to the desired selection. For example, to indicate how to open the <mark>Individuals by class</mark> tab under the <mark>Tabs</mark> section in the <mark>Window</mark> menu the following text would be used: <mark>Window>Tabs> Individuals by class</mark>.

When a word or phrase is emphasized, it is *shown in italics like this*.

Exercises are presented like this:

Exercise 1: Accomplish this

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1. Do this.

2. Then do this.

3. Then do this.

_____

Potential pitfalls and warnings are presented like this.

Tips and suggestions related to using Protégé are presented like this.

Explanations as to what things mean are presented like this.

General notes are presented like this.

Vocabulary explanations and alternative names are presented like this.

Chapter 2 Requirements and the Protégé User Interface

In order to follow this tutorial, you must have Protégé 5, which is available from the Protégé website,[1] and some of the Protégé Plugins which will be described in more detail below. For now, just make sure you have the latest version of Protégé. At the time this is being written the latest version is 5.5 although the tutorial should work for later versions as well.

The Protégé user interface is divided up into a set of major tabs. These tabs can be seen in the ==Window>Tabs== option. This option shows all the UI tabs that are currently loaded into the Protégé environment. Any tabs that are currently opened have a check mark next to them. To see a tab that is not visible just select it from the menu and it will be added to the top with the other major tabs and its menu item will now be checked. You can add additional major tabs to your environment by loading plugins. For example, when we load the SHACL4Protégé plugin the SHACLEditor will be added to the menu.

Each major tab consists of various panes or as Protégé calls them views. Each view can be resized or closed using the icons in the top right corner of every view. The views can also be nested as sub-tabs within each major tab. When there could potentially be confusion between a tab that is a screen all its own (is under the ==Window>Tabs== option) and a view that is a sub-tab we will call the screen tab a major tab. There are many views that are not in the default version of Protégé that can be added via the ==Window>Views== option. The additional views are divided into various categories such as ==Window>Views>Individual views==. Section 5.2 will show an example of adding a new view to a major tab.

Chapter 3 What are OWL Ontologies?

Ontologies are used to capture knowledge about some domain of interest. An ontology describes the concepts in the domain and also the relationships that hold between those concepts. Different ontology languages provide different facilities. The most recent development in standard ontology languages is OWL from the World Wide Web Consortium (W3C). A good primer on the basic concepts of OWL can be found at: https://www.w3.org/TR/owl2-primer/

OWL makes it possible to describe concepts in an unambiguous manner based on set theory and logic. Complex concepts can be built up out of simpler concepts. The logical model allows the use of a reasoner which can check whether all of the statements and definitions in the ontology are mutually consistent and can also recognize which concepts fit under which definitions. The reasoner can therefore help to maintain the hierarchy correctly. This is particularly useful when dealing with cases where classes can have more than one parent. The reasoner can also infer additional information. For example, if two properties are inverses only one value needs to be asserted by the user and the inverse value will be automatically inferred by the reasoner.

3.1 Components of OWL Ontologies

An OWL ontology consists of Classes, Properties, and Individuals. OWL ontologies are an implementation of Description Logic (DL) which is a decidable subset of First Order Logic. A class in OWL is a set, a property is a binary relation, and an individual is an element of a set. Other concepts from set theory are also implemented in OWL such as Disjoint sets, the Empty set (`owl:Nothing`), inverse

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[1] http://protege.stanford.edu

relations, transitive relations, and many more. An understanding of the basic concepts of set theory will help the user get the most out of OWL but is not required. One of the benefits of Protégé is that it presents an intuitive GUI that enables domain experts to define models without a background in set theory. However, developers are encouraged to refresh their knowledge on logic and set theory. A good source is the first 3 chapters in Elements of the Theory of Computation by Lewis and Papadamitrious. Another good source is the PDF document *Overview of Set Theory* available at:
https://www.michaeldebellis.com/post/owl-theoretical-basics

3.1.1 Individuals

Individuals represent objects in the domain of interest. An important difference between OWL and most programming and knowledge representation languages is that OWL does not use the Unique Name Assumption (UNA). This means that two different names could actually refer to the same individual. For example, "Queen Elizabeth", "The Queen" and "Elizabeth Windsor" might all refer to the same individual. In OWL, it must be explicitly stated that individuals are the same as each other, or different from each other. Figure 3.1 shows a representation of some individuals in a domain of people, nations, and relations — in this tutorial we represent individuals as diamonds.
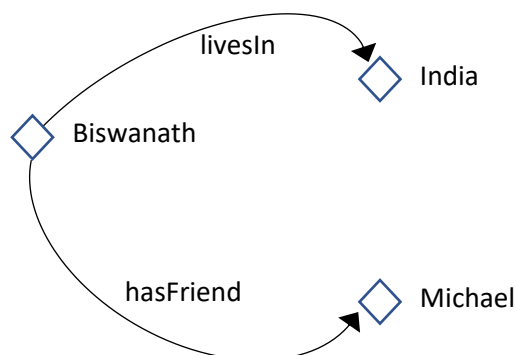
Figure 3.1: Representation of Individuals

Figure 3.2: Representation of Properties

Individuals are also known as *instances*. Individuals can be referred to as *instances of classes*.

3.1.2 Properties

Properties are binary relations between individuals. I.e., properties link two individuals together. For example, the property `hasFriend` might link the individual `Biswanath` to the individual `Michael`, or the property `hasChild` might link the individual `Michael` to the individual `Oriana`. Properties can have inverses. For example, the inverse of `hasChild` is `hasParent`. Properties can be limited to having a single value – i.e., to being functional. They can also be transitive or symmetric. These property characteristics are explained in detail in Section 4.8. Figure 3.2 shows a representation of some properties.

> Properties are similar to properties in Object-Oriented Programming (OOP). However, there are important differences between properties in OWL and OOP. The most important difference is that OWL properties are first class entities that exist independent of classes. OOP developers are encouraged to read: https://www.w3.org/2001/sw/BestPractices/SE/ODSD/
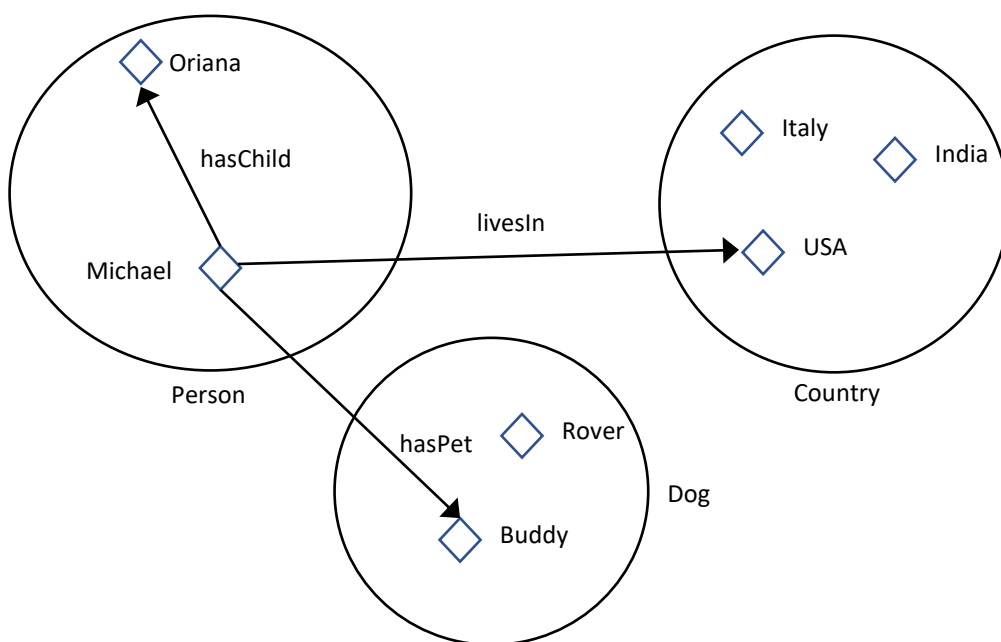
Figure 3.3: Representation of Classes containing Individuals

3.1.3 Classes

OWL classes are sets that contain individuals. They are described using formal (mathematical) descriptions that rigorously define the requirements for membership of the class. For example, the class `Cat` would contain all the individuals that are cats in our domain of interest.[2] Classes may be organized into a superclass-subclass hierarchy, which is also known as a taxonomy. However, taxonomies are often trees. I.e., each node has only one parent node. Class hierarchies in OWL are not restricted to be trees and multiple inheritance can be a powerful tool to represent data in an intuitive manner.

Subclasses specialize (aka *are subsumed by*) their superclasses. For example, consider the classes `Animal` and `Dog` – `Dog` might be a subclass of `Animal` (so `Animal` is the superclass of `Dog`). This says that *All dogs are animals*, *All members of the class* `Dog` *are members of the class* `Animal`. OWL and Protégé

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[2] Individuals can belong to more than one class and classes can have more than one superclass. Unlike OOP where multiple inheritance is typically unavailable or discouraged it is common in OWL.

provide a language that is called Description Logic or DL for short. One of the key features of DL is that these superclass-subclass relationships (aka subsumption relationships) can be computed automatically by a reasoner – more on this later. Figure 3.3 shows a representation of some classes containing individuals – classes are represented as ovals, like sets in Venn diagrams.

In OWL classes can be built up of descriptions that specify the conditions that must be satisfied by an individual for it to be a member of the class. How to formulate these descriptions will be explained as the tutorial progresses.

Chapter 4 Building an OWL Ontology

This chapter describes how to create an ontology of Pizzas. We use Pizzas because it is something almost everyone is familiar with.

Exercise 1: Create a new OWL Ontology

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1. Start Protégé. When Protégé opens for the first time each day it puts up a screen of all the available plugins. You can also bring this up at any time by using File>Check for plugins. You won't need any plugins at this point of the tutorial so just click the Not now button.

2. The Protégé user-interface consists of several tabs such as Active ontology, Entities, etc. When you start Protégé you should be in the Active Ontology tab. This is for overview information about the entire ontology. Protégé always opens with a new untitled ontology you can start with. Your ontology should have an IRI something like: http://www.semanticweb.org/yourname/ontologies/2020/4/untitled-ontology-27 Edit the name of the ontology (the part after the last "/" in this case untitled-ontology-27) and change it to something like PizzaTutorial. Note: the Pizza ontology IRIs shown below (e.g., figure 4.3) show the IRI after I edited the default that Protégé generated for me. Your IRI will look different and will be based on your name or the name of your organization.

3. Now you want to save your new ontology. Select File>Save. This should bring up a window that says: Choose a format to use when saving the 'PizzaTutorial' ontology. There is a drop down menu of formats to use. The default RDF/XML Syntax should be selected by clicking the OK button. This should bring up the standard dialog your operating system uses for saving files. Navigate to the folder you want to use and then type in the file name, something like Pizza Tutorial and select Save.

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> As with any file you work on it is a good idea to save your work at regular intervals so that if something goes wrong you don't lose your work. At certain points in the tutorial where saving is especially important the tutorial will prompt you to do so but it is a good idea to save your work often, not just when prompted.

The next step is to set some preferences related to the names of new entities. Remember than in Protégé any class, individual, object property, data property, annotation property, or rule is referred to as an entity. The term name in OWL can actually refer to two different concepts. It can be the last part of the IRI[3] or it can refer to the annotation property (usually `rdfs:label`) used to provide a more user friendly name for the entity. We will discuss this in more detail below in chapter 7. For now, we just want to set the parameters correctly so that future parts of the tutorial (especially the section on SPARQL queries) will work appropriately.

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[3] An IRI is similar to a URL. This will be discussed in detail below in chapter 7.

Exercise 2: Set the Preferences for New Entities and Rendering

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1. Go to File>Preferences in Protégé. This will bring up a new window with lots and lots of different tabs. Click on the New entities tab. This will bring up a tab that looks similar to figure 4.1. The top part of that tab is a box labeled Entity IRI. It should be set with the parameters as shown in figure 4.1. I.e., Starts with Active ontology IRI. Followed by #. Ends with User supplied name. If the last parameter is set to Auto-generated name change it to User supplied name. That is the parameter most likely to be different but also check the other two as well.

2. Now select the Renderer tab. It should look like figure 4.2. Most importantly, check that Entity rendering is set to Render by entity IRI short name (ID) rather than Render by annotation property. Don't worry if this doesn't completely make sense at this point. The issues here are a bit complex and subtle so we defer them until after you have an understanding of the basic concepts of what an OWL ontology is. We will have a discussion of these details below in chapter 7. For now you just need to make sure that the preferences are set appropriately to work with the rest of the tutorial.
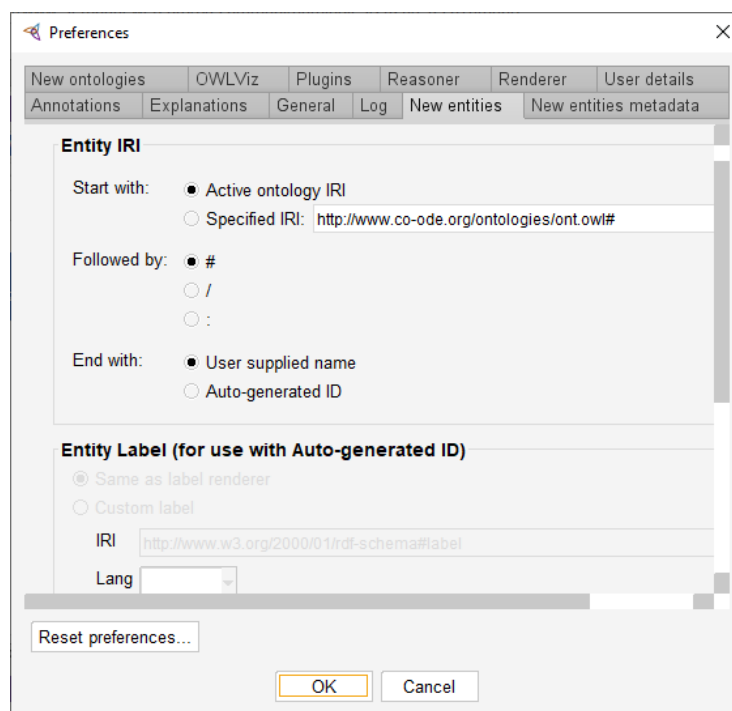
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Figure 4.1: The New entities tab
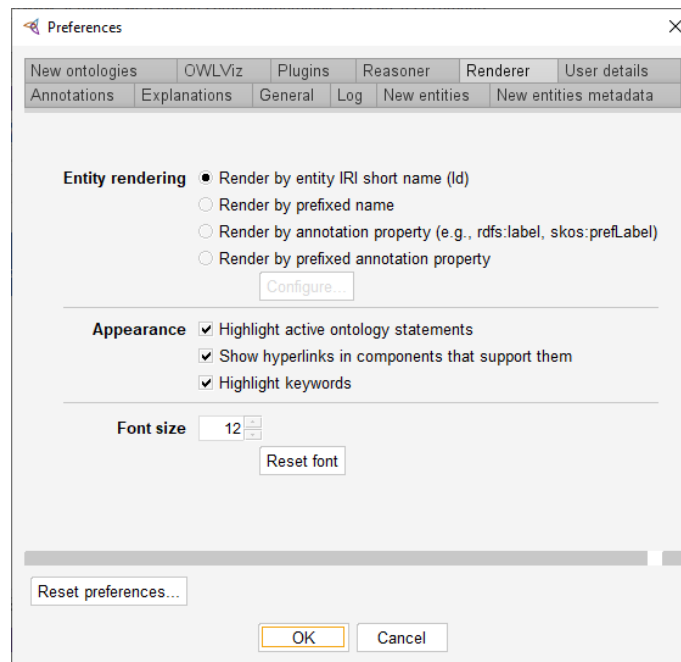
Figure 4.2 Renderer tab
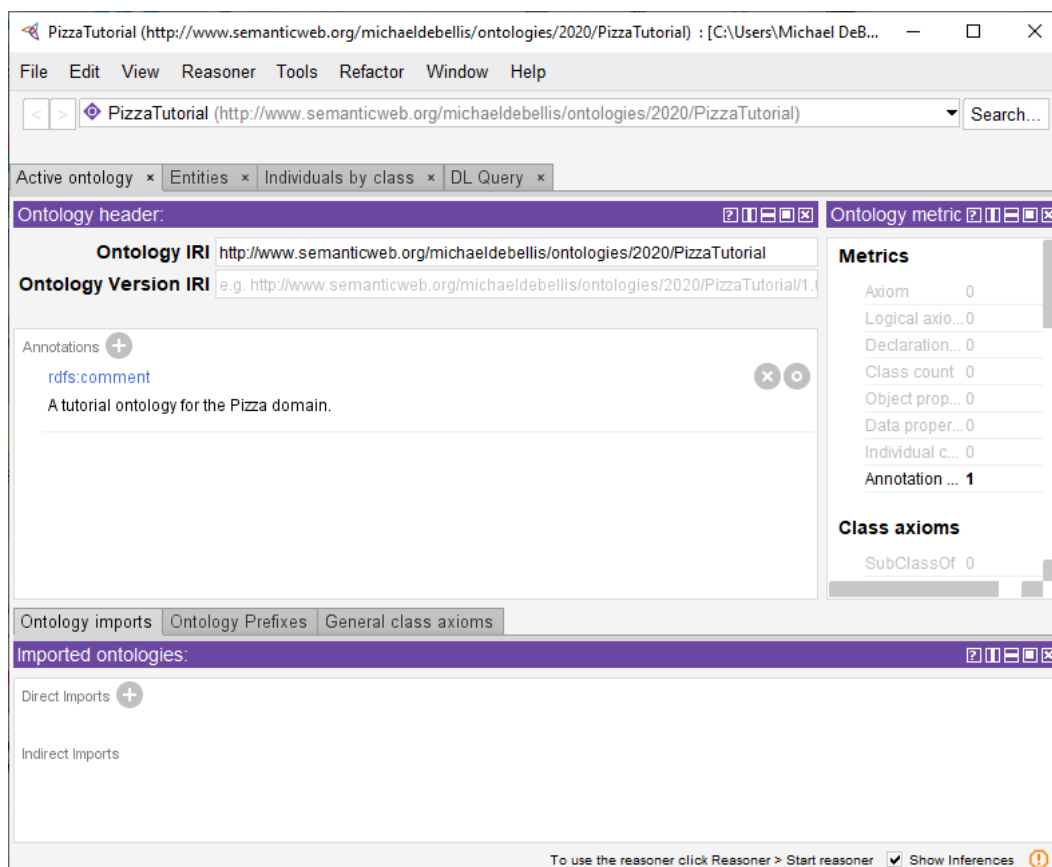
Figure 4.3: The Active Ontology Tab with a New Comment

Exercise 3: Add a Comment Annotation to Your Ontology

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1. Make sure you are in the <mark>Active Ontology</mark> tab. In the view just below the Ontology IRI and Ontology Version IRI fields find the <mark>Annotations</mark> option and click on the <mark>+</mark> sign. This will bring up a menu to create a new annotation on the ontology.

2. The <mark>rdfs:comment</mark> annotation should be highlighted by default. If it isn't highlighted click on it. Then type a new comment into the view to the right. Something like <mark>A tutorial ontology for the Pizza domain.</mark>

3. Click <mark>OK</mark>. Your Active Ontology tab should like Figure 4.3.

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Add Subclass

Add Sibling Class

Delete Class
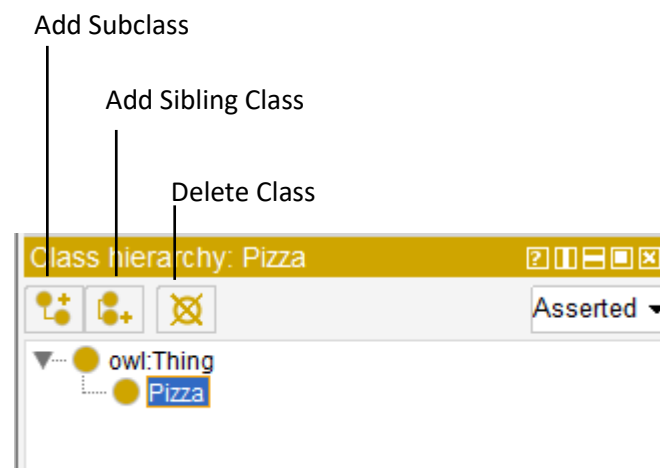
Figure 4.4: The Class Hierarchy View Options

4.1 Named Classes

The main building blocks of an OWL ontology are classes. In Protégé 5, editing of classes can be done in the Entities tab. The <mark>Entities</mark> tab has a number of sub-tabs. When you select it, the default should be the <mark>Class hierarchy</mark> view as shown in Figure 4.5.[4] All empty ontologies contains one class called `owl:Thing`. OWL classes are sets of individuals. The class `owl:Thing` is the class that represents the set containing all individuals. Because of this all classes are subclasses of `owl:Thing`.

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[4] Each of the sub-tabs in the Entities tab also exists as its own major tab. In the tutorial we will refer to tabs like the Class hierarchy tab or Object properties tab and it is up to the user whether to access them from the Entities tab or to create them as independent tabs.

Exercise 4: Create classes: Pizza, PizzaTopping, and PizzaBase

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1. Navigate to the Entities tab[5] with the Class hierarchy view selected. Make sure owl:Thing is selected.

2. Press the Add Subclass icon shown in figure 4.4. This button creates a new subclass of the selected class. In this case we want to create a subclass of `owl:Thing`.

3. This should bring up a dialog titled Create a new class with a field for the name of the new class. Type in Pizza and then select OK.

4. Repeat the previous steps to add the classes `PizzaTopping` and `PizzaBase` ensuring that `owl:Thing` is selected before using the add subclass icon so that all your classes are subclasses of `owl:Thing`. Your user interface should now look like figure 4.5. Don't worry that some of the classes are highlighted in red. That is because the reasoner hasn't run yet. We will address this shortly.

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Figure 4.5 The Classes Sub-Tab in the Entities Tab

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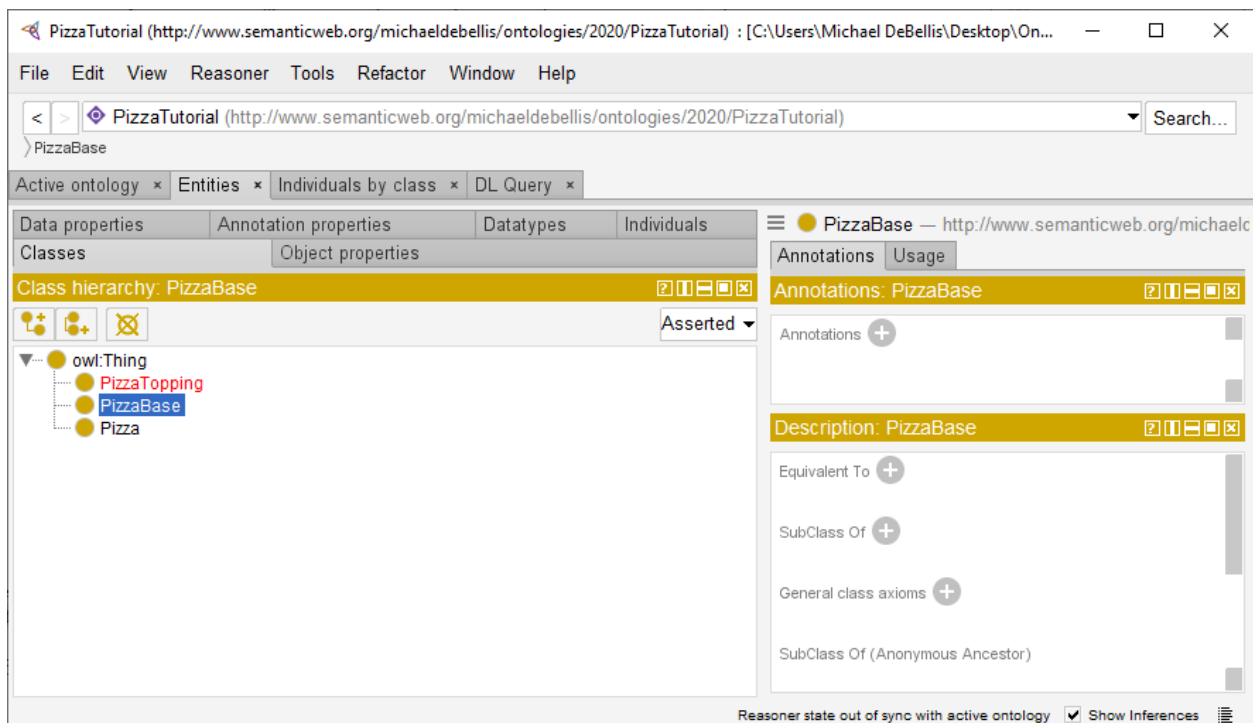There are no mandatory naming conventions for OWL entities. In chapter 7, we will discuss names and labels in more detail. A best practice is to select one set of naming conventions and then abide by that convention across your organization. For this tutorial we will follow the standard where class and individual names start with a capital letter for each word and do not contain spaces. This is known as CamelBack notation. For example: `Pizza`, `PizzaTopping`, etc. Also, we will follow the standard that class names are always singular rather than plural. E.g., `Pizza` rather than `Pizzas`, `PizzaTopping` rather than `PizzaToppings`.

4.2 Using a Reasoner

You may notice that one or more of your classes is highlighted in red as in Figure 4.5. This is because we haven't run the reasoner yet so Protégé has not been able to verify that our new classes have no inconsistencies. When just creating classes and subclasses in a new ontology there is little chance of an inconsistency. However, it is a good idea to run the reasoner often. When there is an inconsistency the sooner it is discovered the easier it is to fix. One common mistake that new users make is to do a lot of development and then run the reasoner only to find that there are multiple inconsistencies which can make debugging significantly more difficult. So let's get into the good habit of running the reasoner often. Protégé comes with some reasoners bundled in and others available as plugins. Since we are going to write some SWRL rules later in the tutorial, we want to use the Pellet reasoner. It has the best support for SWRL at the time this tutorial is being written.

Exercise 5: Install and Run the Pellet Reasoner

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1. Check to see if the Pellet reasoner is installed. Click on the <mark>Reasoner</mark> menu. At the bottom of the menu there will be a list of the installed reasoners such as <mark>Hermit</mark> and possibly <mark>Pellet</mark>. If Pellet is visible in that menu then select it and skip to step 3.

2. If Pellet is not visible then do <mark>File>Check for plugins</mark> and select Pellet from the list of available plugins and then select <mark>Install</mark>. This will install Pellet and you should get a message that says it will take effect the next time you start Protégé. Do a <mark>File>Save</mark> to save your work then quit Protégé and restart it. Then go to <mark>File>Open recent</mark>. You should see your saved Pizza tutorial in the list of recent ontologies. Select it to load it. Now you should see Pellet under the <mark>Reasoner</mark> menu and be able to select it so do so.

3. With Pellet selected in the Reasoner menu execute the command <mark>Reasoner>Start reasoner</mark>. The reasoner should run very quickly since the ontology is so simple. You will notice that the little text message in the lower right corner of the Protégé window has changed to now say <mark>Reasoner active</mark>. The next time you make a change to the ontology that text will change to say: <mark>Reasoner state out of sync with active ontology</mark>. With small ontologies the reasoner runs very quickly, and it is a good idea to get into the habit of running it often, as much as after every change.

4. It is possible that one or more of your classes will still be highlighted in red after you run the reasoner. If that happens do: <mark>Window>Refresh user interface</mark> and any red highlights should go away. Whenever your user interface seems to show something you don't expect the first thing to do is to try this command.

5. One last thing we want to do is to configure the reasoner. By default, the reasoner does not perform all possible inferences because some inferences can take a long time for large and complex ontologies. In this tutorial we will always be dealing with small and simple ontologies so we want to see everything the reasoner can do. Go to: Reasoner>Configure. This will bring up a dialog with several check boxes of inferences that the reasoner can perform. If they aren't all checked then check them all. You may receive a warning that some inferences can take a lot of time, but you can ignore those since your ontology will be small.

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4.3 Disjoint Classes

Having added the classes `Pizza`, `PizzaTopping`, and `PizzaBase` to the ontology, we now want to say that these classes are *disjoint*. I.e., no individual can be an instance of more than one of those classes. In set theory terminology the intersection of these three classes is the empty set: `owl:Nothing`.

Exercise 6: Make Pizza, PizzaTopping, and PizzaBase disjoint from each other

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1. Select the class Pizza in the class hierarchy.

2. Find the Disjoint With option in the Description view and select the (+) sign next to it. See the red circle in figure 4.6.

3. This should bring up a dialog with two tabs: Class hierarchy and Expression editor. You want Class hierarchy for now (we will use the expression editor later). This gives you an interface to select a class that is identical to the Class hierarchy view. Use it to navigate to PizzaBase. Hold down the shift key and select PizzaBase and PizzaTopping. Select OK.

4. Do a Reasoner>Synchronize reasoner. Then look at `PizzaBase` and `PizzaTopping`. You should see that they each have the appropriate disjoint axioms defined to indicate that each of these classes is disjoint with the other two.

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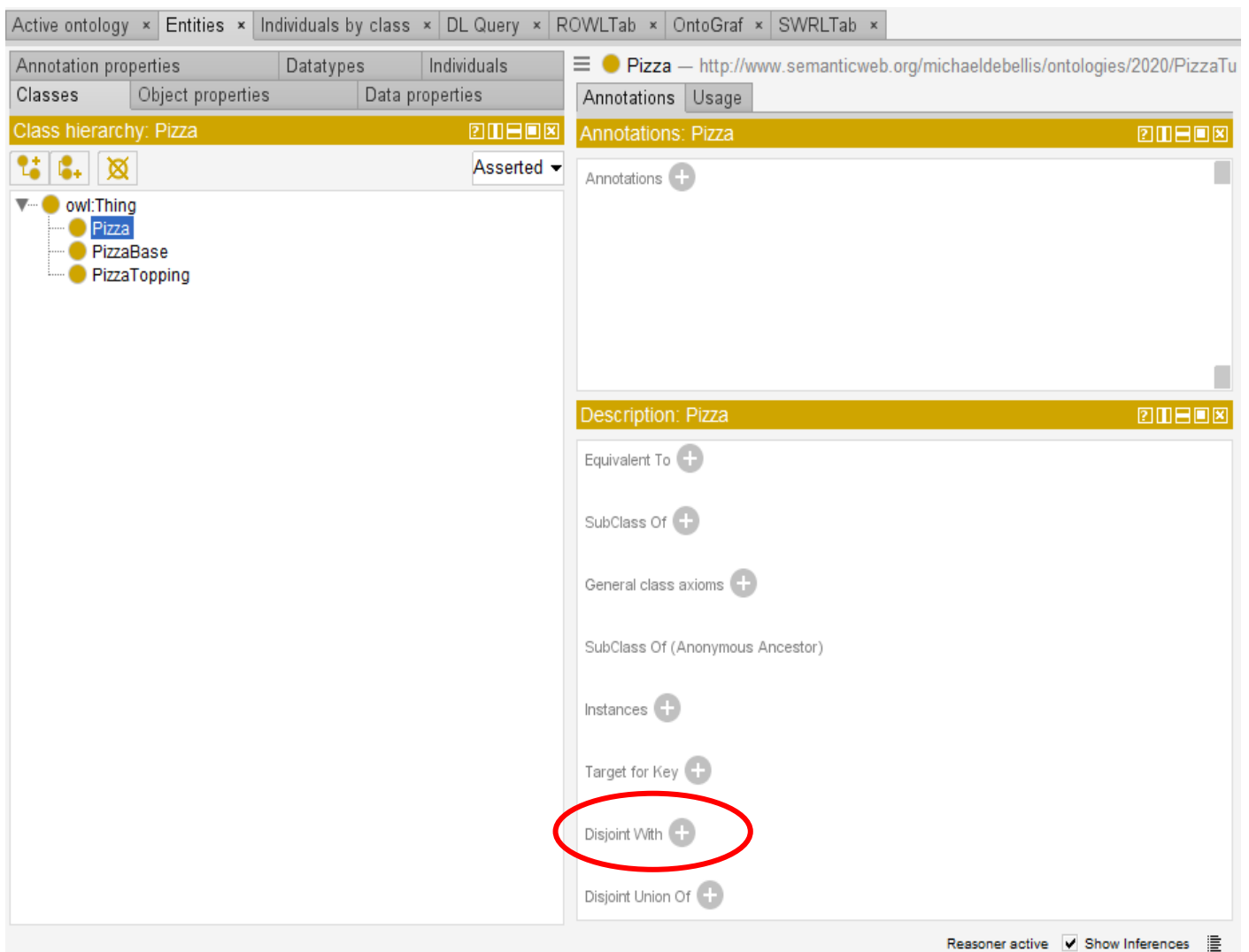
Figure 4.6: The Disjoint Option in the Class Description View

OWL classes are assumed to overlap, i.e., by default they are not disjoint. This is often useful because in OWL, unlike in most object-oriented models, multiple inheritance is not discouraged and can be a powerful tool to model data. If we want classes to be disjoint, we must explicitly declare them to be so. It is often a good development strategy to start with classes that are not disjoint and then make them disjoint once the model is more fully fleshed out as it is not always obvious which classes are disjoint from the beginning.

4.4 Using Create Class Hierarchy
In this section we will use Tools>Create class hierarchy to create multiple classes at once.
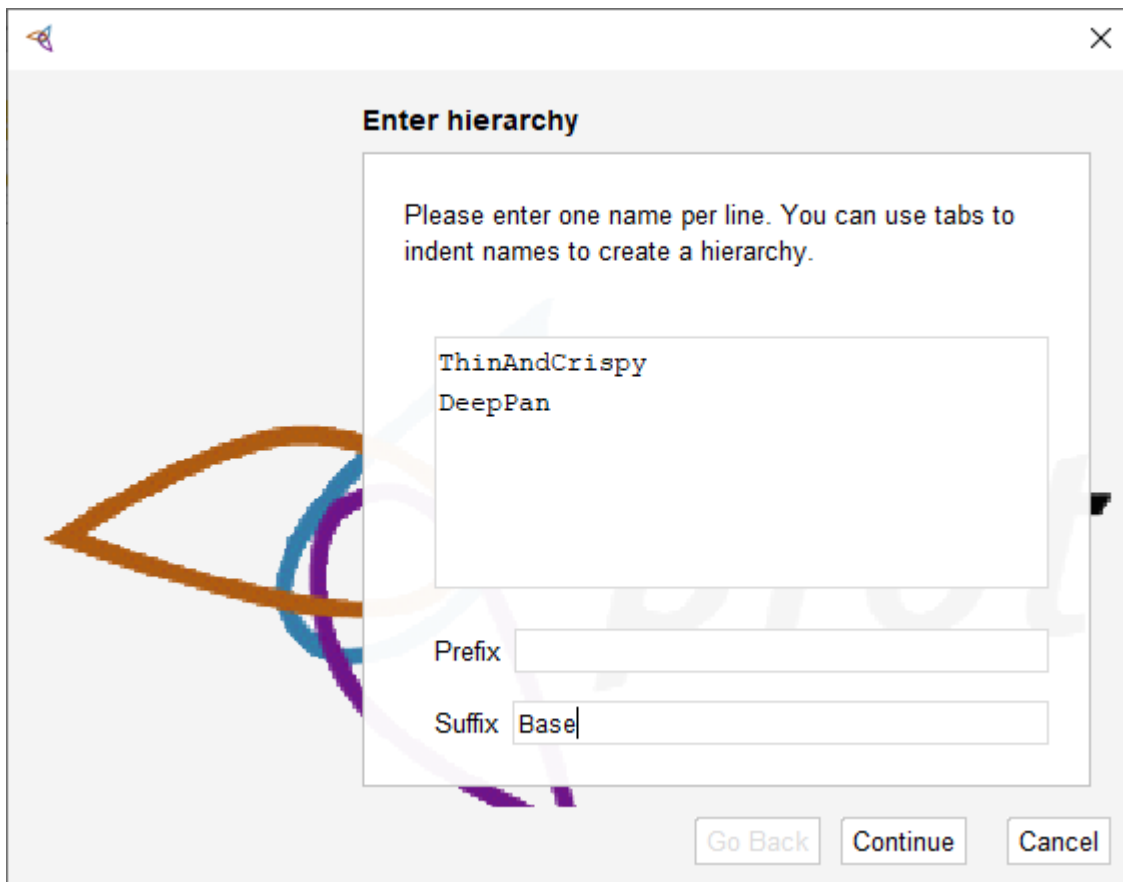
Figure 4.7: The Create class hierarchy wizard

Exercise 7: Use the Create class hierarchy tool to create subclasses of PizzaBase

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1. Select the class PizzaBase in the class hierarchy.

2. With PizzaBase selected use the Tools>Create class hierarchy menu option.

3. This should bring up a wizard that enables you to create a nested group of classes all at once. You should see a window labeled Enter hierarchy where you can enter one name on each line. You can also use the tab key to indicate that a class is a subclass of the class above it. For now we just want to enter two subclasses of `PizzaBase`: `ThinAndCrispyBase` and `DeepPanBase`. One of the things the wizard does is to automatically add a prefix or suffix for us. So just enter ThinAndCrispy, hit return and enter DeepPan. Then in the Suffix field add Base. Your window should look like figure 4.7.

4. Select Continue. This will take you to a window that asks if you want to make sibling classes disjoint. The default should be checked (make them disjoint) which is what we want in this case (a base can't be both deep pan and thin) so just select Finish. Synchronize the reasoner. Your class hierarchy should now look like figure 4.8.

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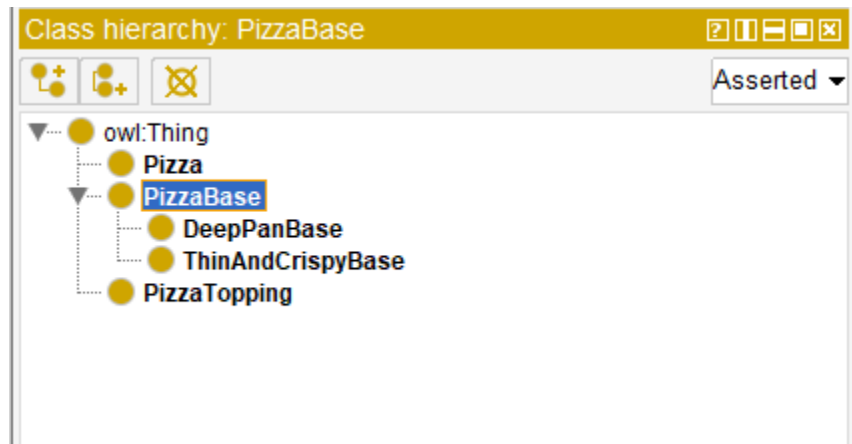
Figure 4.8: The New Class Hierarchy

4.5 Create a PizzaTopping Hierarchy

We will use Tools>Create class hierarchy again but this time to create a more interesting hierarchy with additional subclasses to model the subclasses of `PizzaTopping`.

Exercise 8: Create subclasses of PizzaTopping

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1. Select the class PizzaTopping in the class hierarchy.

2. With PizzaTopping selected use the Tools>Create class hierarchy menu option.

3. This will once again bring up the wizard. We want all our toppings to end in Topping so enter Topping in the Suffix field. Then create the nested structure as shown in figure 4.9. Use the Tab key to indent classes where needed.

4. Select Continue. This will take you to the window that asks if you want to make sibling classes disjoint. We do want this so leave the box checked and click Finish. Synchronize the reasoner. Your class hierarchy should now look like figure 4.10.

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Figure 4.9 Using Create class hieararchy to create `PizzaTopping` subclasses
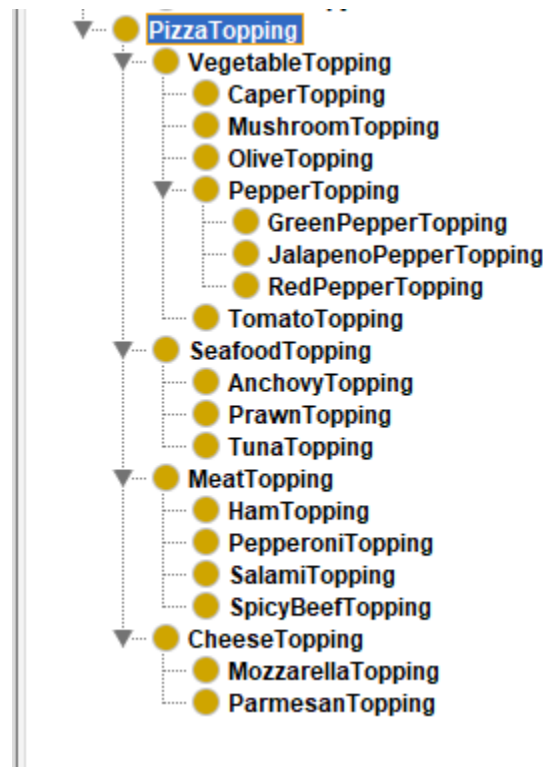
Figure 4.10 The New `PizzaTopping` Class Hierarchy
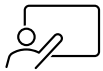
So far, we have created some simple named classes and subclasses which hopefully seem intuitive and obvious. However, what does it actually mean to be a subclass of something in OWL? For example, what does it mean for `VegetableTopping` to be a subclass of `PizzaTopping`? In OWL subclass means *necessary implication*. I.e., if `VegetableTopping` is a subclass of `PizzaTopping` then *all* instances of `VegetableTopping` are also instances of `PizzaTopping`. It is for this reason that we try to have standards such as having all `PizzaTopping` classes end with the word "Topping". Otherwise, it might seem we are saying that anything that is a kind of *Ham* like the *Ham* in your sandwich is a kind of `MeatTopping` or `PizzaTopping` which is not what we mean. For large ontologies strict attention to the naming of classes and other entities can prevent potential confusion and bugs.

4.6 OWL Properties

OWL Properties represent relationships. There are three types of properties, Object properties, Data properties and Annotation properties. Object properties are relationships between two individuals. Data properties are relations between an individual and a datatype such as xsd:string or xsd:dateTime. Annotation properties also usually have datatypes as values although they can have objects. An annotation property is usually meta-data such as a comment or a label. In OWL only individuals can have values for object and data properties, but any entity can have an annotation property value since meta-data applies to all entities. Annotation properties usually can't be reasoned about. For example, SWRL rules which we will cover later cannot view or change the value of annotation properties. In this chapter we will focus on Object properties. Data properties are described in Chapter 5. In the current version of the tutorial we are only discussing the annotation property `rdfs:label` (see chapter 7) however they are fairly intuitive.

Properties may be created using the Object Properties sub-tab of the Entities tab shown in figure 4.11. Just as all OWL classes ultimately are a subclass of `owl:Thing`, all properties are ultimately a sub-property of `owl:topObjectProperty`. A sub-property is similar to a subclass except it is about the tuples in a property. For example, `hasFather` would be a sub-property of `hasParent` because all the tuples in `hasFather` are in `hasParent` but not vice versa. E.g., if `Sasha hasFather Barack` then she also `hasParent Barack`. However, she also `hasParent Michelle` but it is not the case that she `hasFather Michelle`. Rather she `hasMother Michelle`, i.e., `hasMother` is also a sub-property of `hasParent`.

The GUI for entering properties is also similar to that for entering classes. The first icon with one box under another creates a sub-property of the selected property. The second icon showing two boxes at the same level creates a sibling property to the selected property and the icon with an X through a box deletes the selected property.

Exercise 9: Create some properties

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1. Select the Object properties sub-tab of the Entities tab (see figure 4.11).

2. Make sure `owl:topObjectProperty` is selected. Click on the nested box icon at the left to create a new sub-property of `owl:topObjectProperty.` When prompted for the name of the new property type in hasIngredient.

3. Just as you can use a wizard to create multiple classes you can also use one to create multiple properties. Select hasIngredient and then select Tools>Create object property hierarchy. Enter the new property names hasTopping and hasBase. Select Continue and accept the default that the object properties are _not_ disjoint.

4. Synchronize the reasoner. Your window should now look like figure 4.11.

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For those familiar with the Entity-Relationship model, OWL object properties are similar to relations and data properties are similar to attributes. Object properties are similar to properties with a range of some class in OOP and data properties are similar to OOP properties with a range that is a datatype.
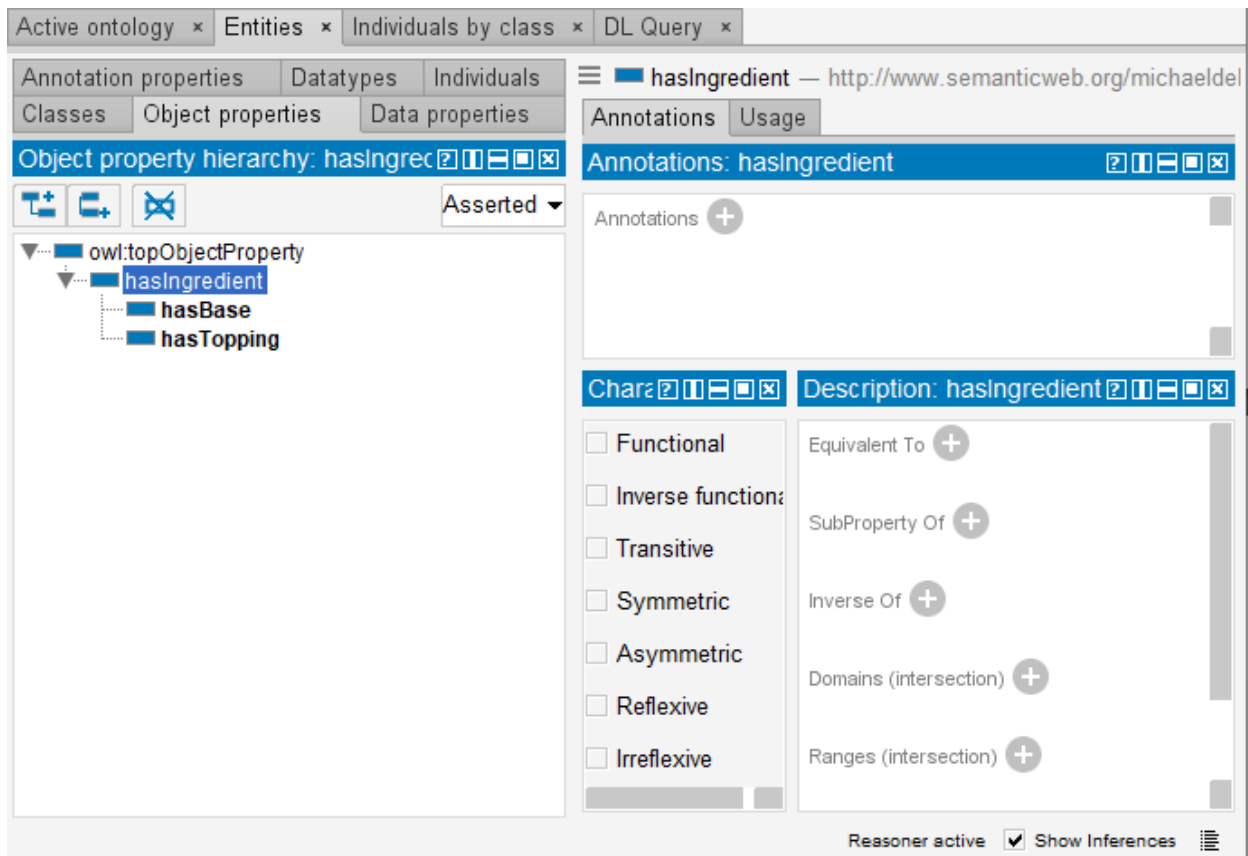
Figure 4.11 Adding Some Object Properties

4.7 Inverse Properties

Each object property may have a corresponding inverse property. If some property links individual a to individual b then its inverse property will link individual b to individual a. For example, in figure 3.3 the individual `Michael hasPet Buddy`. In this example `hasPet` is an object property that maps from a `Person` to their `Pet` which are known as the domain and range of the property. `Michael` is an instance of the `Person` class and `Buddy` is an instance of the `Pet` class. The `hasPet` property points from a `Person` to that person's `Pet`. The inverse property could be `isPetOf` which would be represented by a link between the two individuals going the other way, from `Buddy` to `Michael`. Whenever possible it is desirable to adhere to this type of naming standard with properties. Properties going in one direction as *hasProperty* and their inverses as *isPropertyOf*.

Exercise 10: Create some inverse properties

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1. Use the Object properties tab to create a new object property called `isIngredientOf` (this will be the inverse property of `hasIngredient`). Make sure that `isIngredientOf` is a sibling property if `hasIngredient` and a sub-property of `owl:topObjectProperty.`

2. Click on the Add icon (+) next to Inverse Of in the Description view for `hasIngredient.` You will be presented with a window that shows a nested view of all the current properties. Select hasIngredient to make it the inverse of `isIngredientOf`.

3. Select isIngredientOf and then Tools>Create object property hierarchy. Enter isToppingOf then on a new line enter isBaseOf. As before, select Continue and leave the box for disjoint properties unchecked and select Finish. Repeat step 2 to make `isToppingOf` the inverse of `hasTopping` and `isBaseOf` the inverse of `hasBase`.

4. Synchronize the reasoner. Your window should now look like figure 4.12.

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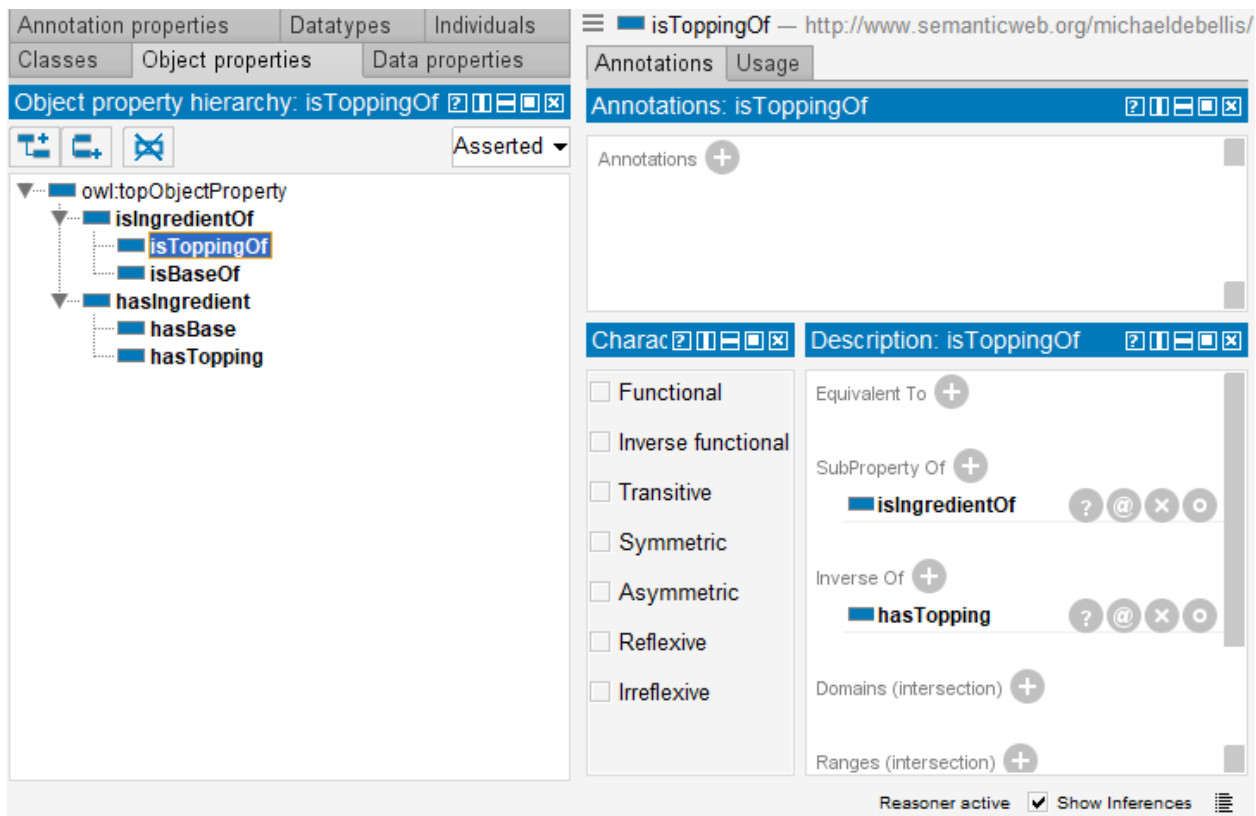
Figure 4.12 Inverse Properties

4.8 OWL Object Property Characteristics

OWL allows the meaning of properties to be enriched through the use of property characteristics. The following sections discuss the various characteristics that properties may have. If you are familiar with basic concepts of relations in set theory these characteristics will already be familiar to you. In figure 4.12 you can see the Characteristics: view for a property as a list of check boxes: Functional, Inverse functional, Transitive, etc.

4.8.1 Functional Properties

If a property is functional, for a given individual, there can be at most one individual that is related to the individual via the property. For example the property `hasBirthMother` -- someone can only have one birth mother. If we say that the individual `Jean hasBirthMother Peggy` and we also say that the individual `Jean hasBirthMother Margaret`, then because `hasBirthMother` is a functional property, we can infer that `Peggy` and `Margaret` must be the same individual. This can happen in OWL because

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unlike many languages it does not have a unique names assumption. Unless specifically stated otherwise, the reasoner can infer that two individuals with different names are actually the same individual. It should be noted however, that if `Peggy` and `Margaret` were explicitly stated to be two different individuals then the above statements would lead the reasoner to infer that there was an inconsistency in the ontology. We will discuss names more in chapter 7.

In section 4.16 we will discuss cardinality restrictions on properties. E.g., that the `hasWheel` property of the `Bicycle` class has a minimum of 2 (allowing for training wheels) whereas `hasWheel` for the `Unicycle` class is defined to be exactly 1. A functional property is equivalent to a property with a cardinality restriction that says it has a maximum of 1 value. The term functional is from mathematics where a function is defined as a relation where each member of the domain has at most one value. For example, the `greaterThan` relation is not functional since for any number X many (in fact an infinite number) can be `greaterThan` X but the `plusOne` relation is functional since for any number X `plusOne` always results in one unique value.

4.8.2 Inverse Functional Properties

If a property is inverse functional then it means that the inverse property is functional. For a given individual, there can be at most one individual related to that individual via the property. Following our example from section 4.8.1 the inverse of `hasBirthMother` would be `isBirthMotherOf`. The `isBirthMotherOf` property would not be functional since a woman can be the birth mother of several children. However, it would be inverse functional since each person has exactly one mother.

4.8.3 Transitive Properties
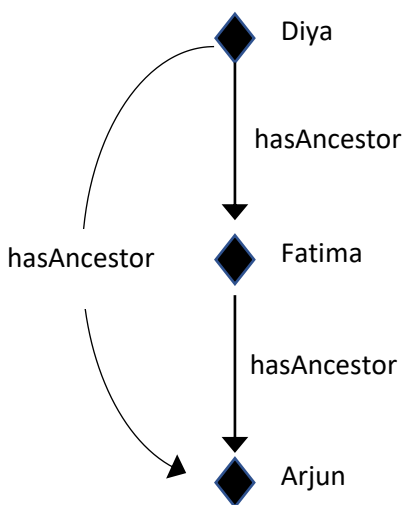
Figure 4.13 Transitive Properties

If a property P is transitive, and P relates individual a to individual b, and also individual b to individual c, then we can infer that individual a is related to individual c via property P. For example, Figure 4.13 shows an example of the transitive property `hasAncestor`. If the individual `Diya` has an ancestor that is `Fatima`, and `Fatima` has an ancestor that is `Arjun`, then we can infer that `Diya` has an ancestor that is `Arjun` – this is indicated by the curved line in Figure 4.13.

An example of the transitive property in mathematics is the > relation. If x > y and y > z then x > z.

Note that if a property is transitive it cannot be functional. Also, if a property is transitive then its inverse property must also be transitive. E.g., the inverse of > is < and < is also transitive. We will see an example of this in chapter 6.

4.8.4 Symmetric and Asymmetric Properties

If a property P is symmetric, and the property relates individual a to individual b then individual b is also related to individual a via property P. The `hasSibling` property or `hasSpouse` are examples of

symmetric properties. If `Michelle hasSpouse Barack,` then `Barack hasSpouse Michelle`. A symmetric property is its own inverse.

An Asymmetric property is a property that can never have symmetric values. If a property P is asymmetric then if a is related to b via that property b cannot be related to a via that property. An example of an asymmetric property is `hasBirthMother`. If Diya `hasBirthMother Fatima,` then it can't be the case that `Fatima hasBirthMother Diya`.

4.8.5 Reflexive and Irreflexive Properties

A reflexive property is a property that always relates an individual to itself. If a property P is reflexive then for all individuals a P will always relate a to a. Equality is the most common example of a reflexive property. For any object a, a is always equal to a. An irreflexive property is… you guessed it… a property that can never relate an individual to itself. The property `hasBirthMother` is an example of an irreflexive property since no person can be their own mother. Note: you should use reflexive properties with care. The domain of a reflexive property is *always* `owl:Thing`. The reasons are complex, see the W3C Owl 2 Specification in the bibliography for more details. The important thing is that if you make a property reflexive that means its domain is `owl:Thing`. For example, if you have a reflexive property and declare its domain to be some class such as `Person` the reasoner will infer that `Person` is equivalent to `owl:Thing` which can cause problems.

4.8.6 Reasoners Automatically Enforce Property Characteristics

The reasoners that work with Protégé automatically enforce all the characteristics that are described above. For example, if the user enters the fact that `Diya hasBirthMother Fatima` and `isBirthMotherOf` is the inverse of `hasBirthMother`, the reasoner will infer that `Fatima isBirthMotherOf Diya`. These types of characteristics can significantly reduce the amount of effort needed to populate an ontology with data about individuals.

4.9 OWL Property Domains and Ranges

Properties may have a *domain* and *range* defined. These terms have the same meaning in OWL as they do in mathematics and set theory. The domain of a property is the set of all objects that can have that property asserted about it. The range is the set of all objects that can be the value of the property. Both the domain and range are optional. In general, it is a good idea to define them because doing so can catch modeling mistakes while defining the model rather than at run time when trying to use it. The domain for an object property must always be a class. For data properties the range is a simple datatype such as `xsd:decimal`. The most common predefined datatypes already exist in Protégé. It is also possible to define new data types although most users will seldom need to do that. For most cases if you are considering defining a new datatype you should probably consider making the property an object property instead and defining a class as the range. For people familiar with Entity-Relation modeling an object property is similar to a relation and a data property is similar to an attribute. For those familiar with set theory a property is identical to a binary relation in set theory.

As an example, in our pizza ontology, the property `hasTopping` would link individuals belonging to the class `Pizza` to individuals belonging to the class `PizzaTopping`. The domain of `hasTopping` is `Pizza` and the range is `PizzaTopping`. Inverse properties have their domains and range swapped. In this example, the inverse of `hasTopping` will be called `isToppingOf`. Thus, the domain for `isToppingOf` is the range of `hasTopping` (`PizzaTopping`) and the range for `isToppingOf` is the domain of `hasTopping` (`Pizza`).

Exercise 11: Define the domain and range of the hasTopping property

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1. Navigate to the Object properties tab. Select the hasTopping property.

2. Click on the Add icon (+) next to Domains (intersection) in the Description view for hasTopping.
You will be presented with a window that shows several tabs. There are multiple ways to define domain
and range. For now we will use the simplest method (and the one most often used). Select the
ClassHierarchy tab. Then select Pizza from the class hierarchy. Your UI should look like figure 4.14.
Click on OK. You should now see Pizza underneath the Domains in the Description view.

3. Repeat step 2 but this time start by using the (+) icon next to the Ranges (intersection) in the
Description for hasTopping. This time select the class PizzaTopping as the range.

4. Synchronize the reasoner. Now select isToppingOf. You should see that the Domain and Range for
isToppingOf have been filled in by the reasoner (see figure 4.15). Since the two properties are inverses
the reasoner knows that the domain for one is the range for the other and vice versa. This is another
example of why frequently running the reasoner can save time and help maintain a valid model. Note that
these values are highlighted in yellow. Any information supplied by the reasoner rather than by the user is
highlighted in this way.

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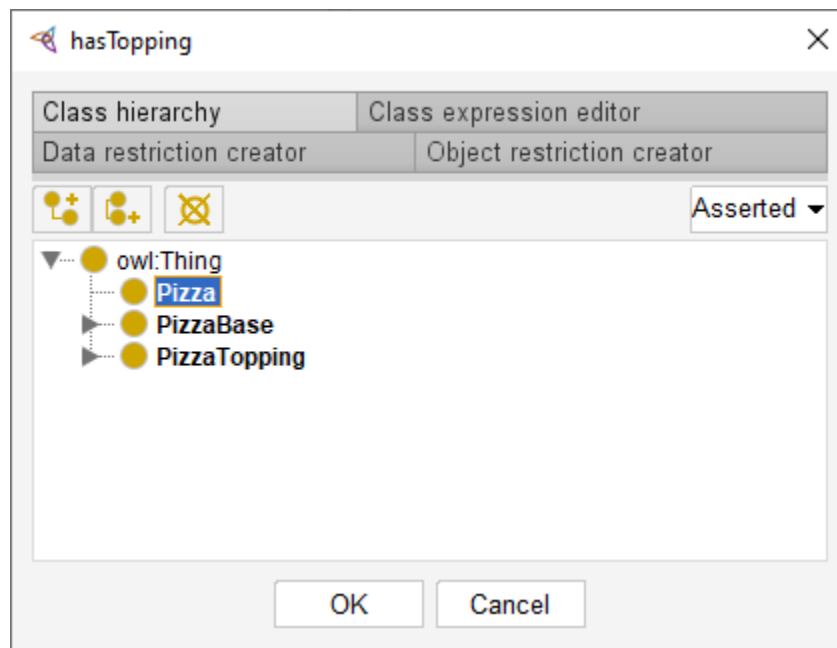
Figure 4.14 Defining the Domain for hasTopping
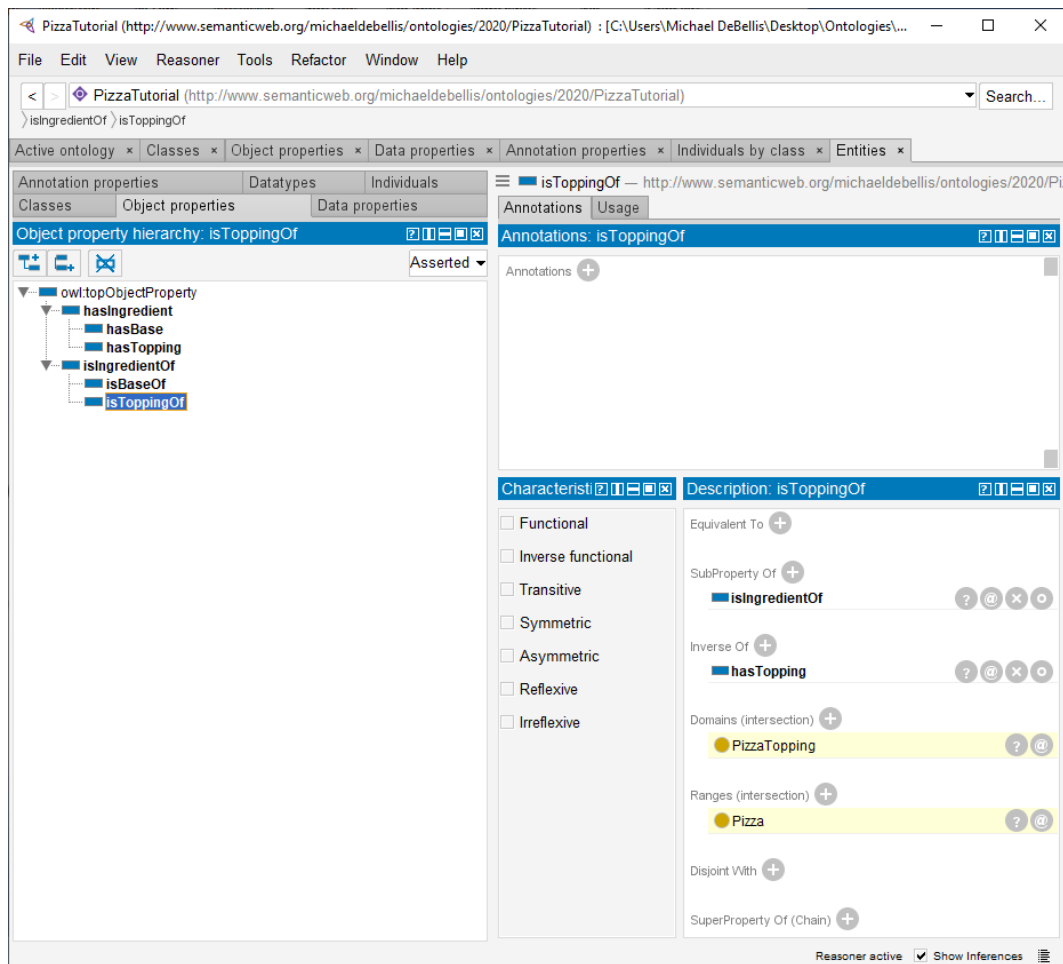
Figure 4.15 Domain and Range inferred by the reasoner

It is possible to specify more than one class as the domain or range of a property. One of the most common mistakes of new users is to do this and expect that the resulting domain/range is the union of the two classes. However, note that next to the Domain and Range in the Description view it says (intersection). This is because the semantics of having 2 or more classes as the domain or range is the *intersection* of those classes *not* the union. E.g., if one defined the domain for a property to be `Pizza` and then added another domain `IceCream` that would mean that for something to be in the domain of that property it would have to be an instance of *both* `Pizza` *and* `IceCream` not (as people often expect) the *union* of those two sets which would be *either* the class `Pizza` *or* the class `IceCream`. Also, note that the domain and range are for inferencing, they are not data integrity constraints. This distinction will be explained in more detail below in the section on SHACL.

Exercise 12: Define the domain and range for the hasBase property

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1. Now we are going to repeat the same activities as in the previous exercise but for another property: `hasBase`. Make sure you are still on the Object properties tab. Select the hasBase property.

2. Click on the Add icon (+) next to Domains (intersection) in the Description view for `hasBase.` Select the ClassHierarchy tab. Then select Pizza from the class hierarchy..

3. Repeat step 2 but this time start by using the (+) icon next to the Ranges (intersection) in the Description for `hasBase`. This time select the class PizzaBase as the range.

4. Synchronize the reasoner. Now select isBaseOf You should see that the Domain and Range for `isBaseOf` have been filled in by the reasoner.

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4.10 Describing and Defining Classes

Now that we have defined some properties, we can use these properties to define some more interesting classes. There are 3 types of classes in OWL:

1. Primitive classes. These are classes that are defined by conditions that are _necessary_ (but not sufficient) to hold for any individuals that are instances of that class or its subclasses. The condition may be as simple as: _Class A is a subclass of class B_. To start with we will define primitive classes first and then defined classes. When the reasoner encounters an individual that is an instance of a primitive class it infers that all the conditions defined for that class must hold for that individual.

2. Defined classes. These are classes that are defined by both _necessary_ and _sufficient_ conditions. When the reasoner encounters an individual that satisfies all the conditions for a defined class it will make the inference that the individual is an instance of that class. The reasoner can also use the conditions defined on classes to change the class hierarchy, e.g., to infer that _Class A is a subclass of Class B_. We will see examples of this later in the tutorial.

3. Anonymous classes. These are classes that you won't encounter much and that won't be discussed much in this tutorial, but it is good to know about them. They are created by the reasoner when you use class expressions. For example, if you define the range of a property to be `PizzaTopping or PizzaBase` then the reasoner will create an anonymous class representing the intersection of those two classes.

4.10.1 Property restrictions

In OWL properties define binary relations with the same semantics and characteristics as binary relations in First Order Logic. There are two types of OWL properties for describing a domain: Object properties and Data properties. Object properties have classes as their domain and range. Data properties have classes as their domain and simple datatypes such as `xsd:string` or `xsd:dateTime` as their range. In figure 3.3 the individual `Michael` is related to the individual USA by the property `livesIn`. Consider all the individuals who are an instance of `Person` and also have the same relation, that each `livesIn` the USA. This group is a set or OWL class such as `USAResidents`. In OWL a class can be defined by describing the various properties and values that hold for all individuals in the class. Such definitions are called _restrictions_ in OWL.

The following are some examples of classes of individuals that we might want to define via property restrictions:

- The class of individuals with at least one `hasChild` relation.
- The class of individuals with 2 or more `hasChild` relations.
- The class of individuals that have at least one `hasTopping` relationship to individuals that are members of `MozzarellaTopping` – i.e. the class of things that have at least a mozzarella topping.
- The class of individuals that are `Pizzas` and only have `hasTopping` relations to instances of the class `VegetableTopping` (i.e., `VegetarianPizza`).

In OWL we can describe all of the above classes using restrictions. OWL restrictions fall into three main categories:

1. Quantifier restrictions. These describe that a property must have some or all values that are of a particular class.
2. Cardinality restrictions. These describe the number of individuals that must be related to a class by a specific property.
3. hasValue restrictions. These describe specific values that a property must have.

We will initially use quantifier restrictions. Quantifier restrictions can be further categorized as *existential* restrictions and *universal* restrictions[6]. Both types of restrictions will be illustrated with examples in this tutorial.

- Existential restrictions describe classes of individuals that participate in at least one relation along a specified property. For example, the class of individuals who have at least one (or some) `hasTopping` relation to instances of `VegetableTopping`. In OWL the keyword `some` is used to denote existential restrictions.
- Universal restrictions describe classes of individuals that for a given property *only* have relations along a property to individuals that are members of a specific class. For example, the class of individuals that only have `hasTopping` relations to instances of the class `VegetableTopping`. In OWL they keyword `only` is used for universal restrictions.

Let's take a closer look at an example of an existential restriction. The restriction `hasTopping some MozzarellaTopping` is an existential restriction (as indicated by the `some` keyword), which restricts the `hasTopping` property, and has a filler `MozzarellaTopping`. This restriction describes the class of individuals that have at least one `hasTopping` relationship to an individual that is a member of the class `MozzarellaTopping`.

> A restriction always describes a class. Sometimes (as we will soon see) it can be a defined class. Other times it may be an anonymous class. In all cases the class contains all of the individuals that satisfy the restriction, i.e., all of the individuals that have the relationships required to be a member of the class. In section 9.2 one of our SPARQL queries will return several anonymous classes.

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[6] These have the same meaning as existential and universal quantification in First Order Logic.

The restrictions for a class are displayed and edited using the <mark>Class Description View</mark> shown in Figure 4.17. The Class Description View holds most of the information used to describe a class. The Class Description View is a powerful way of describing and defining classes. It is one of the most important differences between describing classes in OWL and in other models such as most object-oriented programming languages. In other models there is no formal definition that describes why one class is a subclass of another, in OWL there is. Indeed, the OWL classifier can actually redefine the class hierarchy based on the logical restrictions defined by the user. We will see an example of this later in the tutorial.

> Restrictions are also called axioms in OWL. This has the same meaning as in logic. An axiom is a logical formula defined by the user rather than deduced by the reasoner. As described above, in Protégé all axioms are shown in normal font whereas all inferences inferred by the reasoner are highlighted in yellow.

4.10.2 Existential Restrictions

An existential restriction describes a class of individuals that have at least one (some) relationship along a specified property to an individual that is a member of a specified class or datatype. For example, `hasBase some PizzaBase` describes all of the individuals that have at least one relationship along the `hasBase` property to an individual that is a member of the class `PizzaBase` — in more natural English, all of the individuals that have at least one pizza base.

Exercise 13: Add a restriction to Pizza that specifies a Pizza must have a PizzaBase

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1. Select <mark>Pizza</mark> from the class hierarchy on the <mark>Classes</mark> tab.

2. Click on the Add icon <mark>(+)</mark> next to the <mark>SubClass Of</mark> field in the <mark>Description</mark> view for Pizza.

3. This will bring up a new window with several tab options to define a new restriction. Select the <mark>Object restriction creator</mark>. This tab has the <mark>Restricted property</mark> on the left and the <mark>Restriction filler</mark> on the right.

4. Expand the property hierarchy on the left and select <mark>hasBase</mark> as the property to restrict. Then in the Restriction filler on the right select the class <mark>PizzaBase</mark>. Finally, the Restriction type at the bottom should be set to <mark>Some (existential)</mark>. This should be the default so you shouldn't have to change anything but double check that this is the case. Your window should look like figure 4.16 now.

5. When your UI looks like figure 4.16 click on the <mark>OK</mark> button. That should close the window. Run the reasoner to make sure things are consistent. Your main window should now look like figure 4.17.
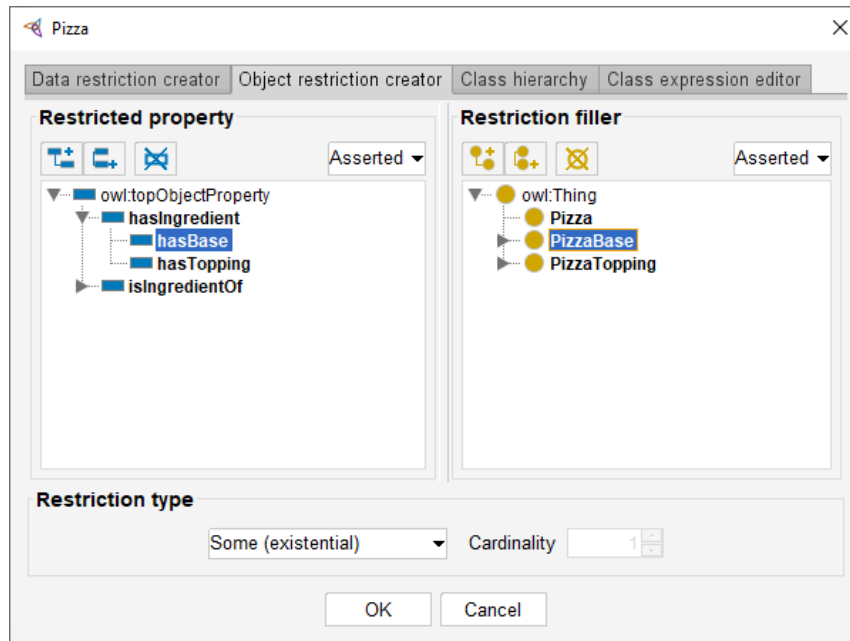
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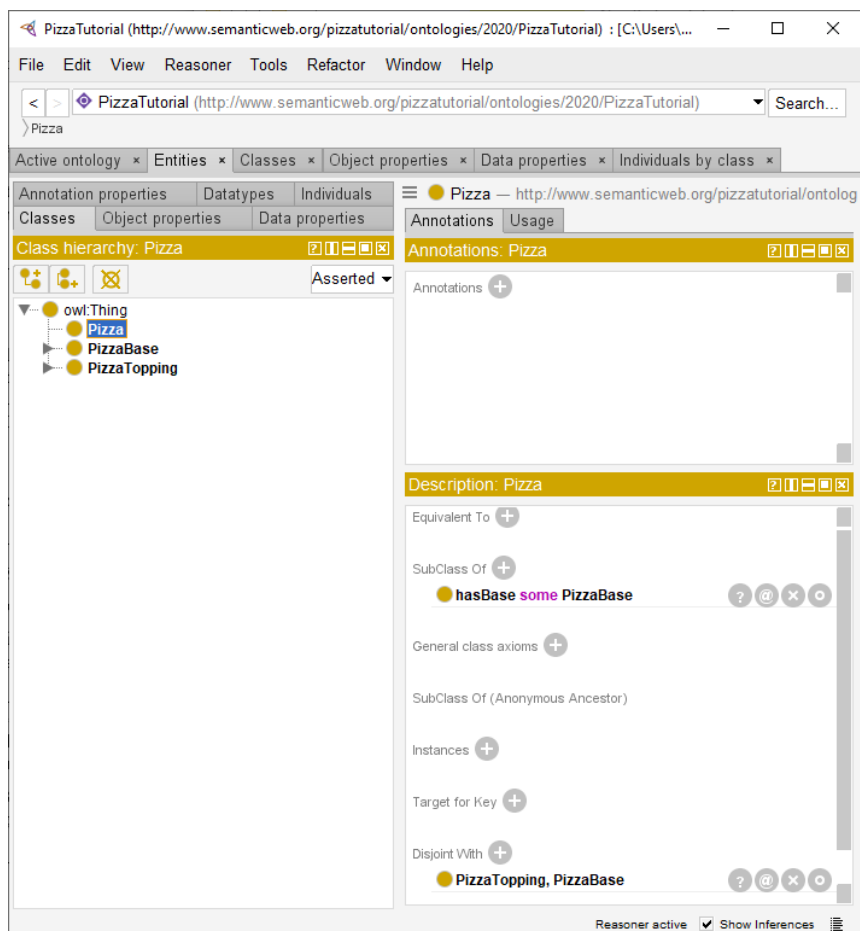Figure 4.16 The Object Restriction Creator Tab

Figure 4.17 The Pizza Class with hasBase Restriction

We have described the class `Pizza` to be to be a subclass of `Thing` and a subclass of the things that have a base which is some kind of `PizzaBase`. Notice that these are necessary conditions — if something is a `Pizza` it is *necessary* for it to be a member of the class `Thing` (in OWL, everything is a member of the class `Thing`) and *necessary* for it to have a kind of `PizzaBase`. More formally, for something to be a `Pizza` it is necessary for it to be in a relationship with an individual that is a member of the class `PizzaBase` via the property `hasBase`.

4.10.3 Creating Subclasses of Pizza

It's now time to add some different kinds of pizzas to our ontology. We will start off by adding a `MargheritaPizza`, which is a pizza that has toppings of mozzarella and tomato. In order to keep our ontology tidy, we will group our different pizzas under the class `NamedPizza`.

Exercise 14: Create Subclasses of Pizza: NamedPizza and MargheritaPizza

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1. Select Pizza from the class hierarchy on the Classes tab.

2. Click on the Add subclass icon at the top left of the Classes tab (look back at figure 4.4 if you aren't certain). You can also move your mouse over the icons and you will see a little pop-up hint for each icon.

3. Protégé will prompt you for the name of the new subclass. Call it NamedPizza.

4. Repeat steps 1-3 this time starting with NamedPizza to create a subclass of NamedPizza. Call it MargheritaPizza.

5. Add a comment to the class `MargheritaPizza` using the Annotations view. This is above the Description view. Add the comment: A pizza that only has Mozzarella and Tomato toppings. Remember that annotation properties are meta-data that can be asserted about any entity whereas object and data properties can only be asserted about individuals. There are a few predefined annotation properties that are included in all Protégé ontologies such as the comment property.

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Having created the class MargheritaPizza we now need to specify the toppings that it has. To do this we will add two restrictions to say that a MargheritaPizza has the toppings MozzarellaTopping and TomatoTopping.

Exercise 15: Create Restrictions that define a MargheritaPizza

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1. Select MargheritaPizza from the class hierarchy on the Classes tab.

2. Click on the Add icon (+) next to the SubClass Of field in the Description view for Pizza.

3. This again brings up the restriction dialogue. This time rather than use the Object restriction creator we will use the Class expression editor tab. Select that tab.

4. Type hasTopping some Mo into the field. Rather than type the rest of the name of the topping now hit <control><space> (hold down the control key and hit the space bar). Protégé should auto-complete the name for you and the field should now contain: hasTopping some MozzarellaTopping. This is a useful technique for any part of the Protégé UI. Whenever you enter the name of some entity you can do

<control><space>. If there is only one possible completion for the string then Protégé will fill in the appropriate name. If there are multiple possible completions Protégé will create a menu with all the possible completions and allow you to select the one you want.

5. Click on OK to enter the new restriction.

6. Repeat steps 1-5 only this time add the restriction hasTopping some TomatoTopping. Remember to use <control><space> to save time typing. Synchronize the reasoner to make sure things are consistent. Your UI should now look similar to figure 4.18.
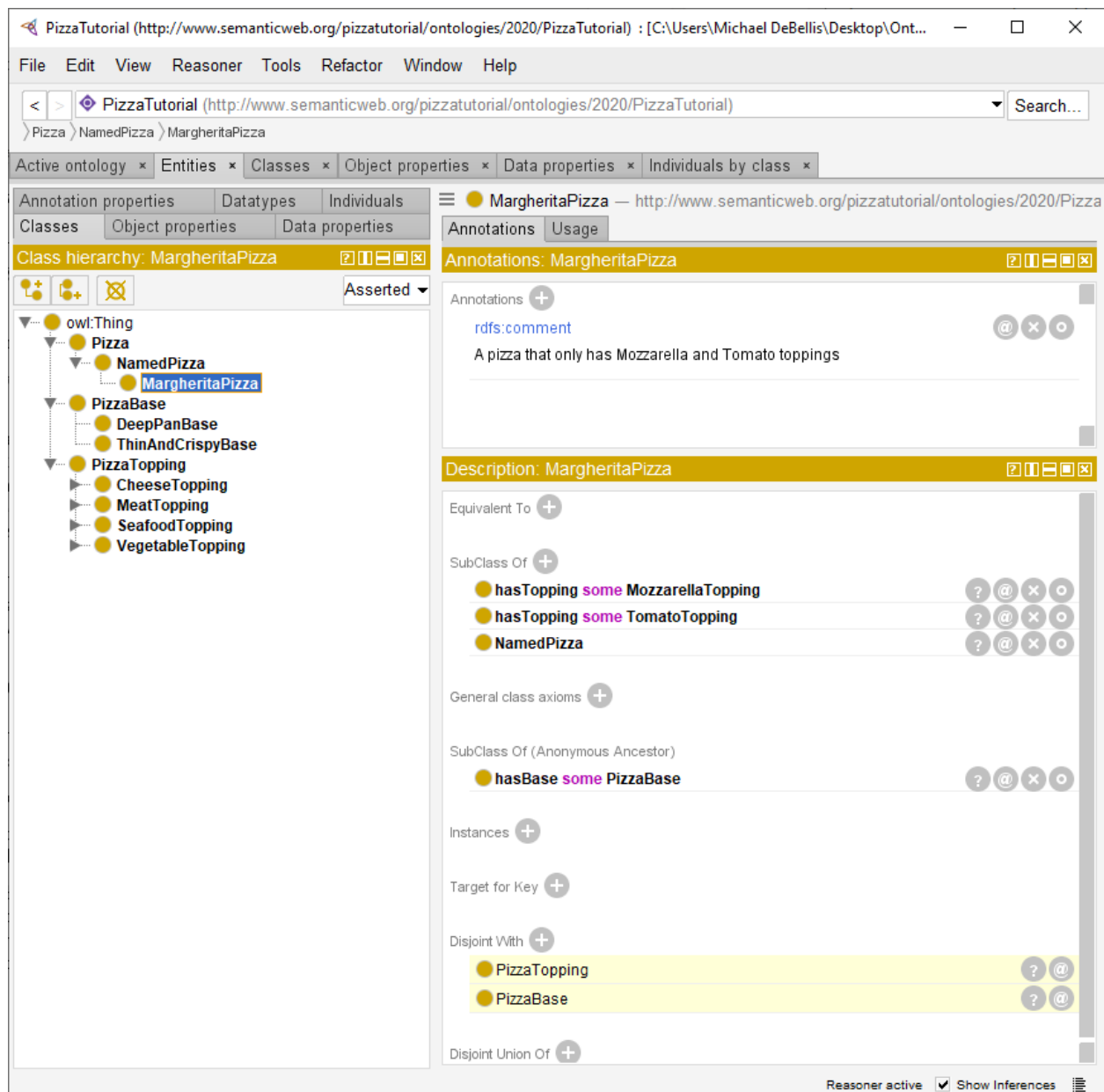
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Figure 4.18 Definition for the class MargheritaPizza

Note in figure 4.18 the two classes listed under <mark>Disjoint With</mark> and highlighted in yellow. This is an example of an inference from the reasoner. When we defined `Pizza`, `PizzaBase`, and `PizzaTopping` we made those 3 classes disjoint. I.e., no individual can be a member of more than one of those classes. Since `MargheritaPizza` is a subclass of `Pizza` it is also disjoint with `PizzaBase` and `PizzaTopping,` so the reasoner has added this information to the definition of `MargheritaPizza` and as with all inferences from the reasoner highlighted the new information in yellow.

We will now create the class to represent an `AmericanaPizza`, which has toppings of pepperoni, mozzarella and tomato. Because the class `AmericanaPizza` is similar to the class `MargheritaPizza` (i.e., an `AmericanaPizza` is almost the same as a `MargheritaPizza` but with an extra topping of pepperoni) we will make a clone of the `MargheritaPizza` class and then add an extra restriction to say that it has a topping of pepperoni.

Exercise 16: Create AmericanaPizza by Cloning MargheritaPizza and Adding Additional Restrictions

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1. Select <mark>MargheritaPizza</mark> from the class hierarchy on the <mark>Classes</mark> tab.

2. Select <mark>Edit>Duplicate selected class</mark>. This will bring up a dialogue for you to duplicate the class. The default is the name of the existing class so there will be a red error message when you start because you need to enter a new name. Change the name from <mark>MargheritaPizza</mark> to <mark>AmericanaPizza</mark>. Leave all the other options as they are and then select <mark>OK</mark>.

3. Make sure that <mark>AmericanaPizza</mark> is still selected. Click on the Add icon <mark>(+)</mark> next to the <mark>SubClass Of</mark> field in the <mark>Description</mark> view for `AmericanaPizza`.

4. Use either the <mark>Object restriction creator</mark> tab or the <mark>Class expression editor</mark> tab to add the additional restriction: <mark>hasTopping some PepperoniTopping</mark>.

5. Click on <mark>OK</mark> to enter the new restriction.

6. Edit the comment annotation on `AmericanaPizza`. It should currently be: <mark>A pizza that only has Mozzarella and Tomato toppings</mark> since it was copied over from `MargheritaPizza`. Note that at the top right of the comment there are three little icons, an <mark>@</mark> sign, an <mark>X</mark> and an <mark>O</mark>. Click on the <mark>O</mark>. This icon is the one you use to edit any existing data in Protégé. This should bring up a window where you can edit the comment. Change it to something appropriate such as: <mark>A pizza that only has Mozzarella, Tomato, and Pepperoni toppings</mark>. Then click on <mark>OK</mark> to enter the edit to the comment.

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Exercise 17: Create AmericanaHotPizza and SohoPizza

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1. An `AmericanaHotPizza` is almost the same as an `AmericanaPizza` but has Jalapeno peppers on it. Create this by cloning the class <mark>AmericanaPizza</mark> and adding an existential restriction along the <mark>hasTopping</mark> property with a filler of <mark>JalapenoPepperTopping</mark>.

2. A `SohoPizza` is almost the same as a `MargheritaPizza` but has additional toppings of olives and parmesan cheese — create this by cloning MargheritaPizza and adding two existential restrictions along the property hasTopping, one with a filler of OliveTopping, and one with a filler of ParmesanTopping.

_____

Exercise 18: Make Subclasses of NamedPizza Disjoint

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1. We want to make these subclasses of NamedPizza disjoint from each other. I.e., any individual can belong to at most one of these classes. To do that first select MargheritaPizza (or any other subclass of `NamedPizza`).

2. Click on the (+) sign next to Disjoint With near the bottom of the Description view. This will bring up a Class hierarchy view. Use this to navigate to the subclasses of `NamedPizza` and use <control><left click> to select all of the other sibling classes to the one you selected. Then select OK. You should now see the appropriate disjoint axioms showing up on each subclass of `NamedPizza`. Synchronize the reasoner. Your UI should look similar to figure 4.19 now.
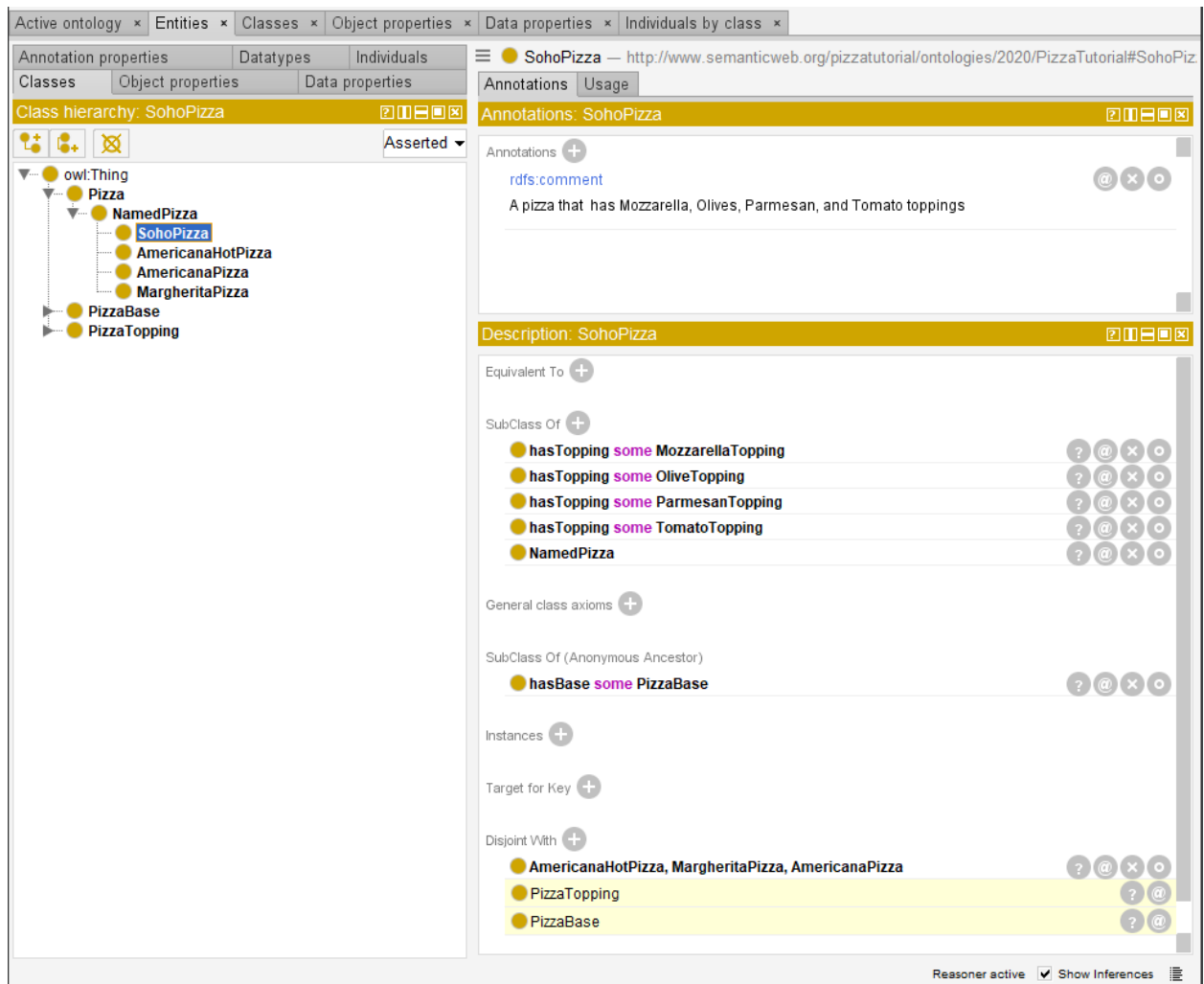

Figure 4.19 Subclasses of NamedPizza are Disjoint

4.10.4 Detecting a Class that can't Have Members

Next, we are going to use the reasoner to detect a class with a definition that means it can never have any members. In the current version of Protégé when the reasoner detects an inconsistency or problem on some operating systems the UI can occasionally lock up and be hard to use. So to make sure you don't lose any of your work save your ontology using File>Save.

Sometimes it can be useful to create a class that we think should be impossible to instantiate to make sure the ontology is modeled as we think it is. Such a class is called a Probe Class.

Exercise 19: Add a Probe Class called ProbeInconsistentTopping

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1. Select the class CheeseTopping from the class hierarchy.

2. Create a subclass of CheeseTopping called ProbeInconsistentTopping.

3. Click on the Add icon (+) next to the SubClass Of field in the Description view for ProbeInconsistentTopping.

4. Select the Class hierarchy tab from the dialogue that pops up. This will bring up a small view that looks like the class hierarchy tab you have been using to add new classes. Use this to navigate to and select the class VegetableTopping. Click on OK.

5. Make sure to save your current ontology file. Now run the reasoner. You should see that ProbeInconsistentTopping is now highlighted in red indicating it is inconsistent.

6. Click on ProbeInconsistentTopping to see why it is highlighted in red. Notice that at the top of the Description view you should now see owl:Nothing under the Equivalent To field. This means that the probe class is equivalent to owl:Nothing. The owl:Nothing class is the opposite of owl:Thing. Whereas all individuals are instances of owl:Thing, no individual can ever be an instance of owl:Nothing. The owl:Nothing class is equivalent to the empty set in set theory.

7. There should be a ? icon just to the right of owl:Nothing. As with any inference of the reasoner it is possible to click on the new information and generate an explanation for it. Do that now, click on the ? icon. This should generate a new window that looks like figure 4.20. The explanation is that ProbeInconsistentTopping is a subclass of CheeseTopping and VegetableTopping but those two classes are disjoint.

8. Click OK to dismiss the window. Delete the class ProbeInconsistentTopping by selecting it and then clicking on the delete class icon at the top of the classes view (see figure 4.4).

9. Synchronize the reasoner.

_____
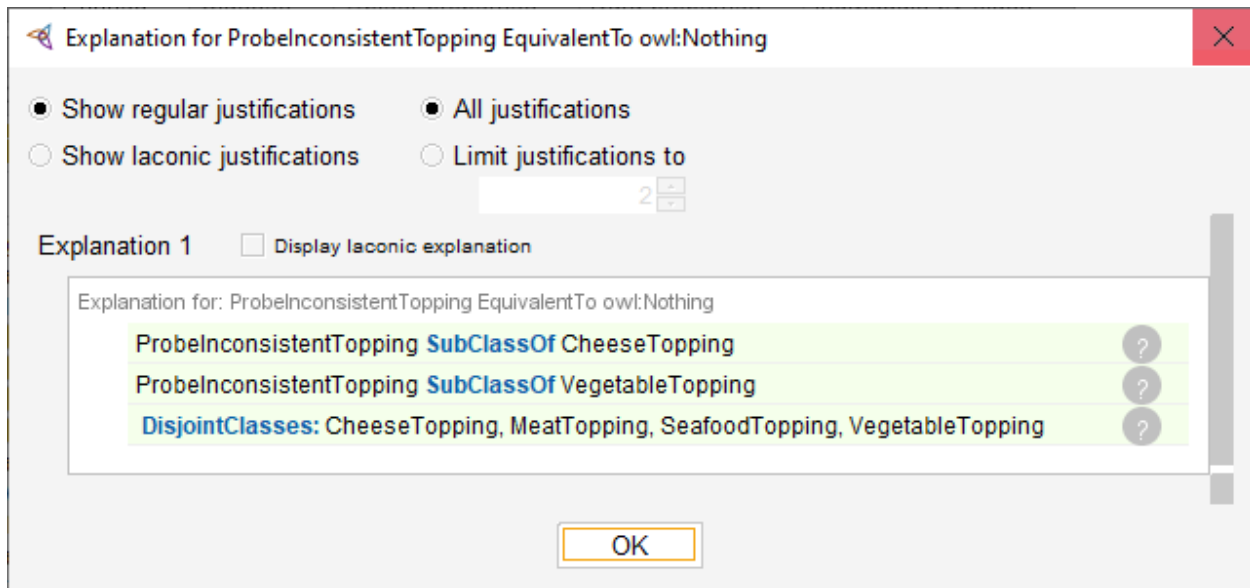
Figure 4.20 Explanation for why `ProbeInconsistentTopping` is equivalent to `owl:Nothing`

4.11 Primitive and Defined Classes (Necessary and Sufficient Axioms)

All of the classes that we have created so far have only used necessary axioms to describe them. Necessary axioms can be read as, *If something is a member of this class then it is necessary to fulfil these conditions*. With necessary axioms alone, we *cannot* say that: *If something fulfils these conditions then it must be a member of this class*.

Let's illustrate this with an example. We will create a subclass of `Pizza` called `CheesyPizza`, which will be a `Pizza` that has at least one kind of `CheeseTopping`.

Exercise 20: Create the CheesyPizza class

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1. Select Pizza in the class hierarchy on the Classes tab.

2. Select the Add Subclass icon (see figure 4.4). Name the new subclass CheesyPizza.

3. Make sure CheesyPizza is selected. Click on the Add icon (+) next to the SubClass Of field in the Description view.

4. Select the Class expression editor tab. Type in the new axiom: hasTopping some CheeseTopping. Remember you can use <control><space> to auto-complete each word in the axiom, e.g., type hasT and then <control><space> to auto-complete the rest. If you haven't typed enough for Protégé to unambiguously choose one entity or Description Logic keyword you will be prompted with a menu of possible completions. Click OK to enter the new restriction axiom.

_____

Note that if you just type a few characters, the number of possible completions may be large resulting in an unwieldy menu. Also, Protégé doesn't do things like type checking on possible completions. For example, if you type "Chee" and do <control><space> you will be prompted with `CheeseTopping` and `CheesyPizza` as possible completions even though a `Pizza` is not in the range of `hasTopping`. This is where the reasoner can also help. If you enter a class that is not in the range of `hasTopping` the reasoner will signal an inconsistency.

Our current description of `CheesyPizza` says that if something is a `CheesyPizza` it is *necessarily* a `Pizza` and it is *necessary* for it to have at least one topping that is a kind of `CheeseTopping`. Now consider some random individual. Suppose that we know that this individual is a member of the class `Pizza`. We also know that this individual has at least one kind of `CheeseTopping`. However, given our current description of `CheesyPizza` this knowledge is not sufficient to determine that the individual is a member of the class `CheesyPizza`. To make this possible we need to change the conditions for `CheesyPizza` from *necessary* conditions to *necessary AND sufficient* conditions. This means that not only are the conditions *necessary* for membership of the class `CheesyPizza`, they are also *sufficient* to determine that any random individual that satisfies them must be a member of the class `CheesyPizza`.

A class (such as all the classes we have defined so far) that only has necessary conditions is called a *primitive class*. A class that has necessary and sufficient conditions is known as a *defined class*. In order to convert necessary conditions to necessary and sufficient conditions, the conditions must be moved from under the SubClass Of header in the class description view to be under the Equivalent To header. This can be done with the menu option: Edit>Convert to defined class.

Exercise 21: Convert CheesyPizza from a Primitive Class to a Defined Class

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1. Make sure CheesyPizza is selected.

2. Select the menu option: Edit>Convert to defined class.

3. Synchronize the reasoner.

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Your screen should now look similar to figure 4.21. Note that when a class is a defined class it is shown in the UI with three horizontal stripes in the circle next to its name.

So far we have seen the reasoner do simple things such as propagate disjoint axioms from super classes down to subclasses. However, the reasoner is capable of doing much more. Now that we have a defined class we can see an example of this. Notice that there are two tabs in the Class hierarchy view. The one shown in figure 4.21 is the asserted hierarchy. This is the hierarchy as defined by user declared axioms. The other tab is the Class hierarchy (inferred) tab. This is the hierarchy as inferred by the reasoner. Up until we created a defined class the two tabs would be identical because we had only primitive classes in the ontology. Now that we have a defined class the inferred hierarchy will look different. Select the Class hierarchy (inferred) tab. Make sure that the reasoner is synchronized (it should say Reasoner active as in figure 4.21). Also, make sure to expand the `CheesyPizza` class in this tab. You should see a screen similar to figure 4.22. As you should see in the inferred tab the reasoner has inferred that all the `Pizza` classes with a cheese topping are subclasses of `CheesyPizza`.
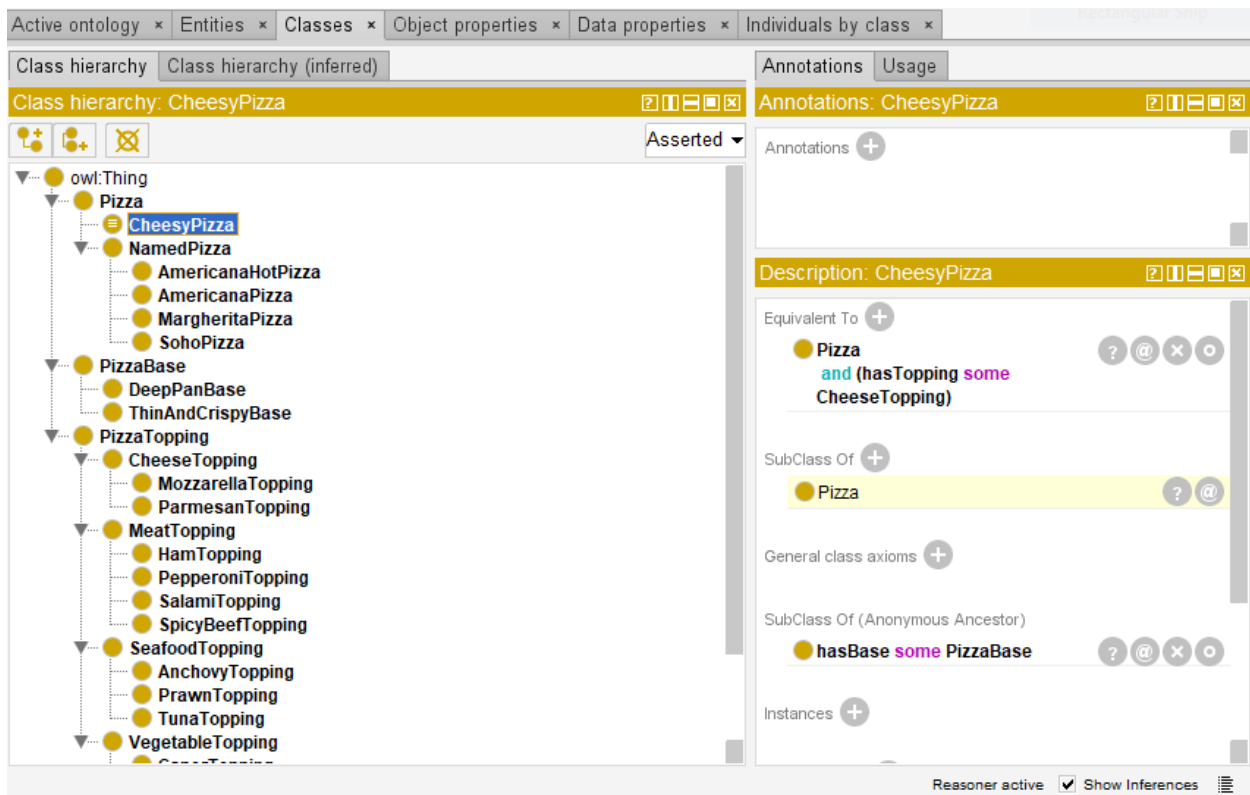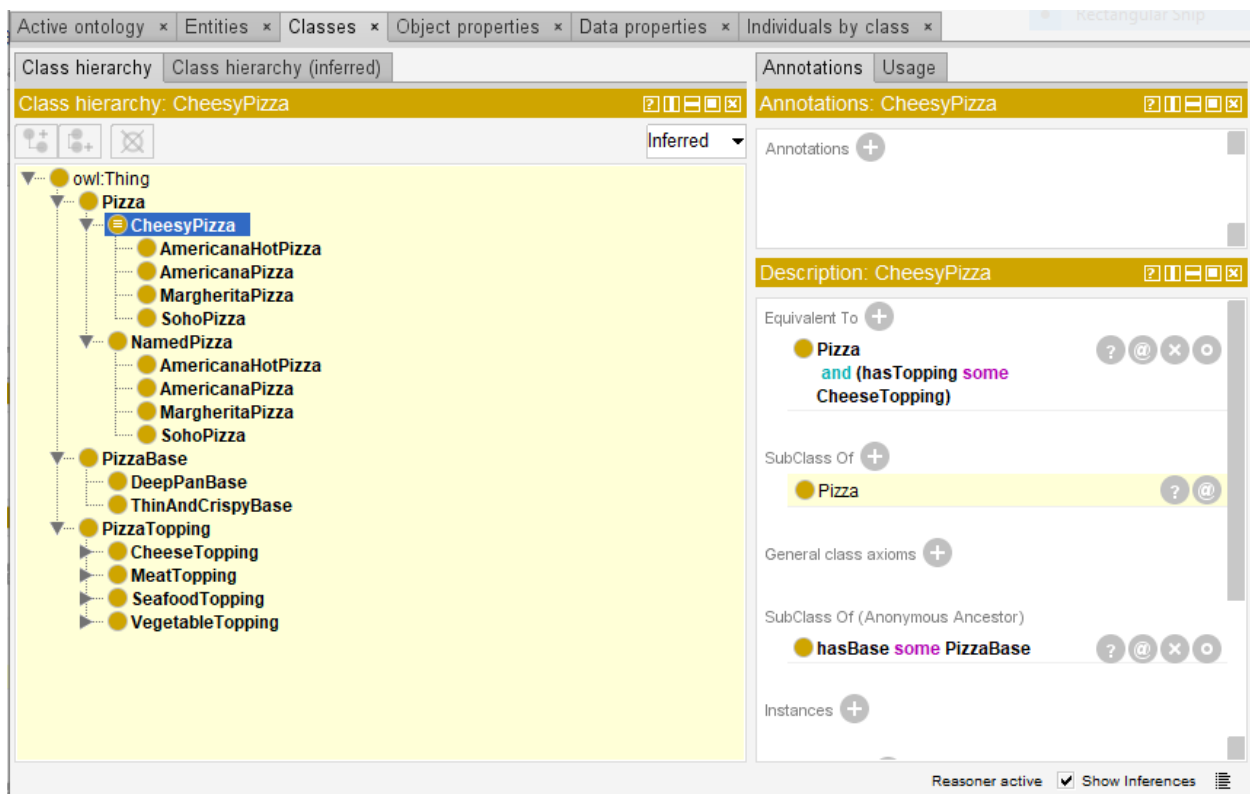
Figure 4.21 CheesyPizza as a Defined Class

Figure 4.22 Classes Inferred by the Reasoner to be subclasses of CheesyPizza

4.12 Universal Restrictions

All of the restrictions we have created so far have been existential restrictions (defined using the `some` DL keyword). Existential restrictions specify the existence of at least one relationship along a given property to an individual that is a member of a specific class (specified by the filler). However, existential restrictions do not mandate that the only relationships for the given property that can exist must be to individuals that are members of the specified filler class.

For example, we could use an existential restriction `hasTopping some MozzarellaTopping` to describe the individuals that have at least one relationship along the property `hasTopping` to an individual that is a member of the class `MozzarellaTopping`. This restriction does not imply that all of the `hasTopping` relationships must be to a member of the class `MozzarellaTopping`. To restrict the relationships for a given property to individuals that are members of a specific class we must use a universal restriction. Universal restrictions correspond to the symbol ∀ in First Order Logic. They constrain the relationships along a given property to individuals that are members of a specific class. For example, the universal restriction ∀ `hasTopping VegetableTopping` describes the individuals all of whose `hasTopping` relationships are to members of the class `VegetableTopping` — the individuals do not have a `hasTopping` relationship to individuals that aren't members of the class `VegetableTopping`.

Suppose we want to create a class called `VegetarianPizza`. Individuals that are members of this class can only have toppings that are a `CheeseTopping` or `VegetableTopping`. To do this we can use a universal restriction:

Exercise 22: Create a Defined Class called VegetarianPizza

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1. Select the Pizza in the Classes tab. Create a subclass of `Pizza` and name it `VegetarianPizza`.

2. Make sure VegetarianPizza is selected. Click on the Add icon (+) next to the SubClass Of field in the Description view.

3. Select the Class expression editor tab from the pop-up window. Type in the Description Logic axiom: hasTopping only (VegetableTopping or CheeseTopping). Click on OK.

4. Make sure VegetarianPizza is still selected. Run the Edit>Convert to defined class command.

5. `VegetarianPizza` should now have three horizontal lines through it just as `CheesyPizza` does. Also, the Equivalent To field in the Description view should have: Pizza and (hasTopping only (CheeseTopping or VegetableTopping)). Note that another way to create defined classes is to enter the Description Logic axiom directly into the Equivalent To field.

6. Synchronize the reasoner.

_____

This means that if something is a member of the class `VegetarianPizza` it is necessary for it to be a kind of `Pizza` and it is necessary for it to only (∀ universal quantifier) have toppings that are kinds of `CheeseTopping` or kinds of `VegetableTopping`. In other words, all `hasTopping` relationships that individuals which are members of the class `VegetarianPizza` participate in must be to individuals that are either members of the class `CheeseTopping` or `VegetableTopping`. The class `VegetarianPizza` also contains individuals that are Pizzas and do not participate in any `hasTopping` relationships.

⚠️ In situations like the above example, a common mistake is to use an intersection instead of a union. For example, CheeseTopping *and* VegetableTopping. Although CheeseTopping and Vegetable might be a natural thing to say in English, this logically means something that is simultaneously a kind of CheeseTopping and VegetableTopping. This is incorrect because we have stated that CheeseTopping and VegetableTopping are disjoint classes and hence no individual can be an instance of both. If we used such a definition the reasoner would detect the inconsistency.

⚠️ In the above example it might have been tempting to create two universal restrictions — one for CheeseTopping (∀ hasTopping CheeseTopping) and one for VegetableTopping (∀ hasTopping VegetableTopping). However, when multiple restrictions are used (for any type of restriction) the total description is taken to be the intersection of the individual restrictions. This would have therefore been equivalent to one restriction with a filler that is the intersection of MozzarellaTopping *and* TomatoTopping — as explained above this would have been logically incorrect.

4.13 Automated Classification and Open World Reasoning

Make sure that the reasoner is synchronized (the little text in the lower right corner should say <mark>Reasoner active</mark>). Now switch from the <mark>Class hierarchy</mark> tab to the <mark>Class hierarchy (inferred)</mark> tab. You may notice something that seems perplexing. The classes MargheritaPizza and SohoPizza both only have vegetable and cheese toppings. So one might expect that the reasoner would classify them as subclasses of VegetarianPizza as it recently (in section 4.11) classified them and others as subclasses of CheesyPizza. The reason this didn't happen is something called the Open World Assumption (OWA). This is one of the concepts of OWL that can be most confusing for new and even experienced users because it is different than the Close World Assumption (CWA) used in most other programming and knowledge representation languages.

In most languages using the CWA we assume that everything that is currently known about the system is already in the database. However, OWL was meant to be a language to bring semantics to the Internet so the language designers chose the OWA. The open world assumption means that we cannot assume something doesn't exist just because it isn't currently in the ontology. The Internet is an open system. The information could be out there in some data source that hasn't yet been integrated into our ontology. Thus, we can't conclude some information doesn't exist unless it is *explicitly stated that it does not exist*. In other words, because something hasn't been stated to be true, it cannot be assumed to be false — it is assumed that the knowledge just hasn't been added to the knowledge base. In the case of our pizza ontology, we have stated that MargheritaPizza has toppings that are kinds of MozzarellaTopping and also kinds of TomatoTopping. Because of the open world assumption, until we explicitly say that a MargheritaPizza only has these kinds of toppings, it is assumed by the reasoner that a MargheritaPizza could have other toppings. To specify explicitly that a MargheritaPizza has toppings that are kinds of MozzarellaTopping or kinds of TomatoTopping and only kinds of MozzarellaTopping or TomatoTopping, we must add what is known as a closure axiom on the hasTopping property.

A closure axiom on a property consists of a universal restriction that says that a property can only be filled by specified fillers. The restriction has a filler that is the union of the fillers that occur in the existential restrictions for the property. For example, the closure axiom on the `hasTopping` property for `MargheritaPizza` is a universal restriction that acts along the `hasTopping` property, with a filler that is the union of `MozzarellaTopping` and also `TomatoTopping`. i.e. `hasTopping only (MozzarellaTopping or TomatoTopping)`.

Exercise 23: Add a Closure Axiom on the hasTopping Property for MargheritaPizza

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1. Make sure that MargheritaPizza is selected in the class hierarchy in the Classes tab.

2. Click on the Add icon (+) next to the SubClass Of field in the Description view.

3. Select the Class expression editor tab from the pop-up window. Type in the Description Logic axiom: hasTopping only (MozzarellaTopping or TomatoTopping).

4. Click on OK.

5. Repeat steps 1-4 but this time click on SohoPizza and use the axiom: hasTopping only (MozzarellaTopping or TomatoTopping or ParmesanTopping or OliveTopping).

6. Synchronize the reasoner.

_____

The previous axioms said that for example that it was necessary for any `Pizza` that was a `MargheritaPizza` to have a `MozzarellaTopping` and a `TomatoTopping`. The new axioms say that a `MargheritaPizza` can _only_ have these toppings and similarly for `SohoPizza` and its toppings. This should supply the needed information for the reasoner to now make them both subclasses of `VegetarianPizza`. Go to the Class hierarchy (inferred) tab. You should now see that `MargheritaPizza` and `SohoPizza` are both classified as subclasses of `VegetarianPizza`. Your UI should now look similar to figure 4.23. Note the various axioms highlighted in yellow. Those are all additional inferences supplied by the reasoner. For experience you might want to click on some of the ? icons next to these inferences to see the explanations generated by the reasoner. As you develop more complex ontologies this is a powerful tool to debug and design your ontology.
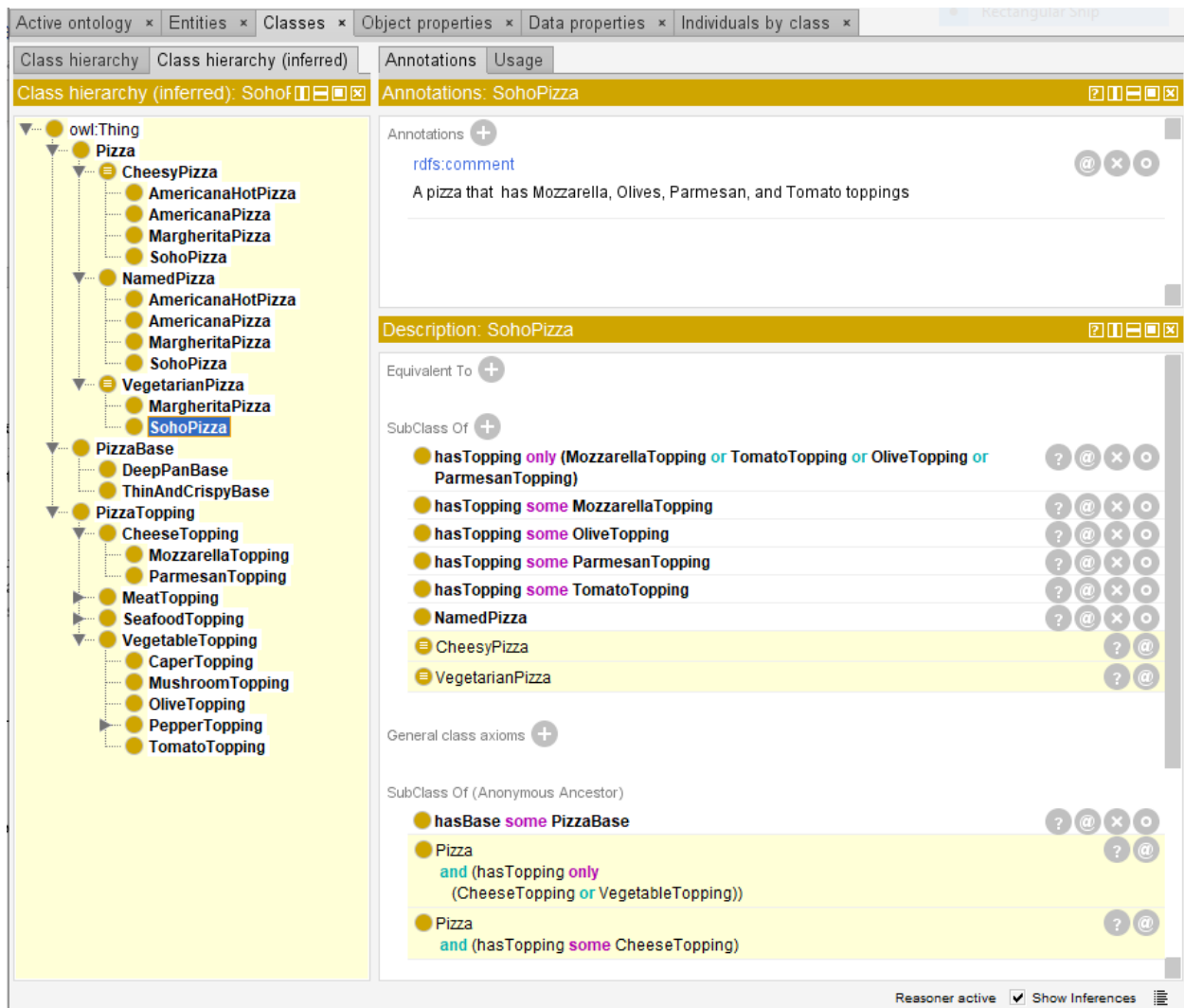
Figure 4.23 The Reasoner Inferred that Margherita and Soho Pizzas are subclasses of VegetarianPizza

4.14 Defining an Enumerated Class

A powerful tool in the object-oriented programming (OOP) community is the concept of design patterns. The idea of a design pattern is to capture a reusable model that is at a higher level of abstraction than a specific code library. One of the first and most common design patterns was the Model-View-Controller pattern first used in Smalltalk and now almost the default standard for good user interface design. Since there are significant differences between OWL and standard OOP the many excellent books on OOP design patterns don't directly translate into OWL design patterns. Also, since the use of OWL is more recent than OOP there does not yet exist the excellent documentation of OWL patterns that the OOP community has. However, there are already many design patterns that have been documented for OWL and that can provide users with ways to save time and to standardize their designs according to best practices.

One of the most common OWL design patterns is an enumerated class. When a property has only a few possible values it can be useful to create a class to represent those values and to explicitly define the class by listing each possible value. We will show an example of such an enumerated class by creating a new

property called `hasSpiciness` with only a few possible values ranging from `Mild` to `Hot`. In this section we will also create the first individuals in our ontology.

Exercise 24: Create an Enumerated Class to Represent the Spiciness of a Pizza

_____

1. Create a new subclass of `owl:Thing` called `Spiciness`.

2. Make sure that Spiciness is selected. Click on the Add icon (+) next to the Instances field in the Description view.

3. You will be prompted with a window that looks like figure 4.24. The diamond icon at the top is for creating a new individual. The circle with an X through it is for deleting an individual. Use the diamond icon to create 3 individuals: Hot, Medium, and Mild, so your UI looks like figure 4.24, then click on OK.

4. You may notice that only one of the new individuals was actually created as an instance of `Spiciness`. That's okay. The next step will supply the reasoner with enough information to make the other two also be instances of `Spiciness`.

5. Make sure that Spiciness is still selected. Click on the Add icon (+) next to the Equivalent To field in the Description view. This time we will create a defined class by directly entering the definition for the class into this field. Select the Class expression editor tab and enter the DL axiom: {Hot, Medium, Mild}. Select OK.

6. Now run the reasoner. You should see that Spiciness is now a defined class and all three individuals: `Hot`, `Medium`, and `Mild`, are now instances of that class.
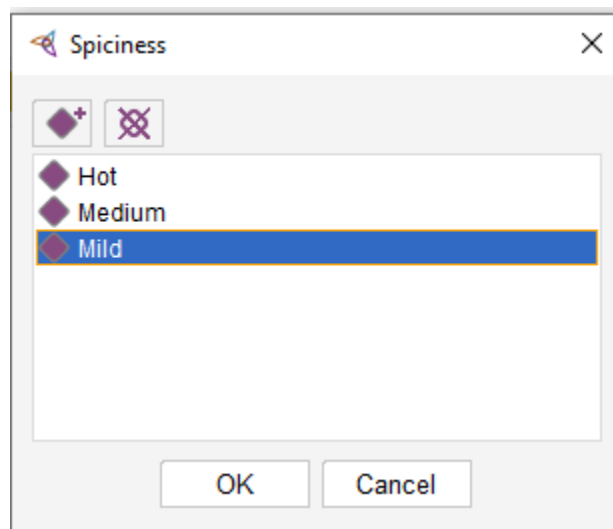
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Figure 4.24 Creating Individuals for an Enumerated Class

4.15 Adding Spiciness as a Property

Next we need to add a property that will define the spiciness of a `PizzaTopping`.

Exercise 25: Create and Use the hasSpiciness Property

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1. Go to the Object properties tab. Create a new property called hasSpiciness. Define its domain to be PizzaTopping and its range to be Spiciness. Run the reasoner so that it knows about the new property.

2. Go back to the Classes tab and select the class JalapenoPepperTopping. Click on the Add icon (+) next to the SubClass Of field. Enter the DL axiom: hasSpiciness value Hot. Remember you can use <control><space> to auto-complete. Click on OK.

3. Note that this is a different kind of restriction than before. Before we were defining abstract restrictions such as `some`. I.e., some value from a class but the specific individual was not specified, as long as it was an individual from that class the restriction was satisfied. Now we are defining a restriction that relates to a specific individual, hence we use the `value` keyword rather than the `some` or `only` keywords.

4. Now we will use this property to define a new class of `Pizza`. Start by creating a new subclass of `Pizza` called SpicyPizza.

5. Make sure that SpicyPizza is selected. Click on the Add icon (+) next to the SubClass Of field. Enter the DL axiom: hasTopping some (hasSpiciness value Hot). This says that a `SpicyPizza` must have a topping that `hasSpiciness` value of `Hot`.

6. Convert SpicyPizza to a defined class by selecting it and using Edit>Convert to defined class. Run the reasoner.

_____

Now go to the Class hierarchy (inferred) tab in the Classes tab (see figure 4.25). You should see that `AmericanHotPizza` is now classified as a subclass of `SpicyPizza` because it has a topping (`JalapenoPepperTopping`) that has a spiciness value of `Hot`.

4.16 Cardinality Restrictions

In OWL we can describe the class of individuals that have at least, at most, or exactly a specified number of relationships with other individuals or datatype values. The restrictions that describe these classes are known as Cardinality Restrictions. For a given property P, a Minimum Cardinality Restriction specifies the minimum number of P relationships that an individual must participate in. A Maximum Cardinality Restriction specifies the maximum number of P relationships that an individual can participate in. A Cardinality Restriction specifies the exact number of P relationships that an individual must participate in. Relationships (for example between two individuals) are only counted as separate relationships if it can be determined that the individuals that are the fillers for the relationships are different from each other.

Let's add a cardinality restriction to our Pizza Ontology. We will create a new subclass of `Pizza` called `InterestingPizza` which will be defied to have 3 or more toppings.
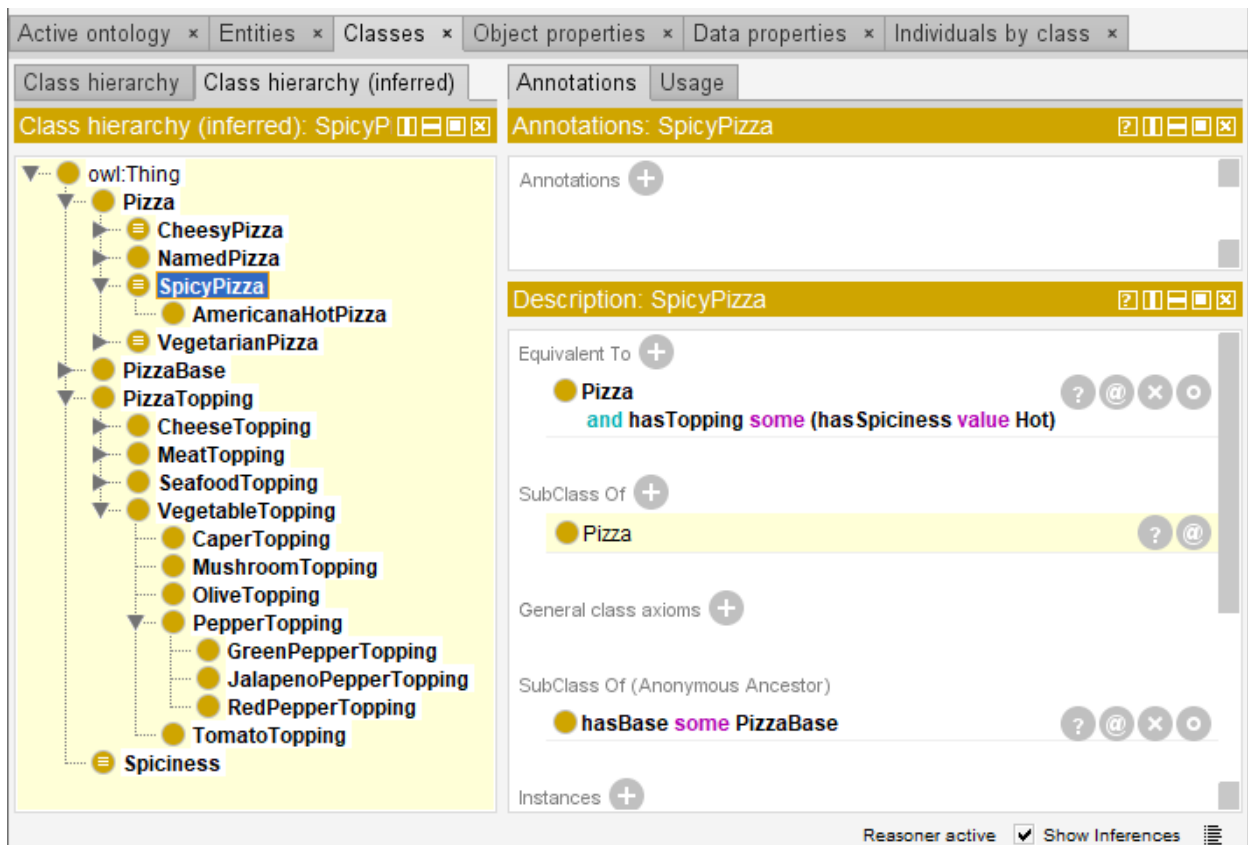
Figure 4.25 AmericanHotPizza classified as SpicyPizza

Exercise 26: Create an InterestingPizza that has at least three toppings

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1. Create a subclass of Pizza called InterestingPizza.

2. Click on the Add icon (+) next to the SubClass Of field. Use the Class expression editor tab and enter hasTopping min 3 PizzaTopping and click on OK.

3. Make sure InterestingPizza is still selected and use the Edit>Convert to defined class option to turn InterestingPizza into a defined class.

4. Run the reasoner.

_____

Go to the Class hierarchy (inferred) tab in the Classes tab and click on InterestingPizza. You should see that there are three Pizza classes that are classified as interesting: AmericanaHotPizza, AmericanaPizza, and SohoPizza.

Chapter 5 Datatype Properties

So far we have been describing object properties. These are properties that have a range that is some class. As with most other object-oriented languages OWL also has the capability to define properties with the range of a simple datatype such as a string or integer. Object purists will argue that everything should be an object. However, to borrow a quote from The Amazing Spiderman: "with great power comes great overhead". I.e., the extra capabilities that one has with a class and an instance also means that instances take up more space and can be slower to process than simple datatypes. For that reason, OWL comes with a large library of pre-existing datatypes that are mostly imported from XML. That is why many of the predefined datatypes in Protégé have a prefix of *xsd* for example `xsd:string` and `xsd:integer`. It is also possible to create new basic datatypes. However, for the majority of use cases, if one needs a datatype that doesn't map to one of the predefined types the best solution is to usually just define a class.

A property with a range that is a simple datatype is known as a datatype property. This is analogous to the distinction between an association and an attribute in the Unified Modeling Language (UML) OOP modeling language. A UML association is similar to an OWL object property and a UML attribute is similar to an OWL datatype property. It is also analogous to the distinction between relations and attributes in entity-relation modeling. A relation in an E/R model is similar to an object property in OWL and an attribute is similar to a datatype property. Because datatypes don't have all the power of OWL objects, many of the capabilities for object properties described in section 4.8 such as having an inverse or being transitive aren't available for datatype properties.

5.1 Defining a Data Property

As with other OWL entities, datatype properties can be defined either via the Data properties tab in the Entities tab or in the Data properties tab available via the Window>Tabs>Data properties option.

We will use datatype properties to describe the calorie content of pizzas. We will then use some numeric ranges to broadly classify particular pizzas as high or low calorie. In order to do this we need to complete the following steps:

1. Create a datatype property `hasCaloricContent`, which will be used to state the calorie content of particular pizzas.
2. Create several example `Pizza` individuals with specific calorie contents.
3. Create two classes broadly categorizing pizzas as low or high calorie.

Exercise 27: Create a Datatype Property called hasCaloricContent

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1. Open a Data properties tab. Select owl:topDataProperty.

2. Click on the Add sub property icon in the upper left corner. This works just the same as the UI for adding object properties.

3. Name the new data property hasCaloricContent and select OK.

4. Click on the (+) icon next to Domains in the Description view for hasCaloricContent. Use the Class hierarchy tab to select the Pizza class as the domain.

5. Click on the (+) icon next to Ranges in the Description view for hasCaloricContent. Select the Built in datatypes tab from the pop-up menu. Select xsd:integer[7] from the rather long menu of possible built-in datatypes. This is the default datatype to use for integer data properties.

6. Click the Functional check box next to the Description view. A Pizza can only have one caloric content and hence is functional. Data properties are often functional.

5. Select OK and run the reasoner. Your UI should look similar to figure 5.1.

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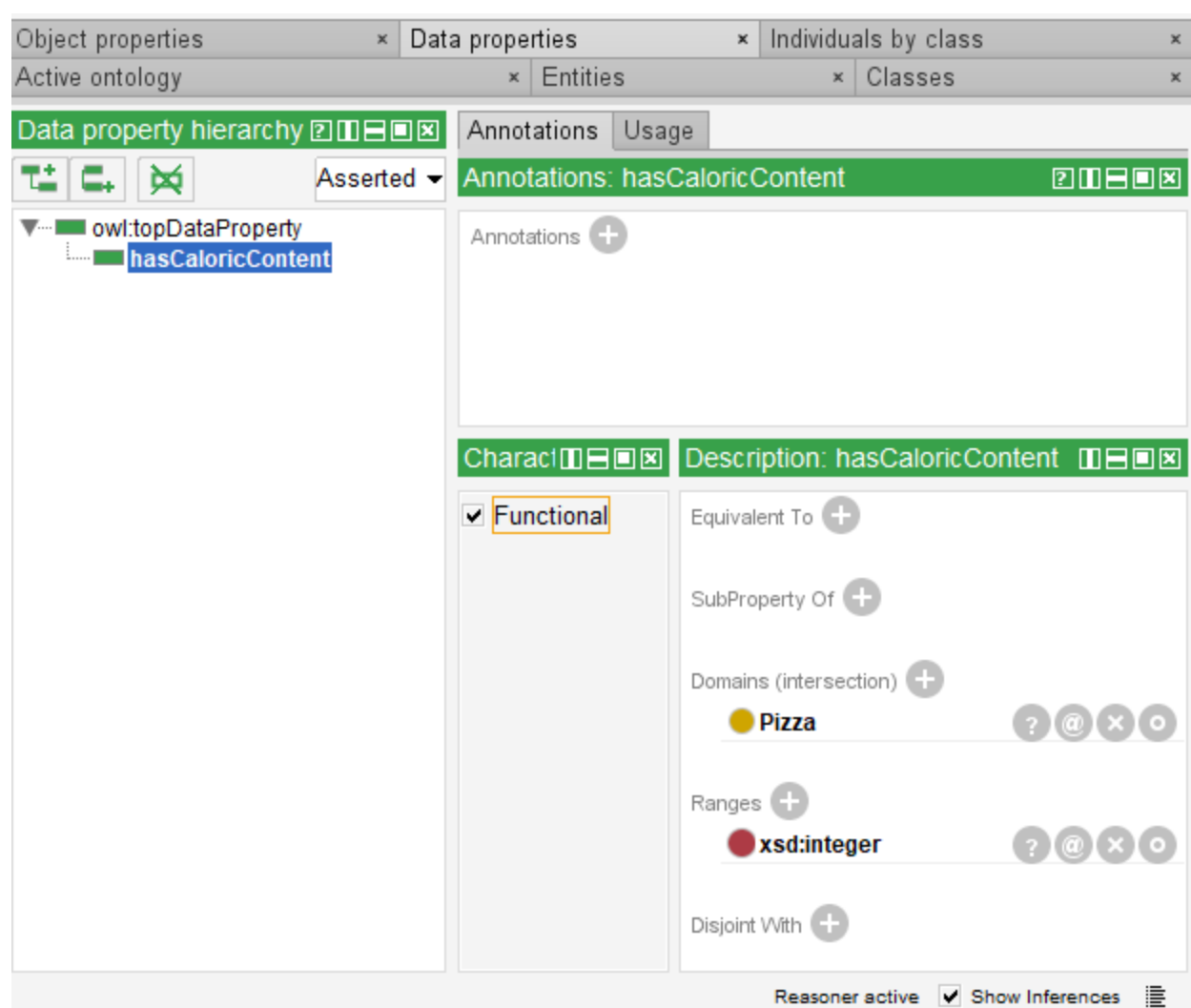
Figure 5.1 hasCaloricContent Data Property

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[7] For historic reasons there are many datatypes that are seldom used, e.g., xsd:int which is similar to xsd:Integer. For numbers, the default datatypes are xsd:integer for integers and xsd:decimal for real numbers. Unless you have a good reason to use a different numeric datatype it is best to stick with these default types. E.g., when you write a SWRL rule if you use a number SWRL will infer that any integers are xsd:integer and any rationals are xsd:decimal.

Note that as with object properties defining a domain and/or range is optional. In general, it is a good practice to do so as it can lead to finding errors in your ontology during the modeling phase rather than at run time.

5.2 Customizing the Protégé User Interface

In order to demonstrate our new data property, we will need to create some instances of the Pizza class and set the value of the data property hasCaloricContent. One of the advantages of Protégé is that it is highly customizable to your specific requirements and work style. There are many views that are available that aren't included in the default Protégé environment because it would be too cluttered. In addition, all of the views that you have already used can be resized, removed, or added to existing tabs. You can also create completely new tabs of your own.

As an example, we are going to first bring up a new major tab called Individuals by class. This tab can be useful to create individuals and to add or edit their object and data property values. We are going to customize this tab to make it easier to use by adding a new view to it.

To begin use the menu option Window>Tabs>Individuals by class to bring up this new tab. Of course, if it already exists in your UI simply select it.

We want to make add a new view as an additional sub-tab in the view that currently has the Annotations and Usage, tabs near the upper right corner[8]. Once you are in the Individuals by class tab select Window>Views>Individual views>Individuals by type (inferred). This will give you a blue outline of the new view. As you move the outline around the existing window it will change depending how you move it, indicating how it will fit into the existing tab after you click. When the blue outline looks like figure 5.2 click left and you will see the new view added as another sub-tab.

After you click your UI should now look similar to figure 5.3. If you clicked somewhere else you can just go to the new view and delete it by clicking the X in the upper right corner of the view and then redo it and position it correctly. At first it may seem a bit unintuitive but after you do it a few times it becomes very easy to position new views.

With this new view you can see the instances of each class displayed beneath the class. Each class can be expanded or contracted to view or hide its particular instances. Since we don't have many instances in our ontology yet the usefulness of this new view isn't that obvious but as we add more instances and as you deal with larger real ontologies in the future, this view can be very helpful to find specific instances of a class. Note that the UI just shows the most direct class (or classes) that the Individual is an instance of. For example, we currently just have three individuals, the three instances of Spiciness: Hot, Medium, and Mild. These are also instances of owl:Thing (as are *all* instances) however the UI only displays them as instances of Spiciness since it is implicit that they are also instances of all the superclasses of Spiciness.

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[8] Your particular Protégé UI may look slightly different than some of the screen snapshots depending on if your organization or another user has already customized the Protégé UI. If you ever want to return a major tab to its default configuration select that tab and use Window>Reset selected tab to default configuration.
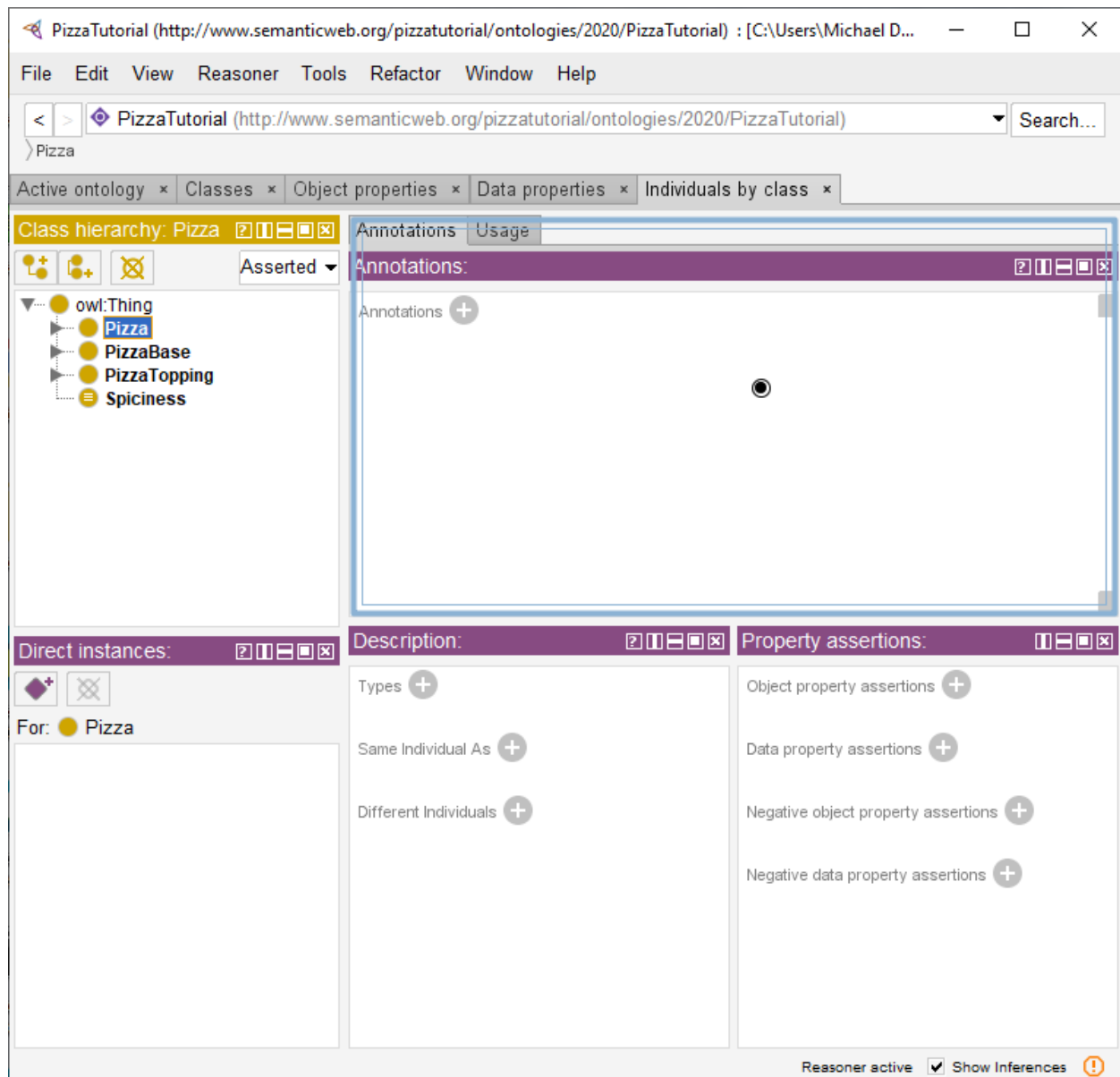
Figure 5.2 Adding a new view to the Individuals by class tab
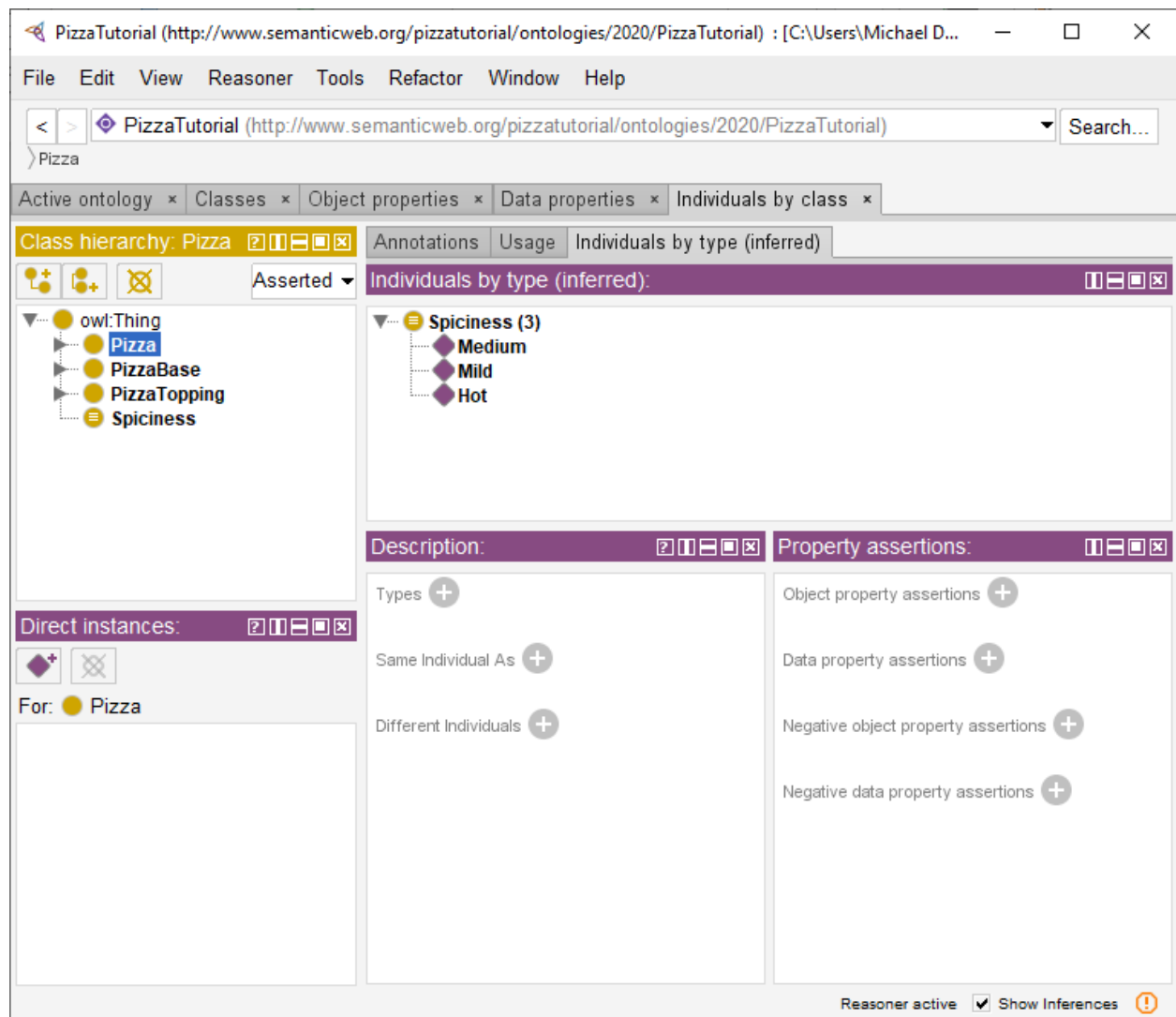
Figure 5.3 A Customized Individuals by class tab

Exercise 28: Create Example Pizza Individuals

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1. We will now add our first actual Pizza. Remain in the Individuals by class tab.

2. Use the Class hierarchy view in the upper left to navigate to MargheritaPizza and select it. There is a view directly under the Class hierarchy tab called Direct instances. Click the little diamond in that view. This will prompt you for the name of your new individual. Call it MargheritaPizza1.

3. Your UI should now look similar to figure 5.4.

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Figure 5.4 Creating Our First Pizza

Exercise 29: Assign a Data Property Values

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1. Remain in the Individuals by class tab. Click on MargheritaPizza1. You should see in the Description view that it is an instance of `MargheritaPizza`. Now you will use the Property assertions view to set the caloric content of `MargheritaPizza1`. This view can be used to set object and data properties.
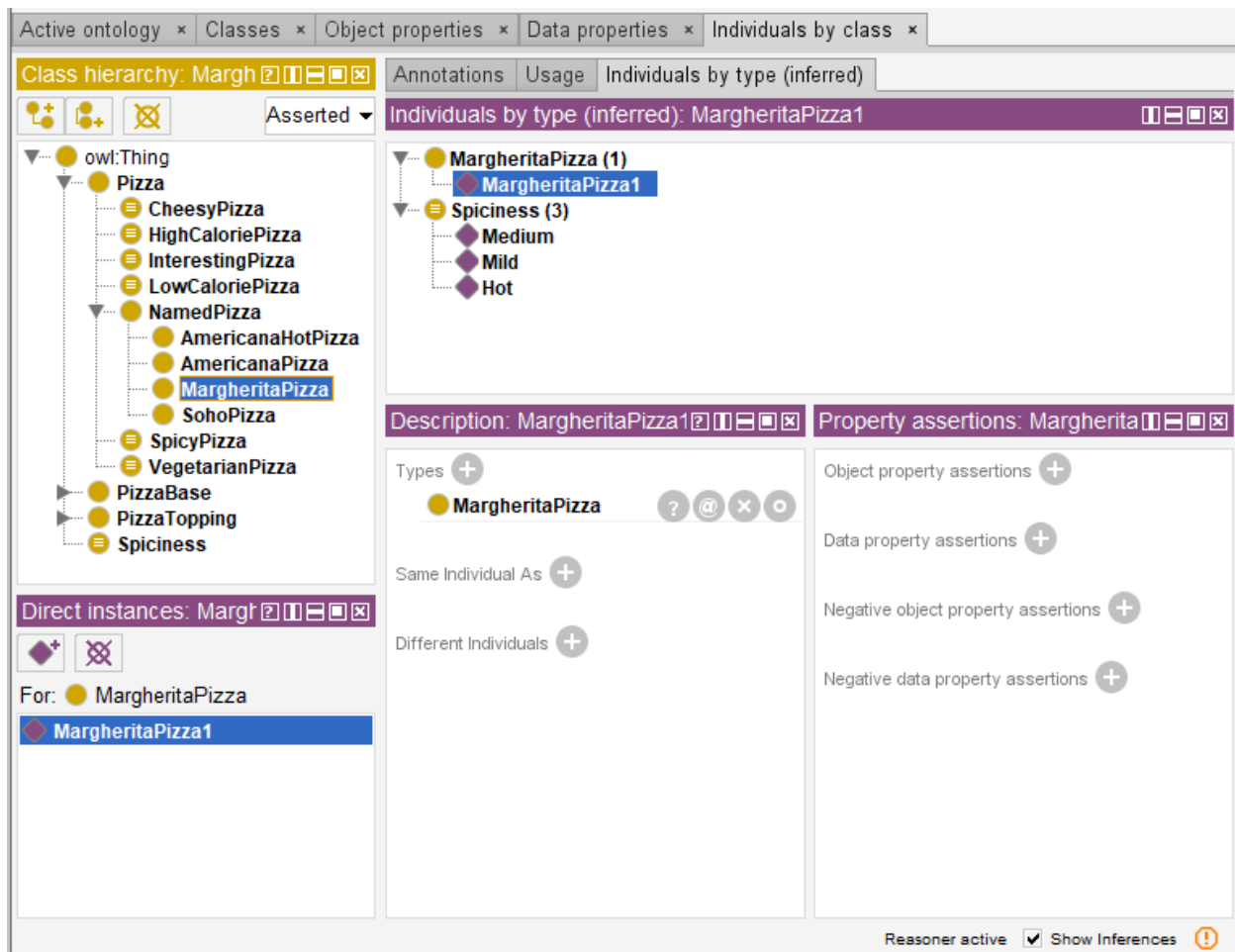
2. Click on the (+) icon next to Data property assertions in the Property assertions view in the lower right.

3. Use the pop-up window to select the data property hasCaloricContent. Then enter 263 as the value and use the menu at the bottom to define the value's datatype to be xsd:integer. Note: this is different than what you did in exercise 27. In exercise 27 you defined the datatype for the *property*. Here you are defining the datatype for *a specific value*. It would be nice if Protégé could just infer the datatypes for you but because datatype definitions can be complex this is harder than it might seem so you need to make sure to explicitly define the datatype for each value. As you get into more realistic ontologies you will often use tools such as Cellfie (described in chapter 8) to load your individual data automatically and those tools can automatically add datatype information for each individual as part of the loading process.

53

4. Your UI should now look similar to figure 5.5. Select OK to enter the new value. Run the reasoner.
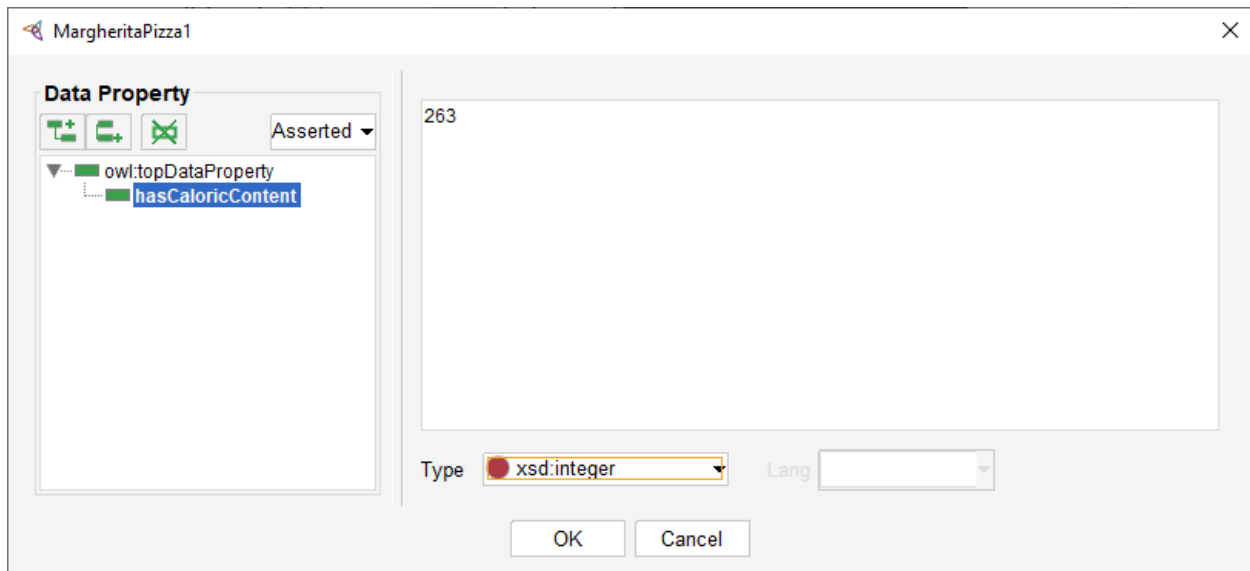
_____

Figure 5.5 hasCaloricContent for MargheritaPizza1

One of the most common sources of errors in ontologies is to have the wrong datatype for data property values. The sooner you catch these errors, the easier they are to debug so it is a good idea to run the reasoner frequently after you enter any values. Note that in some versions of Protégé 5.5. there is a minor bug where the UI may lock up due to an inconsistent data value (e.g., a string value in a property typed for integer). If this happens the best thing to do is save your work if possible, quit Protégé, and then restart it. When you restart it fix the datatype errors *before* you run the reasoner and then run the reasoner to make sure you actually have fixed the error.

Exercise 30: Create More Instances and Data Property Values

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1. Remain in the Individuals by class tab. Click on other `Pizzas` and create instances of them (apx. 5-10) and then fill in their caloric content with values ranging from 200 to 800. Try to have about half of your pizzas higher than 400 calories and half less than 400. The UI retains the datatype from the previous use so once you define the first caloric content you shouldn't need to set the datatype again but it is always a good idea to make sure it is correct, in this case: `xsd:integer`.

2. It is a good idea to adhere to an intuitive naming standard for your instances such as <Class Name><Number> as we did for `MargheritaPizza1`. Depending on the classes you instantiate your pizzas should have names like `MargheritaPizza2`, `SohoPizza1`, etc.

3. Make sure to create an instance of `AmericanaPizza` called `AmericanaPizza1` that `hasCaloricContent` 723.

4. Make sure to run the reasoner after creating all your instances.

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Exercise 31: Create a Datatype Restriction that Every Pizza hasCaloricContent

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1. Navigate to the Classes major tab.

2. Select the Pizza class.

3 Click on the (+) icon next to the SubClass Of field in the Description view. This time let's use the Data restriction tab. Navigate to and select hasCaloricContent in the Restricted property view. In the Restriction filler view scroll down to xsd:integer and select it. The Restriction type should be set to the default which is Some. If it isn't use the menu to change it. Your UI should look like figure 5.6. Click OK.

4. Note that you also could have selected Exactly 1 because a Pizza can only have one caloric content but since you already defined the property to be functional this isn't necessary and either Some or Exactly 1 have the same effect. Just as Protégé usually provides several ways to enter the same information in the user interface OWL often provides different ways to provide the same information in your model. The nice thing is the reasoner lets you not worry so much about which way you do it, as long as your definitions are consistent.

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We have now stated that every `Pizza hasCaloricContent` and that content must be an `integer`. In addition to using the predefined set of datatypes we can further specialize the use of a datatype by specifying restrictions on the possible values. For example, it is easy to specify a range of values for a number.
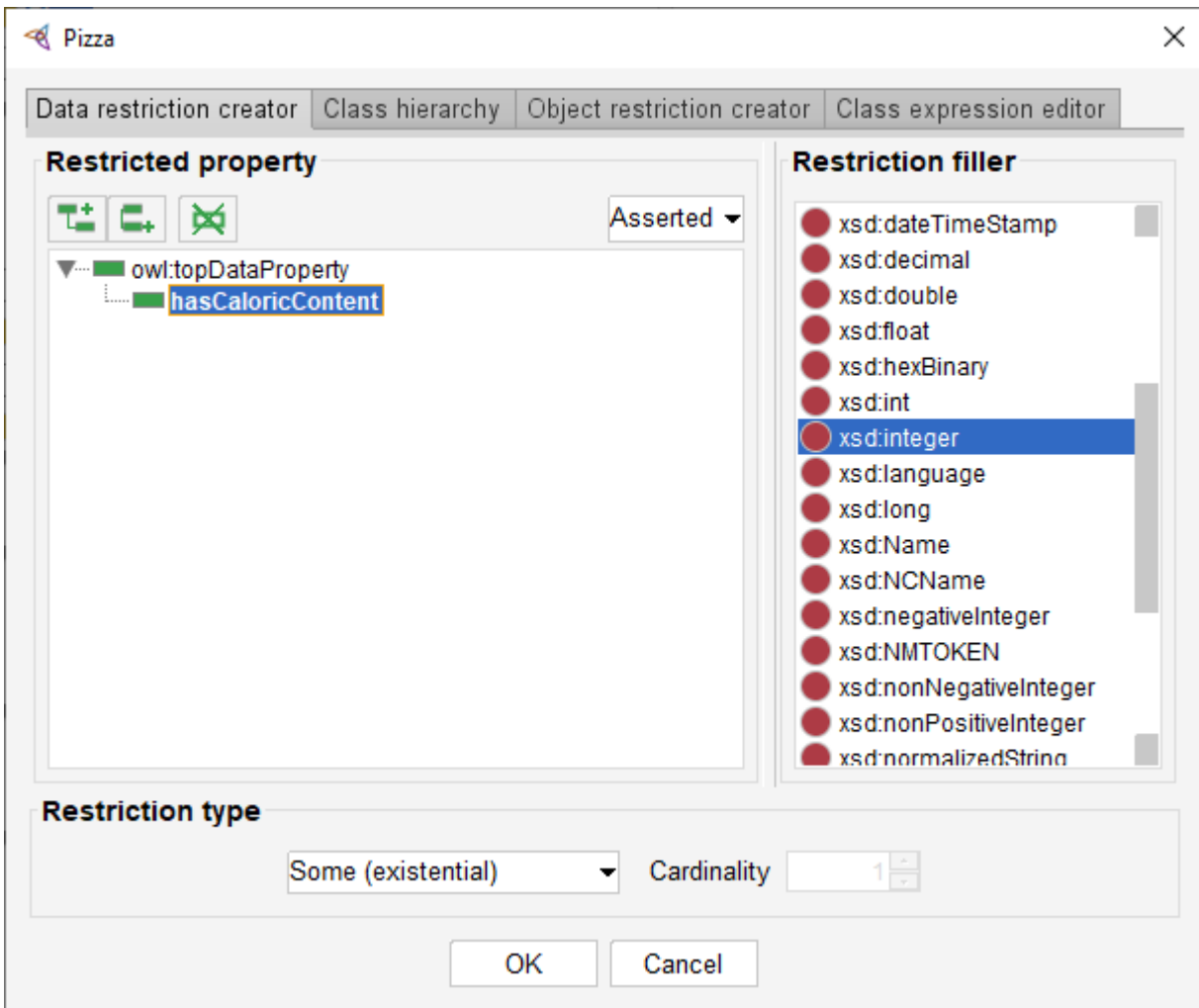
Figure 5.6 Defining the hasCaloricContent data property restriction

Using the datatype property, we have created, we will now create defined classes that specify a range of interesting values. We will define a `HighCaloriePizza` to be any pizza that has a calorific value equal to or higher than 400.

Exercise 32: Create a HighCaloriePizza Defined Class

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1. Navigate to the Classes tab.

2. Select the Pizza class. Create a subclass of Pizza called HighCaloriePizza.

3 Make sure HighCaloriePizza is selected. Click on the (+) icon next to the SubClass Of field in the Description view. In the Class expression editor type hasCaloricContent some xsd:integer[>= 400] and click OK.

4. Make sure HighCaloriePizza is still selected and use Edit>Convert to defined class to make it a defined class.

5. Repeat steps 1-4 but this time create a subclass of `Pizza` called <mark>LowCaloriePizza</mark> and make its definition be: <mark>hasCaloricContent some xsd:integer[< 400]</mark>.

6. Run the reasoner. You should now see that each instance of `Pizza` that `hasCaloricContent` greater than or equal to 400 is classified as a `HighCaloriePizza` and similarly those with less than 400 as `LowCaloriePizza`. See the <mark>Description</mark> view in figure 5.7.
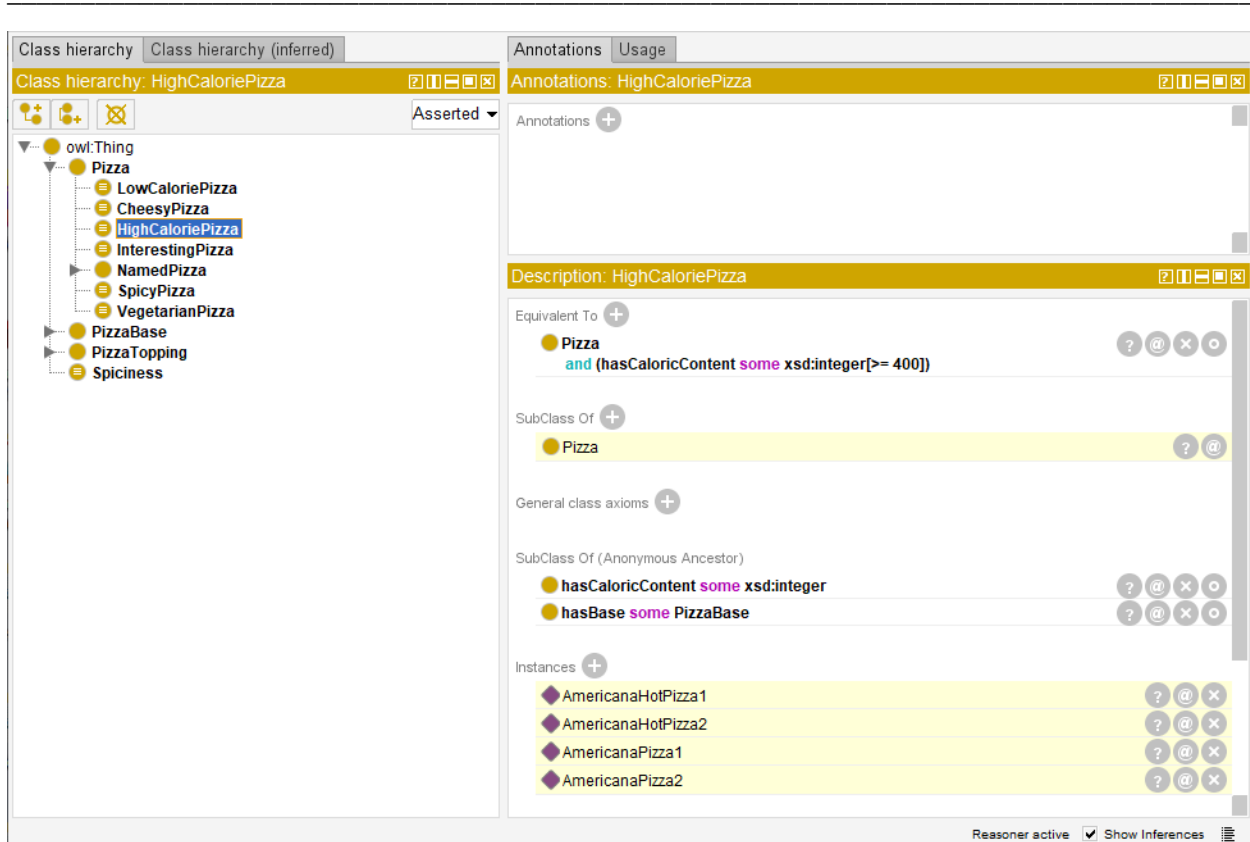
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Figure 5.7 High Calorie Pizzas

Chapter 6 Adding Order to an Enumerated Class

In this chapter we will expand on the enumerated class that we created to model spiciness in chapter 4.14. This chapter will highlight some of the power of object properties in OWL. We are going to create an ordering for the instances of `Spiciness`. I.e., `Hot isSpicierThan Medium` which `isSpicierThan Mild`. To start go to the Object properties tab. Create a new property that is a sub-property of owl:topObjectProperty. Call this property isSpicierThan. Make its domain and range the Spiciness class. Make the property transitive. Transitive means that if X `isSpicierThan` Y and Y `isSpicierThan` Z then X `isSpicierThan` Z. This is of course similar to the greater than and less than relations in math. Create another property called isMilderThan. Make one property the inverse of the other. It doesn't matter which one, you only have to specify that one property is the inverse of another, and the reasoner will realize that both are inverses. Run the reasoner. You will see that the reasoner has inferred the domain and range for `isMilderThan` than as well as the fact that it is transitive and the inverse of `isSpicierThan`.
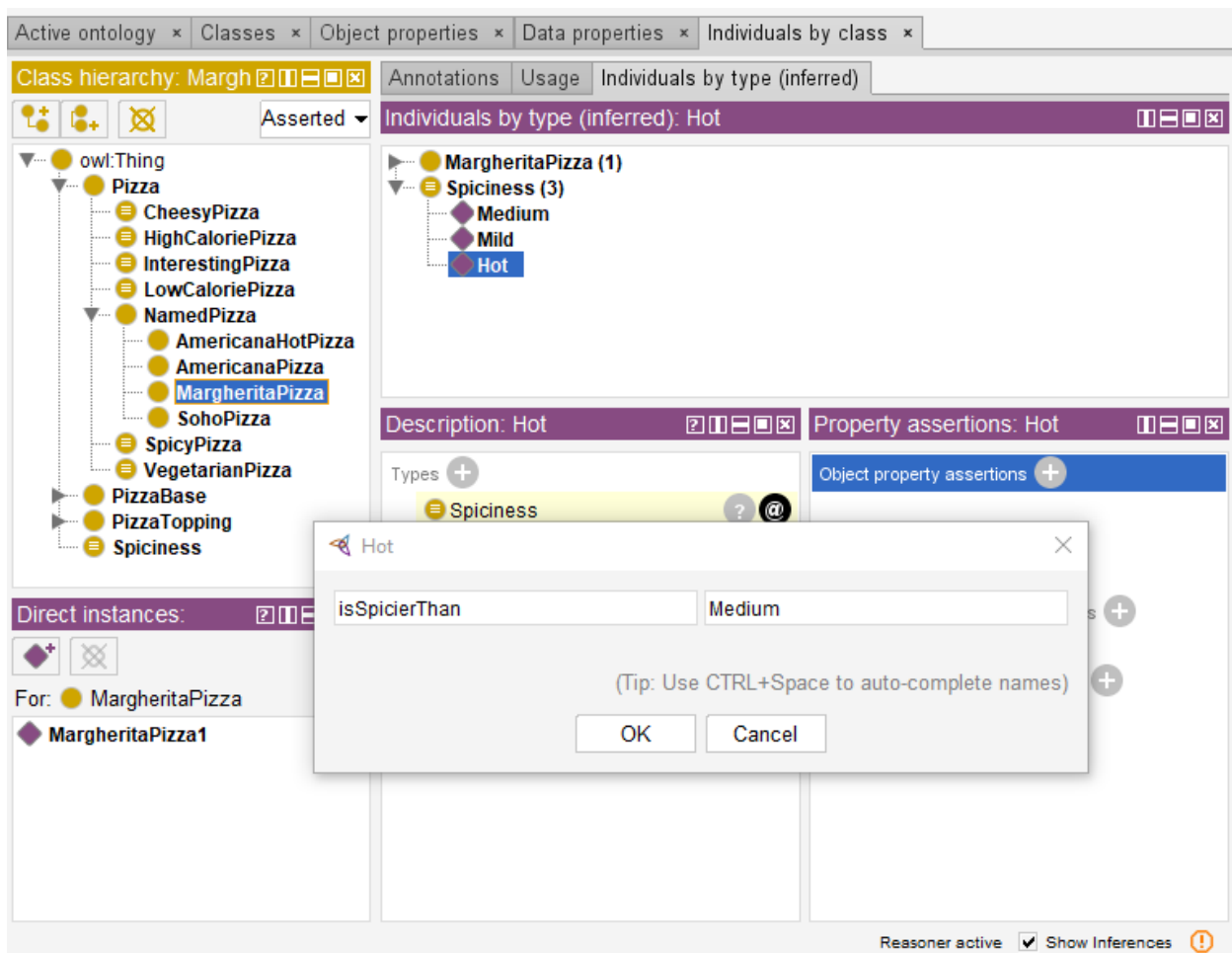

Figure 6.1 Setting isSpicierThan property in the Individuals by class tab

Next go back to the Individuals by class tab. Go to the Individuals by type (inferred) view. You should see the individuals that exist right now. So far we have the example Pizzas you created and the instances of Spiciness: `Hot`, `Medium`, and `Mild`. Click on Hot. Notice that in the Property assertions view in the lower right corner the title should now say: Property assertions: Hot. Click on the (+) icon next to Object property assertions. You will be prompted with a form with two areas to input values. The name of the property goes in the left hand side and the value in the right hand side (see figure 6.1). Type in isSpicierThan as the name of the property. Remember you can use auto-complete so you should only need to type *isS* and type <control><space> and Protégé will fill in the name of the property. Enter Medium as the value. Your UI should look similar to figure 6.1. Select OK. Now click on Medium and set its `isSpicierThan` value to be `Mild`. That is all the data entry you need to do. Now run the reasoner again and click on the `Hot,` `Medium`, and `Mild` individuals. You should see that all the additional `isSpicierThan` and `isMilderThan` values have been filled in for you because the reasoner knows that the two properties are inverses and transitive. For example, `Mild`, which we didn't edit at all, should have two values for `isMilderThan` filled in by the reasoner.

We can use these properties in various ways to reason about the relative spiciness of things. We will show some examples in chapter 8.

This concludes the basics of designing classes and properties with Protégé. There is also a web version of Protégé available at https://webprotege.stanford.edu/# This takes you to a page where you can create an account by providing an email and creating a password. Web Protégé supports multiple users and has extra capabilities such as threaded discussions for collaborative development of ontologies. However, it currently does not support any reasoners, so it is a good idea to bring ontologies developed in WebProtégé into the desktop version to run the reasoner and validate the ontology. See chapter 12 for more on Web Protégé.

Chapter 7 Names: IRI's, Labels, and Namespaces

In exercise 2 we set up some parameters regarding new entity names and rendering without much of an explanation. The concept of a *name* in OWL is a little complex so we wanted to wait until you had a basic grasp of an ontology before diving into these details.

To start with remember that every entity in your ontology has a unique Internationalized Resource Identifier (IRI)[9]. An IRI is similar to a URL. In fact, a URL is a kind of IRI. I.e., all URLs are IRIs but many IRIs are not URLs. A URL is typically meant to identify a specific page meant to be viewed in a browser. An IRI is often at a smaller level of granularity and for *any* kind of resource, not only those meant to be viewed in a browser. If you go to the Active ontology tab in Protégé you will see the Ontology IRI for your ontology. This is the base IRI that all entities have in common. In addition, each entity has a subsequent part that comes after the base IRI that uniquely identifies the IRI for the entity.

You can see this by clicking on any entity and starting (but don't complete) the Refactor>Rename entity command. Click on the Pizza class. Then select Refactor>Rename entity. You will get a pop-up window with the current name: Pizza. However, this is only the final part of the IRI. To see the full IRI click on the check box in the lower right corner that says: Show full IRI. Your full IRI will be different but it will look something like: http://www.semanticweb.org/pizzatutorial/ontologies/2020/PizzaTutorial#Pizza. Uncheck the Show full IRI box and then Cancel the rename command.

If you recall from exercise 2 there are two options when you create a new entity. One is to use a user supplied name. That is the option that you should have selected at the beginning of the tutorial and that should be active now. The other is to use an auto-generated name. This option creates a Universally Unique Identifier (UUID) for the IRI of each entity. A UUID is an ID that is generated by an algorithm and is guaranteed to be unique. There are also two ways to display an entity. One way is to use the last part of the IRI that typically comes after a # sign as in the `Pizza` example above. The other is to use an annotation property called a label. An annotation property is meant to provide meta-data about an entity. Object and data property values can only be asserted on Individuals. However, since all entities have meta-data annotation properties can be asserted on to any entity. There are some annotation properties that are included by default with any Protégé ontology. You can see these by looking at the Annotation properties tab. Note that just as with other properties you can also add your own annotation properties but they should be used for meta-data not for regular data. You will see `rdfs:label` is one of the default annotation properties. When you use UUIDs for your entity IRIs then by default Protégé will automatically use the name you type in for a new entity in the `rdfs:label` annotation property. Although you can also configure Protégé to use other properties if you wish, using the same dialog for entity rendering that you used in exercise 2.

There are advantages and disadvantages to both options and there are options in between such as using both user supplied names for IRIs and using `rdfs:label` for more intuitive names. The details can get complicated and there also isn't universal agreement within the community as to which is generally better. For your first ontology and since you will be using SPARQL I chose to use user supplied entity names because it is the simpler option and is especially better for SPARQL queries as you will see in the

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[9] IRIs are also sometimes called URIs. A URI is the same as an IRI except that URIs only support ASCII characters whereas IRIs can support other character sets such as Kanji. The term people use these days is usually IRI.

next section. Which option you choose for your ontology will depend on the specific requirements you have as well as the standards established by your organization or organizations that you work with.

Finally, another name related concept you should be aware of is the concept of a namespace. If you have worked with most modern programming languages such as Python or Java, you are already familiar with the concept of a namespace. The concept is identical in OWL. A namespace is used to avoid naming conflicts between different ontologies. For example, you may have a class called `Network` in an ontology about telecommunications. You might also have a class called `Network` in an ontology about graph theory. The two concepts are related but are different. Just as with programming languages you use namespace prefixes to determine what specific namespace a name refers to. E.g., in this example you might have the prefix `tc` for the Telecom ontology and `gt` for the Graph Theory ontology. Thus, when you referred to the Network class for the Telecom ontology you would use `tc:Network` and `gt:Network` for the graph theory class.

Note that you already have some experience with other namespaces. The OWL namespace prefix is `owl` and is used to refer to classes such as `owl:Thing` and `owl:Nothing`. The Resource Description Framework Schema (RDFS) is a model that OWL is built on top of and thus some properties that ontologies use such as `rdfs:label` leverage this namespace.

In the bottom view of the ==Active ontology== tab there is a tab called ==Ontology Prefixes==. This tab shows all the current namespace mappings in your ontology. There are certain concepts from OWL, RDF, RDFS, XML and XSD that are required for every ontology, so those namespaces are by default mapped in every new Protégé ontology. There is also a mapping to the empty string for whatever the namespace is for your ontology. This allows you to display and refer to entities in your ontology without entering a namespace prefix. If you look at that tab now you should see a row where the first column is blank, and the second column has the base IRI for your ontology. It should be the same IRI as the ==Ontology IRI== at the top of the Active ontology tab, except it also has a # sign at the end. E.g., the Pizza tutorial developed for this tutorial has an IRI of: http://www.semanticweb.org/pizzatutorial/ontologies/2020/PizzaTutorial and the row that has a blank first column in Ontology Prefixes has the IRI: http://www.semanticweb.org/pizzatutorial/ontologies/2020/PizzaTutorial#.

Chapter 8 A Larger Ontology with some Individuals

The rest of the tutorial requires some data loaded into your ontology. So far, we have mostly been dealing with defining classes and properties. This type of information is known in the semantic web community as T-Box information. The T stands for Terminological. Individuals or instances are known as A-Box. The A stands for Assertional as in specific facts that are asserted about the domain. Typically, there will be a much larger amount of A-Box information than T-Box. The A-Box information is often uploaded from spreadsheets, relational databases or other sources. One tool that is not covered in this tutorial that is useful is called Cellfie. Cellfie is a tool that can take data from spreadsheets and upload it into an ontology mapping the table-based data into objects and property values. For a tutorial on Cellfie see: https://github.com/protegeproject/cellfie-plugin/wiki/Grocery-Tutorial

In addition to using Cellfie, you can use the Individuals by class tab introduced in chapter 5 to create new instances and to create object and data property values for those instances as you did with the `Hot` and `Medium` individuals in chapter 6. However, that can be tedious so to spare you that uninteresting work I've developed a version of the Pizza ontology that has many individuals already created. That ontology should be identical to the ontology you have developed so far except with many additional individuals. You can find this populated Pizza ontology at: https://tinyurl.com/PizzaWDataV2 Go to this URL and download the file to your local machine and then use File>Open. Before you do that, it is probably a good idea to close the current file so that there is no possible confusion between the Pizza ontology you developed and the new one with extra data.

8.1 Get Familiar with the Larger Ontology
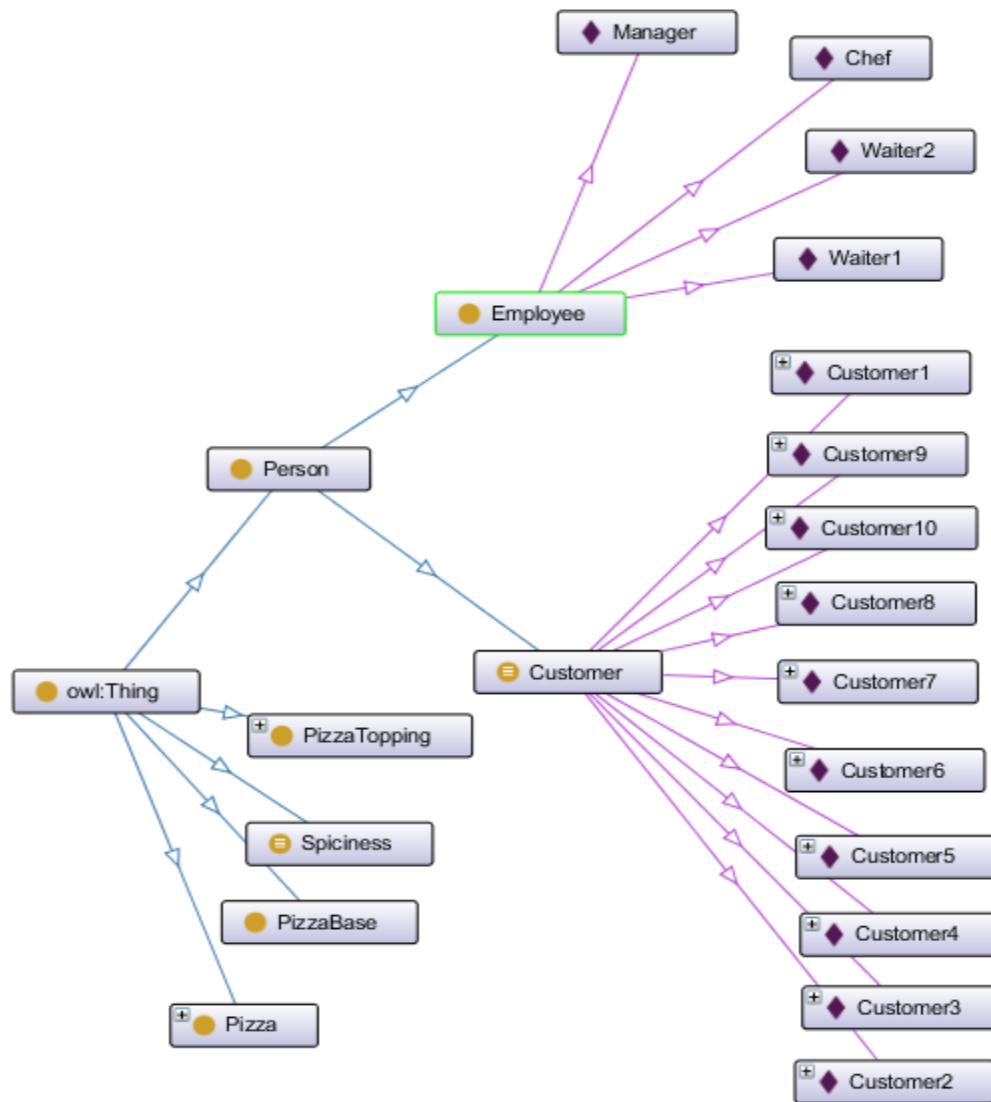

Figure 8.1 Graph of Some of the New Ontology Classes and Individuals

Figure 8.1 uses the OntoGraf tab to visualize some of the new additions to the ontology. There is a new class called `Person` with subclasses `Employee` and `Customer`. `Employee` has 5 individuals: `Manager`, `Chef, Waiter1`, and `Waiter2`. `Customer` has 10 instances.

In addition, if you look at the Object properties tab you will see there are some new properties:

- The property `purchasedByCustomer` has domain `Pizza` and range `Customer`. It maps from an individual `Pizza` to the `Customer` that purchased it. It has an inverse called `purchasedPizza`.
- The property `hasSpicinessPreference` has domain `Customer` and range `Spiciness`. It records the preference the `Customer` has for how spicy they usually like their `Pizza`.

The <mark>Data properties</mark> tab also shows some new properties:

- The `hasDiscount` data property has a domain of `Customer` and a range of `xsd:decimal`. This records the discount (if any) that the `Customer` will get on their next purchase.
- The `numberOfPizzasPurchased` data property has a domain of `Customer` and a range of `xsd:integer`. It records the number of `Pizzas` that each customer has purchased.
- The `ssn` property has a domain of `Employee` and a range of `xsd:string`. It maps from an `Employee` to their social security number. In the United States this is a number that all employers must have in order to process things such as insurance contributions and tax information.
- The `hasPhone` data property has a domain of `Person` and a range of `xsd:string`.

Most of these data properties have additional constraints in addition to their ranges. For example, a discount can only be between 0 and 1 and a phone number and social security number must correspond to a certain format.

Many of these constraints could be expressed via DL axioms that define the range. However, for reasons that will be discussed below, it is often better to represent data integrity constraints using the SHACL language rather than as DL axioms. The general rule of thumb is that DL axioms are for reasoning and SHACL is for data integrity constraints. Of course, this begs the question what is the difference between reasoning and integrity constraints and the distinction is by nature a fuzzy one. However, there are guidelines that we will discuss in the section on SHACL which we hope will help shed some light on the difference.

Finally, viewing the <mark>Individuals by class</mark> tab will help to understand the additional data in the ontology. If you go to that tab, you will see many new individuals. In addition to `Employees` and `Customers` there are instances of the `Pizza` class. You can see all these individuals in the <mark>Individuals by type (inferred)</mark> view in the upper right corner.

Now with more instances you can see the value of the <mark>Individuals by type (inferred)</mark> view. You can expand and contract various classes and see the instances for them[10]. Notice that the 4 `HighCaloriePizzas` are also instances of `Pizza` but they aren't shown under `Pizza` because all instances of `HighCaloriePizza` are always instances of the `Pizza` class. There is only one instance of the `Pizza` class displayed because all the other instances of `Pizza` are also instances of subclasses of `Pizza` so they are shown under those subclasses rather than under `Pizza`. If there are two or more classes that an Individual is an instance of that aren't subclasses of each other then they will all be shown. For example, `MargheritaPizza1` is an instance of both `MargheritaPizza` and `LowCaloriePizza` and it shows up under each class because neither is a subclass of the other. It is possible for a `Pizza` to be a `LowCaloriePizza` and not be a `MargheritaPizza` and vice-versa.

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[10] Note that if you have an instance of a class selected in the <mark>Individuals by type (inferred)</mark> view, you won't be able to collapse that class. E.g., in figure 8.2 we wouldn't be able to collapse the `Employee` class because one of its instances (`Chef`) is selected. To collapse it just select a different instance that isn't an instance of the class you want to collapse.

Figure 8.2 Viewing the New Instances in the Individuals by Class tab

Chapter 9 Queries: Description Logic and SPARQL

Now that we have some individuals in our ontology, we can do some interesting queries. There are several tools for doing queries in Protégé.

9.1 Description Logic Queries

To start with the most straight forward one based on what you have already learned are Description Logic (DL) queries. These are essentially the same kind of statements you have been using to define classes. However, in addition to using such statements to define a class you can use it as a query.

Exercise 33: Try Some Description Logic Queries

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1. To begin with navigate to the DL Query tab. If it doesn't exist create it using: Window>Tabs>DL Query.

2. At the top right of this tab you should see a view that says DL query: and below it Query (class expression).

3 You can enter any DL statement you want in this box and then see all the entities that are subclasses, superclasses, and instances of it. As an example, enter: Customer and purchasedPizza some (hasTopping some (hasSpiciness value Hot)). I.e., all `Customers` who have purchased a `Pizza` that `hasSpiciness Hot`. At first you may not see anything but don't worry there is one more step.

4. Look at the check boxes on the right under Query for. Check Superclasses, Subclasses (although it should already be checked by default) and Instances. Now your UI should look like figure 9.1. You may notice that `owl:Nothing` shows up as a subclass. Don't worry that is actually expected. Remember that `owl:Nothing` is the empty set and the empty set is a subset of every set (including itself) so just as `owl:Thing` is a superclass of every class `owl:Nothing` is a subclass of every class. If you don't want to see `owl:Nothing` you can uncheck the box toward the bottom right that says Display owl:Nothing.

5. Try some additional DL queries such as: hasTopping some (hasSpiciness value Hot) and VegetarianPizza and (hasTopping some (hasSpiciness some (isMilderThan value Hot))). Note that with this last query you are taking advantage of the transitive order you defined for the instances of the `Spiciness` class in chapter 6.

6. You can also do queries for strings in the names of your entities. For example, first do a query simply with Pizza in the query window. Then type in Hot in the Name contains field. This should give you all the classes and individuals with _Hot_ in their name.
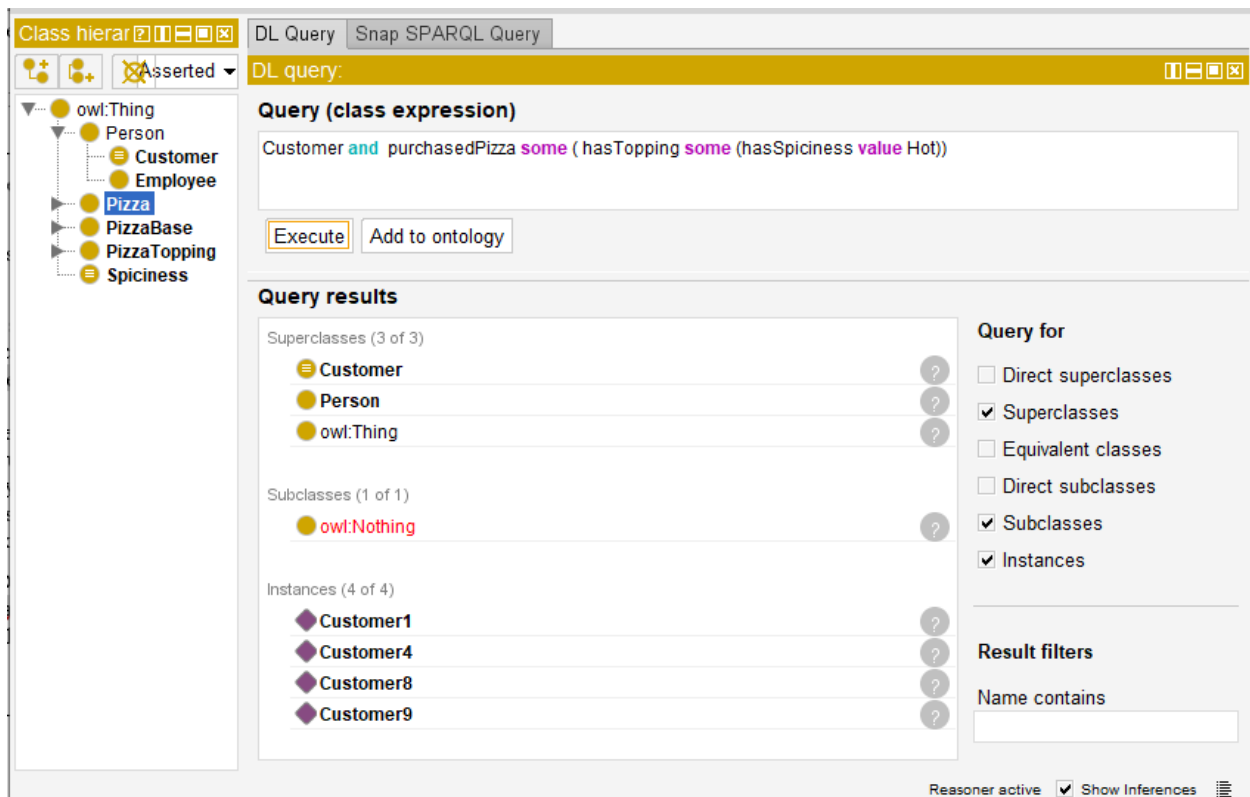
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Figure 9.1 The DL Query Tab

9.2 SPARQL Queries

SPARQL is a powerful language, and one could write a whole book about it. In fact, there are books written about it. The best one I have seen is the O'Reilly book Learning SPARQL by Bob DuCharme. This is an excellent book that not only goes into SPARQL but into topics such as RDF/RDFS and how triples are used to represent all information in OWL. I will only touch on those issues here, there is much more to say about them and DuCharme's book is a great place to learn more. If some of the following is a bit hard to understand don't be discouraged. This is just an attempt to give a very high level introduction to something that requires significant study to really understand.

Essentially SPARQL is to the Semantic Web and Knowledge Graphs as SQL is to relational databases. Just as SQL can do more than just query, it can also assert new information into a database, so SPARQL can as well. The current SPARQL plugins for Protégé are somewhat limited and don't support the statements such as INSERT for entering new data so we will just cover the basics of using SPARQL as a query language but keep in mind there is a lot more to it than what we briefly cover here.

9.21 Some SPARQL Pizza Queries

To start with go to the SPARQL Query tab. If it isn't already there you can as always add it using Window>Tabs>SPARQL Query. This tab consists of two views, the top which holds the query and the bottom which holds the results. There should be some text already there. It may look confusing, but we'll explain it. Just to start with hit the Execute button at the bottom of the tab. You should see a bunch of classes and class expressions returned.

To understand what is going on you first need to understand that each SPARQL query consists of two parts. The first part at the beginning consists of several namespace prefixes. These statements consist of the prefix used for a particular namespace as well as the IRI associated with this namespace. Recall that these concepts were described in chapter 7. You may be wondering where all these prefixes came from since you didn't add them to your ontology. The answer is that every OWL ontology comes with a set of namespaces and prefixes that are required to define the ontology.

Also, to understand SPARQL you need to "peak under the hood" of OWL. So far, we have been discussing concepts in purely logical and set theoretic terms, i.e., at the semantic level. However, like any language or database there is a lower level that describes how the concepts are mapped to actual data. In a relational database the fundamental construct to represent data is a table. In OWL the fundamental construct is a triple. OWL is actually built on top of RDFS which is a language built on top of RDF. RDF (Resource Description Framework) is a language to describe graphs (in the mathematical sense of the term). I.e., to describe nodes and links.

The foundation for RDF graphs are triples consisting of a subject, predicate, and object. This results in what is called an undirected or network graph because objects can be subjects and vice versa. Whenever you define a property in OWL you are defining a predicate. An individual can be a subject or an object (or both). E.g., in our ontology `Customer1 purchasedPizza AmericanaHotPizza1`. In this example `Customer1` is the subject, `purchasedPizza` is the predicate and `AmericanaHotPizza1` is the object.

However, classes and properties themselves are also represented as triples. So for example, when you create the class `Pizza` what Protégé does for you is to add the triple: `Pizza rdf:type owl:Class` to the ontology. I.e., the `Pizza` entity is of type (is an instance of) `owl:Class`. Similarly when you add `NamedPizza` as a subclass of `Pizza`, Protégé adds the triple: `NamedPizza rdfs:subClassOf Pizza`.

Hopefully, now you can make some sense of this initial query. The query is looking for all the entities that are the subjects of triples where the predicate is `rdfs:subClassOf` and the object is any other entity. The *?* before a name indicates that the name is a wildcard that can match anything that fits with the rest of the pattern. This is part of the power of SPARQL, one can match a Subject, an Object, a Predicate or even all three. Making all 3 parts of the pattern wildcards would return every triple in the graph (in this case our entire Pizza ontology) being searched. You may notice that in some cases the object is simply the name of a class while in others it is a class expression with an orange circle in front of it. This is because when defining classes using DL axioms Protégé creates anonymous classes that correspond to various DL axioms.
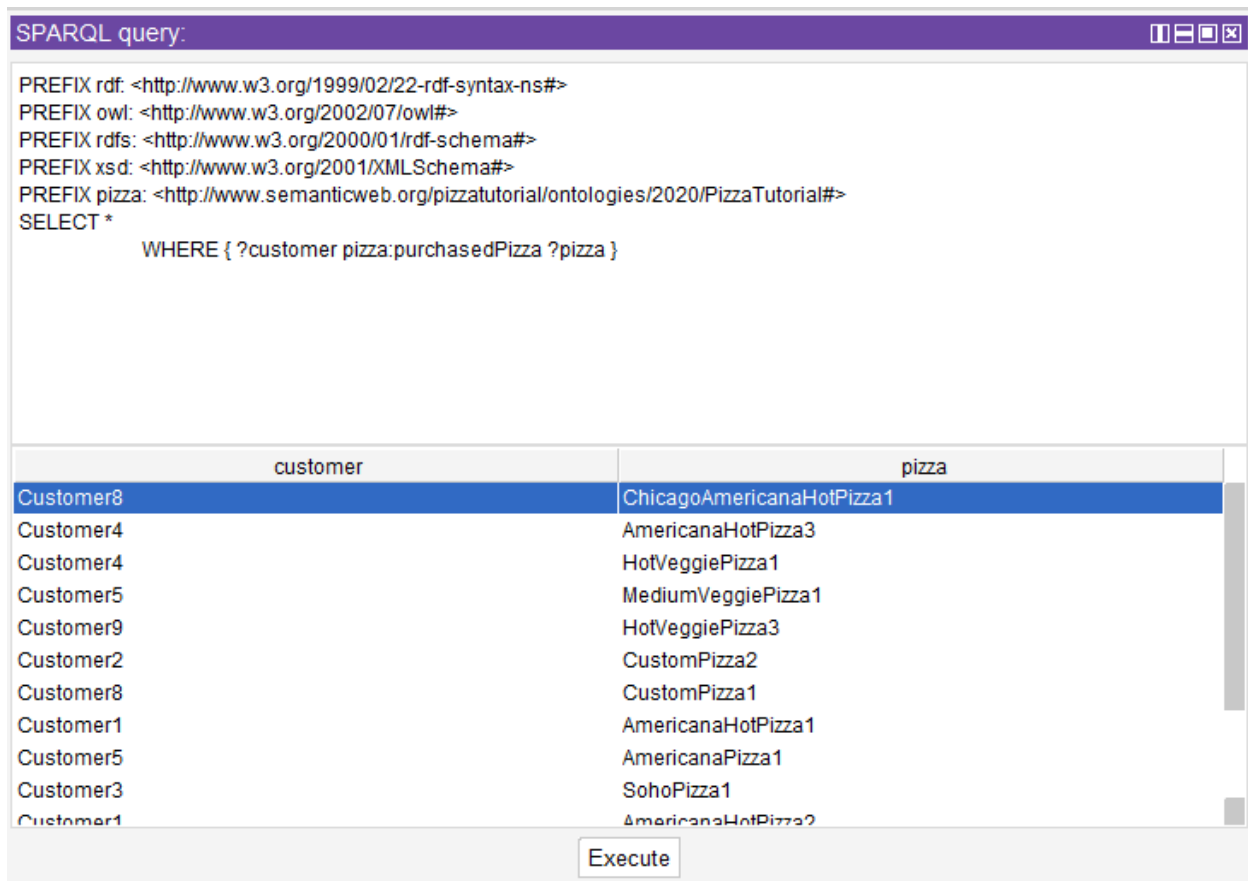
The SELECT part of a SPARQL query determines what data to display. The WHERE part of a query determines what to match in the query. If you want to display everything matched in the WHERE clause you can just use a * for the SELECT clause. The initial default query in this tab is set up with no knowledge of the specific ontology. I.e., it will return all the classes that are subclasses of other classes regardless of the ontology. To get information about `Pizzas` the first thing we need to do is to add another prefix to the beginning of the query. In our case the Pizza ontology has been set up with a mapping to the prefix pizza (you can see this in the ontology prefixes tab in the Active ontology tab discussed in chapter 7). So, add the following to the SPARQL query after the last PREFIX statement:

PREFIX pizza: <http://www.semanticweb.org/pizzatutorial/ontologies/2020/PizzaTutorial#>

We are almost ready to query the actual ontology. For our first query let's find all the Pizzas purchased by a Customer. The SPARQL code for this is:

SELECT * WHERE { ?customer pizza:purchasedPizza ?pizza }

Type that into the query window underneath the prefixes (of course remove the existing query). Hit Execute. Your screen should look similar to figure 9.2.

Figure 9.2 A SPARQL Query

If you examine the output carefully you may notice an issue. `Customer4` only seems to have purchased 2 Pizzas. However, if you examine the data in the Individuals by class tab you will see that she purchased 3. The reason that one of them doesn't show up is that when the data was entered, I typically entered it on the `Customer` instances. However, for one of `Customer4's Pizzas` I entered the data on the `Pizza` instead. I.e., I asserted on `HotVeggiePizza2` that it was `purchasedByCustomer Customer4`. Since `purchasedPizza` and `purchasedByCustomer` are inverses, the reasoner filled in the additional information for me. However, SPARQL doesn't pay attention to information asserted by the reasoner only information asserted by the user. Note: this depends on the implementation of SPARQL. For example, there is another SPARQL implementation available as a Protégé plugin called Snap SPARQL that is aware of reasoner inferences.

However, in the default SPARQL tab that we are using, SPARQL ignores information asserted by the reasoner. This is an issue for other plugins for Protégé as well such as the Individuals matrix. Luckily, there is a simple work around for this issue where information asserted by the reasoner can be saved and reloaded so that it is the same as user defined data. This workaround is described in my blog in the article: https://www.michaeldebellis.com/post/export-inferred-axioms

To further see this, replace the current query (make sure to keep all the prefixes) with:

This will show you the two pizzas where the purchase relation was asserted on the instance of Pizza rather than on the instance of Customer.

Suppose you wanted to see all of the things that are objects of `Customer`? With a couple of new constructs this is simple. First, in SPARQL a shortcut to identify the type of any entity is to use the keyword `a` as the predicate. This is just shorthand for `rdf:type`. Second, when you have multiple statements in a WHERE clause you need to end each one with a period.

Replace the current query with the following:

SELECT *

WHERE { ?customer a pizza:Customer.

      ?customer ?relation ?relatedToCustomer.}

This will provide a long list of everything in the graph that is an object of some instance of the `Customer` class. I.e., any entity that is the object of a predicate with a `Customer` as the subject.

Suppose you wanted to count the number of Pizzas purchased by Customers so far. For this you use the SPARQL function COUNT. Here is what it would look like:

SELECT (COUNT(?pizza) AS ?pcount)

WHERE {?customer pizza:purchasedPizza ?pizza}

Paste that into the SPARQL query view and hit Execute and you should see the returned value: 15. However, remember this isn't really all the `Pizzas` because a few of the purchases were recorded on the `Pizza` rather than on the `Customer`. To get the full number we can take advantage of the fact that we have recorded the number of pizzas that each customer has purchased and use the SPARQL SUM function. That query would be:

SELECT (SUM(?pnumber) AS ?psum)

WHERE { ?customer pizza:numberOfPizzasPurchased ?pnumber}

This should give you the correct number of 17.

9.22 SPARQL and IRI Names

If you recall, at the beginning of the tutorial we changed the preference for creating new entities to *user supplied name* rather than *auto-generated name* which is the default. Now that you have seen examples of using SPARQL we can explain why. With auto-generated names rather than have names such as `Customer` or `purchasedByCustomer` our entities would have names such as `OWLPropertyA4257yri73ff90rmbx` and `OWLClass23gkb0tk5kd30tm`. Thus, the first query would be something like:

```
SELECT * WHERE {?customer pizza:OWLPropertyA4257yri73ff90rmbx ?pizza}
```

and the second query would be:

```
SELECT *

WHERE {?customer a pizza:OWLClass23gkb0tk5kd30tm.
```

70

```
?customer ?relation ?relatedToCustomer.}
```

This would be much less intuitive than the user defined names. There are good reasons to use auto-generated names, especially for large ontologies that are implemented in multiple natural languages. However, for new users, especially those who plan to use SPARQL and SHACL, I think it is more intuitive to start with user supplied names and then progress to auto-generated names if and when the requirements show a true need for them. This approach to developing software incrementally rather than to attempt to design the perfect system that can scale for all possible future requirements is known as the Agile approach to software development. In my experience Agile methods have proven themselves in countless real-world projects to deliver better software on time and on budget than the alternative waterfall approach. For more on Agile methods see: https://www.agilealliance.org/agile101/

This just gives you a basic overview of some of the things that can be done with SPARQL. There is a lot more and if you are interested you should check out DuCharme's book or some of the many SPARQL tools and tutorials on the web. Some of these are in the bibliography.

One final point: features of OWL and SWRL that new users frequently find frustrating are the Open World Assumption (OWA) and lack of non-monotonic reasoning. The OWA was discussed in chapter 4.13. Non-monotonic reasoning will be discussed in section 11.1. For now, though remember that SPARQL is *not* subject to *either* of these restrictions. With SPARQL one can do non-monotonic reasoning and leverage the more common Closed World Assumption (CWA). E.g., one can test if the value for a property on a specific instance exists or not and can take actions if that property does not exist.

Chapter 10 SWRL and SQWRL

The Semantic Web Rule Language (SWRL) was created because there are certain kinds of inferences that can't be done by Description Logic (DL) axioms. Also, in my experience there are also times where an inference can be done using DL, but it can be more intuitive to define that inference as a rule.

There are actually two UI's for SWRL in Protégé. There is the SWRL tab and there is also a Rules view that can be added to the UI as we added a view in section 8.2. The SWRL tab is the one that is being more actively developed and I recommend you always use that. This chapter will focus on the SWRL tab. Everything in this chapter applies to the SWRL tab and will be slightly different in the Rules view. For an overview of the Rules view see the SWRL Process Modeling tutorial listed at the end of this chapter.

Like all rule systems, SWRL consists of a left-hand side (called the antecedent) and a right-hand side (called the consequent). The two are separated by an arrow created with a dash and a greater than character like this: `->`. Each expression in a SWRL rule is separated by a `^` sign. The consequent of the rule fires if and only if *every* expression in the antecedent is satisfied. Since the antecedent can be satisfied multiple times, this means that SWRL rules can do iteration. They will fire for every combination of values that can satisfy the antecedent. All parameters (variables that are wildcards and get bound dynamically as the rule fires) are preceded by a `?`.

SWRL expressions consist of 3 types:

1. Class expressions. This is the name of a class followed by parentheses with a parameter inside. For example Customer(?c) will bind ?c to an instance of the class Customer and (assuming the rest of the antecedent is satisfied) will iterate over each instance of the Customer class.
2. Property expressions. This is the name of a property followed by parentheses and two parameters: the first for the individual that is being tested and the second to bind to the value of that property for that individual. Note that since individuals can have more than one value for a property this can also create iteration, where the rules will iterate over every property value for each individual. E.g., `purchasedPizza(?c, ?p)` will bind ?p to each Pizza `purchased by` each customer ?c.
3. Built-in functions. SWRL has a number of built-in functions for doing mathematical tests, string tests, etc. The SWRL built-ins are documented here: https://www.w3.org/Submission/SWRL/ All SWRL built-ins are prefaced by the `swrlb` prefix. E.g., the math built-in `swrlb:greaterThan(?np, 1)` succeeds if the value of `?np` is greater than 1.

We are going to add two simple SWRL rules to our Pizza ontology to compute discounts for some `Customers`. We are assuming that our `Pizza` restaurant hasn't been in business long, so they want to give a discount to anyone who has purchased more than one `Pizza`. Also, their manager overestimated the love of spicy ingredients of their customers, and they have a lot of Jalapeno peppers that they want to use before they go bad, so they are offering a larger discount to customers who prefer `Hot` pizzas rather than those who prefer `Medium` or `Mild`.

To begin with let's write the first rule to give a 20% discount to all customers who have purchased more than 2 Pizzas and prefer Hot Pizzas.

Exercise 34: Write Your First SWRL Rule

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1. To begin with navigate to or create the <mark>SWRLTab</mark>. If it doesn't already exist use <mark>Window>Tabs>SWRLTab</mark> to create and select it. If you don't have the SWRLTab under the Window>Tabs menu then use <mark>File>Check for plugins</mark> and select the SWRLTab plugin. Remember if you do this you need to restart Protégé for the plugin to be available.

2. The SWRLTab is divided into two main views and then some buttons on the bottom of the tab that relate to DROOLS. The question of when and how to use DROOLS confuses many new users but there is a simple answer: don't use it![11] As you get more experience with SWRL you will start to understand how and when DROOLS is used but for beginners the answer is simple. Think of all those DROOLS buttons as things for power users only. You don't need to use them at all. That is why we installed the Pellet reasoner in section 4.2. The Pellet reasoner supports SWRL and when you run the reasoner it will also automatically run any SWRL rules you have. See the bibliography for a paper on DROOLS.

3. Click on the <mark>New</mark> button at the bottom of the top view. The other buttons should be grayed out since they only apply if you have at least one rule written. This will give you a new pop-up window to write your rule. In the <mark>Name</mark> field at the top call the rule: <mark>HotDiscountRule</mark>. You can skip the comment but if you want to add a comment it is a good habit to get into and you can write something like: <mark>Provide a special discount for customers who prefer hot pizzas</mark>.

4. Now go to the bottom part of the rule window and start writing the rule. To start you want to bind a parameter to each instance of the Customer class[12]. To do this all you need to do is to write: <mark>Customer(?c)</mark>. Note that auto-complete should work in this window but sometimes it may not and you may need to type the complete name. Also, you will see various hints or error messages in the <mark>Status</mark> field as you type which you can mostly ignore for now. E.g., as you type out Customer you will see messages like: <mark>Invalid SWRL atom predicate 'Cus'</mark> until you complete the name of the Customer class. Those messages can help you understand why your rule won't parse as you develop more rules but for now you should be able to ignore them.

5. Now you want to bind a parameter to the number of `Pizzas` that each customer has ordered so far. To do that you first add a <mark>^</mark> character. This stands for the logical *and*. I.e., the rule will fire for every set of bindings that satisfy *all* of the expressions in the antecedent. To test the number of `Pizzas` you use the data property `numberOfPizzasPurchased`. So at this point your rule should look like: <mark>Customer(?c) ^ numberOfPizzasPurchased(?c, ?np)</mark>.

6. Now we want to test the object property `hasSpicinessPreference`. The first parameter will also be `?c`. I.e., we are iterating through each instance of `Customer`, binding it to `?c` and then testing the values of these properties. However, in this case rather than binding the spiciness preference to a parameter we just want to test if it is equal to the instance of `Spiciness Hot`. So we directly reference that instance in the expression resulting in: <mark>^ hasSpicinessPreference(?c, Hot)</mark>.

7. As the last part of the antecedent we want to test that the Customer has purchased more than 1 `Pizza`. We can use the SWRL math built-in <mark>swrlb:greaterThan</mark>. Add <mark>^ swrlb:greaterThan(?np, 1)</mark> That is the last

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[11] For more on DROOLS see the paper: M. J. O'Connor (2012). A Pair of OWL 2 RL Reasoners in the bibliography.

[12] This isn't actually required. You will get the same result without the Customer(?c) expression but it is a good example of how one can use the names of classes to iterate over their instances with SWRL.

part of the antecedent so we write -> to signal the beginning of the consequent. At this point your rule should look like: Customer(?c) ^ numberOfPizzasPurchased(?c, ?np) ^ hasSpicinessPreference(?c, Hot) ^ swrlb:greaterThan(?np, 1) ->

8. Finally, we write the consequent of the rule, the part after the arrow that signifies what to do each time the rule succeeds. We want to give these customers a 20% discount so we write: hasDiscount(?c, 0.2). Whereas the expressions on the left hand side are tests to see if the rule should fire, the expression on the right is an assertion of a new value to be added to the ontology. For those with a logic background the simple way to think of this is that the antecedent is implicitly universally quantified whereas the consequent is implicitly existentially quantified.

9. Thus the whole rule should look like: Customer(?c) ^ numberOfPizzasPurchased(?c, ?np) ^ hasSpicinessPreference(?c, Hot) ^ swrlb:greaterThan(?np, 1) -> hasDiscount(?c, 0.2). Take note that the OK button at the bottom is only possible to select when the rule has a valid syntax. It should be selectable now so select it. You should see the new rule show up at the top of the top most view.

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Note that there is a minor bug in SWRL where sometimes the prefix for the current ontology will be added to all the expressions without a prefix. So at some point you may see that your expressions end up looking like this: pizza:Customer(?c). If this happens don't worry it won't affect the way the rule works at all. If at some point this happens and you want to remove the prefixes there is a way to do this described in my blog: https://www.michaeldebellis.com/post/removing-ontology-prefixes-from-swrl-rules

Next, we want to write a second SWRL rule for other customers who have ordered more than one Pizza but don't prefer Hot Pizzas.

Exercise 35: Write Another SWRL Rule

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1. Make sure you are still in the SWRLTab. Click on the HotDiscountRule and select Clone

2. This should bring up the same window you used to create your first rule with the code for that rule in the window. Change the name of this rule from S1 to LessSpicyDiscountRule.

3. Next edit the test for the Customer's spiciness preference. Rather than just testing if it is Hot we want to test this time if it isMilderThan Hot. This is an example of using the order relation we defined in chapter 6. Change hasSpicinessPreference(?c, Hot) to hasSpicinessPreference(?c, ?spr). Rather than just test if it is equal to Hot we need to bind the preference value to the parameter ?spr. Then after this add the usual and character and the new test, so you should add: ^ isMilderThan(?spr, Hot)

4. Finally, we want to change the discount for these Customers to be 10% rather than 20%. So change the consequent to be: hasDiscount(?c, 0.1).

5. Thus the whole rule should look like: Customer(?c) ^ numberOfPizzasPurchased(?c, ?np) ^ hasSpicinessPreference(?c, ?spr) ^ isMilderThan(?spr, Hot) ^ swrlb:greaterThan(?np, 1) -> hasDiscount(?c, 0.1).

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Now we want to run our rules. Remember there is no need to use those DROOLS buttons. Just synchronize the reasoner and your rules should fire just as other DL axioms that assert values based on

inverses, defined classes, etc. Go back to the Individuals by class tab and look at various Customers. For example, `Customer1` has ordered more than one Pizza and `hasSpicinessPreference` of `Hot` so she has a discount of .2. Note that as with any information asserted by the reasoner, there is a **?** next to the assertion which you can click on and it will provide an explanation about why the value was asserted. This explanation will list the appropriate rule that fired and the values that caused it to fire. If you look at `Customer6`, you will see that he has no discount because he has only purchased one `Pizza`. Finally, if you look at `Customer2`, she has a discount of .1 because she has purchased more than one Pizza but her spiciness preference `isMilderThan Hot`.

In this case the consequent of our rule was to add a data property assertion to an individual. Another possible outcome is to make an individual be an instance of a new class. E.g., if we had a subclass of `Customer` called `PreferredCustomer` and we wanted the result of a rule be to make a `Customer` an instance of `PreferredCustomer` we could have `-> PreferredCustomer(?c)` as the consequent of the rule.

A tool that is useful to debug SWRL rules is the Semantic Query-Enhanced Web Rule Language or SQWRL (pronounced squirrel). SQWRL rules look just like SWRL rules except in the consequent there is a `sqwrl:select` statement that lists every parameter that we want to know the value of every time the rule fires.

Exercise 36: Write a SQWRL Rule

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1. Bring up the SQWRLTab if it doesn't already exist using Windows>Tabs>SQWRLTab. You will see it looks almost identical to the SWRLTab.

2. Let's say we want to see how often the `HotDiscountRule` fires. We can find this out very easily. To start select the HotDiscountRule and clone it. This creates a copy of the rule called S1. Select that rule and then select the Edit button.

3. Change the name of the rule to TestHotDiscountRule.   Replace the consequent (the expression after the arrow) with the following: sqwrl:select(?c, ?np) and select OK. Your SQWRL rule should look like: Customer(?c) ^ numberOfPizzasPurchased(?c, ?np) ^ hasSpicinessPreference(?c, pizza:Hot) ^ swrlb:greaterThan(?np, 1) -> sqwrl:select(?c, ?np). Synchronize the reasoner.

4. Select TestHotDiscountRule then select the Run button at the bottom of the tab. This will create a new tab in the lower view called TestHotDiscountRule. You should see that the rule fired 3 times with ?c equal to Customer4, Customer1, and Customer8 and with ?np equal to 3, 2, and 2.

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This has been a very brief introduction to SWRL. For a somewhat more interesting example based on process modeling see: https://www.michaeldebellis.com/post/swrl_tutorial

Chapter 11 SHACL

Next, we will look at a plugin for SHACL. SHACL stands for Shapes Constraint Language. Note that *shape* in this context has nothing to do with geometric shapes. SHACL is somewhat newer than the other technologies described here. However, it fills an essential gap in the Semantic Web architecture stack, and it is gaining a lot of traction in the world of large-scale corporate development. The reason for SHACL may at first seem a bit hard to grasp. After all many of the constraints that SHACL can define for data can also be defined using Description Logic or SWRL which are more high level and a bit easier to use. So why even bother with SHACL? There are two reasons that SHACL is essential for real world use of Semantic Web and Knowledge Graph technology:

1. The need to define constraints that aren't limited by the Open World Assumption (OWA) and Monotonic reasoning.
2. The fact that real world data is *messy!*

11.1 OWA and Monotonic Reasoning

As described in section 4.13 OWL uses the Open World Assumption (OWA) because it was designed for the Internet. However, the OWA makes certain kinds of constraint validation difficult or impossible. For example, it is common to have a data integrity constraint that all employees must have a social security number. While such an axiom can be defined in OWL it will seldom work when we want it to because of the OWA. The OWA means that there may be a social security number out there somewhere in the Internet but that the system just hasn't found it yet. While this is true, to validate the integrity of corporate data just saying "well it is out there somewhere" won't do. To validate data integrity we need to be able to fire off warnings when required data isn't there so we need to use the Closed World Assumption (CWA).

Monotonic reasoning is a byproduct of the fact that OWL and SWRL are based on logic. The OWL reasoners are essentially theorem provers. If you have ever studied mathematical proofs, you know that one of the classic ways to prove that something is invalid is to show that some variable has two different values. E.g., if our theorem implies that p = True and p = False then we have a contradiction. Each variable can only have one value. This is why SWRL rules can only add values to variables rather than change them. For more on this see the excellent presentation on SWRL by Martin O'Connor: https://protege.stanford.edu/conference/2009/slides/SWRL2009ProtegeConference.pdf

This is why SPARQL often needs to be used rather than SWRL even though SWRL is more abstract and powerful. SWRL does not support non-monotonic reasoning whereas SPARQL does. Similarly, when validating data, we may want to take actions to change it, e.g., to coerce it into a proper standard format. To do that we need to change rather than add a value, i.e., we need non-monotonic reasoning.

11.2 The Real World is Messy

The other reason for SHACL is that real world data is messy. Over the span of this tutorial, you may have experienced a point where you made an error, and the reasoner marked your ontology as invalid. If you haven't, congratulations, but as you work with Protégé more you will experience it. This is another by product of using a logic-based language. Simply having one inconsistency makes the entire model invalid. For small examples this is not a problem. When one has tens, hundreds, or even thousands of individuals it isn't that difficult to find the problem and fix it. However, when dealing with Big Data where one has tens of thousands, millions, or more individuals the prevalence of bad data may be huge.

I.e., it might be the case that we never get the data to satisfy every integrity constraint which would mean the reasoner is never of any use except to tell us that the ontology is not consistent.

Thus, SHACL provides a way to define data integrity constraints that overlap to some degree with what can be defined in OWL and SWRL. For example, both can define the number of values allowed for a specific property. E.g., that each instance of `Employee` must have one and only one social security number (`ssn`). If this were defined as a DL axiom, then the axiom would never fire for employees that had no `ssn` because of the OWA. On the other hand, if an `Employee` accidentally had 2 `ssn` values then the entire ontology would be inconsistent until one value was removed. SHACL on the other hand can handle both these examples and rather than making the entire ontology inconsistent it simply logs warnings at various levels of severity.

11.3 Basic SHACL Concepts

To understand SHACL recall that the language underlying OWL is RDF which describes graphs as triples of the form: Subject Predicate Object. SHACL also works at the level of RDF because some developers may want to simply use that lower level for reasons of efficiency. Thus, RDF can validate an RDF graph as well as an OWL ontology. Fundamentally, SHACL consists of two components:

1. An RDF vocabulary for defining data constraints on RDF graphs (which includes OWL since an OWL ontology is an RDF graph).
2. A reasoner for applying the constraints defined in 1 to a specified data graph such as the Pizza ontology.

One of the most important classes in 1 is a SHACL `Shape`. An instance of the SHACL `Shape` class consists of a set of Targets and Constraints. A Target defines which nodes in the RDF graph that the data constraints apply to. For OWL ontologies this is typically the name of a class which indicates that the constraints apply to all instances of that class. The Constraints define the specific property for the constraint as well as the actual constraints such as the minimum or maximum number of values and the datatype. In the following example, a Target is the `Employee` class in the Pizza ontology. An example constraint is that the `ssn` property must have exactly one value. Another example constraint is that the format of the `ssn` value must be a string of the form: "NNN-NN-NNNN" where each N must be an integer. For more on SHACL see the references in the bibliography.

11.4 The Protégé SHACL Plug-In

To start go to Windows>Tabs and see if you have SHACL Editor as an option. If you don't then go to File>Check for plugins and select the SHACL4Protege Constraint Validator. You need to restart Protégé to see the new plugin so save your work and then quit and start Protégé and load the Pizza ontology with data.

Because editing SHACL is a bit more complex for this version of the tutorial we are only going to view some already written SHACL constraints and see how the validator processes them rather than writing additional constraints. First download the PizzaShapes.txt file to your local hard drive. This file can be found at: https://tinyurl.com/pizzatshapes   Once you have downloaded the file open the SHACL Editor: Window>Tabs>SHACL Editor.

You will see an example shapes file in the editor when it opens but that isn't the shapes file you are looking for. From the editor click on the Open button at the top of the tab and navigate to the PizzaShapes.txt file you downloaded.

There are two shapes in this file, one for the `Employee` class and one for the `Customer` class. So, we want to expand only the `Person` class in the <mark>Class hierarchy</mark> view. We will start with the `Employee` class so select that class which should result in all the instances of `Employee` being displayed in the view below it.

For the SHACL Editor we want the bottom view in the middle to take up as much screen real estate as possible. So, to start we can delete the two views on the far right side of the tab by clicking on the <mark>X</mark> at the top of each tab.

Then drag the SHACL Editor view over to the left just enough so you can see the `Employee` and `Customer` classes and their instances. Your UI should look similar to figure 11.1.

To begin examine the code in the SHACL Editor view. Note that at the beginning there are a list of namespaces, similar to the namespace prefixes in the SPARQL editor. After the prefixes there is the first actual shape which is the <mark>EmployeeShape</mark>. This shape constrains values of properties on instances of `Employee`. The <mark>sh:targetClass</mark> identifies the class that this shape is for. Beneath that are various nodes (as in nodes in a graph, SHACL is also represented as triples) that constrain various properties that apply to the `Employee` class. The first node constrains the cardinality of the `ssn` property to be exactly one (<mark>minCount 1 and maxCount1</mark>). The next also applies to `ssn` and constrains the data further than just saying it must be a string. It must be a string that matches the pattern: <mark>"^\\d{3}-\\d{2}-\\d{4}$"</mark> This is a regex expression that means the pattern must be 3 digits (numeric characters from 0-9), followed by a dash, followed by 2 digits, followed by a dash, followed by 4 digits.

The next 2 nodes deal with the `hasPhone` data property. This property must have at least one value (although possibly more) and must also conform to a similar pattern of 3 digits followed by a dash followed by 3 digits followed by a dash followed by 4 digits. Of course, actual phone numbers can be more complex and varied but this is just a simple example.
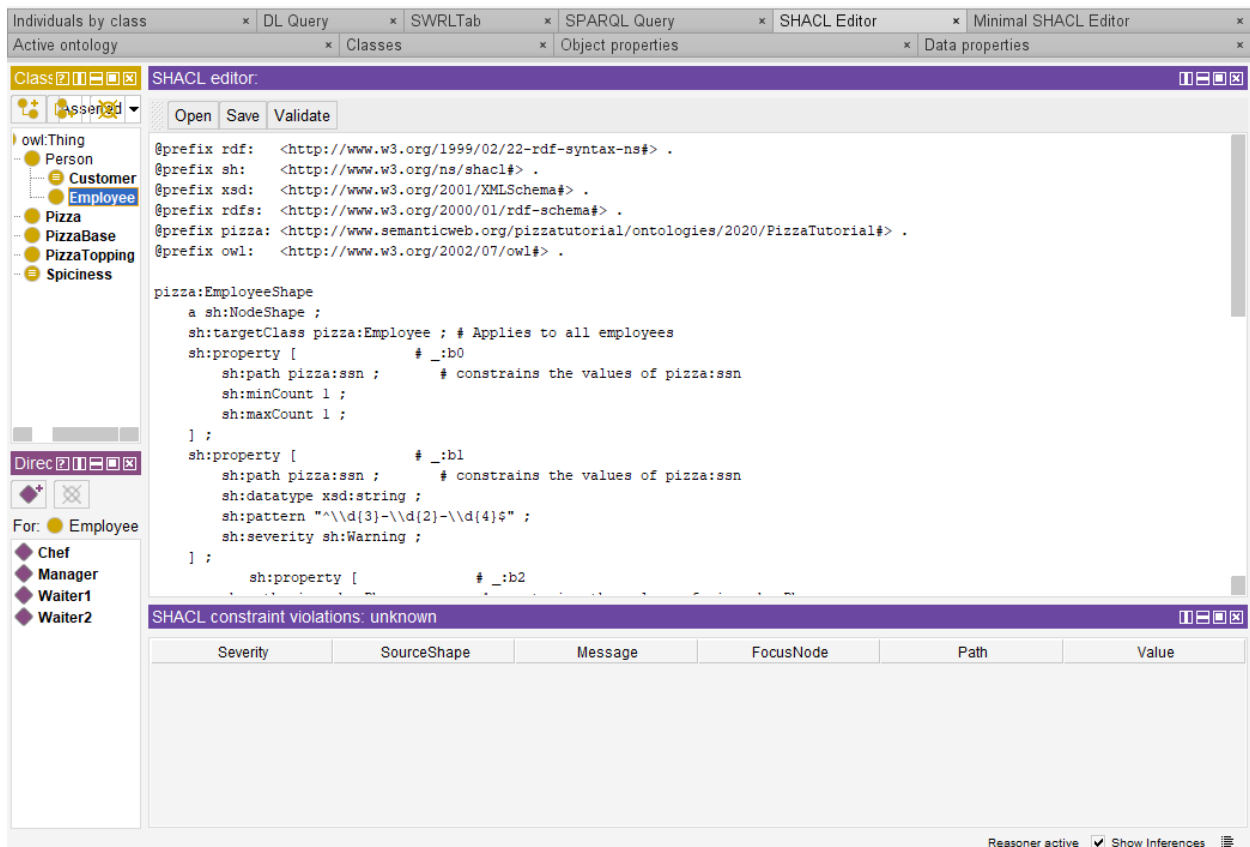
Figure 11.1 The SHACL Editor

Now hit the Validate button. You should see several messages displayed in the long SHACL constraint violations view at the bottom. If you had the `Employee` class selected when you clicked on Validate, then this view should now read: SHACL constraint violations: 5/8. This means that there were 8 constraint violations and 5 of them were on instances of the `Employee` class. You can see the violations that apply to each `Employee` by clicking on each individual. You can resize the various columns in this view which is helpful to view the information you need. The most useful data is in the Message, Path, and Value columns. All the other columns such as Severity and Source can be made as small as possible to make more room for those other columns. If you do this and click on the Chef individual you will see that she has one constraint violation. See figure 11.2.

You can see that the Chef individual has 2 values for the `ssn` property which is more than allowed. If you examine the Chef individual in the Individuals by class view you will see that this is indeed the case.
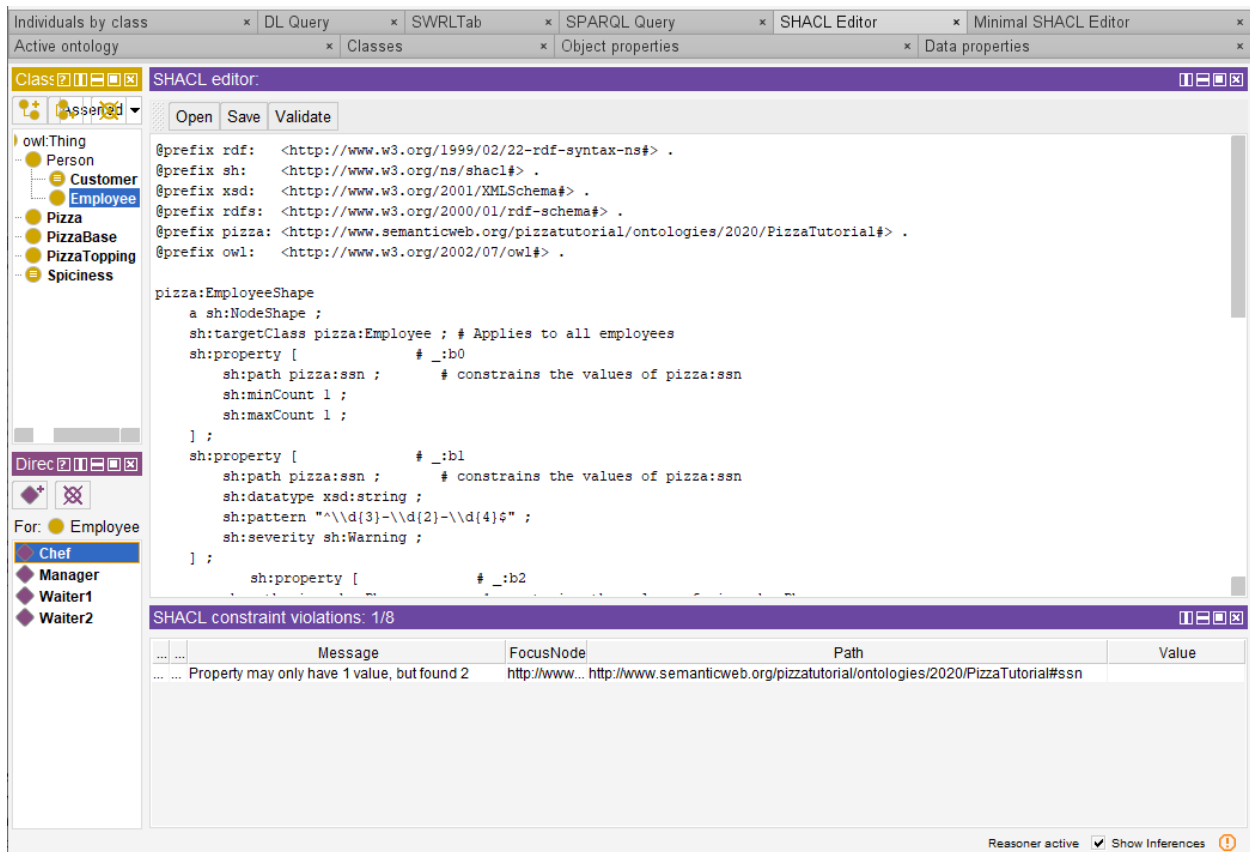
Figure 11.2 Constraint Violation for the Chef Individual

If you click on the Manager individual, you will see that he has a constraint violation because his phone number is not in the proper format. Waiter1 has a similar problem. Waiter2 has missing data. Her `hasPhone` and `ssn` data properties both must have values but don't.

If you move your focus to the Customer class, you can see the remaining 3 constraint violations. `Customer10's hasDiscount` property is greater than 1 which is not allowed. This is defined by the CustomerShape in the `hasDiscount` node with `sh:minInclusive  0.0` and `sh:maxInclusive 1.0`. This is the way you define a minimum and maximum value for a numeric property (note: this applies to the value not to the number of values). Customer2 also has a hasPhone value that doesn't match the defined format and finally Customer3 does not have a value for hasPhone when at least one is required.

Recall that the SHACL constraints themselves are essentially RDF graphs. Figures 11.3 and 11.4 illustrate the `Employee` shape and the `Customer` shape used in the above example as graphed in the Gruff tool from AllegroGraph.
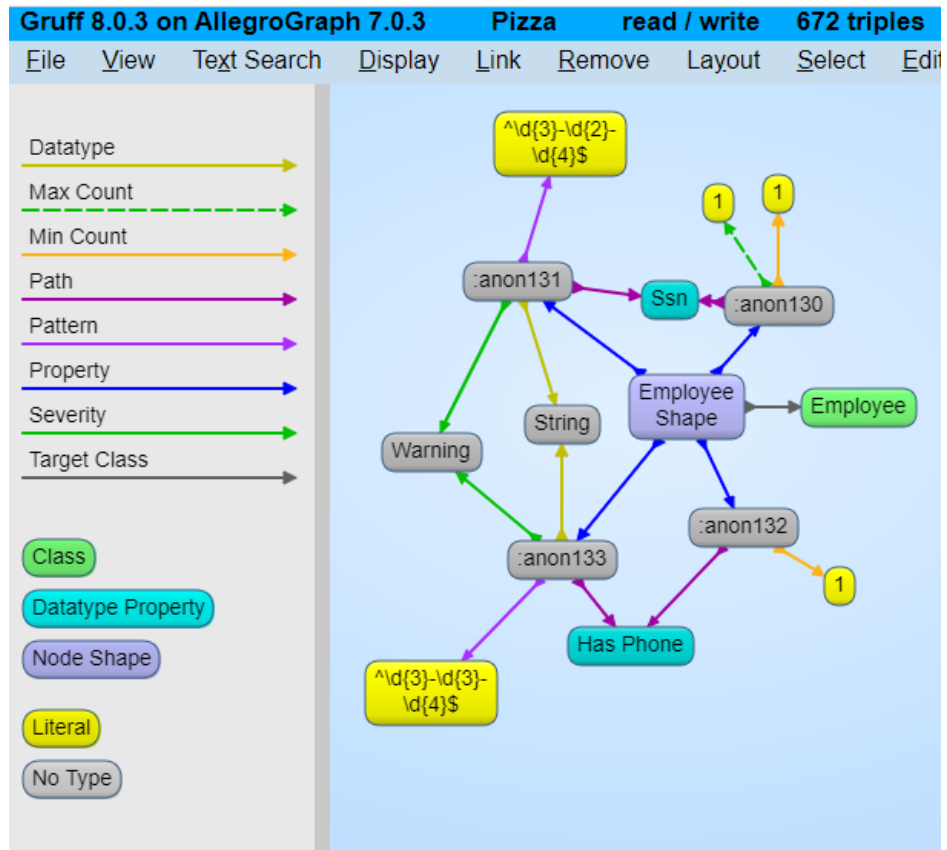
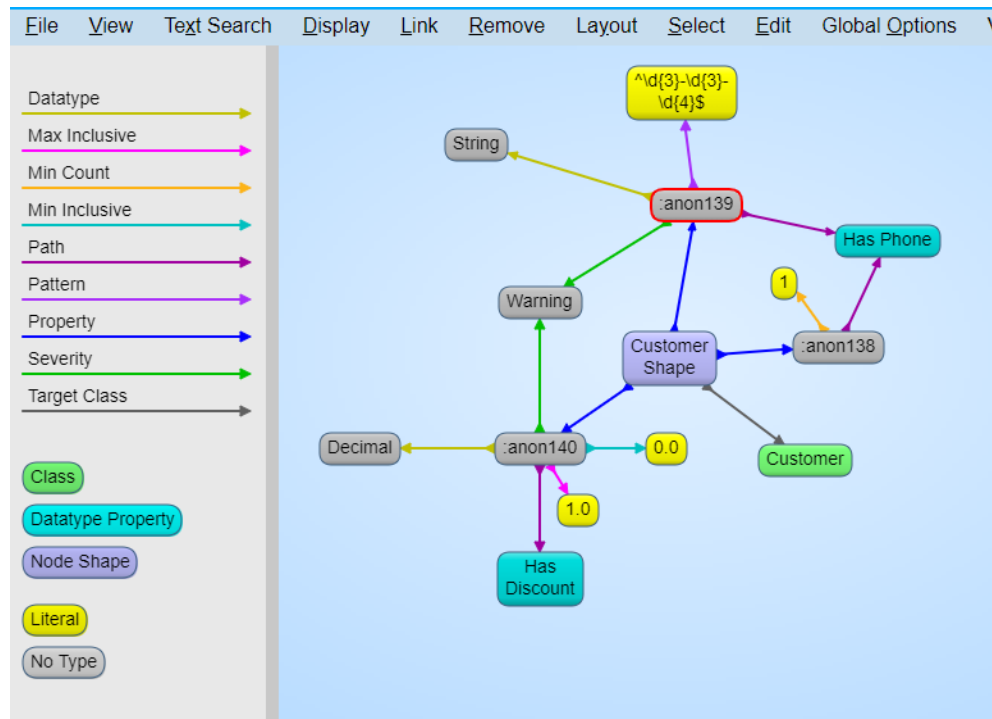Figure 11.3 Gruff Visualization of the EmployeeShape

Figure 11.4 Gruff Visualization of the CustomerShape

This is just the most basic introduction to SHACL. For a more sophisticated tutorial see the Top Quadrant tutorial: https://www.topquadrant.com/technology/shacl/tutorial/ Also, this presentation: https://www.slideshare.net/jelabra/shacl-by-example gives much more detail on SHACL.

Chapter 12 Web Protégé

This tutorial has primarily focused on the desktop version of Protégé because as of this writing Web Protégé doesn't support any reasoners so the majority of the sophisticated capabilities of OWL and Protégé such as defined classes and SWRL rules can't be created in Web Protégé. However, one of my goals in creating this tutorial was to address questions that I've seen frequently asked on the Protégé user support email list and one of the most common question is the difference between Protégé and Web Protégé. We are all used to using tools as services rather than applications installed on our local machines, so people often go to Web Protégé as their default. While Web Protégé lacks reasoner support it can still be extremely useful for collaborative development. This chapter explains the benefits of Web Protégé and some best practices for using the two tools together.

To begin it is recommended that new users start with the desktop version of Protégé[13]. The constraints imposed on the ontology by lack of a reasoner are significant and if one learns only using Web Protégé they will miss many of the benefits of OWL and come away with the idea that Protégé is little more than a traditional object modeling tool. However, once one is familiar with the desktop version it is worth getting familiar with Web Protégé as it can be extremely useful for joint development of an ontology by 2 or more people.

To begin there are two options for Web Protégé:

1. Use the Stanford server at webprotege.stanford.edu
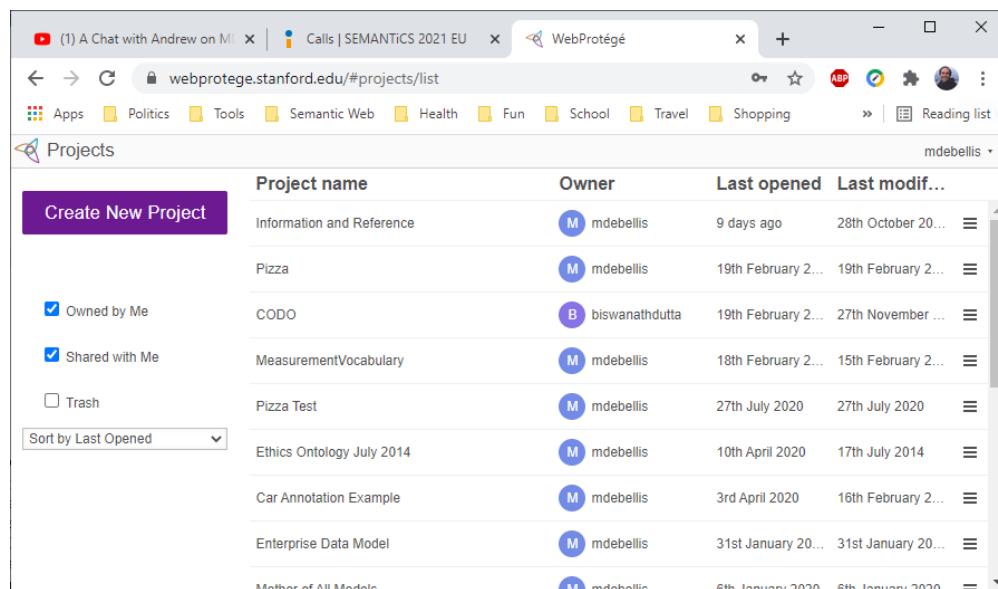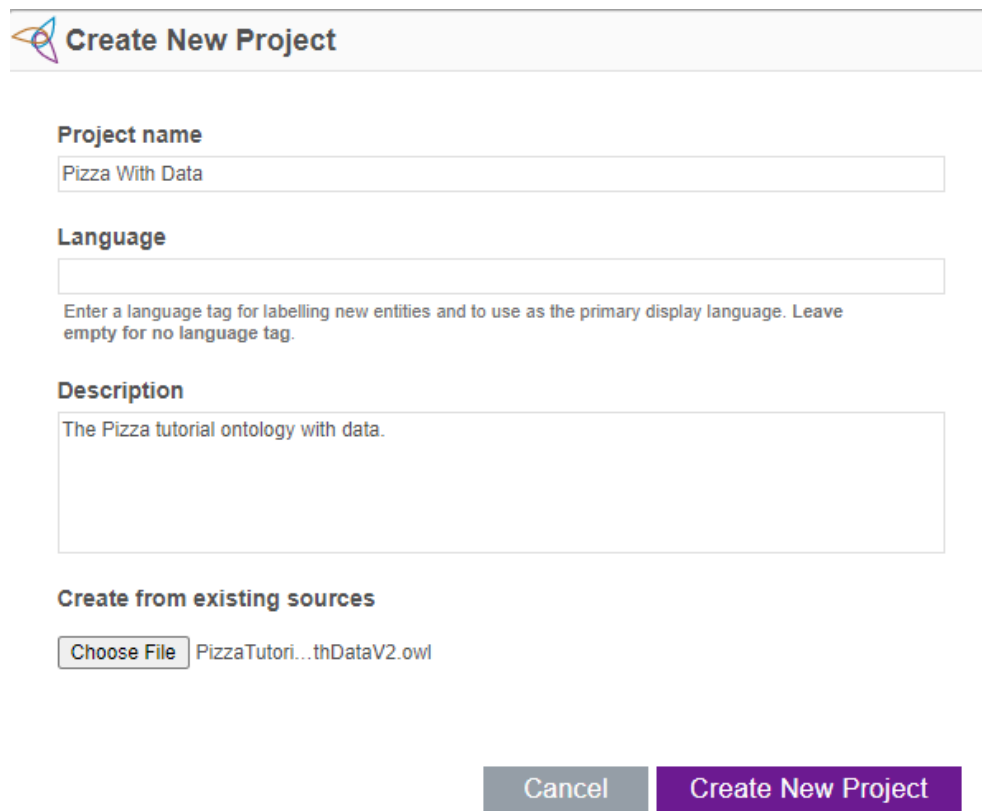2. Download and install the Web Protégé software on your own local server.

Figure 12.1 Web Protégé Projects

Unless you have security requirements at your organization that prohibit you from using the hosted version at Stanford it is best to start with the Stanford server. I won't go into the details of how to install a local Web Protégé server because either way the functionality is the same. To start, let's create a project in Web Protégé for the Pizza tutorial with data ontology. When you first go to webprotege.stanford.edu

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[13] From this point on I will refer to the Desktop version of Protégé as just Protégé.

you will be prompted to create a user ID (your email address) and a password. Once you do that you should have a fresh Web Protégé workspace. Figure 12.1 shows what my Web Protégé workspace currently looks like. Most of the projects are owned by me although note that the CODO project is owned by my colleague Biswanath Dutta. However, I still have complete access to that ontology due to the way Biswanath has configured my access as being able to both view and edit the ontology.

To upload the Pizza ontology, select the large Create New Project button. This will bring up the window shown in figure 12.2. Fill out the project name and description, then select the Choose File button and navigate to where you have the latest version of the Pizza tutorial with data. Note that in the figure I have already done this navigation so there is a value for the file to load. You can leave the Language field blank. Once you have all the fields set up similar to figure 12.2 click the Create New Project button on this dialog (note this is a different button than the one you started from).

Figure 12.2 The Create New Project Dialog

Your workspace should now include your first project. Click on the three horizontal bars at the far right of the project. This should bring up a pop-up menu. Select the Open option. This should bring you into the main Web Protégé UI to browse an ontology.

Before you make changes to the ontology you need to make sure the settings for new entities and rendering are consistent with the settings you used for the Pizza ontology. The default in Web Protégé as with Protégé is to use Auto-Generated UUIDs rather than user supplied names. If you aren't sure about these settings you can go back to exercise 2 at the beginning of chapter 4 and chapter 7 to refresh your memory. There are excellent reasons to use auto-generated UUIDs but for beginners, especially for those who want to learn SPARQL, I think they make learning the basics more difficult so we have been using the alternative of user supplied names. At the top of the Web Protégé UI in the right corner there are

various links: Display, Project, Share,… Click on Project. This will give you a dropdown menu. Select Settings from that menu. Scroll down to New Entity Settings. Change IRI Suffix from Auto-generated Universally Unique ID (UUID) to Supplied name. Leave the rest of the settings as they are and select the Apply button at the bottom right corner of the screen.

When you select Apply, you should return to the main Web Protégé view with the Class hierarchy tab selected. If it doesn't select that tab. Select the Pizza class. Your UI should look like figure 12.3.
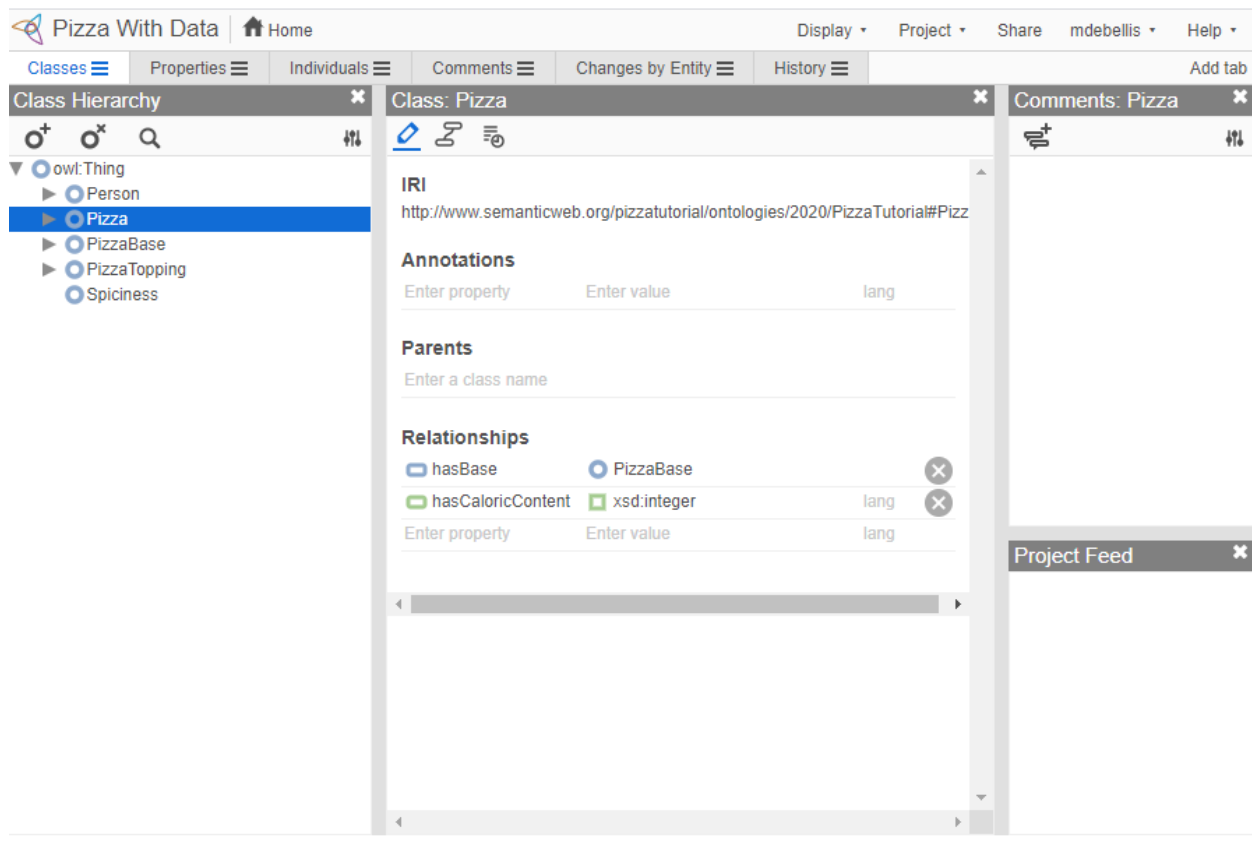

Figure 12.3 Browsing the Pizza Ontology in Web Protégé

Note that the axioms for the Pizza class are there but they are not editable. Protégé uses the reasoner even when entering or editing axioms to ensure that any axioms have the proper syntax so since there is no reasoner in Web Protégé it is not possible to edit axioms (since one might introduce syntactically incorrect axioms) only delete them using the X at the right of each axiom.

Also note the panels on the right: Comments and Project Feed. These are new capabilities in Web Protégé to facilitate collaborative design of ontologies. We will demonstrate that shortly. First, you can navigate the class hierarchy by clicking on the triangles at the left of each class that has at least one subclass. This will expand the class and show its subclasses. Click on Pizza to see its subclasses. For our scenario imagine we are opening a new branch of our pizza store in Chicago and we are dealing with a domain expert in Chicago pizza. As they examine the hierarchy, they are appalled to see that there is no class for ChicagoPizza, a type of deep dish Pizza that first became popular in Chicago. Click on NamedPizza. Then click on the icon at the left corner of the Comments view. If you hover the mouse over this icon you

should see the prompt Start new thread indicating the functionality of this icon. Make sure NamedPizza is still selected and then click on the icon to start a new thread. This will bring up a window titled Edit where you can begin a new thread. Type something like: We need a subclass of NamedPizza called ChicagoPizza. It should have an axiom that requires it to have a DeepPanBase. Then hit the OK button. Your UI should look similar to figure 12.4.
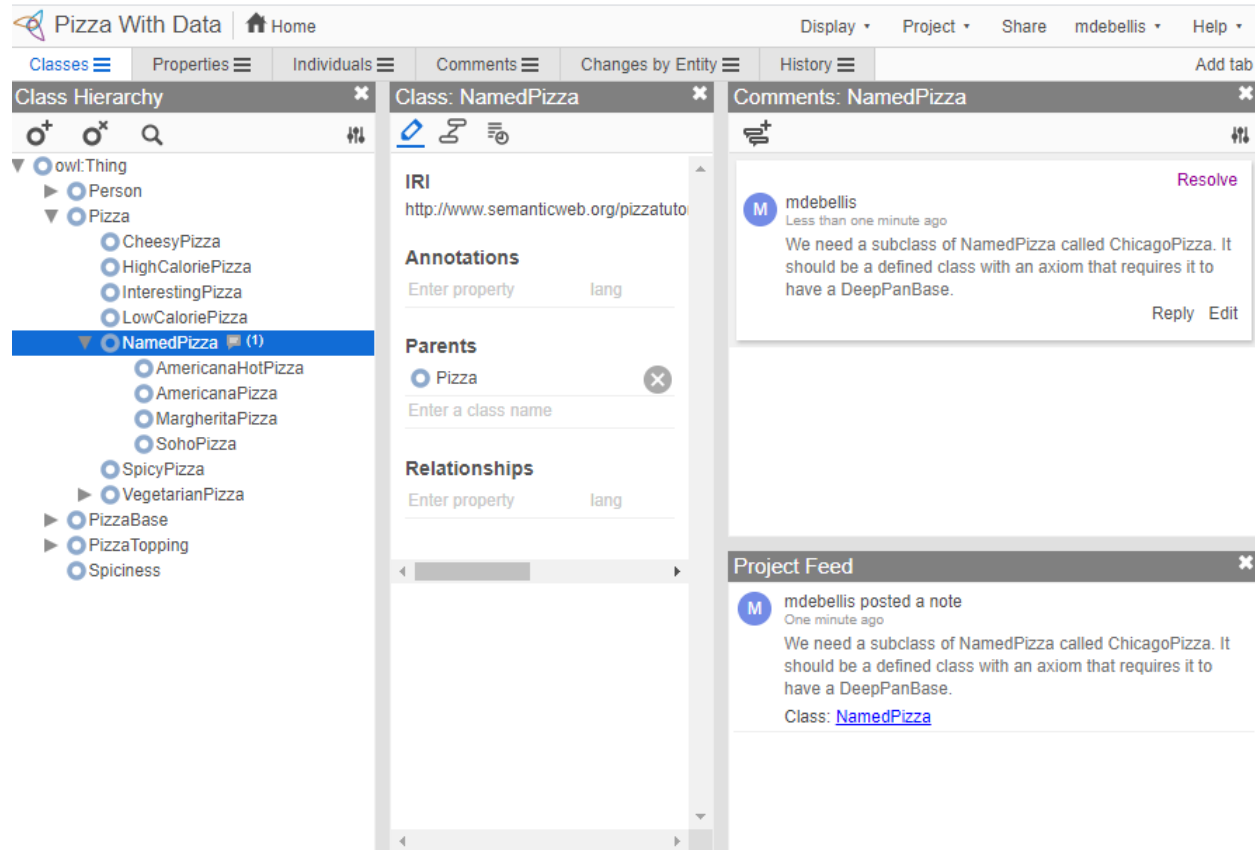

Figure 12.4 Creating a Discussion Thread

Note the new comment in the Comments view and the update in the Project Feed view. The Comments view captures comments made on any entity in the ontology. The Project Feed view captures each change made to the ontology.

To see what threaded discussions look like click on the new comment and select Reply. Add a comment like: I agree, ChicagoPizza is awesome and deserves its own class.

Let's address this comment by creating a new subclass of NamedPizza. Select NamedPizza in the Class Hierarchy view. Note the icon in the upper right corner of this view that looks similar to this: O⁺. When you hover over this icon it should say Create. You can use this icon to create new classes and subclasses. Make sure NamedPizza is still selected and click on this icon to create a new subclass of NamedPizza. This will bring up a dialog titled Create Classes. In the Class names field enter the name ChicagoPizza. You can leave the Language Tag field empty. Click on the Create button. You should now see ChicagoPizza as a new subclass of NamedPizza. Note that at the top of the Project Feed there should be a new entry for your action of creating this new class.

You might be tempted to resolve this thread (note the Resolve link at the top of the initial comment) however, we aren't really done. Remember that we need to not just create the class but also define the axiom that a `ChicagoPizza` must have a `DeepPanBase`. Since we can't add axioms in Web Protégé we need to export our ontology back to Protégé. Typically, we would collect many more comments and changes before exporting but we want to demonstrate how round-trip editing works between Protégé and Web Protégé. We could of course just export the ontology from Web Protégé to Protégé and then create another new Project, but it would be cumbersome to have to constantly create new projects every time you want to make a change in Protégé and if we did this, we would lose our audit trail of comments and changes. Luckily, there is a better way to do it.

To start we need to export the ontology to a file. Note that one of the tabs at the top is History. Select that tab. This tab shows a list of each version of the ontology. There should be 2 versions labelled R1 and R2 (in the right corner of each version). The most recent version is always at the top since that is typically what you want although it is also possible to roll back changes to previous versions. We want to export the latest version R2. Click on the R2 icon. This should give you a drop-down menu with two options: Revert changes in revision 2 and Download revision 2. Select Download revision 2. This will prompt you with the standard file browser for your OS to save a zip file with the new ontology. The ontology is saved with a zip file because ontologies can be large and since Web Protégé is working over a network we may want to limit the network traffic for large ontologies. Select the appropriate place to save the Zip archive file on the machine where you have Protégé. Do the standard things you would do to unzip the file and load it into Protégé. Note that when you unzip the file it will create a directory as well, so the file won't be directly under whatever directory you save it to. Instead, there will be a directory titled something like pizza-with-data-ontologies-owl-REVISION-2 that the OWL file will be in.

Load the downloaded file into Protégé. Go to the Class hierarchy tab and navigate to the new ChicagoPizza class under NamedPizza. Add the axiom (refer back to chapter 4 if you need to remember how to add axioms to classes) hasBase some DeepPanBase. Save the file. Now go back to Web Protégé and your version of the Pizza ontology there. Note that in the upper right corner of the window there are links (drop down menus) such as Display and Project. Select Project and from the drop down menu select Apply External Edits. This will give you a small dialog titled Upload ontologies with a little button to Choose File. Click on Choose File. That will give you the standard OS dialog for selecting a file. Navigate to the file you saved from Protégé and select that then choose OK. That should result in a new pop-up window titled Merge ontologies where you will see the changes (in this case only the addition of the `ChicagoPizza` axiom) and a text box where you can describe the changes. Add an appropriate Commit message or just take the default and select OK. You should get a message that says the changes were successfully applied.

If you navigate back to ChicagoPizza you should see that it now has that axiom. You can also navigate back to NamedPizza. In the right most column, you should see the comments about needing to add `ChicagoPizza` as a subclass. Now that this has been done you can click on the Resolve link in the upper right corner of the comment thread and the comments will be removed from `NamedPizza`.

Chapter 13 Conclusion: Some Personal Thoughts and Opinions

This tutorial is just the entry point to a technology that is entering the *Slope of Enlightenment* in the Gartner technology hype cycle [Gartner Hype Cycle]. Tim Berners-Lee published his paper on the Semantic Web [Berners-Lee 2001] way back in 2001. At least in my experience for most large US corporations the excitement around Machine Learning seemed for a while to eclipse serious interest in OWL, SPARQL, and other Semantic Web technologies in the United States. Then influential technology companies such as Google [Singhal 2012], Facebook [Olanof 2013], and Amazon [Neptune 2017] started to embrace the technology using the term Knowledge Graphs [Noy 2019] and the corporate world is finally realizing that machine learning and knowledge graphs are complimentary not competitive technologies.

The term knowledge graph itself can be used in different ways. The best definition I've heard is that an ontology provides the vocabulary (i.e., essentially the T-Box) and a knowledge graph is an ontology combined with data (A-Box). Although in the corporate world I often hear people simply talk about knowledge graphs without much interest in the distinction between the vocabulary and the data.

There are a number of vendors emerging who are using the technology in very productive ways and are providing the foundation for federated knowledge graphs that can scale to hundreds of millions of triples or more and provide a framework for all corporate data. I've listed several in the bibliography but those are only the ones I've had some experience with. I'm sure there are many others. One of the products I've had the best experience with is the AllegroGraph triplestore and the Gruff visualization tool from Franz Inc. Although Allegro is a commercial tool, the free version supports most of the core capabilities of the commercial version. I've found the Allegro triplestore easy to use on a Windows PC with the Docker tool to emulate a Linux server.

I first started working with classification-based languages when I worked at the Information Sciences Institute (ISI) and used the Loom language [Macgregor 91] to develop B2B systems for the US Department of Defense and their contractors. Since then, I've followed the progress of the technology, especially the DARPA knowledge sharing initiative [Neches 91] and always thought there was great promise in the technology. When I first discovered Protégé it was a great experience. It is one of the best supported and most usable free tools I've ever seen, and it always surprised me that there weren't more corporate users leveraging it in major ways. I think we are finally starting to see this happen and I hope this tutorial helps in a small way to accelerate the adoption of this powerful and robust tool.

Chapter 14 Bibliography

Rather than a standard bibliography, this section is divided into various categories based on resources that will be valuable for future exploration of the technologies and methods described in this tutorial.

14.1 W3C Documents
OWL 2 Primer: https://www.w3.org/TR/owl2-primer/

OWL 2 Specification: https://www.w3.org/TR/owl2-overview/

Semantic Web Primer for Object-Oriented Software Developers: https://www.w3.org/TR/sw-oosd-primer/

SPARQL Specification: https://www.w3.org/TR/sparql11-query/

SWRL Specification and Built-ins: https://www.w3.org/Submission/SWRL/

14.2 Web Sites, Tools, And Presentations.
Agile Alliance: https://www.agilealliance.org/agile101/

Cellfie: https://github.com/protegeproject/cellfie-plugin/wiki/Grocery-Tutorial

Gartner Hype Cycle: https://www.gartner.com/en/research/methodologies/gartner-hype-cycle

Jena: Open Source Java Framework for Semantic Web and Linked Data Applications: https://jena.apache.org/

Open World Assumption (OWA) presentation by Nick Drummond and Rob Shearer: http://www.cs.man.ac.uk/~drummond/presentations/OWA.pdf

Protégé: https://protege.stanford.edu/

Protégé Best Practices. Summary page on my blog for all my articles on Protégé, OWL, SWRL, etc.: https://www.michaeldebellis.com/post/best-practices-for-new-protege-users

SHACL Playground: https://shacl.org/playground/

SWRL Presentation by Martin O'Connor: https://protege.stanford.edu/conference/2009/slides/SWRL2009ProtegeConference.pdf

WebProtégé: https://webprotege.stanford.edu/

WebVOWL: Web-based Visualization of Ontologies: http://vowl.visualdataweb.org/webvowl.html

14.3 Papers
Berners-Lee (2001). The Semantic Web: A new form of Web content that is meaningful to computers will unleash a revolution of new possibilities. With James Hendler and Ora Lassila. Scientific American, May 17, 2001. https://tinyurl.com/BernersLeeSemanticWeb

MacGregor, Robert (1991). "Using a description classifier to enhance knowledge representation". IEEE Expert. 6 (3): 41–46. doi:10.1109/64.87683 https://tinyurl.com/MacGregorLoom

Neches, Robert (1991). Enabling Technology for Knowledge Sharing. With Richard Fikes, Tim Finin, Thomas Gruber, Ramesh Patil, Ted Senator, and William T. Swartout. AI Magazine. Volume 12 Number 3 (1991). https://tinyurl.com/DARPAKnowledgeSharing

Noy, Natasha (2019). Industry-Scale Knowledge Graphs: Lessons and Challenges. With Yuqing Gao, Anshu Jain, Anant Narayanan, Alan Patterson, Jamie Taylor. Communications of the ACM. Vol. 62. No. 8. August 2019. https://tinyurl.com/ACMKnowledgeGraphs

M. J. O'Connor (2012). A Pair of OWL 2 RL Reasoners. With A.K. Das. OWL: Experiences and Directions (OWLED), 9th International Workshop, Heraklion, Greece, 2012. http://ceur-ws.org/Vol-849/paper_31.pdf

Singhal, Amit. (2012). Introducing the Knowledge Graph: things, not strings. Google SVP, Engineering. May 16, 2012. https://www.blog.google/products/search/introducing-knowledge-graph-things-not/

14.4 Books

DuCharme, Bob (2011). Learning SPARQL. O'Reilly Media

Lewis, Harry. (1997). Elements of the Theory of Computation. With Christos Papadimitriou. Prentice-Hall; 2nd edition (August 7, 1997). ISBN-13: 978-0132624787

Segaran, Toby (2009). Programming the Semantic Web: Build Flexible Applications with Graph Data. With Colin Evans and Jamie Taylor. O'Reilly Media; 1st edition (July 28, 2009).

14.5 Vendors

AllegroGraph Triplestore (Franz Inc.): https://franz.com/

Amazon Neptune: https://aws.amazon.com/neptune/

Docker: https://www.docker.com/

Dynaccurate: https://www.dynaccurate.com/

Ontotext: https://www.ontotext.com/

Pool Party: https://www.poolparty.biz/

Stardog: https://www.stardog.com/

Top Quadrant: https://www.topquadrant.com/