Description Logic: Axioms and Rules

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Talk Outline

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- **Description Logics and Reasoning**
  - **Reasoning techniques**
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- **Research Challenges**
- **Summary**

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- W3C Ontology Language WG has taken DAML+OIL as starting point

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- ☞ **Expressive power** determined by
  - Kinds of axiom supported
  - Kinds of class (and property) constructor supported

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- Can use DL reasoning with DAML+OIL
  - Existing $\mathcal{SHIQ}$ implementations support (most of) DAML+OIL

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☞ Ontology **deployment**

- Determine if set of facts are consistent w.r.t. ontology
- Answer queries w.r.t. ontology, e.g., DQL

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  - XML provides syntax transport layer
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  - Further layers (e.g., **rules**) will extend DAML+OIL
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- ☞ Facilitates provision of **reasoning services**
  - Known algorithms
  - Implemented systems
  - Evidence of **empirical tractability** (for ontology reasoning)

Reasoning Support for Ontology Design: OilEd

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  - Explicit $\exists$ (hasClass), $\forall$ (toClass) and cardinality restrictions
  - Boolean connectives ($\sqcap$, $\sqcup$, $\neg$) and nesting
  - Transitive, symmetrical and functional properties
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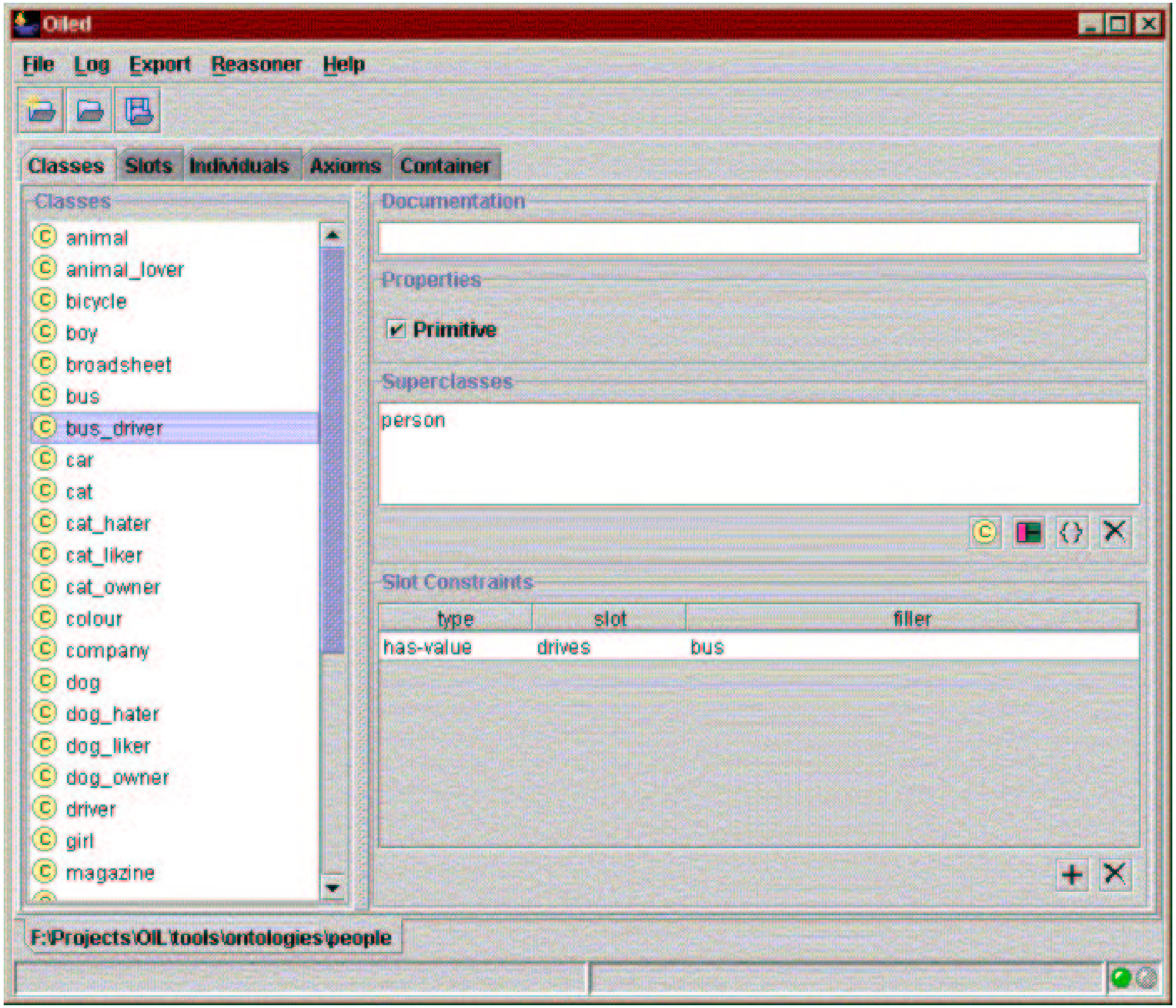
- ☞ **Reasoning support** provided by FaCT system
  - Ontology translated into $\mathcal{SHIQ}$ DL
  - Communicates with FaCT via CORBA interface
  - Indicates inconsistencies and implicit subsumptions

OilEd



OilEd
File
Log
Export
Reasoner
Help
Classes
Slots
Individuals
Axioms
Container
Classes
animal
animal_lover
bicycle
boy
broadsheet
bus
bus_driver
car
cat
cat_hater
cat_liker
cat_owner
colour
company
dog
dog_hater
dog_liker
dog_owner
driver
girl
magazine
Documentation
Properties
Primitive
Superclasses
person
Slot Constraints
type
slot
filler
has-value
drives
bus
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Description Logics and Reasoning

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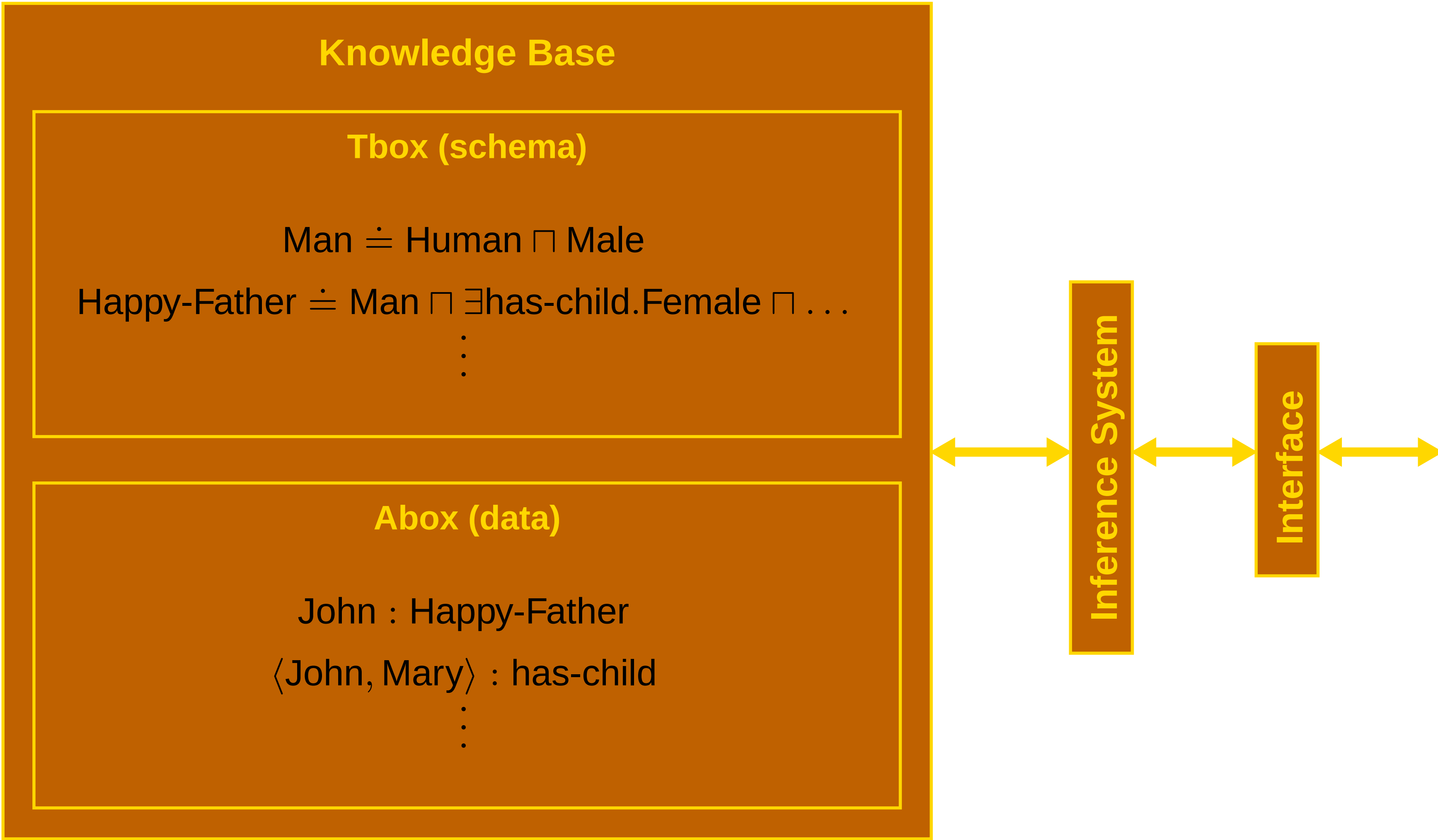
- Key features of DLs are
  - Well defined **semantics** (they are logics)
  - Provision of **inference services**

DL System Architecture



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For example, concept **Happy Father** in $\mathcal{ALC}$:

$$\begin{array}{lll} \text{Man} & \sqcap & \exists\text{has-child.Male} \\ & \sqcap & \exists\text{has-child.Female} \\ & \sqcap & \forall\text{has-child.}(\text{Doctor} \sqcup \text{Lawyer}) \end{array}$$

DL Syntax and Semantics

Semantics given by **interpretation** $\mathcal{I} = (\Delta^{\mathcal{I}}, \cdot^{\mathcal{I}})$

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Constructor	Syntax	Example	Semantics
atomic concept	A	Human	$A^{\mathcal{I}} \subseteq \Delta^{\mathcal{I}}$
atomic role	R	has-child	$R^{\mathcal{I}} \subseteq \Delta^{\mathcal{I}} \times \Delta^{\mathcal{I}}$

and for C, D concepts and R a role name

conjunction	$C \sqcap D$	Human $\sqcap$ Male	$C^{\mathcal{I}} \cap D^{\mathcal{I}}$
disjunction	$C \sqcup D$	Doctor $\sqcup$ Lawyer	$C^{\mathcal{I}} \cup D^{\mathcal{I}}$
negation	$\neg C$	$\neg$Male	$\Delta^{\mathcal{I}} \setminus C$
exists restr.	$\exists R.C$	$\exists$has-child.Male	$\{x \mid \exists y.\langle x, y\rangle \in R^{\mathcal{I}} \wedge y \in C^{\mathcal{I}}\}$
value restr.	$\forall R.C$	$\forall$has-child.Doctor	$\{x \mid \forall y.\langle x, y\rangle \in R^{\mathcal{I}} \implies y \in C^{\mathcal{I}}\}$

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Constructor	Syntax	Example	Semantics
qualified num	$\geqslant nR.C$	$\geqslant 3$ child. female	$\{x \mid \lvert\{y.(\langle x,y\rangle \in R^{\mathcal{I}} \wedge y \in C^{\mathcal{I}})\}\rvert \geqslant n\}$
restrictions	$\leqslant nR.C$	$\leqslant 1$ parent female	$\{x \mid \lvert\{y.(\langle x,y\rangle \in R^{\mathcal{I}} \wedge y \in C^{\mathcal{I}})\}\rvert \leqslant n\}$
inverse role	R^{-}	has-child^{-}	$\{\langle x,y\rangle \mid \langle y,x\rangle \in R^{\mathcal{I}}\}$
trans role	$^{(+)}R$	$^{(+)}$has-ancestor	$R^{\mathcal{I}} = (R^{\mathcal{I}})^{+}$

$$\mathcal{SHIQ}$$

nominals	$\{x\}$	{Italy}	$\{x^{\mathcal{I}}\}$
conc. domain	$f_1,\ldots,f_n.P$	earns spends $<$	$\{x \mid P(f_1^{\mathcal{I}},\ldots,f_n^{\mathcal{I}})\}$

$$\mathcal{SHOIQ}(D_n)$$

$\vdots$

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$A \doteq C$, $A \sqsubseteq C$

Father $\doteq$ Man $\sqcap$ $\exists$has-child.Human

Human $\sqsubseteq$ Animal $\sqcap$ Biped

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Inclusion (GCI) axioms assert subsumption relations

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$\exists$has-degree.Masters $\sqsubseteq$ $\exists$has-degree.Bachelors

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An interpretation $\mathcal{I}$ **satisfies**

$C \doteq D$ iff $C^{\mathcal{I}} = D^{\mathcal{I}}$ $C \sqsubseteq D$ iff $C^{\mathcal{I}} \subseteq D^{\mathcal{I}}$

A **Tbox** $\mathcal{T}$ iff it satisfies every axiom in $\mathcal{T}$ ($\mathcal{I} \models \mathcal{T}$)

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An **Abox** $\mathcal{A}$ iff it satisfies every axiom in $\mathcal{A}$ ($\mathcal{I} \models \mathcal{A}$)

A **KB** $\Sigma = \langle \mathcal{T}, \mathcal{A} \rangle$ iff it satisfies both $\mathcal{T}$ and $\mathcal{A}$ ($\mathcal{I} \models \Sigma$)

Why Tbox and Abox?

- Restricted use of individuals maintains (kind of) **tree model property**
  - Arbitrary but finite directed graph connecting named individuals
  - Named individuals roots of (possibly) infinite trees of anonymous individuals
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- Note that with nominals, Abox becomes syntactic sugar
  - $a : C$ equiv. to $\{a\} \sqsubseteq C$
  - $\langle a, b \rangle : R$ equiv. to $\{a\} \sqsubseteq \exists R.\{b\}$

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Problems are **closely related**:

$C \sqsubseteq_\mathcal{T} D$	iff	$C \sqcap \neg D$ is inconsistent w.r.t. $\mathcal{T}$
C is consistent w.r.t. $\mathcal{T}$	iff	$C \not\sqsubseteq_\mathcal{T} A \sqcap \neg A$

Reasoning Techniques

Subsumption and Satisfiability

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Subsumption transformed into **satisfiability**

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Tableaux algorithm used to test satisfiability

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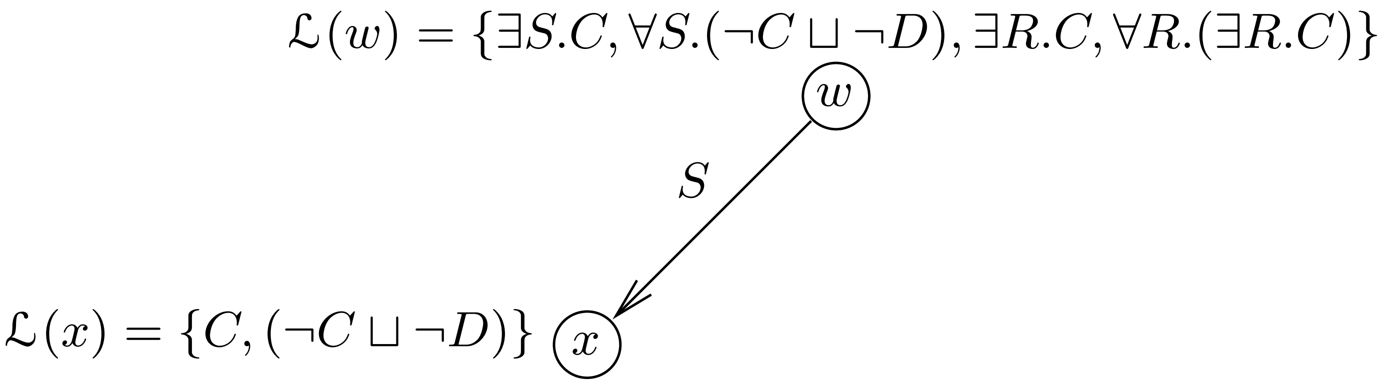

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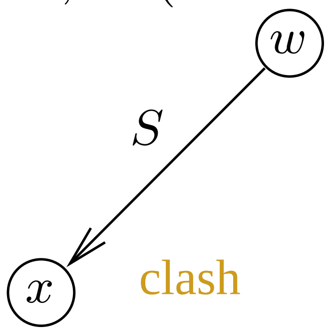

$$\mathcal{L}(x) = \{C, (\neg C \sqcup \neg D), \neg C\}$$

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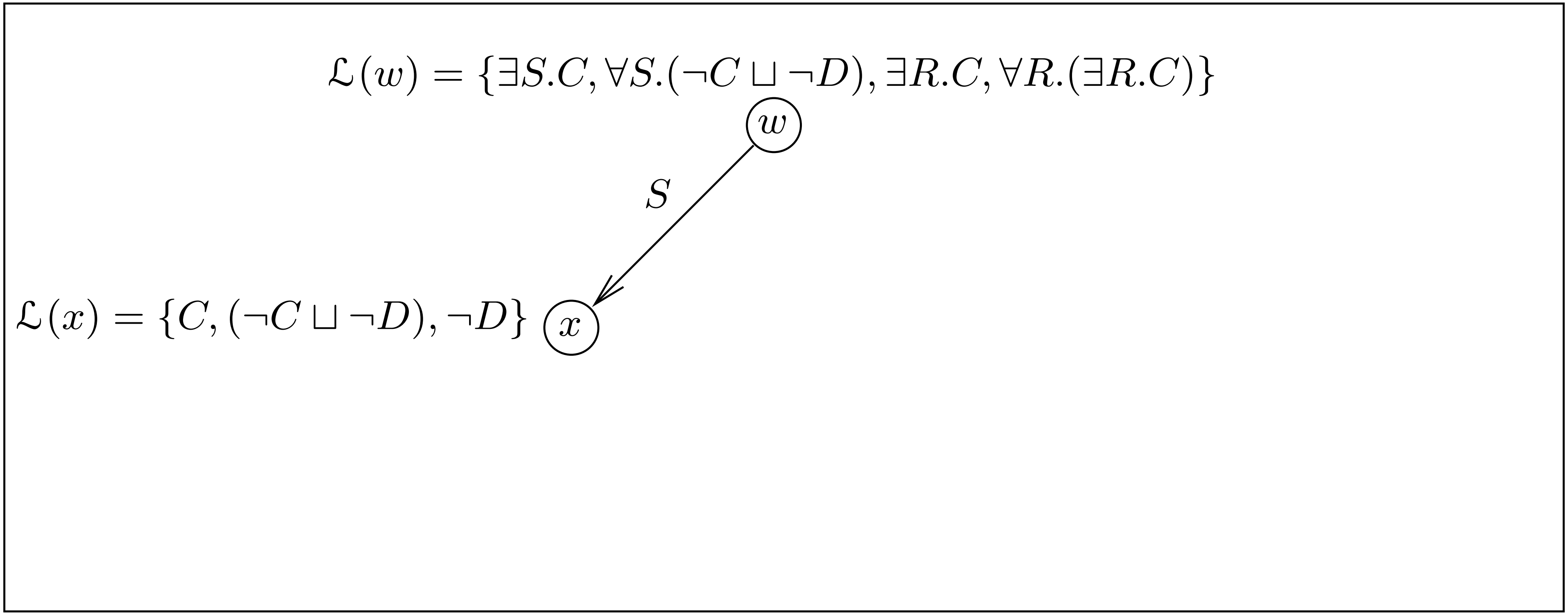

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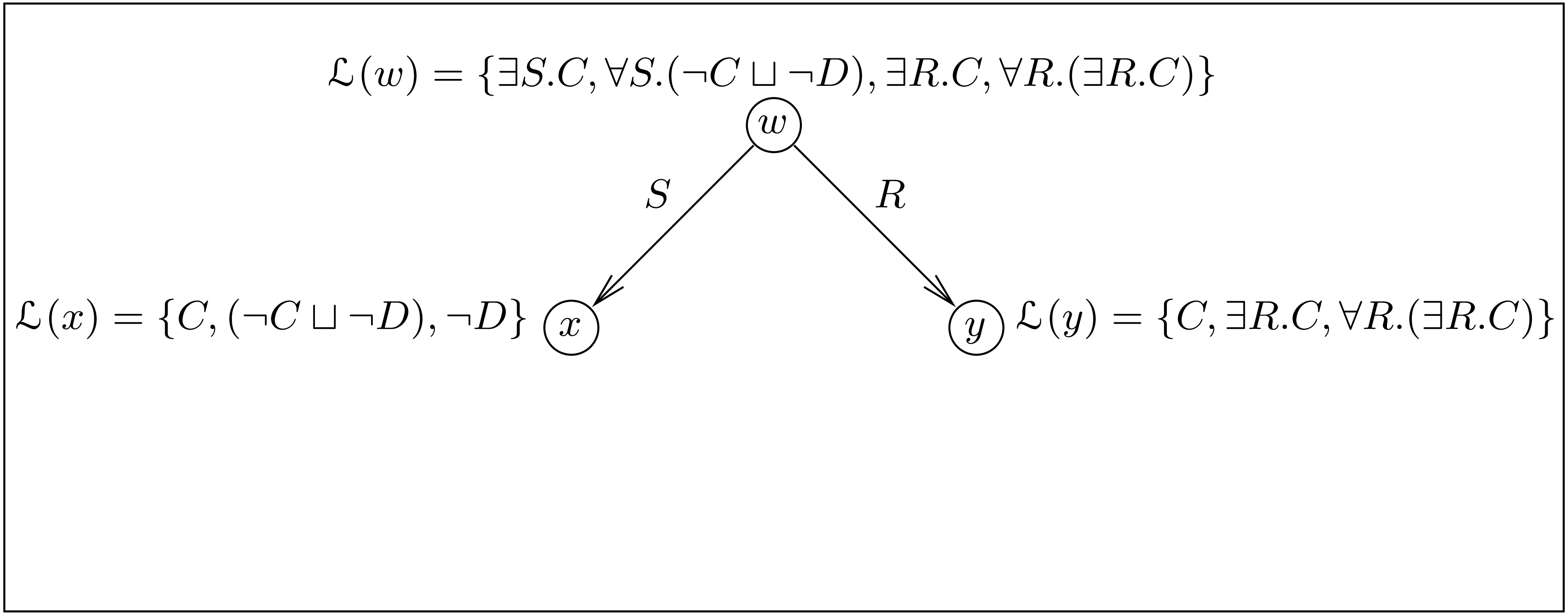

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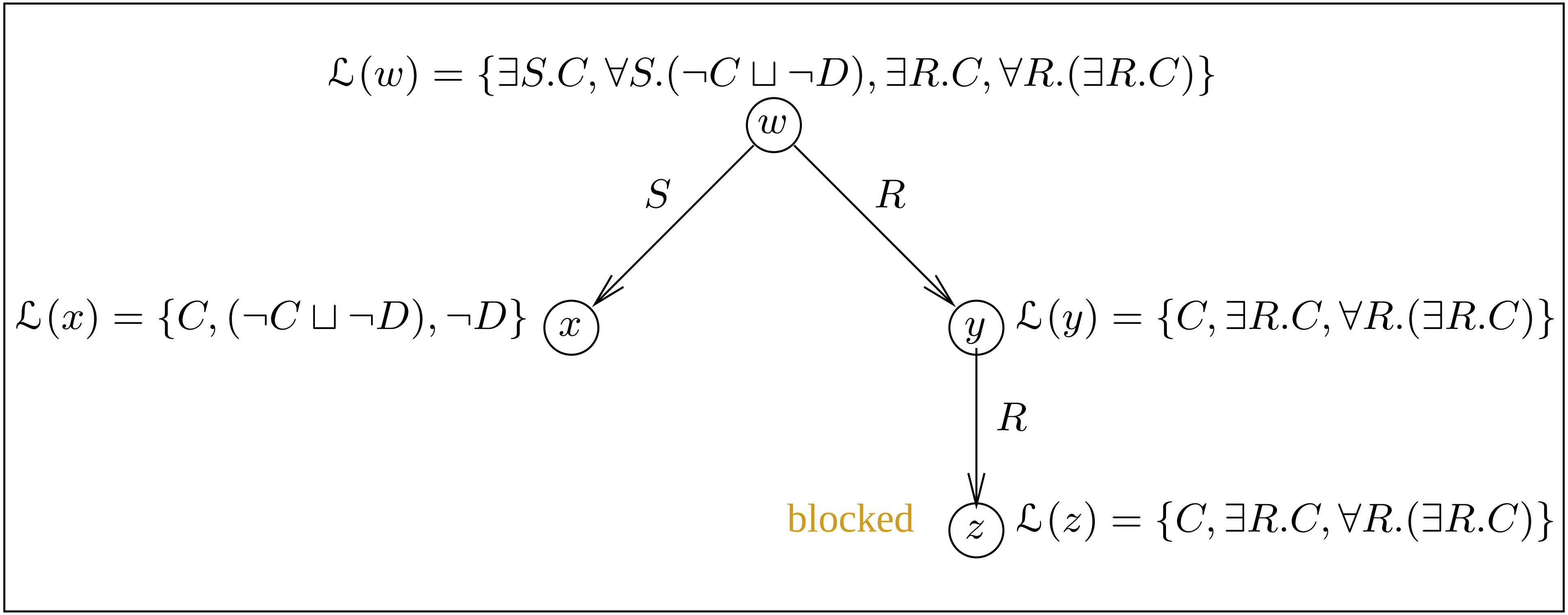

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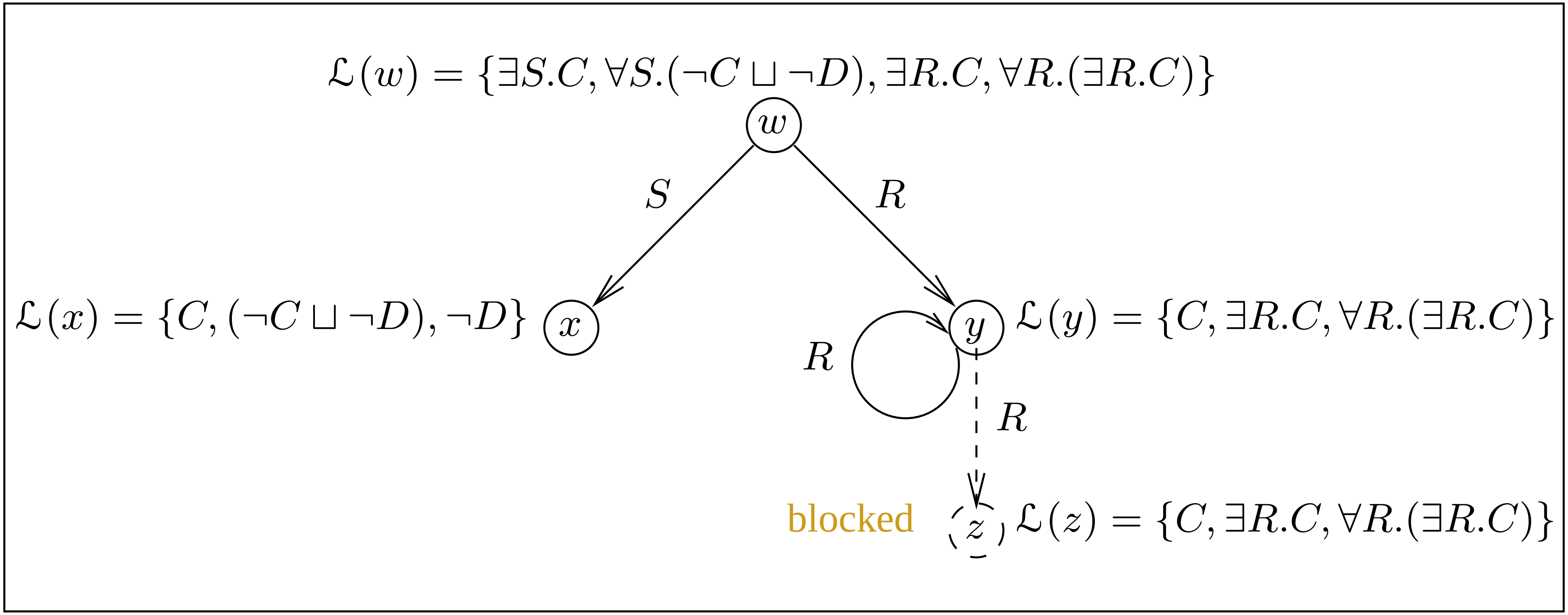

Concept is **satisfiable**: w is a **witness**

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☞ Forest instead of Tree (for Aboxes)

Implementing DL Systems

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- **Highly effective** — essential for usable system
  - E.g., GALEN KB, 30s (with) $\longrightarrow$ months++ (without)

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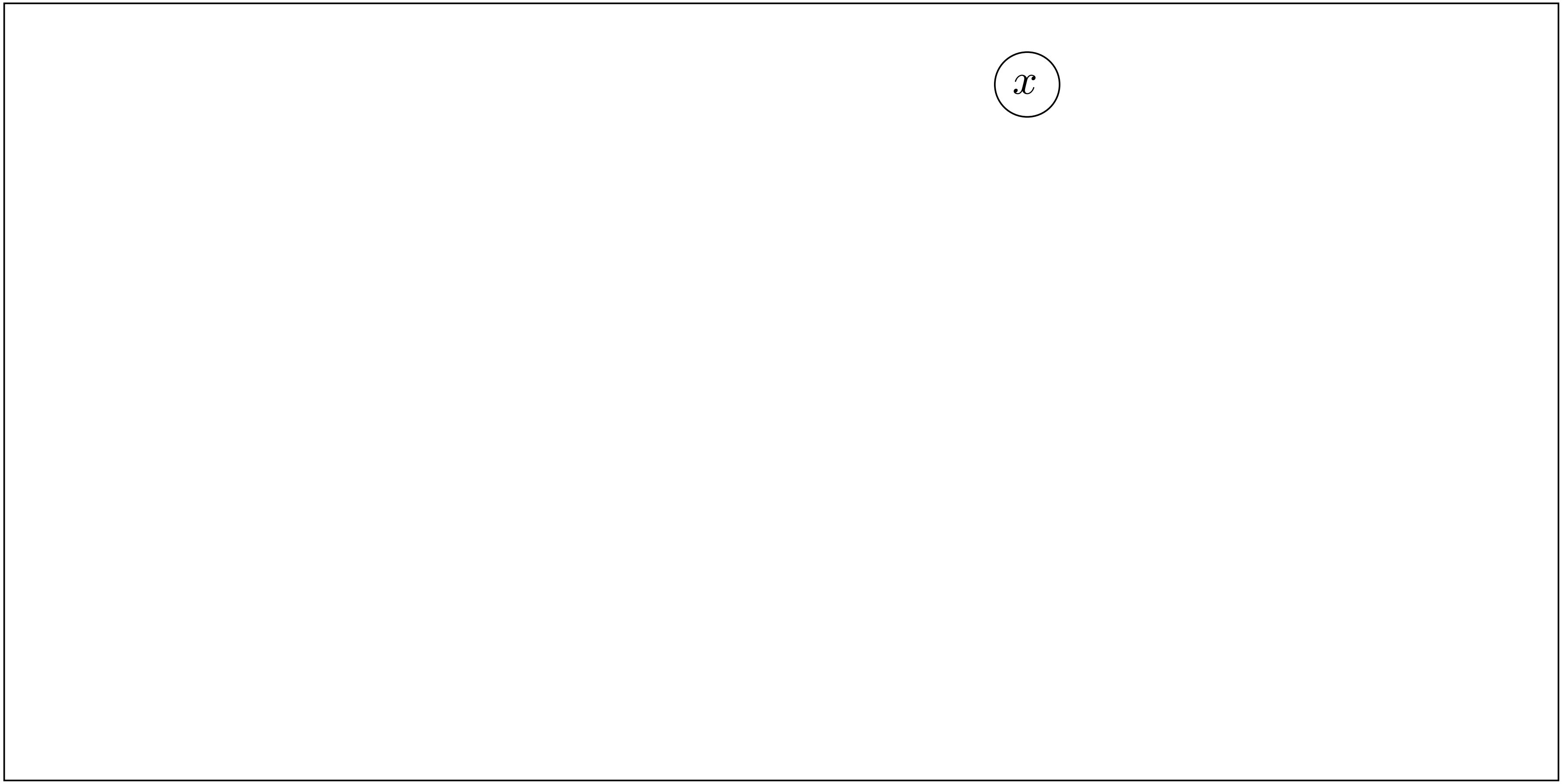

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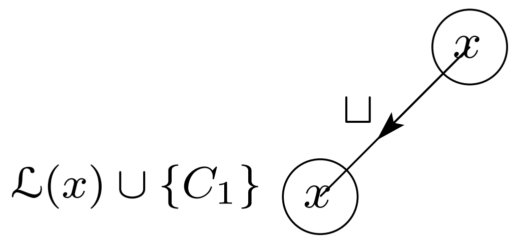

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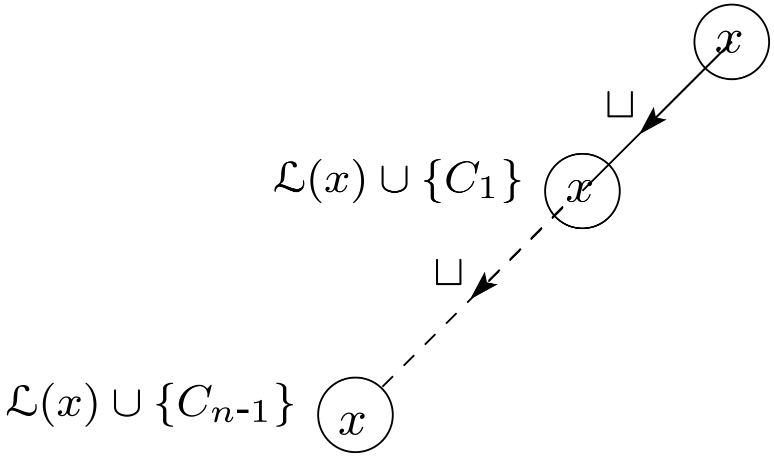

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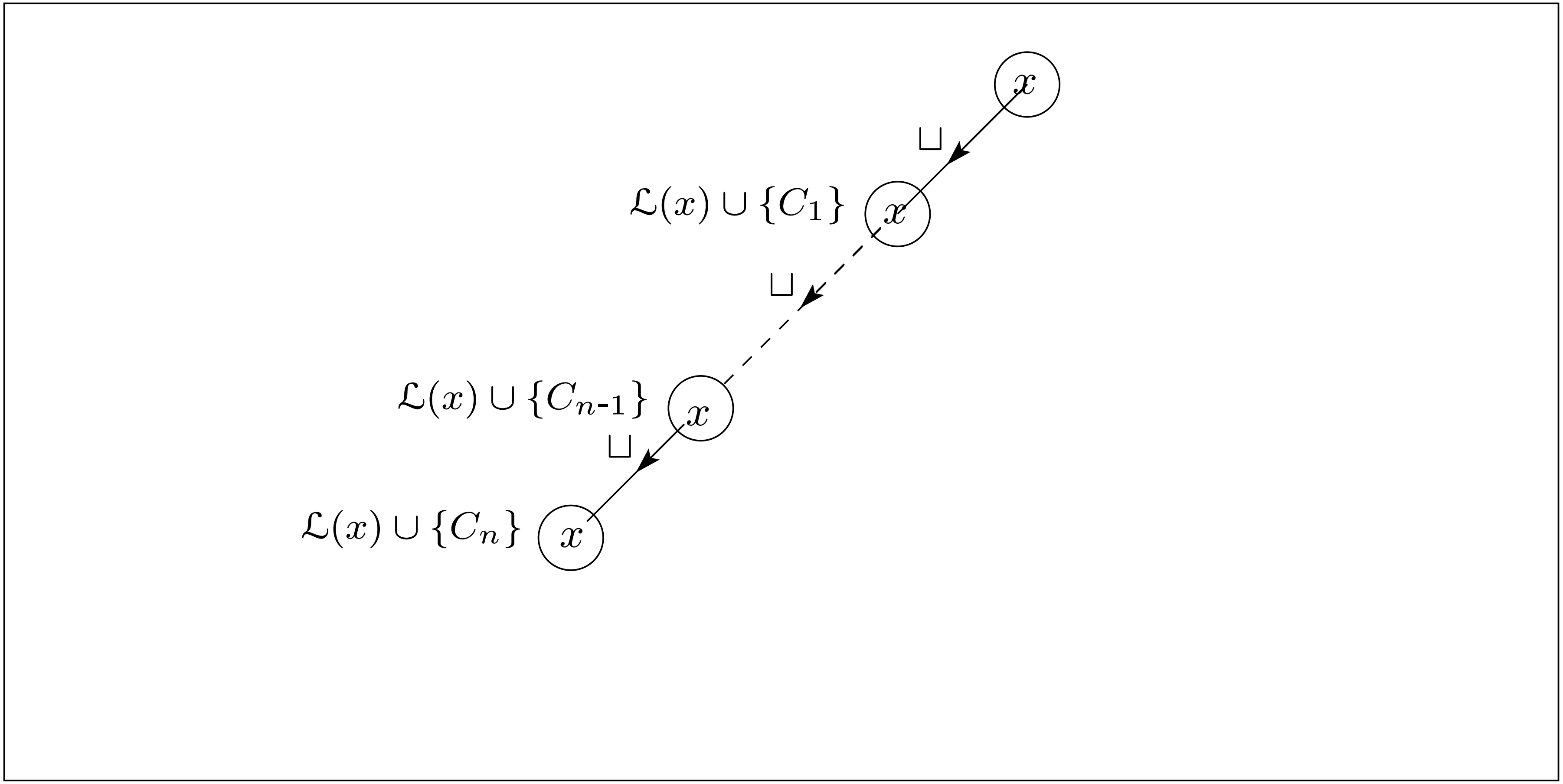

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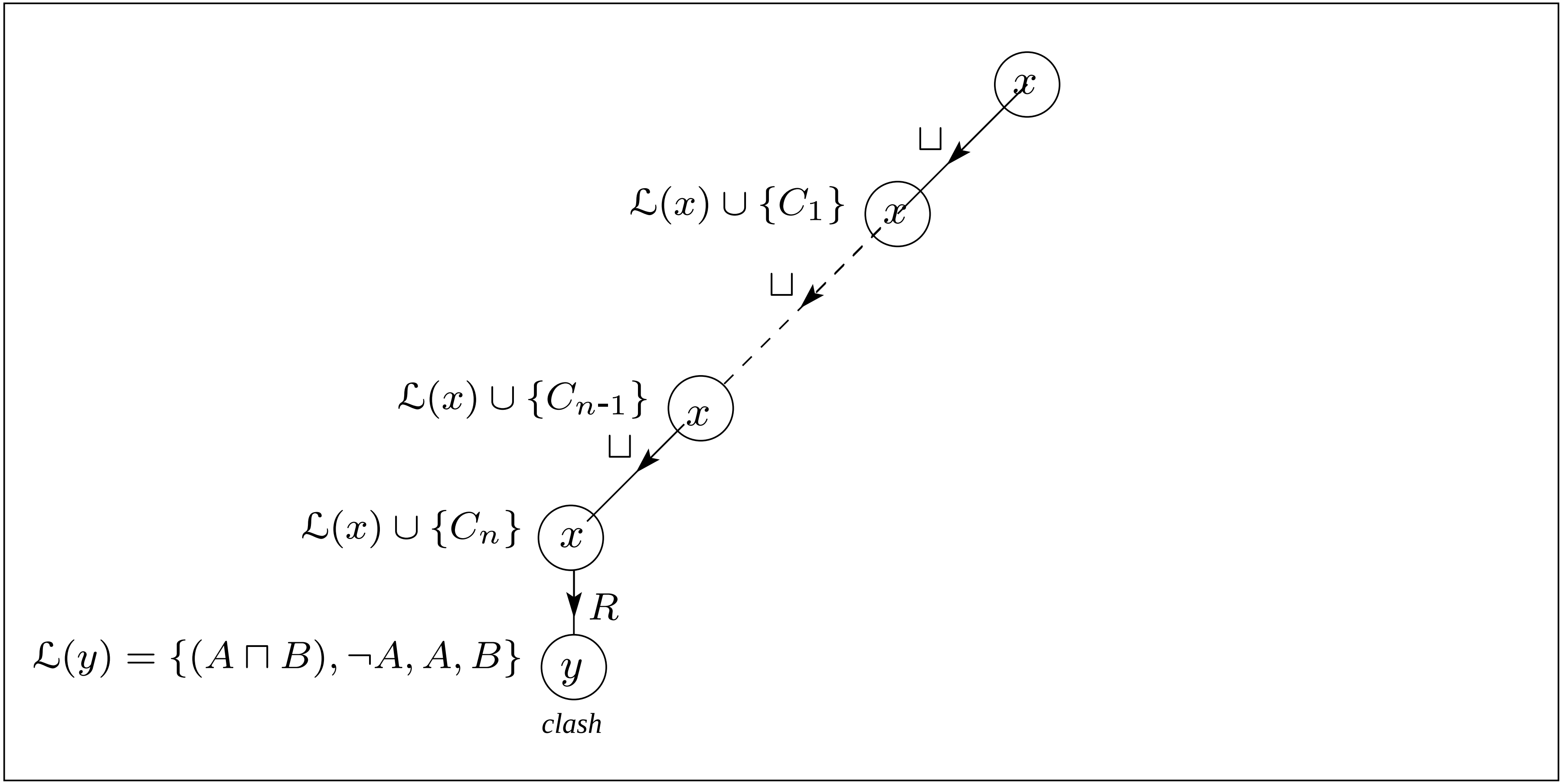

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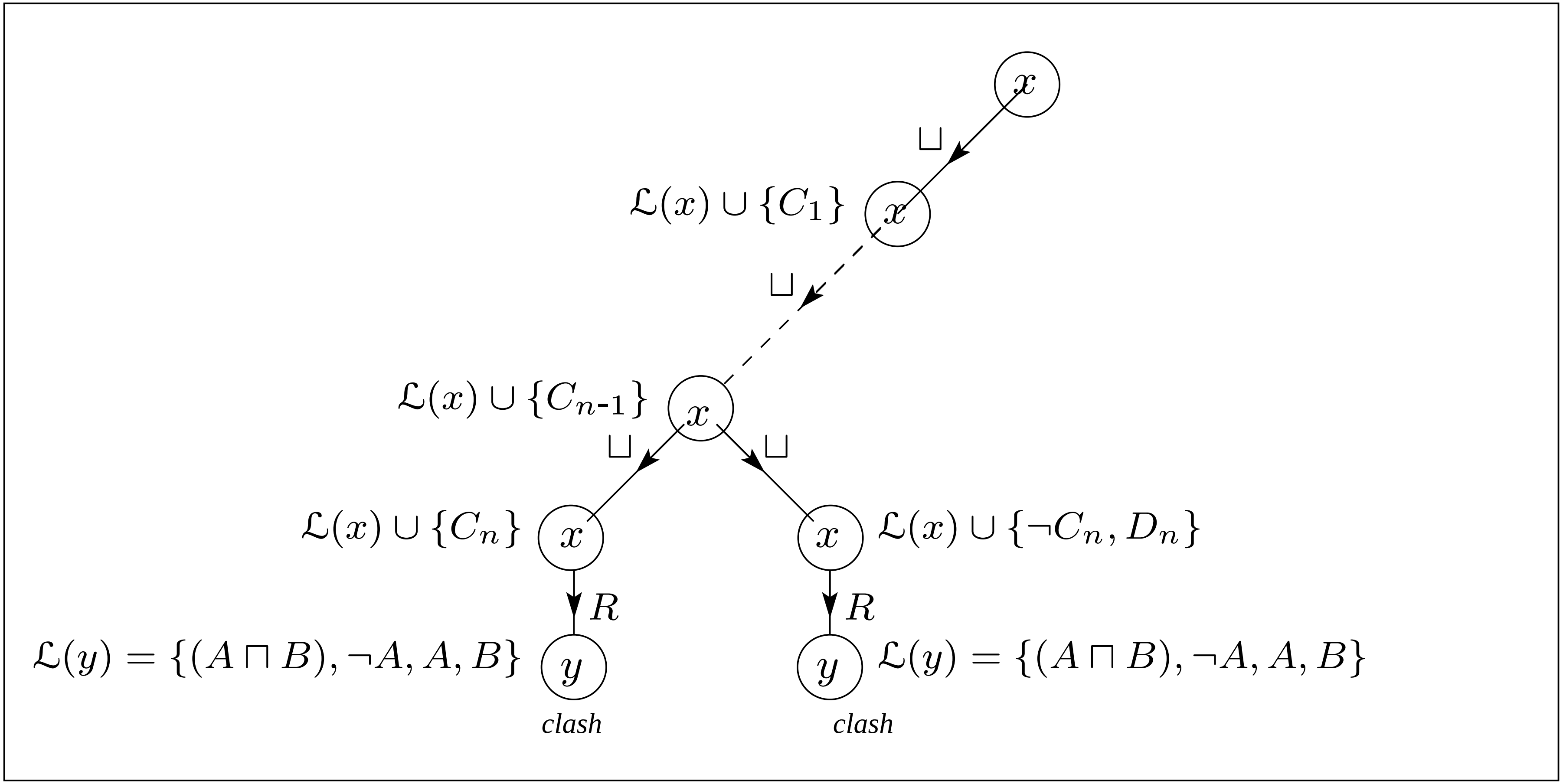

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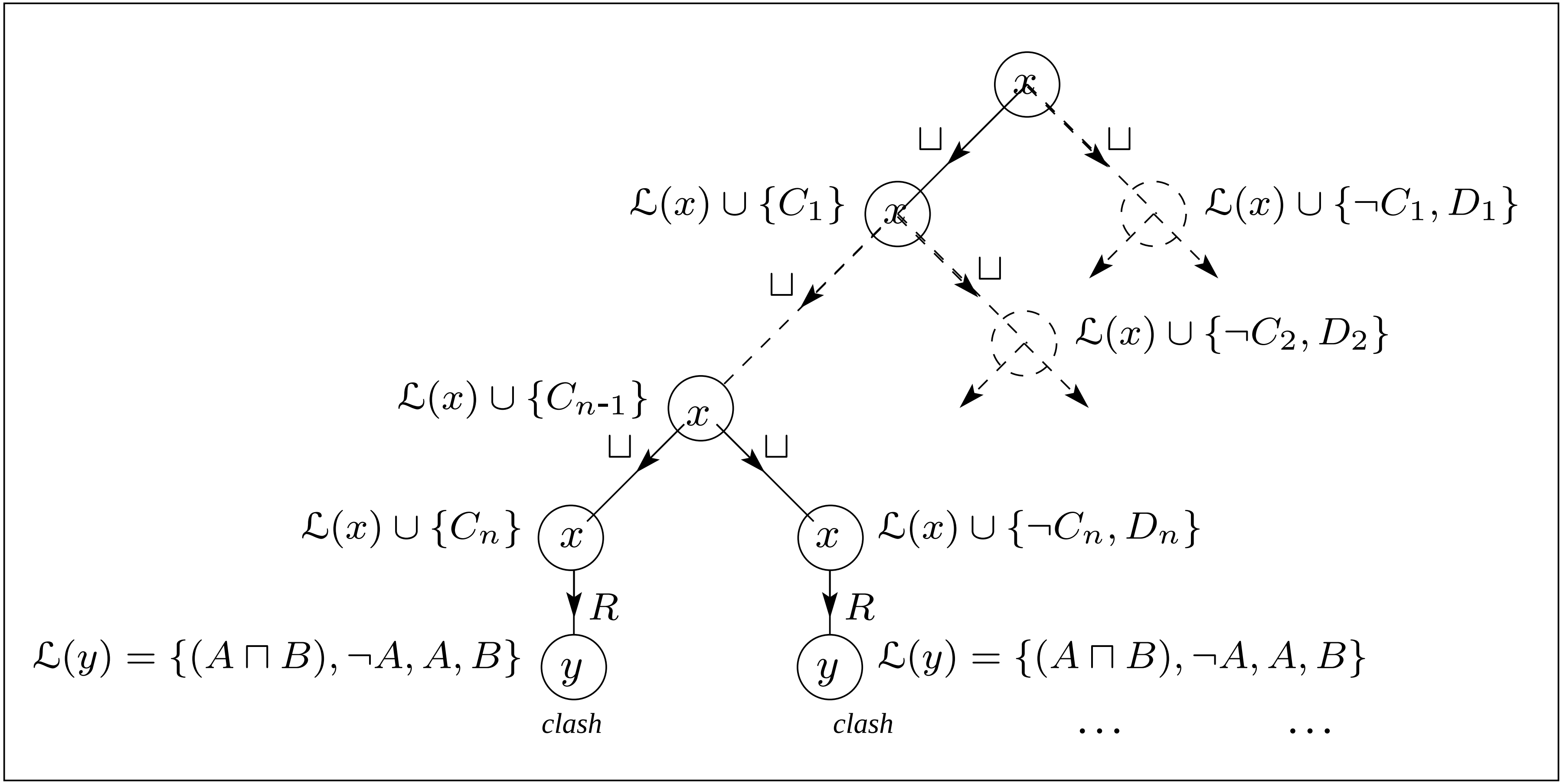

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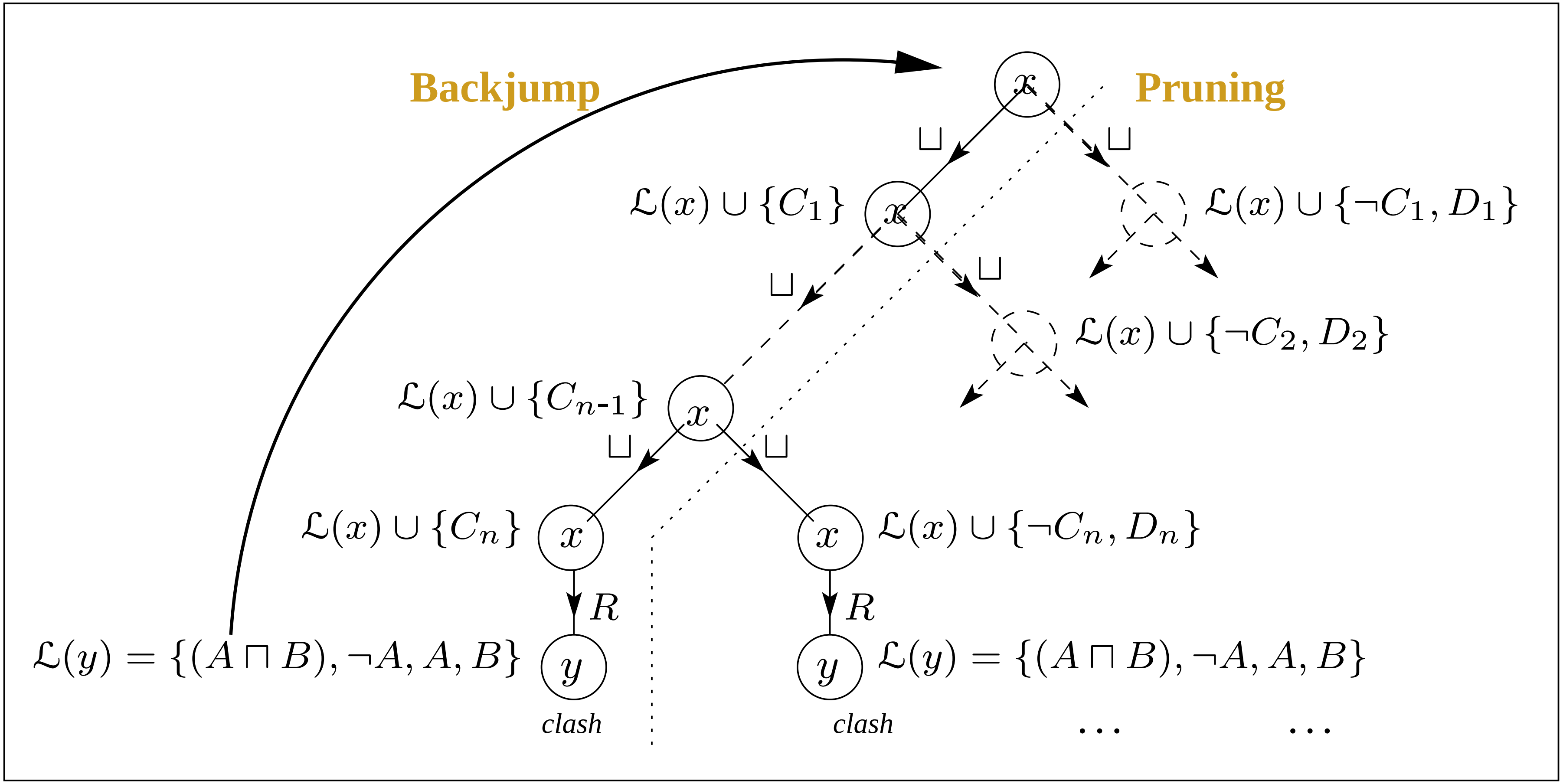

Axioms and Rules

KR Rules (Horn Clauses)

☞ Rules (at least KR rules) can be seen as a form of axiom, e.g.:

$$\begin{aligned} p(x) \leftarrow q(x) \wedge w(x) \quad &\equiv \quad p \sqsubseteq q \sqcap w \\ p(x) \leftarrow q(x) \wedge r(x,y) \wedge w(y) \quad &\equiv \quad p \sqsubseteq q \sqcap \exists r.w \end{aligned}$$

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- Distinguished variables have implicit $\forall$, others have implicit $\exists$, i.e.:

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- Closed world doesn't make sense in ontologies
  - **Don't** want to infer Person $\sqsubseteq$ American just because only have information about Americans

More Complex Examples

☞ E.g., the "discount" example:

$$\begin{aligned} \text{discount}(x, 7\%) \quad \leftarrow \quad & \text{customer}(x) \wedge \text{category}(x, y) \\ & \wedge \text{premium}(y) \wedge \text{buys}(x, z) \wedge \text{product}(z) \\ & \wedge \text{category}(z, w) \wedge \text{luxury}(w) \end{aligned}$$

can be written in DL as:

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☞ May **not** capture intended semantics

- Should be able to fix this by modeling transactions instead of customers

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- Applications can implement many “rule-like” features using queries

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- Can't combine with expressive DLs (and still stay decidable)
  - adding these constructs to $\mathcal{SHIQ}$ leads to undecidability

Intersection of Rules and DLs

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☞ Result is a strange and asymmetrical DL

Other Approaches

☞ Can layer rules on top of DL
  - rule predicates can be DL classes or roles
  - several examples have been implemented
  - best known is Carin system from Levy & Rousset
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- Some existing work on language **fusions** and **hybrid** reasoners

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- **New reasoning tasks**
  - Querying
  - Lcs/matching
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DAML+OIL extends $\mathcal{SHIQ}$ with datatypes and nominals

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☞ Already seeing some (limited) **implementations**

- E.g., Cerebra system (Network Inference)

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- Relatively straightforward (in theory) without **inverse roles**
  - Algorithm for $\mathcal{SHOQ}(\mathbf{D})$ deals with nominals
  - Practical implementation still to be demonstrated

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- Reasoning with **individuals** (Abox)
  - Deployment of web ontologies will mean reasoning with (possibly very large numbers of) individuals
  - Standard Abox techniques may not be able to cope

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  - DL systems shown to work with $\approx$100k concept KB [Haarslev & Möller]
  - But KB only exploited small part of DL language

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- **DAML+OIL** is web ontology language based on **Description Logic**
- Ontology design, integration and deployment **supported by reasoning**
- DLs are **logic based KR formalisms** with emphasis on reasoning
- DL systems provide **efficient reasoning services**
  - Careful choice of logic/algorithm
  - Highly optimised implementation

Resources

Slides from this talk

`www.cs.man.ac.uk/~horrocks/Slides/dagstuhl070202.pdf`

FaCT system

`www.cs.man.ac.uk/fact`

OIL

`www.ontoknowledge.org/oil/`

DAML+OIL

`www.daml.org/language/`

OilEd

`img.cs.man.ac.uk/oil`

I.COM

`www.cs.man.ac.uk/~franconi/icom/`

Select Bibliography

F. Baader, E. Franconi, B. Hollunder, B. Nebel, and H.-J. Profitlich. An empirical analysis of optimization techniques for terminological representation systems or: Making KRIS get a move on. In B. Nebel, C. Rich, and W. Swartout, editors, *Proc. of KR'92*, pages 270–281. Morgan Kaufmann, 1992.

F. Giunchiglia and R. Sebastiani. A SAT-based decision procedure for $\mathcal{ALC}$. In *Proc. of KR'96*, pages 304–314. Morgan Kaufmann, 1996.

V. Haarslev and R. Möller. High performance reasoning with very large knowledge bases: A practical case study. In *Proc. of IJCAI 2001* (to appear).

B. Hollunder and W. Nutt. Subsumption algorithms for concept languages. In *Proc. of ECAI'90*, pages 348–353. John Wiley & Sons Ltd., 1990.

Select Bibliography

I. Horrocks. *Optimising Tableaux Decision Procedures for Description Logics*. PhD thesis, University of Manchester, 1997.

I. Horrocks and P. F. Patel-Schneider. Comparing subsumption optimizations. In *Proc. of DL'98*, pages 90–94. CEUR, 1998.

I. Horrocks and P. F. Patel-Schneider. Optimising description logic subsumption. *Journal of Logic and Computation*, 9(3):267–293, 1999.

I. Horrocks and S. Tobies. Reasoning with axioms: Theory and practice. In *Proc. of KR'00* pages 285–296. Morgan Kaufmann, 2000.

E. Franconi and G. Ng. The i.com tool for intelligent conceptual modelling. In *Proc. of (KRDB'00)*, August 2000.

D. Fensel, F. van Harmelen, I. Horrocks, D. McGuinness, and P. F. Patel-Schneider. OIL: An ontology infrastructure for the semantic web. *IEEE Intelligent Systems*, 16(2):38–45, 2001.

A. Levy and M.-C. Rousset". CARIN: A Representation Language Combining Horn Rules and Description Logics In *Proc. of (ECAI'96)*, 1996.