IS THE SEMANTIC WEB A SMALL WORLD?

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ABSTRACT

In this paper, we describe a structural analysis of social networks on the Semantic Web. We performed a comprehensive analysis of graph-theoretical properties of online social networks based on the Friend-of-a-Friend (FOAF) ontology. Of particular interest were properties related to the small-world phenomenon. More than 1.6 million FOAF documents collected on the Semantic Web were analyzed in depth. Most of the FOAF documents have been created and published by social networking services, blog hosting services, or combinations of the two; only a fractional amount are maintained by individuals. We identified the largest strongly connected components of various community networks and analyzed them in regard to the small-world phenomenon. Interestingly, all components examined exhibited a characteristic path length comparable to the smallest length achievable for a graph of the respective size, and the clustering coefficient was much greater than expected for an equivalent random graph; along with power law degree distributions, both are typical features of small-world graphs.

KEYWORDS

Semantic Web, FOAF, Small Worlds, Social Networks, Graph Theory

1. INTRODUCTION

A social networking service focuses on the creation and verification of online social networks for a specific purpose. Many social networking services are also blog hosting services. As of today, there are more than 300 known social networking services on the Web; MySpace and Friendster are common examples. By the end of 2005, MySpace was receiving more page views than Google. In general, these services allow users to create profiles and perform tasks such as uploading pictures and linking profiles. Social networks connect people with similar interests and expand in private and corporate environments rapidly. Also businesses are starting to use social networks as a means to connect employees. One example is LinkedIn, which connects businesses by industry, function, geography, and area of interest. Networks are particularly beneficial for entrepreneurs and small businesses attempting to expand their contact base. Online social networks make it easier to keep in touch with contacts around the world.

Despite many advances, seamless interoperability between social networking services has remained a utopian dream. There have been attempts to standardize such services through the Semantic Web application Friend-of-a-Friend (FOAF), but this has led to privacy concerns among other issues. FOAF provides information about individuals, groups, companies, and other online resources in a machine-processable format. Information published in the Semantic Web uses terms denoting classes and properties drawn from ontologies, which are documents that declare sets of terms with unique URLs defined by logical relationships and constraints [1, 2].

Currently, the main problem with FOAF is that it does not support progressive disclosure, which is typically used to handle private information. In progressive disclosure, individuals disclose a little information about themselves at a time; as trust builds, they offer more information. FOAF can obscure e-mail addresses so that they cannot be harvested by spammers, but all other information is completely public.

The use of FOAF profiles represents a way to easily exchange information between various social networking services. Some blog hosting services such as LiveJournal and Typepad as well as social networking services like Ecademy and TribeNet support FOAF. At the moment, most of them publish profiles using the FOAF vocabulary on the Semantic Web. This vocabulary has the potential to become an important tool for community management, though. In addition to providing simple directory services, information from FOAF documents could be used to prioritize e-mail from trusted colleagues, provide assistance for new community members, and locate individuals with specific interests or skills.

As online communities evolve, the question arises as to how online social networks are similar to traditional networks. For instance, it is a common theory that any two people, selected randomly, can be connected by a few intermediate acquaintances. Research specific to this so-called small-world phenomenon did not commence until the 1960s, with the formulation and initial mathematical investigation of the problem by Pool and Kochen [3]. The phenomenon was made popular by a famous experiment of Milgram [4] which found that two random US citizens where on average connected by only six acquaintances. In our study, we focus on the structural examination of social networks on the Semantic Web, i.e. online communities based on the FOAF standard, with respect to properties commonly associated with the small-world phenomenon. Watts defines small-world networks in [5] as the coincidence of high local clustering and short global separation. Also typical for small-world graphs is an overabundance of hubs, as noted by Barabási [6]. Hubs are nodes with a relatively high number of connections.

In section 2, we describe the graph-theoretical background of the small-world phenomenon that constitutes the foundation for our analysis. The basics of the FOAF project are introduced briefly in section 3, and the actual design of the experiment is outlined in section 4. In section 5, the results are illustrated. We conclude with a summary of major findings in section 6.

2. THE SMALL-WORLD PHENOMENON

The fascination with the small-world phenomenon in view of social systems is partly motivated by the fact that those systems are constructed in a fashion quite unlike that of physical systems. Social systems seem to violate the transitivity of distances. In physical systems, all lengths between points are related to each other by the triangle inequality. The triangle inequality states that if three points are anywhere in the same space, then they can be connected via the three sides of a triangle; the length of those sides must obey the inequality $d(A,C) \leq d(A,B) + d(B,C)$. It seems that this need not to be true in social systems, since it is possible that person A is well-acquainted with both person *B* and person *C*, while persons *B* and *C* are not even remotely familiar with each other. This feature of interpersonal relationships has much to do with the fact that randomly selected individuals are often more closely related than they might assume.

To clarify our discussion of the small-world phenomenon, we borrow some definitions from graph theory. The networks considered within the scope of this work are represented as strongly connected graphs consisting solely of undifferentiated vertices and unweighted links. As opposed to Watts [7], our links are considered to be directed. Subsequently, directed graphs, characteristic path lengths, and clustering coefficients are defined.

As described by Bang-Jensen and Gutin [8], a directed graph *G* consists of a nonempty set of elements, called vertices, and a list of ordered pairs of these elements, called arcs. The set of vertices of graph *G* is called the vertex set of *G*, denoted by $V(G)$, and the list of arcs is called the arc list of *G,* denoted by $E(G)$. If *v* and *w* are vertices of *G*, then an arc of the form *vw* is said to connect *v* and *w*. In a strongly connected directed graph, it is possible to reach any node starting from any other node by traversing arcs. We consider the maximal strongly connected sub-graphs of social networks for our examinations.

The clustering coefficient γ for vertex v is defined as the fraction of possible arcs in the neighborhood Γ_v of v that are present. The neighborhood of v is the sub-graph that consists of the vertices adjacent to v but not v itself. The clustering coefficient is a measure for the cliquishness of a friendship network. The characteristic path length $L(G)$ is a measure of the mean distance between vertices in a graph. It is defined as the median of the means of the shortest path lengths connecting each vertex $v \in V(G)$ to all other vertices. In contrast to Watts, we consider the analyzed graphs as directed due to the fact that friendships are asymmetric.

A small-world graph is defined as having n vertices with average degree k that exhibits $L \approx L_{random}$, but $\gamma \gg \gamma_{random} \approx k / n$. Determining whether or not a given graph is a small-world graph is possible without knowing its construction or requiring it to be part of a family of graphs. By virtue of this definition, small-world graphs will inevitably have a high representation of cliques, and sub-graphs that are a few arcs shy of being cliques. Cliques are sub-graphs characterized by the presence of connections between any two vertices within them. Furthermore, most pairs of nodes will be connected by at least one short path; this follows from the requirement of short path length.

There are several properties that are commonly associated with small-world networks, although not required for their classification. Typically, there is an overabundance of hubs, which are nodes in the network with a relatively high number of connections. These hubs serve as common connections mediating the short path lengths between other arcs. This property is often analyzed by considering the fraction of nodes in the network with a particular number of connections. Networks with a greater-than-expected number of hubs will have a greater fraction of nodes with high degrees; consequently, the degree distribution will be enriched at high degree values. Specifically, if a network has a degree distribution that fits with a power law distribution, then the network is a small-world graph. In comparison, exponential distributions are characteristic of random networks.

3. The Friend-of-a-Friend Project

The Friend-of-a-Friend (FOAF) project is a community-driven effort to define the necessary RDF vocabulary for expressing the respective metadata. The FOAF ontology depends heavily on W3C standards, specifically XML, XML namespaces, RDF, and OWL. All FOAF documents are well-formed RDF/XML documents. Since FOAF documents adopt the conventions of RDF, object-oriented data structures are represented by listings of typed objects and properties. An FOAF document can be combined with other FOAF documents to create a unified database of information. The specific contents of the FOAF vocabulary are detailed in the FOAF namespace document (available online at *http://xmlns.com/foaf/0.1*). The empirical use of properties in FOAF documents is described by Ding et al. [9], who also call FOAF the second-best populated ontology. The current FOAF literature [10, 11, 12] provides various models of how FOAF documents might be used to support Web-based information systems under the assumption that FOAF documents are widely available. The FOAF project has the potential to drive many new interesting developments in online communities. García-Barriocanal and Sicilia, for instance, present a promising approach using knowledge about social ties for information filtering [13].

4. Experimental Design

This section outlines the experimental design. Section 4.1 presents the infrastructure used for the computations; document identification and discovery is described in section 4.2. In section 4.3, we illustrate the retrieval and fusion of personal information; in section 4.4, the component selection is outlined.

4.1. Infrastructure

A SGI Altix 350 server was used for the sophisticated computations performed. With 740 GFlops/s and 128 GB of shared memory, this system was suitable for the required memory-, CPU-, and I/O-intensive tasks. The system has 32 processors, operating under the control of an LSF batch system. Program performance depends on a good CPU-placement of the programs. Based on the number of CPUs required, the LSF selects the optimal set of CPUs to execute each program with utmost efficiency. This high-performance server built by SGI is maintained at the central information technology service (ZID) of the University of Innsbruck.

4.2. Data Collection

Since an FOAF document does not have a defined fixed structure, we had to develop criteria for determining valid FOAF documents. To this end, the characteristic patterns implied by the ontological semantics and the empirical usage of the FOAF vocabulary were analyzed. We defined FOAF document *D* with the following characteristic patterns: (1) *D* is a valid RDF document that strictly conforms to the W3C recommendations; and (2) *D* defines exactly one instance of *foaf:Person* without referencing it as object of an *foaf:knows* property within *D*. However, *D* may include multiple instances of *foaf:Person* in general. These characteristics are similar to those used in [10]. As opposed to Ding et al., we did not claim explicitly that *D* must use the FOAF namespace. We considered only RDF/XML encoded documents for this analysis.

Based on the above patterns, the conventional Web search engine Google and a semantic crawler were used to discover FOAF documents. The FOAF document discovery was an iterative process consisting of two steps: (1) using Google to discover potential URLs of FOAF documents; and (2) running the semantic crawler to validate and extract new links according to FOAF vocabulary semantics. Through Google, we queried documents containing the string “foaf” and having one of the generally used suffices for RDF documents. Although such suffices are neither sufficient nor necessary for classifying RDF documents, we obtained a significant number of RDF documents with high precision using this approach.

Table 1. Identified communities and valid FOAF documents.

Community	Documents
LiveJournal	976,773
GreatestJournal	398,278
TribeNet	196,455
DeadJournal	39,623
Opera	10,797
Nifty	5,612
Dotnode	3,793
InsaneJournal	3,207
Dion	2,991
Boards (Ireland)	2,905
Elgg	1,930
Typepad	1,880
DeadJournal (Limbo)	1,831
Livedoor	1,240
Blogware	1,057

Community	Documents
OCN	992
Pub	954
Ecademy	873
Boards (Japan)	535
Moblog	357
Mindswap	224
Blogs	210
Blogzine	185
Seesaa	168
Hatena	132
Noblog	91
Deblog	86
Wablog	48
Blogemploi	17
Ublog	10

We used Google’s SOAP-based API to automatically search for FOAF documents with query strings such as “filetype:rdf foaf” and FOAF documents from specific hosts or domains with strings such as “site:www.blogware.com filetype:rdf foaf.” Google’s capability to search for documents having specific file types was useful. However, due to performance reasons Google returns only a small portion of the documents that it has discovered. The API allows 1,000 queries per day and authentication key. With one API-based query, Google provides at most 10 URLs, but it is possible to set the index of the first result to be returned and thus obtain the first 1,000 documents. It would have been possible to discover additional URLs by further specifying the query strings.

The semantics of the FOAF ontology indicate that instances of *foaf:Person* are linked by *foaf:knows* properties. URLs of documents further describing linked *foaf:Person* instances are then indicated by means of *rdfs:seeAlso* properties. These URLs generally refer to other FOAF documents. This idea was reflected in the semantic crawler. Using the documents found with conventional search engines as starting points for the crawler, which took advantage of the semantics of the FOAF vocabulary, nearly 4.5 million FOAF documents were discovered. The online communities are shown in Table 1 along with the number of valid documents. In addition, 2,897 valid FOAF documents were found that did not belong to any of the listed communities. Document discovery was performed in the last quarter of 2006.

4.3. Information Retrieval

Although the FOAF ontology defines unique identifiers for persons in theory, retrieval and particularly fusion of personal information is difficult and error-prone in practice. Aside from the *foaf:knows* property, the most important properties of *foaf:Person* are those used to identify unique individuals, including *foaf:mbox*, *foaf:mbox_sha1sum*, *foaf:homepage*, *foaf:weblog*, *foaf:icqChatID*, *foaf:msnChatID*, *foaf:aimChatID*, *foaf:jabberID*, and *foaf:yahooChatID*. The Semantic Web is based on the principle of partial description. Since FOAF is based on the Semantic Web language RDF, each person is allowed to assert information about others, whether they are friends, acquaintances, or strangers. Hence, FOAF documents rarely describe the entire picture. Identification properties (defined as inverse functional in the FOAF specification) form the basis for the integration of multiple sources found on the Semantic Web describing the same individual. Table 2 shows the use of identification properties in our sample.

Table 2. Use of identification properties.

Property	Use
foaf:weblog	1,466,497
foaf:mbox or foaf:mobx_sha1sum	485,183
foaf:homepage	308,200
foaf:aimChatID	85,245
foaf:yahooChatID	35,679
foaf:msnChatID	30,268
foaf:icqChatID	15,182
foaf:jabberID	2,284

In FOAF documents both, the *foaf:mbox* and the *foaf:mbox_sha1sum* properties refer to personal mailboxes. These properties are defined to be inverse functional in the sense that there is at most one individual who has any particular value for them. The value of the *foaf:mbox_sha1sum* property is a textual representation of the result of applying the SHA1 mathematical function to a mailbox identifier. Only the results of applying the function are stored in our database. If the *foaf:mbox* property was used in an FOAF document, we computed the SHA1 before storing the value. The FOAF specification allows for an individual to have multiple homepages and weblogs but constrains the *foaf:homepage* and *foaf:weblog* properties so that there can be only one particular value for them, i.e. individuals never share a homepage or a weblog. The *foaf:icqChatID*, *foaf:msnChatID*, *foaf:aimChatID*, *foaf:jabberID*, and *foaf:yahooChatID* properties relate instances of *foaf:Person* to an assigned textual identifier in the respective messaging system. Thus, these properties must also be inverse functional.

One of the principles of the Semantic Web is that individuals can express their opinion about any resource. For example, in an FOAF document D_1, assertions can be made about individuals introduced in a document D_2. For that reason, information can be retrieved from a collection of FOAF documents about individuals even if they have not published their own FOAF document. When a person is described in more than one FOAF document, we must fuse personal information from multiple sources. The process of generating aggregated information is called *smushing* and relies on the correct use of identification properties in the case of FOAF.

Table 3. Community members and connections after smushing.

Community	Standard Nodes	Local Sources	Local Sinks	Isolated Nodes	Internal Links	In-Links	Out-Links
TribeNet	189,567	2,233	2,069	2,211	2,351,290	4,336	4,266
GreatestJournal	105,139	7,286	40,466	49,994	554,574	2,345	2,464
LiveJournal	48,955	3,602	811,155	102,269	3,284,343	16,532	1,670
DeadJournal	26,398	2,465	48,976	10,278	199,667	8,513	3,474
Opera	6,581	203	3,998	318	41,387	129	139
Dotnode	3,538	23	296	127	14,172	474	535
Boards (Ireland)	1,545	38	1,166	103	7,759	206	133
Elgg	1,490	61	169	3	9,048	199	97
InsaneJournal	934	33	201	220	2,972	28	38
Boards (Japan)	337	1	154	12	2,091	18	41
Dion	225	93	221	498	797	698	480
Nifty	179	675	2,495	3,438	4,183	403	447
Typepad	185	510	2,315	1,112	4,525	485	690
DJ (Limbo)	160	77	87	1,237	309	2,638	5,658
OCN	14	143	306	999	420	395	505
Blogs	8	33	59	285	76	324	288
Blogemploi	2	4	23	10	32	3	1
Blogzine	0	35	64	303	67	278	270
Livedoor	0	25	51	1,439	62	248	44
Moblog	0	13	19	410	20	132	177
Noblog	0	9	13	153	13	131	97
Deblog	0	8	9	136	9	108	120
Ublog	0	1	1	11	1	0	0
Hatena	0	0	0	174	0	118	0
Seesaa	0	0	0	38	0	30	0
Ecademy	0	0	0	705	0	8	0
Blogware	0	0	0	432	0	8	0
Wablog	0	0	0	50	0	3	0
Mindswap	0	0	0	177	0	2	0
Pub	0	0	0	176	0	0	0

Instances of *foaf:Person* were smushed if (1) they had at least one matching identification property and (2) there was only one possibility for fusion. If a fusion attempt was ambiguous, then the involved nodes were marked and not considered for further investigation. Personal information from multiple FOAF documents was aggregated with caution, since some of the facts were incorrect and others contained contradictions. Errors in FOAF documents could have a significant impact on the results of the analysis. No single value of an inverse functional property occurs more than once in the sets of nodes considered. The numbers and types of community members after smushing are shown in Table 3 along with the number of links within a community and the number of in- and out-links for each community. The high number of local sinks and local sources as well as isolated nodes explains the low probability of two community members being linked. The relation of in- and out-links and the number of nodes indicates that the interconnection between communities is also low. However, we will show that this does not negatively affect the small-world properties of the entire FOAF network.

4.4. Component Selection

As previously mentioned, a directed graph is strongly connected if, for every pair of vertices *u* and *v*, there is a path from *u* to *v* and a path from *v* to *u*. The strongly connected components (SCC) of a directed graph are its maximal strongly connected sub-graphs. The vertices in a SCC must all have an out-degree and an in-degree of at least one. The two standard methods for detecting SCCs are Tarjan's algorithm [14] and the double search algorithm attributed to Kosaraju. Tarjan's algorithm was implemented to find the largest SCCs of the entire FOAF network and the community networks.

Table 4. Metrics, average degree, and maximal degree of the SCCs.

Community	n	k	k_{max}
TribeNet	188,444	12.00	7,712
GreatestJournal	83,911	4,90	552
LiveJournal	46,688	12.19	1,596
DeadJournal	22,085	4.00	102
Opera	5,457	5.49	491
Dotnode	3,492	3.57	232
Elgg	1,392	5.79	1,292
Boards (Ireland)	1,270	4.14	93
InsaneJournal	545	3.50	54
Boards (Japan)	310	5.75	100
Dion	46	2.20	14
Entire Network	357,315	9.56	7,739

Numerically large, sparse, decentralized, and highly clustered networks make the analysis of the small-world characteristics interesting. Table 4 shows that the examined SCCs meet the first three criteria: they have $n \gg 1$ nodes, an average degree $k \ll n$, and maximal degree $k_{max} \ll n$. Section 5 will show that the fourth criterion is also met by the networks.

In Figure 1, the structure of the maximal SCC of the entire FOAF network is shown. All but one of the investigated SCCs of the community networks are part of the maximal SCC of the entire network. According to the figure, 1,031 of the *foaf:Person* instances that belong to multiple communities also belong to the maximal SCC of the entire network. The DeadJournal (Limbo) community, which does not have an SCC of considerable size itself, is present with 523 (nearly 34 percent) of its members. The members of the SCC of the Dion community are not part of the maximal SCC of the entire network. Furthermore, 64 members of the network are independent of any significant community, belong to another community, or cannot be associated to any host.

5. RESULTS

For social networks, the statistics described in section 2 have intuitive meanings: L is the average number of steps in the shortest chain connecting two people; γ_v reflects the extent to which acquaintances of v are also acquaintances of each other; and γ measures the cliquishness of a typical acquaintance circle. The results of the graph analysis are shown in Table 5. Each SCC of the community networks meets both small-world criteria, $L \approx L_{random}$ and $\gamma \gg \gamma_{random}$.

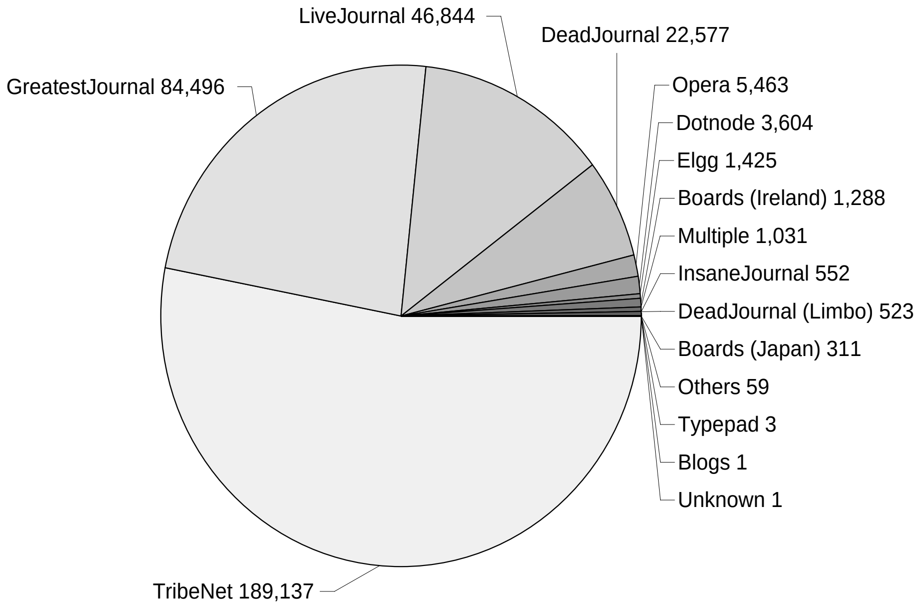

Figure 1. Structure of the largest SCC of the entire FOAF network.

The last line shows the results for the maximal SCC built from all FOAF documents retrieved. From the values in Table 5, we can deduce that the Semantic Web is a small world by comparing its characteristic path length L to the corresponding value for a random graph with the same size and average degree, L_{random}. Moreover, the clustering coefficient γ is much greater than γ_{random} for the corresponding random graph.

Table 5. Characteristic path lengths and clustering coefficients.

Community	**L**	$\mathbf{L_{random}}$	γ	γ_{random}
TribeNet	4.17	6.11	0.22593	0.00006
GreatestJournal	6.82	8.15	0.30736	0.00008
LiveJournal	5.84	5.54	0.16767	0.00024
DeadJournal	9.56	8.10	0.36558	0.00016
Opera	4.98	6.12	0.34159	0.00082
Dotnode	6.82	7.44	0.75798	0.00124
Elgg	6.40	5.29	0.47253	0.00396
Boards (Ireland)	6.28	6.14	0.38295	0.00314
InsaneJournal	7.51	6.09	0.54323	0.00729
Boards (Japan)	4.46	4.44	0.40464	0.01911
Dion	6.57	5.16	0.46630	0.02974
Entire Network	**6.26**	6.84	0.16522	0.00001

The final evidence for the small-world behavior of the FOAF network is the degree distribution according to power laws. The cumulative in- and out-degree distributions for the entire FOAF network are shown in Figure 2 and Figure 3, respectively. The linear regression of both functions gives an exponent of $\alpha \approx -2.1$. All other online communities exhibit comparable degree distributions. Our examination of a portion of the Semantic Web graph shows remarkable agreement with similar experiments on the Web graph reported in [15, 16].

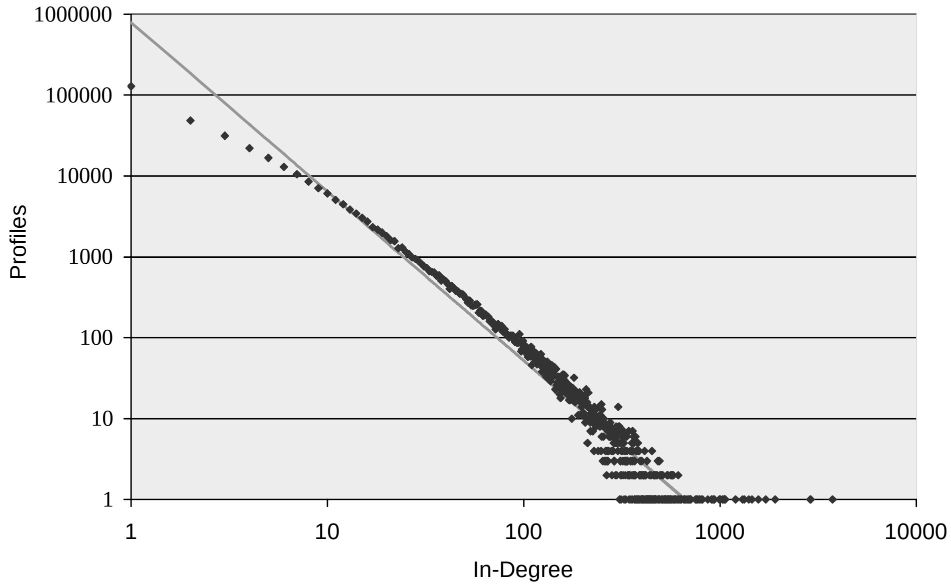

Figure 2. Cumulative in-degree distribution of the entire FOAF network.

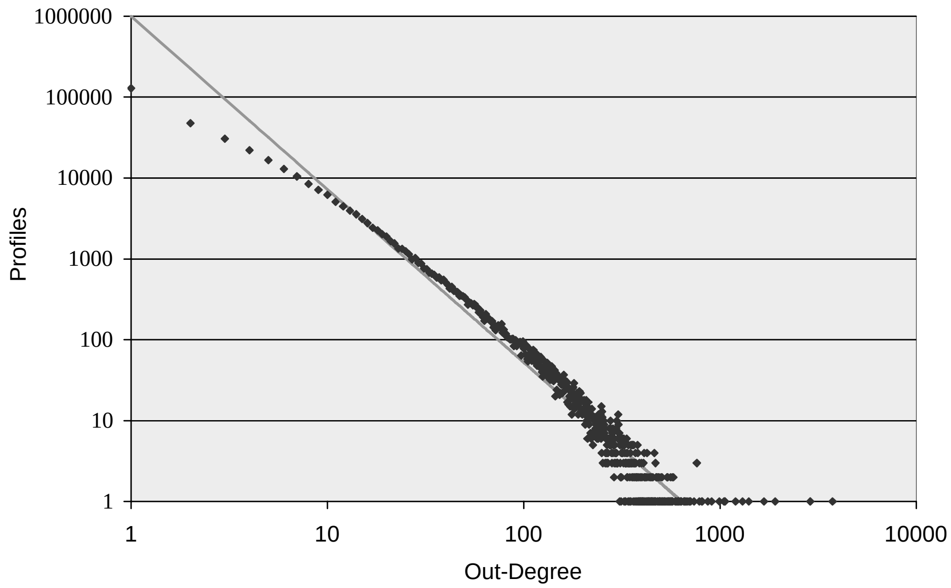

Figure 3. Cumulative out-degree distribution of the entire FOAF network.

The entire FOAF network is a small world with a high clustering coefficient and a power law degree distribution. We also observed that online social networks have a scale-free nature. Indeed, the analysis has been repeated for smaller SCCs of online communities yielding the same conclusions. The results for the eleven community networks are also shown in Table 5.

6. CONCLUSIONS

Twelve real networks were examined, spanning various orders of magnitude in the number of nodes. Each of the graphs exhibits a characteristic path length comparable to the smallest length achievable for a graph of that size. The clustering coefficient is much greater than expected for an equivalent random graph. Hence, according to the definition by Watts, all graphs considered in this study are small-world graphs. This result underpins previous investigations implying that small-world properties exist in real networks that are partly ordered and partly random. We have shown that social networks based on the FOAF vocabulary belong to this interesting group of graphs. However, due to the fact that numerous assumptions must be made, it is difficult to say how the results should be interpreted. It would be unrealistic to relate the findings made to any functional properties of the actual systems. However, the characteristic path length of 6.26 of the entire FOAF network does not contradict the *six degrees of separation* expression often attributed to Milgram at all. Thus, with all the assumptions listed in this paper, we can state that the Semantic Web is a small world.

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