Week 4

COMP62342

Sean Bechhofer, Uli Sattler

sean.bechhofer@manchester.ac.uk,

uli.sattler@manchester.ac.uk

Today

- Some clarifications around last week's coursework
- More on reasoning:
  - extension of the tableau algorithm & discussion of blocking
  - traversal or "how to compute the inferred class hierarchy"
  - OWL profiles
- Snap-On: an ontology-based application
- The OWL API: a Java API and reference implementati
  - creating,
  - manipulating and
  - serialising OWL Ontologies and
  - interacting with OWL reasoners
- **Lab**:
  - OWL API for coursework
  - Ontology Development

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Some clarifications around last week’s coursework

Ontologies, inference, entailments, models

- *OWL* is based on a *Description Logic*
  - we can use DL syntax
  - e.g., $C \sqsubseteq D$ for C SubClassOf D

- An OWL ontology O is a **document:**
  - therefor, it cannot **do** anything: it isn't a piece of software!
  - in particular, an ontology cannot **infer** anything
    (a reasoner may infer something!)

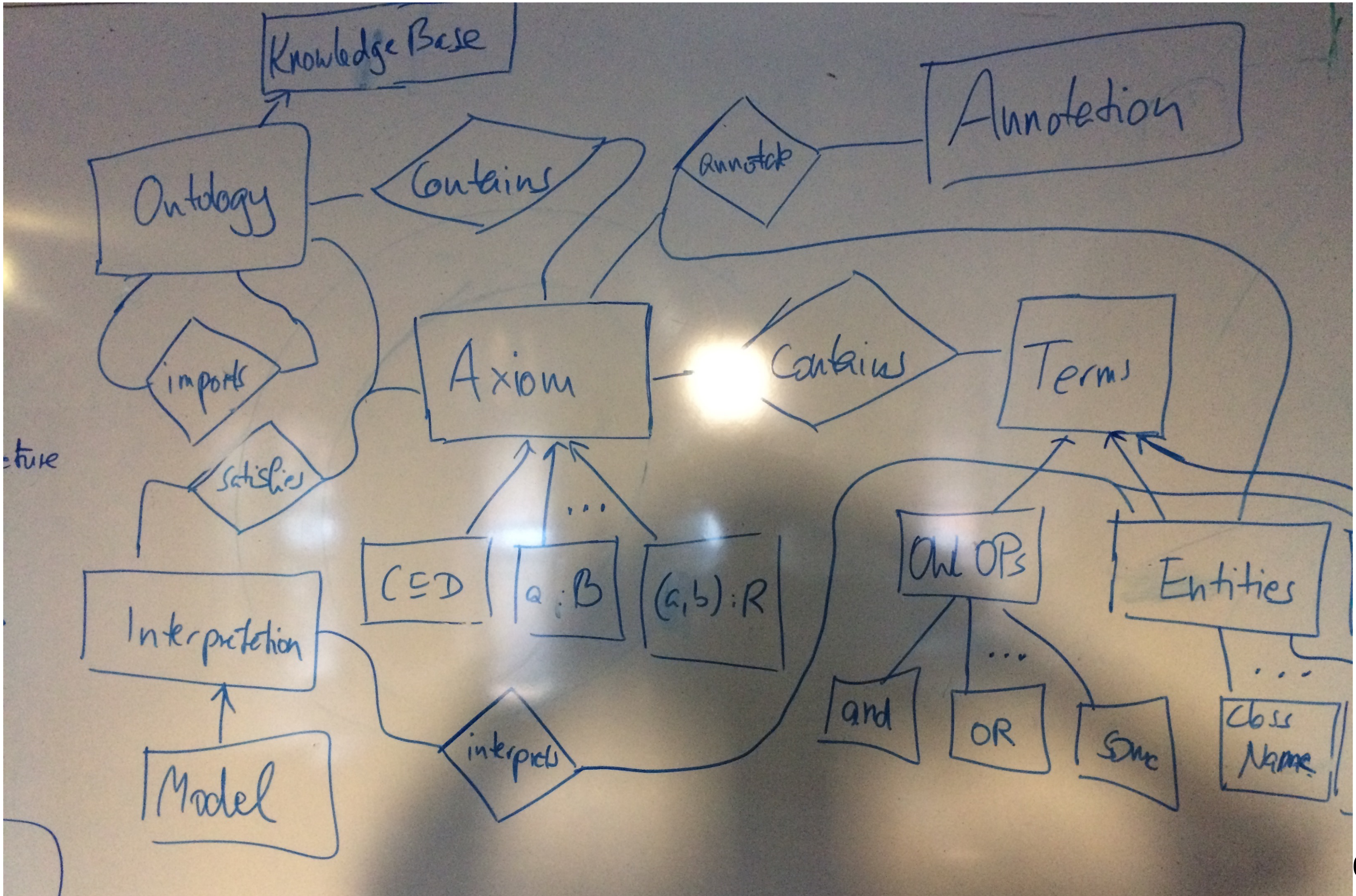
- An OWL ontology O is a **web document:**
  - with 'import' statements, annotations, …
  - corresponds to a **set of logical OWL axioms**, its *imports closure*
  - the OWL API (today) helps you to
    - parse an ontology
    - access its axioms
  - a **reasoner** is only interested in this set of axioms
    - **not** in annotation axioms
    - see https://www.w3.org/TR/owl2-primer/#Document_Information_and_Annotations
    - https://www.w3.org/TR/2012/REC-owl2-syntax-20121211/#Annotations

Ontologies, inference, entailments, models (2)

- We have defined what it means for O to *entail* an *axiom* C SubClassOf D
  - written O $\models$ C SubClassOf D
    or O $\models$ C $\sqsubseteq$ D
  - based on the notion of a *model* I of O
    - i.e., an *interpretation* I that *satisfies* all axioms in O
  - don't confuse 'model' with 'ontology'
    - one ontology can have **many** models
    - the more axioms in O the fewer models O has

- A *DL reasoner* can be used to
  - check *entailments of* an OWL ontology O and
  - compute the *inferred class hierarchy* of O
    - this is also known as *classifying* O
  - e.g., by using a *tableau algorithm*

Learn terms & meaning & relations!



Why?

To
deepen our
understanding of
OWL

More on Reasoning

To
understand
better **what**
reasoners do

Recall Week 2: OWL 2 Semantics: Entailments

Let O be an ontology, α an axiom, and A, B classes, b an individual name:

- O is **consistent** if there exists some model I of O
  - i.e., there is an interpretation that satisfies all axioms in O
  - i.e., O isn't self contradictory
- O **entails** α (written O ⊧ α) if α is satisfied in all models of O
  - i.e., α is a consequence of the axioms in O
- A is **satisfiable** w.r.t. O if O ⊭ A SubClassOf Nothing
  - i.e., there is a model I of O with $A^I \neq \{\}$
- b is an **instance of** A w.r.t. O (written O ⊧ b:A) if $b^I \subseteq A^I$ in every model I of O

Theorem:

1. O is consistent iff O ⊭ Thing SubClassOf Nothing
2. A is satisfiable w.r.t. O iff O ∪ {n:A} is consistent (where n doesn't occur in O)
3. b is an instance of A in O iff O ∪ {b:not(A)} is not consistent
4. O entails A SubClassOf B iff O ∪ {n:A and not(B)} is inconsistent

Recall Week 2: OWL 2 Semantics: Entailments etc.

Let O be an ontology, α an axiom, and A, B classes, b an individual name:

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  - i.e., there is an interpretation that satisfies all axioms in O
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- O **entails** α (written O $\models$ α) if α is satisfied in all models of O
  - i.e., α is a consequence of the axioms in O
- A is **satisfiable** w.r.t. O if O $\not\models$ A SubClassOf Nothing
  - i.e., there is a model I of O with $A^I \neq \{\}$
- b is an **instance of** A w.r.t. O if $b^I \subseteq A^I$ in every model I of O

- O is **coherent** if every class name that occurs in O is satisfiable w.r.t O
- **Classifying O** is a reasoning service consisting of
  1. testing whether O is consistent; if yes, then
  2. checking, for each pair A,B of class names in O plus Thing, Nothing
     O $\models$ A SubClassOf B
  3. checking, for each individual name b and class name A in O, whether O $\models$ b:A

     …and returning the result in a suitable form: O's **inferred class hierarchy**

Week 3: how to test satisfiability …

Before Easter, you saw a **tableau algorithm** that

- takes a class expression C and decides **satisfiability** of C:
  - it answers 'yes' if C is satisfiable
    'no' if C is not satisfiable
  - …and always stops with a yes/no answer:
    it is sound, complete, and terminating

in Negation Normal Form

We saw such a tableau algorithm for ALC:

- ALC is a Description Logic that forms logical basis of OWL,
  only has and, or, not, some, only
- works by trying to generate an interpretation with an instance of C
  - by breaking down class expressions
  - generating new P-successors for some-values from restrictions
    ($\exists P.C$ restrictions in DL)

- we can handle an ontology that is a set of **acyclic SubClassOf axioms**
  - via **unfolding** (check Week 3 slide 24ff)

Week 3: tableau rules

$$x \bullet \{C_1 \sqcap C_2, \ldots\} \quad \rightarrow_{\sqcap} \quad x \bullet \{C_1 \sqcap C_2, C_1, C_2, \ldots\}$$

$$x \bullet \{C_1 \sqcup C_2, \ldots\} \quad \rightarrow_{\sqcup} \quad x \bullet \{C_1 \sqcup C_2, C, \ldots\}$$

For $C \in \{C_1, C_2\}$

$$\begin{tikzcd} x \bullet \{\exists R.C, \ldots\} & \rightarrow_{\exists} & x \bullet \{\exists R.C, \ldots\} \arrow[d, "R"'] \\ & & y \bullet \{C\} \end{tikzcd}$$

$$\begin{tikzcd} x \bullet \{\forall R.C, \ldots\} \arrow[d, "R"'] & \rightarrow_{\forall} & x \bullet \{\forall R.C, \ldots\} \arrow[d, "R"'] \\ y \bullet \{\ldots\} & & y \bullet \{C, \ldots\} \end{tikzcd}$$

Mini-exercise

- Apply the tableau algorithm to test whether A is satisfiable w.r.t.

$\{A \sqsubseteq B \sqcap \exists P.C,$
$B \sqsubseteq C \sqcap \forall P.(\neg C \sqcup D)\}$

{A SubClassOf B and (P some C),
B SubClassOf C and (P only (not C or D)}

This week: GCIs and tableau algorithm

- When writing an OWL ontology in Protégé,
  - axioms are of the form A SubClassOf B with A a class **name**
  - (or A EquivalentTo B with A a class **name)**

  - last week's tableau handles these via **unfolding:**
    - works only for **acyclic** ontologies
    - e.g., not for A SubClass (P some A)

- **but** OWL allows for **general class inclusions (GCIs),**
  - axioms of the form A SubClassOf B with A a class **expression**
  - e.g., (eats some Thing) SubClassOf Animal
  - e.g., (like some Dance) SubClassOf (like some Music)
  - this requires another rule:

$$x \bullet \{\ldots\} \quad \rightarrow_{GCI} \quad x \bullet \{\neg C \sqcup D, \ldots\}$$

for each $C \sqsubseteq D \in O$

Interlude: GCIs

- Assume you have some $C \sqsubseteq D \in O$ and consider an interpretation *I*:
  - If *I* is a model of O, then
    - $C^I \subseteq D^I$, hence
    - $x \in C^I$ implies $x \in D^I$ for each x in the domain of *I, hence*
    - $x \notin C^I$ *or* $x \in D^I$, hence
    - $x \in (C^I \sqcup D^I)$

- This is why our new rule ensure that the interpretation we are trying to construct satisfies all GCIs:

$$x \bullet \{\ldots\} \quad \rightarrow_{GCI} \quad x \bullet \{\neg C \sqcup D, \ldots\}$$

for each $C \sqsubseteq D \in O$

GCIs and tableau algorithm

$x \bullet \{\ldots\} \quad \rightarrow_{GCI} \quad x \bullet \{\neg C \sqcup D, \ldots\}$

for each $C \sqsubseteq D \in O$

- E.g., test whether

  A is satisfiable w.r.t.
  {A SubClassOf (P some A)}
  or $\{A \sqsubseteq \exists P.A\}$

- This rule easily causes **non-termination**
  - if we do not **block**

$$\begin{array}{l} \bullet\ \{A, \neg A \sqcup \exists P.A, \exists P.A\} \\ \downarrow P \\ \bullet\ \{A, \neg A \sqcup \exists P.A, \exists P.A\} \\ \downarrow P \\ \bullet\ \{A, \neg A \sqcup \exists P.A, \exists P.A\} \\ \downarrow P \\ \bullet\ \{A, \neg A \sqcup \exists P.A, \exists P.A\} \\ \downarrow P \\ \ldots \end{array}$$

Blocking

$x \bullet \{\exists R.C, \ldots\} \quad \rightarrow_{\exists} \quad x \bullet \{\exists R.C, \ldots\} \xrightarrow{R} y \bullet \{C\}$

only if x's node label isn't contained in the node label of a predecessor of x

- Blocking ensures termination
  - even on cyclic ontologies
  - even with GCIs
- If x's node label is contained in the label of a predecessor y, we say "*x is blocked by y*"

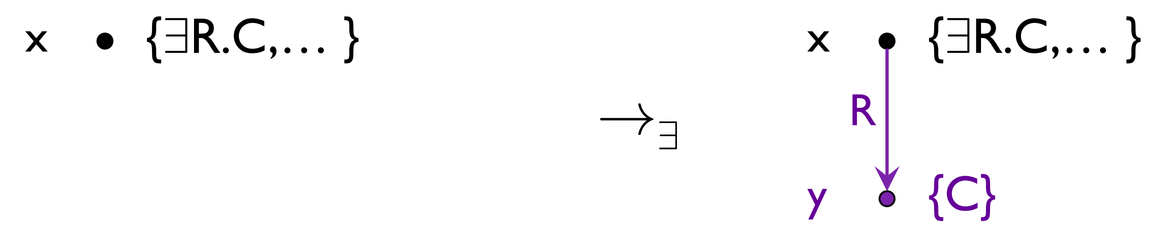
- E.g., test whether A is satisfiable w.r.t. {A SubClassOf (P some A)}
  - here, n2 is blocked by n1

$n1 \bullet \{A, \neg A \sqcup \exists P.A, \exists P.A\}$

$\downarrow P$

$n2 \bullet \{A, \neg A \sqcup \exists P.A, \exists P.A\}$

Blocking



only if x's node label isn't contained in the node label of a predecessor of x

- When blocking occurs, we can build a **cyclic** model from a complete & clash-free completion tree
  - hence soundness is preserved!

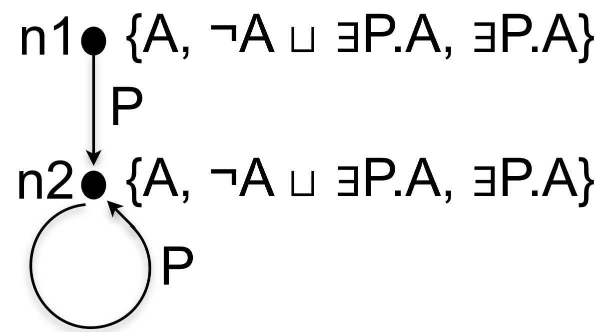


Tableau algorithm with blocking

Our ALC tableau algorithm with blocking is

- **sound**: if the algorithm stops and says “input ontology is consistent” then it is.
- **complete:** if the input ontology is consistent, then the algorithm stop and says so.
- **terminating:** regardless of the size/kind of input ontology, the algorithm stops and says
  - either “input ontology is consistent”
  - or “input ontology is **not** consistent”

- …i.e., a decision procedure for ALC ontologies
  - even in the presence of cyclic axioms!

Tableau algorithm & complexity

not too bad: bounded by number of 'some' expressions in O

Our ALC tableau algorithm has a few sources of **complexity**

- the breadth/out-degree of the tree constructed
- the depth of/path length in tree constructed
- non-determinism due to $\rightarrow_{\sqcup}$ rule from
  - disjunctions in O, e.g., A SubClassOf B
  - SubClassOf axioms in O
  - EquivalentTo axioms in O

•ok/l… r acyclic O … tial for … eneral O: … ct O … each model has a path of length 2^n

hopefully not too bad

1 di… f…

37,778,931,862,957,161,709,568

2 disjunctions per axiom in O for each node in tree

3 nodes with 25 SubClassOf axioms → how many choices?

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Tableau algorithm & complexity

- Without further details: deciding ALC satisfiability
  - only of class expressions is PSpace-Complete
  - of class expressions w.r.t. ontology is ExpTime-complete
  - …**much** higher than intractable/SAT
- Implementation of ALC or OWL tableau algorithm requires **optimisation**
  - there has been a lot of work in the last ~25 years on this
  - you see the fruits in Fact++, Pellet, Hermit, Elk, … reasoners available in Protégé
  - some of them from SAT optimisations, see COMP60332
- Next, I will discuss 1 optimisation: **enhanced traversal**

Naive Classification

- **Remember: Classifying O** is a reasoning service consisting of

1. testing whether O is consistent; if yes, then

    Test:
    is Thing satisfiable w.r.t. O?

2. checking, for each pair A,B of class names in O plus Thing, Nothing whether O ⊧ A SubClassOf B

    Test:
    is A ⊓¬B **un**satisfiable w.r.t. O?

3. checking, for each individual name b and class name A in O, whether O ⊧ b:A

    Test:
    is O ∪ {b:¬A} is **in**consistent?

…and returning the result in a suitable form: O's **inferred class hierarchy**

Naive Classification

- **Remember: Classifying O** is a reasoning service consisting of

1. testing whether O is consistent; if yes, then

Test: is Thing satisfiable w.r.t. O?	1 test

2. checking, for each pair A,B of class names in O plus Thing, Nothing whether O ⊧ A SubClassOf B

Test: is A ⊓¬B **un**satisfiable w.r.t. O?	n^2 tests for O with *n* class names

3. checking, for each individual name b and class name A in O, whether O ⊧ b:A

Test: is O ∪ {b:¬A} is **in**consistent?	*nm* tests for O with *n* class names, *m* individuals

…and returning the result in a suitable form: O's **inferred class hierarchy**

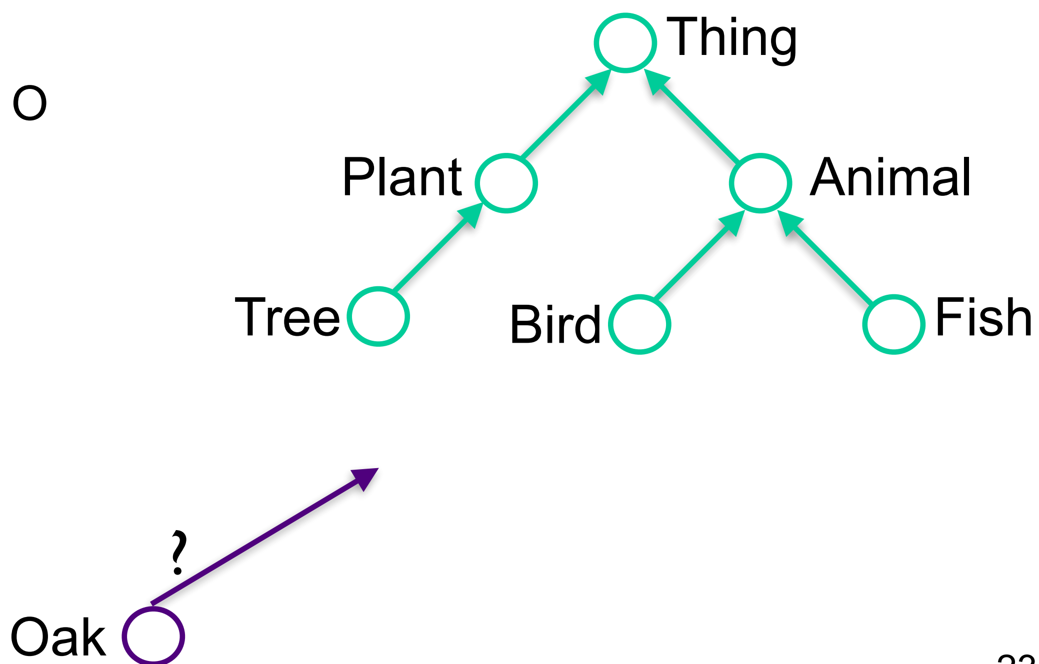
Enhanced Traversal

- **Naive Classification of O** requires 1 + n^2 + nm expensive satisfiability/consistency tests
- …can we do better?

➡ Enhanced Traversal

  - idea: build inferred class hierarchy top-down and bottom-up, "trickling in" each class name in turn

- Assume you have, so far, constructed this hierarchy for O
- Now you "trickle in" Oak



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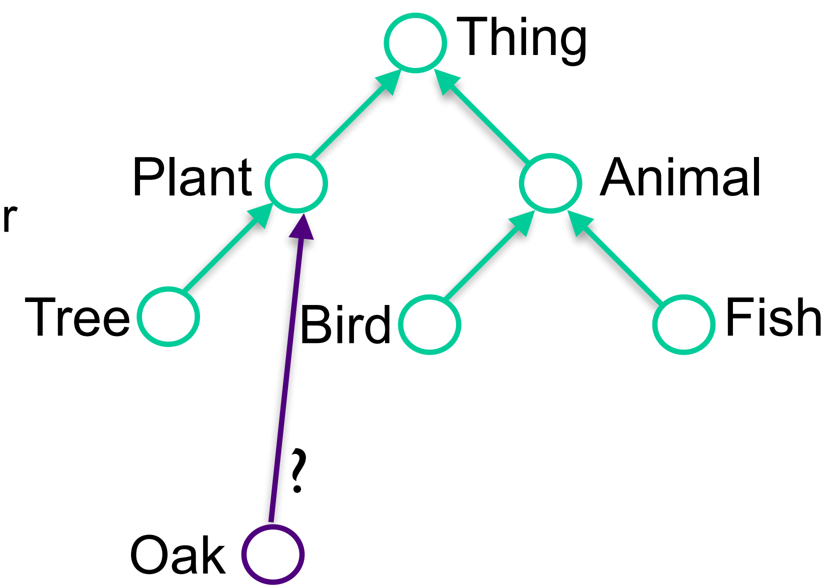
- Assume you have, so far, constructed this hierarchy for O
- Now you “trickle in” Oak: check whether
  - O ⊧ Oak ⊑ Plant?
    yes - continue with Plant’s child



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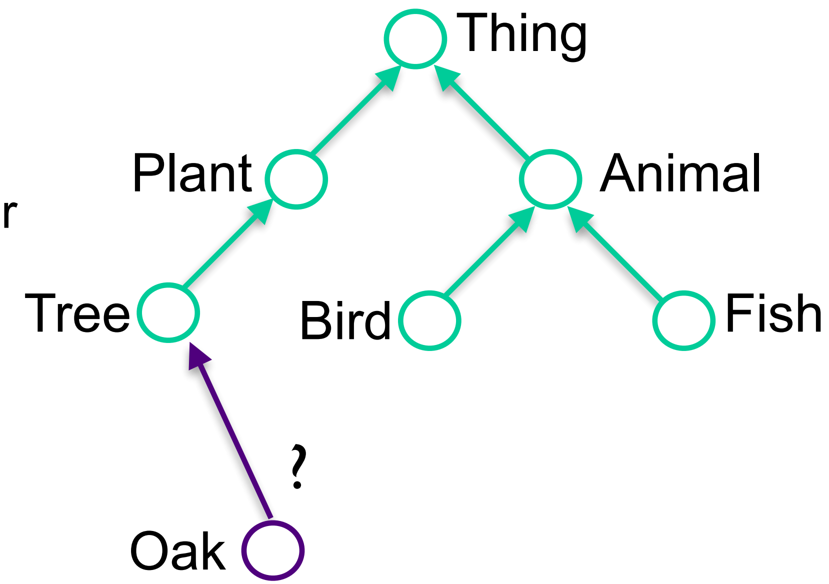
- Now you "trickle in" Oak: check whether
  - O ⊨ Oak ⊑ Plant?
    yes - continue with Plant's child
  - O ⊨ Oak ⊑ Tree?
    yes. Done here, backtrack.



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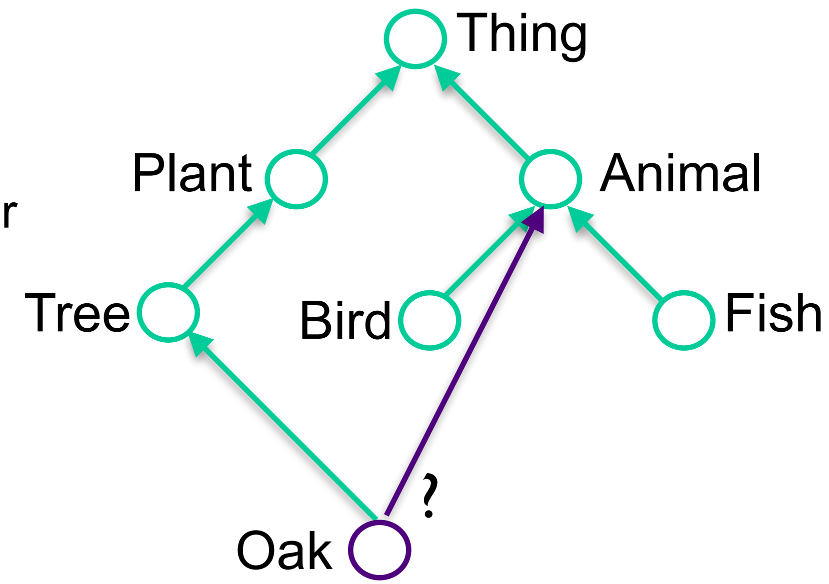
- Assume you have, so far, constructed this hierarchy for O
- Now you "trickle in" Oak: check whether
  - O ⊧ Oak ⊑ Plant?
    yes - continue with Plant's child
  - O ⊧ Oak ⊑ Tree?
    yes. Done here, backtrack.
  - O ⊧ Oak ⊑ Animal?
    No. Done: no more need to test!



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Enhanced Traversal

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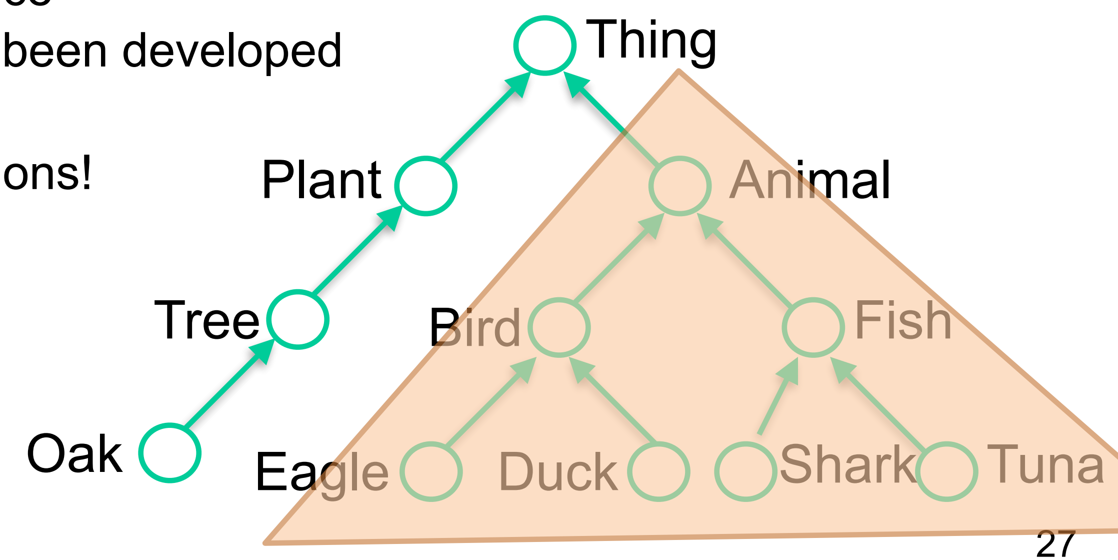
➡ Enhanced Traversal
  - idea: build inferred class hierarchy top-down and bottom-up, “trickling in” each class name in turn

- Potentially avoids many of the n^2 satisfiability/consistency tests
  - very important in practice
  - different variants have been developed
- Just one of many optimisations!



OWL Profiles

Restrictions
of OWL to tame
complexity

OWL Profiles

- Despite all optimisations, classification may still take too long if ontology is
  - **big** (300,000 axioms or more) and/or
  - **rich** (ALC plus inverse properties, atleast, atmost, sub-property chains,…)

- For OWL 2 [*], **profiles** have been designed
  - syntactic fragments of OWL obtained by restricting constructors available

- Each profile is
  - **maximal,** i.e., we know that if we allow more constructors, then computational complexity of reasoning would increase
  - **motivated** by a use case

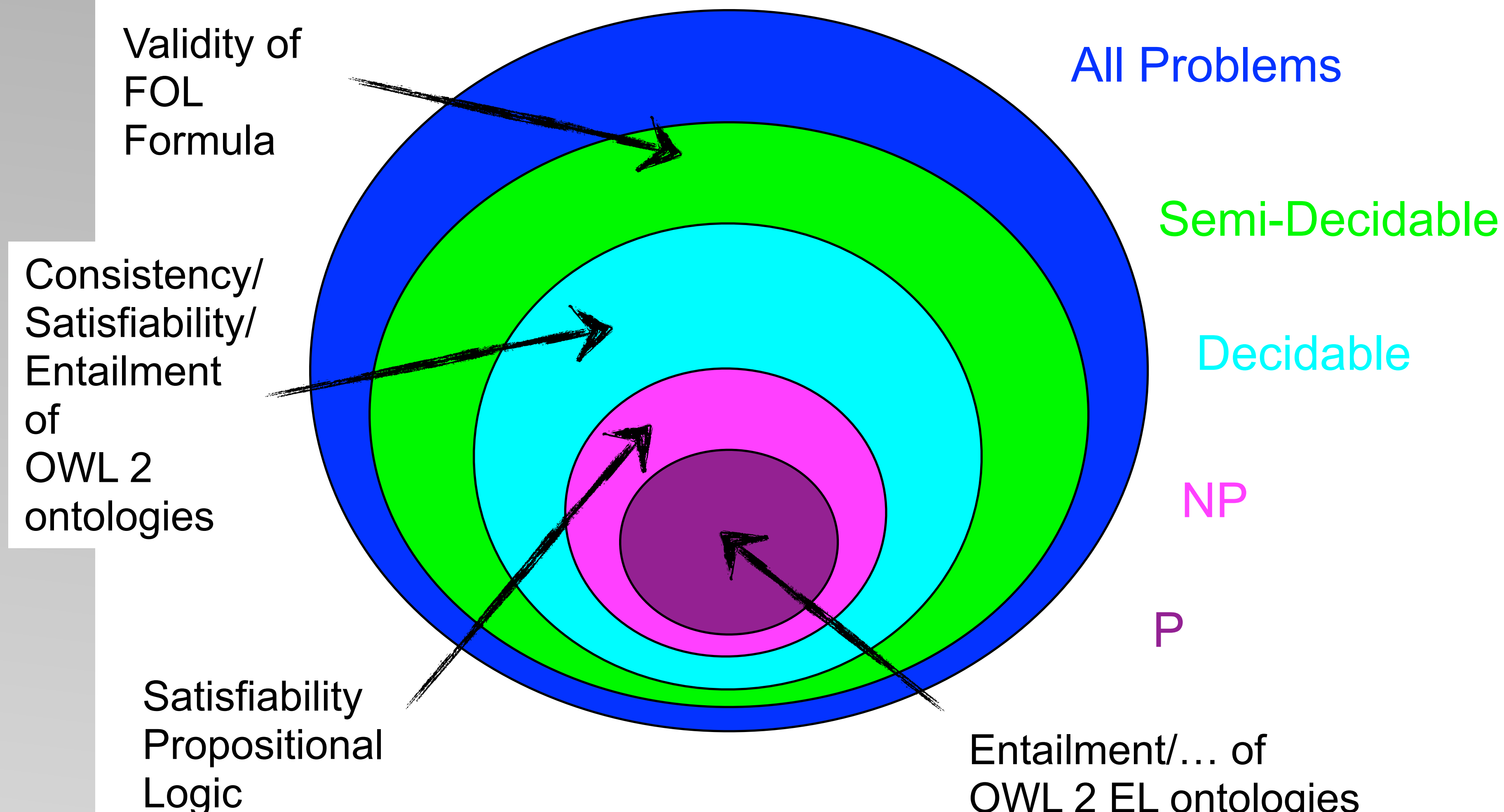
[*] the one we talk about here/you use in Protégé

OWL Profiles

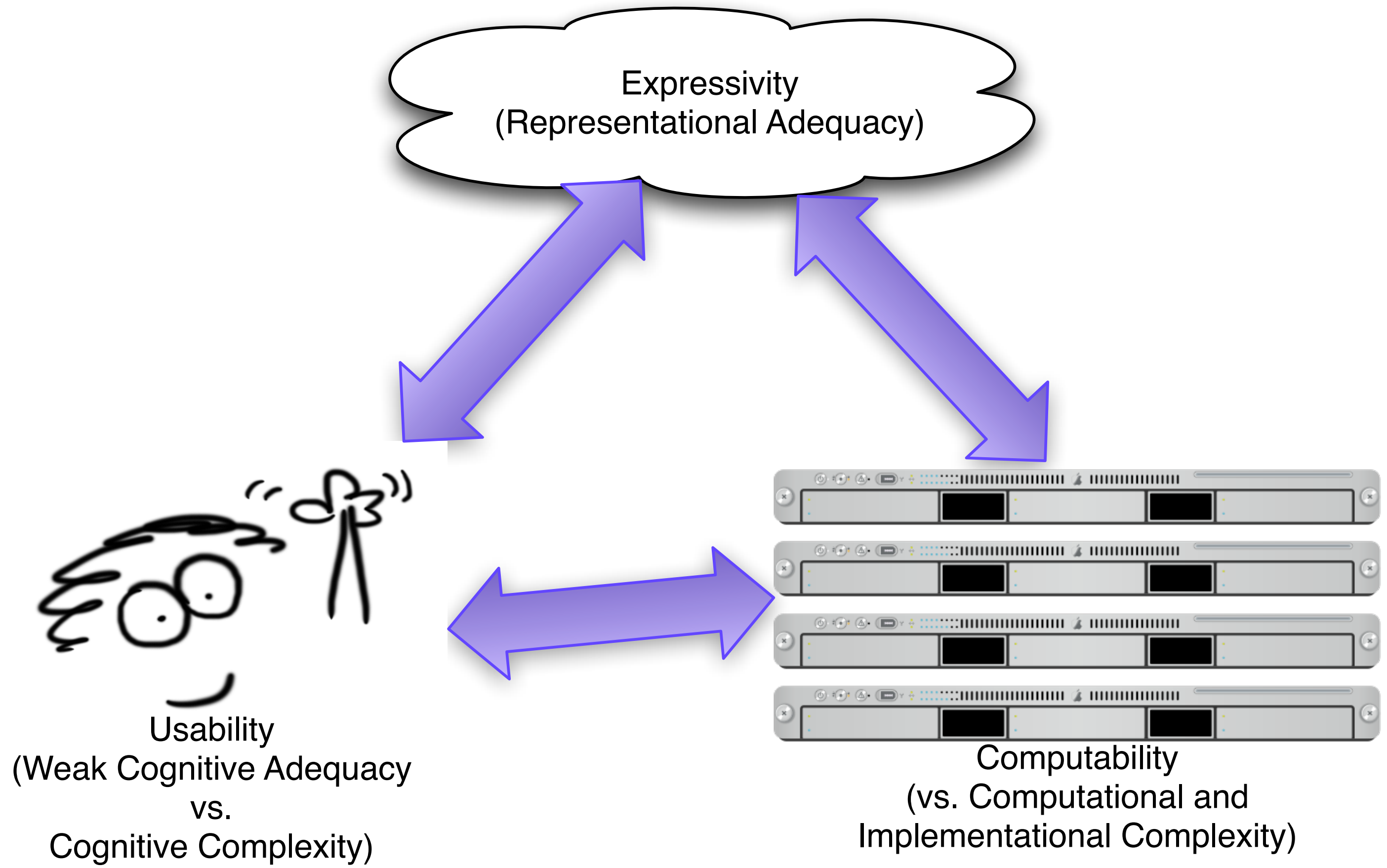
OWL 2 has 3 profiles, roughly defined as follows:

- OWL 2 EL:
  - only and, some, SubProperty, transitive, SubPropertyChain
  - it's a *Horn* logic
    - no *reasoning by case* required,
    - no *disjunction*, not even hidden
  - designed for big class hierarchies
- OWL 2 QL:
  - only restricted some, restricted and, inverseOf, SubProperty
  - designed for querying data in a database through a class-level ontology
- OWL 2 RL:
  - no some on RHS of SubClassOf, …
  - designed to be implemented via a classic rule engine
- For details, see OWL 2 specification!

Some Key Complexity Classes



The design triangle



Summary

OWL reasoning

- is unusual:
  - standard reasoning involves solving **many** reasoning problems/ satisfiability tests
- is decidable:
  - for standard reasoning problems, we have **decision procedures**
  - i.e., a calculus that is sound, complete, and terminating
- can be complex
  - but we know the complexity for many different DLs/OWL variants/profiles
  - and implementations require many good optimisations!

- goes beyond what we have discussed here
  - entailment explanation
  - query answering
  - module extraction
  - …

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Today

- ✓ Some clarifications from last week's coursework
- ✓ More on reasoning:
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    - ✓ traversal or "how to compute the inferred class hierarchy"
    - ✓ OWL profiles
- Snap-On: an ontology-based application
- The OWL API: a Java API and reference implementation for
    - creating,
    - manipulating and
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- **Lab**:
    - OWL API for coursework
    - Ontology Development