The web community has introduced a set of standards and technologies for representing, querying and manipulating a globally distributed data structure known as the Web of Data. The proponents of the Web of Data envision much of the world’s data being interrelated and openly accessible for use by the general public. This vision is analogous in many ways to the web of documents of common knowledge, but instead of making documents and media openly accessible, the focus is on making data openly accessible.

Providing data for public use has stimulated interest in a movement dubbed Open Data [1]. Open Data is analogous in many ways to the open source movement. However, instead of focusing on software, Open Data is focused on the legal and licensing issues around publicly exposed data. Together, various technological and legal tools are laying the groundwork for the future of global-scale data management on the web. As of today, in its early form, the Web of Data hosts a variety of data sets that include encyclopedic facts, drug and protein data, metadata on music, books and scholarly articles, social network representations, geospatial information and many other types of information. The size and diversity of the Web of Data is a demonstration of the flexibility of the underlying standards and the overall feasibility of the project as a whole. The purpose of this article is to provide a review of the technological underpinnings of the Web of Data as well as some of the hurdles that need to be overcome if the Web of Data is to emerge as the de facto medium for data representation, distribution and ultimately, processing.

Technically, on the Web of Data, Uniform Resource Identifiers (URI) are used to identify resources [2]. For example, depending on what is being modeled, a URI can denote a city, a protein, a music album, a scholarly article or a person. In fact, in general any thing can be assigned a URI. An example URI is <http://www.lanl.gov#marko>. This URI denotes the author of this article, Marko. The URI has information pertaining to the what (marko), where (www.lanl.gov) and how (http) of a resource. The URI is more general than the commonly used URL, as URIs are not required to resolve to retrievable digital objects such as documents and media. Instead, URIs can denote abstract concepts such as the person Marko, the class of dogs or the notion of friendship. Finally, the space of all URIs is an inherently distributed and theoretically infinite space. This attribute makes the URI space fit to represent massive amounts of data distributed worldwide. A convenient consequence of this space is that the Web of Data can emerge atop it. However, while URIs can denote things, they cannot denote how things relate to each other. Relating URIs is necessary in order to give greater meaning and context to each datum. Moreover, relating URIs is necessary to create the web aspect of the Web of Data.

The Resource Description Framework (RDF) is a standardized data model for linking URIs in order to create a network/graph of space of all URIs [3]. RDF also supports the linking of URIs to primitive literals such as strings, integers or floating point values. An example RDF statement to denote the fact that “Marko knows Fluffy” is <http://www.lanl.gov#marko, http://xmlns.com/foaf/0.1/knowns, http://www.lanl.gov#fluffy>. In order to make long URIs more readable, namespace prefixes are generally used. With namespace prefixes, the previous statement can be represented as lanl:marko, foaf:knows, lanl:fluffy. All RDF statements have this three
component form, where there exists a subject (lanl:marko), a predicate (foaf:knows) and an object (lanl:fluffy). As such, an RDF statement is also known as a triple.

A URI can be involved in multiple statements. For example, it is possible to state that, while being known by Marko, Fluffy is also a dog, 5 years old and lives in Santa Fe, New Mexico. Data on Santa Fe and data on Fluffy become merged when statements involving their two URIs are joined (directly or indirectly through multiple links). The Web of Data becomes powerful when seemingly different data sets are interlinked. The fact that Fluffy lives in Santa Fe automatically connects data about Fluffy to geographic and encyclopedic data about Santa Fe, New Mexico — its geospatial coordinates, nearby cities, culture, population and so forth. As more and more statements are added to the Web of Data, the Web of Data serves, in a sense, as a global database of interlinked heterogeneous data. The combination of both the URI and the RDF has moved the World Wide Web beyond a web of documents to that of a Web of Data, where the minutiae of information can be represented and interlinked for consumption by both man and machine.

RDF’s original use case has evolved beyond that of a logic-language for knowledge representation and reasoning on the Semantic Web [4]. As the foundational technology of the Web of Data, RDF can be seen as a general-purpose data model. It can be used to model formal knowledge (the Semantic Web), for graph/networks (the Giant Global Graph) and for software and abstract virtual machines (the Web of Programs) to name a few additional applications. In many ways URIs and RDF afford a memory structure analogous to the local memory of a physical machine except that this memory structure is distributed over physical machines worldwide. Each physical machine stores and manages a subset representation of the full Web of Data. RDF can be stored on a physical machine in many ways. A simple, straightforward way is to represent RDF statements in a file — an RDF document. A common misconception is that RDF and RDF/XML are one and the same. RDF is a data model that has various serialized representations with RDF/XML being one such serialization. Other popular serializations include N3 and N-Triple. Thus, there are many types of RDF documents. For the small-scale exposure of RDF data, an RDF document suffices.

For the large-scale exposure and processing of RDF data, an RDF repository known as a triple store or graph database is usually the chosen solution. The expanded use of RDF has been greatly facilitated by the continued increase in the capacity and speed of RDF triple stores. Modern high-end RDF triple stores can hold and process on the order of 10 billion triples. Example high-end triple stores include Neo4j [5] and AllegroGraph [6]. What has been the sole territory of relational database technologies may soon be displaced by the use of RDF and the triple store. Moreover, because RDF is the common data model utilized by triple stores, it is possible to integrate data sets across different triple stores — across different RDF data providers. This integration is conveniently afforded by the URI and RDF as web standards and is a function foreign to the relational database domain. With the Web of Data, no longer is information isolated in individual inaccessible data silos, but instead is exposed in an open and interconnected environment — the web environment. The means to integrate RDF data across different RDF data sets is explained next.

**Linked Data and a Distributed Data Structure**

In an effort to provide a seamless integration between the data provided by different RDF data providers, the Linked Data community is focused on developing the specifications and tools for linking RDF data sets into a single, global Web of Data [7]. Two RDF data sets link together when one data set uses a URI maintained by another. For example, suppose the URI lanl:fluffy is minted and maintained by the Los Alamos National Laboratory (LANL). As previously explained, this URI is denoting something in the world — namely Fluffy. However, it is possible for someone other than LANL to express statements about Fluffy. Assume that the Rensselaer Polytechnic Institute (RPI) mints their own URI rpi:fluffy to denote Fluffy, where rpi is the namespace prefix that resolves to &lt;http://www.rpi.edu#&gt;.

At this point, both lanl:fluffy and rpi:fluffy denote the same thing — they both denote the same real-world object known as Fluffy. This idea is diagrammed in Figure 1a, where the dashed lines identify which worldly things the URIs stand in reference to. In order to link the LANL data set with the RPI data set, LANL can add the RDF statement &lt;lanl:fluffy, owl:sameAs, rpi:fluffy&gt;...
to its data set. This statement states that both \textit{lanl:fluffy} and \textit{rpi:fluffy} denote the same real-world thing, Fluffy. This idea is diagrammed in Figure 1b. Given this statement, it is possible to traverse from \textit{lanl:fluffy} (LANL) to \textit{rpi:fluffy} (RPI) and thus migrate from the LANL data set to the RPI data set. When two data sets denote the same thing, they can be linked.

The Linked Data community is interested in both unifying RDF data sets as well as specifying the behaviors associated with URI resolution. A Linked Data-compliant data provider should return data when a URI is dereferenced – that is, when a representation of the resource being identified by the URI is requested. More specifically, when a URI is dereferenced, a collection of statements associated with that URI should be returned in some RDF serialization such as RDF/XML. Given the example above, if a machine dereferences \textit{lanl:fluffy}, it will get the statement \textit{<lanl:fluffy, owl:sameAs, rpi:fluffy>} returned to it. In other words, LANL returns all the RDF statements for which \textit{lanl:fluffy} is the subject of the triple (i.e., the outgoing edges from \textit{lanl:fluffy}). Now, the machine knows that \textit{lanl:fluffy} and \textit{rpi:fluffy} denote the same thing. Thus, if it wants to know what RPI has stated about Fluffy, it will dereference \textit{rpi:fluffy}. Upon doing so, it should get the statement \textit{<rpi:fluffy, rdf:type, rpi:Dog>} returned to it. To the machine, the Web of Data is one expansive interlinked web of URIs. To the underlying servers, the Web of Data is broken up into multiple RDF subgraphs (multiple data providers) and linked together when one data provider references a URI minted and maintained by another data provider. It is noted that resolving a Linked Data-compliant store’s URI is one way of getting data from the Web of Data. For more complicated data gathering situations, many RDF data providers expose SPARQL end-points to their triple stores. SPARQL is a query language similar to SQL, but focused on graph queries as opposed to table queries [8].

An interesting consequence of the Web of Data is that it can greatly shift the role of application and data providers. Currently, web applications are required to maintain their own data source. For example, Amazon.com maintains its database of books, Springer its database of journal articles and iTunes its database of music metadata. In order for users to utilize this data in interesting ways, these same data providers must provide a front-end application to interact with the data. In this way, data providers and application developers are one in the same entity. This idea is diagrammed in Figure 2a, where each application utilizes its own back-end database to provide its front-end application with data.

With the Web of Data, this model is significantly altered. On the Web of Data, application providers and data providers are cleanly separated. Data providers can provide and interlink book, article and music data on the Web of Data, and application providers can develop software to utilize these data for different end-user services – book recommendations, citation analysis and music metadata population. Moreover, this same data can be utilized by multiple different application developers, which can yield many ways for the end-user to interact with the Web of Data. In other words, Amazon.com’s data might be more efficiently presented and processed if it were open for any developer to create a front-end application for it. This idea is
diagrammed in Figure 2b. The clean separation between data and application providers is already taking place as plenty of interlinked heterogeneous data currently exists on the Web of Data. A few examples are provided here. Book data can be found at Amazon.com’s RDF BookMashup and the RDF representation of Project Gutenberg. Scholarly data is provided by the Digital Bibliography and Library Project (DBLP), ACM, IEEE, amongst many others. Finally, various music data sets exist, such as MusicBrainz and AudioScrobbler. This data is leveraged, as mentioned previously, by resolving URIs. For example, if one dereferences the URI http://rdf.freebase.com/ns/guid.9202a8c04000641f80000000001a49d in a standard web browser, what is returned is a set of RDF statements (as an RDF/XML document) linking this URI to other URIs and literals. Accessible, interlinked, structured data is the point of the Web of Data. An ecology of applications leveraging this data may greatly advance applications and algorithms for processing data as application developers are no longer burdened by the cold-start problem of requiring large amounts of data to initiate a successful service [9]. Nor will consumers be confined to using certain web applications, as application and data are no longer so tightly coupled.

**Linked Process and a Distributed Process Infrastructure**

While the Web of Data and the efforts expended by the Linked Data community have provided a path toward global-scale data management, this model is lacking one important component: an infrastructure for data processing. A significant hurdle to overcome for this community is that of distributed processing on this distributed data structure. Traversing the Web of Data is not quite the same as traversing the web of documents. For the human, it is reasonable to traverse from URI to URI exploring the Web of Data in a manner similar to the way the web of documents is traversed. That is, a human, using a web browser, can resolve URIs and view the RDF data returned. Moreover, various human-friendly RDF browsers exist (usually in the form of web browser plugins) to make it easy for humans to view and traverse the data on the Web of Data.

However, a machine (an application, an algorithm) can traverse the Web of Data much faster than a human manually clicking from URI to URI.

Moreover, there will be orders of magnitude more resources and links on the Web of Data than those found on the web of documents. While a machine can crawl and pull the data to its local environment for processing, this strategy becomes inefficient when the data requirements span large parts of the Web of Data. Again, note that every time a URI is dereferenced, the resolving server prepares an RDF subgraph and returns it (over the wire) to the requesting machine. Thus, traversing the Web of Data requires data to be migrated to the traversing machine and processed remotely from the data source. This architecture is analogous to the current web of documents whereby traversing it pulls HTML documents and media to the requesting machine. For human consumption this transfer is necessary as data/documents must be rendered where the human is physically located – remote from the data source. For a machine (a virtual machine) its physical location need not be a factor in how data is consumed and processed. Thus, for processing large parts of a distributed data structure, a more efficient mechanism would be to migrate the process between data providers so that
information is not pulled over the wire, but instead, processed where the data is maintained. In other words, an efficient mechanism for processing the Web of Data would be to move the process to the data, not the data to the process [10].

For the web of documents, the search engine philosophy of “download and index” has made it possible for end users to find information in a more efficient manner than by simply surfing and bookmarking. With modern commercial triple stores scaling to the order of 10 billion triples, centralized indexing repositories will have to contend with not only the volume of data, but also the computational complexities of analyzing such data in sophisticated ways. The Web of Data provides a much richer machine processable data structure than what is provided by HTML and thus, antiquated keyword search simply does not take significant advantage of what the Web of Data is providing. The future of the Web of Data will be rife with algorithms from many schools of thought such as formal logic, graph analysis, object-oriented programming, etc. [4]. Many of these algorithms will compute across various underlying stores of the Web of Data and will require a distributed Turing complete infrastructure to do so. For any algorithm of sufficient complexity, there is simply too much data to pull over the wire and thus, the Web of Data in its current form greatly reduces what is possible.

This state of affairs is unfortunate. Given the potential role of the Web of Data as the de facto medium for interconnecting data, a distributed computing environment is necessary. The Linked Data community needs a parallel Linked Process effort. In a sense, data providers already expose their processors for public use by way of their SPARQL-endpoints. SPARQL serves as an on-site data processing language. However, this language, being a query language, is not sufficient for representing complex algorithms. What is needed is a framework that is more general purpose and that respects the three following basic requirements:

1. **Safe**: applications must not be able to destroy the integrity of the open processor or its data set when using this infrastructure.
2. **Efficient**: applications must run faster in this infrastructure than is possible when pulling the required data over the wire.
3. **Easy to use**: application developers must be able to utilize common programming languages and packages and be relatively blind to the underlying infrastructure.

Developing a distributed process infrastructure that accounts for these three factors will ultimately drive its adoption. With the widespread adoption of such a processing infrastructure by RDF data providers, the Web of Data will reach a new level of functionality. No longer will the Web of Data be only a database serving data over the wire to third-party applications, but instead, a distributed computing environment supporting complex algorithms that can leverage rich data in ways not previously possible in the history of computing. The unification of Linked Data and Linked Process in many ways is similar to cloud computing. However, with the integration of data sets and hardware processors worldwide, this cloud will be much richer and more decentralized than that which exists with other cloud providers. In this form, the Web of Data will afford the world a democratization of both data and process and may perhaps enjoy a frenzied adoption similar to what has occurred with its predecessor, the web of documents.

**Conclusion**

The Web of Data provides an infrastructure that supports an instantiation of a distributed graph of web resources. This distributed graph is created by many data providers who represent and interrelate their data. What emerges from this collective effort is a publicly accessible global database that can be leveraged by both man and machine to any end they deem appropriate. However, the current instantiation of the Web of Data lacks one crucial component: a distributed processing infrastructure. For the web of documents of common knowledge, the solution to the issue of processing the vast amount of information has been to literally download the entire web and index and process it in a single environment. While the content on the web of documents is distributed, the means by which the information on the web of documents is analyzed is not. The Web of Data need not fall into this same model. With the nearly limitless ways in which RDF data can be processed, it would be a disappointment if the data on the Web of Data were left solely to centralized repositories to store, index and provide query
functionality. Beyond disappointment, it would reduce the potential utility the Web of Data would have given a distributed process infrastructure. By extending the work of the Linked Data community with Linked Process, the Web of Data may one day rise to become the *de facto* medium for representing and processing data much like the web of documents is the *de facto* medium for storing and sharing documents.

### Resources Cited in the Article


6. AllegroGraph is currently available at [www.franz.com/agraph/allegrograph/](http://www.franz.com/agraph/allegrograph/).


