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Build it, and they will come: Applications of semantic technology

Ian Horrocks
Information Systems Group
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University of Oxford

A Brief History of the Semantic Web

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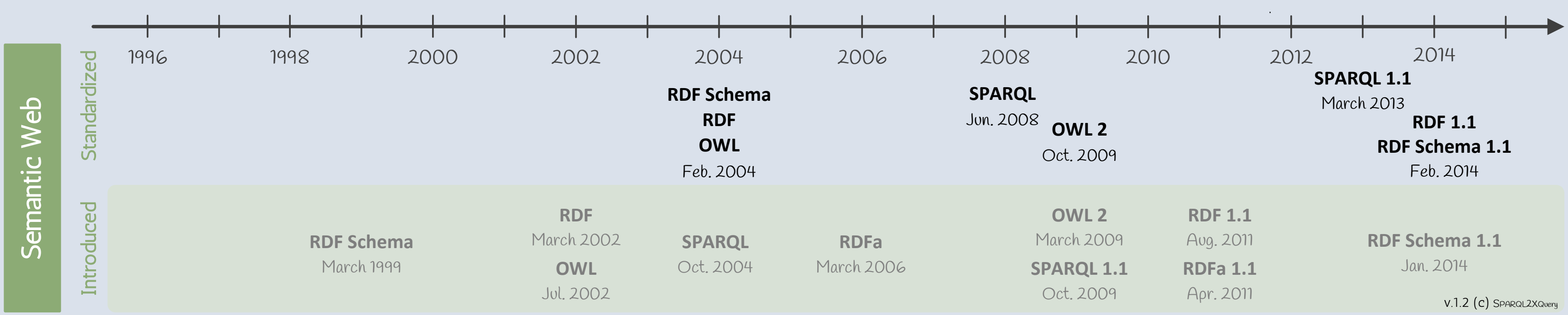

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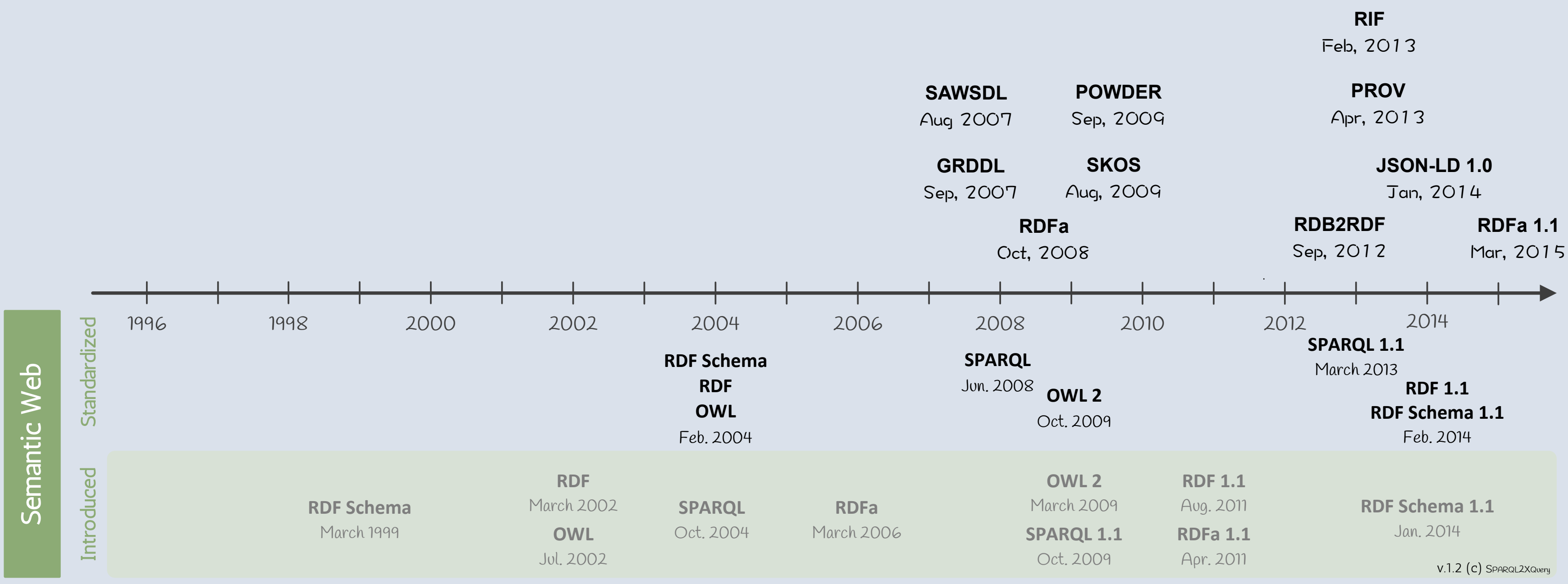

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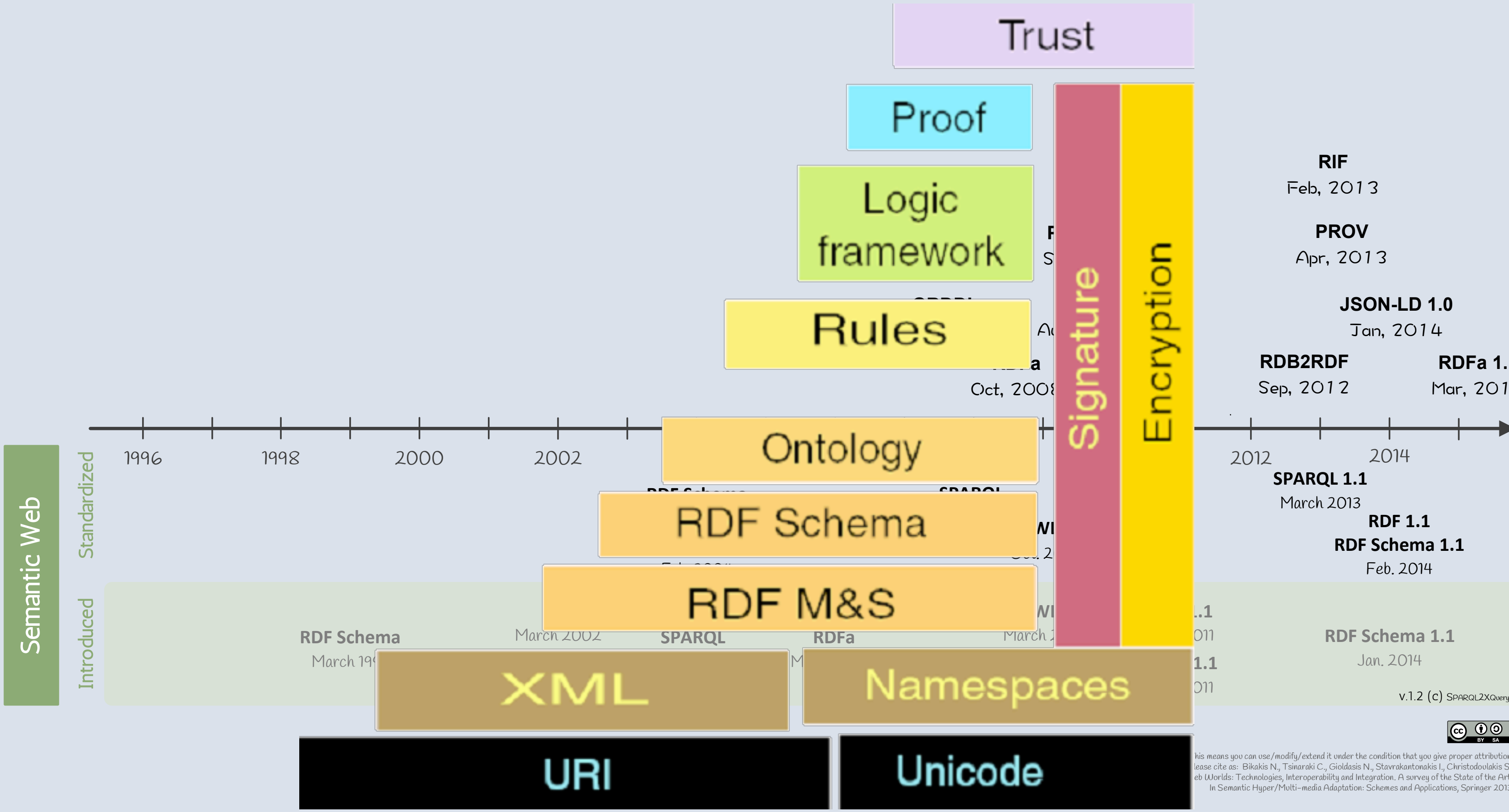

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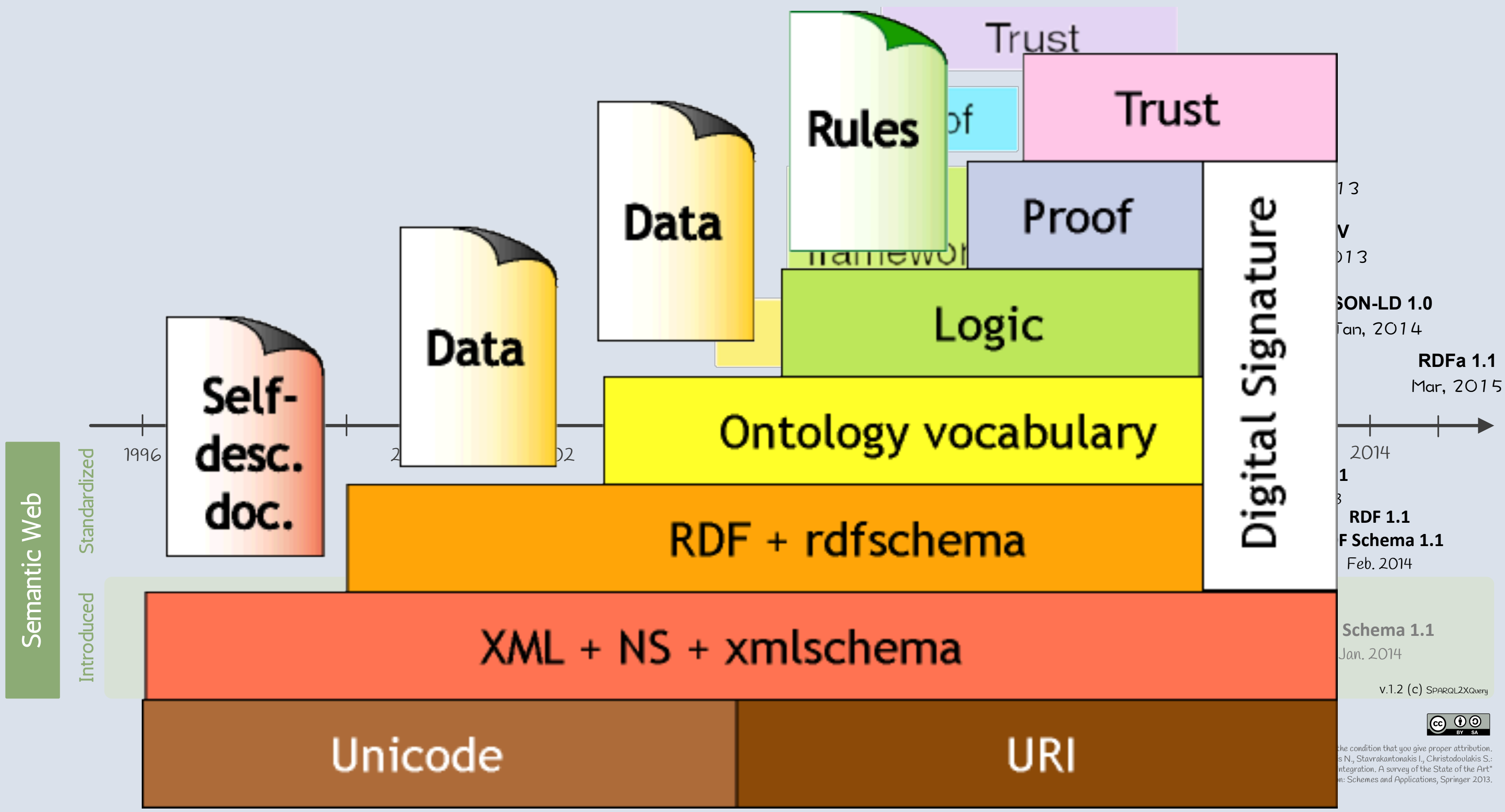

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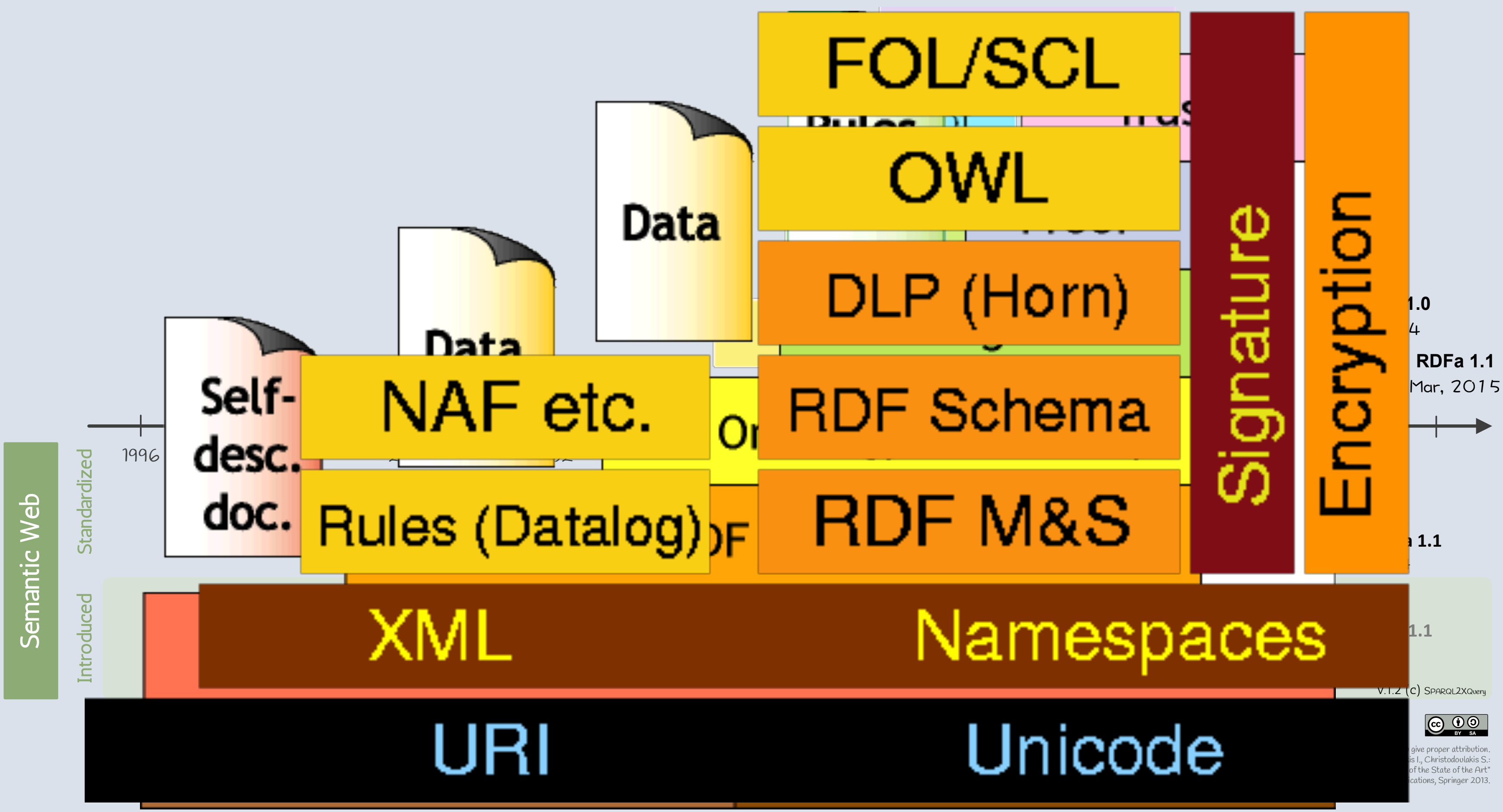

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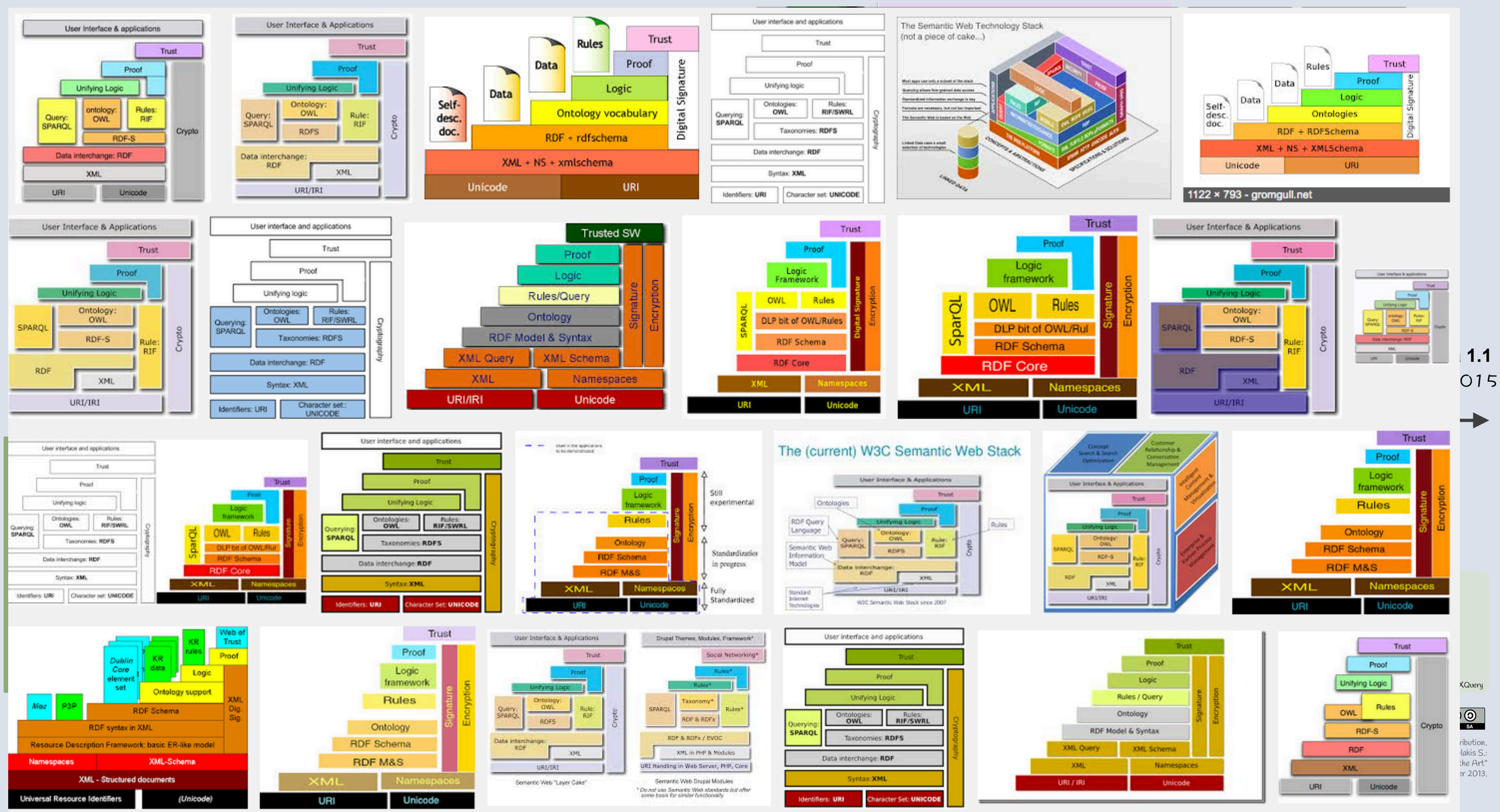

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Why the Angst?

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Why the Angst?

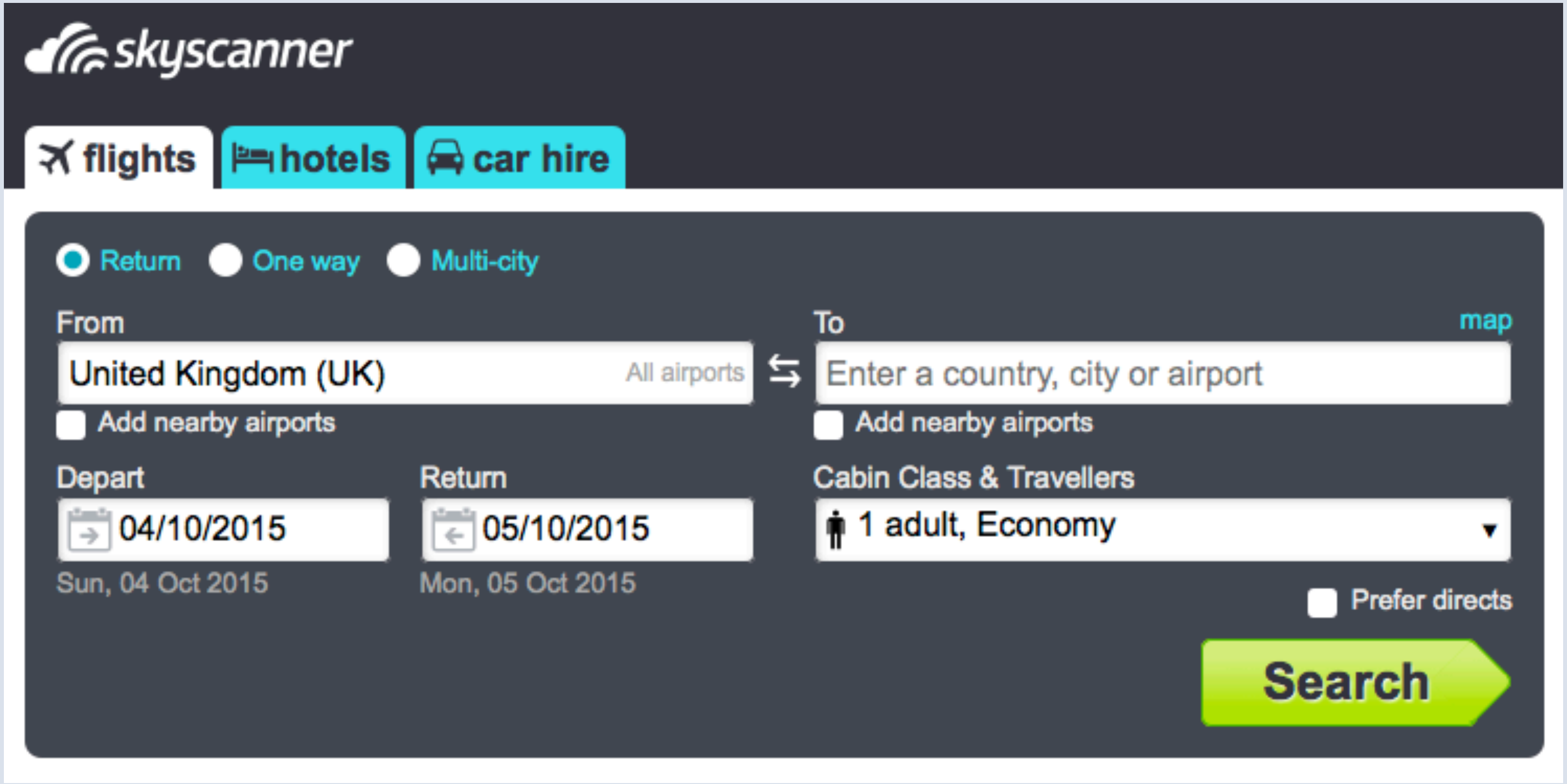
Why the Angst?

“A new form of Web content that is meaningful to computers will **unleash a revolution of new possibilities**”

Why the Angst?

Semantic **Web**

Why the Angst?



Why the Angst?

Google

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Google

- Explicit KR sometimes needed, e.g., **Knowledge Graph**
  - Less rigorous treatment of semantics
  - Not using Semantic Web standards

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Google

- Explicit KR sometimes needed, e.g., **Knowledge Graph**
  - Less rigorous treatment of semantics
  - Not using Semantic Web standards
- **Hiring** Semantic Web people

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Why the Angst?

Semantic Web

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Data Access:

Data Access: Statoil Exploration

- Geologists & geophysicists use data from previous operations in nearby locations to develop stratigraphic models of unexplored areas
  - TBs of relational data
  - using diverse schemata
  - spread over 1,000s of tables
  - and multiple data bases

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- 30-70% of time on data gathering
- 4 day turnaround for new queries

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Data Access

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- 4 day turnaround for new queries

Data Exploitation

- Better use of experts time
- Data analysis "most important factor" for drilling success

Data Access: SIEMENS Energy Services

- Service centres responsible for remote monitoring and diagnostics of 1,000s of gas/steam turbines
- Engineers use a variety of data for visualization, diagnostics and trend detection:
    - several TB of time-stamped sensor data
    - several GB of event data
    - data grows at 30GB per day

Service Requests

- 1,000 requests per center per year
- 80% of time used on data gathering

Diagnostic Functionality

- 2–6 p/m to add new function
- New diagnostics → better exploitation of data


Pipelines from
oil facilities?

$$
\begin{aligned}
Q(?x) \leftarrow\ & (?x, \textsf{rdf:type}, \textsf{:Pipeline}) \wedge \\
& (?x, \textsf{:fromFacility}, ?y) \wedge \\
& (?y, \textsf{rdf:type}, \textsf{:OilFacility})
\end{aligned}
$$

$$Q(?x) \leftarrow (?x, \text{rdf:type}, \text{:Pipeline}) \wedge (?x, \text{:fromFacility}, ?y) \wedge (?y, \text{rdf:type}, \text{:OilFacility})$$

(:p1, rdf:type, :Pipeline)
(:p1, :fromFacility, :f1)
(:f1, rdf:type, :OilFacility)
(:p2, rdf:type, :OilPipeline)
(:p2, :fromFacility, :f2)
(:f2, rdf:type, :OilFacility)
(:p3, rdf:type, :OilPipeline)

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:p1

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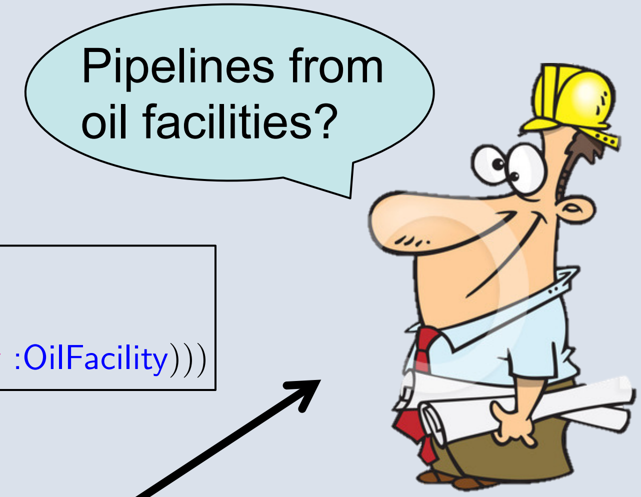


```
SubClassOf(:OilPipeline
  ObjectIntersectionOf(:Pipeline
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```

(:p1, rdf:type, :Pipeline)
(:p1, :fromFacility, :f1)
(:f1, rdf:type, :OilFacility)
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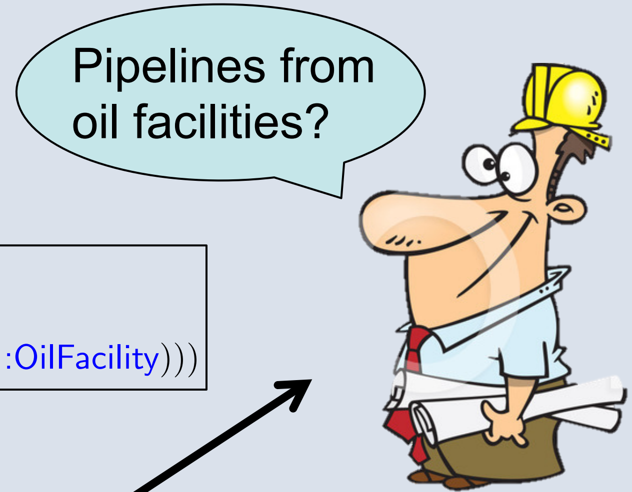

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(:f2, rdf:type, :OilFacility)
(:p3, rdf:type, :OilPipeline)

:p1, :p2, :p3

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Pipelines from oil facilities?

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OWL 2 QL ontology

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rewrite

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$$Q'(?x) \leftarrow (?x, \text{rdf:type}, \text{:Pipeline}) \wedge (?x, \text{:fromFacility}, ?y) \wedge (?y, \text{rdf:type}, \text{:OilFacility}) \vee (?x, \text{rdf:type}, \text{:OilPipeline})$$

(:p1, rdf:type, :Pipeline)
(:p1, :fromFacility, :f1)
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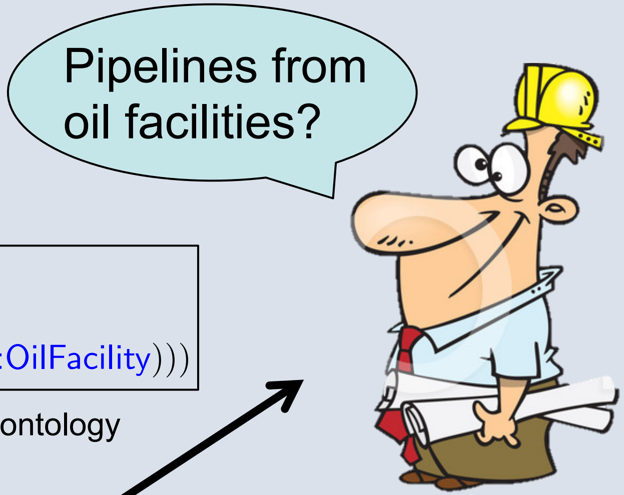

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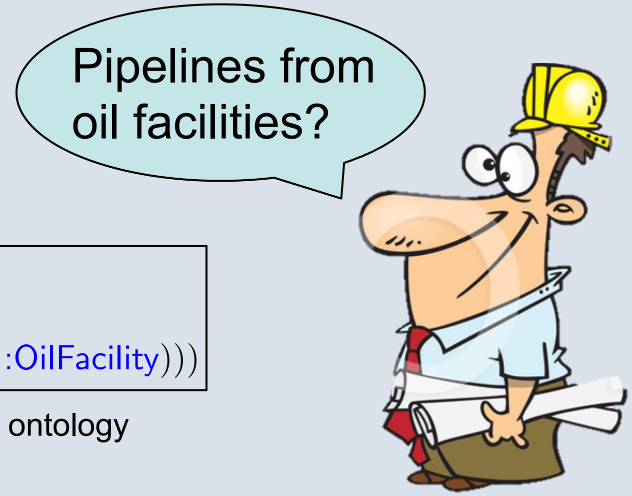

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Pipeline

ID	Oil	From
p1	N	f1
p2	Y	f2
p3	Y	Null

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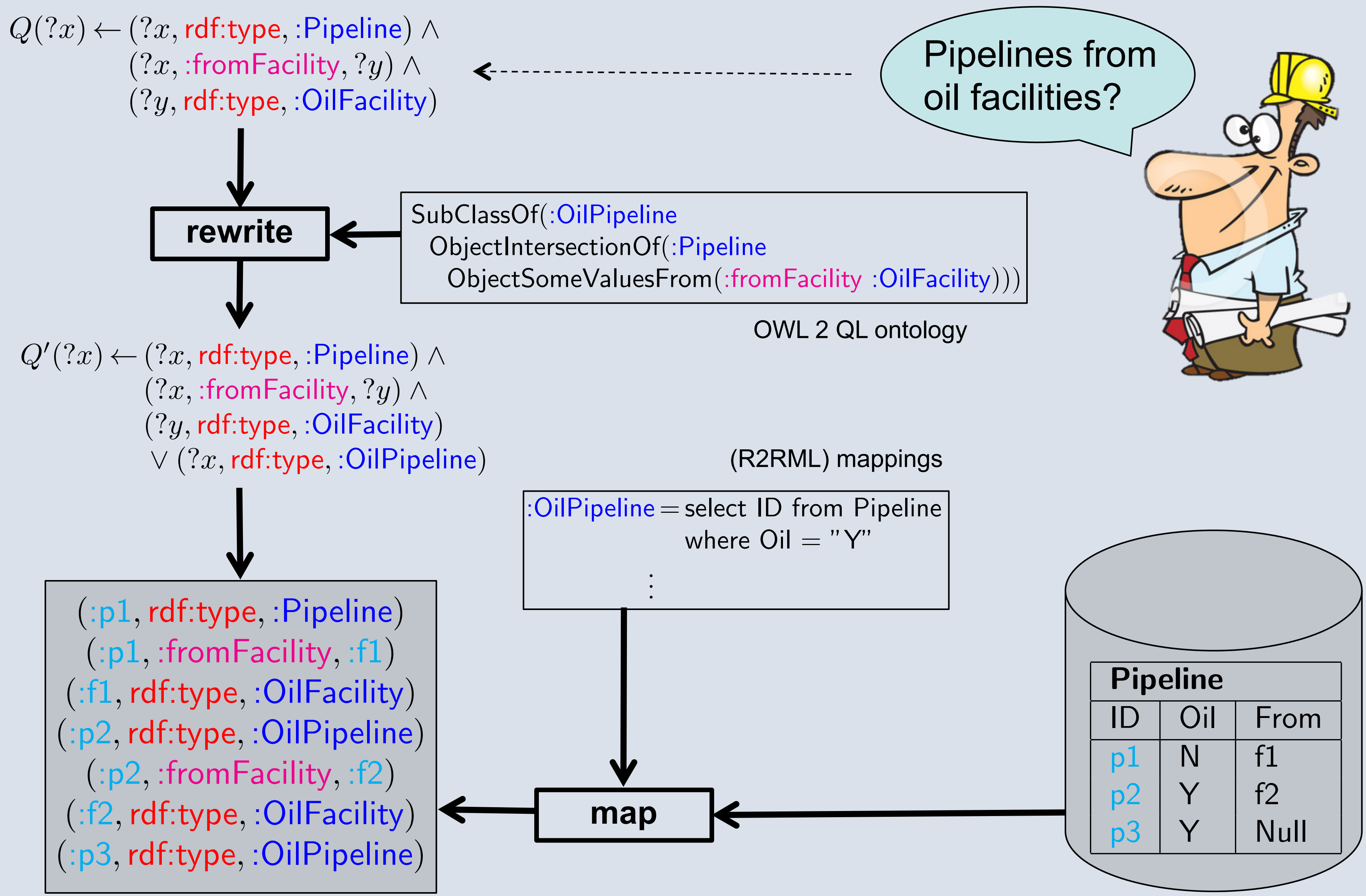

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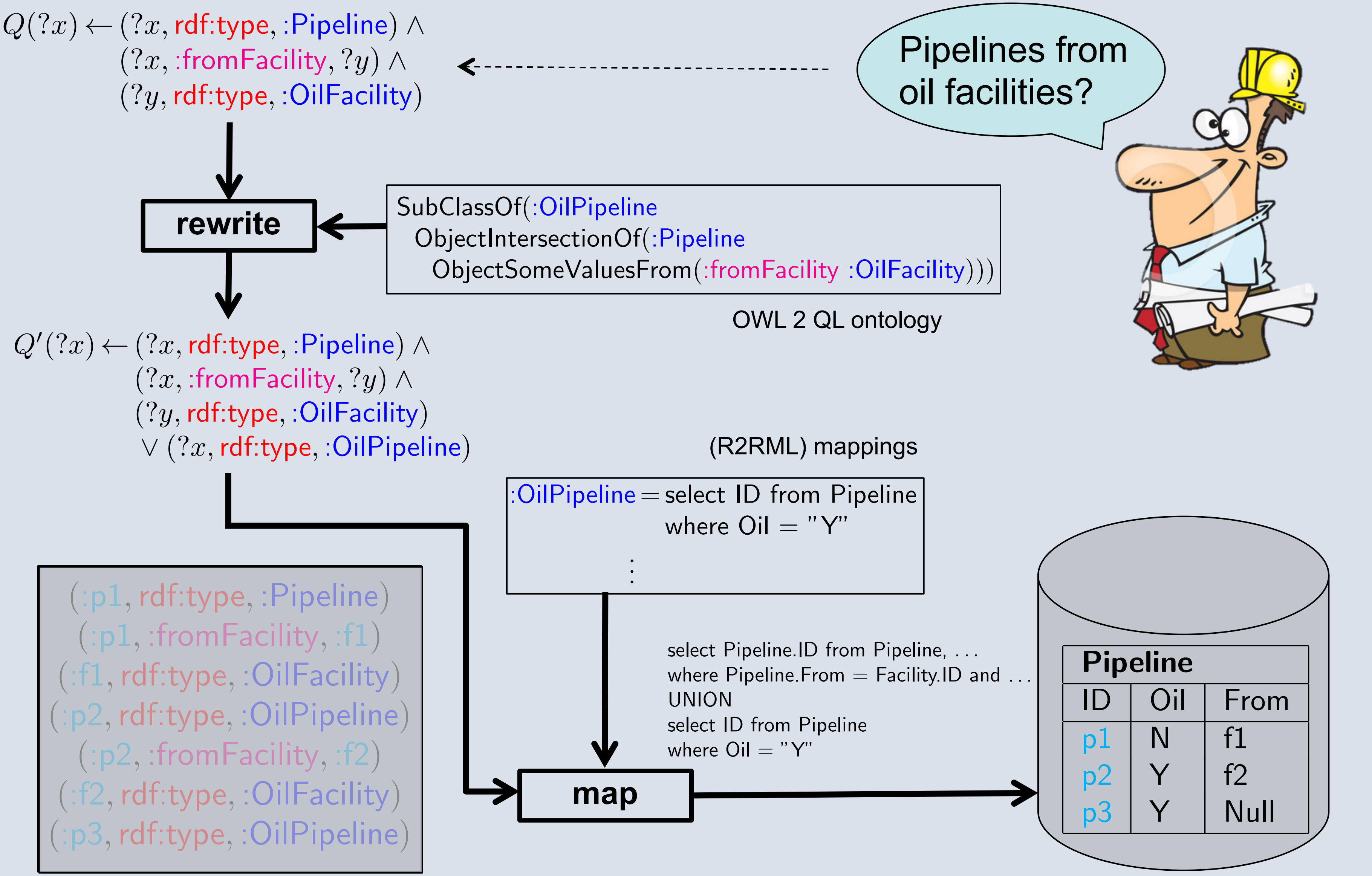

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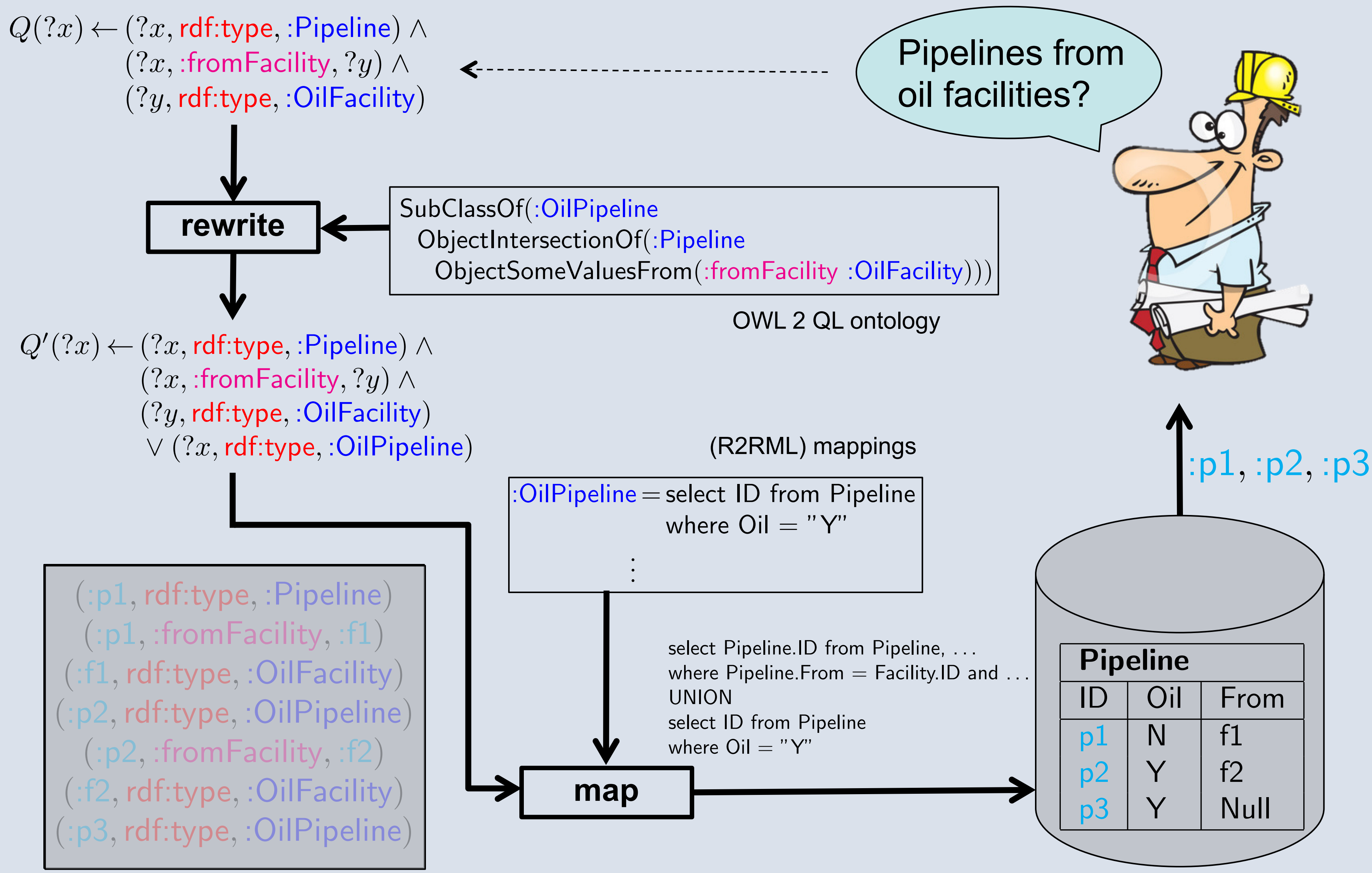
(R2RML) mappings
:OilPipeline = select ID from Pipeline where Oil = "Y"
⋮
select Pipeline.ID from Pipeline, . . .
where Pipeline.From = Facility.ID and . . .
UNION
select ID from Pipeline
where Oil = "Y"
map
(:p1, rdf:type, :Pipeline)
(:p1, :fromFacility, :f1)
(:f1, rdf:type, :OilFacility)
(:p2, rdf:type, :OilPipeline)
(:p2, :fromFacility, :f2)
(:f2, rdf:type, :OilFacility)
(:p3, rdf:type, :OilPipeline)
Pipeline
ID
Oil
From
p1
N
f1
p2
Y
f2
p3
Y
Null



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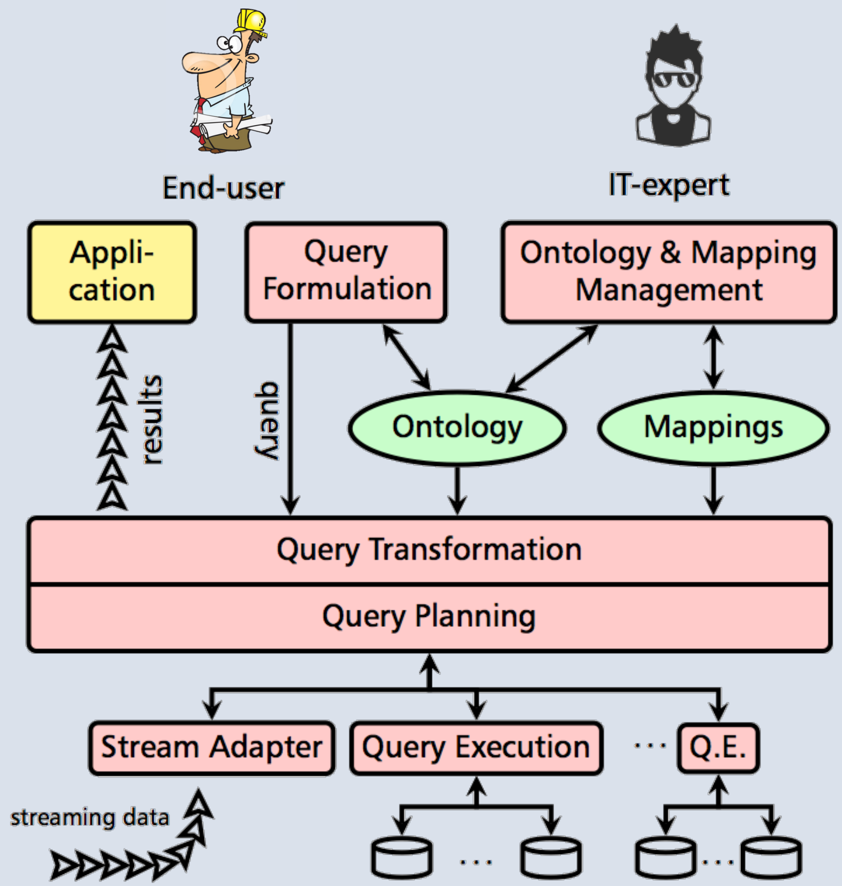
Optique Architecture



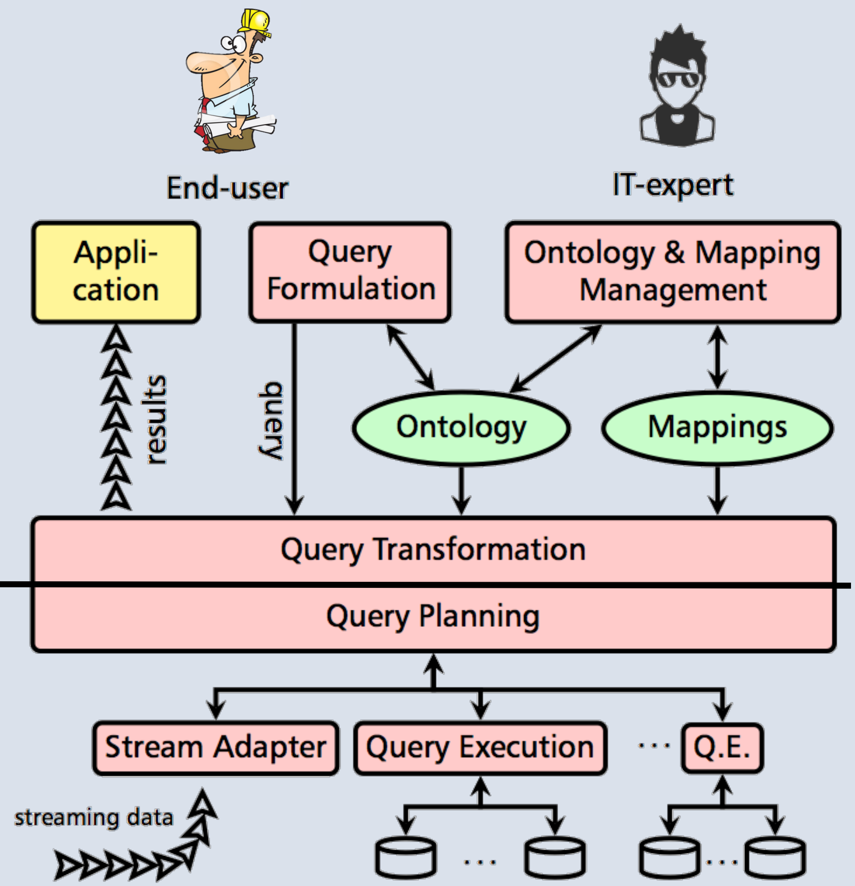
Optique Architecture

Query rewriting:

- uses ontology & mappings
- computationally hard
- ontology & mappings small

Query evaluation:

- ind. of ontology & mappings
- computationally tractable
- data sets very large



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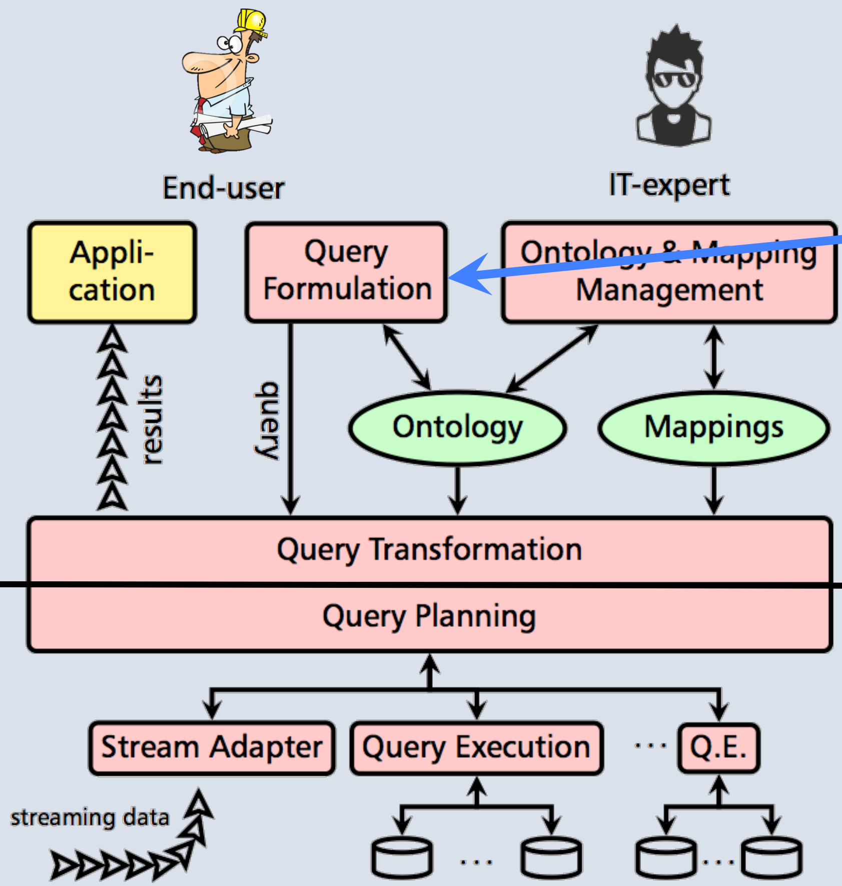
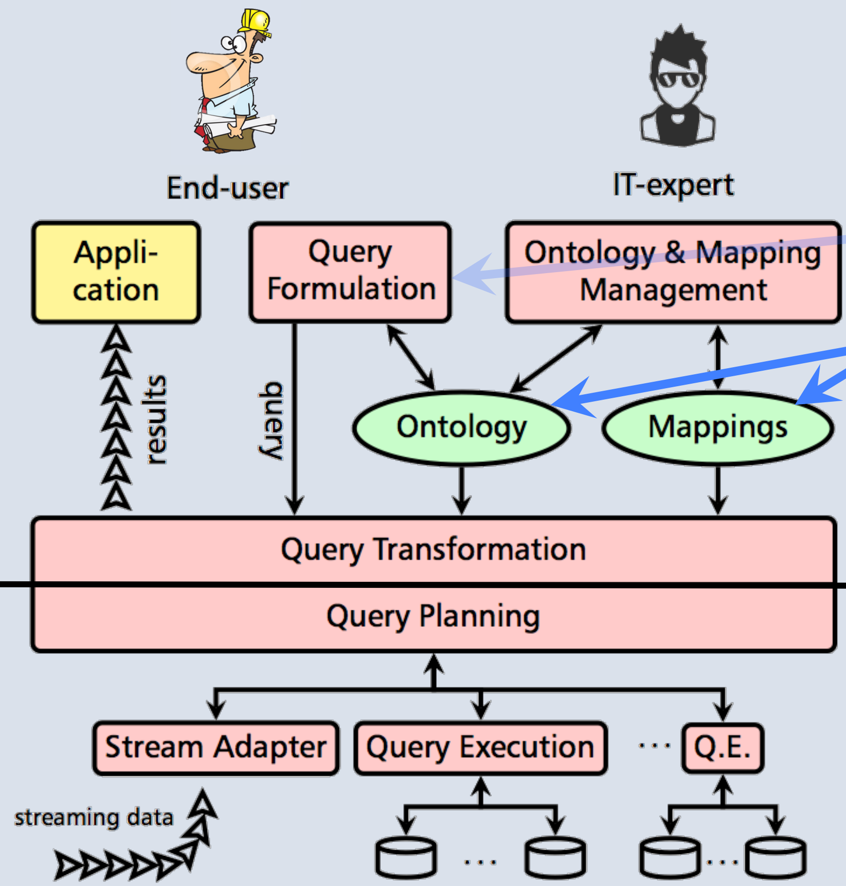


Other features:

support for query formulation

Optique Architecture



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"Bootstrapping" Ontology & mappings

Research Issues

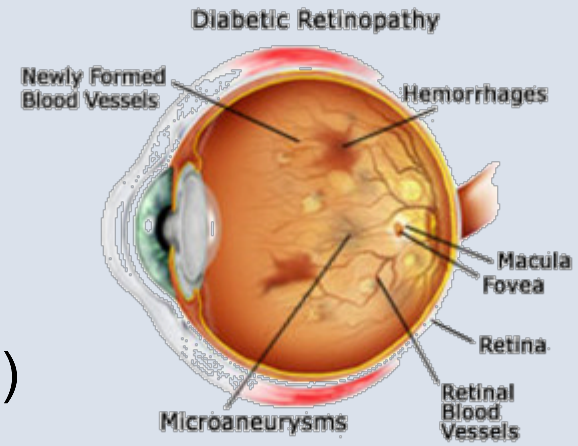
Research Issues

- **Expressive power**:
  - OWL QL (necessarily) has (very) restricted expressive power
  - Could use mappings to translate data into triples and use OWL RL
- **Scalability**:
  - Query size may increase exponentially in size of ontology
  - Rewritten queries may be hard for existing DBMSs
  - Extensive optimisation required [Bagosi et al]
- **Ontology and mapping engineering**:
  - Ontology engineering known to be hard
  - Less known about mappings, but likely to require similar tool support

Data Analysis: KAISER PERMANENTE

Data Analysis: KAISER PERMANENTE

- **HEDIS**[1] is a Performance Measure specification issued by **NCQA**[2]
  - E.g., all diabetic patients must have annual eye exams
- Meeting HEDIS standards is a requirement for government funded healthcare (**Medicare**)
- Checking/reporting is difficult and costly
  - Complex specifications & annual revisions
  - Disparate data sources
  - Ad hoc schemas including implicit information



[1] Healthcare Effectiveness Data and Information Set
[2] National Committee for Quality assurance

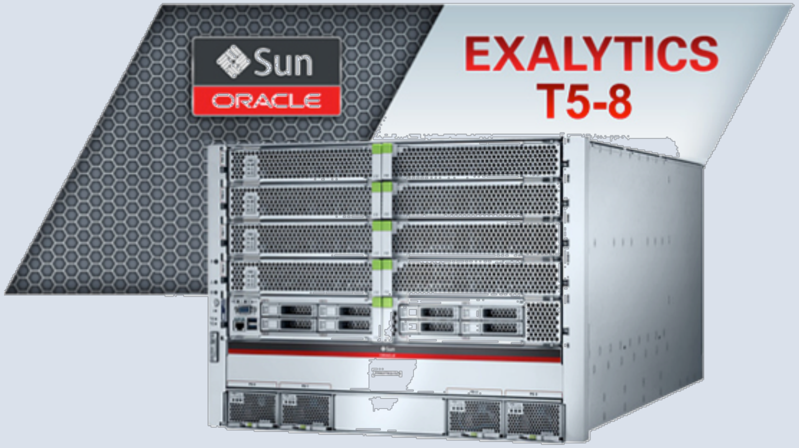
Semantic Technology Solution

Semantic Technology Solution

- Capture HEDIS diabetic care spec using **OWL RL & SWRL**
  - 174 axioms/rules
- Load data into (**RDFox**) triple store
  - Data from 466k patients (Georgia region); approx 100M records
  - Translated into 548M triples (32GB RAM)
- Use **materialisation** and **SPARQL queries** to identify relevant patients and check HEDIS conformance
  - Entire process takes ≈ 7,000s on a commodity server
  - Extends graph to 731M triples (43GB)

RDFox OWL RL Engine

- Targets SOTA **main-memory, mulit-core** architecture
  - Optimized in-memory storage with ‘mostly’ lock-free parallel inserts
  - Commodity server with 128 GB can store $>10^9$ triples
  - 10-20 x speedup with 32/16 threads/cores
  - LUBM 120K in 251s (20M triples/s) on T5-8 with 4TB/1024 threads



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- Native equality reasoning (owl:sameAs) via rewriting
- Incremental reasoning (delete 5k triples from LUBM 50K in <1s)

Research Issues

Research Issues

- **Expressive power**:
  - Capturing HEDIS spec requires negation and aggregation
  - Current solution interleaves SPARQL queries & materialisation
  - Extending RDFox to support aggregation & stratified negation
- **Scalability**:
  - KP have approx 10M patients in total (20 times larger)
  - RDFox can store 10B triples on a 1TB machine [Nenov et al]
  - Working on (semantic) partitioning and distributed materialisation

Observations and **Opinions**

Language Design: Features/Bugs

Language Design: Features/Bugs

RDF blank nodes

- ✗ Existential semantics are not always intuitive or appropriate
- ✗ NP complexity for base layer (compared to AC^0 for DBs)
- ✗ Stack(s) is (are) broken
- ✓ Sometimes useful (of course)
- ✓ Endless entertainment/papers for theoreticians

Open world semantics

- ✗ Not always intuitive or appropriate (for DB people/applications)
- ✗ Difficult to combine with, e.g., defaults and NAF
- ✓ Appropriate for Web
- ✓ Appropriate (often) for data integration

Language Design: Features/Bugs

Only unary and binary predicates

- ✗ "Incompatibility" with DBs
- ✗ Reification costly and problematical
  - Mapping from DBs is non-trivial
  - Canonical URI creation is critical
- ✓ Often sufficient in practice
- ✓ Simple(r) data structures and algorithms

RDF über alles

- ✗ Verbose, and difficult to fully specify/constrain/parse syntax
- ✗ Nonsensical statements (rdf:type, rdf:type: rdf:type)
- ✓ Single storage and querying infrastructure
- ✓ Uniform/combined data and schema queries

Language Design: Features/Bugs

Lacks/includes necessary/useless features

- ✗ Specification should have included _________*
- ✗ Specification should not have included _________*

THERE IS NO ONE PERFECT LANGUAGE

- ✓ Standardisation critical for infrastructure development and uptake
- ✓ RDF+OWL+SPARQL provides a **huge advantage/opportunity**

* Insert favourite/most-hated feature

Barriers to Uptake

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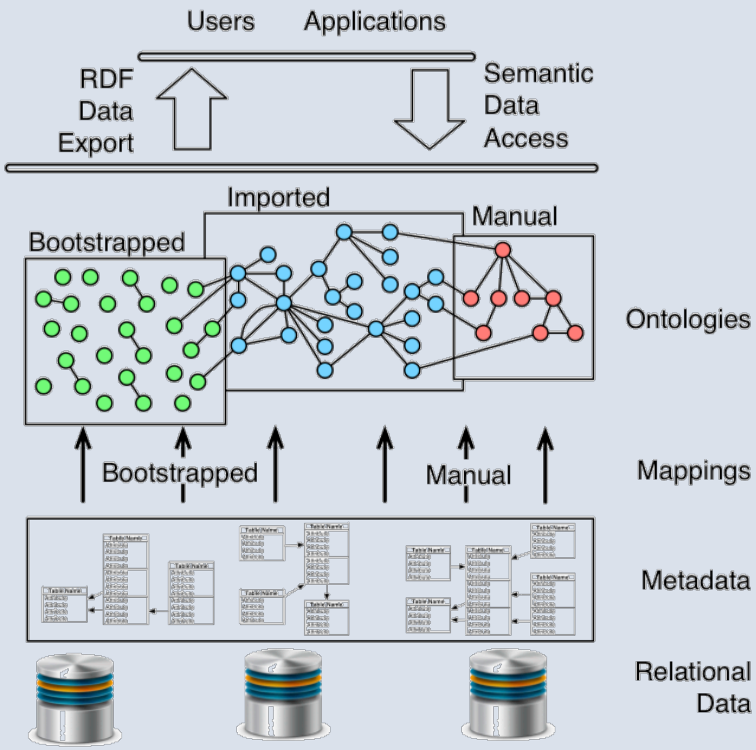
Ontology (and mapping) engineering

- Critically dependent on good quality ontologies (and mappings)
- Sophisticated tools and methodologies available
- But its still hard!



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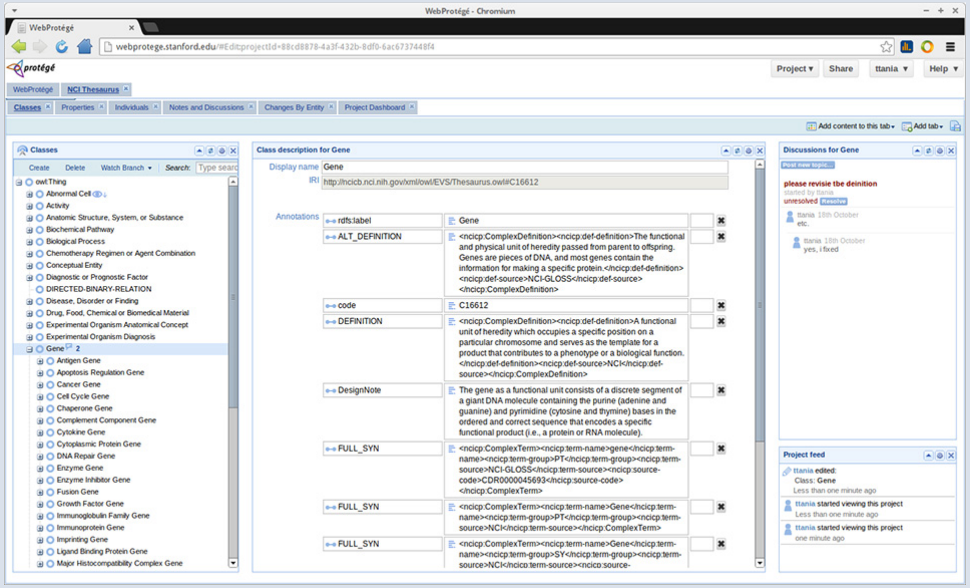

Kudos to Protégé

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Barriers to Uptake

Scalability -v- expressive power

- Users expect semantic technology features in addition to DB features
- RDF entailment already NP-complete
- OWL 2 DL entailment NP-Hard w.r.t. size of data and N2ExpTime-complete w.r.t. size of ontology+data
- OWL 2 profiles "more simply and/or efficiently implemented"
  - OWL 2 QL – AC^0 data complexity (same as DBs)
  - OWL 2 EL – PTime-complete combined and data complexity
  - OWL 2 RL – PTime-complete combined and data complexity
- but at the cost of reduced expressive power

Scalability Beyond the Profiles?

LUBM ontology includes the axioms

```
    SubClassOf(:ResearchAssistant
                 ObjectIntersectionOf(:Person
                 ObjectSomeValuesFrom(:worksFor :ResearchGroup)))
EquivalentClasses(:Employee
                 ObjectIntersectionOf(:Person
                 ObjectSomeValuesFrom(:worksFor :Organization)))
    SubClassOf(:ResearchGroup :Organization)
```

and LUBM 1 data includes 547 instances of :ResearchAssistant

Scalability Beyond the Profiles?

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ObjectIntersectionOf(:Person
ObjectSomeValuesFrom(:worksFor :ResearchGroup)))
EquivalentClasses(:Employee
ObjectIntersectionOf(:Person
ObjectSomeValuesFrom(:worksFor :Organization)))
SubClassOf(:ResearchGroup :Organization)

and LUBM 1 data includes 547 instances of :ResearchAssistant

How many of these RAs are in the answer to the following query?

```
SELECT ?x WHERE { ?x rdf:type :Employee }
```

Scalability Beyond the Profiles?

LUBM ontology includes the axioms

```
    SubClassOf(:ResearchAssistant
                    ObjectIntersectionOf(:Person
                    ObjectSomeValuesFrom(:worksFor :ResearchGroup)))
EquivalentClasses(:Employee
                    ObjectIntersectionOf(:Person
                    ObjectSomeValuesFrom(:worksFor :Organization)))
    SubClassOf(:ResearchGroup :Organization)
```

and LUBM 1 data includes 547 instances of :ResearchAssistant

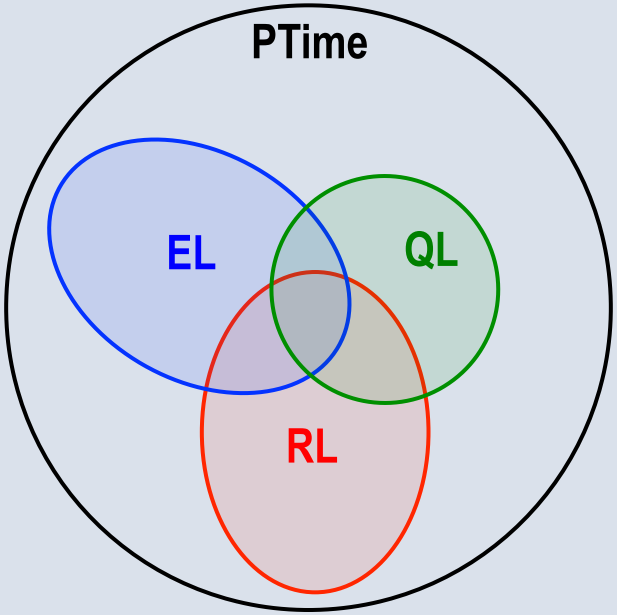
How many of these RAs are in the answer to the following query?

```
SELECT ?x WHERE { ?x rdf:type :Employee }
```

Answer computed by (most) RL reasoners: **none of them**

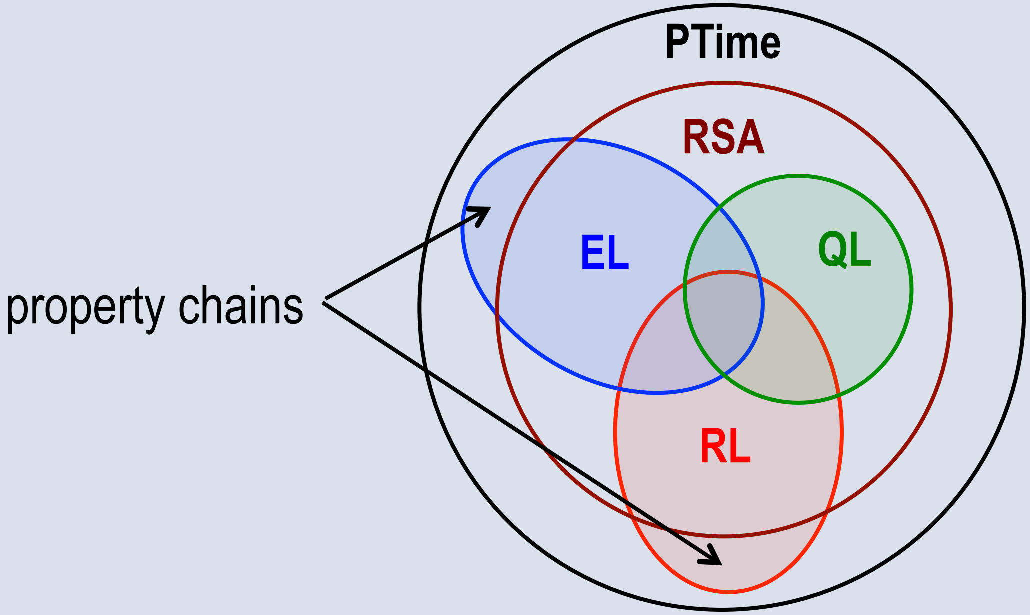
Combined Approach

- Combined approach allows RL reasoners to be used to support scalable query answering for all profiles



Combined Approach

- Combined approach allows RL reasoners to be used to support scalable query answering for all profiles
- And even for many non-profile ontologies in RSA class



Combined Approach

- Combined approach allows RL reasoners to be used to support scalable query answering for all profiles
- And even for many non-profile ontologies in RSA class
- How does it work?
  - Overapproximate $\mathcal{O}$ (e.g., "Skolemise" RHS exstentials) into $\mathcal{O}'$ i.e., $\mathcal{O}' \models \mathcal{O}$
  - Queries answered w.r.t. $\mathcal{O}'$ to give complete but unsound answers
  - Spurious answers are eliminated by a filtration step

Combined Approach

$\mathcal{O} \rightsquigarrow \mathcal{O}'$

$\mathcal{O}$:

SubClassOf(:ResearchAssistant
ObjectIntersectionOf(:Person
ObjectSomeValuesFrom(:worksFor :ResearchGroup)))

$\mathcal{O}'$:

SubClassOf(:ResearchAssistant
ObjectIntersectionOf(:Person
ObjectHasValue(:worksFor :RG1)))
(:RG1, rdf:type, :ResearchGroup)

Combined Approach

$\mathcal{O}$

SubClassOf(:ResearchAssistant
ObjectIntersectionOf(:Person
ObjectSomeValuesFrom(:worksFor :ResearchGroup)))

$\rightsquigarrow$

$\mathcal{O}'$

SubClassOf(:ResearchAssistant
ObjectIntersectionOf(:Person
ObjectHasValue(:worksFor :RG1)))
(:RG1, rdf:type, :ResearchGroup)

Combined Approach

$\mathcal{O} \rightsquigarrow \mathcal{O}'$

$\mathcal{O}$

SubClassOf(:ResearchAssistant
ObjectIntersectionOf(:Person
ObjectSomeValuesFrom(:worksFor :ResearchGroup)))

EquivalentClasses(:Employee
ObjectIntersectionOf(:Person
ObjectSomeValuesFrom(:worksFor :Organization)))

$\mathcal{O}'$

SubClassOf(:ResearchAssistant
ObjectIntersectionOf(:Person
ObjectHasValue(:worksFor :RG1)))
(:RG1, rdf:type, :ResearchGroup)

SubClassOf(:Employee
ObjectIntersectionOf(:Person
ObjectHasValue(:worksFor :ORG1)))
(:ORG1, rdf:type, :Organization)
SubClassOf(ObjectIntersectionOf(:Person
ObjectSomeValuesFrom(:worksFor :Organization))
:Employee)

Combined Approach

$\mathcal{O} \rightsquigarrow \mathcal{O}'$

$\mathcal{O}$

SubClassOf(:ResearchAssistant
ObjectIntersectionOf(:Person
ObjectSomeValuesFrom(:worksFor :ResearchGroup)))

EquivalentClasses(:Employee
ObjectIntersectionOf(:Person
ObjectSomeValuesFrom(:worksFor :Organization)))

SubClassOf(:ResearchGroup :Organization)

$\mathcal{O}'$

SubClassOf(:ResearchAssistant
ObjectIntersectionOf(:Person
ObjectHasValue(:worksFor :RG1)))
(:RG1, rdf:type, :ResearchGroup)

SubClassOf(:Employee
ObjectIntersectionOf(:Person
ObjectHasValue(:worksFor :ORG1)))
(:ORG1, rdf:type, :Organization)
SubClassOf(ObjectIntersectionOf(:Person
ObjectSomeValuesFrom(:worksFor :Organization))
:Employee)

SubClassOf(:ResearchGroup :Organization)

Combined Approach

$\mathcal{O} \rightsquigarrow \mathcal{O}'$

$\mathcal{O}$	$\mathcal{O}'$
SubClassOf(:ResearchAssistant ObjectIntersectionOf(:Person ObjectSomeValuesFrom(:worksFor :ResearchGroup)))	SubClassOf(:ResearchAssistant ObjectIntersectionOf(:Person ObjectHasValue(:worksFor :RG1))) (:RG1, rdf:type, :ResearchGroup)
EquivalentClasses(:Employee ObjectIntersectionOf(:Person ObjectSomeValuesFrom(:worksFor :Organization)))	SubClassOf(:Employee ObjectIntersectionOf(:Person ObjectHasValue(:worksFor :ORG1))) (:ORG1, rdf:type, :Organization) SubClassOf(ObjectIntersectionOf(:Person ObjectSomeValuesFrom(:worksFor :Organization)) :Employee)
SubClassOf(:ResearchGroup :Organization)	SubClassOf(:ResearchGroup :Organization)

$$\mathcal{O}' \cup \{(\text{:RA1}, \text{rdf:type}, \text{:ResearchAssistant})\} \models (\text{:RA1}, \text{rdf:type}, \text{:Employee})$$

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Combined Approach

$\mathcal{O}$ $\rightsquigarrow$ $\mathcal{O}'$

$\mathcal{O}$	$\mathcal{O}'$
SubClassOf(:ResearchAssistant ObjectIntersectionOf(:Person ObjectSomeValuesFrom(:worksFor :ResearchGroup)))	SubClassOf(:ResearchAssistant ObjectIntersectionOf(:Person ObjectHasValue(:worksFor :RG1))) (:RG1, rdf:type, :ResearchGroup)
EquivalentClasses(:Employee ObjectIntersectionOf(:Person ObjectSomeValuesFrom(:worksFor :Organization)))	SubClassOf(:Employee ObjectIntersectionOf(:Person ObjectHasValue(:worksFor :ORG1))) (:ORG1, rdf:type, :Organization) SubClassOf(ObjectIntersectionOf(:Person ObjectSomeValuesFrom(:worksFor :Organization)) :Employee)
SubClassOf(:ResearchGroup :Organization)	SubClassOf(:ResearchGroup :Organization)

$\mathcal{O}' \cup \{(\text{:RA1}, \text{rdf:type}, \text{:ResearchAssistant})\} \models (\text{:RA1}, \text{rdf:type}, \text{:Employee})$

SELECT ?x, ?y WHERE { ?x :worksFor ?z . ?y :worksFor ?z . ?z rdf:type :Employee }

Scalable Query Answering for OWL DL?

Given an **OWL DL ontology** $\mathcal{O}$ dataset $\mathcal{D}$ and query q

- We can transform $\mathcal{O}$ into strictly stronger OWL RL ontology $\mathcal{O}_u$
  - Roughly speaking, Skolemise, and transform $\vee$ into $\wedge$

Scalable Query Answering for OWL DL?

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- RL reasoning w.r.t. $\mathcal{O}_\mathsf{u}$ gives upper bound answer U

$$\mathsf{ans}(q, \langle \mathcal{O}, \mathcal{D} \rangle) \subseteq \mathsf{ans}(q, \langle \mathcal{O}_\mathsf{u}, \mathcal{D} \rangle) = \mathsf{U}$$

Scalable Query Answering for OWL DL?

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$$\mathsf{ans}(q, \langle \mathcal{O}, \mathcal{D} \rangle) \subseteq \mathsf{ans}(q, \langle \mathcal{O}_{\mathsf{u}}, \mathcal{D} \rangle) = \mathsf{U}$$

- If L = U, then both answers are sound and complete

$$\mathsf{L} \subseteq \mathsf{ans}(q, \langle \mathcal{O}, \mathcal{D} \rangle) \subseteq \mathsf{U}$$

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Scalable Query Answering for OWL DL?

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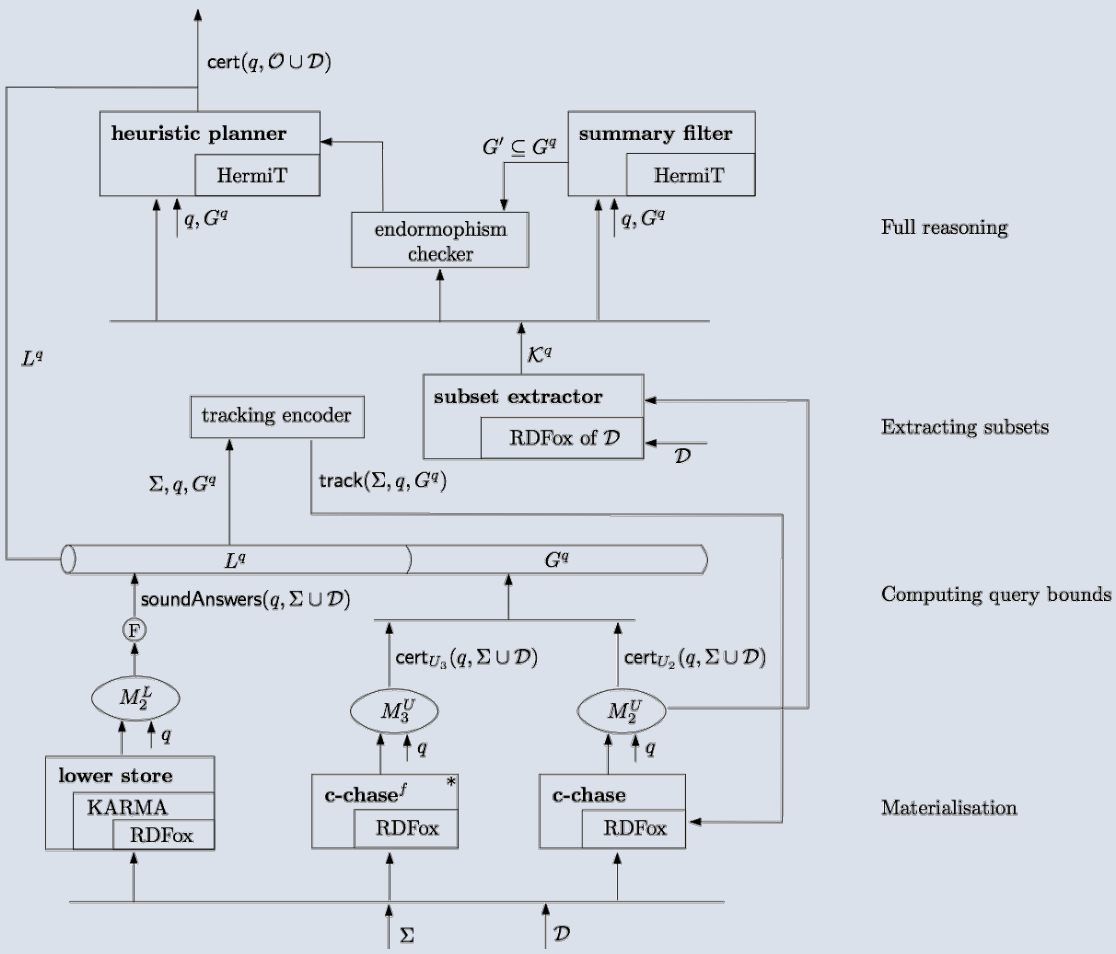
Scalable Query Answering for OWL DL?

- If L ≠ U, then U \ L identifies a (small) set of "possible" answers
  - Delineates range of uncertainty
  - Can more efficiently check possible answers using, e.g., HermiT (but still infeasible if dataset is large)
  - Can use U \ L to identify small(er) "relevant" subset of axioms/data sufficient to check possible answers (using proof tracing)

- Further optimisations
  - Use ELHO "combined" technique to tighten lower bound [Stefanoni et al]
  - Use "summarisation" technique to tighten upper bound [Dolby et al]
  - …

PAGOdA System



PAGOdA System

(b) LUBM query processing

A Perspective on the Semantic Web

A Perspective on the Semantic Web

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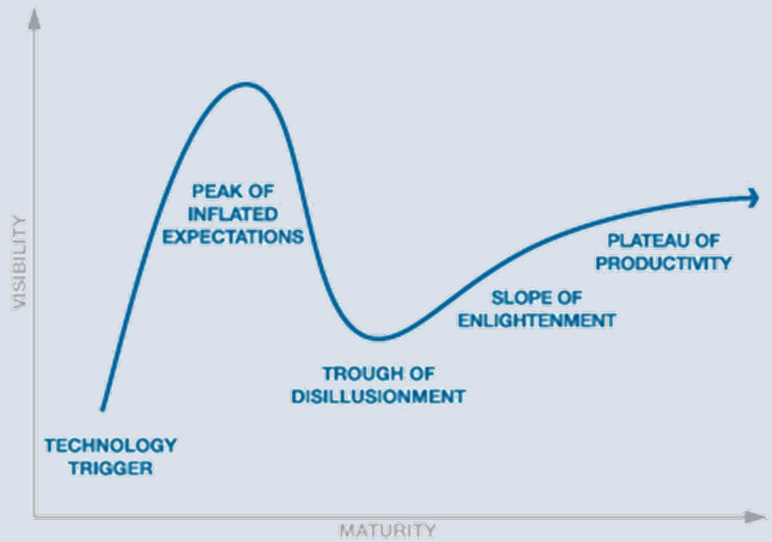
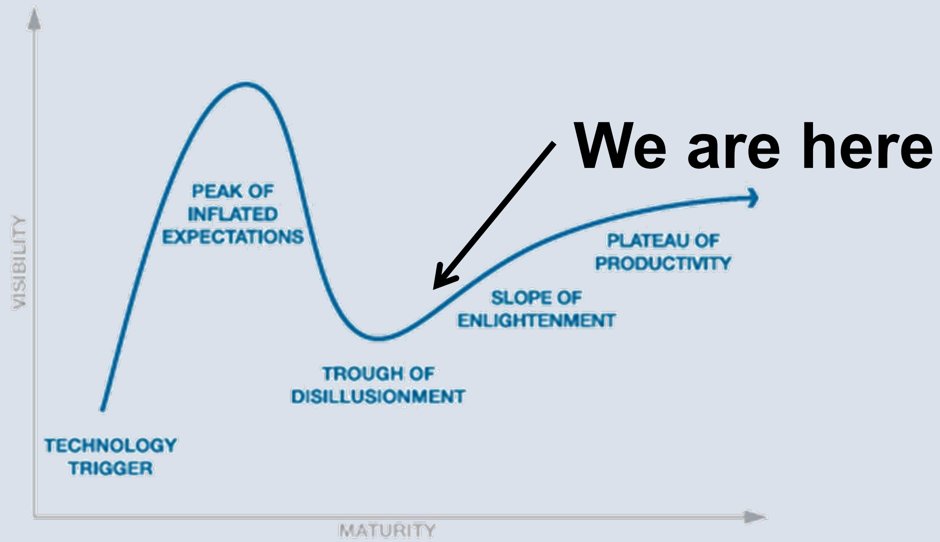
A Perspective on the Semantic Web

- **Graph DB** with rich and flexible schema
- Applications in **data integration and analysis** (as well as the Web)
- **Competing** with Graph/NoSQL DBs, Bigtable, HBase, …
- **RDF+OWL+SPARQL** standards and technologies offer important advantages

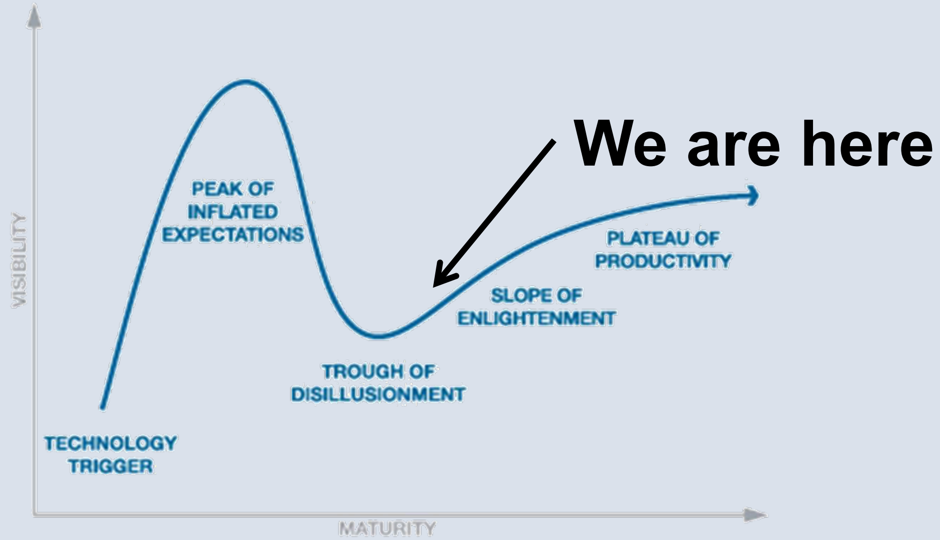
A Perspective on the Semantic Web



A Perspective on the Semantic Web



A Perspective on the Semantic Web



- We have the (right) **languages**
- We have the (right) **technology**
- We have interest and even enthusiasm from (potential) **users**
- All(!) we need to do is **engage** and (continue to) **deploy**

Acknowledgements

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SIXTH FRAMEWORK PROGRAMME

SEVENTH FRAMEWORK PROGRAMME

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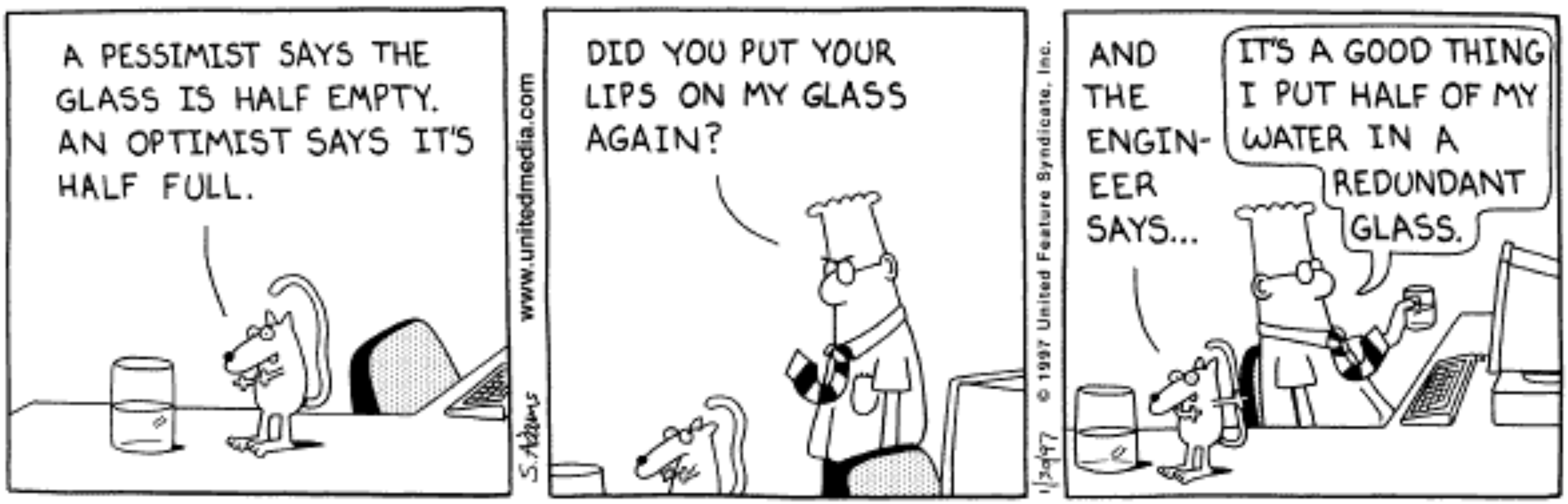
Thank you for listening

Thank you for listening



Any questions?

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