Introduction
Main problem with **semantic networks and frames**
... the lack of **formal semantics**!

Disadvantage of simple **inheritance networks**
... concepts are atomic and do not have any **structure**

⇝ **Brachman’s structural inheritance networks (1977)**
Structural inheritance networks

- Concepts are defined/described using a small set of well-defined operators
- Distinction between conceptual and object-related knowledge
- Computation of subconcept relation and of instance relation
- Strict inheritance (of the entire structure of a concept): inherited properties cannot be overridden
Systems and applications

- **KL-ONE**: First implementation of the ideas (1978)
- then: NIKL, KL-TWO, KRYPTON, KANDOR, CLASSIC, BACK, KRIS, YAK, CRACK …
- later: FaCT, DLP, RACER 1998
- currently: FaCT++, RACER, Pellet.

- **Applications**: First, natural language understanding systems, then configuration systems, and information systems, currently, it is one tool for the Semantic Web

- **Languages**: DAML+OIL, now OWL (Web Ontology Language)
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Description logics

- Previously also known as KL-ONE-alike languages, frame-based languages, terminological logics, concept languages

- Description Logics (DL) allow us
  - to describe concepts using complex descriptions,
  - to introduce the terminology of an application and to structure it (TBox),
  - to introduce objects and relate them to the introduced terminology (ABox),
  - and to reason about the terminology and the objects.
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Male is: the opposite of female
A human is a kind of: living entity
A woman is: a human and a female
A man is: a human and a male
A mother is: a woman with at least one child that is a human
A father is: a man with at least one child that is a human
A parent is: a mother or a father
A grandmother is: a woman, with at least one child that is a parent
A mother-wod is: a mother with only male children

Elizabeth is a woman
Elizabeth has the child Charles
Charles is a man
Diana is a mother-wod
Diana has the child William

Possible Questions:
Is a grandmother a parent?
Is Diana a parent?
Is William a man?
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Informal example

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Concepts and Roles
Atomic concepts and roles

Concept names:
- E.g., Grandmother, Male, ... (in the following usually capitalized)
- We will use symbols such as $A, A_1, \ldots$ for concept names
- Semantics: Monadic predicates $A(\cdot)$ or set-theoretically a subset of the universe $A^I \subseteq \mathcal{D}$.

Role names:
- In our example, e.g., child. Often we will use names such as has-child or something similar (in the following usually lowercase).
- Role names are disjoint from concept names
- Symbolically: $t, t_1, \ldots$
- Semantics: Binary relations $t(\cdot, \cdot)$ or set-theoretically $t^I \subseteq \mathcal{D} \times \mathcal{D}$.
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From (atomic) concept and role names, complex concept and role descriptions can be created. In our example, e.g., “Human and Female.” Symbolically: $C$ for concept descriptions and $r$ for role descriptions. Which particular constructs are available depends on the chosen description logic!

- FOL semantics: A concept description $C$ corresponds to a formula $C(x)$ with the free variable $x$. Similarly with role descriptions $r$: they correspond to formulae $r(x, y)$ with free variables $x, y$.

- Set semantics:

$$C^I = \{ d \in D : C(d) \text{ “is true in” } I \}$$

$$r^I = \{ (d, e) \in D^2 : r(d, e) \text{ “is true in” } I \}$$
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Boolean operators

- **Syntax:** let $C$ and $D$ be concept descriptions, then the following are also concept descriptions:
  - $C \sqcap D$ (concept conjunction)
  - $C \sqcup D$ (concept disjunction)
  - $\neg C$ (concept negation)

- **Examples:**
  - Human $\sqcap$ Female
  - Father $\sqcup$ Mother
  - $\neg$ Female

- **FOL semantics:** $C(x) \land D(x)$, $C(x) \lor D(x)$, $\neg C(x)$

- **Set semantics:** $C^I \cap D^I$, $C^I \cup D^I$, $D \setminus C^I$
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Role restrictions

Motivation:

- Often we want to describe something by restricting the possible “fillers” of a role, e.g. Mother→Mad.
- Sometimes we want to say that there is at least a filler of a particular type, e.g. Grandmother

Idea: Use quantifiers that range over the role-fillers

- Mother ⊓∀has-child.Man
- Woman ⊓∃has-child.Parent

FOL semantics:

\[
(\exists r. C)(x) = \exists y (r(x,y) \land C(y)) \\
(\forall r. C)(x) = \forall y (r(x,y) \rightarrow C(y))
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Set semantics:

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(\exists r. C)^I = \{d \in D : \text{there ex. some } e \text{ s.t. } (d,e) \in r^I \land e \in C^I\} \\
(\forall r. C)^I = \{d \in D : \text{for each } e \text{ with } (d,e) \in r^I, e \in C^I\}
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- Often we want to describe something by restricting the possible “fillers” of a role, e.g. Mother→Woman.
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Idea: Use quantifiers that range over the role-fillers
- Mother ⊓ ∀ has-child Man
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Cardinality restriction

- **Motivation:**
  - Often we want to describe something by restricting the number of possible “fillers” of a role, e.g., a Mother with at least 3 children or at most 2 children.

- **Idea:** We restrict the cardinality of the role filler sets:
  - $\text{Mother} \sqcap \geq 3 \text{has-child}$
  - $\text{Mother} \sqcap \leq 2 \text{has-child}$

- **FOL semantics:**
  
  
  $$(\geq n \ r)(x) = \exists y_1 \ldots y_n (r(x, y_1) \land \cdots \land r(x, y_n) \land y_1 \neq y_2 \land \cdots \land y_{n-1} \neq y_n)$$

  $$(\leq n \ r)(x) = \neg (\geq n + 1 \ r)(x)$$

- **Set semantics:**
  
  $$(\geq n \ r)^\mathcal{I} = \{d \in \mathcal{D} : |\{e \in \mathcal{D} : r^\mathcal{I}(d, e)\}| \geq n\}$$

  $$(\leq n \ r)^\mathcal{I} = \mathcal{D} \setminus (\geq n + 1 \ r)^\mathcal{I}$$
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- **Set semantics:**
  
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  $$(\leq n \ r)' = D \setminus (\geq n + 1 \ r)'$$
Motivation:
- How can we describe the concept “children of rich parents”?

Idea: Define the “inverse” role for a given role (the converse relation)
- has-child$^{-1}$

Example: $\exists \text{has-child}^{-1} \cdot \text{Rich}$

FOL semantics:
$$r^{-1}(x,y) = r(y,x)$$

Set semantics:
$$(r^{-1})^I = \{(d,e) \in D^2 : (e,d) \in r^I\}$$
Inverse roles

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- How can we describe the concept “children of rich parents”?

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- $\text{has-child}^{-1}$

**Example:** $\exists \text{has-child}^{-1}. \text{Rich}$

**FOL semantics:**

$$r^{-1}(x, y) = r(y, x)$$

**Set semantics:**

$$(r^{-1})^I = \{(d, e) \in D^2 : (e, d) \in r^I\}$$
Motivation:

How can we define the role has-grandchild given the role has-child?

Idea: Compose roles (as one can compose binary relations)

has-child ◦ has-child

FOL semantics:

\[(r \circ s)(x, y) = \exists z (r(x, z) \land s(z, y))\]

Set semantics:

\[(r \circ s)^I = \{ (d, e) \in D^2 : \exists f \text{ s.t. } (d, f) \in r^I \land (f, e) \in s^I \}\]
Role composition

■ **Motivation:**
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Role value maps

- **Motivation:**
  - How do we express the concept “women who know all the friends of their children”

- **Idea:** Relate role filler sets to each other
  - \( \text{Woman} \sqcap (\text{has-child} \circ \text{has-friend} \sqsubseteq \text{knows}) \)

- **FOL semantics:**
  \[
  (r \sqsubseteq s)(x) = \forall y (r(x,y) \rightarrow s(x,y))
  \]

- **Set semantics:** Let \( r^\mathcal{I}(d) = \{ e : r^\mathcal{I}(d,e) \} \).
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  \]

- **Note:** Role value maps lead to undecidability of satisfiability testing of concept descriptions!
TBox and ABox
In order to introduce new terms, we use two kinds of terminological axioms:

- $A \overset{\text{def}}{=} C$
- $A \sqsubseteq C$

where $A$ is a concept name and $C$ is a concept description.

A terminology or TBox is a finite set of such axioms with the following additional restrictions:

- no multiple definitions of the same symbol such as $A \overset{\text{def}}{=} C$, $A \sqsubseteq D$
- no cyclic definitions (even not indirectly), such as $A \overset{\text{def}}{=} \forall r \cdot B$, $B \overset{\text{def}}{=} \exists s \cdot A$
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TBoxes: semantics

- TBoxes restrict the set of possible interpretations.
- FOL semantics:
  - $A \sqsubseteq C$ corresponds to $\forall x (A(x) \leftrightarrow C(x))$
  - $A \sqsubseteq C$ corresponds to $\forall x (A(x) \rightarrow C(x))$
- Set semantics:
  - $A \sqsubseteq C$ corresponds to $A^\mathcal{I} \subseteq C^\mathcal{I}$
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- Non-empty interpretations which satisfy all terminological axioms are called models of the TBox.
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- Non-empty interpretations which satisfy all terminological axioms are called **models** of the TBox.
In order to state something about objects in the world, we use two forms of assertions:

- $a : C$
- $(a, b) : r$

where $a$ and $b$ are individual names (e.g., ELIZABETH, PHILIP), $C$ is a concept description, and $r$ is a role description.

An ABox is a finite set of assertions.
**ABoxes: semantics**

- **Individual names** are interpreted as elements of the universe under the unique-name-assumption, i.e., different names refer to different objects.

- **Assertions** express that an object is an instance of a concept or that two objects are related by a role.

- **FOL semantics:**
  - $a : C$ corresponds to $C(a)$
  - $(a, b) : r$ corresponds to $r(a, b)$

- **Set semantics:**
  - $a^\mathcal{I} \in D$
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- **Models** of an ABox and of ABox $+ TBox$ can be defined analogously to models of a TBox.
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Example TBox

\[
\begin{align*}
\text{Male} & \equiv \neg \text{Female} \\
\text{Human} & \sqsubseteq \text{Living_entity} \\
\text{Woman} & \equiv \text{Human} \sqcap \text{Female} \\
\text{Man} & \equiv \text{Human} \sqcap \text{Male} \\
\text{Mother} & \equiv \text{Woman} \sqcap \exists \text{has-child.Human} \\
\text{Father} & \equiv \text{Man} \sqcap \exists \text{has-child.Human} \\
\text{Parent} & \equiv \text{Father} \sqcup \text{Mother} \\
\text{Grandmother} & \equiv \text{Woman} \sqcap \exists \text{has-child.Parent} \\
\text{Mother-without-daughter} & \equiv \text{Mother} \sqcap \forall \text{has-child.Male} \\
\text{Mother-with-many-children} & \equiv \text{Mother} \sqcap (\geq 3 \text{has-child})
\end{align*}
\]
Example ABox

CHARLES: Man
EDWARD: Man
ANDREW: Man
DIANA: Woman
ELIZABETH: Woman

DIANA: Mother-without-daughter
(ELIZABETH, CHARLES): has-child
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Reasoning Services
Some reasoning services

- Does a description $C$ make sense at all, i.e., is it **satisfiable**? A concept description $C$ is satisfiable, if there exists an interpretation $\mathcal{I}$ such that $C^\mathcal{I} \neq \emptyset$.

- Is one concept a specialization of another one, is it subsumed? $C$ is subsumed by $D$ (in symbols $C \sqsubseteq D$) if we have for all interpretations $C^\mathcal{I} \subseteq D^\mathcal{I}$.

- Is $a$ an instance of a concept $C$? $a$ is an instance of $C$ if for all interpretations, we have $a^\mathcal{I} \in C^\mathcal{I}$.

*Note:* These questions can be posed with or without a TBox that restricts the possible interpretations.
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Outlook
Can we reduce the reasoning services to perhaps just one problem?

What could be reasoning algorithms?

What can we say about complexity and decidability?

What has all that to do with modal logics?

How can one build efficient systems?


### Summary: Concept descriptions

<table>
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<tr>
<th>Abstract</th>
<th>Concrete</th>
<th>Interpretation</th>
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<tbody>
<tr>
<td>$A$</td>
<td>$A$</td>
<td>$A^I$</td>
</tr>
<tr>
<td>$C \sqcap D$</td>
<td>(and $C D$)</td>
<td>$C^I \cap D^I$</td>
</tr>
<tr>
<td>$C \sqcup D$</td>
<td>(or $C D$)</td>
<td>$C^I \cup D^I$</td>
</tr>
<tr>
<td>$\neg C$</td>
<td>(not $C$)</td>
<td>$D - C^I$</td>
</tr>
<tr>
<td>$\forall r.C$</td>
<td>(all $r C$)</td>
<td>${d \in D : r^I(d) \subseteq C^I}$</td>
</tr>
<tr>
<td>$\exists r$</td>
<td>(some $r$)</td>
<td>${d \in D : r^I(d) \neq \emptyset}$</td>
</tr>
<tr>
<td>$\geq n r$</td>
<td>(atleast $n r$)</td>
<td>${d \in D :</td>
</tr>
<tr>
<td>$\leq n r$</td>
<td>(atmost $n r$)</td>
<td>${d \in D :</td>
</tr>
<tr>
<td>$\exists r.C$</td>
<td>(some $r C$)</td>
<td>${d \in D : r^I(d) \cap C^I \neq \emptyset}$</td>
</tr>
<tr>
<td>$\geq n r.C$</td>
<td>(atleast $n r C$)</td>
<td>${d \in D :</td>
</tr>
<tr>
<td>$\leq n r.C$</td>
<td>(atmost $n r C$)</td>
<td>${d \in D :</td>
</tr>
<tr>
<td>$r = s$</td>
<td>(eq $r s$)</td>
<td>${d \in D : r^I(d) = s^I(d)}$</td>
</tr>
<tr>
<td>$r \neq s$</td>
<td>(neq $r s$)</td>
<td>${d \in D : r^I(d) \neq s^I(d)}$</td>
</tr>
<tr>
<td>$r \subseteq s$</td>
<td>(subset $r s$)</td>
<td>${d \in D : r^I(d) \subseteq s^I(d)}$</td>
</tr>
<tr>
<td>$g = h$</td>
<td>(eq $g h$)</td>
<td>${d \in D : g^I(d) = h^I(d) \neq \emptyset}$</td>
</tr>
<tr>
<td>$g \neq h$</td>
<td>(neq $g h$)</td>
<td>${d \in D : 0 \neq g^I(d) \neq h^I(d) \neq 0}$</td>
</tr>
<tr>
<td>${i_1, i_2, \ldots, i_n}$</td>
<td>(oneof $i_1 \ldots i_n$)</td>
<td>${i_1^I, i_2^I, \ldots, i_n^I}$</td>
</tr>
<tr>
<td>Abstract</td>
<td>Concrete</td>
<td>Interpretation</td>
</tr>
<tr>
<td>----------</td>
<td>----------</td>
<td>---------------</td>
</tr>
<tr>
<td>t</td>
<td>t</td>
<td>$t^\mathcal{I}$</td>
</tr>
<tr>
<td>f</td>
<td>f</td>
<td>$f^\mathcal{I}$, <em>(functional role)</em></td>
</tr>
<tr>
<td>$r \sqcap s$</td>
<td>(and $r \cdot s$)</td>
<td>$r^\mathcal{I} \cap s^\mathcal{I}$</td>
</tr>
<tr>
<td>$r \sqcup s$</td>
<td>(or $r \cdot s$)</td>
<td>$r^\mathcal{I} \cup s^\mathcal{I}$</td>
</tr>
<tr>
<td>$\neg r$</td>
<td>(not $r$)</td>
<td>$\mathcal{D} \times \mathcal{D} - r^\mathcal{I}$</td>
</tr>
<tr>
<td>$r^{-1}$</td>
<td>(inverse $r$)</td>
<td>${(d,d') : (d',d) \in r^\mathcal{I}}$</td>
</tr>
<tr>
<td>$r \mid_C$</td>
<td>(restr $r \cdot C$)</td>
<td>${(d,d') : (d',d) \in r^\mathcal{I} \land d' \in C^\mathcal{I}}$</td>
</tr>
<tr>
<td>$r^+$</td>
<td>(trans $r$)</td>
<td>$(r^\mathcal{I})^+$</td>
</tr>
<tr>
<td>$r \circ s$</td>
<td>(compose $r \cdot s$)</td>
<td>$r^\mathcal{I} \circ s^\mathcal{I}$</td>
</tr>
<tr>
<td>1</td>
<td>self</td>
<td>${(d,d) : d \in \mathcal{D}}$</td>
</tr>
</tbody>
</table>