Knowledge Representation & Reasoning
&
Introduction To Knowledge Graphs

Week 8 - 10 | Fall 2022

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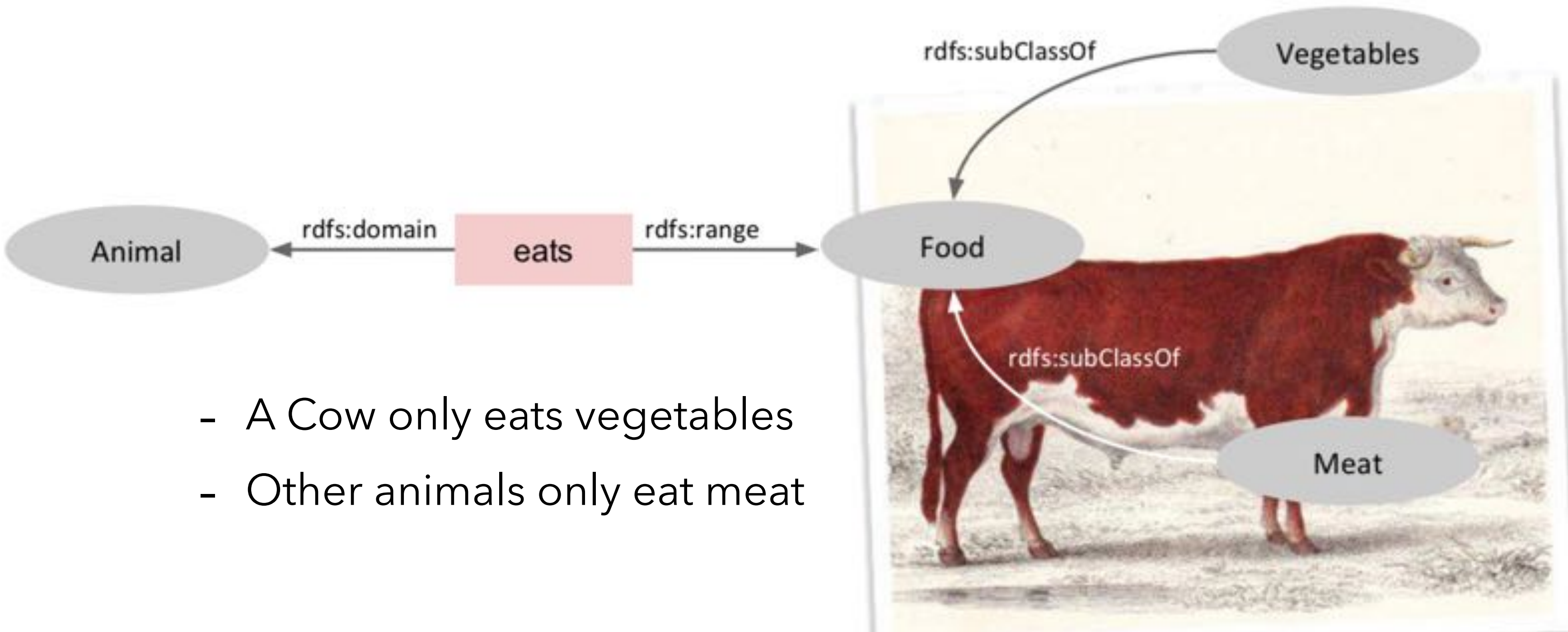
Limitations of RDFS

Where RDF(S) Is Not Sufficient...

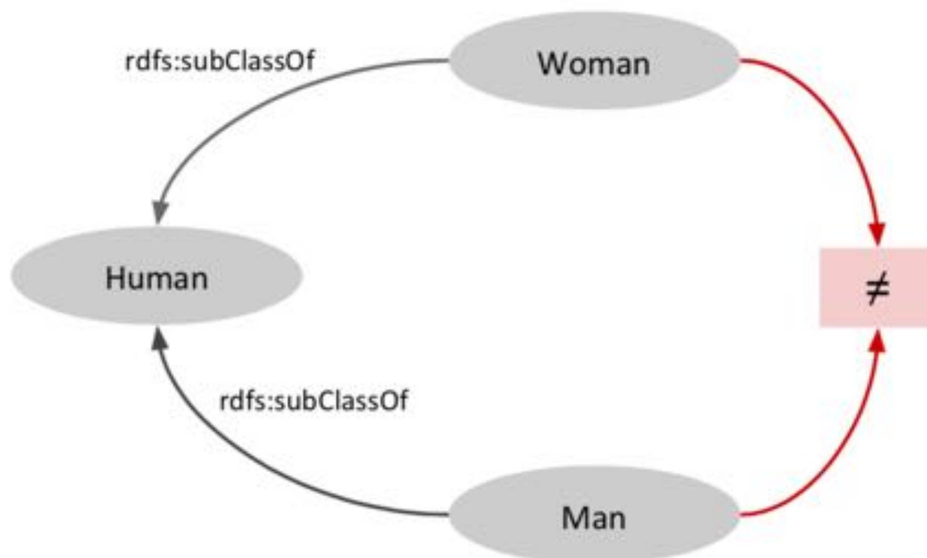
- **Locality of Global Properties**



- A Cow only eats vegetables
- Other animals only eat meat

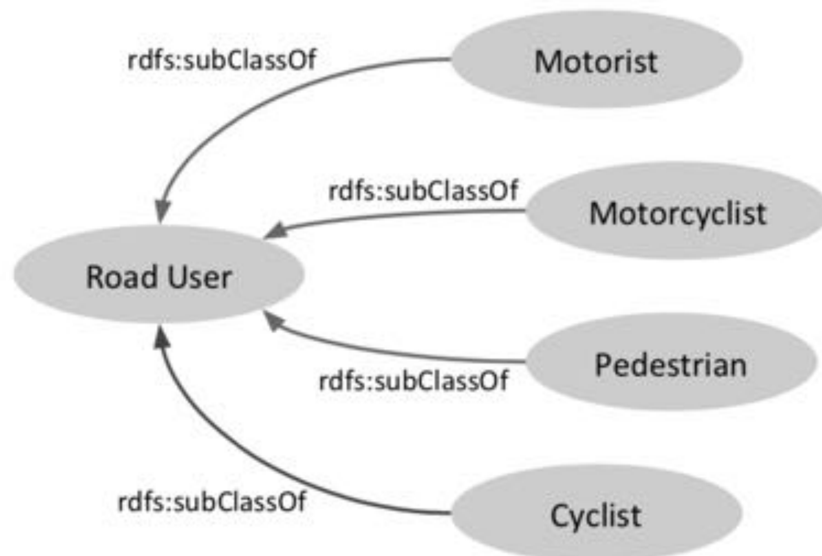
Where RDF(S) Is Not Sufficient...

- **Disjunctive Classes**
  - RDFS Subclass relation cannot express disjunctive class (subclass) membership



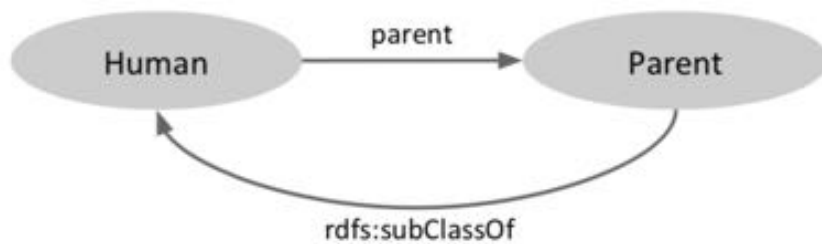
Where RDF(S) Is Not Sufficient...

- **Class Combinations**
  - Combination of classes define a new class
  - New class contains only members from given class combinations



Where RDF(S) Is Not Sufficient…

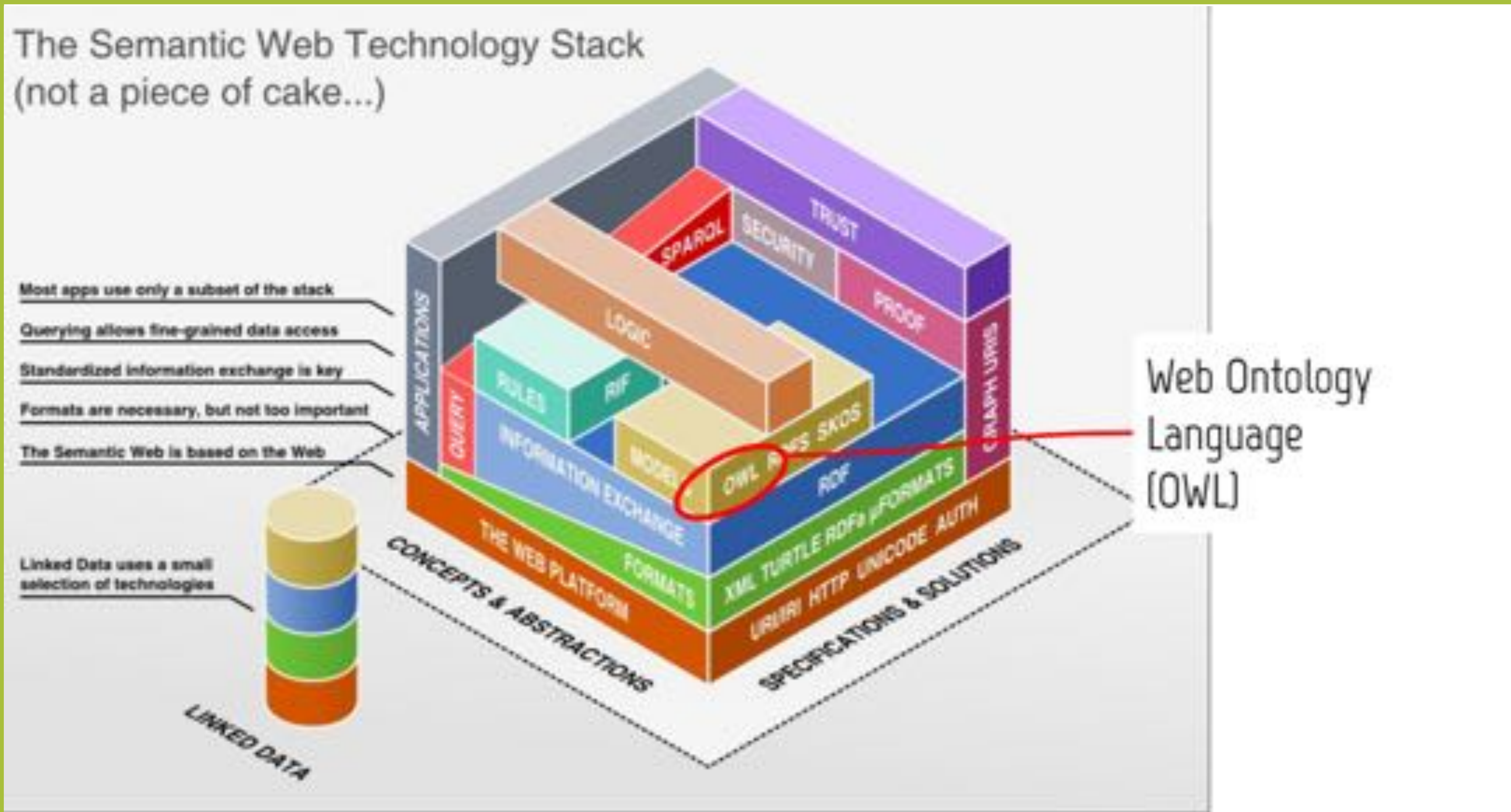
- **Cardinality Constraints**
  - Every human (usually) has two parents



Where RDF(S) Is Not Sufficient…

- **Special Property Constraints**
  - Transitivity (e.g. „is greater than“)
  - Uniqueness (e.g. „is mother of“)
  - Inversiveness (e.g. „is parent of“ and „is child of“)

- **General Problem of RDF(S)**
  - RDF(S) does not have the possibility of **negation**
    - *hpi:harald rdf:type hpi:Vegetarian .*
    - *hpi:harald rdf:type hpi:NonVegetarian .*
    - *…does not automatically generate a contradiction*


The Semantic Web Technology Stack
(not a piece of cake...)
Most apps use only a subset of the stack
Querying allows fine-grained data access
Standardized information exchange is key
Formats are necessary, but not too important
The Semantic Web is based on the Web
Linked Data uses a small selection of technologies
LINKED DATA
APPLICATIONS
QUERY
SPARQL
SECURITY
TRUST
PROOF
LOGIC
RULES
RIF
MODEL
OWL
SKOS
RDF
GRAPH URIS
INFORMATION EXCHANGE
FORMATS
XML TURTLE RDFa µFORMATS
THE WEB PLATFORM
URI/IRI HTTP UNICODE AUTH
CONCEPTS & ABSTRACTIONS
SPECIFICATIONS & SOLUTIONS
Web Ontology Language (OWL)

Web Ontology Language - OWL

Ontologies and Logic

An **ontology** is an **explicit**, **formal specification of a shared conceptualization**.

acc. to Thomas R. Gruber: A Translation Approach to Portable Ontology Specifications. Knowledge Acquisition, 5(2):199-220, 1993.

formal (machine readable) semantics

mathematical logic

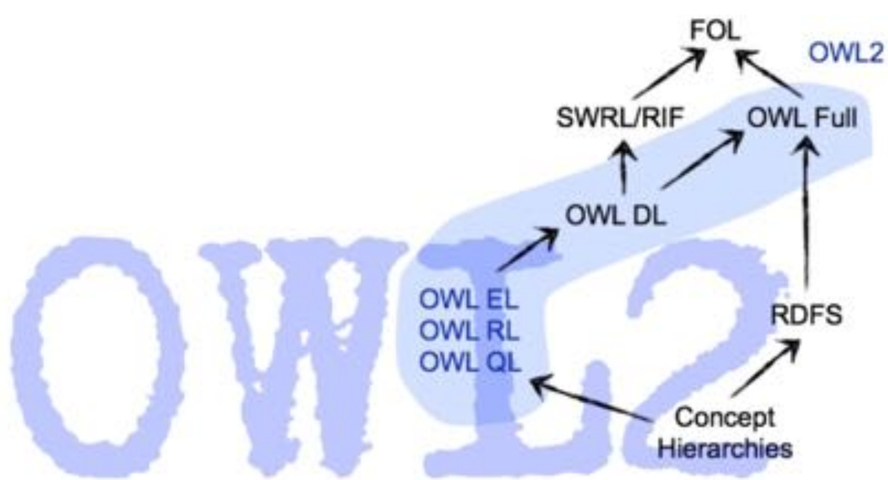
Foundations of Logic

- Definition (for our lecture):
  Logic is the study of how to make formal correct deductions and inferences.

- Why "formal logic"? => to enable automation

Web Ontology Language - OWL

- OWL is a semantic fragment of **First Order Logic (FOL)**
- OWL also exists in different flavors
- OWL EL, OWL RL, OWL QL ⊆ OWL2 DL ⊆ OWL2 Full



OWL2 Is Based on the Description Logic SROIQ(D)

Class Expressions

- Class names A, B
- Conjunction $C \sqcap D$
- Disjunction $C \sqcup D$
- Negation $\neg C$
- Exist. property restriction $\exists R.C$
- Univ. property restriction $\forall R.C$
- Self $\exists S.\mathrm{Self}$
- Greater-than $\geq n\ S.C$
- Less-than $\leq n\ S.C$
- Enumerated classes $\{a\}$

Properties

- Property names R, S, T
- Simple properties S, T
- Inverse properties R^{-}
- Universal property U

Tbox (Class axioms)

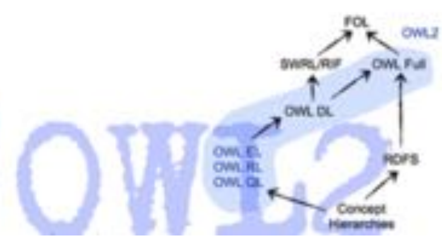
- Inclusion $C \sqsubseteq D$
- Equivalence $C \equiv D$

Rbox (Property Axioms)

- Inclusion $R_1 \sqsubseteq R_2$
- General Inclusion $R^{(-)}_1 \circ R^{(-)}_2 \circ \ldots \circ R^{(-)}_n \sqsubseteq R$
- Transitivity
- Symmetry
- Reflexivity
- Irreflexivity
- Disjunctiveness

Abox (Facts)

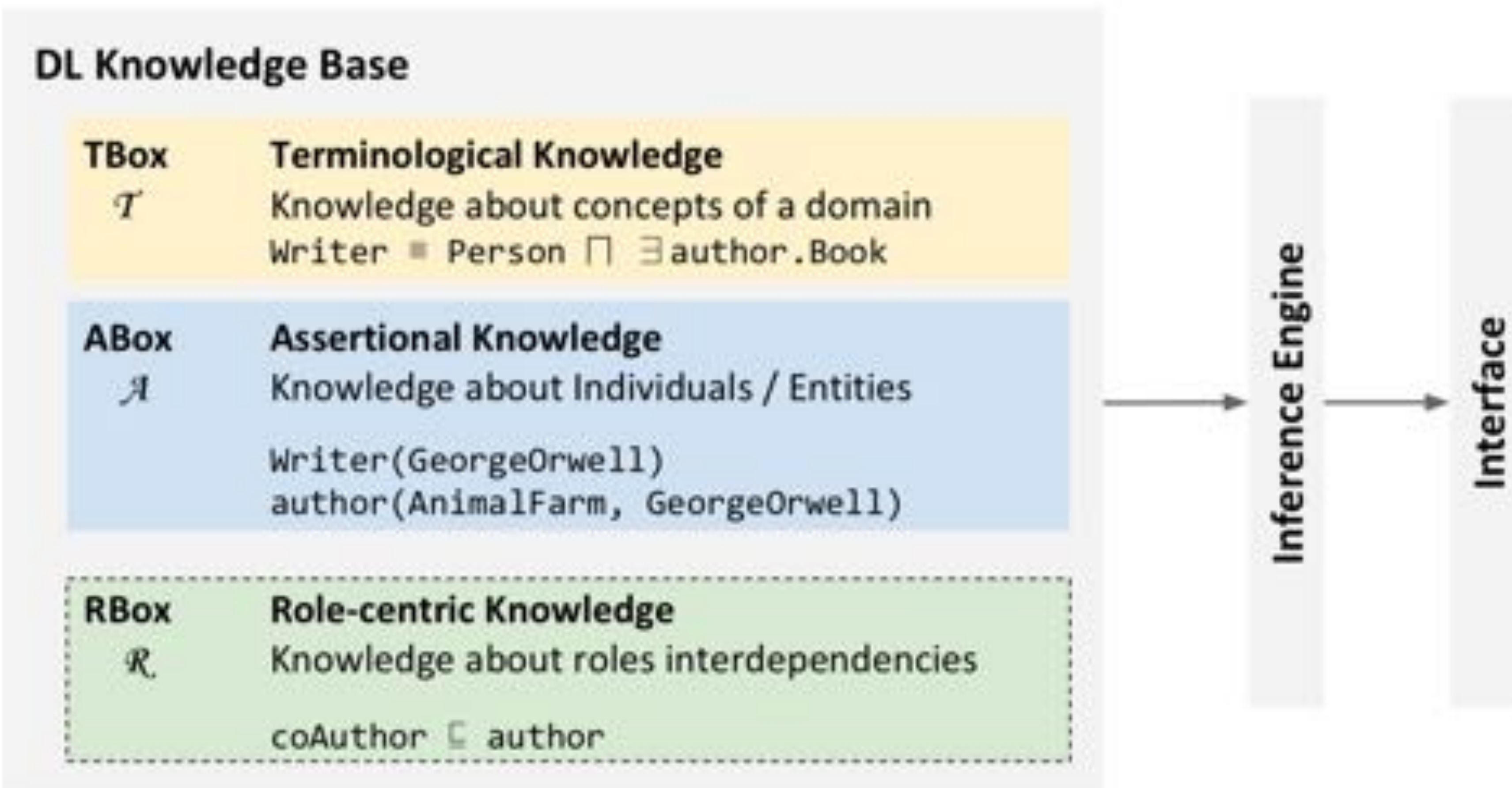
- Class membership $C(a)$
- Property relation $R(a, b)$
- Negated property relation $\neg S(a, b)$
- Equality $a = b$
- Inequality $a \neq b$



Description Logics (DLs)

- DLs are fragments of FOL (*compromise of expressivity and saleability*)
- A DL models **concepts, roles** and **individuals**, and their relationships.
- In DL from *simple descriptions more complex descriptions are created* with the help of constructors
- DLs differ in applied constructors (Expressivity)
- DLs have been developed from “semantic Networks”
- DLs are **decidable** (most of the time)
- DLs possess **sufficient expressivity** (most of the time)
- DLs are related to modal logics
- Example for a DL:
  - W3C Standard OWL 2 DL is based on Description Logics *SROIQ(D)*

General DL Architecture



Description Logics (DLs)

- DLs are a family of logic-based formalisms applied for knowledge representations.
- *ALC (**A**ttribute **L**anguage with **C**omplement)*
  - Is the smallest deductively complete DL
    - **Conjunction, Disjunction, Negation** are class constructors, denoted as $\sqcap$, $\sqcup$, $\neg$
    - Quantifiers restrict domain and range of roles

Attributive Language With Complements (-ALC)

- **Basic Building Blocks:**
  - Classes
  - Roles / Properties
  - Individuals
- Writer (GeorgeOrwell)
  - *Individual GeorgeOrwell is of class Writer*
- Book (NineteenEightyfour)
  - *Individual NineteenEightyfour is of class Book*
- author (NineteenEightyfour, GeorgeOrwell)
  - *The book NineteenEightyfour has the author GeorgeOrwell*

Attributive Language With Complements (-ALC)

- $\mathcal{ALC}$ **Atomic Types**
  - Concept names A,B, ...
  - Special concepts
    - $\top$ - Top (universal concept)
    - $\bot$ - Bottom concept
  - Role names R,S, ...
- $\mathcal{ALC}$ **Constructors**
  - Negation: $\neg C$
  - Conjunction: $C \sqcap D$
  - Disjunction: $C \sqcup D$
  - Existential quantifier: $\exists R.C$
  - Universal quantifier: $\forall R.C$

Attributive Language With Complements (-ALC)

- **Class Inclusion**
  - Novel ⊑ Book
    - *every novel is also a book*
    - equals FOL (∀x) (Novel(x) → Book(x))

- **Class Equivalence**
  - Novel ≡ Prose
    - *all Prose are exactly Novels*
    - equals FOL (∀x) (Novel(x) ↔ Prose(x))

Complex Class Relations

- Conjunction ⊓
- Disjunction ⊔
- Negation ¬

$$\text{Novel} \sqsubseteq (\text{Book} \sqcap \text{Fiction}) \sqcup (\text{Paperback} \sqcap \neg\text{Poetry})$$

$\mathcal{ALC}$

$$(\forall x)(\text{Novel}(x) \rightarrow ((\text{Book}(x) \land \text{Fiction}(x)) \lor (\text{Paperback}(x) \land \neg\text{Poetry}(x)))$$

FOL

ALC - Quantifiers On Roles

- **Strict Binding** of the Range of a Role to a Class
  - $\text{Book} \sqsubseteq \forall \text{author.Writer}$
  - *A Book must be authored by a Writer*
  - $(\forall x)(\text{Book}(x) \rightarrow (\forall y)(\text{author}(x,y) \rightarrow \text{Writer}(y)))$

- **Open Binding** of the Range of a Role to a Class
  - $\text{Book} \sqsubseteq \exists \text{author.Person}$
  - *Every Book has at least one author (who is a person)*
  - $(\forall x)(\text{Book}(x) \rightarrow (\exists y)(\text{author}(x,y) \land \text{Person}(y)))$

Formal Syntax

- Production rules for creating classes in $\mathcal{ALC}$:
  (A is an atomic class, C and D are complex Classes and R a Role)

  - $C, D ::= A \mid \top \mid \bot \mid \neg C \mid C \sqcap D \mid C \sqcup D \mid \exists R.C \mid \forall R.C$

- An $\mathcal{ALC}$ **TBox** contains assertions of the form $C \sqsubseteq D$ and $C \equiv D$, where C, D are complex classes.
- An $\mathcal{ALC}$ **ABox** contains assertions of the form $C(a)$ and $R(a, b)$, where C is a complex Class, R a Role and a, b Individuals.
- An $\mathcal{ALC}$-**Knowledge Base** contains an ABox and a TBox.

Description Logics Family

- $\mathcal{ALC}$: Attribute Language with Complement
- $\mathcal{S}$: $\mathcal{ALC}$ + Transitivity of Roles
- $\mathcal{H}$: Role Hierarchies
- $\mathcal{O}$: Nominals
- $\mathcal{I}$: Inverse Roles
- $\mathcal{N}$: Number restrictions $\leq nR$ etc.
- $\mathcal{Q}$: Qualified number restrictions $\leq nR.C$ etc.
- $(\mathcal{D})$: Datatypes
- $\mathcal{F}$: Functional Roles
- $\mathcal{R}$: Role Constructors

- OWL 2 DL is $\mathcal{SROIQ(D)}$

Open World vs Closed World Assumption

The Open World of Linked Data

- foaf:**publications** rdf:type rdf:Property ;
  rdf:domain foaf:Person ;
  rdf:range foaf:Document .

  dbpedia:Hasso_Plattner_Institute rdf:type dbo:Organisation ;
  foaf:**publications** <https://hpi.de/technical-reports/> .

  foaf:Person ≠ dbo:Organisation

- According to RDF(S) semantics (foaf:publications rdf:domain foaf:Person .) it can be deduced that

  dbpedia:Hasso_Plattner_Institute rdf:type foaf:Person .

No Unique Name Assumption (UNA)

- In Databases, each individual has a single, unique name
- In DLs, individuals may have more than one name
  - Thus, in DLs it is not necessarily true that two individuals with different names are really two different individuals
- Example:
  - Wizard(HarryPotter) hasFriend(HarryPotter, RonWeasley)
    Wizard(RonWeasley)
  - Wizard(HermioneGranger) hasFriend(HarryPotter, HermioneGranger)
- How many friends does Harry Potter have?
  - DBs, with UNA: 2
  - DLs, no UNA: at least 1
    (since we did not explicitly say that RonWeasley and HermioneGranger are different individuals)

The Open World Assumption - OWA

- If we have an **empty** DL ontology, **everything is possible**
- We then **constrain an ontology iteratively,** making it more restrictive as we go.
- We state what is **not possible**, what is **forbidden** or **excluded**.

$$\text{Sheep} \sqsubseteq \text{Animal} \sqcap \forall \text{hasLimbs}.\text{Leg}$$

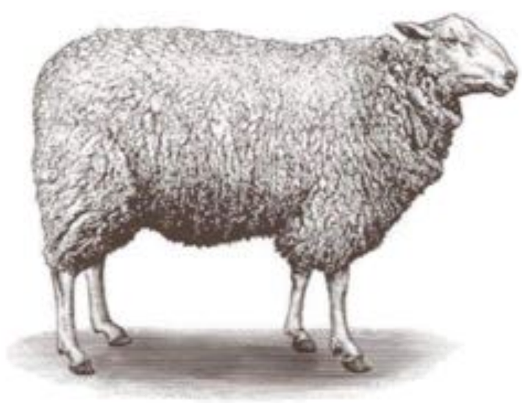
The Open World Assumption - OWA

- Question: Can Sheep fly?

- Answer under OWA assumption:
  - *No idea, but probably yes (according to our knowledge base)*
- In the OWA, unless we have a statement (or we can infer) "sheep can/cannot fly" we return "don't know"

- In the real world, we are used to deal with incomplete information

`A sheep is an animal with 4 legs.`



The Open World Assumption - OWA

- In the Semantic Web / Linked Data we expect people to extend our own models (but we don't worry in advance how)

- The OWA assumes incomplete information by default

- Therefore, we can intentionally underspecify our models
  and allow others to reuse and extend

```
A sheep is an animal with 4 legs that
(if lifted) can fly
```

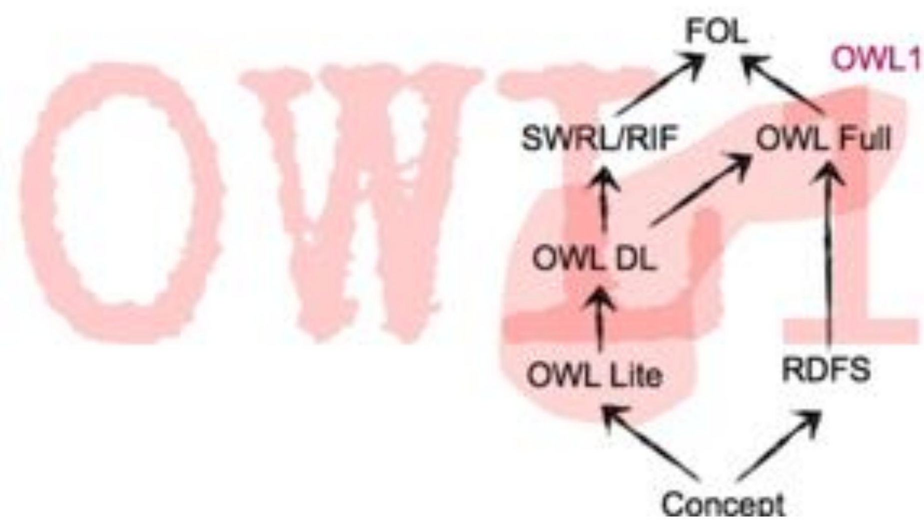
OWL Syntax Variations

Web Ontology Language - OWL

- OWL [$\mathcal{SHOIN}(\mathcal{D})$] W3C Recommendation since 2004
- OWL [$\mathcal{SROIQ}(\mathcal{D})$] W3C Recommendation since 2009
- An OWL Ontology consists of
  - Classes / properties / individuals (instances of classes)
- **Open World Assumption**
  - ‘Absence of information must not be valued as negative information’
  - e.g. : sitsNextTo (PersonA, PersonB)
  - PersonA may also sit next to another person…
- **No Unique Name Assumption**
  - ‘Difference must be expressed explicitly’
  - e.g. : PersonA possibly denotes the same individual as PersonB

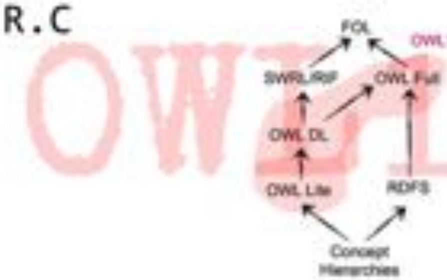
Web Ontology Language - OWL

- OWL is a semantic fragment of FOL
- OWL1 also exists in different flavours
  - OWL Lite ⊆ OWL1 DL ⊆ OWL1 Full



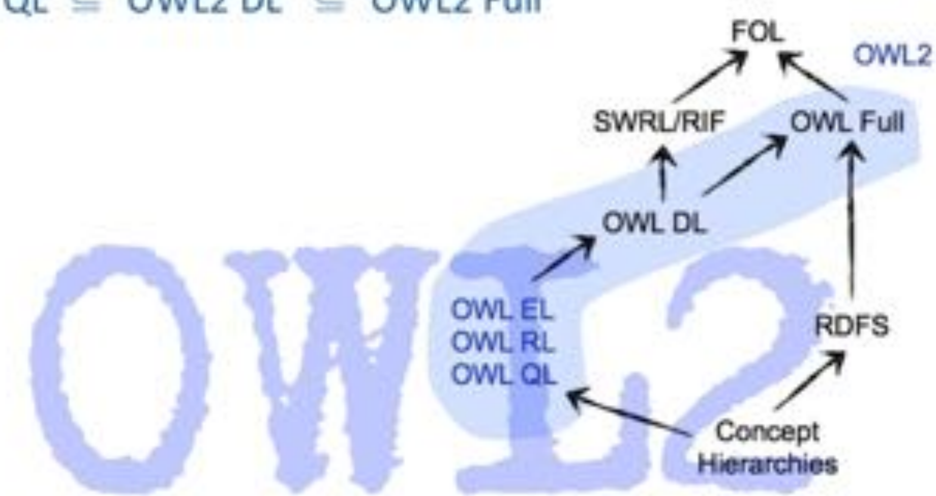
OWL1 Is Based on $\mathcal{SHOIN(D)}$

- **Axioms**
  - **TBox**: subclass relationships $C \sqsubseteq D$ ($\mathcal{H}$)
  - **RBox**: subproperty relationships $R \sqsubseteq S$ ($\mathcal{H}$),
    inverse properties R^{-} ($\mathcal{I}$), transitivity $\sqsubseteq^{+}$ ($\mathcal{S}$)
  - **ABox**: facts for classes C(a), properties R(a,b),
    equality a=b, difference $a \neq b$
- **Class constructors**:
  - conjunction $C \sqcap D$, disjunction $C \sqcup D$, negation $\neg C$ of classes
  - property restrictions: universal $\forall$R.C and existential $\exists$R.C
  - number restrictions: $\leq n$ R and $\geq n$ R ($\mathcal{N}$)
  - closed classes (nominals): {a} ($\mathcal{O}$)
- Datatypes ($\mathcal{D}$)



Web Ontology Language - OWL

- OWL is a semantic fragment of FOL
- OWL2 also exists in different flavours
  - OWL EL, OWL RL, OWL QL ⊆ OWL2 DL ⊆ OWL2 Full



OWL2 Is Based on $\mathcal{SROIQ}(\mathcal{D})$

Class Expressions

- Class names A, B
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- Inclusion $R_1 \sqsubseteq R_2$
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- Transitivity
- Symmetry
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- Irreflexivity
- Disjunctiveness

Abox (Facts)

- Class membership $C(a)$
- Property relation $R(a,b)$
- Negated property relation $\neg S(a,b)$
- Equality $a=b$
- Inequality $a \neq b$

OWL Syntax Variants

- OWL2 can be represented in different Syntax variants
  - **Functional Syntax:** substitutes abstract syntax of OWL1
  - **RDF/XML-Syntax:** extension of existing OWL/RDF
  - **OWL/XML-Syntax:** independent XML serialisation
  - **Manchester-Syntax:** machine readable syntax, esp. for ontology editors
  - **Turtle:** concise and easy readable

OWL2 Functional Syntax Example

$$\text{HappyPerson} \equiv \forall \text{hasChild.HappyPerson} \sqcap \exists \text{hasChild.HappyPerson}$$

```
Ontology(
  Declaration(Class(:HappyPerson))
  EquivalentClasses(:HappyPerson
    ObjectIntersectionOf(
      ObjectAllValuesFrom(:hasChild :HappyPerson)
      ObjectSomeValuesFrom(:hasChild :HappyPerson)
    )
  )
)
```

- Functional Syntax is easy to define, no RDF restrictions, more compact

OWL2 RDF/XML Syntax Example

$$\mathrm{HappyPerson} \equiv \forall \mathrm{hasChild.HappyPerson} \sqcap \exists \mathrm{hasChild.HappyPerson}$$

```
<?xml version="1.0"?>
<rdf:RDF xmlns=...>
<owl:ObjectProperty rdf:about="http://example.org/turtle#hasChild"/>

<owl:Class rdf:about="http://example.org/turtle#HappyPerson">
  <owl:equivalentClass>
    <owl:Class>
      <owl:intersectionOf rdf:parseType="Collection">
        <owl:Restriction>
          <owl:onProperty rdf:resource="http://example.org/turtle#hasChild"/>
          <owl:allValuesFrom rdf:resource="http://example.org/turtle#HappyPerson"/>
        </owl:Restriction>
        <owl:Restriction>
          <owl:onProperty rdf:resource="http://example.org/turtle#hasChild"/>
          <owl:someValuesFrom rdf:resource="http://example.org/turtle#HappyPerson"/>
        </owl:Restriction>
      </owl:intersectionOf>
    </owl:Class>
  </owl:equivalentClass>
</owl:Class>
</rdf:RDF>
```

OWL2 OWL/XML Syntax Example

- HappyPerson ≡ ∀hasChild.HappyPerson ⊓ ∃hasChild.HappyPerson

```
<?xml version="1.0"?>
<Ontology xmlns="http://www.w3.org/2002/07/owl#"....>

  <Declaration>
    <Class abbreviatedIRI=":HappyPerson"/>
  </Declaration>
  <EquivalentClasses>
    <Class abbreviatedIRI=":HappyPerson"/>
      <ObjectIntersectionOf>
        <ObjectAllValuesFrom>
          <ObjectProperty abbreviatedIRI=":hasChild"/>
          <Class abbreviatedIRI=":HappyPerson"/>
        </ObjectAllValuesFrom>
        <ObjectSomeValuesFrom>
          <ObjectProperty abbreviatedIRI=":hasChild"/>
          <Class abbreviatedIRI=":HappyPerson"/>
        </ObjectSomeValuesFrom>
      </ObjectIntersectionOf>
  </EquivalentClasses>
</Ontology>
```

OWL2 Manchester Syntax Example

$\text{HappyPerson} \equiv \forall \text{hasChild.HappyPerson} \sqcap \exists \text{hasChild.HappyPerson}$

```
Ontology:

  ObjectProperty: hasChild

  Class: HappyPerson

  EquivalentTo:
        (hasChild only HappyPerson)
         and (hasChild some HappyPerson)
```

OWL2 Turtle Syntax Example

HappyPerson ≡ ∀hasChild.HappyPerson ⊓ ∃hasChild.HappyPerson

```
:HappyPerson a owl:Class ;
   owl:equivalentClass  [
   a owl:Class ;
   owl:intersectionOf ([ a owl:Restriction ;
                         owl:onProperty :hasChild ;
                         owl:allValuesFrom :HappyPerson  ]
                       [ a owl:Restriction ;
                         owl:onProperty :hasChild ;
                         owl:someValuesFrom :HappyPerson ]
                       )
    ] .
```

OWL Basic Building Blocks

OWL Basic Building Blocks

- OWL namespace:
  @prefix owl: <http://www.w3.org/2002/07/owl#>

- There is a Turtle Syntax for OWL

- **OWL axioms** consist of the following **three building blocks:**
  - **Classes**
    - *comparable with classes in RDFS*
  - **Individuals**
    - *comparable with class instances in RDFS*
  - **Properties**
    - *comparable with properties in RDFS*

OWL Classes

- There exist two predefined classes
  - ***owl:Thing*** *(class that contains all individuals)*
  - ***owl:Nothing*** *(empty class)*
- **Definition** of a class
  - :Book a **owl:Class .**

equivalent expression in description logics

$$\top \equiv C \sqcup \neg C$$

$$\bot \equiv C \sqcap \neg C$$

OWL Individuals

- **Definition of individuals** via class membership
  - :NineteenEightyfour a :Book .
  - Book(NineteenEightyfour)
- Individuals can also be defined without class membership as **named individuals**
  - :HaraldSack a **owl:NamedIndividual .**

OWL Object Properties

- There exist two property variants:
  - *Object properties*
  - *Datatype properties*

- Object properties have **classes** as range
  - :author a **owl:ObjectProperty .**

- Domain and Range of object properties
  :author a **owl:ObjectProperty ;**
  - *rdfs:domain :Book ;*
  - *rdfs:range :Writer .*

OWL Datatype Properties

- Datatype properties have **datatypes** as range
  - :publicationYear a **owl:DatatypeProperty .**

- Domain and Range of datatype properties
  - :publicationYear a **owl:DatatypeProperty ;**
    - *rdfs:domain :Book ;*
    - *rdfs:range xsd:integer*

OWL Properties and Individuals

```
:Book a owl:Class .
:Writer a owl:Class .

:author a owl:ObjectProperty ;
        rdfs:domain :Book ;
        rdfs:range  :Writer .

:publicationYear a owl:DatatypeProperty ;
                 rdfs:domain :Book ;
                 rdfs:range xsd:integer .

:GeorgeOrwell a Writer .
:NineteenEightyFour a :Book ;
                    :author :GeorgeOrwell ;
                    :publicationYear 1948 .
```

OWL Class Hierarchies

```
:Novel a owl:Class ;
       rdfs:subClassOf :Book .
:Book a owl:Class ;
      rdfs:subClassOf :Work .
:Work a owl:Class .
```

$Novel \sqsubseteq Book$
$Book \sqsubseteq Work$

- Via inference it can be entailed that :Novel is also a subclass of :Work

OWL Class Hierarchies and Disjunctiveness

```
:Book a owl:Class .
:Writer a owl:Class .
:Novel a owl:Class ;
       rdfs:subClassOf :Book .
:Poet a owl:Class ;
      rdfs:subClassOf :Writer .

:Book owl:disjointWith :Writer .
```

$\text{Novel} \sqsubseteq \text{Book}$
$\text{Poet} \sqsubseteq \text{Writer}$
$\text{Book} \sqcap \text{Writer} \sqsubseteq \perp$

- via inference it can be entailed that :Novel and :Poet are also disjoint classes

OWL Class Hierarchies and Disjunctiveness

- OWL provides a **shortcut** to define several classes to be disjunctive

```
[] a owl:AllDisjointClasses ;
     owl:members
       ( :Book
         :Writer
         :Vegetable
         :Furniture
         :Car ) .
```

OWL Class Hierarchies and Equivalence

```
:Writer a owl:Class .
:Author a owl:Class .
:Poet a owl:Class ;
      rdfs:subClassOf :Writer .

:Writer owl:equivalentClass :Author .
```

$$Poet \sqsubseteq Writer$$
$$Writer \equiv Author$$

- via inference it can be entailed that :Poet is also an :Author

OWL Individuals

```
:NineteenEightyfour a :Novel ;
           :author :GeorgeOrwell ;
           :publicationYear 1948 ;
           owl:sameAs :ARX012345 .

:Novel a owl:Class ;
       rdfs:subClassOf :Book .

:Book a owl:Class.
```

- via inference it can be entailed that :ARX012345 is a :Book
  difference of Individuals via **owl:differentFrom**

```
:ARX012345 a :Novel ;
           owl:differentFrom :ARX012346 .
```

OWL Class Hierarchies and Disjunctiveness

- OWL provides a **shortcut** to define several individuals to be different

```
[] a owl:AllDifferent ;
   owl:distinctMembers
     ( :NineteenEightyfour
       :AnimalFarm
       :BraveNewWorld
       :Simulacron5 ) .
```

OWL Closed Classes - Nominals

```
:Novel a owl:Class .
:AnimalFarm a :Novel .
:NineteenEightyfour a :Novel .

:NovelsInStore a owl:Class ;
     owl:oneOf
     ( :AnimalFarm
       :NineteenEightyfour ) .
```

$NovelsInStore \sqsubseteq \{AnimalFarm, NineteenEightyfour\}$

- There are only two novels available in the store.

OWL Logical Class Constructors

- logical AND (conjunction):
  - **owl:intersectionOf** $\sqcap$
- logical OR (disjunction):
  - **owl:unionOf** $\sqcup$
- logical negation:
  - **owl:complementOf** $\neg$

- **Logical constructors are applied to create complex class descriptions from atomic classes.**

OWL Logical Class Constructors

```
:Book a owl:Class .

:ThingsInStore a owl:Class .

:BooksInStore a owl:Class ;
      owl:intersectionOf (:ThingsInStore :Book) .
```

$\text{BooksInStore} \equiv \text{ThingsInStore} \sqcap \text{Books}$

- The class :BooksInStore results from the intersection of all individuals of the classes :ThingsInStore and :Book

OWL Logical Class Constructors

```
:Book a owl:Class ;
      owl:equivalentClass [
         owl:unionOf ( :Novel
                       :Poetry
                       :NonFiction )
] .
```

$Book \equiv Novel \sqcup Poetry \sqcup NonFiction$

- Novels, poetry, and non-fiction are also books

OWL Logical Class Constructors

```
:Book a owl:Class ;
      rdfs:subClassOf [
      owl:complementOf :Writer
] .
```

Book ⊑ ¬Writer

- semantically equivalent assertion:

```
:Book a owl:Class ;
      owl:disjointWith :Writer .
```

OWL Property Restrictions

OWL Property Restrictions

- OWL property restrictions are used to describe complex classes via properties

- Restrictions on values:
  - **owl:hasValue**
  - **owl:allValuesFrom**
  - **owl:someValuesFrom**

- Restrictions on cardinality:
  - **owl:cardinality**
  - **owl:minCardinality**
  - **owl:maxCardinality**

OWL Property Restrictions With Constants

```
:OrwellsBooks a owl:Class ;
              rdfs:subClassOf
                [ a owl:Restriction ;
                  owl:onProperty :author ;
                  owl:hasValue :GeorgeOrwell ] .
```

$OrwellsBooks \sqsubseteq author.(GeorgeOrwell)$

- Class :OrwellsBooks is described via fixed value assignment (=constant) of the individual :GeorgeOrwell to the property :author

OWL Property Restriction With Strict Binding

```
:Poetry a owl:Class ;
        rdfs:subClassOf
          [ a owl:Restriction ;
            owl:onProperty :author ;
            owl:allValuesFrom :Poet ] .
```

$\text{Poetry} \sqsubseteq \forall \text{author}.\text{Poet}$

- **owl:allValuesFrom**
  fixes all instances of a specific class C as allowed range for a property p (strict binding) $\forall p.C$

OWL Property Restriction With Loose Binding

```
:Reader a owl:Class ;
        rdfs:subClassOf
          [ a owl:Restriction ;
            owl:onProperty :reads ;
            owl:someValuesFrom :Book ] .
```

$\text{Reader} \sqsubseteq \exists \text{reads.Book}$

- **owl:someValuesFrom**
  describes that there must exist an individual for p and fixes its range to class C (loose binding) $\exists p.C$

OWL Cardinality Restrictions

```
:Tetralogy a owl:Class ;
           rdfs:subClassOf
             [ a owl:Restriction ;
               owl:onProperty :hasVolumes ;
               owl:cardinality 4 ] .
```

Tetralogy ⊑ (=4)hasVolumes

- **owl:cardinality** restricts to an exact number
- **owl:minCardinality / owl:maxCardinality** restricts to upper / lower bounds

OWL Property Relationships

OWL Property Relationships

- **Property hierarchies** can be created via specialisations: rdfs:subPropertyOf
- **Inverse properties** are defined via owl:inverseOf
- **Identical properties** are defined via owl:equivalentProperty

```
:isMadeOf a owl:ObjectProperty ;
        rdfs:subPropertyOf :consistsOf .

:reads a owl:ObjectProperty ;
        owl:inverseOf :isReadBy .

:composedOf a owl:ObjectProperty ;
        owl:equivalentProperty :consistsOf .
```

$isMadeOf \sqsubseteq consistsOf$
$reads^{-} \equiv isReadBy$
$composedOf \equiv consistsOf$

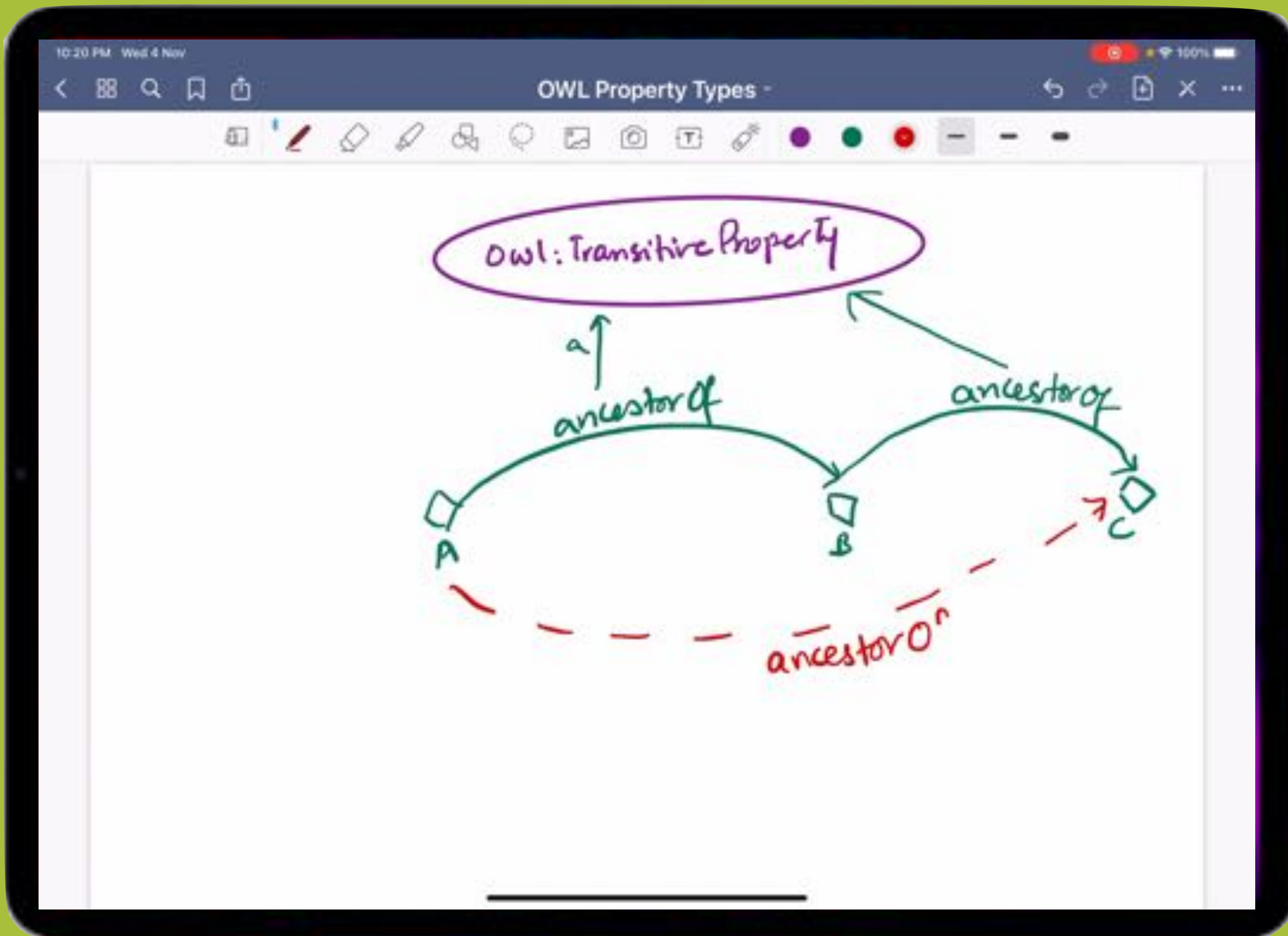
OWL Property Relationships

- owl:TransitiveProperty
  - e.g. if isPartOf(a,b) and isPartOf(b,c) then it holds that isPartOf(a,c)
- owl:SymmetricProperty
  - e.g. if isNeighbourOf(a,b) then it holds that isNeighbourOf(b,a)
- owl:FunctionalProperty
  - e.g. if hasMother(a,b) and hasMother(a,c) then it holds that b=c
- owl:InverseFunctionalProperty
  - e.g. if isMotherOf(b,a) and isMotherOf(c,a) then it holds that b=c

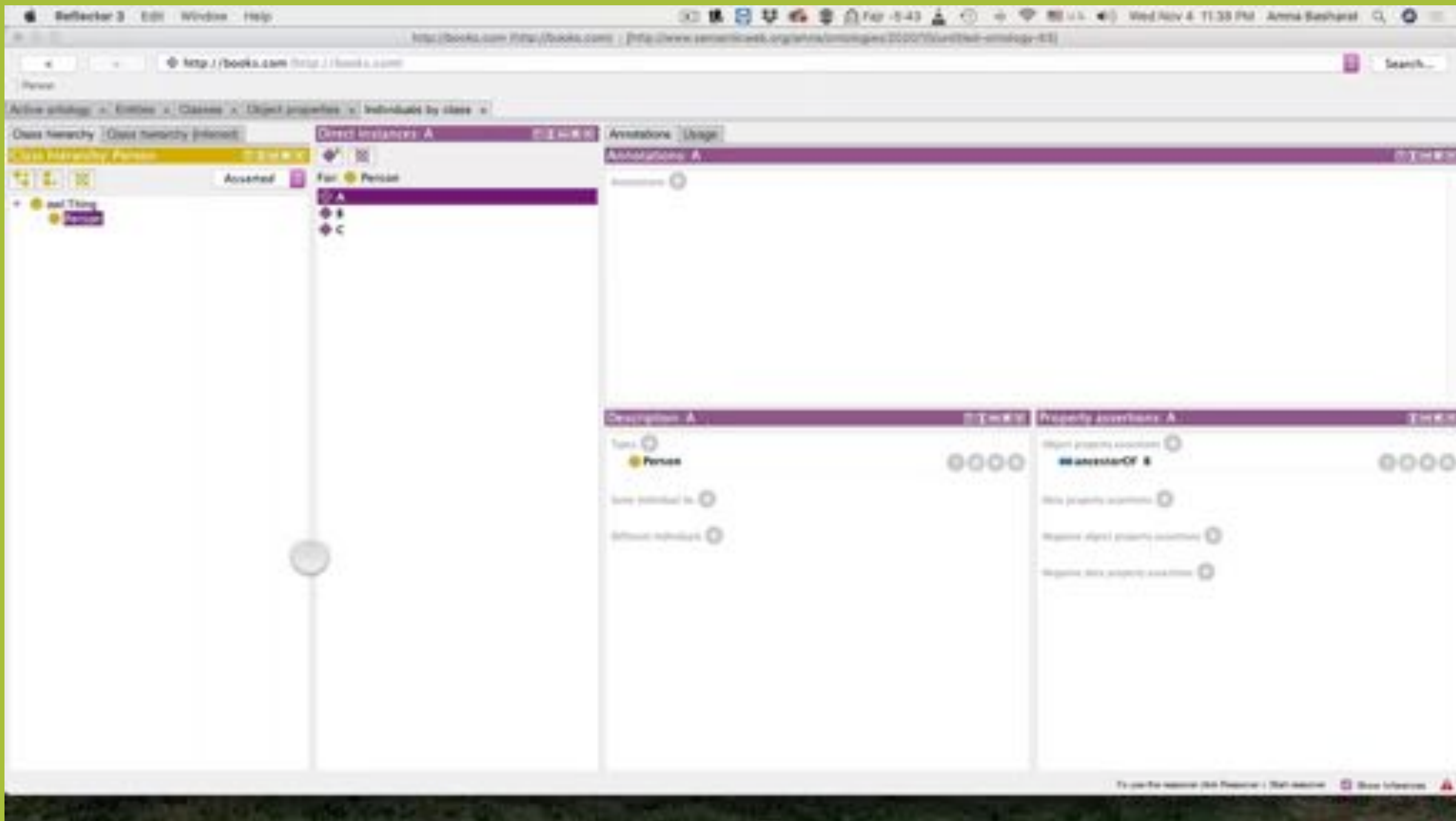
OWL Transitive Properties

```
:isPublishedBefore a owl:ObjectProperty ;
                   a owl:TransitiveProperty ;
                   rdfs:domain owl:Book ;
                   rdfs:range owl:Book .

:AnimalFarm a owl:Book ;
            :isPublishedBefore :NineteenEightyfour .

:BraveNewWorld a :Book ;
               :isPublishedBefore :AnimalFarm .
```

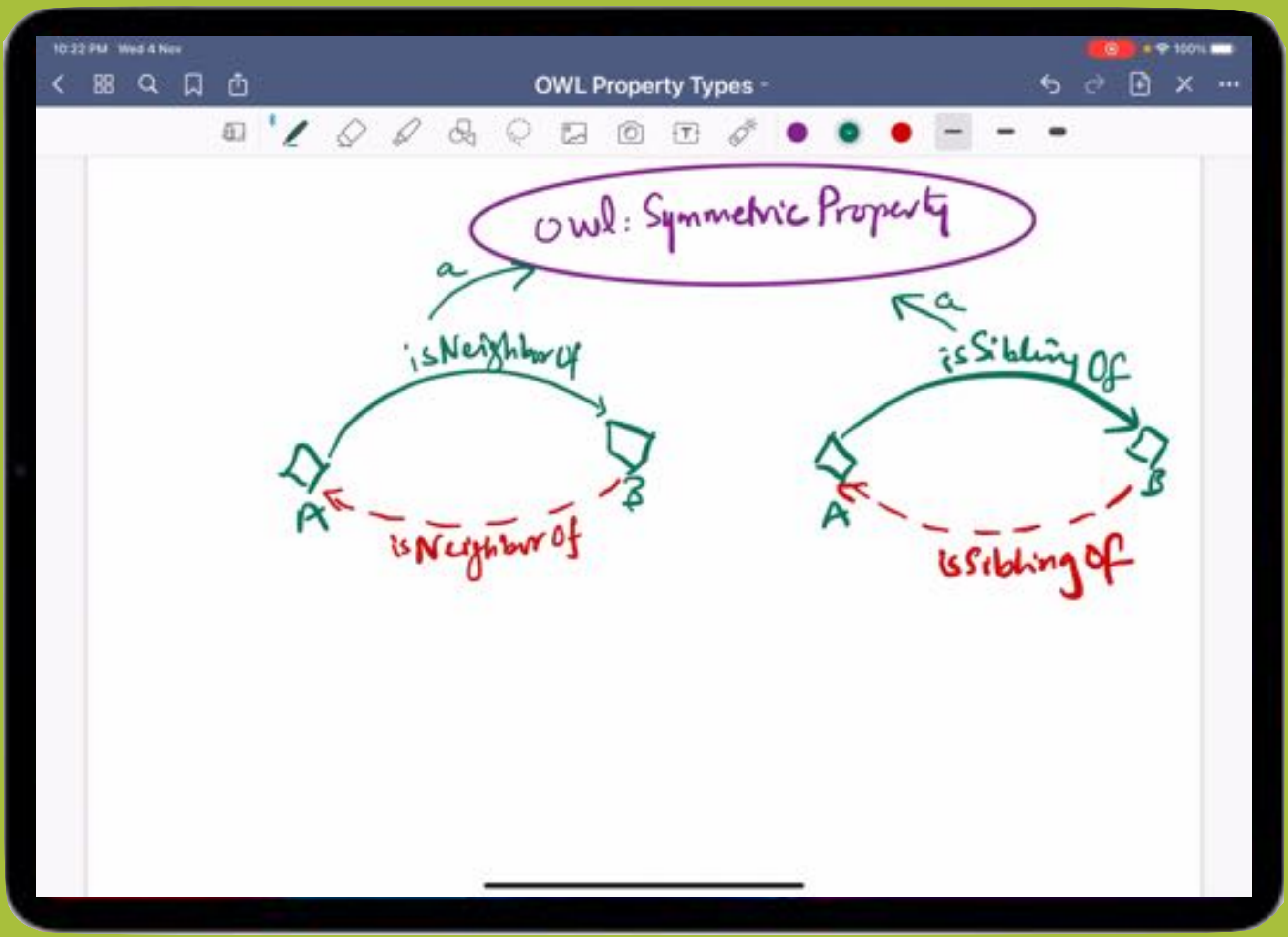
- Via inference it can be entailed that :BraveNewWorld has been published before :NineteenEightyFour



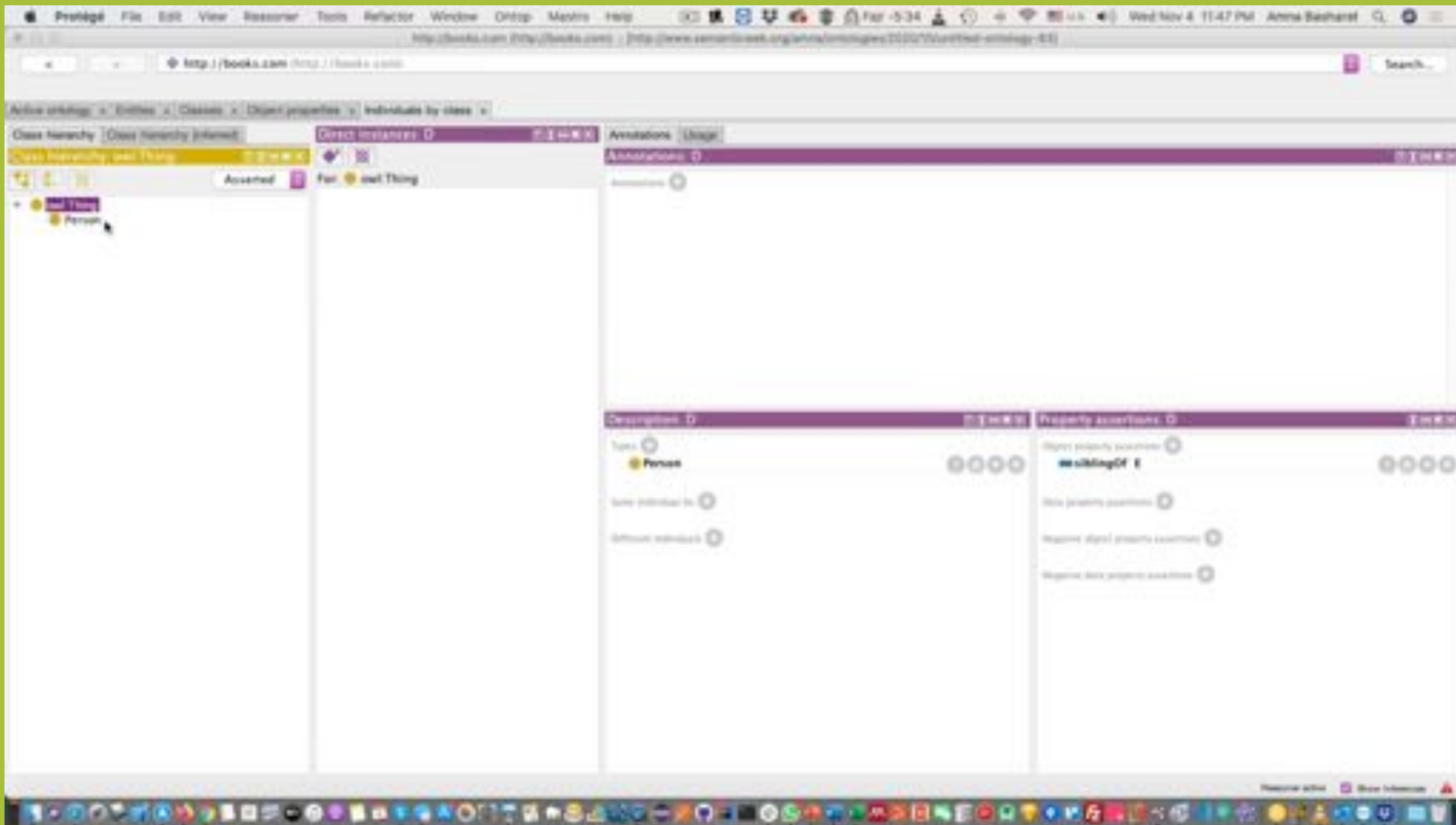
Transitive Property Illustration



Transitive Property Illustration (Protege)



Symmetric Property Illustration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Class hierarchy
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owl:Thing
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Direct instances
For: owl:Thing
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Usage
Description
Types
Person
Property assertions
siblingOf
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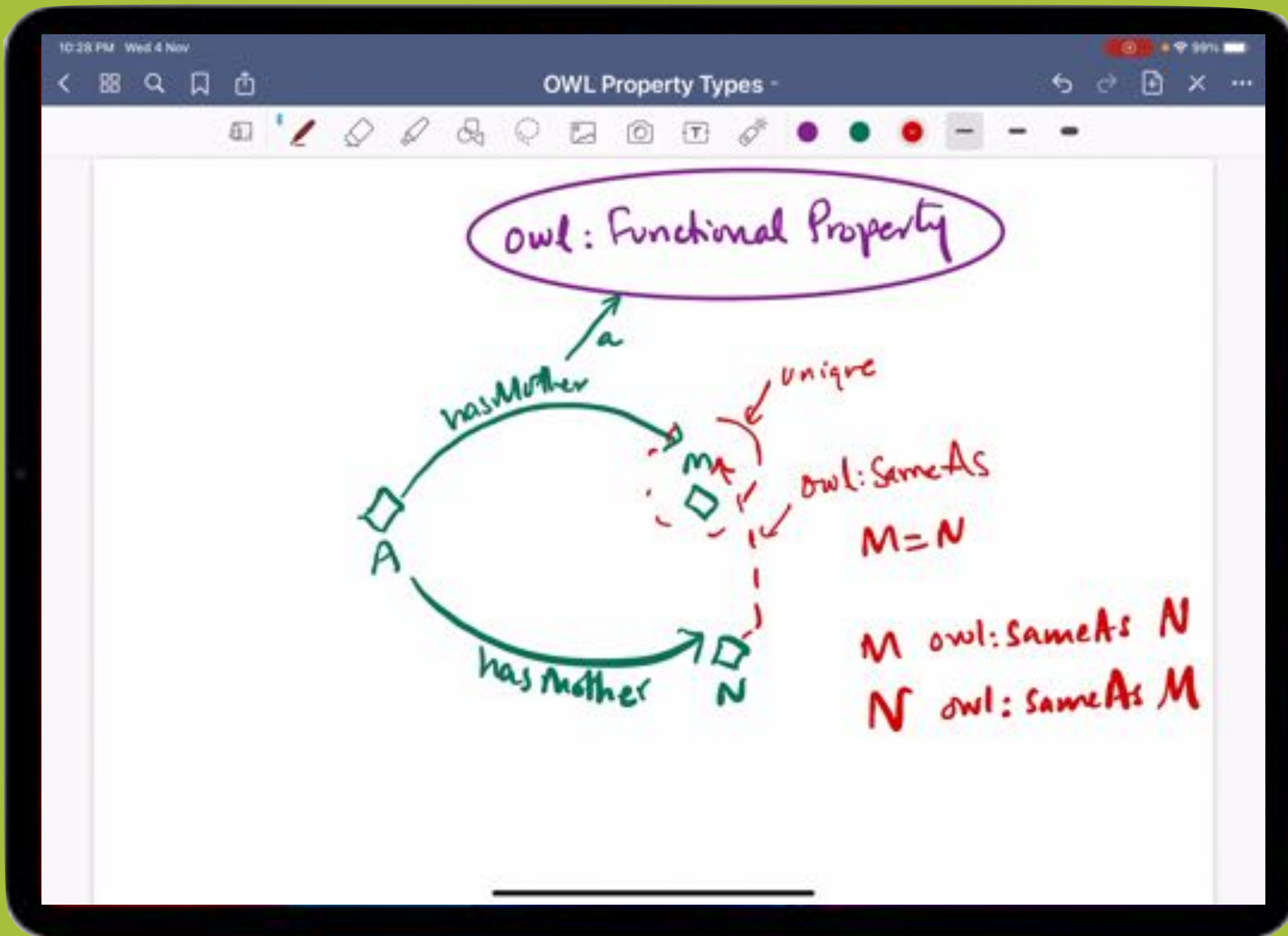
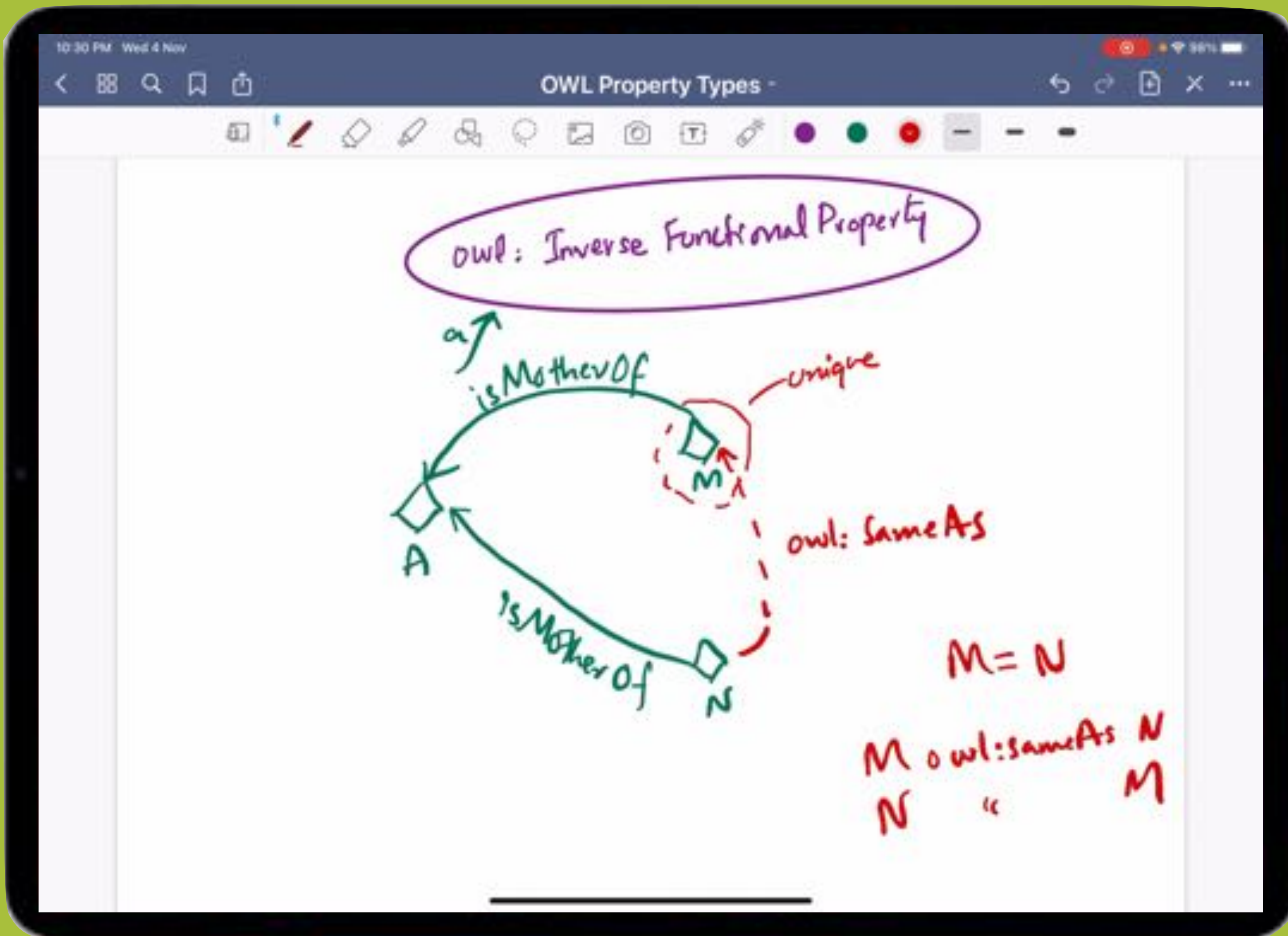
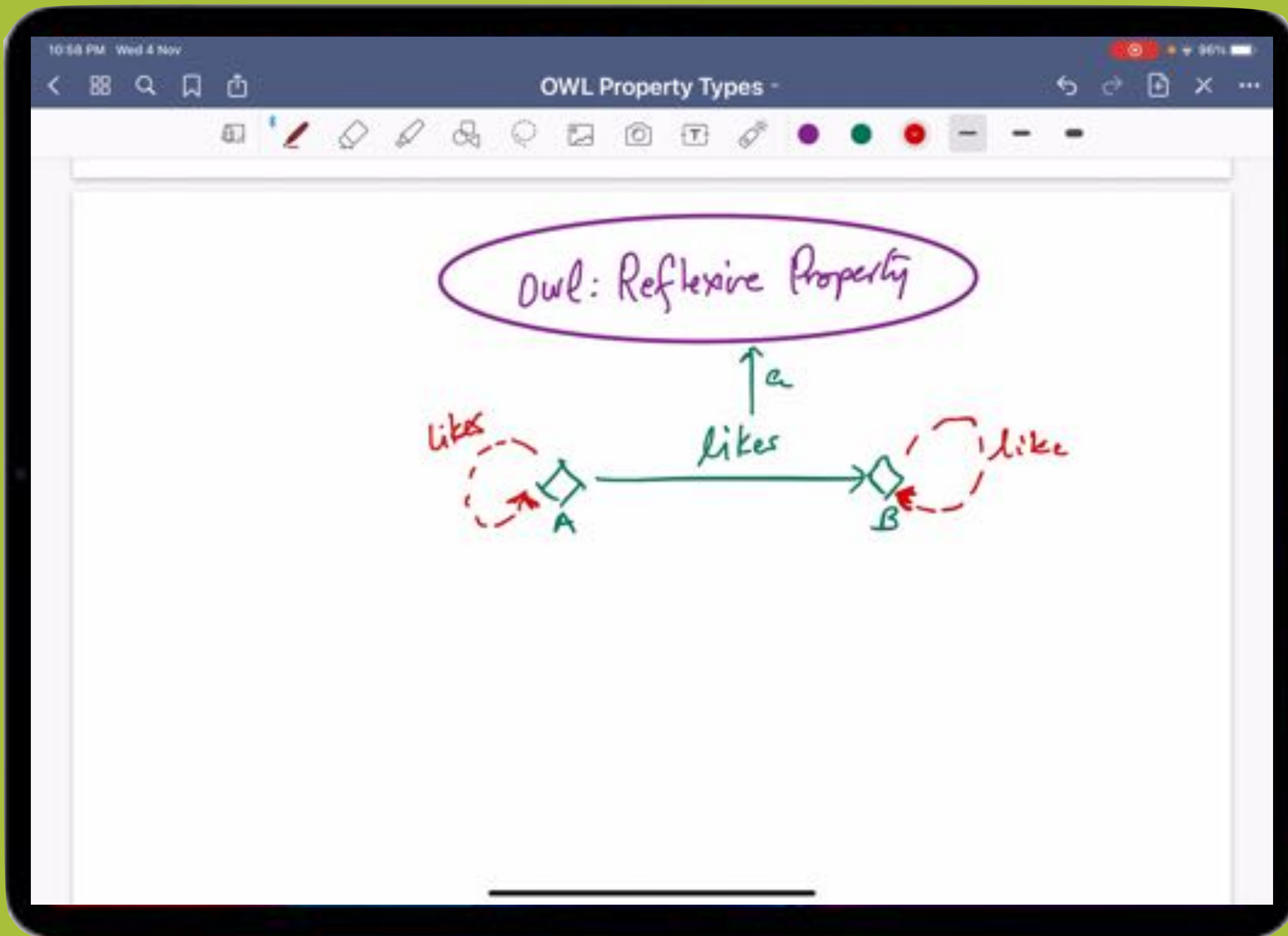


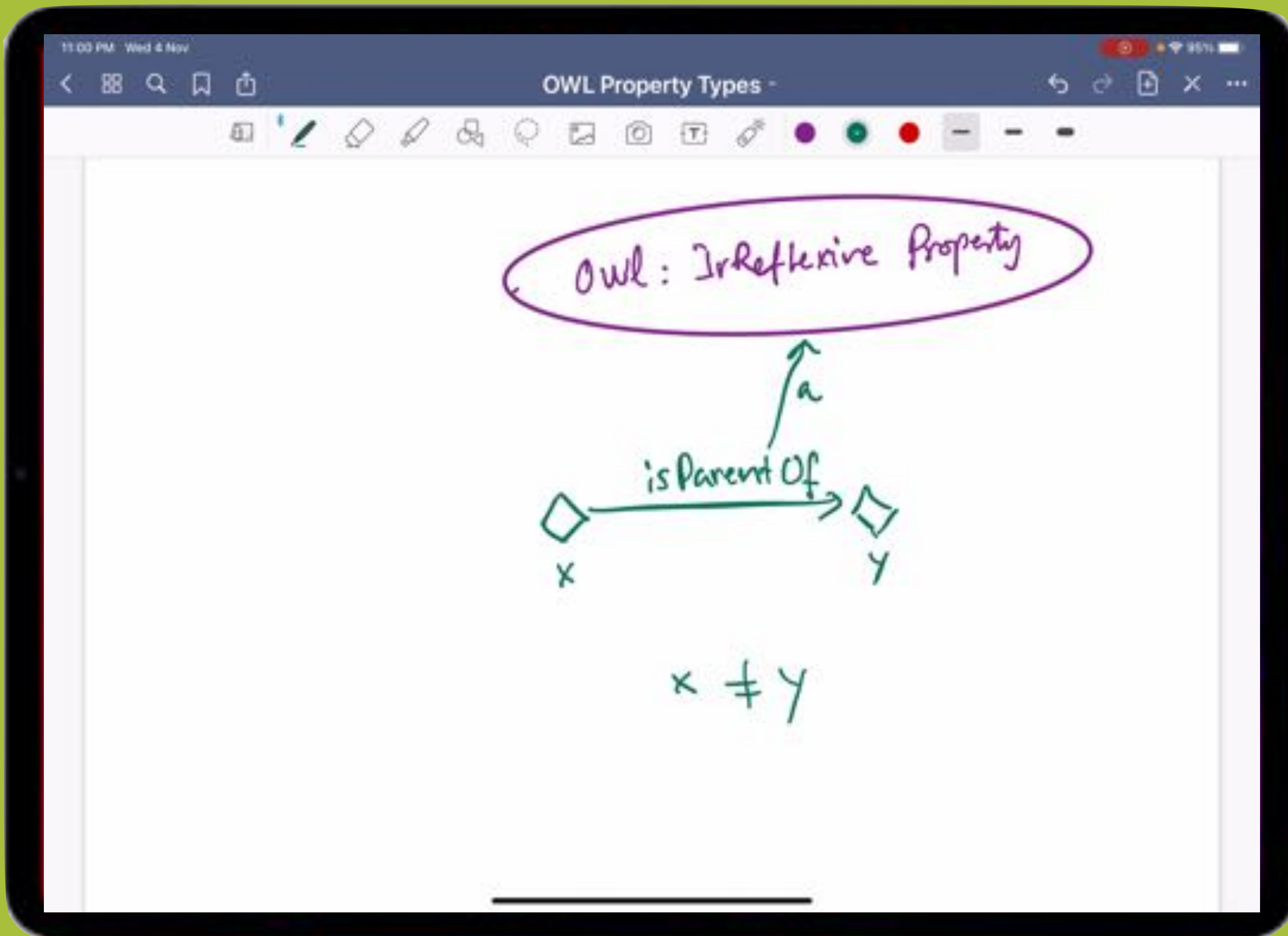
Functional Property Illustration



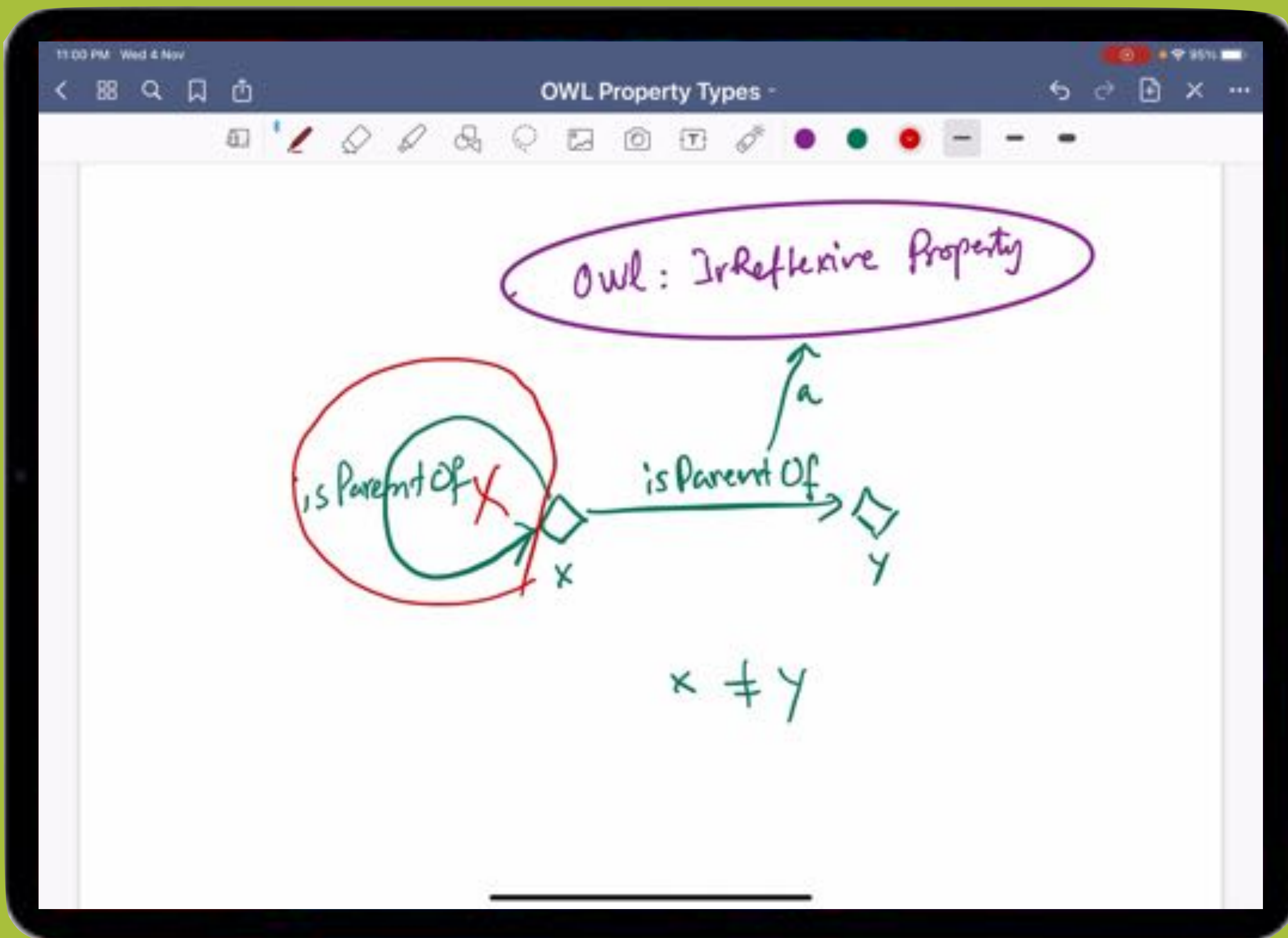
Inverse Functional Property Illustration



Reflexive Property Illustration



IrReflexive Property Illustration



IrReflexive Property

OWL More Property Relationships

- **Asymmetric properties** via owl:AsymmetricProperty
  - e.g. if it holds that isLeftOf(a,b) then it is <u>NOT</u> isLeftOf(b,a)
- **Reflexive properties** via owl:ReflexiveProperty
  - e.g. isRelatedTo(x,x)
- **Irreflexive properties** via owl:IrreflexiveProperty
  - e.g. If isParentOf(x,y) then $x \neq y$

OWL Disjunctive Properties

- Two properties R and S are **disjunctive**, if two individuals x, y are never related via both properties

```
:hasParent a owl:opbjectProperty ;
                 owl:propertyDisjointWith :hasChild.
```

- Shortcut for several **disjunctive properties**

```
[] rdf:type owl:AllDisjointProperties ;
   owl:members
      ( :hasParent
        :hasChild
        :hasGrandchild ).
```

OWL Negated Property Instantiation

- Two individuals can be explicitly defined to be not related with each other via a given property.

$\neg$isBrother(GeorgeOrwell,AldousHuxley)

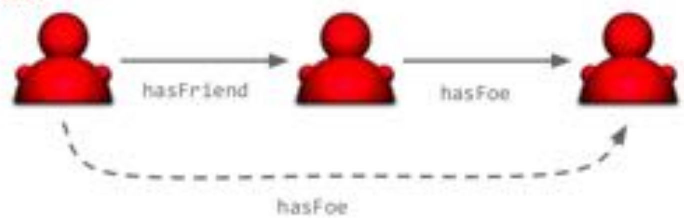
```
[] rdf:type owl:NegativePropertyAssertion ;
   owl:sourceIndividual :GeorgeOrwell ;
   owl:assertionProperty :isBrother ;
   owl:targetIndividual :AldousHuxley .
```

OWL Property Chaining

- **Complex Roles** (properties) can be constructed from simple roles (**RBox**)
  - *'the friends of my friends are also my friends'*

```
hasFriend a owl:TransitiveProperty .
```

- But: „*The foes of my friends are also my foes.*"
  - cannot be expressed in that way



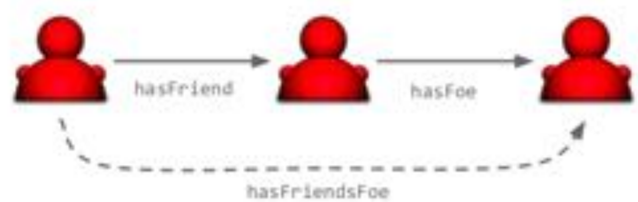
- in FOL it can be expressed as a rule (axiom):
  - $\forall x, y, z: hasFriend(x, y) \land hasFoe(y, z) \rightarrow hasFriendsFoe(x, z)$

OWL Property Chaining

- General Role Inclusion (**Property chaining**)

```
:hasFriendsFoe a owl:ObjectProperty ;
   owl:propertyChainAxiom  ( :hasFriend :hasFoe ) .
```

- not allowed for datatype properties



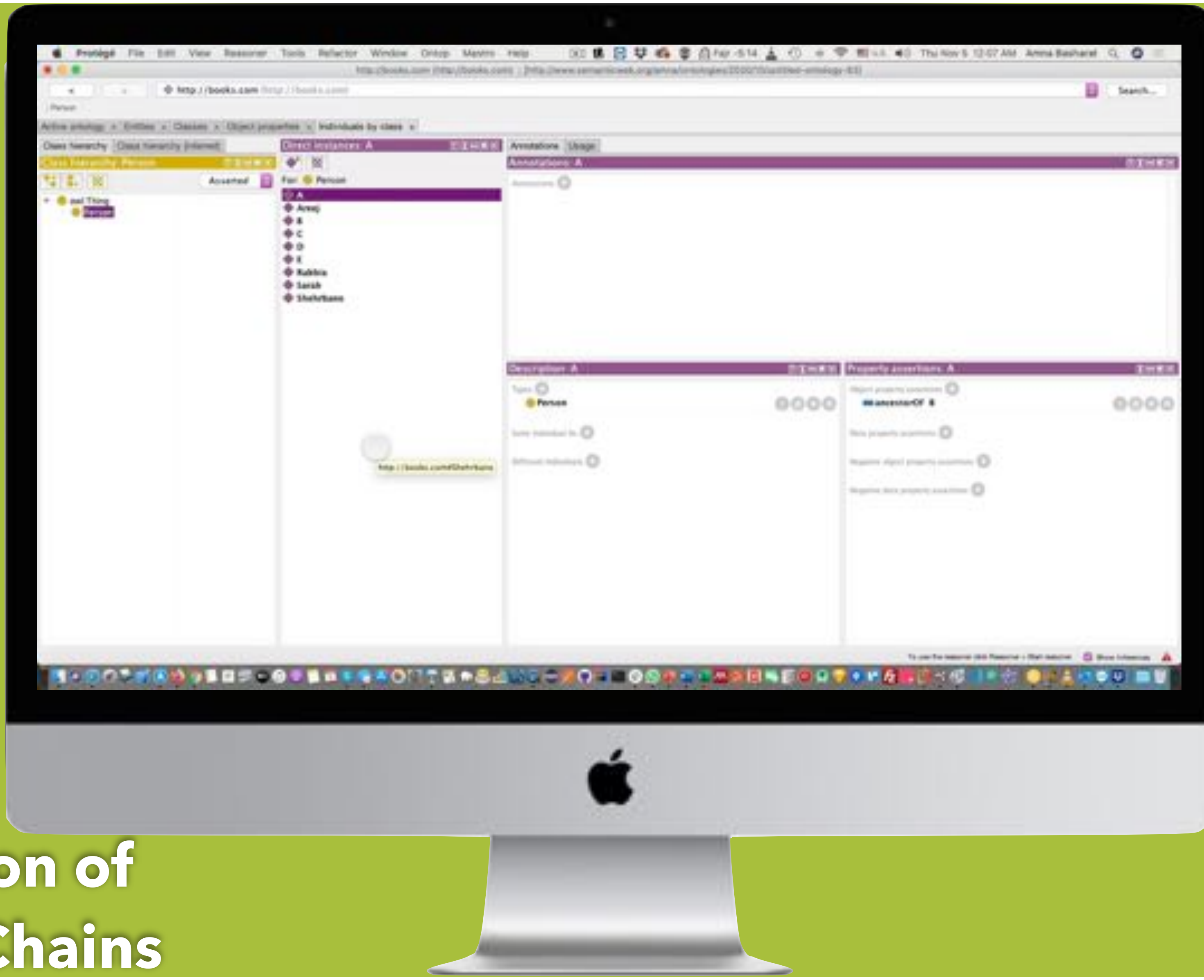


Illustration of PropertyChains

OWL Qualified Number Restrictions

- Class constructors with **number restrictions on properties connected with a range constraint**

SuccessfulAuthor ⊑ ≥1 notableWork.Bestseller

```
:SuccessfulAuthor a owl:Class;
    rdfs:subClassOf [
      a owl:Restriction ;
      owl:onProperty :notableWork ;
      owl:minQualifiedCardinality  "1"^^xsd:nonNegativeInteger ;
      owl:onClass :Bestseller ] .
```

- owl:maxQualifiedCardinality, owl:minQualifiedCardinality, owl:qualifiedCardinality

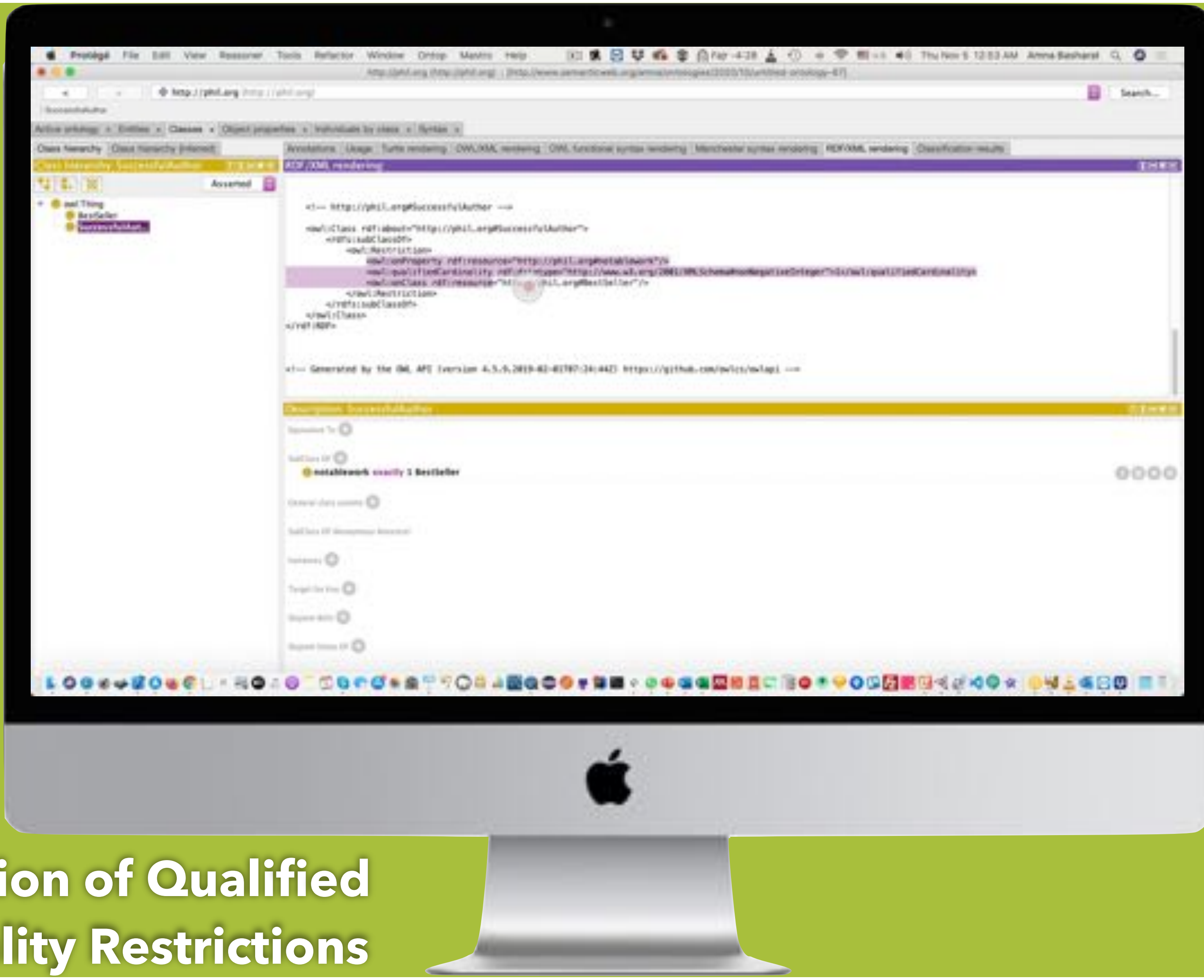


Illustration of Qualified Cardinality Restrictions

OWL Reflexive Property Restriction

- Classes that contain individuals that are related to themselves for specific properties

Philosopher ⊑ knows.self

```
:Philosopher a owl:Class ;
    rdfs:subClassOf [
      a owl:Restriction ;
      owl:onProperty :knows ;
      owl:hasSelf "true"^^xsd:boolean ] .
```

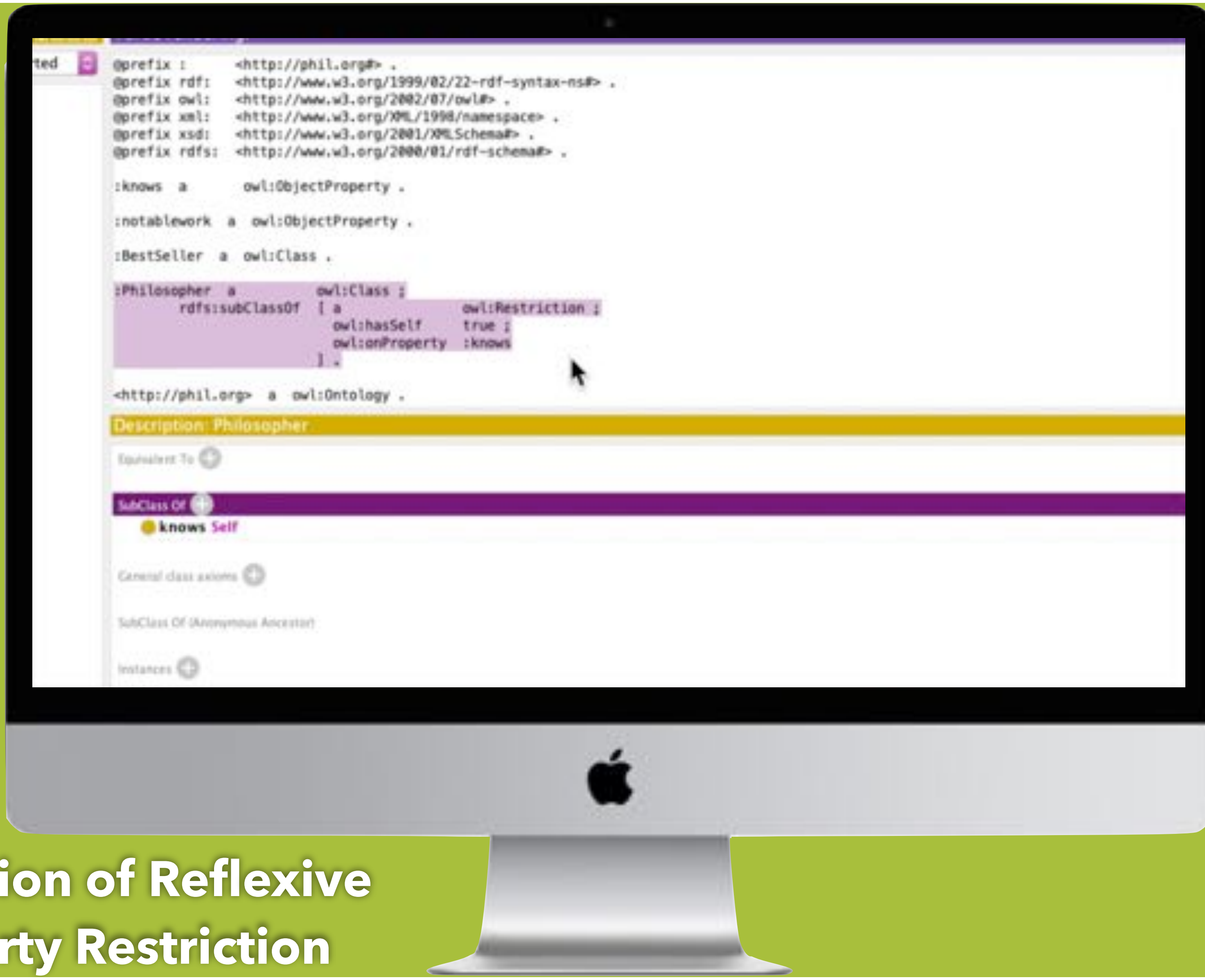


Illustration of Reflexive Property Restriction

Syntax Variation Examples

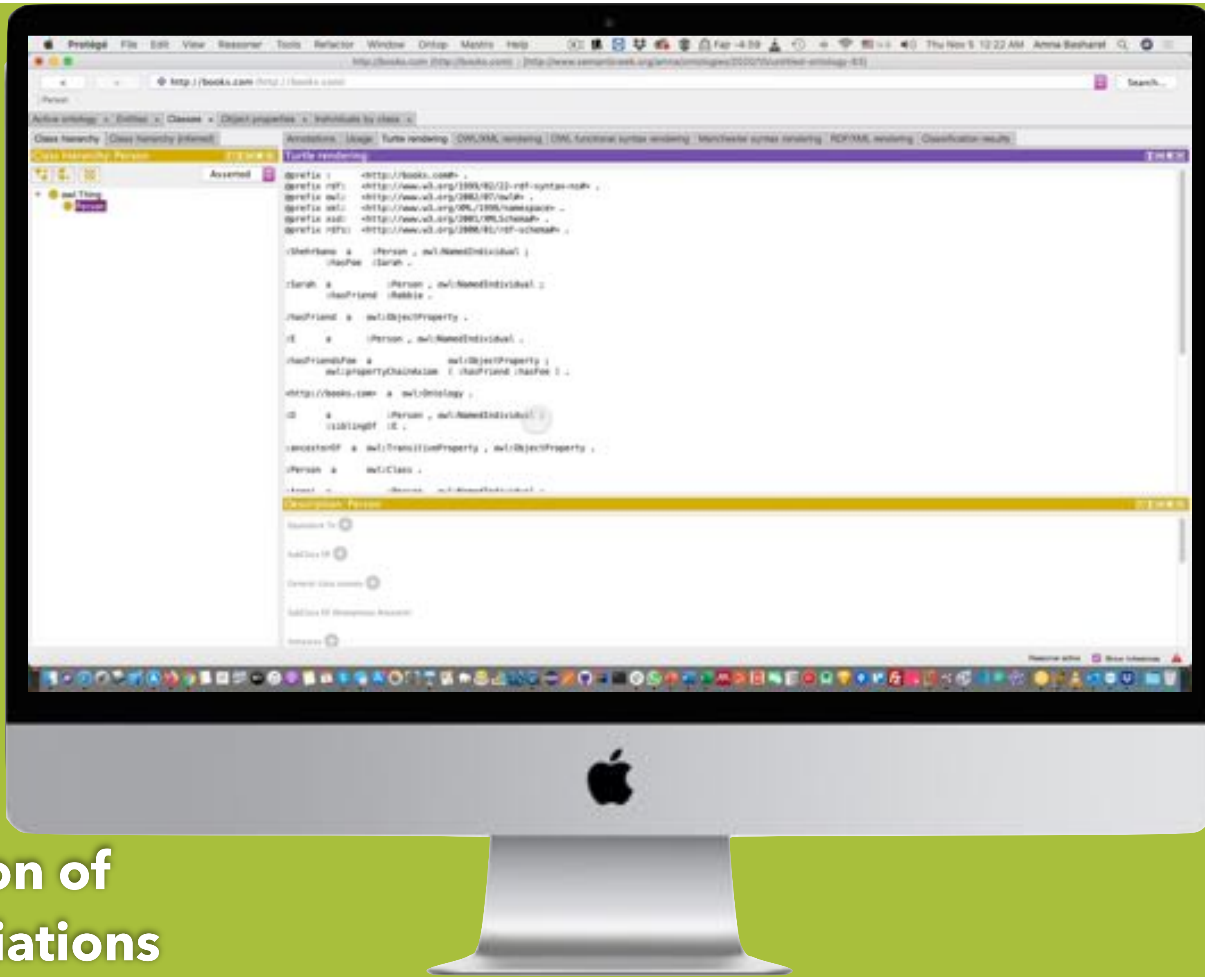


Illustration of Syntax Variations

Beyond OWL

Beyond OWL

- More **expressivity** also means more **complexity**
  - This might lead to **undecidability** (as for FOL)
- Do we really need more expressivity than OWL DL offers?
- Consider the following example:
  - 'A squanderer is a person whose expenses are higher than his income'

- $\mathtt{Squanderer} \sqsubseteq \mathtt{Person}$
- $\mathtt{Squanderer} \sqsubseteq \mathtt{hasExpenses}.\top$
- $\mathtt{Squanderer} \sqsubseteq \mathtt{hasIncome}.\top$

?

- We need a constructor to combine Classes and Properties
- **Problem:** Mixing of TBox and ABox

Rules - Beyond OWL

- The following example can be expressed via a FOL-Rule:
  - 'A squanderer is a person whose expenses are higher than his income'

$$
\begin{aligned}
\mathrm{Person}(x) \ &\wedge\ \mathrm{hasIncome}(x,y) \\
&\wedge\ \mathrm{hasExpenses}(x,z) \\
&\wedge\ (z > y) \\
&\rightarrow\ \mathrm{Squanderer}(x)
\end{aligned}
$$

- Arithmetics can be part of rules and modelled like a predicate
  - $(z > y) \triangleq \mathrm{greaterThan}(z,y)$