Implementing DL Systems

Naive Implementations

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

- 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., $(\text{domain } R.C) \equiv \exists R.\top \sqsubseteq C$
  - (FL) encodings introduce (large numbers of) axioms
  - **BUT** even simple domain encoding is **disastrous** with large numbers of roles

Highly Optimised Implementation

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

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

Useful techniques include

- Normalisation and simplification of concepts
  - Refinement of technique first used in $\mathcal{KRIS}$ 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

- 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.:
  - $(D \sqcap C) \sqcap (A \sqcap D) \longrightarrow A \sqcap C \sqcap D$
  - $\forall R.\top \longrightarrow \top$
  - $\ldots \sqcap C \sqcap \ldots \sqcap \neg C \sqcap \ldots \longrightarrow \bot$
- 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

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

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

Absorption I

- 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

- Transform GCIs into primitive definitions, e.g.
  - $\mathsf{CN} \sqcap C \sqsubseteq D \longrightarrow \mathsf{CN} \sqsubseteq D \sqcup \neg C$
  - $\mathsf{CN} \sqcup C \sqsupseteq D \longrightarrow \mathsf{CN} \sqsupseteq D \sqcap \neg C$
- Absorb into existing primitive definitions, e.g.
  - $\mathsf{CN} \sqsubseteq A$, $\mathsf{CN} \sqsubseteq D \sqcup \neg C \longrightarrow \mathsf{CN} \sqsubseteq A \sqcap (D \sqcup \neg C)$
  - $\mathsf{CN} \sqsupseteq A$, $\mathsf{CN} \sqsupseteq D \sqcap \neg C \longrightarrow \mathsf{CN} \sqsupseteq A \sqcup (D \sqcap \neg C)$
- 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

Useful techniques include

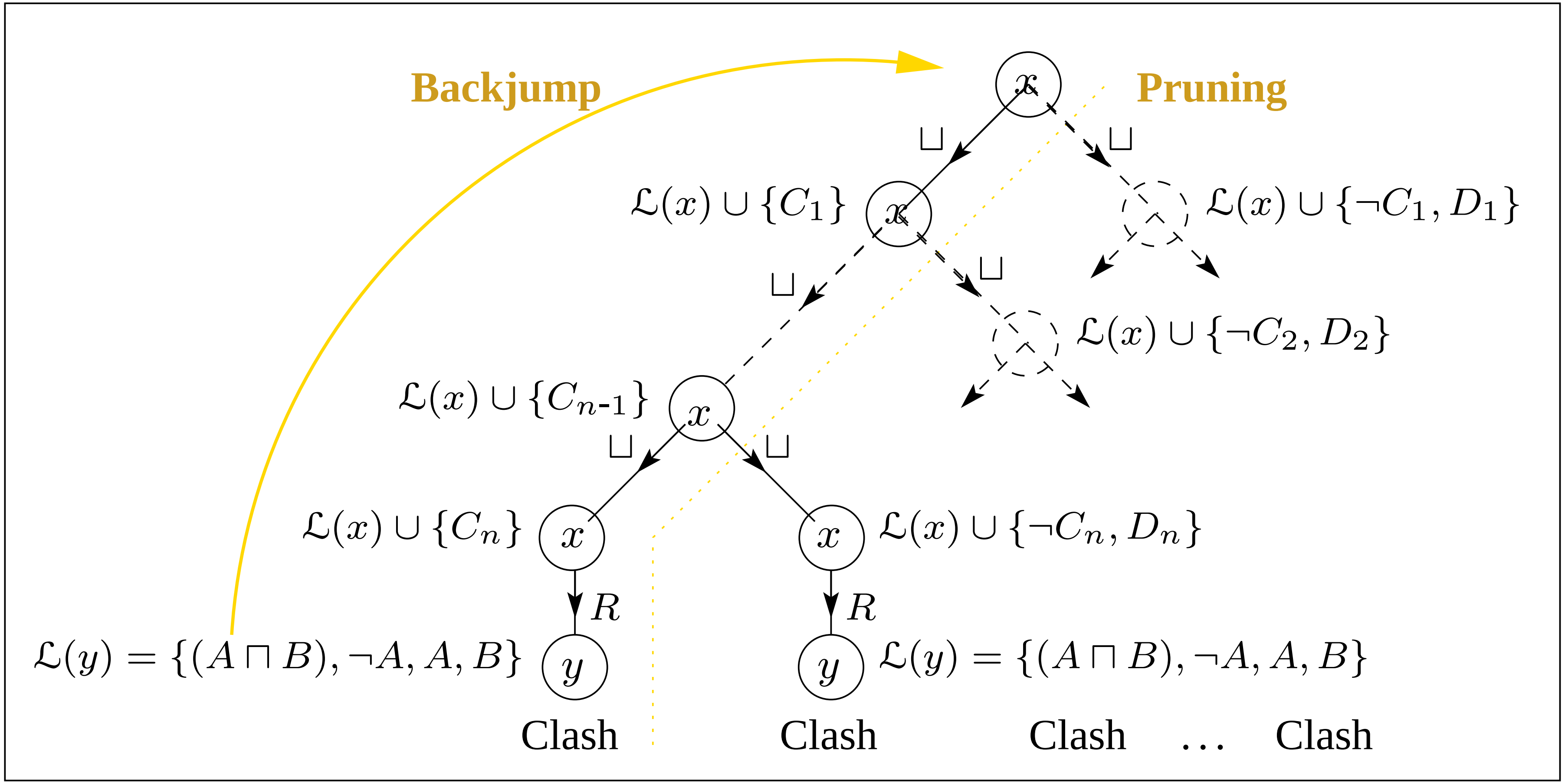
- Avoiding redundancy in search branches
  - Davis-Putnam style semantic branching search
  - Syntactic branching with no-good list
- Dependency directed backtracking
  - Backjumping
  - Dynamic backtracking
- Caching
  - Cache partial models
  - Cache satisfiability status (of labels)
- Heuristic ordering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

Dependency Directed Backtracking

- 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**

Backjumping

E.g., if $\exists R.\neg A \sqcap \forall R.(A \sqcap B) \sqcap (C_1 \sqcup D_1) \sqcap \ldots \sqcap (C_n \sqcup D_n) \subseteq \mathcal{L}(x)$



Caching

- 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

- 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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