Downscaling Entity Registries for Poorly-Connected Environments

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Abstract. Emerging online applications based on the Web of Objects or Linked open Data typically assume that connectivity to data repositories and entity resolution services are always available. This may not be a valid assumption in many cases. Indeed, there are about 4.5 billion people in the world who have no or limited Internet access. Many data-driven applications may have a critical impact on the life of those people, but are inaccessible to those populations due to the architecture of today's data registries. In this proposal, we point out the limitations of current entity registries when deployed in poorly connected or ad-hoc environments. We then outline a research agenda based on a hybrid model mixing decentralized and hierarchical infrastructures to support data-driven application in environments with limited Internet connectivity.

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Christophe Gueret is a researcher at the Vrije Universiteit Amsterdam. His research interests are in the publication and consumption of Linked Data, the analysis of complex data networks, and the interplay between Semantic Web challenges and Computational Intelligence techniques. He is a renown expert in the fields of Linked Data publication and analysis. He is currently leading the SemanticXO project, which aims to provide an infrastructure to support data-driven processes for the XO computers in the context of the One Laptop per Child (OLPC)[3] initiative.

3 Description of the Proposed Research Problem

Data registries are critical components of today's Internet architecture and are widely used in every-day Web activities. For example, domain name registries are databases containing registered Internet domain names. They are necessary for all Web users wishing to visit a website knowing its URL (e.g., hostname) rather than its IP address. Thanks to the Domain Name System (DNS) infrastructure,

[3] `http://one.laptop.org/`

such information can be obtained by recursively resolving a domain name to an IP address.

Another example of registry is the Digital Object Architecture (DOA, see Section 6). It allows to assign unique identifiers to digital objects (e.g., scientific publications) which can then be univocally accessed by users. Their identity will thus last in time even if their physical location may change (similarly to the IP address associated to a domain name, which often changes over time).

In addition to those traditional registries offering hash-table like functionalities, online infrastructures and applications are increasingly turning to more flexible registries containing information about general objects or entities (i.e., *object registries* and *entity registries*) to power data-driven applications. Emerging examples of that trend are DBPedia[4] and Freebase (now owned by Google)[5] which, given an entity identifier (e.g., a URI), provide semi-structured metadata about the entity. Another example are the registries used for the Web of Objects, which mediate information between networks of digital devices connecting to each other, enabling information publication or integration in sensor networks or smart building contexts for example.

In situations where such registries are not continuously accessible, however, the user experience can be strongly limited. As a basic example, if the DNS server used by a client computer is not connected to the rest of the DNS hierarchy, then a very restricted set of Internet domains can be resolved to their IP addresses. In an object registry context, discontinued access to the registry typically results in the impossibility to publish data or issue object queries.

In this proposal, we argue that data registries increasingly represent an essential part of today's Internet ecology (see Section 6 for a few examples), but that their current architecture precludes their use in many important contexts. For example, we can envision ad-hoc environment where the nodes self-organize without having access to third-party registries. In such transient and poorly-connected environments, nodes have a clear need to discover, connect, and exchange (structured) information with related entities locally and should be able to do so without resorting to any outside registry. Another interesting context is data-intensive object applications, where nodes have to discover and exchange data about very large numbers of entities and should be able to do so in a peer-to-peer manner whenever possible.

In the rest of this proposal, we propose to systematically explore a different, hybrid architectural approach to overcome the limitations of existing registry solutions for poorly connected environments. First, we point out the limitations of current registry architectures, before proposing a research agenda towards a solution taking into account limited connectivity and enabling the management of digital information in ad-hoc and poorly connected environments. We plan to design, implement, and evaluate our hybrid entity registry architecture in real ad-hoc deployments. As a starting point, we plan to focus on the OLPC XO context to provide a working solution and enable Open Data and Linked Entity

[4] http://dbpedia.org/
[5] http://www.freebase.com/

applications for the billions of people who are currently cut-out of wide area networks.

4 Description of the Significance and Relevance of the Problem to Global Internet Availability and/or Infrastructure for the Developing World

There are about 4.5 billion people in the world today who have no or limited Internet access. In addition, there are increasingly many contexts where Internet access is only intermittently available, for instance for sensor networks, mobile applications, or environments where the Internet connection is shared and restricted. In such contexts, supporting alternative registry solutions is *essential* to support all data-driven application relying on the publication or querying of semi-structured entities or objects. As a concrete example, we present below the issues we faced in the context of the One Laptop Per Child project.

4.1 Use case: Internet-less Mesh Networks

A rapidly increasing number of applications—such as open social applications, applications relying on governmental data (data.gov) or Linked Open Data[6]—assume an ubiquitous and continuous access to the Internet in order to power data sharing and data-enabled applications. As pointed out in our previous work [9], this is not a safe assumption as there is more than half of the world's population who is cut-out from wide area networks. However, people who do not have access to the Internet still generate data and need to consume knowledge. For example, children who benefit from the "One Laptop Per Child" organization project, which aims at providing low-cost laptops (called XO) to developing countries, can be connected to each other. XO laptops are used at school while connected to school servers, but also at home where connectivity typically cannot be ensured. In such networks, access to centralized registries (e.g., DNS or global object registries) is intermittent at best. When functionalities based on such registries are needed (e.g., entity resolution or entity linking), they have to be emulated or replaced within the local network, and then possibly integrated to the centralized infrastructure when the link to the wide-area network is reestablished.

We can for example imagine a XO laptop connected to a server (e.g., at school) downloading some Web pages or Wikipedia articles. Afterwards, the laptop is moved to a different location with no Internet connectivity but with the possibility to connect to other XO laptops. This scenario enables the sharing of previously downloaded documents with others who had no possibility to obtain them from the Internet, and the local publication of new entities.

In this context, it is often important to identify entities in all documents to enable entity-centric document aggregation, semantic of faceted search. Such aggregations may, for example, support learning applications that present the

[6] `http://linkeddata.org/`

set of documents users should read when they want to learn about a specific entity (e.g., "Malaria").

Extraction entities from HTML text may be performed automatically by tools running on the XO laptops or even manually exploiting crowdsourcing, which can address the problem of limited computational resources available [6]. After an entity occurrence is identified in the text, it has to be uniquely identified by associating it with the right entity ID in order to foster automated processing. XO users can also create new entities themselves (e.g., through data acquisition, document authoring or enrichment), which then should be propagated and shared to the rest of the local community. For those different tasks, an entity registry containing a relevant set of entity descriptions and identifiers is necessary to streamline and support all data-driven applications in the ad-hoc network.

5 Description of the Proposed Research Methodology

This proposal addresses the problem of data sharing and resolution problems in ad-hoc or intermittently-connected environments. Specifically, we plan to focus on the problems of entity publication and entity resolution when only intermittent connectivity is available. Entity publication refer to the dissemination of (new) semi-structured data about a given entity using a repository (hence, we support a full *read-write* model, contrary for example to the current DNS, which is *read-mostly*). Entity resolution, on the other hand, refers to the retrieval of entity metadata given an entity key (such as a hostname, a URI, or a label).

We envisioned several potential solutions to this problem [5], like lazy-replication or solutions based on IPV6 technologies. In the following, we outline what we believe is the ideal solution to our problem, that is a hybrid architecture based on Distributed Hash Tables and eventual consistency principles to support entity registries in ad-hoc settings while still supporting synchronization with a centralized infrastructure whenever available.

5.1 Decentralized Entity Registry

Distributed Hash-Tables (DHTs), such as Chord[7] or our P-Grid system [1], provide decentralized, scalable hash-table-like functionalities that could be used to store entity identifiers as well as related meta information in ad-hoc environment. Through dynamic load-balancing and replication, those networks provide fault-tolerant and efficient networking primitives where arbitrary requests can typically be resolved in $O(log(N))$ messages, where N is the number of nodes in the P2P network, from any entry point to the network.

P2P technologies have been proposed in the past to enhance or supplant DNS infrastructures[8], most often to provide an alternative to ICANN or to support

[7] `http://pdos.csail.mit.edu/chord/`

[8] see for instance `http://blogs.computerworld.com/17444/p2p_dns_to_take_on_icann_after_us_domain_seizures`

P2P file exchange. Most of such efforts had limited success so far. We think that the CoralCDN [7] system, in particular, is relevant to our scenario, since it takes advantage of highly efficient P2P mechanisms (P2P DNS and distributed sloppy hash tables) to create content distribution networks. It however suffers from several severe limitations in our context, including some reliance on high-bandwidth and wide-area connectivity and the lack of mechanisms to serve structured entity content.

We thus plan to consider a DHT-based CDN as a starting point, but will enhance the infrastructure with a native entity storage system (such as our recent dipLODocus system [10]), and with semi-structured capabilities (e.g., supporting declarative queries, extending for instance our GridVine query execution mechanisms [3]).

Using this infrastructure, we will then explore the best possible way to support both entity publication and entity search in ad-hoc networks. Entity publication will be based on gossiping mechanisms to inform the neighborhood of a peer that new entity metadata is available. Entity search, on the other hand, will be based on a mix of several indices (structured inverted indices, triple-table indices) to efficiently answer all queries.

The performance evaluation of this decentralized entity registry will follow standard principles. We plan to study and optimize the performance of our system under churn, using the open-source OLTPBench infrastructure[9] that we recently published.

5.2 Caching & Eventual Consistency

Even though supporting a full-fledge entity registry in ad-hoc settings is a necessity, there are many cases where some of the nodes might connect to centralized infrastructures intermittently. Thus, we believe that it is also essential to be able to cache authoritative or centralized information, and to be able to dynamically synchronize data with such infrastructures.

In that context, we plan to study two main problems. First, efficient caching of authoritative entity data. Depending on the context of the application, some core nucleus of the entity data can be identified (e.g., DBPedia entity data for Linked Open Data). In such a case and if the entity nucleus can be bulk-installed on each node, then many of the entity operations can be resolved locally without resorting to any third-party infrastructure. The main research issues we plan to tackle in that context are to identify such a nucleus automatically, and to efficiently bulk-load the data. Once available on one node of the ad-hoc environment, the entity nucleus should be replicated to other nodes appropriately in order to provide high-availability of entity data even if the network gets partitioned or some of the nodes go offline.

The second problem we want to study deals with data synchronization and consistency. In that context, we will in particular study the important problem of de-duplicating entity data (i.e., detecting and removing duplicates in decentralized settings). Also, we plan to design efficient bulk-synchronization mechanisms

[9] `http://oltpbenchmark.com/`

(based for instance on hashes or sketches) to restore consistency with the centralized or hierarchical registry whenever it is available. In that sense, we will support *eventual* (or t-connected [8]) consistency models when possible. Our solution will be evaluated by running live experiments in ad-hoc environments and by measuring the time taken to reestablish data consistency using different techniques.

6 Description of any Known Related or Similar Research and Innovative Aspects of this Proposal

There already exists many solutions to resolve entity names and/or get structured information about entities. One example of entity registry has been proposed in the context of the Okkam project[10], where the envisioned system stores a number of entity profiles which can be accessed via keywords or structured queries. More recently, the popularity of Linked Data made it possible to connect large entity datasets and to make them accessible via open (SPARQL) endpoints. Additionally to these, we can imagine the adoption of well established platforms like, for instance, DNS or DOA and to extend such technologies to entity registries.

6.1 DNS

The Domain Name System (DNS) is the system used on the Internet to resolve domain names to their corresponding IP addresses. Domain resolution works in a hierarchical manner; the top of the domain name space is served by so-called *root* name servers, pointing to *authoritative* name servers maintaining authoritative information for the top-level domains (a.k.a. "TLDs", such as ".ch" or ".com"). The authoritative name servers responsible for the TLDs point in turn to further name servers, responsible for second-level domains (e.g., "unifr.ch"), and so on and so forth to process each domain name label iteratively until the last iteration, which returns the IP address of the domain name queried. In practice, domain names are often cached at various levels, for instance at the client-side, or at the level of the DNS server provided by the Internet Service Provider in order to limit the load on authoritative DNS servers.

Though originally not designed for this purpose, it is be possible to extend the current DNS infrastructure to create a full-fledge entity registry. In that context, we recently suggested an extension of the DNS [4] to serve authoritative metadata about Internet domains, leveraging both the DNS Text Record field (DNS TXT) and new cryptographic features (DNSSEC).

6.2 DOA

The aim of the Digital Object Architecture (DOA)[11] is the management of digital entities in a network over potentially very long timeframes. There are three distinct components in the DOA:

[10] `http://www.okkam.org/`
[11] `http://www.cnri.reston.va.us/doa.html`

– Resolution System (Handle System)
– Digital Object Repository (DORepository)
– Digital Object Registry (DORegistry)

The principal function of the Handle system is to map known identifiers into handle records, containing useful information about the digital object being identified (e.g., IP address, public key, URL etc.). Every identifier has two parts: a naming authority (or prefix) and a unique local name under the naming authority suffix, separated by / (e.g. "10.1045/january99-bearman").

The collection of all local names defined under a certain prefix defines the local handle namespace under that prefix (something similar to a root zone in the case of DNS). The DORegistry provides services like browsing, searching, repository and federation for collections of digital objects that can be distributed across multiple sites including other DO Registries. The DO Registry can be set for different types of metadata schemata and can be customized to provide different search, federation, handle registration, event management and other services.

The most popular application of this system is the use of Digital Object Identifiers (DOIs) to identify digital versions of written publications (e.g., scientific articles). Such identifiers, by means of an ID resolution, will lead not only to the digital object but also to its metadata. The important benefit of using DOIs are persistent citations (i.e., the location of the digital object may change over time but the identifiers will remain the same and its resolution will lead to the new location).

6.3 Linked Data

The Linked Data movement[12] has been pushing towards publishing and interlinking public data in standard formats, which enables the automated discovery, management and integration of structured resources online. The adopted technology is based on HTTP URIs and RDF. The resolution of an entity given its identifier boils down to three steps in that context:

1. discovering the IP address where the HTTP URI is supposed to be hosted (for example using the DNS)
2. contacting the corresponding server and negotiating the content (e.g., to serve a human-readable version of the RDF data if the client is a Web browser)
3. retrieve the structured description of the entity over HTTP.

This process is commonly called entity *dereferencing* since it is similar to general URI dereferencing on the Web[13].

[12] http://linkeddata.org/
[13] http://www.w3.org/2001/tag/doc/httpRange-14/2007-05-31/HttpRange-14

6.4 The Entity Name System

In the context of the Okkam project, the Entity Name System (ENS) [2] has been proposed. It is defined as a service to resolve entity names to their global identifiers (called Okkam IDs). This is made available thanks to a repository of entity profiles described as a set of attribute-value pairs, and a mix of matching components that select the correct identifiers for an entity request which may be submitted in the form of a structured (i.e., attribute-value) or unstructured (i.e., keyword) query.

6.5 Limitations of Current Entity Registries

The existing data and entity registries are a critical asset for many Internet applications. However, all current architectures present limitations when we consider a situation with limited network connectivity or ad-hoc environments. If we imagine networks of computers with no connectivity to external Internet resources, it becomes clear that DNS-based entity registries typically do not work properly as only partial information will be cached in local and accessible DNS nodes. Moreover, data in the cache may not be up-to-date as DNS nodes may not frequently communicate with the rest of the DNS infrastructure. Similarly, clients may not be able to resolve DOI if the servers of the naming authority which issued such IDs is not reachable through the network. Entity registries like the Okkam ENS or LOD end-points are all based on centralized solutions which limit their reliability: In ad-hoc environments, such central resolution points may or may not be reachable at a given point in time.

For the reasons mentioned above, we claim that a decentralized, hybrid solution enriched with full replication of some seed content and dynamic synchronization would be a better approach for an entity registry in ad-hoc environments. A decentralized system based, for example, on structured P2P networks can provide better connectivity thanks to cheap P2P communications and can tolerate the situation in which registry servers are not constantly available.

7 Description of Deliverables

D1 [Month 2]: State-of-the-art in Entity Registries and Entity Resolution
D2 [Month 5]: First prototype and performance evaluation of the local entity registry
D3 [Month 8]: Decentralized entity registry with dynamic replication
D4 [Month 15]: Deployment of the decentralized entity registry on XO laptops with support for entity publication, entity search, and eventual consistency with a centralized architecture.

8 Proposed Timeline

The bulk of our work will be spread over a 12-month period. Our work will be divided in two work packages, one per Ph.D. student working on the project.

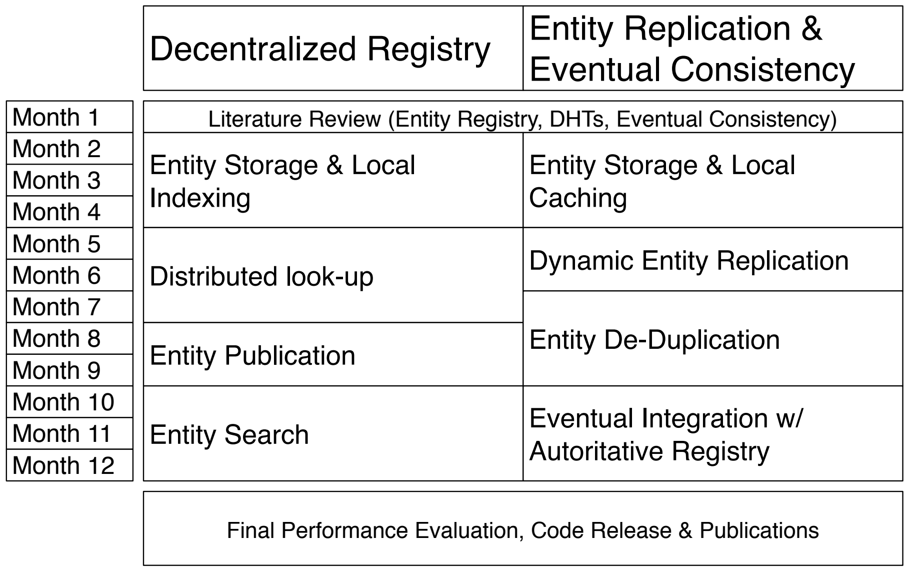

Fig. 1. Project Timeline

The first Ph.D. student will be responsible for designing, building and evaluating the decentralized entity registry based on a DHT an on a local, native, entity storage back-end (see Section 5.1). The second Ph.D. student will work in parallel on entity caching, replication, de-duplication and *eventual* integration with a central hierarchical repository (see Section 5.2). Our complete timeline is shown in Figure 1. This is obviously a rather tight schedule, following the timeframe allowed by the program. However, we believe that our research plan is realistic, given the strong expertise that we have in the fields related to our proposal.

9 Proposed Allocation of Research Grant Funds

If our application is successful, we plan to use the allocated research funds as follows:

70'000$ [**x 2**] **:** salary + overheads for two Ph.D. students working full-time on the project during one year

10'000$: budget for conference presentations & travels

10'000$: XO laptops, deployment server

40'000$: the rest of the budget will be spent to support the salary of an engineer working part-time and helping the Ph.D. students to implement and deploy the registry.

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