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Semantic Technologies: Beyond the Semantic Web

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The Semantic Web

- Web "invented" by **Tim Berners-Lee** (an Oxford graduate!), then a physicist working at CERN
- His original vision of the Web was much more **ambitious** than the reality of the existing (syntactic) Web:

"… a set of **connected applications** … forming a **consistent logical web of data** … information is given **well-defined meaning**, better enabling computers and people to work in cooperation …"

- This vision of the Web has become known as the **Semantic Web**
- Latest (refined) definition:

  "a web of data that can be processed directly and indirectly by machines"

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Semantic Technologies

- Initial focus was on necessary **underpinning**, including:

Semantic Technologies

- Initial focus was on necessary **underpinning**, including:
  - Languages

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Semantic Technologies

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  - Storage and querying

Semantic Technologies

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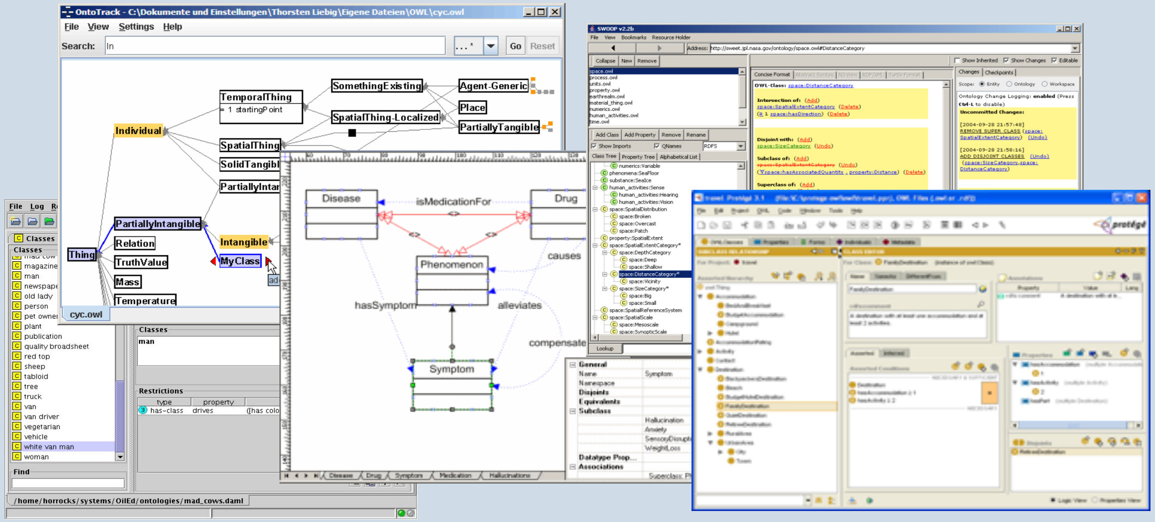
  - Development tools



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Semantic Technologies

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  - Development tools
- Resulting **robust infrastructure** used in SW applications

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Semantic Technologies

- Initial focus was on necessary **underpinning**, including:
  - Languages
  - Storage and querying
  - Development tools
- Resulting **robust infrastructure** used in SW applications
- Also increasingly used in **“Intelligent Information System”** applications

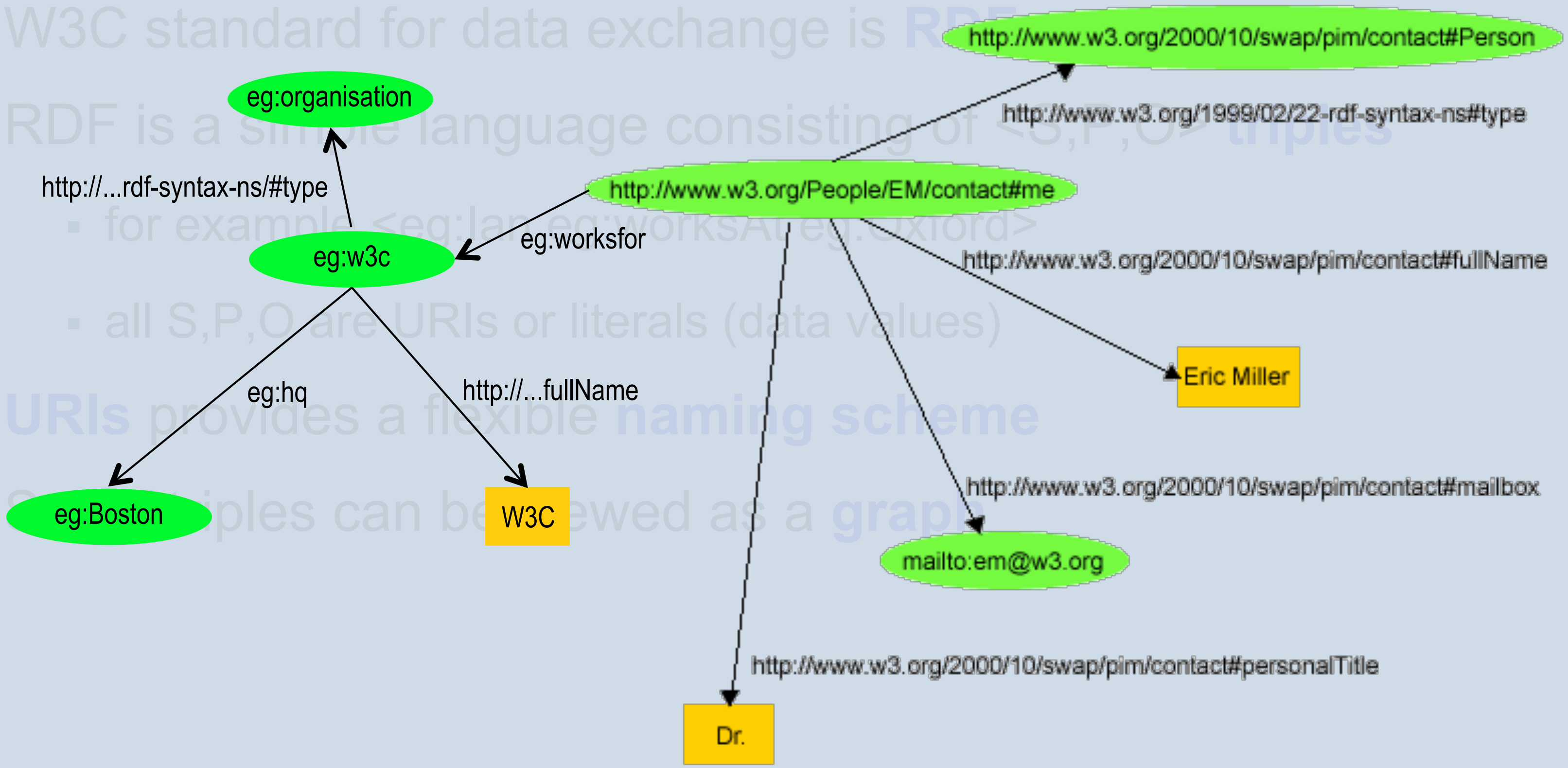
How Does it Work?

❶ Standardised language for exchanging data

- W3C standard for data exchange is **RDF**
- RDF is a simple language consisting of <S P O> **triples**
  - for example <eg:Ian eg:worksAt eg:Oxford>
  - all S,P,O are URIs or literals (data values)
- **URIs** provides a flexible **naming scheme**
- Set of triples can be viewed as a **graph**

How Does it Work?

❶ **Standardised language for exchanging data**



How Does it Work?

RDF

❶ **Standardised language for exchanging data**

- W3C s
- RDF i ... triples
  - for
  - all
- URIs p
- Set of

Triple		
S	**P**	**O**
em1234	rdf:type	Person
em1234	name	“Eric Miller”
em1234	title	“Dr”
em1234	mailbox	mailto:em@w3.org
em1234	worksfor	w3c
w3c	rdf:type	organisation
w3c	hq	Boston
w3c	name	“W3C”
…	…	…

How Does it Work?

❶ Standardised language for exchanging data

- W3C standard for data exchange is RDF
- RD
- URI
- Set

PERSON				
ID	**NAME**	**TITLE**	**MAILBOX**	**WORKSFOR**
em1234	“Eric Miller”	“Dr”	mailto:em@w3.org	w3c
...	...	...	...	...

ORGANISATION		
ID	**NAME**	**HQ**
w3c	“W3C”	Boston
...	...	...

...

How Does it Work?

❷ **Standardised language for exchanging vocabularies/schemas**

- W3C standard for vocabulary/schema exchange is **OWL**
- OWL provides for rich conceptual schemas, aka **ONTOLOGIES**

$$\mathsf{Heart} \sqsubseteq \mathsf{MuscularOrgan} \sqcap \exists \mathsf{isPartOf}.\mathsf{CirculatorySystem}$$

$$\mathsf{HeartDisease} \equiv \mathsf{Disease} \sqcap \exists \mathsf{affects}.\mathsf{Heart}$$

$$\mathsf{VascularDisease} \equiv \mathsf{Disease} \sqcap \exists \mathsf{affects}.(\exists \mathsf{isPartOf}.\mathsf{CirculatorySystem})$$

How Does it Work?

❸ **Standardised language for querying ontologies+data**

- W3C standard for querying is **SPARQL**
- SPARQL provides a rich query language comparable to SQL
  - ?x worksfor ?y .
    ?y rdf:type organisation .
    ?y hq Boston .
  - Select ?x
    where { ?x worksfor ?y .
    ?y rdf:type organisation .
    ?y hq Boston . }
  - Q(?x) ← worksfor(?x,?y) ∧ organisation(?y) ∧ hq(?y,Boston)

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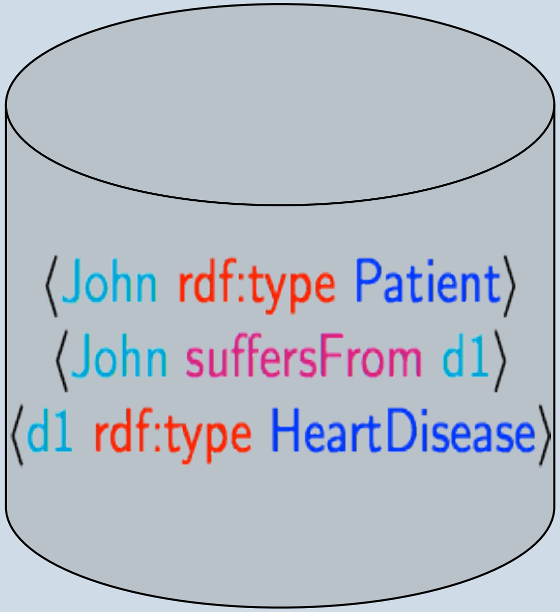
How Does it Work?



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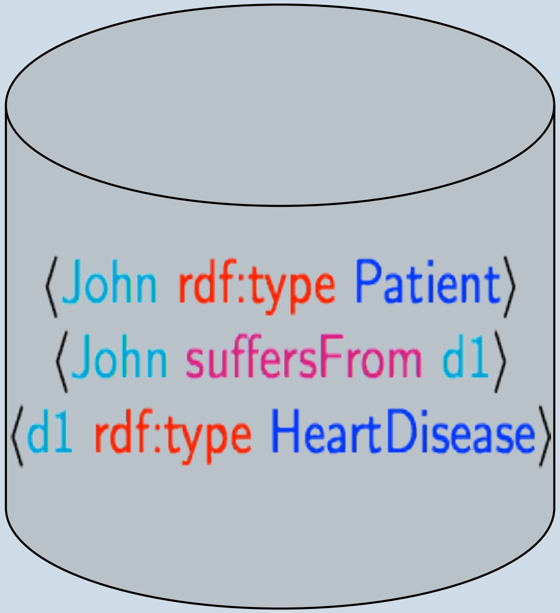

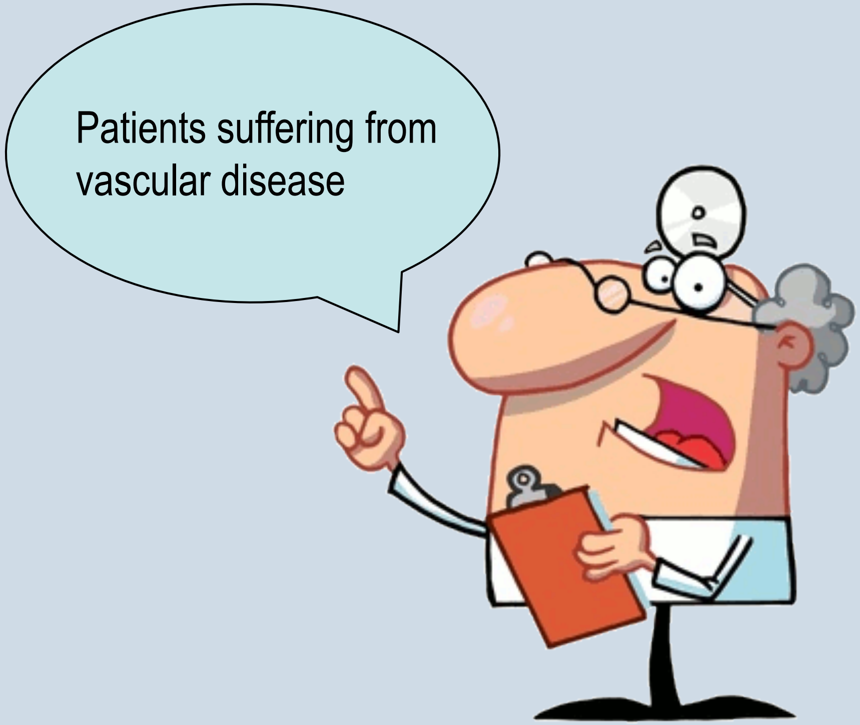

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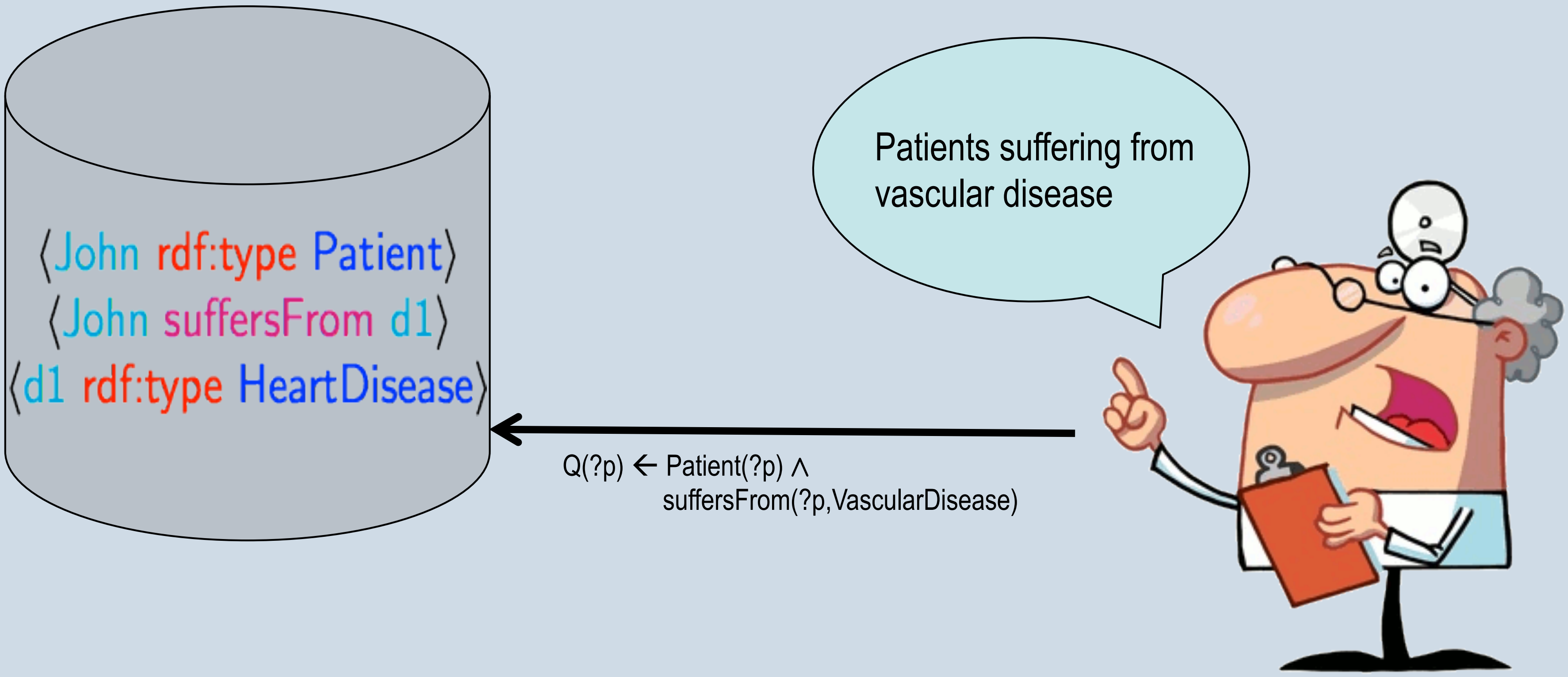

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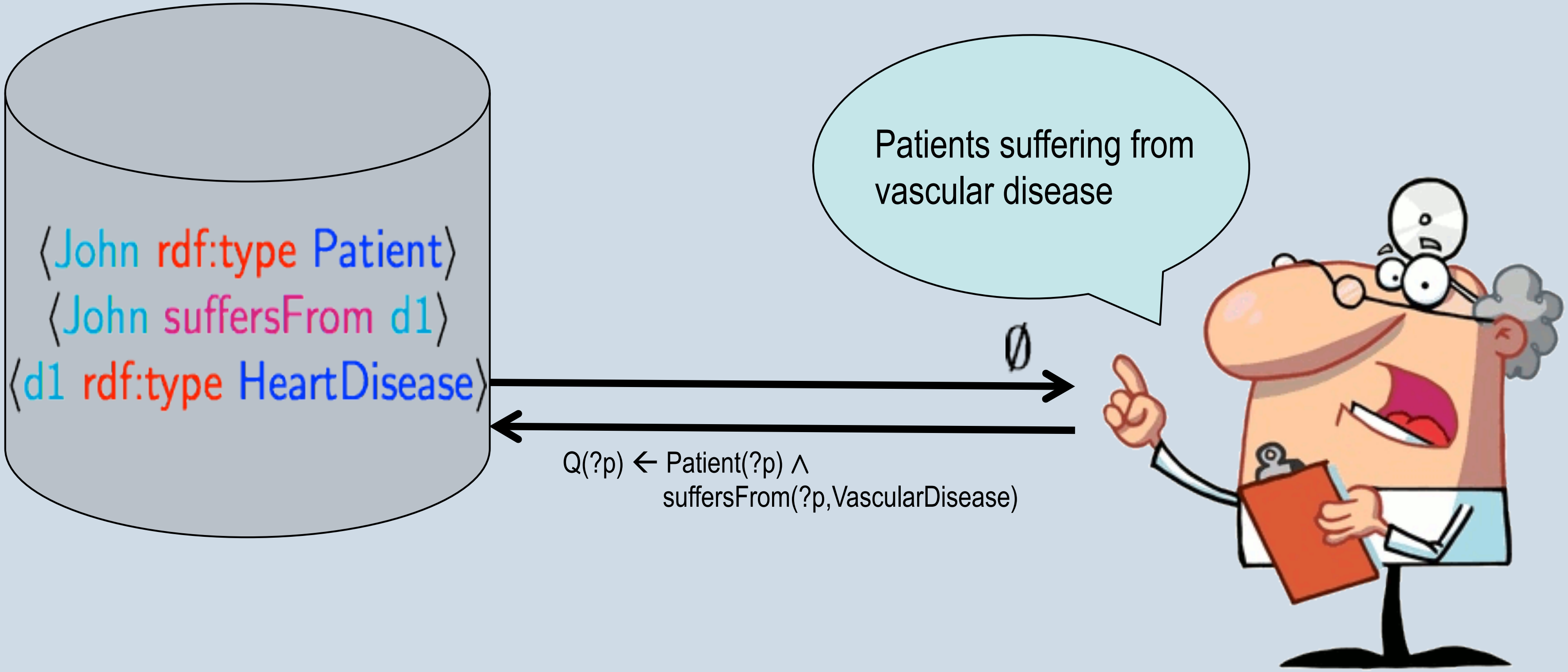

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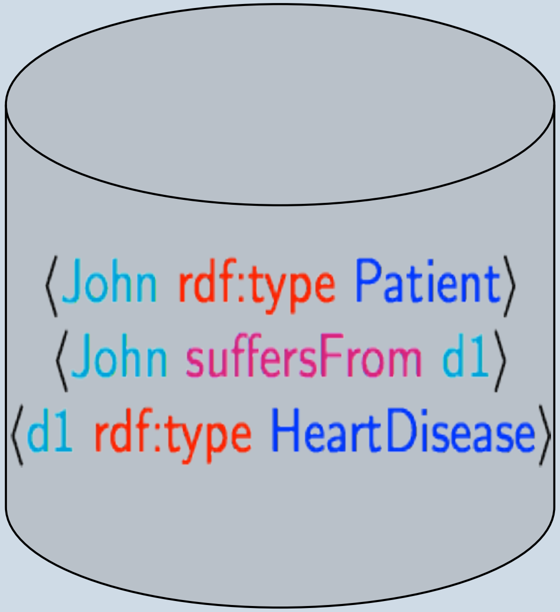

$$
\begin{aligned}
\mathsf{Heart} &\sqsubseteq \mathsf{MuscularOrgan} \sqcap \\
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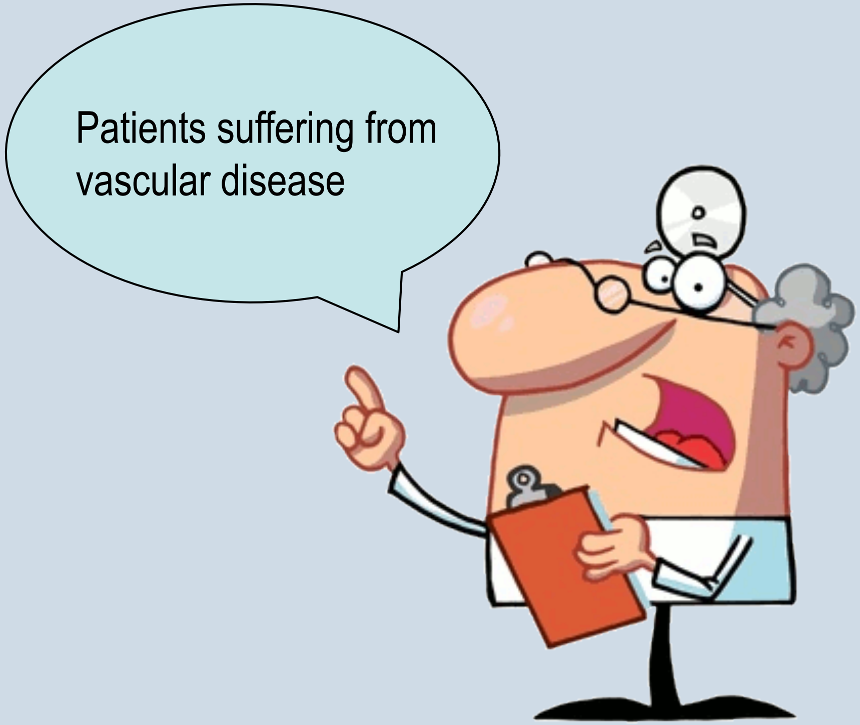

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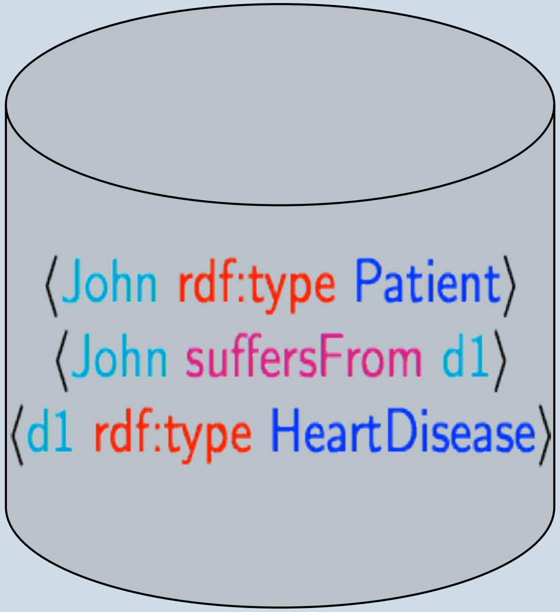

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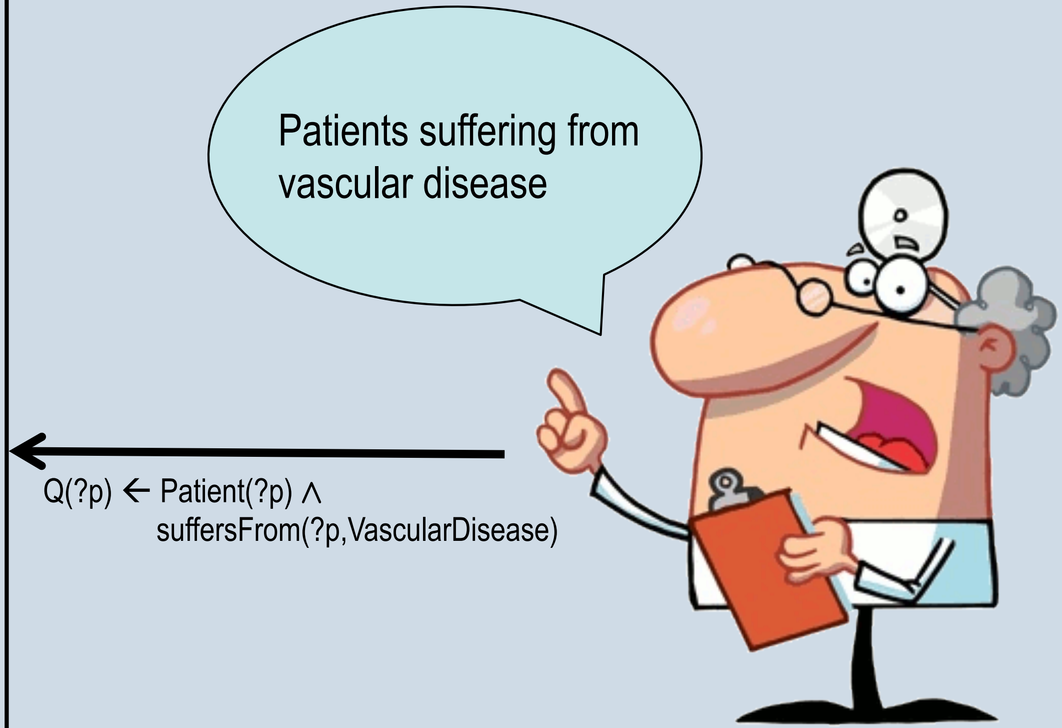

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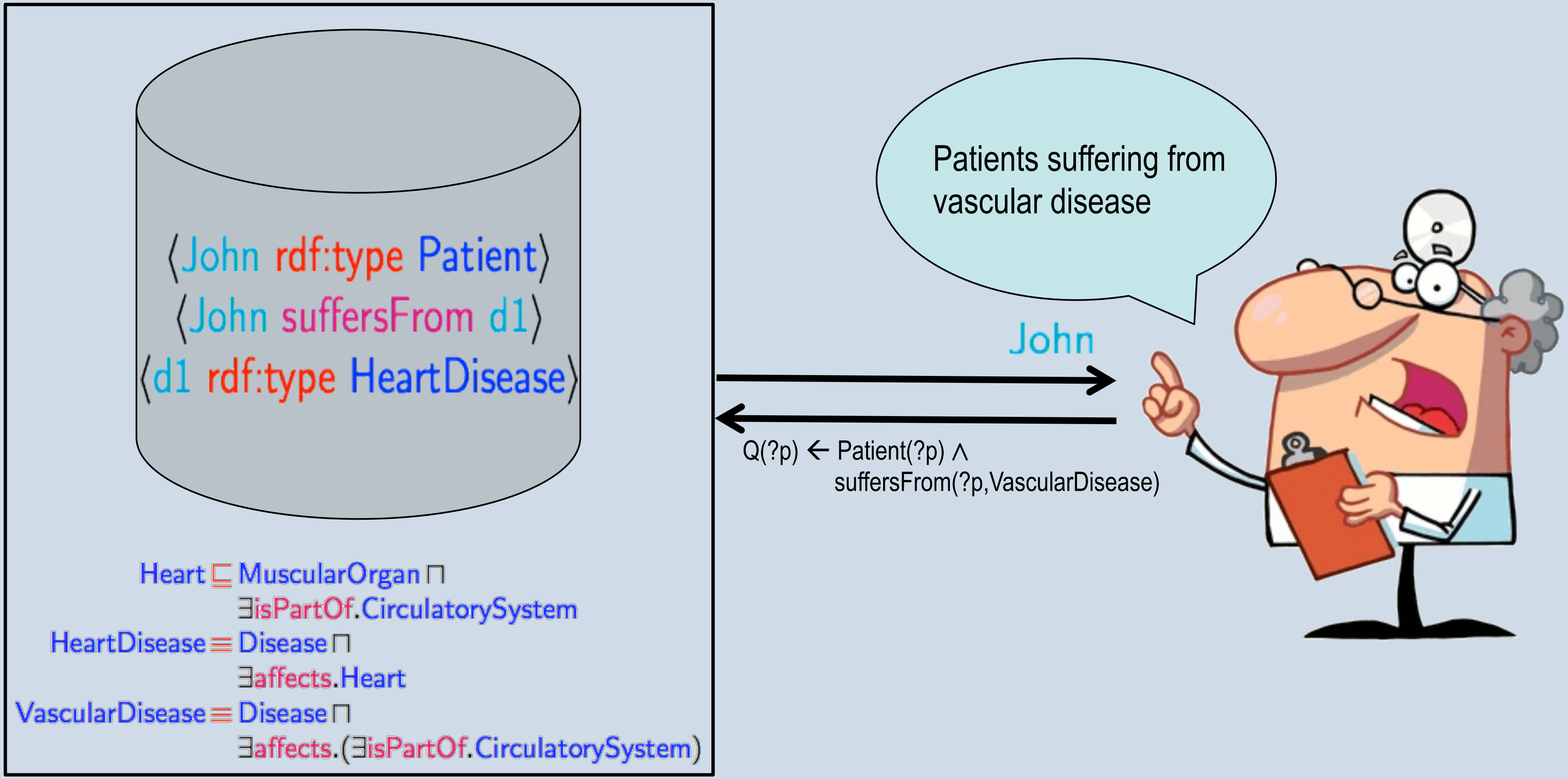

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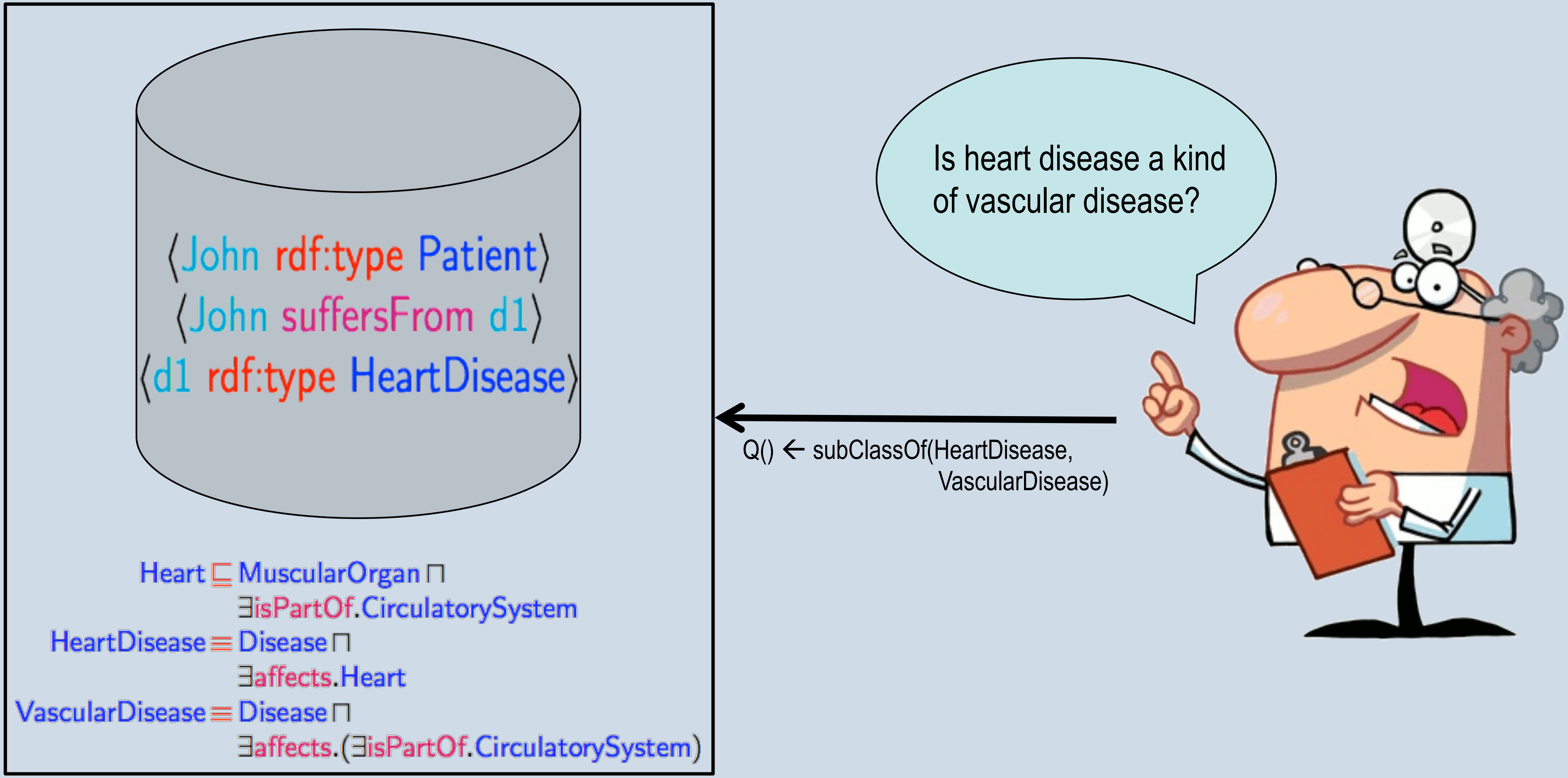

How Does it Work?

⟨John rdf:type Patient⟩
⟨John suffersFrom d1⟩
⟨d1 rdf:type HeartDisease⟩

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\end{aligned}$$

Is heart disease a kind of vascular disease?

YES

Q() ← subClassOf(HeartDisease, VascularDisease)

How Does it Work?

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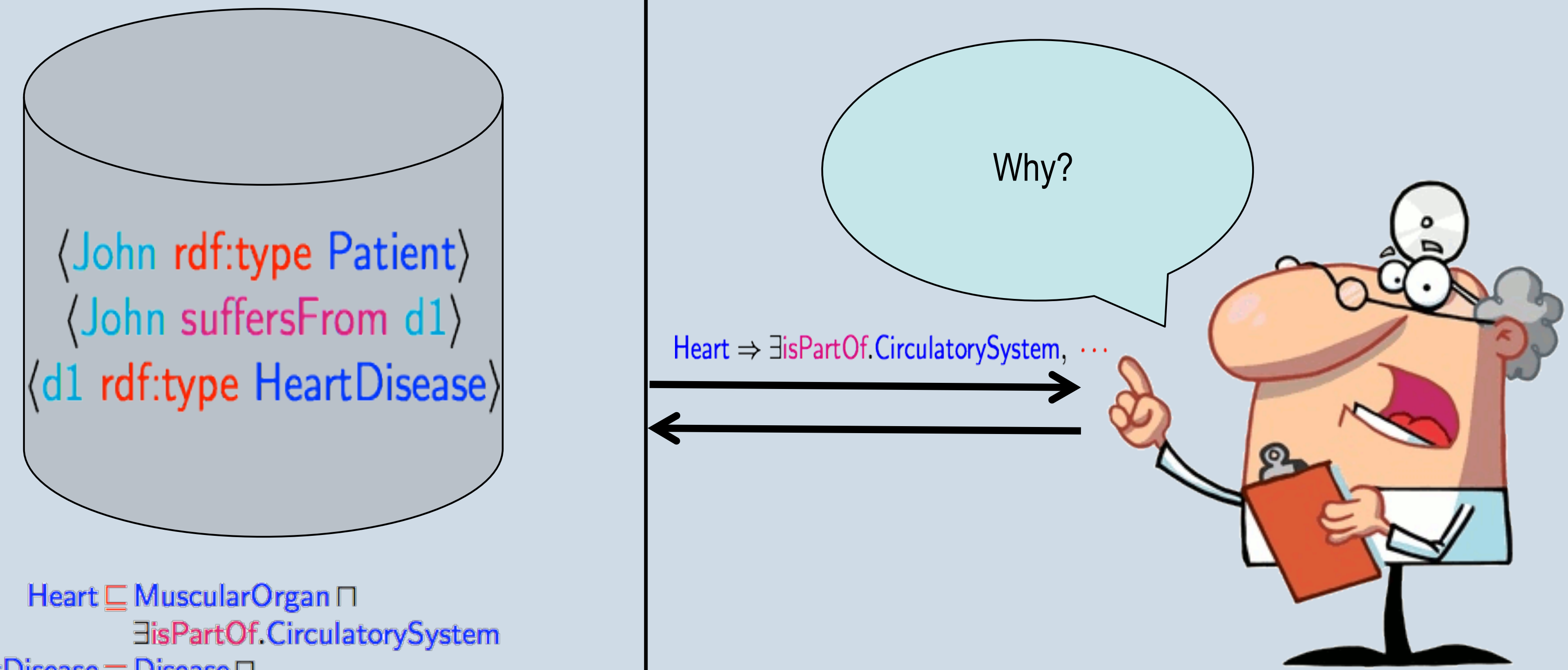

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Applications: Semantic Web

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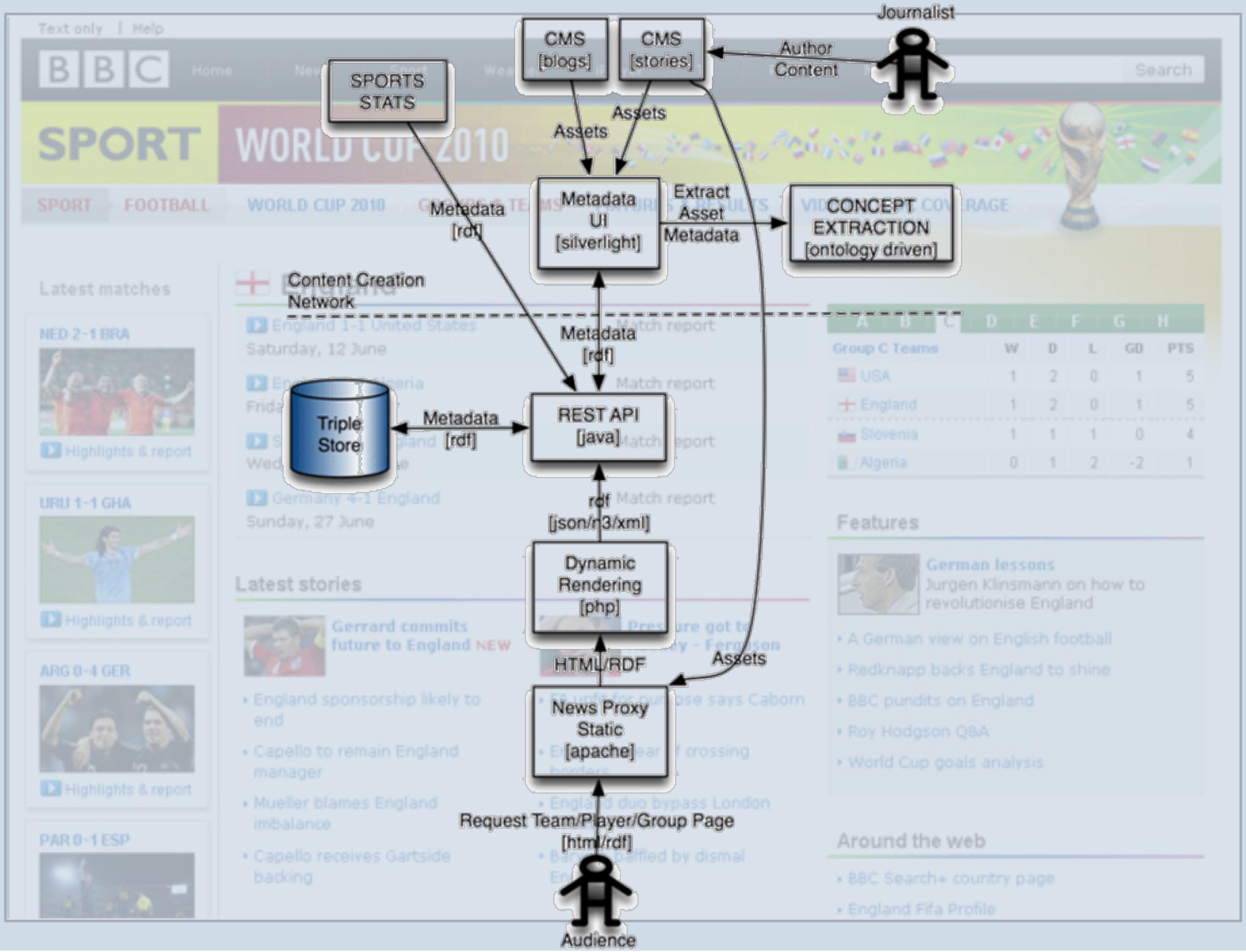
Applications: Semantic Web



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Applications: Semantic Web

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Applications: HCLS

- **SNOMED-CT** (Clinical Terms) ontology
  - provides common vocabulary for recording clinical data
  - used in healthcare systems of more than 15 countries, including Australia, Canada, Denmark, Spain, Sweden and the UK
  - “classified and checked for equivalencies” using ontology reasoners
- **OBO foundry** includes more than 100 biological and biomedical ontologies

  “continuous integration server running Elk and/or HermiT 24/7 checking that multiple independently developed ontologies are mutually consistent”
- **Siemens** “actively building OWL based clinical solutions”

Applications: Energy Supply Industry

- **EDF Energy** offer personalised energy saving advice to every customer

- **OWL ontology** used to model relevant environmental factors

- **HermiT reasoner** used to match customer circumstances with relevant pieces of advice

Applications: Intelligent Mobile Platform

- **Samsung** developing Intelligent Moblile Platform to support context-aware applications
- IMP monitors environment via **sensor data** (GPS, compass, accelerometer, ...)
- **OWL ontology** used to model environment and **infer context** (e.g., coffee with friends)
- Applications exploit context to enable more **intelligent behaviour**

Applications: Oil and Gas Industry

- **Statoil** use data to inform production and exploration management

  Large and complex data sets are difficult and time consuming to use

- Semantic technology can **improve access** to relevant data

- Test deployment in EU project Optique

Theory $\rightsquigarrow$ Practice

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Theory $\rightsquigarrow$ Practice

- OWL based on **description logic** $\mathcal{SROIQ}$

Theory $\rightsquigarrow$ Practice

- OWL based on **description logic** $\mathcal{SROIQ}$
- DLs are a family of FOL fragments
  - Clear semantics
  - Well understood computational properties (e.g., decidability, complexity)
  - Simple goal directed reasoning algorithms

Theory ⇝ Practice

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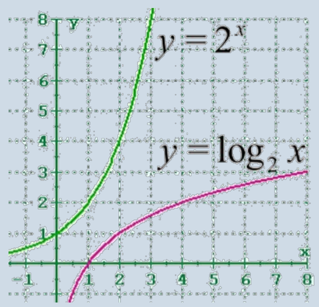
  - N2ExpTime-comlete combined complexity
  - NP-hard data complexity (-v- logspace for databases)



Theory $\leadsto$ Practice

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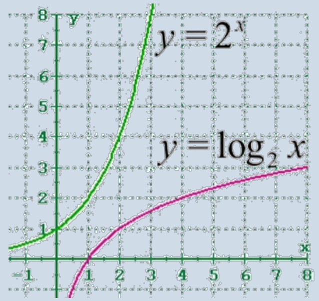

How can we provide robustly scalable query answering?

and now:

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What Are Description Logics?

What Are Description Logics?

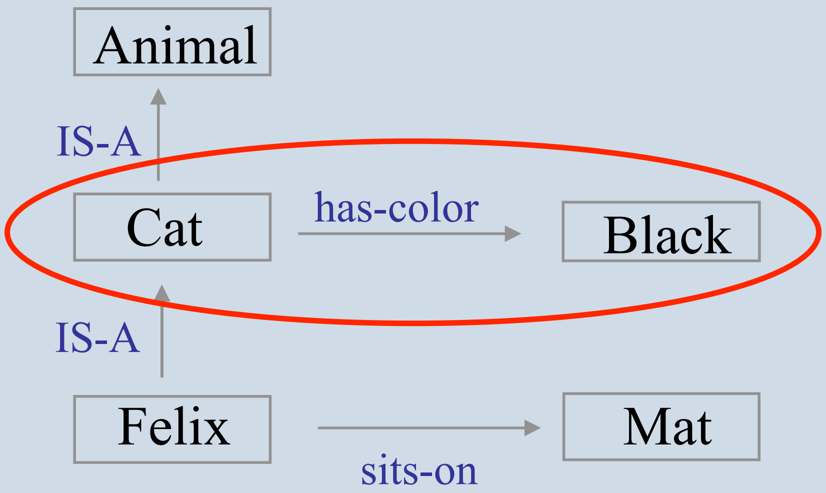
- Decidable fragments of First Order Logic

Thank you for listening

Any questions?

What Are Description Logics?

- A family of logic based Knowledge Representation formalisms
  - Originally descended from semantic networks and KL-ONE
  - Describe domain in terms of concepts (aka classes), roles (aka properties, relationships) and individuals



•[Quillian, 1967]

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What Are Description Logics?

- Modern DLs (after Baader et al) distinguished by:
  - Fully fledged logics with formal semantics
    - Decidable fragments of FOL (often contained in C2)
    - Closely related to Propositional Modal/Dynamic Logics & Guarded Fragment
  - Computational properties well understood (worst case complexity)
  - Provision of inference services
    - Practical decision procedures (algorithms) for key problems (satisfiability, subsumption, query answering, etc)
    - Implemented systems (highly optimised)
- The basis for widely used ontology languages

DL Syntax

- Signature
  - Concept (aka class) names, e.g., Cat, Animal, Doctor
    - Equivalent to FOL unary predicates
  - Role (aka property) names, e.g., sits-on, hasParent, loves
    - Equivalent to FOL binary predicates
  - Individual names, e.g., Felix, John, Mary, Boston, Italy
    - Equivalent to FOL constants

DL Syntax

- Operators
  - Many kinds available, e.g.,
    - Standard FOL Boolean operators (⊓, ⊔, ¬)
    - Restricted form of quantifiers (∃, ∀)
    - Counting (≥, ≤, =)
    - …

DL Syntax

- Concept expressions, e.g.,
  - $\text{Doctor} \sqcup \text{Lawyer}$
  - $\text{Rich} \sqcap \text{Happy}$
  - $\text{Cat} \sqcap \exists \text{sits-on}.\text{Mat}$
- Equivalent to FOL formulae with one free variable
  - $\text{Doctor}(x) \vee \text{Lawyer}(x)$
  - $\text{Rich}(x) \wedge \text{Happy}(x)$
  - $\text{Cat}(x) \wedge \exists y.(\text{sits-on}(x, y))$

DL Syntax

- Special concepts
  - $\top$ (aka top, Thing, most general concept)
  - $\bot$ (aka bottom, Nothing, inconsistent concept)

  used as abbreviations for
  - $(A \sqcup \neg A)$ for any concept A
  - $(A \sqcap \neg A)$ for any concept A

DL Syntax

- Role expressions, e.g.,
  - loves^-
  - $\text{hasParent} \circ \text{hasBrother}$
- Equivalent to FOL formulae with two free variables
  - $\text{loves}(y, x)$
  - $\exists z.(\text{hasParent}(x, z) \wedge \text{hasBrother}(z, y))$

DL Syntax

- "Schema" Axioms, e.g.,
  - Rich $\sqsubseteq$ ¬Poor (concept inclusion)
  - Cat $\sqcap$ ∃sits-on.Mat $\sqsubseteq$ Happy (concept inclusion)
  - BlackCat $\equiv$ Cat $\sqcap$ ∃hasColour.Black (concept equivalence)
  - sits-on $\sqsubseteq$ touches (role inclusion)
  - Trans(part-of) (transitivity)
- Equivalent to (particular form of) FOL sentence, e.g.,
  - $\forall$x.(Rich(x) $\rightarrow$ ¬Poor(x))
  - $\forall$x.(Cat(x) $\wedge$ ∃y.(sits-on(x,y) $\wedge$ Mat(y)) $\rightarrow$ Happy(x))
  - $\forall$x.(BlackCat(x) $\leftrightarrow$ (Cat(x) $\wedge$ ∃y.(hasColour(x,y) $\wedge$ Black(y)))
  - $\forall$x,y.(sits-on(x,y) $\rightarrow$ touches(x,y))
  - $\forall$x,y,z.((sits-on(x,y) $\wedge$ sits-on(y,z)) $\rightarrow$ sits-on(x,z))

DL Syntax

- "Data" Axioms (aka Assertions or Facts), e.g.,
  - BlackCat(Felix) (concept assertion)
  - Mat(Mat1) (concept assertion)
  - Sits-on(Felix,Mat1) (role assertion)
- Directly equivalent to FOL "ground facts"
  - Formulae with no variables

DL Syntax

- A set of axioms is called a TBox, e.g.:

$\{$Doctor $\sqsubseteq$ Person,
Parent $\equiv$ Person $\sqcap$ $\exists$hasChild.Person,
HappyParent $\equiv$ Parent $\sqcap$ $\forall$hasChild.(Do

- A set of facts is called an ABox, e.g

$\{$HappyParent(John),
hasChild(John,Mary)$\}$

Note

Facts sometimes written
John:HappyParent,
John hasChild Mary,
$\langle$John,Mary$\rangle$:hasChild

- A Knowledge Base (KB) is just a TBox plus an Abox
  - Often written $\mathcal{K} = \langle \mathcal{T}, \mathcal{A} \rangle$

The DL Family

- Many different DLs, often with "strange" names
  - E.g., $\mathcal{EL}$, $\mathcal{ALC}$, $\mathcal{SHIQ}$
- Particular DL defined by:
  - Concept operators ($\sqcap$, $\sqcup$, $\neg$, $\exists$, $\forall$, etc.)
  - Role operators ($^{-}$, $\circ$, etc.)
  - Concept axioms ($\sqsubseteq$, $\equiv$, etc.)
  - Role axioms ($\sqsubseteq$, Trans, etc.)

The DL Family

- E.g., $\mathcal{EL}$ is a well known “sub-Boolean” DL
  - Concept operators: $\sqcap$, $\neg$, $\exists$
  - No role operators (only atomic roles)
  - Concept axioms: $\sqsubseteq$, $\equiv$
  - No role axioms
- E.g.:

$$\text{Parent} \equiv \text{Person} \sqcap \exists \text{hasChild.Person}$$

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The DL Family

- $\mathcal{ALC}$ is the smallest propositionally closed DL
  - Concept operators: $\sqcap$, $\sqcup$, $\neg$, $\exists$, $\forall$
  - No role operators (only atomic roles)
  - Concept axioms: $\sqsubseteq$, $\equiv$
  - No role axioms
- E.g.:

$$\text{ProudParent} \equiv \text{Person} \sqcap \forall \text{hasChild.}(\text{Doctor} \sqcup \exists \text{hasChild.Doctor})$$

The DL Family

- $\mathcal{S}$ used for $\mathcal{ALC}$ extended with (role) transitivity axioms
- Additional letters indicate various extensions, e.g.:
  - $\mathcal{H}$ for role hierarchy (e.g., hasDaughter $\sqsubseteq$ hasChild)
  - $\mathcal{R}$ for role box (e.g., hasParent $\circ$ hasBrother $\sqsubseteq$ hasUncle)
  - $\mathcal{O}$ for nominals/singleton classes (e.g., {Italy})
  - $\mathcal{I}$ for inverse roles (e.g., isChildOf $\equiv$ hasChild$^-$)
  - $\mathcal{N}$ for number restrictions (e.g., $\geqslant 2$hasChild, $\leqslant 3$hasChild)
  - $\mathcal{Q}$ for qualified number restrictions (e.g., $\geqslant 2$hasChild.Doctor)
  - $\mathcal{F}$ for functional number restrictions (e.g., $\leqslant 1$hasMother)
- E.g., $\mathcal{SHIQ}$ = $\mathcal{S}$ + role hierarchy + inverse roles + QNRs

The DL Family

- Numerous other extensions have been investigated
  - Concrete domains (numbers, strings, etc)
  - DL-safe rules (Datalog-like rules)
  - Fixpoints
  - Role value maps
  - Additional role constructors ($\cap$, $\cup$, $\neg$, $\circ$, id, …)
  - Nary (i.e., predicates with arity >2)
  - Temporal
  - Fuzzy
  - Probabilistic
  - Non-monotonic
  - Higher-order
  - …

DL Semantics

Via translaton to FOL, or directly using FO model theory:

Interpretation function $\mathcal{I}$ Interpretation domain $\Delta^{\mathcal{I}}$

Individuals $i^{\mathcal{I}} \in \Delta^{\mathcal{I}}$

John

Mary

Concepts $C^{\mathcal{I}} \subseteq \Delta^{\mathcal{I}}$

Lawyer

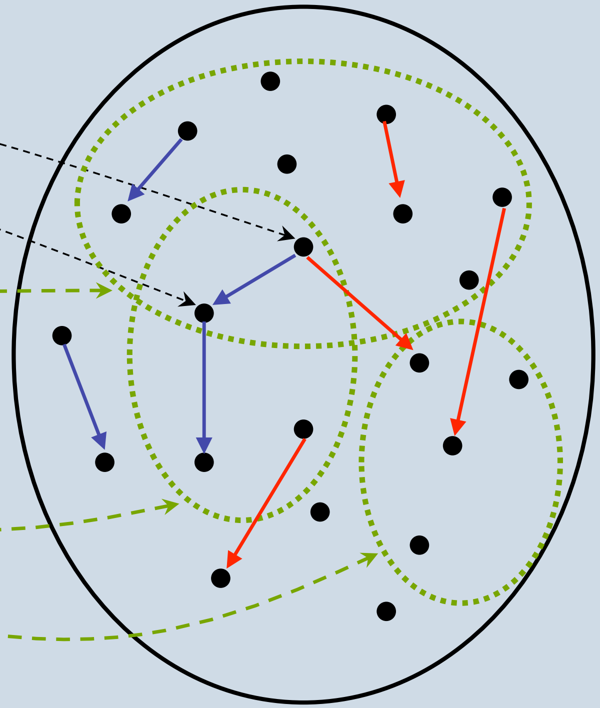
Doctor

Vehicle

Roles $r^{\mathcal{I}} \subseteq \Delta^{\mathcal{I}} \times \Delta^{\mathcal{I}}$

hasChild

owns



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DL Semantics

- Interpretation function extends to concept expressions in the obvious(ish) way, e.g.:

$$
\begin{aligned}
(C \sqcap D)^{\mathcal{I}} &= C^{\mathcal{I}} \cap D^{\mathcal{I}} \\
(C \sqcup D)^{\mathcal{I}} &= C^{\mathcal{I}} \cup D^{\mathcal{I}} \\
(\neg C)^{\mathcal{I}} &= \Delta^{\mathcal{I}} \setminus C^{\mathcal{I}} \\
\{x\}^{\mathcal{I}} &= \{x^{\mathcal{I}}\} \\
(\exists R.C)^{\mathcal{I}} &= \{x \mid \exists y. \langle x, y \rangle \in R^{\mathcal{I}} \wedge y \in C^{\mathcal{I}}\} \\
(\forall R.C)^{\mathcal{I}} &= \{x \mid \forall y. (x, y) \in R^{\mathcal{I}} \Rightarrow y \in C^{\mathcal{I}}\} \\
(\leqslant n R)^{\mathcal{I}} &= \{x \mid \#\{y \mid \langle x, y \rangle \in R^{\mathcal{I}}\} \leqslant n\} \\
(\geqslant n R)^{\mathcal{I}} &= \{x \mid \#\{y \mid \langle x, y \rangle \in R^{\mathcal{I}}\} \geqslant n\}
\end{aligned}
$$

DL Semantics

- Given a model M = $\langle D, \cdot^I \rangle$
  - $M \models C \sqsubseteq D$ iff $C^I \subseteq D^I$
  - $M \models C \equiv D$ iff $C^I = D^I$
  - $M \models C(a)$ iff $a^I \in C^I$
  - $M \models R(a,b)$ iff $\langle a^I, b^I \rangle \in R^I$
  - $M \models \langle \mathcal{T}, \mathcal{A} \rangle$ iff for every axiom $ax \in \mathcal{T} \cup \mathcal{A}$, $M \models ax$

DL Semantics

- Satisfiability and entailment
  - A KB $\mathcal{K}$ is satisfiable iff there exists a model M s.t. $\mathrm{M} \vDash \mathcal{K}$
  - A concept C is satisfiable w.r.t. a KB $\mathcal{K}$ iff there exists a model $\mathrm{M} = \langle \mathrm{D}, \cdot^{\mathrm{I}} \rangle$ s.t. $\mathrm{M} \vDash \mathcal{K}$ and $\mathrm{C}^{\mathrm{I}} \neq \emptyset$
  - A KB $\mathcal{K}$ entails an axiom ax (written $\mathcal{K} \vDash \mathrm{ax}$) iff for every model M of $\mathcal{K}$, $\mathrm{M} \vDash \mathrm{ax}$ (i.e., $\mathrm{M} \vDash \mathcal{K}$ implies $\mathrm{M} \vDash \mathrm{ax}$)

DL Semantics

E.g.,

$\mathcal{T}$ = {Doctor $\sqsubseteq$ Person, Parent $\equiv$ Person $\sqcap$ $\exists$hasChild.Person,
HappyParent $\equiv$ Parent $\sqcap$ $\forall$hasChild.(Doctor $\sqcup$ $\exists$hasChild.Doctor)}

$\mathcal{A}$ = {John:HappyParent, John hasChild Mary, John hasChild Sally,
Mary:$\neg$Doctor, Mary hasChild Peter, Mary:($\leq$ 1 hasChild)

- ✓ $\mathcal{K} \models$ John:Person ?
- ✓ $\mathcal{K} \models$ Peter:Doctor ?
- ✓ $\mathcal{K} \models$ Mary:HappyParent ?
- What if we add "Mary hasChild Jane" ?

  $\mathcal{K} \models$ Peter = Jane
- What if we add "HappyPerson $\equiv$ Person $\sqcap$ $\exists$hasChild.Doctor" ?

  $\mathcal{K} \models$ HappyPerson $\sqsubseteq$ Parent

DL and FOL

- Most DLs are subsets of C2
  - But reduction to C2 may be (highly) non-trivial
    - Trans(R) naively reduces to $\forall x, y, z. R(x, y) \wedge R(y, z) \rightarrow R(x, z)$
- Why use DL instead of C2?
  - Syntax is succinct and convenient for KR applications
  - Syntactic conformance guarantees being inside C2
    - Even if reduction to C2 is non-obvious
  - Different combinations of constructors can be selected
    - To guarantee decidability
    - To reduce complexity
  - Decidability/complexity landscape mapped out in great detail
    - See http://www.cs.man.ac.uk/~ezolin/dl/

Complexity of reasoning in Description Logics

Note: the information here is (always) incomplete and updated often

Base description logic: $\mathcal{A}$ttributive $\mathcal{L}$anguage with $\mathcal{C}$omplements

$\mathcal{ALC}$ ::= ⊥ | A | ¬C | $C \wedge D$ | $C \vee D$ | ∃$R.C$ | ∀$R.C$

Concept constructors:

- [ ] $\mathcal{F}$ – functionality[2]: (≤1 R)
- [x] $\mathcal{N}$ – (unqualified) number restrictions: (≥n R), (≤n R)
- [ ] $\mathcal{Q}$ – qualified number restrictions: (≥n $R.C$), (≤n $R.C$)
- [x] $\mathcal{O}$ – nominals: {a} or {a_1,...,a_n} ("one-of" constructor)
- [ ] μ – least fixpoint operator: $\mu X.C$
- [ ] $R \subseteq S$ – role-value-maps
- [ ] $f = g$ – agreement of functional role chains ("same-as")

Role constructors: (trans) (reg)

- [x] $\mathcal{I}$ – role inverses: R^{-}
- [ ] ∩ – role intersection[3]: $R \cap S$
- [ ] ∪ – role union: $R \cup S$
- [ ] ¬ – role complement: full
- [ ] o – role chain (composition): RoS
- [ ] * – reflexive-transitive closure[4]: R^*
- [ ] id – concept identity: $id(C)$
- Forbid complex roles[5] in number restrictions[6]

TBox is *internalized* in extensions of $\mathcal{ALCIO}$, see [76, Lemma 4.12], [54, p.3]

- (•) Empty TBox
- ( ) Acyclic TBox ($A \equiv C$, A is a concept name; no cycles)
- ( ) General TBox ($C \sqsubseteq D$ for arbitrary concepts C and D)

Role axioms (RBox): (OWL-Lite) (OWL-DL) (OWL 1.1)

- [x] $\mathcal{S}$ – Role transitivity: Trans(R)
- [x] $\mathcal{H}$ – Role hierarchy: $R \subseteq S$
- [ ] $\mathcal{R}$ – Complex role inclusions: Ro$S \subseteq R$, Ro$S \subseteq S$
- [ ] s – some additional features

(Reset) You have selected the Description Logic: $\mathcal{SHOIN}$

Complexity of reasoning problems[7]

Reasoning problem	Complexity[8]	Comments and references
Concept satisfiability	**NExpTime-complete**	• Hardness of even $\mathcal{ALCFIO}$ is proved in [76, Corollary 4.13]. In that paper, the result is formulated for $\mathcal{ALCQIO}$, but only number restrictions of the form (≤1R) are used in the proof. • A different proof of the NExpTime-hardness for $\mathcal{ALCFIO}$ is given in [54] (even with 1 nominal, and role inverses not used in number restrictions). • Upper bound for $\mathcal{SHOIQ}$ is proved in [77, Corollary 6.31] with numbers coded in unary (for binary coding, the upper bound remains an open problem for all logics in between $\mathcal{ALCNIO}$ and $\mathcal{SHOIQ}$. • **Important:** in number restrictions, only *simple* roles (i.e. which are neither transitive nor have a transitive subroles) are allowed; otherwise we gain undecidability even in $\mathcal{SHN}$; see [46]. • **Remark:** recently [47] it was observed that, in many cases, one can use transitive roles in number restrictions – and still have a decidable logic! So the above notion of a *simple* role could be substantially extended.
ABox consistency	**NExpTime-complete**	By reduction to concept satisfiability problem in presence of nominals shown in [69, Theorem 3.7].

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Complexity Measures

- Taxonomic complexity
  - Measured w.r.t. total size of “schema” axioms
- Data complexity
  - Measured w.r.t. total size of “data” facts
- Query complexity
  - Measured w.r.t. size of query
- Combined complexity
  - Measured w.r.t. total size of KB (plus query if appropriate)

Complexity Classes

- LogSpace, PTime, NP, PSpace, ExpTime, etc
  - worst case for a given problem w.r.t. a given parameter
  - X-hard means at-least this hard (could be harder);
    in X means no harder than this (could be easier);
    X-complete means both hard and in, i.e., exactly this hard
    - e.g., $\mathcal{SROIQ}$ KB satisfiability is 2NExpTime-complete w.r.t. combined complexity and NP-hard w.r.t. data complexity
- Note that:
  - this is for the worst case, not a typical case
  - complexity of problem means we can never devise a more efficient (in the worst case) algorithm
  - complexity of algorithm may, however, be even higher (in the worst case)

DLs and Ontology Languages

- W3C's OWL 2 (like OWL, DAML+OIL & OIL) based on DL
  - OWL 2 based on $\mathcal{SROIQ}$, i.e., $\mathcal{ALC}$ extended with transitive roles, a role box nominals, inverse roles and qualified number restrictions
    - OWL 2 EL based on $\mathcal{EL}$
    - OWL 2 QL based on DL-Lite
    - OWL 2 EL based on $\mathcal{DLP}$
  - OWL was based on $\mathcal{SHOIN}$
    - only simple role hierarchy, and unqualified NRs

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Class/Concept Constructors

OWL Constructor	DL Syntax	Example
intersectionOf	$C_1 \sqcap \ldots \sqcap C_n$	Human $\sqcap$ Male
unionOf	$C_1 \sqcup \ldots \sqcup C_n$	Doctor $\sqcup$ Lawyer
complementOf	$\neg C$	$\neg$Male
oneOf	$\{x_1\} \sqcup \ldots \sqcup \{x_n\}$	{john} $\sqcup$ {mary}
allValuesFrom	$\forall P.C$	$\forall$hasChild.Doctor
someValuesFrom	$\exists P.C$	$\exists$hasChild.Lawyer
maxCardinality	$\leqslant n P$	$\leqslant$1hasChild
minCardinality	$\geqslant n P$	$\geqslant$2hasChild

Ontology Axioms

OWL Syntax	DL Syntax	Example
subClassOf	$C_1 \sqsubseteq C_2$	Human $\sqsubseteq$ Animal $\sqcap$ Biped
equivalentClass	$C_1 \equiv C_2$	Man $\equiv$ Human $\sqcap$ Male
subPropertyOf	$P_1 \sqsubseteq P_2$	hasDaughter $\sqsubseteq$ hasChild
equivalentProperty	$P_1 \equiv P_2$	cost $\equiv$ price
transitiveProperty	$P^+ \sqsubseteq P$	ancestor$^+$ $\sqsubseteq$ ancestor

OWL Syntax	DL Syntax	Example
type	$a : C$	John : Happy-Father
property	$\langle a, b \rangle : R$	$\langle$John, Mary$\rangle$: has-child

- An Ontology is *usually* considered to be a TBox
  - but an OWL ontology is a mixed set of TBox and ABox axioms

Other OWL Features

- XSD datatypes and (in OWL 2) facets, e.g.,
  - integer, string and (in OWL 2) real, float, decimal, datetime, …
  - minExclusive, maxExclusive, length, …
  - PropertyAssertion(hasAge Meg "17"^^xsd:integer)
  - DatatypeRestriction(xsd:integer xsd:minInclusive "5"^^xsd:integer xsd:maxExclusive "10"^^xsd:integer)

  These are equivalent to (a limited form of) **DL concrete domains**

- Keys
  - E.g., HasKey(Vehicle Country LicensePlate)
    - Country + License Plate is a unique identifier for vehicles

  This is equivalent to (a limited form of) **DL safe rules**

Obvious Database Analogy

- Ontology axioms analogous to DB **schema**
  - Schema describes structure of and constraints on data
- Ontology facts analogous to DB **data**
  - Instantiates schema
  - Consistent with schema constraints
- But there are also important differences…

Obvious Database Analogy

Database:

- Closed world assumption (**CWA**)
  - Missing information treated as false
- Unique name assumption (**UNA**)
  - Each individual has a single, unique name
- Schema behaves as **constraints** on structure of data
  - Define legal database states

Ontology:

- Open world assumption (**OWA**)
  - Missing information treated as unknown
- **No UNA**
  - Individuals may have more than one name
- Ontology axioms behave like **implications** (inference rules)
  - Entail implicit information

Database -v- Ontology

E.g., given the following **ontology/schema**:

$\text{HogwartsStudent} \equiv \text{Student} \sqcap \exists\, \text{attendsSchool.Hogwarts}$

$\text{HogwartsStudent} \sqsubseteq \forall \text{hasPet.(Owl or Cat or Toad)}$

$\text{hasPet} \equiv \text{isPetOf}^{-}$ (i.e., hasPet inverse of isPetOf)

$\exists \text{hasPet}.\top \sqsubseteq \text{Human}$ (i.e., domain of hasPet is Human)

$\text{Phoenix} \sqsubseteq \forall \text{isPetOf.Wizard}$ (i.e., only Wizards have Phoenix pets)

$\text{Muggle} \sqsubseteq \neg \text{Wizard}$ (i.e., Muggles and Wizards are disjoint)

Database -v- Ontology

And the following **facts/data**:

HarryPotter: Wizard
DracoMalfoy: Wizard
HarryPotter hasFriend RonWeasley
HarryPotter hasFriend HermioneGranger
HarryPotter hasPet Hedwig

Query: Is Draco Malfoy a friend of HarryPotter?

- DB: No
- Ontology: Don’t Know

  OWA (didn’t say Draco was not Harry’s friend)

Database -v- Ontology

And the following **facts/data**:

HarryPotter: Wizard
DracoMalfoy: Wizard
HarryPotter hasFriend RonWeasley
HarryPotter hasFriend HermioneGranger
HarryPotter hasPet Hedwig

Query: How many friends does Harry Potter have?

- DB: 2
- Ontology: at least 1

  No UNA (Ron and Hermione may be 2 names for same person)

Database -v- Ontology

And the following **facts/data**:

HarryPotter: Wizard
DracoMalfoy: Wizard
HarryPotter hasFriend RonWeasley
HarryPotter hasFriend HermioneGranger
HarryPotter hasPet Hedwig

➔ **RonWeasley ≠ HermioneGranger**

Query: How many friends does Harry Potter have?

- DB: 2
- Ontology: at least 2

  OWA (Harry may have more friends we didn't mention yet)

Database -v- Ontology

And the following **facts/data**:

HarryPotter: Wizard
DracoMalfoy: Wizard
HarryPotter hasFriend RonWeasley
HarryPotter hasFriend HermioneGranger
HarryPotter hasPet Hedwig
RonWeasley ≠ HermioneGranger

➔ **HarryPotter: ∀hasFriend.{RonWeasley} ⊔ {HermioneGranger}**

Query: How many friends does Harry Potter have?

- DB: 2
- Ontology: 2!

Database -v- Ontology

Inserting new facts/data:

Dumbledore: Wizard
Fawkes: Phoenix
Fawkes isPetOf Dumbledore

$\exists$hasPet.$\top \sqsubseteq$ Human
Phoenix $\sqsubseteq \forall$isPetOf.Wizard

What is the response from DBMS?

- Update rejected: **constraint violation**

  Domain of hasPet is Human; Dumbledore is not Human (CWA)

What is the response from Ontology reasoner?

- **Infer** that Dumbledore is Human (domain restriction)
- Also infer that Dumbledore is a Wizard (only a Wizard can have a pheonix as a pet)

DB Query Answering

- Schema plays **no role**
  - Data must explicitly satisfy schema constraints
- Query answering amounts to **model checking**
  - I.e., a “look-up” against the data
- Can be very **efficiently implemented**
  - Worst case complexity is low (logspace) w.r.t. size of data

Ontology Query Answering

- Ontology axioms play a powerful and **crucial role**
  - Answer may include implicitly derived facts
  - Can answer conceptual as well as extensional queries
    - E.g., Can a Muggle have a Phoenix for a pet?
- Query answering amounts to **theorem proving**
  - I.e., logical entailment
- May have very **high worst case complexity**
  - E.g., for OWL, NP-hard w.r.t. size of data
    (upper bound is an open problem)
  - Implementations may still behave well in typical cases
  - Fragments/profiles may have much better complexity

Ontology Based Information Systems

- Analogous to **relational database management systems**
  - Ontology ≈ schema; instances ≈ data
- Some important (**dis**)**advantages**
  - \+ (Relatively) easy to maintain and update schema
    - Schema plus data are integrated in a logical theory
  - \+ Query answers reflect both schema and data
  - \+ Can deal with incomplete information
  - \+ Able to answer both intensional and extensional queries
  - Semantics can seem counter-intuitive, particularly w.r.t. data
    - Open -v- closed world; axioms -v- constraints
  - Query answering (logical entailment) may be much more difficult
    - Can lead to scalability problems with expressive logics

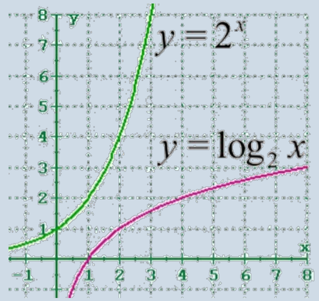
Ontology Based Information Systems

- Analogous to **relational** … **ement systems**
  - Ontology ≈ sche…
- Some important (…
  - \+ (Relatively) …
    - Schema…
  - \+ Query ans…
  - \+ Can deal w…
  - \+ Able to ans… …ries
  - Semantics ca… …w.r.t. data
    - Open -v- clo…
  - Query answering (… …much more difficult
    - Can lead to scalability p… …pressive logics

Back to our Scheduled Program

Theory $\rightsquigarrow$ Practice

- OWL based on **description logic $\mathcal{SROIQ}$**
- DLs are a family of FOL fragments
  - Clear semantics
  - Well understood computational properties (e.g., decidability, complexity)
  - Simple goal directed reasoning algorithms
- OWL is decidable, but highly **highly intractable**
  - N2ExpTime-comlete combined complexity
  - NP-hard data complexity (-v- logspace for databases)



How can we provide robustly scalable query answering?

Various Approaches — Different Tradeoffs

❶ Use full power of OWL and a complete reasoner:

✓ Well-suited for modeling complex domains

✓ Reliable answers

✗ High worst-case complexity

✗ Scalability problems for large ontologies & datasets

Complete OWL reasoners:

- E.g., FaCT++, **HermiT**, Pellet, ...
- Based on (hyper)tableau (model construction) theorem provers
- Highly optimised implementations effective on many ontologies, but not robust and unlikely to scale to large data sets

(Hyper)tableau — How Does It Work?

Standard technique based on (hyper-) **tableau**

- Reasoning tasks reducible to (un)**satisfiability**
  - E.g., KB ⊨ HeartDisease ⊑ VascularDisease iff KB ∪ {x:(HeartDisease ⊓ ¬VascularDisease)} is *not* satisfiable

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x : HeartDisease $\sqcap$ $\neg$VascularDisease

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x : Disease

x : ∃affects.Heart

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y : MuscularOrgan

y : ∃isPartOf.CirculatorySystem

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x : HeartDisease
x : Disease
x : $\exists$affects.Heart
(x, y) : affects
y : Heart
y : MuscularOrgan
y : $\exists$isPartOf.CirculatorySystem
(y, z) : isPartOf
z : CirculatorySystem

x : $\neg$VascularDisease
x : $\neg$Disease $\sqcup$ $\neg\exists$affects.($\exists$isPartOf.CirculatorySystem)

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(x, y) : affects
y : Heart
y : MuscularOrgan
y : ∃isPartOf.CirculatorySystem
(y, z) : isPartOf
z : CirculatorySystem

x : ¬VascularDisease
x : ¬Disease ⊔ ¬∃affects.(∃isPartOf.CirculatorySystem)

(Hyper)tableau — How Does It Work?

Standard technique based on (hyper-) **tableau**

- Reasoning tasks reducible to (un)**satisfiability**
  - E.g., KB $\models$ HeartDisease $\sqsubseteq$ VascularDisease iff KB $\cup$ {x:(HeartDisease $\sqcap$ ¬VascularDisease)} is *not* satisfiable
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x : $\neg\exists$affects.($\exists$isPartOf.CirculatorySystem)
x : $\forall$affects.($\forall$isPartOf.$\neg$CirculatorySystem)
y : $\forall$isPartOf.$\neg$CirculatorySystem
z : $\neg$CirculatorySystem

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Note similarity to chase!

Various Approaches — Different Tradeoffs

❷ Use a suitable "profile" and specialised reasoner:

OWL 2 defines language subsets, aka **profiles** that can be "more simply and/or efficiently implemented"

- **OWL 2 EL**
  - Based on $\mathcal{EL}^{++}$
  - PTime-complete for combined and data complexity
- **OWL 2 QL**
  - Based on DL-Lite
  - AC^0 data complexity (same as DBs)
- **OWL 2 RL**
  - Based on "**Description Logic Programs**" ($\approx$ DL $\cap$ LP)
  - PTime-complete for combined and data complexity

Various Approaches — Different Tradeoffs

❷ Use a suitable “profile” and specialised reasoner:

✓ Tractable query answering

✓ Reliable answers (for inputs in the profile)

✗ Restricted expressivity of the ontology language

✗ Reasoners reject inputs outside profile

OWL 2 EL ontology reasoners:

- E.g., CEL, ELK, ...
- Based on “consequence based” (deduction) theorem provers
- Target HCLS applications where many ontologies are (mainly) in the EL profile

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Consequence Based — How Does It Work?

- Normalise ontology axioms to standard form:

$$A \sqsubseteq B \quad A \sqcap B \sqsubseteq C \quad A \sqsubseteq \exists R.B \quad \exists R.B \sqsubseteq C$$

- Saturate using inference rules (for $\mathcal{EL}$):

$$\frac{A \sqsubseteq B \quad B \sqsubseteq C}{A \sqsubseteq C} \qquad \frac{A \sqsubseteq B \quad A \sqsubseteq C \quad B \sqcap C \sqsubseteq D}{A \sqsubseteq D}$$

$$\frac{A \sqsubseteq \exists R.B \quad B \sqsubseteq C \quad \exists R.C \sqsubseteq D}{A \sqsubseteq D}$$

- Extension to $\mathcal{EL}^{++}$ requires (many) more rules

Consequence Based — Example

$$\mathsf{OrganTransplant} \equiv \mathsf{Transplant} \sqcap \exists \mathsf{site}.\mathsf{Organ}$$
$$\mathsf{HeartTransplant} \equiv \mathsf{Transplant} \sqcap \exists \mathsf{site}.\mathsf{Heart}$$
$$\mathsf{Heart} \sqsubseteq \mathsf{Organ}$$

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$$\exists \mathsf{site}.\mathsf{Organ} \sqsubseteq \mathsf{SO}$$

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$$\exists \mathsf{site}.\mathsf{Heart} \sqsubseteq \mathsf{SH}$$
$$\mathsf{Transplant} \sqcap \mathsf{SH} \sqsubseteq \mathsf{HeartTransplant}$$

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SEVENTH FRAMEWORK PROGRAMME

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$\mathsf{Heart} \sqsubseteq \mathsf{Organ}$

$\mathsf{HeartTransplant} \sqsubseteq \mathsf{SO}$

$\mathsf{HeartTransplant} \sqsubseteq \mathsf{OrganTransplant}$

Schema Reasoning — Solved Problem?

	SNOMED CT	GALEN	FMA	GO
Logic	$\mathcal{EL}$	$\mathcal{EL}$	$\mathcal{EL}$	$\mathcal{EL}$
#classes	315,489	23,136	78,977	19,468
#properties	58	950	7	1
#axioms	430,844	36,547	121,712	28,897
$\#\sqsubseteq$	$> 10^{11}$	$> 10^{8}$	$> 10^{9}$	$> 10^{8}$
ELK (1 worker)	13.15	1.33	0.44	0.20
ELK (4 workers)	5.02	0.77	0.39	0.19

	Plant Anat.	SWEET-P	NCI-2	DOLCE-P
Logic	$\mathcal{SHIF}$	$\mathcal{SHOIN}$	$\mathcal{ALCH}$	$\mathcal{SHOIN}$
#classes	19,145	1,728	70,576	118
#properties	82	145	189	264
#axioms	35,770	2,419	100,304	265
$\#\sqsubseteq$	$> 10^{8}$	$> 10^{6}$	$> 10^{9}$	$> 10^{4}$
HermiT	11.2	11.2	—	105.1
Pellet	87.2	—	172.0	105.1
FaCT++	22.9	0.2	60.7	—

Schema Reasoning — Solved Problem?

- Full expressive power may be needed to model, e.g.:
  - *non-viral pneumonia* (negation)
  - *infectious pneumonia* is caused by a *virus* or a *bacterium* (disjunction)
  - *double pneumonia* occurs in two *lungs* (cardinalities)
  - *groin* has a part that is part of the *abdomen*, and has a part that is part of the *leg* (inverse properties)
- Single non-EL axiom may incur massive performance penalty

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SEVENTH FRAMEWORK PROGRAMME

MORe Modular Reasoner

- Integrates powerful (slower) and weaker (faster) reasoners
- Exploits module extraction techniques to identify subset of ontology that can be completely classified using fast reasoner.
- Slower reasoner performs as few computations as possible
- Bulk of computation delegated to faster reasoner
- Current prototype integrates **HermiT** and **ELK** [1]

[1] Armas Romero, Cuenca Grau, and Horrocks. Modular Combination of Reasoners for Ontology Classification. In Proc. of ISWC 2012 (to appear).

MORe Modular Reasoner

Ontology	$\|\mathcal{O} \setminus \mathcal{O}_{\mathcal{L}}\|$	$\|\Sigma^{\mathcal{L}}\|$	$\|\mathcal{M}_{[\mathcal{O},\overline{\Sigma^{\mathcal{L}}}]}\|$	Classif. time (seconds)			
				HermiT	MORe		
					total	HermiT	ELK
GO	0	100%	0%	7.1	2.2 (↓69.0%)	0	0.1
Gazeteer	0	100%	0%	838.1	28.2 (↓96.6%)	0	15.6
NCI	65	94.9%	15.4%	84.1	28.6 (↓66.0%)	15.8	3.3
Protein	12	98.1%	6.6%	11.4	2.9 (↓74.6%)	0.4	0.9
Biomodels	22,079	45.2%	66.4%	741.4	575.6 (↓22.4%)	540.1	2.6
cellCycle	1	$> 99.9\%$	$< 0.1\%$	–	13.9 (–)	<0.1	4.9
NCI+CHEBI	65	95.6%	10.3%	116.6	34.0 (↓70.8%)	16.3	4.1
NCI+GO	65	96.7%	10.4%	110.0	37.6 (↓65.8%)	17.6	3.2
NCI+Mouse	65	96.0%	13.3%	93.7	31.0 (↓66.9%)	16.6	2.6

OWL 2 EL — Data Retrieval Queries?

- PTime potentially problematical for very large datasets

OWL 2 EL — Data Retrieval Queries?

- PTime potentially problematical for very large datasets
- Various approaches:
  - Materialise taxonomy and use DBMS (incomplete reasoning)
  - "Combined approach" using materialisation + OBDA [2]
  - Datalog engine with (some form of) query rewriting [3]
  - Highly optimised ABox reasoners [4]

[2] Kontchakov, Lutz, Toman, Wolter, Zakharyaschev: The Combined Approach to Ontology-Based Data Access. IJCAI 2011.

[3] Stefanoni, Motik, Horrocks: Small Datalog Query Rewritings for EL. DL 2012

[4] Kazakov, Kroetzsch, Simancik: Practical Reasoning with Nominals in the EL Family of Description Logics. KR 2012

Various Approaches — Different Tradeoffs

❷ Use a suitable "profile" and specialised reasoner:

✓ LogSpace query answering (in size of data)

✓ Reliable answers (for inputs in the profile)

✗ Restricted expressivity of the ontology language

✗ Reasoners reject inputs outside profile

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OWL 2 QL ontology reasoners:

- E.g., QuOnto, **Requiem**, ...
- Based on query rewriting technique — ontology used to rewrite (expand) query
- Targets applications where data stored in RDBMS — aka **Ontology Based Data Access** (OBDA)

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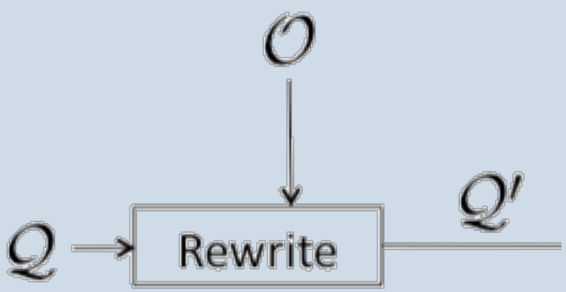

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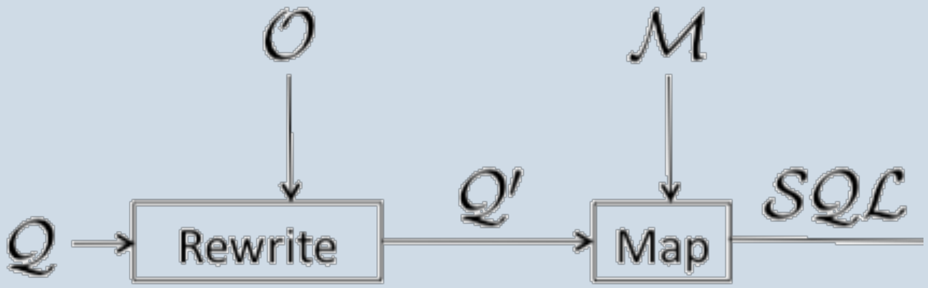

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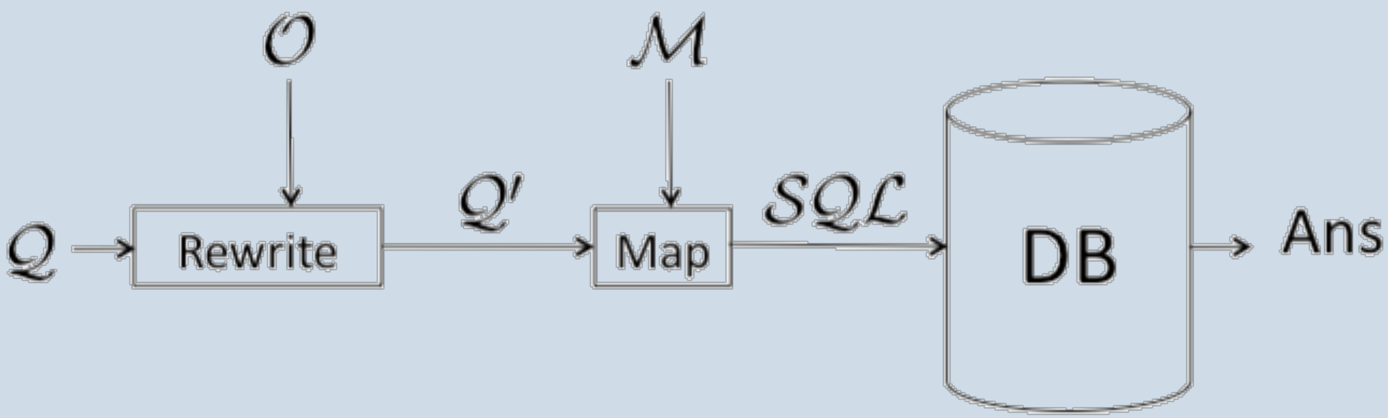
- **Evaluate** (SQL) query against DB



Query Rewriting — Example

$$\mathcal{O} \begin{cases} \text{Doctor} \sqsubseteq \exists \text{treats}.\text{Patient} \\ \text{Consultant} \sqsubseteq \text{Doctor} \end{cases}$$

$$\mathcal{Q} \quad Q(x) \leftarrow \text{treats}(x, y) \wedge \text{Patient}(y)$$

$$\mathcal{M} \begin{cases} \text{Doctor} & \mapsto & \text{SELECT Name FROM Doctor} \\ \text{Patient} & \mapsto & \text{SELECT Name FROM Patient} \\ \text{treats} & \mapsto & \text{SELECT DName, PName FROM Treats} \end{cases}$$

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$$Q' \left\{ \begin{array}{l} Q(x) \leftarrow \text{treats}(x, y) \wedge \text{Patient}(y) \\ Q(x) \leftarrow \text{Doctor}(x) \wedge \text{Patient}(f(x)) \\ Q(x) \leftarrow \text{treats}(x, f(x)) \wedge \text{Doctor}(x) \\ Q(x) \leftarrow \text{Doctor}(x) \\ Q(x) \leftarrow \text{Consultant}(x) \end{array} \right.$$

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- $Q(x) \leftarrow \mathsf{treats}(x, y) \wedge \mathsf{Patient}(y)$
- ~~$Q(x) \leftarrow \mathsf{Doctor}(x) \wedge \mathsf{Patient}(f(x))$~~
- ~~$Q(x) \leftarrow \mathsf{treats}(x, f(x)) \wedge \mathsf{Doctor}(x)$~~
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Doctor	$\mapsto$	SELECT Name FROM Doctor
Patient	$\mapsto$	SELECT Name FROM Patient
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$\mathcal{M}$:
- Doctor $\mapsto$ SELECT Name FROM Doctor
- Patient $\mapsto$ SELECT Name FROM Patient
- treats $\mapsto$ SELECT DName, PName FROM Treats

$\mathcal{SQL}$:

SELECT Name FROM Doctor UNION
SELECT DName FROM Treats, Patient WHERE PName=Name

Query Rewriting — Issues

❶ Rewriting

- May be large (worst case exponential in size of ontology)
- Queries may be hard for existing DBMSs
- Ongoing work on OBDA optimisation techniques, e.g., [5]

❷ Mappings

- May be difficult to develop and maintain
- Little work in this area to date

[5] Rodriguez-Muro, Calvanese: High Performance Query Answering over DL-Lite Ontologies. KR 2012

Various Approaches — Different Tradeoffs

❸ Use full power of OWL and incomplete reasoner:

- ✓ Well-suited for modeling complex domains
- ✓ Favourable scalability properties
- ✓ Flexibility: no inputs rejected
- ✗ Incomplete answers (and degree of incompleteness not known)

OWL 2 RL ontology reasoners:

- E.g., Oracle's Semantic Datastore, Sesame, Jena, OWLim, ...
- Based on RDF triple stores and chase-like materialisation
- Widely used in practice to reason with large datasets
- Complete (only) for RL ontologies and ground atomic queries

Materialisation — How Does It Work?

Given (RDF) data DB, ontology $\mathcal{O}$ and query $\mathcal{Q}$:

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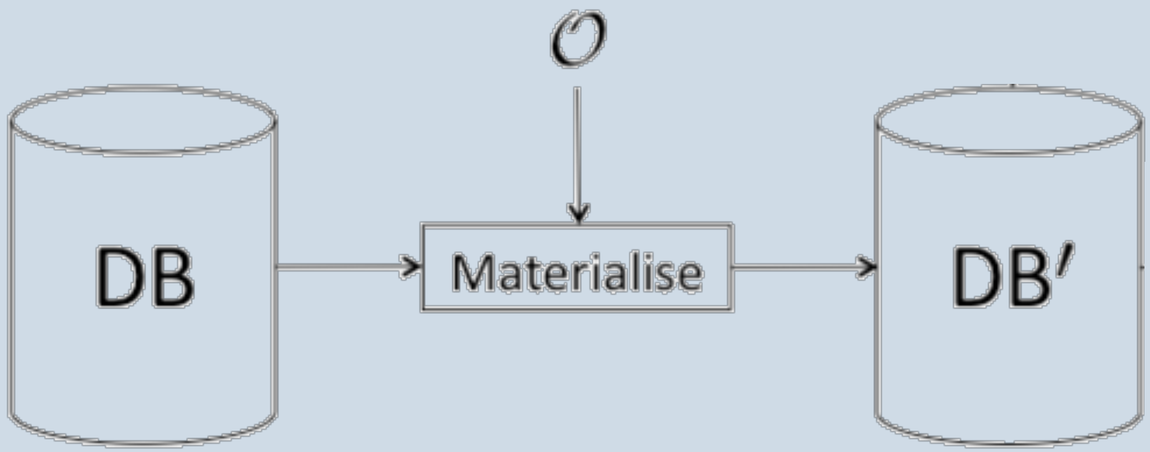
- **Materialise** (RDF) data DB $\rightarrow$ DB$'$ s.t. evaluating $\mathcal{Q}$ w.r.t. DB$'$ equivalent to answering $\mathcal{Q}$ w.r.t. DB and $\mathcal{O}$

  nb: Closely related to **chase** procedure used with DB dependencies



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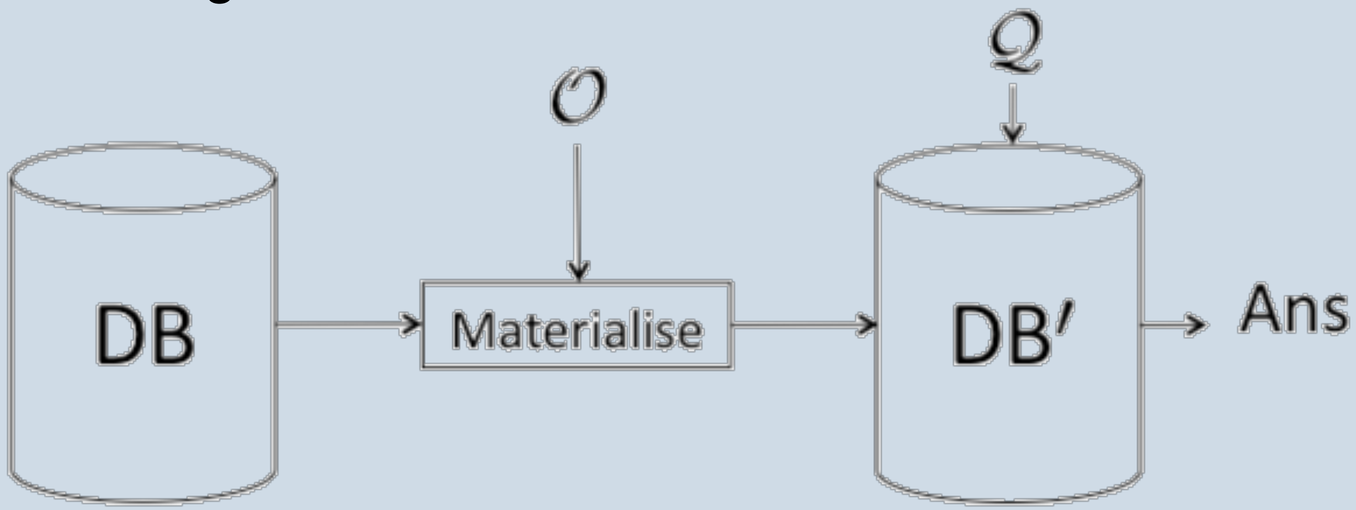
- **Evaluate** $\mathcal{Q}$ against DB′



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$$\mathcal{O} \begin{cases} \mathsf{Doctor} \equiv \exists \mathsf{treats}.\mathsf{Patient} \\ \mathsf{Consulatant} \sqsubseteq \mathsf{Doctor} \end{cases}$$

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Dealing With Frequently Changing Data

Adding data is relatively easy

- Monotonicity of FOL means that extending existing materialisation is sound
- Can still be quite costly if naively implemented

Changing/retracting data is much harder

- Naive solution requires all materialised facts to be discarded
- Re-materialisation very costly for large data sets
- But incremental reasoning is possible using view maintenance based techniques [6]

[6] Motik, Horrocks, and Kim. Delta-reasoner: a semantic web reasoner for an intelligent mobile platform. In Proc. of WWW 2012.

Dealing with Incompleteness

- Materialisation based reasoning complete for **OWL 2 RL** profile (and ground atomic queries)
- But for ontologies **outside the profile**:
  - Reasoning may be incomplete
  - Incompleteness difficult to measure via empirical testing
- Possible solutions offered by recent work:
  - **Measuring and repairing incompleteness**
  - **Chase materialisation**
  - **Computing upper and lower bounds**

Measuring and Repairing Incompleteness

- Use ontology $\mathcal{O}$ (and query $\mathcal{Q}$) to generate a test suite

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Measuring and Repairing Incompleteness

- Use ontology $\mathcal{O}$ (and query $\mathcal{Q}$) to generate a test suite
- A **test suite** for $\mathcal{O}$ is a pair $\mathbf{S} = \langle \mathbf{S}_\bot, \mathbf{S}_Q \rangle$
  - $\mathbf{S}_\bot$ a set of ABoxes that are unsatisfiable w.r.t. $\mathcal{O}$
  - $\mathbf{S}_Q$ a set of paris $\langle \mathcal{A}, \mathcal{Y} \rangle$ with $\mathcal{A}$ an ABox and $\mathcal{Y}$ a query

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- A **reasoner** $\mathcal{R}$ passes $\mathbf{S}$ if:
  - $\mathcal{R}$ finds $\mathcal{O} \cup \mathcal{A}$ unsatisfiable for each $\mathcal{A} \in \mathbf{S}_\bot$
  - $\mathcal{R}$ complete for $\mathcal{Y}$ w.r.t. $\mathcal{O} \cup \mathcal{A}$ for each $\langle \mathcal{A}, \mathcal{Y} \rangle \in \mathbf{S}_Q$

[7] Cuenca Grau, Motik, Stoilos, and Horrocks. Completeness Guarantees for Incomplete Ontology Reasoners: Theory and Practice. JAIR, 43:419-476, 2012.

Chase Materialisation

- Applicable to **acyclic** ontologies
  - Acyclicity can be checked using, e.g., graph based techniques (weak acyclicity, joint acyclicity, etc.)
  - Many realistic ontologies turn out to be acyclic
- Given acyclic ontology $\mathcal{O}$, can apply chase materialisation:
  - Ontology translated into existential rules (aka dependencies)
  - Existential rules can introduce fresh Skolem individuals
  - Termination guaranteed for acyclic ontologies

[8] Cuenca Grau et al. Acyclicity Conditions and their Application to Query Answering in Description Logics. In Proc. of KR 2012.

Chase Materialisation — Example

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Skolems

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Skolems (→ $\text{treats}(d_2, f(d_2))$, $\text{treats}(c_1, f(c_1))$)

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Skolems

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$$\mathcal{Q}_2 \quad Q(x) \leftarrow \mathsf{treats}(x, y) \wedge \mathsf{Patient}(y) \quad \rightsquigarrow \quad \{d_1, d_2, c_1\}$$

Computing Lower and Upper Bounds

- RL reasoning w.r.t. OWL ontology $\mathcal{O}$ gives lower bound answer ***L***

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- Transform $\mathcal{O}$ into strictly stronger OWL RL ontology
  - Transform ontology into Datalog$^{\pm,\vee}$ rules
  - Eliminate $\vee$ by transforming to $\wedge$
  - Eliminate existentials by replacing with Skolem constants
  - Discard rules with empty heads
  - Transform rules into OWL 2 RL ontology $\mathcal{O}'$

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Computing Lower and Upper Bounds

- RL reasonting w.r.t. $\mathcal{O}$' gives (complete but unsound) upper bound answer ***U***

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Computing Upper Bound — Example

$$\mathcal{O} \begin{cases} \mathsf{Doctor} \equiv \exists \mathsf{treats}.\mathsf{Patient} \\ \mathsf{Consulatant} \sqsubseteq \mathsf{Doctor} \end{cases}$$

$$\mathrm{DB} \begin{cases} \mathsf{treats}(d_1, p_1) \\ \mathsf{Patient}(p_1) \\ \mathsf{Doctor}(d_2) \\ \mathsf{Consultant}(c_1) \end{cases}$$

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Computing Lower and Upper Bounds

- RL reasonting w.r.t. $\mathcal{O}'$ gives (complete but unsound) upper bound answer ***U***

- If ***L*** = ***U***, then both answers are sound and complete
- If ***L*** ≠ ***U***, then ***U*** \ ***L*** identifies a (small) set of "possible" answers
  - Indicates range of uncertainty
  - Can (more efficiently) check possible answers using, e.g., HermiT
  - Future work: use ***U*** \ ***L*** to identify (small) "relevant" subset of data needed to efficiently compute exact answer

[9] Zhou, Cuenca Grau, and Horrocks. Efficient Upper Bound Computation of Query Answers in Expressive Description Logics. In Proc. of DL 2012, volume 846 of CEUR.

Discussion

Numerous **exciting developments** & research areas

- Rewriting: optimisations, extensions (datalog engines), etc.
- Materialisation: chase, repair, truth maintenance, upper bounds etc.
- Combined techniques (materialisation+rewriting), Datalog
- Specialised RDF stores, Column stores, massive parallelism, etc.
- Parameterised complexity, new query evaluation techniques, etc.

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Consider **progress on schema reasoning**:

Year	$\mathcal{O}$-size	Complete	Time (s)
1995	3,000	No	10^5
1998	3,000	Yes	300
2005	30,000	Yes	30
2010	400,000	Yes	5

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Looking forward to similar progress on query answering!

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$$\text{Semantics} \sqcap \text{Scalability} \not\models \bot \ !$$

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Acknowledgements

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DARPA

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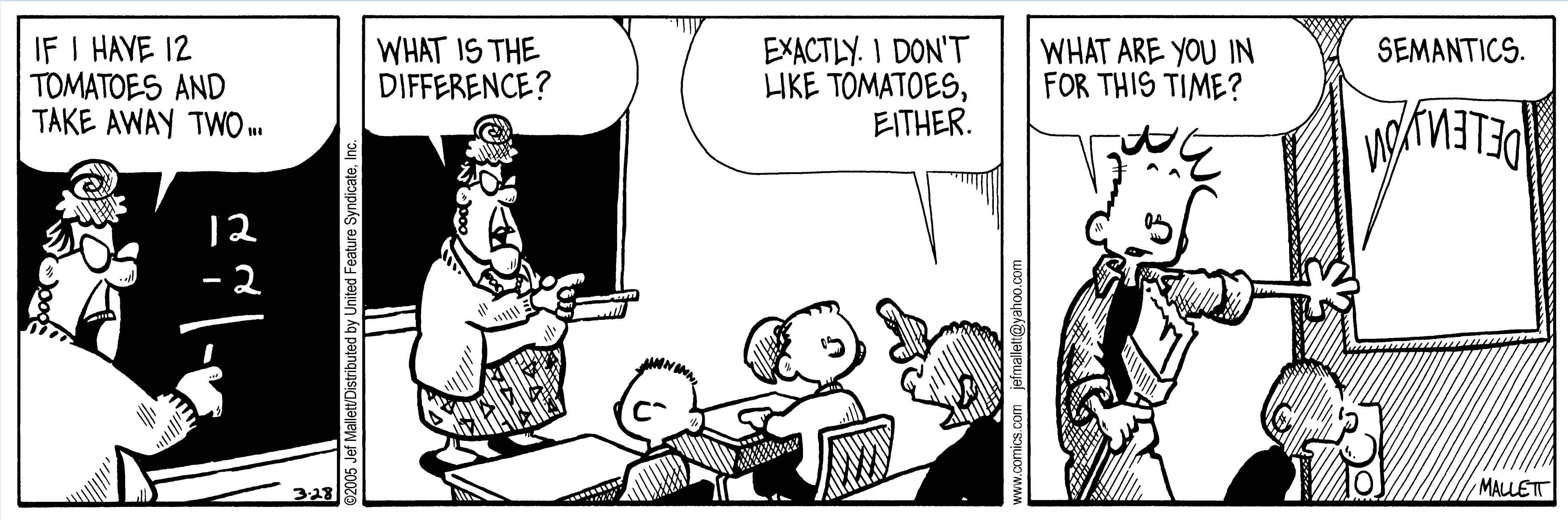
Thank you for listening



Any questions?

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