Semantics and Conceptual Modelling

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Outline

1. Introduction
2. Ontology and conceptual models
   - Semantics of relations
   - FOs and CDMLs
   - More choices
   - Analysing other diagrams
3. Language design
   - Principles
   - Toward logics for CDMLs
   - Logic-based profiles for CDMLs
4. Time and conceptual models
   - Choices
   - Logic-based Temporal EER
   - Semantics of essential and immutable parts
Dissecting the title

- **Semantics**, which has different meanings:

- **Conceptual modelling**
Dissecting the title

- **Semantics**, which has different meanings:
  - *Logic*: formal meaning of the ‘things’ represented with the syntax of a language
  - *Subject domain*: meaning of something (e.g., the definition, characteristics of ‘course’, ‘professor’, ‘attend’ etc.)

- **Conceptual modelling**
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  - *Subject domain*: meaning of something (e.g., the definition, characteristics of ‘course’, ‘professor’, ‘attend’ etc.)

- **Conceptual modelling**
  - The process of creating conceptual models
  - Conceptual data models, like those represented in EER, UML Class diagram notation, ORM
  - Other conceptual models, such as conceptual graphs, petri nets, ....
“Conceptual model”
“Conceptual model”
Dissecting the title

• ‘real’ conceptual models vs ‘computational-conceptual’ models
  • Conceptual models *do not* have implementation decisions embedded in them
  • Some models do have some computational decisions; e.g., PK/FK, data types
Dissecting the title

‘real’ conceptual models vs ‘computational-conceptual’ models

- Conceptual models *do not* have implementation decisions embedded in them
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Difference(s) between conceptual models and ontologies (simplified/shorthand):

- Conceptual models (in CS&IT) are application *dependent*
- Ontologies are (in theory at least) application *independent*
Ontology provides the common vocabulary and constraints that hold across the applications.

Conceptual model shows what is stored in that particular application.

Implementation the actual information system that stores and manipulates the data.
Dissecting the title

- How/where is ontology possibly useful for conceptual models and modelling?
  - Use ontology to improve the quality of a conceptual model
  - Reuse (part of) an ontology in a conceptual model
  - Use ontology to decide which language features should be available in a conceptual modelling language
  - Language ideally is logic-based so as to be (somewhat) precise
What we will cover in the 3 sessions

1. Ontology
2. Languages for conceptual modelling
3. Temporal aspects (time permitting)
Flavour of things to come: Ontology

- What are the core constructs (e.g., what’s a relation?) and [how] does that affect the language?
- Do we need foundational ontology choices for modelling and if so, how?
- Modelling patterns—are some better than others, and if so: why?
- Refining aggregation/part-whole relations
Example scenario: isiZulu term bank (simplified)
After logical and ontological analysis
(still a small ‘toy’ example)
Flavour of things to come: language design

- How to give a formal semantics to the diagrams or controlled natural language?
- What does an ontologically well-founded logic (language) for conceptual modelling look like?
- What’s the use of formalising it anyway?
Conceptual data models–UML Class Diagram, inferences

\[ B \subseteq A \]
\[ C \subseteq A \]
\[ D \subseteq B \]
\[ D \subseteq C \]
\[ B \cap C \subseteq \bot \]

\[ \forall x (B(x) \rightarrow A(x)) \]
\[ \forall x (C(x) \rightarrow A(x)) \]
\[ \forall x (D(x) \rightarrow B(x)) \]
\[ \forall x (D(x) \rightarrow C(x)) \]
\[ \forall x (B(x) \wedge C(x) \rightarrow \bot) \]
Conceptual data models—UML Class Diagram, inferences

A

{disjoint}

B  C

D

B ⊆ A  ∀x(B(x) → A(x))
C ⊆ A  ∀x(C(x) → A(x))
D ⊆ B  ∀x(D(x) → B(x))
D ⊆ C  ∀x(D(x) → C(x))
B ∩ C ⊆ ⊥  ∀x(B(x) ∧ C(x) → ⊥)
Conceptual data models–EER diagram, inferences

\[
\begin{align*}
R &\subseteq [i]A \cap [j]C \\
S &\subseteq [i]D \cap [j]B \\
A &\subseteq 1[i]R \\
C &\subseteq 1[j]R \\
B &\subseteq \exists[i]R
\end{align*}
\]

\[
\begin{align*}
\forall x, y (R(x, y) &\implies A(x) \land C(y)) \\
\forall x, y (S(x, y) &\implies D(x) \land B(y)) \\
\forall x (A(x) &\implies \exists^=1 y (R(x, y))) \\
\forall y (C(y) &\implies \exists^=1 x (R(x, y))) \\
\forall y (B(y) &\implies \exists x (S(x, y)))
\end{align*}
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Conceptual data models–EER diagram, inferences

\[
R \subseteq [i]A \cap [j]C \\
S \subseteq [i]D \cap [j]B \\
A \sqsubseteq 1[i]R \\
C \sqsubseteq 1[j]R \\
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\forall x, y(R(x, y) \rightarrow A(x) \land C(y)) \\
\forall x, y(S(x, y) \rightarrow D(x) \land B(y)) \\
\forall x(A(x) \rightarrow \exists=1y(R(x, y))) \\
\forall y(C(y) \rightarrow \exists=1x(R(x, y))) \\
\forall y(B(y) \rightarrow \exists x(S(x, y)))
\]
Typical *computational* usages for conceptual models

- **Reasoning over conceptual models to improve their quality**

- **Use of conceptual models during runtime**
  - Verification and validation [Cabot et al.(2008), Nizol et al.(2014)] (e.g., scalable test data generation [Smaragdakis et al.(2009)])
  - Designing [Bloesch and Halpin(1997)] and executing [Calvanese et al.(2010)] queries with the model’s vocabulary; VQF/QBD [So{\l}u et al.(2017)]
  - Querying databases during the stage of query compilation [Toman and Weddell(2011)]

- Ontology-based data access and integration (tries both)
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Elements in conceptual data models

- Class/Entity type
- Association/relationship/fact type, $n \geq 2$
- Attribute or Value Type
- One or more language specific elements, such as qualified association, aggregation association, objectified fact type
- Plethora of constraints
Poll: are teaches and taught by two relations?
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no... (more about that in the next slides)
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Poll: How do you map UML’s association ends (or ORM’s roles) to an OWL object property (or vv.)?
Poll: are teaches and taught by two relations?
  - no... (more about that in the next slides)

Poll: How do you map UML’s association ends (or ORM’s roles) to an OWL object property (or vv.)?
  - Bit tricky, you have to make a modelling decision... (more about that later)

⇒ These two questions surface as a consequence of different ontological commitments as to what a relation or relationship really is (or what you’re convinced of it is)
A few more modelling questions for relations

- Should you introduce a minimum amount of properties, or many?
- Always (try to) declare domain and range axioms?
- Use explicit inverses (extending the vocabulary) or not?
- What about ternaries?
- How to find and fix mistakes and pitfalls?
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A note from philosophy

- Relations investigated in philosophy
  - Nature and properties of some specific relations (parthood, portions, participation, causation)
  - ‘Categories’ of relations (material, formal)
  - Nature of relation itself (standard, positionalist, anti-positionalist)

- Some results more useful for ontologies and conceptual modelling than others, some even for tool development
On relations

- Early ideas were put forward by [Williamson(1985)] and have been elaborated on and structured in [Fine(2000), van Inwagen(2006), Leo(2008), Cross(2002)]

- Three different ontological commitments about relations and relationships, which are, in Fine’s [Fine(2000)] terminology, the *standard view*, the *positionalist*, and the *anti-positionalist* commitment
The ‘standard view’ commitment

- Relies on linguistics and the English language in particular
- Take the fact *John loves Mary*, then one could be led to assume that *loves* is the name of the relation and *John* and *Mary* are the objects participating in the relation
- Then *Mary loves John* is not guaranteed to have the same truth value as the former fact—changing the verb does, i.e., *Mary is loved by John*
- We (seem to) have two relations, *loves* and its inverse *is loved by*
Problems with the ‘standard view’ (1/2)

- For names $a$ and $b$, $a$ loves $b$ holds iff what $a$ denotes (in the reality we aim to represent) loves what $b$ denotes.

- *John loves Mary* is not about language but about John loving Mary, so John and Mary are non-linguistic; cf. *‘cabeza’ translates into ‘head’*
For names $a$ and $b$, $a$ loves $b$ holds iff what $a$ denotes (in the reality we aim to represent) loves what $b$ denotes.

*John loves Mary* is not about language but about John loving Mary, so John and Mary are non-linguistic; cf. ‘cabeza’ translates into ‘head’

Then, that John loves Mary and Mary is being loved by John refer to only one state of affairs between John and Mary

Why should we want, let alone feel the need, to have *two relations* to describe it?
Toward the ‘positionalist’ commitment

- Designate the two aforementioned facts to be relational expressions and not to let the verb used in the fact automatically also denote the name of the relation.
- Then we can have many relational expressions standing in for the single relation that captures the state of affairs between John and Mary.
- In analogy, we can have many relational expressions for one relationship at the type level.
Second, the specific order of the relation: changing the order does not mean the same for verbs that indicate an asymmetric relation; different for some other languages.
Problems with the ‘standard view’ (2/2)

- Second, the specific order of the relation: changing the order does not mean the same for verbs that indicate an asymmetric relation; different for some other languages.

- Consider *John kills the dragon*. In Latin we have:
  - *Johannus anguigenam caedit*, or
  - *anguigenam caedit Johannus*, or
  - *Johannus caedit anguigenam*,
  which all refer to the same state of affairs

- But *Johannum anguigena caedit* is a different story altogether

- Likewise for *John loves Mary* and *
  - Johannus Mariam amat* versus
  - *Johannum Maria amat*. 
Toward the ‘positionalist’ commitment

- A linguistic version of *argument places (roles)* thanks to the nominative and the accusative that are linguistically clearly indicated.
- The order of the argument places is not relevant for the relation itself.
Toward the ‘positionalist’ commitment

- A linguistic version of *argument places (roles)* thanks to the nominative and the accusative that are linguistically clearly indicated.
- The order of the argument places is not relevant for the relation itself.
- English without such declensions that change the terms so as to disambiguate the meaning of a relational expression.
- *Inverses for seemingly asymmetrical relations necessarily exist in reality and descriptions of reality in English, but not in other languages even when they represent the same state of affairs???*
Toward the ‘positionalist’ commitment

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- English without such declensions that change the terms so as to disambiguate the meaning of a relational expression.
- *Inverses for seemingly asymmetrical relations necessarily exist in reality and descriptions of reality in English, but not in other languages even when they represent the same state of affairs??*
- Asymmetric *relational expressions*, but this does not imply that the relation it verbalises is asymmetric.
The ‘positionalist’ commitment

- Binary relation *killing* and identify the argument places—“argument positions” [Fine(2000)] to have “distinguishability of the slots” [Cross(2002)]—*killer* and *deceased* (loosely, a place for the nominative and a place for the accusative), assign *John* to *killer* and *the dragon* to *deceased* and order the three elements in any arrangement.

- Relation(ship) and several distinguishable ‘holes’ and we put each object in its suitable hole.
The ‘positionalist’ commitment

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- Relation(ship) and several distinguishable ‘holes’ and we put each object in its suitable hole.

- There are no asymmetrical relations, because a relationship $R$ and its inverse $R^-$, or their instances, say, $r$ and $r'$, are *identical*, i.e., the *same thing* [Williamson(1985), Fine(2000), Cross(2002)].
A conceptual view of the positionalist commitment—Mary&John/John&theDragon
A conceptual view of the positionalist commitment—generally
The ‘positionalist’ commitment

- **Ingredients**
  1. an $n$-ary relationship $R$ with $A_1,\ldots,A_m$ participating object types ($m \leq n$),
  2. $n$ argument places $\pi_1,\ldots,\pi_n$, and
  3. $n$ assignments $\alpha_1,\ldots,\alpha_n$ that link each object $o_1,\ldots,o_n$ (each object instantiating an $A_i$) to an argument place ($\alpha \mapsto \pi \times o$)
The ‘positionalist’ commitment

Ingredients

(i) an \( n \)-ary relationship \( R \) with \( A_1, \ldots, A_m \) participating object types \((m \leq n)\),

(ii) \( n \) argument places \( \pi_1, \ldots, \pi_n \), and

(iii) \( n \) assignments \( \alpha_1, \ldots, \alpha_n \) that link each object \( o_1, \ldots, o_n \) (each object instantiating an \( A_i \)) to an argument place \( (\alpha \mapsto \pi \times o) \)

\( R, \pi_1, \pi_2, \pi_3, r \in R, o_1 \in A_1, o_2 \in A_2, o_3 \in A_3 \), then any of \( \forall x, y, z \left( R(x, y, z) \rightarrow A_1(x) \wedge A_2(y) \wedge A_3(z) \right) \) and its permutations with corresponding argument places—i.e., \( R[\pi_1, \pi_2, \pi_3] \), and e.g., \( R[\pi_2, \pi_1, \pi_3] \), and \([\pi_2\pi_3]R[\pi_1]\)—all denote the same SoA under the same assignment \( o_1 \) to \( \pi_1 \), \( o_2 \) to \( \pi_2 \), and \( o_3 \) to \( \pi_3 \) for the extension

Thus, \( r(o_1, o_2, o_3) \), \( r(o_2, o_1, o_3) \), and \( o_2 o_3 r o_1 \) are different representations of the same SoA where objects \( o_1, o_2, \) and \( o_3 \) are related to each other by means of relation \( r \).
Problems with the ‘positionalist’ commitment

- From an ontological viewpoint, it requires identifiable argument positions to be part of the fundamental furniture of the universe.
- Then also in the signature of the formal language.
From an ontological viewpoint, it requires identifiable argument positions to be part of the fundamental furniture of the universe.

Then also in the signature of the formal language

Symmetric relations and relationships, such as adjacent to, are problematic:

i. Take $\pi_a$ and $\pi_b$ of a symmetric binary relation $r$, assign $o_1$ to position $\pi_a$ and $o_2$ to $\pi_b$ in state $s$.

ii. One can do a reverse assignment of $o_1$ to position $\pi_b$ and $o_2$ to $\pi_a$ in state $s'$

iii. But then $o_1$ and $o_2$ do not occupy the same positions as they did in $s$, so $s$ and $s'$ must be different, which should not be the case.
The ‘anti-positionalist’ commitment

- No argument positions, but just a relation and objects that yield states by “combining” into “a single complex” [Fine(2000)]
The ‘anti-positionalist’ commitment

- No argument positions, but just a relation and objects that yield states by “combining” into “a single complex” [Fine(2000)]
- Solves the problems with the standard view
- Solves the positionalist’s problem with symmetric relations
- But it needs a substitution relation
- (How to formalise this idea in a KR language is another problem)
A conceptual view of positionalist and anti-positionalist—Mary&John/John&theDragon
A conceptual view of the positionalist and anti-positionalist—generally

- Note: UML Class Diagrams, ORM, ER all positionalist
  [Keet and Fiolottrani(2013)], most of DL and FOL with standard view
Exercise: Conceptual data models–EER diagram (again)

Task: Explain the contents of this slide
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What are the core elements in conceptual models?

Exercise: name all language features of EER or of UML Class Diagrams, or ...
What are the core elements in conceptual models?

- Exercise: name all language features of EER or of UML Class Diagrams, or ...
- e.g., both have attributes, but not in the same way
- ORM has value types; how does that differ in theory from the attributes, if at all?
- Which elements are present in non-CDMLs?
What are the core elements in conceptual models?

- Exercise: name all language features of EER or of UML Class Diagrams, or ...
- e.g., both have attributes, but not in the same way
- ORM has value types; how does that differ in theory from the attributes, if at all?
- Which elements are present in non-CDMLs?
- Let's first make an inventory of what we have in the (CDML) languages, then improve on that
Metamodel: overview

- Captures all structural elements in the selected CDMLs
  [Keet and Fillottrani(2015)]
- Captures also their relations and constraints
- Describes the rules in which they may be combined
- The metamodel is designed in UML Class Diagram notation, formalized in FOL (precision) and OWL (practical usability)\(^1\)

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\(^1\) Fillottrani, P.R., Keet, C.M.. *KF metamodel formalization*. Technical Report, Arxiv.org
Ontology and conceptual models

Static entities in EER, UML CD, ORM

Disjointness axioms among the subclasses of Relationship are:

\{\text{PartWhole}, \text{Attributive property}, \text{Subsumption}\} and
\{\text{Qualified relationship}, \text{Attributive property}, \text{Subsumption}\}
Their constraints

- **Constraint**
  - **Relationship constraint**
    - **Uniqueness constraint**
      - Internal uniqueness
      - External uniqueness
    - **Disjointness constraint**
      - **Disjoint roles**
      - **Disjoint object types**
    - **Equality constraint**
      - **Role equality**
      - **Relationship equality**
    - **Join constraint**
      - **Join-disjointness constraint**
    - **Transitivity**
    - **Irreflexivity**
    - **Antisymmetry**
    - **Local reflexivity**
    - **Symmetry**

- **Value constraint**
  - **Value type constraint**
  - **Role value constraint**
  - **Attribute value constraint**
  - **Compleness constraint**
  - **Value comparison constraint**

- **Mandatory constraint**
  - **Mandatory**
  - **Disjunctive mandatory**
  - **Strongly intransitive**

- **Subset constraint**
  - **Cardinality constraint**
    - Compound cardinality constraint
    - Attituitive property cardinality
    - Object type cardinality

- **Identification constraint**
  - **External identification**
  - **Internal identification**
  - **Qualified identification**
  - **Weak identification**
  - **Single identification**

- **Complete**

- **Disjoint**

- **Join-disjointness constraint**

- **Intransitivity**

- **Incomplete**

- **Join-equality constraint**
  - **Join-disjointness constraint**

- **Join-subset constraint**

- **Irreflexive**

- **Local reflexivity**

- **Reflexivity**

- **Symmetric**

- **Antisymmetric**

- **Complete**

- **Compleness**

- **Disjoint**

- **Global reflexivity**

- **Purely reflexive**

- **Role equality**

- **Relationship equality**

- **Role value constraint**

- **Role type constraint**

- **Symmetry**

- **Transitive**

- **Value type constraint**

- **Weak identification**

- **Whole**

- **Completeness**

- **Whole**

- **Disjoint**

- **Complete**

- **Disjoint**

- **Complete**
Selection of constraints between the entities
Selection of constraints between them

**Figure:** Metamodel fragment for value properties and simple attributes; Dimensional attribute is a reified version of the ternary relation dimensional attribution, and likewise for Dimensional value type and dimensional value typing.
Selection of constraints between them

Figure: Value type, role, and attribute value constraints.
Now back to those attributes and value types

- Structurally, they are different.
- What does Ontology say?
Now back to those attributes and value types

- Structurally, they are different.
- What does Ontology say?
- First distinctions:

  **Universalism**
  
  $a \xrightarrow{\text{inst}} F$
  
  $b \xrightarrow{\text{inst}} F$

  **Trope theory**
  
  $a \xleftarrow{\text{inst}} a_F \xrightarrow{\in} |F| \xrightarrow{\approx} b_F \xleftarrow{\text{inst}} b$

  **Universals + Tropes**
  
  $a \xleftarrow{\text{inst}} a_F \xrightarrow{\in} F$
  
  $b \xleftarrow{\text{inst}} b_F \xrightarrow{\in} F$

- Universalism: $a$, $b$ instantiate $F$ (and $F$ is wholly present in $a$ and $b$)
- Tropes: $a_F$ is the $F$-trope of $a$, inheres in $a$, and $F$ as equivalence class of resembling tropes
- Merger: universalism adopted to classify the tropes
Now back to those attributes and value types

- Structurally, they are different.
- What does Ontology say?
- First distinctions:
  - **Universalism**: \( a, b \) instantiate \( F \) (and \( F \) is wholly present in \( a \) and \( b \))
  - **Tropes**: \( a_F \) is the \( F \)-trope of \( a \), inheres in \( a \), and \( F \) as equivalence class of resembling tropes
  - **Merger**: universalism adopted to classify the tropes
- Secondary distinctions: how they appear in a foundational ontology
Example: UFO
Outline of DOLCE categories
Example: DOLCE’s basic relations w.r.t. qualities
Exercise: what do others say about attributes/qualities?

- BFO
- GFO
- SUMO
- Yamato
Exercise: what do others say about attributes/qualities?

- BFO
- GFO
- SUMO
- Yamato
Various commitments regarding ‘attributes’

- ‘attribute’ (attribution, quality) is a unary entity;
  - e.g., UFO: trope theory; DOLCE: universalism
  - choice of foundational ontology affects what we (assume to) have in our conceptual model
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- attribute is a binary relation between class & data type
  - e.g., OWL’s DataProperty; UML’s attribute
  - ignores foundational ontologies
Various commitments regarding ‘attributes’

- ‘attribute’ (attribution, quality) is a unary entity;
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- attribute is a binary relation between class & data type
  - e.g., OWL’s DataProperty; UML’s attribute
  - ignores foundational ontologies
- Trade-offs
  - More compact notation with attributes
  - Modelling is based on arbitrary (practical, application) decisions
    - increases chance of incompatibilities across diagrams
    - less reusable within and across models
    - instability of model
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Lots of fun problems, widely investigated
Converged to a set of common part-whole relations for conceptual modelling
Which I’d like to cover, but there are already two talks about mereology at ISAO’18
UML’s aggregation, part-whole relations, and mereology

- Lots of fun problems, widely investigated
- Converged to a set of common part-whole relations for conceptual modelling
- Which I’d like to cover, but there are already two talks about mereology at ISAO’18
- Therefore, for now:
  - Only the next slide as a summary (based on Keet and Artale(2008))
  - Turns out the ‘common’ ones may not be that common (paper at FOIS’18, Keet and Khumalo(2018))
Common part-whole relations on conceptual modelling (informally)

- parthood
  - s-parthood (objects)
  - spatial parthood
  - containment (3D objects)
- involvement (processes)
- location (2D objects)
- stuff part (different stuffs)
- portion (same stuff)
- membership (object/role-collective)
- constitution (stuff-object)
- participation (object-process)
- mpart [in discourse only]
Ontology and conceptual models

Refining ‘object type’—somehow

- OntoClean and hierarchies in CDMs; e.g., OntoUML
- Stuff and quantities
  - e.g., need to design a model for a database for tracking food stuffs
  - Ingredients, quantities, masses, amounts of matter, ....
  - Can a FO help you with that? if so, which one(s)?
Ontology and conceptual models

Stuff (informally)

* Volume of Container $\geq$
  * Quantity of Amount of Stuff that is contained in it

** Here one plugs in an ontology of physical quantities, units, and measurements

(more details in [Keet (2016)])
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Conceptual models/diagrams in biology
The main elements in STELLA)
From STELLA model to ontology

- Key aspects in the ecological model:
  - A Stock correspond to a noun (particular or universal)
  - Flow to verb
  - Converter to attribute related to Flow or Stock
  - Action Connector relates the former

- How could that map to elements in ontologies?
  - Object is candidate for an endurant
  - Event or activity for a method or perdurant
  - Converter an attribute or property
  - Action Connector candidate for relationship between any two of Flow, Stock and Converter

- Analysis and details in [Keet(2005)]
Another diagram, in Pathway Studio’s notation

(Degradation of the RAR and RXR by the proteasome)
Pathway Studio’s legend

- Protein
- Small Molecule
- Disease
- Treatment
- Cell Object
- Cell Process
- Functional Class
- Complex

Protein shapes:
- Protein kinases
- Phosphatases
- Ligands
- Transcription factors
- Receptors

- Regulation
- DirectRegulation
- ChemicalReaction
- Expression
- MolTransport
- MolSynthesis
- ProtModification
- PromoterBinding
- Binding
Guidance in this process?

- Methodology for conceptual models: from **Diagram to Domain Ontology**, **DiDON** [Keet(2012)]
- ONSET to compare FOs (ontological commitments, content, practical) [Khan and Keet(2012)]

http://www.meteck.org/files/onset/
Guidance in this process?

- Methodology for conceptual models: from Diagram to Domain Ontology, DiDON [Keet(2012)]
- ONSET to compare FOs (ontological commitments, content, practical) [Khan and Keet(2012)]
- How to use the FO with the conceptual (data) model?
  - UML stereotypes
  - ‘subclassing’ the FO
  - Design new language with additional constructs (formal semantics with a many-sorted logic)
Outline

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   - Logic-based profiles for CDMLs
4. Time and conceptual models
   - Choices
   - Logic-based Temporal EER
   - Semantics of essential and immutable parts
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Guidance on language design

- A logic/language can be seen as a ‘product’/solution that solves a problem
- In analogy of other products: is there a development process, with requirements to meet etc.?
- No methodology for design of a logic
- There is one for design of Domain Specific languages (DSLs) [Frank(2013)]
- Adapt that for our purpose
1. Clarification of Scope and Purpose
   1a. Determine scope, benefits
   1b. Long-term perspective
   1c. Economics, feasibility

2. Analysis of Generic Requirements
   2/3a. Consult requirements catalogue
   2/3b. Use scenarios
   2/3c. Assign priorities

3. Analysis of Specific Requirements
   234. Ontological analysis of language features
         4a. Specify syntax and semantics
         4b. Define glossary
         4c. Define metamodel

4. Language Specification
   5a. Create sample diagrams
   5b. Evaluate notation

5. Design of Graphical Notation

6. Development of Modelling Tool

7. Evaluation and Refinement
   7a. Test cases
   7b. Analyse against requirements
   7c. Analyse effect of use against current practice
“234. Ontological analysis of language features”

- Affordances and features of the logic concern:
  - Ability to represent the conceptualisation/reality more or less precisely with more or less constraints; e.g.
    - $\text{Human} \sqsubseteq \exists \text{hasPart.Eye}$ or $\text{Human} \sqsubseteq 2 \text{hasPart}$ (OWL DL)
    - $\text{Human} \sqsubseteq 2 \text{hasPart.Eye}$ (OWL 2 DL)
“234. Ontological analysis of language features”

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    - $\text{Human} \sqsubseteq = 2 \text{hasPart.Eye}$ (OWL 2 DL)

- whether the language contributes to support, or even shape, the conceptualisation and one’s analysis for the conceptual (data) model, or embeds certain philosophical assumptions and positions
Choices – ontology

- Whether the roles that objects play are fundamental components of relationships (positionalist) or not (standard view); i.e.: if roles should be elements of the language; e.g.
  - $\exists teaches \sqsubseteq Course$ and $\exists teaches^{-} \sqsubseteq Prof$ (most DLs, FOL)
  - $teach \sqsubseteq [lect]Prof \sqcap [taught]Course$ ($DLR$ family, DBs)

---

[Diagram with nodes and edges representing the relationships between objects and their roles]
Choices – ontology

- Whether the roles that objects play are fundamental components of relationships (positionalist) or not (standard view); i.e.: if roles should be elements of the language; e.g.
  - $\exists teach \sqsubseteq Course$ and $\exists teach^{-} \sqsubseteq Prof$ (most DLs, FOL)
  - $teach \sqsubseteq [lect]Prof \sqcap [taught]Course$ ($DL\mathcal{R}$ family, DBs)

- 4D view on the world (space-time worms) or 3D objects with optional temporal extension
- Inherent vagueness (rough, fuzzy), or the world is crisp
Choices – (im)precision in elements

- Whether refinements on the kinds of general elements—that then have their own representation element—would result in a different (better) conceptual model. e.g.:
  - Add element for aggregation or parthood (in addition to not just Relationship and subsumption)
  - not just Object type but also, say, sortal with rigid property
    \( (\forall x \phi(x) \rightarrow \square \phi(x)) \) or class with anti-rigid property
    \( (\forall x \phi(x) \rightarrow \neg \square \phi(x)) \), with stereotypes or separate graphical elements
  - If binary relationships only (cf. \( n \)-aries), would the modeller assume there are only binaries in the world?
Choices – (im)precision in elements

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    \[(\forall x \phi(x) \rightarrow \Box \phi(x))\] or class with anti-rigid property 
    \[(\forall x \phi(x) \rightarrow \neg \Box \phi(x))\], with stereotypes or separate graphical elements
  - If binary relationships only (cf. n-aries), would the modeller assume there are only binaries in the world?

- ‘truly conceptual’ or or also somewhat computational; i.e., to represent only what vs. what & how
  - data types of attributes (UML) or not (ER), with attribute being 
    \[A \mapsto C \times \text{Datatype}\]
Choices – (im)precision in elements

Whether refinements on the kinds of general elements—that then have their own representation element—would result in a different (better) conceptual model. e.g.:

- Add element for aggregation or parthood (in addition to not just Relationship and subsumption)
- not just Object type but also, say, sortal with rigid property $(\forall x \phi(x) \rightarrow \Box \phi(x))$ or class with anti-rigid property $(\forall x \phi(x) \rightarrow \neg \Box \phi(x))$, with stereotypes or separate graphical elements
- If binary relationships only (cf. n-aries), would the modeller would assume there are only binaries in the world?

‘truly conceptual’ or or also somewhat computational; i.e., to represent only what vs. what & how

- data types of attributes (UML) or not (ER), with attribute being $A \mapsto C \times \text{Datatype}$

What should be named?
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The choices in UML, ER, ORM

- Ontology: positionalist, 3D, crisp world
- Features: $n$-aries, UML with aggregation, just object types, ER no datatypes
- Data showed that UML has disproportionately
  - fewer $n$-aries (look across is ambiguous)
  - more aggregation (if the construct is there, modellers see it everywhere?)
Table: Popular logics for logic-based reconstructions of CDMLs assessed against a set of requirements (1/2).

<table>
<thead>
<tr>
<th>Language features</th>
<th>DL-Lite$_A$</th>
<th>$DL^R_{ifd}$</th>
<th>OWL 2 DL</th>
<th>FOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>– standard view</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>– with datatypes</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>– no parthood primitive</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>– no $n$-aries</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>+ 3D</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>– very few features; large feature mismatch</td>
<td>+ little feature mismatch</td>
<td>± some feature mismatch, with overlapping sets</td>
<td>+ little feature mismatch</td>
<td></td>
</tr>
<tr>
<td>– formalisation to complete</td>
<td>+ formalisation exist</td>
<td>– formalisation to complete</td>
<td>± formalisation exist</td>
<td></td>
</tr>
</tbody>
</table>
Table: Popular logics for logic-based reconstructions of CDMLs assessed against a set of requirements (2/2).

<table>
<thead>
<tr>
<th>DL-Lite&lt;sub&gt;A&lt;/sub&gt;</th>
<th>DLR&lt;sub&gt;ifd&lt;/sub&gt;</th>
<th>OWL 2 DL</th>
<th>FOL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Computation and implementability</strong></td>
<td> </td>
<td> </td>
<td> </td>
</tr>
<tr>
<td>+ PTIME (TBox); AC&lt;sup&gt;0&lt;/sup&gt; (ABox)</td>
<td>± EXPTIME-complete</td>
<td>± N2EXPTIME-complete</td>
<td>– undecidable</td>
</tr>
<tr>
<td>+ very scalable (TBox and ABox)</td>
<td>± somewhat scalable (TBox)</td>
<td>± somewhat scalable (TBox)</td>
<td>– not scalable</td>
</tr>
<tr>
<td>+ several reasoners</td>
<td>– no implementation</td>
<td>+ several reasoners</td>
<td>– few reasoners</td>
</tr>
<tr>
<td>+ linking with ontologies doable</td>
<td>– no interoperability</td>
<td>+ linking with ontologies doable</td>
<td>– no interoperability with existing infrastructures</td>
</tr>
<tr>
<td>+ ‘integration’ with OntoIOP</td>
<td>– no integration with OntoIOP</td>
<td>+ ‘integration’ with OntoIOP</td>
<td>+ ‘integration’ with OntoIOP</td>
</tr>
<tr>
<td>+ modularity infrastructure</td>
<td>– modularity infrastructure</td>
<td>+ modularity infrastructure</td>
<td>– modularity infrastructure</td>
</tr>
</tbody>
</table>
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234. Ontological analysis of language features
Language design

Logic-based profiles for CDMLs

1. Clarification of Scope and Purpose
   1a. Determine scope, benefits
   1b. Long-term perspective
   1c. Economics, feasibility

2. Analysis of Generic Requirements
   2/3a. Consult requirements catalogue

3. Analysis
   **Scope**: main conceptual modelling languages
   **Goals**: at least mode interoperability and at least to some extent runtime use of conceptual models for ‘intelligent systems’ or ontology or conceptual model-driven information systems

4. Evaluation and Refinement
   7a. Test cases
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   2/3a. Consult requirements catalogue
   Use scenarios
   Use priorities

3. Analysis of Specific Requirements

Requirements & priorities: language feature lists based on experimental evaluation of 101 publicly available conceptual models
Keet, C.M., Fillottrani, P.R. An analysis and characterisation of publicly available conceptual models. ER'15. Springer LNCS vol 9381, 585-593

7. Evaluation and Refinement
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   34. Ontological analysis of language features
       4a. Specify syntax and semantics
       4b. Define glossary
       4c. Define metamodel

4. Language Specification
   - Create sample diagrams
   - Create notation

Ontological analysis:
- positionalist, 3D, crisp
- ontology-driven metamodel


7. Test cases
   7a. Test cases
   7b. Analyse against requirements
   7c. Analyse effect of use against current practice
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Syntax & semantics:
- positionalist, core, and three language profiles
- tailor-made optimal DLs
- glossary with ontology-driven metamodel
Logic foundation for profiles

- How to formalise the diagrams in which logic?
- Which DL (or other logic) is most appropriate, and why?
- Analyse contents of publicly available conceptual data models [Fillottrani and Keet(2015)]
- Try as high a coverage of the most used features
Considerations in the formalisation

- Positionalist relations and relationships complicates formalisation (computationally more costly), and implementation ($\mathcal{DLR}$ has one very much proof-of-concept implementation [Calvanese et al. (2011)])
- Did both positionalist and standard core, with algorithm
Orchestration of profiles and algorithms

Definitions 1 and 2

Definitions 3, 4, and Algorithm 1

Definitions 5 and 6

Definitions 7, 8, and Algorithm 2

Definitions 9, 10, and Algorithm 3

Interoperability tool
Definition (Positionalist core profile)

Given a conceptual model in any of the analysed CDMLs, we construct a knowledge base in $\mathcal{DC}_p$ by applying the rules:

- we take the set all of object types $A$, binary relationships $P$, datatypes $T$ and attributes $a$ in the model as the basic elements in the knowledge base.
- for each binary relationship $P$ formed by object types $A$ and $B$, we add to the knowledge base the assertions $\geq 1[1]P \sqsubseteq A$ and $\geq 1[2]P \sqsubseteq B$.
- for each attribute $a$ of datatype $T$ within an object type $A$, including the transformation of ORM’s Value Type following the rule given in [Fillottrani and Keet(2014)], we add the assertion $A \sqsubseteq \exists a. T \sqcap \leq 1a$.
- subsumption between two object types $A$ and $B$ is represented by the assertion $A \sqsubseteq B$.

Continues on next slide....
Language design

Logic-based profiles for CDMLs

Definition (Positionalist core profile)

Given a conceptual model in any of the analysed CDMLs, we construct a knowledge base in $DC_P$ by applying the rules:

... continued from previous slide

- for each object type cardinality $m..n$ in relationship $P$ with respect to its $i$-th component $A$, we add the assertions $A \sqsubseteq \leq n[i]P \sqcap \geq m[i]P$.

- we add for each mandatory constraints of a concept $A$ in a relationship $P$ the axiom $A \sqsubseteq \geq 1[1]P$ or $A \sqsubseteq \geq 1[2]P$ depending on the position played by $A$ in $P$. This is a special case of the previous one, with $n = 1$.

- for each single identification in object type $A$ with respect to an attribute $a$ of datatype $T$ we add the axiom id $A.a$. 
Positionalist Core profile in DL syntax

$\mathcal{DC}_p$ can be represented by the following DL syntax. Starting from atomic elements, we can construct binary relations $R$, arbitrary concepts $C$ and axioms $X$ according to the rules:

\[
\begin{align*}
  C &\rightarrow \top | A | \leq k[i]R | \geq k[i]R | \forall a. T | \exists a. T | \leq 1 a | C \sqcap D \\
  R &\rightarrow \top_2 | P | (i : C) \\
  X &\rightarrow C \sqsubseteq D | \text{id } C a
\end{align*}
\]

where $i = 1, 2$ and $0 < k$. For convenience of presentation, we use the numbers 1 and 2 to name the role places, but they can be any number or string and do not impose an order.
Positionalist Core profile in DL, semantics (1/2)

Definition

An $\mathcal{DC}_p$ interpretation $\mathcal{I} = (\cdot^\mathcal{I}_C, \cdot^\mathcal{I}_T, \cdot^\mathcal{I})$ for a knowledge base in $\mathcal{DC}_p$ consists of a set of objects $\Delta^\mathcal{I}_C$, a set of datatype values $\Delta^\mathcal{I}_T$, and a function $\cdot^\mathcal{I}$ satisfying the constraints shown in Table 3. It is said that $\mathcal{I}$ satisfies the assertion $C \sqsubseteq D$ iff $C^\mathcal{I} \subseteq D^\mathcal{I}$; and it satisfies the assertion id $C$ a iff exists $T$ such that $C^\mathcal{I} \subseteq (\exists a. T \sqcap \leq 1a)^\mathcal{I}$ (mandatory 1) and for all $v \in T^\mathcal{I}$ it holds that $\#\{c | c \in C^\mathcal{I} \land (c, v) \in a^\mathcal{I}\} \leq 1$ (inverse functional).
Positionalist Core profile in DL, semantics (2/2)

Table: Semantics of $\mathcal{DC}_p$.

$$
\begin{align*}
\top^\mathcal{I} &\subseteq \Delta_\mathcal{C}^\mathcal{I} \\
A^\mathcal{I} &\subseteq \top^\mathcal{I} \\
\top_2^\mathcal{I} &= \top^\mathcal{I} \times \top^\mathcal{I} \\
P^\mathcal{I} &\subseteq \top_2^\mathcal{I} \\
T^\mathcal{I} &\subseteq \Delta_T^\mathcal{I} \\
a^\mathcal{I} &\subseteq \top^\mathcal{I} \times \Delta_T^\mathcal{I} \\
(C \cap D)^\mathcal{I} &= C^\mathcal{I} \cap D^\mathcal{I} \\
(\leq k[i]R)^\mathcal{I} &= \{c \in \Delta_\mathcal{C}^\mathcal{I} \mid \#\{(d_1, d_2) \in R^\mathcal{I}.d_i = c\} \leq k\} \\
(\geq k[i]R)^\mathcal{I} &= \{c \in \Delta_\mathcal{C}^\mathcal{I} \mid \#\{(d_1, d_2) \in R^\mathcal{I}.d_i = c\} \geq k\} \\
(\exists a.T)^\mathcal{I} &= \{c \in \Delta_\mathcal{C}^\mathcal{I} \mid \exists b \in T^\mathcal{I}.(c, b) \in a^\mathcal{I}\} \\
(\forall a.T)^\mathcal{I} &= \{c \in \Delta_\mathcal{C}^\mathcal{I} \mid \forall v \in \Delta_T^\mathcal{I}.(c, v) \in a^\mathcal{I} \rightarrow v \in T^\mathcal{I}\} \\
(\leq 1 a)^\mathcal{I} &= \{c \in \Delta_\mathcal{C}^\mathcal{I} \mid \#\{(c, v) \in a^\mathcal{I}\} \leq 1\} \\
(i : C)^\mathcal{I} &= \{(d_1, d_2) \in \top_2^\mathcal{I} \mid d_i \in C^\mathcal{I}\} 
\end{align*}
$$
Some observations

- All the entities in the core profile sum up to 87.57% of the entities in all the analysed models, covering 91.88% of UML models, 73.29% of ORM models, and 94.64% of ER/EER models.

- Excluded due to their low incidence in the model set (despite overlap): Role (DL role component) and Relationship (DL role) Subsumption, and Completeness and Disjointness constraints.
Some observations

- All the entities in the core profile sum up to 87.57% of the entities in all the analysed models, covering 91.88% of UML models, 73.29% of ORM models, and 94.64% of ER/EER models.
- Excluded due to their low incidence in the model set (despite overlap): Role (DL role component) and Relationship (DL role) Subsumption, and Completeness and Disjointness constraints.
- No completeness and disjointness, so reasoning is quite simple.
- Can code negation only with cardinality constraints [Baader et al.(2008), chapter 3], but then we need to reify each negated concept as a new idempotent role, which is not possible to get from the $DC_p$ rules.
- Can embed $DC_p$ into $DLR$, but latter is more expressive than needed.
Standard core profile

- Convert $\mathcal{DC}_p$ into a standard core, $\mathcal{DC}_s$

**Definition**

Given a conceptual model in any of the analysed CDMLs, we construct a knowledge based in $\mathcal{DC}_s$ by applying Algorithm 1 to its $\mathcal{DC}_p$ knowledge base.

- With inverse relations to keep connected both relationships generated by reifying roles
- DL syntax approximation (noting construction rules from $\mathcal{DC}_p$):

$$
C \rightarrow \top_1 | A | \forall R . A | \exists R . A | \leq k R | \geq k R | \forall a . T | \exists a . T | \leq 1 a . T | C \sqcap D \\
R \rightarrow \top_2 | P | P^- \\
X \rightarrow C \sqsubseteq D | \text{id } C a
$$
Positionalist to standard choices

teacher and taughtBy are named association ends, not a name of the association (DL role). Options to formalise it:

- make each association end a DL role, teacher and taughtBy, then choose:
  - declare them inverse of each other with teacher $\equiv$ taughtBy$^-$
  - do not declare them inverses
- ‘bump up’ either teacher or taughtBy to DL role, and use the other through a direct inverse and do not extend vocabulary with the other (teacher and teacher$^-$ cf. adding also taughtBy)
Algorithm 1 Positionalist Core to Standard Core

\( P \) an atomic binary relationship; \( D_P \) domain of \( P \); \( R_P \) range of \( P \)

if \( D_P \neq R_P \) then

Rename \( P \) to two ‘directional’ readings, \( Pe_1 \) and \( Pe_2 \)

Make \( Pe_1 \) and \( Pe_2 \) a DL relation (role)

Type the relations with \( \top \sqsubseteq \forall Pe_1 . D_P \sqcap \forall Pe_1^- . R_P \)

Declare inverses with \( Pe_1 \equiv Pe_2^- \)

else

if \( D_P = R_P \) then

if \( i = 1,2 \) is named then

\( Pe_i \leftarrow i \)

else

\( Pe_i \leftarrow \) user-added label or auto generated label

end if

Make \( Pe_i \) a DL relation (role)

Type one \( Pe_i \), i.e., \( \top \sqsubseteq \forall Pe_i . D_P \sqcap \forall Pe_i^- . R_P \)

Declare inverses with \( Pe_i \equiv Pe_2^- \)

end if

end if
Some observations on $\mathcal{DC}_s$

- Simple, too
- Main reasoning problem still class subsumption and equivalence
- At most the DL $\mathcal{ALNI}$ (called $\mathcal{PL}_1$ in [Donini et al. (1991)])
- $\mathcal{PL}_1$ has polynomial subsumption; data complexity unknown
- Tweaking with interaction between role inclusions and number restrictions, and UNA: $DL$-$Lite_{\text{core}}^{(\mathcal{HN})}$ (NLOGSPACE)
- As aside: adding class disjointness, then reduction to $DL$-$Lite_{\text{bool}}^{(\mathcal{HN})}$ (NP-hard) [Artale et al. (2009)]
Sample diagrams using all DCₚ features
Sample diagrams using all $\mathcal{DC}_5$ features
Sample diagrams using all $\mathcal{DC}_S$ features
Or as business rules (fragment shown)

- Each popular science book is reviewed by at least 2 reviewers.
- Each reviewer may review a popular science book.
- Each book must be published by exactly one publisher.
- Each publisher has one HQ.
Steps UML diagram to $\mathcal{DC}_s$

- (Recall $\mathcal{DC}_s$ is obtained from $\mathcal{DC}_p +$ Algorithm 1)
- Obtain set of OTs ($\{\text{Person, ...}\}$) and DTs ($\{\text{Name, ...}\}$)

1. bump up the association end names to DL roles
2. type the relationships with:
   - $\top \sqsubseteq \forall$ has member
   - $\sqsubseteq \forall$ has member
   - $\top \sqsubseteq \forall$ has member
   - $\sqsubseteq \forall$ has member
3. declare inverses, $\equiv$ has member

Repeat for each association in UML diagram

Step 3 of $\mathcal{DC}_p$ definition: attributes. e.g., for Person’s Name:

- $\top \sqsubseteq \exists$ Name
- $\sqsubseteq \leq 1$ Name

Step 4: subsumptions; e.g., Popular science book $\sqsubseteq$ Book

Step 5 and 6: cardinalities. e.g., $\sqsubseteq \geq 1$ has member

Finally, identifiers; e.g. ISBN for Book, adding id Book ISBN to the $\mathcal{DC}_s$ knowledge base
Steps UML diagram to $\mathcal{DC}_s$

- (Recall $\mathcal{DC}_s$ is obtained from $\mathcal{DC}_p +$ Algorithm 1)
- Obtain set of OTs ($\{\text{Person, ...}\}$) and DTs ($\{\text{Name, ...}\}$)
- For Relationships, use Algorithm 1:
  1. bump up the association end names to DL roles
  2. type the relationships with:
     \[
     \top \sqsubseteq \forall \text{has member. Affiliation} \sqcap \forall \text{has member}^- \cdot \text{Person}
     \]
     \[
     \top \sqsubseteq \forall \text{has. Person} \sqcap \forall \text{has}^- \cdot \text{Affiliation}
     \]
  3. declare inverses, $\text{has member} \equiv \text{has}^-$
- Repeat for each association in UML diagram
Steps UML diagram to $\mathcal{DC}_S$

- (Recall $\mathcal{DC}_S$ is obtained from $\mathcal{DC}_p +$ Algorithm 1)
- Obtain set of OTs (\{Person, \ldots\}) and DTs (\{Name, \ldots\})
- For Relationships, use Algorithm 1:
  1. bump up the association end names to DL roles
  2. type the relationships with:
     $$\top \sqsubseteq \forall \text{has member}.\text{Affiliation} \sqcap \forall \text{has member}^- . \text{Person}$$
     $$\top \sqsubseteq \forall \text{has}.\text{Person} \sqcap \forall \text{has}^- . \text{Affiliation}$$
  3. declare inverses, \text{has member} \equiv \text{has}^-

Repeat for each association in UML diagram

- Step 3 of $\mathcal{DC}_p$ definition: attributes. e.g., for Person’s Name:
  $$\text{Person} \sqsubseteq \exists \text{Name}.\text{String} \sqcap \leq 1 \text{Name}$$
Steps UML diagram to $\mathcal{DC}_s$

- (Recall $\mathcal{DC}_s$ is obtained from $\mathcal{DC}_p +$ Algorithm 1)
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  3. declare inverses, $\text{has member} \equiv \text{has}^{-}$

Repeat for each association in UML diagram
- Step 3 of $\mathcal{DC}_p$ definition: attributes. e.g., for Person’s Name:

  $\text{Person} \sqsubseteq \exists \text{Name}.\text{String} \sqcap \leq 1 \text{Name}$

- Step 4: subsumptions; e.g., $\text{Popular\_science\_book} \sqsubseteq \text{Book}$
Steps UML diagram to $\mathcal{D}_s$

- (Recall $\mathcal{D}_s$ is obtained from $\mathcal{D}_p +$ Algorithm 1)
- Obtain set of OTs ($\{\text{Person, ...}\}$) and DTs ($\{\text{Name, ...}\}$)
- For Relationships, use Algorithm 1:
  1. bump up the association end names to DL roles
  2. type the relationships with:
     \[
     T \sqsubseteq \forall \text{has member}.\text{Affiliation} \sqcap \forall \text{has member}^- . \text{Person} \\
     T \sqsubseteq \forall \text{has}.\text{Person} \sqcap \forall \text{has}^- . \text{Affiliation}
     \]
  3. declare inverses, $\text{has member} \equiv \text{has}^-$
- Repeat for each association in UML diagram
- Step 3 of $\mathcal{D}_p$ definition: attributes. e.g., for Person’s Name:
  \[
  \text{Person} \sqsubseteq \exists \text{Name}.\text{String} \sqcap \leq 1 \text{Name}
  \]
- Step 4: subsumptions; e.g., $\text{Popular science book} \sqsubseteq \text{Book}$
- Step 5 and 6: cardinalities. e.g. $\text{Affiliation} \sqsubseteq \geq 1 \text{has member}$
Steps UML diagram to $\mathcal{DC}_s$

- (Recall $\mathcal{DC}_s$ is obtained from $\mathcal{DC}_p +$ Algorithm 1)
- Obtain set of OTs ($\{\text{Person}, \ldots\}$) and DTs ($\{\text{Name}, \ldots\}$)
- For Relationships, use Algorithm 1:
  1. bump up the association end names to DL roles
  2. type the relationships with:
     $$\top \sqsubseteq \forall \text{has member. Affiliation} \sqcap \forall \text{has member}^- . \text{Person}$$
     $$\top \sqsubseteq \forall \text{has. Person} \sqcap \forall \text{has}^- . \text{Affiliation}$$
  3. declare inverses, has member $\equiv$ has $^-$
- Repeat for each association in UML diagram
- Step 3 of $\mathcal{DC}_p$ definition: attributes. e.g., for Person's Name:
  $$\text{Person} \sqsubseteq \exists \text{Name. String} \sqcap \leq 1 \text{Name}$$
- Step 4: subsumptions; e.g., Popular science book $\sqsubseteq$ Book
- Step 5 and 6: cardinalities. e.g. Affiliation $\sqsubseteq \geq 1$ has member
- Finally, identifiers; e.g. ISBN for Book, adding id Book ISBN to the $\mathcal{DC}_s$ knowledge base
### Profile comparison on language and complexity

<table>
<thead>
<tr>
<th>Profile</th>
<th>Main features</th>
<th>Approx. DL</th>
<th>Subsumption complexity</th>
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</thead>
<tbody>
<tr>
<td>$DC_p$</td>
<td>positionalist, binary relationships, identifiers, cardinality constraints, attribute typing, mandatory attribute and its functionality</td>
<td>$DLR$</td>
<td>EXPTIME</td>
</tr>
<tr>
<td>$DC_s$</td>
<td>standard view, binary relationships, inverses</td>
<td>$ALN\overline{I}$</td>
<td>P</td>
</tr>
<tr>
<td>$DC_{UML}$</td>
<td>relationship subsumption, attribute cardinality</td>
<td>$DL$-Lite$^{HN}_{core}$</td>
<td>NLOGSPACE</td>
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<td>$DC_{EER}$</td>
<td>ternary relationships, attribute cardinality, external keys</td>
<td>$DL$-Lite$^{N}_{core}$</td>
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<tr>
<td>$DC_{ORM}$</td>
<td>entity type disjunction, relationships complement, relationship subsumption, complex identifiers (‘multi attribute keys’)</td>
<td>$DLR_{ifd}$</td>
<td>EXPTIME</td>
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<tr>
<td></td>
<td></td>
<td>$CFD_{\overline{nc}}$</td>
<td>P</td>
</tr>
</tbody>
</table>
Discussion

- ‘Uninteresting’ logics for automated reasoning over conceptual models
- But
Discussion

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- But
- assuming that also the reconstructions of $\mathcal{DC}_p$ and $\mathcal{DC}_{ORM}$ will be lower than EXPTIME (tbd),
- They’re good/excellent for use of conceptual models during runtime; e.g.:
Discussion

- ‘Uninteresting’ logics for automated reasoning over conceptual models
- But
- assuming that also the reconstructions of $\mathcal{DC}_p$ and $\mathcal{DC}_{ORM}$ will be lower than EXPTIME (tbd),
- They’re good/excellent for use of conceptual models during runtime; e.g.:
  - Scalable test data generation [Smaragdakis et al.(2009)]
  - Designing [Bloesch and Halpin(1997)] and executing [Calvanese et al.(2010)] queries with the model’s vocabulary
  - Querying databases during the stage of query compilation [Toman and Weddell(2011)]
First attempt to scope and structure the logic design process, with ontological considerations.

Can do with a broader systematic investigation on alternative design choices and their consequences.

Identified alternate choices effectively addressed by multiple compatible profiles with algorithms for conversions.
First attempt to scope and structure the logic design process, with ontological considerations

Can do with a broader systematic investigation on alternative design choices and their consequences

Identified alternate choices effectively addressed by multiple compatible profiles with algorithms for conversions

‘good’ logic
  - matches the implicit ontological commitments
  - that fits needs here is ‘less good’ in precision
  - turns out to be a *family* of compatible logics + algorithms
Toward applicability

- Profiles may be applied as back-end of CASE tool, OBDA
- Will allow modeller to model in their graphical notation of choice, yet be compatible with the rest
- Transformations and inter-model assertions of approximate entities and of modelling patterns [Fillottrani and Keet(2014), Khan et al.(2016), Fillottrani and Keet(2017)]
Exercise: design your own (two options)

- Informal $\rightarrow$ formal
  - Take some graphical modelling language (e.g., flowcharts) or a CNL (e.g., Simplified English; see also CNL 2018 paper)
  - Examine the elements ontologically
  - Design a logic for it

- Requirements $\rightarrow$ language
  - Consider some task or thing (e.g., student enrolment process, event management)
  - Devise requirements for the language to be able to model such tasks/things
  - Design a language for it (logic/diagram notation/CNL)
Outline

1. Introduction

2. Ontology and conceptual models
   - Semantics of relations
   - FOs and CDMLs
   - More choices
   - Analysing other diagrams

3. Language design
   - Principles
   - Toward logics for CDMLs
   - Logic-based profiles for CDMLs

4. Time and conceptual models
   - Choices
   - Logic-based Temporal EER
   - Semantics of essential and immutable parts
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Examples

- CDM: ‘RentalCar must be returned *before* Deposit is reimbursed’
- CDM: ‘Employee will receive a bonus after 2 years of employment’
Examples

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- CDM: ‘Employee will receive a bonus after 2 years of employment’
- Domain ontology: ‘Biopsy, planned’ (in SNOMED CT)
- Domain ontology: ‘HairLoss during the treatment Chemotherapy’;
  Butterfly is a transformation of (used to be) Caterpillar.
Examples

- CDM: ‘RentalCar must be returned before Deposit is reimbursed’
- CDM: ‘Employee will receive a bonus after 2 years of employment’
- Domain ontology: ‘Biopsy, planned’ (in SNOMED CT)
- Domain ontology: ‘HairLoss during the treatment Chemotherapy’; Butterfly is a transformation of (used to be) Caterpillar.
- a brain is an essential part of a human (for the entire human’s lifetime)
- a boxer’s hands are essential parts of the boxer (for as long as he’s a boxer)
What are the main choices regarding time?

1. Annotation model ‘about time’ vs reasoning over temporal knowledge

2. The main options ontologically w.r.t. the latter:

3. The representation
What are the main choices regarding time?

1. Annotation model ‘about time’ vs reasoning over temporal knowledge
2. The main options ontologically w.r.t. the latter:
   - Chronons (successive points) vs dense time
   - Linear vs branching time
   - 3-dimensional objects + time vs 4-dimensional ‘space-time worms’
3. The representation
What are the main choices regarding time?

1. Annotation model ‘about time’ vs reasoning over temporal knowledge
2. The main options ontologically w.r.t. the latter:
   - Chronons (successive points) vs dense time
   - Linear vs branching time
   - 3-dimensional objects + time vs 4-dimensional ‘space-time worms’
3. The representation
   - Add ‘t’; e.g., $R(x, y, t)$ “$R$ holds between $x$ and $y$ at time $t”$ and 4-D fluents/$n$-ary approach
   - Temporal logic; include constructors in the language, e.g. $\Diamond^+ “at some time in the future”$ (cf. “$\exists “some”$”), availing of $\textit{Since}$ and/or $\textit{Until}$ operators
Additions to CDMLs

- Mostly linear time (makes more sense in a database setting, cf CTL in formal methods)
- Chronons (fits more easily with snapshots of databases)
- 3D most popular, with a few extensions, notably to ER and EER
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Example: TREND with $\text{DLR}_{US}$

- Approach the same as before:
  - Graphical notation
  - Pick a logic or design one
  - Do the logic-based reconstruction
- The very expressive (well, undecidable) $\text{DLR}_{US}$ [Artale et al. (2002)]
- $ER_{VT}$ extended into $EER_{VT}^{++}$ and now TREND
**DLR_{US} (the essence of it)**

- **DLR_{US}** [Artale et al. (2002)] combines the PTL with the `Since` and `Until` and the DL DLR [Calvanese and De Giacomo (2003)], i.e., a expressive fragment of $L \{ \text{since, until} \}$
  - Classes, $n$-ary relations ($n > 2$), role components
  - Binary constructors ($\sqcap, \sqcup, \mathcal{U}, \mathcal{S}$) for relations of the same arity, and all boolean constructors for both class and relation expressions
  - **For both classes and relations**: temporal operators $\diamondsuit^+$, $\oplus$, and their past counterparts can be defined via $\mathcal{U}$ and $\mathcal{S}$: $\diamondsuit^+ C \equiv \top \cup C$, $\oplus C \equiv \bot \cup C$, etc; $\square^+$ and $\square^-$ as $\square^+ C \equiv \neg \diamondsuit^+ \neg C$ and $\square^- C \equiv \neg \diamondsuit^- \neg C$. $\diamondsuit^*$ and $\square^*$ as $\diamondsuit^* C \equiv C \sqcup \diamondsuit^+ C \sqcup \diamondsuit^- C$ and $\square^* C \equiv C \sqcap \square^+ C \sqcap \square^- C$.

- Interpreted in *temporal models* over $\mathcal{T}$ (where $\mathcal{T} = \langle \mathcal{T}_p, < \rangle$), which are triples of the form $\mathcal{I} \equiv \langle \mathcal{T}, \Delta, \cdot \mathcal{I}(t) \rangle$, where $\Delta$ is the *domain* of $\mathcal{I}$ and $\cdot \mathcal{I}(t)$ an *interpretation function* s.t., for every $t \in \mathcal{T}$, every $C$, and $R$, we have $C^{\mathcal{I}(t)} \subseteq \Delta$ and $R^{\mathcal{I}(t)} \subseteq (\Delta)^n$. 
For each TREND conceptual data model, there is an equi-satisfiable $\mathcal{DLR}_{US}$ knowledge base. Given the set-theoretic semantics for TREND, modelling notions such as satisfiability, subsumption, and derivation of new constraints have been defined (as for $ER_{VT}$ in [Artale et al.(2007a)]).

Textual and a graphical syntax along with a model-theoretic semantics as a temporal extension of the EER semantics.

TREND [Keet and Berman(2017)] supports timestamping for classes, attributes, and relationships.

Status classes [Artale et al.(2007a)] and Status relations [Artale et al.(2008)] constrain evolution of an instance’s (relation’s) membership in a class (relationship) along its lifespan.
Example TREN and logic and text-based notations

\((D_{EVM}^-)\) Mandatory dynamic evolution, past; e.g., Frog and the Tadpole it used to be.

- \(o \in \text{Frog}^{\mathcal{I}(t)} \rightarrow \exists t' < t. o \in \text{DEV}^{\mathcal{I}(t')}_{\text{Tadpole,Frog}}\)
- \(\text{Frog} \sqsubseteq \Diamond^- \text{DEV}_{\text{Tadpole,Frog}}\)
- Diagram:

  ![Diagram]

  Each Frog was an Tadpole before, but is not an Tadpole now.
Example TRENDS diagram
Examples

- CDM: ‘RentalCar must be returned before Deposit is reimbursed’; e.g., $\textit{reimbursement} \sqsubseteq \diamondsuit \! -$ return
- Domain ontology: ‘Biopsy, planned’ (in SNOMED CT); with $\diamondsuit^+ \textit{Biopsy}$
Examples

- CDM: ‘RentalCar must be returned before Deposit is reimbursed’; e.g., \(\text{reimbursement} \subseteq \bigtriangleup \neg \text{return}\)
- Domain ontology: ‘Biopsy, planned’ (in SNOMED CT); with \(\bigtriangleup^+ \text{Biopsy}\)
- brain, hands, and boxer: next slides
Resolving the brain, hands, and boxer

- Need to represent difference between essential vs mandatory vs immutable parts and wholes, but cannot un 'plain' UML (or EER or ORM)

- Brain is an essential part of Human
- Heart is a mandatory part of Human but a heart can be transplanted
- Hand is an immutable part of Boxer but a human can do without hands

More generally: the life cycle semantics of parts and wholes
Defining participation in the relation

- Two criteria: (i) nature of the dependence relationship between the classes and (ii) strength of the participation
Defining participation in the relation

- Two criteria: (i) nature of the dependence relationship between the classes and (ii) strength of the participation

1. **Generic Dependence – Mandatory Part**. The whole must have a part at each instant of its lifetime. Thus, the presence of the part is mandatory, but it can be replaced over time (e.g., the human heart example).

2. **Unconditional Specific Dependence – Essential Part**. The part is mandatory, but it cannot be replaced without destroying the whole (e.g., the human brain example).

3. **Conditional Specific Dependence – Immutable Part** (also called *conditionally essential part*). The part is mandatory and cannot be replaced, but only as long as the whole belongs to the class that describes it (e.g., the boxer’s hand example).
Status relations (included in TREND)

- **Scheduled**: a relation is scheduled if its instantiation is known but its membership will only become effective some time later. e.g., a new pillar for the Sagrada Familia’s interior is scheduled to become part of that church.

- **Active**: the status of a relation is active if the particular relation fully instantiates the type-level relation and only active classes can participate into an active relation; e.g., the Mont Blanc mountain is part of the Alps mountain range.
Status relations (included in TRENDS)

- **Suspended**: to capture a temporarily inactive relation; e.g., an instance of a CarEngine is removed from the instance of a Car it is part of for purpose of maintenance.

- **Disabled**: to model expired relations that never again can be used; e.g., to represent the donor of an organ who has donated that organ and one wants to keep track of who donated what to whom.
Status relations
Constraints and logical implications

**PROPOSITION (Status Relations: Logical Implications)**

Given the set of axioms $\Sigma_{st}$ ($\text{RExists-} \text{RSch2}$), an $n$-ary relation (where $n \geq 2$) $R \sqsubseteq U_1 : C_1 \sqcap \ldots \sqcap U_n : C_n$, the following logical implications hold:

(RAct) Active will possible evolve into Suspended or Disabled.

$\Sigma_{st} \models R \sqsubseteq \Box^+ (R \sqcup \text{Suspended-R} \sqcup \text{Disabled-R})$

(RDisab3) Disabled will never become active anymore.

$\Sigma_{st} \models \text{Disabled-R} \sqsubseteq \Box^+ \neg R$

(RDisab4) Disabled classes can participate only in disabled relations.

$\Sigma_{st} \models \text{Disabled-C}_i \sqcap \Diamond \neg \exists [U_i] R \sqsubseteq \exists [U_i] \text{Disabled-R}$
**Proposition (Status Relations: Logical Implications—cont’d)**

**RDIsab5** *Disabled relations involve active, suspended, or disabled classes.*

\[
\text{Disabled-R} \subseteq U_i : (C_i \sqcup \text{Suspended-C}_i \sqcup \text{Disabled-C}_i), \text{ for all } i = 1, \ldots, n.
\]

**RSch3** *Scheduled persists until active.*

\[
\Sigma_{st} \models \text{Scheduled-R} \sqsubseteq \text{Scheduled-R} \cup R
\]

**RSch4** *Scheduled cannot evolve directly to Disabled.*

\[
\Sigma_{st} \models \text{Scheduled-R} \sqsubseteq \oplus \neg \text{Disabled-R}
\]

**RSch5** *Scheduled relations do not involve disabled classes.*

\[
\text{Scheduled-R} \sqsubseteq U_i : \neg \text{Disabled-C}_i, \text{ for all } i = 1, \ldots, n.
\]
Life cycles

A. whole's lifetime

B. part's lifetime
Mandatory & Exclusive

\[
\begin{align*}
(M_{\text{ManP}}) & \quad W \subseteq \exists [\text{whole}] \text{PartWhole} & \text{Mandatory Part} \\
(M_{\text{ManW}}) & \quad P \subseteq \exists [\text{part}] \text{PartWhole} & \text{Mandatory Whole} \\
(E_{\text{ExLP}}) & \quad P \subseteq \exists^{\leq 1} [\text{part}] \text{PartWhole} & \text{Exclusive Part} \\
(E_{\text{Exlw}}) & \quad W \subseteq \exists^{\leq 1} [\text{whole}] \text{PartWhole} & \text{Exclusive Whole}
\end{align*}
\]
Rigidity

Definition (Rigid (+R))

A rigid property $\phi$ is a property that is essential to all its instances, i.e.,
\[ \forall x \phi(x) \rightarrow \Box \phi(x) \]

Definition (Anti-Rigid (∼R))

An anti-rigid property $\phi$ is a property that is not essential to all its instances, i.e.,
\[ \forall x \phi(x) \rightarrow \neg \Box \phi(x) \]

(Rigid) $C \subseteq \Box^* C$

(A-Rigid) $C \subseteq \Diamond^* \neg C$

(A-sub-R) $C_A \subseteq C_R$
Essential parts and wholes

- *Essential parts* are global properties of rigid wholes that can be formalized in $\mathcal{DLR}_{US}$ with:
  
  (RigidW) $W \sqsubseteq \Box^*W$ \hspace{1cm} *Rigid Whole*
  
  (EssP) $W \sqsubseteq \exists[\text{whole}]\Box^*\text{PartWhole}$ \hspace{1cm} *Essential Part*

- Likewise for *essential whole*
  
  (RigidP) $P \sqsubseteq \Box^*P$ \hspace{1cm} *Rigid Part*
  
  (EssW) $P \sqsubseteq \exists[\text{part}]\Box^*\text{PartWhole}$ \hspace{1cm} *Essential Whole*
Additional axioms for Immutable

(SusW)  Suspended-PartWhole ⊑ whole : Suspended-W  _Suspended Whole_

(SusP)  Suspended-PartWhole ⊑ part : Suspended-P  _Suspended Part_

(DisP)  Disabled-PartWhole ⊑ part : Disabled-P  _Disabled Part_

(DisW)  Disabled-PartWhole ⊑ whole : Disabled-W  _Disabled Whole_

(SchPW)  PartWhole ⊑ ♦ ¬ Scheduled-PartWhole  _Scheduled Part-Whole_

(SchP)  Scheduled-PartWhole ⊑ part : Scheduled-P  _Scheduled Part_

(SchW)  Scheduled-PartWhole ⊑ whole : Scheduled-W  _Scheduled Whole_
Immutable part

Theorem (Immutable Parts)

Let $W_R$ be a rigid class (i.e., $W_R \subseteq \Box^* W_R$), $W$ be an anti-rigid class (i.e., $W \subseteq \Diamond^* \neg W$) s.t. $W \subseteq W_R$, and $\text{PartWhole} \subseteq \text{part}: P \sqcap \text{whole}: W$ be a generic part-whole relation satisfying $\Sigma_{st}$. Then, for each whole, $o_w$, of type $W$ there exists an immutable part, $o_p$, of type $P$ that is temporally related to $o_w$ with the relation:

- $p_2$ holds if $(\text{ManP}), (\text{SusW}), (\text{DisW})$ hold.
- $p_4$ holds if $(\text{ManP}), (\text{SusW}), (\text{DisW}), (\text{DisP})$ hold.
- $p_3$ holds if $(\text{ManP}), (\text{SusW}), (\text{DisW}), (\text{SchPW}), (\text{SchP})$ hold.
- $p_1$ holds if $(\text{ManP}), (\text{SusW}), (\text{DisW}), (\text{DisP}), (\text{SchPW}), (\text{SchP})$ hold.
Immutable whole

Theorem (Immutable Wholes)

Let $P_R$ be a rigid class (i.e., $P_R \subseteq \Box^* P_R$), $P$ be an anti-rigid class (i.e., $P \subseteq \Diamond^* \neg P$) s.t. $P \subseteq P_R$, and $\text{PartWhole} \subseteq \text{part} : P \sqcap \text{whole} : W$ be a generic part-whole relation satisfying $\Sigma_{st}$. Then, for each part, $o_P$, of type $P$ there exists an immutable whole, $o_W$, of type $W$ that is temporally related to $o_P$ with the relation:

- $w_2$ holds if $(\text{ManW}), (\text{SusP}), (\text{DisP})$ hold.
- $w_4$ holds if $(\text{ManW}), (\text{SusP}), (\text{DisP}), (\text{DisW})$ hold.
- $w_3$ holds if $(\text{ManW}), (\text{SusP}), (\text{DisP}), (\text{SchPW}), (\text{SchW})$ hold.
- $w_1$ holds if $(\text{ManW}), (\text{SusP}), (\text{DisP}), (\text{DisW}), (\text{SchPW}), (\text{SchW})$ hold.
Life cycles

A. whole's lifetime

\[ p1 \rightarrow p2 \rightarrow p3 \rightarrow p4 \]

B. part's lifetime

\[ w1 \rightarrow w2 \rightarrow w3 \rightarrow w4 \]

p4 holds if (\text{MANP}), (\text{SusW}), (\text{DisW}), (\text{DisP}) hold.
The Boxer’s hand (with p4)

1. \text{Human} \sqsubseteq \Box^* \text{Human} \\
2. \text{HumanHandPW} \sqsubseteq \text{PartWhole} \\
3. \text{HumanHandPW} \sqsubseteq \text{part} : \text{Hand} \sqcap \text{whole} : \text{Human} \\
4. \text{Boxer} \sqsubseteq \Diamond^\ast \neg \text{Boxer} \\
5. \text{Boxer} \sqsubseteq \text{Human} \\
6. \text{Boxer} \sqsubseteq \exists^{-2}[\text{whole}] \text{HumanHandPW} \\
7. \text{Suspended-HumanHandPW} \sqsubseteq \text{whole} : \text{Suspended-Boxer} \\
8. \text{Disabled-HumanHandPW} \sqsubseteq \text{part} : \text{Disabled-Hand} \\
9. \text{Disabled-HumanHandPW} \sqsubseteq \text{whole} : \text{Disabled-Boxer} \\
10. \Sigma_{st} \models \text{R} \sqsubseteq \Box^{+} (\text{R} \sqcap \text{Suspended-R} \sqcup \text{Disabled-R}) \\
11. \Sigma_{st} \models \text{Disabled-C}_{1} \sqcap \Diamond \neg \exists[U_{1}] \text{R} \sqsubseteq \exists[U_{1}] \text{Disabled-R}
The Boxer’s hand (with p4)

1. $\text{Human} \sqsubseteq \square^* \text{Human}$
2. $\text{HumanHandPW} \sqsubseteq \text{PartWhole}$
3. $\text{HumanHandPW} \sqsubseteq \text{part:Hand} \sqcap \text{whole:Human}$
4. $\text{Boxer} \sqsubseteq \Diamond^* \lnot \text{Boxer}$
5. $\text{Boxer} \sqsubseteq \text{Human}$
6. $\text{Boxer} \sqsubseteq \exists^2 \text{[whole]} \text{HumanHandPW}$
7. $\text{Suspended-HumanHandPW} \sqsubseteq \text{whole:Suspended-Boxer}$
8. $\text{Disabled-HumanHandPW} \sqsubseteq \text{part:Disabled-Hand}$
9. $\text{Disabled-HumanHandPW} \sqsubseteq \text{whole:Disabled-Boxer}$
10. $\Sigma_{st} \models R \sqsubseteq \square^+ (R \sqcup \text{Suspended-R} \sqcup \text{Disabled-R})$
11. $\Sigma_{st} \models \text{Disabled-C_1} \sqcap \Diamond \exists[U_1] R \sqsubseteq \exists[U_1] \text{Disabled-R}$
The Boxer’s hand (with p4)
Summary

- Semantics of elements in conceptual modelling languages
  - Relations (standard view vs. positionalism)
  - Attributions
- Ontology-informed language design process
  - Principal design choices
  - Profiles
- Temporal conceptual models
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Thank you!

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