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# Implementing DL Systems

# Naive Implementations

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Problems include:

- ☞ Space usage
  - Storage required for tableaux datastructures
  - Rarely a serious problem in practice
- ☞ Time usage
  - Search required due to non-deterministic expansion
  - **Serious** problem in practice
  - Mitigated by:
    - Careful **choice of algorithm**
    - Highly **optimised implementation**

# Careful Choice of Algorithm

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- 👉 Transitive roles instead of transitive closure
  - Deterministic expansion of  $\exists R.C$ , even when  $R \in \mathbf{R}_+$
  - (Relatively) simple blocking conditions
  - Cycles **always** represent (part of) cyclical models
- 👉 Direct algorithm/implementation instead of encodings
  - GCI axioms can be used to “encode” additional operators/axioms
  - Powerful technique, particularly when used with FL closure
  - Can encode cardinality constraints, inverse roles, range/domain, ...
    - E.g.,  $(\text{domain } R.C) \equiv \exists R.T \sqsubseteq C$
  - (FL) encodings introduce (large numbers of) axioms
  - **BUT** even simple domain encoding is **disastrous** with large numbers of roles

# Highly Optimised Implementation

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Optimisation performed at 2 levels

- ☞ Computing **classification** (partial ordering) of concepts
  - Objective is to minimise number of subsumption tests
  - Can use standard order-theoretic techniques
    - ➔ E.g., use **enhanced traversal** that exploits information from previous tests
  - Also use structural information from KB
    - ➔ E.g., to select order in which to classify concepts
- ☞ Computing **subsumption** between concepts
  - Objective is to minimise cost of single subsumption tests
  - Small number of hard tests can dominate classification time
  - Recent DL research has addressed this problem (with considerable success)

# Optimising Subsumption Testing

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**Optimisation techniques** broadly fall into 2 categories

☞ Pre-processing optimisations

- Aim is to **simplify KB** and facilitate subsumption testing
- Largely algorithm independent
- Particularly important when KB contains GCI axioms

☞ Algorithmic optimisations

- Main aim is to **reduce search space** due to non-determinism
- Integral part of implementation
- But often generally applicable to search based algorithms

# Pre-processing Optimisations

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Useful techniques include

- 👉 Normalisation and simplification of concepts
  - Refinement of technique first used in *KRIS* system
  - Lexically normalise and simplify all concepts in KB
  - Combine with lazy unfolding in tableaux algorithm
  - Facilitates early detection of inconsistencies (clashes)
- 👉 Absorption (simplification) of general axioms
  - Eliminate GCIs by absorbing into “definition” axioms
  - Definition axioms efficiently dealt with by lazy expansion
- 👉 Avoidance of potentially costly reasoning whenever possible
  - Normalisation can discover “obvious” (un)satisfiability
  - Structural analysis can discover “obvious” subsumption

# Normalisation and Simplification

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☞ Normalise concepts to standard form, e.g.:

- $\exists R.C \longrightarrow \neg \forall R.\neg C$
- $C \sqcup D \longrightarrow \neg(\neg C \sqcap \neg D)$

☞ Simplify concepts, e.g.:

- $(D \sqcap C) \sqcap (A \sqcap D) \longrightarrow A \sqcap C \sqcap D$
- $\forall R.\top \longrightarrow \top$
- $\dots \sqcap C \sqcap \dots \sqcap \neg C \sqcap \dots \longrightarrow \perp$

☞ Lazily unfold concepts in tableaux algorithm

- Use names/pointers to refer to complex concepts
- Only add structure as required by progress of algorithm
- Detect clashes between lexically equivalent concepts

$\{\text{HappyFather}, \neg\text{HappyFather}\} \longrightarrow \text{clash}$

$\{\forall\text{has-child}.\text{Doctor} \sqcup \text{Lawyer}, \exists\text{has-child}.\text{Doctor} \sqcap \neg\text{Lawyer}\} \longrightarrow \text{search}$

# Absorption I

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- ☞ Reasoning w.r.t. set of GCI axioms can be very costly
  - GCI  $C \sqsubseteq D$  adds  $D \sqcup \neg C$  to **every** node label
  - Expansion of disjunctions leads to search
  - With 10 axioms and 10 nodes search space already  $2^{100}$
  - GALEN (medical terminology) KB contains **hundreds** of axioms
- ☞ Reasoning w.r.t. “primitive definition” axioms is relatively efficient
  - For  $CN \sqsubseteq D$ , add  $D$  **only** to node labels containing  $CN$
  - For  $CN \sqsupseteq D$ , add  $\neg D$  **only** to node labels containing  $\neg CN$
  - Can expand definitions lazily
    - ➔ Only add definitions **after** other local (propositional) expansion
    - ➔ Only add definitions one step at a time

# Absorption II

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- ➡ Transform GCIs into primitive definitions, e.g.
  - $CN \sqcap C \sqsubseteq D \longrightarrow CN \sqsubseteq D \sqcup \neg C$
  - $CN \sqcup C \sqsupseteq D \longrightarrow CN \sqsupseteq D \sqcap \neg C$
- ➡ Absorb into existing primitive definitions, e.g.
  - $CN \sqsubseteq A, CN \sqsubseteq D \sqcup \neg C \longrightarrow CN \sqsubseteq A \sqcap (D \sqcup \neg C)$
  - $CN \sqsupseteq A, CN \sqsupseteq D \sqcap \neg C \longrightarrow CN \sqsupseteq A \sqcup (D \sqcap \neg C)$
- ➡ Use lazy expansion technique with primitive definitions
  - Disjunctions only added to “relevant” node labels
- ➡ Performance improvements often too large to measure
  - At least **four orders of magnitude** with GALEN KB

# Algorithmic Optimisations

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Useful techniques include

- 👉 Avoiding redundancy in search branches
  - Davis-Putnam style semantic branching search
  - Syntactic branching with no-good list
- 👉 Dependency directed backtracking
  - Backjumping
  - Dynamic backtracking
- 👉 Caching
  - Cache partial models
  - Cache satisfiability status (of labels)
- 👉 Heuristic ordering of propositional and modal expansion
  - Min/maximise constrainedness (e.g., MOMS)
  - Maximise backtracking (e.g., oldest first)

# Dependency Directed Backtracking

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- ➡ Allows rapid recovery from bad branching choices
- ➡ Most commonly used technique is **backjumping**
  - Tag concepts introduced at branch points (e.g., when expanding disjunctions)
  - Expansion rules combine and propagate tags
  - On discovering a clash, identify most recently introduced concepts involved
  - Jump back to relevant branch points **without exploring** alternative branches
  - Effect is to prune away part of the search space
  - Performance improvements with GALEN KB again **too large to measure**



# Caching

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- ☞ Cache the satisfiability status of a node label
  - Identical node labels often recur during expansion
  - Avoid re-solving problems by caching satisfiability status
    - ➔ When  $\mathcal{L}(x)$  initialised, look in cache
    - ➔ Use result, or add status once it has been computed
  - Can use sub/super set caching to deal with similar labels
  - Care required when used with blocking or inverse roles
  - Significant performance gains with some kinds of problem
- ☞ Cache (partial) models of concepts
  - Use to detect “obvious” non-subsumption
  - $C \not\sqsubseteq D$  if  $C \sqcap \neg D$  is satisfiable
  - $C \sqcap \neg D$  satisfiable if models of  $C$  and  $\neg D$  can be merged
  - If not, continue with standard subsumption test
  - Can use same technique in sub-problems

# Summary

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- ➡ Naive implementation results in effective non-termination
- ➡ Problem is caused by non-deterministic expansion (**search**)
  - GCIs lead to huge search space
- ➡ Solution (partial) is
  - Careful choice of logic/algorithm
  - Avoid encodings
  - Highly optimised implementation
- ➡ Most important optimisations are
  - Absorption
  - Dependency directed backtracking (backjumping)
  - Caching
- ➡ Performance improvements can be very large
  - E.g., more than **four orders of magnitude**

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