Converging on a Semantic Interoperability Framework for the European Data Space for Science, Research and Innovation (EOSC)

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Abstract

Semantic interoperability (SI) is at the heart of the FAIR principles and of the design of large scale cross disciplinary infrastructures. The European Open Science Cloud (EOSC) is a European-wide effort towards such an infrastructure, aiming to deepen the regional research collaboration and realising a shared data space for science, research and innovation. In this context, the research community's voice is represented by the EOSC Association (EOSC-A) and a number of advisory groups with a broad range of representatives from different stakeholder organisations. The advisory group on metadata and data quality has formed a task force focusing on developing and implementing recommendations for SI (EOSC SI Task Force) with the ambition to converge on globally relevant and scalable SI solutions for EOSC. This paper provides context to SI in EOSC, the various components contributing to it, as well as some views on the socio-technical challenges to arriving at a consensus. In particular, the paper provides motivation for exploring the heterogeneity of SI solutions demonstrated across scientific communities and insight into the task force's planned approach to conduct a survey to identify relevant components and structures. The paper is also an invitation to the global community to align and engage with the task force's activities going forward.

Keywords

Semantic interoperability, European Open Science Cloud, Crosswalk, Roadmap, Interoperable, FAIR Principles, definitions, linked data, machine actionability

1. Rationale and Main Audience

At a time of ever-increasing amounts of data being produced, it is impossible for the average researcher to navigate and exploit this wealth of information without the support of computers and software tools. To make it possible for the “machines” to better support “humans” in this task, the ecosystem of data services must evolve to fully realise the promise of the FAIR Data Principles [1]—that is machine-actionable, Findable, Accessible, Interoperable, and Reusable data and services. The European Open Science Cloud (EOSC) is a European-wide effort to address this challenge and to create a shared data space for science, research and innovation and interoperability will be a major component of the solution. In 2021, the EOSC Executive Board Working Groups FAIR and Architecture published a set of recommendations and principles to guide the creation of the EOSC Interoperability Framework[2] organised into four layers of interoperability, where the Semantic interoperability Layer combines a machine-based view with the human aspects of aligning concepts in service agreements and other communications of relevance to EOSC. Here, semantic interoperability (SI) is defined as a quality that ensures that the precise format and meaning of exchanged data and information is preserved and understood throughout exchanges between parties, in other words “what is sent is what is understood”[2].

Metadata, metadata schemas, and models of knowledge such as controlled vocabularies, taxonomies, and ontologies provide the necessary context to extract meaningful information from data. In more general terms, a semantic artefact is a formalisation of a conceptualisation that can be exchanged and used by machines to encode and decode information as data in a predictiable way. The formalisations can range from simple lists of terms to thesauri, ontologies and higher-order logics and they can be serialised using a variety of digital representation formats, such as RDF, Turtle, OWL-RDF, XML, JSON-LD [3]. Just as data themselves should be FAIR, so should these metadata schemas and semantic artefacts used to encode and decode them (i.e. principle I2 of the FAIR principles[1]). Several initiaives have concluded that semantic artefacts and metadata schemas are key components in solutions for SI and have proposed recommendations to make semantic artefacts FAIR [3] [4] [5].

Semantic artefacts are heterogeneous and often overlap in their coverage because they have been created by different communities and thus independently optimised for different operations, developed to target specific issues, modelled according disparate principles, and conflicting ontological commitments. This is a source of the lack of SI across (meta)data that use different semantic artefacts. Looking at the requirements of machine-actionability [6]

2nd Workshop on Ontologies for FAIR and FAIR Ontologies (Onto4FAIR), 9th Joint Ontology Workshops (JOWO 2023), co-located with FOIS 2023, 19-20 July, 2023, Sherbrooke, Québec, Canada
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CEUR Workshop Proceedings (CEUR-WS.org)

Box 1 Machine-Readability, Machine-Interpretability, Machine-Actionability by Weiland [6]

Machine-readable are those elements in bit-sequences that are clearly defined by structural specifications, such as data formats like CSV, JSON, or XML, or resources and literals in RDF.
Machine-interpretable are those elements in bit-sequences that are **machine-readable** and can be related with semantic artefacts in a given context and therefore have a defined purpose, such as referencing defined and registered ontology terms that provide meaning to resource in RDF triple.
Machine-actionable are those elements in bit-sequences that are **machine-interpretable** and belong to a type of element for which operations have been specified in symbolic grammar, thus linking types of metadata statements to operations such as logical reasoning for OWL-based (meta)data and other rule-based operations such as unit conversion or other data conversions. Thus, machine-actionability is not a Boolean category but describes a continuum where the machine-actionability of a given type of element increases with the number of easily applicable operations available for it.

(see Box 1), it becomes clear that only machine-interpretable semantic artefacts can result in machine-actionable (meta)data. This also illustrates why SI plays a central role in the design of large-scale infrastructures that rely on ecosystems of interconnected and services and data. As the prerequisite of machine-actionability, SI enables different systems or technologies to understand and exchange information with each other in a meaningful way, using common or carefully aligned semantic artefacts. In the research context, it enables researchers, publishers, and data repositories to share, integrate, and reuse research data and findings across different platforms and disciplines. It allows for improved data discoverability, accessibility, and reuse, as well as enabling more efficient and effective scientific collaboration and knowledge sharing. In other words, without SI, there is no machine-actionability, and without machine-actionability, there can be no support from machines in managing and organising the increasing amounts of (meta)data being produced worldwide.

SI is particularly important in the context of interdisciplinary research, where data from different disciplines need to be integrated and analysed. At the same time, interdisciplinary research represents the greatest challenge to SI. Due to the increasing diversity and complexity of disciplines' topics, domain specific terminology and knowledge organising systems evolve around specific distinct bodies of work [7]. Epistemic rigour inside of a domain and innovative thinking inventing new kinds of terminologies are like natural enemies of any SI [8]. Overcoming this challenge requires working on 'as common as it can be' semantic artefacts (vocabularies, ontologies) and shared (meta)data schemas, so the main schemas and artefacts can be shared across different disciplines (see an example for sensitive data in [9] or [10] for interoperability across different geographical areas). However, to cope with the inherent diversity, SI solutions should explore the ability of machines to recognize synonymous terms and schemas. Achieving this requires specifying mappings at different levels: across semantic artefacts and ultimately data structures/models. In addition, cross-domain methods and tools for data harmonisation which are usable and interpretable by each type of stakeholder are needed. While the problem is clear, finding and implementing good practices is still a struggle also because of different contexts and goals. This paper presents shared conceptualisations of this problem as an outcome of the EOSC Association SI Task Force (TF SI). It starts with a presentation of the conceptual framework of SI based on the EOSC Interoperability Framework followed by a highlight of the main socio-technical challenges. It then presents the methodology considered by the TF to investigate further the diversity of approaches to solve SI, with the ultimate goal to map out practices across different stakeholders/actors, contexts and domains.

2. Conceptual Background of SI

To conceptualise an architecture enabling SI, the EOSC Interoperability Framework [2] investigated different existing community practices through a short survey and derived from the results a conceptual architecture centred around the concept of FAIR Digital Object presented in the Figure 1. Components are associated with an identifier scheme to form FAIR Digital Objects. The Semantic Governance Content is a purely social component requiring a consensus among the different stakeholders involved in the design of global infrastructure to agree on the rules governing SI in light of the guiding FAIR Principles. The **Semantic Business Objects** component is both social and technical and aggregates different levels of formalisation of the semantics, i.e., semantic artefacts and metadata schemas. Although presented here separately, these two categories are tightly intertwined as for example the Conceptual Metadata Framework provides a common terminology based on existing generic standards (e.g. PROV, ISO11179). Along with this **Conceptual Metadata Framework**, two additional metadata goals have been considered: minimum metadata (addressing general concepts) and domain metadata (addressing domain specific needs). This view provides flexibility for service provider/consumers from the different domains to decide how formal and machine-readable semantic artefact will be used to exchange FAIR Digital Objects. This flexibility comes at a cost when compared with a scenario of uniformity: It requires building bridges or mappings between the different approaches to make sure they will be working together. Finally the third component of the conceptual framework, the **Semantic Functional content**, is a technical component considering the different types of services that would be necessary to support SI. Three different services have been identified: the metadata catalogue, the semantic artefact catalogue and the mapping repository. This framework provides a high level overview of what is necessary to consider to enable SI in a large scale infrastructure for science. However, it does not consider the challenges and needs that should be addressed.

If we look into the details of the implementation of SI, an interesting viewpoint to understand what SI actually implies on a conceptual level proposes to take a look at how we, as humans, communicate semantic content in natural language. Here, successful communication relies on the sender and the receiver of the message sharing the same background knowledge. They not only have to share the **meaning** for each **term** used in a message and must be able to identify its **referent** (i.e., the object designated by the term) but they also have to share the same syntactical and grammatical conventions for formulating sentences using terms. The structure of a sentence provides different syntactic positions with associated semantic roles for its terms. This structure significantly contributes to the meaning of the sentence. Data and metadata schemas reflect this structure by specifying slots for each relevant position, with associated constraints that characterise the corresponding semantic role [11]. To achieve SI, we need term mappings for terms that share the same meaning and the same referent (terminological interoperability), and we need schema crosswalks that align slots that share

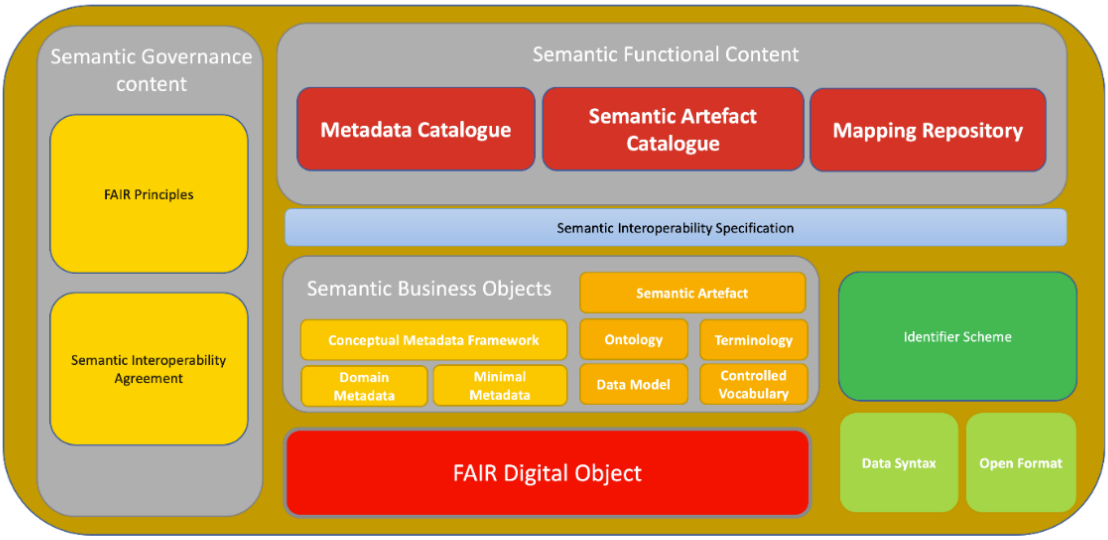

Figure 1: Semantic view on EOSC IF [2]: The EOSC Executive board Working Group on FAIR and architecture identified three main blocks to support SI (Figure 1): the Semantic Governance Content, the Semantic Business Objects and the Semantic Functional Content.

the same constraints across data and metadata schemas that model the same type of statement (schematic interoperability) [12]. Schema crosswalks are thus a set of rules that defines how (meta)data elements or attributes (i.e., slots) from one schema or format can be aligned and mapped to the equivalent (meta)data elements or attributes in another schema or format, for example to align and map the metadata elements of a dataset described in a DataCite [13] or Dublin Core metadata schema[1] to the corresponding metadata elements in a repository-specific schema used by a data repository or data aggregator, such as the European Data Portal[2] or the DataONE[3]. This alignment and mapping can be performed manually or automatically using software tools. This view highlights the complexity of the semantic interoperability and is deeply grounded into the Semantic Web/Linked Data Framework and Knowledge Graphs.

3. Technical and Social Challenges of SI

SI can be built by interlinking resources as proposed by Berners-Lee, Hendler et Lassila (2001) [14] in the so-called semantic web [15]. In addition, achieving SI requires a concerted effort to standardise data formats and metadata, adopt common vocabularies, and ontologies and data schemas, and adhere to established protocols and guidelines e.g. [16] [17]. The use of semantic technologies, such as RDF, OWL, and SPARQL, should facilitate the process of SI in scientific data publication, if correctly disseminated and adopted. However, these technical standards haven't been adopted by many communities, which then developed their own semantic silos leveraging

[1] DCMI Schemas http://dublincore.org/schemas/
[2] https://data.europa.eu/en
[3] https://www.dataone.org/

often other tools and formats. We are therefore faced with the challenge to propose practical solutions to integrate the existing solutions taking into account the diversity of approaches to implement SI. One of the key elements of such a practical solution is the necessity to share metadata schemas and semantic artefacts in machine readable and/or machine actionable formats and to make them accessible to machines through a standardised API. This will enable the creation of transversal and innovative services such as an index of concepts/terms and relations for fast retrieval and reuse ([18] [19]. Another challenge is to define a set of technical good practices for communities that haven't implemented any SI solutions to avoid the explosion of heterogeneous technical solutions. As there is currently no consensus on a common metadata model or even common semantic artefacts, achieving SI across communities requires to align the various existing information systems using several levels of mappings: schema crosswalks, term-mappings, data mappings, ontological mappings, logical mappings, applicable in practice and adopted by research communities. For this purpose, these mappings should be made themselves FAIR and it is necessary to develop a common model for exchanging and sharing the various types of mappings. This common model should support quality assessment (e.g., minimum information standards, mapping provenance), rules and constraints on semantic models and documentation. It should rely on existing models such as SSSOM[4] (Simple Standard for Sharing Ontological Mappings), SPIN[5], LinkML[6], RML[7]. This "standardisation" effort is currently supported by the project FAIR Impact[8], which aims at proposing a common model to share FAIR mappings of various kinds and good practices for mappings.

While there are tools developed by communities supporting the creation of mappings, there is a clear need for more generic tools and for services to share and maintain machine actionable mappings and crosswalks i.e. repositories for mappings, crosswalks such as the EMBL-EBI Ontology Xref Service (OxO[9]) and the Metadata Schema and Crosswalk Registry (MSCR[10]), currently developed in the FAIRCORE4EOSC[11] project. This service will avoid that mappings stay buried as part of the semantic artefacts as it is a common practice.

Whether versed in semantic technologies or novice, the designers and developers of community data infrastructures face a wide range of intricate tasks and obstacles that require expertise and innovative solutions and services. Based on the needs of represented communities in the task force, we identified major technical challenges faced by semantic experts to be prioritised in the domain of SI:

- Ontology selection, management and alignment taking into account semantic heterogeneity and conflict resolution (and developing robust mapping techniques).
- Ensuring quality and accuracy of semantic annotations and managing evolving ontologies (e.g. extensions of existing semantic artefacts);

[4]https://mapping-commons.github.io/sssom/spec/
[5]https://spinrdf.org/
[6]https://linkml.io
[7]https://rml.io/specs/rml/
[8]https://fair-impact.eu/
[9]https://www.ebi.ac.uk/spot/oxo/
[10]https://faircore4eosc.eu/eosc-core-components/metadata-schema-and-crosswalk-registry-mscr
[11]https://faircore4eosc.eu/

- Addressing scalability and performance issues (and designing efficient reasoning algorithms or considering unstructured and semi-structured data plus Semantic data integration and fusion with compliance with semantic web standards);
- Promoting adoption of semantic technologies (by e.g. effective visualisation and user interface design) and collaboration and coordination among stakeholders;
- Addressing privacy and security concerns (e.g. interoperability with legacy systems).

Overcoming these challenges requires deep knowledge of the semantic technologies but more importantly, innovative tools, services and approaches with a strong focus on User Experience (UX) to facilitate the work of the experts. In order to address the technical challenges effectively, a deeper understanding of SI practices within specific communities is essential. It can help identify successful approaches, their locations, their application, and their underlying motivations. Furthermore, it can help spot gaps and ways to overcome them. In the best case, this leads to a change in practices within Semantic Web communities, such as improving existing tools, publishing metadata schemas and semantic artefacts in machine readable format. To gain such understanding, the EOSC SI Task Force will engage with various communities and collect information through a landscaping exercise leveraging a survey described in the following sections.

As of now, there are as many semantic interoperability implementations as scientific communities and research infrastructures. This includes the technical solutions but also the metadata schemas and the semantic artefacts as well as the methods to build them and share them. One of the main challenges is the lack of information regarding the different solutions and good practices used by communities and more importantly the lack of convergence towards common solutions and common practices. Such convergence would ease the development of semantic interoperability at a larger scale and across disciplines. Some initiatives such as FAIR Implementation Profile workshops facilitate the capture and documentation of community practices in the selection of semantic artefacts and metadata schemas and should support cross-community convergence [20]. In general, though, this remains a challenge as communities often have different and diverging conceptualisations of the world, enhanced by the growing diversity of scientific communities and purposes. A solution to reconcile these divergences will be the use of mappings. However, for it to work at scale, it actually requires convergence on a common model and framework to make them FAIR.

Another major challenge is the lack of expertise to deal with semantics and semantic interoperability. This should be addressed through public and shared good practices for developing FAIR Semantic artefacts, curating semantic data annotation and more as well as transversal training to handle the various technical frameworks (Linked Data, SKOS, OWL, RDF, JSON-LD,..). To support this initiative and convince the community of the benefit to work on SI, we need to converge on a common understanding and semantic literacy, with clear and agreed upon definitions for concepts such as ‘SI’, ‘term-mappings’, ‘schema crosswalks’, and ‘machine-actionability’.

Sharing semantic artefacts, metadata schemas and mappings and making them re-usable requires a governance model for their evolution, adaptation and individual extension. Providing a simple mechanism for change management as basic provenance information in the metadata, e.g. introduction of status expressions (“proposal”, “valid”, “superseded”, “retired”) for the life cycle, versioning, timestamp of semantic artefacts would align with the FAIR Principle I.2. The

ISO 19135 (Procedures for item registration) specifies procedures for establishing, maintaining, and publishing registers of unique, unambiguous, and permanent identifiers. Such proposed process models, defined roles and responsibilities in the management and maintenance of digital objects could be adopted in approval procedures of semantic artefacts. The governance and maintenance body of semantic artefacts while ensuring sustainability might include domain experts under rotating leadership.

These societal challenges are tightly connected to the technical challenges and as we mentioned earlier, each mature community with existing research data infrastructures are tackling the challenges in their own way. To enable convergence, it is therefore key to understand the existing landscape of solutions and to evaluate their divergences both at technical level but more importantly at the societal level. This would allow us to propose common solutions for communities which didn't yet start their SI journey, therefore, reducing the gap between the infrastructures and easing their integration in the SI landscape.

4. Landscaping Method

The first version of the EOSC Interoperability Framework [2] was based, among other sources, on a survey conducted to assess the knowledge and practices related to interoperability from different stakeholders. Taking into account new developments and ongoing efforts in the field, we want to interview semantic or data management experts involved in cluster projects, EOSC projects, or research infrastructures. With this interview series, we do not claim to be able to provide a statistically relevant base but rather aim at a qualitative, in-depth analysis of this landscape and of possible solutions to face the challenges identified in this paper. In addition, we want to provide a knowledge base of existing approaches exploiting the many resources from the previously mentioned community events and extending it with the results from the planned survey. We intend to use the Data Stewardship Wizard[12] in combination with nanopublications to describe these practices and resources in a systematic and machine readable way. The survey goals are:

- To investigate how communities are addressing the SI challenge;
- To reveal possible hurdles for solving the problem; and
- To identify and describe resources supporting SI and catalogue them.

For the landscaping effort we intend to use a two-step method: First, online interviews will be conducted with semantic experts involved in research infrastructures and cluster projects about their approach to handle SI challenges based on a questionnaire. This will be followed by an analysis of the outcome resulting in descriptions of resources as nanopublications using the Data Stewardship Wizard. The questionnaire will help interviewers to follow a common scheme to collect information about used approaches. We will ask about specific resources used, reasons that lead to the choice, and if no resource is used, the difficulties and challenges that the interviewee's community has experienced. If the question is not understood, we provide explanations and reformulate the question to be well understood. Following this pattern, the output will be both machine-readable and comparable but also a text-rich description about

[12]https://ds-wizard.org/

the reasons, problems and challenges described by the experts. The questionnaire is structured around the following sections [21]:

- **General information** includes information about the represented community, created data types and used data repositories.
- **FAIR related information** asks about the awareness related to FAIR Principles and interoperability challenges and if the community has elaborated a roadmap for FAIR implementation including a strategy for SI.
- **Metadata related information** asks about the metadata schemas used to describe data, how this is generated, where it is exposed and whether it is used for data discoverability. We also want to know if schema crosswalks are used and if metadata quality is validated.
- **Semantic interoperability related information**: ask which semantic artefacts are used for metadata. We follow with questions about used services (e.g. SPARQL endpoints) supporting their management, mappings and crosswalks as well as their governance.

5. Conclusion

At first glance, one might think that SI is easy to implement—all you have to do is specify mappings for terms that refer to the same entity across different controlled vocabularies. SI is so much more than that. Achieving SI is a complex task that involves various challenges, ranging from understanding what SI involves conceptually, to the technical and societal challenges of its successful implementation in practice. Any strategy for achieving SI must take this complexity into account, especially considering that individual experts will ultimately be responsible for the adoption and implementation of SI within their research areas. Therefore, landscape studies in the form of interviews of these experts play a central role in identifying the reasons for the success of one strategy and the failure of another in fulfilling the specific requirements of the different use cases. Survey and responses will enable to make recommendations on semantic interoperability for the further development and realisation of a FAIR EOSC.

Acknowledgments

This research is a product of the Task Force "Semantic Interoperability" of the EOSC Association, the legal entity established to govern the European Open Science Cloud (EOSC). Complementary support and information were provided through European projects projects "EOSC-Life" (N°824087), "EOSC-Future" (N°101017536) and "FAIR Impact" (N°101057344).

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