THE UNIVERSITY of EDINBURGH
informatics

Semantic Web Systems

Description Logics & OWL

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In the previous lecture

- Merging graphs that contain blank nodes can be problematic.
- SPARQL OPTIONAL.

Query

```
PREFIX info:  <http://somewhere/peopleInfo#> .
PREFIX vcard:  <http://www.w3.org/2001/vcard-rdf/3.0#> .
SELECT ?name ?age
WHERE
{
  ?person   vcard:FN   ?name .
   OPTIONAL  {  ?person   info:age   ?age . }
}
```

In the previous lecture

- Linked Data principles
  - Naming things with URIs.
  - Making URIs dereferenceable.
  - Providing useful RDF information.
  - Including links to other things.

In this lecture

- More expressive languages for building sophisticated ontologies.
- Description Logics.
- OWL.

Description Logics

- Description Logics
  - allow formal concept definitions to be expressed,
  - in a form that allows reasoning.
- Example concept definitions:
  - Woman ≡ Person ⊓ Female
  - Man ≡ Person ⊓ ¬Woman
- Not a single logic, but a family of KR logics.
- Subsets of first-order logic.
- Well-defined model theory.
- Known computational complexity.

Description Logics

- A classifier (a reasoning engine) can be used to construct the class hierarchy from the definitions of individual concepts in the ontology.
- Concept definitions are composed from primitive elements and so the ontology is more maintainable.

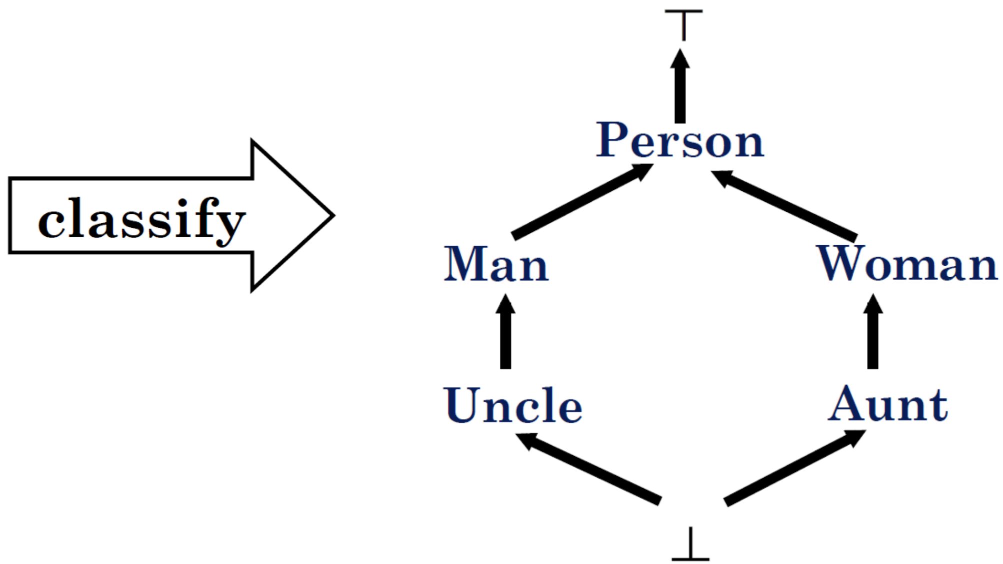
$\mathbf{Man} \equiv \mathbf{d}_1$

$\mathbf{Aunt} \equiv \mathbf{d}_4$

$\mathbf{Uncle} \equiv \mathbf{d}_3$

$\mathbf{Woman} \equiv \mathbf{d}_2$

$\mathbf{Person} \equiv \mathbf{d}_5$



Description Logic Terminology

- Description Logics separate assertions and concept definitions:
- **A Box**: Assertions
  - e.g. hasChild(john, mary).
  - This is the **knowledge base (KB)**.
- **T Box**: Terminology
  - The definitions of concepts in the ontology
  - Example axioms for definitions
    - $C \sqsubseteq D$ [C is a subclass of D, D subsumes C]
    - $C \equiv D$ [C is defined by the expression D]

Description Logic Terminology

- Concept: class, category or type
- Role: binary relation
  - Attributes are functional roles
- Subsumption:
  - D subsumes C if C is a **subclass** of D – i.e. all Cs are Ds
- Unfoldable terminologies:
  - The defined concept does not occur in the defining expression:
  - C ≡ D where C does not occur in the expression D.
- Language families
  - AL: Attributive Language
  - ALC adds **full** negation to AL

Language Elements for Concept Expressions

Symbol	Description	Example	Read
$\top$	all concept names	$\top$	top
$\bot$	empty concept	$\bot$	bottom
$\sqcap$	*intersection* or *conjunction* of concepts	$C \sqcap D$	C and D
$\sqcup$	*union* or *disjunction* of concepts	$C \sqcup D$	C or D
$\neg$	*negation* or *complement* of concepts	$\neg C$	not C
$\forall$	*universal restriction*	$\forall R.C$	all R-successors are in C
$\exists$	*existential restriction*	$\exists R.C$	an R-successor exists in C
$\sqsubseteq$	Concept *inclusion*	$C \sqsubseteq D$	all C are D
$\equiv$	Concept *equivalence*	$C \equiv D$	C is equivalent to D
$\doteq$	Concept *definition*	$C \doteq D$	C is defined to be equal to D
:	Concept *assertion*	$a : C$	a is a C
:	Role *assertion*	$(a, b) : R$	a is R-related to b

Universal restriction

- Universal restriction - also called value restriction: $\forall R.C$

  The set $\{x | \forall y, R(x, y) \Rightarrow y \in C\}$

  The set of things x such that for all y where x and y are related by R, y is in C.

- e.g. $\forall$hasChild.Doctor i.e. $\{x | \forall y, hasChild(x, y) \Rightarrow y \in Doctor\}$
  - The set of individuals **all** of whose children are doctors.
  - That is, anything that is the object of the relation hasChild must be in class Doctor, regardless of what the subject is.
  - Note that this set includes anyone who has **no** child! Why?

Existential restriction

- Existential restriction - also called exists restriction: $\exists R.C$

  The set $\{x | \exists y, R(x, y) \wedge y \in C\}$

  The set of things x such that there exists a y where x and y are related via R and y is in class C.

- e.g. $\exists hasChild.Doctor$ i.e. $\{x | \exists y, hasChild(x, y) \wedge y \in Doctor\}$
  - The set of individuals with at least one child who is a doctor.
  - The set is empty if no one is a parent or if no parent has a child who is a doctor.

Description Logic naming

Three basic logics:

- $\mathcal{AL}$ Attributive language - basic language which allows:
  - **atomic** negation
  - concept intersection
  - universal restrictions
  - limited existential quantification
- $\mathcal{FL}$ Frame based description language, allows:
  - concept intersection
  - universal restrictions
  - limited existential quantification
  - role restriction
- $\mathcal{EL}$ allows:
  - concept intersection
  - existential restrictions (of full existential quantification)

Description Logic naming

Followed by any of the following extensions:

$\mathcal{F}$ Functional Properties

$\mathcal{E}$ Full existential qualification (Existential restrictions that have fillers other than owl:Thing).

$\mathcal{U}$ Concept union.

$\mathcal{C}$ Complex concept negation.

$\mathcal{H}$ Role hierarchy (subproperties - rdfs:subPropertyOf).

$\mathcal{R}$ Limited complex role inclusion axioms; reflexivity and irreflexivity; role disjointness.

$\mathcal{O}$ Nominals. (Enumerated classes of object value restrictions - owl:oneOf, owl:hasValue).

$\mathcal{I}$ Inverse properties.

$\mathcal{N}$ Cardinality restrictions (owl:cardinality, owl:maxCardinality).

$\mathcal{Q}$ Qualified cardinality restrictions (available in OWL 2, cardinality restrictions that have fillers other than owl:Thing).

$(\mathcal{D})$ Use of datatype properties, data values or data types.

Description Logic naming

Some canonical DLs that do not exactly fit this convention are:

$\mathcal{S}$ An abbreviation for $\mathcal{ALC}$ with transitive roles.

$\mathcal{FL}^-$ A sub-language of $\mathcal{FL}$, which is obtained by disallowing role restriction. This is equivalent to $\mathcal{AL}$ without atomic negation.

$\mathcal{FL}_o$ A sub-language of $\mathcal{FL}^-$, which is obtained by disallowing limited existential quantification.

$\mathcal{EL}^{++}$ Alias for $\mathcal{ELRO}$

Common DLs

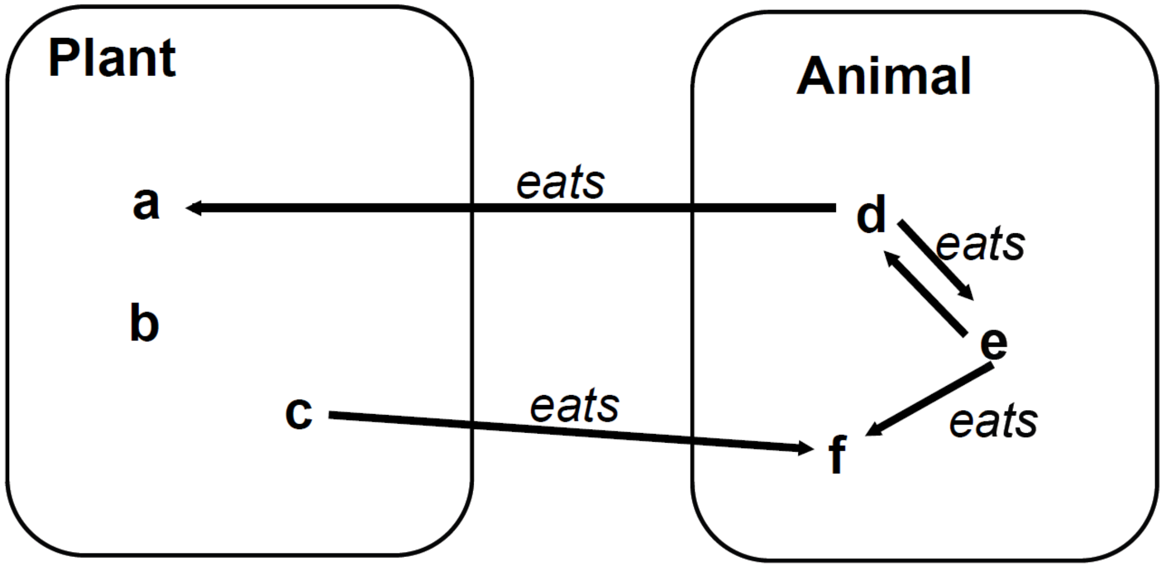
- $\mathcal{ALC}$ is the most common DL. It is $\mathcal{AL}$ with complement of any concept allowed, **not just atomic concepts**.
- $\mathcal{SHIQ}$ is the logic $\mathcal{ALC}$ plus extended cardinality restrictions, and transverse and inverse roles.
- The Protégé editor supports $\mathcal{SHOIN}^{(\mathcal{D})}$
- OWL-2 provides the expressiveness of $\mathcal{SROIQ}^{(\mathcal{D})}$
- OWL-DL is based on $\mathcal{SHOIN}^{(\mathcal{D})}$
- OWL-Lite is based on $\mathcal{SHIF}^{(\mathcal{D})}$

Example concept expressions

- Parent ≡ *"Persons who have (amongst other things) some children"*
    - Person $\sqcap$ $\exists$hasChild.$\top$
- ParentOfBoys ≡ *"Persons who have some children, and only have children that are male"*
    - Person $\sqcap$ ($\exists$hasChild. $\top$) $\sqcap$ ($\forall$hasChild.Male)
- ScottishParent ≡ *"Persons who **only** have children who drink (amongst other things) some IrnBru"*
    - Person $\sqcap$ ($\forall$hasChild. ($\exists$drink.IrnBru))

Value and exists restrictions

{a, b, c, d, e, f} are instances; Plant and Animal are classes

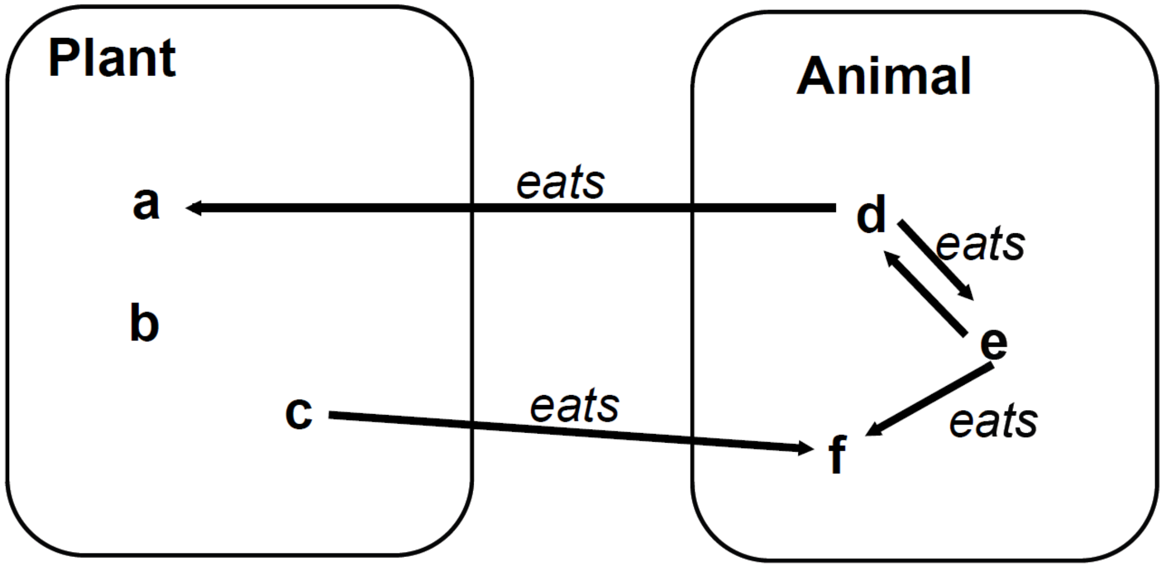


$Plant \sqcap Animal \sqsubseteq \bot$ (disjointness)

$\top \sqsubseteq Plant \sqcup Animal$ (partition)

Value and exists restrictions

{a, b, c, d, e, f} are instances; Plant and Animal are classes



$\exists$ eats.Animal = {c, d, e} $\forall$ eats.Animal = {a, b, c, e, f}

$\exists$ eats.Animal $\sqcap$ $\forall$ eats.Animal = {c, e}

Model theory

Δ^I universal domain of individuals, let

Δ^I ={a, b, c, d, e, f}

$eats^I$ set of pairs for the relation eats, let

$eats^I$ = {<d,a>,<d,e>,<e,d>,<e,f>,<c,f>}

For all concepts C:

i) $C^I \subseteq \Delta^I$

ii) $C^I \neq \emptyset$

Let $Animal^I$ = {d, e, f}

$\therefore$ $(\neg Animal)^I$ = {a, b, c}

$\therefore$ $(\forall eats.Animal)^I$ = {a, b, c, e, f}

$\therefore$ $(\exists eats.\ Animal)^I$ = {c, d, e}

Inference

MeatEater ≡ $\forall$eats. Animal = {a, b, c, e, f}

Vegetarian ≡ $\forall$eats. ¬Animal = {a, b, f}

Omnivore ≡ $\exists$eats. Animal = {c, d, e}

Inference:

From the above classes we can see that:

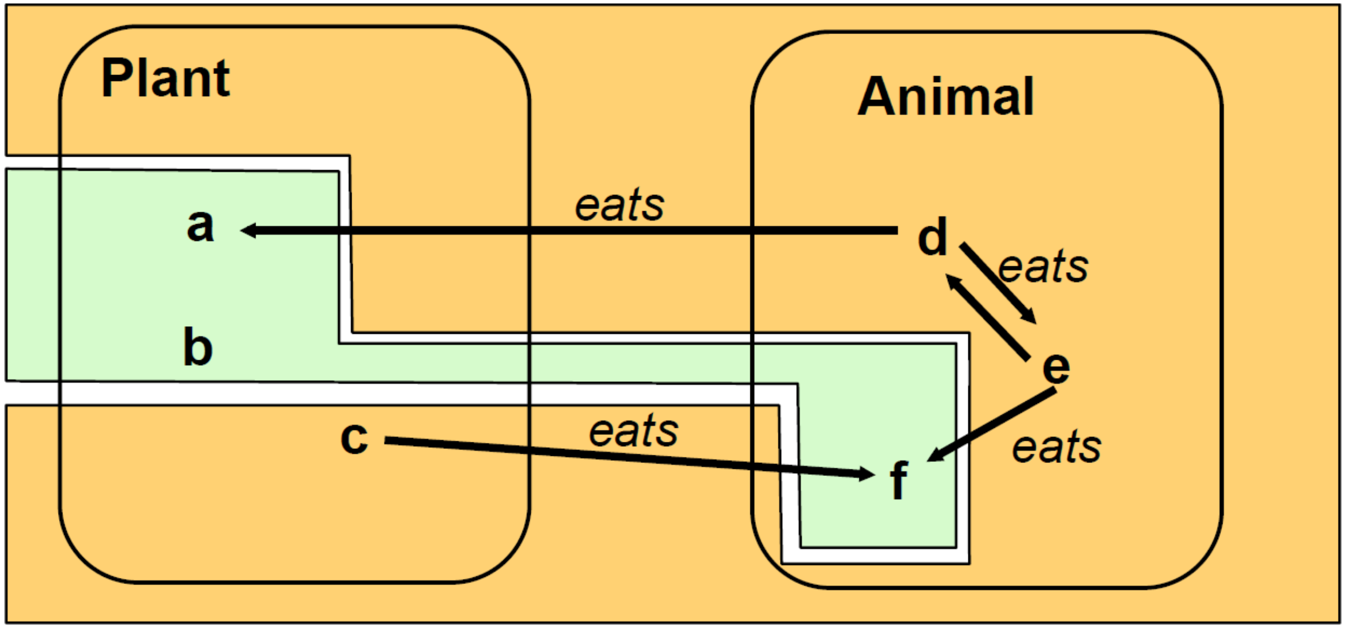
- MeatEater subsumes Vegetarian
- Vegetarian is disjoint from Omnivore

in this model, with these definitions.

The problem is to prove this for ALL models.

Value and exists restrictions

{a, b, c, d, e, f} are instances; Plant and Animal are classes



Vegetarian = {a, b, f}
Omnivore = {c, d, e}
disjoint?

MeatEater = {a, b, c, e, f}

DL Inference

- Inference can be expressed in terms of the model
  - **Satisfiability** of C: C^I is non-empty
  - **Subsumption:** $C \sqsubseteq D$ iff $C^I \subseteq D^I$ ("C is subsumed by D")
  - **Equivalence:** $C \equiv D$ iff $C^I = D^I$
  - **Disjointness:** $(C \sqcap D) \sqsubseteq \bot$ iff $C^I \cap D^I \equiv \varnothing$
- Tractable/terminating inference algorithms exist

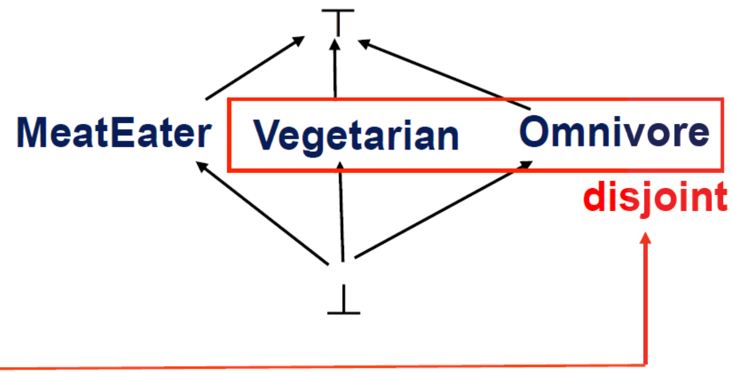
DL Inference

$MeatEater \equiv \forall eats.\ Animal$

$Vegetarian \equiv \forall eats.\ \neg Animal$

$Omnivore \equiv \exists eats.\ Animal$

Query	Answer
$Vegetarian \sqsubseteq MeatEater$	No
$(MeatEater \sqcap Vegetarian) \sqsubseteq \bot$	No
$(Omnivore \sqcap Vegetarian) \sqsubseteq \bot$	Yes



DL inference

Inference has 2 equivalent notions – so implementing one lets us prove all 4 properties

- Reduction to subsumption $\sqsubseteq$:
  - Unsatisfiability of C: $C \sqsubseteq \bot$
  - Equivalence: $C \equiv D$ iff $C \sqsubseteq D$ and $D \sqsubseteq C$
  - Disjointness: $(C \sqcap D) \sqsubseteq \bot$
- Reduction to unsatisfiability $C^I = \varnothing$:
  - Subsumption: $C \sqsubseteq D$ iff $(C \sqcap \neg D)$ is **unsatisfiable** i.e. $C \sqcap \neg D \sqsubseteq \bot$
  - Equivalence: $C \equiv D$ iff $(C \sqcap \neg D)$ and $(D \sqcap \neg C)$ are unsatisfiable
  - Disjointness: $(C \sqcap D)$ is unsatisfiable

DL Summary

- DLs are a family of languages based on subsets of first-order logic.
  - The level of expressivity depends on the attributes of the language.
  - Attributes are indicated by letters; DL language names consist of a series of these letters. The expressivity of any DL language can therefore be inferred from its name.
- DLs allow complex expressions of how concepts relate to one another.
- There are many algorithms (e.g. Tableaux Algorithms) that allow efficient reasoning over DLs.

OWL

Web Ontology Language: OWL

- Web Ontology Language (OWL) is W3C Recommendation for an ontology language for the web
  - Has an XML syntax
- OWL is layered on RDF and RDFS (other W3C standards)
  - Conforms to the RDF/RDFS semantics
  - OWL has 3 versions:
    - OWL-Lite – the simpler OWL DL
    - OWL-DL – more expressive DL
    - OWL-Full – not confined to DL, closer to FOL
  - OWL DLs extend ALC
    - Allow instances to be represented (A Box)
    - Provides datatypes
    - Provides number restrictions
- OWL 1.1 and 2 extend OWL DL

OWL Object Properties

OWL makes a distinction between Object types and Datatypes Object types and Object properties are the same as in ALC

CN, DN	Atomic concepts	Non-empty sets CN^I, $DN^I \subseteq \Delta^I$
$\bot^I$	owl:Nothing	ϕ
$\top^I$	owl:Thing	Δ^I
$(\neg C)^I$	Full Negation	$\Delta^I \setminus C^I$
$(C \sqcup D)^I$	Union	$C^I \cup D^I$
$(C \sqcap D)^I$	Intersection	$C^I \cap D^I$
$(\forall R.C)^I$	Value restriction	$\{x \in \Delta^I \mid \forall y <x,y> \in R^I \Rightarrow y \in C^I\}$
$(\exists R.C)^I$	Full existential quantification	$\{x \in \Delta^I \mid \exists y <x,y> \in R^I \wedge y \in C^I\}$

Terminological axioms: Inclusions and equalities

Concepts: $C \sqsubseteq D$ iff $C^I \subseteq D^I$

$C \equiv D$ iff $C^I = D^I$

OWL Datatypes

Datatypes Δ^I_D are distinct from Object types Δ^I.

- A datatype relation U, e.g. age, relates an object type, e.g. Person to an integer
  - $\exists$ age.Integer (the set of things that have some Integer as age)
- Datatypes correspond to XML Schema types
- OWL also provides hasValue: U:v to represent specific datatype values
  - age:29 (the set of things age 29)

D	Data Range	$D^I \subseteq \Delta_D^I$
$(\forall U.D)^I$	Value restriction	$\{x \in \Delta^I \mid \forall y \langle x,y\rangle \in U^I \Rightarrow y \in D^I\}$
$(\exists U.D)^I$	Full existential quantification	$\{x \in \Delta^I \mid \exists y \langle x,y\rangle \in U^I \wedge y \in D^I\}$

OWL Number Restrictions

OWL adds (unqualifying) number restrictions to ALC

- ≥ n R
  - Defines the set of instances, x, for which there are n or more instances, y, such that R(x, y)
  - BusyParent ≡ ≥ 3 hasChild
- ≤ n R
  - Defines the set of instances, x, for which there are n or less instances, y, such that R(x, y)

≥ n R	**Minimum cardinality**	$\{x \in \Delta^I \mid \#(\langle x,y\rangle \in R^I) \geq n\}$
≤ n R	**Maximum cardinality**	$\{x \in \Delta^I \mid \#(\langle x,y\rangle \in R^I) \leq n\}$

Datatypes Δ^I_D and Object types Δ^I

BN, CN	Non-empty sets BN^I, $CN^I \subseteq \Delta^I$
D	$D^I \subseteq \Delta_D{}^I$
$(B \sqcup C)^I$	$\{x \in \Delta^I \mid x \in B^I \vee x \in C^I\}$
$(B \sqcap C)^I$	$\{x \in \Delta^I \mid x \in B^I \wedge x \in C^I\}$
$(\forall R.C)^I$	$\{x \in \Delta^I \mid \forall y\ (\langle x,y\rangle \in R^I \Rightarrow y \in C^I)\}$
$(\exists R.C)^I$	$\{x \in \Delta^I \mid \exists y\ \langle x,y\rangle \in R^I \wedge y \in C^I\}$
$(\forall U.D)^I$	$\{x \in \Delta^I \mid \forall y\ (\langle x,y\rangle \in U^I \Rightarrow y \in D^I)\}$
$(\exists U.D)^I$	$\{x \in \Delta^I \mid \exists y\ \langle x,y\rangle \in U^I \wedge y \in D^I\}$

OWL-DL Cardinality

BN, CN	Non-empty sets $BN^I, CN^I \subseteq \Delta^I$
$(\forall R.C)^I$	$\{x \in \Delta^I \mid \forall y\ (\langle x,y \rangle \in R^I \Rightarrow y \in C^I)\}$
$(\exists R.C)^I$	$\{x \in \Delta^I \mid \exists y\ \langle x,y \rangle \in R^I \wedge y \in C^I\}$
$(\geq n\ R)^I$	$\{x \in \Delta^I \mid \#(\langle x,y \rangle \in R^I) \geq n\}$
$(\leq n\ R)^I$	$\{x \in \Delta^I \mid \#(\langle x,y \rangle \in R^I) \leq n\}$

OWL-DL Cardinality

Bicycle $\equiv \geq 2$ hasWheel $\sqcap \leq 2$ hasWheel $\sqcap$ $\forall$hasPart.$\neg$Engine

- Unicyles would have 1 wheel, tricycles 3 wheels, motorcycles would have 2 wheels and an Engine......
- hasWheel is needed, rather than hasPart, as OWL-DL cannot specify the type of the range to be Wheel
  - Define hasWheel a subProperty of hasPart
  - Range of hasWheel: Wheel

OWL domain and range axioms

Domain and range specifications

domain(R, C) :: $(\geq 1\ R) \sqsubseteq C$

Consider:

1) $\exists$hasChild.Male : anything with a male child

2) Person $\sqcap$ $\exists$hasChild.Male : person with a male child:

The Person intersection in 2) is implicit in 1) if the domain of hasChild is defined as Person

range(R, C) :: $\top \sqsubseteq \forall R.C$

OWL abstract syntax

- The ALC-style syntax is not suitable for the WWW
- OWL needs to conform to the RDF/XML syntax

OWL/ALC DL Syntax		OWL Abstract Syntax
(¬C)	Full Negation	< complementOf C >
(C ⊔ D)	Union	< unionOf C D >
(C ⊓ D)	Intersection	< intersectionOf C D >
(∀R.C)	Value restriction	< Restriction < onProperty R > < allValuesFrom C >>
(∃R.C)	Full existential quantification	< Restriction < onProperty R > < someValuesFrom C >>
(C ⊓ D) = ⊥	Disjoint concepts	< disjoint C D >
C ⊑ D	Subclass of /subsumes	< C <subClassOf D>>
C ≡D	Equivalent	<C <equivalentClass D>>

OWL in RDF/XML format (not examinable)

Class definitions C ⊑ D and Property restrictions ∀R.C in RDF/XML syntax: DieselEngine is a subclass of Engine: DieselEngine ⊑ Engine

```
<owl:Class rdf:ID ="DieselEngine">
  <rdfs:subClassOf rdf:resource="&base;Engine"/>
</owl:Class>
```

CarPart is a subclass of the parts of the Car: CarPart ⊑ ∀partOf.Car

```
<owl:Class rdf:ID="CarPart">
  <rdfs:subClassOf>
    <owl:Restriction>
      <owl:onProperty rdf:resource="&base;partOf"/>
      <owl:allValuesFrom rdf:resource="#Car"/>
    </owl:Restriction>
  </rdfs:subClassOf>
</owl:Class>
```

<owl:Class> is used to specify the rdf:type

rdf:ID introduces new terms (compare with rdf:about to refer to terms)

&base; is a namespace (assumed to be defined)

OWL in RDF/XML format (not examinable)

CarEngine is equivalent to the intersection of Engine and ∀partOf.Car : CarEngine ≡ Engine ⊓ ∀partOf.Car

```
<owl:Class rdf:ID=”CarEngine">
  <owl:equivalentClass>!
    <owl:Class>
    <owl:intersectionOf rdf:parseType=“Collection”>
        <owl:Class rdf:about=“#Engine”/>
      <owl:Restriction>
        <owl:onProperty rdf:resource=“&base;partOf”/>
        <owl:allValuesFrom rdf:resource=“#Car”/>
      </owl:Restriction>
    </owl:intersectionOf>
    </owl:Class>
  </owl:equivalentClass>
</owl:Class>
```

Protégé reads and writes this syntax.

Use HP’s Jena toolkit in Java applications that need to read/write/manipulate RDF/S or OWL.

OWL Summary

OWL:

- Is a web-compatible ontology language
- Syntax based on RDF/XML
- Semantics compatible with RDF and RDFS
- OWL-Lite and OWL-DL have a formal interpretation based on DLs
- Extensive documentation at http://www.w3c.org
- Editing Tools: Protégé 4

Reading

- Ian Horrocks, Peter F. Patel-Schneider, and Frank van Harmelen. *From SHIQ and RDF to OWL: The making of a web ontology language*. J. of Web Semantics, 1(1):7-26, 2003.
- Non-compulsory additional reading: SWWO Ch11 & Ch12

Task

- Write down a few universal and existential restriction statements in DL.
- Add some OWL cardinality restriction statements.