Reasoning with Expressive Description Logics

Logical Foundations for the Semantic Web

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Talk Outline

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Introduction to Description Logics

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- Introduction to Description Logics
- The Semantic Web: Killer App for (DL) Reasoning?
  - Web Ontology Languages
  - DAML+OIL Language

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- Description Logic Reasoning
- Research Challenges

Introduction to Description Logics

What are Description Logics?

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☞ A family of logic based Knowledge Representation formalisms

- Descendants of **semantic networks** and **KL-ONE**
- Describe domain in terms of **concepts** (classes), **roles** (relationships) and **individuals**

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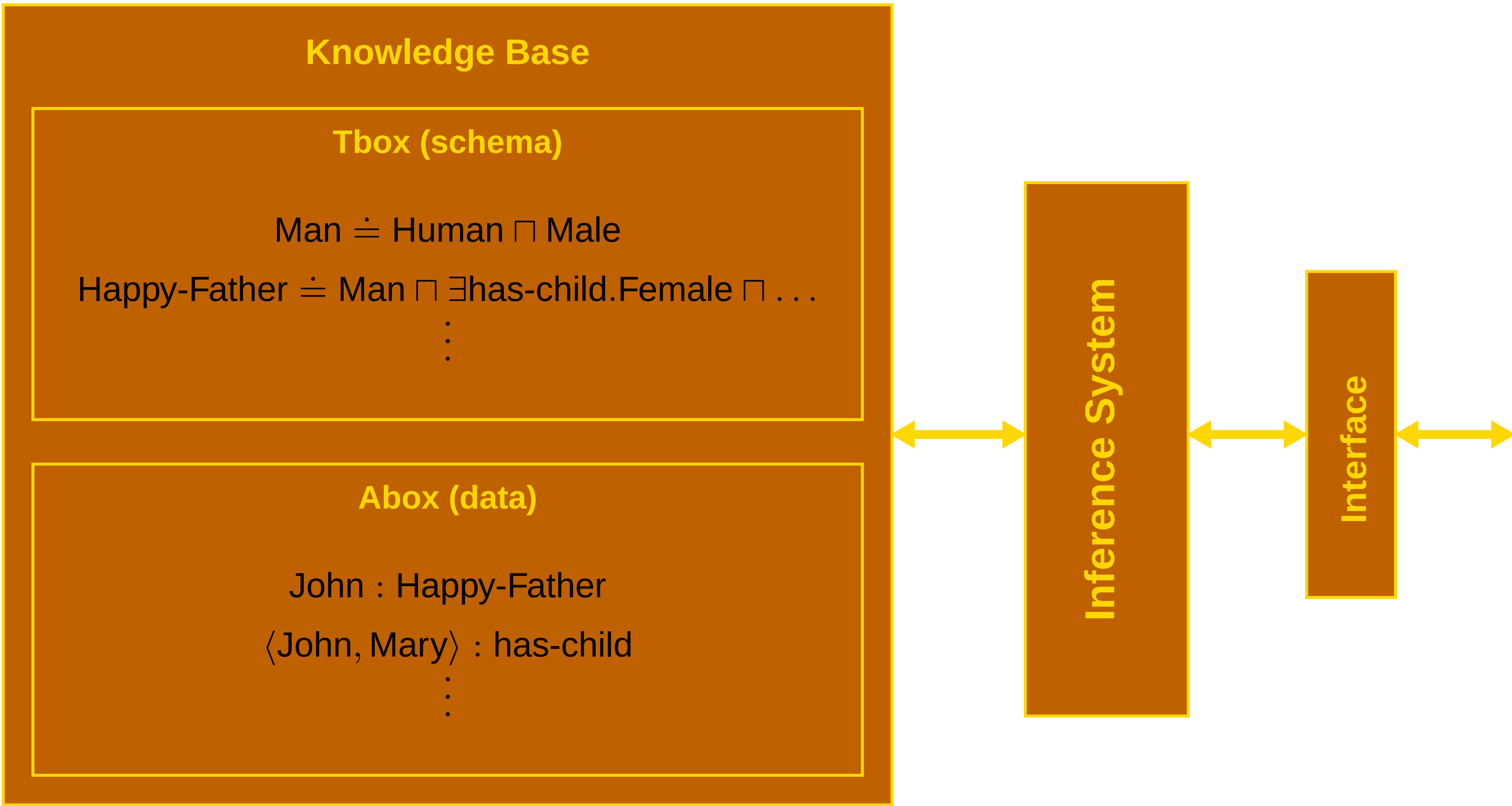
- A family of logic based Knowledge Representation formalisms
  - Descendants of **semantic networks** and **KL-ONE**
  - Describe domain in terms of **concepts** (classes), **roles** (relationships) and **individuals**
- Distinguished by:
  - **Formal semantics** (model theoretic)
    - Decidable fragments of FOL
    - Closely related to Propositional Modal & Dynamic Logics
  - Provision of **inference services**
    - Sound and complete decision procedures for key problems
    - Implemented systems (highly optimised)

DL Architecture



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- ☞ Development of **tableau algorithms** and **complexity results**
- ☞ Tableau-based systems for **Pspace** logics (e.g., Kris, Crack)
- ☞ Investigation of optimisation techniques

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Phase 3:

- Tableau algorithms for **very expressive** DLs
- **Highly optimised** tableau systems for **ExpTime** logics (e.g., FaCT, DLP, Racer)
- Relationship to modal logic and decidable fragments of FOL

Latest Developments

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- ☞ Mature **implementations**

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- ☞ Mainstream **applications** and Tools
  - **Databases**
    - Consistency of conceptual schemata (EER, UML etc.)
    - Schema integration
    - Query subsumption (w.r.t. a conceptual schema)
  - Ontologies and **Semantic Web** (and **Grid**)
    - Ontology engineering (design, maintenance, integration)
    - Reasoning with ontology-based markup (meta-data)
    - Service description and discovery

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- ☞ **Commercial** implementations
  - Cerebra system from Network Inference Ltd

The Semantic Web

The Semantic Web Vision

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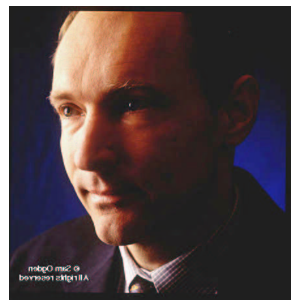

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  - To facilitate buyer–seller communication in **e-commerce**
  - In semantic based **search**
  - To provide richer **service descriptions** that can be more flexibly interpreted by intelligent agents

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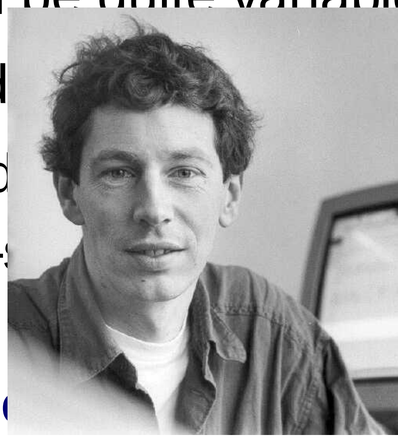

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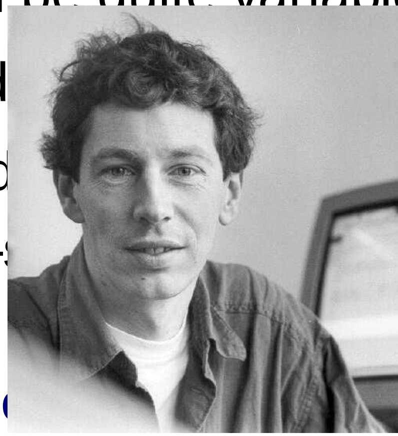

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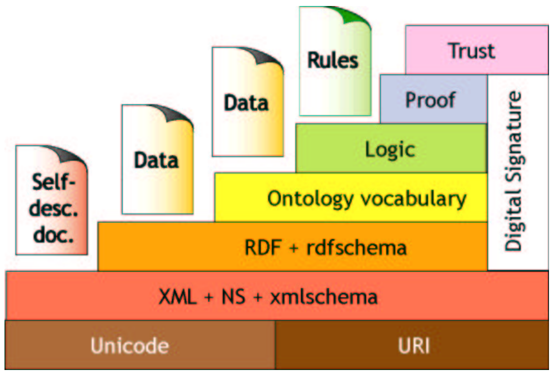

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  - E.g., Person **subclass of** Animal whose parents are all Persons
- Uses RDF for class/property membership assertions (Abox)
  - E.g., john **instance of** Person; $\langle$john, mary$\rangle$ instance of parent

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  - Various **constructors** provided for building class expressions
- **Expressive power** determined by
  - Kinds of constructor provided
  - Kinds of axiom allowed

DAML+OIL Class Constructors

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Constructor	DL Syntax	Example	(Modal Syntax)
intersectionOf	$C_1 \sqcap \ldots \sqcap C_n$	Human $\sqcap$ Male	$C_1 \wedge \ldots \wedge C_n$
unionOf	$C_1 \sqcup \ldots \sqcup C_n$	Doctor $\sqcup$ Lawyer	$C_1 \vee \ldots \vee C_n$
complementOf	$\neg C$	$\neg$Male	$\neg C$
oneOf	$\{x_1 \ldots x_n\}$	{john, mary}	$x_1 \vee \ldots \vee x_n$
toClass	$\forall P.C$	$\forall$hasChild.Doctor	$[P]C$
hasClass	$\exists P.C$	$\exists$hasChild.Lawyer	$\langle P \rangle C$
maxCardinalityQ	$\leqslant n P.C$	$\leqslant 1$hasChild.Male	$[P]_{n+1} C$
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☞ Arbitrarily complex **nesting** of constructors

- E.g., Person $\sqcap$ $\forall$hasChild.(Doctor $\sqcup$ $\exists$hasChild.Doctor)

RDFS Syntax

```
<daml:Class>
  <daml:intersectionOf rdf:parseType="daml:collection">
    <daml:Class rdf:about="#Person"/>
    <daml:Restriction>
      <daml:onProperty rdf:resource="#hasChild"/>
      <daml:toClass>
        <daml:unionOf rdf:parseType="daml:collection">
          <daml:Class rdf:about="#Doctor"/>
          <daml:Restriction>
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Semantics

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☞ Semantics defined by **interpretations**: $\mathcal{I} = (\Delta^{\mathcal{I}}, \cdot^{\mathcal{I}})$

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- roles $\longrightarrow$ binary relations over $\Delta^{\mathcal{I}}$ (subsets of $\Delta^{\mathcal{I}} \times \Delta^{\mathcal{I}}$)
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☞ Interpretation function $\cdot^{\mathcal{I}}$ **extended** to concept expressions

- $(C \sqcap D)^{\mathcal{I}} = C^{\mathcal{I}} \cap D^{\mathcal{I}} \quad (C \sqcup D)^{\mathcal{I}} = C^{\mathcal{I}} \cup D^{\mathcal{I}} \quad (\neg C)^{\mathcal{I}} = \Delta^{\mathcal{I}} \setminus C^{\mathcal{I}}$
- $\{x_n, \ldots, x_n\}^{\mathcal{I}} = \{x_n^{\mathcal{I}}, \ldots, x_n^{\mathcal{I}}\}$
- $(\forall R.C)^{\mathcal{I}} = \{x \mid \forall y.(x, y) \in R^{\mathcal{I}} \Rightarrow y \in C^{\mathcal{I}}\}$
- $(\exists R.C)^{\mathcal{I}} = \{x \mid \exists y.\langle x, y\rangle \in R^{\mathcal{I}} \wedge y \in C^{\mathcal{I}}\}$
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- $(\geqslant nR.C)^{\mathcal{I}} = \{x \mid \#\{y \mid \langle x, y\rangle \in R^{\mathcal{I}} \wedge y \in C^{\mathcal{I}}\} \geqslant n\}$

DAML+OIL Axioms

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sameClassAs	$C_1 \equiv C_2$	Man $\equiv$ Human $\sqcap$ Male
disjointWith	$C_1 \sqsubseteq \neg C_2$	Male $\sqsubseteq \neg$Female
sameIndividualAs	$\{x_1\} \equiv \{x_2\}$	{President_Bush} $\equiv$ {G_W_Bush}
differentIndividualFrom	$\{x_1\} \sqsubseteq \neg\{x_2\}$	{john} $\sqsubseteq \neg${peter}
subPropertyOf	$P_1 \sqsubseteq P_2$	hasDaughter $\sqsubseteq$ hasChild
samePropertyAs	$P_1 \equiv P_2$	cost $\equiv$ price
inverseOf	$P_1 \equiv P_2^-$	hasChild $\equiv$ hasParent$^-$
transitiveProperty	$P^+ \sqsubseteq P$	ancestor$^+$ $\sqsubseteq$ ancestor
uniqueProperty	$\top \sqsubseteq \leqslant 1 P$	$\top \sqsubseteq \leqslant 1$hasMother
unambiguousProperty	$\top \sqsubseteq \leqslant 1 P^-$	$\top \sqsubseteq \leqslant 1$hasSSN$^-$

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☞ $\mathcal{I}$ **satisfies** $C_1 \sqsubseteq C_2$ iff $C_1^{\mathcal{I}} \subseteq C_2^{\mathcal{I}}$; satisfies $P_1 \sqsubseteq P_2$ iff $P_1^{\mathcal{I}} \subseteq P_2^{\mathcal{I}}$

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sameClassAs	$C_1 \equiv C_2$	Man $\equiv$ Human $\sqcap$ Male
disjointWith	$C_1 \sqsubseteq \neg C_2$	Male $\sqsubseteq \neg$Female
sameIndividualAs	$\{x_1\} \equiv \{x_2\}$	{President_Bush} $\equiv$ {G_W_Bush}
differentIndividualFrom	$\{x_1\} \sqsubseteq \neg\{x_2\}$	{john} $\sqsubseteq \neg${peter}
subPropertyOf	$P_1 \sqsubseteq P_2$	hasDaughter $\sqsubseteq$ hasChild
samePropertyAs	$P_1 \equiv P_2$	cost $\equiv$ price
inverseOf	$P_1 \equiv P_2^-$	hasChild $\equiv$ hasParent$^-$
transitiveProperty	$P^+ \sqsubseteq P$	ancestor$^+$ $\sqsubseteq$ ancestor
uniqueProperty	$\top \sqsubseteq \leqslant 1 P$	$\top \sqsubseteq \leqslant 1$hasMother
unambiguousProperty	$\top \sqsubseteq \leqslant 1 P^-$	$\top \sqsubseteq \leqslant 1$hasSSN$^-$

- ☞ $\mathcal{I}$ **satisfies** $C_1 \sqsubseteq C_2$ iff $C_1^\mathcal{I} \subseteq C_2^\mathcal{I}$; satisfies $P_1 \sqsubseteq P_2$ iff $P_1^\mathcal{I} \subseteq P_2^\mathcal{I}$
- ☞ $\mathcal{I}$ satisfies ontology $\mathcal{O}$ (is a **model** of $\mathcal{O}$) iff satisfies every axiom in $\mathcal{O}$

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  - Not appropriate to form new datatypes using ontology language
- Practical reasons:
  - Ontology language remains **simple and compact**
  - **Semantic integrity** of ontology language not compromised
  - **Implementability** not compromised — can use hybrid reasoner
    - Only need sound and complete decision procedure for $d_1^{\mathcal{I}} \cap \ldots \cap d_n^{\mathcal{I}}$, where d_i is a (possibly negated) datatype

Reasoning with DAML+OIL

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  - **Querying** class and instance data w.r.t. ontologies
    - Determine if set of facts are consistent w.r.t. ontologies
    - Determine if individuals are instances of ontology classes
    - Retrieve individuals/tuples satisfying a query expression
    - Check if one description more general than another w.r.t. ontology
    - . . .

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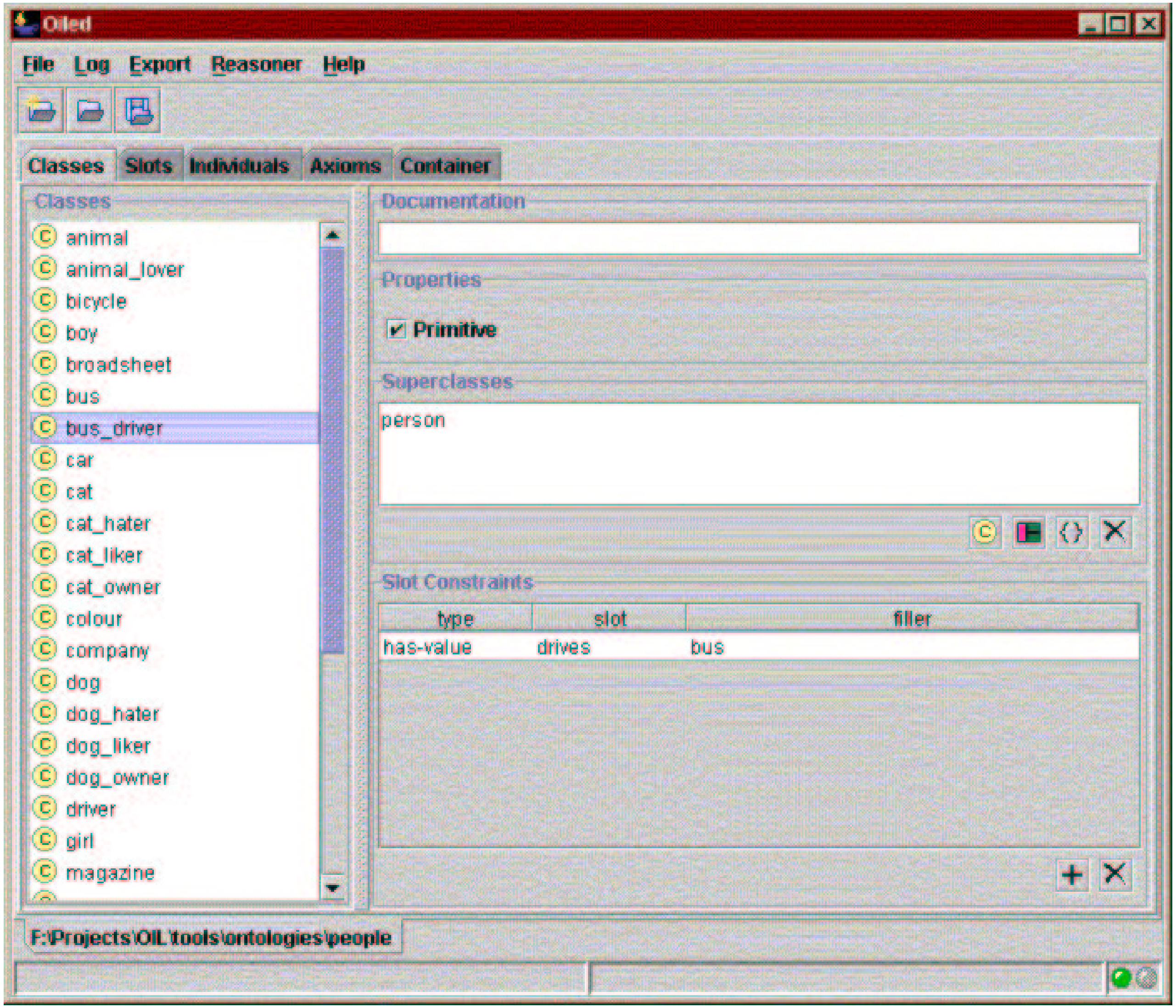
- Problems all **reducible** to consistency (satisfiability):
  - $C \sqsubseteq_{\mathcal{O}} D$ iff $C \sqcap \neg D$ not consistent w.r.t. $\mathcal{O}$
  - $i \in_{\mathcal{O}} C$ iff $\mathcal{O} \cup \{i \in \neg C\}$ is **not** consistent

Reasoning Support for Ontology Design: OilEd



Description Logic Reasoning

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- Return "C is consistent" **iff** C is consistent
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- $\mathbf{T}$ **fully expanded** if no rules are applicable
- C satisfiable iff fully expanded clash free $\mathbf{T}$ found
  - Trivial correspondence between such a $\mathbf{T}$ and a model of C

Tableaux Rules for $\mathcal{ALC}$

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$x \bullet \{C_1 \sqcap C_2, \ldots\}$	$\rightarrow_{\sqcap}$	$x \bullet \{C_1 \sqcap C_2, C_1, C_2, \ldots\}$
$x \bullet \{C_1 \sqcup C_2, \ldots\}$	$\rightarrow_{\sqcup}$	$x \bullet \{C_1 \sqcap C_2, C, \ldots\}$ for $C \in \{C_1, C_2\}$
$x \bullet \{\exists R.C, \ldots\}$	$\rightarrow_{\exists}$	$x \bullet \{\exists R.C, \ldots\}$ $R \downarrow$ $y \bullet \{C\}$
$x \bullet \{\forall R.C, \ldots\}$ $R \downarrow$ $y \bullet \{\ldots\}$	$\rightarrow_{\forall}$	$x \bullet \{\forall R.C, \ldots\}$ $R \downarrow$ $y \bullet \{C, \ldots\}$

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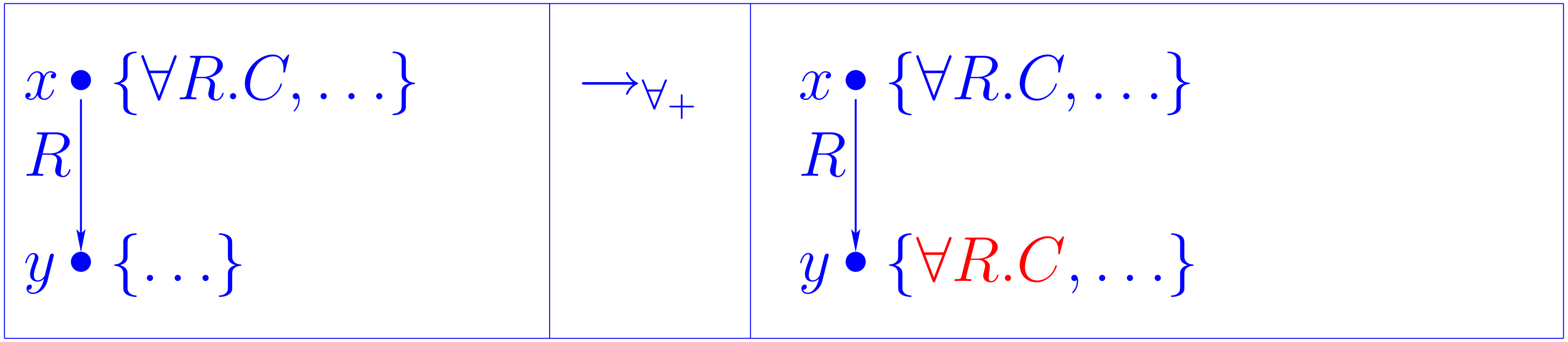

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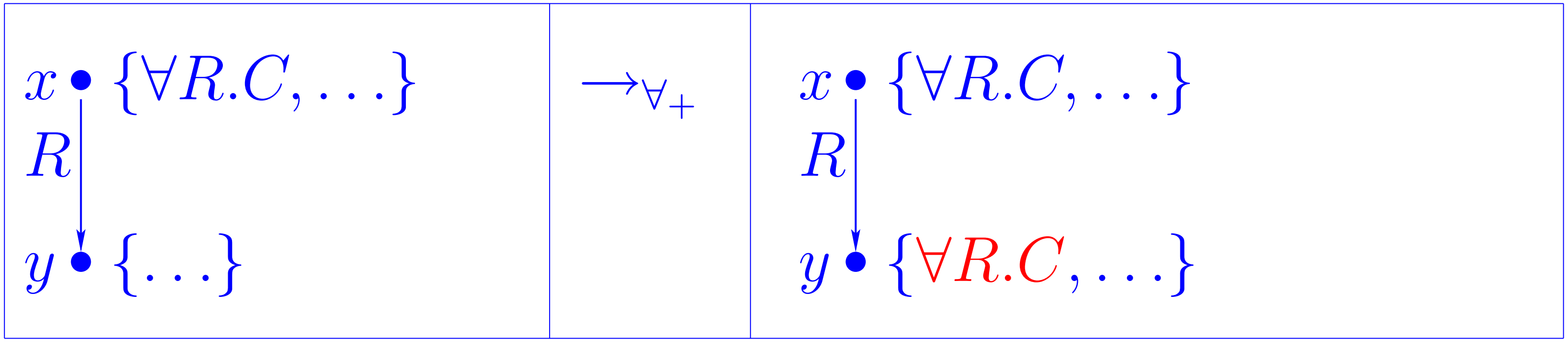

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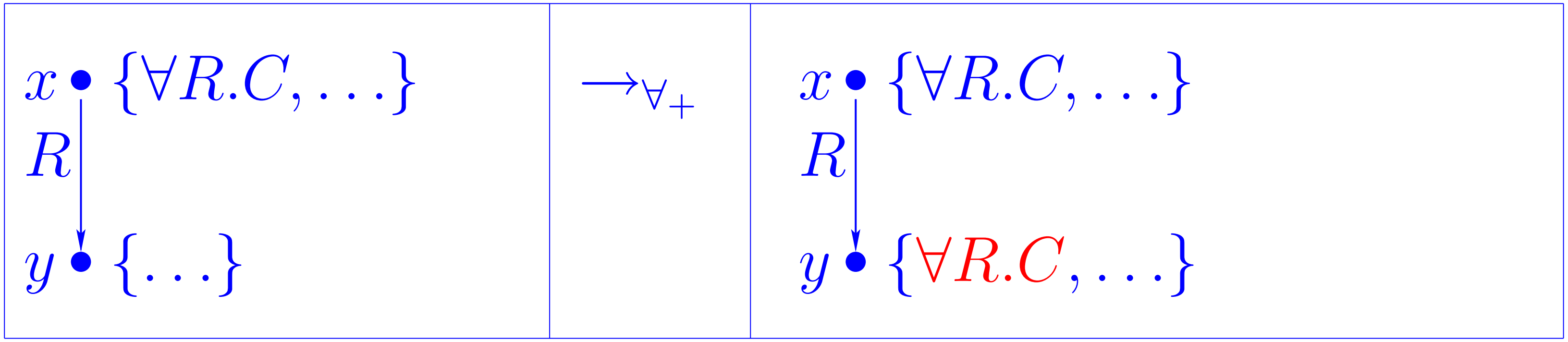

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- No longer naturally terminating (e.g., if $C = \exists R.\top$)
- Need blocking
  - Simple blocking suffices for $\mathcal{ALC}$ plus transitive roles
  - I.e., do not expand node label if ancestor has superset label
  - More expressive logics (e.g., with inverse roles) need more sophisticated blocking strategies

Tableaux Algorithm — Example

Test satisfiability of $\exists S.C \sqcap \forall S.(\neg C \sqcup \neg D) \sqcap \exists R.C \sqcap \forall R.(\exists R.C)\}$ where R is a **transitive** role

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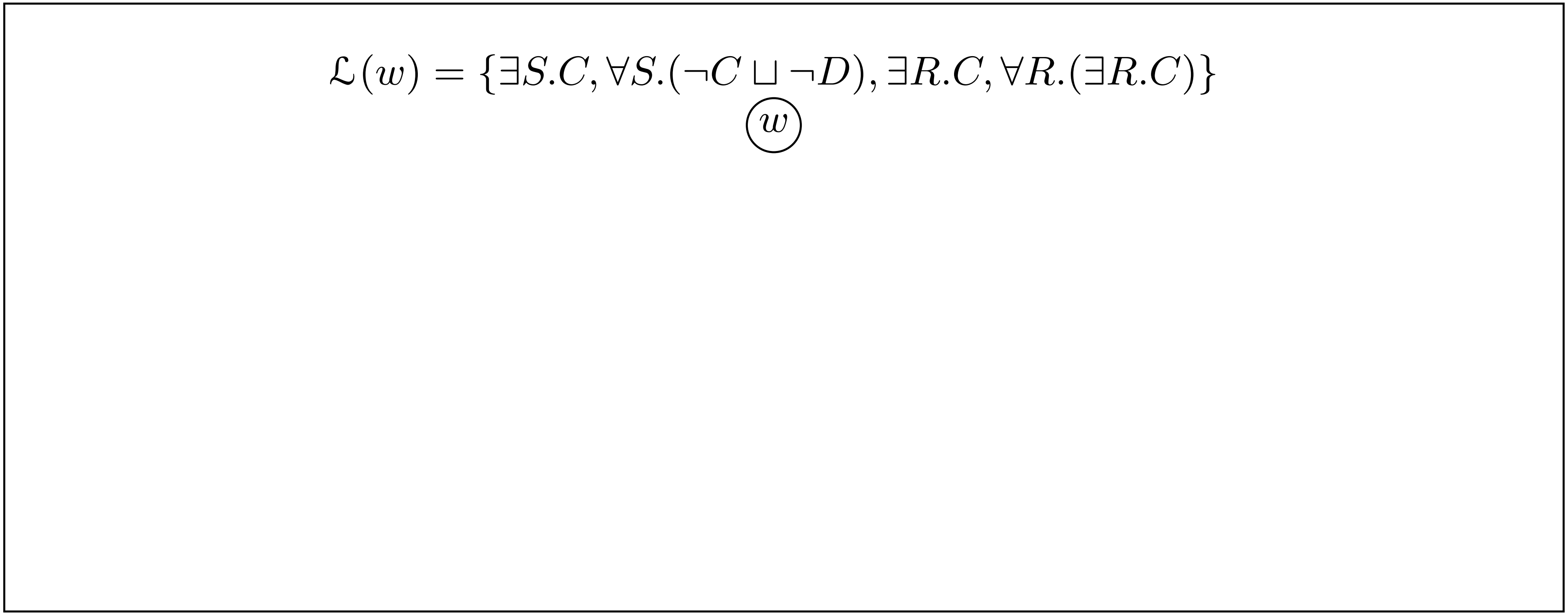

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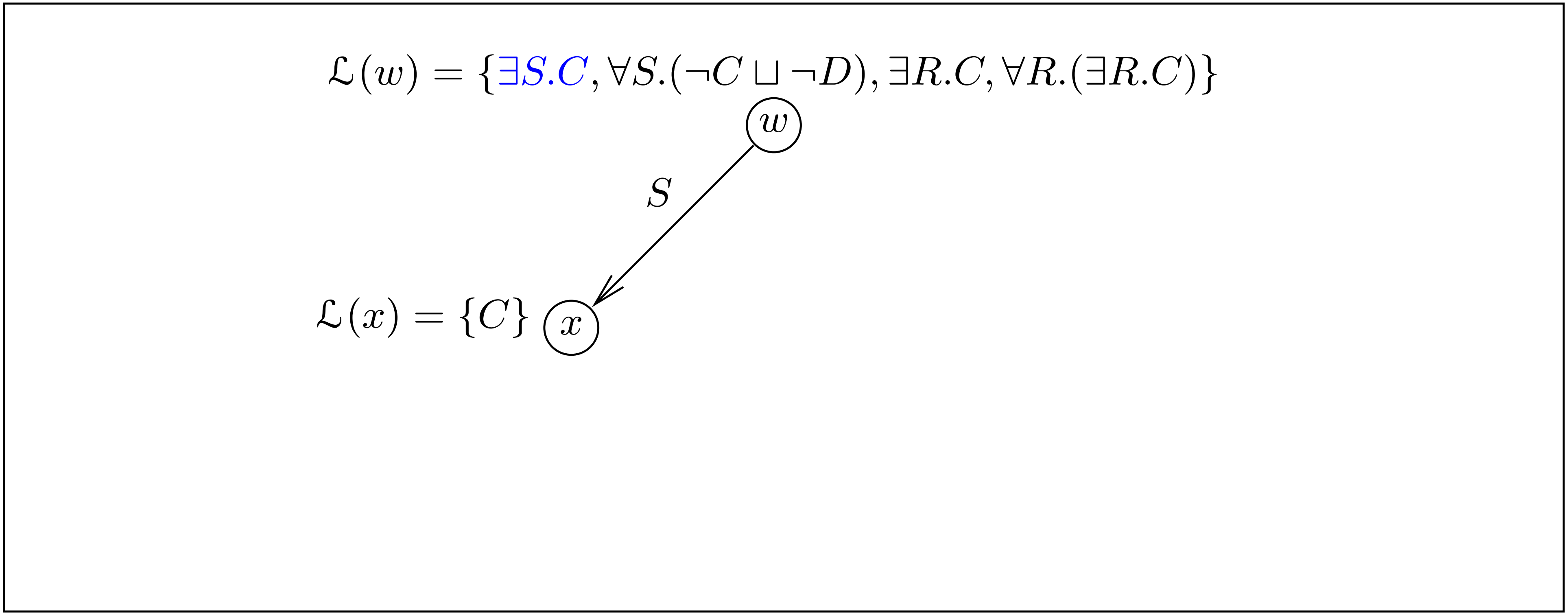

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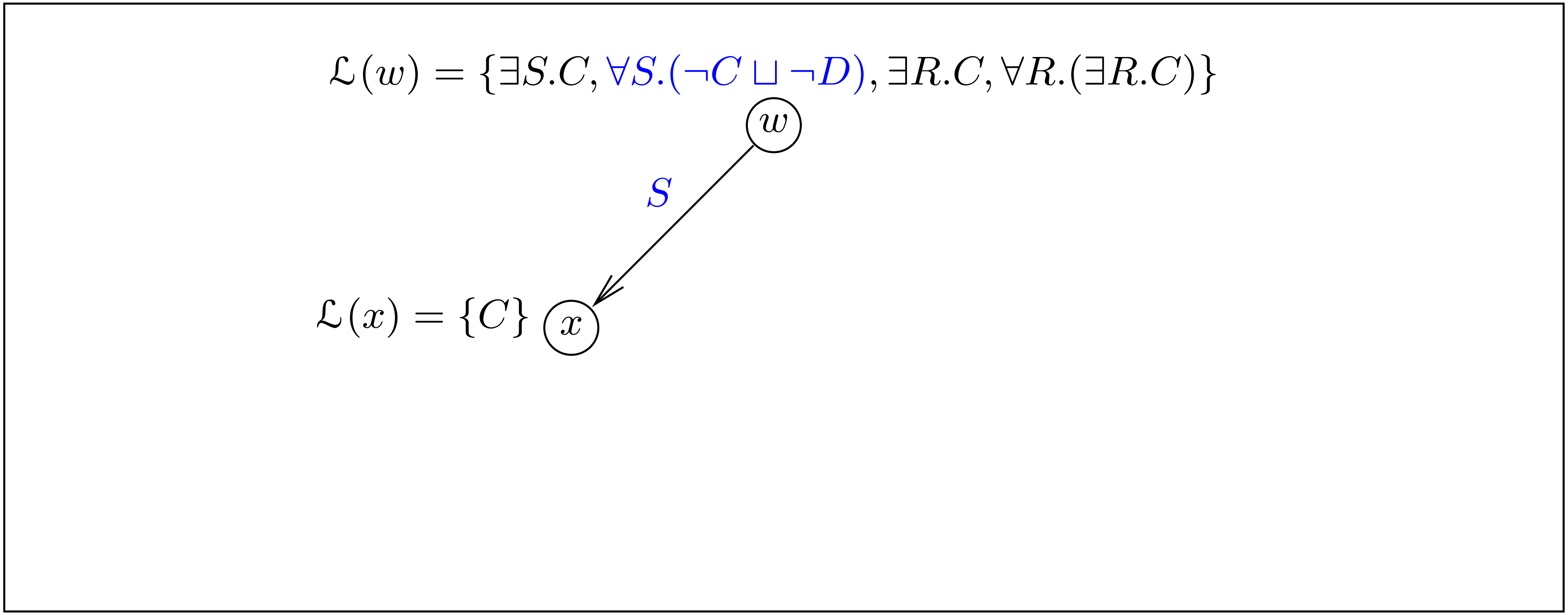

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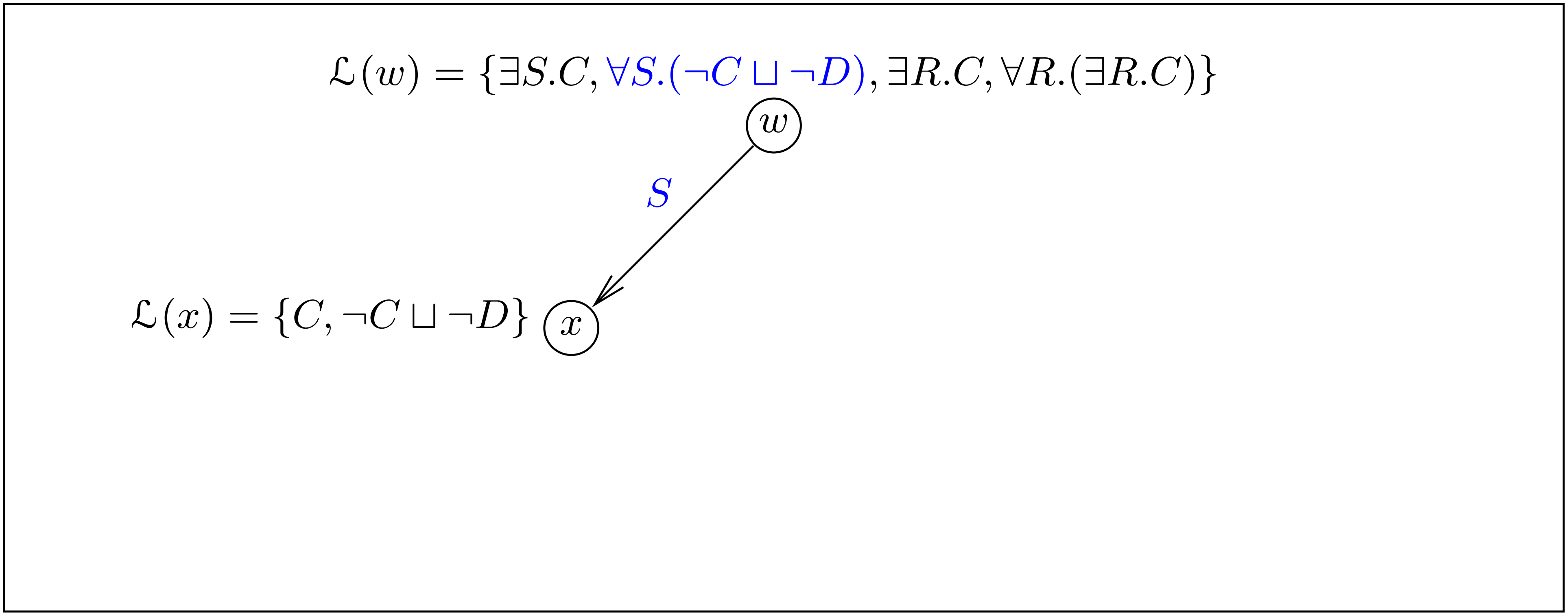

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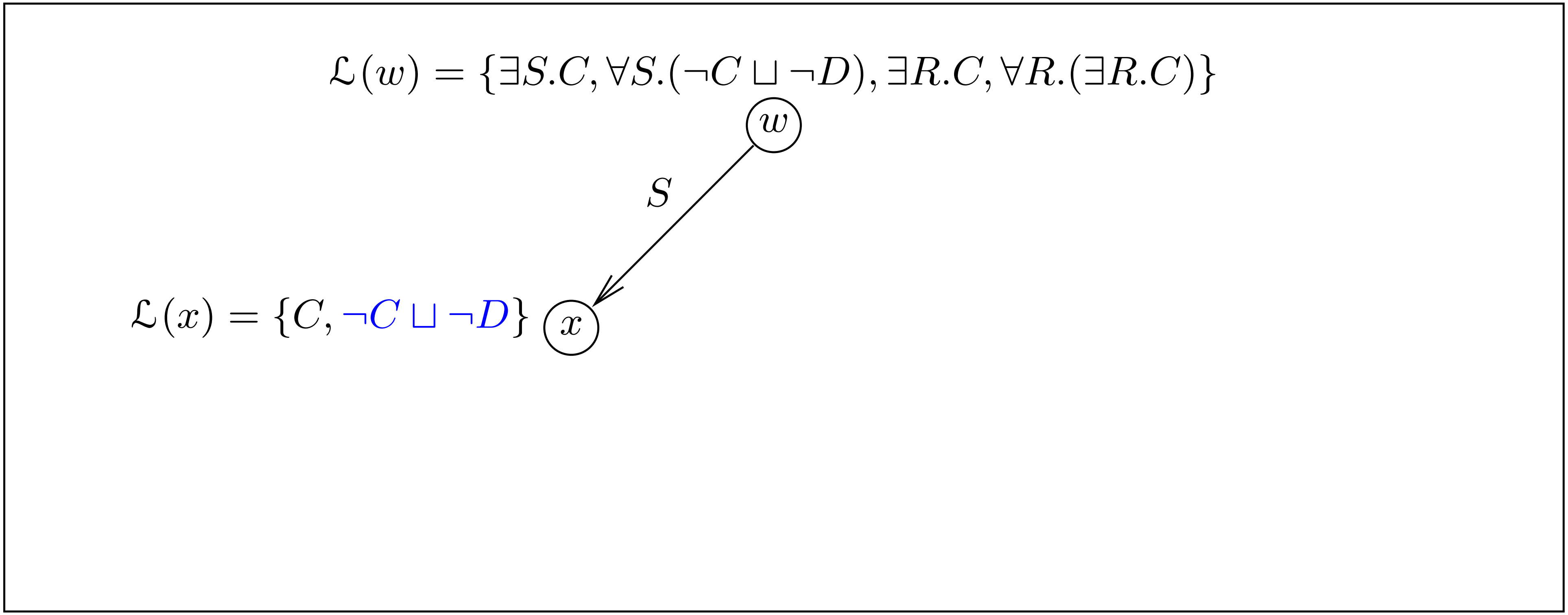

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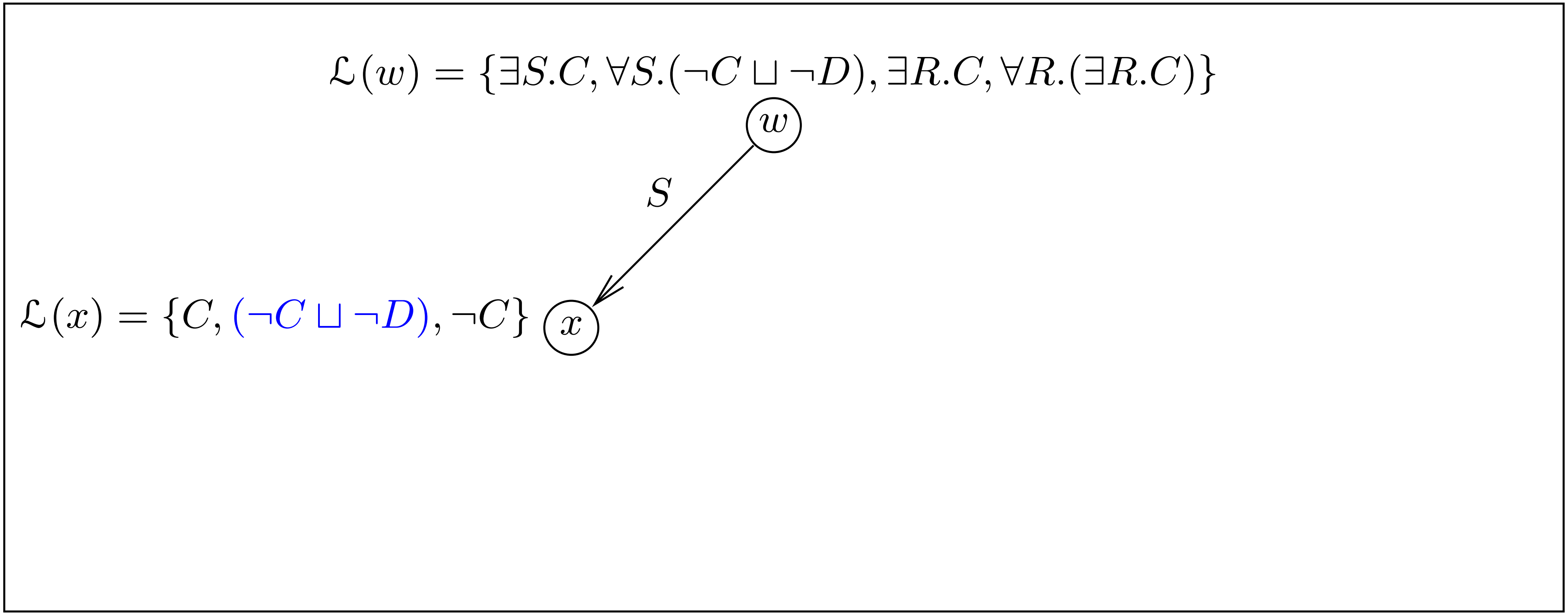

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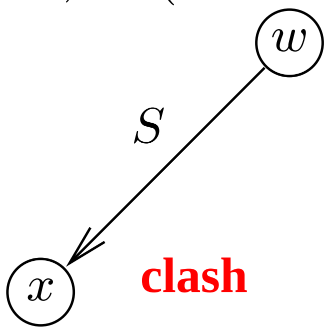

$$\mathcal{L}(x) = \{C, (\neg C \sqcup \neg D), \neg C\}$$

clash

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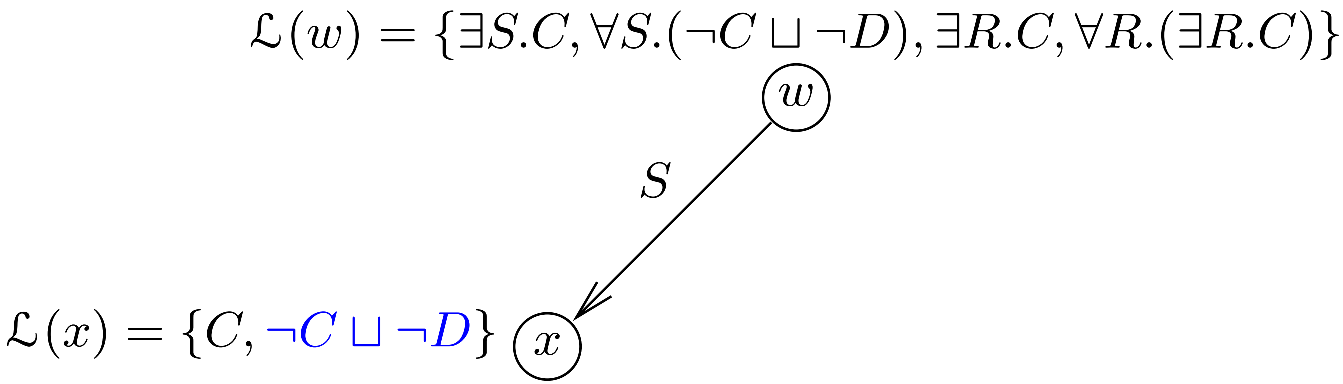

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Test satisfiability of $\exists S.C \sqcap \forall S.(\neg C \sqcup \neg D) \sqcap \exists R.C \sqcap \forall R.(\exists R.C)\}$ where R is a **transitive** role

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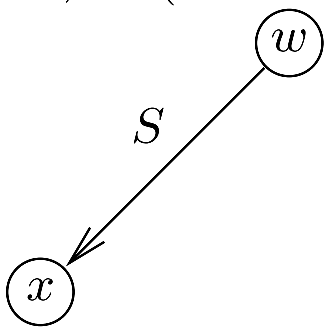

$$\mathcal{L}(x) = \{C, {\color{blue}(\neg C \sqcup \neg D)}, \neg D\}$$

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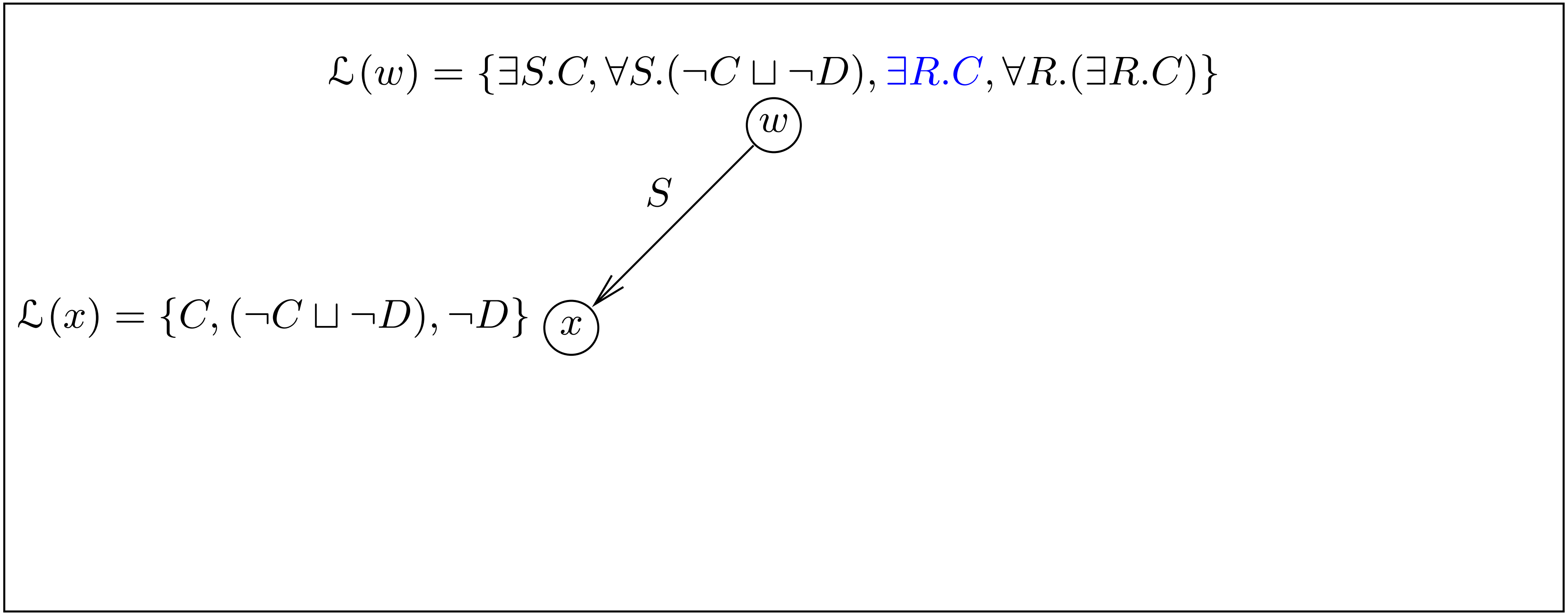

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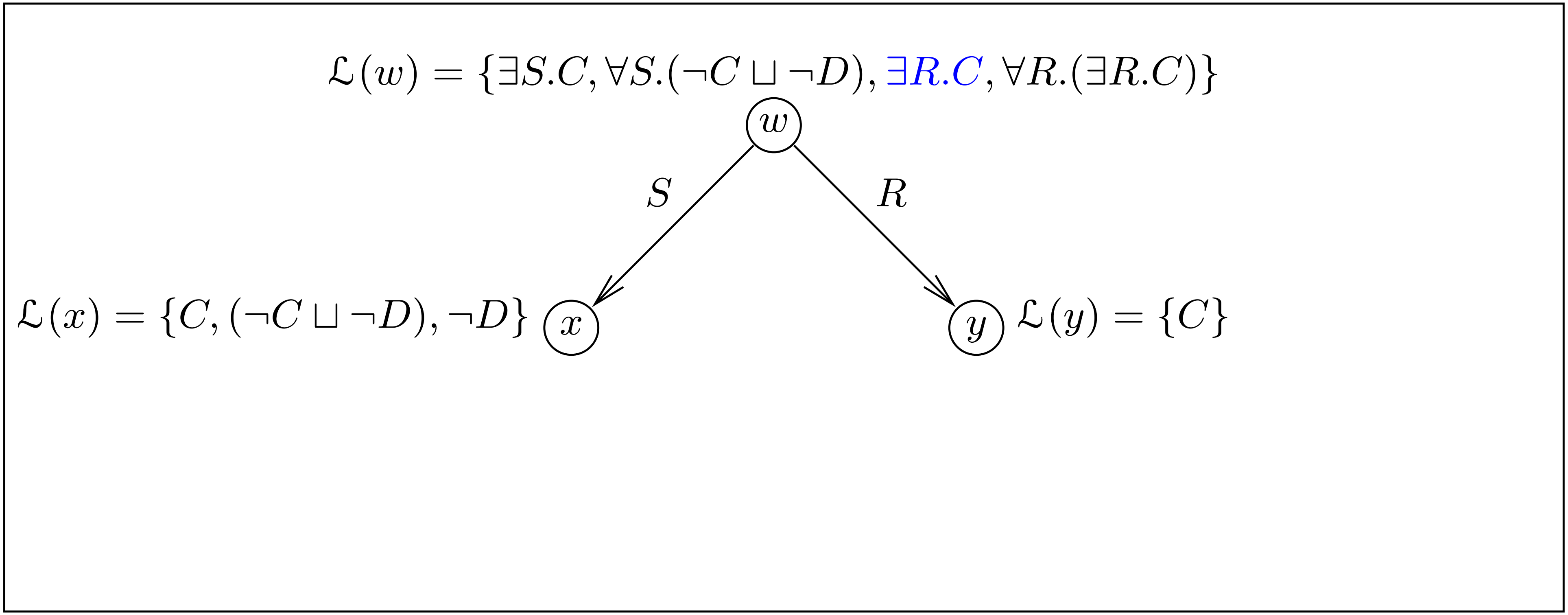

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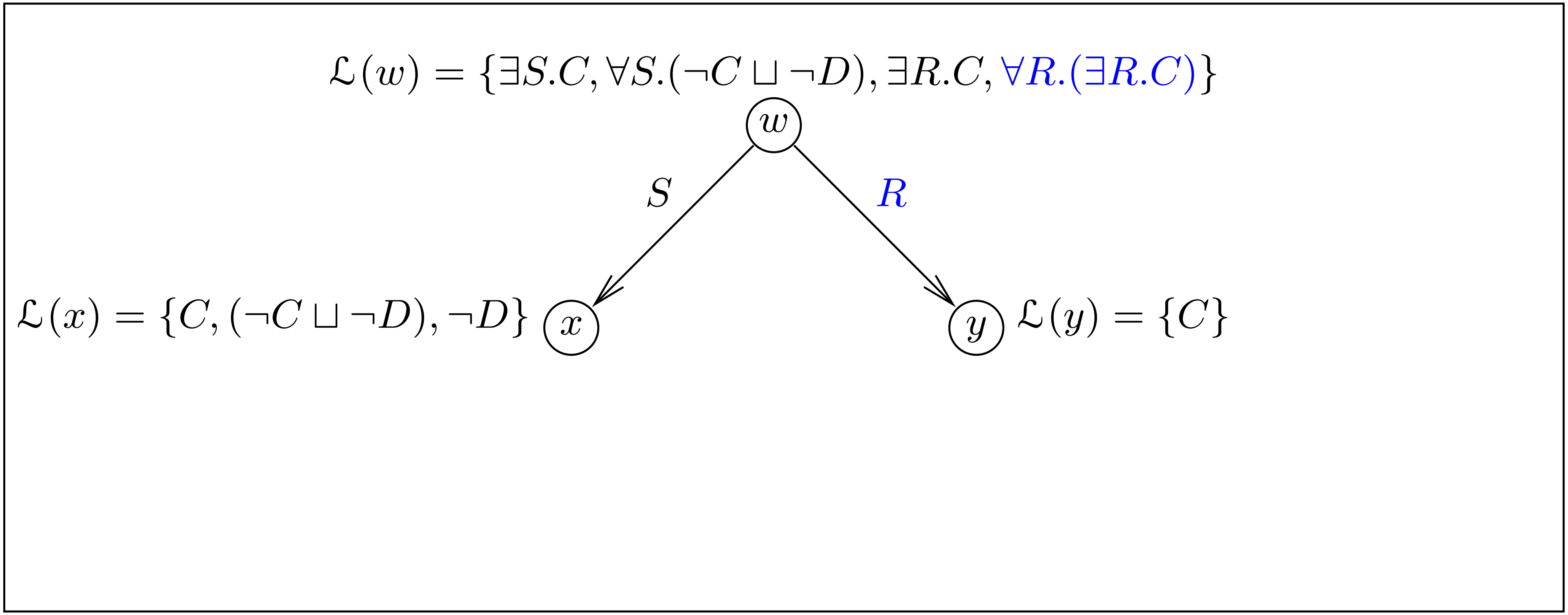

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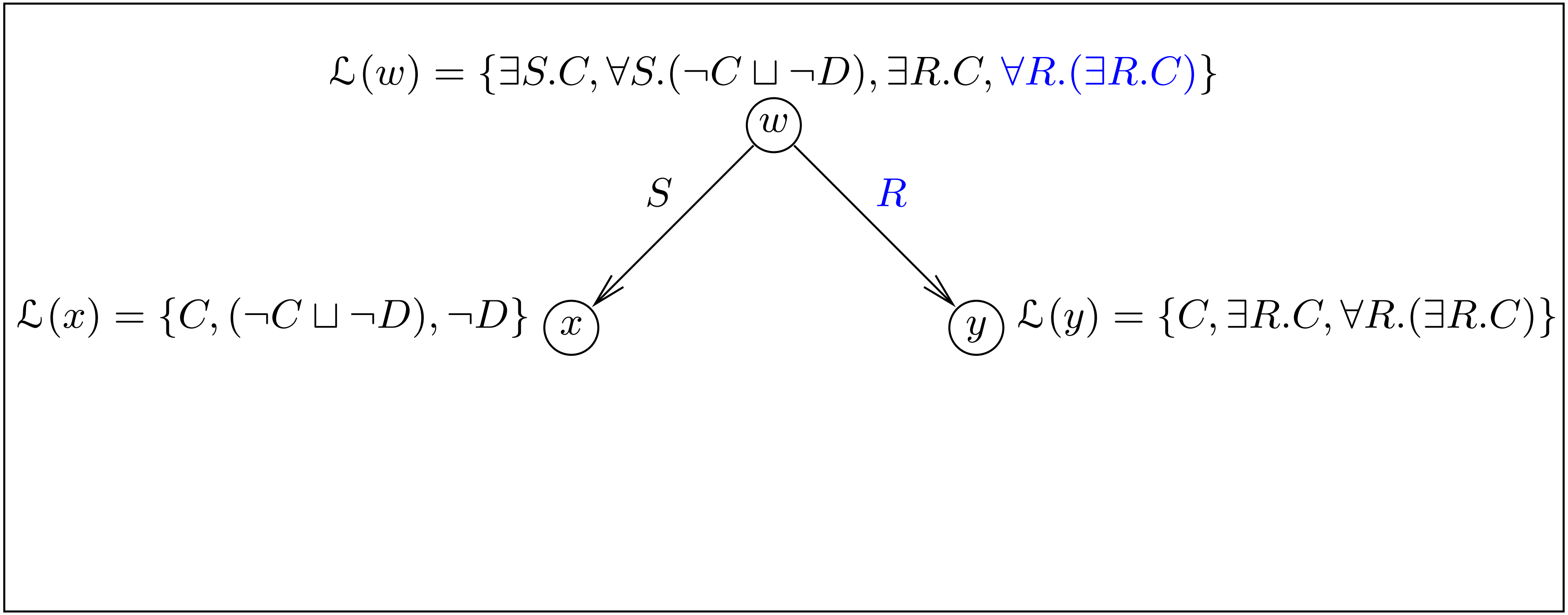

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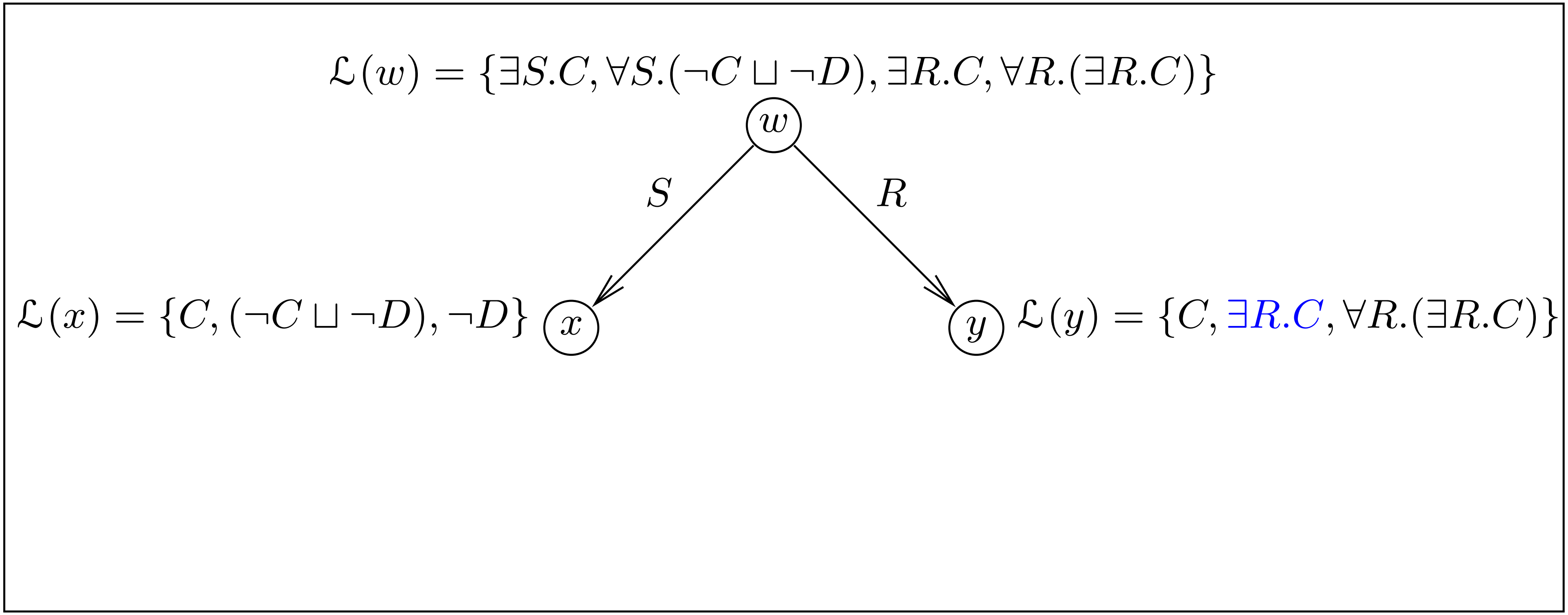

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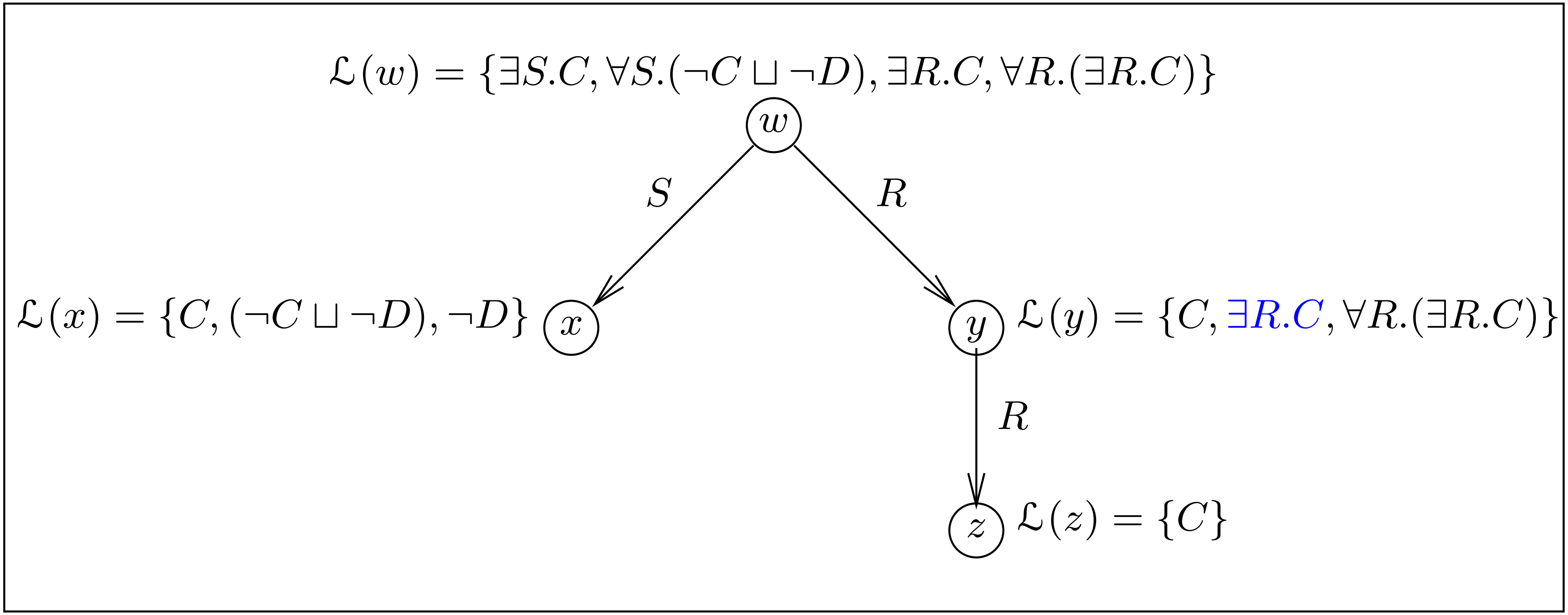

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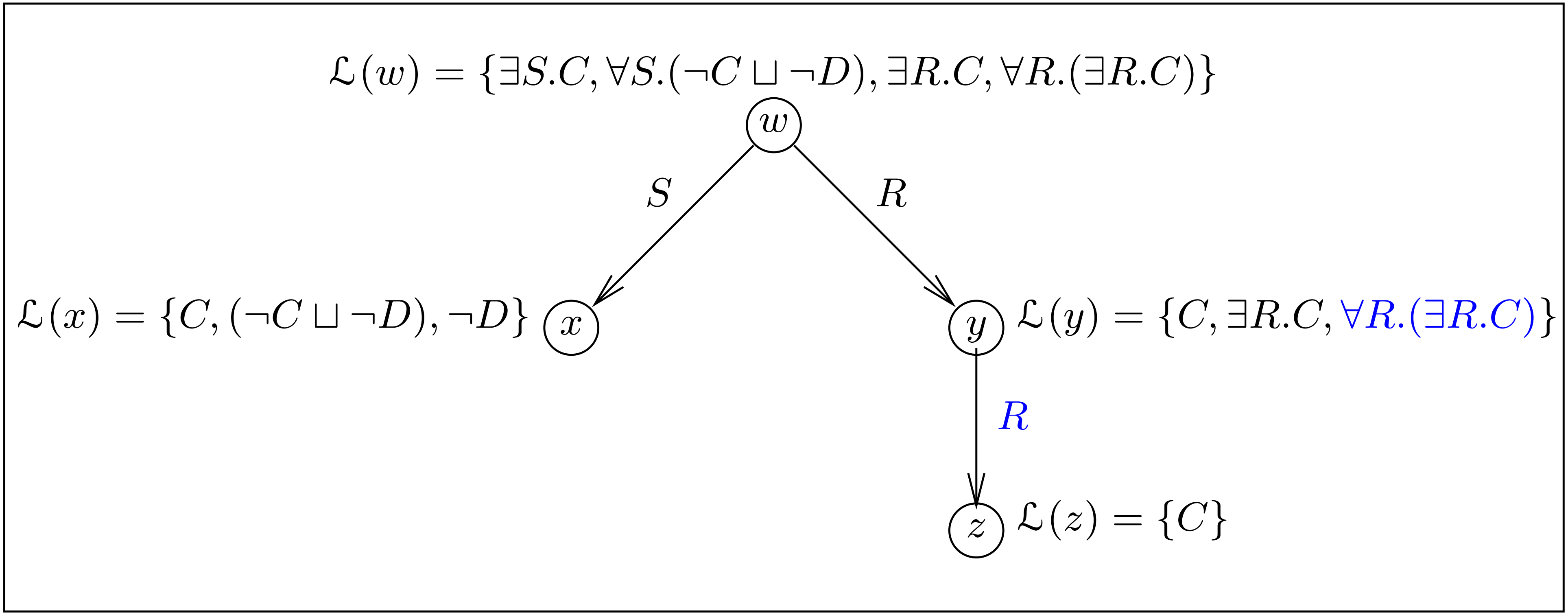

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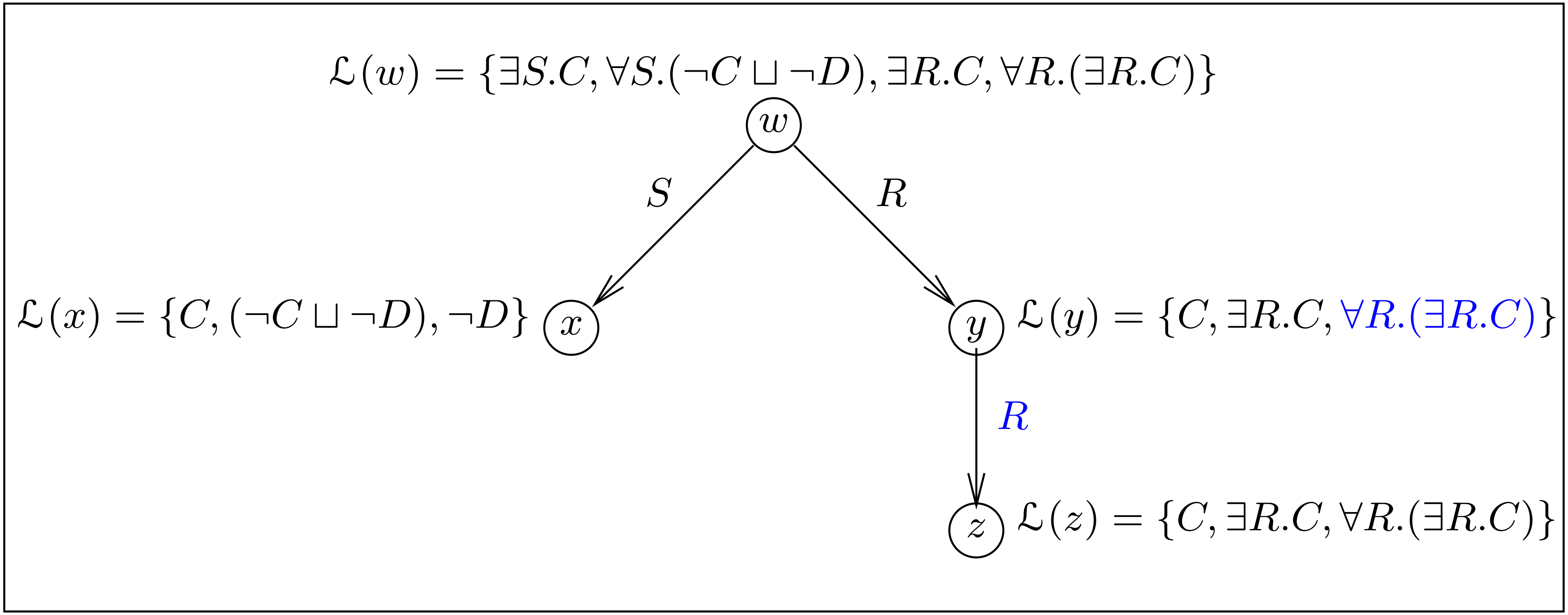

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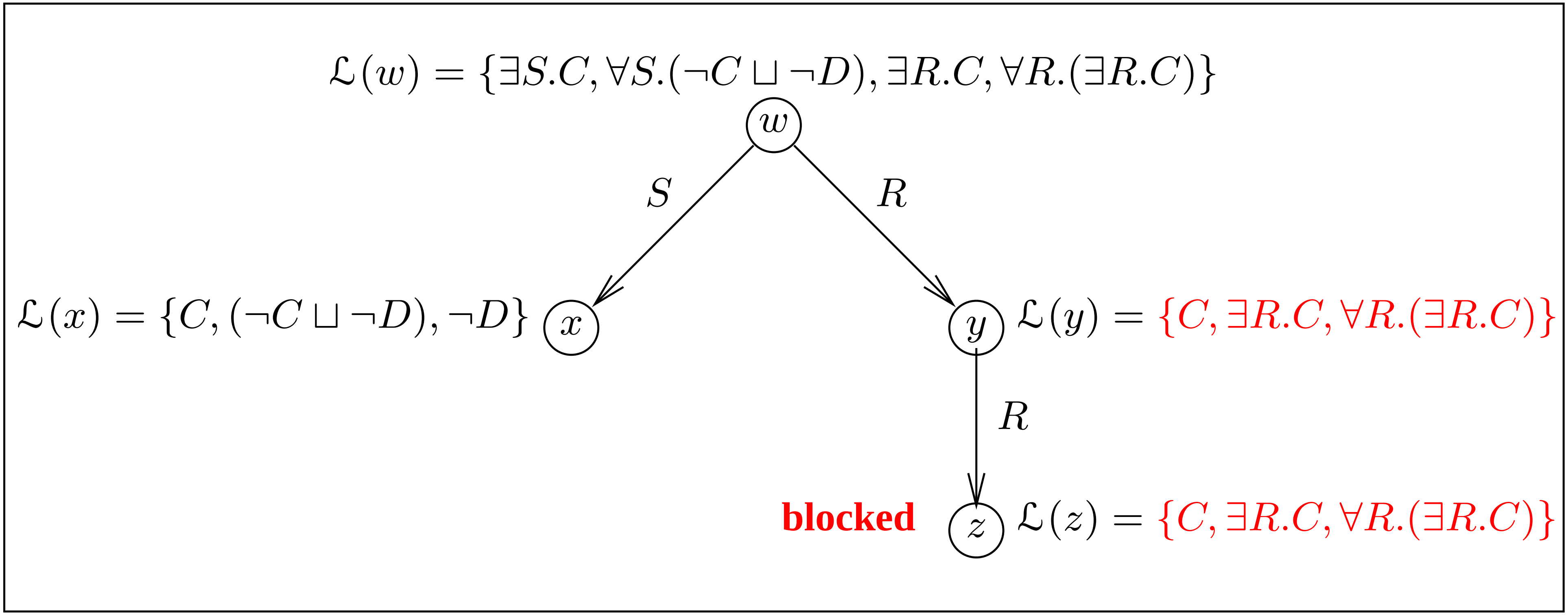

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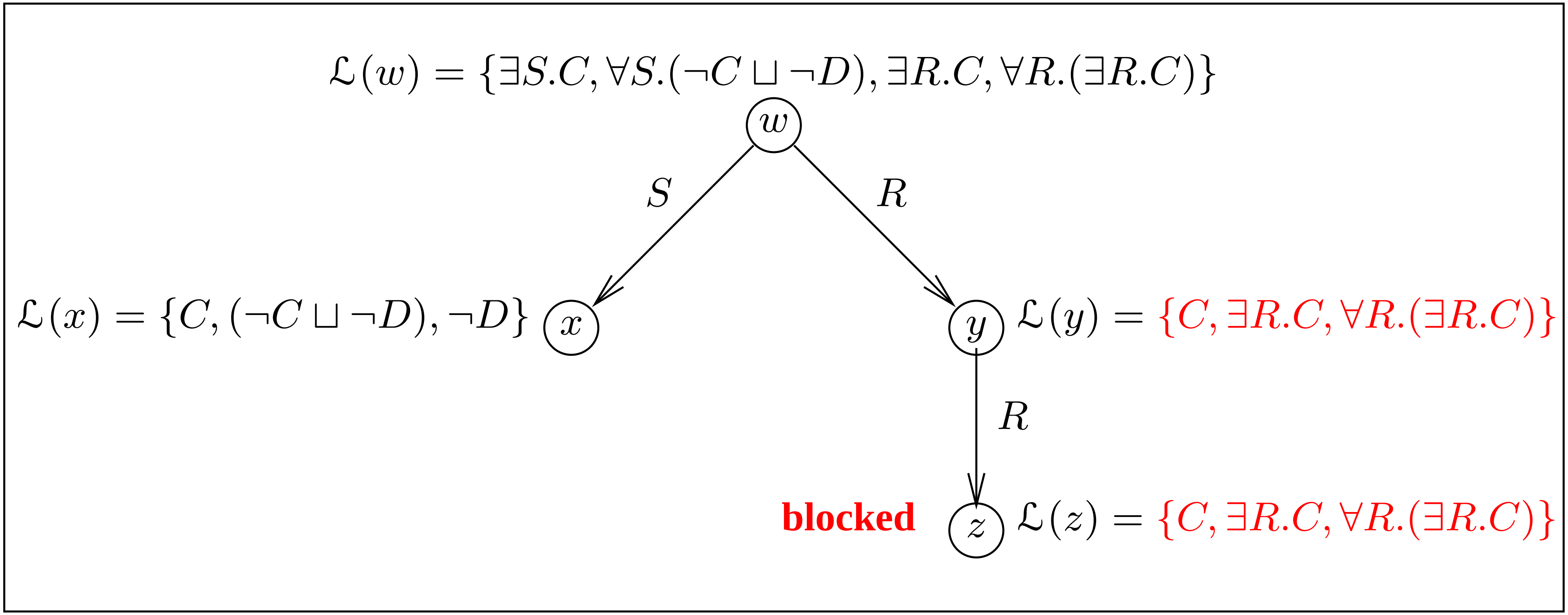

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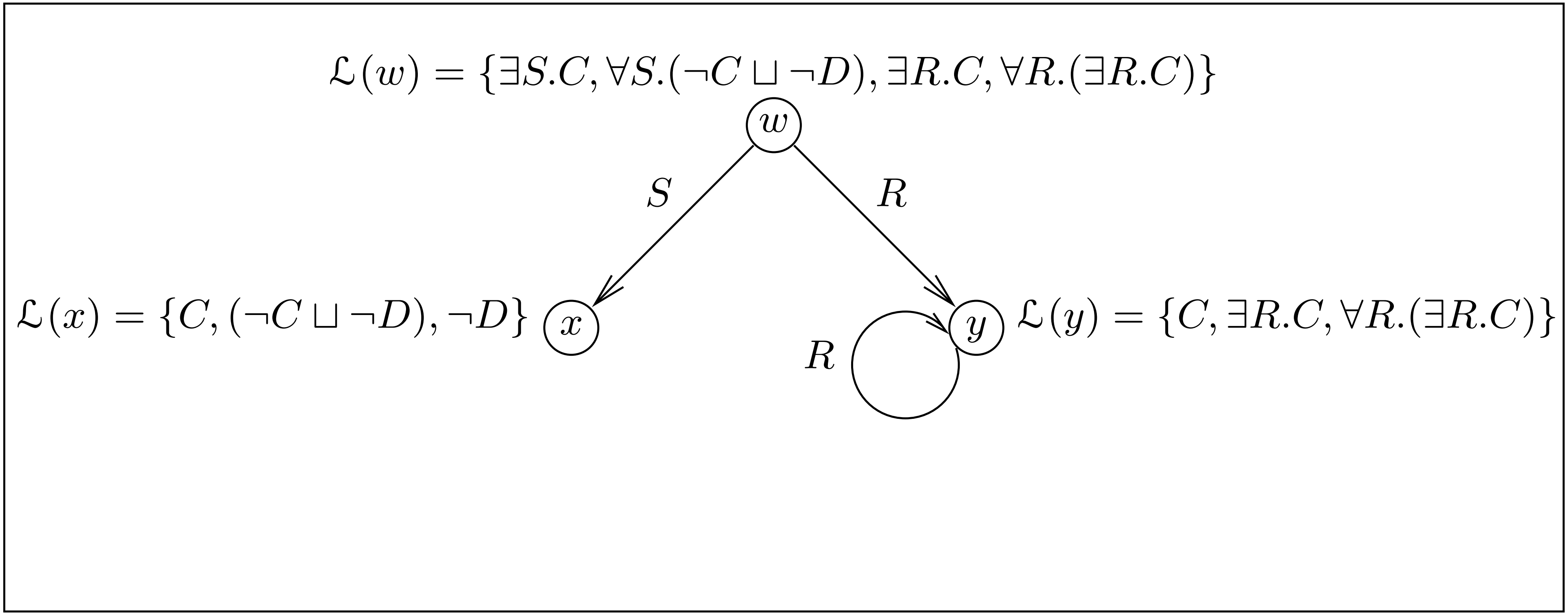

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☞ **Forest** instead of Tree (for Aboxes)
- Root nodes correspond to individuals in Abox

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- ☞ Optimised **subsumption** testing (search for models)
  - Normalisation and simplification of concepts
  - Absorption (simplification) of general axioms
  - Davis-Putnam style semantic branching search
  - Dependency directed backtracking
  - Caching of satisfiability results and (partial) models
  - Heuristic ordering of propositional and modal expansion
  - ...

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  - Cerebra system (Network Inference), Racer system (Hamburg)

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- **Standard solution** is weaker semantics for nominals
  - Treat nominals as (disjoint) primitive classes
  - Loose some inferential power, e.g., w.r.t. max cardinality

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  - **Deployment** of web ontologies will mean reasoning with (possibly very large numbers of) individuals/tuples
  - Unlikely that standard **Abox** techniques will be able to cope

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- “**Non-Standard Inferences**”, e.g., LCS, matching
  - To support ontology integration
  - To support “bottom up” design of ontologies

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- **DL Reasoning** based on tableau algorithms
- **Highly Optimised** implementations used in DL systems
- **Challenges** remain
  - Reasoning with full DAML+OIL/OWL language
  - (Convincing) demonstration(s) of scalability
  - New reasoning tasks
  - Development of (high quality) tools and infrastructure

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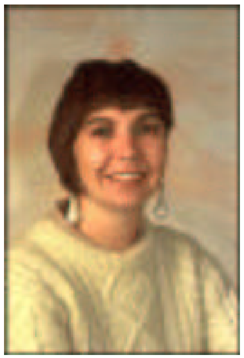

Resources

Slides from this talk

http://www.cs.man.ac.uk/~horrocks/Slides/ed02.pdf

FaCT system (open source)

http://www.cs.man.ac.uk/FaCT/

OilEd (open source)

http://oiled.man.ac.uk/

OIL

http://www.ontoknowledge.org/oil/

DAML+OIL

http://www.w3c.org/Submission/2001/12/

W3C Web-Ontology (WebOnt) working group (OWL)

http://www.w3.org/2001/sw/WebOnt/ **DL Handbook** — available autumn 2002 from Cambridge University Press

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