

General Terminology Induction in OWL

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1 Introduction

An ontology is a machine-processable representation of knowledge about a domain of interest. Ontologies are encoded in formal languages, such as the Web Ontology Language [8], OWL, underpinned by expressive Description Logics, DLs [1]. OWL ontologies are widely-used to represent and share knowledge in application areas such as medicine, biology, astronomy, defence and others.¹ An ontology can contain data and background knowledge (terminology) where both may be incomplete. One might benefit from finding informative correlations in their data taking background knowledge into account. Those correlations may suggest new axioms for the background knowledge or start new inquiries about the data.

However, the problem of terminology induction is generally hard. Firstly, an ideal solution should represent a coherent, self-contained, expert-level modelling. Due to high expressivity of OWL and its Open World Assumption (OWA), the search space can be vast or even infinite depending on the language chosen. Secondly, as usual, the quality of the result depends on the quality of the data which can be incorrect, noisy or insufficient. Ideally, new knowledge should respect the existing knowledge along with the data in order to be maximally informative and avoid contradictions.

Thus, some restrictions and assumptions that simplify the problem are necessary. Another consequence is that any induced knowledge is hypothetical only and requires a domain expert judgement. The contributions of this paper² are as follows.

- We state the problem of general terminology induction, i.e. learning sets, called *hypotheses*, of general class inclusions, GCIs, from data (ABox) and background knowledge (TBox).
- We view the problem as multi-objective and define quality criteria for a hypothesis: readability, logical quality, and statistical quality. We define hypothesis quality measures that respect the OWA, interactions between axioms in the hypothesis, and interaction of the hypothesis with the background knowledge.
- We have designed and implemented methods to compute the quality measures.
- We have designed, implemented and evaluated an anytime algorithm for general terminology induction. We have gained insights into the structure of the search space and developed heuristics to find out promising hypotheses. The experiments show that we can indeed learn interesting hypotheses.

¹ <http://bioportal.bioontology.org/>

² This is an abridged version of [14].

2 Preliminaries

We assume the reader to be familiar with DLs [1] and OWL [8]. The following nomenclature is used throughout this paper. $\mathcal{O} = \mathcal{T} \cup \mathcal{A}$ is an ontology where \mathcal{T} , \mathcal{A} are TBox and ABox, respectively. N_C, N_R, N_I are disjoint and countably infinite sets of class, property, and individual names, respectively. Σ is a signature, $\tilde{\mathcal{T}}, \tilde{\mathcal{A}}, \tilde{\mathcal{O}}$ are signatures of $\mathcal{T}, \mathcal{A}, \mathcal{O}$, respectively. $ind(\mathcal{O}) = N_I \cap \tilde{\mathcal{O}}$ is a set of individual names occurring in \mathcal{O} . α is a general class inclusion, GCI, also called *axiom*. A, B, X, Y are atomic classes (class names), C, D are complex classes (class expressions), R is a property, a, b, c, d are individuals. $mod(\mathcal{O}, \Sigma)$ is a module [7] of an ontology \mathcal{O} given a signature Σ . \mathbb{C} is a set of (possibly complex) classes. H is a hypothesis, \mathbb{H} is a set of hypotheses. In the following, ABox and TBox are called *data* and *background knowledge*, respectively.

3 Related Work

Ontology learning approaches can be characterised along several dimensions. The first one is a type of the data source, e.g. texts, RDF(S), an oracle (a domain expert), positive and negative examples for a class along with the ABox. The second one is a type of the output knowledge, e.g. class descriptions, class inclusions, and its expressivity. The third dimension is methods used: natural language processing, machine learning, association rules mining, oracle queries, Formal Concept Analysis (FCA), least common subsumer (LCS) computation, etc. The fourth dimension is semantics used that can differ from the OWL semantics, e.g. the Closed World Assumption (CWA). One more characteristic is appreciation of available background knowledge. Finally, the degree of domain expert involvement in the learning process greatly varies across approaches. A survey can be found in [12].

We concentrate on learning from instance-level data, i.e. both class and property assertions. Among the approaches aimed at this type of input data are class description learning, CDL [3, 5, 11], knowledge base completion, KBC [2], association rules mining, ARM [17].

The main method of CDL is machine learning, in particular, Inductive Logic Programming, ILP [13]. The goal is to find a “good” description (class expression) of a given class name from a set of positive and negative examples [11] for it, i.e. learning is *supervised*. The class description must cover all positive and none of the negative examples. Learning is essentially a search in the space of class expressions guided by refinement operators and heuristics. The background knowledge can be used to optimize the search by exploiting the classification hierarchy. To supervise learning, a domain expert has to provide additional information in form of positive and negative examples for a given class, which can be difficult. As a consequence, there are techniques to sample examples from data. In particular, instances of the class are taken as its positive examples and the CWA is made to obtain its negative examples. However, this way can cause problems [10]. Another method of CDL is finding the least common subsumer (LCS) [3]. LCS is computed from the most specific class (MSC) of each instance of a target class. The method, however, is only applicable to weakly expressive languages.

KBC is based on Formal Concept Analysis (FCA) [6]. It is aimed at acquiring (in some sense) complete knowledge bases, in contrast to CDL. KBC requires to define a

set of class expressions in advance which can be hard. The degree of domain expert involvement is high as the expert judges axioms and has to supply a counterexample in the case of rejection. One more limitation is that standard FCA can only be applied under the CWA and the OWA of OWL requires modifications of FCA [2].

ARM is yet another approach to ontology learning [17]. Association rules are mined from transaction tables where columns are predefined class expressions which, similarly to the case of KBC, can be difficult to define in advance. In contrast to KBC, ARM, however, permits acquiring axioms that have counterexamples. In contrast to CDL, ARM induces class inclusions and demands neither positive nor negative examples. The approach focuses on weakly expressive languages. Among other restrictions are its CWA and little appreciation of interaction between induced axioms and the background knowledge, as well as mutual interactions between induced axioms, since they are acquired independently.

Thus, ontology learning approaches simplify the problem in different aspects. As a result, there is no approach that has all following capabilities: learns sets of GCIs, appreciates interactions between axioms within the set and interactions of the set with the background knowledge, uses standard OWL semantics, requires no supervision, does not demand frequent human interventions.

4 Settings and Assumptions

This paper is aimed at addressing the problem of inducing general terminological knowledge from data and background knowledge. New knowledge is acquired in the form of *hypotheses*. A hypothesis is a set of axioms which does not contradict the input ontology, i.e. is *consistent* with it, and carries new information, i.e. is *informative* for it.

Definition 1. (*Hypothesis*) An axiom α is informative for an ontology \mathcal{O} if $\mathcal{O} \not\models \alpha$. A set H of axioms (GCIs) is called a hypothesis for an ontology \mathcal{O} if H is consistent with \mathcal{O} , i.e. $\mathcal{O} \cup H \not\models \top \sqsubseteq \perp$, and each $\alpha \in H$ is informative for \mathcal{O} .

A hypothesis is evaluated by *quality criteria*: *readability*, *statistical quality*, and *logical quality*. Clearly, a hypothesis can be better on one criterion and worse on another. Therefore, we view terminology induction as a multi-objective problem where objectives are *quality measures* corresponding to the quality criteria. Hypotheses are presented to a domain expert who accepts some of them and rejects others. In order to suggest, or *recommend*, good hypotheses first, a preference relation based on quality measures is imposed on the set of hypotheses. In this paper, we apply the following *settings*.

- (i) We use OWL and its standard semantics.
 - (a) We allow for the usual OWA, i.e. for an instance a and a class C it is possible that $\mathcal{O} \not\models C(a)$ and $\mathcal{O} \not\models (\neg C)(a)$. As a consequence, data can be regarded as just “incomplete”.
 - (b) Data normally consists of both class and property assertions, e.g. people with family relations, proteins with interactions between them.
 - (c) We consider any logic for which subsumption, $\mathcal{O} \models C \sqsubseteq D$, and instance checking, $\mathcal{O} \models C(a)$, are decidable. We use OWL ontologies and reasoners.

- (ii) Any input ontology \mathcal{O} is consistent, i.e. data contains no noise which causes inconsistency.
- (iii) Learning is *unsupervised*, i.e. no additional information is required in the form of positive or negative examples.
- (iv) A set \mathbb{C} of target (possibly complex) classes is fixed and finite.

The goal of induction is finding good hypotheses over classes \mathbb{C} , or \mathbb{C} -*hypotheses*. In the following, we only consider \mathbb{C} -hypotheses and omit \mathbb{C} from the name. We also define $\mathbb{C}^- := \mathbb{C} \cup \{\neg C \mid C \in \mathbb{C}\}$.

Definition 2. (\mathbb{C} -Hypothesis) Given an ontology \mathcal{O} , a hypothesis H for \mathcal{O} is called a \mathbb{C} -hypothesis if $\alpha \in H$ implies $\alpha = C \sqsubseteq D$, where $C, D \in \mathbb{C}^-$.

It makes sense to establish a correspondence, sufficient for the task at hand, between an ontology \mathcal{O} and classes \mathbb{C} , which we call *projection*.

Definition 3. (Projection) A projection π of an ontology \mathcal{O} to \mathbb{C} is

$$\pi(\mathcal{O}, \mathbb{C}) := \{D(a) \mid \mathcal{O} \models D(a) \wedge D \in \mathbb{C}^- \wedge a \in \text{ind}(\mathcal{O})\}.$$

Thus, a projection is a set of positive and negative class assertions over classes \mathbb{C} entailed by \mathcal{O} . A projection can be viewed as a table where rows are labelled with individuals $\text{ind}(\mathcal{O})$ and columns are labelled with classes \mathbb{C} . Each cell with indices a, C can contain one of three possible values: “1” if $\mathcal{O} \models C(a)$, “0” if $\mathcal{O} \models \neg C(a)$, “?” if $\mathcal{O} \not\models C(a)$ and $\mathcal{O} \not\models \neg C(a)$. Although there are similarities with a transaction table of ARM, our table view is imaginary only and it permits question marks. We will use the table view for better presentation of examples, see Example 1 and Table 1.

Example 1. Given $\mathbb{C} = \{A, B, \exists R.B\}$, $\mathcal{T} = \emptyset$,

$$\begin{aligned} \mathcal{A} = & \{A(a_1), A(a_2), A(a_3), A(a_4), (\neg A)(b), (\neg A)(c), B(c) \\ & R(a_1, b), R(a_2, b), R(a_3, b), R(a_4, c)\}. \end{aligned}$$

We use the projection to evaluate how well a hypothesis fits the *known* data assuming it is correct on the *unknown* data. Indeed, due to the OWA, a hypothesis can make *assumptions* on the unknown data by turning question marks into ones or zeros. If a hypothesis makes too many assumptions, it may be too “strong”, e.g. $H = \{\top \sqsubseteq \Box_{C \in \mathbb{C}} C\}$. Therefore, it is necessary to evaluate how “brave” a hypothesis is.

	A	B	$\exists R.B$
a_1	1	?	?
a_2	1	?	?
a_3	1	?	?
a_4	1	?	1
b	0	?	?
c	0	1	?

Definition 4. (Assumption) An assumption of a hypothesis H in an ontology \mathcal{O} given \mathbb{C} is

Table 1

$$\psi(H, \mathcal{O}, \mathbb{C}) := \{D(a) \mid \mathcal{O} \not\models D(a) \wedge \mathcal{O} \cup H \models D(a) \wedge D \in \mathbb{C}^- \wedge a \in \text{ind}(\mathcal{O})\}.$$

As a consequence, $\psi(H, \mathcal{O}, \mathbb{C}) \cap \pi(\mathcal{O}, \mathbb{C}) = \emptyset$ for any hypothesis H . Requiring $\mathcal{O} \not\models (\neg D)(a)$ in Definition 4 is not necessary because if $\mathcal{O} \models (\neg D)(a)$ then H is not

a hypothesis due its inconsistency with \mathcal{O} . Hypotheses making fewer assumptions are preferred according to Occam’s razor.

One can think of suggesting hypotheses as single axioms. However, this approach ignores interactions between axioms that can influence the quality of the hypothesis. Two axioms, which are logically “good” individually, do not necessarily create a logically “good” hypothesis. For example, a hypothesis can become *redundant*, e.g. $H = \{A \sqsubseteq B, \neg B \sqsubseteq \neg A\}$, see Section 5.2. In fact, a set of two logically “good” axioms is not necessarily a hypothesis. For example, given that $\{A \sqsubseteq B\}$ and $\{B \sqsubseteq C\}$ are hypotheses for \mathcal{O} , a set $\{A \sqsubseteq B, B \sqsubseteq C\}$ is not a hypothesis for \mathcal{O} if $\mathcal{O} \models (A \sqcap \neg C)(a)$. Similar to logical quality, two axioms which are statistically “good” individually may not create a “good” hypothesis.

5 Quality Criteria and Measures for a Hypothesis

5.1 Syntactic Length as a Readability Measure

Readability is the ease with which a hypothesis can be read and understood by a human. One of possible measures of readability is the usual *syntactic length* of a hypothesis.

Definition 5. (*Syntactic Length*) Let A, C, D be (possibly complex) classes, $A \in N_C$ a class name, $R \in N_R$ a property name, $a \in N_I$ an individual name. The syntactic length of a GCI is defined as follows: $|C \sqsubseteq D| := |C| + |D|$, where $|\top| = |\perp| = |A| := 1$, $|\neg C| := 1 + |C|$, $|C \sqcap D| = |C \sqcup D| := 1 + |C| + |D|$, $|\exists R.C| = |\forall R.C| := 1 + |C|$, $|\geq n R.C| = |\leq n R.C| := 1 + n + |C|$. The syntactic length of a hypothesis H is $|H| := \sum_{\alpha \in H} |\alpha|$.

5.2 Logical Quality

Logical quality evaluates logical properties of a hypothesis: *logical strength* and *redundancy*. Logical strength is commonly called generality in machine learning.

Definition 6. (*Logical Strength*) A hypothesis H is weaker (more general) than another hypothesis H' if $H' \models H$ and $H \neq H'$.

A hypothesis can contain axioms which are superfluous, or *redundant*, within the hypothesis, even if those axioms are informative. For example, axiom $A \sqsubseteq C$ is redundant in hypothesis $\{A \sqsubseteq B, B \sqsubseteq C, A \sqsubseteq C\}$ and axiom $\neg B \sqsubseteq \neg A$ is redundant in hypothesis $\{A \sqsubseteq B, \neg B \sqsubseteq \neg A\}$. Axioms can also have *redundant parts*. For example, D is a redundant part of axiom $A \sqsubseteq C \sqcap D$ in hypothesis $\{A \sqsubseteq B \sqcap D, A \sqsubseteq C \sqcap D\}$.

Definition 7. (*Redundancy*) A hypothesis H is redundant if there exists a hypothesis H' such that $H' \equiv H$ and $|H'| < |H|$. Otherwise, H is non-redundant.

Lemma 1. If a hypothesis H is non-redundant, then $|H| = \min\{|H'| \mid H' \equiv H\}$.

We define the logical strength and redundancy of a hypothesis H regardless of \mathcal{O} . The reason is that an axiom $\alpha \in H$, which is informative for \mathcal{O} and non-redundant in H , can be interesting, even if it is not informative for $\mathcal{O} \cup H \setminus \{\alpha\}$. Such axiom reveals yet only implicit (and possibly unknown) relation between classes. Additionally, the search for good hypotheses would require entailment checking $\mathcal{O} \cup H \models H'$ which could make it infeasible for hard ontologies.

5.3 Statistical Quality

Statistical quality criteria are aimed at selecting hypotheses that best represent data given background knowledge. In order to comply with the standard OWL semantics and its OWA, we consider the statistical quality of a hypothesis as two-fold. Firstly, hypotheses fit data and background knowledge differently. Secondly, hypotheses make different number of assumptions in data given background knowledge, i.e. some hypotheses are more cautious than others.

Fitness and Braveness In order to evaluate the statistical quality of a hypothesis, we exploit the idea that axioms can encode regularities in the data. Those regularities can be used to “compress” the data, i.e. to present it in a shorter way. This is the fundamental principle of the *minimum description length induction* [4, 16]. According to it, the better a hypothesis fits the data, the shorter description of the data it provides.

A standard way of measuring the description length is using syntactic measures. However, syntactic measures do not respect logical interactions of a hypothesis with data and background knowledge. Therefore, we introduce a semantic measure of the description length. We define fitness and braveness of a hypothesis as follows.

Definition 8. (*Description Length, Fitness, Braveness*) *The description length of an ABox \mathcal{B} given an ontology $\mathcal{O} = \mathcal{T} \cup \mathcal{A}$ is*

$$\text{minSize}(\mathcal{B}, \mathcal{O}) := \min\{|\mathcal{B}'| \mid \mathcal{B}' \cup \mathcal{O} \equiv \mathcal{B} \cup \mathcal{O}\}.$$

Given an ontology \mathcal{O} , a set \mathbb{C} of classes, and a hypothesis H , let $\pi := \pi(\mathcal{O}, \mathbb{C})$ and $\psi := \psi(H, \mathcal{O}, \mathbb{C})$. Then

- (i) *fitness of H is $\text{fit}(H, \mathcal{O}, \mathbb{C}) := |\pi| - \text{minSize}(\pi, \mathcal{T} \cup H)$,*
- (ii) *braveness of H is $\text{bra}(H, \mathcal{O}, \mathbb{C}) := \text{minSize}(\psi, \mathcal{O})$.*

As a consequence of Definition 8, all semantically equivalent hypotheses have the same fitness and the same braveness which is stated by Lemma 2.

Lemma 2. *Given an ontology \mathcal{O} , a set \mathbb{C} of classes, and two hypotheses H_1, H_2 , if $H_1 \equiv H_2$ then $\text{fit}(H_1, \mathcal{O}, \mathbb{C}) = \text{fit}(H_2, \mathcal{O}, \mathbb{C})$ and $\text{bra}(H_1, \mathcal{O}, \mathbb{C}) = \text{bra}(H_2, \mathcal{O}, \mathbb{C})$.*

Fitness of a hypothesis indicates how well the projection can be shrunk using the hypothesis and background knowledge, i.e. a better shrinkage corresponds to a better fitness. Braveness of a hypothesis measures how many assumptions it makes in the data given the background knowledge.

As a consequence of Definition 8, fitness and braveness are semantically sound and syntax independent measures of the statistical quality of a hypothesis. They take into account both the interaction of a hypothesis with the background knowledge and interactions between axioms within the hypothesis. The measures respect the standard OWL semantics, in particular, they deal with its OWA and, consequently, with incomplete data. Finally, they demand no supervision, such as positive or negative examples, and no additional information besides the input ontology.

6 General Terminology Induction

According to Definition 1, we only consider hypotheses which are logically sound, i.e. informative and consistent with the background knowledge and data. The goal of the induction is finding among those hypotheses ones which have maximal fitness and minimal braveness, or better represent the data.

We impose a readability constraint on a hypothesis: it must not exceed a given syntactic length. The logical weakness of a hypothesis is reflected by its braveness: weaker hypotheses have a lower braveness and are preferred (respecting their fitness) according to Occam’s razor. A redundant hypothesis has the same fitness and braveness as its non-redundant counterpart but a greater length that might be occupied by better axioms. We state the problem of general terminology induction in OWL as follows.

Definition 9. (*General Terminology Induction*) *Given an ontology \mathcal{O} and a set \mathbb{C} of classes, the problem of general terminology induction is to find all best hypotheses which do not exceed length ℓ .*

Thus, as in ILP, we view induction as search in the space of hypotheses restricted by a language bias, determined by \mathbb{C} and ℓ in our case. We regard the process of constructing hypotheses as being equivalent to ranking them in a justified way which is based on fitness and braveness.

7 Implementation and Evaluation

7.1 Implementation

Tools and Hardware All algorithms are implemented in Java 7 using OWL API (3.5.0). We use the OWL 2 DL reasoner FaCT++ (1.6.3) [15] which supports incremental reasoning. The experiments are executed on the following machine: Linux Ubuntu 14.04.2 LTS (64 bit), Intel Core i5-3470 3.20 GHz, 8 GB RAM.

7.2 Evaluation

Evaluation Goals The experiments are aimed at answering the following questions.

- Q1 Where are we likely to find good hypotheses: in more expressive languages for \mathbb{C} or bigger values of ℓ ?
- Q2 How does expressivity of the language and maximal length of a hypothesis influence the performance of computing the fitness and braveness?
- Q3 Can we acquire hypotheses that seem plausible, so that we can use them to enrich our background knowledge, or that tell us interesting information about our data?

Choice of Ontologies We conduct the empirical evaluation on a corpus of ontologies selected from related work [10, 5] including DL-Learner datasets,³ Protégé OWL,⁴ and TONES⁵ repositories. The Kinship ontology is obtained from UCI Machine Learning Repository.⁶ We have selected the ontologies based on the following criteria. Firstly, data contains both class and property assertions, at least 15 individuals. Secondly, ontology classification takes less 10 minutes. Thirdly, we are sufficiently confident that we understand the topic of the ontology. The corpus is available online.⁷

Table 2 describes the corpus where we use the following metrics. $|ind(\mathcal{A})|$, CA , RA are numbers of individuals, concept and property assertions in the ABox, respectively. $degree(\mathcal{A})$, $conn(\mathcal{A})$ are the average degree and average number of individuals in a connected component, respectively. $|\tilde{\mathcal{A}}|$, $|\tilde{\mathcal{T}}|$ are sizes of the ABox and TBox signature. $Jac(\tilde{\mathcal{A}}, \tilde{\mathcal{T}})$ is the Jaccard index⁸ of ABox and TBox signatures, $open(\mathcal{A}, \mathcal{T})$ is the average number of question marks per individual-class name pair.

	DL	$ ind(\mathcal{A}) $	CA	RA	$degree(\mathcal{A})$	$conn(\mathcal{A})$	$ \tilde{\mathcal{A}} $	$ \tilde{\mathcal{T}} $	$Jac(\tilde{\mathcal{A}}, \tilde{\mathcal{T}})$	$open(\mathcal{A}, \mathcal{T})$
Alzheimer	\mathcal{AL}	150	106	854	5.7	150	40	0	0	0.96
Arch	\mathcal{ALC}	19	26	26	1.4	3.8	10	13	0.77	0.53
BasicFamily	\mathcal{ALCI}	31	50	95	3.1	10.3	6	6	1	0.67
Carcinogenesis	$\mathcal{ALC}(\mathcal{D})$	22372	22372	40666	1.8	65.8	113	146	0.77	0.65
Cinema	\mathcal{ALCOF}	45	45	76	1.7	45	7	37	0.19	0.88
Earthrealm	$\mathcal{SHOIN}(\mathcal{D})$	171	179	203	1.2	7.4	23	2482	0.01	0.89
Economy	$\mathcal{ALCH}(\mathcal{D})$	482	649	555	1.2	5.3	29	380	0.04	0.94
Financial	\mathcal{ALCOLF}	17941	17941	47248	2.6	8970.5	52	76	0.68	0.54
GeoSkills	$\mathcal{ALCHOIN}(\mathcal{D})$	2592	4681	3896	1.5	13.9	569	618	0.90	0.69
Heart	$\mathcal{AL}(\mathcal{D})$	280	275	1080	3.9	280	9	11	0.82	0.90
Kinship	\mathcal{ACT}	24	116	40	1.7	12	18	4	0.16	0.81
KRK	\mathcal{SHI}	420	525	1508	3.6	4	25	40	0.55	0.65
Mammographic	$\mathcal{AL}(\mathcal{D})$	975	975	2883	3.0	975	18	22	0.82	0.97
MDM073	$\mathcal{ALCHOF}(\mathcal{D})$	112	130	169	1.5	2.0	82	215	0.38	0.51
Mutagenesis	$\mathcal{AL}(\mathcal{D})$	14145	14145	26533	1.9	61.5	60	91	0.66	0.99
NTN	$\mathcal{SHOIN}(\mathcal{D})$	724	724	1636	2.3	2.8	64	78	0.82	0.96
Suramin	$\mathcal{AL}(\mathcal{D})$	2979	2979	6008	2.0	175.2	20	49	0.41	0.97

Table 2: Ontologies and their metrics

Evaluation Setup To answer the raised questions, we set up the following experimental pipeline. We choose maximal length ℓ from $\{2, 4, 6, 8, 10\}$. In order to generate classes

³ <https://github.com/AKSW/DL-Learner>

⁴ http://protegewiki.stanford.edu/index.php/Protege_Ontology_Library

⁵ <http://owl.cs.manchester.ac.uk/repository/>

⁶ <https://archive.ics.uci.edu/ml/datasets/Kinship>

⁷ http://www.cs.man.ac.uk/~sazonauv/tbox_induction/corpus/

⁸ the size of the intersection divided by the size of the union

\mathbb{C} , we use signature $\Sigma := \widetilde{M}$, where $M = \top\perp\text{-module}(\mathcal{T}, \widetilde{\mathcal{A}})$. We investigate 5 class languages G_i , such that $G_i \subseteq G_{i+1}$ (duplicates are avoided by the means of OWL's structural equivalence):

$$\begin{aligned} G_1 &:= \{X \mid X \in \Sigma\}; \\ G_2 &:= G_1 \cup \{X_M \mid X_M \text{ is a possibly complex subclass in } M\}; \\ G_3 &:= G_2 \cup \{X \sqcap Y \mid X, Y \in \Sigma\}; \\ G_4 &:= G_3 \cup \{\exists R.X \mid X, R \in \Sigma\}; \\ G_5 &:= G_4 \cup \{X \sqcap \exists R.Y \mid X, Y, R \in \Sigma\}. \end{aligned}$$

Given an ontology \mathcal{O} , for each combination of a class language G and maximal length ℓ we run the algorithm (see [14] for details) with 10 minutes timeout. Once the algorithm terminates, we record the fitness and braveness of each hypothesis and the average hypothesis evaluation time which comprises computing its fitness and braveness. Finally, we store up to 100 best hypotheses.

7.3 Results

The dependence of fitness and braveness on language and length is shown on Figure 1. The values obtained are normalised, i.e. divided by the maximal value. Then, the values are aggregated across the corpus and the average value is reported per cell.

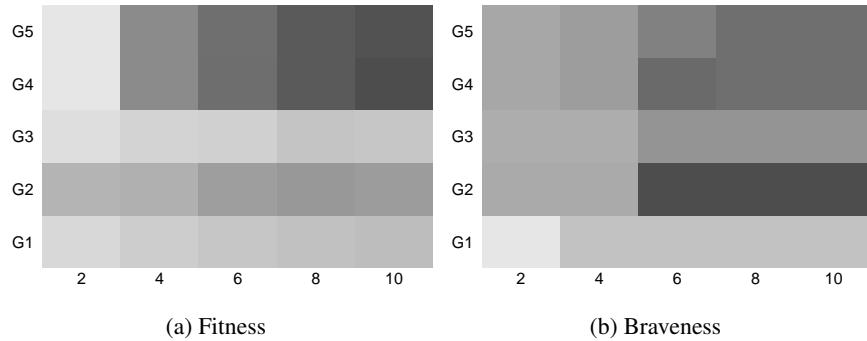


Fig. 1: Dependence of fitness (a) and braveness (b) on language expressivity and maximal length: darker colours reflect greater numbers

Our first observation is that some languages and lengths result in no hypotheses induced which happens if a class language is not expressive enough or hypothesis length is too low. We aggregate and average only over non-empty values. An expected observation is that increasing expressivity is useless if an ontology is poor, e.g. contains few relations in the data and axioms in the background knowledge. On the other hand, if an ontology is rich, increasing expressivity may or may not be fruitful.

Figure 1 shows that increasing length always results in hypotheses of higher fitness and mostly, but not always, of higher braveness since added axioms may make no assumptions or repeat the assumptions already made. Increasing expressivity also generally leads to higher fitness and higher braveness. However, the changes are not as gradual as for length, in particular, braveness seems irregular. Interestingly, we observe

that G_2 consistently outperforms G_3 in fitness, despite $G_2 \sqsubseteq G_3$, which can be explained as follows. On the one hand, the search space considerably increases from G_2 to G_3 . On the other hand, G_3 appears to be less fruitful than G_2 (compare to G_4 and G_5). As a result, it becomes harder to find equally good hypotheses in the same time. Thus, the answer to Q2 is that increasing expressivity and length promises better fitness but commonly worse braveness.

We also observe that the average hypothesis evaluation time does not vary widely. Thus, the answer to Q2 is that performance does not degrade significantly for higher expressivity and length. The performance of evaluating a hypothesis is as follows: less than 0.1 second for 8 ontologies, from 0.1 to 1 second for 4 ontologies, from 1 to 10 seconds for 4 ontologies, and around 15 seconds for 1 ontology. The results can be found online.⁹

Ontology	Examples of hypotheses
Alzheimer	$Drug \sqsubseteq \exists getsReplacedBy.Substituent$ $Substituent \sqsubseteq \exists hasPolatisation.Polar$ $\exists hasPolatisation.Polar \sqsubseteq \exists isHAcceptor.HAcceptor$
Arch	$construction \sqsubseteq \exists hasPillar.pillar$ $\exists hasParallelpipe.wedge \sqsubseteq \exists hasPillar.freeStandingPillar$ $\exists touches.pillar \sqsubseteq \exists leftof.pillar$
BasicFamily	$\exists hasChild.Person \sqsubseteq Person$ $\exists hasParent.Person \sqsubseteq Person$ $\exists hasParent.Female \sqsubseteq \exists hasParent.Male$
Cinema	$Movie \sqsubseteq \exists hasForActor.Actor$ $Movie \sqsubseteq \exists hasGenre.Genre$ $\exists hasForActor.\{Eastwood\} \sqsubseteq \exists hasGenre.\{Western\}$ $\exists hasForDirector.\{Burton\} \sqsubseteq \exists hasForActor.\{Depp\}$
Earthrealm	$\exists hasDefaultUnit.BaseUnit \sqsubseteq \exists hasDefaultUnit.ComplexUnit$ $\exists hasDefaultUnit.\{second\} \sqsubseteq TimeRelatedQuantity$ $\exists hasDefaultUnit.\{meterPerSecond\} \sqsubseteq DrySeasonDuration$
Economy	$Nation \equiv IndependentState$ $\exists economyType.EconomicDevelopmentLevel \sqsubseteq \exists economyType.IMFDevelopmentLevel$
Financial	$Account \sqsubseteq \exists hasStatementIssuanceFrequency.Monthly$ $\exists isOwnerOf.Account \sqsubseteq Client$
Mammographic	$\exists hasMargin.spiculated \sqsubseteq \exists hasShape.irregular$ $\exists hasShape.irregular \sqsubseteq \exists hasDensity.low$
Mutagenesis	$Compound \sqsubseteq \exists hasBond.Bond1$ $\exists inBond.Hydrogen3 \sqsubseteq Bond1$ $\exists inBond.Oxygen40 \sqsubseteq \exists inBond.Nitrogen38$
NTN	$Man \equiv \forall spouseOf.Woman$ $\exists knows.Man \sqsubseteq Man$ $\exists relativeOf.Man \sqsubseteq Man$

Table 3: Examples of hypotheses induced within 10 minutes

In order to answer Q3, we act as domain experts and eyeball the induced hypotheses. We aim at finding plausible and interesting hypotheses. Some results are shown in Table 3. Firstly, we observe that induced hypotheses can, in fact, enrich the background knowledge, see Table 3. If the background knowledge is poor, as in **BasicFamily** and

⁹ http://www.cs.man.ac.uk/~sazonauv/tbox_induction/results/

Cinema, or even absent, as in **Alzheimer**, hypotheses seem to be a good starting point for modellers. If the background knowledge is incomplete, hypotheses appear to be interesting missing bits, e.g. for **Economy**, **Financial**, **NTN**, and **Mutagenesis**.

Secondly, we observe that hypotheses can reveal interesting relations in our data. This can expose new knowledge about the domain and help to understand the data. For example, hypotheses discover relations between particular actors, directors, and movie genres from **Cinema**. Another example is **Mammographic** where we can learn relations between diagnostic observations, e.g. having irregular shape implies having lower density. Such hypotheses can potentially inform doctors of yet unknown relations in their data, facilitate future research in the domain, and lead to data improvements, e.g. a supplement of images of tumours that have irregular shape and high density.

Thirdly, hypotheses can contain “strange” axioms which may help us highlight, on the one hand, odd or erroneous modelling and, on the other hand, inaccurate or abnormal data. We observe this for **Arch** inducing $\exists \text{touches}.\text{pillar} \sqsubseteq \exists \text{leftof}.\text{pillar}$ (why is there nothing to the right?) and for **Earthrealm** inducing $\exists \text{hasDefaultUnit}.\{\text{meterPerSecond}\} \sqsubseteq \text{DrySeasonDuration}$ (wrong unit?). Thus, we can answer Q3 positively.

Although we use different settings and the goal of induction is different, we make some comparison of our results with related work. In particular, we consider the supervised CDL and its implementation DL-Learner [11]. Given a set of positive and negative examples for a target class *construction* in **Arch**, it searches for definition $\text{construction} \equiv \exists \text{hasPillar}.(\text{freeStandingPillar} \sqcap \exists \text{leftof}.\exists \text{supports}.\top)$. As Table 3 shows, our approach induces a weaker definition of *construction* along with some related knowledge. For **Cinema** we observe that descriptions of different movie types are induced, e.g. $\text{EastwoodMovie} \sqsubseteq \exists \text{hasForActor}.\{\text{Eastwood}\}$, $\text{EastwoodMovie} \sqsubseteq \exists \text{hasForGenre}.\{\text{Western}\}$. For **NTN** the definition $\text{Man} \equiv \forall \text{spouseOf}.\text{Woman}$ is induced. Thus, although our approach is unsupervised, it shows the potential to learn class definitions.

8 Discussion and Future Work

The evaluation shows that our approach is able to induce interesting hypotheses. On the one hand, they can potentially be helpful to build and improve the background knowledge. On the other hand, hypotheses seemingly discover new knowledge about the domain and help us understand the data. Interestingly, they may help us identify modelling errors and data flaws.

Although the search space is vast, general terminology induction is feasible. It is encouraging given that statistically and logically sound measures are used to evaluate a hypothesis and this requires reasoning. We observe that larger and more expressive hypotheses are generally better and still feasible.

As for future work, we will investigate more informed ways of constructing a set of promising initial classes, e.g. using techniques from CDL, along with new algorithms and heuristics for search space exploration. We will also attempt to extend the methodology to deal with noisy data that causes inconsistency, e.g. using techniques from [9]. We plan to investigate learning property hierarchies.

We intend to go beyond the corpus and carry out case studies with domain experts to evaluate our approach in more detail. We also consider other scenarios, e.g. how acceptance or rejection of a hypothesis affects other hypotheses, how hypotheses can be used for predicting class memberships of individuals, terminology abduction and “what if” analysis of data under the OWA.

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