The Ins and Outs of Racer

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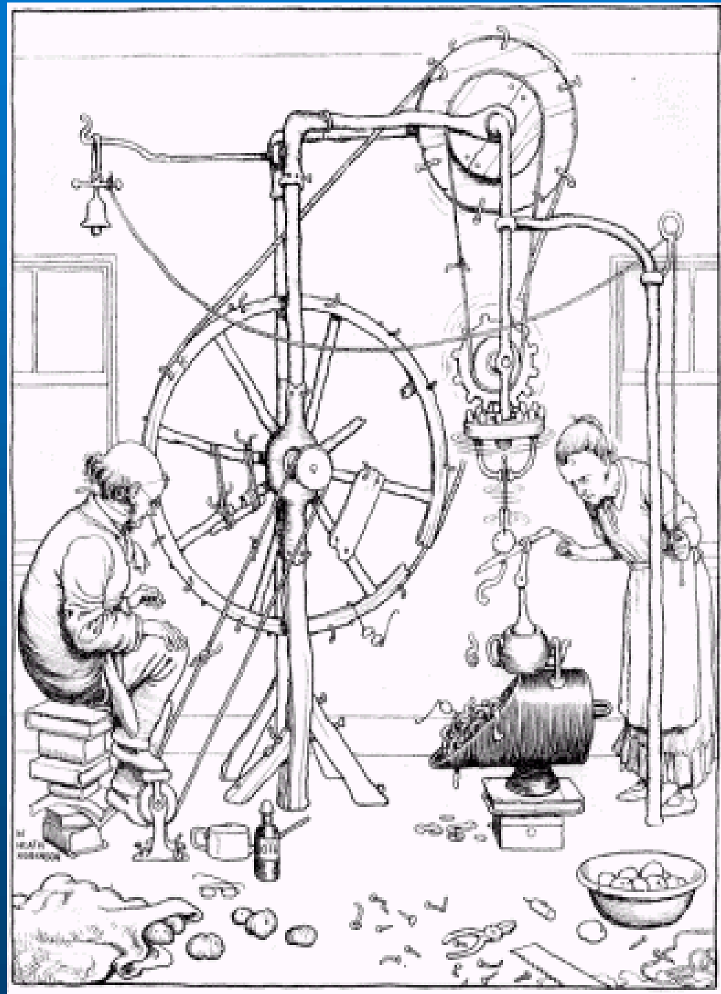
Racer

- Logic SHIQ(D_n)$^-$
  - ALC, transitive roles, role hierarchies, inverses, qualified number restrictions
  - Concrete domains without feature paths
- T-boxes (with GCIs)
- A-boxes (each associated with a T-box)
  - Set of assertions of the form
    - i:C
    - (i, j):R

Views on the Architecture

- Racer as a tool for ontology management (T-box)
- Racer as a testbed for AI/DB research (T-box, A-box, …)
- Racer as part of applications (interfaces)



The Professor's invention for peeling potatoes.

Inference Problems

- T-box
  - Parents, Children, Synonyms
- A-box
  - Consistency
  - Instance test i :? C
  - Instance retrieval {i | i mentioned in A, i :? C}

Overview of the Talk

- The engines under the hood
- Supporting classification
  - E.g. for ontology development
- Supporting instance retrieval
  - E.g. for NL interpretation

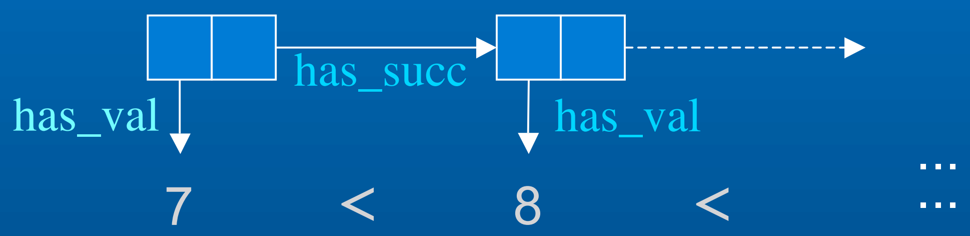
The Engines Under the Hood ...

- Tableau prover for deciding A-box consistency for the logic SHIQ(D_n)$^-$ [Hor-Sat-Tob, BaHo, HaMo]
- Additional provers for various algebraic structures and formalisms […]

$\mathbb{N}$	linear inequations with order constraints and integer coefficients
$\mathbb{Z}$	interval constraints
$\mathbb{R}$	linear inequations with order constraints and rational coefficients
$\mathbb{C}$	nonlinear multivariate inequations with integer coefficients
Strings	equality and inequality

Concrete Domains

- **What cannot be expressed in Racer at the conceptual level due to syntax restrictions?**



- **No restrictions on A-box structures**

Natural Numbers (Cardinals)

```
(define-concrete-domain-attribute year :type cardinal)
(define-concrete-domain-attribute days-in-month :type cardinal)

(implies Month (and (>= days-in-month 28) (<= days-in-month 31)))

(equivalent month-inleapyear
            (and Month
                 (divisible year 4)
                 (or (not-divisible year 100)
                     (divisible year 400))))

(equivalent February
            (and Month
                 (<= days-in-month 29)
                 (or (not month-inleapyear)
                     (= days-in-month 29))
                 (or month-inleapyear
                     (= days-in-month 28))))
```

Constraints and Queries

```
(instance feb-2003 February)
(constrained feb-2003 year-1 year)
(constrained feb-2003 days-in-feb-2003 days-in-month)
(constraints (= year-1 2003))

(instance feb-2000 February)
(constrained feb-2000 year-2 year)
(constrained feb-2000 days-in-feb-2000 days-in-month)
(constraints (= year-2 2000))
```

- **(concept-instances month-in-leapyear)**
- **(concept-instances (not month-in-leapyear))**
- **(constraint-entailed? (= days-in-feb-2000 29))**
- **(constraint-entailed? (<> days-in-feb-2003 29))**

There's more to Racer ...

- ... than a collection of optimized (inference) engines
- For many inference problems:
- Motto: Avoid using the optimized tableaux prover (and the other provers) at all!
- So, exploit given information,
  - (implies a (and b c (some r D)))
- … and do not compute anything twice
- Nevertheless: the tableau prover is important

Some Optimizations

- Inspired by FaCT [Horrocks] (but Racer does it for A-boxes)
  - Dependency-directed backtracking
  - Semantic branching, BCP
  - Caching, model merging
    - notion of a pseudo model
  - Optimized blocking (partially implemented in Racer)

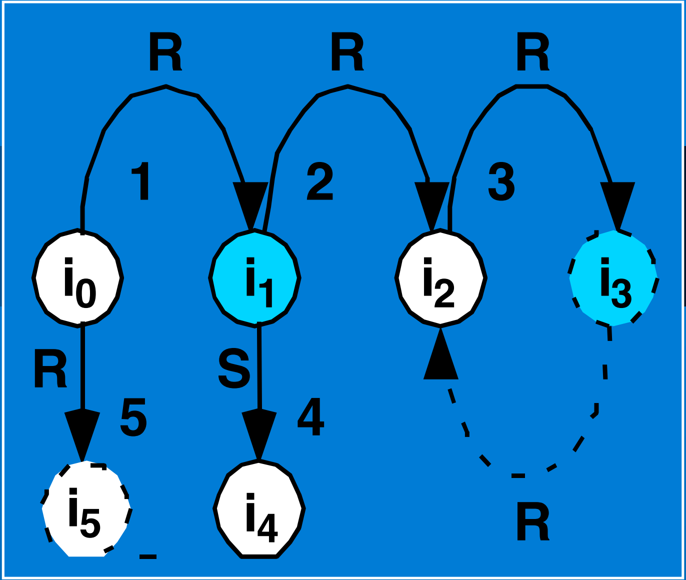
Optimizations specific to Racer

- SAT and ASAT reasoning
  - Language-adaptive selection of applicable optimization techniques
  - Dependency-directed backtracking (also for concrete domain reasoning)
  - Extended caching (in particular, satisfiable concepts)
  - Process qualified number restrictions with
    - Simplex procedure (concept consistency)
    - Signature calculus
  - Incremental constraint solving (mostly)

Pitfalls in Caching

- Assume a pseudo model for concept D is cached in step 7, i.e. D is satisfiable
- After step 8 concept C is marked as unsatisfiable
- The cache entry for D is still marked as satisfiable
- After backtracking to step 2, we proceed with step 9 and erroneously cache a pseudo model for concept E, i.e. E is satisfiable

↳ The cache entry of D depends on C and must be invalidated if C is marked as unsatisfiable



$\mathsf{E} \sqsubseteq (\exists R.C) \sqcup (\exists R.D)$

$\mathsf{C} \sqsubseteq (\exists R.D) \sqcap (\exists S.X) \sqcap \forall S.(\neg X \sqcap A)$

$\mathsf{D} \sqsubseteq \exists R.C$

1. $\{i_0 : E\}$
2. $\{i_0 : E, i_0 : \exists R.C\} \vee \{i_0 : E, i_0 : \exists R.D\}$
3. $\{i_1 : C\}$
4. $\{i_1 : C, i_1 : \exists R.D, i_1 : \exists S.X, i_1 : \forall S.\neg X \sqcap A\}$
5. $\{i_2 : D\}$
6. $\{i_2 : D, i_2 : \exists R.C\}$
7. $\{i_3 : C\}$
8. $\{i_4 : X, i_4 : A, i_4 : \neg X\}$
9. $\{i_5 : D\}$

Dealing with Qualifying Number Restrictions

- (-> ALCQ [Baader-Hollunder])
- Additional level of nondeterminism
- Basically: for each (<= n R C)
  try either C or ~C for each filler of R
  where ~C is the negation normal
  form of (not C)
- Merge fillers as appropriate

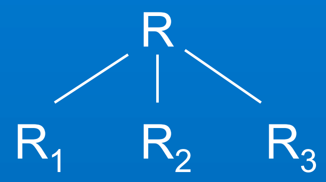
Standard Tableau Rules

- At least rule: $\Box_{\geq n}$ R.C
  - if necessary, create n distinct R-successors which become members of C
- At most rule: $\Box_{\leq n}$ R.C
  - if there exist more than n R-successors which are members of C, then merge two (non-distinct) of these R-successors
- Choose rule:
  - if there exists an R-successor whose membership for C or ~C is unknown, determine whether this successor is a member of C or ~C

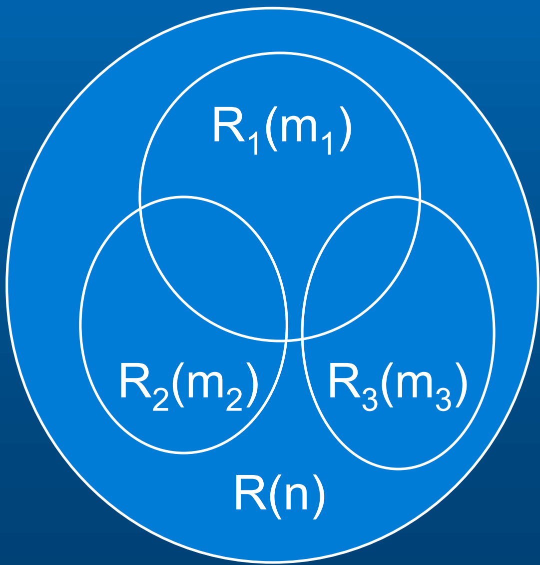
- Treatment of numbers is highly inefficient
- Individual-wise computation of set cardinalities
- No representation of sets
- Blind search tries to fulfill at least and at most restrictions

Standard Tableaux Rules: Example

- Assume $n=3$, $m_1=2$, $m_2=2$, $m_3=2$
- $(a,b_1):R_1$, $(a,b_2):R_1$, $(a,c_1):R_2$, $(a,c_2):R_2$, $(a,d_1):R_3$, $(a,d_2):R_3$, $c_1:C$, $c_2:C$, $d_1:\neg C$, $d_2:\neg C$, $b_1 \neq b_2$, $c_1 \neq c_2$, $d_1 \neq d_2$
- 6 R-successors, only 3 allowed
- Try to replace b_1 with c_1, or c_2, or ...
- After replacing b_1 with c_1: $(a,c_1):R_1$, $(a,b_2):R_1$, $(a,c_1):R_2$, $(a,c_2):R_2$, $(a,d_1):R_3$, $(a,d_2):R_3$, $c_1:C$, $c_2:C$, $d_1:\neg C$, $d_2:\neg C$, $c_1 \neq b_2$, $c_1 \neq c_2$, $d_1 \neq d_2$
- ...
- Eventually the calculus recognizes the unsatisfiability



$$\exists_{<n} R \sqcap \exists_{>m_1} R_1 \sqcap \exists_{>m_2} R_2 \sqcap \exists_{\geq m_3} R_3 \sqcap \forall R_2 . C \sqcap \forall R_3 . \neg C$$

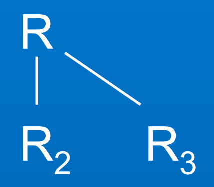


Idea: Use Gomory Algorithm

- Inspired by work of [Ohlbach]
- Compute system of linear equations
- Integrated into tableau prover for dealing with concept consistency
- Simplex procedure cannot be (naively) applied for deciding full
  A-box consistency
- Another idea: Use placeholders
  – > Signature Calculus

Computation with Placeholders...

- ...cannot be done in a simple way:
  $\exists_{\leq n} R \sqcap \exists_{\geq m_2} R_2 \sqcap \exists_{\geq m_3} R_3 \sqcap \forall R_2 . C \sqcap \forall R_3 . \neg C$



- Automatic generation of required placeholders for subroles
- New kind of constraint: $(ind_1, ind_2){:}\langle n, \{R,S,...\}\rangle$

Signature

- $(i, j){:}\langle m_2,\{R_2\}\rangle$, $(i, k)\langle m_3,\{R_3\}\rangle$
- $j{:}C$, $k{:}\neg C$
- Signature merge rule:

Eliminated if zero

- $(i,l){:}\langle 1,\{R_2,R_3\}\rangle$, $(i, j){:}\langle m_2-1,\{R_2\}\rangle$, $(i, k)\langle m_3-1,\{R_3\}\rangle$
- or
- $(i,l){:}\langle p+1,\{R_2,R_3\}\rangle$, $(i, j){:}\langle m_2-1,\{R_2\}\rangle$, $(i, k)\langle m_3-1,\{R_3\}\rangle$
- $l{:}C, l{:}\neg C$

Additional Rules

- Choose rule
- Additional clash triggers

Dealing with Inverse Roles and A-boxes

- Use of the A-box reasoning kernel to deal with inverse roles
- Blocking (-> see SHIQ-Papers [Horr-Satt-Tob])
  - dynamic blocking, pairwise blocking
- No trace technique, additional role constraints
- If something is "propagated back", all constraints are recomputed (within backtracking context!)
- Caveat: technique relies on caching
- Caching techniques still have to be devised for inverse roles

Dependencies and Pseudo Models

- If an A-box is consistent, generate a pseudo model for each individual
- If an A-box is inconsistent, collect those assertions that were involved in a clash in all branches of the search tree

Concrete domain reasoners

- Simplex algorithm (incremental)
  - for linear inequations with orders over the reals
  - for min/max restrictions over the integers
- Gomory algorithm
  - for linear inequations with orders over cardinals
- Groebner Bases, Buchberger algorithm
  - for multivariate non-linear inequations over complex numbers
- String (in)equation solver

Optimizations for Concrete Domains

- Incremental constraint solving for R
- Dependency-directed backtracking
- Keep constraint systems minimal
- Avoiding copies of constraint systems during backtracking
- Use Simplex as preprocessor for N

Overview of the Talk

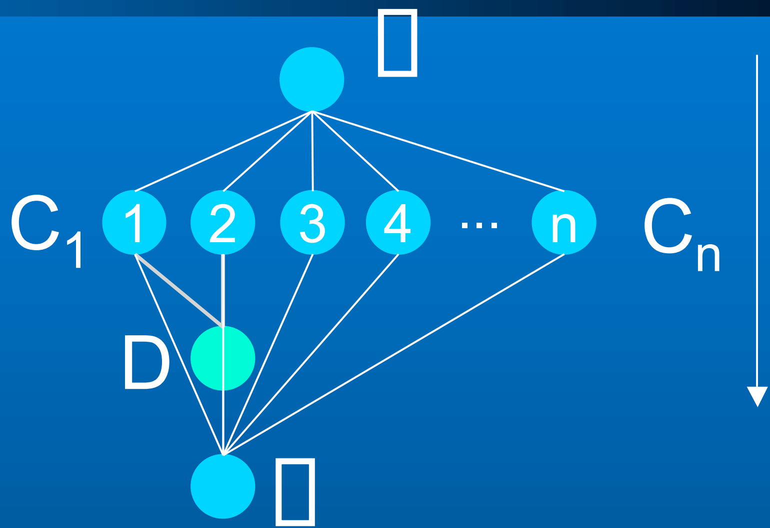
- The engines under the hood
- Supporting classification
  - E.g. for ontology development
  - Finding synonyms of *bottom*
- Supporting instance retrieval

Ontology Development: T-boxes

- Optimizations of
  - KRIS [Baader et al.] (taxonomy, lazy unfolding)
  - FaCT [Horrocks]
    (GCI absorption, model merging)
- Optimizations specific to Racer:
  - Different transformation of general axioms
    - domain and range restrictions
    - lazy unfolding of negated atomic concepts
  - Determine classification order
    (topological sorting)
  - Clustering of nodes

TBox Classification: Inserting a Concept

- **Insert new concept D into existing taxonomy w.r.t subsumption relationship**
- **1. Top-search phase**
  - **traverse from top**
  - **determine parents of D**
    - **C_1 and C_2**
  - **$SAT(\neg C_1 \sqcap D)$, ..., $SAT(\neg C_n \sqcap D)$**
- **2. Bottom-search phase**
  - **traverse from bottom**
  - **determine children of D**
    - **C_3 and C_4**
  - **$SAT(C_1 \sqcap \neg D)$, ..., $SAT(C_n \sqcap \neg D)$**



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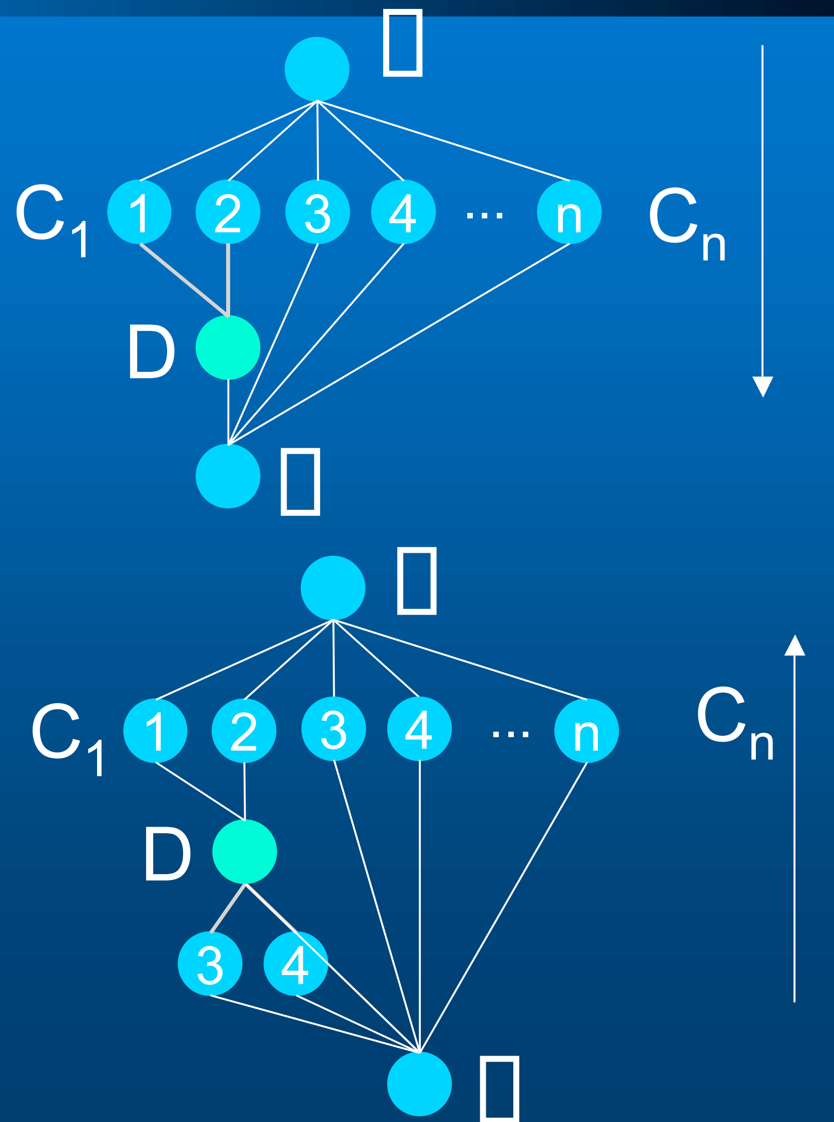
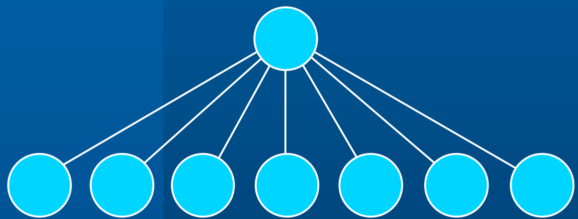


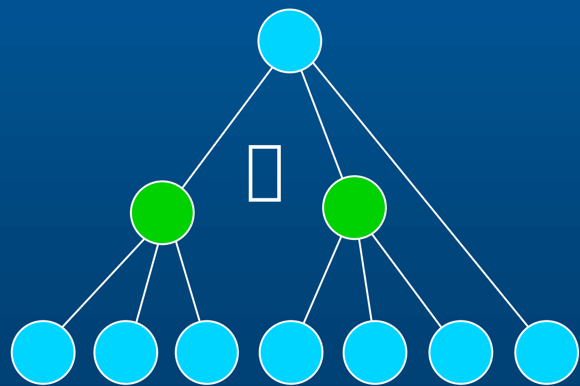
Topological Sorting

- GCI absorption yields only primitive concept definitions
- Definition order
- Bottom-search phase can be omitted
- But: Beware of cycles
- Refers-to relation
- Sets of concept names
- Quasi definition order
- Serialization of the partial order

Clustering

- Introduce virtual concepts (buckets)
- Reduce the no. of children
- □= 10 : max no. children without bucket
- □ = 15 : max no. of buckets per concept
- Possibly: restructuring necessary





Domain and Range Restrictions

- $A \sqsubseteq C$ (all x . x: (or (not A) B))
- Lazy Unfolding: $A \sqsubseteq C$, $A = C$
- Generalized Lazy Unfolding:
  - (some R. top) $\sqsubseteq$ C — domain restriction
  - top $\sqsubseteq$ (all R. C) — range restriction
- To be considered
  - for model merging
  - for the refers-to relation

Hard for Racer ...

... and probably other tableau reasoners

- **Qualified domain and range restrictions**
  - **(some R. D) $\sqsubseteq$ C**
  - **D $\sqsubseteq$ (all R. C)**
- **Cycles**
  (even if no meta constraints remain)
- **Inverse roles**
  (no caching,
  more complex blocking condition)

Overview of the Talk

- The engines under the hood
- Supporting classification
- Supporting instance retrieval
  – E.g. for NL interpretation, Semantic Web, etc.

Optimizations specific to Racer

- A-box reasoning
  - graph transformation
  - fast non-instance test based on pseudo models for concepts and individuals
  - dependency-driven divide-and-conquer for instance checks
  - fast candidate elimination by subsumption-based caching

Instance retrieval

- Given an A-box A, a T-box T, and a concept C, find those individuals i mentioned in A for which it can be shown that $i^I \in C^I$ for all models I of T.
- Different types of applications
  - One single "static" A-box
    lots of queries
  - Many A-boxes wrt. a single T-box,
    A-boxes computed on the fly,
    few queries for each A-box, result set small
    (example: NL application)

Linear instance retrieval

- **Collect each i mentioned in A s.t. instance?(i,C)**
- **instance?(i,C) = ¬ASAT(A ∪ {i:¬C})**
- **"Expensive" ASAT test**
- **Guards required**
  - **individual model merging possible, individual-concept(i)**
  - **subsumes?(¬C, individual-concept(i))**
- **"Expensive" ASAT test only if guards do not indicate non-instance result for i**

Binary instance retrieval

- **Observation:**
  - One individual considered at a time
- **New idea: consider sets of individuals at a time**
  - Take a set of candidates {i, j, k, ...} (which are assumed to be instances of C) and check the result of ASAT($A \cup \{i{:}\neg C, j{:}\neg C, k{:}\neg C, \ldots\}$)
  - If "yes" -> all candidates are ruled out
  - If "no" -> partition the set of candidates (binary partition) and recurse until a singleton set of candidates is derived

Dependency-based instance retrieval

- If ASAT(A ∪ {i:¬C, j:¬C, k:¬C, ...}) returns "no"
- and during all attempts to construct a completion, there is only one individual involved in a clash according to dependency tracking,
  - then this individual can be removed from the set of candidates. It is a member of the result set.
  - else if more then one individual is involved: partition the set of candidates and recurse until a singleton candidate set is derived

Index-based instance retrieval

- **Index:**
  - **associated_inds:**
    Set of concept names -> P(Set of inds)

$$
\begin{array}{l}
\textbf{if } \exists N \in CN : N \in synonyms(C) \textbf{ then} \\
\quad \text{return } \bigcup_{D \in descendants(C)} associated\_inds(D) \\
\textbf{else} \\
\quad known\_results := \bigcup_{D \in descendants(C)} associated\_inds(D) \\
\quad candidates := \bigcup_{P \in parents(C)} (\bigcup_{D \in descendants(P)} associated\_inds(D)) \\
\quad \text{return } known\_results \cup instance\_retrieval(C, A, candidates \setminus known\_results) \\
\textbf{end if}
\end{array}
$$

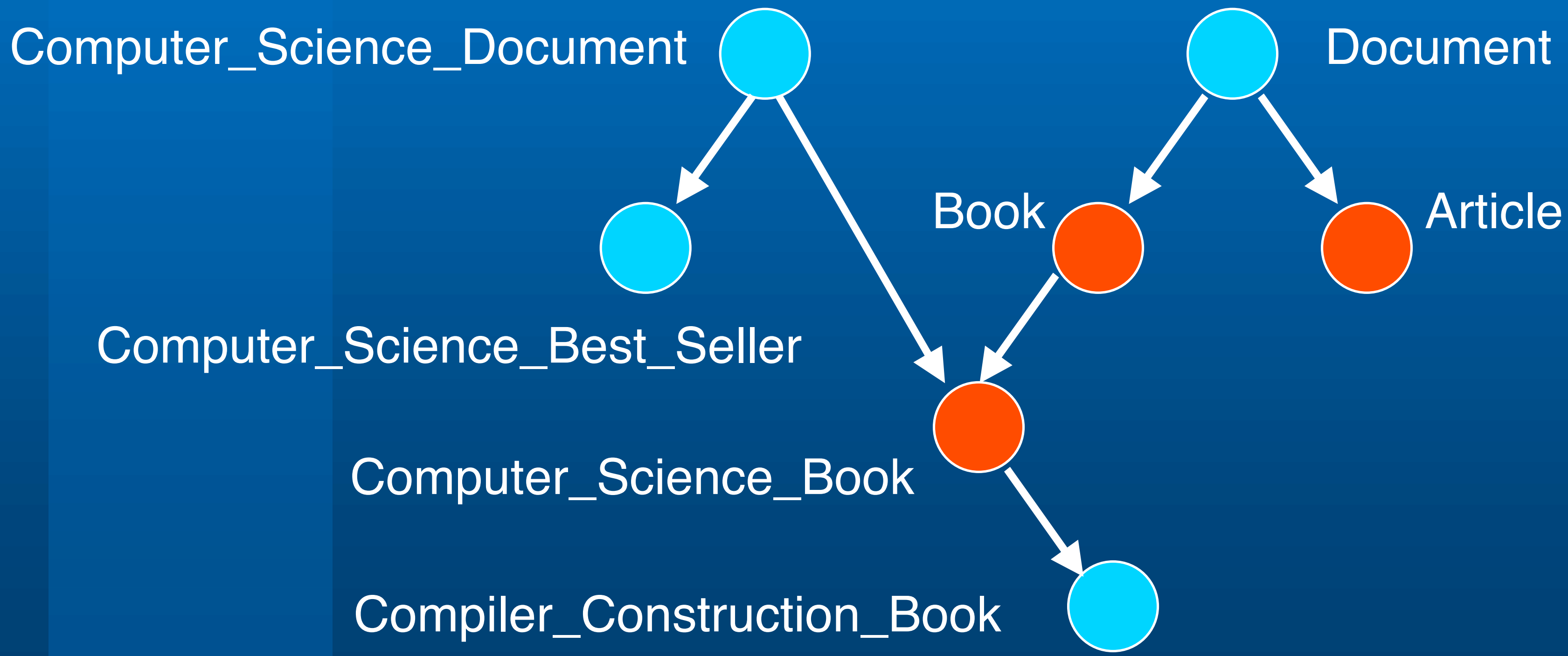
- **Index associated_inds is expensive to compute**

Index computation:

- One-individual-at-a-time approach
- Sets-of-individuals-at-a-time approach

Partial Indexing

- **Racer Server running with subsumption-based instance retrieval enabled**



Partial Indexing

- Index computation from
  - Initial A-box instance assertions
  - Previous instance retrieval queries
  - Previous queries for the direct types of an individual

Retrieval: Exploiting the Index

- Find known results
  - Collect individuals from descendants
- Find candidates
  - Collect individuals from ancestors
- Find non-candidates
  - Collect those candidates for which the direct-types are known and less specific than query concept C
  - Collect those candidates that previously did not qualify to to instances of an ancestor concept

Conclusions

- Racer is more than a tableau prover
- Tableau prover returns more than "satisfiable" or "not-satisfiable"
- Dealing with A-boxes causes overhead for pure concept consistency
- Many optimizations:
  No single trick does the job!
- Extensions become harder and harder…

Future Work

- Optimizations for filler retrieval
- Feature chains in predicate exists restrictions (with restr. on GCIs)
- UNA optional
- Nominals
- Incremental A-box reasoning
- Output of models
- Acyclic role axioms