Description Logics: $\mathcal{ALC}$

Outline

Topics:

1. Introduction to description logics
2. The description logic $\mathcal{ALC}$
3. Extensions to $\mathcal{ALC}$
4. A tableau algorithm for $\mathcal{ALC}$

Introduction

Description logics

- A DL is a formalism for expressing *concepts*, their attributes (or associated *roles*), and the *relationships* between them.
    - E.g. *Person* could be a concept and a role could be *ParentOf*.
- Can be regarded as a KR system based on a *structured representation of knowledge*.
- Most DLs are fragments of FOL, written in a distinct syntax.

Predecessors of DLs

- Semantic networks of the 70s
- Frame-based systems

Why Description Logics?

Ideal AI case:

- Approaches have scientific (logical) and engineering aspects
- *Scientific*: Analyse the problem formally and in detail
- *Engineering*: Get something working quickly and efficiently
- Success:

  When these two approaches coincide – efficient implementations of (formally) well-understood systems.

- Description Logic research has (arguably) reached this point

Background: Concepts, Roles, Constants

- In a description logic, there are sentences that will be true or false (as in FOL).
  - These are restricted to *subsumption* and *instance* assertions.
- In addition, there are three sorts of expressions that act like nouns and noun phrases in English:
  - *Concepts* are like category nouns: Person, Female, GraduateStudent
  - *Roles* are like relational nouns: AgeOf, ParentOf, AreaOfStudy
    - Specify attributes of concepts and their types
  - *Constants* are like proper nouns: John, Mary
- These correspond to unary predicates, binary predicates and constants (respectively) in FOL.
- Unlike in FOL, concepts need not be atomic and can have structure.

DL Knowledge Bases

An KB in a DL contains two parts:

- Define terminology: *TBox*
  - E.g. $MWD \doteq Mother \sqcap \forall ParentOf.\neg Female$
- Give assertions: *ABox*
  - E.g. $MWD(sue)$.

DL Knowledge Bases: TBox

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- *Complex concepts* using constructors
  - E.g. $\mathit{Mother} \sqcap \forall \mathit{ParentOf}.\neg \mathit{Female}$

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- *Complex concepts* using constructors
  - E.g. $\mathit{Mother} \sqcap \forall \mathit{ParentOf}.\neg \mathit{Female}$
- *Assertions* concerning complex concepts
  - E.g. $\mathit{MWD} \doteq \mathit{Mother} \sqcap \forall \mathit{ParentOf}.\neg \mathit{Female}$
    $\mathit{Mother} \sqsubseteq \mathit{Female}$

DL Knowledge Bases: ABox

ABox: Assertions that individuals satisfy certain concepts and roles.

- Think of as a (very) simple relational database.
- E.g. $\mathit{MWD}(\mathit{Mary})$, $\mathit{ParentOf}(\mathit{Mary}, \mathit{John})$.

DL: Advantages

- Well-defined formal semantics.
- Known (and often good) complexity characteristics or implementations.
- Relatively easy to specify DL knowledge bases, in a structured hierarchical fashion.
- DLs constitute a *large* family of approaches.
    - Can tailor a language to a specific application.

Applications

Useful whenever a common vocabulary is important.

E.g.:

- Enhanced database systems
  - *DL-Lite*
- Medical informatics: SnoMed, Galen
  - $\mathcal{EL}$
- Semantic Web
  - Next generation web
  - *OWL*: W3C recommendation.

☞ We'll look at perhaps the most central DL, $\mathcal{ALC}$.

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Main components of the TBox:

- Concepts: Represent classes of individuals
- Roles: Represent binary relations between individuals
- Complex concepts using constructors

Examples:

- Concept names: Person, Female
- Role names: ParentOf, HasHusband
- Individual names (in the ABox): John, Mary

The Logic $\mathcal{ALC}$: Language

Logical symbols:

- Propositional constructors: $\sqcap$, $\sqcup$, $\neg$
- Other restrictions: $\forall$, $\exists$
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Concept construction

- Let C and D be concepts and R a role.
- $\neg C$, $C \sqcap D$, $C \sqcup D$ are concepts.
- $\forall R.C$, $\exists R.C$ are concepts.

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  - E.g. $Female \sqcap Human$

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- $\forall R.C$ is the concept of things such that all things that are R related to it are C's.
  - E.g. $\forall ParentOf.Female$: things all of whose children are female

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- $\forall R.C$ is the concept of things such that all things that are R related to it are C's.
    - E.g. $\forall ParentOf.Female$: things all of whose children are female
- $\exists R.C$ is the concept of things such that some thing R related to it is a C.
    - $\exists ParentOf.Female$: things with a female child

The Logic $\mathcal{ALC}$: Knowledge Bases

Axioms (assertions) in the TBox:

- Subsumption: $C \sqsubseteq D$ where C and D are concepts
- Equivalence axioms: $C \doteq D$ where C and D are concepts

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Assertions in the ABox:

- $C(a)$ where C is a concept and a is an individual name.
- $R(a, b)$ where R is a role name, a and b are individual names.

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DL knowledge base:

- Set of TBox statements
- Set of ABox statements

Examples

TBox:

- $\mathit{Person} \sqsubseteq \mathit{Animal} \sqcap \mathit{Biped}$
- $\mathit{Woman} \doteq \mathit{Person} \sqcap \mathit{Female}$
- $\mathit{Mother} \doteq \mathit{Woman} \sqcap \exists \mathit{ParentOf}.\mathit{Person}$
- $\mathit{Parent} \doteq \mathit{Mother} \sqcup \mathit{Father}$
- $\mathit{Man} \doteq \mathit{Person} \sqcap \neg \mathit{Woman}$
- $\mathit{MotherWithoutDaughter} \doteq \mathit{Mother} \sqcap \forall \mathit{ParentOf}.\neg \mathit{Female}$
- $\mathit{GrandMother} \doteq \mathit{Woman} \sqcap \exists \mathit{ParentOf}.\mathit{Parent}$

ABox:

- $\mathit{GrandMother}(\mathit{Sally})$
- $(\mathit{Person} \sqcap \mathit{Male})(\mathit{John})$

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- Domain Δ: non-empty set of objects
- Interpretation function $.^{\mathcal{I}}$: Maps structures into the domain.
- Recall, Brachman and Levesque write this as $\mathcal{I} = \langle D, I \rangle$.

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Then:

- $.^{\mathcal{I}}$ maps every concept name A to a subset $A^{\mathcal{I}} \subseteq \Delta$
- $.^{\mathcal{I}}$ maps every role name R to a binary relation $R^{\mathcal{I}} \subseteq \Delta \times \Delta$
- $.^{\mathcal{I}}$ maps individual names a to elements of $\Delta : a^{\mathcal{I}} \in \Delta$
- $\top^{\mathcal{I}} = \Delta$ and $\bot^{\mathcal{I}} = \emptyset$.

Semantics for Complex Concepts

Assume C, D are concepts, and R is a role.

- $(\neg C)^{\mathcal{I}} = \Delta \setminus C^{\mathcal{I}}$
- $(C \sqcap D)^{\mathcal{I}} = C^{\mathcal{I}} \cap D^{\mathcal{I}}$
- $(C \sqcup D)^{\mathcal{I}} = C^{\mathcal{I}} \cup D^{\mathcal{I}}$
- $(\forall R.C)^{\mathcal{I}} = \{x \mid y \in C^{\mathcal{I}}$ for every y s.t. $(x, y) \in R^{\mathcal{I}}\}$
- $(\exists R.C)^{\mathcal{I}} = \{x \mid y \in C^{\mathcal{I}}$ for some y s.t. $(x, y) \in R^{\mathcal{I}}\}$

Semantics for Axioms and Assertions

Assume C, D are concepts, R is a role, a and b are individual names.
Let $\mathcal{I} = (\Delta, .^{\mathcal{I}})$ be an interpretation.

- $C \sqsubseteq D$ is true in $\mathcal{I}$ iff $C^{\mathcal{I}} \subseteq D^{\mathcal{I}}$
- $C \doteq D$ is true in $\mathcal{I}$ iff $C^{\mathcal{I}} = D^{\mathcal{I}}$
- $C(a)$ is true in $\mathcal{I}$ iff $a^{\mathcal{I}} \in C^{\mathcal{I}}$
- $R(a, b)$ is true in $\mathcal{I}$ iff $(a^{\mathcal{I}}, b^{\mathcal{I}}) \in R^{\mathcal{I}}$

Reasoning in $\mathcal{ALC}$

- Sentences: Axioms or assertions
- $\mathcal{I}$ is a *model* for a sentence S iff S is true in $\mathcal{I}$
- $\mathcal{I}$ is a model for a DL knowledge base K iff it is a model for every sentence in K
- Models of K are denoted by $[K]$
- S is *entailed* by K, written $K \models S$ iff $[K] \subseteq [S]$
  (I.e. every model of K is a model of S.)

Types of Reasoning in $\mathcal{ALC}$

K a DL knowledge base;
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- Concept satisfiability: $K \not\models C \sqsubseteq \bot$
- Disjoint concepts: $K \models C \sqcap D \sqsubseteq \bot$

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Let b be a new individual

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- Disjoint concepts:
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Aside: Extensions to $\mathcal{ALC}$

Extended concepts

- Number restrictions: $(\leq nR.C)$ and $(\geq nR.C)$

Role operators

- Inverse roles: R^- where R is a role

Role axioms

- Role hierarchy: $R \sqsubseteq S$ where R and S are roles
  ☞ So far have just used $\sqsubseteq$ for concepts.
- Transitive roles: $R \in R^+$ where R is a role

Extensions to $\mathcal{ALC}$: Examples

- $\mathit{ParentWithManySons} \doteq (\geq 3 \mathit{ParentOf}.\mathit{Male})$
- $\exists \mathit{ParentOf}^{-}.\mathit{Citizen} \sqsubseteq \mathit{Citizen}$
- $\mathit{ParentOf} \sqsubseteq \mathit{AncestorOf}$
- $\mathit{AncestorOf} \in R^{+}$

Extensions to $\mathcal{ALC}$: Semantics

- $(\leq nR.C)^{\mathcal{I}} = \{x \mid \ |\{y \in C^{\mathcal{I}} \mid (x,y) \in R^{\mathcal{I}}\}| \ \leq n\}$
- $(\geq nR.C)^{\mathcal{I}} = \{x \mid \ |\{y \in C^{\mathcal{I}} \mid (x,y) \in R^{\mathcal{I}}\}| \ \geq n\}$
- Inverse roles: $(R^{-})^{\mathcal{I}} = \{(y,x) \mid (x,y) \in R^{\mathcal{I}}\}$
- $R \sqsubseteq S$ is true in I iff $R^{\mathcal{I}} \subseteq S^{\mathcal{I}}$ for roles R and S.
- $R \in R^{+}$ is true in I iff
  $(x,z) \in R^{\mathcal{I}}$ whenever $(x,y) \in R^{\mathcal{I}}$ and $(y,z) \in R^{\mathcal{I}}$

A Tableau Algorithm for $\mathcal{ALC}$

Goal: Show $KB \models A \sqsubseteq B$ by showing $KB \cup \{A \sqcap \neg B\}$ unsatisfiable.

Assume an *unfoldable terminology*:

- Axioms are of the form $A \sqsubseteq C$ and $A \doteq C$ where A is a concept name.
- For each concept name A, at most one axiom of the form $A \sqsubseteq C$ or $A \doteq C$.
- Axioms are acyclic:
  - $A \sqsubseteq C$ or $A \doteq C$ *directly uses* a concept name A_1 iff A_1 occurs in C.
  - $A \sqsubseteq C$ or $A \doteq C$ *uses* a concept name A_1 iff it directly uses A_1 or it directly uses a concept name A_2 and A_2 uses A_1.
  - $A \sqsubseteq C$ or $A \doteq C$ is *acyclic* iff it does not use A.

General Method

Show $KB \models A \sqsubseteq B$ by showing $KB \cup \{A \sqcap \neg B\}$ is unsatisfiable.

Try to prove concept (un)satisfiability by constructing a model.

- A *tableau* is a graph representing such a model.
- A set of tableau *expansion rules* is used to construct the tableau.
- Either a model is constructed or a contradiction is found.

General Method

At the start:

- Assume an unfoldable terminology.
- Assume that all axioms are of the form $P \doteq Q$
  - This can be done by replacing any axiom of the form $A \sqsubseteq B$ by $A \doteq B \sqcap C$ where C is a new concept name.

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If the query is $A \sqsubseteq B$:

- *negate* the query to get $A \sqcap \neg B$ (to show unsatisfiable);
- *unfold* the negated query;
- *convert* to *negation normal form*.

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☞ Once the negated query has been unfolded, the rest of the KB can be ignored.

To Start

Unfold:

Expand every concept name occurring in the (negated) query.

- I.e. if concept C appears in the query and $C \doteq D$ is in the KB, replace C by D in the query.
  - Recall that for $C \doteq D$ in the KB, C is a concept name and D is an arbitrary $\mathcal{ALC}$ concept expression.

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Unfold:

Expand every concept name occurring in the (negated) query.

- I.e. if concept C appears in the query and $C \doteq D$ is in the KB, replace C by D in the query.
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Negation normal form:

Negation occurs only in front of concept names

- $\neg(C \sqcap D)$ gives $\neg C \sqcup \neg D$, and
  $\neg(C \sqcup D)$ gives $\neg C \sqcap \neg D$
- $\neg\exists R.C$ gives $\forall R.\neg C$, and
  $\neg\forall R.C$ gives $\exists R.\neg C$
- $\neg\neg C$ gives C

Algorithm

- Use a tree to represent the model being constructed
- Each node x represents an individual, labelled with a set $L(x)$ of concepts it has to satisfy
  - $C \in L(x)$ implies $x \in C^{\mathcal{I}}$
- Each edge (x, y) represents a pair occurring in the interpretation of a role, labelled with the role name
  - $R = L((x, y))$ implies $(x, y) \in R^{\mathcal{I}}$

To Determine the Satisfiability of a Concept C

- Initialise the tree T with a single node x with $L(x) = \{C\}$.
- Expand by repeatedly applying a set of *expansion rules*.
- T is *fully expanded* when none of the rules can be applied.
- T contains a *clash* when, for a node y and a concept D,
  $\bot \in L(y)$ or $\{D, \neg D\} \subseteq L(y)$.
- If T can't be expanded without producing a clash, the concept is unsatisfiable.

Expansion Rules

($\sqcap$-rule) If $(C_1 \sqcap C_2) \in L(x)$ and $\{C_1, C_2\} \not\subseteq L(x)$ then:
Add C_1 and C_2 to $L(x)$.

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($\sqcup$-rule) If $(C_1 \sqcup C_2) \in L(x)$ and $\{C_1, C_2\} \cap L(x) = \emptyset$ then:
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If this leads to a clash, go back and add C_2 to $L(x)$.

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($\exists$-rule) If $\exists R.C \in L(x)$ and there is no y s.t. $L((x, y)) = R$ and $C \in L(y)$ then:
Create a new node y and edge (x, y) with $L(y) = C$ and $L((x, y)) = R$.

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Create a new node y and edge (x, y) with $L(y) = C$ and $L((x, y)) = R$.

($\forall$-rule) If $\forall R.C \in L(x)$ and there is some y s.t. $L((x, y)) = R$ and $C \notin L(y)$ then:
Add C to $L(y)$.

Interpreting a tree T

- If T contains a clash the concept C is unsatisfiable.
- If T is fully expanded and clash-free, then C is satisfiable.
- In the second case, construct a model I as follows:
  - $\Delta = \{x \mid x \text{ is a node in } T\}$.
  - $A^{\mathcal{I}} = \{x \in \Delta \mid A \in L(x)\}$ for all concept names A in C.
  - $R^{\mathcal{I}} = \{(x, y) \mid (x, y) \text{ is an edge in } T \text{ and } L((x, y)) = R\}$.

Termination of the Algorithm

- The $\sqcap$-, $\sqcup$-and $\exists$-rules can only be applied once to a concept in $L(x)$.
- The $\forall$-rule can be applied many times to a given $\forall R.C$ expression in $L(x)$, but only once to a given edge (x, y).
- Applying any rule to a concept C extends the labelling with a concept strictly smaller than C.

☞ Therefore the algorithm must terminate.

Tableau Algorithm: Example 1

DL knowledge base:

- $vegan \doteq person \sqcap \forall eats.plant$
- $vegetarian \doteq person \sqcap \forall eats.(plants \sqcup dairy)$

Query: $vegan \sqsubseteq vegetarian$

Convert to:

- $vegan \sqcap \neg vegetarian$ is unsatisfiable ?

Example 1

- Unfold and normalise $vegan \sqcap \neg vegetarian$:
  $person \sqcap \forall eats.plant \sqcap (\neg person \sqcup \exists eats.(\neg plant \sqcap \neg dairy))$

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  $person \sqcap \forall eats.plant \sqcap (\neg person \sqcup \exists eats.(\neg plant \sqcap \neg dairy))$
- Initialise T to $L(x)$ to contain:
  $person \sqcap \forall eats.plant \sqcap (\neg person \sqcup \exists eats.(\neg plant \sqcap \neg dairy))$

Example 1

- Unfold and normalise $vegan \sqcap \neg vegetarian$:
  $person \sqcap \forall eats.plant \sqcap (\neg person \sqcup \exists eats.(\neg plant \sqcap \neg dairy))$
- Initialise T to $L(x)$ to contain:
  $person \sqcap \forall eats.plant \sqcap (\neg person \sqcup \exists eats.(\neg plant \sqcap \neg dairy))$
- Apply $\sqcap$-rule and add to $L(x)$:
  $\{person, \forall eats.plant, \neg person \sqcup \exists eats.(\neg plant \sqcap \neg dairy)\}$

Example 1

- Apply $\sqcup$-rule to $\neg person \sqcup \exists eats.(\neg plant \sqcap \neg dairy)$:
  Add $\neg person$ to $L(x)$: Clash
  Go back and add $\exists eats.(\neg plant \sqcap \neg dairy)$ to $L(x)$

Example 1

- Apply $\sqcup$-rule to $\neg person \sqcup \exists eats.(\neg plant \sqcap \neg dairy)$:
  Add $\neg person$ to $L(x)$: Clash
  Go back and add $\exists eats.(\neg plant \sqcap \neg dairy)$ to $L(x)$
- Apply $\exists$-rule to $\exists eats.(\neg plant \sqcap \neg dairy)$:
  Create new node y and new edge (x, y):
  $L(y) = \{\neg plant \sqcap \neg dairy\}$; $L((x, y)) = eats$

Example 1

- Apply $\sqcup$-rule to $\neg person \sqcup \exists eats.(\neg plant \sqcap \neg dairy)$:
  Add $\neg person$ to $L(x)$: Clash
  Go back and add $\exists eats.(\neg plant \sqcap \neg dairy)$ to $L(x)$
- Apply $\exists$-rule to $\exists eats.(\neg plant \sqcap \neg dairy)$:
  Create new node y and new edge (x, y):
  $L(y) = \{\neg plant \sqcap \neg dairy\}$; $L((x, y)) = eats$
- Apply $\forall$-rule to $\forall eats.plant$ in $L(x)$ and $L((x, y)) = eats$:
  Add $plant$ to $L(y)$

Example 1

- Apply $\sqcap$-rule to $\neg plant \sqcap \neg dairy$ in $L(y)$:
  Add $\{\neg plant, \neg dairy\}$ to $L(y)$: Clash

Example 1

- Apply $\sqcap$-rule to $\neg plant \sqcap \neg dairy$ in $L(y)$:
  Add $\{\neg plant, \neg dairy\}$ to $L(y)$: Clash
- Conclusion
  - Both applications of the $\sqcup$-rule lead to clashes
  - So $vegan \sqcap \neg vegetarian$ is unsatisfiable
  - So $vegan \sqsubseteq vegetarian$

Example 2

- Query: $vegetarian \sqsubseteq vegan$
- Convert to: $vegetarian \sqcap \neg vegan$ is satisfiable ?
- Unfold and normalise $vegetarian \sqcap \neg vegan$:
  $person \sqcap \forall eats.(plant \sqcup dairy) \sqcap (\neg person \sqcup \exists eats.\neg plant)$
- Initialise T to $L(x)$ to contain:
  $\{person \sqcap \forall eats.(plant \sqcup dairy) \sqcap (\neg person \sqcup \exists eats.\neg plant)\}$

Example 2

- Apply $\sqcap$-rule and add to $L(x)$:
  $\{person, \forall eats.(plant \sqcup dairy), \neg person \sqcup \exists eats.\neg plant\}$

Example 2

- Apply $\sqcap$-rule and add to $L(x)$:
  $\{person, \forall eats.(plant \sqcup dairy), \neg person \sqcup \exists eats.\neg plant\}$
- Apply $\sqcup$-rule to $\neg person \sqcup \exists eats.\neg plant$:
  Add $\neg person$ to $L(x)$: Clash
  Go back and add $\exists eats.\neg plant$ to $L(x)$

Example 2

- Apply $\sqcap$-rule and add to $L(x)$:
  $\{person, \forall eats.(plant \sqcup dairy), \neg person \sqcup \exists eats.\neg plant\}$
- Apply $\sqcup$-rule to $\neg person \sqcup \exists eats.\neg plant$:
  Add $\neg person$ to $L(x)$: Clash
  Go back and add $\exists eats.\neg plant$ to $L(x)$
- Apply $\exists$-rule to $\exists eats.\neg plant$:
  Create new node y and new edge (x, y)
  $L(y) = \{\neg plant\}$; $L((x, y)) = eats$

Example 2

- Apply $\forall$-rule to $\forall eats.(plant \sqcup dairy)$ in $L(x)$ and $L((x, y)) = eats$:
  Add $plant \sqcup dairy$ to $L(y)$

Example 2

- Apply $\forall$-rule to $\forall eats.(plant \sqcup dairy)$ in $L(x)$ and $L((x, y)) = eats$:
  Add $plant \sqcup dairy$ to $L(y)$
- Apply $\sqcup$-rule to $plant \sqcup dairy$ in $L(y)$:
  Add $plant$ to $L(y)$: Clash
  Go back and add $dairy$ to $L(y)$

Example 2

- Apply $\forall$-rule to $\forall eats.(plant \sqcup dairy)$ in $L(x)$ and $L((x,y)) = eats$:
  Add $plant \sqcup dairy$ to $L(y)$
- Apply $\sqcup$-rule to $plant \sqcup dairy$ in $L(y)$:
  Add $plant$ to $L(y)$: Clash
  Go back and add $dairy$ to $L(y)$
- Conclusion
  - No rules are applicable, so T is fully expanded
  - So $vegetarian \sqcap \neg vegan$ is satisfiable
  - So $vegetarian \not\sqsubseteq vegan$

The Brachman&Levesque DL and $\mathcal{ALC}$

Constructor	B&L	$\mathcal{ALC}$
Conj.	(AND A B)	$A \sqcap B$
Univ. quant.	(ALL R C)	$\forall R.C$
Exist. quant.		$\exists R.C$
Unqual. exist. quant.	(EXISTS 1 R)	$\exists R.\top$
Number restriction	(EXISTS n R)	
Role filler	(FILLS R a)	
Assertion	$a \rightarrow C$	$C(a)$

- $\mathcal{FL}^-$ consists of Conj., Univ. quant., and Unqual. exist. quant.
- The B&L DL is slightly more general than $\mathcal{FL}^-$.
- $\mathcal{ALC}$ is $\mathcal{FL}^-$ plus $\top$, $\bot$, and general negation.
- The extension to $\mathcal{ALC}$ for a role filler would use $\forall R.\{a\}$.

References

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