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PDP-DREAM Software for Integrating Multimedia Data with Interoperable Repositories*

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Abstract

Integrating multimedia data in a meaningful way requires keeping track of the who, what, where, when, and how of many kinds of data and metadata in different formats. The PORTAL-DOORS-Project (PDP) was formed to design and build the Nexus-PORTAL-DOORS-Scribe (NPDS) cyberinfrastructure for managing and distributing resource data and metadata in a manner compatible with both the established lexical web and the developing semantic web. PDP-DREAM software, archived at `github.com/bhavius/pdp-dream`, represents the first publicly available, open-source implementation of NPDS. It provides RESTful web services for software agents and user-friendly web applications for human agents so that individuals and organizations can create and publish their own problem-oriented and domain-specific repositories customized for their own purposes. In this report, we also introduce the NpdsQuads format with an approach to formatting the comments of N-quads files as name-value pairs for content from NPDS records which can be exported from and imported to NPDS repositories. We then describe the use of these tools in the curation of the PDP-DREAM ontology, which serves as the foundational ontology for the NPDS cyberinfrastructure. Finally, we discuss the planned use of PDP-DREAM software in a medical imaging clinical trial for multiple sclerosis.

Keywords

Data stewardship, metadata management, multimedia data integration, foundational ontology, NpdsQuads, PDP-DREAM.

Contents

The Challenge of Multimedia Data Integration

One of the core challenges of multimedia data integration is managing data resource metadata in such a way that humans or software agents can determine how two different types of data resources relate to each other, a complex task due to the proliferation of metadata formats, no one of which is best for every type of resource [1]. Formal semantic markup based on formal ontologies can provide the needed context and meaning, enabling advanced, context-aware image segmentation and other applications (for example, see [2] and [3]). However, for descriptions, whether lexical or semantic, to be of use, the user or automated agent must be able to discover them. Other projects, such as [4], have developed monolithic web services for semantic discovery of a particular kind of resource with the intent that their approach could be extended to other resource types in the future. The NPDS cyberinfrastructure differs from these approaches in that it was designed from the beginning as a web infrastructure to promote distributed sharing of repository records, breaking through organizational and disciplinary silos, using a common messaging protocol that supports conveying any kind of lexical text, microformat, and/or semantic markup and content [5].

History of the PORTAL-DOORS Project

The PORTAL-DOORS Project began in 2005 originating with work on the ManRay web-enabled ontology for nuclear medicine and radiopharmaceuticals published in 2006 as the “ManRay Project” [6]. That year in 2006, the name “ManRay” was retained solely for the specific example of the ManRay ontology, while the name “PORTAL-DOORS” was used for the generalized infrastructure project that included ManRay and other problem-oriented and domain-specific ontologies, registries, and directories. Thus, the PORTAL-DOORS Project (PDP) for the PORTAL-DOORS System comprised a collection of data repositories with resource entities represented by lexical metadata in Problem-Oriented-Registry of Tags And Labels (PORTAL) servers and semantic

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metadata in Domain Ontology-Oriented Resource System (DOORS) servers [5]. Independent organizations can host and curate their own repositories of resource descriptions grouped into services by problem domain rather than by resource type, and maintain those independent repositories in a flexible and extensible manner while maintaining compatibility with the core principles and scheme of the system [5]. Bridging the gap in content between the lexical web and semantic web with a hybrid system that can manage and distribute both semantic and lexical data and metadata for any kind of resource entity [5] was one of the important original aims of PDP in 2006 which remains relevant today now in 2021.

In 2009, subsequent work introduced the Nexus registrar to combine record curation and serving of records for both PORTAL and DOORS data and the novel phrase Hierarchically Distributed Mobile Metadata (HDMM) for the architectural style shared by IRIS-DNS and PORTAL-DOORS [7], [8]. Later versions reserved the name Nexus for use with the novel term diristry (an abridgement of directory and registry) for the read-only web service that combined lexical PORTAL and semantic DOORS representations of resource entities, and introduced the name Scribe for the registrar with a separate read-write web service [9]. Then in 2019, the PDP design principles originally expounded in the early PDP 'blueprint' papers [5], [8] were renamed the DREAM principles with the acronym DREAM for the phrase *Discoverable Data with Reproducible Results for Equivalent Entities with Accessible Attributes and Manageable Metadata* [10], [11]. These DREAM principles extended the original PDP principles with the critically important addition of the "equivalent entities" principles necessary for reproducibility in science and answering the question of "same, similar, related, or different?" [12]. These DREAM principles now also inform the design of the NPDS Learning, Intelligence, aNd Knowledge System (NPDS-LINKS), a suite of applications under development that interoperate with NPDS data repositories [13].

An important aspect of the PORTAL-DOORS cyberinfrastructure when first proposed was its design and specification as an architectural style and message exchange protocol that would remain independent of hardward platforms and software solution stacks. It was never intended to be an isolated software "application" or a single implementation of a software solution, but rather an architectural-style and design-principle guided specification for a messaging protocol to enable the distribution, sharing, and exchange of open public data and metadata, as well as appropriately protected and secured, closed private data and metadata. With this approach to its abstract design and specification, software developers could build different concrete implementations independently on different hardware platforms and software solution stacks as demonstrated in 2017 by Craig *et al.* [14]. Those two different software solution stacks demonstrated message exchange between one with C# and the Microsoft ASP.Net framework and the other with JavaScript and Node.js framework for web applications, the former storing data records in a Microsoft SQL Server database collection of tables and the latter storing data records as MongoDB documents.

PDP-DREAM Software

Released in June 2021, PDP-DREAM Aoraki provides the first implementation of the NPDS cyberinfrastructure [15] that we have made available publicly at github.com/bhavius/pdp-dream with a solution stack as open source software. This Microsoft Visual Studio software solution for the Microsoft .NET platform of technologies (including Microsoft SQL Server and Microsoft Internet Information Server) can be configured to support multiple problem-oriented domain-specific web services with one or more of the four types of data repositories (Nexus, PORTAL, DOORS, Scribe) on multiple web sites. In addition to the RESTful web API services, the software collection also provides web applications for viewing and editing records via a tabular user interface built on the Telerik Kendo UI library with the Telerik UI for ASP.NET Core components. These Nexus and Scribe web apps have been designed for a broad user audience, enabling support for content management and curation of data records to meet the needs of any field of study. We have developed additional user interfaces for specific use cases and will make some of these examples available with future versions of PDP-DREAM named Cervin and Gangkhar. PDP-DREAM Aoraki will be maintained in Microsoft .NET 6, whereas PDP-DREAM Cervin and Gangkhar will be developed and maintained in Microsoft .NET 7 and 8, respectively. PDP-DREAM software includes its own secure identity authentication and authorization (SIAA) user account system to allow the web site administrator to control access to individual records or entire repositories and allow contributing curators of data records to mark their own records selectively as private if so desired or otherwise leave them unmarked with their default status as public. Administrators can manage different web sites by supporting independent collections of user accounts with the PDP-DREAM SIAA system and its multi-tenancy identity services for distinct groups or organizations associated with different web sites. Live operational versions of PDP-DREAM software have been running continously since 2007 on various Nexus read-only sites and Scribe read-write sites, serving over a dozen problem-oriented domain-specific repositories (see list at www.portaldoors.org). PDP-DREAM Aoraki 10.0.1 represents the most recent version of our open source software for .NET 6 current with this report published in December 2021. Current features of PDP-DREAM Aoraki will be frozen for this .NET 6 version. All new features will be developed in PDP-DREAM Cervin with the .NET 7 version, and will not be backported to PDP-DREAM Aoraki.

NPDS Quads

N-quads and N-triples provide a simple syntax for representing semantic descriptions [16]. The N-quad format extends the N-triple syntax by allowing the inclusion of a fourth token for the graph label, following the subject, verb, and object tokens [16]. The subject, object, and graph label tokens may be either IRIs or blank nodes, an object token may also be a literal. When the fourth graph label token is not blank, it identifies the triple as belonging to a specific labeled graph, enabling the author to place different subject-verb-object statements in different contexts [16]. Recognizing the value of this approach with its simpler syntax that may help lower barriers to entry for the semantic web when compared to the additional complexities of RDF and OWL syntax for the semantic web, we have made N-quads the authoritative syntax representation for the PDP-DREAM ontology. However, we will also continue to maintain additional representations with versions converted to RDF/XML syntax and OWL/XML syntax from the N-quads syntax. Moreover, we have developed a file format that we have named "NpdsQuads" which provides conventions for embedding the content of NPDS records in the comments of an N-quads docu-

Table 1: NpdsQuads usage levels and directions

Level	Import from NpdsQuads to NPDS	Export from NPDS to NpdsQuads
Minimal	Read an NpdsQuads file as a standard N-quads document by ignoring any comments for the NPDS records.	Write only the N-quad lines for a set of NPDS records without any NPDS comment lines.
Moderate	Read the uncommented N-quads and the commented NPDS infosubset instance attribute name-value pairs of interest, using only the text of the first pair encountered for the attribute pair of the infosubset principal instance.	For each NPDS record infosubset, write the given attribute name-value pair for the infosubset principal instance.
Maximal	Read the uncommented N-quads and the commented NPDS records from the blocks of attribute name-value pairs as completely as possible, including all non-principal instances for each NPDS record infosubset.	Write all NPDS records with comment lines for all instances of each infosubset of each record, sequentially ordering attribute name-value pairs by priority index for multiple instances of each infosubset.

ment. Our goal in designing this format with its set of conventions has been to represent the infoset from an NPDS record as fully as possible while still maintaining simplicity and compactness of notation. We remain especially concerned with implementing the important principle of reducing complexity by simplifying and avoiding any nested embedding of things within things (ie, recursive or iterated structures within structures).

However, by original design [5], [8], the infoset content of an NPDS record remains inherently hierarchical (and possibly distributed) in nature with an infoset containing mutiple infosubsets each of which may consist of multiple instances with multiple attributes. Therefore, we have reduced and simplified each NPDS infosubset to a single name-value pair. For example, in an NPDS record, the resource entity representation must have at least one EntityLabel as the CanonicalLabel and may have multiple additional EntityLabels as the AliasLabels, each with attributes indicating its priority, whether it is resolvable as a URI, whether it is private, when it was last updated, etc. NpdsQuads reduces this complexity to a single name-value pair consisting of the name "EntityLabel" and the IRI value for the CanonicalLabel. Analogous simplifications have been made as conventions for the other infosubsets that constitute the entire infoset for an NPDS record. This simplified NpdsQuads format has been intended to supplement, and not to replace, the original NPDS message-exchange protocol [5], [8], which provides for transfer of complete intact NPDS records as specified in the NPDS cyberinfrastructure XML Schema file npdsroot.xsd that accompanies the PDP-DREAM software. Theoretically, it is possible to establish additional conventions for an extended and enhanced variant of the "NpdsQuads" format, one which could support lossless data transfer and exchange of NPDS records in their entirety, but we have not yet implemented this enhanced variant of the NpdsQuads format.

Organization of an N-quad document [16] into uncommented blocks of N-quad statement lines and commented blocks of NPDS statement lines containing name-value pairs for the NPDS records constitute the key distinguishing features of our NpdsQuads format. Each commented statement line that begins with a single hash ("#") character followed by any of a set of keywords that correspond to infosubsets in an NPDS record, a colon (":"), and an additional text string together function as a name-value pair. For more flexibility in making blocks of lines more easily human-readable, we allow any number of non-line-break white-space characters between any two consecutive tokens of the name-value pair line. In this regard concerning human readability, we note that the N-quad standard does not allow splitting a quad across multiple lines [16]. As a result of that standard, an N-quad file can contain long text lines that do not fit visibly within a text editor window, and thus, cannot be easily read by humans. Therefore, we have also enabled a feature in our NpdsQuads format to allow an alternative (and possibly redundant) representation of an N-quad to be split across multiple lines so that a human reader can view an entire N-quad or NpdsQuad without any horizontal line scrolling right-and-left in the text editor window. When the N-quad is present redundantly in both single-line and multi-line versions, precedence is given to the single-line version for compatibility with the original N-quad standard.

In an NpdsQuad file, the format permits expression of each N-quad as a sequence of four lines, with each line starting with four hashes ("####") followed by one of the four tokens (subject, verb, object, graph label) of the N-quad. Human readers can more easily skim through this alternative one-token-per line representation, while parsing software may optionally compare it to the uncommented, single-line N-quad representation to check for errors. Additionally, blank lines serve as markers to separate the file content into blocks of non-blank lines, each of which corresponds to a representation of a single NPDS record. An NpdsQuads document can serve as input for any parser that processes standard N-quads documents, which can be configured to use or ignore as much or as little of the additional information as preferred for the implementation of the parser, its use case scenario intended for either import or export (see Table 1). Analogously, human readers and software agents may flexibly choose which information they represent as name-value pair comments .

PDP-DREAM Ontology

Foundational, or upper-level, ontologies provide a basic framework of concepts and relationships on which domain ontologies can build by introducing more specialized concepts [17]. Craig *et al.* [18] developed a foundational ontology to formalize the logical relationships among the entities relevant to the NPDS cyberinfrastructure, in particular, those corresponding to the objects in the original XML Schema [5], [8] representing the entity-level, record-level, and infoset-level metadata that describe each entity, NPDS record, or NPDS component service. This ontology allowed for conversion of lexical metadata from a PORTAL record into semantic metadata for a DOORS record, also combined as a Nexus Record [18]. The PDP-DREAM ontology expands on this work by creating a formal ontology based not only on the information model that represents the NPDS cyberinfrastructure, but

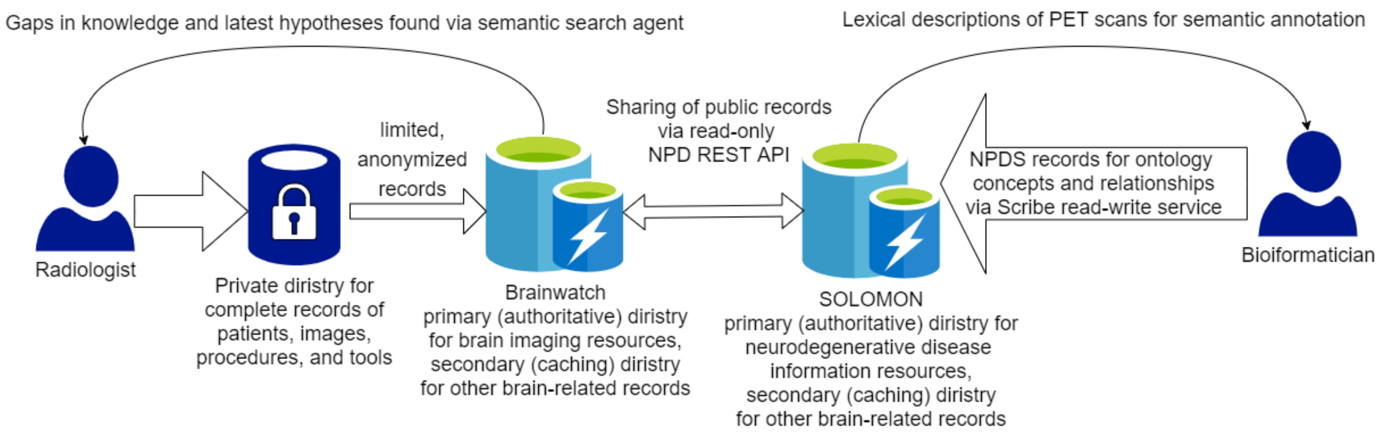

Figure 1: Example use case of PDP-DREAM Software applied to biomedical imaging informatics to foster collaboration between radiologists and bioinformaticians in the study of neurodegenerative diseases.

also on all aspects of the principles that motivate PDP [11]. While the scope of the PDP-DREAM ontology has been extended to include the critically important "equivalent entities" principle [12], we continue to maintain the approach of creating a just-right-sized ontology that covers the needed concepts and relationships while remaining small and modular enough for ease of maintenance in the future [18].

The original version of the PDP-DREAM Ontology served as a controlled vocabulary of some of the core design principles grouped into modules that corresponded to four branches of the PDP: DREAM Principles, HDMM architectural style, NPDS cyberinfrastructure, and FAIR metrics [11]. A second version added content intended to aid with software-assisted peer review through comparison of research claims [19]. Our goals for the third major revision are 4-fold: 1. Document more completely the entire collection of PDP and NPDS design principles. 2. Group them into a hierarchy with the most general goals at the top, the design principles that serve them in the middle, and individual design choices in the PDP and related projects at the bottom. 3. Represent principles as reified subject-verb-object triples in order to enable comparison and contrast of principles from both PDP and non-PDP sources. 4. Create a Nexus diristry that will serve as a living document in which each record corresponds to a class, property, or instance in the ontology, enabling a collaborative curation and more efficient search of the ontology. Researchers have been developing tools to support collaborative ontology design via knowledge bases and web services for over 20 years, with notable examples including Ontolingua Server [20], OntoEdit [21], WebProtégé as a web-based version of the popular Protégé ontology editor [22]. Although PDP-DREAM software does not currently include a GUI optimized for ontology development, the online distributed nature of the NPDS cyberinfrastructure facilitates sharing of ontologies. Ontologies maintained openly online may be less likely to disappear after the project developing loses funding and/or maintenance support. In addition, such online ontologies provide a bridge to the semantic web for those organizations not dedicated to creation and curation of ontologies and semantic web content.

To rebuild systematically the full scope of the PDP-DREAM ontology, the authors and four additional student volunteers reviewed the previously published PORTAL-DOORS papers dated from 2006 through 2020 listed and publicly available at https://www.portal-doors.net/PDP/Site/Papers. The authors worked individually, while the volunteers worked in two teams of two persons to compile lists of pairs of quotes representing principle-example pairs. Each team classified the principles according to whether it related to NPDS, HDMM, FAIR Metrics, NPDS-LINKS, or none of the preceding and created a simplified representation of each principle as a subject-verb-object triple using English phrases. We then recorded all of these responses, along with the NPDS entity labels of the source publications, URLs of electronic copies of the documents, and page numbers of the quotes.

For each principle so identified, we created a Nexus record in a dedicated PDP-DREAM diristry. We then created an N-quad summarizing the principle to serve as its semantic description, introducing new ontology classes, individuals, and properties as needed. We generated a unique graph label for each principle so that it would be possible to refer back to it in other descriptions. Having compiled a list of putative design principles with examples and source documents, we created a new version of the PDP-DREAM ontology with classes and properties needed to describe each principle. Each principle itself belongs to the class Principle or a sub-class thereof. Principle is itself a subclass of Claim, which includes any claim, including the concrete examples of principles. Whereas a Claim can represent any statement, a Principle represents a generalization derived from Examples.

Application to Multiple Sclerosis Study

Brain Health Alliance will collaborate with medical imaging sites to conduct a clinical trial, called the EPSMS Study, with an exploratory study of entire-body PET scans of multiple sclerosis patients compared with healthy research subjects participating as normal controls [23]. We will use a collection of Nexus diristries to store descriptions of patients, PET image data sets, biochemical assays, psychometric questionnaires, imaging procedures, medical scanners, and computing hardware and software. Cross-referenced semantic descriptions of tools and technologies will enable collaborating sites to ensure that results are comparable and reproducible, while rich metadata for all results data will enable construction of a more complete picture of the physical and mental state of each patient through multimedia data integration. This application to and use of the PDP-DREAM Software for the EPSMS Study will serve to demonstrate the ability of the software to support both secure private repositories for tracking patient information collected in the study in compliance with required protections on personally identifiable health information, and also the use of publicly accessible data repositories for the sharing of appropriately anonymized and de-identified metadata and data as described in the EPSMS research protocol [23].

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