
DAML+OIL and Description Logic Reasoning

Ian Horrocks

horrocks@cs.man.ac.uk

University of Manchester

Manchester, UK

Talk Outline

Talk Outline

The Semantic Web and DAML+OIL

Talk Outline

The Semantic Web and DAML+OIL
Description Logics and Reasoning
Reasoning techniques
Implementing DL systems

Talk Outline

The Semantic Web and DAML+OIL
Description Logics and Reasoning
 Reasoning techniques
 Implementing DL systems
Research Challenges

Talk Outline

The Semantic Web and DAML+OIL
Description Logics and Reasoning
 Reasoning techniques
 Implementing DL systems
Research Challenges
Summary

The Semantic Web and DAML+OIL

Semantic Web Ontology Languages

US **DAML** programme (in cooperation with W3C and a cast of thousands)
aim to develop so-called **Semantic Web**

Semantic Web Ontology Languages

US **DAML** programme (in cooperation with W3C and a cast of thousands) aim to develop so-called **Semantic Web**

- ☞ Most existing Web resources only human understandable
 - Markup (HTML) provides **rendering information**
 - Textual/graphical information for **human consumption**

Semantic Web Ontology Languages

US **DAML** programme (in cooperation with W3C and a cast of thousands) aim to develop so-called **Semantic Web**

- ☞ Most existing Web resources only human understandable
 - Markup (HTML) provides **rendering information**
 - Textual/graphical information for **human consumption**
- ☞ Semantic Web aims at machine understandability
 - **Semantic** markup will be added to web resources
 - Markup will use **Ontologies** for shared understanding

Semantic Web Ontology Languages

US **DAML** programme (in cooperation with W3C and a cast of thousands) aim to develop so-called **Semantic Web**

- ➡ Most existing Web resources only human understandable
 - Markup (HTML) provides **rendering information**
 - Textual/graphical information for **human consumption**
- ➡ Semantic Web aims at machine understandability
 - **Semantic** markup will be added to web resources
 - Markup will use **Ontologies** for shared understanding
- ➡ Requirement for a suitable ontology language
 - Compatible with existing Web standards (XML, RDF, RDFS)
 - Captures common KR idioms
 - Formally specified and of adequate expressive power
 - Can provide reasoning support

Semantic Web Ontology Languages

US **DAML** programme (in cooperation with W3C and a cast of thousands) aim to develop so-called **Semantic Web**

- ➔ Most existing Web resources only human understandable
 - Markup (HTML) provides **rendering information**
 - Textual/graphical information for **human consumption**
- ➔ Semantic Web aims at machine understandability
 - **Semantic** markup will be added to web resources
 - Markup will use **Ontologies** for shared understanding
- ➔ Requirement for a suitable ontology language
 - Compatible with existing Web standards (XML, RDF, RDFS)
 - Captures common KR idioms
 - Formally specified and of adequate expressive power
 - Can provide reasoning support
- ➔ DAML-ONT language developed to meet these requirements

OIL and DAML+OIL

Meanwhile, somewhere in darkest Europe...

OIL and DAML+OIL

Meanwhile, somewhere in darkest Europe...

- 👉 **OIL** language already developed to meet similar requirements

OIL and DAML+OIL

Meanwhile, somewhere in darkest Europe...

- ☞ **OIL** language already developed to meet similar requirements
 - Extends existing Web standards (XML, RDF, RDFS)
 - Intuitive (frame) syntax plus high expressive power
 - Well defined semantics via mapping to *SHIQ* DL
 - Can use DL systems to reason with OIL ontologies

OIL and DAML+OIL

Meanwhile, somewhere in darkest Europe...

- ☞ **OIL** language already developed to meet similar requirements
 - Extends existing Web standards (XML, RDF, RDFS)
 - Intuitive (frame) syntax plus high expressive power
 - Well defined semantics via mapping to *SHIQ* DL
 - Can use DL systems to reason with OIL ontologies
- ☞ Two efforts merged to produce single language, **DAML+OIL**

OIL and DAML+OIL

Meanwhile, somewhere in darkest Europe...

- ➔ **OIL** language already developed to meet similar requirements
 - Extends existing Web standards (XML, RDF, RDFS)
 - Intuitive (frame) syntax plus high expressive power
 - Well defined semantics via mapping to *SHIQ* DL
 - Can use DL systems to reason with OIL ontologies
- ➔ Two efforts merged to produce single language, **DAML+OIL**
- ➔ Detailed specification agreed by **Joint EU/US Committee on Agent Markup Languages**

OIL and DAML+OIL

Meanwhile, somewhere in darkest Europe...

- ➡ **OIL** language already developed to meet similar requirements
 - Extends existing Web standards (XML, RDF, RDFS)
 - Intuitive (frame) syntax plus high expressive power
 - Well defined semantics via mapping to *SHIQ* DL
 - Can use DL systems to reason with OIL ontologies
- ➡ Two efforts merged to produce single language, **DAML+OIL**
- ➡ Detailed specification agreed by **Joint EU/US Committee on Agent Markup Languages**
- ➡ Proposed W3C Ontology Language WG will take DAML+OIL as starting point (?)

DAML+OIL Language Overview

DAML+OIL is an **ontology** language

DAML+OIL Language Overview

DAML+OIL is an **ontology** language

- ☞ Describes **structure** of the domain (i.e., a Tbox)
 - RDF used to describe specific **instances** (i.e., an Abox)

DAML+OIL Language Overview

DAML+OIL is an **ontology** language

- ➔ Describes **structure** of the domain (i.e., a Tbox)
 - RDF used to describe specific **instances** (i.e., an Abox)
- ➔ Structure described in terms of **classes** (concepts) and **properties** (roles)

DAML+OIL Language Overview

DAML+OIL is an **ontology** language

- ➔ Describes **structure** of the domain (i.e., a Tbox)
 - RDF used to describe specific **instances** (i.e., an Abox)
- ➔ Structure described in terms of **classes** (concepts) and **properties** (roles)
- ➔ Ontology consists of set of **axioms**
 - E.g., asserting class subsumption/equivalence

DAML+OIL Language Overview

DAML+OIL is an **ontology** language

- ➔ Describes **structure** of the domain (i.e., a Tbox)
 - RDF used to describe specific **instances** (i.e., an Abox)
- ➔ Structure described in terms of **classes** (concepts) and **properties** (roles)
- ➔ Ontology consists of set of **axioms**
 - E.g., asserting class subsumption/equivalence
- ➔ Classes can be names or **expressions**
 - Various **constructors** provided for building class expressions

DAML+OIL Language Overview

DAML+OIL is an **ontology** language

- ➔ Describes **structure** of the domain (i.e., a Tbox)
 - RDF used to describe specific **instances** (i.e., an Abox)
- ➔ Structure described in terms of **classes** (concepts) and **properties** (roles)
- ➔ Ontology consists of set of **axioms**
 - E.g., asserting class subsumption/equivalence
- ➔ Classes can be names or **expressions**
 - Various **constructors** provided for building class expressions
- ➔ **Expressive power** determined by
 - Kinds of axiom supported
 - Kinds of class (and property) constructor supported

DAML+OIL Overview: Class Constructors

Constructor	DL Syntax	Example
intersectionOf	$C_1 \sqcap \dots \sqcap C_n$	Human \sqcap Male
unionOf	$C_1 \sqcup \dots \sqcup C_n$	Doctor \sqcup Lawyer
complementOf	$\neg C$	\neg Male
oneOf	$\{x_1 \dots x_n\}$	{john, mary}
toClass	$\forall P.C$	\forall hasChild.Doctor
hasClass	$\exists P.C$	\exists hasChild.Lawyer
hasValue	$\exists P.\{x\}$	\exists citizenOf.{USA}
minCardinalityQ	$\geq_n P.C$	≥ 2 hasChild.Lawyer
maxCardinalityQ	$\leq_n P.C$	≤ 1 hasChild.Male
cardinalityQ	$=_n P.C$	$= 1$ hasParent.Female

DAML+OIL Overview: Class Constructors

Constructor	DL Syntax	Example
intersectionOf	$C_1 \sqcap \dots \sqcap C_n$	Human \sqcap Male
unionOf	$C_1 \sqcup \dots \sqcup C_n$	Doctor \sqcup Lawyer
complementOf	$\neg C$	\neg Male
oneOf	$\{x_1 \dots x_n\}$	{john, mary}
toClass	$\forall P.C$	\forall hasChild.Doctor
hasClass	$\exists P.C$	\exists hasChild.Lawyer
hasValue	$\exists P.\{x\}$	\exists citizenOf.{USA}
minCardinalityQ	$\geq n P.C$	≥ 2 hasChild.Lawyer
maxCardinalityQ	$\leq n P.C$	≤ 1 hasChild.Male
cardinalityQ	$= n P.C$	$= 1$ hasParent.Female

👉 XMLS **datatypes** as well as classes

DAML+OIL Overview: Class Constructors

Constructor	DL Syntax	Example
intersectionOf	$C_1 \sqcap \dots \sqcap C_n$	Human \sqcap Male
unionOf	$C_1 \sqcup \dots \sqcup C_n$	Doctor \sqcup Lawyer
complementOf	$\neg C$	\neg Male
oneOf	$\{x_1 \dots x_n\}$	{john, mary}
toClass	$\forall P.C$	\forall hasChild.Doctor
hasClass	$\exists P.C$	\exists hasChild.Lawyer
hasValue	$\exists P.\{x\}$	\exists citizenOf.{USA}
minCardinalityQ	$\geq n P.C$	≥ 2 hasChild.Lawyer
maxCardinalityQ	$\leq n P.C$	≤ 1 hasChild.Male
cardinalityQ	$= n P.C$	$= 1$ hasParent.Female

- ➔ XMLS **datatypes** as well as classes
- ➔ Arbitrarily complex **nesting** of constructors
 - E.g., \forall hasChild.(Doctor \sqcup \exists hasChild.Doctor)

DAML+OIL Overview: Axioms

Axiom	DL Syntax	Example
subClassOf	$C_1 \sqsubseteq C_2$	Human \sqsubseteq Animal \sqcap Biped
sameClassAs	$C_1 \doteq C_2$	Man \doteq Human \sqcap Male
subPropertyOf	$P_1 \sqsubseteq P_2$	hasDaughter \sqsubseteq hasChild
samePropertyAs	$P_1 \doteq P_2$	cost \doteq price
sameIndividualAs	$\{x_1\} \doteq \{x_2\}$	{President_Bush} \doteq {G_W_Bush}
disjointWith	$C_1 \sqsubseteq \neg C_2$	Male $\sqsubseteq \neg$ Female
differentIndividualFrom	$\{x_1\} \sqsubseteq \neg\{x_2\}$	{john} $\sqsubseteq \neg$ {peter}
inverseOf	$P_1 \doteq P_2^-$	hasChild \doteq hasParent ⁻
transitiveProperty	$P^+ \sqsubseteq P$	ancestor ⁺ \sqsubseteq ancestor
uniqueProperty	$\top \sqsubseteq \leq 1P$	$\top \sqsubseteq \leq 1$ hasMother
UnambiguousProperty	$\top \sqsubseteq \leq 1P^-$	$\top \sqsubseteq \leq 1$ isMotherOf ⁻

DAML+OIL Overview: Axioms

Axiom	DL Syntax	Example
subClassOf	$C_1 \sqsubseteq C_2$	Human \sqsubseteq Animal \sqcap Biped
sameClassAs	$C_1 \doteq C_2$	Man \doteq Human \sqcap Male
subPropertyOf	$P_1 \sqsubseteq P_2$	hasDaughter \sqsubseteq hasChild
samePropertyAs	$P_1 \doteq P_2$	cost \doteq price
sameIndividualAs	$\{x_1\} \doteq \{x_2\}$	{President_Bush} \doteq {G_W_Bush}
disjointWith	$C_1 \sqsubseteq \neg C_2$	Male $\sqsubseteq \neg$ Female
differentIndividualFrom	$\{x_1\} \sqsubseteq \neg\{x_2\}$	{john} $\sqsubseteq \neg$ {peter}
inverseOf	$P_1 \doteq P_2^-$	hasChild \doteq hasParent ⁻
transitiveProperty	$P^+ \sqsubseteq P$	ancestor ⁺ \sqsubseteq ancestor
uniqueProperty	$\top \sqsubseteq \leq 1P$	$\top \sqsubseteq \leq 1$ hasMother
UnambiguousProperty	$\top \sqsubseteq \leq 1P^-$	$\top \sqsubseteq \leq 1$ isMotherOf ⁻

➔ Axioms (mostly) **reducible to subClass/PropertyOf**

DAML+OIL

DAML+OIL

☞ Is a **Description Logic**

DAML+OIL

☞ Is a **Description Logic** (but don't tell anyone)

DAML+OIL

- ➔ Is a **Description Logic** (but don't tell anyone)
- ➔ More precisely, DAML+OIL is *SHIQ*

DAML+OIL

- ➔ Is a **Description Logic** (but don't tell anyone)
- ➔ More precisely, DAML+OIL is *SHIQ*
 - Plus **nominals**

DAML+OIL

- ☞ Is a **Description Logic** (but don't tell anyone)
- ☞ More precisely, DAML+OIL is *SHIQ*
 - Plus **nominals**
 - Plus **datatypes** (simple concrete domains)

DAML+OIL

- ☞ Is a **Description Logic** (but don't tell anyone)
- ☞ More precisely, DAML+OIL is *SHIQ*
 - Plus **nominals**
 - Plus **datatypes** (simple concrete domains)
 - With RDFS based syntax

DAML+OIL

- ☞ Is a **Description Logic** (but don't tell anyone)
- ☞ More precisely, DAML+OIL is *SHIQ*
 - Plus **nominals**
 - Plus **datatypes** (simple concrete domains)
 - With RDFS based syntax
- ☞ *SHIQ*/DAML+OIL was not built in a day (or even a year)
 - *SHIQ* is based on 15+ years of DL research

DAML+OIL

- ➔ Is a **Description Logic** (but don't tell anyone)
- ➔ More precisely, DAML+OIL is *SHIQ*
 - Plus **nominals**
 - Plus **datatypes** (simple concrete domains)
 - With RDFS based syntax
- ➔ *SHIQ*/DAML+OIL was not built in a day (or even a year)
 - *SHIQ* is based on 15+ years of DL research
- ➔ Can use DL reasoning with DAML+OIL
 - Existing *SHIQ* implementations support (most of) DAML+OIL

Why Reasoning Services?

Reasoning is important for:

Why Reasoning Services?

Reasoning is important for:

☞ **Ontology design**

- Check class consistency and (unexpected) implied relationships
- Particularly important with large ontologies/multiple authors

Why Reasoning Services?

Reasoning is important for:

☞ **Ontology design**

- Check class consistency and (unexpected) implied relationships
- Particularly important with large ontologies/multiple authors

☞ **Ontology integration**

- Assert inter-ontology relationships
- Reasoner computes integrated class hierarchy/consistency

Why Reasoning Services?

Reasoning is important for:

☞ Ontology **design**

- Check class consistency and (unexpected) implied relationships
- Particularly important with large ontologies/multiple authors

☞ Ontology **integration**

- Assert inter-ontology relationships
- Reasoner computes integrated class hierarchy/consistency

☞ Ontology **deployment**

- Determine if set of facts are consistent w.r.t. ontology
- Determine if individuals are instances of ontology classes

Why Reasoning Services?

Reasoning is important for:

☞ **Ontology design**

- Check class consistency and (unexpected) implied relationships
- Particularly important with large ontologies/multiple authors

☞ **Ontology integration**

- Assert inter-ontology relationships
- Reasoner computes integrated class hierarchy/consistency

☞ **Ontology deployment**

- Determine if set of facts are consistent w.r.t. ontology
- Determine if individuals are instances of ontology classes

“The Semantic Web needs a logic on top” (Henry Thompson)

Why Decidable Reasoning?

Set of operators/axioms restricted so that reasoning is **decidable**

Why Decidable Reasoning?

Set of operators/axioms restricted so that reasoning is **decidable**

☞ Consistent with Semantic Web's **layered architecture**

Why Decidable Reasoning?

Set of operators/axioms restricted so that reasoning is **decidable**

- ☞ Consistent with Semantic Web's **layered architecture**
 - XML provides syntax transport layer
 - RDF provides basic relational language
 - RDFS provides basic ontological primitives
 - DAML+OIL provides (decidable) logical layer
 - Further layers (e.g., **rules**) will extend DAML+OIL
 - ➔ Extensions will almost certainly be **undecidable**

Why Decidable Reasoning?

Set of operators/axioms restricted so that reasoning is **decidable**

- ☞ Consistent with Semantic Web's **layered architecture**
 - XML provides syntax transport layer
 - RDF provides basic relational language
 - RDFS provides basic ontological primitives
 - DAML+OIL provides (decidable) logical layer
 - Further layers (e.g., **rules**) will extend DAML+OIL
 - ➔ Extensions will almost certainly be **undecidable**
- ☞ Facilitates provision of **reasoning services**

Why Decidable Reasoning?

Set of operators/axioms restricted so that reasoning is **decidable**

- ☞ Consistent with Semantic Web's **layered architecture**
 - XML provides syntax transport layer
 - RDF provides basic relational language
 - RDFS provides basic ontological primitives
 - DAML+OIL provides (decidable) logical layer
 - Further layers (e.g., **rules**) will extend DAML+OIL
 - ➔ Extensions will almost certainly be **undecidable**
- ☞ Facilitates provision of **reasoning services**
 - Known algorithms
 - Implemented systems
 - Evidence of **empirical tractability**

Reasoning Support for Ontology Design: OilEd

OilEd is a DAML+OIL **ontology editor** with DL reasoning support

Reasoning Support for Ontology Design: OilEd

OilEd is a DAML+OIL **ontology editor** with DL reasoning support

- ➔ **Frame based** interface (inspired by Protégé)
 - Classes defined by superclass(es) plus slot constraints

Reasoning Support for Ontology Design: OilEd

OilEd is a DAML+OIL **ontology editor** with DL reasoning support

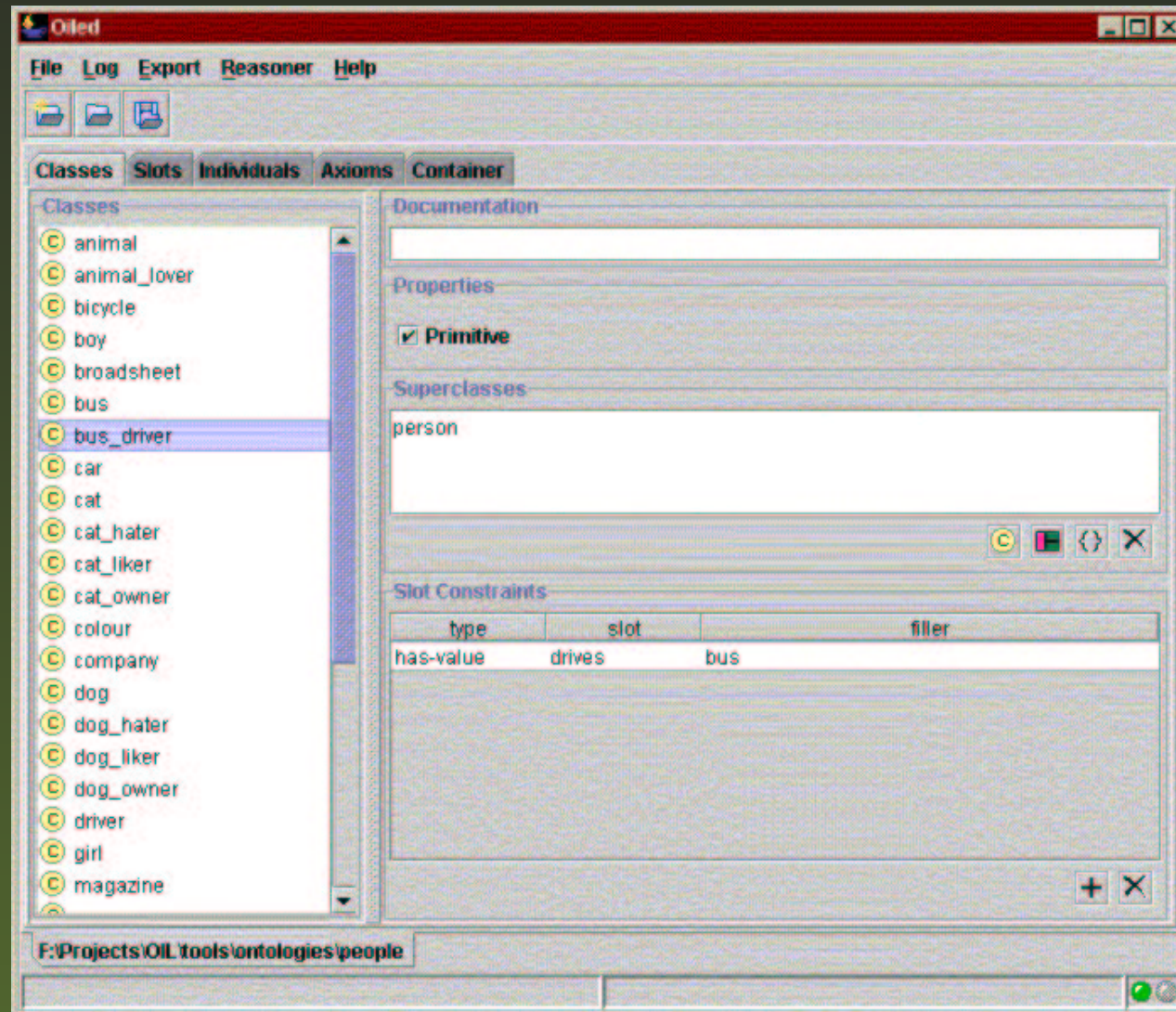
- ➡ **Frame based** interface (inspired by Protégé)
 - Classes defined by superclass(es) plus slot constraints
- ➡ Extended to **clarify semantics** and capture whole language
 - Primitive (\sqsubseteq) and defined (\doteq) classes
 - Explicit \exists (hasClass), \forall (toClass) and cardinality restrictions
 - Boolean connectives (\sqcap , \sqcup , \neg) and nesting
 - Transitive, symmetrical and functional properties
 - Disjointness, inclusion (\sqsubseteq) and equality (\doteq) axioms
 - Fake individuals

Reasoning Support for Ontology Design: OilEd

OilEd is a DAML+OIL **ontology editor** with DL reasoning support

- ➡ **Frame based** interface (inspired by Protégé)
 - Classes defined by superclass(es) plus slot constraints
- ➡ Extended to **clarify semantics** and capture whole language
 - Primitive (\sqsubseteq) and defined (\doteq) classes
 - Explicit \exists (hasClass), \forall (toClass) and cardinality restrictions
 - Boolean connectives (\sqcap , \sqcup , \neg) and nesting
 - Transitive, symmetrical and functional properties
 - Disjointness, inclusion (\sqsubseteq) and equality (\doteq) axioms
 - Fake individuals
- ➡ **Reasoning support** provided by FaCT system
 - Ontology translated into *SHIQ* DL
 - Communicates with FaCT via CORBA interface
 - Indicates inconsistencies and implicit subsumptions

OilEd



Description Logics and Reasoning

What are Description Logics?

What are Description Logics?

A family of logic based Knowledge Representation formalisms

What are Description Logics?

A family of logic based Knowledge Representation formalisms

- ➔ Based on **concepts** (classes) and **roles**
 - Concepts (classes) are interpreted as sets of objects
 - Roles are interpreted as binary relations on objects

What are Description Logics?

A family of logic based Knowledge Representation formalisms

- ➔ Based on **concepts** (classes) and **roles**
 - Concepts (classes) are interpreted as sets of objects
 - Roles are interpreted as binary relations on objects
- ➔ Descendants of **semantic networks** and **KL-ONE**

What are Description Logics?

A family of logic based Knowledge Representation formalisms

- ➔ Based on **concepts** (classes) and **roles**
 - Concepts (classes) are interpreted as sets of objects
 - Roles are interpreted as binary relations on objects
- ➔ Descendants of **semantic networks** and **KL-ONE**
- ➔ **Decidable fragments** of FOL
 - Many DLs are fragments of L2, C2 or the **Guarded Fragment**

What are Description Logics?

A family of logic based Knowledge Representation formalisms

- ➔ Based on **concepts** (classes) and **roles**
 - Concepts (classes) are interpreted as sets of objects
 - Roles are interpreted as binary relations on objects
- ➔ Descendants of **semantic networks** and **KL-ONE**
- ➔ **Decidable fragments** of FOL
 - Many DLs are fragments of L2, C2 or the **Guarded Fragment**
- ➔ Closely related to **propositional modal logics**

What are Description Logics?

A family of logic based Knowledge Representation formalisms

- ➔ Based on **concepts** (classes) and **roles**
 - Concepts (classes) are interpreted as sets of objects
 - Roles are interpreted as binary relations on objects
- ➔ Descendants of **semantic networks** and **KL-ONE**
- ➔ **Decidable fragments** of FOL
 - Many DLs are fragments of L2, C2 or the **Guarded Fragment**
- ➔ Closely related to **propositional modal logics**
- ➔ Also known as terminological logics, concept languages, etc.

What are Description Logics?

A family of logic based Knowledge Representation formalisms

- ➔ Based on **concepts** (classes) and **roles**
 - Concepts (classes) are interpreted as sets of objects
 - Roles are interpreted as binary relations on objects
- ➔ Descendants of **semantic networks** and **KL-ONE**
- ➔ **Decidable fragments** of FOL
 - Many DLs are fragments of L2, C2 or the **Guarded Fragment**
- ➔ Closely related to **propositional modal logics**
- ➔ Also known as terminological logics, concept languages, etc.
- ➔ Key features of DLs are
 - Well defined **semantics** (they are logics)
 - Provision of **inference services**

Short History of Description Logics

Short History of Description Logics

Phase 1:

- ➔ Incomplete systems (Back, Classic, Loom, ...)
- ➔ Based on **structural algorithms**

Short History of Description Logics

Phase 1:

- ➔ Incomplete systems (Back, Classic, Loom, ...)
- ➔ Based on **structural algorithms**

Phase 2:

- ➔ Development of **tableau algorithms** and complexity results
- ➔ Tableau-based systems (Kris, Crack)
- ➔ Investigation of optimisation techniques

Short History of Description Logics

Phase 1:

- ➔ Incomplete systems (Back, Classic, Loom, ...)
- ➔ Based on **structural algorithms**

Phase 2:

- ➔ Development of **tableau algorithms** and complexity results
- ➔ Tableau-based systems (Kris, Crack)
- ➔ Investigation of optimisation techniques

Phase 3:

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

Latest Developments

Phase 4:

☞ Mature **implementations**

Latest Developments

Phase 4:

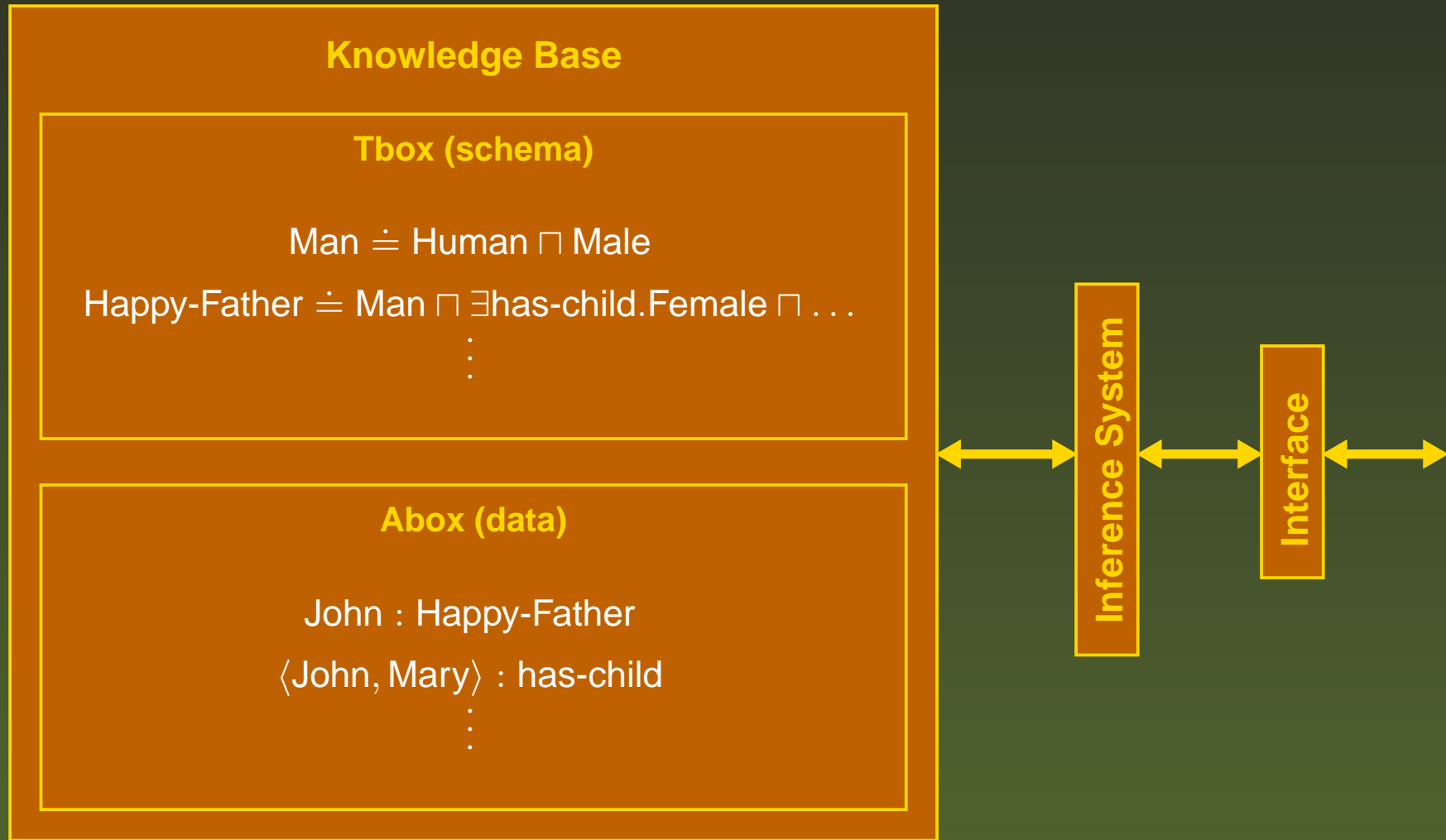
- ☞ Mature **implementations**
- ☞ Mainstream **applications** and Tools
 - Databases
 - Consistency of conceptual schemata
 - Schema integration
 - Query subsumption (w.r.t. a conceptual schema)
 - Ontologies and Semantic Web
 - Design and Maintenance
 - Integration
 - Deployment

Latest Developments

Phase 4:

- ☞ Mature **implementations**
- ☞ Mainstream **applications** and Tools
 - Databases
 - Consistency of conceptual schemata
 - Schema integration
 - Query subsumption (w.r.t. a conceptual schema)
 - Ontologies and Semantic Web
 - Design and Maintenance
 - Integration
 - Deployment
- ☞ **Commercial** implementations
 - Cerebra system from Network Inference Ltd

DL System Architecture



DL Constructors

Particular DLs characterised by **set of constructors** provided for building complex concepts and roles from simpler ones

DL Constructors

Particular DLs characterised by **set of constructors** provided for building complex concepts and roles from simpler ones

➡ Usually include at least:

- Conjunction (\sqcap), disjunction (\sqcup), negation (\neg)
- Restricted (guarded) forms of quantification (\exists , \forall)

DL Constructors

Particular DLs characterised by **set of constructors** provided for building complex concepts and roles from simpler ones

- ➡ Usually include at least:
 - Conjunction (\sqcap), disjunction (\sqcup), negation (\neg)
 - Restricted (guarded) forms of quantification (\exists , \forall)
- ➡ This basic DL is known as *ALC*

DL Constructors

Particular DLs characterised by **set of constructors** provided for building complex concepts and roles from simpler ones

➡ Usually include at least:

- Conjunction (\sqcap), disjunction (\sqcup), negation (\neg)
- Restricted (guarded) forms of quantification (\exists , \forall)

➡ This basic DL is known as *ALC*

For example, concept **Happy Father** in *ALC*:

Man \sqcap \exists has-child.Male
 \sqcap \exists has-child.Female
 \sqcap \forall has-child.(Doctor \sqcup Lawyer)

DL Syntax and Semantics

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

DL Syntax and Semantics

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

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	$\Delta^{\mathcal{I}} \setminus C^{\mathcal{I}}$
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	$\{x \mid \forall y. \langle x, y \rangle \in R^{\mathcal{I}} \implies y \in C^{\mathcal{I}}\}$

Other DL Constructors

Many different DLs/DL constructors have been investigated, e.g.

Other DL Constructors

Many different DLs/DL constructors have been investigated, e.g.

Constructor	Syntax	Example	Semantics
number restr.	$\geq nR$	≥ 3 has-child	$\{x \mid \{y.\langle x, y \rangle \in R^{\mathcal{I}}\} \geq n\}$
	$\leq nR$	≤ 1 has-mother	$\{x \mid \{y.\langle x, y \rangle \in R^{\mathcal{I}}\} \leq n\}$
inverse role	R^-	has-child ⁻	$\{\langle x, y \rangle \mid \langle y, x \rangle \in R^{\mathcal{I}}\}$
trans. role	R^*	has-child [*]	$(R^{\mathcal{I}})^*$
concrete domain	$f_1, \dots, f_n.P$	earns spends <	$\{x \mid P(f_1^{\mathcal{I}}, \dots, f_n^{\mathcal{I}})\}$
	⋮		

DL Knowledge Base (Tbox)

Terminological part (**Tbox**) is set of axioms describing **structure** of domain

DL Knowledge Base (Tbox)

Terminological part (**Tbox**) is set of axioms describing **structure** of domain

Definition axioms introduce macros/names for concepts

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

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

$$\text{Human} \sqsubseteq \text{Animal} \sqcap \text{Biped}$$

DL Knowledge Base (Tbox)

Terminological part (**Tbox**) is set of axioms describing **structure** of domain

Definition axioms introduce macros/names for concepts

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

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

$$\text{Human} \sqsubseteq \text{Animal} \sqcap \text{Biped}$$

Inclusion (GCI) axioms assert subsumption relations

$$C \sqsubseteq D \quad (\text{note } C \doteq D \text{ equivalent to } C \sqsubseteq D \text{ and } D \sqsubseteq C)$$

$$\exists \text{has-degree.Masters} \sqsubseteq \exists \text{has-degree.Bachelors}$$

DL Knowledge Base (Tbox)

Terminological part (**Tbox**) is set of axioms describing **structure** of domain

Definition axioms introduce macros/names for concepts

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

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

$$\text{Human} \sqsubseteq \text{Animal} \sqcap \text{Biped}$$

Inclusion (GCI) axioms assert subsumption relations

$$C \sqsubseteq D \quad (\text{note } C \doteq D \text{ equivalent to } C \sqsubseteq D \text{ and } D \sqsubseteq C)$$

$$\exists \text{has-degree.Masters} \sqsubseteq \exists \text{has-degree.Bachelors}$$

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

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

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

DL Knowledge Base (Abox)

Assertional part (**Abox**) is set of axioms describing **concrete situation**

DL Knowledge Base (Abox)

Assertional part (**Abox**) is set of axioms describing **concrete situation**

Concept assertions

$a : C$

John : $\text{Man} \sqcap \exists \text{has-child.Female}$

DL Knowledge Base (Abox)

Assertional part (**Abox**) is set of axioms describing **concrete situation**

Concept assertions

$a : C$

John : $\text{Man} \sqcap \exists \text{has-child.Female}$

Role assertions

$\langle a, b \rangle : R$

$\langle \text{John}, \text{Mary} \rangle : \text{has-child}$

DL Knowledge Base (Abox)

Assertional part (**Abox**) is set of axioms describing **concrete situation**

Concept assertions

$a : C$

John : $\text{Man} \sqcap \exists \text{has-child.Female}$

Role assertions

$\langle a, b \rangle : R$

$\langle \text{John}, \text{Mary} \rangle : \text{has-child}$

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

$a : C$ iff $a^{\mathcal{I}} \in C^{\mathcal{I}}$ $\langle a, b \rangle : R$ iff $\langle a^{\mathcal{I}}, b^{\mathcal{I}} \rangle \in R^{\mathcal{I}}$

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} ($\mathcal{I} \models \Sigma$)

Basic Inference Problems

Basic Inference Problems

Subsumption (structure knowledge, compute taxonomy)

$C \sqsubseteq D$? Is $C^{\mathcal{I}} \subseteq D^{\mathcal{I}}$ in all interpretations?

Basic Inference Problems

Subsumption (structure knowledge, compute taxonomy)

$C \sqsubseteq D ?$ Is $C^{\mathcal{I}} \subseteq D^{\mathcal{I}}$ in all interpretations?

Subsumption w.r.t. Tbox \mathcal{T}

$C \sqsubseteq_{\mathcal{T}} D ?$ Is $C^{\mathcal{I}} \subseteq D^{\mathcal{I}}$ in all models of \mathcal{T} ?

Basic Inference Problems

Subsumption (structure knowledge, compute taxonomy)

$C \sqsubseteq D$? Is $C^{\mathcal{I}} \subseteq D^{\mathcal{I}}$ in all interpretations?

Subsumption w.r.t. Tbox \mathcal{T}

$C \sqsubseteq_{\mathcal{T}} D$? Is $C^{\mathcal{I}} \subseteq D^{\mathcal{I}}$ in all models of \mathcal{T} ?

Consistency

Is C consistent w.r.t. \mathcal{T} ? Is there a model \mathcal{I} of \mathcal{T} s.t. $C^{\mathcal{I}} \neq \emptyset$?

Basic Inference Problems

Subsumption (structure knowledge, compute taxonomy)

$C \sqsubseteq D$? Is $C^{\mathcal{I}} \subseteq D^{\mathcal{I}}$ in all interpretations?

Subsumption w.r.t. Tbox \mathcal{T}

$C \sqsubseteq_{\mathcal{T}} D$? Is $C^{\mathcal{I}} \subseteq D^{\mathcal{I}}$ in all models of \mathcal{T} ?

Consistency

Is C consistent w.r.t. \mathcal{T} ? Is there a model \mathcal{I} of \mathcal{T} s.t. $C^{\mathcal{I}} \neq \emptyset$?

KB Consistency

Is $\langle \mathcal{T}, \mathcal{A} \rangle$ consistent? Is there a model \mathcal{I} of $\langle \mathcal{T}, \mathcal{A} \rangle$?

Basic Inference Problems

Subsumption (structure knowledge, compute taxonomy)

$C \sqsubseteq D$? Is $C^{\mathcal{I}} \subseteq D^{\mathcal{I}}$ in all interpretations?

Subsumption w.r.t. Tbox \mathcal{T}

$C \sqsubseteq_{\mathcal{T}} D$? Is $C^{\mathcal{I}} \subseteq D^{\mathcal{I}}$ in all models of \mathcal{T} ?

Consistency

Is C consistent w.r.t. \mathcal{T} ? Is there a model \mathcal{I} of \mathcal{T} s.t. $C^{\mathcal{I}} \neq \emptyset$?

KB Consistency

Is $\langle \mathcal{T}, \mathcal{A} \rangle$ consistent? Is there a model \mathcal{I} of $\langle \mathcal{T}, \mathcal{A} \rangle$?

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

Subsumption and Satisfiability

Subsumption transformed into **satisfiability**

Subsumption and Satisfiability

Subsumption transformed into **satisfiability**

Tableaux algorithm used to test satisfiability

Subsumption and Satisfiability

Subsumption transformed into **satisfiability**

Tableaux algorithm used to test satisfiability

☞ Try to build **model** (witness) of concept C

Subsumption and Satisfiability

Subsumption transformed into **satisfiability**

Tableaux algorithm used to test satisfiability

- ➔ Try to build **model** (witness) of concept C
- ➔ Model represented by **tree** T
 - Nodes in T correspond to individuals in model
 - Nodes labeled with sets of subconcepts of C
 - Edges labeled with role names in C

Subsumption and Satisfiability

Subsumption transformed into **satisfiability**

Tableaux algorithm used to test satisfiability

- ➔ Try to build **model** (witness) of concept C
- ➔ Model represented by **tree** T
 - Nodes in T correspond to individuals in model
 - Nodes labeled with sets of subconcepts of C
 - Edges labeled with role names in C
- ➔ Start from **root node** labeled $\{C\}$

Subsumption and Satisfiability

Subsumption transformed into **satisfiability**

Tableaux algorithm used to test satisfiability

- ➔ Try to build **model** (witness) of concept C
- ➔ Model represented by **tree** T
 - Nodes in T correspond to individuals in model
 - Nodes labeled with sets of subconcepts of C
 - Edges labeled with role names in C
- ➔ Start from **root node** labeled $\{C\}$
- ➔ Apply **expansion rules** to node labels until
 - Rules correspond with language constructs
 - Expansion completed (tree represents valid model)
 - Contradictions prove there is no model

Subsumption and Satisfiability

Subsumption transformed into **satisfiability**

Tableaux algorithm used to test satisfiability

- ➔ Try to build **model** (witness) of concept C
- ➔ Model represented by **tree** T
 - Nodes in T correspond to individuals in model
 - Nodes labeled with sets of subconcepts of C
 - Edges labeled with role names in C
- ➔ Start from **root node** labeled $\{C\}$
- ➔ Apply **expansion rules** to node labels until
 - Rules correspond with language constructs
 - Expansion completed (tree represents valid model)
 - Contradictions prove there is no model
- ➔ Non-deterministic expansion \longrightarrow **search** (e.g., $C \sqcup D$)

Subsumption and Satisfiability

Subsumption transformed into **satisfiability**

Tableaux algorithm used to test satisfiability

- ➔ Try to build **model** (witness) of concept C
- ➔ Model represented by **tree** T
 - Nodes in T correspond to individuals in model
 - Nodes labeled with sets of subconcepts of C
 - Edges labeled with role names in C
- ➔ Start from **root node** labeled $\{C\}$
- ➔ Apply **expansion rules** to node labels until
 - Rules correspond with language constructs
 - Expansion completed (tree represents valid model)
 - Contradictions prove there is no model
- ➔ Non-deterministic expansion \longrightarrow **search** (e.g., $C \sqcup D$)
- ➔ **Blocking** ensures termination (with expressive DLs)

Tableaux Expansion

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

Tableaux Expansion

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

$$\mathcal{L}(w) = \{\exists S.C, \forall S.(\neg C \sqcup \neg D), \exists R.C, \forall R.(\exists R.C)\}$$

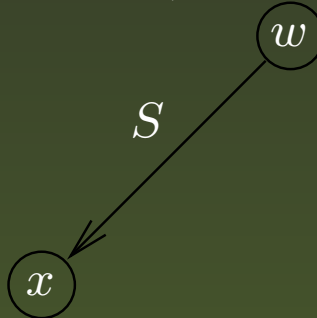
w

Tableaux Expansion

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

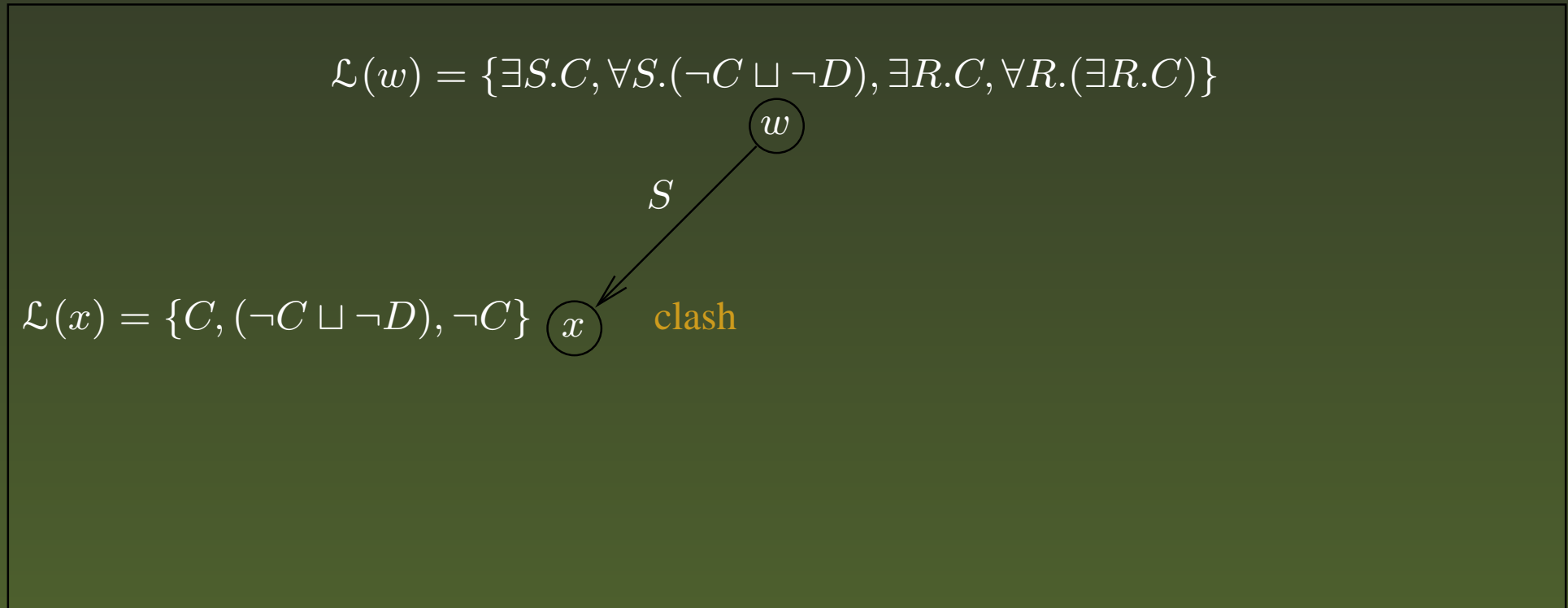
$$\mathcal{L}(w) = \{\exists S.C, \forall S.(\neg C \sqcup \neg D), \exists R.C, \forall R.(\exists R.C)\}$$

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



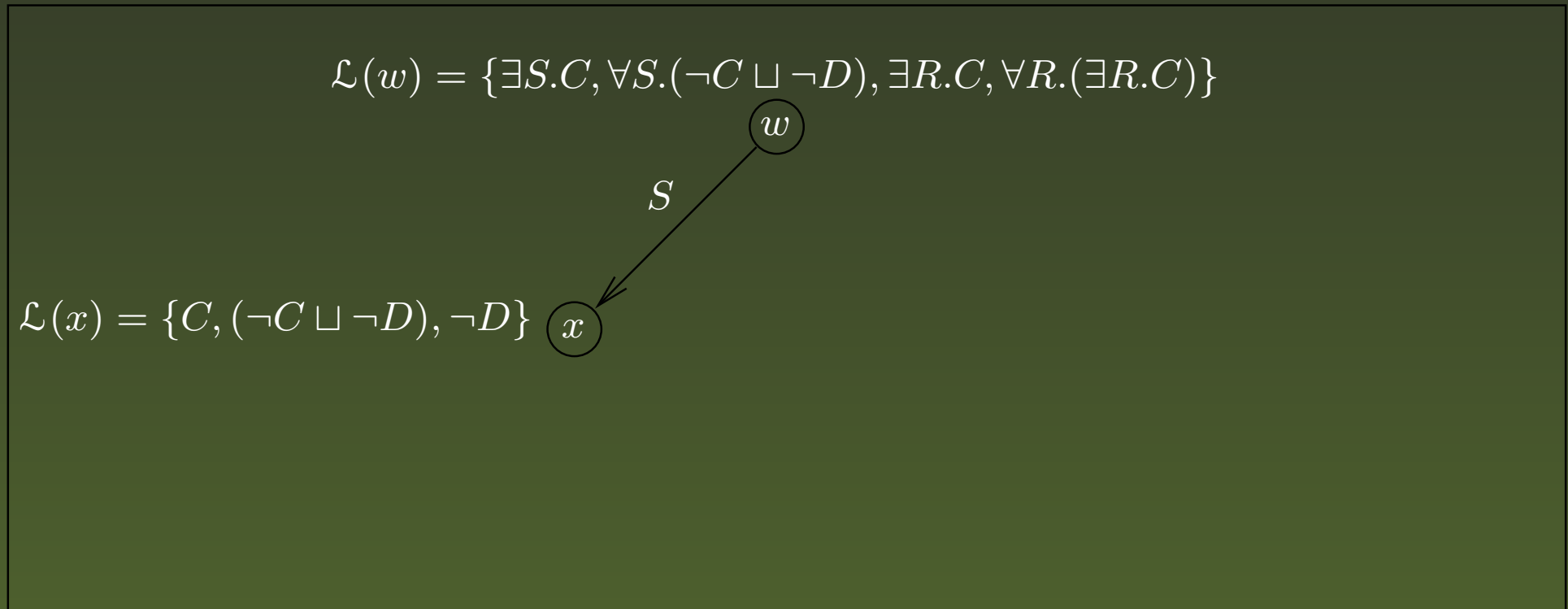
Tableaux Expansion

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



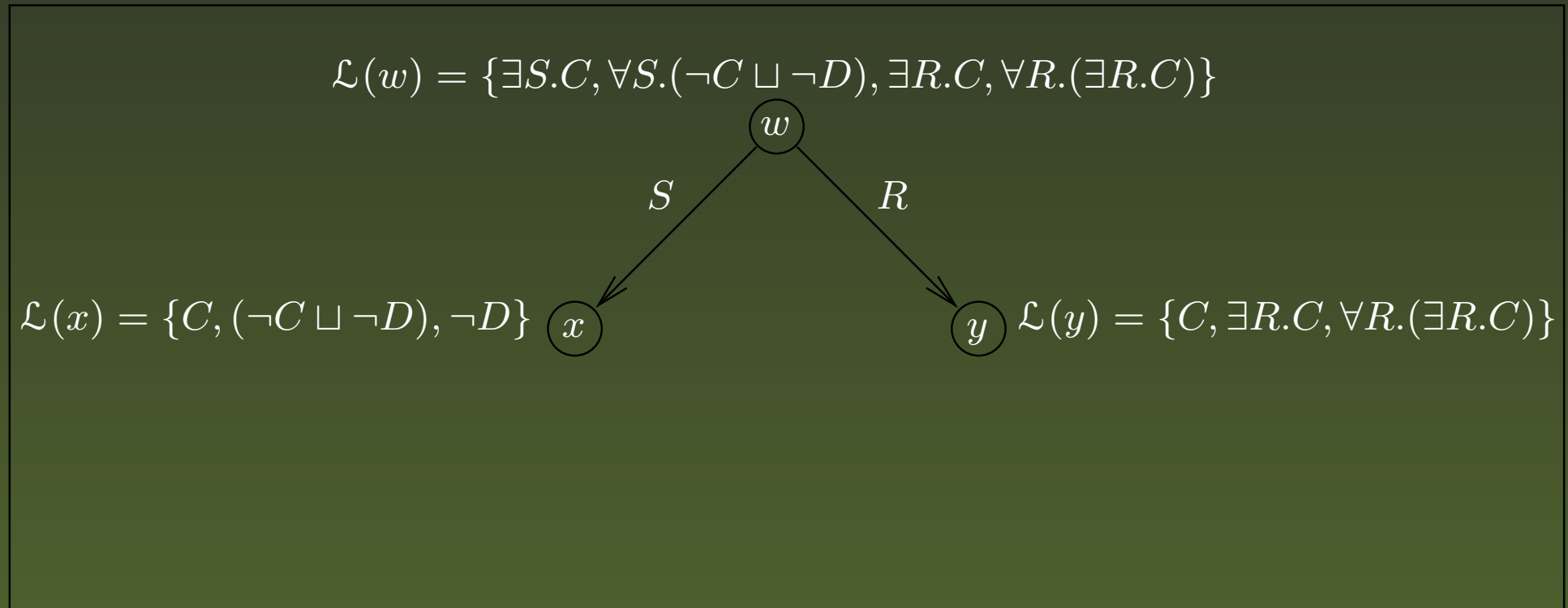
Tableaux Expansion

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



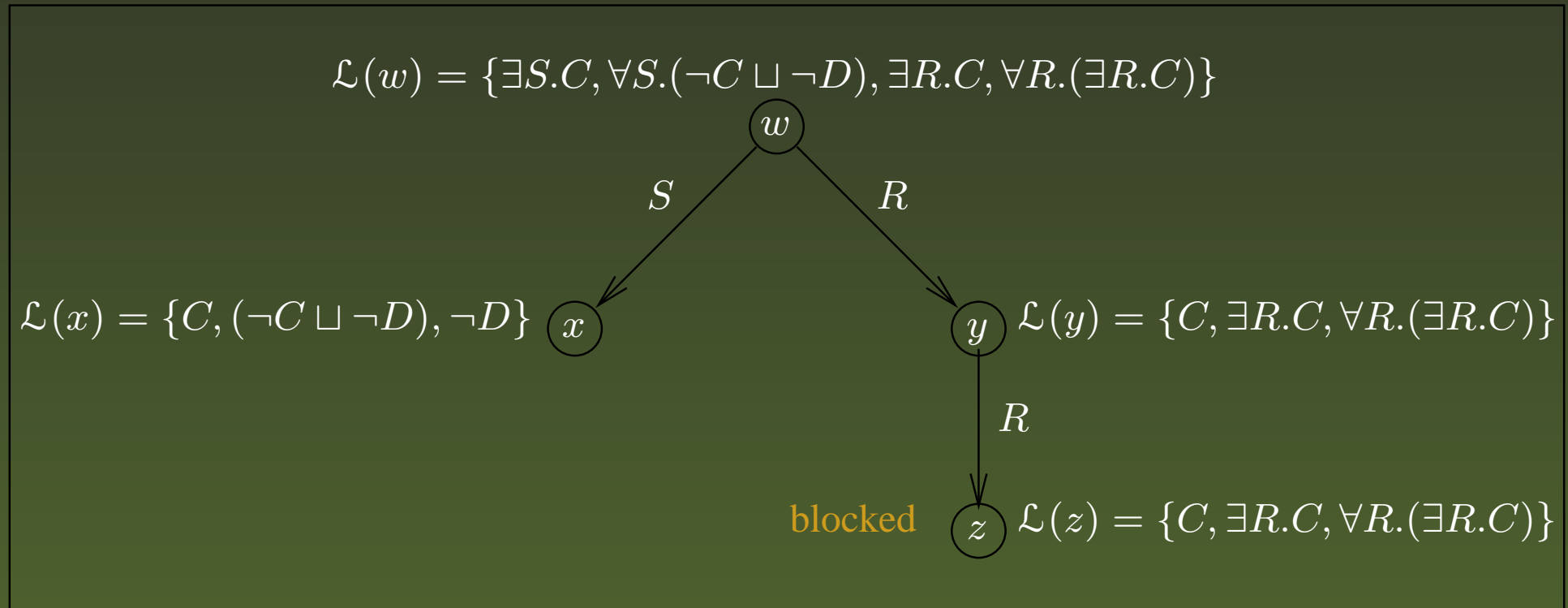
Tableaux Expansion

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



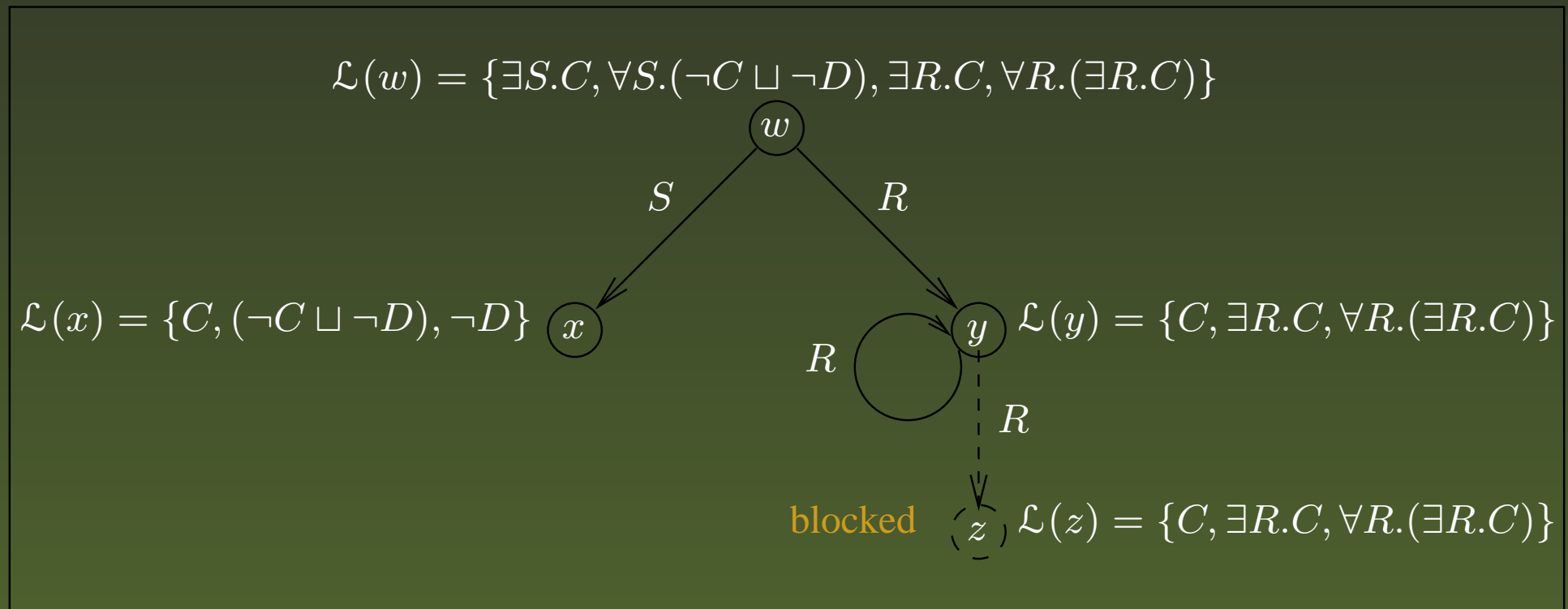
Tableaux Expansion

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



Tableaux Expansion

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



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

More Advanced Techniques

More Advanced Techniques

Satisfiability w.r.t. a Terminology

☞ For each GCI $C \sqsubseteq D \in \mathcal{T}$, add $\neg C \sqcup D$ to **every** node label

More Advanced Techniques

Satisfiability w.r.t. a Terminology

☞ For each GCI $C \sqsubseteq D \in \mathcal{T}$, add $\neg C \sqcup D$ to **every** node label

More expressive DLs

More Advanced Techniques

Satisfiability w.r.t. a Terminology

- ☞ For each GCI $C \sqsubseteq D \in \mathcal{T}$, add $\neg C \sqcup D$ to **every** node label

More expressive DLs

- ☞ Basic technique can be extended to deal with
 - Role inclusion axioms (role hierarchy)
 - Number restrictions
 - Inverse roles
 - Concrete domains
 - Aboxes
 - etc.

More Advanced Techniques

Satisfiability w.r.t. a Terminology

- ☞ For each GCI $C \sqsubseteq D \in \mathcal{T}$, add $\neg C \sqcup D$ to **every** node label

More expressive DLs

- ☞ Basic technique can be extended to deal with
 - Role inclusion axioms (role hierarchy)
 - Number restrictions
 - Inverse roles
 - Concrete domains
 - Aboxes
 - etc.
- ☞ Extend **expansion rules** and use more sophisticated **blocking** strategy

More Advanced Techniques

Satisfiability w.r.t. a Terminology

- ➡ For each GCI $C \sqsubseteq D \in \mathcal{T}$, add $\neg C \sqcup D$ to **every** node label

More expressive DLs

- ➡ Basic technique can be extended to deal with
 - Role inclusion axioms (role hierarchy)
 - Number restrictions
 - Inverse roles
 - Concrete domains
 - Aboxes
 - etc.
- ➡ Extend **expansion rules** and use more sophisticated **blocking** strategy
- ➡ Forest instead of Tree (for Aboxes)

Implementing DL Systems

Naive Implementations

Problems include:

Naive Implementations

Problems include:

☞ **Space** usage

Naive Implementations

Problems include:

☞ **Space** usage

- Storage required for tableaux datastructures

Naive Implementations

Problems include:

☞ **Space** usage

- Storage required for tableaux datastructures
- Rarely a serious problem in practice

Naive Implementations

Problems include:

☞ **Space** usage

- Storage required for tableaux datastructures
- Rarely a serious problem in practice
- But problems can arise with inverse roles and cyclical KBs

Naive Implementations

Problems include:

☞ **Space** usage

- Storage required for tableaux datastructures
- Rarely a serious problem in practice
- But problems can arise with inverse roles and cyclical KBs

☞ **Time** usage

Naive Implementations

Problems include:

☞ **Space** usage

- Storage required for tableaux datastructures
- Rarely a serious problem in practice
- But problems can arise with inverse roles and cyclical KBs

☞ **Time** usage

- Search required due to non-deterministic expansion

Naive Implementations

Problems include:

☞ **Space** usage

- Storage required for tableaux datastructures
- Rarely a serious problem in practice
- But problems can arise with inverse roles and cyclical KBs

☞ **Time** usage

- Search required due to non-deterministic expansion
- **Serious** problem in practice

Naive Implementations

Problems include:

☞ **Space** usage

- Storage required for tableaux datastructures
- Rarely a serious problem in practice
- But problems can arise with inverse roles and cyclical KBs

☞ **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

Careful Choice of Algorithm

➔ **Transitive roles** instead of transitive closure

Careful Choice of Algorithm

- ➔ **Transitive roles** instead of transitive closure
 - Deterministic expansion of $\exists R.C$, even when $R \in \mathbf{R}_+$

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

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) valid cyclical models

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) valid cyclical models
- ➔ **Direct algorithm**/implementation instead of encodings

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) valid cyclical models
- ➔ **Direct algorithm**/implementation instead of encodings
 - GCI axioms can be used to “encode” additional operators/axioms

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) valid 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

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) valid 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, ...

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) valid 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., $(\text{domain } R.C) \equiv \exists R.\top \sqsubseteq C$

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) valid 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

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) valid 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

Modern systems include **MANY** optimisations, e.g.:

Highly Optimised Implementation

Modern systems include **MANY** optimisations, e.g.:

☞ Optimised **classification**

- Use enhanced traversal (exploit information from previous tests)
- Use structural information to select classification order

Highly Optimised Implementation

Modern systems include **MANY** optimisations, e.g.:

- ➡ Optimised **classification**
 - Use enhanced traversal (exploit information from previous tests)
 - Use structural information to select classification order
- ➡ Optimised **subsumption** testing

Highly Optimised Implementation

Modern systems include **MANY** optimisations, e.g.:

➔ Optimised **classification**

- Use enhanced traversal (exploit information from previous tests)
- Use structural information to select classification order

➔ Optimised **subsumption** testing

- Normalisation and simplification of concepts

Highly Optimised Implementation

Modern systems include **MANY** optimisations, e.g.:

➔ Optimised **classification**

- Use enhanced traversal (exploit information from previous tests)
- Use structural information to select classification order

➔ Optimised **subsumption** testing

- Normalisation and simplification of concepts
- Absorption (simplification) of general axioms

Highly Optimised Implementation

Modern systems include **MANY** optimisations, e.g.:

➡ Optimised **classification**

- Use enhanced traversal (exploit information from previous tests)
- Use structural information to select classification order

➡ Optimised **subsumption** testing

- Normalisation and simplification of concepts
- Absorption (simplification) of general axioms
- Davis-Putnam style semantic branching search

Highly Optimised Implementation

Modern systems include **MANY** optimisations, e.g.:

➡ Optimised **classification**

- Use enhanced traversal (exploit information from previous tests)
- Use structural information to select classification order

➡ Optimised **subsumption** testing

- Normalisation and simplification of concepts
- Absorption (simplification) of general axioms
- Davis-Putnam style semantic branching search
- Dependency directed backtracking

Highly Optimised Implementation

Modern systems include **MANY** optimisations, e.g.:

➔ Optimised **classification**

- Use enhanced traversal (exploit information from previous tests)
- Use structural information to select classification order

➔ Optimised **subsumption** testing

- Normalisation and simplification of concepts
- Absorption (simplification) of general axioms
- Davis-Putnam style semantic branching search
- Dependency directed backtracking
- Caching

Highly Optimised Implementation

Modern systems include **MANY** optimisations, e.g.:

➔ Optimised **classification**

- Use enhanced traversal (exploit information from previous tests)
- Use structural information to select classification order

➔ Optimised **subsumption** testing

- Normalisation and simplification of concepts
- Absorption (simplification) of general axioms
- Davis-Putnam style semantic branching search
- Dependency directed backtracking
- Caching
- Heuristic ordering of propositional and modal expansion

Dependency Directed Backtracking

Dependency Directed Backtracking

- ➔ Allows **rapid recovery** from bad branching choices

Dependency Directed Backtracking

- ➔ Allows **rapid recovery** from bad branching choices
- ➔ Most commonly used technique is **backjumping**

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)

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**

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

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

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

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

Backjumping

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

Backjumping

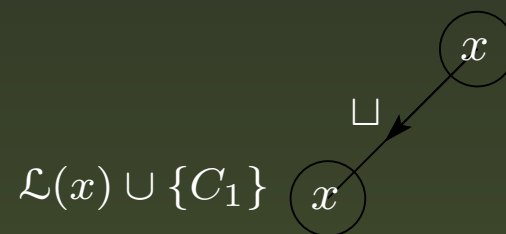
E.g., if $\exists R. \neg A \sqcap \forall R. (A \sqcap B) \sqcap (C_1 \sqcup D_1) \sqcap \dots \sqcap (C_n \sqcup D_n) \subseteq \mathcal{L}(x)$



x

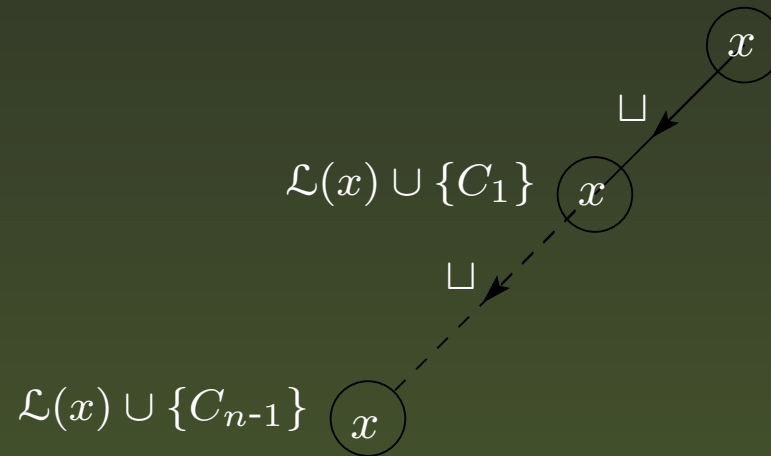
Backjumping

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



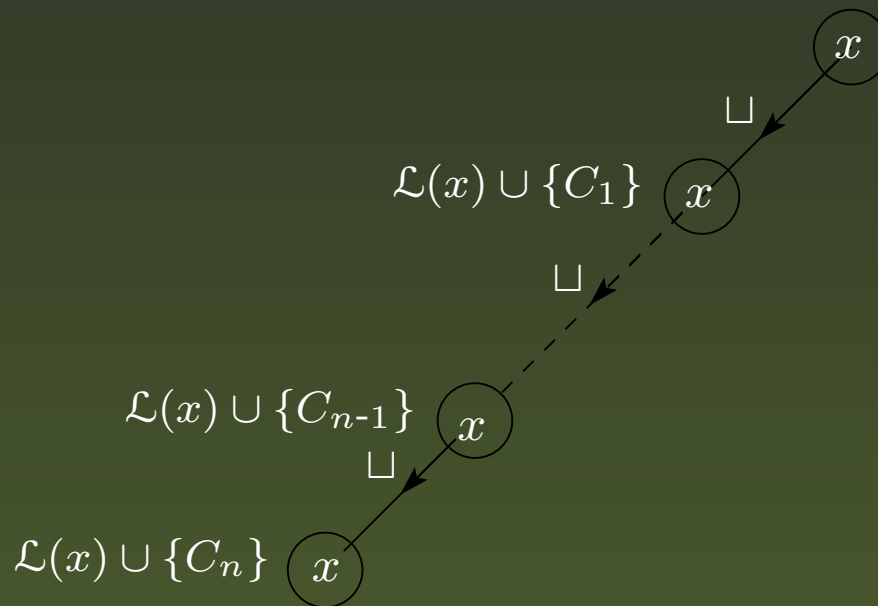
Backjumping

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



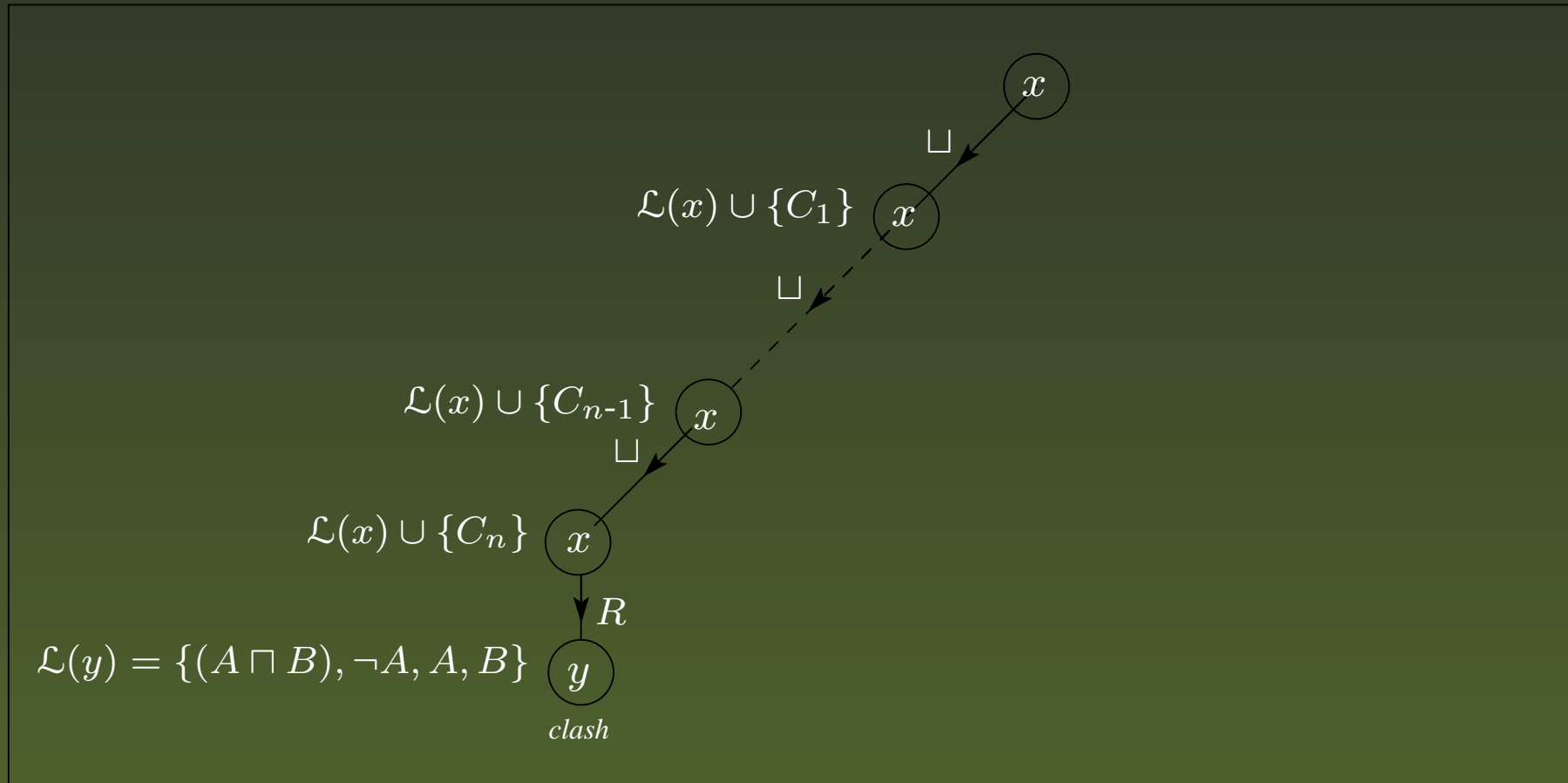
Backjumping

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



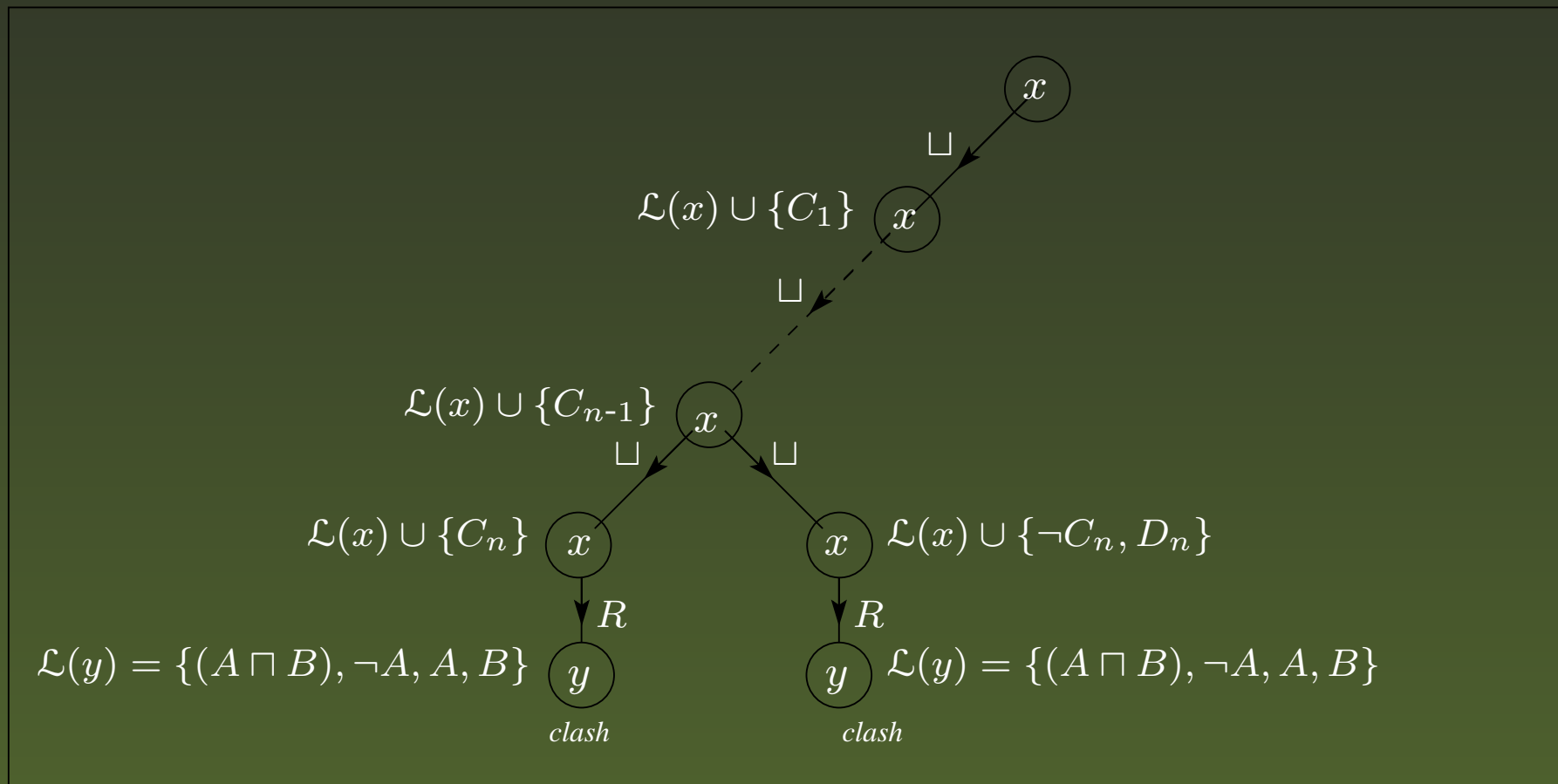
Backjumping

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



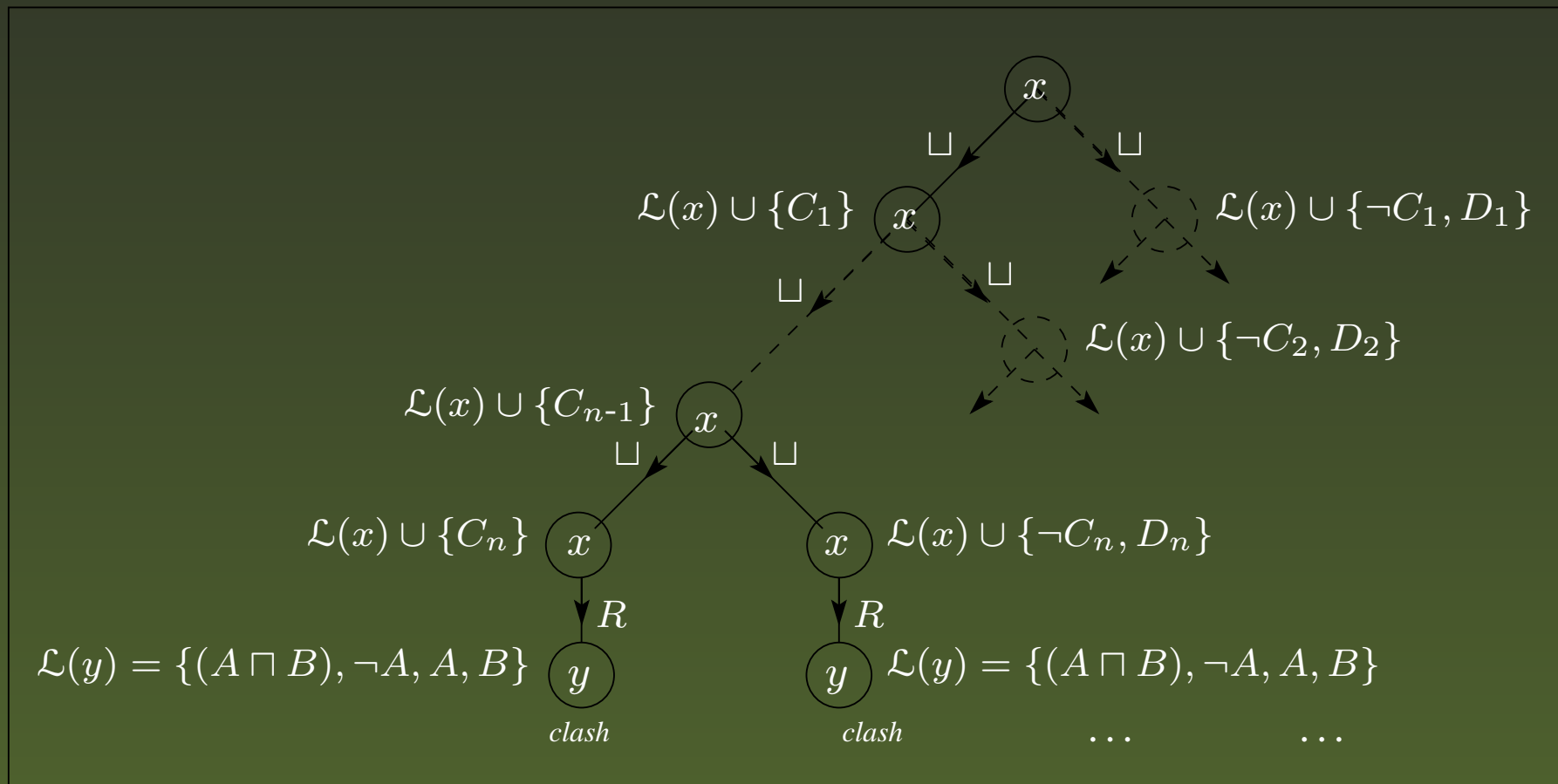
Backjumping

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



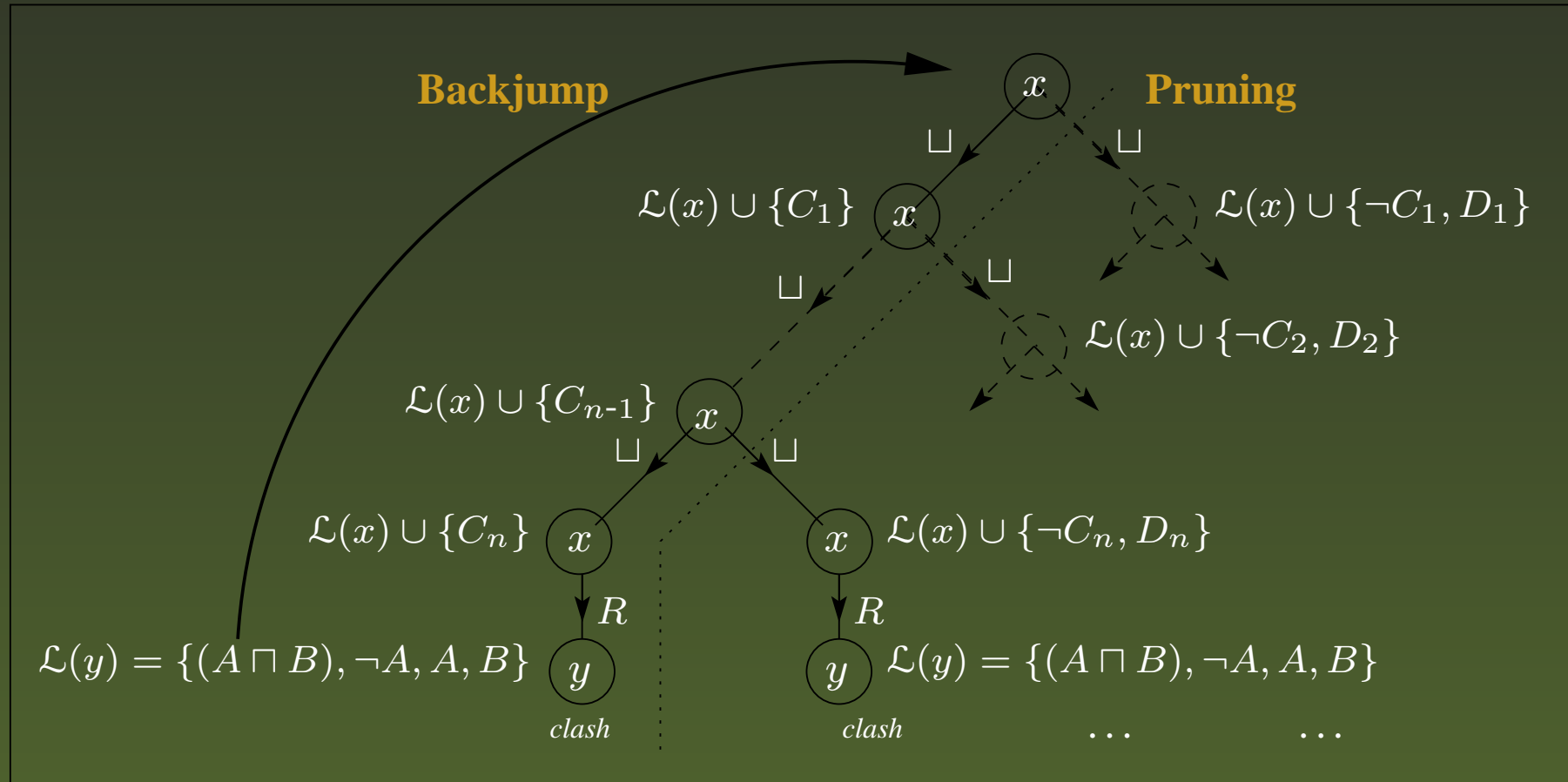
Backjumping

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



Backjumping

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



Research Challenges

Research Challenges

Increased expressive power

- Datatypes
- Nominals
- Extensions to DAML+OIL

Research Challenges

Increased expressive power

- Datatypes
- Nominals
- Extensions to DAML+OIL

Performance

- Inverse roles and qualified number restrictions
- Very large KBs
- Reasoning with individuals

Research Challenges

Increased expressive power

- Datatypes
- Nominals
- Extensions to DAML+OIL

Performance

- Inverse roles and qualified number restrictions
- Very large KBs
- Reasoning with individuals

Tools and Infrastructure

- Support for large scale ontological engineering and deployment

Research Challenges

Increased expressive power

- Datatypes
- Nominals
- Extensions to DAML+OIL

Performance

- Inverse roles and qualified number restrictions
- Very large KBs
- Reasoning with individuals

Tools and Infrastructure

- Support for large scale ontological engineering and deployment

New reasoning tasks

- Querying
- Lcs/matching
- Sanctioning
- ...

Increased Expressive Power: Datatypes

DAML+OIL extends *SHIQ* with datatypes and nominals

Increased Expressive Power: Datatypes

DAML+OIL extends *SHIQ* with datatypes and nominals

Datatypes

Increased Expressive Power: Datatypes

DAML+OIL extends *SHIQ* with datatypes and nominals

Datatypes

- ➔ DAML+OIL has simple form of datatypes
 - Unary predicates plus disjoint abstract/datatype domains

Increased Expressive Power: Datatypes

DAML+OIL extends $SHIQ$ with datatypes and nominals

Datatypes

- ➔ DAML+OIL has simple form of datatypes
 - Unary predicates plus disjoint abstract/datatype domains
- ➔ **Theoretically** not particularly challenging
 - Existing work on concrete domains [Baader & Hanschke, Lutz]
 - Algorithm already known for $SHOQ(\mathcal{D})$ [Horrocks & Sattler]

Increased Expressive Power: Datatypes

DAML+OIL extends $SHIQ$ with datatypes and nominals

Datatypes

- ➡ DAML+OIL has simple form of datatypes
 - Unary predicates plus disjoint abstract/datatype domains
- ➡ **Theoretically** not particularly challenging
 - Existing work on concrete domains [Baader & Hanschke, Lutz]
 - Algorithm already known for $SHOQ(D)$ [Horrocks & Sattler]
- ➡ May be **practically** challenging
 - All XMLS datatypes supported

Increased Expressive Power: Datatypes

DAML+OIL extends \mathcal{SHIQ} with datatypes and nominals

Datatypes

- ➔ DAML+OIL has simple form of datatypes
 - Unary predicates plus disjoint abstract/datatype domains
- ➔ **Theoretically** not particularly challenging
 - Existing work on concrete domains [Baader & Hanschke, Lutz]
 - Algorithm already known for $\mathcal{SHOQ}(\mathcal{D})$ [Horrocks & Sattler]
- ➔ May be **practically** challenging
 - All XMLS datatypes supported
- ➔ Already seeing some (limited) **implementations**
 - E.g., Cerebra system (Network Inference)

Increased Expressive Power: Nominals

Nominals

Increased Expressive Power: Nominals

Nominals

- ➔ DAML+OIL has **oneOf** constructor
 - Extensionally defined concepts, e.g., $\{Mary\}^{\mathcal{I}} = \{Mary\}$
 - Equivalent to nominals in modal logic

Increased Expressive Power: Nominals

Nominals

- ➔ DAML+OIL has **oneOf** constructor
 - Extensionally defined concepts, e.g., $\{Mary\}^{\mathcal{I}} = \{Mary\}$
 - Equivalent to nominals in modal logic
- ➔ Theoretically **very challenging**

Increased Expressive Power: Nominals

Nominals

- ➡ DAML+OIL has **oneOf** constructor
 - Extensionally defined concepts, e.g., $\{Mary\}^{\mathcal{I}} = \{Mary\}$
 - Equivalent to nominals in modal logic
- ➡ Theoretically **very challenging**
 - Resulting logic has known high complexity (NExpTime)

Increased Expressive Power: Nominals

Nominals

- ➡ DAML+OIL has **oneOf** constructor
 - Extensionally defined concepts, e.g., $\{Mary\}^{\mathcal{I}} = \{Mary\}$
 - Equivalent to nominals in modal logic
- ➡ Theoretically **very challenging**
 - Resulting logic has known high complexity (NExpTime)
 - No known “practical” algorithm

Increased Expressive Power: Nominals

Nominals

- ☞ DAML+OIL has **oneOf** constructor
 - Extensionally defined concepts, e.g., $\{Mary\}^{\mathcal{I}} = \{Mary\}$
 - Equivalent to nominals in modal logic
- ☞ Theoretically **very challenging**
 - Resulting logic has known high complexity (NExpTime)
 - No known “practical” algorithm
 - Not obvious how to extend tableaux techniques in this direction
 - ➔ Loss of tree model property
 - ➔ Spy-points: $\top \sqsubseteq \exists R.\{Spy\}$
 - ➔ Finite domains: $\{Spy\} \sqsubseteq \leq n R^-$

Increased Expressive Power: Nominals

Nominals

- ➡ DAML+OIL has **oneOf** constructor
 - Extensionally defined concepts, e.g., $\{Mary\}^{\mathcal{I}} = \{Mary\}$
 - Equivalent to nominals in modal logic
- ➡ Theoretically **very challenging**
 - Resulting logic has known high complexity (NExpTime)
 - No known “practical” algorithm
 - Not obvious how to extend tableaux techniques in this direction
 - ➔ Loss of tree model property
 - ➔ Spy-points: $\top \sqsubseteq \exists R.\{Spy\}$
 - ➔ Finite domains: $\{Spy\} \sqsubseteq \leq_n R^-$
- ➡ Relatively straightforward (in theory) without **inverse roles**
 - Algorithm for $\mathcal{SHOQ}(\mathbf{D})$ deals with nominals
 - Practical implementation still to be demonstrated

Increased Expressive Power: Extensions

➔ DAML+OIL **not expressive enough** for all applications

Increased Expressive Power: Extensions

- ➔ DAML+OIL **not expressive enough** for all applications
- ➔ Extensions **wish list** includes:
 - Feature chain (path) agreement, e.g., output of component of composite process equals input of subsequent process
 - Complex roles/role inclusions, e.g., a city located in part of a country is located in that country
 - Rules—proposal(s) already exist for “datalog/LP style rules”
 - Temporal and spatial reasoning
 - . . .

Increased Expressive Power: Extensions

- ➡ DAML+OIL **not expressive enough** for all applications
- ➡ Extensions **wish list** includes:
 - Feature chain (path) agreement, e.g., output of component of composite process equals input of subsequent process
 - Complex roles/role inclusions, e.g., a city located in part of a country is located in that country
 - Rules—proposal(s) already exist for “datalog/LP style rules”
 - Temporal and spatial reasoning
 - ...
- ➡ May be impossible/undesirable to resist such extensions

Increased Expressive Power: Extensions

- ➡ DAML+OIL **not expressive enough** for all applications
- ➡ Extensions **wish list** includes:
 - Feature chain (path) agreement, e.g., output of component of composite process equals input of subsequent process
 - Complex roles/role inclusions, e.g., a city located in part of a country is located in that country
 - Rules—proposal(s) already exist for “datalog/LP style rules”
 - Temporal and spatial reasoning
 - . . .
- ➡ May be impossible/undesirable to resist such extensions
- ➡ Extended language sure to be **undecidable**

Increased Expressive Power: Extensions

- ➡ DAML+OIL **not expressive enough** for all applications
- ➡ Extensions **wish list** includes:
 - Feature chain (path) agreement, e.g., output of component of composite process equals input of subsequent process
 - Complex roles/role inclusions, e.g., a city located in part of a country is located in that country
 - Rules—proposal(s) already exist for “datalog/LP style rules”
 - Temporal and spatial reasoning
 - ...
- ➡ May be impossible/undesirable to resist such extensions
- ➡ Extended language sure to be **undecidable**
- ➡ How can extensions best be **integrated** with DAML+OIL?

Increased Expressive Power: Extensions

- ➡ DAML+OIL **not expressive enough** for all applications
- ➡ Extensions **wish list** includes:
 - Feature chain (path) agreement, e.g., output of component of composite process equals input of subsequent process
 - Complex roles/role inclusions, e.g., a city located in part of a country is located in that country
 - Rules—proposal(s) already exist for “datalog/LP style rules”
 - Temporal and spatial reasoning
 - ...
- ➡ May be impossible/undesirable to resist such extensions
- ➡ Extended language sure to be **undecidable**
- ➡ How can extensions best be **integrated** with DAML+OIL?
- ➡ How can reasoners be developed/adapted for extended languages
 - Some existing work on language **fusions** and **hybrid** reasoners

Performance Problems

- ➔ Evidence of **empirical tractability** mostly w.r.t. \mathcal{SHF} — problems can arise when systems extended to \mathcal{SHIQ}

Performance Problems

- ➔ Evidence of **empirical tractability** mostly w.r.t. \mathcal{SHF} — problems can arise when systems extended to \mathcal{SHIQ}
- ➔ Important **optimisations** no longer (fully) work
 - E.g., problems with caching as cached models can affect parent

Performance Problems

- ➔ Evidence of **empirical tractability** mostly w.r.t. \mathcal{SHF} — problems can arise when systems extended to \mathcal{SHIQ}
- ➔ Important **optimisations** no longer (fully) work
 - E.g., problems with caching as cached models can affect parent
- ➔ **Qualified number restrictions** can also cause problems
 - Even relatively small numbers can mean significant non-determinism

Performance Problems

- ➔ Evidence of **empirical tractability** mostly w.r.t. \mathcal{SHF} — problems can arise when systems extended to \mathcal{SHIQ}
- ➔ Important **optimisations** no longer (fully) work
 - E.g., problems with caching as cached models can affect parent
- ➔ **Qualified number restrictions** can also cause problems
 - Even relatively small numbers can mean significant non-determinism
- ➔ Reasoning with **very large KBs/ontologies**
 - Web ontologies can be expected to grow very large

Performance Problems

- ➔ Evidence of **empirical tractability** mostly w.r.t. \mathcal{SHF} — problems can arise when systems extended to \mathcal{SHIQ}
- ➔ Important **optimisations** no longer (fully) work
 - E.g., problems with caching as cached models can affect parent
- ➔ **Qualified number restrictions** can also cause problems
 - Even relatively small numbers can mean significant non-determinism
- ➔ Reasoning with **very large KBs/ontologies**
 - Web ontologies can be expected to grow very large
- ➔ Reasoning with **individuals** (Abox)
 - Deployment of web ontologies will mean reasoning with (possibly very large numbers of) individuals
 - Unlikely that standard Abox techniques will be able to cope

Performance Solutions (Maybe)

Performance Solutions (Maybe)

➔ Excessive **memory usage**

Performance Solutions (Maybe)

☞ Excessive **memory usage**

- Problem exacerbated by over-cautious double blocking condition (e.g., root node can never block)
- Promising results from more precise blocking condition [Sattler & Horrocks]

Performance Solutions (Maybe)

- ➡ Excessive **memory usage**
 - Problem exacerbated by over-cautious double blocking condition (e.g., root node can never block)
 - Promising results from more precise blocking condition [Sattler & Horrocks]
- ➡ **Qualified number restrictions**

Performance Solutions (Maybe)

☞ Excessive **memory usage**

- Problem exacerbated by over-cautious double blocking condition (e.g., root node can never block)
- Promising results from more precise blocking condition [Sattler & Horrocks]

☞ **Qualified number restrictions**

- Problem exacerbated by naive expansion rules
- Promising results from optimised expansion using Algebraic Methods [Haarslev & Möller]

Performance Solutions (Maybe)

- ➔ **Excessive memory usage**
 - Problem exacerbated by over-cautious double blocking condition (e.g., root node can never block)
 - Promising results from more precise blocking condition [Sattler & Horrocks]
- ➔ **Qualified number restrictions**
 - Problem exacerbated by naive expansion rules
 - Promising results from optimised expansion using Algebraic Methods [Haarslev & Möller]
- ➔ **Caching** and merging

Performance Solutions (Maybe)

- ➔ **Excessive memory usage**
 - Problem exacerbated by over-cautious double blocking condition (e.g., root node can never block)
 - Promising results from more precise blocking condition [Sattler & Horrocks]
- ➔ **Qualified number restrictions**
 - Problem exacerbated by naive expansion rules
 - Promising results from optimised expansion using Algebraic Methods [Haarslev & Möller]
- ➔ **Caching** and merging
 - Can still work in some situations (work in progress)

Performance Solutions (Maybe)

- ➡ Excessive **memory usage**
 - Problem exacerbated by over-cautious double blocking condition (e.g., root node can never block)
 - Promising results from more precise blocking condition [Sattler & Horrocks]
- ➡ **Qualified number restrictions**
 - Problem exacerbated by naive expansion rules
 - Promising results from optimised expansion using Algebraic Methods [Haarslev & Möller]
- ➡ **Caching** and merging
 - Can still work in some situations (work in progress)
- ➡ Reasoning with **very large KBs**

Performance Solutions (Maybe)

- ➔ Excessive **memory usage**
 - Problem exacerbated by over-cautious double blocking condition (e.g., root node can never block)
 - Promising results from more precise blocking condition [Sattler & Horrocks]
- ➔ **Qualified number restrictions**
 - Problem exacerbated by naive expansion rules
 - Promising results from optimised expansion using Algebraic Methods [Haarslev & Möller]
- ➔ **Caching** and merging
 - Can still work in some situations (work in progress)
- ➔ Reasoning with **very large KBs**
 - DL systems shown to work with $\approx 100k$ concept KB [Haarslev & Möller]
 - But KB only exploited small part of DL language

Tools and Infrastructure

Tools and infrastructure required in order support use of DAML+OIL

Tools and Infrastructure

Tools and infrastructure required in order support use of DAML+OIL

☞ Ontology **design and maintenance**

Tools and Infrastructure

Tools and infrastructure required in order support use of DAML+OIL

☞ Ontology **design and maintenance**

- Several **editors** available, e.g, OilEd (Manchester), OntoEdit (Karlsruhe), Protégé (Stanford)

Tools and Infrastructure

Tools and infrastructure required in order support use of DAML+OIL

☞ Ontology **design and maintenance**

- Several **editors** available, e.g, OilEd (Manchester), OntoEdit (Karlsruhe), Protégé (Stanford)
- Need integrated **environments** including modularity, versioning, visualisation, explanation, high-level languages, . . .

Tools and Infrastructure

Tools and infrastructure required in order support use of DAML+OIL

☞ Ontology **design and maintenance**

- Several **editors** available, e.g, OilEd (Manchester), OntoEdit (Karlsruhe), Protégé (Stanford)
- Need integrated **environments** including modularity, versioning, visualisation, explanation, high-level languages, . . .

☞ Ontology **Integration**

Tools and Infrastructure

Tools and infrastructure required in order support use of DAML+OIL

☞ Ontology **design and maintenance**

- Several **editors** available, e.g, OilEd (Manchester), OntoEdit (Karlsruhe), Protégé (Stanford)
- Need integrated **environments** including modularity, versioning, visualisation, explanation, high-level languages, . . .

☞ Ontology **Integration**

- Some tools available, e.g., Chimera (Stanford)

Tools and Infrastructure

Tools and infrastructure required in order support use of DAML+OIL

☞ Ontology **design and maintenance**

- Several **editors** available, e.g, OilEd (Manchester), OntoEdit (Karlsruhe), Protégé (Stanford)
- Need integrated **environments** including modularity, versioning, visualisation, explanation, high-level languages, . . .

☞ Ontology **Integration**

- Some tools available, e.g., Chimera (Stanford)
- Need integrated **environments** . . .

Tools and Infrastructure

Tools and infrastructure required in order support use of DAML+OIL

☞ Ontology **design and maintenance**

- Several **editors** available, e.g, OilEd (Manchester), OntoEdit (Karlsruhe), Protégé (Stanford)
- Need integrated **environments** including modularity, versioning, visualisation, explanation, high-level languages, . . .

☞ Ontology **Integration**

- Some tools available, e.g., Chimera (Stanford)
- Need integrated **environments** . . .
- Can learn from DB integration work [Lenzerini, Calvanese et al]

Tools and Infrastructure

Tools and infrastructure required in order support use of DAML+OIL

☞ Ontology **design and maintenance**

- Several **editors** available, e.g, OilEd (Manchester), OntoEdit (Karlsruhe), Protégé (Stanford)
- Need integrated **environments** including modularity, versioning, visualisation, explanation, high-level languages, . . .

☞ Ontology **Integration**

- Some tools available, e.g., Chimera (Stanford)
- Need integrated **environments** . . .
- Can learn from DB integration work [Lenzerini, Calvanese et al]

☞ **Reasoning** engines

Tools and Infrastructure

Tools and infrastructure required in order support use of DAML+OIL

☞ Ontology **design and maintenance**

- Several **editors** available, e.g, OilEd (Manchester), OntoEdit (Karlsruhe), Protégé (Stanford)
- Need integrated **environments** including modularity, versioning, visualisation, explanation, high-level languages, . . .

☞ Ontology **Integration**

- Some tools available, e.g., Chimera (Stanford)
- Need integrated **environments** . . .
- Can learn from DB integration work [Lenzerini, Calvanese et al]

☞ **Reasoning** engines

- Several DL systems available

Tools and Infrastructure

Tools and infrastructure required in order support use of DAML+OIL

☞ Ontology **design and maintenance**

- Several **editors** available, e.g, OilEd (Manchester), OntoEdit (Karlsruhe), Protégé (Stanford)
- Need integrated **environments** including modularity, versioning, visualisation, explanation, high-level languages, . . .

☞ Ontology **Integration**

- Some tools available, e.g., Chimera (Stanford)
- Need integrated **environments** . . .
- Can learn from DB integration work [Lenzerini, Calvanese et al]

☞ **Reasoning** engines

- Several DL systems available
- Need for improved usability/connectivity

Tools and Infrastructure

Tools and infrastructure required in order support use of DAML+OIL

☞ Ontology **design and maintenance**

- Several **editors** available, e.g, OilEd (Manchester), OntoEdit (Karlsruhe), Protégé (Stanford)
- Need integrated **environments** including modularity, versioning, visualisation, explanation, high-level languages, . . .

☞ Ontology **Integration**

- Some tools available, e.g., Chimera (Stanford)
- Need integrated **environments** . . .
- Can learn from DB integration work [Lenzerini, Calvanese et al]

☞ **Reasoning** engines

- Several DL systems available
- Need for improved usability/connectivity

☞ . . .

New Reasoning Tasks

New Reasoning Tasks

☞ Querying

New Reasoning Tasks

Querying

- Retrieval (instances of a concept) and realisation (most specific class of instance) wont be sufficient

New Reasoning Tasks

Querying

- Retrieval (instances of a concept) and realisation (most specific class of instance) wont be sufficient
- Minimum requirement will be conjunctive query style language [Tessaris & Horrocks]

New Reasoning Tasks


Querying

- Retrieval (instances of a concept) and realisation (most specific class of instance) wont be sufficient
- Minimum requirement will be conjunctive query style language [Tessaris & Horrocks]
- May also need to answer “what can I say about x ?” style of query [Bechhofer & Horrocks]

New Reasoning Tasks

Querying

- Retrieval (instances of a concept) and realisation (most specific class of instance) wont be sufficient
- Minimum requirement will be conjunctive query style language [Tessaris & Horrocks]
- May also need to answer “what can I say about x ?” style of query [Bechhofer & Horrocks]

 **Explanation** (e.g., to support ontology design) [McGuinness, Borgida et al]

New Reasoning Tasks

👉 Querying

- Retrieval (instances of a concept) and realisation (most specific class of instance) wont be sufficient
- Minimum requirement will be conjunctive query style language [Tessaris & Horrocks]
- May also need to answer “what can I say about x ?” style of query [Bechhofer & Horrocks]


👉 **Explanation** (e.g., to support ontology design) [McGuinness, Borgida et al]


👉 **Least common subsumer** and/or matching (e.g., to support ontology integration and “bottom up” design) [Baader, Küsters & Molitor]

New Reasoning Tasks

Querying

- Retrieval (instances of a concept) and realisation (most specific class of instance) wont be sufficient
- Minimum requirement will be conjunctive query style language [Tessaris & Horrocks]
- May also need to answer “what can I say about x ?” style of query [Bechhofer & Horrocks]

 **Explanation** (e.g., to support ontology design) [McGuinness, Borgida et al]

 **Least common subsumer** and/or matching (e.g., to support ontology integration and “bottom up” design) [Baader, Küsters & Molitor]

 ...

Summary

Summary

➔ **Ontologies** will play key role in **Semantic Web**

Summary

- ➔ **Ontologies** will play key role in **Semantic Web**
- ➔ **DAML+OIL** is web ontology language based on **Description Logic**

Summary

- ➔ **Ontologies** will play key role in **Semantic Web**
- ➔ **DAML+OIL** is web ontology language based on **Description Logic**
- ➔ Ontology design, integration and deployment **supported by reasoning**

Summary

- ➔ **Ontologies** will play key role in **Semantic Web**
- ➔ **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

Summary

- ➔ **Ontologies** will play key role in **Semantic Web**
- ➔ **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

Summary

- ➔ **Ontologies** will play key role in **Semantic Web**
- ➔ **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
- ➔ Still many **challenges** for DL and Semantic Web research
 - Expressive power
 - Performance
 - Tools and infrastructure
 - New reasoning tasks

Resources

Slides from this talk

www.cs.man.ac.uk/~horrocks/Slides/hp-labs.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 *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.