A Panoramic Approach to Integrated Evaluation of Ontologies in the Semantic Web

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Abstract. As the sheer volume of new knowledge increases, there is a need to find effective ways to convey and correlate emerging knowledge in machine-readable form. The success of the Semantic Web hinges on the ability to formalize distributed knowledge in terms of a varied set of ontologies. We present Pan-Onto-Eval, a comprehensive approach to evaluating an ontology by considering its structure, semantics, and domain. We provide formal definitions of the individual metrics that constitute Pan-Onto-Eval, and synthesize them into an integrated metric. We illustrate its effectiveness by presenting an example based on multiple ontologies for a University.

Keywords: Ontologies, Semantic Web, Open Evaluation, Ontology Ranking

1 Introduction

An important goal of the Semantic Web [1] is to enable agents to discover knowledge that is distributed across the Web. The distributed knowledge needs to be formalized in the form of ontologies so that relevant subsets may be selected for different purposes. As stated by Sabou et al [2], this necessitates an efficient way to evaluate and rank ontologies. Ontology evaluation is also important for the related problems of ontology discovery, reasoning and modularization [2].

Tartir et al [8] and Sabou et al [2] have compiled various metrics that can be used to evaluate ontologies. Ding et al [3] and Patel et al [4] have proposed evaluation metrics based on a popularity measure that is derived from Google's Page Rank algorithm [5]. A number of semantic search engines like Swoogle [3, 6], OntoKhoj [4] and OntoSelect [7] are based mainly on the popularity measure. Ontology evaluation and ranking can be used for selecting relevant knowledge resources [8] and for determining their quality. Moreover, ontology evaluation can be an efficient basis for comparing several ontologies, as shown in our previous work [9].

Ontology summarization is the extraction of a snapshot of an ontology that contains the most important characteristics of the ontology (concepts and relations that represent the thematic categories of the ontology). Zhang et al [10,11] have introduced ontology summarization for better understanding and improved alignment of similar ontologies. The primary idea underlying their work is the extraction of relevant vocabularies from ontologies based on notions such as RDF[1] sentences and RDF graphs. They have not applied it to the evaluation of ontologies. To our

[1] http://www.w3.org/RDF/

knowledge there has been limited work on the use of ontology summaries for the purpose of ontology evaluation. Another important aspect is with regard to scalability. Current evaluation methodologies are not scalable for a large ontology. An intuitive way to handle this problem might be to modularize ontologies according to usage patterns (Sabou et al [2] and Noy [12]). However, on-the-fly modularization of ontologies based on queries is challenging due to the significant computation cost required for ontology modularization *per se*. This motivated us to use summaries of ontologies as the basis of our evaluation computation instead of dealing with the entire ontology.

In this paper, we propose a novel way of evaluating ontologies based on our ontology summarization technique [13] that focuses on multiple semantic dimensions of ontologies. In view of the extensive diversity of ontologies, we need an integrated approach to ontology evaluation that considers its domain as well as structural and semantic perspectives.

2. Related Work

Several research efforts have tried to classify different methods for evaluating ontologies based on these objectives [14,15]. Some work (Swoogle [3,6], OntoSelect [7] and OntoKhoj [4]) focus on measurement of the authoritativeness of an ontology by utilizing relevant and important cross-references of the ontology and rank them similar to PageRank [5]. However, Alani et al [16] pointed out that cross-references between ontologies might not be always available and hence evaluation based solely on this criterion might fail. Furthermore, even though an ontology might be well connected with several other ontologies, they might cover topics differently and have different semantic implications. Thus, the importance of an ontology cannot be captured simply by calculating its degree of reference.

Structural richness is a measure of the topological aspect (depth and height) of an ontology. Tartir et al [8] have termed it as “inheritance richness.” This criterion measures how the information is distributed over the entire ontology and determines whether the ontology is domain-specific (the depth is greater than the width) or generic (the width is greater than the depth). Another approach is to determine the significance of a particular concept based on the number of super and sub concepts [16-18]. In [16], two very important metrics have been considered: density measure and centrality measure [18]. Density is determined based on the number of super and sub concepts of the given concept. Centrality is a measure of how far a concept is from the root concept in its hierarchy, relative to the length of the longest path from the root to a leaf node containing the concept. It is assumed that concepts in the center of an ontology are the most representative. This kind of evaluation relies largely on the structural aspect of concepts in ontologies.

Relational richness is a measure that captures how a concept is related to other concepts. According to Tartir et al [8], relational richness of an ontology is defined as the ratio of the number of non-IS-A relations to the total number of relations in the ontology. This definition, however, is somewhat simplistic. It is because this approach does not take into account the roles of concept, domain (subject) or range (object), for a given relation. A similar concern for relational richness can be found in Sabou et al [2] where no model has been defined. It takes all relations into account regardless of the fact that there may be more than one concept hierarchy in a single ontology. Thus, it is important that the set of relations pertaining to a hierarchy should be treated separately from those in different hierarchies. Otherwise the thematic differences between these hierarchies cannot be correctly captured; this measure cannot properly reflect the perspective of an ontology. Existing studies are limited in measuring the semantics of relations in an ontology. In our model, we take the roles of the concepts involved in relations into consideration and additional categories of relations for ontology evaluation.

3. Proposed Model – Fundamental Concepts

We now present our ontology evaluation model, called Pan-Onto-Eval that builds on our previous work on ontology summarization [13]. Ontology summarization aims to extract a snapshot of an ontology that contains the most important characteristics of the ontology (concepts and relations that represent the thematic categories of the ontology). Our measurement represents a comprehensive perspective on the following four important issues: a) *Triple Centricity*, b) *Theme Centricity*, c) *Structure Centricity* and d) *Domain Centricity*. We hypothesize that all these features are highly related to each other so that an integrated model can serve efficiently as the basis of evaluation metrics. We elaborate on these fundamental concepts below.

a) *Triple Centricity*: This is the central feature of our model. In an ontology O, the relations (denoted by R) can be either IS-A relations (denoted by R^S) exclusively or non-IS-A relations (denoted by R^N): $R^S \subset R$, $R^N \subset R$ and $R^N \cap R^S = \varphi$. Given any non-IS-A relation, a concept can be either a domain concept (DC) or a range concept (RC) depending upon its role in the relation. A concept associated with a non-IS-A relation can be either a *DC* or a *RC*.

Regarding the triple centric evaluation, we say that an ontology is meaningful when there are many diverse relationships, i.e., domain concepts associated with other concepts through diverse relations. Hence we analyze their roles with relations (i.e. whether they are domain or range concepts) and their importance (the measurement of concept importance) described in our work on ontology summarization [13]. Furthermore, we analyze how the range concepts are associated within these domains as the range concepts play an important role, i.e., the information source, to the domain concepts. In this way, we evaluate an ontology from a triple centric perspective that is distinct from other works [8, 16-18].

b) *Theme Centricity:* This refers to the classification of non-IS-A relations in an ontology. This is a measure that efficiently reflects the importance of non-ISA relations in the evaluation of any ontology in terms of relational richness. Tartir et al [8] stated “An ontology that contains many relations other than class-subclass relations is richer than a taxonomy with only class-subclass relationships”. Sabou et al [2] considered relations as a primary criterion for the summary extraction of ontologies. However, they concentrated on a quantitative aspect such as the percentage of non-IS-A vs. IS-A relations [8] and did not take into account how these non-IS-A relations are distributed over an ontology.

In our work, seven broad thematic categories for classification of non-IS-A relations inspired by UMLS [19] have been defined as follows: Compositional, Attributive, Spatial, Functional, Temporal, Comparative and Conceptual. It is evident from the justification provided for the triple centric approach that the relations between domain and range concepts carry different semantic ‘senses’. This classification thus provides for better understanding of the thematic categories of the ontology so that it may facilitate effective ontology evaluation and querying. This is because it allows one to map relations existing in query triples to those contained in the ontology.

c) ***Structure Centricity***: This measure describes the topology (i.e., shape and size) of concept hierarchies of an ontology. Consider two topologies [8, 9]: The top-shaped hierarchy has a characteristic such that the breadth of class hierarchies decreases as the depth increases. This ontology is more generalized in its thematic category. On the other hand, the pyramidal hierarchy has a characteristic such that the breadth of class hierarchies increases as the depth increases. They are more domain-specific. However, in reality, ontologies have more irregular shape in terms of the breadth-depth ratio. Previous works [8, 9]only consider the average number of sub-classes of a given hierarchy. Thus, this measure would not be appropriate for evaluating diverse structural aspects of ontology. From a structural perspective, we may want to analyze the distribution of non-IS-A relations. If a relation appears at a high level, it might be too abstract. Otherwise, it might be too specific.

d) ***Domain Centricity***: An ontology may consist of more than one IS-A hierarchy. Each of these hierarchies might suggest that their *thematic category* (or semantic implication) is different. In other words, each hierarchy contributes differently to the semantics of the ontology as a whole. Each hierarchy consists of some domain concepts typed under their own root; the specific perspective of these hierarchies may be characterized by their relations and range concepts. That is why we analyze the semantic richness of a hierarchy based on the comprehensiveness criterion (in Section 4) and incorporate the measure into an ontology evaluation score. We assume that this approach is more appropriate than taking the ontology as a whole because it considers the semantics and distribution of information across the ontology.

4. Pan-Onto-Eval Metrics

We now formalize our ontology evaluation metrics of the Pan-Onto-Eval. The evaluation metric is defined by considering the following five qualitative aspects of ontology: (1) *Information content*, (2) *Relational Richness* (3) *Inheritance Richness*, (4) *Dimensional Richness*, and (5) *Domain Importance*. In the Pan-Onto-Eval, for a given ontology, we independently analyze each hierarchy that exists under the root of the ontology independently and combine information from multiple hierarchies into information representing the ontology as a whole.

We define the parameters that will be used in the formula:

M: Number of range concepts in H

Mi: Number of selected range concepts with the thematic category i in the summary

N: Number of domain concepts in H
Ni: Number of selected domain concepts in the thematic category i in the summery
Q: Number of the thematic categories of relations in H
Q': Total number of thematic categories (in our model it is seven)
R: Number of non-IS-A relations in H
R_t(RC): number of relations classified under the thematic category t for a range concept RC
R(i): Number of relations selected in the thematic category i in the summary.
R(DC): Number of relations associated with the domain concept DC
S(DC_i) Number of direct sub-concept (children) under the domain concept DC_i in H
α: Normalization function (a sigmoid function is used in the analysis)
K: number of hierarchies in the ontology

1) ***Information Content (IC)*** measures how well information involving relations *R* is distributed over an IS-A hierarchy *H* in an Ontology *O*. Our hypothesis with regard to *IC* is that a well spread distribution of important relations with respect to domain concepts *DC* in *H* indicates richness of information. For this purpose, we borrow the basic formula for information entropy[20] to determine degree of information content of ontologies. We measure the number of relations in terms of the number of range concepts RC that are associated with the hierarchy *H*.

Information Addition (IA) measures how important a Range Concept (RC) is as compared to other *RCs* associated with a hierarchy. This can be represented as the ratio of the number of observed relations associated with a thematically categorized *RC* to the maximum number of possible relations of the *RC*. The maximum number of possible relations of a *RC* is defined using the pigeon hole principle[2] as follows:

$$IA(RC) = \frac{\sum_{t=1}^{Q} R_t(RC)}{R - M + 1} \tag{1}$$

Entropy of the Hierarchy E(H) is the amount of uncertainty associated with the relational association of the *RC* to the hierarchy *H*. In other words, the overall uncertainty of associated *RCs* can be measured as below.

$$E(H) = -\sum_{i=1}^{M} IA(RC_i) \bullet \log_2 IA(RC_i) \tag{2}$$

We now formally define *Information Content* (*IC)* of an IS-A hierarchy *H* as:

$$IC(H) = R \bullet \alpha \bullet \frac{1}{E(H)} \tag{3}$$

A high value for *IC* implies that the information content of the hierarchy *H* in an ontology is rich due to rich relationships defined in *H*.

2) ***Relational Richness (RR)***: This metric measures the degree of important relations in a particular hierarchy of an ontology. We define *RR* for the hierarchy *H* as follows:

[2] http://zimmer.csufresno.edu/~larryc/proofs/proofs.pigeonhole.html

$$RR(H) = \frac{1}{Q} \bullet \sum_{t=1}^{Q} R(t) \tag{4}$$

This metric equation captures the important relations associated with the range concepts that are scanned while generating the summary.

3) *Inheritance Richness (IR)* captures whether the hierarchical (IS-A) relations are rich both structurally as well as in their information content. This is important because a concept may have a rich set of sub-concepts but without carrying much information *per se*. Such cases have been ignored in the metric definition of previous works [8]. We define *IR* of a particular hierarchy *H* as:

$$IR(H) = \frac{1}{N} \sum_{i=1}^{N} S(DG) \bullet R(DG) \tag{5}$$

4) *Dimensional Richness (DR)* measures the richness of the thematic categories of relations in a hierarchy of an ontology. This shows the different ways that an ontology hierarchy can satisfy queries based on their summary content. We formally define *DR* of an IS-A hierarchy *H* as:

$$DR(H) = \frac{Q}{Q'} \sum_{i=1}^{Q} N_i \bullet M_i \tag{6}$$

The first factor of Equation 6 indicates the relative coverage of thematic categories for an ontology. The second factor indicates the richness of all of these categories in terms of the number of important (selected) range concepts and their domain concepts. If the value of *DR* is high then it suggests that the corresponding ontology carries a rich semantic dimensionality with a very high ratio of the identified categories versus the total number of defined categories. It also indicates either a very high density of selected range concepts and/or a very high density of corresponding domain concepts in the ontology summary. This means that the ontology is rich in certain thematic categories and queries based on those categories can be best served.

5) Domain Importance (DMI): This metric provides an insight to the richness of the core domain(s) of interest that a particular hierarchy H_k contains when compared to other hierarchies of the same ontology. This metric is basically a compound metric of the previous three metrics. We define *Domain Factor* (*DMF*) and *Domain Importance* (*DMI*) as follows:

$$DMF(H_k) = IC(H_k) + IR(H_k) + DR(H_k) + RR(H_k) \tag{7}$$

$$DMI(H_k) = \frac{DMF(H_k)}{\underset{i=1}{\overset{k}{MAX}}(DMF(H_i))} \tag{8}$$

If *DMI* is closer to the maximum possible value, this means that the domain represented by this hierarchy is important compared to other hierarchies.

Ontology Evaluation Score (ρ): For a given ontology *O*, we analyze the richness of each hierarchy within *O* separately and according to respective criteria. We can now combine them together into a single model that can effectively evaluate ontologies. In order to combine the individual analysis of hierarchies, we compute it as the product of the average of *DMI* and the maximum *DMF* (the best one). We formalize the ontology evaluation score (denoted by ρ) as follows:

$$\rho(o) = \underset{i=1}{\overset{k}{MAX}}(DMF(H_i)) \bullet \frac{1}{K} \bullet \sum_{i=1}^{K} DMI(H_i) \qquad \textbf{(9)}$$

5. Experimental Results

We analyze three related university ontologies (O_1[3] O_2[4], O_3[5]) and evaluate them according to the proposed model. As preprocessing, we convert the DAML files to OWL using a converting tool[6] and generate summaries. The application is implemented using the Protégé OWL 3.3 beta API on a Windows machine. Table 1 shows the analysis of ontology University-I. We analyze the 9 hierarchies among 11 (denoted as H_i) in the ontology excluding two hierarchies (they have single concept with no relation). Hierarchy H_6 has the highest number of associated non-IS-A relations (12) and the highest number of range concepts (9) while H_5 has the maximum number of domain concepts (5) and the maximum levels.

It is interesting to note that although H_6 and H_7 are structurally and relationally rich than the others yet they have a low *Information Content* (IC). This is because the relations are not distributed evenly throughout the hierarchy and most of the domain-concepts in the hierarchy are weakly associated with range concepts in terms of information distribution. Hierarchy H_5 has the highest *Domain Importance* (DMI) value and thus is considered the best hierarchy of this ontology. This accounts for the high *Inheritance Richness* (IR) score and *Dimensional Richness* (DR) score as compared to other hierarchies and hence shows how important it is to have high-weight relations associated with the concepts (and sub-concepts) of a hierarchy. The contributing factor is the dimensional variety of the summary which reflects the rich categorical coverage of the hierarchy as a whole. This hierarchy is rooted at the domain-concept '*Document*' and covers the *attributive*, *functional* and *temporal* aspects evenly. The next best hierarchy is H_7 rooted at the concept '*Organization*' with the majority of relations falling under the categories *conceptual* and *attributive*. Close to this hierarchy is H_6 rooted at '*Organism*'. The rest of the hierarchies have pretty low *DMI* values. The evaluation score of the University-I (ρ) is 6.109.

Analyzing Table 2 indicates that the University–II ontology is an instantiation of the University-I. It is interesting to see that the new hierarchy (having a single concept

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[3] http://www.ksl.stanford.edu/projects/DAML/ksl-daml-desc.daml
[4] http://www.ksl.stanford.edu/projects/DAML/ksl-daml-instances.daml
[5] http://www.cs.umd.edu/projects/plus/DAML/onts/univ1.0.daml
[6] http://www.mindswap.org/2002/owl.shtml

‘Chimaera-Export-Enable’) adds no richness to the ontology. An important observation is that the best hierarchy in this ontology is H_6 as compared to its parent ontology where the best hierarchy is H_5. This is because of the partial use of the University-I ontology. This leads to a lowering of the *DR* value and the *RR* value of H_5. The evaluation score of the ontology (ρ) is 3.909.

Table 1. Evaluation of University – I

	H_1	H_2	H_3	H_4	H_5	H_6	H_7	H_8	H_9
Number of relations (R)	2	1	3	3	4	12	11	1	3
Number of range concepts (M)	2	1	3	3	4	9	7	1	3
Number of Domain concepts (N)	1	1	1	1	5	4	2	1	1
Information content (IC)	2	1	3	3	4	3	3.52	1	3
Inheritance richness (IR)	0	0	0	0	4	3	1	0	0
Dimensional richness (DR)	0.57	0.14	1.28	1.28	1.7	1.4	3.4	0.14	0.57
Relational richness (RR)	1	1	1	1	1.33	2.4	2.75	1	1.5
Domain factor (DMF)	2.57	2.14	3.28	3.28	8.03	7.05	7.15	2.14	3.07
Domain importance (DMI)	0.29	0.27	0.38	0.38	1	0.87	0.89	0.27	0.37

Table 2. Evaluation of University - II

	H_1	H_2	H_3	H_4	H_5	H_6	H_7	H_8
Number of relations (R)	0	1	3	0	2	6	5	2
Number of range concepts (M)	0	1	3	0	2	6	3	2
Number of Domain concepts (N)	1	1	1	1	5	4	2	1
Information content (IC)	0	1	3	0	2	6	2.9	2
Inheritance richness (IR)	0	0	0	0	0	0	0	0
Dimensional richness (DR)	0	0.14	1.28	0	0.57	1.71	2.85	0.57
Relational richness (RR)	0	1	1	0	1	2	1.25	1
Domain factor (DMF)	0	2.14	3.28	0	2.57	4.71	4.68	2.57
Domain importance (DMI)	0	0.454	0.696	0	0.546	1	0.99	0.546

Table 3. Evaluation of University - III

	H_1	H_2	H_3	H_4	H_5	H_6	H_7
Number of relations (R)	1	3	1	6	2	0	0
Number of range concepts (M)	1	2	1	4	2	0	0
Number of Domain concepts (N)	1	16	2	4	7	2	3
Information content (IC)	1	1.95	1	3.3	2	0	0
Inheritance richness (IR)	0	7	0	8	0	0	0
Dimensional richness (DR)	0.14	0.57	0.14	1.28	0.57	0	0
Relational richness (RR)	1	1	1	1	1	0	0
Domain factor (DMF)	2.14	9.22	2.14	10.83	2.57	0	0
Domain importance (DMI)	0.198	0.851	0.198	1	0.237	0	0

The third ontology, University-III, has been analyzed in Table 3. This ontology is different semantically from the previous two ontologies although there are common concepts among them. This is because the associated relations (and hence the semantic categories) are quite different. H_4 is rooted at ‘*Person*’ and has 4 *DCs*, 4 *RCs* and 6 Relations. Incidentally, this hierarchy is structurally the best among the seven hierarchies of the ontology. If we compare H_4 with H_2 (rooted at '*Employee*') we will see the number of *RCs* and relations in H_2 are smaller compared to H_4. Although the number of *DCs* in H_2 is 16 (four times that of H_4) yet the *IR* value (7) is lower than that of H_4 (8). This is because most of the inheritances in H_2 are void relationally (3 Relations and 2 *RCs*). This means they have no semantic importance although they are very rich structurally. The second best structurally rich hierarchy is H_5 (7 *DCs*). But this hierarchy has low *DMI* due to low dimensional richness, in spite of *IC* being high. The other important factor for such a low *DMI* is that the relations are associated with the leaf concepts of the hierarchy and hence the *IR* value is 0 (compared to 8 of H_4 and 7 of H_5). The evaluation score of the University-III (ρ) is 4.567.

We give a comparative analysis of these three ontologies in Figure 1 showing the break-up of the average contribution of each of the metrics for the final evaluation score.

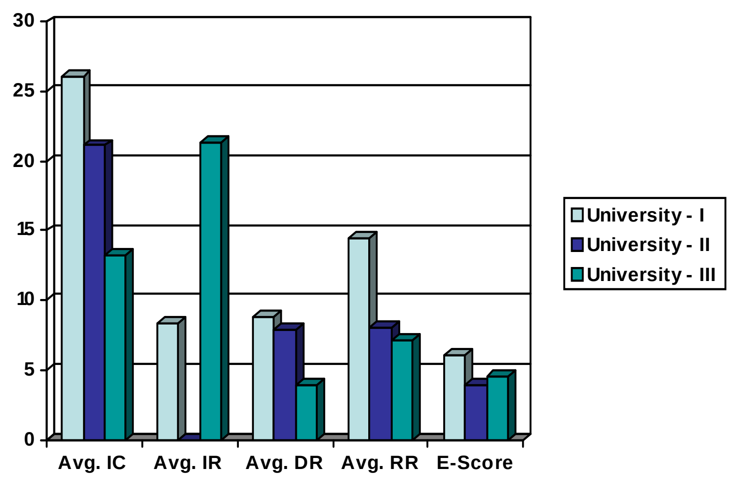

Fig. 1. Comparison of the three ontologies (IC, IR, DR, RR are scaled by factor 10)

7. Conclusion

This paper has presented Pan-Onto-Eval, a comprehensive approach to evaluating an ontology by considering various aspects like structure, semantics, and domain. The main contribution of this paper is a formal treatment of the model for an automated and integrated evaluation of ontologies. The experimental results of the university ontologies demonstrate the essence and benefits of the proposed model. This work is limited by a lack of rigorous evaluation by experts. The summarization technique that is an important basis could have been fully explored and the thematic categories may further be expanded for real world applications. Overall, the model has great potential on evaluation and selection of distributed knowledge in the Semantic Web.

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