Semantic Networks and Description Logics

Description Logics – Implementation Techniques

Knowledge Representation and Reasoning

January 9, 2006
Description Logics – Implementation Techniques

Motivation

Classification

Subsumption Tests

Provisional Balance

Tableau Proofs

Preprocessing
Motivation

- It is easy to write a subsumption checker for, e.g., $\mathcal{ALC}$
- It is also easy to extend this to a small TBox/Abox system
- On top of that we need
  1. a graphical user interface
  2. an application interface with the right kind of services
  3. an efficient implementation of the basic reasoning services
- Possible areas of optimization:
  1. Classification
  2. Subsumption test
  3. Preprocessing the KB
Classification: Sorting in Partial Orders

- Compute the hierarchy induced by the subsumption relationship (similar to sorting)
- Also important in other contexts
- Incremental creation
  1. Find immediate subsumers and subsumees in hierarchy
  2. Place new concept at this place (and delete superfluous links)
Worst-Case Lower Bound for Classification

- Count number of subsumption tests
- What is the worst case?
- Worst case: All concepts are unrelated
- $O(n^2)$ for $n$ being the number of concept names.
- Analytical comparison (for the average case) between different methods is probably difficult because it is unknown, how many partial orders exist for a given number of elements.
- Empirical comparisons are the best we can hope for
Method 0: Brute force

The brute-force method. For each new concept $C$:

- For each concept $D$ in the hierarchy, check
  - whether $C$ subsumes $D$ and
  - whether $D$ subsumes $C$.
- Compute from those the immediate subsumers and subsumees
- $2n$ tests for each new concept
- $\sum_{i=0}^{n-1} 2i = n \times (n - 1)$ for the whole KB
Method 1: Simple Traversal

- **Top search**: Traverse hierarchy top down (e.g. depth-first), and try to identify direct subsumers by checking subsumption and mark subsumption failures.

- **Bottom search**: dual, from bottom element
Method 2: Smart Traversal

- Exploit information from previous subsumption tests
- Use information about positive results in the top search path
  
  Subsumption test:
  - positive
  - negative
  - no test

- Use information about negative results in the top search path
  
  Subsumption test:
  - positive
  - negative
  - no test
Three Alternatives

- **Note:** Smart traversal is provably as good as simple traversal (counting the number of subsumption tests) and the additional overhead is negligible (0.5% of the subsumption costs in a typical KB)

- **Alternatives:**
  1. Depth-first search using only positive information
  2. Breadth-first search using only negative information
  3. Depth-first search using both negative and positive information

- **Our results:** **Breadth-first** search is best. Using only positive information does not help much.
Smart Traversal: Bottom Search

- Dual optimization to top search (starting at bottom)
- In addition, it is sufficient to consider only nodes that are subsumed by all immediate subsumers!
Number of Subsumption Tests Relative to “Brute Force” Method

- In 1992, we evaluated the effects of different techniques.
- On real KBs, the book keeping overhead turned out to be relatively low compared with the time for subsumption checking.
- We measured the effects on randomly generated KBs modeled after the structure of real KBs.
Method 3: Insertion into Chains

- Building up a linearly ordered list incrementally, it is a good idea to use binary search for identifying the next insertion point.

- Idea:
  - Compute a good chain-covering of the partial order, i.e., a set of linearly ordered chains covering all elements.
  - Minimal chain covering is (of course) NP-hard. Therefore we used a heuristic.
  - Do a binary search in all chains.
  - and apply the same propagation of positive and negative information as in the smart traversal.
  - One gets a super-set of the set of immediate subsumers (and subsumees).
  - in most typical cases a little bit worse than with smart traversal (approx. 10%).
  - better only if the connectedness of the order was higher than in typical KBs.
### Results for Chain Insertion

<table>
<thead>
<tr>
<th>Type of KB</th>
<th>No. of nodes</th>
<th>Average degree</th>
<th>Average no. of pred. &amp; succ.</th>
<th>Breadth</th>
<th>Depth</th>
<th>Relative no. of comparisons</th>
</tr>
</thead>
<tbody>
<tr>
<td>real KB</td>
<td>184</td>
<td>1.71</td>
<td>5.67</td>
<td>105</td>
<td>6</td>
<td>103.7%</td>
</tr>
<tr>
<td></td>
<td>241</td>
<td>1.91</td>
<td>6.38</td>
<td>124</td>
<td>6</td>
<td>100.3%</td>
</tr>
<tr>
<td></td>
<td>254</td>
<td>1.99</td>
<td>13.02</td>
<td>135</td>
<td>6</td>
<td>91.8%</td>
</tr>
<tr>
<td></td>
<td>269</td>
<td>1.72</td>
<td>5.16</td>
<td>164</td>
<td>7</td>
<td>107.9%</td>
</tr>
<tr>
<td></td>
<td>330</td>
<td>1.85</td>
<td>8.13</td>
<td>141</td>
<td>12</td>
<td>110.0%</td>
</tr>
<tr>
<td>random KB</td>
<td>298</td>
<td>2.36</td>
<td>8.88</td>
<td>142</td>
<td>8</td>
<td>115.7%</td>
</tr>
<tr>
<td></td>
<td>583</td>
<td>2.58</td>
<td>12.24</td>
<td>330</td>
<td>7</td>
<td>114.5%</td>
</tr>
<tr>
<td></td>
<td>992</td>
<td>2.73</td>
<td>16.77</td>
<td>478</td>
<td>10</td>
<td>111.7%</td>
</tr>
<tr>
<td></td>
<td>1263</td>
<td>3.18</td>
<td>16.61</td>
<td>661</td>
<td>11</td>
<td>108.9%</td>
</tr>
<tr>
<td></td>
<td>1659</td>
<td>3.19</td>
<td>18.86</td>
<td>927</td>
<td>10</td>
<td>110.3%</td>
</tr>
<tr>
<td></td>
<td>2389</td>
<td>3.50</td>
<td>25.49</td>
<td>1188</td>
<td>10</td>
<td>111.3%</td>
</tr>
<tr>
<td></td>
<td>3658</td>
<td>3.82</td>
<td>27.20</td>
<td>1703</td>
<td>8</td>
<td>105.3%</td>
</tr>
<tr>
<td></td>
<td>3905</td>
<td>4.04</td>
<td>33.95</td>
<td>1858</td>
<td>11</td>
<td>99.9%</td>
</tr>
<tr>
<td>random partial orders</td>
<td>301</td>
<td>7.67</td>
<td>42.11</td>
<td>88</td>
<td>8</td>
<td>73.2%</td>
</tr>
<tr>
<td></td>
<td>301</td>
<td>6.40</td>
<td>10.43</td>
<td>168</td>
<td>6</td>
<td>102.7%</td>
</tr>
<tr>
<td></td>
<td>301</td>
<td>4.22</td>
<td>5.68</td>
<td>205</td>
<td>4</td>
<td>101.3%</td>
</tr>
<tr>
<td></td>
<td>586</td>
<td>9.93</td>
<td>72.55</td>
<td>144</td>
<td>9</td>
<td>67.2%</td>
</tr>
<tr>
<td></td>
<td>586</td>
<td>10.39</td>
<td>20.42</td>
<td>301</td>
<td>7</td>
<td>103.3%</td>
</tr>
<tr>
<td></td>
<td>586</td>
<td>7.72</td>
<td>11.50</td>
<td>353</td>
<td>5</td>
<td>102.9%</td>
</tr>
<tr>
<td></td>
<td>995</td>
<td>5.52</td>
<td>250.24</td>
<td>85</td>
<td>28</td>
<td>16.2%</td>
</tr>
<tr>
<td></td>
<td>995</td>
<td>16.40</td>
<td>62.88</td>
<td>354</td>
<td>9</td>
<td>91.4%</td>
</tr>
<tr>
<td></td>
<td>995</td>
<td>13.58</td>
<td>28.38</td>
<td>506</td>
<td>6</td>
<td>105.1%</td>
</tr>
<tr>
<td></td>
<td>1266</td>
<td>5.78</td>
<td>321.19</td>
<td>100</td>
<td>30</td>
<td>12.9%</td>
</tr>
<tr>
<td></td>
<td>1266</td>
<td>18.22</td>
<td>76.87</td>
<td>438</td>
<td>9</td>
<td>89.8%</td>
</tr>
<tr>
<td></td>
<td>1266</td>
<td>17.82</td>
<td>41.70</td>
<td>592</td>
<td>6</td>
<td>101.1%</td>
</tr>
</tbody>
</table>
Exploiting the Concept Structure

1. If a concept is defined conjunctively, i.e.,

\[ A \doteq X \cap Y \cap \ldots \cap Z \]

all atomic concepts \((X, Y, Z)\) are obviously super-concepts. So one can mark these concepts as subsuming (and can propagate this information).

2. Primitive concepts (introduced with \(\sqsubseteq\)) can be ignored in the bottom search phase, if we classify in definition order (i.e., before a term is used, it will be defined).

3. Primitive components of a concept are the undefined concepts in the unfolded form of a concept. A subsumption test between two conjunctively defined concepts can only be successful if the primitive components are in an set-inclusion relationship.
Caching and Lazy Unfolding

- Instead of unfolding a concept and then testing subsumption, one can delay the expansion of a defined concept until no other way to prove unsatisfiability is possible.

- Instead of testing for clashes of primitive concepts, we also look for clashes on the level of named, defined concepts.

- Finally, we can in addition also look for clashes implied by the subsumption hierarchy, e.g., Man and $\neg$Human form a clash.

- These optimization saved roughly 50% of the runtime on the realistic KBs.
The described methods (and a few others) were used in speeding up the KRIS system.

We achieved a speedup factor of around 400.

The difference between a first prototype implementation that just implements the principles and a highly optimized system can be huge – in particular when we are dealing with worst-case exponential time/space problems.

Interestingly, the method we believed to be superior (chain insertion) was not effective at all.

One has to look for what typical cases require – and these cases might not be easily recognizable as polynomial special cases.

There are techniques especially geared towards more expressive DLs – and some we will have a short look at.
Semantic Branching in Tableau Proofs

Consider the System: \( S = \{ x : (A \sqcup B), x : (A \sqcup C) \} \)

Ordinarily,

- we would first try out \( A \) and \( B \), nondeterministically.
- Then we would make another nondeterministic choice between \( A \) and \( C \).

if \( A \) leads to clash, we would try that out twice.

Use *semantic branching* instead (similar to what is done in the Davis-Putnam procedure)

Branch over \( A \) and \( \neg A \)!

This avoids double work on \( A \) and leads to **tighter constraints** (when using \( \neg A \) in the other branch)

Experience shows that the additional overhead for propagating \( \neg A \) is usually negligible

*Local simplification* becomes possible
Boolean Constraint Propagation

- When using semantic branching, we can also simplify disjunctions by propagating the concepts, we have branched on, using *Boolean constraint propagation* (aka *unit propagation*).

- Example:

  \[ S = \{ x : (C \sqcup (D_1 \sqcap D_2)), x : (\neg D_1 \sqcup \neg D_2 \sqcup C), x : \neg C \} \]

- Because of \( x : \neg C \), this can be simplified to

  \[ S = \{ x : (D_1 \sqcap D_2), x : (\neg D_1 \sqcup \neg D_2 \sqcup C), x : \neg C \} \]

- This in turn can be simplified to

  \[ S = \{ x : (D_1 \sqcap D_2), x : C, x : \neg C \} \]

- This is easily be detected as unsatisfiable!

- Note that no nondeterministic branching was necessary!
More Methods for Speeding up Tableau Proofs

- **Dependency-directed backtracking**: Try to detect the reason for a clash and jump back (instead of exploring fruitless alternatives)
- **Heuristic guided search**: Branch on the right disjunct
- **MOMS heuristic**: Branch on the disjunct with the maximum number of occurrences in disjunctions of minimum size.
- Seems not to be a good heuristic in DLs.
- The best heuristic seems to be **oldest first**, which selects a disjunct from the disjunction depending on the least recent branching point
- Other techniques such as caching tableau trees and reusing them are also possible
Avoiding Internalization

- **Internalization** is a powerful technique to deal with general concept inclusion statements (we have seen in the last lecture).

- However, it introduces a lot of *non-deterministic choices*. Remember: \( C_i \sqsubseteq D_i \) is translated into \( D_i \sqcup \neg C_i \), which is enforced on every domain element (using the quasi-universal role).

- Each inclusion statement leads to a nondeterministic choice point for each element!

- Avoid if possible:
  
  - Collect multiple primitive definitions:
    
    \[(A \sqsubseteq C_1), \ldots (A \sqsubseteq C_n) \iff (A \sqsubseteq C_1 \cap \ldots \cap C_n)\]

  - Partition the terminology into two parts \( T_u \) and \( T_g \), where the former is unfoldable and the latter is the general part. Then we can apply *lazy unfolding* to all statements in \( T_u \).
Absorption

- Since general inclusion statements lead to nondeterminism, it is a good idea to reduce these as much as possible.
- Use the following equivalences to absorb general inclusion statements into primitive concept definitions:

\[
C_1 \cap C_2 \sqsubseteq D \iff C_1 \sqsubseteq D \cap \neg C_2 \\
C \sqsubseteq D_1 \cap D_2 \iff (C \sqsubseteq D_1), (C \sqsubseteq D_2)
\]

- Example Absorption. Assume: Geometric-figure \sqsubseteq Figure, Geometric-figure \cap \exists \text{angles}.Three \sqsubseteq \exists \text{sides}.Three.
- The latter inclusion statement can be massaged into:

\[
\text{Geometric-figure} \sqsubseteq \exists \text{sides}.Three \cup \neg \exists \text{angles}.Three
\]
- Then it can be absorbed into:

\[
\text{Geometric-figure} \sqsubseteq \text{Figure} \cap \exists \text{sides}.Three \cup \neg \exists \text{angles}.Three
\]
- Using this technique can make a huge difference
Conclusion

- Implementing inference methods for DLs is easy – if we do not care about efficiency
- The difference between a prototype implementation and a carefully optimized system can be several orders of magnitude
- Optimizations are possible on classification level, the subsumption testing level, and the tableau proof level
- These optimization should be geared towards the typical case
- It is nearly impossible to decide analytically, which method is the right one, only empirical comparisons can help here
- **Note**: Although there exists now a number of efficient DL methods, in general there will remain the problem that sometimes these systems just have to give up because a subsumption query is too difficult!