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Acknowledgements

I would like to acknowledge and thank my colleagues at the University Of Manchester and also Stanford University for proof reading this tutorial/guide and making helpful comments and suggestions as to how it could be improved. In particular I would like to thank my immediate colleagues: Alan Rector, Nick Drummond, Hai Wang and Julian Seidenberg at the University Of Manchester, who suggested changes to early drafts of the tutorial in order to make things clearer and also ensure the technical correctness of the material. Alan was notably helpful in suggesting changes that made the tutorial flow more easily. I am grateful to Chris Wroe and Robert Stevens who conceived the original idea of basing the tutorial on an ontology about pizzas. Finally, I would also like to thank Natasha Noy from Stanford University for using her valuable experience in teaching, creating and giving tutorials about Protégé to provide detailed and useful comments about how initial drafts of the tutorial/guide could be made better.

This work was supported in part by the CO-ODE project funded by the UK Joint Information Services Committee and the HyOntUse Project (GR/S44686) funded by the UK Engineering and Physical Science Research Council and by 21XS067A from the National Cancer Institute.

http://www.co-ode.org
Chapter 1

Introduction

This guide introduces Protégé 4 for creating OWL ontologies. Chapter 3 gives a brief overview of the OWL ontology language. Chapter 4 focuses on building an OWL-DL ontology and using a Description Logic Reasoner to check the consistency of the ontology and automatically compute the ontology class hierarchy. Chapter 7 describes some OWL constructs such as hasValue Restrictions and Enumerated classes, which aren’t directly used in the main tutorial.

1.1 Conventions

Class, property and individual names are written in a sans serif font like this.

Names for user interface views are presented in a style ‘like this’.

Where exercises require information to be typed into Protégé 4 a type writer font is used like this.

Exercises and required tutorial steps are presented like this:

Exercise 1: Accomplish this

1. Do this.
2. Then do this.
3. Then do this.
Tips and suggestions related to using Protégé 4 and building ontologies are presented like this.

Explanation as to what things mean are presented like this.

Potential pitfalls and warnings are presented like this.

General notes are presented like this.

Vocabulary explanations and alternative names are presented like this.
Chapter 2

Requirements

In order to follow this tutorial you must have Protége 4, which is available from the Protége website \(^1\), and the Protége Plugins which are available via the CO-ODE web site \(^2\). It is also recommended (but not necessary) to use the OWLViz plugin, which allows the asserted and inferred classification hierarchies to be visualised, and is available from the CO-ODE web site, or can be installed when Protége 4 is installed. For installation steps, please see the documentation for each component.

\(^1\)http://protege.stanford.edu
\(^2\)http://www.co-ode.org
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). Like Protégé, OWL makes it possible to describe concepts but it also provides new facilities. It has a richer set of operators - e.g. intersection, union and negation. It is based on a different logical model which makes it possible for concepts to be defined as well as described. Complex concepts can therefore be built up in definitions out of simpler concepts. Furthermore, the logical model allows the use of a reasoner which can check whether or not all of the statements and definitions in the ontology are mutually consistent and can also recognise 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.

3.1 Components of OWL Ontologies

OWL ontologies have similar components to Protégé frame based ontologies. However, the terminology used to describe these components is slightly different from that used in Protégé. An OWL ontology consists of Individuals, Properties, and Classes, which roughly correspond to Protégé frames Instances, Slots and Classes.

3.1.1 Individuals

Individuals, represent objects in the domain in which we are interested. An important difference between Protégé and OWL 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 to each other — otherwise they might be the same as each other, or they might be different to each other. Figure 3.1 shows a representation of some individuals in some domain—in this tutorial we represent individuals as diamonds in diagrams.

\footnote{1http://www.w3.org/TR/owl-guide/}

\footnote{2Also known as the domain of discourse.}
3.1.2 Properties

Properties are binary relations\textsuperscript{3} on individuals - i.e. properties link two individuals together\textsuperscript{4}. For example, the property hasSibling might link the individual Matthew to the individual Gemma, or the property hasChild might link the individual Peter to the individual Matthew. Properties can have inverses. For example, the inverse of hasOwner is isOwnedBy. Properties can be limited to having a single value - i.e. to being functional. They can also be either transitive or symmetric. These ‘property characteristics’ are explained in detail in Section 4.8. Figure 3.2 shows a representation of some properties linking some individuals together.

---

\textsuperscript{3}A binary relation is a relation between two things.

\textsuperscript{4}Strictly speaking we should speak of ‘instances of properties’ linking individuals, but for the sake of brevity we will keep it simple.
3.1.3 Classes

OWL classes are interpreted as sets that contain individuals. They are described using formal (mathematical) descriptions that state precisely 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. Classes may be organised into a superclass-subclass hierarchy, which is also known as a taxonomy. Subclasses specialise (‘are subsumed by’) their superclasses. For example consider the classes Animal and Cat – Cat might be a subclass of Animal (so Animal is the superclass of Cat). This says that, ‘All cats are animals’, ‘All members of the class Cat are members of the class Animal’, ‘Being a Cat implies that you’re an Animal’, and ‘Cat is subsumed by Animal’. One of the key features of OWL-DL is that these superclass-subclass relationships (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 circles or ovals, rather like sets in Venn diagrams.

The word concept is sometimes used in place of class. Classes are a concrete representation of concepts.

In OWL classes are 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.

---

Vocabulary

The word concept is sometimes used in place of class. Classes are a concrete representation of concepts.
Chapter 4

Building An OWL Ontology

This chapter describes how to create an ontology of Pizzas. We use Pizzas because we have found them to provide many useful examples.¹

Exercise 2: Create a new OWL Ontology

1. Start Protégé
2. When the Welcome To Protégé dialog box appears, press the ‘Create New OWL Ontology’.
4. You will also want to save your Ontology to a file on your PC. You can browse your hard disk and save your ontology to a new file, you might want to name your file ‘pizza.owl’. Once you choose a file press ‘Finish’.

After a short amount of time, a new empty Protégé file will have been created and the ‘Active Ontology Tab’ shown in Figure 4.1 will be visible. As can be seen from Figure 4.1, the ‘Active Ontology Tab’ allows information about the ontology to be specified. For example, the ontology URI can be changed, annotations on the ontology such as comments may be added and edited, and namespaces and imports can be set up via this tab.

¹The Ontology that we will create is based upon a Pizza Ontology that has been used as the basis for a course on editing DAML+OIL ontologies in OilEd (http://oiled.man.ac.uk), which was taught at the University Of Manchester.
Figure 4.1: The Active Ontology Tab
Exercise 3: Add a comment to the ontology

1. Ensure that the ‘Active Ontology Tab’ is selected.

2. In the ‘Ontology Annotations’ view, click the add icon (+) next to Annotations. An editing window will appear in the table. Select ‘comment’ from the list of built in annotation URIs and type your comment in the text box in the right hand pane.

3. Enter a comment such as "A pizza ontology that describes various pizzas based on their toppings." and press OK to assign the comment. The annotations view on the ‘Active Ontology Tab’ should look like the picture shown in Figure 4.2.

4.1 Named Classes

As mentioned previously, an ontology contains classes – indeed, the main building blocks of an OWL ontology are classes. In Protégé 4, editing of classes is carried out using the ‘Classes Tab’ shown in Figure 4.3. The initial class hierarchy tree view should resemble the picture shown in Figure 4.4. The empty ontology contains one class called Thing. As mentioned previously, OWL classes are interpreted as sets of individuals (or sets of objects). The class Thing is the class that represents the set containing all individuals. Because of this all classes are subclasses of Thing.\(^2\)

Let’s add some classes to the ontology in order to define what we believe a pizza to be.

\(^2\)Thing is part of the OWL Vocabulary, which is defined by the ontology located at http://www.w3.org/2002/07/owl/\#
Figure 4.3: The Classes Tab

Figure 4.4: The Class Hierarchy Pane
Exercise 4: Create classes Pizza, PizzaTopping and PizzaBase

1. Ensure that the ‘Classes Tab’ is selected.

2. Press the ‘Add subclass’ button shown in Figure 4.4. This button creates a new class as a subclass of the selected class (in this case we want to create a subclass of Thing).

3. A dialog will appear for you to name your class, enter Pizza (as shown in Figure 4.5) and hit return.

4. Repeat the previous steps to add the classes PizzaTopping and also PizzaBase, ensuring that Thing is selected before the ‘Add subclass’ button is pressed so that the classes are created as subclasses of Thing.

The class hierarchy should now resemble the hierarchy shown in Figure 4.6.

**TIP**

After creating Pizza, instead of re-selecting Thing and using the ‘Create subclass’ button to create PizzaTopping and PizzaBase as further subclasses of Thing, the ‘Add sibling class’ button (shown in Figure 4.4) can be used. While Pizza is selected, use the ‘Create sibling class’ button to create PizzaTopping and then use this button again (while PizzaTopping is selected) to create PizzaBase as sibling classes of PizzaTopping – these classes will of course still be created as subclasses of Thing, since Pizza is a subclass of Thing.

**Vocabulary**

A class hierarchy may also be called a taxonomy.

**TIP**

Although there are no mandatory naming conventions for OWL classes, we recommend that all class names should start with a capital letter and should not contain spaces. (This kind of notation is known as CamelCase notation and is the notation used in this tutorial). For example Pizza, PizzaTopping, MargheritaPizza. Alternatively, you can use underscores to join words. For example Pizza_Topping. Which ever convention you use, it is important to be consistent.
4.2 Disjoint Classes

Having added the classes Pizza, PizzaTopping and PizzaBase to the ontology, we now need to say these classes are disjoint, so that an individual (or object) cannot be an instance of more than one of these three classes. To specify classes that are disjoint from the selected class click the ‘Disjoints classes’ button which is located at the bottom of the ‘Class Description’ view.

**Exercise 5: Make Pizza, PizzaTopping and PizzaBase disjoint from each other**

1. Select the class Pizza in the class hierarchy.

2. Press the ‘Disjoint classes’ button in the ‘class description’ view, this will bring up a dialog where you can select multiple classes to be disjoint. This will make PizzaBase and PizzaTopping (the sibling classes of Pizza) disjoint from Pizza.

Notice that the disjoint classes view now displays PizzaTopping and PizzaBase. Select the class PizzaBase. Notice that the disjoint classes view displays the classes that are now disjoint to PizzaBase, namely Pizza and PizzaTopping.
OWL Classes are assumed to ‘overlap’. We therefore cannot assume that an individual is not a member of a particular class simply because it has not been asserted to be a member of that class. In order to ‘separate’ a group of classes we must make them disjoint from one another. This ensures that an individual which has been asserted to be a member of one of the classes in the group cannot be a member of any other classes in that group. In our above example Pizza, PizzaTopping and PizzaBase have been made disjoint from one another. This means that it is not possible for an individual to be a member of a combination of these classes – it would not make sense for an individual to be a Pizza and a PizzaBase!

4.3 Using Create Class Hierarchy To Create Classes

In this section we will use the ‘Create Class Hierarchy’ tool to add some subclasses of the class PizzaBase.
Exercise 6: Use the ‘Create Class Hierarchy’ Tool to create ThinAndCrispy and DeepPan as subclasses of PizzaBase

1. Select the class PizzaBase in the class hierarchy.

2. From the Tools menu on the Protégé menu bar select ‘Create Class Hierarchy...’.

3. The tools shown in Figure 4.7 will appear. Since we preselected the PizzaBase class, the first radio button at the top of the tool should be prompting us to create the classes under the class PizzaBase. If we had not preselected PizzaBase before starting the tool, then the tree could be used to select the class.

4. Press the ‘Next’ button on the tool—The page shown in Figure 4.8 will be displayed. We now need to tell the tool the subclasses of PizzaBase that we want to create. In the large text area, type in the class name ThinAndCrispyBase (for a thin based pizza) and hit return. Also enter the class name DeepPanBase so that the page resembles that shown in Figure 4.8.

5. Hit the ‘Next’ button on the tool. The tool checks that the names entered adhere to the naming styles that have previously been mentioned (No spaces etc.). It also checks for uniqueness – no two class names may be the same. If there are any errors in the class names, they will be presented on this page, along with suggestions for corrections.

6. Hit the ‘Next’ button on the tool. Ensure the tick box ‘Make all new classes disjoint’ is ticked — instead of having to use the disjoint classes view, the tool will automatically make the new classes disjoint for us.

After the ‘Next’ button has been pressed, the tool creates the classes, makes them disjoint. Click ‘Finish’ to dismiss the tool. The ontology should now have ThinAndCrispyBase and also DeepPanBase.
as subclasses of PiezaBase. These new classes should be disjoint to each other. Hence, a pizza base cannot be both thin and crispy and deep pan. It isn’t difficult to see that if we had a lot of classes to add to the ontology, the tool would dramatically speed up the process of adding them.

On page one of the ‘Create class hierarchy wizard’ the classes to be created are entered. If we had a lot of classes to create that had the same prefix or suffix we could use the options to auto prepend and auto append text to the class names that we entered.

Creating Some Pizza Toppings

Now that we have some basic classes, let’s create some pizza toppings. In order to be useful later on the toppings will be grouped into various categories — meat toppings, vegetable toppings, cheese toppings and seafood toppings.

Exercise 7: Create some subclasses of PizzaTopping

1. Select the class PizzaTopping in the class hierarchy.

2. Invoke the ‘Create class hierarchy...’ tool in the same way as the tool was started in the previous exercise.

3. Ensure PizzaTopping is selected and press the ‘Next’ button.

4. We want all our topping classes to end in topping, so in the ‘Suffix all in list with’ field, enter Topping. The tool will save us some typing by automatically appending Topping to all of our class names.

5. The tool allows a hierarchy of classes to be entered using a tab indented tree. Using the text area in the tool, enter the class names as shown in Figure 4.9. Note that class names must be indented using tabs, so for example SpicyBeef, which we want to be a subclass of Meat is entered under Meat and indented with a tab. Likewise, Pepperoni is also entered under Meat below SpicyBeef and also indented with a tab.

6. Having entered a tab indented list of classes, press the ‘Next’ button and then make sure that ‘Make all primitive siblings disjoint’ check box is ticked so that new sibling classes are made disjoint with each other.

7. Press the ‘Finish’ button to create the classes. Press ‘Finish’ again to close the tool.

The class hierarchy should now look similar to that shown in Figure 4.10 (the ordering of classes may be slightly different).
Figure 4.9: Topping Hierarchy

Figure 4.10: Class Hierarchy
Up to this point, we have created some simple named classes, some of which are subclasses of other classes. The construction of the class hierarchy may have seemed rather intuitive so far. 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, or for TomatoTopping to be a subclass of VegetableTopping? In OWL, subclass means necessary implication. In other words, if VegetableTopping is a subclass of PizzaTopping then ALL instances of VegetableTopping are instances of PizzaTopping, without exception — if something is a VegetableTopping then this implies that it is also a PizzaTopping as shown in Figure 4.11.\(^a\)

\(^a\)It is for this reason that we seemingly pedantically named all of our toppings with the suffix of ‘Topping’, for example, HamTopping. Despite the fact that class names themselves carry no formal semantics in OWL (and in other ontology languages), if we had named HamTopping Ham, then this could have implied to human eyes that anything that is a kind of ham is also a kind of MeatTopping and also a PizzaTopping.

### 4.4 OWL Properties

OWL Properties represent relationships. There are two main types of properties, Object properties and Datatype properties. Object properties are relationships between two individuals. In this chapter we will focus on Object properties; datatype properties are described in Chapter 5. Object properties link an individual to an individual. OWL also has a third type of property — Annotation properties\(^3\). Annotation properties can be used to add information (metadata — data about data) to classes, individuals and object/datatype properties. Figure 4.12 depicts an example of each type of property.

Properties may be created using the ‘Object Properties’ tab shown in Figure 4.13. Figure 4.14 shows the buttons located in the top left hand corner of the ‘Object Properties’ tab that are used for creating OWL properties. As can be seen from Figure 4.14, there are buttons for creating Datatype properties, \(^3\)Object properties and Datatype properties may be marked as Annotation properties
An object property linking the individual Matthew to the individual Gemma

A datatype property linking the individual Matthew to the data literal ‘25’, which has a type of an xsd:integer.

An annotation property, linking the class ‘JetEngine’ to the data literal (string) ‘Matthew Horridge’.
Object properties and Annotation properties. Most properties created in this tutorial will be **Object properties**.

**Exercise 8: Create an object property called** hasIngredient

1. Switch to the ‘Object Properties’ tab. Use the ‘Add Object Property’ button (see Figure 4.14) to create a new Object property.

2. Name the property to **hasIngredient** using the ‘Property Name Dialog’ that pops up, as shown in Figure 4.15 (The ‘Property Name Dialog’).
Although there is no strict naming convention for properties, we recommend that property names start with a lower case letter, have no spaces and have the remaining words capitalised. We also recommend that properties are prefixed with the word ‘has’, or the word ‘is’, for example hasPart, isPartOf, hasManufacturer, isProducerOf. Not only does this convention help make the intent of the property clearer to humans, it is also taken advantage of by the ‘English Prose Tooltip Generator’\(^\text{a}\), which uses this naming convention where possible to generate more human readable expressions for class descriptions.

\(^\text{a}\)The English Prose Tooltip Generator displays the description of classes etc. in a more natural form of English, making is easy to understand a class description. The tooltips pop up when the mouse pointer is made to hover over a class description in the user interface.

Having added the hasIngredient property, we will now add two more properties — hasTopping, and hasBase. In OWL, properties may have sub properties, so that it is possible to form hierarchies of properties. Sub properties specialise their super properties (in the same way that subclasses specialise their superclasses). For example, the property hasMother might specialise the more general property of
hasParent. In the case of our pizza ontology the properties hasTopping and hasBase should be created as sub properties of hasIngredient. If the hasTopping property (or the hasBase property) links two individuals this implies that the two individuals are related by the hasIngredient property.

Exercise 9: Create hasTopping and hasBase as sub-properties of hasIngredient

1. To create the hasTopping property as a sub property of the hasIngredient property, select the hasIngredient property in the property hierarchy on the ‘Object Properties’ tab.

2. Press the ‘Add subproperty’ button. A new object property will be created as a sub property of the hasIngredient property.

3. Name the new property to hasTopping.

4. Repeat the above steps but name the property hasBase.

Note that it is also possible to create sub properties of datatype properties. However, it is not possible to mix and match object properties and datatype properties with regards to sub properties. For example, it is not possible to create an object property that is the sub property of a datatype property and vice-versa.

4.5 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, Figure 4.16 shows the property hasParent and its inverse property hasChild — if Matthew hasParent Jean, then because of the inverse property we can infer that Jean hasChild Matthew.

Inverse properties can be createdpecified using the inverse property view shown in Figure 4.17. For
completeness we will specify inverse properties for our existing properties in the Pizza Ontology.

**Exercise 10: Create some inverse properties**

1. Use the ‘Add object property’ button on the ‘Object Properties’ tab to create a new Object property called `isIngredientOf` (this will become the inverse property of `hasIngredient`).

2. Press the add icon (+) next to ‘Inverse properties’ button on the ‘Property Description’ view shown in Figure 4.17. This will display a dialog from which properties may be selected. Select the `hasIngredient` property and press ‘OK’. The property `hasIngredient` should now be displayed in the ‘Inverse Property’ view.

3. Select the `hasBase` property.

4. Press add icon (+) next to ‘Inverse properties’ on the ‘Property Description’ view. Create a new property in this dialog called `isBaseOf`. Select this property and click ‘OK’. Notice that `hasBase` now has a inverse property assigned called `isBaseOf`. You can optionally place the new `isBaseOf` property as a sub-property of `isIngredientOf` (N.B This will get inferred later anyway when you use the reasoner).

5. Select the `hasTopping` property.

6. Press add icon (+) next to ‘Inverse properties’ on the ‘Property Description’ view. Use the property dialog that pops up to create the property `isToppingOf` and press ‘OK’.
4.6 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:

4.6.1 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. Figure 4.18 shows an example of a functional property hasBirthMother — something 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. It should be noted however, that if Peggy and Margaret were explicitly stated to be two different individuals then the above statements would lead to an inconsistency.

![Figure 4.18: An Example Of A Functional Property: hasBirthMother](image)

<table>
<thead>
<tr>
<th>Vocabulary</th>
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<tbody>
<tr>
<td>Functional properties are also known as single valued properties and also features.</td>
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</table>

4.6.2 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. Figure 4.19 shows an example of an inverse functional property isBirthMotherOf. This is the inverse property of hasBirthMother — since hasBirthMother is functional, isBirthMotherOf is inverse functional. If we state that Peggy is the birth mother of Jean, and we also state that Margaret is the birth mother of Jean, then we can infer that Peggy and Margaret are the same individual.

4.6.3 Transitive Properties

If a property is transitive, and the property 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 4.20 shows an example of the transitive property hasAncestor. If the individual Matthew has an ancestor that is Peter, and Peter has an ancestor that is William, then we can infer that Matthew has an ancestor that is William — this is indicated by the dashed line in Figure 4.20.

4The name Peggy is a diminutive form for the name Margaret
4.6.4 Symmetric 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 $P$. Figure 4.21 shows an example of a symmetric property. If the individual Matthew is related to the individual Gemma via the hasSibling property, then we can infer that Gemma must also be related to Matthew via the hasSibling property. In other words, if Matthew has a sibling that is Gemma, then Gemma must have a sibling that is Matthew. Put another way, the property is its own inverse property.

We want to make the hasIngredient property transitive, so that for example if a pizza topping has an ingredient, then the pizza itself also has that ingredient. To set the property characteristics of a property the property characteristics view shown in Figure 4.22 which is located in the lower right hand corner of
Exercise 11: Make the hasIngredient property transitive

1. Select the hasIngredient property in the property hierarchy on the ‘Object Properties’ tab.

2. Tick the ‘Transitive’ tick box on the ‘Property Characteristics View’.

3. Select the isIngredientOf property, which is the inverse of hasIngredient. Ensure that the transitive tick box is ticked.

If a property is transitive then its inverse property should also be transitive.\(^a\)

\(^a\)At the time of writing this must be done manually in Protégé 4. However, the reasoner will assume that if a property is transitive, its inverse property is also a transitive.

Note that if a property is transitive then it cannot be functional.\(^a\)

\(^a\)The reason for this is that transitive properties, by their nature, may form ‘chains’ of individuals. Making a transitive property functional would therefore not make sense.

We now want to say that our pizza can only have one base. There are numerous ways that this could be accomplished. However, to do this we will make the hasBase property functional, so that it may have
only one value for a given individual.

**Exercise 12: Make the hasBase property functional**

1. Select the hasBase property.
2. Click the ‘Functional’ tick box on the ‘Property Characteristics View’ so that it is ticked.

If a datatype property is selected, the property characteristics view will be reduced so that only options for ‘Allows multiple values’ and ‘Inverse Functional’ will be displayed. This is because OWL-DL does not allow datatype properties to be transitive, symmetric or have inverse properties.

4.6.5 Antisymmetric properties

If a property $P$ is antisymmetric, and the property relates individual $a$ to individual $b$ then individual $b$ cannot be related to individual $a$ via property $P$. Figure 4.23 shows an example of a antisymmetric property. If the individual Robert is related to the individual David via the isChildOf property, then it can be inferred that David is not related to Robert via the isChildOf property. It is, however, reasonable to state that David could be related to another individual Bill via the isChildOf property. In other words, if Robert is a child of David, then David cannot be a child of Robert, but David can be a child of Bill.

4.6.6 Reflexive properties

A property $P$ is said to be reflexive when the property must relate individual $a$ to itself. In Figure 4.24 we can see an example of this: using the property knows, an individual George must have a relationship to itself using the property knows. In other words, George must know herself. However, in addition, it is possible for George to know other people; therefore the individual George can have a relationship with individual Simon along the property knows.
4.6.7 Irreflexive properties

If a property $P$ is irreflexive, it can be described as a property that relates an individual $a$ to individual $b$, where individual $a$ and individual $b$ are not the same. An example of this would be the property $\text{motherOf}$: an individual Alice can be related to individual Bob along the property $\text{motherOf}$, but Alice cannot be $\text{motherOf}$ herself (Figure 4.25).

4.7 Property Domains and Ranges

Properties may have a domain and a range specified. Properties link individuals from the domain to individuals from the range. For example, in our pizza ontology, the property $\text{hasTopping}$ would probably link individuals belonging to the class $\text{Pizza}$ to individuals belonging to the class of $\text{PizzaTopping}$. In this case the domain of the $\text{hasTopping}$ property is $\text{Pizza}$ and the range is $\text{PizzaTopping}$ — this is depicted in Figure 4.26.
Figure 4.26: The domain and range for the `hasTopping` property and its inverse property `isToppingOf`. The domain of `hasTopping` is `Pizza` the range of `hasTopping` is `PizzaTopping` — the domain and range for `isToppingOf` are the domain and range for `hasTopping` swapped over.

![Diagram showing domain and range for `hasTopping` and `isToppingOf` properties]

**Property Domains And Ranges In OWL** — It is important to realise that in OWL domains and ranges should *not* be viewed as constraints to be checked. They are used as 'axioms' in reasoning. For example if the property `hasTopping` has the domain set as `Pizza` and we then applied the `hasTopping` property to `IceCream` (individuals that are members of the class `IceCream`), this would generally not result in an error. It would be used to infer that the class `IceCream` must be a subclass of `Pizza`! *

*An error will only be generated (by a reasoner) if `Pizza` is disjoint to `IceCream`.

We now want to specify that the `hasTopping` property has a range of `PizzaTopping`. To do this the range view shown in Figure 4.27 is used.

**Exercise 13: Specify the range of `hasTopping`**

1. Make sure that the `hasTopping` property is selected in the property hierarchy on the ‘Object Properties’ tab.

2. Press the ‘add’ icon (+) next to ‘Ranges’ on the ‘Property Description’ view (Figure 4.27). A dialog will appear that allows a class to be selected from the ontology class hierarchy.

3. Select `PizzaTopping` and press the ‘OK’ button. `PizzaTopping` should now be displayed in the range list.
It is possible to specify multiple classes as the range for a property. If multiple classes are specified in Protégé 4 the range of the property is interpreted to be the intersection of the classes. For example, if the range of a property has the classes Man and Woman listed in the range view, the range of the property will be interpreted as Man union Woman.

To specify the domain of a property the domain view shown in Figure 4.28 is used.

**Exercise 14: Specify Pizza as the domain of the hasTopping property**

1. Make sure that the hasTopping property is selected in the property hierarchy on the ‘Object Properties’ tab.
2. Press the ‘add’ icon (+) next to ‘Domains’ on the ‘Propert Description’ view. A dialog will appear that allows a class to be selected from the ontology class hierarchy.
3. Select Pizza and press the OK button. Pizza should now be displayed in the domain list.

This means that individuals that are used ‘on the left hand side’ of the hasTopping property will be inferred to be members of the class Pizza. Any individuals that are used ‘on the right hand side’ of the hasTopping property will be inferred to be members of the class PizzaTopping. For example, if we have individuals a and b and an assertion of the form a hasTopping b then it will be inferred that a is a member of the class Pizza and that b is a member of the class PizzaTopping”.

*aThis will be the case even if a has not been asserted to be a member of the class Pizza and/or b has not been asserted to be a member of the class PizzaTopping.*
Take a look at the isToppingOf property, which is the inverse property of hasTop-
ing. Notice that Protégé has automatically filled in domain and range of the isToppingOf property because the domain and range of the inverse property were specified. The range of isToppingOf is the domain of the inverse property hasTop-
ing, and the domain of isToppingOf is the range of the inverse property hasTop-
ing. This is depicted in Figure 4.26.

Exercise 15: Specify the domain and range for the hasBase property and its inverse property is-
BaseOf

1. Select the hasBase property.
2. Specify the domain of the hasBase property as Pizza.
3. Specify the range of the hasBase property as PizzaBase.
4. Select the isBaseOf property. Notice that the domain of isBaseOf is the range of the inverse property hasBase and that the range of isBaseOf is the domain of the inverse property hasBase.
5. Make the domain of the isBaseOf property PizzaBase.
6. Make the range of the isBaseOf property Pizza.
In the previous steps we have ensured that the domains and ranges for properties are also set up for inverse properties in a correct manner. In general, domain for a property is the range for its inverse, and the range for a property is the domain for its inverse — Figure 4.26 illustrates this for the \texttt{hasTopping} and \texttt{isToppingOf}.

Although we have specified the domains and ranges of various properties for the purposes of this tutorial, we generally advise against doing this. The fact that domain and range conditions do not behave as constraints and the fact that they can cause ‘unexpected’ classification results can lead problems and unexpected side effects. These problems and side effects can be particularly difficult to track down in a large ontology.

### 4.8 Describing And Defining Classes

Having created some properties we can now use these properties to describe and define our Pizza Ontology classes.

#### 4.8.1 Property Restrictions

Recall that in OWL, properties describe binary relationships. Datatype properties describe relationships between individuals and data values. Object properties describe relationships between two individuals. For example, in Figure 3.2 the individual \texttt{Matthew} is related to the individual \texttt{Gemma} via the \texttt{hasSibling} property. Now consider all of the individuals that have a \texttt{hasSibling} relationship to some other individual. We can think of these individuals as belonging the *class of individuals* that have some \texttt{hasSibling} relationship. The key idea is that a class of individuals is described or defined by the relationships that these individuals participate in. In OWL we can define such classes by using *restrictions*.

A *restriction* describes a class of individuals based on the relationships that members of the class participate in. In other words a *restriction* is a kind of *class*, in the same way that a named class is a kind of class.

**Restriction Examples**

Let’s take a look at some examples to help clarify the kinds of classes of individuals that we might want to describe based on their properties.

- The class of individuals that have at least one \texttt{hasSibling} relationship.
• The class of individuals that have at least one `hasSibling` relationship to members of `Man` – i.e. things that have at least one sibling that is a man.

• The class of individuals that only have `hasSibling` relationships to individuals that are `Women` – i.e. things that only have siblings that are women (sisters).

• The class of individuals that have more than three `hasSibling` relationships.

• 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 one kind of mozzarella topping.

• The class of individuals that only have `hasTopping` relationships to members of `VegetableTopping` – i.e. the class of individuals that only have toppings that are vegetable toppings.

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

- Quantifier Restrictions
- Cardinality Restrictions
- hasValue Restrictions.

We will initially use quantifier restrictions, which can be further categorised into existential restrictions and universal restrictions. Both types of restrictions will be illustrated with examples throughout the tutorial.

Existential and Universal Restrictions

- Existential restrictions describe classes of individuals that participate in at least one relationship along a specified property to individuals that are members of a specified class. For example, “the class of individuals that have at least one (some) `hasTopping` relationship to members of `MozzarellaTopping`”. In Protégé 4 the keyword ‘some’ is used to denote existential restrictions. ⁵

- Universal restrictions describe classes of individuals that for a given property only have relationships along this property to individuals that are members of a specified class. For example, “the class of individuals that only have `hasTopping` relationships to members of `VegetableTopping`”. In Protégé 4 the keyword ‘only’ is used. ⁶

Let’s take a closer look at the example of an existential restriction. The restriction `hasTopping some MozzarellaTopping` is an existential restriction (as indicated by the `some` keyword), which acts along 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`. This restriction is depicted in Figure 4.29 — The diamonds in the Figure represent individuals. As can be seen from Figure 4.29, the restriction is a class which contains the individuals that satisfy the restriction.

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⁵Existential restrictions may be denoted by the `existential quantifier` (∃). They are also known as ‘someValuesFrom’ restrictions in OWL speak.

⁶Universal restrictions may be denoted by the `universal quantifier` (∀), which can be read as only. They are also known as ‘allValuesFrom’ restrictions in OWL speak.
Figure 4.29: The Restriction `hasTopping some Mozzarella`. This restriction describes the class of individuals that have at least one topping that is Mozzarella.

**Meaning**

A restriction describes an anonymous class (an unnamed class). The anonymous 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.

The restrictions for a class are displayed and edited using the ‘Class Description View’ shown in Figure 4.30. The ‘Class Description View’ is the ‘heart of’ the ‘Classes’ tab in Protege, and holds virtually all of the information used to describe a class. At first glance, the ‘Class Description View’ may seem complicated, however, it will become apparent that it is an incredibly powerful way of describing and defining classes.

Restrictions are used in OWL class descriptions to specify anonymous superclasses of the class being described.

### 4.8.2 Existential Restrictions

Existential restrictions are by far the most common type of restrictions in OWL ontologies. 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. 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.
“Equivalent class header” A list of equivalent classes appear here. The classes are sometimes referred to as a Necessary & sufficient criteria.

“Subclass of header” A list of subclasses appear here. These classes are sometimes referred to as Necessary criteria.

“Inferred/Inherited header” A list of conditions that have been inherited from superclasses will be displayed here.

Figure 4.30: The Class Description View
Existential restrictions are also known as *Some Restrictions*, or as *some values from restrictions*.

Other tools, papers and presentations might write the restriction \( \text{hasBase some PizzaBase} \) as \( \exists \text{hasBase PizzaBase} \) — this alternative notation is known as DL Syntax (Description Logics Syntax), which is a more formal syntax.

**Exercise 16: Add a restriction to Pizza that specifies a Pizza must have a PizzaBase**

1. Select *Pizza* from the class hierarchy on the ‘Classes’ tab.
2. Select the ‘Add’ icon (+) next to ‘Superclasses’ header in the ‘Class Description View’ shown in Figure 4.31 in order to create a necessary condition.
3. Press the ‘Add Class’ button shown in Figure 4.31. This will open a text box in the Class Description view where we can enter our restrictions as shown in Figure 4.32.

The create restriction text box allows you construct restrictions using class, property and individual names. You can drag and drop classes, properties and individuals into the text box or type them in, the text box with check all the values you enter and alert you to any errors. To create a restriction we have to do three things:

- Enter the property to be restricted from the property list.
- Enter a type of restriction from the restriction types e.g. ‘some’ for an existential restriction.
- Specify a filler for the restriction.
Exercise 17: Add a restriction to Pizza that specifies a Pizza must have a PizzaBase (Continued...)

1. You can either drag and drop hasBase from the property list into the create restriction text box, or type it in.

2. Now add the type or restriction, we will use an existential restriction so type ‘some’.

3. Specify that the filler is PizzaBase — to do this either: type PizzaBase into the filler edit box, or drag and drop PizzaBase into the text box as shown in Figure 4.32.

4. Press ‘Enter’ to create the restriction and close the create restriction text box. If all information was entered correctly the dialog will close and the restriction will be displayed in the ‘Class Description View’. If there were errors they will be underlined in red in the text box, a popup will give some hints to the cause of the error — if this is the case, recheck that the type of restriction, the property and filler have been specified correctly.

A very useful feature of the expression builder is the ability to ‘auto-complete’ class names, property names and individual names. Auto completion is activated by pressing ‘alt tab’ or ‘Ctrl-Space’ on the keyboard. In the above example if we had typed Pi into the expression editor and pressed the tab key, the choices to complete the word Pi would have popped up in a list as shown in Figure 4.32. The up and down arrow keys could then have been used to select PizzaBase and pressing the Enter key would complete the word for us.

The class description view should now look similar to the picture shown in Figure 4.33.
Figure 4.32: Creating a restriction in the text box, with auto-complete

Figure 4.33: class description view: Description of a Pizza
Figure 4.34: A Schematic Description of a Pizza — In order for something to be a Pizza it is necessary for it to have a (at least one) PizzaBase — A Pizza is a subclass of the things that have at least one PizzaBase.

We have described the class Pizza 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 — This is depicted in Figure 4.34.

When restrictions are used to describe classes, they actually specify anonymous superclasses of the class being described. For example, we could say that MargheritaPizza is a subclass of, amongst other things, Pizza and also a subclass of the things that have at least one topping that is MozzarellaTopping.

Creating Some Different Kinds Of Pizzas

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 18: Create a subclass of Pizza called NamedPizza, and a subclass of NamedPizza called MargheritaPizza**

1. Select the class Pizza from the class hierarchy on the ‘Classes’ tab.
2. Press the ‘Add subclass’ button to create a new subclass of Pizza, and name it NamedPizza.
3. Create a new subclass of NamedPizza, and name it MargheritaPizza.
4. Add a comment to the class MargheritaPizza using the ‘Annotations’ view that is located next to the class hierarchy view: A pizza that only has Mozarella and Tomato toppings – it’s always a good idea to document classes, properties etc. during ontology editing sessions in order to communicate intentions to other ontology builders.

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 19: Create an existential (some) restriction on MargheritaPizza that acts along the property hasTopping with a filler of MozzarellaTopping to specify that a MargheritaPizza has at least one MozzarellaTopping**

1. Make sure that MargheritaPizza is selected in the class hierarchy.
2. Use the ‘Add’ button on the ‘Subclasses’ section of the ‘Class Description view’ (Figure 4.30) to open a text box.
3. Type hasTopping as the property to be restricted in the text box.
4. Type ‘some’ to create the existential restriction.
5. Type the class MozzarellaTopping as the filler for the restriction — remember that this can be achieved by typing the class name MozzarellaTopping into the filler edit box, or by using drag and drop from the class hierarchy.
6. Press ‘Enter’ to create the restriction — if there are any errors, the restriction will not be created, and the error will be highlighted in red.

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Now specify that MargheritaPizza also have TomatoTopping.

**Exercise 20:** Create a existential restriction (some) on MargheritaPizza that acts along the property hasTopping with a filler of TomatoTopping to specify that a MargheritaPizza has at least one TomatoTopping

1. Ensure that MargheritaPizza is selected in the class hierarchy.
2. Use the ‘Add’ button on the ‘Subclasses’ section of the ‘Class Description View’ (Figure 4.30) to display open the text box.
3. Type hasTopping as the property to be restricted.
4. Type ‘some’ to create the existential restriction.
5. Type the class TomatoTopping as the filler for the restriction.
6. Click ‘Enter’ to create restriction dialog to create the restriction.

The ‘Class Description View’ should now look similar to the picture shown in Figure 4.35.

**MEANING**

We have added restrictions to MargheritaPizza to say that a MargheritaPizza is a NamedPizza that has at least one kind of MozzarellaTopping and at least one kind of TomatoTopping. More formally (reading the class description view line by line), if something is a member of the class MargheritaPizza it is necessary for it to be a member of the class NamedPizza and it is necessary for it to be a member of the anonymous class of things that are linked to at least one member of the class MozzarellaTopping via the property hasTopping, and it is necessary for it to be a member of the anonymous class of things that are linked to at least one member of the class TomatoTopping via the property hasTopping.

Now create the class to represent an Americana Pizza, which has toppings of pepperoni, mozzarella
and tomato. Because the class AmericanaPizza is very similar to the class MargheritaPizza (i.e. an Americana pizza is almost the same as a Margherita pizza 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 21: Create AmericanaPizza by cloning and modifying the description of MargheritaPizza**

1. Select the class MargheritaPizza in the class hierarchy on the Classes tab.
2. Select “Duplicate selected class from the ‘Edit’ menu. A dialog will appear for you to name the new class, this will be created with exactly the same conditions (restrictions etc.) as MargheritaPizza.
3. Ensuring that AmericanaPizza is still selected, select the ‘Add’ icon (+) next to the “Superclasses” header in the class description view, as we want to add a new restriction to the necessary conditions for AmericanaPizza.
4. Type the property hasTopping as the property to be restricted.
5. Type ‘some’ to create the existential restriction.
6. Specify the restriction filler as the class PepperoniTopping by either typing PepperoniTopping into the text box, or by using drag and drop from the class hierarchy.
7. Press OK to create the restriction.
The `Class Description View` should now look like the picture shown in Figure 4.36.

**Exercise 22: Create an AmericanHotPizza and a SohoPizza**

1. An AmericanHotPizza is almost the same as an AmericanaPizza, but has Jalapeno peppers on it — create this by cloning the class AmericanaPizza and adding an existential restriction along the hasTopping property with a filler of JalapenoPepperToppping.

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 ParmezanTopping.

For AmericanHot pizza the class description view should now look like the picture shown in Figure 4.37. For SohoPizza the class description view should now look like the picture shown in 4.38.

Having created these pizzas we now need to make them disjoint from one another:

**Exercise 23: Make subclasses of NamedPizza disjoint from each other**

1. Select the class MargheritaPizza in the class hierarchy on the ‘Classes’ tab.

2. Press the ‘Add all siblings’ button on the ‘Disjoints view’ to make the pizzas disjoint from each other.
4.9 Using A Reasoner

One of the key features of ontologies that are described using OWL-DL is that they can be processed by a reasoner. One of the main services offered by a reasoner is to test whether or not one class is a subclass of another class. By performing such tests on the classes in an ontology it is possible for a reasoner to compute the inferred ontology class hierarchy. Another standard service that is offered by reasoners is consistency checking. Based on the description (conditions) of a class the reasoner can check whether or not it is possible for the class to have any instances. A class is deemed to be inconsistent if it cannot possibly have any instances.

Reasoners are also known as classifiers.

4.9.1 Invoking The Reasoner

Protégé 4 allows different OWL reasoners to be plugged in, the reasoner shipped with Protégé is called Fact++. The ontology can be ‘sent to the reasoner’ to automatically compute the classification hierarchy, and also to check the logical consistency of the ontology. In Protégé 4 the ‘manually constructed’ class hierarchy is called the asserted hierarchy. The class hierarchy that is automatically computed by the reasoner is called the inferred hierarchy. To automatically classify the ontology (and check for inconsistencies) the ‘Classify...’ action should be used. This can be invoked via the ‘Classify...’ button in the Reasoner drop down menu shown in Figure 4.39. When the inferred hierarchy has been computed, an inferred hierarchy window will pop open on top the existing asserted hierarchy window as shown in Figure 4.40. If a class has been reclassified (i.e. if it’s superclasses have changed) then the class name will appear in a blue colour in the inferred hierarchy. If a class has been found to be inconsistent it’s icon will be highlighted in red.

7Known as subsumption testing — the descriptions of the classes (conditions) are used to determine if a superclass/subclass relationship exists between them.
4.9.2 Inconsistent Classes

In order to demonstrate the use of the reasoner in detecting inconsistencies in the ontology we will create a class that is a subclass of both CheeseTopping and also VegetableTopping. This strategy is often used as a check so that we can see that we have built our ontology correctly. Classes that are added in order
to test the integrity of the ontology are sometimes known as *Probe Classes*.

**Exercise 24: Add a Probe Class called* ProbeInconsistentTopping which is a subclass of both CheeseTopping and VegetableTopping*

1. Select the class *CheeseTopping* from the class hierarchy on the Classes tab.
2. Create a subclass of *CheeseTopping* named *ProbeInconsistentTopping*.
3. Add a comment to the *ProbeInconsistentTopping* class that is something along the lines of, “This class should be inconsistent when the ontology is classified.”. This will enable anyone who looks at our pizza ontology to see that we deliberately meant the class to be inconsistent.
4. Ensure that the *ProbeInconsistentTopping* class is selected in the class hierarchy, and then select the “Subclass Of” header in the ‘Class Description View’.
5. Click on the ‘superclasses’ button on the ‘Class Description View’. This will display a dialog containing the class hierarchy from which a class may be selected. Select the class *VegetableTopping* and then press the OK button. The class *VegetableTopping* will be added as a superclass, so that the class description view should look like the picture in Figure 4.41.

![Figure 4.41: The Class Description View Displaying ProbeInconsistentTopping](image)
If we study the class hierarchy, `ProbeInconsistentTopping` should appear as a subclass of `CheeseTopping` and as a subclass of `VegetableTopping`. This means that `ProbeInconsistentTopping` is a `CheeseTopping` and a `VegetableTopping`. More formally, all individuals that are members of the class `ProbeInconsistentTopping` are also (necessarily) members of the class `CheeseTopping` and (necessarily) members of the class `VegetableTopping`. Intuitively this is incorrect since something cannot simultaneously be both cheese and a vegetable!

**Exercise 25: Classify the ontology to make sure *ProbeInconsistentTopping* is inconsistent**

1. Press the ‘Classify...’ button on the Reasoner drop down menu to classify the ontology.

After a few seconds the inferred hierarchy will have been computed and the *inferred hierarchy* window will pop open (if it was previously closed). The hierarchy should resemble that shown in Figure 4.42 — notice that the class `ProbeInconsistentTopping` is highlighted in red, indicating that the reasoner has found this class to be inconsistent (i.e. it cannot possibly have any individuals as members).
Why did this happen? Intuitively we know something cannot at the same time be both cheese and a vegetable. Something should not be both an instance of *CheeseTopping* and an instance of *VegetableTopping*. However, it must be remembered that we have chosen the names for our classes. As far as the reasoner is concerned names have no meaning. The reasoner cannot determine that something is inconsistent based on names. The actual reason that *ProbInconsistentTopping* has been detected to be inconsistent is because its superclasses *VegetableTopping* and *CheeseTopping* are disjoint from each other — remember that earlier on we specified that the four categories of topping were disjoint from each other. Therefore, individuals that are members of the class *CheeseTopping* cannot be members of the class *VegetableTopping* and vice-versa.

To close the inferred hierarchy use the small white cross on a red background button on the top right of the inferred hierarchy window.

**Exercise 26:** Remove the disjoint statement between *CheeseTopping* and *VegetableTopping* to see what happens

1. Select the class *CheeseTopping* using the class hierarchy.

2. The ‘Disjoints view’ should contain *CheeseTopping*’s sibling classes: *VegetableTopping*, *SeafoodTopping* and *MeatTopping*. Select *VegetableTopping* in the Disjoints view.

3. Press the ‘Delete selected row’ button on the Disjoints view to remove the disjoint axiom that states *CheeseTopping* and *VegetableTopping* are disjoint.

4. Press ‘Classify...’ on the Reasoner drop down menu to send the ontology to the reasoner. After a few seconds the ontology should have been classified and the results displayed.
It should be noticeable that `ProbeInconsistentTopping` is no longer inconsistent! This means that individuals which are members of the class `ProbeInconsistentTopping` are also members of the class `CheeseTopping` and `VegetableTopping` — something can be both cheese and a vegetable! This clearly illustrates the importance of the careful use of disjoint axioms in OWL. OWL classes ‘overlap’ until they have been stated to be disjoint from each other. If certain classes are not disjoint from each other then unexpected results can arise. Accordingly, if certain classes have been incorrectly made disjoint from each other then this can also give rise to unexpected results.

**Exercise 27: Fix the ontology by making `CheeseTopping` and `Vegetable` disjoint from each other**

1. Select the class `CheeseTopping` using the class hierarchy.
2. The ‘Disjoints view’ should contain `MeatTopping` and `SeafoodTopping`.
3. Press the ‘Add disjoint class’ button on the disjoint classes view to display a dialog which classes may be picked from. Select the class `VegetableTopping` and press the OK button. `CheeseTopping` should once again be disjoint from `VegetableTopping`.
4. Test that the disjoint axiom has been added correctly — Press ‘Classify...’ on the Reasoner drop down menu to send the ontology to the reasoner. After a few seconds the ontology should have been classified, and `ProbeInconsistentTopping` should be highlighted in red indicating that it is once again inconsistent.

### 4.10 Necessary And Sufficient Conditions (Primitive and Defined Classes)

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

A class that only has necessary conditions is known as a **Primitive 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 28: Create a subclass of Pizza called CheesyPizza and specify that it has at least one topping that is a kind of CheeseTopping

1. Select Pizza in the class hierarchy on the ‘Classes’ tab.
2. Press the ‘Add subclass’ button to create a subclass of Pizza. Name it CheesyPizza.
3. Make sure that CheesyPizza is selected in the class hierarchy. Select the ‘Add’ icon (+) next to the “Superclasses” header in the class description view.
4. Type hasTopping as the property to be restricted.
5. Type ‘some’ to create the existential restriction.
6. Finally type CheeseTopping and press ‘Enter’ to close the dialog and create the restriction.

The ‘Class Description View’ should now look like the picture shown in Figure 4.43.

Our description of CheesyPizza states that if something is a member of the class CheesyPizza it is necessary for it to be a member of the class Pizza and it is necessary for it to have at least one topping that is a member of the class CheeseTopping.

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. We have used necessary conditions to say this. 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
Figure 4.44: The Description of CheesyPizza (Using Necessary AND Sufficient Conditions)

are also sufficient to determine that any (random) individual that satisfies them must be a member of the class CheesyPizza.

A class that has at least one set of necessary and sufficient conditions is known as a Defined Class.

Necessary conditions are simply called Superclasses in Protégé 4. Necessary and sufficient condition are called Equivalent classes.

In order to convert necessary conditions to necessary and sufficient conditions, the conditions must be moved from under the “Superclasses” header in the class description view to be under the “Equivalent classes” header. This can be done with the ‘Convert to defined class’ option in the ‘Edit’ menu.

Exercise 29: Convert the necessary conditions for CheesyPizza into necessary & sufficient conditions

1. Ensure that CheesyPizza is selected in the class hierarchy.
2. In the ‘Edit’ menu select ‘Convert to defined class’.

The ‘Class Description View’ should now look like the picture shown in Figure 4.44.
NECESSARY CONDITIONS

If an individual is a member of 'NamedClass' then it must satisfy the conditions. However if some individual satisfies these necessary conditions, we cannot say that it is a member of 'Named Class' (the conditions are not 'sufficient' to be able to say this) - this is indicated by the direction of the arrow.

NECESSARY & SUFFICIENT CONDITIONS

If an individual is a member of 'NamedClass' then it must satisfy the conditions. If some individual satisfies the conditions then the individual must be a member of 'NamedClass' - this is indicated by the double arrow.

**Figure 4.45:** Necessary And Sufficient Conditions

**MEANING**

We have converted our description of CheesyPizza into a definition. If something is a CheesyPizza then it is necessary that it is a Pizza and it is also necessary that at least one topping that is a member of the class CheeseTopping. Moreover, if an individual is a member of the class Pizza and it has at least one topping that is a member of the class CheeseTopping then these conditions are sufficient to determine that the individual must be a member of the class CheesyPizza. The notion of necessary and sufficient conditions is illustrated in Figure 4.45.

To summarise: If class A is described using necessary conditions, then we can say that if an individual is a member of class A it must satisfy the conditions. We cannot say that any (random) individual that satisfies these conditions must be a member of class A. However, if class A is now defined using necessary and sufficient conditions, we can say that if an individual is a member of the class A it must satisfy the conditions and we can now say that if any (random) individual satisfies these conditions then it must be a member of class A. The conditions are not only necessary for membership of A but also sufficient to determine that something satisfying these conditions is a member of A.

How is this useful in practice? Suppose we have another class B, and we know that any individuals that are members of class B also satisfy the conditions that define class A. We can determine that class B is subsumed by class A — in other words, B is a subclass of A. Checking for class subsumption is a key task of a description logic reasoner and we will use the reasoner to automatically compute a classification hierarchy in this way.

**NOTE**

In OWL it is possible to have multiple sets of necessary & sufficient conditions. This is discussed later in section 7.5
4.10.1 Primitive And Defined Classes

Classes that have at least one set of necessary and sufficient conditions are known as defined classes — they have a definition, and any individual that satisfies the definition will belong to the class. Classes that do not have any sets of necessary and sufficient conditions (only have necessary conditions) are known as primitive classes. In Protégé 4 defined classes have a class icon with three horizontal white lines in them. Primitive classes have a class icon that has a plain yellow background. It is also important to understand that the reasoner can only automatically classify classes under defined classes - i.e. classes with at least one set of necessary and sufficient conditions.

4.11 Automated Classification

Being able to use a reasoner to automatically compute the class hierarchy is one of the major benefits of building an ontology using the OWL-DL sub-language. Indeed, when constructing very large ontologies (with upwards of several thousand classes in them) the use of a reasoner to compute subclass-superclass relationships between classes becomes almost vital. Without a reasoner it is very difficult to keep large ontologies in a maintainable and logically correct state. In cases where ontologies can have classes that have many superclasses (multiple inheritance) it is nearly always a good idea to construct the class hierarchy as a simple tree. Classes in the asserted hierarchy (manually constructed hierarchy) therefore have no more than one superclass. Computing and maintaining multiple inheritance is the job of the reasoner. This technique\(^8\) helps to keep the ontology in a maintainable and modular state. Not only does this promote the reuse of the ontology by other ontologies and applications, it also minimises human errors that are inherent in maintaining a multiple inheritance hierarchy.

Having created a definition of a CheesyPizza we can use the reasoner to automatically compute the subclasses of CheesyPizza.

**Exercise 30: Use the reasoner to automatically compute the subclasses of CheesyPizza**

1. Press the ‘Classify...’ button on the Reasoner drop down menu (See Figure 4.39).

After a few seconds the inferred hierarchy should have been computed and the inferred hierarchy window will pop open (if it was previously closed). The inferred hierarchy should appear similar to the picture shown in Figure 4.46. Figures 4.47 and 4.48 show the OWLViz display of the asserted and inferred hierarchies respectively. Notice that classes which have had their superclasses changed by the reasoner are shown in blue.

\(^8\)Sometimes known as ontology normalisation.
Figure 4.46: The Asserted and Inferred Hierarchies Displaying The Classification Results For CheesyPizza

Figure 4.47: OWLViz Displaying the Asserted Hierarchy for CheesyPizza

Figure 4.48: OWLViz Displaying the Inferred Hierarchy for CheesyPizza
The reasoner has determined that MargheritaPizza, AmericanaPizza, AmericanHotPizza and SohoPizza are subclasses of CheesyPizza. This is because we defined CheesyPizza using necessary and sufficient conditions. Any individual that is a Pizza and has at least one topping that is a CheeseTopping is a member of the class CheesyPizza. Due to the fact that all of the individuals that are described by the classes MargheritaPizza, AmericanaPizza, AmericanHotPizza and SohoPizza are Pizzas and they have at least one topping that is a CheeseTopping the reasoner has determined that these classes must be subclasses of CheeseTopping.

*Or toppings that belong to the subclasses of CheeseTopping

It is important to realise that, in general, classes will never be placed as subclasses of primitive classes (i.e. classes that only have necessary conditions) by the reasoner. The exception to this is when a property has a domain that is a primitive class. This can coerce classes to be reclassified under the primitive class that is the domain of the property — the use of property domains to cause such effects is strongly discouraged.

4.12 Universal Restrictions

All of the restrictions we have created so far have been existential restrictions (some). 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 are given the symbol ∀. They constrain the relationships along a given property to individuals that are members of a specific class. For example the universal restriction ∀ hasTopping MozzarellaTopping describes the individuals all of whose hasTopping relationships are to members of the class MozzarellaTopping — the individuals do not have a hasTopping relationships to individuals that aren’t members of the class MozzarellaTopping.
Universal restrictions are also known as *AllValuesFrom Restrictions*.

The above universal restriction $\forall$ hasTopping MozzarellaTopping also describes the individuals that do not participate in any hasTopping relationships. An individual that does not participate in any hasTopping relationships whatsoever, by definition does not have any hasTopping relationships to individuals that aren’t members of the class MozzarellaTopping and the restriction is therefore satisfied.

For a given property, universal restrictions do not specify the existence of a relationship. They merely state that if a relationship exists for the property then it must be to individuals that are members of a specific class.

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

**Exercise 31: Create a class to describe a VegetarianPizza**

1. Create a subclass of Pizza, and name it VegetarianPizza.
2. Making sure that VegetarianPizza is selected, click on the ‘Add’ icon (+) next to the “Superclasses” header in the ‘Class Description View’.
3. Type hasTopping as the property to be restricted.
4. Type ‘only’ in order to create a universally quantified restriction.
5. For the filler we want to say CheeseTopping or VegetableTopping. We place this inside brackets so write a open bracket followed by the class CheeseTopping either by typing CheeseTopping into the filler box. We now need to use the unionOf operator between the class names. We can add this operator by simply typing or. Next insert the class VegetableTopping by typing it. You should now have hasTopping only (CheeseTopping or VegetableTopping) in the text box.
6. Press ‘OK’ to close the dialog and create the restriction — if there are any errors (due to typing errors etc.) they will be underlined in red.

At this point the class description view should look like the picture shown in Figure 4.49.
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 ⊓ VegetableTopping. This reads, 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 obviously incorrect as demonstrated in section 4.9.2. If the classes CheeseTopping and VegetableTopping were not disjoint, this would have been a logically legitimate thing to say – it would not be inconsistent and therefore would not be ‘spotted’ by the reasoner.

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.

Currently VegetarianPizza is described using necessary conditions. However, our description of a VegetarianPizza could be considered to be complete. We know that any individual that satisfies these conditions must be a VegetarianPizza. We can therefore convert the necessary conditions for Vegetari-
anPizza into necessary and sufficient conditions. This will also enable us to use the reasoner to determine the subclasses of VegetarianPizza.

**Exercise 32: Convert the necessary conditions for VegetarianPizza into necessary & sufficient conditions**

1. Ensure that VegetarianPizza is selected in the class hierarchy.
2. In the ‘Edit’ menu select ‘Convert to defined class’.

The ‘Class Description View’ should now look like the picture shown in Figure 4.50.

**MEANING**

We have converted our description of VegetarianPizza into a definition. If something is a VegetarianPizza, then it is necessary that it is a Pizza and it is also necessary that all toppings belong to the class CheeseTopping or VegetableTopping. Moreover, if something is a member of the class Pizza and all of it’s toppings are members of the class CheeseTopping or the class VegetableTopping then these conditions are sufficient to recognise that it must be a member of the class VegetarianPizza. The notion of necessary and sufficient conditions is illustrated in Figure 4.45.

### 4.13 Automated Classification and Open World Reasoning

We want to use the reasoner to automatically compute the superclass-subclass relationship (subsumption relationship) between MargheritaPizza and VegetarianPizza and also, SohoPizza and VegetarianPizza. Recall that we believe that MargheritaPizza and SohoPizza should be vegetarian pizzas (they should be subclasses of VegetarianPizza). This is because they have toppings that are essentially vegetarian toppings — by our definition, vegetarian toppings are members of the classes CheeseTopping or VegetableTopping and their subclasses. Having previously created a definition for VegetarianPizza (using a set of necessary and sufficient conditions) we can use the reasoner to perform automated classification
and determine the vegetarian pizzas in our ontology.

**Exercise 33: Use the reasoner to classify the ontology**

1. Press the ‘Classify...’ button in the Reasoner Drop Down menu.

You will notice that MargheritaPizza and also SohoPizza have not been classified as subclasses of VegetarianPizza. This may seem a little strange, as it appears that both MargheritaPizza and SohoPizza have ingredients that are vegetarian ingredients, i.e. ingredients that are kinds of CheeseTopping or kinds of VegetableTopping. However, as we will see, MargheritaPizza and SohoPizza have something missing from their definition that means they cannot be classified as subclasses of VegetarianPizza.

Reasoning in OWL (Description Logics) is based on what is known as the open world assumption (OWA). It is frequently referred to as open world reasoning (OWR). The open world assumption means that we cannot assume something doesn’t exist until 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 MargheritaTopping and only kinds of MozzarellaTopping or MargheritaTopping, we must add what is known as a closure axiom on the hasTopping property.

### 4.13.1 Closure Axioms

A closure axiom on a property consists of a universal restriction that acts along the property to say that it can only be filled by the 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. $\forall$ hasTopping (Mozzarella-... 

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9 Also referred to as a closure restriction.

10 And technically speaking the classes for the values used in any hasValue restrictions (see later).
Figure 4.51: Class Description View: Margherita Pizza With a Closure Axiom for the \texttt{hasTopping} property

\begin{itemize}
\item \texttt{laTopping} $\sqsubseteq$ \texttt{TomatoTopping}).
\end{itemize}

\textbf{Exercise 34: Add a closure axiom on the \texttt{hasTopping} property for MargheritaPizza}

\begin{enumerate}
\item Make sure that \texttt{MargheritaPizza} is selected in the class hierarchy on the ‘\textbf{Classes}’ tab.
\item Press the ‘\textbf{Add}’ icon (+) on the ‘\textbf{Class Description}’ view to open the edit text box.
\item Type \texttt{hasTopping} as the property to be restricted.
\item Type ‘\texttt{only}’ to create the universal restriction.
\item Open brackets and type \texttt{MozzarellaTopping} or \texttt{TomatoTopping} close bracket.
\item Press ‘\textbf{OK}’ to create the restriction and add it to the class \texttt{MargheritaPizza}.
\end{enumerate}

The class description view should now appear as shown in Figure 4.51.
This now says that if an individual is a member of the class \texttt{MargheritaPizza} then it must be a member of the class \texttt{Pizza}, \textit{and} it must have at least one topping that is a kind of \texttt{MozzarellaTopping} \textit{and} it must have at least one topping that is a member of the class \texttt{TomatoTopping} \textit{and} the toppings must \textit{only} be kinds of \texttt{MozzarellaTopping} or \texttt{TomatoTopping}.

A common error in situations such as above is to only use universal restrictions \textit{in} descriptions. For example, describing a \texttt{MargheritaPizza} by making \textit{it} a subclass of \texttt{Pizza} and then only using $\forall$ has\texttt{Topping} (Mozzarella\texttt{Topping} $\sqcup$ Tomato\texttt{Topping}) without any existential restrictions. However, because of the semantics of the universal restriction, \texttt{this actually means} either: things that are \texttt{Pizza}s and only have toppings that are \texttt{MozzarellaTopping} or \texttt{TomatoTopping}, OR, things that are \texttt{Pizza}s and \textit{do not have any} toppings at all.

\textbf{Exercise 35: Add a closure axiom on the \texttt{hasTopping} property for \texttt{SohoPizza}}

1. Make sure that \texttt{SohoPizza} is selected in the class hierarchy on the ‘Classes’ tab.
2. Press the ‘Add’ icon (+) on the ‘Class Description’ view to open the edit text box.
3. Type \texttt{hasTopping} as the property to be restricted.
4. Type ‘\textit{only}’ to create the universal restriction.
5. Open brackets and type \texttt{MozzarellaTopping} or \texttt{TomatoTopping} or \texttt{ParmezanTopping} or \texttt{OliveTopping} close bracket.
6. Press ‘\texttt{OK}’ to create the restriction and add \textit{it} to the class \texttt{SohoPizza}.

For completeness, \texttt{we will add closure axioms for the \texttt{hasTopping} property to \texttt{AmericanaPizza}} and also \texttt{AmericanHotPizza}. At this point it may seem like tedious work to enter these closure axioms by hand. Fortunately Protégé 4 has the capability of creating closure axioms for us.

\textbf{Exercise 36: Automatically create a closure axiom on the \texttt{hasTopping} property for \texttt{AmericanaPizza}}

1. Select \texttt{AmericanaPizza} in the class hierarchy on the Classes tab.
2. Select ‘\textit{Add covering axiom}’ from the ‘\texttt{Edit}’ menu
Exercise 37: Automatically create a closure axiom on the `hasTopping` property for AmericanHot-Pizza

1. Select `AmericanHotPizza` in the class hierarchy on the Classes tab.
2. Select ‘Add covering axiom’ from the ‘Edit’ menu

Having added closure axioms on the `hasTopping` property for our pizzas, we can now use the reasoner to automatically compute classifications for them.

Exercise 38: Use the reasoner to classify the ontology

1. Press the ‘Classify...’ button on the reasoner drop down menu to invoke the reasoner.

After a short amount of time the ontology will have been classified and the ‘Inferred Hierarchy’ pane will pop open (if it is not already open). This time, `MargheritaPizza` and also `SohoPizza` will have been classified as subclasses of `VegetarianPizza`. This has happened because we specifically ‘closed’ the `hasTopping` property on our pizzas to say exactly what toppings they have and `VegetarianPizza` was defined to be a `Pizza` with only kinds of `CheeseTopping` and only kinds of `VegetableTopping`. Figure 4.52 shows the current asserted and inferred hierarchies. It is clear to see that the asserted hierarchy is simpler and ‘cleaner’ than the ‘tangled’ inferred hierarchy. Although the ontology is only very simple at this stage, it should be becoming clear that the use of a reasoner can help (especially in the case of large ontologies) to maintain a multiple inheritance hierarchy for us.
4.14 Value Partitions

In this section we create some Value Partitions, which we will use to refine our descriptions of various classes. Value Partitions are not part of OWL, or any other ontology language, they are a ‘design pattern’. Design patterns in ontology design are analogous to design patterns in object oriented programming — they are solutions to modelling problems that have occurred over and over again. These design patterns have been developed by experts and are now recognised as proven solutions for solving common modelling problems. As mentioned previously, Value Partitions can be created to refine our class descriptions, for example, we will create a Value Partition called ‘SpicinessValuePartition’ to describe the ‘spiciness’ of PizzaToppings. Value Partitions restrict the range of possible values to an exhaustive list, for example, our ‘SpicinessValuePartition’ will restrict the range to ‘Mild’, ‘Medium’, and ‘Hot’. Creating a ValuePartition in OWL consists of several steps:

1. Create a class to represent the ValuePartition. For example to represent a ‘spiciness’ ValuePartition we might create the class SpicinessValuePartition.
2. Create subclasses of the ValuePartition to represent the possible options for the ValuePartition. For example we might create the classes Mild, Medium and Hot as subclasses of the SpicinessValuePartition class.
3. Make the subclasses of the ValuePartition class disjoint.
4. Provide a covering axiom to make the list of value types exhaustive (see below).
5. Create an object property for the ValuePartition. For example, for our spiciness ValuePartition, we might create the property hasSpiciness.
6. Make the property *functional*.

7. Set the range of the property as the ValuePartition class. For example for the hasSpiciness property the range would be set to **SpicinessValuePartition**.

Let’s create a ValuePartition that can be used to describe the spiciness of our pizza toppings. We will then be able to classify our pizzas into spicy pizzas and non-spicy pizzas. We want to be able to say that our pizza toppings have a spiciness of either ‘mild’, ‘medium’ or ‘hot’. Note that these choices are mutually exclusive – something cannot be both ‘mild’ and ‘hot’, or a combination of the choices.

**Exercise 39: Create a ValuePartition to represent the spiciness of pizza toppings**

1. Create a new class as a sub class of **Thing** called **ValuePartition**.

2. Create a sub class of **ValuePartition** called **SpicinessValuePartition**.

3. Create three new classes as subclasses of **SpicinessValuePartition**. Name these classes **Hot**, **Medium**, and **Mild**.

4. Make the classes **Hot**, **Medium**, and **Mild** disjoint from each other. You can do this by selecting the class **Hot**, and selecting ‘**Make all primitive siblings disjoint**’ from the ‘**Edit**’ menu.

5. In the ‘**Object Property Tab**’ create a new Object Property called **hasSpiciness**. Set the range of this property to **SpicinessValuePartition**. Make this new property functional by ticking the functional box.

6. Add a covering axiom to the **SpicinessValuePartition**. Highlight **SpicinessValuePartition** in the class hierarchy, in the class description view select the add equivalent class icon (+) and type **Hot or Medium or Mild** in the dialog box.

Let’s look at the SpicinessValuePartitionClass (refer to Figure 4.53 and Figure 4.54):
4.14.1 Covering Axioms

As part of the ValuePartition pattern we use a covering axiom. A covering axiom consists of two parts: The class that is being ‘covered’, and the classes that form the covering. For example, suppose we have three classes A, B and C. Classes B and C are subclasses of class A. Now suppose that we have a covering axiom that specifies class A is covered by class B and also class C. This means that a member of class A must be a member of B and/or C. If classes B and C are disjoint then a member of class A must be a member of either class B or class C. Remember that ordinarily, although B and C are subclasses if A an individual may be a member of A without being a member of either B or C.

In Protégé 4 a covering axiom manifests itself as a class that is the union of the classes being covered, which forms a superclass of the class that is being covered. In the case of classes A, B and C, class A would have a superclass of B ∪ C. The effect of a covering axiom is depicted in Figure 4.55.

![Figure 4.55: A schematic diagram that shows the effect of using a Covering Axiom to cover class A with classes B and C](image)

Our SpicinessValuePartition has a covering axiom to state that SpicinessValuePartition is covered by the classes Mild, Medium and Hot — Mild, Medium and Hot are disjoint from each other so that an individual cannot be a member of more than one of them. The class SpicinessValuePartition has a superclass that is Mild ∪ Medium ∪ Hot. This covering axiom means that a member of SpicinessValuePartition must be a member of either Mild or Medium or Hot.

The difference between not using a covering axiom, and using a covering axiom is depicted in Figure 4.56. In both cases the classes Mild, Medium and Hot are disjoint — they do not overlap. It can be seen that in the case without a covering axiom an individual may be a member of the class SpicinessValuePartition...
and still not be a member of Mild, Medium or Hot — SpicinessValuePartition is not covered by Mild, Medium and Hot. Contrast this with the case when a covering axiom is used. It can be seen that if an individual is a member of the class SpicinessValuePartition, it must be a member of one of the three subclasses Mild, Medium or Hot — SpicinessValuePartition is covered by Mild, Medium and Hot.

Figure 4.56: The effect of using a covering axiom on the SpicinessValuePartition

4.15 Adding Spiciness to Pizza Toppings

We can now use the SpicinessValuePartition to describe the spiciness of our pizza toppings. To do this we will add an existential restriction to each kind of PizzaTopping to state its spiciness. Restrictions will take the form, hasSpiciness some SpicinessValuePartition, where SpicinessValuePartition will be one of Mild, Medium or Hot.

We can do this for each topping as we have already done when describing pizzas or we can use the Matrix Plugin (see ??) to speed up the process.

Exercise 40: Specify hasSpiciness restrictions on PizzaToppings

1. Make sure that JalapenoPepperTopping is selected in the class hierarchy.
2. Use the ‘Add’ button on the “Superclasses” section of the ‘Class Description view’ which opens a dialog.
3. Select the ‘Class expression editor’ tab.
4. Type hasSpiciness some Hot to create the existential restriction. Remember you can use autocomplete to speed up the process.
5. Press ‘OK’ to create the restriction — if there are any errors, the restriction will not be created, and the error will be highlighted in red.
6. Repeat this for each of the bottom level PizzaToppings (those that have no subclasses).

To complete this section, we will create a new class SpicyPizza, which should have pizzas that have spicy toppings as its subclasses. In order to do this we want to define the class SpicyPizza to be a Pizza
Figure 4.57: The definition of SpicyPizza

that has at least one topping (hasTopping) that has a spiciness (hasSpiciness) that is Hot. This can be accomplished in more than one way, but we will create a restriction on the hasTopping property, that has a restriction on the hasSpiciness property as its filler.

Exercise 41: Create a SpicyPizza as a subclass of Pizza

1. Create a subclass of Pizza called SpicyPizza.
2. With SpicyPizza selected in the class hierarchy, select the “Equivalent Class” header in the class description view.
3. Press the ‘Add class’ button on the class description view to open a text box.
4. Type hasTopping as the property to be restricted.
5. Type ‘some’ as the type of restriction.
6. The filler should be: PizzaTopping and hasSpiciness some Hot. This filler describes an anonymous class, which contains the individuals that are members of the class PizzaTopping and also members of the class of individuals that are related to the members of class Hot via the hasSpiciness property. In other words, the things that are PizzaToppings and have a spiciness that is Hot. To create this restriction in the text box type,‘ (PizzaTopping and (hasSpiciness some Hot)), including the brackets.
7. Finally, select the ‘Convert to defined class’ option in the ‘Edit’ menu.

The class description view should now look like the picture shown in Figure 4.57
Our description of a SpicyPizza above says that all members of SpicyPizza are Pizza and have at least one topping that has a Spiciness of Hot. It also says that anything that is a Pizza and has at least one topping that has a spiciness of Hot is a SpicyPizza.

In the final step of Exercise 41 we created a restriction that had the class expression (PizzaTopping and hasSpiciness some Hot) rather than a named class as its filler. This filler was made up of an intersection between the named class PizzaTopping and the restriction hasSpiciness some Hot. Another way to do this would have been to create a subclass of PizzaTopping called HotPizzaTopping and define it to be a hot topping by having a necessary condition of hasSpiciness some Hot. We could have then used hasTopping some HotPizzaTopping in our definition of SpicyPizza. Although this alternative way is simpler, it is more verbose. OWL allows us to essentially shorten class descriptions and definitions by using class expressions in place of named classes as in the above example.

We should now be able to invoke the reasoner and determine the spicy pizzas in our ontology.

**Exercise 42: Use the reasoner to classify the ontology**

1. Press ‘Classify...’ in the Reasoner drop down menu to invoke the reasoner and classify the ontology.

After the reasoner has finished, the ‘Inferred Hierarchy’ class pane will pop open, and you should find that AmericanHotPizza has been classified as a subclass of SpicyPizza — the reasoner has automatically computed that any individual that is a member of AmericanHotPizza is also a member of SpicyPizza.

### 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 to each other. For example, Figure 4.58 depicts the individual Matthew related to the individuals Nick and the individual Hai via the worksWith property. The individual Matthew satisfies a minimum cardinality restriction of
Let’s add a cardinality restriction to our Pizza Ontology. We will create a new subclass of Pizza called InterestingPizza, which will be defined to have three or more toppings.

**Exercise 43: Create an InterestingPizza that has at least three toppings**

1. Switch to the Classes tab and make sure that the Pizza class is selected.
2. Create a subclass of Pizza called InterestingPizza.
3. Select the “Equivalent class” header in the class description view.
4. Press the ‘Add class’ button to open a text box.
5. Type hasTopping as a property to be restricted.
6. Type ‘min’ to create a minimum cardinality restriction.
7. Specify a minimum cardinality of three by typing 3 into the text box.
8. Press the ‘Enter’ to close the dialog and create the restriction.
9. The class description view should now have a “Subclass of” condition of Pizza, and a “Equivalent class” condition of hasTopping min 3. We need to make Pizza part of the necessary and sufficient conditions. Select the ‘Convert to defined class’ option in the ‘Edit’ menu.

The class description view should now appear like the picture shown in Figure 4.59.
Figure 4.59: The Class Description View Displaying the Description of an InterestingPizza

What does this mean? Our definition of an InterestingPizza describes the set of individuals that are members of the class Pizza and that have at least three hasTopping relationships with other (distinct) individuals.

Exercise 44: Use the reasoner to classify the ontology

1. Press ‘Classify...’ in the Reasoner drop down menu.

After the reasoner has classified the ontology, the ‘Inferred Hierarchy’ window will pop open. Expand the hierarchy so that InterestingPizza is visible. Notice that InterestingPizza now has subclasses Ameri-
canaPizza, AmericanHotPizza and SohoPizza — notice MargheritaPizza has not been classified under InterestingPizza because it only has two distinct kinds of topping.

4.17 Qualified Cardinality Restrictions

In the previous section we described cardinality restrictions - specifies the exact number of P relationships that an individual must participate in. In this section we focus on Qualified Cardinality Restrictions (QCR), which are more specific than cardinality restrictions in that they state the class of objects within the restriction. Let’s add a Qualified Cardinality Restriction to our pizza ontology. To do this, we will create a subclass of NamedPizza, called Four Cheese Pizza, which will be defined as having exactly four
cheese toppings.

**Exercise 45: Create a Four Cheese Pizza that has exactly four cheese toppings (Figure 4.60)**

1. Switch to the Classes tab and make sure the NamedPizza class is selected
2. Create a subclass of Pizza called FourCheesePizza
3. Select the 'Superclasses' header in the class description view
4. Press the '+' button to open a text box
5. Type `hasTopping` for the property
6. Type `exactly` to create an exact cardinality restriction
7. Specify a QCR of four by typing `4` into the text box
8. Type `CheeseTopping` to specify the type of topping
9. Click OK and create the restriction

Our definition of a FourCheesePizza describes the set of individuals that are members of the class `NamedPizza` and that have exactly four `hasTopping` relationships with individuals of the CheeseTopping class. With this description a FourCheesePizza can still also have other relationships to other kinds of toppings. In order for us to say that we just want it to have four cheese toppings and no other toppings we must add the keyword 'only' (the universal quantifier). This means that the only kinds of topping allowed are cheese toppings.

An unqualified cardinality restriction is exactly the same as a qualified cardinality restriction with a filler of `Thing`. eg. `hasTopping min 3` is the same as `hasTopping min 3 Thing`. 
Chapter 5

Datatype Properties

In Section 4.4 of Chapter 4 we introduced properties in OWL, but only described object properties—that is, relationships between individuals. In this chapter we will discuss and show examples of Datatype properties. Datatype properties link an individual to an XML Schema Datatype value or an rdf literal. In other words, they describe relationships between an individual and data values. Most of the property characteristics described in Chapter 4 cannot be used with datatype properties. We will describe those characteristics of properties that are applicable to data properties later in this chapter.

Datatype properties can be created using the ‘Datatype Properties view’ in either the ‘Entities’ or ‘Datatype Properties tab’ shown in Figure 5.1.

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:

- Create a datatype property hasCalorificContentValue, which will be used to state the calorie content of particular pizzas.
- Create several example pizza individuals with specific calorie contents.
- Create two classes broadly categorising pizzas as low or high calorie.

Now let us do this in Protégé.

A datatype property can be used to relate an individual to a concrete data value that may be typed or untyped.

**Exercise 46: Create a datatype property called** hasCalorificContentValue

1. Switch to the ‘Datatype Properties’ tab. Use the ‘Add Datatype Property’ button to create a new Datatype property called hasCalorificContentValue.

There is nothing intrinsic to data properties to prevent us from performing class-level classification, but
Exercise 47: Create example pizza individuals

1. Ensure the ‘Entities Tab’ or ‘Individuals Tab’ is selected and that the ‘Individuals view’ is visible (by default in the entities tab it will be one of the views stacked at the bottom left of the tab).

2. Press the ‘Add individual’ button and create an individual called Example-Margherita.

3. In the ‘Individual Description view’ add a type of Margherita. In the dialog that appears you can do this with either the ‘Class hierarchy’ or the ‘Class expression editor’.

4. In the ‘Property assertions view’ add a ‘Data property assertion’ and in the dialog shown in Figure 5.2 ensure hasCalorificContentValue is selected as the property, integer is selected as the type and a value of 263 is entered.

5. Create several more example pizza individuals with different calorie contents including an instance of QuattroFormaggio with 723 calories.
A datatype property can also be used in a restriction to relate individuals to members of a given datatype. Built in datatypes are specified in the XML schema vocabulary and include integers, floats, strings, booleans etc.

**Exercise 48: Create a datatype restriction to state that all Pizzas have a calorific value**

1. Ensure the ‘Entities’ or ‘Classes’ Tab is selected
2. Select Pizza and in the ‘Class Description view’ and add a superclass. This brings up the editor dialog.
3. In the dialog select the ‘Data restriction creator’ shown in Figure 5.3. This operates in the same way as the object restriction creator, but the filler is a named datatype.
4. Make sure the type of restriction is set to ‘some’.
5. Select hasCaloricContentValue as the property being restricted.
6. Finally, choose the datatype integer
7. Press ‘OK’. The restriction hasCaloricContentValue some integer is now shown in the superclasses.

We have now stated that all pizzas have at least one calorific value (and that value must be an integer).
Figure 5.3: Creating a some restriction using a data property
In addition to using the predefined set of datatypes we can further specialise 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.

Using the datatype property we have created, we will now create defined classes that specify a range of interesting values. We will create definitions that use the `minInclusive` and `maxExclusive` facets that can be applied to numeric datatypes. `HighCaloriePizza` will be defined to be any pizza that has a calorific value equal to or higher than 400.

Exercise 49: Create a `HighCaloriePizza` that has a calorific value higher than or equal to 400

1. Ensure the ‘Classes Tab’ or ‘Entities Tab’ is selected.
2. Create a subclass of Pizza called `HighCaloriePizza`.
3. In the ‘Class Description view’ click the ‘+’ button in the ‘Superclasses section’ to add a new restriction.
4. In the ‘Class expression editor’, type `Pizza that hasCalorificContentValue some integer[>= 400]` and click ‘OK’.
5. Convert the class to a defined class (‘Ctrl-D’ or ‘Command-D’ on a mac). You should now have a class defined as in Figure 5.4.
6. Create a `LowCaloriePizza` in the same way, but define it as being equivalent to Pizza and hasCalorificContentValue some integer[< 400] (any pizza that has a calorific value less than 400). Notice that the definition does not overlap with `HighCaloriePizza`.

You now have two categories of pizza that should cover any individual that has had its calorie content specified. We should now be able to test if the classification holds for the example individuals we created.
Figure 5.5: Individuals classified as being members of *HighCaloriePizza*

We will use the reasoner to perform instance classification.

**Exercise 50: Classify pizza individuals based on their** hasCalorificContentValue

1. Select a reasoner from the ‘Reasoner menu’ or press ‘Classify’ if one is already selected. The reasoner should classify and show the inferred class hierarchy.

2. Select *HighCaloriePizza*. You should be able to see inferences shown in the ‘Class Description view’ in yellow with a dashed border.

3. Check the ‘Members’ section (see Figure 5.5). It should include your instance of ‘QuattroFormaggio’ and perhaps other individuals which you specified as having a calorie value equal to or over 400.

4. Select *LowCaloriePizza*. Check the ‘Members’ section. It should include your instance of ‘ExampleMargherita’ and perhaps other individuals which you specified as having a calorie value lower than 400.

Finally, think about how many different calorie values can be held by an individual pizza. Of course, the answer is only one. Remember that there is a property characteristic that states that a property with that characteristic can only be held by an individual once. By describing an object property as *functional* we state that any given individual can be related to *at most* one other individual along that property. We can also use the functional characteristic on data properties (This is currently the only characteristic
it is possible to use on data properties) By making hasCalorificContentValue functional we are saying that any one pizza can only ever have one calorie value.

Exercise 51: Making the hasCalorificContentValue datatype property functional

1. Go to the ‘Datatype Properties’ tab and select hasCalorificContentValue
2. In the ‘Data Type Characteristics’ pane, click the ‘functional’ radio button.
3. Test that this works by creating a pizza individual that has two calorie values. This should cause the ontology to become inconsistent.

There are several ways to model units in OWL, but we will not be reasoning about them so have chosen to keep the example simple. In this example the units are implicit in the name of the property (calories) and are used universally throughout our ontology.
Chapter 6

More On Open World Reasoning

The examples in this chapter demonstrate the nuances of Open World Reasoning.

We will create a NonVegetarianPizza to complement our categorisation of pizzas into VegetarianPizzas. The NonVegetarianPizza should contain all of the Pizzas that are not VegetarianPizzas. To do this we will create a class that is the complement of VegetarianPizza. A complement class contains all of the individuals that are not contained in the class that it is the complement to. Therefore, if we create NonVegetarianPizza as a subclass of Pizza and make it the complement of VegetarianPizza it should contain all of the Pizzas that are not members of VegetarianPizza.

Exercise 52: Create NonVegetarianPizza as a subclass of Pizza and make it disjoint to Vegetarian-Pizza

1. Select Pizza in the class hierarchy on the ‘Classes’ tab. Press the ‘Add subclass’ button to create a new class as the subclass of Pizza.

2. Name the new class NonVegetarianPizza.

3. Make NonVegetarianPizza disjoint with VegetarianPizza — while NonVegetarian-Pizza is selected, press the ‘Add disjoint class’ button on the disjoint classes view.
We now want to define a **NonVegetarianPizza** to be a **Pizza** that is not a **VegetarianPizza**.

**Exercise 53: Make VegetarianPizza the complement of VegetarianPizza**

1. Make sure that **NonVegetarianPizza** is selected in the class hierarchy on the ‘**Classes**’ tab.

2. Double click on **Pizza** in the ‘**Superclasses**’ section of the ‘Class Description View’, and edit to create **Pizza and not VegetarianPizza**.

3. Press OK to create and assign the expression. If everything was entered correctly then the expression editor will close and the expression will have been created. (If there are errors, check the spelling of “VegetarianPizza”).

**TIP**

A very useful feature of the expression editor is the ability to ‘auto complete’ class names, property names and individual names. The auto completion for the inline expression editor is activated using the tab key. In the above example if we had typed `Vege` into the inline expression editor and pressed the tab key, the choices to complete the word Vege would have popped up in a list as shown in Figure 6.1. The up and down arrow keys could then have been used to select **VegetarianPizza** and pressing the Enter key would complete the word for us.

The class description view should now resemble the picture shown in 6.2. However, we need to add **Pizza** to the necessary and sufficient conditions as at the moment our definition of **NonVegetarianPizza** says that an individual that is not a member of the class **VegetarianPizza** (everything else!) is a **NonVegetarianPizza**.

**Exercise 54: Add Pizza to the necessary and sufficient conditions for NonVegetarianPizza**

1. Make sure **NonVegetarianPizza** is selected in the class hierarchy on the ‘**Classes**’ tab.

2. Convert the superclass to an equivalent class. Either select ‘**Edit — Convert to defined class**’ or copy and paste the superclass you just edited from the superclasses to the equivalent classes section. Note that before pasting you should select the ‘**Equivalent classes**’ header.

The ‘Class Description View’ should now look like the picture shown in Figure 6.3.
Figure 6.1: Class Description View: Expression Editor Auto Completion

Figure 6.2: The Class Description View Displaying \texttt{NonVegetarianPizza} as a primitive class
The complement of a class includes all of the individuals that are not members of the class. By making NonVegetarianPizza a subclass of Pizza and the complement of VegetarianPizza we have stated that individuals that are Pizza’s and are not members of VegetarianPizza must be members of NonVegetarianPizza. Note that we also made VegetarianPizza and NonVegetarianPizza disjoint so that if an individual is a member of VegetarianPizza it cannot be a member of NonVegetarianPizza.

**Exercise 55: Use the reasoner to classify the ontology**

1. Press the ‘Classify...’ button in the Reasoner toolbar. After a short time the reasoner will have computed the inferred class hierarchy, and the inferred class hierarchy pane will pop open.

The inferred class hierarchy should resemble the picture shown in Figure 6.4. As can be seen, MargheritaPizza and SohoPizza have been classified as subclasses of VegetarianPizza. AmericanaPizza and AmericanHotPizza have been classified as NonVegetarianPizza. Things seemed to have worked. How-
ever, let’s add a pizza that does not have a closure axiom on the hasTopping property.

**Exercise 56: Create a subclass of NamedPizza with a topping of Mozzarella**

1. Create a subclass of NamedPizza called **UnclosedPizza**.
2. Making sure that **UnclosedPizza** is selected in the ‘Class Description View’ select the “Superclasses” header.
3. Press the ‘Add class’ button to display restriction text box.
4. Type **hasTopping** as the property to be restricted.
5. Type ‘**some**’ in order to create an existential restriction.
6. Type **MozzarellaTopping** into text box to specify that the toppings must be individuals that are members of the class **MozzarellaTopping**.
7. Press ‘**Enter**’ to close the dialog and create the restriction.

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**MEANING**

If an individual is a member of **UnclosedPizza** it is necessary for it to be a **NamedPizza** and have at least one **hasTopping** relationship to an individual that is a member of the class **MozzarellaTopping**. Remember that because of the Open World Assumption and the fact that we have not added a closure axiom on the hasTopping property, an **UnclosedPizza** might have additional toppings that are not kinds of **MozzarellaTopping**.

**Exercise 57: Use the reasoner to classify the ontology**

1. Press ‘**Classify...**’ in the Reasoner drop down menu.

Examine the class hierarchy. Notice that **UnclosedPizza** is neither a **VegetarianPizza** or **NonVegetarianPizza**.
As expected (because of Open World Reasoning) UnclosedPizza has not been classified as a VegetarianPizza. The reasoner cannot determine UnclosedPizza is a VegetarianPizza because there is no closure axiom on the hasTopping and the pizza might have other toppings. We therefore might have expected UnclosedPizza to be classified as a NonVegetarianPizza since it has not been classified as a VegetarianPizza. However, Open World Reasoning does not dictate that because UnclosedPizza cannot be determined to be a VegetarianPizza it is not a VegetarianPizza — it might be a VegetarianPizza and also it might not be a VegetarianPizza! Hence, UnclosePizza cannot be classified as a NonVegetarian-Pizza.
Chapter 7

Creating Other OWL Constructs In Protégé 4

This chapter discusses how to create some other owl constructs using Protégé 4. These constructs are not part of the main tutorial and may be created in a new Protégé 4 project if desired.

7.1 Creating Individuals

OWL allows us to define individuals and to assert properties about them. Individuals can also be used in class descriptions, namely in hasValue restrictions and enumerated classes which will be explained in section 7.2 and section 7.3 respectively. To create individuals in Protégé 4 the ‘Individuals Tab’ is used.

Suppose we wanted to describe the country of origin of various pizza toppings. We would first need to add various ‘countries’ to our ontology. Countries, for example, ‘England’, ‘Italy’, ‘America’, are typically thought of as being individuals (it would be incorrect to have a class England for example, as it’s members would be deemed to be, ‘things that are instances of England’). To create this in our Pizza Ontology we
will create a class `Country` and then 'populate' it with individuals:

**Exercise 58: Create a class called `Country` and populate it with some individuals**

1. Create `Country` as a subclass of `Thing`.
2. Switch to the 'Individuals Tab' shown in Figure 7.1.
3. Press the 'Add individual' button shown in Figure 7.2. (Remember that 'Individual' is another name for 'Instance' in ontology terminology).
4. Name the new Individual `Italy`.
5. Select the 'Add' icon (+) next to the 'Types' header from the 'Individual Types View' located in the centre of the Individual tab. Choose `Country` from the class hierarchy, this will make `Italy` an individual of the class `Country`.
6. Use the above steps to create some more individuals that are members of the class `Country` called `America`, `England`, `France`, and `Germany`.

Recall from section 3.1.1 that OWL does not use the Unique Name Assumption (UNA). Individuals can therefore be asserted to be the 'Same As' or 'Different From' other individuals. In Protégé 4 these assertions can be made using the 'SameAs' and 'DifferentFrom' sections of the 'Individual Description'
Having created some individuals we can now use these individuals in class descriptions as described in section 7.2 and section 7.3.

### 7.2 hasValue Restrictions

A hasValue restriction, denoted by the symbol \( \ni \), describes the set of individuals that have at least one relationship along a specified property to a specific individual. For example, the hasValue restriction \( \text{hasCountryOfOrigin} \ni \text{Italy} \) (where \( \text{Italy} \) is an individual) describes the set of individuals (the anonymous class of individuals) that have at least one relationship along the \( \text{hasCountryOfOrigin} \) property to the specific individual \( \text{Italy} \). For more information about hasValue restrictions please see Appendix A.2.

Suppose that we wanted to specify the origin of ingredients in our pizza ontology. For example, we might want to say that mozzarella cheese (\( \text{MozzarellaTopping} \)) is from \( \text{Italy} \). We already have some countries in our pizza ontology (including \( \text{Italy} \)), which are represented as individuals. We can use a hasValue
Exercise 59: Create a hasValue restriction to specify that MozzarellaTopping has Italy as its country of origin.

1. Switch to the ‘Object Properties’ tab. Create a new object property and name it hasCountryOfOrigin.
2. Switch to the ‘Classes’ tab and select the class MozzarellaTopping.
3. Press the ‘Add’ button on the ‘Superclasses’ section of the ‘Class Description View’ to open the editor.
4. Type hasCountryOfOrigin as the property to be restricted.
5. Type value as the type of restriction to be created.
6. Enter Italy as the individual to complete the restriction. You can either type this in or drag and drop from the individuals window.
7. Press ‘Enter’ to close the dialog and create the restriction.

The ‘Class Description View’ should now look similar to the picture shown in Figure 7.3.

MEANING

The conditions that we have specified for MozzarellaTopping now say that: individuals that are members of the class MozzarellaTopping are also members of the class CheeseTopping and are related to the individual Italy via the hasCountryOfOrigin property and are related to at least one member of the class Mild via the hasSpiciness property. In more natural English, things that are kinds of mozzarella topping are also kinds of cheese topping and come from Italy and are mildly spicy.
With current reasoners the classification is not complete for individuals. Use individuals in class descriptions with care — unexpected results may be caused by the reasoner.

7.3 Enumerated Classes

As well as describing classes through named superclasses and anonymous superclasses such as restrictions, OWL allows classes to be defined by precisely listing the individuals that are the members of the class. For example, we might define a class DaysOfTheWeek to contain the individuals (and only the individuals) Sunday, Monday, Tuesday, Wednesday, Thursday, Friday and Saturday. Classes such as this are known as enumerated classes.

In Protégé 4 enumerated classes are defined using the ‘Class Description View’ expression editor – the individuals that make up the enumerated class are listed (separated by spaces) inside curly brackets. For example \{Sunday Monday Tuesday Wednesday Thursday Friday Saturday\}. The individuals must first have been created in the ontology. Enumerated classes described in this way are anonymous classes – they are the class of the individuals (and only the individuals) listed in the enumeration. We can attach these individuals to a named class in Protégé 4 by creating the enumeration as a “Equivalent class” condition.

**Exercise 60: Convert the class Country into an enumerated class**

1. Switch the ‘Classes’ tab and select the class Country.
2. Select the “Equivalent class” header in the ‘Class Description View’.
3. Press the ‘Add class’ button, a text box will appear.
4. Type \{America, England, France, Germany, Italy\} into the text box. (Remember to surround the items with curly brackets). Remember that the auto complete function is available — to use it type the first few letters of an individual and press the tab key to get a list of possible choices.
5. Press the enter key to accept the enumeration and close the expression editor.

The ‘Class Description View’ should now look similar to the picture shown in Figure 7.4.
This means that an individual that is a member of the **Country** class must be one of the listed individuals (i.e one of **America England France Germany Italy**). More formally, the class country is equivalent to (contains the same individuals as) the anonymous class that is defined by the enumeration — this is depicted in Figure 7.5.

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**Figure 7.5:** A Schematic Diagram Of The **Country** Class Being Equivalent to an Enumerated Class

### 7.4 Annotation Properties

OWL allows classes, properties, individuals and the ontology itself (technically speaking the ontology header) to be annotated with various pieces of information/meta-data. These pieces of information may take the form of auditing or editorial information. For example, comments, creation date, author, or, references to resources such as web pages etc. OWL-Full does not put any constraints on the usage of annotation properties. However, OWL-DL does put several constraints on the usage of annotation properties — two of the most important constraints are:

- The filler for annotation properties must either be a data literal\(^1\), a URI reference or an individual.
- Annotation properties cannot be used in property axioms — for example they may not be used in the property hierarchy, so they cannot have sub properties, or be the sub property of another

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\(^1\)A data literal is the character representation of a datatype value, for example, “Matthew”, 25, 3.11.
property. The also must not have a domain and a range set for them.

OWL has five pre-defined annotation properties that can be used to annotate classes (including anonymous classes such as restrictions), properties and individuals:

1. **owl:versionInfo** — in general the range of this property is a string.
2. **rdfs:label** — has a range of a string. This property may be used to add meaningful, human readable names to ontology elements such as classes, properties and individuals. **rdfs:label** can also be used to provide multi-lingual names for ontology elements.
3. **rdfs:comment** — has a range of a string.
4. **rdfs:seeAlso** — has a range of a URI which can be used to identify related resources.
5. **rdfs:isDefinedBy** — has a range of a URI reference which can be used to reference an ontology that defines ontology elements such as classes, properties and individuals.

For example the annotation property **rdfs:comment** is used to store the comment for classes in Protégé 4. The annotation property **rdfs:label** could be used to provide alternative names for classes, properties etc.

There are also several annotation properties which can be used to annotate an ontology. The ontology annotation properties (listed below) have a range of a URI reference which is used to refer to another ontology. It is also possible to the use the **owl:VersionInfo** annotation property to annotate an ontology.

- **owl:priorVersion** — identifies prior versions of the ontology.
- **owl:backwardsCompatibleWith** — identifies a prior version of an ontology that the current ontology is compatible with. This means that all of the identifiers from the prior version have the same intended meaning in the current version. Hence, any ontologies or applications that reference the prior version can safely switch to referencing the new version.
- **owl:incompatibleWith** — identifies a prior version of an ontology that the current ontology is not compatible with.

To create annotation properties use the appropriate annotation property view in each of the ‘Active Ontology’, ‘Classes’, ‘Object Property’ and ‘Datatype Property’ Tabs. You can manage your annotation using the ‘Annotations Properties’ Tab, new annotation properties can be created by pressing the ‘create Annotation Property’ button on the ‘Annotation Property’ Tab. To use annotation properties the annotations views shown in Figure 7.6 is used. An annotations view is located on the Classes, Properties, Individuals and Active Ontology tab for annotation classes, properties, individuals and the ontology respectively. Annotations can also be added to restrictions and other anonymous classes by right clicking (ctrl click on a Mac) in the class description view and selecting ‘Edit annotation properties...’.

### 7.5 Multiple Sets Of Necessary & Sufficient Conditions

In OWL it is possible to have multiple sets of necessary and sufficient conditions (Equivalent classes) as depicted in Figure 7.7. In the ‘Class Description View’, multiple sets of necessary and sufficient
conditions are represented using multiple “Equivalent class” headers with necessary and sufficient conditions listed under each header as shown in Figure 7.7. To create a new set of necessary and sufficient conditions, use the ‘Add’ icon (+) next to the “Equivalent class” header. The Equivalent classes can then be written into the ‘Class description’ dialog box that appears.

![Figure 7.6: An annotations view](image)

![Figure 7.7: Necessary Conditions, and Multiple Sets of Necessary And Sufficient Conditions](image)
Exercise 61: Create a class to define a Triangle using multiple sets of Necessary & Sufficient conditions

1. Create a subclass of Thing named Polygon.
2. Create a subclass of Polygon named Triangle.
3. Create an object property named hasSide.
4. Create an object property named hasAngle.
5. On the ‘Classes’ tab select the Triangle class. Select the “Equivalent class” header in the ‘Class Description View’. Press the ‘Add class’ button on the ‘Class Description View’ to open a text box.
6. Type hasSide for the property.
7. Type exactly to create the restriction.
8. Type 3 and press Enter to exit the text box and create the restriction.
9. Select the “Equivalent class” header in the ‘Class Description View’. Press the ‘Add class’ button on the ‘Class Description View’ to open a text box.
10. Type hasAngle for the property.
11. Type exactly to create the restriction.
12. Type 3 and press Enter to exit the text box and create the restriction.
13. Drag Polygon from under the “Superclasses” header and drop it onto the hasSide exactly 3 restriction.
14. Select the hasAngle exactly 3 restriction. Click the ‘Add class’ button to display a dialog containing the class hierarchy. Select the Polygon class and click the ‘OK’ button to close the dialog.

The ‘Class Description View’ should now look like the picture shown in Figure 7.8.
Appendix A

Restriction Types

This appendix contains further information about the types of property restrictions in OWL. It is intended for readers who aren’t too familiar with the notions of logic that OWL is based upon.

All types of restrictions describe an unnamed set that could contain some individuals. This set can be thought of as an anonymous class. Any individuals that are members of this anonymous class satisfy the restriction that describes the class (Figure A.1). Restrictions describe the constraints on relationships that the individuals participate in for a given property.

When we describe a named class using restrictions, what we are effectively doing is describing anonymous superclasses of the named class.

A.1 Quantifier Restrictions

Quantifier restrictions consist of three parts:

1. A quantifier, which is either the existential quantifier (some), or the universal quantifier (only).
2. A property, along which the restriction acts.
3. A filler that is a class description.

For a given individual, the quantifier effectively puts constraints on the relationships that the individual participates in. It does this by either specifying that at least one kind of relationship must exist, or by specifying the only kinds of relationships that can exist (if they exist).

Figure A.1: Restrictions Describe Anonymous Classes Of Individuals
A.1.1 someValuesFrom – Existential Restrictions

Existential restrictions, also known as ‘someValuesFrom’ restrictions, or ‘some’ restrictions are denoted in DL-syntax using $\exists$ – a backwards facing $E$. Existential restrictions describe the set of individuals that have at least one specific kind of relationship to individuals that are members of a specific class. Figure A.2 shows an abstracted schematic view of an existential restriction, $\exists\text{prop}\text{ClassA}$ – i.e. a restriction along the property $\text{prop}$ with a filler of $\text{ClassA}$. Notice that all the individuals in the anonymous class that the restriction defines have at least one relationship along the property $\text{prop}$ to an individual that is a member of the class $\text{ClassA}$. The dashed lines in Figure A.2 represent the fact that the individuals may have other $\text{prop}$ relationships with other individuals that are not members of the class $\text{ClassA}$ even though this has not been explicitly stated — The existential restriction does not constrain the $\text{prop}$ relationship to members of the class $\text{ClassA}$, it just states that every individual must have at least one $\text{prop}$ relationship with a member of $\text{ClassA}$ — this is the open world assumption (OWA).

For a more concrete example, the existential restriction, $\exists\text{hasTopping}\text{MozzarellaTopping}$, describes the set of individuals that take part in at least one $\text{hasTopping}$ relationship with an other individual that is a member of the class $\text{MozzarellaTopping}$ — in more natural English this restriction could be viewed as describing the things that ‘have a Mozzarella topping’. The fact that we are using an existential restriction to describe the group of individuals that have at least one relationship along the $\text{hasTopping}$ property with an individual that is a member of the class $\text{MozzarellaTopping}$ does not mean that these individuals only have a relationship along the $\text{hasTopping}$ property with an individual that is a member of the class $\text{MozzarellaTopping}$ (there could be other $\text{hasTopping}$ relationships that just haven’t been explicitly specified).

A.1.2 allValuesFrom – Universal Restrictions

Universal restrictions are also known as ‘allValuesFrom’ restrictions, or ‘only’ restrictions since they constrain the filler for a given property to a specific class. Universal restrictions are given the symbol $\forall$ – i.e. an upside down $A$. Universal restrictions describe the set of individuals that, for a given property, only have relationships to other individuals that are members of a specific class. A feature of universal restrictions, is that for the given property, the set of individuals that the restriction describes will also contain the individuals that do not have any relationship along this property to any other individuals. A universal restriction along the property $\text{prop}$ with a filler of $\text{ClassA}$ is depicted in Figure A.3. Once again, an important point to note is that universal restrictions do not ‘guarantee’ the existence of a relationship for a given property. They merely state that if such a relationship for the given property exists, then it
must be with an individual that is a member of a specified class.

Let’s take a look at an example of a universal restriction. The restriction, \( \forall \) hasTopping TomatoTopping describes the anonymous class of individuals that only have hasTopping relationships to individuals that are members of the class TomatoTopping, OR, individuals that definitely do not participate in any hasTopping relationships at all.

A.1.3 Combining Existential And Universal Restrictions in Class Descriptions

A common ‘pattern’ is to combine existential and universal restrictions in class definitions for a given property. For example the following two restrictions might be used together, \( \exists \) hasTopping MozzarellaTopping, and also, \( \forall \) hasTopping MozzarellaTopping. This describes the set of individuals that have at least one hasTopping relationship to an individual from the class MozzarellaTopping, and only hasTopping relationships to individuals from the class MozzarellaTopping.

It is worth noting that is particularly unusual (and probably an error), if when describing a class, a universal restriction along a given property is used without using a ‘corresponding’ existential restriction along the same property. In the above example, if we had only used the universal restriction \( \forall \) hasTopping Mozzarella, then we would have described the set of individuals that only participate in the hasTopping relationship with members of the class Mozzarella, and also those individuals that do not participate in any hasTopping relationships – probably a mistake.

A.2 hasValue Restrictions

A hasValue restriction, denoted by the symbol \( \ni \), describes an anonymous class of individuals that are related to another specific individual along a specified property. Contrast this with a quantifier restriction where the individuals that are described by the quantifier restriction are related to any individual from a specified class along a specified property. Figure A.4 shows a schematic view of the hasValue restriction \( prop \ni abc \). This restriction describes the anonymous class of individuals that have at least one relationship along the prop property to the specific individual abc. The dashed lines in Figure A.4 represent the fact that for a given individual the hasValue restriction does not constrain the property used in the restriction to a relationship with the individual used in the restriction i.e. there could be other relationships along the prop property. It should be noted that hasValue restrictions are semantically equivalent to an existential restriction along the same property as the hasValue restriction, which has a filler that is an enumerated class that contains the individual (and only the individual) used in the hasValue restriction.
Figure A.4: A Schematic View Of The hasValue Restriction, $\text{prop} \ni \text{abc}$ — dashed lines indicate that this type of restriction does not constrain the property used in the hasValue restriction solely to the individual used in the hasValue restriction.

A.3 Cardinality Restrictions

Cardinality restrictions are used to talk about the number of relationships that an individual may participate in for a given property. Cardinality restrictions are conceptually easier to understand than quantifier restrictions, and come in three flavours: Minimum cardinality restrictions, Maximum cardinality restrictions, and Cardinality restrictions.

A.3.1 Minimum Cardinality Restrictions

Minimum cardinality restrictions specify the minimum number of relationships that an individual must participate in for a given property. The symbol for a minimum cardinality restriction is the ‘greater than or equal to’ symbol ($\geq$). For example, the minimum cardinality restriction, $\geq \text{hasTopping} 3$, describes the individuals (an anonymous class containing the individuals) that participate in at least three hasTopping relationships. Minimum cardinality restrictions place no maximum limit on the number of relationships that an individual can participate in for a given property.

A.3.2 Maximum Cardinality Restrictions

Maximum cardinality restrictions specify the maximum number of relationships that an individual can participate in for a given property. The symbol for maximum cardinality restrictions is the ‘less than or equal to’ symbol ($\leq$). For example, the maximum cardinality restriction, $\leq \text{hasTopping} 2$, describes the class of individuals that participate in at most two hasTopping relationships. Note that maximum cardinality restrictions place no minimum limit on the number of relationships that an individual must participate in for a specific property.

A.3.3 Cardinality Restrictions

Cardinality restrictions specify the exact number of relationships that an individual must participate in for a given property. The symbol for a cardinality restrictions is the ‘equals’ symbol ($=$). For example,
the cardinality restriction, $= \text{hasTopping} 5$, describes the set of individuals (the anonymous class of individuals) that participate in exactly five $\text{hasTopping}$ relationships. Note that a cardinality restriction is really a syntactic short hand for using a combination of a minimum cardinality restriction and a maximum cardinality restriction. For example the above cardinality restriction could be represented by using the intersection of the two restrictions: $\leq \text{hasTopping} 5$, and, $\geq \text{hasTopping} 5$.

A.3.4 The Unique Name Assumption And Cardinality Restrictions

OWL does not use the Unique Name Assumption (UNA)\(^1\). This means that different names may refer to the same individual, for example, the names “Matt” and “Matthew” may refer to the same individual (or they may not). Cardinality restrictions rely on ‘counting’ distinct individuals, therefore it is important to specify that either “Matt” and “Matthew” are the same individual, or that they are different individuals. Suppose that an individual “Nick” is related to the individuals “Matt”, “Matthew” and “Matthew Horridge”, via the $\text{worksWith}$ property. Imagine that it has also been stated that the individual “Nick” is a member of the class of individuals that work with at the most two other individuals (people). Because OWL does not use the Unique Name Assumption, rather than being viewed as an error, it will be inferred that two of the names refer to the same individual\(^2\).

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\(^1\)Confusingly, some reasoners (such as RACER) do use the Unique Name Assumption!

\(^2\)If “Matt”, “Matthew” and “Matthew Horridge” have been asserted to be different individuals, then this will make the knowledge base inconsistent.
Appendix B

Complex Class Descriptions

An OWL class is specified in terms of its superclasses. These superclasses are typically named classes and restrictions that are in fact anonymous classes. Superclasses may also take the form of ‘complex descriptions’. These complex descriptions can be built up using simpler class descriptions that are cemented together using logical operators. In particular:

- **AND (\(\cap\))** — a class formed by using the AND operator is known as an *intersection* class. The class is the *intersection* of the individual classes.
- **OR (\(\cup\))** — A class formed by using the OR operator is known as a *union* class. The class formed is the *union* of the individual classes.

### B.1 Intersection Classes (\(\cap\))

An intersection class is described by combining two or more classes using the AND operator (\(\cap\)). For example, consider the intersection of *Human* and *Male* — depicted in Figure B.1. This describes an anonymous class that contains the individuals that are members of the class *Human* and the class *Male*. The semantics of an intersection class mean that the anonymous class that is described is a subclass of *Human* and a subclass of *Male*.

The anonymous intersection class above can be used in another class description. For example, suppose we wanted to build a description of the class *Man*. We might specify that *Man* is a subclass of the anonymous class described by the intersection of *Human* and *Male*. In other words, *Man* is a subclass of *Human* and *Male*.

### B.2 Union Classes (\(\cup\))

A union class is created by combining two or more classes using the OR operator (\(\cup\)). For example, consider the union of *Man* and *Woman* — depicted in Figure B.2. This describes an anonymous class that contains the individuals that belong to either the class *Man* or the class *Woman* (or both).
The anonymous class that is described can be used in another class description. For example, the class `Person` might be equivalent of the union of `Man` and `Woman`.

Figure B.1: The intersection of Human and Male (Human ∩ Male) — The shaded area represents the intersection

Figure B.2: The union of Man and Woman (Man ∪ Woman) — The shaded area represents the union
Appendix C

Plugins

C.1 Installing Plugins

Plugins can be found and installed by hand or automatically using auto-update 1

Many Protégé 4 plugins are listed on the Protégé wiki 2

To install a plugin by hand simply download the .jar file (unzip if necessary) and move it to the plugins/ folder in your Protégé installation.

Plugins will be available on a restart (remember to save your work before shutting Protégé ).

C.2 Useful Plugins

C.2.1 Matrix Plugin

Adding existential restrictions on many classes can be very time consuming.

Fortunately, the Matrix Plugin can help to speed things up. Once installed (see ??), the matrix plugin provides several table-style views of the ontology and some default tabs to get you started. One of these views (the Class Matrix) can be used to add existential restrictions along specified properties to many classes in a quick and efficient manner.

As an example this is how you would use the Class Matrix to add spiciness to PizzaToppings:

1. Show the ‘Matrix’ Tab from the ‘Tabs’ menu.
2. In the Matrix Tab the ‘Class Matrix’ view is shown on the left by default. This is shown in figure C.1. You should also be able to see a class hierarchy and property view on the right.

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1http://protegewiki.stanford.edu/index.php/EnablePluginAutoUpdate
2http://protegewiki.stanford.edu/index.php/Protege-OWL_4.0
3. Drag and drop the `hasSpiciness` property from the ‘properties palette’ into the empty pane of the ‘Class Matrix’ view. You should see a new column created with the title ‘hasSpiciness (some)’.

4. For each pizza topping in the class hierarchy enter a spiciness value. You can do this using drag and drop from the ‘Classes palette’ view or by typing directly into the appropriate cell. Remember you can use the auto completion to help fill in the values for you. You should end up with values for your `PizzaTopping` as shown in Figure C.2.

5. If you return to the ‘EntitiesTab’ or ‘Classes Tab’ you will see each topping now has an existential superclass filled in.
Figure C.2: Matrix Tab: With restrictions entered