Description Logics: a Nice Family of Logics — Modularity —

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Plan for today

1. What is modularity good for?
2. Modules for reuse
3. Summary and Outlook

And now . . .

1. What is modularity good for?
2. Modules for reuse
3. Summary and Outlook

What can I do with my ontology?

Ontology users and engineers want to use ontologies to

- represent and archive knowledge **(M)**
  in a structured way
- compute inferences from archived knowledge **(M)**
  e.g., classification, query answering
- explain inferences **(M)**
  justifications = pinpointing, abduction
- reuse (parts of) other ontologies to build their ontology **(M)**
  import
- expose the logical structure of the represented knowledge **(M)**
  comprehension

(M) = modularity helps

What can I do with my ontology?

Building and using an ontology often requires

- fast reasoning **(M)**
  expressivity ↔ complexity; optimisations, incremental reasoning
- collaborative development **(M)**
- version control **(M)**
- *efficient* reuse **(M)**
- an understanding of the ontology's content and structure **(M)**
  comprehension

(M) = modularity helps

A priori vs. a posteriori modularisation

A priori (not covered today)

- At first, a modular structure is decided on.
- Then, the ontology is developed and used according to that structure.

A posteriori

- The ontology is regarded as a monolithic entity.
- At some point, a module is extracted
  or the ontology is decomposed into several modules.

And now . . .

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Comparing two ontologies

Assume that . . .

- you want to buy a medical ontology from me
- I offer two medical ontologies $\mathcal{O}_1$ and $\mathcal{O}_2$

Q: which one do you choose?

Possible A: the one that contains more knowledge.

Q: how do you measure the amount of knowledge in $\mathcal{O}_i$?

Possible A: ~~Number of axioms?~~

- Well, compare $\{A \sqsubseteq B,\ B \sqsubseteq A\}$ vs. $\{A \equiv B\}$
- or $\{A \sqsubseteq B,\ B \sqsubseteq A \sqcup \neg A,\ A \sqcap \neg A \sqsubseteq B\}$ vs. $\{A \equiv B\}$

Possible A: Number of entailments? Number of models?

Ontologies and their entailments

Think of axioms as **generating entailments** – e.g.:

$$\left.\begin{array}{l} A \sqsubseteq \exists r.B \\ \exists r.\top \sqsubseteq C \sqcap D \end{array}\right\} \models \quad A \sqsubseteq D$$

Q: how many entailments can a TBox have?

A: ∞

$A \sqsubseteq D \quad A \sqsubseteq D \sqcup A \quad A \sqsubseteq D \sqcup (A \sqcap D), \quad \ldots$

Ontologies and their models

Think of axioms as **restricting possible models**

Axioms "filter out" unwanted models – e.g.:

- $\mathtt{Hand} \sqsubseteq \exists \mathtt{hasPart.Finger}$

  $\leadsto$ models cannot have instances of `Hand` with no `hasPart`-edge to an instance of `Finger`

- $\mathtt{Hand} \sqsubseteq = 5\, \mathtt{hasPart.Finger}$

  $\leadsto$ models cannot have instances of `Hand` with $\neq 5$ `hasPart`-edges to instances of `Finger`

Q: how many models can a TBox have?

A: 0 ∞

Next attempt at "more" entailments/models

We cannot compare *numbers* of entailments or models

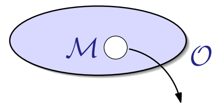
But we can use set inclusion:
"$\mathcal{O}$ knows at most as much as $\mathcal{O}'$" if

- every entailment of $\mathcal{O}$ is one of $\mathcal{O}'$:
  $\{\eta \mid \mathcal{O} \models \eta\} \subseteq \{\eta \mid \mathcal{O}' \models \eta\}$ or
- every model of $\mathcal{O}'$ is one of $\mathcal{O}$:
  $\{\mathcal{I} \mid \mathcal{I} \models \mathcal{O}'\} \subseteq \{\mathcal{I} \mid \mathcal{I} \models \mathcal{O}\}$

Problem:

How do we test these conditions?

Knowledge w.r.t. a signature



Let's reformulate the initial dialogue.
Assume that ...

- you want to buy **a subset of** a medical ontology $\mathcal{O}$ from me that covers the subdomain of, say, diseases
- I offer two subsets $\mathcal{M}_1$ and $\mathcal{M}_2$

Q: which one do you choose?

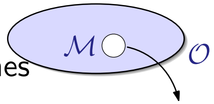
Possible A: the one that "knows more" about diseases!

Q: which is the **best subset** I can offer?

Possible A: a **module for diseases**

- $\mathcal{M} \subseteq \mathcal{O}$ that knows as much as $\mathcal{O}$ about diseases:
  $\mathcal{M}$ **indistinguishable** from $\mathcal{O}$ w.r.t. all terms relevant for diseases
- $\mathcal{M}$ as small as possible

Inseparability w.r.t. a signature



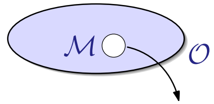
Definition

- **Signature** Σ = a set of concept/role names
- The signature of axiom (ontology) X
  = all concept/role names in X
- $\mathcal{O}_1$ and $\mathcal{O}_2$ are **Σ-inseparable w.r.t. a logic $\mathcal{L}$**,
  written $\mathcal{O}_1 \equiv^{\mathcal{L}}_{\Sigma} \mathcal{O}_2$, if: [Konev et al. 2009]
  for all $\eta \in \mathcal{L}$ with $\mathrm{sig}(\eta) \subseteq \Sigma$,

$$\mathcal{O}_1 \models \eta \quad \text{iff} \quad \mathcal{O}_2 \models \eta$$

- $\mathcal{O}$ is a **Σ-conservative extension (Σ-dCE)** of $\mathcal{M}$ w.r.t. $\mathcal{L}$
  if $\mathcal{M} \subseteq \mathcal{O}$ and $\mathcal{M} \equiv^{\mathcal{L}}_{\Sigma} \mathcal{O}$ [Ghilardi et al. 2006]
  Alternative names:
  - $\mathcal{M}$ **covers** $\mathcal{O}$ for Σ w.r.t. $\mathcal{L}$
  - $\mathcal{M}$ **is a module of** $\mathcal{O}$ for Σ w.r.t. $\mathcal{L}$

Choosing the signature Σ



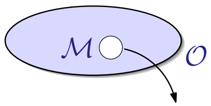
Definition (repeated from previous slide)

$\mathcal{O}$ is a Σ-module of $\mathcal{M}$ w.r.t. $\mathcal{L}$
if $\mathcal{M} \subseteq \mathcal{O}$ and $\mathcal{M} \equiv^{\mathcal{L}}_{\Sigma} \mathcal{O}$

The signature Σ ...

- can be seen as a "topic"
- that the module is required to cover
- is difficult to formulate:
  Q: how many interesting entailments in $\Sigma = \{\texttt{Disease}\}$ can $\mathcal{O}$ possibly have?

Choosing the logic $\mathcal{L}$



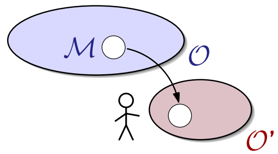
Definition (repeated from previous slide)

$\mathcal{O}$ is a Σ-module of $\mathcal{M}$ w.r.t. $\mathcal{L}$
if $\mathcal{M} \subseteq \mathcal{O}$ and $\mathcal{M} \equiv^{\mathcal{L}}_{\Sigma} \mathcal{O}$

Choice of $\mathcal{L}$ depends on your usage of the module:

- for ontology design: subsumptions betw. (complex?) concepts
- for ontology usage: your favourite query language

Modules for reuse



If we want to reuse module $\mathcal{M}$,
we need a stronger guarantee:

$$\mathcal{M} \cup \mathcal{O}' \equiv^{\mathcal{L}}_{\Sigma} \mathcal{O} \cup \mathcal{O}' \quad \text{for all } \mathcal{O}'$$

i.e., we can safely import $\mathcal{M}$ into any $\mathcal{O}'$

Ensured by two additional requirements:

Lemma [Konev et al. 2009]

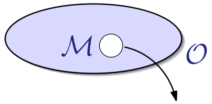
If $\mathcal{M} \subseteq \mathcal{O}$ and $\mathcal{M} \equiv^{\mathcal{L}}_{\Sigma} \mathcal{O}$, then $\mathcal{M} \cup \mathcal{O}' \equiv^{\mathcal{L}}_{\Sigma} \mathcal{O} \cup \mathcal{O}'$, for

1. every $\mathcal{O}'$ with $\mathrm{sig}(\mathcal{O}) \cap \mathrm{sig}(\mathcal{O}') \subseteq \Sigma$,
2. expressive enough $\mathcal{L}$, e.g. $\mathcal{SROIQ}$ (OWL).

(1) means that $\mathcal{O}'$ may reuse only terms from Σ

How is a minimal Σ-module extracted?

Simple module extraction algorithm:



- $\mathcal{M} \leftarrow \mathcal{O}$
- While $\mathcal{M} \setminus \{\alpha\} \equiv_\Sigma^\mathcal{L} \mathcal{O}$, for some $\alpha \in \mathcal{M}$,
  do $\mathcal{M} \leftarrow \mathcal{M} \setminus \{\alpha\}$
- Output $\mathcal{M}$

Observation:

Different orders of choosing α
can lead to different minimal modules

Example

Let $\Sigma = \{\mathsf{Knee}, \mathsf{HingeJoint}\}$. Suppose *Galen* contains:

$$\begin{aligned}
\mathsf{Knee} &\equiv \mathsf{Joint} \sqcap \exists \mathsf{hasPart.Patella} \sqcap \\
&\qquad \exists \mathsf{hasFunct.Hinge} && (1)\\
\mathsf{Patella} &\sqsubseteq \mathsf{Bone} \sqcap \mathsf{Sesamoid} && (2)\\
\mathsf{Ginglymus} &\equiv \mathsf{Joint} \sqcap \exists \mathsf{hasFunct.Hinge} && (3)\\
\mathsf{Joint} \sqcap \exists \mathsf{hasPart.(Bone} \sqcap \mathsf{Sesamoid)} &\sqsubseteq \mathsf{Ginglymus} && (4)\\
\mathsf{Ginglymus} &\equiv \mathsf{HingeJoint} && (5)\\
\mathsf{Meniscus} &\equiv \mathsf{FibroCartilage} \sqcap \exists \mathsf{locatedIn.Knee} && (6)
\end{aligned}$$

$\subseteq$-Minimal module for Σ? $\{(1), (2), (4), (5)\}$ and $\{(1), (3), (5)\}$

Note that a module for Σ does not necessarily contain

- all axioms that use terms from Σ
- only axioms that only use terms from Σ

Bad news for expressive ontology languages?

Big, sad theorem [Ghilardi et al. 2006]

Let $\mathcal{O}_1, \mathcal{O}_2$ be ontologies in $\mathcal{L}$ and Σ a signature.

Determining whether $\mathcal{O}_1 \equiv_\Sigma^\mathcal{L} \mathcal{O}_2$ is

ExpTime-complete	for	$\mathcal{L} = \mathcal{EL}$
2ExpTime-complete	for	$\mathcal{ALC} \leqslant \mathcal{L} \leqslant \mathcal{ALCQI}$, and
undecidable	for	$\mathcal{L} \geqslant \mathcal{ALCQO}$, including OWL

(even if $\mathcal{O}_1, \mathcal{O}_2$ are in $\mathcal{ALC}$).

Consequences for modules of expressive DLs

Extracting modules is highly complex for expressive DLs.

What to do?

1. Give up? No: modules clearly too important
2. Reduce expressivity of logic? Yes! (Not covered here.)
3. Approximate for expressive logics? Yes – but from the *right* direction!

Next: 2 approximations, i.e., sufficient conditions for inseparability

1. based on semantic locality
2. based on syntactic locality

[Cuenca Grau et al. 2009]

Model-theoretic inseparability

Remember: $\mathcal{O}_1 \equiv^{\mathcal{L}}_{\Sigma} \mathcal{O}_2$ if:
for all $\eta \in \mathcal{L}$ with $\mathsf{sig}(\eta) \subseteq \Sigma$,

$$\mathcal{O}_1 \models \eta \quad \text{iff} \quad \mathcal{O}_2 \models \eta$$

Good news: $\Uparrow$

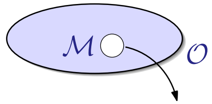
$$\{\mathcal{I}|_\Sigma \mid \mathcal{I} \models \mathcal{O}_1\} = \{\mathcal{I}|_\Sigma \mid \mathcal{I} \models \mathcal{O}_2\}$$

- i.e., $\mathcal{O}_1$ and $\mathcal{O}_2$ have the same models modulo Σ ($\mathcal{I}|_\Sigma$ is the restriction of $\mathcal{I}$ to Σ)
- shorthand: $\mathcal{O}_1 \equiv^{\mathsf{mod}}_{\Sigma} \mathcal{O}_2$ (model-inseparable)
- this notion does not depend on $\mathcal{L}$

Bad news: $\mathcal{O}_1 \equiv^{\mathsf{mod}}_{\Sigma} \mathcal{O}_2$ is undecidable already for $\mathcal{ALC}$!

Semantic locality

We can approximate model-inseparability, exploiting that $\mathcal{M}$ is a subset of $\mathcal{O}$



$$\mathcal{M} \equiv^{\mathsf{mod}}_{\Sigma} \mathcal{O}$$

$$\Updownarrow$$

every $\mathcal{I} \models \mathcal{M}$ can be extended to $\mathcal{J} \models \mathcal{O}$ with $\mathcal{I}|_\Sigma = \mathcal{J}|_\Sigma$

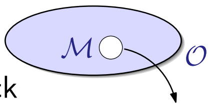
$$\Uparrow$$

every $\mathcal{I} \models \mathcal{M}$ can be extended to $\mathcal{J} \models \mathcal{O}$ with $\mathcal{I}|_\Sigma = \mathcal{J}|_\Sigma$
and $\forall X \notin \Sigma : X^{\mathcal{J}} = \emptyset$

$$\Updownarrow$$

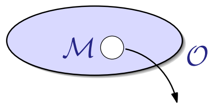
every $\alpha \in \mathcal{O} \setminus \mathcal{M}$ is **semantically local w.r.t. $\Sigma \cup \mathsf{sig}(\mathcal{M})$**:
α, with all terms not in $\Sigma \cup \mathsf{sig}(\mathcal{M})$ replaced by $\bot$, is a tautology

From semantic to syntactic locality



- Semantic locality involves tautology check
  $\rightsquigarrow$ can be tested using a reasoner
  $\rightsquigarrow$ has the same complexity as standard reasoning
- A syntactic approximation that can be tested in poly-time:
  syntactic locality
  (describes "obviously" sem. local axioms via a grammar)
- Both notions lead to modules that are
  - $(\Sigma \cup \mathsf{sig}(\mathcal{M}))$-inseparable from $\mathcal{O}$
  - not necessarily minimal

Module extraction with locality



Module extraction algorithm:

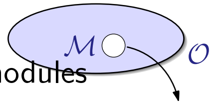
- $\mathcal{M} \leftarrow \emptyset$
- While α **not local** w.r.t. $\Sigma \cup \mathsf{sig}(\mathcal{M})$, for some $\alpha \in \mathcal{O} \setminus \mathcal{M}$,
  do $\mathcal{M} \leftarrow \mathcal{M} \cup \{\alpha\}$
- Output $\mathcal{M}$

Variations:

- this notion: (semantic/syntactic) $\bot$-module
- dual notion: (semantic/syntactic) $\top$-module
- smaller modules by nesting $\top$- and $\bot$-module extraction: $\top\bot^*$-modules

Summary locality-based modules

Locality-based modules . . .



- are "good approximations" of minimal modules because they guarantee $\mathcal{M} \equiv^{\mathcal{L}}_{\Sigma} \mathcal{O}$
- are not necessarily minimal (but in practice often small enough)
- can be extracted in polynomial time (syntactic locality)
- are even **self-contained:**

  $$\mathcal{M} \equiv^{\mathcal{L}}_{\Sigma \cup \mathsf{sig}(\mathcal{M})} \mathcal{O}$$

  and **depleting:**

  $$\mathcal{O} \setminus \mathcal{M} \equiv^{\mathcal{L}}_{\Sigma \cup \mathsf{sig}(\mathcal{M})} \emptyset$$

  and thus **unique**
- contain all justifications for any α with $\mathsf{sig}(\alpha) \subseteq \Sigma$

$\rightsquigarrow$ **Cheap is cheerful! :)**

And now . . .

Summary on modularity

- Inseparability/coverage is a guarantee relevant (not only) for reuse
- Approximation of minimal covering modules via locality
- Modules based on syntactic locality can be extracted efficiently in logics up to $\mathcal{SROIQ}$ (OWL 2)
- Tool support for extracting modules:
  http://owl.cs.manchester.ac.uk/modularity
  http://owlapi.sourceforge.net/
- This line of research is rather new for DLs and ontology languages, and many questions are (half)open.

See also . . .

. . . slides from ESSLLI 2013 course "Modularity in Ontologies":
http://www.informatik.uni-bremen.de/~ts/teaching/2013_modularity/

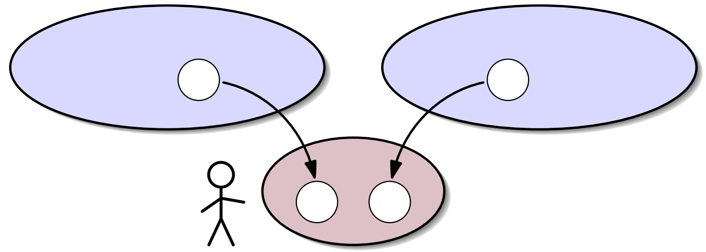
. . . the references at the end of this presentation

We're almost done! :)

Appendix and References

An import/reuse scenario

"Borrow" knowledge from external ontologies

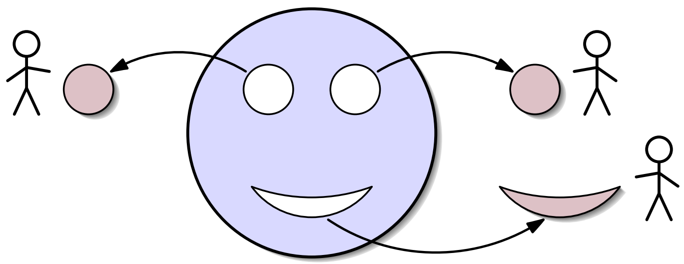


- Provides access to well-established knowledge
- Doesn't require expertise in external disciplines

This scenario is well-understood and implemented.

A collaboration scenario

Collaborative ontology development

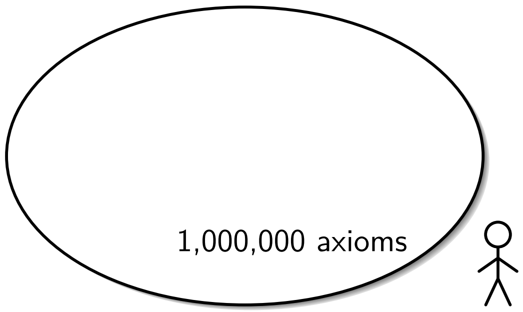


- Developers work (edit, classify) locally
- Extra care at re-combination
- Prescriptive/analytic behaviour

This approach is mostly understood, but not implemented yet.

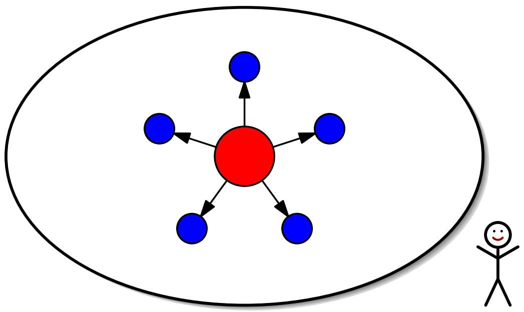
Understanding and/or structuring an ontology

Compute the modular structure of an ontology



Understanding and/or structuring an ontology

Compute the modular structure of an ontology



This is work in progress.

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