



# Practical webby FDOs with RO-Crate and FAIR Signposting

**Document Version**  
Submitted manuscript

[Link to publication record in Manchester Research Explorer](#)

**Citation for published version (APA):**

Soiland-Reyes, S., Sefton, P., Leo, S., Castro, L. J., Weiland, C., & Van De Sompel, H. (2024). Practical webby FDOs with RO-Crate and FAIR Signposting: Experiences and lessons learned. Manuscript submitted for publication. In *Open Conference Proceedings: International FAIR Digital Objects Implementation Summit 2024* (Vol. 4). TIB Open Publishing.

**Published in:**  
Open Conference Proceedings

**Citing this paper**

Please note that where the full-text provided on Manchester Research Explorer is the Author Accepted Manuscript or Proof version this may differ from the final Published version. If citing, it is advised that you check and use the publisher's definitive version.

**General rights**

Copyright and moral rights for the publications made accessible in the Research Explorer are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.







**Takedown policy**

If you believe that this document breaches copyright please refer to the University of Manchester's Takedown Procedures [<http://man.ac.uk/04Y6Bo>] or contact [uml.scholarlycommunications@manchester.ac.uk](mailto:uml.scholarlycommunications@manchester.ac.uk) providing relevant details, so we can investigate your claim.



# Practical webby FDOs with RO-Crate and FAIR Signposting

## Experiences and lessons learned

Stian Soiland-Reyes<sup>1,2</sup>, Peter Sefton<sup>3</sup>, Simone Leo<sup>4</sup>, Leyla Jael Castro<sup>5</sup>,  
Claus Weiland<sup>6</sup>, and Herbert Van de Sompel<sup>7</sup>

<sup>1</sup>The University of Manchester, UK

<sup>2</sup>University of Amsterdam, The Netherlands

<sup>3</sup>University of Queensland, Australia

<sup>4</sup>Centro di Ricerca Sviluppo e Studi Superiori in Sardegna (CRS4), Italy

<sup>5</sup>ZB MED Information Centre for Life Sciences, Germany

<sup>6</sup>Senckenberg – Leibniz Institution for Biodiversity and Earth System Research, Germany

<sup>7</sup>DANS, The Netherlands

\*Correspondence: Stian Soiland-Reyes, [soiland-reyes@manchester.ac.uk](mailto:soiland-reyes@manchester.ac.uk)

**Abstract:** Research Object Crate (RO-Crate) is a lightweight method to package research outputs along with their metadata. Signposting provides a simple yet powerful approach to navigate scholarly objects on the Web. Combining these technologies form a “webby” implementation of the FAIR Digital Object principles which is suitable for retrofitting to existing data infrastructures or even for ad-hoc research objects using regular Web hosting platforms. Here we give an update of recent community development and adoption of RO-Crate and Signposting. It is notable that programmatic access and more detailed profiles have received high attention, as well as several FDO implementations that use RO-Crate.

**Keywords:** FDO, Web, RO-Crate, Signposting, metadata, linkset, community

## 1 Signposting

The Signposting [1] effort started around 2015 in an attempt to address a long-standing problem regarding machine interaction with scholarly objects on the web. Omnipresent landing pages support human interaction with scholarly objects by providing descriptive metadata and links to content. But those pages are not optimised for use by machine agents that navigate the scholarly web. For example, how can a robot determine which links on a landing page lead to content and which to metadata? And, how can a bot distinguish those links from the myriad of other links on the page? Signposting addresses this by suggesting some purposely simple, yet standard-based patterns for using typed web links [2] to unambiguously point from a landing page to descriptive metadata (`describedby` link), content resources (`item` link), persistent identifier (`cite-as` link), etc.

## 1.1 FAIR Signposting

It is fair to say that the Signposting effort initially did not gather a lot of attention nor momentum. But that changed when, in 2020, the [FAIR Signposting Implementation Guideline](#) was published. FAIR Signposting goes beyond merely suggesting patterns as it specifies concrete, well-documented and illustrated recipes that developers can follow to add Signposting support to repository platforms or to implement compliance checks in FAIR assessment tools. It provides details regarding the precise semantics of the select set of link relation types, their cardinality, best practice recommendations for license and vocabulary URIs, levels of support, etc.

## 1.2 Web technologies in Signposting

Web links [2] used by Signposting primarily take the form of additional `Link:` headers in the HTTP response to a given resource, with `rel=` indicating the link relations as standardised in the [IANA registry](#), e.g.:

```
Link: <https://schema.org/LearningResource>;rel="type"
Link: <https://w3id.org/a2a-fair-metrics/103-fdo-gr2-pid-record/>;
    rel="cite-as"
Link: <https://example.com/103-fdo-gr2-pid-record/metadata>;
    rel="describedby";type="text/plain"
```

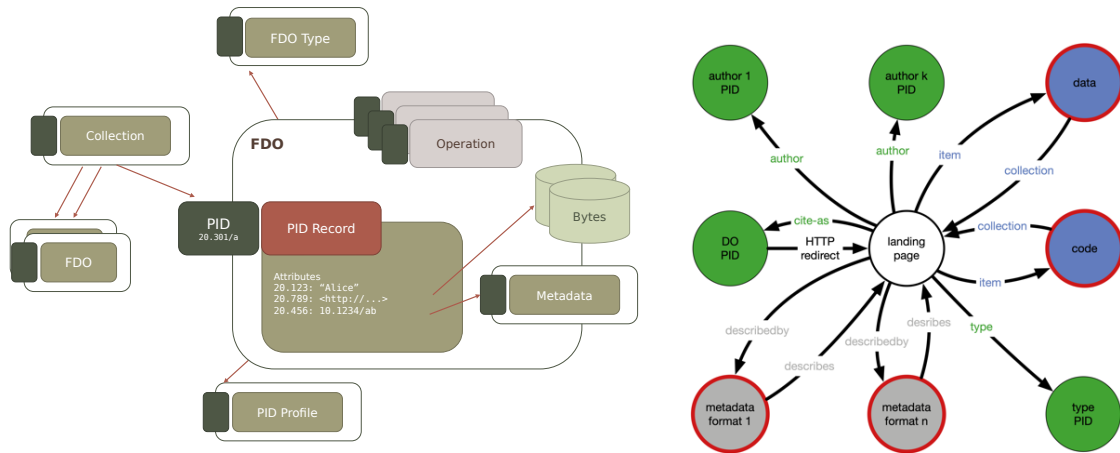
FAIR Signposting is a profile for systematic use of a handful of link relations in [level 1](#), adding bi-directional completeness in [level 2](#). This non-intrusive addition of links means Signposting can be added to any kind of Web resource (including large data), and then inspected by using the regular HTTP method `GET`, or `HEAD` to avoid potentially costly content retrieval. However, adding HTTP-level Signposting requires control of the Web server, and injecting headers can be cumbersome in some Web server frameworks.

Signposting can also be embedded in HTML-based *landing pages* by adding the corresponding `<link href="..." rel="..." />` element within the page `<head>`, just like the familiar `rel="stylesheet"` link relation. This option is useful when developer control is limited to HTML templates, e.g. in a content delivery network (CDN) or GitHub Pages [3], however the HTML approach do not as easily provide inverse links back to the landing page (e.g. `rel="describes"`).

In addition to the two previously mentioned Signposting approaches, typed links can also be provided in stand-alone documents named *link sets*. Two serialisations for linksets are defined in [4]: the text-based `application/linkset` format that is equivalent to the content of the HTTP Link header, and the JSON-based `application/linkset+json` format. Linksets are an attractive option when large collections of links need to be shared. They are made discoverable by means of links with the `rel="linkset"` relation (or `rel="api-catalogue"` for service descriptions). In theory, linkset representations can also be used in non-Web contexts such as the Handle system or local filesystems.

## 1.3 Signposting as web-centric implementation of FDO

An extra boost for Signposting came when it became clear [6] that FAIR Signposting essentially provides a web-centric model (Figure 1, right) for the notion of the FAIR Digital Object (Figure 1, left) [7]. FAIR Signposting exposes the topology of a FDO on the web and does so by using the simplest possible ingredients. The choice for



**Figure 1.** An identified FAIR Digital Object (left) capture a digital object in a PID Record through attributes and associated types, profiles and metadata, each of which may be other FDOs. FAIR Signposting (right) implements FDO using link relations to the persistent identifier (*cite-as*), the type PID (*type*), data/code (*item*), and metadata (*describedby*). FDO attribute shown as signposting include PIDs of *author* and *license* (not shown). Figure adapted from [5], [6].

simplicity is motivated by a desire to minimise implementation and maintenance costs and is inspired by experience with numerous standardisation efforts over the years. The choice for web-centricity is about the availability of off-the-shelf tools and expertise as well as a realistic prospect of long-term sustainability.

Table 1 shows the correspondence between FAIR Signposting link relations and FDO concepts [8]. Note that while kernel attributes `author` and `license` are part of FAIR Signposting, any additional type-specific attributes should be provided by the metadata resource (e.g. a RO-Crate Metadata File), although [extension relations](#) are also possible.

**Table 1.** Link relations and corresponding FDO concepts, using FAIR Signposting and FAIRiCAT.

Link relation/attribute	FDO concept
Any <code>rel=</code> after PID redirect	FDO/PID Record (PID Profile: Signposting)
<code>rel=cite-as</code>	PID (persistent identifier)
<code>rel=linkset</code>	FDO Record (PID Profile: Linkset)
<code>rel=describedby</code>	Metadata, or Metadata FDO if PID
<code>rel=describes</code>	FDO Record that has this metadata
<code>rel=item</code>	Bit-sequence
<code>rel=collection</code>	FDO Collection, or FDO Record for a bitstream
<code>rel=type</code>	FDO Type
<code>type=</code> ON <code>rel=item</code> OR <code>rel=describes</code>	MIME type of bitstream
<code>rel=profile</code>	PID Profile
<code>profile=</code> ON <code>rel=describes</code>	FDO Type of Metadata (e.g. PID Profile: RO-Crate <a href="https://w3id.org/ro/crate">https://w3id.org/ro/crate</a> )
<code>rel=author</code> OR <code>rel=license</code>	Kernel attributes
<code>rel=api-catalogue</code> to linkset	FDO Collection of FDO Operations
<code>rel=service-desc</code> OR <code>rel=service-doc</code>	FDO Operation

## 1.4 Signposting improves FAIR consumption

The EOSC [task force](#) for FAIR Metrics and Data Quality organised a series of “Apples to apples” hackathons and workshops, and have reported on FAIR Signposting and its uptake [9]. It highlights Signposting as a mechanism for guiding FAIR consuming machine-agents to locate the globally unique identifiers, data records and metadata records, and the challenge for FAIR assessment tools to make consistent evaluations without these elements.

A series of detailed benchmarks for Signposting have been created by the hackathons [10], that include identified test cases for each FAIR principle. For instance, [55-rda-r1-01m-t5-type-unresolve](#) is a negative test case of a Signposting FDO where each of the `rel=type` has resolution errors. Such benchmarks are used by evaluation tools like [F-UJI](#), as well as Signposting clients like the [signposting](#) Python library and command line tool.

Recently, additional tests for “Webby FDO” using Signposting have been added, e.g. [108-fdo-gr3-bit-sequence-metadata-pid](#) verifies FDO principle [FDO-GR3](#) to reference a bit-sequence, alongside a PID, type PID and metadata PID. Work to further mature FDO benchmarks continues as part of a FDO Forum task force.

## 1.5 Growing adoption through Support Actions and Hackathons

The FAIR-IMPACT project’s first [support action](#) funded 18 participants contributing to FAIR assessments as well as 14 participants implementing Signposting and RO-Crate in their repositories and code bases. Among the latter, Signposting support was developed for University of Novi Sad’s Research Information System [DOSIRD UNS](#), Simula created a [Signposting extension](#) for CKAN to be used by the [Norwegian Research Data Archive](#) [11], [ZB MED](#) developed Signposting for GitHub Pages [3], [12].

Signposting *linkset* support was developed for [InvenioRDM](#) (used by Zenodo) and using HTML headers in Tunisia’s [Scientific and Technical Information Portal](#) by Tunisia National University Center of Scientific and Technical Documentation. EURAC Research’s [Environmental Data Portal](#) also added detailed signposting and new metadata serialisations, here the use of profiles in signposting was highlighted. The Digital Repository of Ireland (DRI) has implemented Signposting [13], adding detailed linksets at Level 2.

Several FAIR-IMPACT participants had planned to work on [Signposting support in Dataverse](#), but that was concurrently implemented by the Dataverse community and relatively complete. For these participants, focus moved to upgrading and testing Signposting in their instances, as well as contributing to RO-Crate support in Dataverse to support richer metadata (see section 2.6).

When reaching out to the US NIH’s Generalist Repository Ecosystem Initiative ([GREI](#)), among its members (including Dataverse and InvenioRDM/Zenodo, Figshare, OSF, Vivli, Mendeley Data and Dryad), many indicated they were developing support for Signposting as well as user-provided metadata.

A growing list of [adopters of Signposting](#), including repositories and data platforms, shows the interest in and feasibility of implementing Signposting. In addition to the above, earlier adopters include repositories [WorkflowHub](#) (Signposting to RO-Crate using profile), [DSpace](#), [DSpace-CRIS](#), and [the DANS Data Stations](#). Journal system and preprint server support include [Episciences Overlay Journals](#), [HAL Science](#) and [Open Journal System](#).

As part of the ELIXIR Biohackathon [12], the [Signposting Sniffing](#) plugin for Chromium-based browsers was developed and tested with signposting in the [HoloFood Data Portal](#). The plugin supports both HTML- and HTTP-based Signposting, and can be used to debug and discover signposting.

These adopters highlight that it is easy to retrofit Signposting, but that the learning curve of other FAIR standards means that providing detailed metadata is more demanding.

## 2 RO-Crate community updates

The [RO-Crate community](#) supports and promotes FAIRification of research outcomes and provides tools for researchers to improve FAIRness. RO-Crate [14] makes it easy to package research outcomes in the form of digital objects together with their corresponding metadata, using and extending [schema.org](#) to describe an RO-crate package as a dataset and all its elements (i.e, research outcomes). Thanks to the use of [profiles](#), researchers can choose a description that best suits their needs. A [Profile Crate](#) provides a specification including types and properties tailored to a specific domain or community (effectively a *PID Profile* that lists *FDO Types*). In this section we provide an update on recent new community adoption of RO-Crate, see also [14] for existing adoptions.

### 2.1 Workflows and provenance

Workflow Run RO-Crate [15] is a set of three RO-Crate profiles to capture the provenance of computational workflow execution: [Process Run Crate](#), which deals with possibly composite computations not necessarily described by a formal workflow; [Workflow Run Crate](#), which extends Process Run Crate with specifications to represent computations orchestrated by a workflow; [Provenance Run Crate](#), which extends Workflow Run Crate with guidelines on how to represent the execution of the various tools used by the workflow. The profiles are developed by a working group that includes workflow developers and users, workflow engine developers and users and other members interested in the provenance of workflow execution. Workflow Run RO-Crate is already implemented by six workflow engines: Galaxy, COMPSs, StreamFlow, WfExS-backend, Sapporo and Autosubmit, enabling interoperable comparisons between heterogeneous workflow executions.

#### 2.1.1 Executable papers

[LivePublication](#) [16] is a proof of concept of an *executable paper*, whose interactive visualisation and statistical calculations can be regenerated on the fly taking into consideration data sources updated after the paper's publication date. Here RO-Crate enables execution on the Globus infrastructure through an innovative use of individual RO-Crates and containers for each computable element of the paper, nested within a top-level Crate for the paper. This novel approach shows how it is possible to use RO-Crate as a machine-actionable object, which does not rely on bundling an underlying workflow representation in an existing workflow language.

#### 2.1.2 TRE-FX and TREs

Trusted Research Environments (TREs) are used to provide computational analysis access to sensitive data. An architecture for federated analytics running workflows

across such TREs [17] developed the Five Safes Crate profile [18], where the crate goes through manual and automatic review processes which are tracked within the crate and abstracts the workflow run requests so the federated analytics APIs are interoperable across different workflow engines [19].

## 2.2 RO-Crate and FDO

RO-Crate has previously been proposed as a mechanism for implementing FDO [20], in particular for metadata FDOs. The FDO approach fosters self-contained and machine-actionable knowledge units which persistently bind necessary contextual metadata and typed operation semantics to enable processing of their actual content across different data spaces [21].

One way to implementing FAIR Digital Object is using dedicated network protocols including the Handle system and the Digital Object Interface Protocol (DOIP) [22], [23]. In addition, an implementation path for web-based or “webby” FDOs [24] has been proposed to build on common web technologies [25]. This approach uses RO-Crate to provision structured metadata based on schema.org and its extension [Bioschemas](#) [26], deployed on the Web with persistent identifiers and FAIR Signposting [12].

### 2.2.1 Distributed FDO architectures

The [DeSci Nodes](#) system has developed a *Distributed Persistent Identifier (dPID)* concept which acts as an overlay of the Interplanetary File System (IPFS) [27]. APIs for the DeSci use detached RO-Crates with dPID references. This is a novel FDO implementation that challenges both the traditional centralised FDO approach using the Handle system, as well as the mostly web-based RO-Crate ecosystem.

Further considerations of FDO and Linked Data as distributed systems [28] evaluates FDO approaches in terms of capabilities based on existing frameworks (including the FAIR and FDO principles themselves), and highlights that the FDO community should take advantage of lessons learnt by the Linked Data community (avoiding similar mistakes, e.g. with relation to rigidity), and utilise fully the mature and modern capabilities of the Web technology stack, e.g. multiplexed streams.

## 2.3 Webby FDOs in biodiversity

The Biodiversity Digital Twin ([BioDT](#)) project is developing a specimen profile [29] that combines the Handle system and RO-Crate. A similar hybrid approach is taken for “retrofitting” Signposting to a FDO approach based on the digital object server [Cordra](#) in Senckenberg’s [WildLIVE Portal](#) [24]. This deployment injects Signposting headers as part of the public [nginx](#) server without modifying the proxied Cordra instance, except adding a single API method to generate the Signposting links [12] (Figure 2). Semantic mappings across biodiversity vocabularies [30] can also benefit from the use of RO-Crate, as a way to capture multiple mappings and to version and attribute the mapped semantic artefacts.

## 2.4 Using the Crate-O editor and building ad-hoc vocabularies

The [Crate-O](#) tool has been developed by Language Data Commons of Australia ([LDA](#)) as a general-purpose RO-Crate editor as a successor or alternative to [Describe](#). This browser-based tool can use the [file system access API](#), currently implemented in the

Signposting.org metadata: this page should be cited as <https://wildlive.senckenberg.de/api/objects/wildlive/d18c5732e22926188a5c>

Signposting.org metadata: this page is described by <https://wildlive.senckenberg.de/api/call?objectId=wildlive/d18c5732e22926188a5c&method=getAsROcrate> (application/ld+json) with a profile at <https://w3id.org/ro/crate>

Signposting.org metadata: this page is licensed according to <http://spdx.org/licenses/CC-BY-4.0>

Signposting.org metadata: this page is authored by <https://orcid.org/0000-0002-2631-4601>

Signposting.org metadata: this page has an item at [https://wildlive.senckenberg.de/api/objects/wildlive/753bd418dff80facaa43?payload=CamTrapImport\\_2019-09-06\\_AdditionalStations\\_LaCachuela\\_201\\_A\\_55.MP4\\_2019-09-05\\_07-46-16\\_frame\\_2.PNG](https://wildlive.senckenberg.de/api/objects/wildlive/753bd418dff80facaa43?payload=CamTrapImport_2019-09-06_AdditionalStations_LaCachuela_201_A_55.MP4_2019-09-05_07-46-16_frame_2.PNG) (image/png)

Signposting.org metadata: this page has an item at [https://wildlive.senckenberg.de/api/objects/wildlive/94a90b3c837167db4591?payload=CamTrapImport\\_2019-09-06\\_AdditionalStations\\_LaCachuela\\_201\\_A\\_55.MP4\\_2019-09-05\\_07-46-16\\_frame\\_115.PNG](https://wildlive.senckenberg.de/api/objects/wildlive/94a90b3c837167db4591?payload=CamTrapImport_2019-09-06_AdditionalStations_LaCachuela_201_A_55.MP4_2019-09-05_07-46-16_frame_115.PNG) (image/png)

Signposting.org metadata: this page has an item at [https://wildlive.senckenberg.de/api/objects/wildlive/67b38d91b3cc5c6b2091?payload=CamTrapImport\\_2018-09-06\\_AdditionalStations\\_LaCachuela\\_201\\_A\\_110.MP4\\_2019-09-05\\_07-46-16\\_frame\\_2.PNG](https://wildlive.senckenberg.de/api/objects/wildlive/67b38d91b3cc5c6b2091?payload=CamTrapImport_2018-09-06_AdditionalStations_LaCachuela_201_A_110.MP4_2019-09-05_07-46-16_frame_2.PNG) (image/png)

Signposting.org metadata: this page has an item at [https://wildlive.senckenberg.de/api/objects/wildlive/9ab252d55853ecf91e64?payload=CamTrapImport\\_2018-09-06\\_AdditionalStations\\_LaCachuela\\_201\\_A\\_110.MP4\\_2019-09-05\\_07-46-16\\_frame\\_57.PNG](https://wildlive.senckenberg.de/api/objects/wildlive/9ab252d55853ecf91e64?payload=CamTrapImport_2018-09-06_AdditionalStations_LaCachuela_201_A_110.MP4_2019-09-05_07-46-16_frame_57.PNG) (image/png)



**Figure 2.** Signposting detected in the WildLIVE portal by the *Signposting Sniffing* browser detailing a data capture event. The link relations provide the set of the images contained in a capture event, metadata like license and authorship, and an RO-Crate comprising the actual content such as annotations (e.g. AI-based taxon identification).

Chrome and Edge browsers to describe any local folder with resources from the Web as an RO-Crate, or be embedded in an online service to work with any browser with server-side crates. It supports any schema.org type and property, pluggable with other *rdfs* vocabularies. A *mode file* selection indicates recommended and required properties; mode files combine schema information on classes, properties and defined terms, with RO-Crate Profile rules on how they may be defined. Notably this tool is also intended for creation of such “ad-hoc” vocabularies without need of Semantic Web, and is effectively a lightweight user interface for building *Profile Crates* using “Schema.org style Schemas” (SOSSs). There are a number of *tools* associated with Crate-O which can create HTML documentation and Crate-O mode files from SOSSs, provide simple validation against a profile and infer schemas from example documents.

## 2.5 Cultural heritage preservation in LDaCA

The Language Data Commons of Australia Program (*LDaCA*) contributes to language research and cultural heritage preservation by archiving Australian Indigenous languages, regional languages of the Pacific, and Australian English, and making such data and annotations publicly available. LDaCA and the *Pacific and Regional Archive for Digital Sources in Endangered Cultures (PARADISEC)* use *RO-Crate* with an *RO-Crate profile*, as an interchange and archive format for language data, and is providing data discovery portals and API access to data using RO-Crate-centric APIs. For instance, the *LDaCA data portal* uses *detached RO-crates* for FDO-style navigation of centralised API resources.

## 2.6 Dataverse integration

In the research data repository software *Dataverse* [31], *RO-Crate support* is implemented by multiple plugins. The *AROMA* (ARP RO-Crate Manager) [32], used by Hungarian repository *CONCORDA*, extends *Dataverse* for dynamic metadata editing using the *Describe Crate Builder Web* component. The FAIR-IMPACT support action (section 1.5) saw community development of import, *export* and *preview* plugins for RO-Crate



in Dataverse, and also for the Electronic Lab Notebook format (ELN), which is based on RO-Crate and also supported by the research platform RSpace [33].

### 3 Discussion

“Webby FDOs” are being implemented by a range of adaptations that use Signposting and/or RO-Crate, in many cases accelerated by relatively modest support action funding (5 days FTE) or implemented at hackathons. This hints that these technologies are easy to deploy and developed, however there are some divergence between the approaches, which could be seen as a hindrance for full machine actionability.

Further documentation of the “Webby FDO” approach should specify concrete and testable recommendations (e.g. specifying a Signposting PID Profile), and the community should further develop the use of Profile Crate as a mechanism to formalise domain-specific PID Profiles, which should be made discoverable in a profile registry (in development).

The hybrid FDO approaches from biodiversity that combine the Handle system, Signposting and RO-Crate shows possible alignment across “FDO flavours”. Further development of the Signposting benchmarks and a common FDO testing framework should guide the FDO community towards a more unified ecosystem of FDO implementations.

### Underlying and related material

Training material [34]: <https://doi.org/10.5281/zenodo.10892090>

Presentation slides [35]: <https://doi.org/10.5281/zenodo.10847062>

Signposting Benchmarks [10]: <https://w3id.org/a2a-fair-metrics>

### Author contributions

Contributions according to CRediT taxonomy: SSR: Conceptualization, Project administration, Software, Visualization, Writing – original draft, Writing – review & editing. PS: Conceptualization, Project administration, Software, Supervision, Writing – review & editing. SL: Software, Supervision, Validation, Writing – review & editing. LJC: Investigation, Supervision, Validation, Writing – review & editing. CW: Investigation, Software, Supervision, Validation, Writing – review & editing. HVS: Conceptualization, Project administration, Visualization, Writing – original draft, Writing – review & editing.

### Competing interests

SSR & HVS organised the FAIR-IMPACT support action, where LJC was one of the awardees. The authors declare that they have no other competing interests.

### Funding

This work was partially funded by the European Union programme Horizon Europe under grant agreements HORIZON-INFRA-2021-EOSC-01-05 101057344 (FAIR-IMPACT), HORIZON-INFRA-2021-EMERGENCY-01 101046203 (BY-COVID), HORIZON-INFRA-2021-EOSC-01 101057388 (EuroScienceGateway), HORIZON-INFRA-2021-TECH-01 101057437 (BioDT), and by UK Research and Innovation (UKRI) under the UK government’s Horizon Europe funding guarantee grants 10038992 (FAIR-IMPACT), 10038963

(EuroScienceGateway), 10038930 (BioDT). LJC's work is partially supported by the NFDI4DataScience project, funded by the German Research Foundation (DFG), project number 460234259.

## Acknowledgements

We would like to acknowledge the [RO-Crate Community](#), the [Signposting community](#), the Apples-to-Apples hackathon participants and the FAIR-IMPACT Support Action #2 participants.

## References

- [1] H. Van de Sompel, et al. "Signposting the scholarly Web." (2024), [Online]. Available: <https://signposting.org/> (visited on 03/27/2024).
- [2] M. Nottingham, *Web Linking*, RFC 8288, Oct. 2017. DOI: [10.17487/RFC8288](https://doi.org/10.17487/RFC8288).
- [3] R. Ravinder, N. Quiñones, and D. Rebholz-Schuhmann, "A lightweight approach to FDOs via Bioschemas, RO-Crate and Signposting on GitHub Pages," in *International FAIR Digital Objects Implementation Summit 2024*, P. Wittenburg, L. Lannom, S. El-Gebali, C. Biniossek, D. Betz, and P. Budroni, Eds., ser. Open Conference Proceedings, vol. 4, TIB Open Publishing, 2024.
- [4] E. Wilde and H. Van de Sompel, *Linkset: Media Types and a Link Relation Type for Link Sets*, RFC 9264, Jul. 2022. DOI: [10.17487/RFC9264](https://doi.org/10.17487/RFC9264).
- [5] S. Soiland-Reyes, "FAIR Research Objects and Computational Workflows – A Linked Data Approach," PhD thesis (draft), Ph.D. dissertation, Jan. 2024. DOI: [10.5281/zenodo.10468447](https://doi.org/10.5281/zenodo.10468447). [Online]. Available: <https://s11.no/2023/phd/background/>.
- [6] H. Van de Sompel, *FAIR Digital Objects and FAIR Signposting*, May 2023. DOI: [10.5281/zenodo.7977333](https://doi.org/10.5281/zenodo.7977333).
- [7] European Commission and Directorate-General for Research and Innovation, *Turning FAIR into reality – Final report and action plan from the European Commission expert group on FAIR data*. Publications Office, 2018. DOI: [10.2777/1524](https://doi.org/10.2777/1524).
- [8] A. Ivonne, B. Christophe, B. Daan, et al., *FAIR Digital Object technical overview*, version PEN 2.0, FAIR Digital Object Forum, Apr. 2023. DOI: [10.5281/zenodo.7824714](https://doi.org/10.5281/zenodo.7824714).
- [9] M. Wilkinson, S.-A. Sansone, M. Grootveld, et al., *Report on FAIR Signposting and its Uptake by the Community*, Jan. 2024. DOI: [10.5281/zenodo.10490289](https://doi.org/10.5281/zenodo.10490289).
- [10] S. Soiland-Reyes, A. Gaignard, W. Steinhoff, M. Wilkinson, and H. Van de Sompel, *Benchmarks for apples-to-apples FAIR Signposting*, 2024. [Online]. Available: <https://w3id.org/a2a-fair-metrics/> (visited on 03/27/2024).
- [11] A. Fouillaux and A. Hasan, "Enhancing FAIR data practices in the Norwegian Research Data Archive: Towards research objects and improved interoperability," in *International FAIR Digital Objects Implementation Summit 2024*, P. Wittenburg, L. Lannom, S. El-Gebali, C. Biniossek, D. Betz, and P. Budroni, Eds., ser. Open Conference Proceedings, vol. 4, TIB Open Publishing, 2024.
- [12] S. Soiland-Reyes, L. J. Castro, R. Ravinder, et al., "BioHackEU23 report: Enabling FAIR Digital Objects with RO-Crate, Signposting and Bioschemas," *BioHackrXiv*, Jan. 2024. DOI: [10.37044/osf.io/gmk2h](https://doi.org/10.37044/osf.io/gmk2h).
- [13] M. Dias, "FAIR Signposting helps users to navigate the Scholarly Web," Digital Repository of Ireland, Tech. Rep., Jan. 2024. [Online]. Available: <https://dri.ie/news/fair-signposting-helps-users-to-navigate-the-scholarly-web/> (visited on 04/08/2024).

- 
- [14] S. Soiland-Reyes, P. Sefton, M. Crosas, et al., “Packaging research artefacts with RO-Crate,” *Data Science*, vol. 5, no. 2, pp. 97–138, Jul. 2022, ISSN: 2451-8484. DOI: [10.3233/ds-210053](https://doi.org/10.3233/ds-210053).
- [15] S. Leo, M. R. Crusoe, L. Rodríguez-Navas, et al., *Recording provenance of workflow runs with RO-Crate*, 2023. DOI: [10.48550/arXiv.2312.07852](https://doi.org/10.48550/arXiv.2312.07852). arXiv: [2312.07852](https://arxiv.org/abs/2312.07852) [cs.DL].
- [16] A. Ellerm, M. Gahegan, and B. Adams, “Livepublication: The science workflow creates and updates the publication,” in *2023 IEEE 19th International Conference on e-Science (e-Science)*, 2023, pp. 1–10. DOI: [10.1109/e-Science58273.2023.10254857](https://doi.org/10.1109/e-Science58273.2023.10254857).
- [17] T. Giles, S. Soiland-Reyes, J. Couldridge, et al., *TRE-FX: Delivering a federated network of trusted research environments to enable safe data analytics*, Nov. 2023. DOI: [10.5281/zenodo.10055354](https://doi.org/10.5281/zenodo.10055354).
- [18] S. Soiland-Reyes, S. Wheeler, T. Giles, C. Goble, and P. Quinlan, *TRE-FX technical documentation - Five Safes RO-Crate*, version 0.4, Dec. 2023. DOI: [10.5281/zenodo.10376350](https://doi.org/10.5281/zenodo.10376350).
- [19] S. Soiland-Reyes, S. Wheeler, T. Giles, P. Quinlan, and C. Goble, “Five Safes RO-Crate: FAIR Digital Objects for Trusted Research Environments for Health Data Research,” in *International FAIR Digital Objects Implementation Summit 2024*, P. Wittenburg, L. Lannom, S. El-Gebali, C. Biniossek, D. Betz, and P. Budroni, Eds., ser. Open Conference Proceedings, vol. 4, TIB Open Publishing, 2024.
- [20] L. J. Castro, S. Soiland-Reyes, and D. Rebholz-Schuhmann, “Ro-crates meets fair digital objects,” *Proceedings of the Conference on Research Data Infrastructure*, vol. 1, Sep. 2023. DOI: [10.52825/cordi.v1i.396](https://doi.org/10.52825/cordi.v1i.396).
- [21] P. Wittenburg, U. Schwardmann, C. Bianchi, and C. Weiland, “Fdos to enable cross-silo work,” *Proceedings of the Conference on Research Data Infrastructure*, vol. 1, Sep. 2023, ISSN: 2941-296X. DOI: [10.52825/cordi.v1i.263](https://doi.org/10.52825/cordi.v1i.263).
- [22] B. Christophe, H. Maggie, L. Larry, P. Andreas, S. Ulrich, and W. Peter, *Implementation of Attributes, Types, Profiles and Registries*, version 0.4, Apr. 2023. DOI: [10.5281/zenodo.7825573](https://doi.org/10.5281/zenodo.7825573).
- [23] “Digital Object Interface Protocol Specification, version 2.0,” DONA Foundation, Tech. Rep., 2018, DOIPV2.0. [Online]. Available: <https://hdl.handle.net/0.DOIP/DOIPV2.0>.
- [24] C. Weiland, M. Beukes, J. Grieb, M. Jansen, K. Wesche, and A. Wolodkin, “Employing “Webby” FAIR Digital Objects to support large-scale ecosystem monitoring and mitigation of biodiversity loss in the anthropocene,” in *International FAIR Digital Objects Implementation Summit 2024*, P. Wittenburg, L. Lannom, S. El-Gebali, C. Biniossek, D. Betz, and P. Budroni, Eds., ser. Open Conference Proceedings, vol. 4, TIB Open Publishing, 2024.
- [25] S. Soiland-Reyes, P. Sefton, L. J. Castro, et al., “Creating lightweight FAIR Digital Objects with RO-Crate,” *Research Ideas and Outcomes*, vol. 8, 2022. DOI: [10.3897/rio.8.e93937](https://doi.org/10.3897/rio.8.e93937).
- [26] A. Gray, C. Goble, R. Jimenez, and Bioschemas Community, “Bioschemas: From potato salad to protein annotation,” in *Proceedings of the ISWC 2017 posters & demonstrations and industry tracks*, ser. CEUR Workshop Proceedings, vol. 1963, 2017. [Online]. Available: <https://ceur-ws.org/Vol-1963/paper579.pdf>.
- [27] A. Vukolov, E. Van Winkle, E. Schultes, et al., “An overview of decentralized web technologies as a foundation for future IPFS-centric FDOs,” in *International FAIR Digital Objects Implementation Summit 2024*, P. Wittenburg, L. Lannom, S. El-Gebali, C. Biniossek, D. Betz, and P. Budroni, Eds., ser. Open Conference Proceedings, vol. 4, TIB Open Publishing, 2024.

- [28] S. Soiland-Reyes, C. Goble, and P. Groth, "Evaluating FAIR Digital Object and Linked Data as distributed object systems," *PeerJ Computer Science*, 2024, (accepted). DOI: [10.7717/peerj-cs.1781](https://doi.org/10.7717/peerj-cs.1781). arXiv: [2306.07436](https://arxiv.org/abs/2306.07436).
- [29] J. Lopez Gordillo and S. Islam, "FDO as an interoperability framework for the biodiversity digital twin project," in *International FAIR Digital Objects Implementation Summit 2024*, P. Wittenburg, L. Lannom, S. El-Gebali, C. Biniossek, D. Betz, and P. Budroni, Eds., ser. Open Conference Proceedings, vol. 4, TIB Open Publishing, 2024.
- [30] J. Grieb, C. Weiland, A. Wolodkin, J. Lopez Gordillo, and S. Islam, "Implementing FAIR semantic mappings leveraging on RO-Crate," in *International FAIR Digital Objects Implementation Summit 2024*, P. Wittenburg, L. Lannom, S. El-Gebali, C. Biniossek, D. Betz, and P. Budroni, Eds., ser. Open Conference Proceedings, vol. 4, TIB Open Publishing, 2024.
- [31] A. Trisovic, "Cluster analysis of open research data: A case for replication metadata," *International Journal of Digital Curation*, vol. 17, no. 1, Feb. 2023, ISSN: 1746-8256. DOI: [10.2218/ijdc.v17i1.833](https://doi.org/10.2218/ijdc.v17i1.833).
- [32] Z. Tóth, "Az RO-Crate alapú kutatási objektum csomagolás keretrendszere az ELKH ARP platformban," in *Új technológiákkal, új tartalmakkal a jövő digitális transzformációja felé: 32. Networkshop: országos konferencia: 2023. április 12-14. Pannon Egyetem, Veszprém*, ser. NWS, HUNGARNET Egyesület, Dec. 2023. DOI: [10.31915/nws.2023.9](https://doi.org/10.31915/nws.2023.9).
- [33] R. Macneil and T. Mathes, "Implementation of PIDs and plans for FDOs in the RSpace digital research platform," in *International FAIR Digital Objects Implementation Summit 2024*, P. Wittenburg, L. Lannom, S. El-Gebali, C. Biniossek, D. Betz, and P. Budroni, Eds., ser. Open Conference Proceedings, vol. 4, TIB Open Publishing, 2024.
- [34] L. J. Castro, S. Soiland-Reyes, J. Grieb, and C. Weiland, *Practical web-based FDOs with RO-Crate and FAIR Signposting*, Training material, International FAIR Digital Objects Implementation Summit 2024, Mar. 2024. DOI: [10.5281/zenodo.10892090](https://doi.org/10.5281/zenodo.10892090).
- [35] S. Soiland-Reyes and H. Van de Sompel, *Signposting and RO-Crate: experiences and lessons learned*, Presentation, International FAIR Digital Objects Implementation Summit 2024, Mar. 2024. DOI: [10.5281/zenodo.10847062](https://doi.org/10.5281/zenodo.10847062).