Semantics for the Web of Things

Modeling the Physical World as a Collection of Things and Reasoning with their Descriptions

Victor Charpenay

Universität Passau
Siemens AG

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Introduction

The Web of Things is the latest field of research around sensing and actuation.

1948	Cybernetics
1993	Ubiquitous Computing
1998	Ambient Intelligence
2000	Wireless Sensor Networks
2000	Internet of Things
2001	Pervasive Computing
2007	Cyber-Physical Systems
2009	**Web of Things**

Table: Chronological evolution of research in cybernetics

The Web Thing Interface

The Web Thing API, following the principles of REST, eases the development of sensor mash-ups.

```
{wt}
{wt}/model
{wt}/properties
{wt}/properties/{id}
{wt}/actions
{wt}/actions/{id}
{wt}/actions/{id}/{actionId}
{wt}/things
{wt}/things/{id}
{wt}/subscriptions
```

Figure: Web Thing API specification (endpoint URLs)

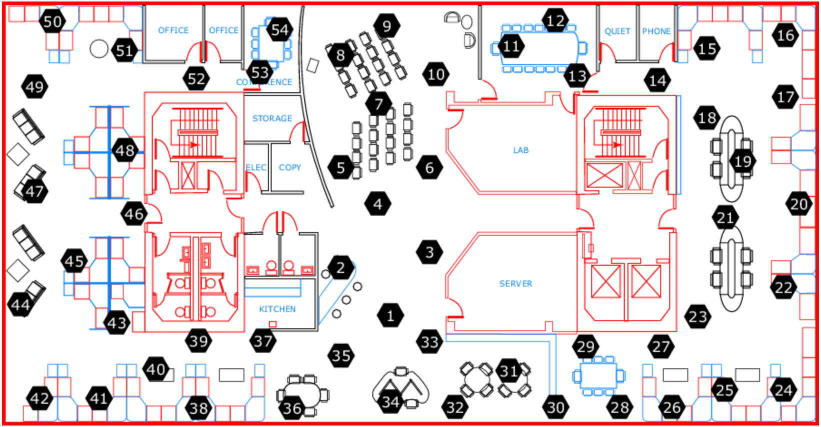


Figure: Map of Intel Labs

Problem Statement

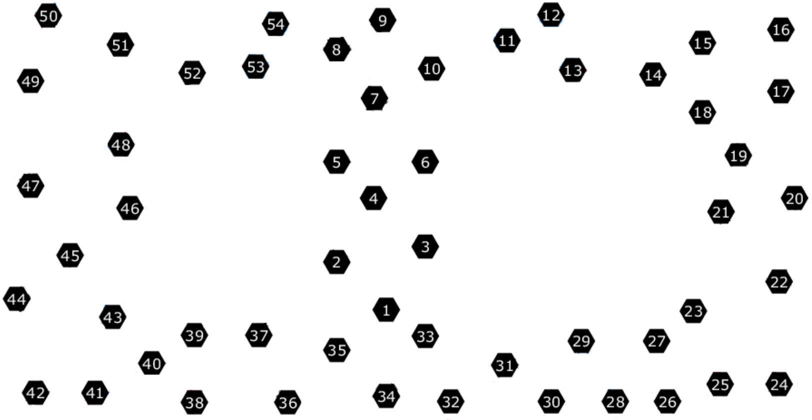


Figure: *Sensor* map of Intel Labs

Problem Statement

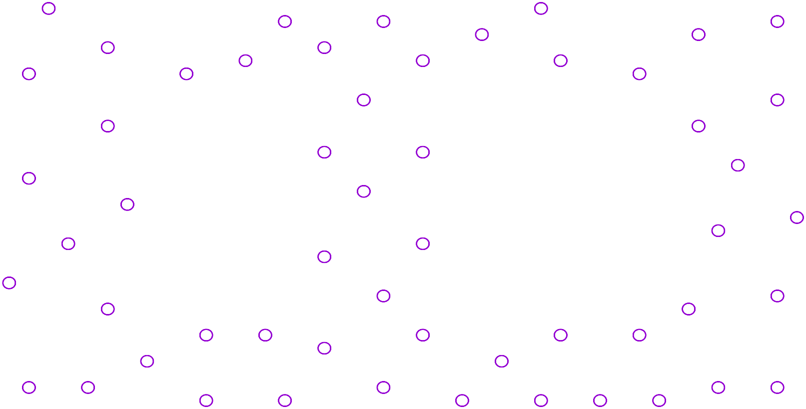


Figure: *Thing* map of Intel Labs

Problem Statement

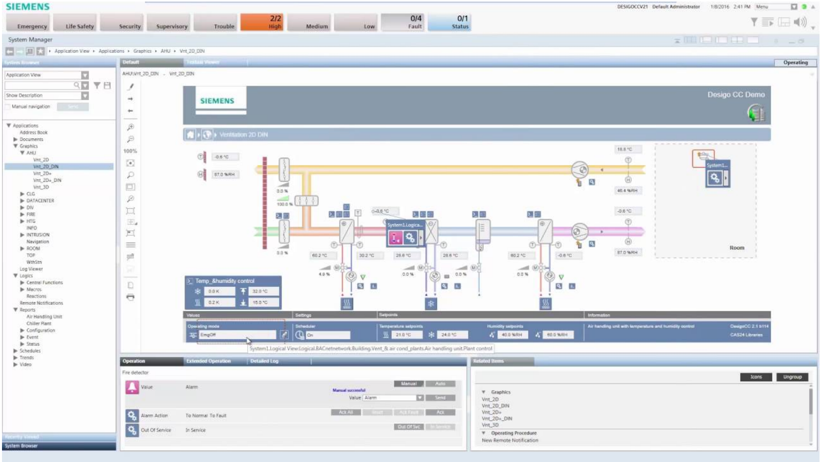


Figure: Desigo CC user interface

Problem Statement

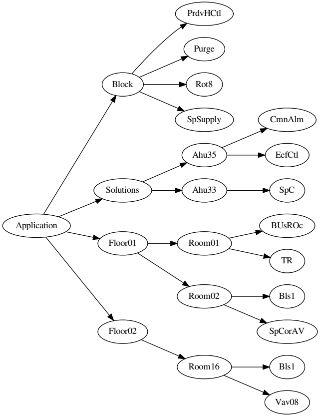


Figure: Desigo CC node hierarchy

Statistics:

- 929 nodes (i.e. 'things')
- 1842 parent/child relations

Interpretation:

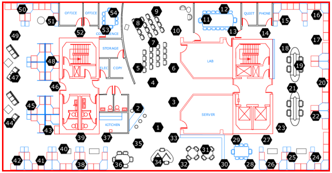
- `Ahu35` ≡ air handling unit
- `Bls1` ≡ window blinds
- ...

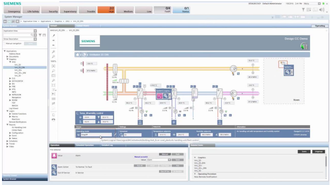
Intel Labs

Dataset to study device **interactions**. No contextual information.

Desigo CC

Limited **semantic modeling**. No automated reasoning.





Problem

How to describe ‘things’ on the Web of Things such that sensors and actuators can interact autonomously in a Web of Things system?

Assumptions

- A Web of Things system is described by a graph of interactions
- Knowledge graphs are the base modeling approach

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A Web of Things system is a **multi-agent system** characterized by pairwise interactions between **servients** (servers and clients).

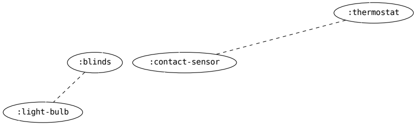

Figure: Graph of interactions for a room

The enviroment of a Web of Things system is described by a **knowledge graph**.

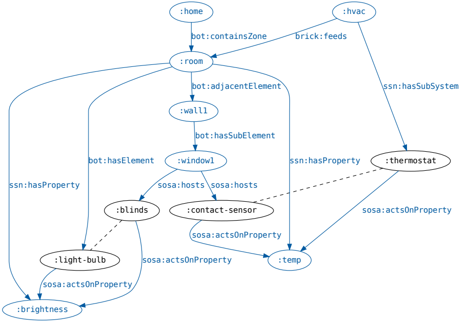

Figure: Knowledge graph for a room

Structure of the Presentation

1. Modeling 'Things' on the Web of Things
   → **Vocabulary** used in the knowledge graph
2. Reasoning with Thing Descriptions
   → **Rules** included in the knowledge graph
3. Exchanging Thing Descriptions
   → **Serialization** of (pieces of) the knowledge graph

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Modeling ‘Things’ on the Web of Things

What is a ‘Thing’?

“Every kind of thing can have its own kind of reason for being a thing.”
— Patrick Hayes (The Second Naive Physics Manifesto)

UNIVERSITÄT PASSAU

The Linked Open Vocabulary platform for the IoT (LOV4IoT) is a catalogue of vocabularies (sets of class, property and individual names) with more than 460 entries.

Some of them have been standardized:

- Sensor, Observation, Sample, and Actuator (SOSA)
- Semantic Sensor Network (SSN)
- Smart Appliance Reference (SAREF)
- Smart Energy-Aware System (SEAS)

Other Standard Information Models

Standard	Vocabulary Mapping
BLE GATT	-
OPC-UA	-
BACnet	BACowl
oneM2M	oneM2M Base ontology, **WoT Cloud**
OCF	**WoT Cloud**
IPSO/LWM2M	**WoT Cloud**
EDDL	Siemens OSF
eCl@ss	eCl@ssOWL
IFC	ifcOWL
Project Haystack	**HTO**, Brick

Table: Communication standards related to WoT with a mapping of their information model to a vocabulary

Most conceptualizations (vocabularies and information models) are redundant and thus could be semantically **aligned**.

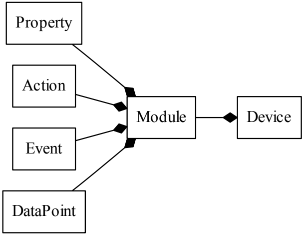

Figure: oneM2M

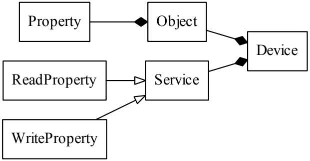

Figure: BACnet

Alignments between Standards

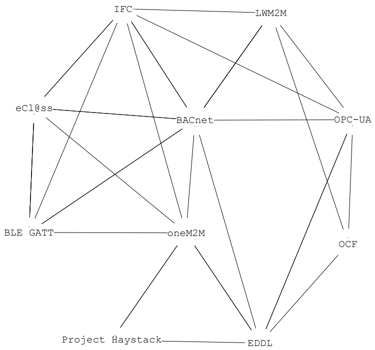

Figure: Graph of alignments constructed from lexical equivalences between standard information models

Standard	Degree	Farness
BLE GATT	7	1.6
OPC-UA	6	1.4
BACnet	**12**	1.2
oneM2M	8	**1.1**
OCF	3	1.7
LWM2M	6	1.5
EDDL	7	1.3
eCl@ss	7	1.5
IFC	8	1.2
Project Haystack	3	1.7

Table: Graph statistics with respect to vertices

A **Thing** has interaction affordances to read/write a **Property**, invoke a **Action** or subscribe to a **Event**.

- A `saref:TemperatureSensor` has an affordance to read/write a `om:Temperature` property
- A `saref:LightSwitch` has an affordance to toggle its `saref:OnOffState`
- A `saref:SmokeSensor` has an affordance to subscribe to the `saref:Smoke` event
- ...

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The Thing Description Vocabulary

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Alignments in LOV4IoT

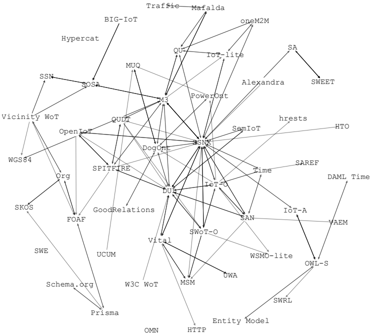


Figure: Graph of alignments extracted from Web ontology alignments declared within LOV4IoT

Ontology	In-Degree	Farness	PageRank
SSNX	**27**	**1.875**	**0.039067**
DUL	20	2.167	0.023299
M3	13	2.23	0.022743
SOSA	8	2.938	0.006796
DogOnt	8	2.417	0.024721
QU	7	2.604	0.013021
MSM	6	2.667	0.008613
FOAF	6	3.021	0.015887
SSN	6	3.75	0.005725
SPITFIRE	5	2.375	0.009752
IoT-O	5	2.5	0.013867
SAN	5	2.625	0.00999
Vital	5	2.708	0.015621
OWL-S	5	3.542	0.017288
SWEET	5	3.792	0.005171

Table: Graph statistics with respect to vertices

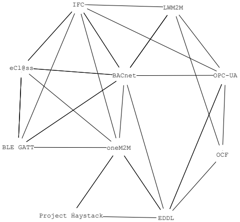
A **Thing** (TD) is either a **System** (SSN), a **Platform** (SOSA) or a **FeatureOfInterest** (SOSA).

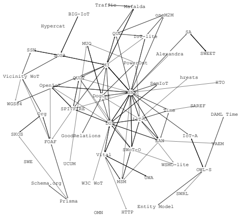
a sensor	an energy consumption meter
an iPhone	a LoRa communication device
a tree	a window
the Coal Oil Point reserve	a room
...	...

Table: Examples of potential instances of 'things'

Contribution

The Thing Description (TD) model: an RDF vocabulary to describe servient interaction affordances, with alignment to existing vocabularies[1].





[1] V. Charpenay, S. Kaebisch, and H. Kosch, *Introducing Thing Descriptions and Interactions: An Ontology for the Web of Things*, in Joint Proceedings of the 3rd Stream Reasoning (SR 2016) and the 1st Semantic Web Technologies for the Internet of Things (SWIT 2016) workshops, Kobe, 2016.

Reasoning with Thing Descriptions

"Knowledge is power"
— Thomas Hobbes (Leviathan)

Web ontologies define **rules** (or axioms) over a vocabulary.

$$x[\text{hasState} \Rightarrow \text{State}] :- x{:}\text{Device} \; .$$

$$y{:}\text{Actuator} :- x[\text{madeByActuator} \rightarrow y] \; .$$

$$x[\text{containsZone} \rightarrow z] :- \\ x[\text{containsZone} \rightarrow y] \text{ and } y[\text{containsZone} \rightarrow z] \; .$$

...

Table: Examples of ontological rules

Rule inference can help discover new relations between ‘things’, i.e. new potential interactions between agents.

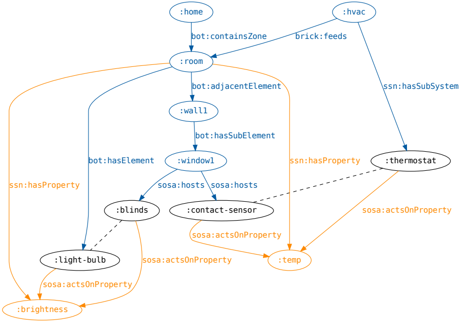


Figure: Knowledge graph *with inference* for a room

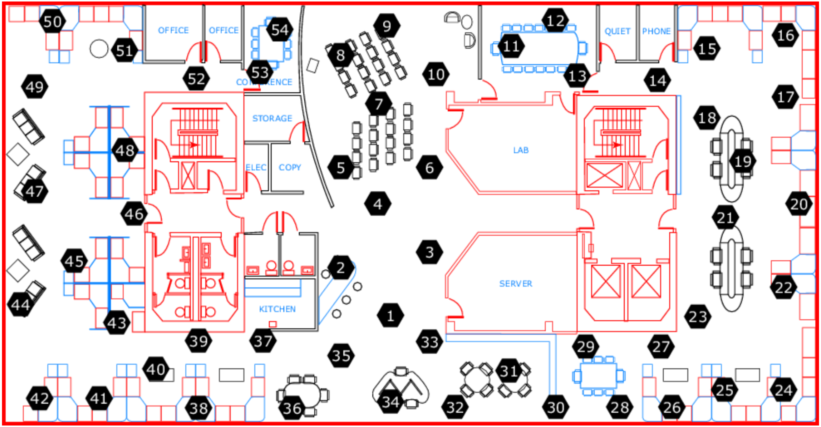


Figure: Map of Intel Labs

Analysis of the Graph of Interactions

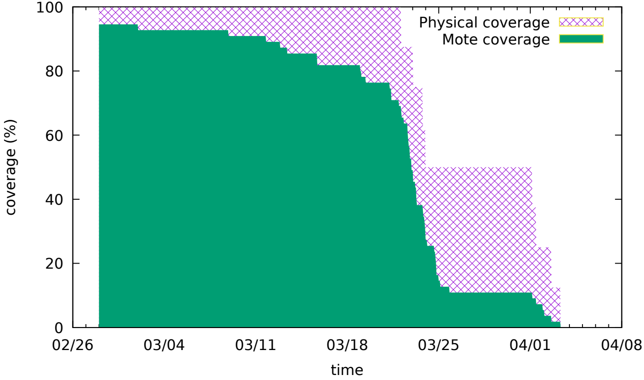


Figure: Sensor (mote) and knowledge (physical) coverage of the Intel Labs sensor network over the period February 28th – April 3rd, 2004

Analysis of the Graph of Interactions

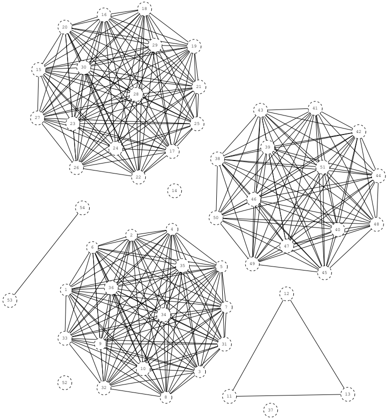
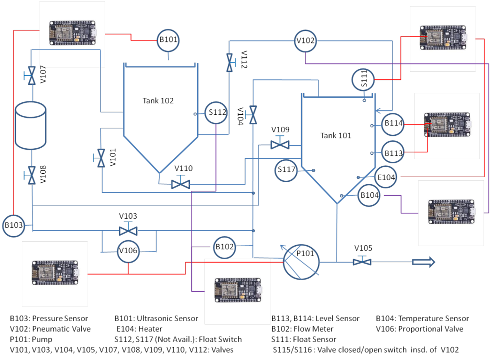


Figure: Graph of interactions of the Intel Labs sensor network

Another Web of Things System



(a) Logical Circuit

(b) Model

Figure: A water management plant

Analysis of the Graph of Interactions

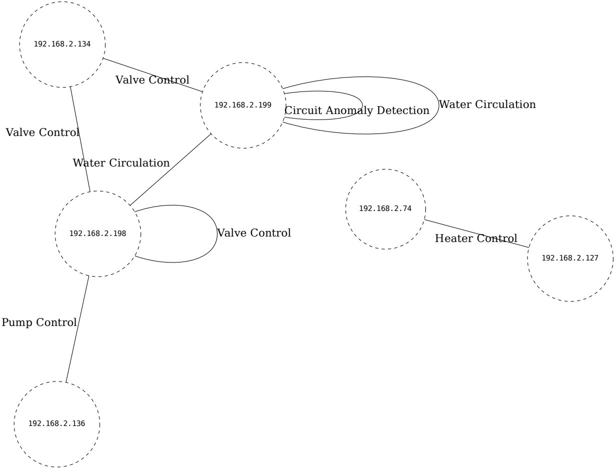
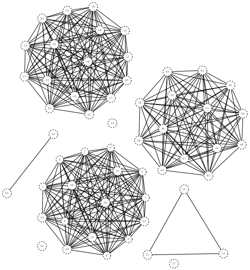
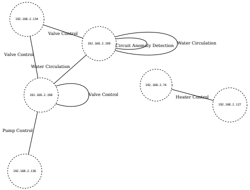


Figure: Graph of interactions for the water management plant model

Contribution

A semantic discovery framework on the Web of Things as a query answering problem over Web ontologies and Thing Description documents[2]





[2] V. Charpenay, S. Käbisch, and H. Kosch, *A Framework for Semantic Discovery on the Web of Things*, Studies on the Semantic Web, pp. 147–162, 2018.

Exchanging Thing Descriptions

Contextualization

"*Context of use*: discourse that surrounds a language unit and helps to determine its interpretation."
— WordNet (available at `http://wordnet-rdf.princeton.edu`)

Autonomous agents on the Web of Things are self-aware and numerous.

- TD document served by every servient
- RDF on constrained devices (8-64kB RAM, low-power)?

The **Embedded Web** is a set of technologies and architecture choices to adapt the Web to embedded environments.

Web	Embedded Web
HTTP	CoAP
XML	EXI
JSON	EXI4JSON, CBOR
HTML	CoRE Link
RDF	HDT, RDF/EXI
JSON-LD	**Binary object notation**
LDP	LDP over CoAP
SPARQL	**Frame matching**

Table: Web standards and equivalent Embedded Web technologies

HDT is a binary format including **headers**, a **dictionary** and **triples** encoded as adjacency lists.

1	31.638	
2	eastWall	
3	radiator1	(individual names occuring at least twice)
4	radiator2	
5	southWall	
6	legoland	(other individual names)
6	east	
7	south	
8	Radiator	(class names and individual names occurring only as value)
9	Site	
10	Space	
11	Wall	
1	`rdf:type`	
2	containsElement	
3	hasOrientation	(property names)
4	hasSpace	
5	hasSubElement	

Properties	1 2 0 1 3 5 0 1 0 1 0 1 3 5 0 1 4
Values	10 0 2 5 0 11 0 6 0 4 0 8 0 8 0 11 0 7 0 3 0 9 0 1

k^2-triples is an alternative to HDT using **k^2-tree indexing** for triples instead of a bitmap.

0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

1000 1100 1000 1000 0100 1000
...

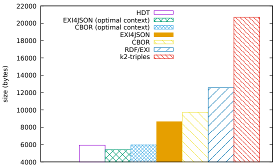
Limitation

HDT (and k^2-triples) strongly couple dictionary and triples, which leads to a significant overhead when exchange triples.

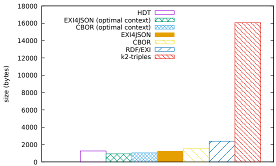
Approach

- Binary object notation (EXI4JSON, CBOR)
- Shared dictionary (JSON-LD context)

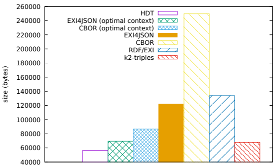
Evaluation (Whole Datasets)



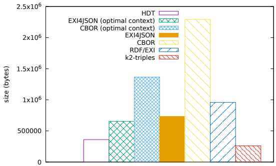
(a) BTCSAMPLE



(b) NODE



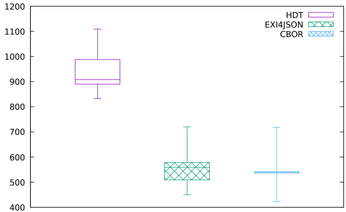
(c) SSP



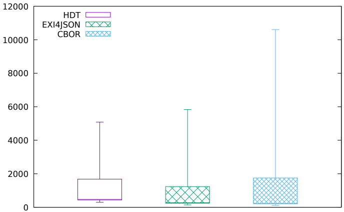
(d) DESIGO

Figure: Size of datasets serialized in compact binary formats

Evaluation (Piecewise Serialization)



(a) SSP (environmental and traffic monitoring)



(b) DESIGO (building automation)

Figure: Size distribution for piecewise serializations

RDF queries can also be shared and processed in a compact form (as JSON-LD frames); main memory overhead comes from intermediate mappings only.

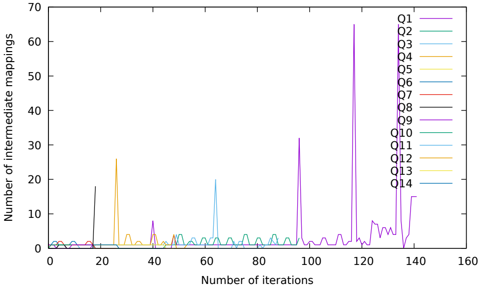
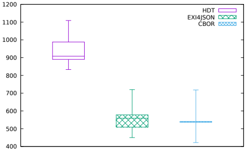
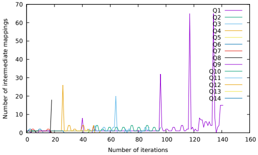


Figure: Intermediate Mappings for the LUBM Benchmark

Contribution

A binary object notation for Thing Descriptions[3]





[3] V. Charpenay, S. Käbisch, and H. Kosch, *Towards a Binary Object Notation for RDF*, in Proceedings of the 15th Extended Semantic Web Conference (ESWC), Heraklion, 2018.

Conclusion & Perspectives

Contributions

- Thing Description model with alignments
- A semantic discovery framework (existential reasoning)
- A binary object notation for Thing Descriptions

Software

- Thingweb Directory
- μRDF.js

Standards

- W3C Thing Description Ontology

Future (On-Going) Work

The Thing Description ontology should be further aligned with other information models, at the instance level.

Thing	
Project Haystack	Battery
oneM2M	Push Button
LWM2M	Accelerometer
Property	
Project Haystack	Luminance
onem2M	Liquid Level
LWM2M	Loudness
Action	
...	...

Table: Alignment of WoT concepts with WordNet

Bibliography

Bibliography

- V. Charpenay, S. Käbisch, and H. Kosch, *Introducing Thing Descriptions and Interactions: An Ontology for the Web of Things*, in Joint Proceedings of the 3rd Stream Reasoning (SR 2016) and the 1st Semantic Web Technologies for the Internet of Things (SWIT 2016) workshops, Kobe, 2016.
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