Observation Centric Sensor Data Model

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Abstract. Management of sensor data requires metadata to understand the semantics of observations. While e-science researchers have high demands on metadata, they are selective in entering metadata. The claim in this paper is to focus on the essentials, i.e., the actual observations being described by location, time, owner, instrument, and measurement. The applicability of this approach is demonstrated in two very different case studies.

1 Introduction

E-science applications are getting more and more important due to the significantly increasing amount of sensor data. The general direction in many disciplines is increasing temporal and spatial resolution of sensor data and therefore requires tools to manage and process these data. Furthermore, funding organizations are promoting and encouraging sustainability of funded experiments by making data re-usable.

Data considered in an e-science application are sensor measurements either collected online called \textit{sensing} or resulted from manual collection and analysis called \textit{sampling} \cite{1,2}. Furthermore, data about sensor measurements are collected like e.g. data quality, annotations, descriptive data (referred to as metadata), meaning of data, collecting person, sampling method, used instruments, maintenance applied on the instrument, etc.

Computer scientists looking at e-science applications can recognize a data management problem. The typical computer science approach is requirements analysis, design, implementation, and deployment of a data and metadata system. Within the requirements engineering phase, available standards for storing metadata are investigated. However, in many environmental projects there are no computer scientists involved and there is no budget for building specialized applications. Available standards are usually domain specific - e.g. for hydrologists, biologists, or geologists. However, many projects are interdisciplinary. If every partner in an interdisciplinary project uses its own domain specific standard, the data are hard to share within the project. Further, there are only limited open source data and metadata management systems available, which are usable for non computer scientists. We computer scientists have to think
out of the box to provide tools to enable the environmental engineers to help themselves.

An observation made after a data engineering development cycle in an environmental research project is that requirements of researchers using the e-science application are high resulting in many *required* data, however, the willingness to provide and manually enter these data is rather low. Therefore, a classical data engineering approach is not applicable, since the gap of expectations and contributions is unresolvable by software. We computer scientists have to understand how these researchers use the data.

Researchers in an environmental research project describe their field site based on a map, indicating time and location when instruments have been deployed and what specific observations they have made. Researchers are often not familiar with data models or concepts like metadata, databases or query languages. For these users the *data* includes the actual measurements, their knowledge about the field site, the deployment and the execution of the experiment - these are *observations* made by the researcher in the duration of the experiment. Many of these data are not written down or written in a physical notebook. Many information are implicit knowledge within a certain domain, like e.g. the method on how to perform a certain measurement.

Based on this experience, the data model of e-science applications must be based on observations and should provide support structures to organize access to observations. The challenges are the high number of parameters contained in an observation, many of them will not be known at the design phase of the e-science application. Therefore, the approach must be extensible on representing what has been measured. Further, the support structure needed in the project will evolve. At the beginning there are only few observations, thus no deep hierarchies are necessary. However, with 1000 observations several levels may be beneficial in a support hierarchy. Therefore, the definition and granularity of support structures must evolve. Finally, all projects vary so much that a single, specific data model due to variety of disciplines and their combinations is not feasible, however a general guideline on how to design the data model is beneficial.

In this paper, a guideline for developing an observation based data model is provided. Furthermore, an open source infrastructure is described which has been used for implementing the proposed data model. The proposed implementation allows easy extension of observed parameters and support structures by enabling researchers to provide additional metadata. Further, the adaptation of the user interface to incorporate these extensions is rather simple.

### 2 Related work

Most e-science projects like e.g. Kepler [34] or Taverna [56] provide metadata management infrastructure components. Often these projects rely on metadata standards like e.g. TransducerML [7] or WaterML [8] documenting sensors, actuators, or manual observations. These projects require quite some infrastructure
and are often closed groups. Many of the projects do not have the resources to setup and maintain such an infrastructure.

There are obviously specific metadata standards like e.g. for seismographic research [9]. But, as argued above specific metadata standards are domain specific and therefore less beneficial in interdisciplinary projects since each domain has its own vocabulary.

Standards like Observations and Measurements in the Sensor Web Enablement initiative describe a meta language on describing observations similar to the one proposed in this paper. The difficulty we experienced is that the complexity of the data model in the standard requires to explicate a lot of knowledge of the scientists, which is not providing any obvious benefit to them and as a consequence they are not providing the information. The proposed much simpler data model covers the core information and therefore lowers the entry barrier to new contributors.

Web 2.0 based open projects are e.g. MyExperiment [10] or DataFed [11] providing access to sensor data and data processing instructions. The access to the data is per data set. There is no possibility to query data from different data set. Metadata are documented inside a single data set. This makes these approaches not applicable for a data sharing infrastructure for data and metadata.

Data models providing the expected degree of freedom for querying data are quite similar to the one proposed in this paper. These approaches are based on data warehouse database structure like e.g. used by Microsoft [12,13] or [14] providing generic data models supporting to extend the controlled vocabulary. In both cases many metadata are mandatory by the provided schema. We argue in this paper that researchers see the need for these metadata but are not willing to add these metadata since it is too time consuming for them. The approach in [14] addresses an institutional data integration approach where it is reasonable to assume the availability of these metadata. In the Web 2.0 based open, interdisciplinary community approach as proposed in this paper, this assumption is not supported by the performed case studies.

3 Data Model Requirements

The core of e-science applications are the collected data, called observations. An observation must answer the following five questions:

- What has been observed?
- Where has it happened?
- Which instrument has been used and how has the measurement been performed?
- When has it happened?
- Who has made the observation?

The questions are answered by statements either explicated in the observation or derivable via other observations. To answer questions, either free text or

http://www.opengeospatial.org/projects/groups/sensorweb
structured information is used. Structured information may be facts or refer to concepts defined e.g. in the support structure of the data model. An example of a fact is the sensor position in an agreed upon coordinate system (e.g. WGS 84). A concept representing a location is for example ZI3098 describing the room 3098 in building Zilverling at University of Twente in the Netherlands, which is the office of Andreas Wombacher. A fact is understandable in a commonly agreed reference system. A concept requires a semantic description of the concept, thus a description of its meaning.

As stated in the introduction, the requirement of researchers using e-science application exists of having many metadata. However, the motivation and willingness of researchers to insert these metadata is limited. Case studies have shown that all metadata additional to the five questions are supporting information in describing observations or concepts and are negligible until required. These data are helpful, but not essential to access or to process observations. Thus, although the requirement of having many metadata exists in practice inserting these metadata has low priority for researchers.

Observations and concepts are application specific. Especially in inter-disciplinary applications, like the e-science application Record [15], it is very difficult

- to establish a single ontology to accommodate the views of the different disciplines in a homogeneous way, and
- to foresee all possible extensions coming up during the runtime of the e-science project since manual entering metadata is expensive, the set of required information is preferably short; however, later on there might be a strong demand to invest in additional mandatory information.

As a consequence, the five W-questions have to be answered by every observation, however, a high flexibility of the applied data model is required dependent on a "need to query".

4 Approach

The approach is based on describing observations by answering the five questions mentioned before. In the following the questions are discussed briefly and an indication is given on how the particular question is answered. Fig. 1 illustrates the observations and their relations to potential concepts. The arrows $O \rightarrow Q \rightarrow C$ means that concept $C$ answers question $Q$ for observation $O$.

4.1 What [Observation Type]

There are three basic types of observations:

Sampled observations contain information about the measured physical described by a parameter-value pair. Parameters (like e.g. temperature) are usually measured by an instrument (like e.g. a thermometer) resulting in parameter values (like e.g. $20^\circ$Celsius). Parameter values are specified using a physical unit (like e.g. $^\circ$Celsius). Different disciplines may use different physical units: e.g.
Chloride in a solution is either measured in 1 mg/L or 0.028206358 mmol/L. Measured values can be scalar values, but may also have higher dimensions, like e.g. a distributed temperature sensor providing 2000 values per measurement along a fiber optics cable.

**Sensed observations** represent streaming sensor data or data collected in a logger (flash disk memory) and retrieved periodically. Sensed observations are treated different to sampled observations since sensing results often in huge data volumes where only the **what** and **when** part varies. Therefore, sensed observations point to a view system answering **what** and **when** questions. The separation of sensing and view system is indicated by a dashed box in Fig. 1.

Sampled and sensed observations are based on parameter-value pairs. Please be aware, that parameters (like e.g. temperature) are syntactic names describing an equally named corresponding concept (temperature as a physical property of a system that underlies the common notions of hot and cold) called **parameter**. Thus, the semantic description of parameters is not contained in these observations, but is explicated in parameter concepts. This name equivalence is indicated by dashed arrows in Fig. 1.

A **deployment observation** describes in free text the placement of a sensor at a specific location and time.

**4.2 Which [Instrument] and How to measure [Method]**

Observations are related to instruments, i.e. measuring devices or methods. Measuring devices are often used in a unique way following a specific protocol. Therefore, we see the measurement method (how to measure) closely related to the

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Fig. 1. Data model
instrument used. An instrument is therefore not a generic description of a generic device but a specific instrument used for acquiring a specific sampled or sensed observation. It therefore contains information on how the sample is processed to generate a measurement, thus being comparable to a procedure or a protocol. Semantic descriptions may contain a unique device number such as a serial number provided by the manufacturer or through radio-frequency identification (RFID) tags or a MAC address for networked devices. In case of deployment observations instrument entities are used to answer which instrument has been deployed. However, the question on how the deployment has been performed is part of the deployment observation itself and corresponds to what has been done in deployment observation.

4.3 Where [Location]

Locations are specified in a commonly agreed reference system. The reference system can be a coordinate system, then the location is specified as a fact. However, it can also be a system of conceptual locations, like a room number in a building or the name of a bore hole (piezometer) at a field site. In case locations are conceptualized then the meaning of location concepts has to be specified. To describe the meaning a coordinate system may be used. The conceptualization of locations is indicated by a dashed box in Fig 1.

Locations may not be single points but may represent a spatial form or a volume. Examples are the location of a fiber optics cable used by a distributed temperature sensor, which is a free form line in the 3D space, or the laser beam of a lidar representing radial lines changing over time, or a 3D surface measurement of self-potential describing the naturally occurring electrical potential variations at the Earth’s surface.

Locations of sampled observations are usually derived from the location of the instrument used to perform the sampling. The same applies often to sensed observations. In this case, the location of a sensed or sampled observation is not explicated but derived from the corresponding deployment observation of the associated instrument. Some observations may vary location over time, like e.g. the GPS coordinates of a car driving around or the moving laser beam of a lidar. Thus, the location information may be part of a sensed observation rather than a deployment observation.

4.4 When [Time]

Time is usually specified as a fact in a commonly agreed reference system. Challenges with time are time zones, which have to be handled. Further, day light savings may result in two observations at the same point in time: one from the hour before setting back the time and the second from the hour after the time has been set back. To avoid this duplication of times, day light savings are usually avoided by fixing the time to e.g. UTC+1 without daylight savings.

An issue with time specifications is the handling of time intervals. A measurement may require a period of time, while the resulting observation is assigned
a point in time. The specific time within the period is used to associate the observations with has to be agreed upon: often the used point in time is the start, the end, or the middle of the time period required for the measurement.

4.5 Who [Observer]

Explicating the experimentalist who made the observation is giving the person credit for the acquired data - as a kind of ownership. A social dimension of explicating the observer is that the reputation of the person may be used as an indication of data quality or reliability of the observation and the applied method in acquiring that observation. Trust in observations is based on personal relationships between researchers acquiring and processing observations. The users are explicated as concepts in the proposed data model. The semantic descriptions of a user are potentially contact details, research interest, and a matching of the concept (digital identity) to a real person.
4.6 Example

To illustrate the data model we discuss a water sample taken by Tobias Vogt in the RECORD project. Tobias takes on 24th April 2008 a water sample by filling a bottle with water pumped out of a monitoring-well with name 'R005'. The sample is analyzed the next day (25th April 2008) in the lab for inorganic chemistry parameters, like e.g. 'Nitrate', 'Nitrite', 'Chloride', 'Ammonia'. The information who, when, and what is documented on a wiki page Record:Sample_Tvogt_0804555 (Fig. 2) directly. The what in this page are the measured inorganic values.

Figure 3 schematically depicts the information and their semantic definition, where the wiki pages (Fig. 2) representing entities observed in the use case are white shapes, the semantic description of annotations are gray shapes, and the actual annotations and their values are displayed in white rectangles within white shapes. The thick arrows represent semantic annotations, where the annotation consists of an entity and not an actual value. The thin arrows represent Web links indicating that the semantic description of an annotation is also directly accessible.

In the center of Fig. 3 the wiki page Record:Sample_Tvogt_0804555 (see also Fig. 2) is depicted. On this page, the question when is directly answered by annotation date. The what question is answered by the different annotations like Nitrate, Nitrite, Chloride, Ammonia, and several others which are not depicted here (Fig. 3). The question who, which and where are answered by pointing to entities represented as individual wiki pages connected via the semantic annotations contact, instrument and location. The difference between a user and a value of Ammonia is that users are based on an enumerable set of entities, while...
Ammonia values are reel numbers and therefore potentially infinite many. Each semantic annotation is explained on a single wiki page. This page contains the agreed upon understanding of the project partners on what they mean by the particular annotation.

5 Entity Resolution

Entity resolution aims at the avoidance of using several terms for the same concept or using the same term for different concepts. The issue is to ensure that the same term is always used for the same concept. Entity resolution conflicts are hardly avoidable. While references to not defined concepts can be identified quite easily, the wrong usage of an existing concept is much harder to detect. We propose an editor to manually detect entity resolution conflicts and to invite users to resolve these conflicts.

Please be aware that the view system concepts are high volume data. However, the parameters used in these concepts are the same for one sensed observation. Therefore, manual entity resolution conflicts can easily be checked for sensed observations and the corresponding view system concepts. In general, the users have to follow the following policy.

- New users must check concept descriptions first before using a concept.
- If a user expects a different semantics for a concept, a discussion on disambiguating the concept is initiated and the conflict is resolved by affected people.
- If a disambiguation conflict can not be resolved, the editor has to mediate.
- If a user requires a concept being semantically different to all existing concepts, she can create it.

As a consequence, concepts are the results of a community process specified in a policy.

An example observed in the Record case study is the parameter concept "Chloride" which had different semantics for hydrologists and biologists. The ambiguity has been resolved by introducing the concepts "Chloride aqua" and "Chloride solid".

The advantages of defining concepts in an incremental community process compared to an ontology based approach is not requiring a consensus process before starting collecting observations, but having the disambiguation discussions parallel to the collection of observations. The disadvantage of the proposed approach is the dynamics of the data model hindering e.g. the creation of user interfaces for query support. Based on our experience from the case studies, an ontology may also change over time and user interfaces are expensive to implement especially in an environmental research project with a run-time of four years without a budget for implementing or adapting e.g. user interfaces.
6 Implementation

Implementing the proposed approach requires a flexible storage solution supporting community based inserting and editing of stored concepts and observations. Relational databases are based on a schema and changing the schema is expensive, thus, representing the data in a fixed schema is not feasible. An alternative is to keep the schema flexible and use a lot of references, however, this reduce the query performance. Further a particular user interface has to be designed for inserting and editing the data.

The implementation in this paper is not proposing a particular relational schema, but is based on a community driven ontology development using RDF triples and using relational tables (representing view system concepts) one per sensed observation. The Semantic MediaWiki [16] is used for the community driven maintenance of observations, as well as the user, location, parameter and instrument concepts. Using the wiki facilitates use of free text to describe semantics of concepts as well as high flexibility in semantically annotating observations to answer the five questions. Annotations are internally represented as RDF triples. Further, the wiki provides an authentication mechanism and a user management to document each change made by a user. The sensed observations are partly stored in the wiki maintaining a link to a stream data management system maintaining the sensed data (view system concepts). The used stream data management system is GSN [17].

Data access is provided by clustering concepts and therefore creating a hierarchical support structure to navigate the data. Further, the wiki provides a proprietary query language and a SPARQL query endpoint has been installed. Further, the DrillDown extension [18] of the wiki allows to navigate data along the five dimensional space (see Fig 7).

Fig. 4. Usage Relation
7 Infrastructure

The implementation described before is based on the following infrastructure consisting of components and web interfaces and their relations as depicted in Figure 4. The core is the mysql database which is used by the Semantic Mediawiki supporting to combine free text and semantic annotations, and GSN for handling the streaming data. The phpAdmin web interface is used to manage the database. Further, a LDAP server is used for managing access control of all used components and web interfaces. Introducing an LDAP server was necessary since managing user accounts for all the different systems was not manageable any more. The LDAP server is managed by the phpLDAPAdmin web application. A SVN versioning server allows version control of configuration files of GSN as well as Java code fragments used for processing streaming data. The SVN is made available via a WebDAV web interface as well as a WebSVN interface.

For monitoring the infrastructure the tools cacti and nagios are used. Nagios pulls regularly the components of the infrastructure by checking the availability of ports, polling SNMP information, like e.g. the number of process instances running. Nagios has been configured to insert information into the Semantic Mediawiki documenting state changes in the monitored infrastructure. Visualizations of monitored parameters of the infrastructure are provided by cacti. Cacti is a ring buffer based data storage and visualization tool.

An excel macro is available to provide mass upload of samples.

Based on the generic sensor data and metadata, several specialized applications for accessing GSN and Semantic MediaWiki data:

- **Data Frequency**: is an application documenting the frequency of streaming data in a time window of a predefined size. This application allows to related the expected amount of sensed data documented in metadata with the actual observed sensed data. This information gives an indication on the data quality and allows to preselect time intervals with sufficient available sensed data.

- **DTS Archive**: is an application providing specialized storage structures for a Distributed Temperature Sensor (DTS) sensing temperature along a fiber optics cable up to a length of 4 km every 1.5 meters every 10 minutes. The fiber optics cable has been deployed in the water to detect surface water and ground water exchange.

- **Stream Data Annotation**: annotations are made by individual users and comparable to tagging in Web 2.0 these annotations are used to classify data and use the annotations as a selection criteria later on, like e.g. find all data annotated with "checked". This application allows to annotate sensed data. Annotations of sampled data are handled in the Semantic MediaWiki.

- **Data Graph**: is an application for graphing sensed data and annotating the graphs with semantic annotations from the Semantic MediaWiki provided by a user or automatically generated e.g. by nagios. The graphing application allows to zoom in and out and is maintaining specialized storage structures to be able to graph also data from several years.
In Fig. 5, more details about the Semantic MediaWiki are provided: It is based on the MediaWiki software also used by Wikipedia. The Semantic MediaWiki is an extension of the MediaWiki introducing semantic annotations. Further extensions on the same level are AddPage and SvnRepository implemented by us. AddPage is a very simple REST interface to insert a new or overwrite an existing wiki page. SvnRepository enables to refer in the wiki to files contained in the SVN repository. All versions and comments are available in the wiki. This allows to document code in the wiki and use it in GSN.

On top of the Semantic MediaWiki there are six main extensions being used in this infrastructure. Semantic DrillDown allows to navigate wiki pages along several dimensions and therefore is very suitable to provide access to content without predefining an access structure. Semantic ResultFormats is an extension providing different writers for the result of a semantic query in the wiki specific query language. It allows to make query results accessible in many different forms, like e.g. as a table, a timeline, or a Google Map. Semantic MapPoints should be part of Semantic ResultFormats but is still independent. It allows to display the SPARQL or wiki query result in a geo-referenced image. The plan is to integrate this with Semantic ResultFormats. This is an important extension for the case studies since both work with specific coordinate systems (Swiss Coordinates and a proprietary one) and therefore are not applicable to Google Maps. Further, this extension allows to use own, more detailed and more up to date images for visualizing the query results. The SPARQL query Function extension allows to use the available SPARQL endpoint for queries inside a wiki page. The internal wiki query language is fast but has limited expressiveness, while SPARQL is more expressive it is sometimes also slower.

The DataGraph and GSN Access extensions enable the output of the applications described above to be contained in a wiki page. Since graphs are essential for discussing scientific results the DataGraph extension allows to include graphs in a wiki page. In addition to the graphs, GSN Access allows also to document the actual query resulting in the graph, as well as providing access to the raw data used for the graph. This is an essential part in data provenance.

![Data Graph Viewer](Data Graph Viewer)

Fig. 5. Mediawiki and extensions
The described infrastructure has been used in the case studies described next and are currently applied in two additional case studies in the Netherlands.

8 Case studies

The presented approach has been applied on two ongoing case studies in different domains running now for several years.

8.1 Record project

Record [15] is a CCES\(^5\) funded Swiss interdisciplinary research project to predict consequences of river restoration on river and ground water quality. Without detailed environmental process understanding, predictions on revitalization remain speculations. Therefore, integrated models have to be developed, which are able to combine data from different disciplines such as hydrology, geology, geophysics, biogeochemistry and ecology. A unique data set is generated based on observations such as surveys, continuous monitoring (sensing and sampling) including field and lab experiments. Innovative sensor technologies and data management tools are developed together with the SwissExperiment platform project. This heterogeneous set of data has to be linked and jointly analyzed. For better data sharing the proposed data model has been applied to the Record project.

![Fig. 6. Record Data](http://www.cces.ethz.ch/)

Since April 2007 we collected the data volume as indicated in the two charts in Fig 6. On the right side the number of sensed observations are depicted. The gauge bar describes water level data acquired by a Canton (province), which

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\(^5\) Competence Center Environment and Sustainability (CCES)

http://www.cces.ethz.ch/
has been integrated in the system. The raw sensed bar indicates sensed observations made by sensors deployed by the Record project members. The processed observations are manually cleaned observations derived from raw observations. Not all raw observations have been added to the system, therefore the volume of processed observations is bigger. The sensed observations are available via about 60 view systems (see left side Fig. 4).

The data volumes of the remaining concepts and observations are depicted on the left side of Fig. 6. About 50 users have been involved in the project. The high number of parameters illustrates the complexity of the use case caused mainly by the high parameter number in sampled observations provided by a rather low number of instruments. The about 230 locations are well described and contain many additional information like e.g. drilling profiles of bore holes. Many of the about 1300 sampled observations are well described and many of them contain direct location information. Therefore, the number of deployment observations is rather low with about 60.

In a small user survey performed after 2.5 years of the project start with 12 participants the indication was that people are working irregularly with the system and like it mainly for downloading and uploading observations. The participants indicated all sampled and sensed data as their particular interest.

8.2 SensorDataLab

The SensorDataLab [19] is a case study at University of Twente providing a test bed for sensor data management operated now for two years. SensorDataLab provides a localization scenario with several localization sensor infrastructures
of several costs and precision. The approximately 60 sensors are deployed over a floor of the computer science building at University of Twente.

Compared to the Record case study, there are much less user, parameter, location and instrument concepts, and sampled observations. However, the Sensor-DataLab provides more deployment and sensed observations. Further, a generic observation has been introduced describing an observation on the running sensor infrastructure. A generic observation can be manually created by a user or is created automatically by an SNMP-based IT monitoring application. So far, about 3000 generic observations have been made.

The navigation of generic or deployment observations requires more flexible navigation than in the record use case. Therefore, the DrillDown extension is facilitated to navigate the observations along the five questions, i.e., the five dimensions. It provides access to the observation by constraining each dimension individually in arbitrary order. It provides a very flexible access to observations which is also applicable to high volumes of observations.

In this example the set of about 120 deployment observations is searched to find a deployment observation which most likely took place in August 2008 (time) in room Zilverling R3057 (location) for a Bluetooth Access Scanner (instrument). The deployment observations are first constrained in the time dimension by selecting month August 2008 (deployment date=Aug 2008) in which we expect the deployment has been done performed reducing the relevant observations to 24. Next, we constrain the observations by location (deployment building location=Zilverling R3057) further reducing the deployment observations to three (see Fig 7; the two constraints are highlighted in the upper box; the remaining instruments are highlighted in the lower box). However, none of the remaining deployment observations are related to a Bluetooth Access Scanner instrument. Therefore, we release the time constraint again and select the instrument type to end up with 20 observations in which we can find the targeted one. In fact, the deployment did not take place in August 2008 but in September 2008.

The navigation using the DrillDown extension provides a OLAP navigation capabilities on an RDF store and is based on pre-structured dimensions. The hierarchy per dimension can be adjusted but may require explication of additional annotations of an observation. The aim is to make these hierarchies more dynamic to support queries for defining hierarchy levels per dimension.

9 Conclusion and Future Work

The presented approach is an observation based approach of managing sensed and sampled observations with an initial minimal set of metadata. This approach provides higher probability that the researchers indeed manually enter metadata. The observation focused data model does not limit the query expressiveness or the navigation in the data set as illustrated in the second use case.

In future work, the question on how to collect metadata will be further explored in particular whether and how metadata can be acquired automatically.

\(^{6}\) Simple Network Management Protocol
Further, improvements on the query user interface will be explored and tested in the use cases.

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