The Entity Registry System: Implementing 5-Star Linked Data Without the Web

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Abstract. Linked Data applications often 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 Web 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 paper, we propose and evaluate a new open-source system that can be used as a general-purpose entity registry suitable for deployment in poorly-connected or ad-hoc environments.

1 Introduction

There is an estimated number of 2 billion individuals that have access to the Internet and can thus use centralized cloud hosted solutions for sharing data. Many of these centralized solutions are well-known (Facebook, Wikipedia, WikiData, etc.) and make it possible to share semi-structured data about online entities. Unfortunately, the populations who do not have seamless data connectivity cannot rely on such data sharing solutions even if they have computers that are interconnected through local mesh networks.

The OLPC (One-Laptop-Per-Child) initiative³ is bringing Information and Communication Technology (ICT) to young learners in the poorest areas of the world so that necessitous children can benefit from using ICT tools to develop new skills too and from working collaboratively using multi-media applications. So far, two million children world-wide have been introduced to ICT by the OLPC foundation. Studies have shown that such programs lead to an increase of the children’s problem solving capabilities and general computer skills.

One important technical problem remains, however: all the data created by the children on their learning devices (e.g., OLPC XO-1) stays on the device. The devices are most often used in a closed network, disconnected from the Internet, and all sharing mechanisms are synchronous. In addition to the XOs, there is an increase in the amount of low-resource computing devices (PlugPCs,

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³ http://one.laptop.org/
tablets, etc.) that are made available to increase the ICT reach to those that currently cannot benefit from it.

Due to the broader availability of devices, new problems arise. Even if everyone gets an Internet-enabled device, not everyone will actually get seamless access to the Internet in developing countries. Most notably, there are even some cases where countries are deliberately cut from the Internet for political or cultural reasons.

Accelerating the adoption of Linked Open Data (LOD) and data-intensive applications in developing regions with limited Internet connectivity hence requires adaptation to the specific challenges posed by the living conditions of those 5 billion world citizens not having constant Internet access. Among several challenges we previously highlighted [2], the Entity Registry System (ERS) project tackles the design of an entity registry that can be globally edited using a swarm of small devices interconnected in an intermittent way. The goal of this registry is to replace the Web as a platform to publish linked data whenever the latter is not available. The ERS allows linked data to be put into use in the many regions where Internet connectivity is not guaranteed.

Providing and consuming linked data without the Web yields a number of issues. In this work, we focus our efforts around the following questions:

- How can non-colliding unique identifiers for resources be minted in a uncoordinated way?
- How can data accessibility be ensured when the original data host is offline?
- What is the best internal representation for entity descriptions made of the contributions from several nodes?
- How can the registry storing all entity data be loosely-coupled to the Web?
- How can one optimize transactional synchronization for loosely-connected devices?

This project investigates these questions in the context of the use of LOD principles on XOs and PlugPCs having intermittent Internet connectivity. We have implemented and open-sourced the ERS system that enabled data sharing in mixed environments, and are now testing and deploying the system in the context of several OLPC initiatives.

The rest of this paper is organized as follows. In Section 2 we introduce the problem of data sharing and the different technical solutions to it. This section is followed by Section 3 where the Entity Registry System (ERS) is introduced along with a reference implementation (Section 4). We analyze the performances of the reference implementation in Section 5 and conclude in Section 6.

2 Sharing structured data

We consider the following task: a user wants to associate a number of properties to an entity identified with a unique identifier. This description has to be open and accessible to other users (read only or read+write depending on the situation).

The most common approach to process such a task nowadays consists in setting up a centralized server, backed up with a cluster for scalability. Every
time the application has access to that server it can modify the content of the database, creating and deleting entities as well as updating their description. While this is by far the most popular approach, its main drawback is the loss of functionality as soon as the connection to the central server becomes unavailable.

A second approach consists in adding a temporary offline storage and special synchronization routines on the client (c.f., for instance, Mendeley or Evernote desktop applications). In that way, a temporary loss of connectivity can be compensated by the use of cached data and the synchronization of edits as soon as the connection returns. This approach is particularly suitable when the loss of connection is an exceptional event and when only when a handful of individuals have access to the data. It is facilitated by recent developments of W3C recommendations (e.g., Web Storage). This approach is impractical as soon as disruptions are more frequent, or are the default mode, or when more people need to have access to the data.

Some systems assuming a perpetual un-connected state, e.g., many former-generation GPS navigation systems that solely rely on their local database. This leads to a third approach that consists in a locally accessible data source whose availability is guaranteed locally and can be made available sporadically through ad-hoc network access. The main drawback of this approach is that it is then much harder to expose the local data to other systems (c.f. PageKite4).

Figure 1 gives a simple pictorial comparison of those three approaches. Up to now, the vast majority of linked data solutions were built following a centralized paradigm: the data is put in one location and accessed by a client application hosted at another location. As mentioned above, this system architecture fails as soon as the connection becomes unavailable.

![Fig. 1: The evolution from fully centralized solution to fully decentralized alternatives](http://pagekite.net/)

With ERS, we aim to provide a local system that can also operate in connected settings. In our approach, we want to seamlessly transition from decentralized to centralized settings depending on the current connectivity. We model a group of XOs/PlugPCs/Tablets/etc. as a swarm of devices that operate in a finite context. Even though Internet connectivity is limited, we assume devices can directly communicate (e.g., through a mesh network or an infrastructure network in a class room).

4 [http://pagekite.net/](http://pagekite.net/)
In the following, we first give an overview of the system in Section 3, and then describe our reference implementation in Section 4.

3 The Entity Registry System (ERS)

The Entity Registry System (ERS) for storing semi-structured descriptions of entities is designed around lightweight components that collaboratively support data sharing and data-intensive applications in intermittently connected settings. It is compatible with the RDF data model and makes uses of both Internet and local networks to share data, but does not base its content publication strategy on the Web. No single component is required to hold a complete copy of the registry. The global content consists of the union of what every component decides to share.

3.1 Components

ERS is articulated around three types of components: Contributors, Bridges, and the Global Server. The components can be deployed on any kind of hardware ranging from low-cost computing devices such as the RaspberryPi\(^5\) to fully-fledged data centers.

"Contributor" component Contributors read and edit the contents of the registry. They may create and delete entities, look for entities, and contribute to the description of the entities. Every contribution made by a contributor is identified by its name within the system so that the collectively-created description of an entity can be traced back to individual contributions. Contributors are free to make any statement about any entity in the system. They use a local data-store in which they persist the description of the entities.

Contributors can also cache the contribution of others. In particular, a data replication mechanism ensures that the descriptions of entities relevant to a contributor are made available on his own store. For example, a contributor storing some properties for an entity \(X\) will trigger a synchronization process for getting everything everyone said about \(X\) for local use.

The identifier for the entities can be freely picked by developers using ERS. The only constraint is that this identifier must be a URN and contain a path, as follows: \texttt{urn:ers:<path>:<identifier>}. The path can be a UDC class\(^6\), the name of the software that created the entity, a FQDN from the LOD. Part of the goals of the project is to investigate how some URNs end up being preferred over others as part of a collaborative reinforcement process similar to the one driving data sets re-use on the LOD [4]. We choose URNs because the identifiers are not meant to be resolvable outside ERS, an optional "global server" can establish the connection between ERS and the Web of Data.

\(^5\) http://www.raspberrypi.org/

\(^6\) http://www.udcc.org/
"Bridge" component Bridges do not directly contribute to the content of the registry. They are used to connect isolated closed networks and improve the availability of the individual descriptions shared by the contributors. Bridges can theoretically store content coming from any contributor, but will typically store the data only for a limited amount of time (e.g., using soft states) due to their limited capacity. To summarize, bridges have two core functionalities: distribution of local data in semi-connected networks and synchronization to other closed networks.

The synchronization process with the bridges is simple and consists in i) sending to the bridge every new description from the contributors, and ii) getting back descriptions that are useful to the devices (that is, retrieving data for entities that the contributors have already considered or are requesting).

The major challenge for the bridges is to maintain the integrity of the data they store. Therefore, the goal is to provide the right transaction mechanisms that allow to maintain a consistent state of the data and the best possible performance even when multiple contributors are editing and looking-up the entities. Another goal is to achieve a separation of concern by leveraging the knowledge about the different contexts defined by the distinct contributor networks.

"Global server" component ERS deployments can feature any number of bridges and contributors. In addition, some use-cases may require the presence of a global server that contains a copy of all the data provided individually by the contributors. The global server provides a single, read-only, entry point to the registry. It exposes the contents of the ERS to other systems, for instance to the Web of Data. This global server is connected to the bridges and keeps copies of everything that transits through them. Like the bridges, the presence of this global server is optional.

When used, the global server harvests data from the bridges. The server aggregates the individual contributions every contributor made to the entities and expose this information as an integrated, read-only, dataset. The main challenge for the global server is scalability (c.f. Section 5).

3.2 Usage

Figure 2 shows an example deployment featuring three different physical locations, 8 contributors, two bridges, and a global server. The contributors are devices creating, consuming and storing structured data about entities. One bridge is used to ensure information flow and data distribution between the nodes of “physical location 2” (exhibiting poor connectivity) and those of “physical location 1”. The second bridge is located in a separated network where both physical locations can connect to. In this scenario, the second bridge is used for synchronization and data flow between the two separated networks. The global server is used to expose the entities within ERS as de-referencable HTTP URIs.

Concretely, ERS can for instance be used for asynchronous sending of messages between XO laptops in schools or collaboratively editing a multi-lingual corpus.
Mailing application  The mailing application lets every XO having ERS installed on it send and receive mails with any other XOs. To send a mail, the software creates a new entity and associates to it the message, the name of the creator and the name of the target device. This description gets then automatically replicated to the target device, eventually transiting through a bridge. On the receiver side, the messaging application only has to display in the receive box every entity description that has been targeted for this device but created by another device. Links between messages can be established by referring to the unique identifiers of the entities.

Multi-lingual tagging  With the increase of connectivity and the pressure towards the uniformization of communications, there is a need for crowdsourcing language preservation and cultural heritage [1]. In this scenario, ERS is used to power up a social gaming where users can tag items with the name of that item in their own language and also connect items to each others to group them. A user can play that game at School, take the game back home and continue playing it with his parents, and then return to school to share the new results with his peers. ERS also makes it easy to gather the globally crowdsourced content by monitoring the content of bridges or using a global server.

4 Reference implementation

In this section, we give a detailed overview of the reference implementation of ERS. All of the concepts we mention in this paper are implemented and available as open source code from the “ers-devs” group on GitHub⁷. The following description is organized around three subsections, each of them describing one of our components in more detail.

⁷ [https://github.com/ers-devs](https://github.com/ers-devs)
4.1 Contributors

We choose to use CouchDB\textsuperscript{8} to persist all the data locally and perform the different synchronizations. The main advantage of CouchDB is that it provides built-in mechanisms for flexible replication of the data using the ad-hoc mesh network capabilities of the XO laptops. The CouchDB replication system can be configured to match our needs (create triggers and filters based on the descriptions).

Internally, CouchDB defines \textit{documents} that are used to store and replicate payloads of JSON data. There are different encoding choices that can be made to use this system to store RDF data. Taking our inspiration from previous work (\textit{LD-In-Couch}\textsuperscript{9}), we experimented with different storage representation.

\textbf{Storing of predicate/object pairs} The two options here are reified statement or array of values. We want to allow several values to be associated with the same property. As properties are unique in CouchDB, this is only possible by either storing all the values as an array or storing an array of properties coupled with an array of values. Let us consider the following N-Quads:

\begin{verbatim}
 ers:message1 ers-prop:body "hello world" ers:xo1 .
 ers:message1 ers-prop:to ers:xo2 ers:xo1 .
 ers:message1 ers-prop:to ers:xo3 ers:xo1 .
\end{verbatim}

These can either be expressed using the predicate as keywords (Listing 1.1) or two synchronized arrays (Listing 1.2).

\begin{verbatim}
Listing 1.1: JSON Model 1 - use predicate as key
{
  "_id": "message1 xo1",
  "body": ["hello world"],
  "to": ["xo2", "xo3"]
}
\end{verbatim}

\begin{verbatim}
Listing 1.2: JSON Model 2 - use two synchronized arrays of p/o values
{
  "_id": "message1 xo1",
  "p": ["body", "to"],
  "v": ["hello world", "xo2", "xo3"]
}
\end{verbatim}

An estimate of disk space required for storing the standard \textit{SP2}bench dataset using these serialization models is given in Table 1. For this experiment we switched off the database file compression in CouchDB. Disk usage is very similar in all three cases and thus not a decisive factor.

\textbf{Usage of documents} We also considered several options for storing entities using CouchDB:

\textsuperscript{8} \url{http://couchdb.apache.org/}
\textsuperscript{9} \url{https://github.com/mhausenblas/ld-in-couch}
| Serialisation | Size (kB/1K triples) |
|---------------|----------------------|
| N-Triples     | 157                  |
| Model 1       | 143                  |
| Model 2       | 157                  |
| Document per quad | 418                |

Table 1: Storage requirements of different serialization models.

1. **Create one document per entity.** Every contributor will be updating the same document associated to a particular entity he/she wants to edit. This approach gives good read performance, as all the data needed by a contributor interested in the entity is available in one go. However, synchronization becomes extremely problematic because documents must be merged during replication while accounting for users with different access rights editing various parts of a document at different times. CouchDB does not have out-of-the-box support for such features (it can only replicate documents without transformation). Moreover, some entities can grow very large despite only a small portion of them ever being queried or modified. This leads to inefficient I/O and disk space usage, especially since CouchDB updates by appending new versions at the end of the documents.

2. **Create one document per contribution made to the description of an entity.** In RDF terms, this translates to one document per entity x graph combination. The synchronization process only has to ensure documents are made available as is to the nodes that need them, since in our system, a graph can only have one author and one set of R/W permissions, and thus the potential for conflict is essentially eliminated. I/O and disk space are better used, as only portions of a entity that have changed are transmitted. Read performance, however, will be worse because a client will now have to do several lookups to fetch and load all the documents describing a particular entity.

3. **More granular approaches,** such as one document per graph-entity-property combination, or even one document per quad. These offer little benefit, as the I/O and storage overhead as well as the read performance quickly become unacceptable.

We performed several experiments to help us pick the best solution, and in the end chose **one document per graph-entity combination** as the best of both worlds in terms of complexity and performance.

### 4.2 Bridges

We now describe the intermediate level in our global system architecture, the Bridges.

Implementation-wise, Bridges are actually very similar to Contributors. They use the same internal data model and are also based on CouchDB. The main difference is in the contributor-bridge and bridge-bridge synchronization rules. The three situations are presented here for comparison:
**Contributor-Contributor Synchronisation** Apart from their locally generated data, contributors only accept annotations that are specifically addressed to them (by marking the corresponding graph with a specific property). Contributors make public all data that is not explicitly marked as private. Contributors also temporarily cache the results to recent queries. Therefore, through either replication or querying its neighbors, a contributor has access to:

1. The public data authored by the neighboring contributors
2. The data specifically addressed to it by any contributor in the system
3. The recently accessed data (if the query is made public) of all the contributors in the neighborhood. This effectively produces a distributed cache that greatly accelerates access to common data.

**Contributor-Bridge Synchronisation** Unlike a Contributor, a Bridge accepts *all* non-private data from nodes connected to it. All data in a Bridge is made available to connected contributors. The Bridge does not contribute any data itself and is generally headless (i.e. has no GUI for data input).

Note that a Bridge also accepts cached query data. Due to its larger storage capacity (which is needed anyway because it aggregates data from multiple Contributors), a Bridge can afford to maintain a larger cache for a longer period of time, and can thus act as a sort of second-level cache. Note also that no data on a Bridge is stored permanently - data that has not been needed for a long period of time is garbage-collected to make room for new information.

**Bridge-Bridge Synchronisation** Bridges also share all data between them, with no authorship filters, except for the cached query data. This is because such data is generally only useful at a local level (e.g., within a classroom). A cache acting on a more global level would be too large, and this role is mostly fulfilled by the global server anyways.

### 4.3 Global server

The last element in our reference implementation is the so-called *Global Server*. While other elements in the hierarchy are centered around sporadic or ad-hoc connectivity, a *Global Server* is an optional, always-on component. A single instance of a *Global Server* might not always store the entirety of data, but can store references to other servers providing such information, thereby acting like a typical registry for non-local content. Relaying data from other instances does not require caching on the server, since we assume the other global servers will be always available.

Due to the distributed nature of how data is processed, cached and forwarded in ERS, providing a consistent storage layer is not trivial. To achieve the desired consistency, we implemented a transaction layer on top of our data store. Using traditional distributed transaction schemes from relational database management systems is out of scope for us for two reasons: First, allowing multi-side distributed transactions would severely slow down the overall performance, and second, even if the *Global Server* is considered to be always available, this is not
true for contributing bridges. Thus, the goal must be to achieve the best possible throughput on slow dial-up connections even if the connection is dropped multiple times.

The foundation for the storage layer of the *Global Server* is a cluster of Apache Cassandra nodes with an additional abstraction layer for storing RDF inside the cluster based on CumulusRDF [3]. While Cassandra natively offers no support for transactions or atomic operations on data stored in the cluster, we added support for atomic operations in the RDF layer.

The overall data model of the entity registry is shown in Figure 3. There are two important semantic properties that are visible in this figure. First, the properties of specific entities have no connections between each other, this means that for a given triple \( t = \{s, p, o\} \) with \( s \in S, p \in P, o \in O \) there can be no two triples that share the same predicate and object. For example, the case \( T = [t_1 = \{s_1, p, o\}, t_2 = \{s_2, p, o\}] \) is undefined because it violates this property, \( t_1 \) and \( t_2 \) sharing the same predicate and object. This effectively describes a uniqueness constrain on all triples on the \( p \) and \( o \) attributes. The second semantic property is that modifications on the graph of entities are typically separated by the context in which they operate, making it less likely that collisions between different contexts will occur. These contexts typically follow the same structure as the different contributor/bridge landscapes.

Concerning links, only connections between entities are allowed. For simplicity, a connection between an entity is seen as bidirectional. On the storage side we model this as two entries in the graph, one describing the original connection and a second entry describing the inverse relation. This allows us to navigate the path in both ways and to keep the original semantics about how the connection was created.

![Fig. 3: Entity Model Overview](image)

Inside our thin application layer sitting on top of Cassandra, we define the following atomic operations: *Insert entity (IE)*, *Insert property of an entity (IP)*, *Update property of an entity (UP)*, *Delete property of an entity (DP)*, *Delete entity (DE)*, *Shallow entity copy (SC)*, *Deep copy of an entity (DC)*, *Insert bidirectional link between two entities (IL)*, *Delete link between two entities (DL)*.
Since transaction support must be implemented on a higher level we define a multi-level locking scheme that allows hierarchical locking of the different elements of an entity. In contrast to traditional relational databases our locking approach has the possibility to lock an entity even if it does not exist by referencing the unique ID of the entity in our lock table. This allows a strict serialization of conflicting operations, even for insertions. The two hierarchical locks are: $L_{E+P}$ and $L_E$. The former locks based on the entity ID and the property, while the latter locks the complete entity. While two $L_{E+P}$ locks can be compatible in case they differ in one of the two parts, two $L_P$ locks are not compatible. Table 2 shows the compatibility for all kinds of operations with these different lock types. Since all property locks are compatible we can achieve a high throughput for most of the incoming operations. For the two lock types, we match the following operations. Using the fine granular $L_{E+P}$ we can run the following operations: IP, UP, DP, SC, IL, DL. Using the $L_E$ lock we can execute: IE, DE, DC. For links and shallow copies the matching property is either sameAs or linksTo. We experimentally test the performance of such atomic operations in the following.

|                  | $L_{E_a+P_c}$ | $L_{E_a+P_d}$ | $L_{E_b+P_c}$ | $L_{E_b+P_d}$ | $L_{E_a}$ | $L_{E_b}$ |
|------------------|---------------|---------------|---------------|---------------|-----------|-----------|
| $L_{E_a+P_c}$    | ✓             | ✓             | ✓             | ✓             | ✓         | ✓         |
| $L_{E_a+P_d}$    | ✓             | ✓             | ✓             | ✓             | ✓         | ✓         |
| $L_{E_b+P_c}$    | ✓             | ✓             | ✓             | ✓             | ✓         | ✓         |
| $L_{E_b+P_d}$    | ✓             | ✓             | ✓             | ✓             | ✓         | ✓         |
| $L_{E_a}$        | ×             | ×             | ✓             | ✓             | ✓         | ✓         |
| $L_{E_b}$        | ✓             | ✓             | ✓             | ✓             | ✓         | ✓         |

Table 2: Operation Compatibility

In the spirit of web-scale NoSQL data stores we defer conflict resolution of failed transactions to the application layer.

5 Performance

This section reports on some testing we did to measure the performance of different aspects of the system under various scenarios.

5.1 Local Tests

The first tests cover the local aspect of the system, which is to say the interaction between Contributors and Bridges in particular.

Experimental Setup For the experiments in this section we used 4 OLPC XO-1 configured as Contributor nodes. The laptops run the local component of
the ERS over CouchDB 1.2.1. The XO-1 hardware platform is characterized by
433 MHz x86 AMD Geode LX-700 CPU, 256MB total RAM, and 1024 MB of
NAND flash memory. Software-wise, the laptops run a custom desktop interface
(Sugar) on top of Linux.

The laptops were configured in a mesh network that is typical of their most
frequent use case. Some experimental scenarios also include a Bridge node, in our
case a Raspberry Pi, which is a popular low-cost embedded computing platform
fitted with an ARM1176JZF-S 700 MHz CPU, 256MB of RAM and SD card
storage (8GB). The Pi also runs Linux.

**Local Read/Write Performance Under Replication** For our first experi-
ment, we set up the XOs to use the ERS API to continuously write new random
documents to their internal store, while at the same time receiving the writes
of other XOs in the mesh network through replication, as well as performing
queries in parallel. As an indication of the *read performance*, we measured the
average latency for the queries within a 5-minute period. For measuring the *write
performance*, at the end of the 5 minutes, the total number of documents in the
XO’s stores was counted. The write performance was then calculated as:

\[
\text{Write Performance} = \frac{\text{Total Number Of Documents}}{\text{NumberOfNodesInMesh} \cdot \text{ElapsedTime}}
\]

The number of nodes in the mesh was varied from 1 to 4, without a bridge
node, undergoing all-to-all (mesh) replication. One final scenario was added fea-
turing 4 nodes with star replication via a Bridge. The results are shown in
Table 3.

| Network Size | Repl. Type | Read Latency (sec) | Write Performance, docs/sec |
|--------------|------------|--------------------|----------------------------|
| 1            | all-to-all | 0.24               | 7.31                       |
| 2            | all-to-all | 0.36               | 4.65                       |
| 3            | all-to-all | 0.55               | 3.23                       |
| 4            | all-to-all | 1.01               | 2.95                       |
| 4+bridge     | star       | 0.98               | 5.56                       |

Table 3: Local Read/Write Performance Under Replication

It can be seen that all-to-all replication has a significant effect on both read
and write performance. As the number of nodes increases, the write performance
converges to about 45% of the 1-node case (which is equivalent to no replication).
However, the performance drop can be satisfactorily addressed through the use
or star replication via a Bridge node.

### 5.2 Global server

For the following experiments, we used 5 servers part of our cluster in Switzerland
(8-cores i7 Intel CPU, 8GB total RAM memory, Gigabit Ethernet, Linux kernel
3.2.0, Java SE 1.6). All of them are running a Cassandra instance with replication level 2.

In the experiments, we varied different parameters impacting the overall performance. We looked mainly at the overall throughput of our transaction implementation but in addition varied the write consistency of the cluster between ALL and ANY.

One of the machines runs the ERS Java program that was built on top of cumulusRDF. It is the access point of our ERS system as well as the central coordinator for transactional support. However, as the support is implemented at the Java application layer and not at the Cassandra level, it is not yet distributed. A future approach using ZooKeeper, Chubby or Cage is envisioned. The clients were running on a different machine to better load balance and to involve the network delay.

We use two different locking granularities as follows: for simple operations of inserts, updates, and deletes we lock at the predicate (E+P) level, but for cloning operations we lock at the entity level, since cloning operations would have involved more overhead to iterate the entire transaction and lock every triples. Thus, a coarser lock is used for this purpose.

In case a transaction has a lock contention conflict, it is aborted and restarted for a maximum of 10 times before considering it an aborted transaction.

The total dataset size we used is about 10M triples with 1M unique entities and between 8-12 properties per entity. The total size on disk is 2.7GB.

**Throughput** At first, we analyze the overall throughput of the cluster depending on the different operations we perform. We differentiate between basic operations that modify properties of existing entities and linking operations that insert a bidirectional link between two existing entities. We use a pool with a varying number of clients (2-64). For the basic operations shown in Figure 4, we can see that the throughput is maximized at around 64 parallel clients. Delete operations have the highest throughput as they only require simple marking of a record in the cluster with a tombstone by Cassandra. For linking the situation is slightly different as it requires to bundle two operations—two inserts—in one atomic operation, adding additional overhead.

Another important operation is cloning an entity. There exist two different kinds of clone operations: a shallow copy and a deep clone. While the shallow copy basically only inserts a single link between the old and the new entity, the deep copy entirely copies the current version of the set of properties and links to the new entity. Figure 5 compares the results. As expected, the shallow copy outperforms the deep copy by a factor of 2-3. Figure 5 also shows the throughput we obtain using a very cheap device (a RaspberryPI) as a bridge.

**Transaction Rate vs Conflict Rate** In a next series of experiments, we wish to observe the impact of our locking strategy on the overall transaction throughput. Therefore, we use 32 parallel clients, each executing 10k transactions sequentially. To simulate conflicts between two clients, every client uses a
Fig. 4: Throughput for different operations in ERS. All transactions per clients are executed sequentially, but all clients run in parallel.

Fig. 5: Throughput for cloning operations and throughput for using a RaspberryPi bridge.

specified list of input entities to perform either an insert of a new link, an update or a delete of a link. From the original number of 1M entities, we decrease the number of entities to choose from equally for each client. Therefore, the probability of a conflict increases. Figure 6 shows the results of this experiment. The top Figure 6a shows the transaction throughput when increasing number of conflicts. As expected, the throughput decreases, as it essentially serializes when only a single entity is used.

Figure 6b analyzes the average number of retries a successful transactions needs before it can be executed. The number of retries defines the latency of a successful transaction. It allows to not only compensate for transaction bottlenecks but for dropped connections as well.
Fig. 6: Impact of conflicts on transaction throughput. Figure 6a shows the with increasing probability of a locking conflict and Figure 6b shows the number of retries per successful transaction.

6 Conclusions

In this work, we have presented and evaluated ERS, a new entity registry system enabling the sharing and multipartite editing of entity data in poorly-connected contexts. ERS is available as an open-source package and is currently being integrated in several environments, including the Sugar desktop environment\textsuperscript{10}. Our hope is that ERS contributes to bridging the gap between highly-connected settings where LOD sharing and data-intensive applications abound, and the rest of the world (representing several billion persons), where data connectivity cannot be taken as granted.

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