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UNIVERSITY OF
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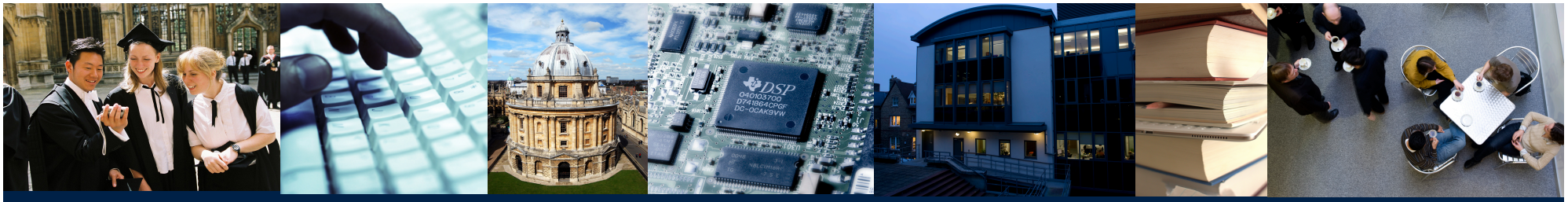

Semantics $\sqcap$ Scalability $\models \bot$?

Ian Horrocks
Information Systems Group
Department of Computer Science
University of Oxford

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"

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)
- Set of triples can be thought of as a graph

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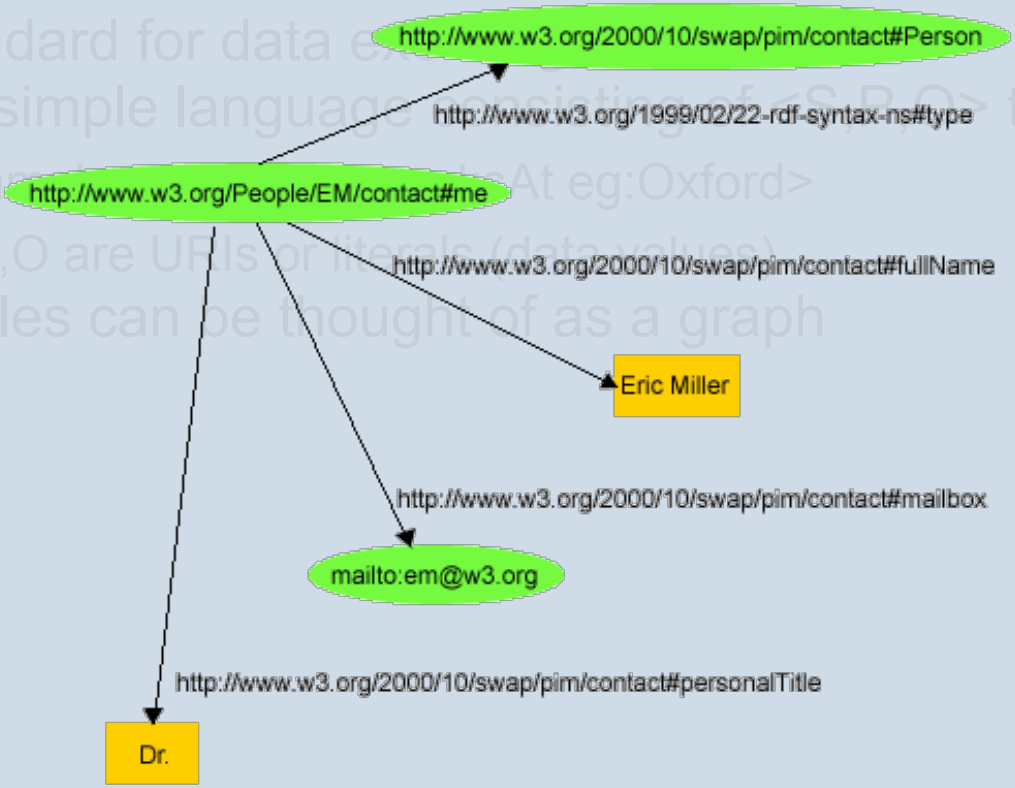

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❷ **Standardised language for exchanging schemas**

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❷ Standardised language for exchanging schemas

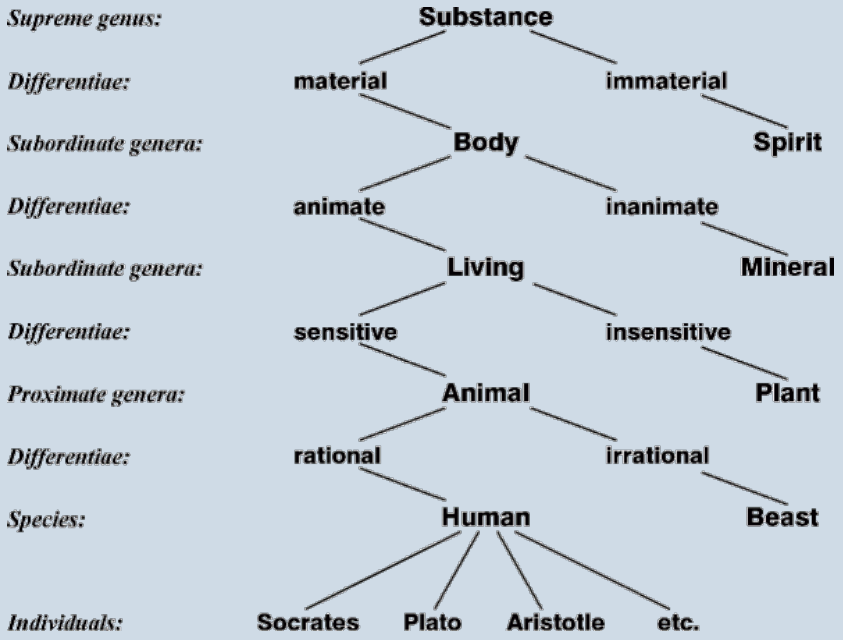
- Use of URIs provides a flexible **naming** scheme
- Also need to exchange **semantics** of data
- RDF(S) provides basic capabilities
  - subclass, subproperty, range and domain
- **OWL** is W3C standard for schema exchange
  - rich language for conceptual schemas, aka **ONTOLOGIES**

What is an Ontology?

What is an Ontology?

A fundamental branch of **metaphysics**

- Studies “being” or “existence” and their **basic categories**
- Aims to find out what **entities** and **types of entities** exist



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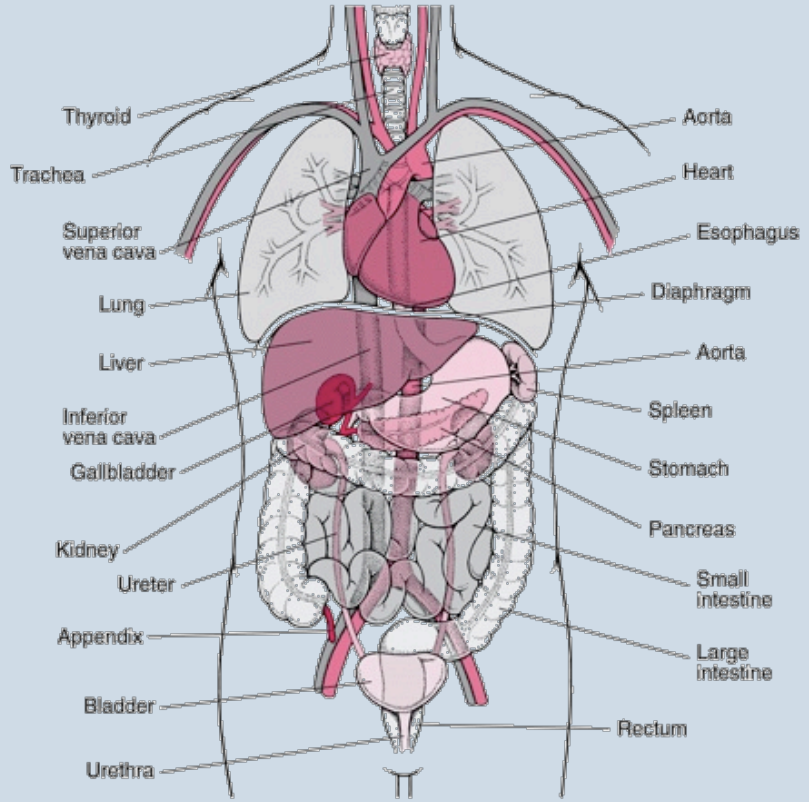

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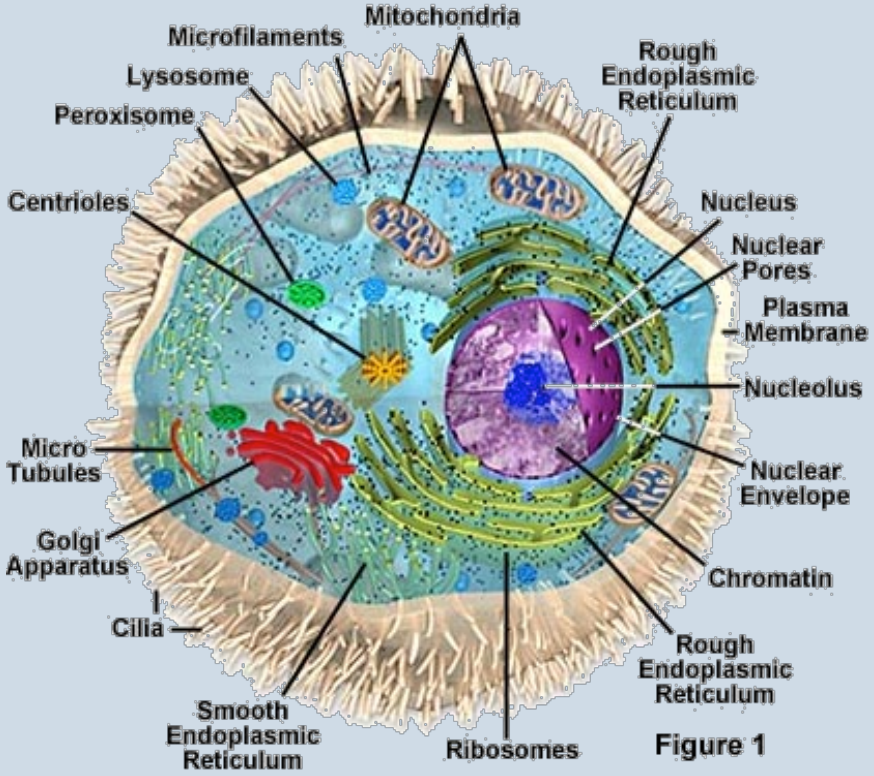

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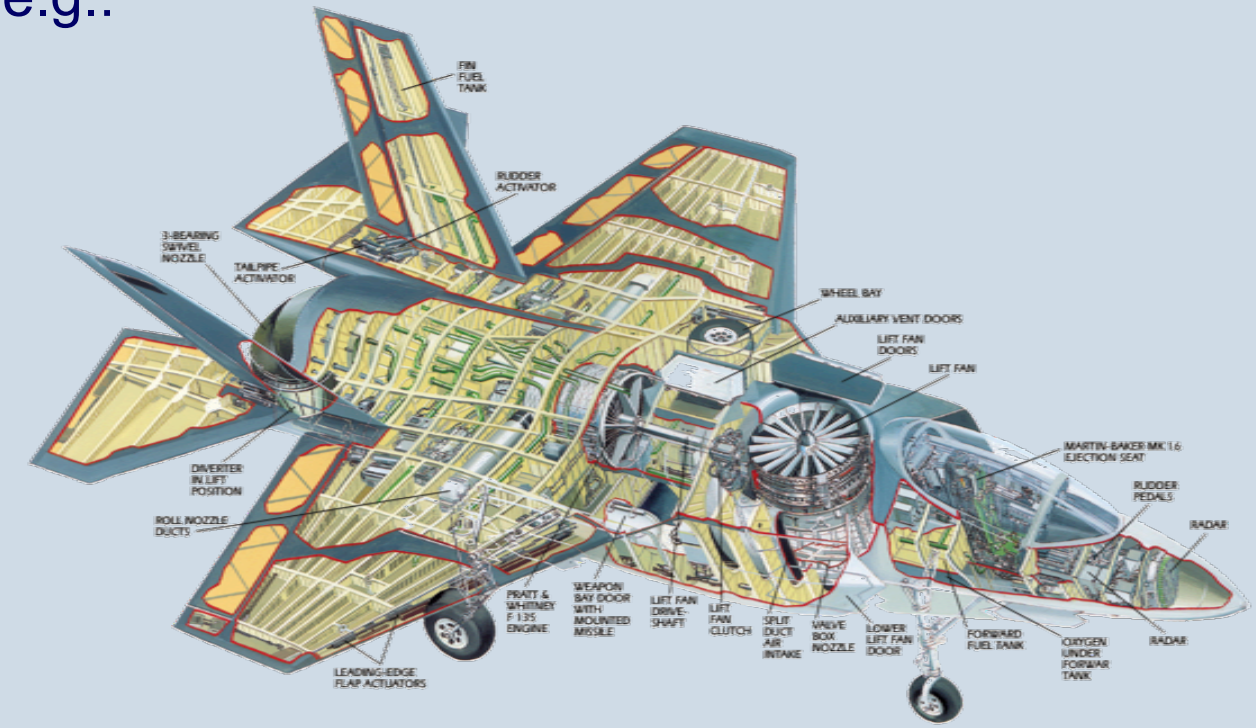

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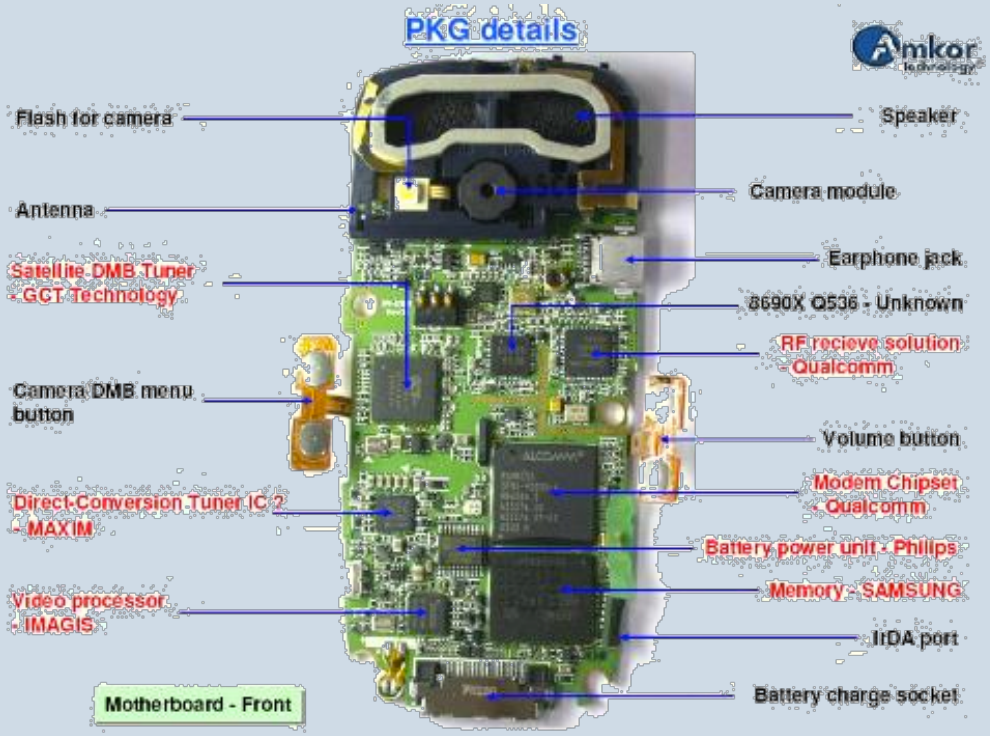
  - …



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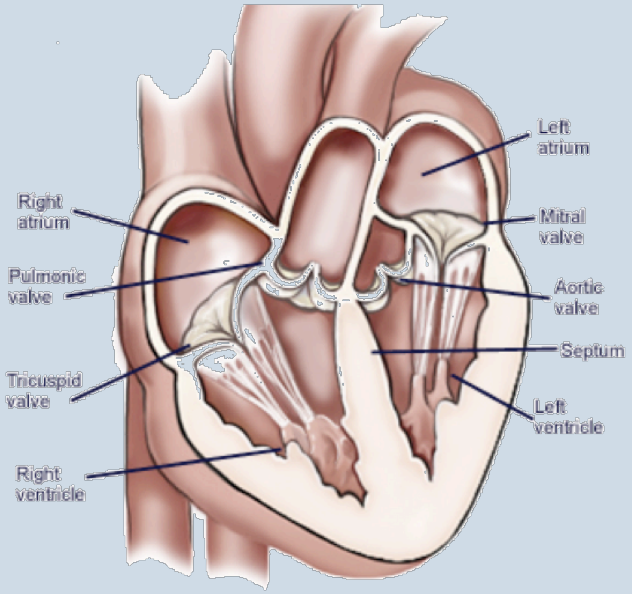
- Specifies **meaning** (semantics) of terms

Heart is a muscular organ that is part of the circulatory system



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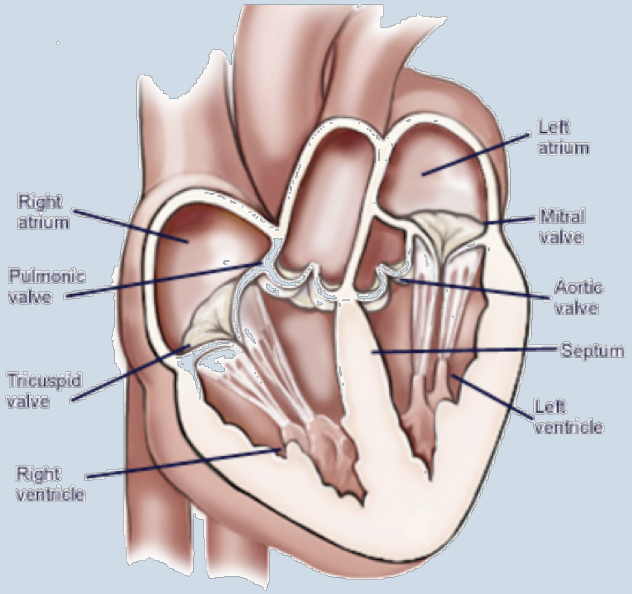
  Heart is a muscular organ that is part of the circulatory system

- **Formalised** using suitable logic

$$\forall x.[\mathsf{Heart}(x) \rightarrow \mathsf{MuscularOrgan}(x) \wedge \exists y.[\mathsf{isPartOf}(x,y) \wedge \mathsf{CirculatorySystem}(y)]]$$



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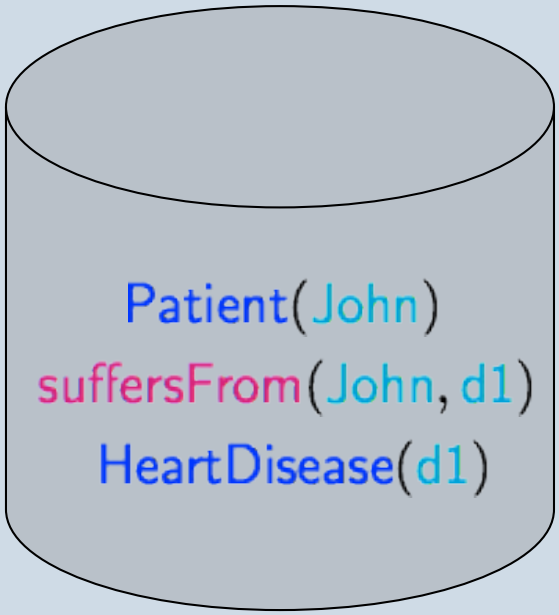

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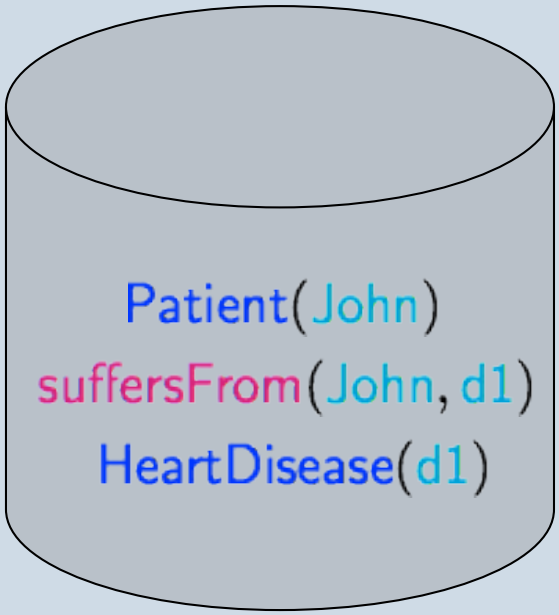

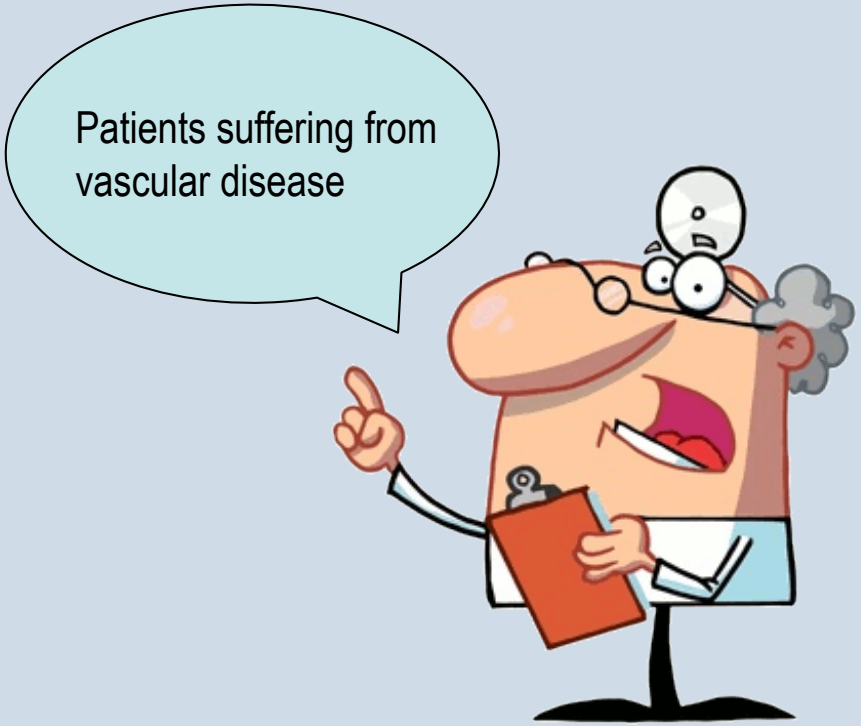

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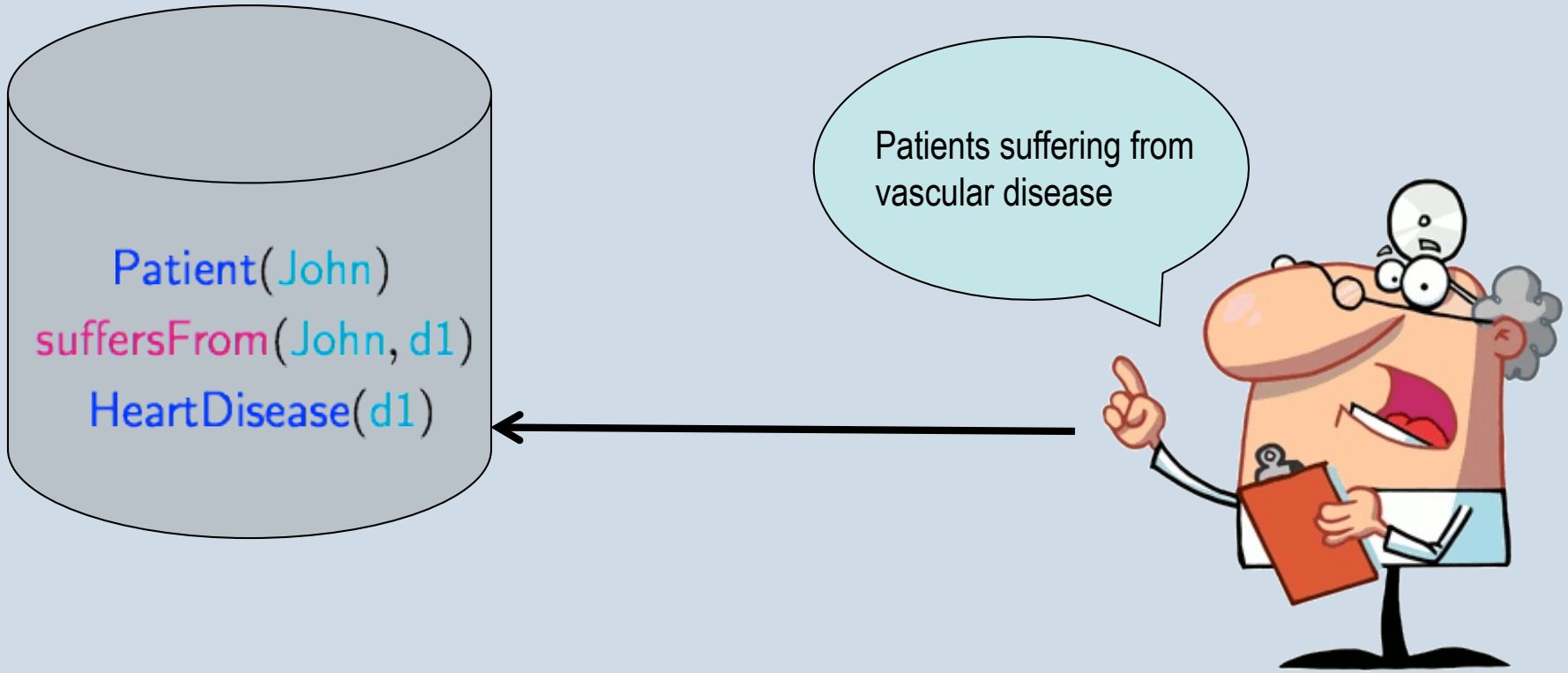

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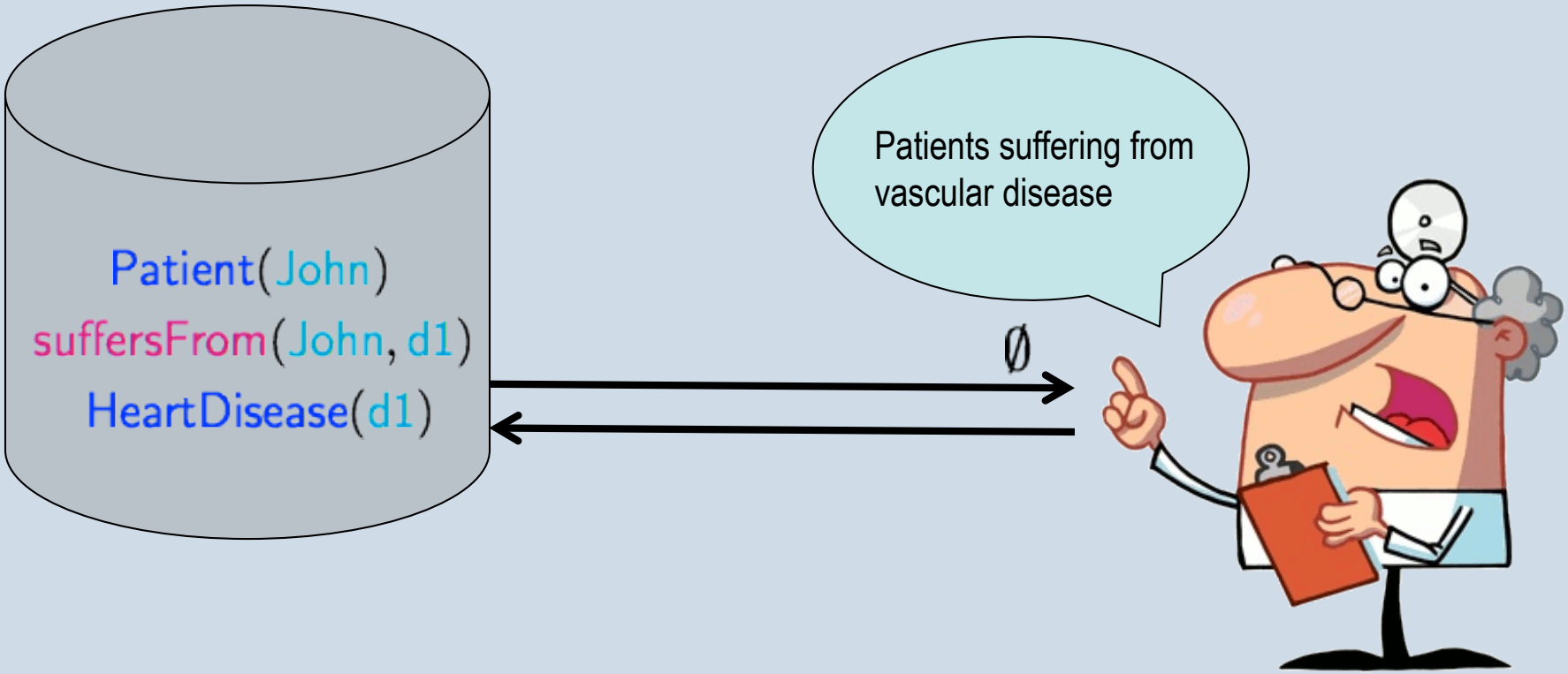

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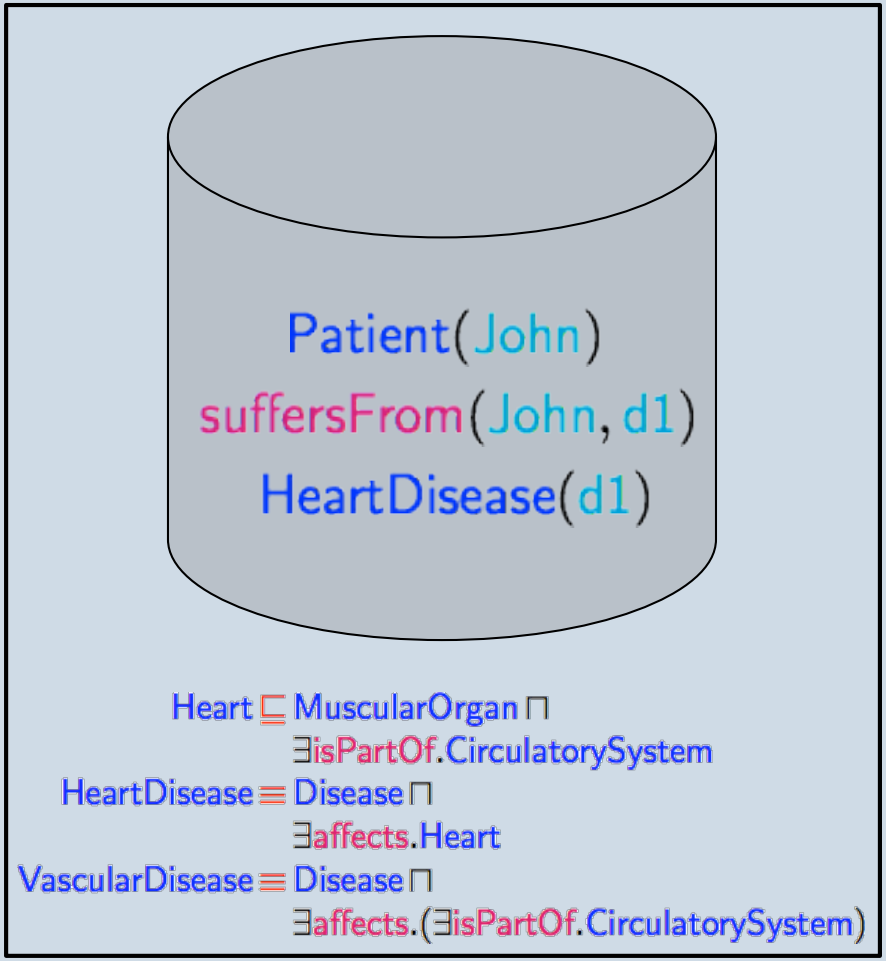

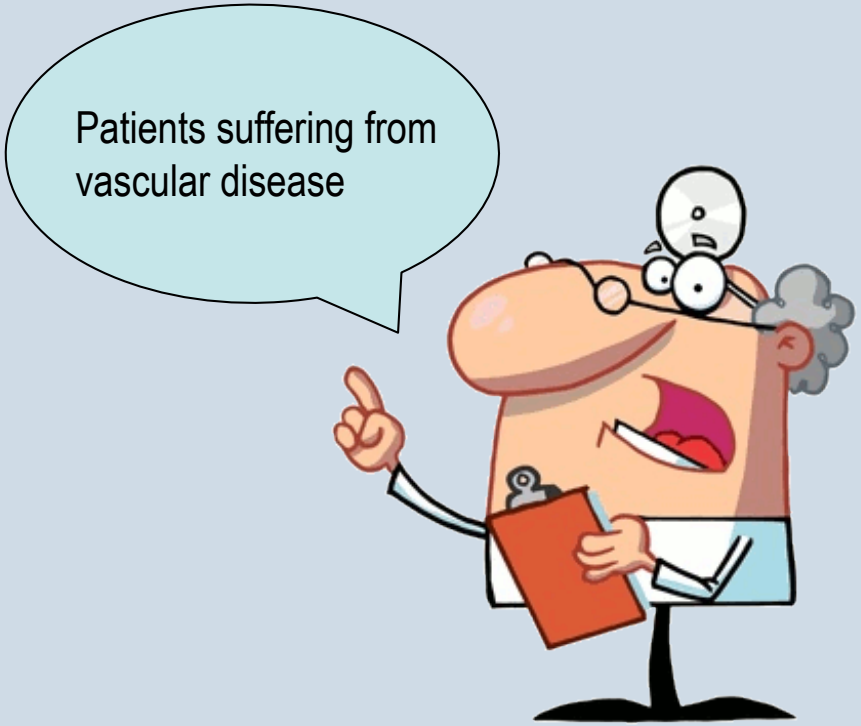

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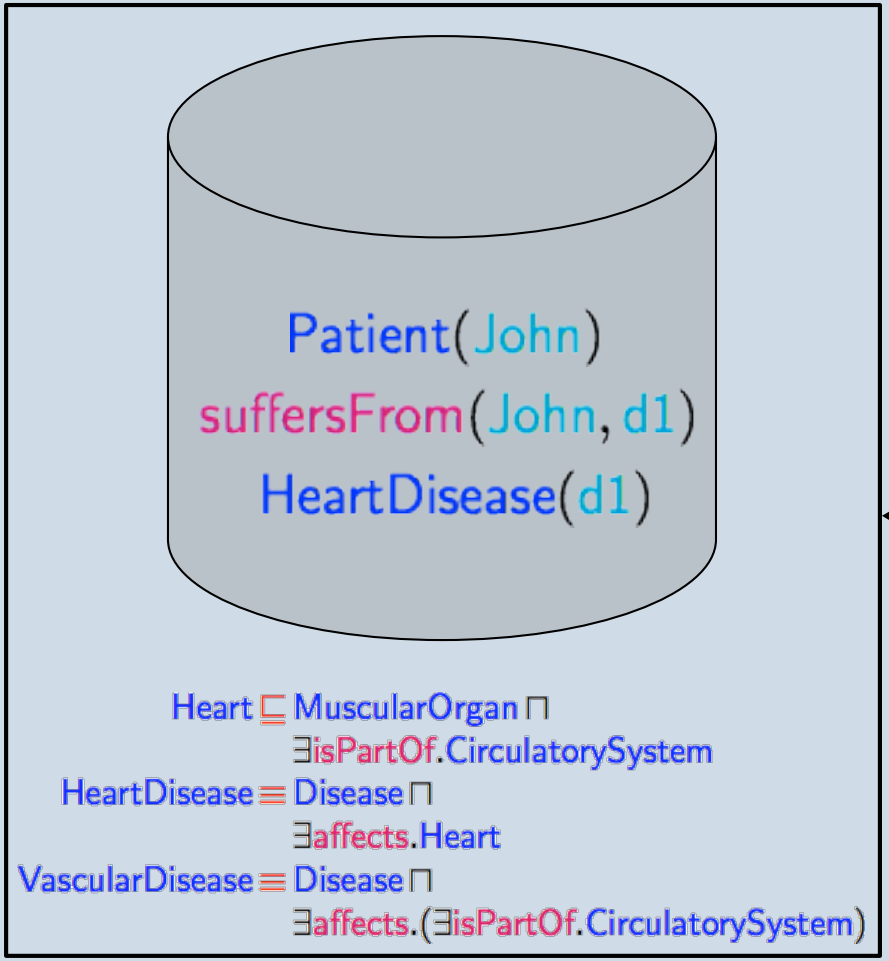

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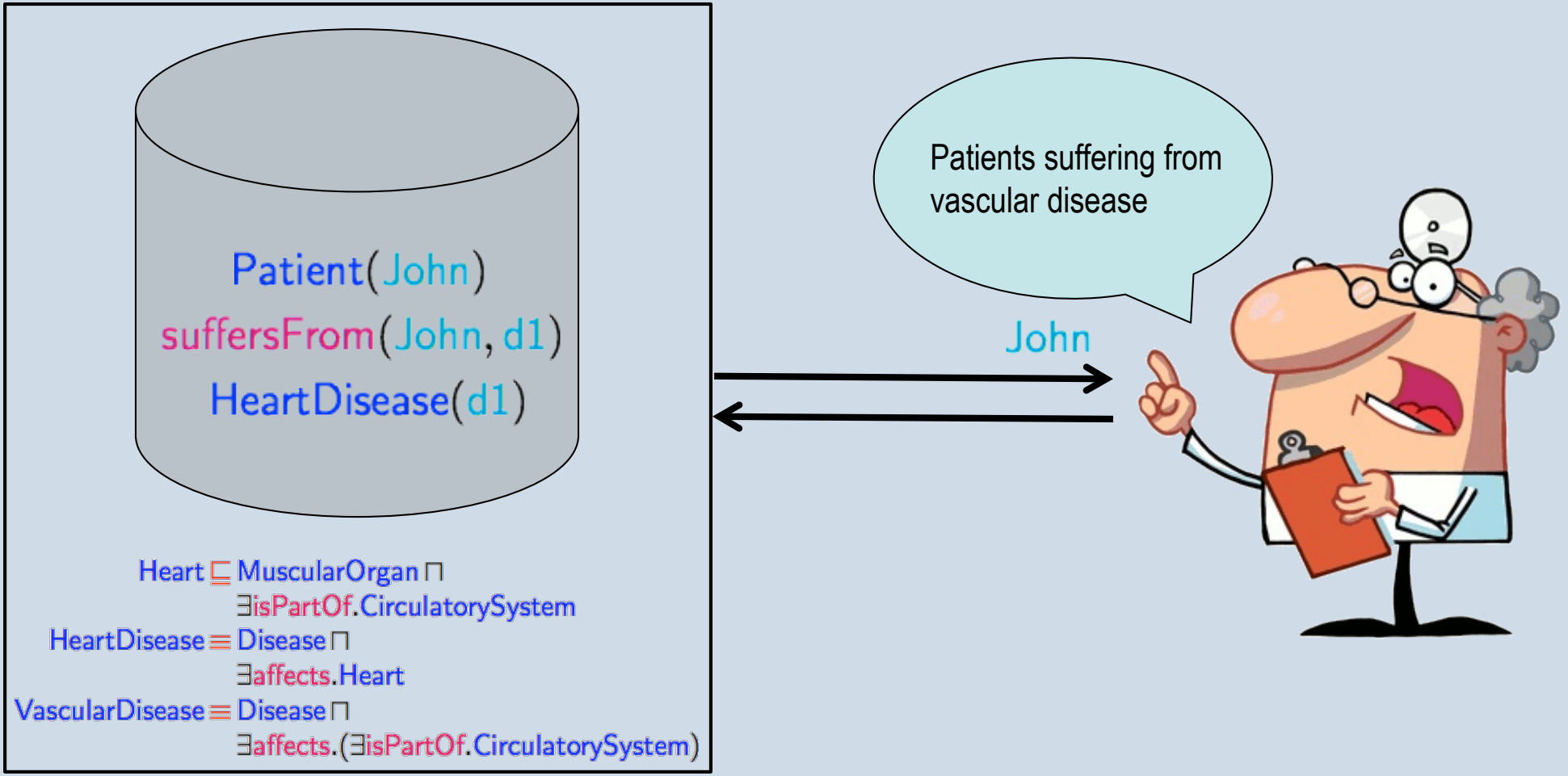

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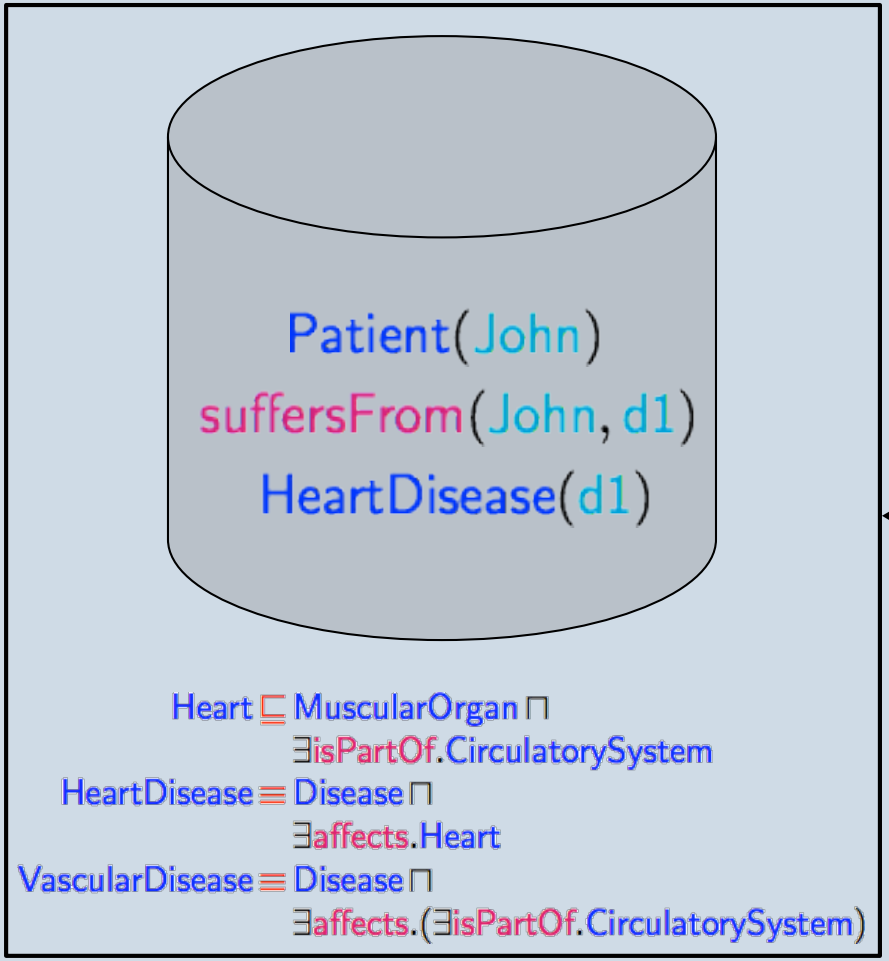

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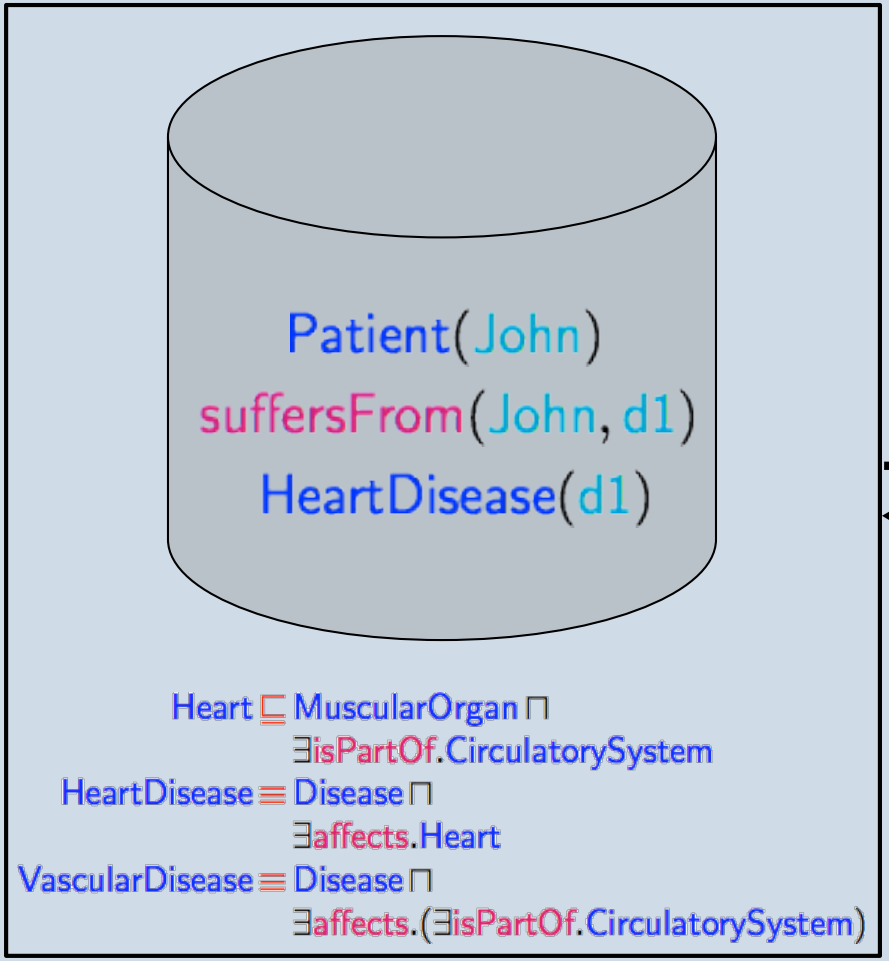

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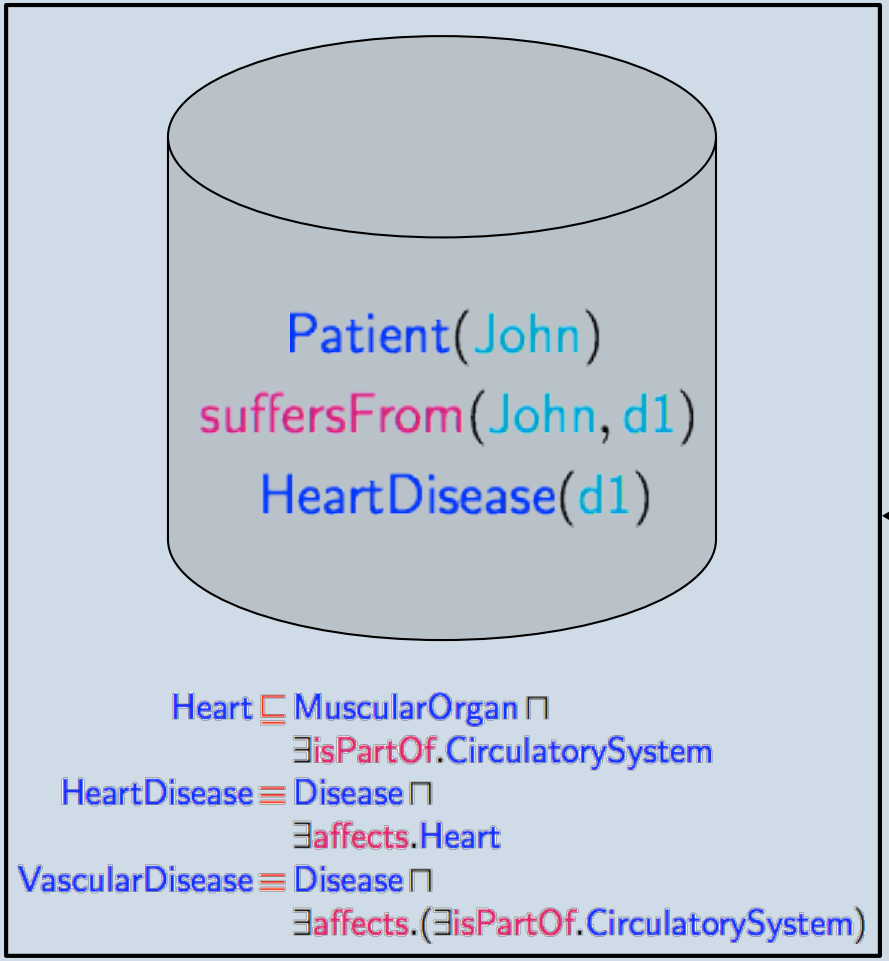

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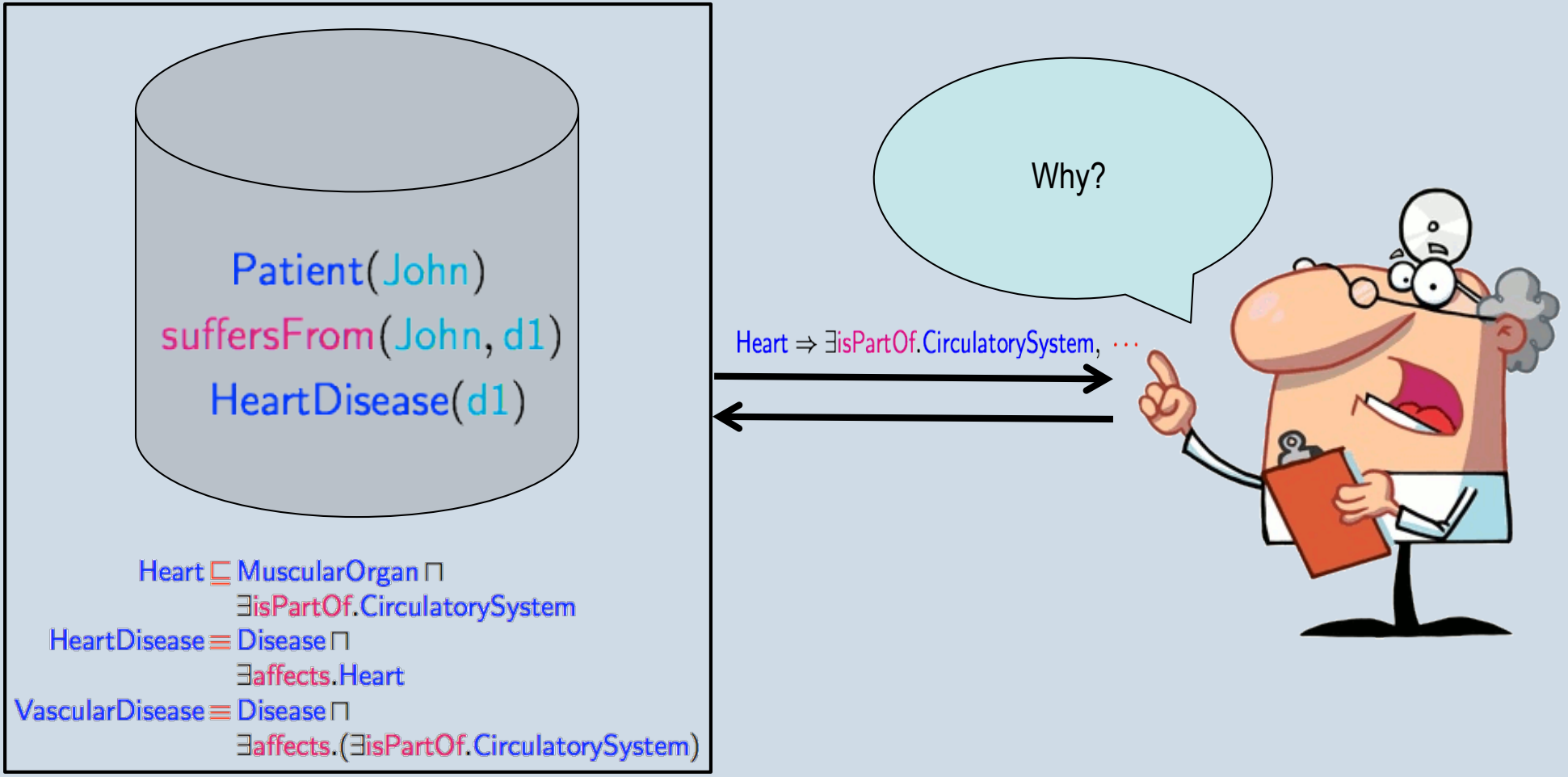

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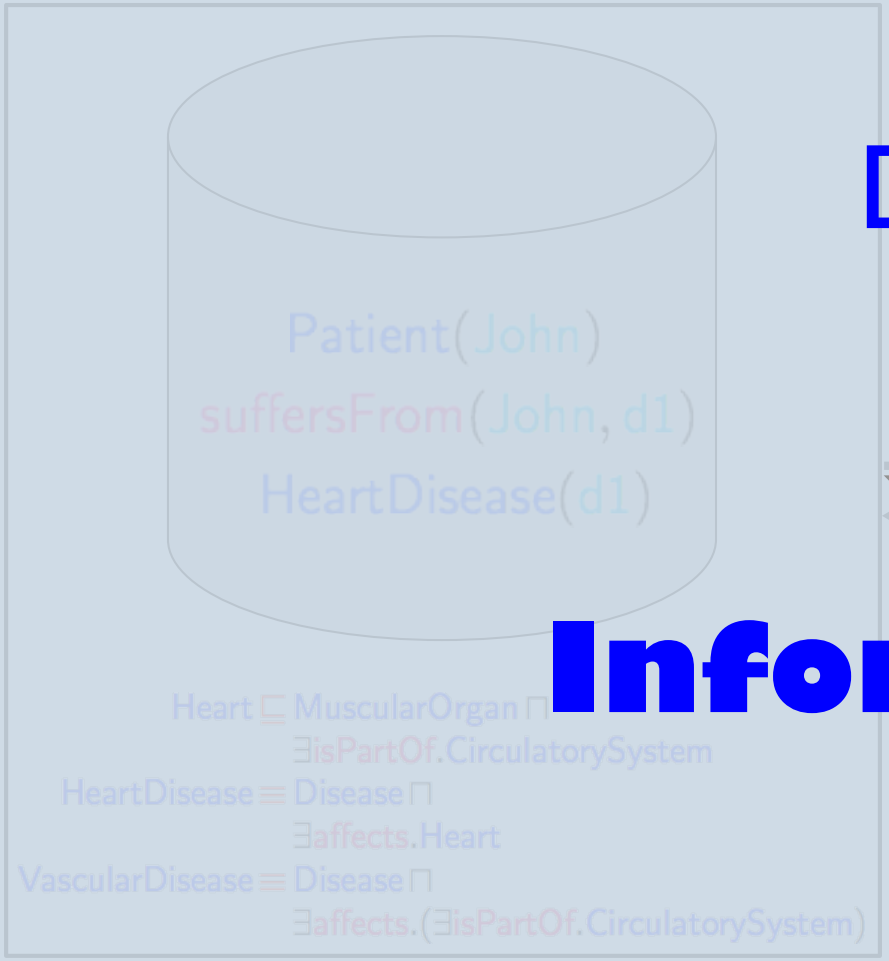

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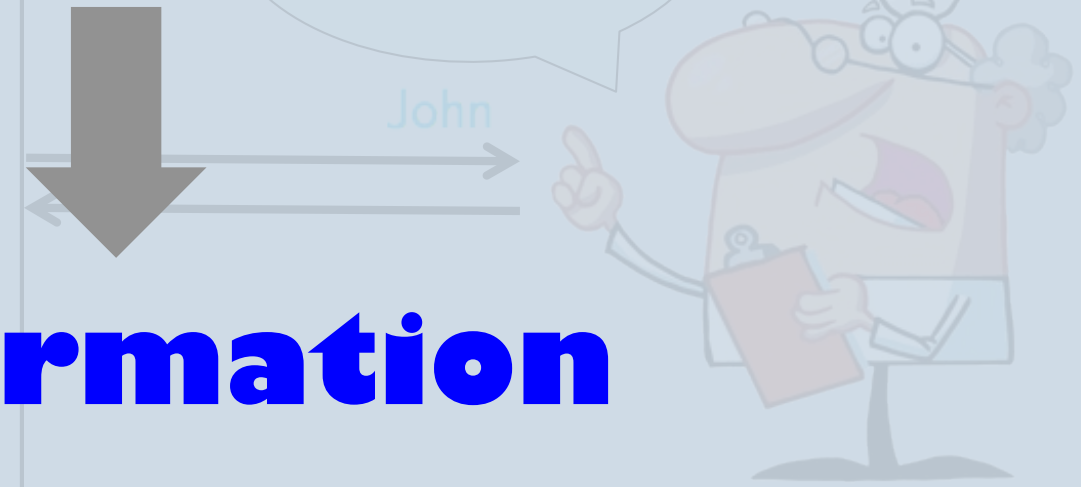

Information

Applications: Semantic Web

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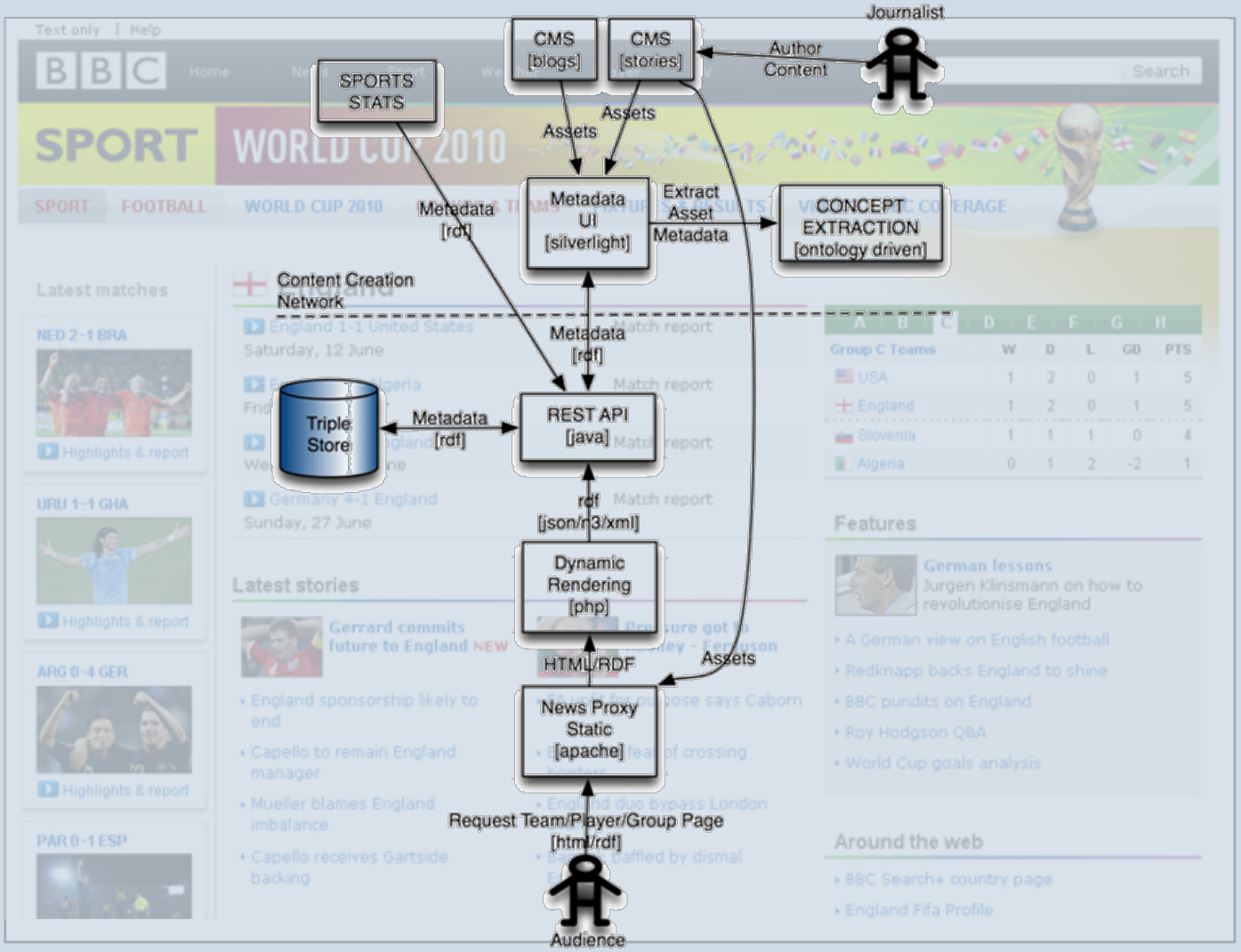

Applications: Semantic Web

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
- Using ontologies to **improve access** to relevant data
- Statoil estimate that this could add **€1B/year** to their net income

Applications: Energy Supply Industry

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

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

- **Oxford's 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, ...)
- Reasoning enabled semantic data store used to **infer context**
- Applications exploit context to enable more **intelligent behaviour**

Research ⇝ Practice

- Selecting **suitable language**/logic
  - expressiveness -v- computability tradeoff

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I1 $\dfrac{}{M \sqcap A \sqsubseteq A}$

I2 $\dfrac{}{M \sqsubseteq \top}$

R1 $\dfrac{M \sqsubseteq A_1 \quad \ldots \quad M \sqsubseteq A_n}{M \sqsubseteq C} : \prod_{i=1}^{n} A_i \sqsubseteq C \in \mathcal{O}$

R2 $\dfrac{M \sqsubseteq \exists R.N \quad N \sqsubseteq \bot}{M \sqsubseteq \bot}$

R3 $\dfrac{M \sqsubseteq \exists R_1.N \quad M \sqsubseteq \forall R_2.A}{M \sqsubseteq \exists R_1.(N \sqcap A)} : R_1 \sqsubseteq_{\mathcal{O}} R_2$

R4 $\dfrac{M \sqsubseteq \exists R_1.N \quad N \sqsubseteq \forall R_2.A}{M \sqsubseteq A} : R_1 \sqsubseteq_{\mathcal{O}} R_2^-$

R5 $\dfrac{\begin{array}{l} M \sqsubseteq \exists R_1.N_1 \quad N_1 \sqsubseteq B \\ M \sqsubseteq \exists R_2.N_2 \quad N_2 \sqsubseteq B \\ M \sqsubseteq \leqslant 1 S.B \end{array}}{M \sqsubseteq \exists R_1.(N_1 \sqcap N_2)} : \begin{array}{l} R_1 \sqsubseteq_{\mathcal{O}} S \\ R_2 \sqsubseteq_{\mathcal{O}} S \end{array}$

R6 $\dfrac{\begin{array}{l} M \sqsubseteq \exists R_1.N_1 \quad M \sqsubseteq B \\ N_1 \sqsubseteq \exists R_2.(N_2 \sqcap A) \\ N_1 \sqsubseteq \leqslant 1 S.B \quad N_2 \sqcap A \sqsubseteq B \end{array}}{M \sqsubseteq A \quad M \sqsubseteq \exists R_2^-.N_1} : \begin{array}{l} R_1 \sqsubseteq_{\mathcal{O}} S^- \\ R_2 \sqsubseteq_{\mathcal{O}} S \end{array}$

Research ⇝ Practice

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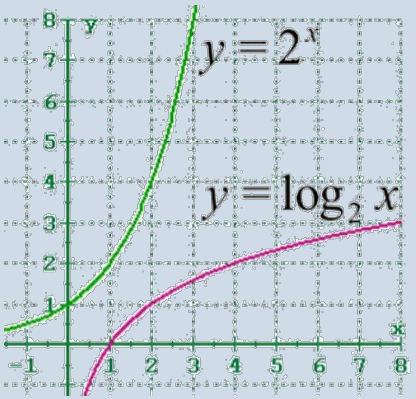
  - $\mathcal{SROIQ}$ is 2NExpTime (-v- logspace for databases)



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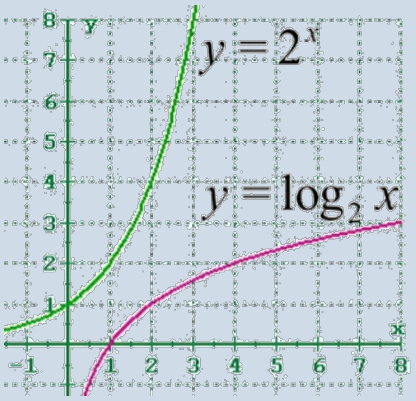
  - OWL based on $\mathcal{SROIQ}$ DL
- Dealing with **computational intractability**
  - $\mathcal{SROIQ}$ is 2NExpTime (-v- logspace for databases)
  - Goal directed algorithms and highly optimised implementations effective for schema reasoning



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	—

Query Answering Still Problematical

Large datasets → conflicting requirements

- Modeling complex application domains requires:
  Rich ontology languages
- Fine-grained information access requires:
  Powerful query languages
- Processing large datasets requires:
  Scalable reasoning
- Applications (often) require:
  Reliable answers (guaranteed sound and complete)

Various Approaches — Different Tradeoffs

❶ Use full power of OWL and complete reasoner

input: any OWL ontology, dataset and query

output: sound and complete query answer

❷ Use a suitable "profile" and specialised reasoner:

input: restricted OWL ontology; any dataset and query

output: sound and complete query answer

❸ Use full power of OWL and incomplete reasoner

input: any OWL ontology, dataset and query

output: sound but (possibly) incomplete query answer

Various Approaches — Different Tradeoffs

❶ Use full power of OWL and complete reasoner:

✓ Well-suited for modeling complex domains

✓ Reliable answers

✗ High worst-case complexity

✗ Scalability problems for large datasets

Complete ontology reasoners:

- E.g., FaCT++, **HermiT**, Pellet, ...
- Based on (hyper)tableau (model construction) theorem provers
- Proof needed for each answer tuple
- Unlikely to scale to very large datasets

Various Approaches — Different Tradeoffs

❷ Use a suitable "profile" and specialised reasoner:

✓ Tractable query answering in size of data

✓ Reliable answers (for inputs in the profile)

✗ Restricted expressivity of the ontology language

✗ Reasoners reject inputs outside profile

OWL 2 QL ontology reasoners:

- E.g., QuOnto, **Requiem**, ...
- Based on query rewriting technique — ontology used to rewrite (expand) query
- Data in scalable (relational) data stores

Query Rewriting

Given ontology $\mathcal{O}$ query $\mathcal{Q}$ and mappings $\mathcal{M}$:

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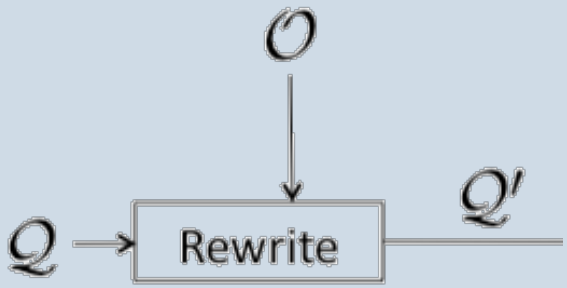
- **Rewrite** $\mathcal{Q} \rightarrow \mathcal{Q}'$ s.t. answering $\mathcal{Q}'$ without $\mathcal{O}$ equivalent to answering $\mathcal{Q}$ w.r.t. $\mathcal{O}$ *for any dataset*



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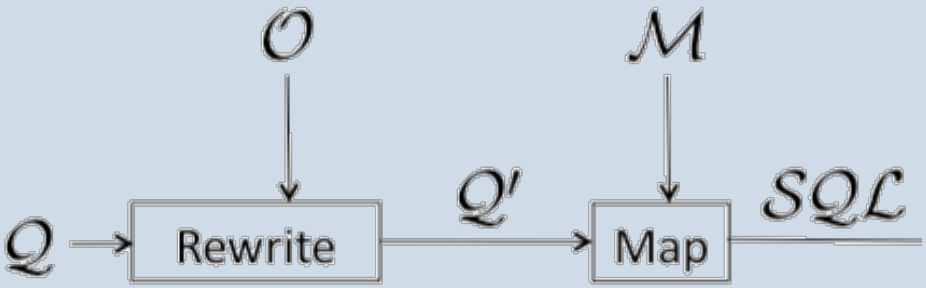
- **Map** ontology queries → DB queries (typically SQL) using mappings $\mathcal{M}$ to rewrite $\mathcal{Q}$' into a DB query



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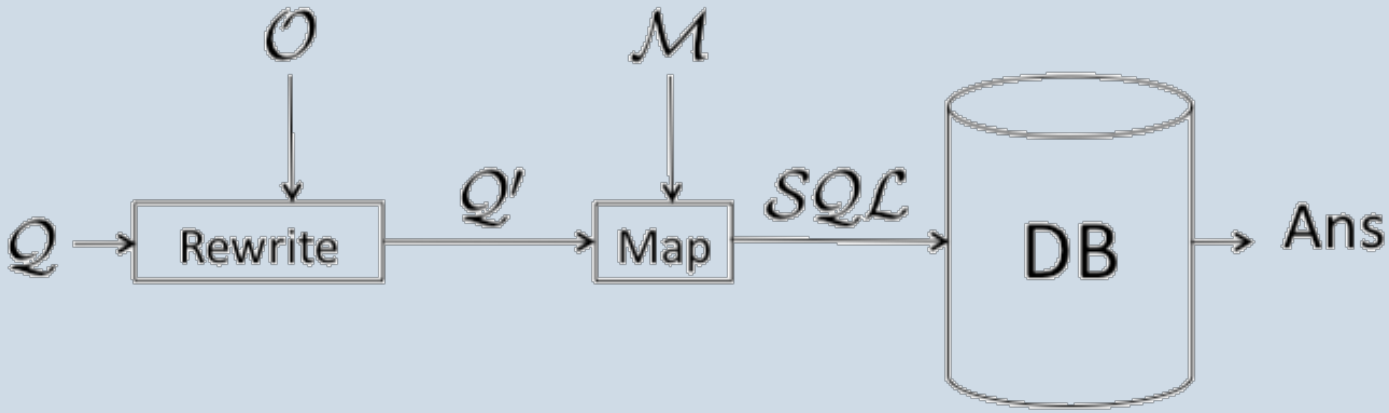
- **Map** ontology queries → DB queries (typically SQL) using mappings $\mathcal{M}$ to rewrite $\mathcal{Q}$' into a DB query
- **Evaluate** (SQL) query against DB



Query Rewriting — Example

$$\mathcal{O} \left\{ \begin{array}{r} \text{Doctor} \sqsubseteq \exists \text{treats}.\text{Patient} \\ \text{Consultant} \sqsubseteq \text{Doctor} \end{array} \right.$$

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

$$\mathcal{M} \left\{ \begin{array}{rcl} \text{Doctor} & \mapsto & \text{SELECT Name FROM Doctor} \\ \text{Patient} & \mapsto & \text{SELECT Name FROM Patient} \\ \text{treats} & \mapsto & \text{SELECT DName, PName FROM Treats} \end{array} \right.$$

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Query Rewriting — Example

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$$\mathcal{SQL} \left\{ \begin{array}{l} \text{SELECT Name FROM Doctor UNION} \\ \text{SELECT DName FROM Treats, Patient WHERE PName=Name} \end{array} \right.$$

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)
- ✗ Materialisation based techniques assume static data

Incomplete ontology reasoners:

- E.g., Oracle's Semantic Datastore, Sesame, Jena, OWLim, ...
- Based on RDF triple stores and deductive DB technologies
- Widely used in practice to reason with large datasets

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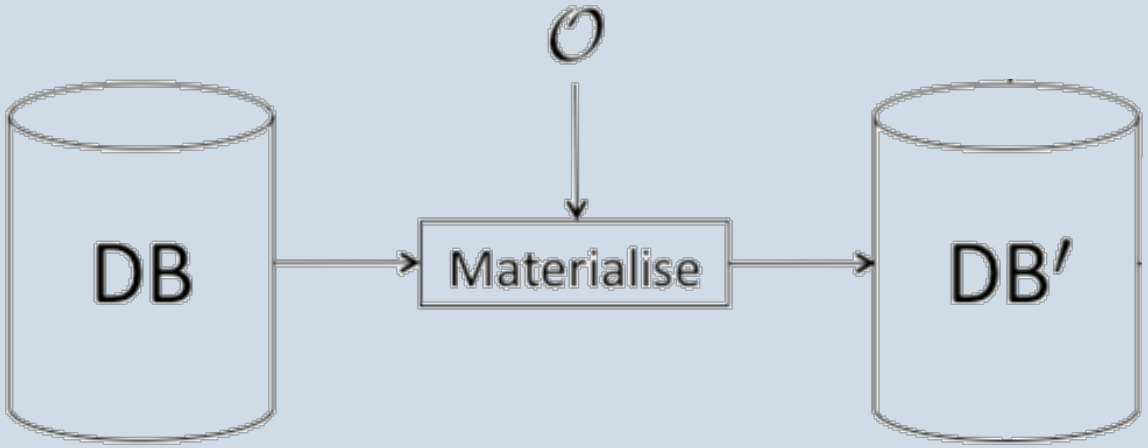

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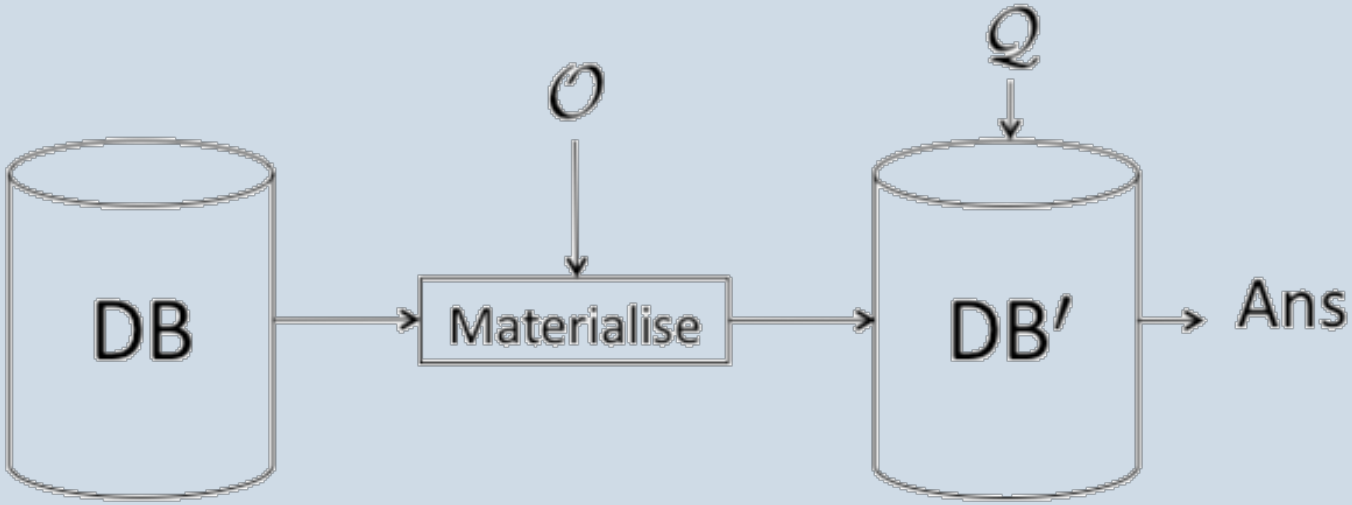
- **Evaluate** $\mathcal{Q}$ against DB′



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Materialisation — Issues

❶ **Frequently changing data**

- Materialisation is time consuming
- Need to re-materialise whenever ontology or data changes
- Data may change very frequently

❷ **Incompleteness**

- Difficult to predict and/or quantify
- May be unacceptable in some applications

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

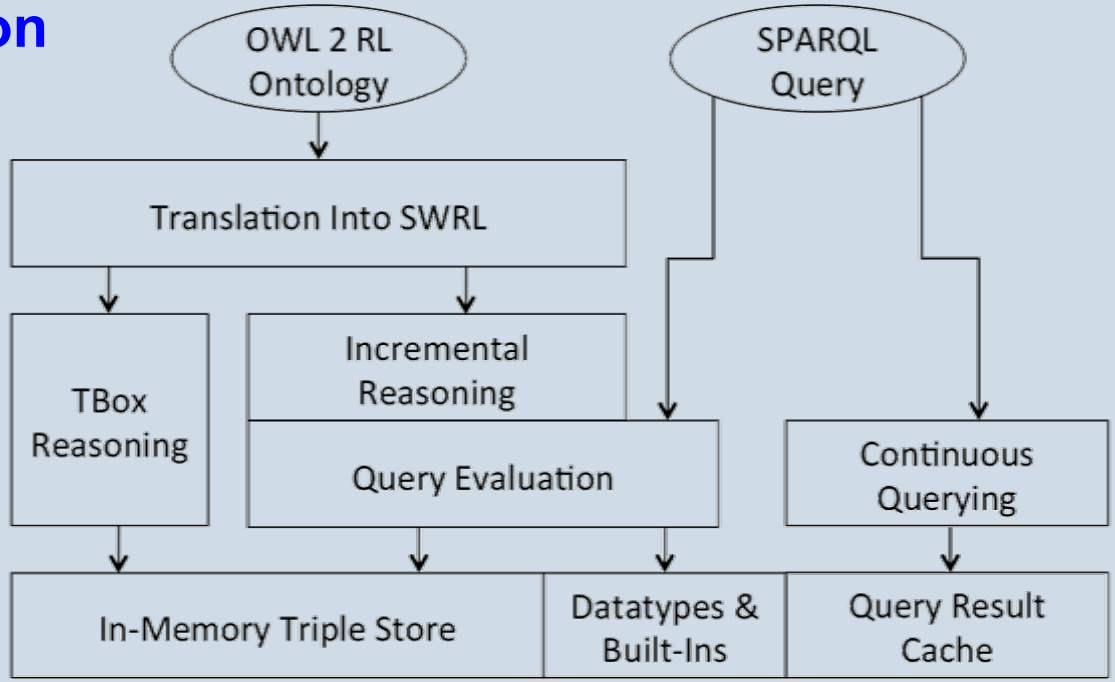
Changing/retracting data is much harder

- Naive solution requires all materialised facts to be discarded
- Re-materialisation very costly for large data sets

Samsung Delta-Reasoner

Incremental materialisation

- Ontology translated into rules
- Separates TBox and ABox reasoning
- Initial materialisation of ABox
- View Maintenance for incremental reasoning



Supports

- OWL 2 RL ontology axioms and SWRL rules
- SPARQL queries, including registration of continuous queries

Samsung Delta-Reasoner

Test Ontologies:

	TBox axioms	Class assertions	Property assertions	DL expressivity
VICODI	223	33,238	82,943	$\mathcal{ALHI}(\mathbf{D})$
SEMINTEC	219	17,941	47,299	$\mathcal{ALHIF}$
LUBM	93	18,128	82,415	$\mathcal{ALEHI}^{+}(\mathbf{D})$

Loading and (incremental) materialisation times (ms):

	Load	Materialise	Update
VICODI	2127	2820	156
SEMINTEC	1048	1123	157
LUBM	2597	818	135

After changing 1,000 triples at random

Dealing with Incompleteness

- Materialisation based reasoning complete for **OWL 2 RL** profile
- But for ontologies **outside the profile**:
  - Reasoning may be incomplete
  - Incompleteness difficult to measure via empirical testing
- Possible solutions offered by recent work on:
  - **Measuring and repairing incompleteness**
  - **Chase materialisation**

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  - $\mathbf{S}_\bot$ a set of ABoxes that are unsatisfiable w.r.t. $\mathcal{O}$
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  - $\mathbf{S}_Q$ a set of paris $\langle \mathcal{A}, \mathcal{Y} \rangle$ with $\mathcal{A}$ an ABox and $\mathcal{Y}$ a query
- 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 $\langle \mathcal{A}, \mathcal{Y} \rangle \in \mathbf{S}_Q$

Measuring and Repairing Incompleteness

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classify: classifies $\mathcal{T}$ with complete reasoner; extends $\mathcal{T}$ with new subsumptions; calls rl with input $\mathcal{Q}$, $\mathcal{A}$ and extended TBox

Measuring and Repairing Incompleteness

Example — consider the following $\mathcal{T}$, $\mathcal{Q}$ and test suite:

$$\mathcal{T} = \left\{ \begin{array}{r} \exists \text{takes.MathCo} \sqsubseteq \text{St} \\ \text{CalcCo} \sqsubseteq \text{MathCo} \\ \text{MathSt} \sqsubseteq \exists \text{takes.MathCo} \\ \text{St} \sqcap \text{Prof} \sqsubseteq \bot \end{array} \right\}$$

$$\mathcal{Q} = \{\text{St}(x) \wedge \text{takesCo}(x, y) \wedge \text{MathCo}(y) \rightarrow Q(x)\}$$

$$\mathcal{A}_1 = \{\text{takesCo}(c, d), \text{MathCo}(d)\}$$
$$\mathcal{A}_3 = \{\text{takesCo}(c, d), \text{CalcCo}(d)\}$$
$$\mathcal{A}_5 = \{\text{MathSt}(c)\}$$

$$\mathcal{A}_2 = \{\text{takesCo}(c, c), \text{MathCo}(c)\}$$
$$\mathcal{A}_4 = \{\text{takesCo}(c, c), \text{CalcCo}(c)\}$$
$$\mathcal{A}_6 = \{\text{St}(c), \text{Prof}(c)\}$$

rdf: Fails all tests (✗)

rdfs: Fails all tests (✗)

rl: Fails for $\mathcal{A}_5$ (✗)

classify: Passes all tests (✓)

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

Chase Materialisation — Example

$$\mathcal{O} \left\{ \begin{array}{rl} \mathsf{Doctor} & \equiv \exists \mathsf{treats}.\mathsf{Patient} \\ \mathsf{Consulatant} & \sqsubseteq \mathsf{Doctor} \end{array} \right.$$

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Numerous **exciting developments** & research areas

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Acknowledgements

EPSRC Engineering and Physical Sciences Research Council

SIXTH FRAMEWORK PROGRAMME

SEVENTH FRAMEWORK PROGRAMME

DARPA

UNIVERSITY OF OXFORD DEPARTMENT OF COMPUTER SCIENCE

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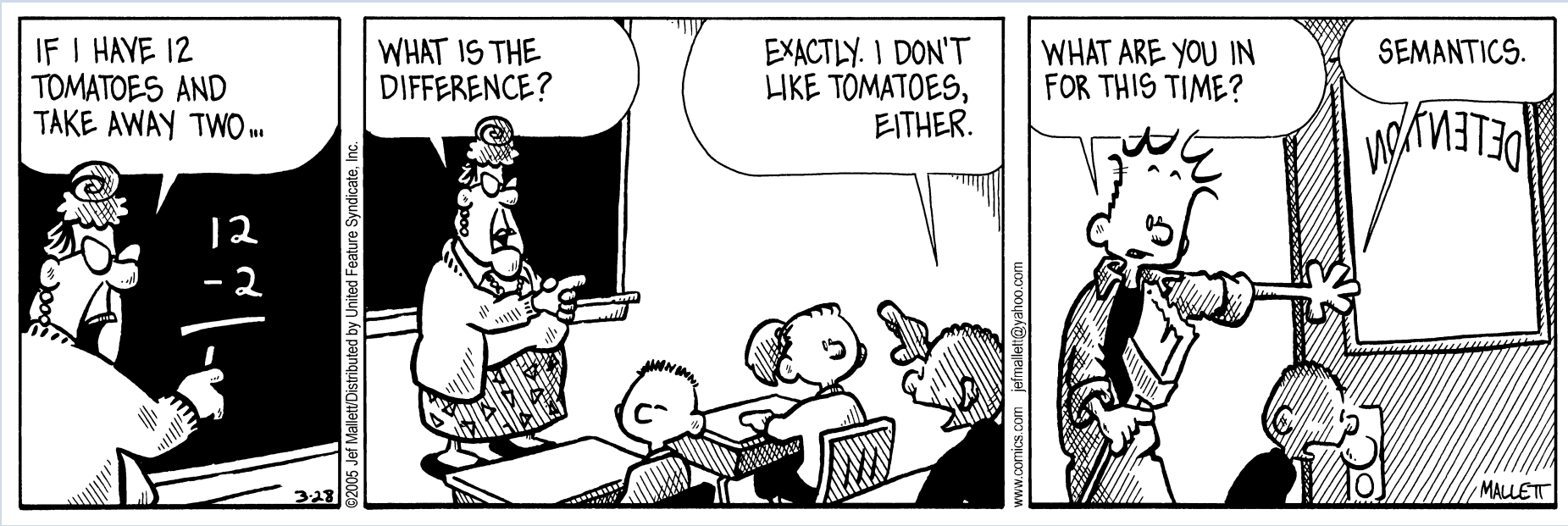
Thank you for listening



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