Ontological Analysis of FAIR Supporting Resources

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Abstract

Aligning with the FAIR Principles is a key requirement for European-funded research. However, different interpretations of the FAIR Principles lead to diverging evaluations of how to implement them. Previous research introduced the FAIR Implementation Profile (FIP) as a driver to accelerate broad community convergence on FAIR implementation options. To scale FIP creation and analysis, we established a decentralised socio-technical ecosystem, supported by a lightweight FIP ontology including a typology of FAIR Supporting Resources (FSRs). However, categorising FSR instances is sometimes challenging, suggesting that there are unclarities in the FSR type definitions. This paper presents an ontological analysis of the FSR typology, aiming to improve its accuracy in supporting the peer-reviewed curation process of FSR descriptions provided by a wide community of FIP users. Using the Unified Foundational Ontology (UFO) as a reference, we analysed class definitions and demonstrated UFO's capability to resolve controversies leading to disambiguation of FSRs of type FAIR Specification and FAIR Practice.

Keywords

FAIR Principles,, FAIR Implementation Profiles,, ontology analysis,, FAIR Supporting Resources

1. Introduction

The FAIR Principles [1] have gained growing attention in global research over the last decade as the means to make data Findable, Accessible, Interoperable and Reusable. In recent years, making data FAIR has become a common requirement for securing research funding in Europe [2]. Despite these signs of uptake, the FAIR Principles leave ample room for interpretation on

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how to implement their requirements, making both funders and research communities uncertain about these new mandates [3, 4].

To make FAIRification more systematic and efficient, the GO FAIR Foundation (GFF), in collaboration with the ENVRI[1] initiative, developed a questionnaire-based approach to capture community-specific *FAIR Implementation Profiles (FIPs)* [5]. A *FIP* is a list of declared technological choices intended to implement each of the FAIR Principles, made as a common decision by the members of a community. By making these declarations openly accessible and FAIR, they become a driver for broad community convergence on the optimal reuse of these resources [6]. *FIPs* have become increasingly widespread with more than 200 published profiles and 100 registered communities[2].

These developments require up-scaling approaches to *FIP* creation, dissemination and analysis. In recent years, a decentralised, socio-technical ecosystem supporting the composition of *FIPs*, their representation, curation (formal peer-review) and discovery has been developed. The core of this ecosystem is a lightweight *FIP* ontology[3] including a typology of *FAIR Supporting Resources (FSRs)*. *FSRs* are resources that support the FAIRification process. *FSR* subclasses represent resource types that are essential to implement the FAIR Principles, the so-called *FAIR Enabling Resources (FERs)*, instances of which are used to compose a particular *FIP*. Creating a *FIP* is not a trivial task and it is advisable to get support from a FAIR expert. To guide communities in going FAIR, GFF has developed a Three Point FAIRification Framework (3PFF) with an associated Capacity Building Programme to train data stewards on how to facilitate *FIP* events with the participation of interested communities of practice [7]. In these sessions, *FIP* users are guided in providing descriptions of existing *FSR* instances of their choice and in classifying them into the appropriate *FSR* types. However, *FSR* instances can sometimes fall into more than one class making it a challenge to properly classify these resources.

Therefore, to improve the common understanding of *FIP*-related concepts, this paper aims to start an ontological analysis of the *FIP* ontology, focusing on resolving classification issues within some *FSR* types. By refining these definitions, the *FIP* ontology should be better suited to serve as a semantic layer for providing a reference knowledge base *FSRs*. Furthermore, we tried to identify important properties to be defined in the metadata schemas for describing the instances of different types. However, a key challenge is to maintain backward compatibility within the system, to ensure that legacy *FIPs* and existing users can continue using it without disruption.

The paper is further organised as follows: Section 2 provides background information on related work for landscaping the communities' infrastructure and for ontological analysis aimed to clarify its representation; Section 3 describes the components of the *FIP* ecosystem; Section 4 explains the *FIP* ontology; Section 5 analyses detected curation challenges of community-provided *FSR* instances; Section 6 exemplifies, using the *FSR* description of the Research Object Crates, how ontological analysis can help reveal ontological shortcomings and how to resolve them; Section 7 concludes with a future outlook and next steps.

[1]https://envri.eu
[2]http://v2.fairconnect.pro/dashboard
[3]https://w3id.org/fair/fip

2. Background information

The *FIP* approach is accompanied by the definition of resource classes explicitly designed to address each of the FAIR Principles. This was preceded by a thorough analysis of the FAIR Principles by considering how various aspirational FAIR behaviours might be instantiated in different types of (mostly existing) resources. The type definitions of the *FERs* follow the interpretations published on the GFF website[4], which are based on an analysis made with the involvement of a broader expert community [4]. The *FER* types proposed for *FIPs* rely largely on the provided examples in the implementation considerations of this work. Nonetheless, the *FIP* questionnaire sometimes deviates from the suggestions of [4] by using a more practical approach to guide the user in the choice of technology. The most obvious change in the *FIP* approach is the interpretation of R1.3, which considers the *FIP* itself as a list of community-specific standards. Other interpretations come to different conclusions on the recommendations to be given to data providers to make their data FAIR. For example, Buttigieg [8] advises to use resources similar to *FERs* for some principles, but for others they provide more generic guidelines addressing the method rather than suitable resources. Another interpretation is provided by [9] using OntoUML to design a FAIR Principles Schema. While the *FIP* approach identifies enabling resources to achieve a certain FAIR behaviour, Bernasconi et al. [9] analyse the behaviour itself for potential improvement. For example, for F1 it suggests that data should be equipped with globally unique and persistent identifiers, while the *FER* type associated with F1 in the *FIP* is *Identifier Service*, which provides for any digital object (1) algorithms guaranteeing global uniqueness, (2) a policy document that guarantees persistence and (3) resolution of the identifier to machine-actionable metadata describing the object and its location[5]. One instance of this type is the B2Handle, which is a distributed service that manages persistent identifiers for data hosted on EUDAT[6].

By providing *FIPs*, communities contribute to a knowledge base of *FSRs*, which can be found and reused by other interested parties. To be findable, the resources must be described following an agreed pattern and classification. Note that repositories for collecting community standards and technologies are being offered by FAIRSharing[7] [10] and recently also by FAIR-IMPACT[8]. GFF makes an effort to interoperate with both by including references to the respective records.

While the value of *FIPs* for facilitating the FAIR onboarding of communities has been repeatably demonstrated [11–15], the *FSR* instances provided by the user community lead sometimes to unresolved discussions in their curation process, requiring compromises. In this paper, we chose to use the Unified Foundational Ontology (UFO) as a reference for conducting an ontological analysis [16] of the *FSR* typology. UFO supplies basic concepts for objects and events, their classification, relations and attributes, and helpful tools are available to do this type of analysis, like the OntoUML Visual Paradigm plugin. With UFO, we have secured to uncover important conceptual distinctions that would be otherwise ignored in informal characterisations of the different types of *FSRs*.

[4]https://www.gofair.foundation/interpretation
[5]https://w3id.org/fair/fip/terms/Identifier-service
[6]http://purl.org/np/RAJZDDm6ganlkehRZa2NxGoDmT0fOHIyIoSdhj9ifKzeU
[7]https://fairsharing.org/
[8]https://catalogue.fair-impact.eu/

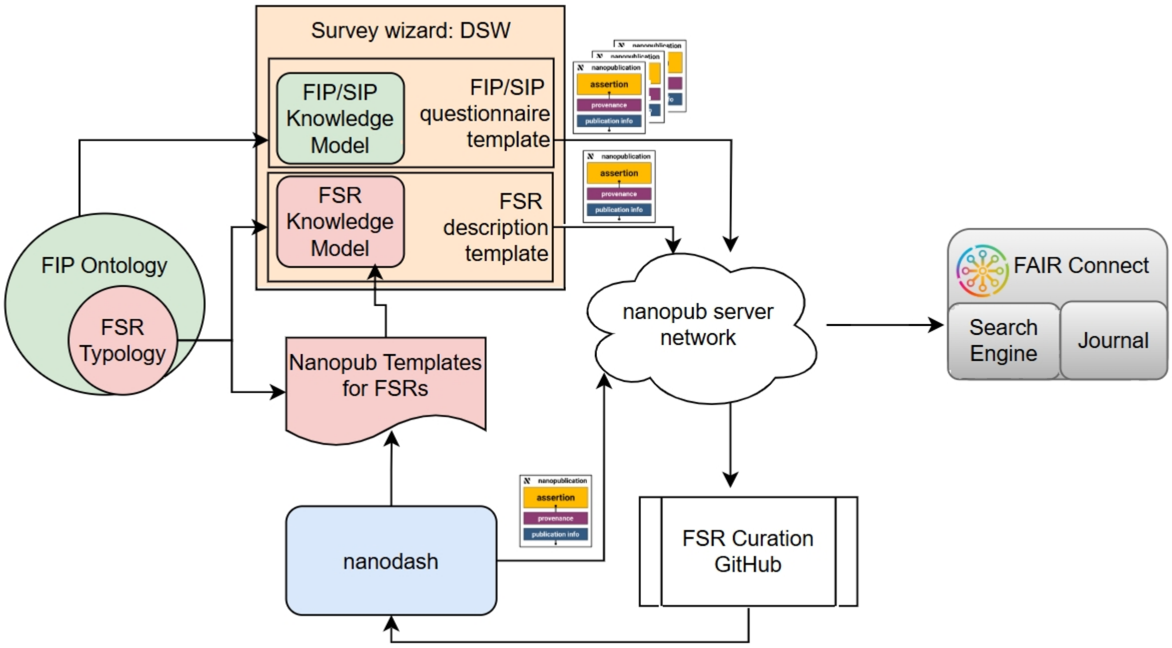

Figure 1: *FIP* Ecosystem: Overview of involved components.

3. *FIP* ecosystem

To support the creation of *FIPs*, the "*FIP* questionnaire"[9] was compiled, which is a set of questions covering the FAIR Principles, with the answers identifying resources enabling the FAIRification of (meta)data. FAIR answers to these questions are given by means of a *FIP ontology*, which semantically defines the different types of resources empowering the FAIRification work. Initially it described resources essential in enabling the FAIR Principles (*FERs*), but it was expanded to include all resources supporting the FAIRification process, using the broader *FSR* type. Using a similarly conceived "SIP questionnaire", these resources can be compiled into a *Semantic Implementation Profile (SIP)*. We developed the following collaboration tools to leverage the *FIP* ontology (see Figure 1):

- *Nanopublications* [17] are small, machine-readable RDF knowledge graphs, composed of an *assertion* and its *provenance* and *publication* metadata. They are persisted in the distributed *nanopub server network* [18], and reachable through a trustworthy, non-corruptible and persistent URI. We have extended the use of assertions from the original intent of providing scientific contributions as single statements [19] to assertions of any kind, such as metadata of digital objects. In [20], nanopublications are discussed as valid FAIR Digital Object implementations. The nanopublication schema[10] enables tools like *nanodash*[11] and the *survey wizard* (see below) to use the nanopub infrastructure as a

[9]http://bit.ly/FIPminiquestionnaire
[10]http://www.nanopub.org/2024/WD-guidelines-20240419/
[11]https://github.com/knowledgepixels/nanodash

publication mechanism.

- The *survey wizard* hosts, like the *FIP*[12] and SIP[13] Wizard, are two Data Stewardship Wizard (DSW) instances, that make use of knowledge models to design project templates. In our context, the knowledge models are based on the *FIP* ontology to create questionnaires that allow the compilation of *FIPs* and *SIPs* respectively, and their publication in different formats, including nanopublications.
- The *FSR* curation GitHub repository[14] provides an environment for curating *FSR* descriptions. A Github action[15] automatically lists new *FSR* nanopublications, which are then reviewed by at least two GFF trained FAIR experts, following well-documented curation guidelines and a process of iterative improvements. The curation process assesses the usefulness of a resource in its function to FAIRify data, and verifies its correct alignment with the appropriate *FSR* classes based on their definition in the *FIP* ontology, but does not assess the degree of FAIRness. It also provides a quality check of the completeness of the metadata description and suggests improvements where appropriate. A successful review leads to an approval nanopublication (using a dedicated template[16]) and a curation badge being assigned in the wizard. This process helps prevent duplication, inadequate descriptions, unhelpful *FSRs*, and maintains the integrity of the *FIP* approach. In addition, the process is documented, providing an invaluable insight into the debates and diverging interpretations leading to the final *FSR* classifications.
- *FAIR Connect*[17] acts as an index and search engine for finding published *FSRs*. The search results include metadata information, such as the GFF curation status and popularity with *FAIR Implementation Communities (FICs)*.

4. FIP Ontology

The *FIP* ontology, as shown in Figure 2, was conceptualised in 2020, introducing five main classes and associated properties in the *FIP* ontology. At the core of the ontology is the *FIP Declaration* class that states that a *FIC* declares the use of a *FER*. The *FIP Declaration* refers to a *FIP Question* that refers to a *FAIR Principle*. *FERs* are essential to the operationalisation of the FAIR Principles, providing the functions needed to achieve some aspect of FAIR behaviour. By request of the ENVRI communities, we introduced a more flexible representation of the *FERs*, allowing the description of *available FER* and *FER in development* as sub-classes of *FER* to reflect the rapid developments in the area of FAIR implementation. In alignment with these two sub-classes, we introduced flexible properties to define the use of these *FERs*: next to *declares-current-use-of*, which must be an *available FER*, one can *declare-planned-use-of* a *FER*, which should be accompanied by a *declares-planned-replacement-of* a *FER*. Each *FIP Declaration* is complemented

[12]https://fip-wizard.ds-wizard.org/
[13]https://sip-wizard.ds-wizard.org/
[14]https://github.com/gofair-foundation/fsr_curation
[15]https://github.com/gofair-foundation/qualification-issue-creation-action
[16]https://nanodash.petapico.org/publish?25&template=https://w3id.org/np/RAi7_UxEF3TTPBp7lmWOVvKR-jUmZgDfY_ZIe57dqbOnQ&template-version=latest
[17]https://fairconnect.pro/

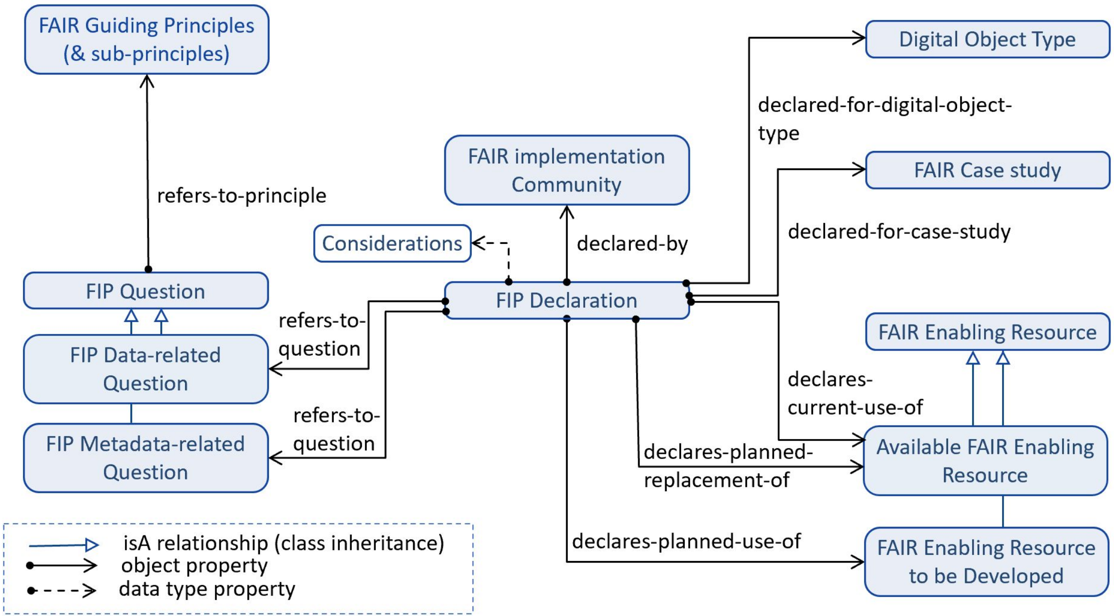

Figure 2: Core classes of the *FIP* ontology

by the data type property *considerations* to allow the description of the community requirements and constraints that led to the implementation choice.

Figure 3 gives an overview of the types of *FERs* used to address each of the principles, which can be grouped into three main types: services, specifications and policies. However, in practice, an *FER* instance can encompass multiple subtypes within one parent type, like DCAT[18], which is a specification for a *Metadata Schema*, *Structured Vocabulary*, a *Semantic Model* and a *Provenance Model*.

To provide more information about instances of the different *FSR* types, metadata templates in nanodash and corresponding metadata description templates in the DSW are provided. We used core metadata elements for all types like `rdfs:label`, `rdfs:comment`, `rdf:type`, and `rdfs:seeAlso`, plus specific elements for each of the types to better describe their particular features. For example, in the nanopub template for *identifier services*, we added the predicate *implements* using the object property URI `http://usefulinc.com/ns/doap#implements` to define which specification the service is based on. In this way, the templates enable relationships between *FSR* nanopublication instances.

The EOSC Association's Semantic Interoperability Task Force designed a survey to capture the semantic interoperability practices from across different communities of practices, consequently the *FIP* ontology was extended with additional concepts and relationships to address semantic interoperability aspects [21].

The SIP application of the ontology adapted the *FIP Declaration* concept to *SIP Declaration*, by introducing two new optional relations with the associated objects: *declared-for-case-study* with

[18]https://www.w3.org/TR/vocab-dcat-3/

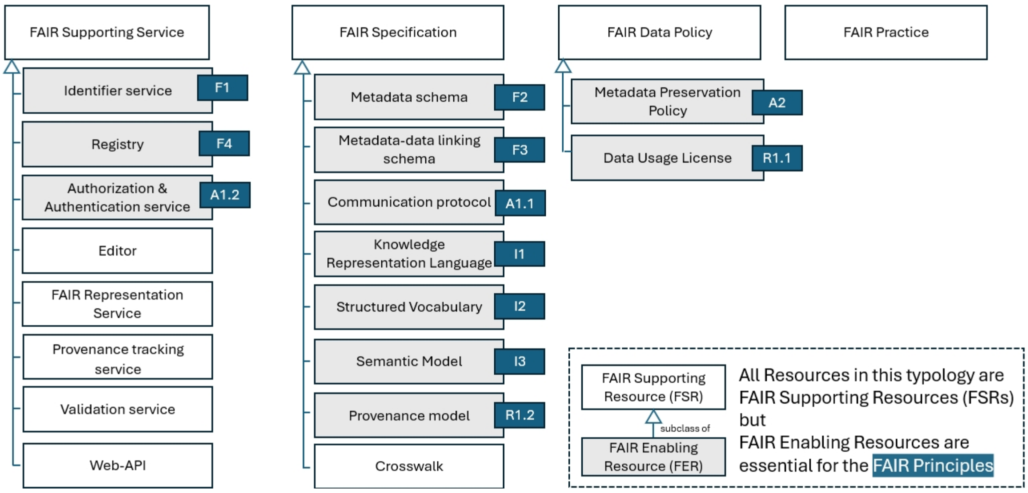

Figure 3: *FAIR Supporting Resources* versus *FAIR Enabling Resources*.

range: *FAIR case study* and *declared-for-digital-object-type* with range: *Digital Object Type*. These relations were then also taken up in the *FIP* approach, as providing explicit choices for a specific digital object type makes the profile more meaningful. In terms of the *FSR* types included, the SIP focuses on *Metadata Schemas*, semantic artefacts (which include *Structured Vocabularies* and *Semantic Models*), *Provenance Models*, but also on *Crosswalks* (e.g., mappings between schemas). In addition, it uses services for the generation, transformation, and validation of resources, such as *Editor*, *Validator Service, FAIR Representation Service, Web API, provenance Tracking Service*. *FAIR Practice* was introduced as a class for representing combinations of specifications and services. These new classes required an extension of the *FIP* ontology beyond the FER typology, introducing the *FSR* as a superclass with *FAIR Supporting Services* and *FAIR Specifications* as main subclasses (see Figure 3). For completeness, it should be noted that the *FSR* typology includes other classes, such as, e.g., *FAIR Data Stewardship Event*, which are ignored here since they are beyond the scope of this paper.

5. *FSR* curation challenges

Considering that the *FIP* is a collection of community-selected (or -created) resources that provide the answers to the various FAIR Principles, and an *FSR* can be any resource created in any context, it is understandable that achieving a straightforward one-to-one correspondence between principles and resources is more of an exception than a norm. This is not inherently problematic (after all, *FSRs* can provide -sometimes partial- solutions to multiple FAIR concerns), but it does lead to ambiguities, for instance when *FSR* types with potentially competing scopes are combined. The assignment of *FSR* types is currently subjective and disagreements can occur, which becomes evident in the peer-review curation process documented as GitHub issues.

An *FSR* that showcases this phenomenon is Research Object Crate (RO-Crate)[19], as reported

[19]https://www.researchobject.org/ro-crate/

in GitHub issue 119[20]. A nanopublication for this *FSR* is available[21], and the GitHub issue also points to an existing duplicate which has only *Metadata Schema* listed as its *FSR* type. Both nanopublications were authored by the same individual, so the nanopublication with the older date should have been replaced with the newest one. The latter describes RO-Crate as a *Metadata Schema*, *Structured Vocabulary* and *Semantic Model*, which is entirely justified, because, as pointed out in the documentation[22], the metadata schema is defined in JSON-LD, reusing schema.org vocabularies and includes qualified relations to other standards like Portland Common Data Model[23] and Dublin Core Terms[24]. As argued by the lead of this paper (GitHub user `mabablue`), additional types should be included in the description:

1. *Provenance Model* ,as also described in the RO-Crate project in the *FIP* Wizard[25] created (but not yet available as a nanopublication) by Stian Soiland-Reyes[26], who is a co-developer of RO-Crate;
2. *Metadata-Data Linking Schema*, as RO-Crate packages research data with their metadata.

When all categories apply, the categorisation might lose its usefulness. On the other hand, specifications can include all these different aspects, as it applies in the example given. However, when constructing a specification type *FSR*, it is best practice not to mix *FAIR Supporting Services* and *FAIR Specification.* A potential alternative is to consider the RO-Crate specification to be a complex *FSR*, composed of multiple sub-*FSRs* with their own types. Another option would be to categorise the RO-Crate approach as a *FAIR Practice*, which suggests the combined use of a set of *FSRs* to reach a FAIRification goal.

6. Ontological analysis of the *FSR* typology

The *FIP* ontology started with twelve *FER* types focusing on the implementation of the FAIR Principles. However, it gradually expanded over time, driven by requests of the communities of practice, such as those from the ENVRI-FAIR project. This expansion requires refinement to provide clear descriptions of *FSRs*, and to ensure interoperability with existing relevant semantic artefacts. Not refining the ontology bears the risk of inconsistencies, inaccuracies and/or bad practices creeping into its application for *FSR* descriptions. To mitigate this risk, we performed an ontological analysis focusing on some aspects of the *FSR* typology, based on the Unified Foundational Ontology (UFO) [22]. A foundational ontology defines a system of domain-independent categories and their relations, providing a means for semantic clarification of a subject domain. Conducting ontological analysis involves the definition of mappings between modelling constructs (the *FIP* ontology) and the concepts in a reference ontology (UFO) to identify ontological shortcomings. This may include construct excess (no mapping possible), overload (a single modelling construct can represent multiple ontological concepts), redundancy

[20] https://github.com/gofair-foundation/fsr_curation/issues/119
[21] http://purl.org/np/RAcYMfIt1ICpNTg0RCiR0QHfNoSUU-b-5Yw3w06HSL9VA
[22] https://www.researchobject.org/ro-crate/1.1/structure.html
[23] https://pcdm.org/2016/04/18/models
[24] https://www.dublincore.org/specifications/dublin-core/dcmi-terms/
[25] https://fip-wizard.ds-wizard.org/wizard/projects/c8e39b76-8964-4222-b41b-d3bc83f8193b
[26] https://orcid.org/0000-0001-9842-9718

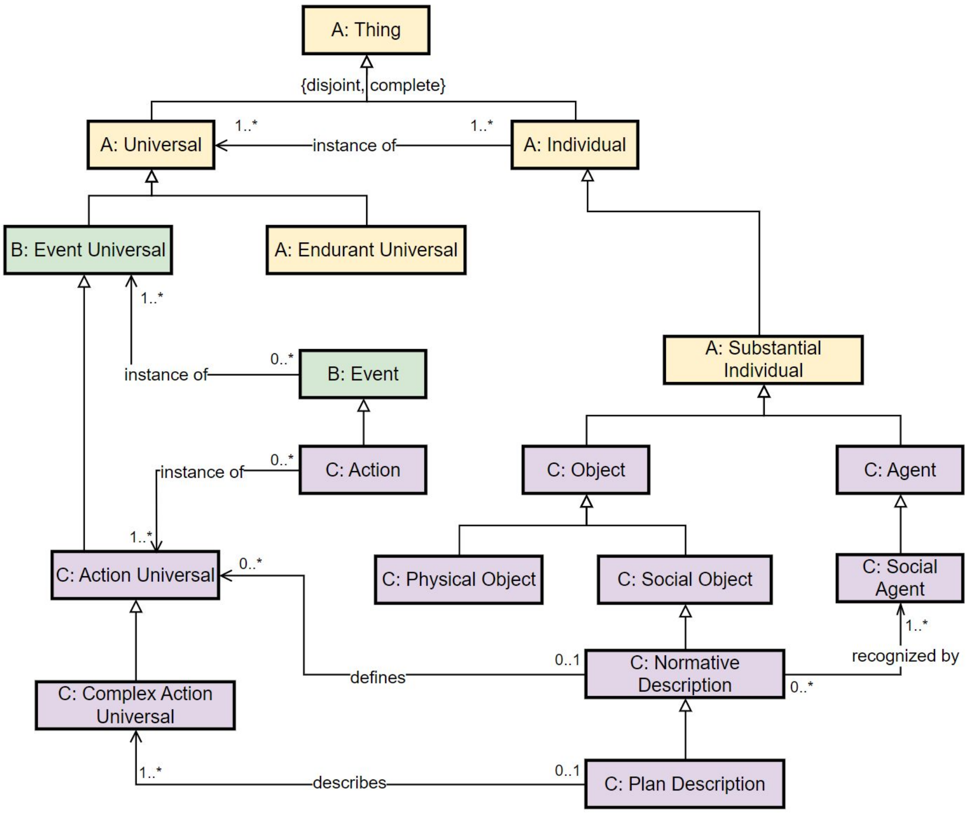

Figure 4: A fragment of UFO-A (A: yellow), UFO-B (B: green) and UFO-C (C: violet)

(multiple modelling concepts can represent the same ontological concept) and deficit (lack of expressivity of the modelling language to represent relevant phenomena in a domain) [23]. In the cases where the reference ontology is a foundational ontology, the mappings between their concepts is also called grounding.

To facilitate the readability of the notions used, we apply different styles from here on: `UFO concepts` and «meta-properties». The parts of UFO [22] used in our analysis comprise three layers. UFO-A, an ontology of `Endurants` such as `Objects`, `Qualities`, `Relators`, and `Dispositions`; UFO-B introduces `Perdurants` like `Events` and the relations between enduring and perduring individuals; and UFO-C, which specialises the other two layers focusing on social aspects of reality including notions for `Plans`, `Goals`, `Agents`, `Commitments`, and `Normative Descriptions` (see Figure 4).

UFO makes a fundamental distinction between `Individuals`, which are entities existing in reality with a unique identity, and `Universals`, which are abstract patterns of features that can manifest in various individuals. Unlike `Perdurants`, `Endurants` are individuals that are wholly present whenever they are present. `Substantials` are existentially-independent `Endurants`, whereas `Moments` are individuals dependent on their bearers. `Substantial Universals` are kinds of universals whose individuals are substantial individuals [22]. Based on UFO's theory of types there is an essential difference between Sortals and Non-Sortals:

«Sortal universals» are Substantial Universals that embody a principle of identity for their individuals. «Kinds» are rigid sortals in case this also applies to its instances, and «Collective Universals» represent collections of individuals with homogeneous structure. «Phases» and «Roles» are anti-rigid specialisations of identity providers, the first are influenced by changes in intrinsic properties (e.g., teenager, adult), and the latter are relationally dependent «Sortal Universals» (e.g., student, professor). In contrast, «Mixin Universals» are universals that do not carry a unique principle of identity for their instances, as they can be of multiple kinds. «Categories» represent rigid and relationally independent mixin universals that aggregate essential properties common to different kinds. «Role Mixins» represent anti-rigid and relationally dependent non-sortal universals that aggregate properties common to different roles.

UFO-C [24] differentiates between Agents and Objects as subtypes of Substantial Individuals. Agents are Agentive Substantial Individuals that are classified as Physical Agents (e.g., a person) or Social Agents. Objects are Non-agentive Substantial Individuals that are classified as Physical Objects (e.g., a car) and Social Objects, like languages or norms. A Normative Description defines one or more rules acknowledged by at least one Social Agent, like organizations or communities. A Plan Description is a specialization of a Normative Description that describes Complex Action Universals (such as Processes). Action Universals are Event Universals (Perdurants) as described in UFO-B. Intentional Moments reside in Agents, and can be mental or social. Intentions are Mental Moments, and prompt the Agent to perform Actions, which can be complex or atomic. Social Moments are types of Intentional Moments that are generated by Social Actions.

Mapping the UFO concepts and meta-properties to the *FIP* ontology it becomes clear that all *FSR* instances can be considered as Individuals while *FSR* types can be considered as Universals. Further, we can map *FSRs* to Endurants and «Categories», as they represent an aggregation of different «Kinds». As defined in the *FIP* ontology, *FAIR Specifications* are "precise descriptions of features, requirements, constraints" and therefore we suggest to map them to *Normative Descriptions*, which are endorsed by one or more *FICs*. FICs can be mapped to Collective Social Agents that bear Intentions to implement the FAIR Principles. All specific *FAIR Specification* types like *Metadata Schema* can be considered to be «Subkinds». *FAIR Practices* can be interpreted as Plan Descriptions (see Figure 5) that describe Complex Actions like the proper usage of a required *FSR* or a combination of *FSRs* to achieve a FAIRification goal. *FAIR Policies* can be distinguished from *FAIR Practices* by the level of commitment of FIC members, to align with the rules defined in the policy. *FIP Declarations* are Perdurants that might be classified as Communicative Act that can result in Normative Descriptions, like the *FIPs* which are recognized by *FICs*.

Considering the possible classification options for the *FSR* instance RO-Crate, it can be inferred from the mapping provided that:

- Complex *FSR*: a specification may intertwine different specification types like *Metadata Schema* and *Provenance Model* in one semantic artefact, and thus may not be individually divisible.
- *FAIR Practice*: is a description of how to carry out a complex action that requires *FSRs*,

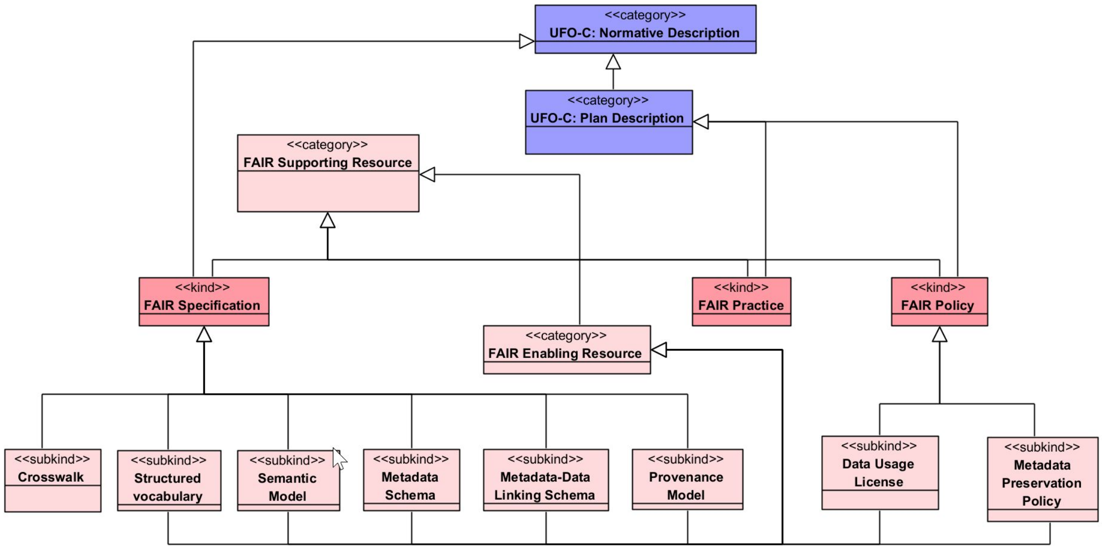

Figure 5: Possible mappings of selected *FSR* classes to UFO meta-properties and UFO-C Classes (violet).

which may include specifications.

- Multiple subtypes of *FAIR Specifications* may be applied, but it is crucial to avoid mixing between «Kinds» (services and specifications). This rule is not reflected in the ontology and therefore we recommend to explicitly state this rule in the guidelines for the *FSR* instance descriptions.

The analysis results in a refined definition for *FAIR Practice*: "A method description detailing the use of a specific resource or a combination of resources as applied by a community to achieve FAIR processing of information." Additionally, the metadata template for this type has been enhanced as follows:

- To include statements about employed *FSRs* the object predicate `http://purl.org/dc/terms/requires` is used.
- To include statements about the supporting *FIC* the object property `https://w3id.org/fair/fip/terms/declared-by` is used.

We applied the improved template to describe the RELIANCE Research Object Practice, which recommends the use of the *FAIR Specification* RO-Crate and the *Registry* ROHub[27], and the GFF OSF Practice[28], which advocates to register all the relevant artefacts created for a 3PFF event in the Open Science Framework. We will also provide clear guidelines on how to provide *FSR* instance descriptions to prevent poor type allocations. We plan to verify whether the suggested changes reduce ambiguities regarding the classification of *FSRs* with multiple types by analysing issue resolution in the Curation GitHub repository.

[27] https://w3id.org/np/RAq2HHTwWLjZzP-gIJIRJiQJpjd4KTrMn-WLvnKo1mXdU
[28] https://w3id.org/np/RADBsQ41yWver59fedlE0kx3gUDaWMplqM8-BzgOYxUz8

7. Final Remarks

By conducting ontological analysis using an upper ontology such as UFO as a reference, it becomes possible to offer clarifications in the classification process when submitting a nanopublication description of a specific *FSR*. This is also instrumental for qualifying *FSR* descriptions. As demonstrated in this paper on the *FAIR Practice* example these clarifications will help to improve the concept definitions, the user guidance text in the wizards and the metadata templates for *FSR* instances. We could also clarify that RO-CRATE is best described by classifying it to multiple *FER* types of kind specification. Further analysis is needed to enhance the *FIP* ontology and fine-tune the definitions of its classes for other *FSR* types. Moreover, we want to improve the metadata descriptions of *FSR* types by analysing relations between different types. Validation of the improved ontology and metadata schemas will be performed using real-world example *FSRs*, covering both new instances and existing resources to ensure backwards compatibility.

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