ABSTRACT
Social content such as blogs, tweets, news etc. is a rich source of interconnected information. We identify a set of requirements for the meaningful exploitation of such rich content, and present a new data model, called S3, which is the first to satisfy them. S3 captures social relationships between users, and between users and content, but also the structure present in rich social content, as well as its semantics. We provide the first top-k keyword search algorithm taking into account the social, structured, and semantic dimensions and formally establish its termination and correctness. Experiments on real social networks demonstrate the efficiency and qualitative advantage of our algorithm through the joint exploitation of the social, structured, and semantic dimensions of S3.

1. INTRODUCTION
The World Wide Web (or Web, in short) was designed for users to interact with each other by means of pages interconnected with hyperlinks. Thus, the Web is the earliest inception of an online social network (whereas “real-life” social networks have a much longer history in social sciences). However, the technologies and tools enabling large-scale online social exchange have only become available recently. A popular model of such exchanges features: social network users, who may be connected to one another, data items, and the possibility for users to tag data items, i.e., to attach to an item an annotation expressing the user’s view or classification of the item. Variants of this “user-item-tag” (UIT) model can be found e.g., in [18, 21, 30]. In such contexts, a user, called seeker, may ask a query, typically as a set of keywords. The problem then is to find the best query answers, taking into account both the relevance of items to the query, and the social proximity between the seeker and the items, based also on tags. Today’s major social networks e.g., Facebook [7], all implement some UIT variant. We identify a set of basic requirements which UIT meets:

R0. UIT models explicit social connections between users, e.g., u1 is a friend of u0 in Figure 1, to which we refer throughout this paper unless stated otherwise. It also captures user endorsement (tags) of data items, as UIT search algorithms exploit both the user endorsement and the social connections to return items most likely to interest the seeker, given his social and tagging behavior.

R1. The current wealth of publishing modes (through social networks, blogs, interlinked Web pages etc.) allows many different relations between items. For example, document d1 replies to document d0 (think for instance of opposite-viewpoint articles in a heated debate), while document d2 comments on the paragraph of d0 identified by the URI d0.3.2. The model must capture relations between items, in particular since they may lead to implicit relations between users, according to their manipulations of items. For instance, the fact that u0 posted d0 as a reply to d0, posted by u0 entails that u2 at least read d0, and thus some form of exchange has taken place between u0 and u2: if one looked for explicit social connections only, we would wrongly believe that u0 and u2 have no relation to each other.

R2. Items shared in social media often have a rich structured content. For instance, the article d0 comprises many sections, and paragraphs, such as the one identified by the URI d0.3.2. Document structure must be reflected in the model in order to return useful document fragments as query results, instead of a very large document or a very small snippet of a few words (e.g., exactly the search keywords). Document structure also helps discern when users have really interacted through content. For instance, u0 has interacted with u0, since u0 comments on the fragment d0.3.2 of u0’s article d0. In contrast, when user u4 tags with “university” the fragment d0.3.3 of d0, disjoint from d0.3.2, u4 may not even have read the same text as u3, thus the two likely did not interact.

R3. Item and tag semantics must be modelled. Social Web data encapsulates users’ knowledge on a multitude of topics; ontologies, either general such as DBPedia or Google’s Knowledge Base, or application-specific, can be leveraged to give query answers which cannot be found without relying on semantics. For instance, assume u1 looks for information about university graduate: document d1 states that u2 holds a M.S. degree. Assume a knowledge base specifies that a M.S. is a degree and that someone...
having a degree is a graduate. The ability to return as result the snippet of \( d_1 \) most relevant to the query is directly conditioned by the ability to exploit the ontology (and the content-based interconnections along the path: \( u_1 \) friend of \( v_0 \), \( u_0 \) posted \( d_0 \), \( d_1 \) replied to \( d_0 \)).

R4. In many contexts, tagging may apply to tags themselves, e.g., in annotated corpora, where an annotation (tag) obtained from an analysis can further be annotated with provenance details (when and how the annotation was made) or analyzed in its turn. Information from higher-level annotations is obviously still related to the original document. The model should allow expressing higher-level tags, to exploit their information for query answering.

R5. The data model and queries should have well-defined semantics, to precisely characterize computed results, ensure correctness of the implementation, and allow for optimization.

R6. The model should be generic (not tied to a particular social network model), extensible (it should allow easy extension or customization, as social networks and applications have diverse and rapidly evolving needs), and interoperable, i.e., it should be possible to get richer / more complete answers by integrating different sources of social connections, facts, semantics, or documents. This ensures in particular independence from any proprietary social network viewpoint, usefulness in a variety of settings, and a desirable form of “monotonicity”: the more content is added to the network, the more its information value increases.

This work makes the following contributions.

1. We present \( \mathcal{S}_3 \), a novel data model for structured, semantic-rich content exchanged in social applications: it is the first model to meet the requirements R0 to R6 above.

2. We revisit top-k social search for keyword queries, to retrieve the most relevant document fragments w.r.t. the social, structural, and semantical aspects captured by \( \mathcal{S}_3 \). We identify a set of desirable properties of the score function used to rank results, provide a novel query evaluation algorithm called \( \mathcal{S}_3 \mathcal{K} \) and formally establish its termination correctness; the algorithm intelligently exploits the score properties to stop as early as possible, to return answers fast, with little evaluation effort. \( \mathcal{S}_3 \mathcal{K} \) is the first to formally guarantee a specific result in a structured, social, and semantic setting.

3. We implemented \( \mathcal{S}_3 \mathcal{K} \) based on a concrete score function (extending traditional ones from XML keyword search) and experimented with three real social datasets. We demonstrate the feasibility of our algorithm, and its qualitative advantage over existing approaches: it finds relevant results that would be missed by ignoring any dimension of the graph.

An \( \mathcal{S}_3 \) instance can be exploited in many other ways: through structured XML and/or RDF queries as in [9], searching for users, or focusing on annotations as in [4]; one could also apply graph mining etc. In this paper, we first describe the data model, and then revisit the top-k document search problem, since it is the most widely used (and studied) in social settings.

In the sequel, Section 2 presents the \( \mathcal{S}_3 \) data model, while Section 3 introduces a notion of generic score and instantiates it through a concrete score. Section 4 describes \( \mathcal{S}_3 \mathcal{K} \); we present experiments in Section 5, then discuss related works in Section 6 and conclude.

2. DATA MODEL

We now describe our model integrating social, structured, and semantic-rich content into a single weighted RDF graph, and based on a small set of \( \mathcal{S}_3 \)-specific RDF classes and properties. We present weighted RDF graphs in Section 2.1, and show how they model structured social networks in Section 2.2. We add to our model structured documents in Section 2.3, and tags and user-document interactions in Section 2.4; Section 2.5 introduces our notion of social paths. Table 1 recap the main notations of our data model.

<table>
<thead>
<tr>
<th>URIs</th>
<th>Literals</th>
<th>Keywords</th>
<th>Ext. ( k ) extension of ( k )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Omega ) users</td>
<td>( D ) documents</td>
<td>( T ) tags</td>
<td>I graph instance</td>
</tr>
</tbody>
</table>

Table 1: Main data model notations.

Figure 2: RDF (top) and RDFS (bottom) statements.
explicitly present in G, a rule adds some triples that directly follow from them. For instance, continuing the previous example,

\[ u_1 \text{ hasFriend } u_0, \text{ hasFriend } \rightarrow \text{ Person } \vdash \text{ RDF } \quad u_0 \text{ type } \text{ Person} \]

Applying immediate entailment \( \vdash \text{ RDF} \) repeatedly until no new triple can be derived is known to lead to a unique, finite fixpoint graph, known as the saturation (a.k.a. closure) of G. RDF entailment is part of the RDF standard itself; the answers to a query on G must take into account all triples in its saturation, since the semantics of an RDF graph is its saturation [27].

In the following, we assume, without loss of generality, that all RDF graphs are saturated; many saturation algorithms are known, including incremental [10] or massively parallel ones [26].

**Weighted RDF graph** Relationships between documents, document fragments, comments, users, keywords etc. naturally form a graph. We encode each edge from this graph by a weighted RDF triple of the form \((s, p, o, w)\), where \((s, p, o)\) is a regular RDF triple, and \(w \in [0, 1]\) is termed the weight of the triple. Any triple whose weight is not specified is assumed to be of weight 1.

We define the saturation of a weighted RDF graph as the saturation derived only from its triples whose weight is 1. Any entailment rule of the form \(a, b \vdash \text{ RDF} \) applies only if the weight of \(a\) and \(b\) is 1; in this case, the entailed triple directly follows from the weight 1 triples whose weight is not specified is assumed to be of weight 1.

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**Graph instance I and S3 namespace** We use \( I \) to designate the weighted RDF instance we work with. The RDF Schema statements in \( I \) allow a semantic interpretation of keywords, as follows:

**Definition 2.1 (Keyword extension).** Given an S3 instance \( I \) and a keyword \( k \in K \), the extension of \( k \), denoted \( \text{Ext}(k) \), is defined as follows:

- \( k \in \text{Ext}(k) \)
- For any triple of the form \( b \vdash k \in I \), \( b \in \text{Ext}(k) \).

For example, given the keyword degree, and assuming that M.S. is a degree in I, we have M.S. \( \in \text{Ext}(\text{degree}) \). The extension of \( k \) does not generalize it, in particular it does not introduce any loss of precision: whenever \( k' \) is in the extension of \( k \), the RDF schema in I ensures that \( k' \) is an instance, or a specialization (particular case) of \( k \). This is in coherence with the principles behind the RDF schema language.

For our modeling purposes, we define below a small set of RDF classes and properties used in \( I \); these are shown prefixed with the S3 namespace. The next sections show how I is populated with triples derived from the users, documents and their interactions.

### 2.2 Social network

We consider a set of social network users \( \Omega \subseteq U \), i.e., each user is identified by a URI. We introduce the special RDF class S3:user, and for each user \( u \in \Omega \), we add: \( u \text{ type } \text{ S3:user} \in I \).

1One could generalize this to support inference over triples of any weight, leading to e.g., “\( u \) is of type Person with a weight of 0.5”, in the style of probabilistic databases.

2One could also allow a keyword \( k' \in \text{Ext}(k) \) which is only close to (but not a specialization of) \( k \), e.g., “student” in \( \text{Ext} (“graduate”) \), at the cost of a loss of precision in query results. We do not pursue this alternative here, as we chose to follow standard RDF semantics.

To model the relationships between users, such as “friend”, “coworker” etc., we introduce the special property S3:social, and model any concrete relationship between two users by a triple whose property specializes S3:social. Alternatively, one may see S3:social as the generalization of all social network relationships.

Weights are used to encode the strength \( w \) of each relationship going from a user \( u_1 \) to a user \( u_2 \): \( u_1 \text{ S3:social } u_2 \in I \). As customary in social network data models, the higher the weight, the closer we consider the two users to be.

**Extensibility** Depending on the application, it may be desirable to consider that two users satisfying some condition are involved in a social interaction. For instance, if two people have worked the same year for a company of less than 10 employees (such information may be in the RDF part of our instance), they must have worked together, which could be a social relationship. This is easily achieved with a query that retrieves all such user pairs (in SPARQL or in a more elaborate language) if the condition also carries over the documents, and builds a \( u \text{ workedWith } u' \) triple for each such pair of users. Then it suffices to add these triples to the instance, together with the triple: workedWith \( \text{S3:social} \).

### 2.3 Documents and fragments

We consider that content is created under the form of structured, tree-shaped documents, e.g., XML, JSON, etc. A document is an unranked, ordered tree of nodes. Let \( N \) be a set of node names (for instance, the set of allowed XML element and attribute names, or the set of node names allowed in JSON). Any node has a URI. We denote by \( D \subseteq U \) the set of all node URIs. Further, each node has a name \( \text{from} N \), and a content, which we view as a set of keywords from \( K \): consider each text appearing in a document has been broken into words, stop words have been removed, and the remaining words have been stemmed to obtain our version of the node’s text content. For example, in Figure 1, the text of \( d_1 \) might become \{“M.S.”, “UAlberta”, “2012”\}.

We term any subtree rooted at a node in document \( d \) a fragment of \( d \), implicitly defined by the URI of its root node. The set of fragments (nodes) of a document \( d \) is denoted \( \text{Frag}(d) \). We may use \( f \) to refer interchangeably to a fragment or its URI. If \( f \) is a fragment of \( d \), we say \( d \) is an ancestor of \( f \).

To simplify, we use document and fragment interchangeably; both are identified by the URI of their unique root node.

**Document-derived triples** We capture the structural relationships between documents, fragments and keywords through a set of RDF statements using S3-specific properties. We introduce the RDF class S3:doc corresponding to the documents, and we translate:

- Each document \( d \in D \) into a triple \( \text{type } d \text{ type } \text{ S3:doc} \);
- Each document \( d \in D \) and fragment rooted in a node \( n \) of \( d \) into \( n \text{ S3:partOf } d \);
- Each node \( n \) and keyword \( k \) appearing in the content of \( n \) into \( n \text{ S3:contains } k \);
- Each node \( n \) whose name is \( m \) into \( n \text{ S3:nodeName } m \).

**Example 2.1.** Based on the sample document shown in Figure 1, the following triples are part of:

\[
\begin{align*}
\text{do.3.2 & S3:partOf do.3} \\
\text{do.3 & S3:partOf d1} & \text{d1 contains "M.S."} \\
\text{d0.3 & S3:partOf d1} & \text{d1:nodeName text}
\end{align*}
\]

The following constraints, part of I, model the natural relationships between the S3:doc class and the properties introduced above:

\[
\begin{align*}
\text{S3:partOf } & \leftrightarrow \text{S3:doc} \\
\text{S3:partOf } & \leftrightarrow \text{S3:doc}
\end{align*}
\]
which read: the relationship S3:partOf connects pairs of fragments (or documents); S3:contains describes the content of a fragment; and S3:nodeName names associates names to fragments.

**Fragment position** We will need to assess how closely related a given fragment is to one of its ancestor fragments. For that, we use a function \( pos(d, f) \) which returns the position of fragment \( f \) within document \( d \). Concretely, \( pos \) can be implemented for instance by assigning Dewey-style IDs to document nodes, as in [19, 22]. Then, \( pos(d, f) \) returns the list of integers \((i_1, \ldots, i_n)\) such that the path starting from \( d \)'s root, then moving to its \( i_1 \)-th child, then to this node's \( i_2 \)-th child etc. ends in the root of the fragment \( f \). For instance, in Figure 1, \( pos(d_0, 3.2, d_0) \) may be \((3, 2)\).

### 2.4 Relations between structure, semantics, users

We now show how dedicated S3 classes and properties are used to encode all kinds of connections between users, content, and semantics in a single S3 instance.

**Tags** A typical user action in a social setting is to tag a data item, reflecting the user’s opinion that the item is related to some concept or keyword used in the tag. We introduce the special class S3:relatedTo to account for the multiple ways in which a user may consider that a fragment is related to a keyword. We denote by \( T \) the set of all tags.

For example, in Figure 1, \( u_4 \) tags \( d_{0.5.1} \) with the keyword “university”, leading to the triples:

\[
\text{a type S3:relatedTo} \quad \text{a S3:hasSubject} \quad \text{d}_{0.5.1} \\
\text{a S3:hasKeyword} \quad \text{university} \quad \text{a S3:hasAuthor} \quad u_4
\]

In this example, \( a \) is a tag (or annotation) resource, encapsulating the various tag properties: its content, who made it, and on what. The tag subject (the value of its S3:hasSubject property) is either a document or another tag. The latter allows to express higher-level annotations, when an annotation (tag) can itself be tagged.

A tag may lack a keyword, i.e., it may have no S3:hasKeyword property. Such no-keyword tags model endorsement (support), such as like on Facebook, retweet on Twitter, or +1 on Google+.

Tagging may differ significantly from one social setting to another. For instance, star-based rating of restaurants is a form of tagging, topic-based annotation of text by expert human users is another, and similarly a natural language processing (NLP) tool may tag a text snippet as being about some entity. Just like the S3:social property can be specialized to model arbitrary social connections between users, subclasses of S3:relatedTo can be used to model different kinds of tags. For instance, assuming \( u_3 \) is a tag produced by a NLP software, this leads to the I triples:

\[
\text{a type NLP:recognize} \quad \text{NLP:recognize} \quad \text{S3:relatedTo}
\]

**User actions on documents** Users post (or author, or publish) content, modeled by the dedicated property S3:postedBy. Some of this content may be comments on (or replies / answers to) other fragments; this is encoded via the property S3:commentsOn.

**Example 2.2.** In Figure 1, \( d_2 \) is posted by \( u_3 \), as a comment on \( d_{0.3.2} \), leading to the following 1 triples:

\[
d_2 \text{S3:postedBy} \quad u_3 \quad d_2 \text{S3:commentsOn} \quad d_{0.3.2}
\]

As before, we view any concrete relation between documents e.g., answers to, retweets, comments on, is an old version of etc. as a specialization (sub-property) of S3:commentsOn; the corresponding connections lead to implicit S3:commentsOn triples, as explained in Section 2.1. Similarly, forms of authorship connecting users to their content are modeled by specializing S3:postedBy.
DEFINITION 2.2 (DOCUMENT VERTICAL NEIGHBORHOOD). Two documents are vertical neighbors if one of them is a fragment of the other. The function \( \text{neigh} : U \to 2^U \) returns the set of vertical neighbors of an URI.

In Figure 3, URI0 and URI0.0.0 are vertical neighbors, so are URI0 and URI0.1, but URI0.0.0 and URI0.1 are not. In the sequel, due to the strong connections between nodes in the same vertical neighborhood, we consider (when describing and exploiting social paths) that a path entering through any of them can exit through any other; a vertical neighborhood acts like a single node only and exactly from the perspective of a social path\(^\dagger\). We can now define social paths:

DEFINITION 2.3 (SOCIAL PATH). A social path (or simply a path) in \( I \) is a chain of network edges such that the end of each edge and the beginning of the next one are either the same node, or vertical neighbors.

We may also designate a path simply by the list of nodes it traverses, when the edges taken along the path are clear. In Figure 3, \( u_2 \xrightarrow{u_0} \text{S3:hasAuthor} \xrightarrow{a_0} \text{URI0.0.0} \xrightarrow{\text{URI0.0.0}} \text{URI0.0} \) is an example of such a path (the dashed line: URI0.0.0 \( \xrightarrow{\text{URI0}} \) URI0, is not an edge in the path but a connection between vertical neighbors, URI0.0.0 been the end of an edge and URI0 the beginning of the next edge). Also, in this Figure, there is no social path going from \( u_2 \) to \( u_1 \) avoiding \( u_0 \), because it is not possible to move from URI0.1 to URI0.0.0 through a vertical neighborhood.

**Social path notations** The set of all social paths from a node \( x \) (or one of its vertical neighbors) to a node \( y \) (or one of its vertical neighbors) is denoted \( x \leadsto y \). The length of a path \( p \) is denoted \( |p| \). The restriction of \( x \leadsto y \) to paths of length exactly \( n \) is denoted \( x \leadsto^n y \), while \( x \leadsto^\leq_n y \) holds the paths of at most \( n \) edges.

**Path normalization** To harmonize the weight of each edge in a path depending on its importance, we introduce path normalization, which modifies the weights of a path’s edges as follows. Let \( n \) be the endpoint of a social edge in a path, and \( e \) be the next edge in this path. The normalized weight of \( e \) for this path, denoted \( e_{\cdot,n:w} \), is defined as:

\[
e_{\cdot,n:w} = e.w / \sum_{e' \in \text{out}(\text{neigh}(n))} e'.w
\]

where \( e.w \) is the weight of \( e \), and \( \text{out}(\text{neigh}(n)) \) the set of network edges outgoing from any vertical neighbor of \( n \). This normalizes the weight of \( e \) w.r.t. the weight of edges outgoing from any vertical neighbor of \( n \). Observe that \( e_{\cdot,n:w} \) depends on \( n \), however \( e \) does not necessarily start in \( n \), but in any of its vertical neighbors. Therefore, \( e_{\cdot,n:w} \) indeed depends on the path (which determines the vertical neighbor \( n \) of \( e \)'s entry point).

In the following, we assume all social paths are normalized.

**Example 2.3.** In Figure 3, consider the path:

\[
p = u_2 \xrightarrow{u_0} \text{S3:hasAuthor} \xrightarrow{a_0} \text{URI0.0.0} \xrightarrow{\text{URI0.0.0}} \text{URI0.0}
\]

Its first edge is normalized by the edges leaving \( u_0 \); one leading to URI0 (weight 1) and the other leading to S3 (weight 0.3). Thus, its normalized weight is \( 1/(1 + 0.3) = 0.77 \).

Its second edge exits URI0.0.0 after a vertical neighborhood traversal URI0.0.0 \( \xrightarrow{\text{URI0.0.0}} \) URI0.0.0. It is normalized by the edges leaving \( \text{neigh}(\text{URI0}) \), i.e., all the edges leaving a fragment of URI0. Its normalized weight is \( 1/(1 + 1 + 1 + 1) = 0.25 \).

Thus, simple changes to the path normalization introduced below.\(^\dagger\)In other contexts, e.g., to determine their relevance w.r.t. a query, vertical neighbors are considered separately.

S3 meets the requirements from Section 1, as follows. Generi-

city, extensibility and interoperability (R6) are guaranteed by the reliance on the Web standards RDF (Section 2.1) and XML/JSON (Section 2.3). These enable specializing the S3 classes and proper-
ties, e.g., through application-dependent queries (see Extensibility in Section 2.2). Our document model (Section 2.3) meets require-

3. QUERIES AN S3 INSTANCE

Users can search S3 instances through keyword queries; the an-

swer consists of the k top-score fragments, according to a joint structural, social, and semantic score. Section 3.1, defines queries and their answers. After some preliminaries, we introduce a generic score, which can be instantiated in many ways, and a set of feasibil-

ity conditions on the score, which suffice to ensure the termination and correctness of our query answering algorithm (Section 3.3). We present our concrete score function in Section 3.4.

3.1 Queries

S3 instances are queried as follows:

DEFINITION 3.1 (QUERY). A query is a pair \((u, φ)\) where \( u \) is a user and \( φ \) is a set of keywords.

We call \( u \) the seeker. We define the top-k answers to a query as the \( k \) documents or fragments thereof with the highest scores, further satisfying the following constraint: the presence of a document or fragment at a given rank precludes the inclusion of its vertical neighbors at lower ranks in the results\(^\ddagger\). As customary, top-k answers are ranked using a score function \( s(φ, d) \) that returns for a document \( d \) and query \( φ \) a value in \( \mathbb{R} \), based on the graph \( I \).

DEFINITION 3.2 (QUERY ANSWER). A top-k answer to the query \( q \) using the score \( s \), denoted \( T_{k,q}(q) \), is recursively defined as a top-k−1 answer, plus a document with the best score among those which are neither fragments nor ancestors of the documents in the top-k−1 answer.

Observe that a query answer may not be unique. This happens as soon as several documents have equal scores for the query, and this score happens to be among the \( k \) highest.

3.2 Connecting query keywords and documents

Answering queries over I requires finding best-scoring docu-

ments, based on the direct and indirect connections between documents, the seeker, and search keywords. The connection can be direct, for instance, when the document contains the keyword, or indirect, when a document is connected by a chain of relationships to a search keyword \( k \), or to some keyword from \( k \)'s extension.

We denote the set of direct and indirect connections between a document \( d \) and a keyword \( k \) by \( \text{con}(d, k) \). It is a set of three-tuples \((\text{type}, \text{frag}, \text{src})\) such that:

- \( \text{type} \in \{\text{S3:contains}, \text{S3:relatedTo}, \text{S3:commentsOn}\} \) is the type of the connection,
- \( f \in \text{Frag}(d) \) is the fragment of \( d \) (possibly \( d \) itself) due to which \( d \) is involved in this connection,
- \( \text{src} \in \Omega \cup D \) (users or documents) is the source (origin) of this connection (see below).

\(^\ddagger\)This assumption is standard in XML keyword search, e.g., [6].
Below we describe the possible situations which create connections. Let \( d, d' \) be documents or tags, and \( f, f' \) be fragments of \( d \) and \( d' \), respectively. Further, let \( k, k' \) be keywords such that \( k' \in \text{Ext}(k) \), and \( src \in \Omega \cup D \) be a user or a document.

**Documents connected to the keywords of their fragments** If the fragment \( f \) contains a keyword \( k \), then:

\[
(S3:\text{contains}, d, d) \in \text{con}(d, k)
\]

which reads: “\( d \) is connected to \( k \) through a \( S3:\text{contains} \) relationship due to \( f \).” This connection holds even if \( f \) contains not \( k \) itself, but some \( k' \in \text{Ext}(k) \). For example, in Figure 1, if the keyword “university” appears in the fragment whose URI is \( d_2.7.5 \), then \( \text{con}(d_2, \text{“university”}) \) includes \( (S3:\text{contains}, d_2.7.5, d_2) \).

Observe that a given \( k' \) and \( f \) may lead to many connections, if \( k' \) specializes several keywords and/or if \( f \) has many ancestors.

**Connections due to tags** For every tag \( a \) of the form

- \( a \in \text{type} S3:\text{relatedTo} \ a \in S3:\text{hasSubject} f \)
- \( a \in S3:\text{hasAuthor} \ src \ a \in S3:\text{Keyword} k' \)

\( \text{con}(d, k) \) includes \( (S3:\text{relatedTo}, f, src) \). In other words, whenever a fragment \( f \) of \( d \) is tagged by a source \( src \) with a specialization of the keyword \( k \), this leads to a \( S3:\text{relatedTo} \) connection between \( d \) and \( k \) due to \( f \), whose source is the tag author \( src \). For instance, the tag \( a \) of \( u_4 \) in Figure 1 creates the connection \( (S3:\text{relatedTo}, d_0.5.1, u_4) \) between \( d_0 \) and “university”.

More generally, if a tag \( a \) on fragment \( f \) has any type of connection (not just \( S3:\text{hasKeyword} \)) to a keyword \( k \) due to source \( src \), this leads to a connection \( (S3:\text{relatedTo}, f, src) \) between \( d \) and \( k \). The intuition is that the tag adds its connections to the tagged fragment and, transitively, to its ancestors. (As the next section shows, the importance given to such connections decreases as the distance between \( d \) and \( f \) increases.)

If the tag \( a \) on \( f \) is a simple endorsement (it has no keyword), the tag inherits \( d \)'s connections, as follows. Assume \( d \) has a connection of type \( \text{type} \) to a keyword \( k \): then, \( a \) also has a \( \text{type} \) connection to \( k \), whose source is \( src \), the tag author. The intuition is that when \( src \) endorses \( f \) a fragment, \( src \) agrees with its content, and thus connects the tag, to the keywords related to that fragment and its ancestors. For example, if a user \( u_5 \) endorsed \( d_0 \) in Figure 1 through a no-keyword tag \( a_5 \), the latter tag is related to “university” through:

\( (S3:\text{relatedTo}, d_0.5.1, u_5) \).

**Connections due to comments** When a comment \( f \) is connected to a keyword, this also connects any ancestor \( d \) of \( f \) to that keyword; the connection source carries over, while the type of \( d \)'s connection is \( S3:\text{commentsOn} \). For instance, in Figure 1, since \( d_2 \) is connected to “university” through \( (S3:\text{contains}, d_2.7.5, d_2) \) and since \( d_2 \) is a comment on \( d_0.3.2 \), it follows that \( d_0 \) is also related to “university” through \( (S3:\text{commentsOn}, d_0.3.2, d_2) \).

### 3.3 Generic score model

We introduce a set of proximity notions, based on which we state the conditions to be met by a score function, for our query evaluation algorithm to compute a top-k query answer.

**Path proximity** We consider a measure of proximity along one path, denoted \( \overrightarrow{\text{prox}} \), between 0 and 1 for any path, such that:

- \( \overrightarrow{\text{prox}}(()) = 1 \), i.e., the proximity is maximal on an empty path (in other words, from a node to itself).
- for any two paths \( p_1 \) and \( p_2 \), such that the start point of \( p_2 \) is in the vertical neighborhood of the end point of \( p_1 \):

\[
\overrightarrow{\text{prox}}(p_1 || p_2) \leq \min(\overrightarrow{\text{prox}}(p_1), \overrightarrow{\text{prox}}(p_2)),
\]

where \( || \) denotes path concatenation. This follows the intuition that proximity along a concatenation of two paths is at most the one along each of these two components paths: proximity can only decrease as the path gets longer.

**Social proximity** associates to two vertices connected by at least one social path, a comprehensive measure over all the paths between them. We introduce such a global proximity notion, because different paths traverse different nodes, users, documents and relationships, all of which may impact the relation between the two vertices. Considering all the paths gives a qualitative advantage to our algorithm, since it enlarges its knowledge to the types and strength of all connections between two nodes.

#### Definition 3.3 (Social Proximity). The social proximity measure \( \text{prox} : (\Omega \cup D \cup T)^2 \rightarrow [0, 1] \), is an aggregation along all possible paths between two users, documents or tags, as follows:

\[
\text{prox}(a, b) = \oplus_{\text{path}}(\{|\overrightarrow{\text{prox}}(p), |p|\}, p \in a \sim ~ b),
\]

where \( | | \) is the number of vertices in a path and \( \oplus_{\text{path}} \) is a function aggregating a set of values from \( [0, 1] \times \mathbb{N} \) into a single scalar value.

Observe that the set of all paths between two nodes may be infinite, if the graph has cycles; this is often the case in social graphs. For instance, in Figure 3, a cycle can be closed between \((u_0, u_1, u_0)\). Thus, in theory, the score is computed over a potentially infinite set of paths. However, in practice, our algorithm works with bounded social proximity values, varying only on paths of a bounded length:

\[
\text{prox}^\le_{\mathbb{N}}(a, b) = \oplus_{\text{path}}(\{|\overrightarrow{\text{prox}}(p), |p|\}, p \in a \sim \le_{\mathbb{N}, b})
\]

Based on the proximity measure, and the connections between keywords and documents introduced in Section 3.2, we define:

#### Definition 3.4 (Generic Score). Given a document \( d \) and a query \( q = (u, \phi) \), the score of \( d \) for \( q \) is:

\[
\text{score}(d, (u, \phi)) = \oplus_{\text{gen}}((\{k, \text{type}, \text{pos}(d, f), \text{prox}(u, src)\} | k \in \phi, (\text{type}, f, src) \in \text{con}(d, k))
\]

where \( \oplus_{\text{gen}} \) is a function aggregating a set of \((\text{keyword}, \text{relation}-\text{ship type}, \text{importance of fragment} f \text{ in} \ d, \text{social proximity})\) tuples into a value from \([0, 1]\).

Importantly, the above score reflects the semantics, structure, and social content of the S3 instance, as follows:

- First, \( \oplus_{\text{gen}} \) aggregates over the keywords in \( \phi \). Recall that tuples from \( \text{con}(d, k) \) account not only for \( k \) but also for keywords \( k' \in \text{Ext}(k) \). This is how semantics is injected into the score.
- Second, the score of \( d \) takes into account the relationships between fragments of \( d \), and keywords \( k \), or \( k' \in \text{Ext}(k) \), by using the sequence \( \text{pos}(d, f) \) (Section 2.3) as an indication of the structural importance of the fragment within the document. If the sequence is short, the fragment is likely a large part of the document. Document structure is therefore taken into account here both directly through \text{pos}, and indirectly, since the \text{con} tuples also propagate relationships from fragments to their ancestors (Section 3.2).
- Third, the score takes into account the social component of the graph through \text{prox}: this accounts for the relationships between the seeker \( u \), and the various parties (users, documents and tags), denoted \( src \), due to which \( f \) may be relevant for \( k \).

**Feasibility properties** For our query answering algorithm to converge, the generic score model must have some properties which we describe below.

1. **Relationship with path proximity** This refers to the relationship between path proximity and score. First, the score should only
increase if one adds more paths between a seeker and a data item. Second, the contribution of the paths of length \( n \in \mathbb{N} \) to the social proximity can be expressed using the contributions of shorter “prefixes” of these paths, as follows. We denote by \( ppSet^n(a, b) \) the set of the path proximity values for all paths from \( a \) to \( b \) of length \( n \):

\[
ppSet^n(a, b) = \{ \text{prox}_p(p) \mid p \in a \stackrel{n}{\rightarrow} b \}
\]

Then, the first property is that there exists a function \( U_{\text{prox}} \) with values in \([0, 1]\), taking as input (i) the bounded social proximity for path of length at most \( n - 1 \), (ii) the proximity along paths of length \( n \), and (iii) the length \( n \), and such that:

\[
\text{prox}^n(a, b) = \text{prox}^{n-1}(a, b) + U_{\text{prox}}(\text{prox}^{n-1}(a, b), ppSet^n(a, b), n)
\]

2. Long paths attenuation

The influence of social paths should decrease as they get longer; intuitively, the farther away two items are, the weaker their connection and thus their influence on the score. More precisely, there exists a bound \( B_{\text{prox}}^n \) tending to 0 as \( n \) grows, and such that:

\[
B_{\text{prox}}^n \geq \text{prox} - \text{prox}^n
\]

3. Score soundness

The score of a document should be positively correlated with the social proximity from the seeker to the document fragments that are relevant for the query.

Denoting \( \text{score}_{[g]} \) the score where the proximity function \( \text{prox} \) is replaced by a continuous function \( g \) having the same domain \((\Omega \cup D \cup T)^2, g \rightarrow \text{score}_{[g]} \) must be monotonically increasing and continuous for the uniform norm.

4. Score convergence

This property bounds the score of a document and shows how it relates to the social proximity. It requires the existence of a function \( B_{\text{score}} \) which takes a query \( q = (u, \phi) \) and any source \( B \geq 0 \), known to be an upper bound on the social proximity between the seeker and any source: for any \( d \), query keyword \( k \), and \((\text{type}, f, src) \in \text{con}(d, k) \), we know that \( \text{prox}(u, src) \leq B \).

\( B_{\text{score}} \) must be positive, and satisfy, for any \( q \):  
- for any document \( d \), \( \text{score}(d, q) \leq B_{\text{score}}(q, B) \);
- \( \lim_{B \rightarrow 0} (B_{\text{score}}(q, B)) = 0 \) (tends to 0 like \( B \)).

We describe a concrete feasible score, i.e., having the above properties, in the next section.

3.4 Concrete score

We start by instantiating \( \text{prox}^2 \), \( \text{prox} \) and \( \text{score} \).

Social proximity

Given a path \( p \), we define \( \text{prox}_p(p) \) as the product of the normalized weights (recall Section 2.5) found along the edges of \( p \). We define our concrete social proximity function \( \text{prox}(a, b) \) as a weighted sum over all paths from \( a \) to \( b \):

\[
\text{prox}(a, b) = C_\gamma \times \sum_{p \in a \rightarrow b} \frac{\text{prox}_p(p)}{|p|^\beta}
\]

where \( \gamma > 1 \) is a scalar coefficient, and \( C_\gamma = \frac{\gamma - 1}{\beta} \) is introduced to ensure that \( \text{prox} \leq 1 \). Recall that by Definition 3.3, \( \text{prox} \) requires a \( \oplus_{\text{path}} \) aggregation over the (social proximity, length) pairs of the paths between the two nodes. Hence, this concrete social proximity corresponds to choosing:

\[
\oplus_{\text{path}}(S) = C_\gamma \times \sum_{(s, p, len) \in S} \frac{sp}{len}
\]

where \((sp, len)\) is a (social proximity, length) pair from its input.

Example 3.1. Social proximity

Let us consider in Figure 3 the social proximity from \( u_0 \) to \( uri10 \), using the \( \text{prox}^2 \) and \( \oplus_{\text{path}} \) previously introduced. An edge connects \( u_0 \) directly to \( uri10 \), leading to the normalized path \( p \):

\[
p = u_0 \oplus_{\text{S3:postedBy URI0}} \frac{1}{\gamma \times |p|} \rightarrow uri10
\]

which accounts for a partial social proximity:

\[
\text{prox}^{\leq 1}(u_0, uri10) = \frac{\text{prox}^2(p)}{\gamma |p|} = \frac{1}{(1 + 0.3) \gamma}
\]

This social proximity generalizes Katz distance [17]; other common distances may be used, e.g., SimRank [14].

Score function

We define a simple concrete \( S3 \) score function which, for a document \( d \), is the product of the scores of each query keyword in \( d \). The score of a keyword is summed over all the connections between the keyword and the document. The weight for a given connection and keyword only depends on the social distance between the seeker and the sources of the keyword, and the structural distance between the fragment involved in this relation and \( d \), namely the length of pos(\( d, f \)). Both distances decrease exponentially as the path length grows. Formally:

Definition 3.5 (\( S3_k \) score).

Given a query \((u, \phi)\), the \( S3_k \) score of a document \( d \) for the query is defined as:

\[
\text{score}(d, (u, \phi)) = \prod_{k \in \Phi} \left( \sum_{\text{relprox}(type, f, src) \in \text{con}(d, k)} \eta_{\text{relprox}} \times \text{prox}(u, src) \right)
\]

for some damping factor \( \eta \leq 1 \).

Recall from Definition 3.4 that an aggregation function \( \oplus_{\text{gen}} \) combines the contributions of (keyword, relationship type, importance, social proximity) tuples in the score. The above definition corresponds to the following \( \oplus_{\text{gen}} \) aggregators:

\[
\oplus_{\text{gen}}(S) = \prod_{k \in \Phi} \left( \sum_{\text{relprox}(type, k, type, rel, prox) \in S} \eta_{\text{relprox}} \times \text{prox} \right)
\]

Note that if we ignore the social aspects and restrict ourselves to top-k search on documents (which amounts to \( \text{prox} = 1 \)), \( \oplus_{\text{gen}} \) gives the best score to the lowest common ancestor (LCA) of the nodes containing the query keywords. Thus, our score extends typical XML IR works, e.g., [6] (see also Section 6).

Obviously, there are many possible ways to define \( \oplus_{\text{gen}} \) and \( \oplus_{\text{path}} \) depending on the application. In particular, different types of connections may not be accounted for equally; our algorithm only requires a feasible score (with the feasibility properties).

Theorem 3.1 (Score feasibility).

The \( S3_k \) score function (Definition 3.5) has the feasibility properties (Section 3.3).

The proof appears in our technical report [3].

4. QUERY ANSWERING ALGORITHM

In this section, we describe our Top-k algorithm called \( S3_k \), which computes the answer to a query over an \( S3 \) instance using our \( S3_k \) score, and formally state its correctness.

4.1 Algorithm

The main idea, outlined in Algorithm 1, is the following. The instance is explored starting from the seeker and going to other vertices (users, documents, or resources) at increasing distance. At the \( n \)-th iteration, the \( I \) vertices explored are those connected to the seeker by at least a path of length at most \( n \). We term exploration border the set of graph nodes reachable by the seeker through a path of length exactly \( n \). Clearly, the border changes as \( n \) grows.

During the exploration, documents are collected in a set of candidate answers. For each candidate \( c \), we maintain a score interval: its currently known lowest possible score, denoted \( c \cdot \text{lower} \), and its
Algorithm 1: S3k – Top-k algorithm.

Input : a query \( q = (u, \phi) \)
Output: the best \( k \) answers to \( q \) over an S3 instance \( I \), T\textsubscript{k,u}(q)

1. \( \text{candidates} \leftarrow \emptyset \)
2. \( \text{discarded} \leftarrow \emptyset \)
3. \( \text{borderPath} \leftarrow \emptyset \)
4. \( \forall \text{allProx} \leftarrow \text{set} \)
5. \( \text{threshold} \leftarrow \infty \)
6. \( n \leftarrow 0 \)
7. while not \( \text{StopCondition(candidates)} \) do
8. \( n \leftarrow n + 1 \)
9. \( \text{ExploreStep()} \)
10. \( \text{ComputeCandidatesBounds()} \)
11. \( \text{CleanCandidatesList()} \)
12. return \( \text{candidates}[0,k-1] \)

\( q = (u, \phi) \): Query seeker \( u \) and keyword set \( \phi \)
\( k \): Result size
\( n \): Number of iterations of the main loop of the algorithm
\( \text{candidates} \): Set of documents and/or fragments which are candidate query answers at a given moment
\( \text{discarded} \): Set of documents and/or fragments which have been ruled out of the query answer
\( \text{borderPath} \): Path of documents from node \( u \) to node \( v \) explored at the last iteration \( v \approx u \)
\( \text{allProx} \): Bounded social proximity \( \text{prox}_{\text{all Prox}} \) between the seeker \( u \) and all nodes \( v \), taking into account all the paths from \( u \) to \( v \) known so far
\( \text{connect} \): Connections between the seeker and the candidate
\( \text{threshold} \): Upper bound on the score of the documents not visited yet

Table 3: Main variables used in our algorithms.

Algorithm 2: Algorithm StopCondition

Input: \( \text{candidates} \) set
Output: \( \text{true} \) if \( \text{candidates}[0,k-1] \) is \( T\textsubscript{k,u}(q) \), \( \text{false} \) otherwise
1. if \( \exists d, d' \in \text{candidates}, j, k - 1, d \in \text{neighbor}(d') \) then
2. return \( \text{false} \)
3. \( \text{min_topk_lower} \leftarrow \infty \)
4. foreach \( c \in \text{candidates}[0,k-1] \) do
5. \( \text{min_topk_lower} \leftarrow \min(\text{min_topk_lower}, c.k_lower) \)
6. \( \text{max_non_topk_upper} \leftarrow \text{candidates}[k].k_upper \)
7. return \( \max(\text{max_non_topk_upper}, \text{threshold}) \leq \text{min_topk_lower} \) // Boolean result

highest possible score, denoted \( c.k_upper \). These scores are updated as new paths between the seeker and the candidates are found. Candidates are kept sorted by their highest possible score; the \( k \) first are the answer to the query when the algorithm stops, i.e., when no candidate document outside the current \( k \) can have an upper bound above the minimum lower bound within the top \( k \) ranks.

Further, the search algorithm relies on three tables:
- \( \text{borderPath} \) is a table storing, for a node \( v \) in \( I \), the set of paths of length \( n \) between \( u \) (the seeker) and \( v \), where \( n \) is the current distance from \( u \) that the algorithm has traversed.
- \( \text{allProx} \) is a table storing, for a node \( v \) in \( I \), the proximity between \( u \) and \( v \) taking into account all the paths known so far from \( u \) to \( v \). Initially, its value is 0 for any \( v \neq u \).
- \( \text{connect} \) is a table storing for a candidate \( c \) the set of connections (Section 3.2) discovered so far between the seeker and \( c \).

These tables are updated during the search. While they are defined on all the I nodes, we only compute them gradually, for the nodes on the exploration border.

Termination condition

Of course, search should not explore the whole graph, but instead stop as early as possible, while returning the correct result. To this aim, we maintain during the search an upper bound on the score of score of all documents unexplored so far, named \( \text{threshold} \). Observe that we do not need to return the exact score of our results, and indeed we may never narrow down the (lower bound, upper bound) intervals to single numbers; we just need to make sure that no document unexplored so far is in the top \( k \). Algorithm 2 outlines the procedure to decide whether the search is complete: when (i) the candidate set does not contain documents such that one is a fragment of another, and (ii) no document can have a better score than the current top \( k \).

Any-time termination

Alternatively, the algorithm can be stopped at any time (e.g., after exhausting a time budget) by making it return the \( k \) best candidates based on their current upper bound score.

Graph exploration

Algorithm 3 describes one search step (iteration), which visits nodes at a social distance \( n \) from the seeker. For the ones that are documents or tags, the \( \text{GetDocuments} \) algorithm (see hereafter) looks for related documents that can also be candidate answers (these are added to \( \text{candidates} \)); \( \text{discarded} \) keeps track of related documents with scores too low for them to be candidates. The \( \text{allProx} \) table is also updated using the \( U_{\text{prec}} \) function, whose existence follows from the first score feasibility property (Section 3.3), to reflect the knowledge acquired from the new exploration border (\( \text{borderPath} \)). Observe that Algorithm 3 computes \( \text{prox}_{\text{all Prox}} \) iteratively using the first feasibility property; at iteration \( n \), \( \text{allProx}[s] = \text{prox}_{\text{all Prox}}(u, s) \).

Computing candidate bounds

The \( \text{ComputeCandidatesBounds} \) algorithm (shown in [3]) maintains during the search the lower and upper bounds of the \( \text{candidates} \), as well as \( \text{threshold} \). A candidate’s lower bound is computed as its score where its social proximity to the user is approximated by its bounded version, based only on the paths explored so far:

\[ \omega_{\text{gen}}(\{(ku, \text{type}, \text{pos}(d, f), \text{allProx}[s])\} \mid ku \in \phi, (\text{type}, \text{f}, s) \in \text{conn}(d, ku)) \]

This is a lower bound because, during exploration, a candidate can only get closer to the seeker (as more paths are discovered).

A candidate’s upper bound is computed as its score, where the social proximity to the user is replaced by the sum between the bounded proximity and the function \( B_{\text{prox}} \), whose existence follows from the long path attenuation property (Section 3.3).

\( \text{Algorithm 3: Algorithm ExploreStep} \)

Update: \( \text{borderPath} \) and \( \text{allProx} \)
1. if \( n = 1 \) then
2. \( \text{borderPath} \leftarrow \text{out}(\{u\}) \)
3. else
4. foreach \( v \in \text{borderPath} \) do
5. \( \text{newBorderPath}[v] \leftarrow \emptyset \)
6. \( \text{newProx}(p, v) \leftarrow \text{allProx}[v] + U_{\text{prec}}(\text{allProx}[v], \{\text{Type}(d, f), p \in \text{borderPath}[v]\}, n) \)
7. \( \text{allProx} \leftarrow \text{newProx} \)

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The latter is guaranteed to offset the difference between the bounded and actual social proximity:

\[ \mathcal{H}_\text{gen}(\{(kw, type, pos(d, f)) \mid kw \in \phi, (type, f, src) \in \text{con}(d, kw)\}) \]

The above bounds rely on \( \text{con}(d, k) \), the set of all connections between a candidate \( d \) and a query keyword \( k \) (Section 3.2); clearly, the set is not completely known when the search starts. Rather, connections accumulate gradually in the \( \text{connect} \) table (Algorithm GetDocuments), whose tuples are used as approximate (partial) \( \text{con}(d, k) \) information in ComputeCandidateBounds.

Finally, ComputeCandidateBounds updates the relevance threshold using the known bounds on score and prox. The new bound estimates the best possible score of the unexplored documents.

Cleaning the candidate set Algorithm CleanCandidateList removes from candidates documents that cannot be in the answer, i.e., those for which \( k \) candidates with better scores are sure to exist, as well as those having a candidate neighbor with a better score. The algorithm is delegated to [3].

Getting candidate documentsGiven a candidate document or tag \( x \), Algorithm GetDocuments checks whether some documents unexplored so far, reachable from \( x \) through a chain of S3:partOf, S3:commentsOn, S3:commentsOn, S3:hasSubject, or S3:hasSubject edges, are candidate answers. If yes, they are added to candidates and the information necessary to estimate their score is recorded in connect. The algorithm is detailed in [3].

4.2 Correctness of the algorithm

The theorems below state the correctness of our algorithm for any score function with the feasibility properties identified in Section 3.3. The proofs are quite involved, and they are delegated to [3]. The core of the proofs is showing how the score feasibility properties entail a set of useful properties, in particular related to early termination (convergence).

**Theorem 4.1 (Stop correctness).** When a stop condition is met, the first \( k \) elements in candidates are a query answer.

We say the tie of two equal-score documents \( d, d' \) is breakable if examining a set of paths of bounded length suffices to decide their scores are equal. (In terms of our score feasibility properties, this amounts to \( B_H^n_{\text{con}} = 0 \) for some \( n \).) Our generic score function (Definition 3.5) does not guarantee all ties are breakable. However, any finite-precision number representation eventually brings the lower and upper bounds on \( d \) and \( d' \)’s scores too close to be distinguished, de facto breaking ties.

**Theorem 4.2 (Correctness with breakable ties).** If there exists a query answer of size \( k \) and all ties are breakable then Algorithm 1 returns a query answer of size \( k \).

**Theorem 4.3 (Anytime correctness).** Using anytime termination, Algorithm 1 eventually returns a query answer.

In our experiments (Section 5), the threshold-based termination condition was always met, thus we never needed to wait for convergence of the lower and upper bound scores.

5. IMPLEMENTATION & EXPERIMENTS

We describe experiments creating and querying S3 instances. We present the datasets in Section 5.1, while Section 5.2 outlines our implementation and some optimizations we brought to the search algorithm. We report query processing times in Section 5.3, study the quality of our returned results in Section 5.4, and then we conclude.

![Figure 4: Statistics on our instances.](image)

### 5.1 Datasets, queries, and systems

**Datasets** We built three datasets, \( I_1 \), \( I_2 \), and \( I_3 \), based respectively on content from Twitter, Vodkaster, and Yelp.

The instance \( I_1 \) was constructed starting from tweets obtained through the public streaming Twitter API. Over a one-day interval (from May 2nd 2014 16h44 GMT to May 3rd 2014 12h44 GMT), we gathered roughly one million tweets. From every tweet that is not a retweet, we created a document having three nodes (i) a text node: from the text field of the tweet, we extracted named entities and words (using the Twitter NLP tools library [20]) and matched them against a general-purpose ontology we created from DBPedia (see below); (ii) a date node, and (iii) a geo node: if the tweet included a human readable location, we inserted it in this node. The RDF graph of our instance was built from DBPedia datasets, namely: Mapping-based Types, Mapping-based Properties, PersonalData and Lexicalizations Dataset. These were chosen as they were the most likely to contain concepts (names, entities etc.) occurring in tweets. Tweet text was *semantically enriched* (connected to the RDF graph) as follows: within the text fields, we replaced each word \( w \) for which a triple of the form \( \text{ufo:name} w \) holds in the DBPedia knowledge base, by the respective URI \( u \).

When a tweet \( t' \) authored by user \( u \) is a retweet of another tweet \( t \), for each hashtag \( h \) introduced by \( t' \), we added to \( I_1 \) the triples: a type S3:relatedTo, a S3:hasSubject \( h \), and a S3:hasKeyword \( h \). When a tweet \( t' \) is a reply to another tweet \( t \), we considered \( t' \) a comment on \( t \). Whenever \( t \) was present in our dataset, we added the corresponding S3:commentsOn triple in \( I_1 \). The set of users \( \Omega_t \) corresponds to the set of user IDs having posted tweets, and we created links between users as follows. We assigned to every pair of users \((a, b)\) a value \( u_{\text{assoc}}(a, b) = t \cdot j_{\text{cat}}(a, b) + (1 - t) \cdot j_{\text{assoc}}(a, b) \), where \( j_{\text{cat}} \) and \( j_{\text{assoc}} \) give the Jaccard similarities of the sets of keywords appearing in each user’s posts, respectively, in each user’s comments. Whenever this similarity was above a threshold, we created an edge of weight \( u_{\text{assoc}} \) between the two users. Through experiments on this dataset, we set the threshold to 0.1.

The instance \( I_2 \) uses data from Vodkaster, a French social network dedicated to movies. The data comprises follower relations between the users and a list of comments on the movies, in French, along with their author. Whenever user \( u \) follows user \( v \) we in-

---

\[\text{I}_1(\text{Twitter})\]

<table>
<thead>
<tr>
<th>Users</th>
<th>492,244</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3:social edges</td>
<td>17,544,347</td>
</tr>
<tr>
<td>Documents</td>
<td>467,710</td>
</tr>
<tr>
<td>Fragments (non-root)</td>
<td>1,273,800</td>
</tr>
<tr>
<td>Tags</td>
<td>609,476</td>
</tr>
<tr>
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</tr>
<tr>
<td>Tweets</td>
<td>999,375</td>
</tr>
<tr>
<td>Retweets</td>
<td>85%</td>
</tr>
<tr>
<td>Reply to users’ status</td>
<td>6.9%</td>
</tr>
<tr>
<td>String-keyword associations extracted from DBPedia</td>
<td>3,301,425</td>
</tr>
<tr>
<td>S3:social edges per user having any (average)</td>
<td>317</td>
</tr>
<tr>
<td>Nodes (without keywords)</td>
<td>2,972,560</td>
</tr>
<tr>
<td>Edges (without keywords)</td>
<td>24,554,029</td>
</tr>
</tbody>
</table>

\[\text{I}_2(\text{Vodkaster})\]

<table>
<thead>
<tr>
<th>Users</th>
<th>366,715</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3:social edges (yelp-friend)</td>
<td>3,888,711</td>
</tr>
<tr>
<td>Documents (movie comments)</td>
<td>94,155</td>
</tr>
<tr>
<td>Documents (reviews)</td>
<td>3,905,529</td>
</tr>
<tr>
<td>Fragments (non-root)</td>
<td>2,064,371</td>
</tr>
<tr>
<td>Keywords</td>
<td>2,427,871</td>
</tr>
<tr>
<td>Movies</td>
<td>5,328</td>
</tr>
<tr>
<td>Businesses</td>
<td>11,184</td>
</tr>
</tbody>
</table>

\[\text{I}_3(\text{Yelp})\]

<table>
<thead>
<tr>
<th>Users</th>
<th>33,981,425</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3:social edges</td>
<td>3,301,425</td>
</tr>
<tr>
<td>Documents</td>
<td>94,155</td>
</tr>
<tr>
<td>Documents (movie comments)</td>
<td>3,905,529</td>
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<td>Movies</td>
<td>5,328</td>
</tr>
<tr>
<td>Businesses</td>
<td>11,184</td>
</tr>
</tbody>
</table>
cluded u vdk:follow v 1 in I2, where vdk:follow is a custom sub-
property of S3:social. We translate the first comment on each film
into a document; each additional comment was then considered a
comment on the first. The text of each comment was stemmed, then
each stemmed sentence was made a fragment of the comment.

The instance I1 is based on Yelp [29], a crowd-sourced reviews
website about businesses. This dataset contains a list of textual re-
views of businesses, and the friend list of each user. As for I2,
we considered that the first review of a business is commented on by
the subsequent reviews of the same business. For each user u friend
with user v, we added u yelp:friend v 1 to I3, where yelp:friend
is a S3:social subproperty modeling social Yelp connections. Re-
views were also semantically enriched using DBPedia.

Table 4 shows the main features of the three quite different data
instances. I1 is by far the largest. I2 was not matched with a knowl-
edge base since its content is in French; I2 and I3 have no tags.

Queries For each instance we created workloads of 100 queries, based
on three independent parameters:

- \( f \), the keyword frequency: either rare, denoted ‘−’ (among
  the 25\% least frequent in the document set), or common, de-
  noted ‘+’ (among the 25\% most frequent)
- \( l \), the number of keywords in the query: 1 or 5
- \( k \), the expected number of results: 5 or 10

This lead to a total of 8 workloads, identified by \( gset_{f,l,k} \), for
each dataset. To further analyze the impact of varying \( k \), we added
10 more workloads for I1, where \( f \in \{+,-\} \), \( l = 1 \) and \( k \in [1, 5, 10, 50] \) (used in Figure 7).

Systems Our algorithms were fully implemented in Python 2.7; the
code has about 6K lines. We stored some data tables in PostgreSQL
9.3, while others were built in memory, as we explain shortly. All
our experiments were performed on a 4 cores Intel Xeon E3-1230
V2 @3.30GHz with 16Go of RAM, running Debian 8.1.

No existing system directly compares with ours, as we are the
first to consider fine-granularity content search with semantics in a
social network. To get at least a rough performance comparison,
we used the Java-based code provided by the authors of the top-k
social search system described in [18], based on the UFT (user, item
and tag) model, and referred to as TopkS from now on. The data model
of TopkS is rather basic, since its documents (items) have no inter-
nal structure nor semantics and tags have no semantic connection
between them. Further, (user, user, weight) tuples reflect weight
links between users. TopkS computes a social score and a content-
based score for each item; the overall item score is then \( \alpha \times \) social
score + (1 – \( \alpha \)) × content score, where \( \alpha \) is a parameter of TopkS.

We adapted our instances into TopkS’s simpler data model. From
I1, we created \( I_1' \) as follows: (i) the relations between users were
kept with their weight; (ii) every tweet was merged with all its
retweets and replies into a single item, and (iii) every keyword \( k \)
in the content of a tweet that is represented by item \( i \) posted by
user \( u \) led to introducing the (user, item, tag) triple \( (u, i, k) \). To
obtain \( I_2' \) and \( I_2'' \), each movie or business becomes an item, each
word extracted from a review leads to a (user, item, tag) tuple.

5.2 Implementation and optimizations

We briefly discuss our implementation, focusing on optimiza-
tions w.r.t. the conceptual description in Section 4.

The first optimization concerns the computation of \( \text{prox} \), re-
quired for the score (Definition 3.5). While the score involves
connections between documents and keywords found on any path,
in practice \( S3_k \) explores paths (and nodes) increasingly far from

the seeker, and stores such paths in borderPath, which may grow
very large and hurt performance. To avoid storing borderPath,
we compute for each explored vertex \( \text{u} \) the weighted sum over all
paths of length \( n \) from the seeker to this vertex:

\[
\text{borderProx}(u, n) = \sum_{p \in (u \rightarrow v), |p| = n} p^\alpha \Sigma(p) \frac{1}{n^\gamma}
\]

and compute prox directly based on this value.

Furthermore, Algorithm GetDocuments considers documents
reachable from \( u \) through edges labeled S3:partOf, S3:commentsOn,
S3:commentsOn, or S3:hasSubject. Reachability by such edges defines a partition of the documents into connected components. Further, by construction of con tuples (Section 3.2), connections carry over from one fragment to another, across such edges. Thus, a fragment matches the query keywords iff its com-
ponent matches it, leading to an efficient pruning procedure: we compute and store the partitions, and test that each keyword (or extension thereof) is present in every component (instead of frag-
ment). Partition maintenance is easy when documents and tags are added, and more expensive for deletions, but luckily these are rarer.

The query answering algorithm creates in RAM the allProx
table and two sparse matrices, computed only once: distance, en-
coding the graph of network edges in I (accounting for the verti-
cal neighborhood), and component, storing the component of each
fragment or tag. Thus, Algorithm 3, which computes allProx and
finds new components to explore, relies on efficient matrix and vec-
tor operations. For instance, the new distance vector borderProx
w.r.t. the seeker at step \( n + 1 \) is obtained by multiplying the dis-
tance matrix with the previous distance vector from step \( n \). The
documents and the RDF graph, on the other hand are not stored in
RAM, and are queried using a PostgreSQL database.

The search algorithm can be parallelized in two ways. First,
within an iteration, we discover new documents in different compo-
nents in parallel. Second, when borderProx is available in the cur-
rent iteration, we can start computing the next borderProx using
the distance matrix. More precisely, Algorithm 3 (ExploreStep)
can be seen as consisting of two main blocks: (i) computing the new
borderProx using the (fixed) distance matrix and the previ-
ous borderProx (lines 1-12 except line 10); (ii) computing
allProx using the new borderProx and the previous allProx
(lines 13-16) plus the call to GetDocuments (line 10). The lat-
ter algorithm consists of two parts: (iii) identifying the newly dis-
covered components, respectively (iv) testing the documents they
contain. We used 8 concurrent threads, each running a task of one
of the forms (i)-(iv), above, and synchronized them with a custom

Figure 5: Query answering times on I1 (Twitter).
5.3 Query answering times

Figures 5 and 6 show the running times of $S3_k$ on the $I_1$ and $I_3$ instances; the results on the smaller instance $I_2$ are similar [3]. We used different values of the $\gamma$ social proximity damping factor (Section 3.4) and the $\alpha$ parameter of TopkS. For each workload, we plot the average time (over its 100 queries). All runs terminated by reaching the threshold-based stop condition (Algorithm 2).

A first thing to notice is that while all running times are comparable, TopkS runs consistently faster. This is mostly due to the different proximity functions: our $prox$, computed from all possible paths, has a much broader scope than TopkS, which explores and uses only one (shortest) path. In turn, as we show later, we return a significantly different set of results, due to $prox$’s broader scope and to considering document structure and semantics.

Decreasing the $\gamma$ in $S3_k$ reduces the running time. This is expected, as $\gamma$ gives more weight to nodes far from the seeker, whose exploration is costly. Similarly, increasing $\alpha$ in TopkS forces to look further in the graph, and affects negatively its performance.

The influence of $k$ is more subtle. When the number of candidates is low and the exploration of the graph is not too costly, higher $k$ values allow to include most candidates among the $k$ highest-scoring ones. This reduces the exploration needed to refine their bounds enough to clarify their relative ranking. In contrast, if the number of candidates is important and the exploration costly, a small $k$ value significantly simplifies the work. This can be seen in Figure 7 where, with frequent keywords, increasing $k$ does not affect the 3 fastest quartiles but significantly slows down the slowest quartile, since the algorithm has to look further in the graph.

The same figure also shows that rare-keyword workloads (whose labels start by $-\Delta$) are easier to evaluate than the frequent-keyword ones (workload labels starting with $\Delta$). This is because finding rare keywords tends to require exploring longer paths. Social damping at the end of such paths is high, allowing to decide that possible matches found even farther from the seeker will not make it into the top-$k$. In contrast, matches for frequent keywords are found soon, while it is still possible that nearby exploration may significantly change their relative scores. In this case, more search and computations are needed before the top-$k$ elements are identified.

5.4 Qualitative comparison

We compare now the answers of our $S3_k$ algorithm and those of TopkS from a qualitative angle. $S3_k$ follows links between documents to access further content, while TopkS does not; we term graph reachability the fraction of candidates reached by our algorithm which are not reachable by the TopkS search. Further, while $S3_k$ takes into account semantics by means of semantic extension (Definition 2.1), TopkS only relies on the query keywords. We call semantic reachability the ratio between the number of candidates examined by an algorithm without expanding the query, and the number of candidates examined with query expansion. Observe that some $S3_k$ candidates may be ignored by TopkS due to the latter’s lack of support for both semantics and connections between documents. Finally, we report two measures of distance between the results of the two algorithms. The first is the intersection size, i.e., the fraction of $S3_k$ results that TopkS also returned. The second, $L_1$, is based on Spearman’s well-known foot rule distance between lists, defined as:

$$L_1(r_1, r_2) = 2(k - |r_1 \cap r_2|)(k + 1) \sum_{i \in r_1 \cap r_2} |\tau_j(i) - \tau_2(i)| - \sum_{i \in r_1 \setminus r_2} \tau_1(i) - \sum_{i \in r_2 \setminus r_1} \tau_2(i)$$

where $\tau_j(i)$ is the rank of item $i$ in the list $r_j$.

The averages of these 4 measures over the 8 workloads on each instance appear in Figure 8. The ratios are low, and show that different candidates translate in different answers (the low $L_1$ stands witness for this). Few $S3_k$ results can be attained by an algorithm such as TopkS, which ignores semantics and relies only on the shortest path between the seeker and a given candidate.

5.5 Experiment conclusion

Our experiments have demonstrated first the ability of the $S3$ data model to capture very different social applications, and to query them meaningfully, accounting for their structure and enriching them with semantics. Second, we have shown that $S3_k$ query answering can be quite efficient, even though considering all paths between the seeker and a candidate answer slows it down...
w.r.t. simpler algorithms, which rely on a shortest-path model. We have experimentally verified the expected impact of the social damping factor $\gamma$ and of the result size $k$ on running time. Third, and most importantly, we have shown that taking into account in the relevance model the social, structured, and semantic aspects of the instance bring a qualitative gain, enabling meaningful results that would not have been reachable otherwise.

6. RELATED WORK

Prior work on keyword search in databases spreads over different research directions:

Top-k search in a social environment uses UIT models [18, 21, 30] we outlined in Section 1. Top-k query results are found based on a score function accounting for the presence of each keyword in the tags of a candidate item, and a simple social distance based on the length of the social edge paths; query answering algorithms are inspired from the general top-k framework of [8]. As documents are considered atomic, and relations between them are ignored, requirements R1, R2 and R4 are not met. Further, the lack of semantics also prevents R5. Recent developments tend to focus on performance and scalability, or the integration of more attributes such as locality or temporality [7, 16], without meeting the abovementioned requirements. Location and time can be added to generic scores but this is outside of the scope of this paper.

Semi-structured document retrieval based on keywords relies mostly on the Least Common Ancestors approach, by which a set of XML nodes containing the requested keywords are resolved into one result item, their common ancestor node [6, 23]. This field pioneered by [11], encompassed by our model, generalizes LCA constraints but lacks both social and semantics, and thus meets only R2. Other recent developments in this area, including more flexible and comprehensive reasoning patterns, have been presented in [2] but have the same limitations. IR-style search in relational databases [12, 13] considers key-foreign key relationships between items, but ignores text structure, semantics, and social aspects.

Semantic search on full-text documents, either via RDF [15, 25] or a semantic similarity measure [24], allows to query interconnected, semantic rich unstructured textual documents or entities, thus meeting R1, R5 and R6. Efforts to consider XML structure in such semantics-rich models [9] also enable R2.

Personalized IR in a social context adapts the answers to a user’s query, taking into account her interests and those of her direct and indirect social connections [5]; this meets R1 but not R2 nor R3.

All the aforementioned models can be seen as partial views over the S3 model we devised, and they could easily be transcribed into it modulo some minor variations; for instance, Facebook’s GraphSearch [7] is a restricted form of SPARQL query one could ask over an S3 instance. Slight adaptations may be needed for social contexts tolerating similarity between keywords that goes beyond the strict specialization relation (in RDF sense) we consider. We have hinted in Section 2 how this could be included.

7. CONCLUSION

We devised the S3 data model for structured, semantic-rich content exchanged in social applications. We also provided the S3k top-k keyword search algorithm, which takes into account the social, structural and semantical aspects of S3. Finally, we demonstrated the practical interest of our approach through experiments on three real social networks.

Next, we plan to extend S3k to a massively parallel in-memory computing model to make it scale further. We also consider generating user-centric knowledge bases to be used in S3k, to further adapt results to the user’s semantic perspective.

References