Fedora

An Architecture for Complex Objects and their Relationships

Carl Lagoze, Sandy Payette, Edwin Shin, Chris Wilper

Computing and Information Science, Cornell University

{lagoze, payette, eddie, cwilper}@cs.cornell.edu

Abstract. The Fedora architecture is an extensible framework for the storage, management, and dissemination of complex objects and the relationships among them. Fedora accommodates the aggregation of local and distributed content into digital objects and the association of services with objects. This allows an object to have several accessible representations, some of them dynamically produced. The architecture includes a generic RDF-based relationship model that represents relationships among objects and their components. Queries against these relationships are supported by an RDF triple store. The architecture is implemented as a web service, with all aspects of the complex object architecture and related management functions exposed through REST and SOAP interfaces. The implementation is available as open-source software, providing the foundation for a variety of end-user applications for digital libraries, archives, institutional repositories, and learning object systems.

1 Introduction

As demonstrated by this special issue of *Journal of Digital Libraries*, there is widespread interest in the representation, management, dissemination, and preservation of complex digital content. At a minimum, technologies for representing digital content should be able to match the richness, and complexity of well-established physical formats. They should allow the representation of a variety of structural organizations, such as chapters and verses. They should accommodate the flexible combination of different genre of materials such as text and images in multiple layouts. They should allow the aggregation of content from multiple sources and the association of metadata with the elements of the aggregation. In addition, freed of the constraints of physical media, they should do more. Exploiting their networked context, they should allow aggregation of content regardless of its physical location. By leveraging local and remote computing power they should permit programmatic and user-directed manipulation of document content.

The Fedora Project [4] is an ongoing research and implementation effort to provide the framework for creation and management of existing and evolving forms of digital content. The roots of the project lie in DARPA-funded research in the early 1990's that defined the notion of a *digital object* [27] and implemented Dienst [28], a networked digital library architecture with protocol-based dissemination of digital objects in multiple formats. Follow-on research extended these initial concepts with the notion of *active digital objects* [21] and *distributed active relationships* [20]. These concepts were refined and prototyped in a CORBA-based Fedora (Flexible Extensible Digital Object Repository Architecture) [33] as part of research with CNRI [32] and in the context of the NSF-funded Prism Project [15]. This prototype provided the context for a variety of research initiatives most notably in the areas of fine-grained policy enforcement [34] and preservation [35].

The transition of Fedora from a research prototype to production repository software began when the University of Virginia Library, seeking a solution for managing increasingly complex digital content, experimented with the Fedora architecture [41]. This experimentation took place in the context of innovations in humanities research [47]. The experimentation proved successful, providing the basis for subsequent funding from the Andrew W. Mellon Foundation to Cornell and Virginia [36] to fully develop Fedora and make it available to libraries, museums, archives, and content managers, which all face increasing variety in the digital content that they manage [42]. Mellon-funded development continues through 2007.

Version 2 of Fedora is now available as open source digital object repository software that provides a rich context for information organization, representation, and management. At its core is an object model with a number of features. The Fedora digital object model allows the aggregation of local and distributed data in multiple formats. Web-accessible services may then be associated with the aggregated data. As a result an object is accessible in multiple representations, some of them direct transcriptions of aggregated data, and some of them produced dynamically by the associated web services. Other notable features of Fedora include support for versioning of objects and their components, support for multiple metadata descriptions of objects and their components, and fine granularity access control over digital objects and their parts. The richness of the document model and extensibility of the Fedora architecture has led to its deployment in a variety of domains including institutional repositories for scholarly publishing [43], library systems [51], and learning systems [46].

Arguably one of the most important features of Fedora is that it is implemented as a set of web services and its full functionality, including its rich document model, is exposed through well-defined web service APIs. These APIs provides full programmatic management of digital objects as well and search and access to multiple representations of objects. As such, Fedora is particularly well-suited to co-exist in a broader web service framework and act as the foundation layer for a variety of application front-ends and user interfaces. This distinguishes Fedora from other complex object systems that are either vertical applications for storing and manipulating complex objects through a fixed user and management interface (e.g., DSpace [40], arXiv [1], ePrints [2]), or that define a wrapper format for representing complex objects (METS [10], MPEG-21 DIDL[26], IEEE LOM [8]). Fedora is compatible with the latter category of systems due to its ability to both ingest content in these formats and export contained digital objects in any of these XML representations. This allows Fedora to comfortably co-exist in the archival framework defined by OAIS [13]. Another architecture which handles complex objects, associates them with services, and uses RDF to express relationships among those objects is Los Alamos National Laboratory's aDORe architecture [48] in which objects are encoded using DIDL [17], and object dissemination services are available via OAI-PMH [29], and OpenURL [31].

The latest release of Fedora augments the digital object model by providing the infrastructure for expressing relationships among objects and their components. Examples of relationships between digital objects include well-known management relationships such as the organization of items in a collection, structural relationships such as the part-whole links between individual chapters and a book, and semantic relationships useful in digital library organization such as those expressed within the Functional Requirements for Bibliographic Records (FRBR) [6]. Fedora expresses relationships by defining a base relationship ontology using RDFS [18] and provides a slot in the digital object abstraction for RDF expression of relationships based on this ontology. Assertions from other ontologies may also be included along with the base Fedora relationships. All relationships are reflected in a native RDF triple-store using Kowari [45]. The query interface to this triple-store is exposed as a web service, providing a rich information foundation for external services.

This paper describes the Fedora architecture for representing complex digital objects and the relationships among them. It is organized as follows. In Section 2 we describe the Fedora digital object model and the APIs that allows access and management of it. In Section 3 we describe the components of the Fedora server architecture, which provide the context for the object model. Following that, in Section 4 we describe the Fedora relationship model that provides a common framework for describing, storing, and querying relationships among objects and their components. Section 5 concludes the paper with future plans for Fedora.

2 Fedora model for complex objects

The Fedora object model supports the expression of many kinds of complex objects, including documents, images, electronic books, multi-media learning objects, datasets, computer programs, and other compound information entities. Fedora supports aggregation of any combination of media types into complex objects, and allows the association of services with objects that produce dynamic or computed content. The Fedora model also allows the assertion of relationships among objects so that a set of related Fedora objects can represent the items in a managed collection, the components of a structural object like the chapters of a book, or a semantic (e.g., topic-oriented) set of resources.

Fedora defines a powerful object model for expressing this variety of complex content and their relationships. This object model can be understood from two perspectives.

1. The *representational* perspective defines a simplified abstraction for understanding Fedora objects, where each object is modeled as a uniquely identified resource projecting one or more views, or *representations*. From this perspective the internal structure of a digital object is opaque; however, relationships among objects are observable.
2. The *functional* perspective reveals the object components that underlie the representational perspective and provides the basis for understanding how the Fedora object model relates to the management services exposed in the Fedora repository architecture.

2.1 Representational View

The representational perspective of the Fedora object model asserts that each digital object can disseminate one or more representations of itself, and that each object can be related to one or more other objects. A familiar example of digital object with multiple representations is a document or image where the content is available in multiple formats. All digital objects, and their individual representations, are identified with Uniform Resource Identifiers (URIs). These URIs are specified using the "info" scheme and conform to the syntax described at [9]. This perspective hides complexity and exposes only the access points to content stored in a Fedora repository.

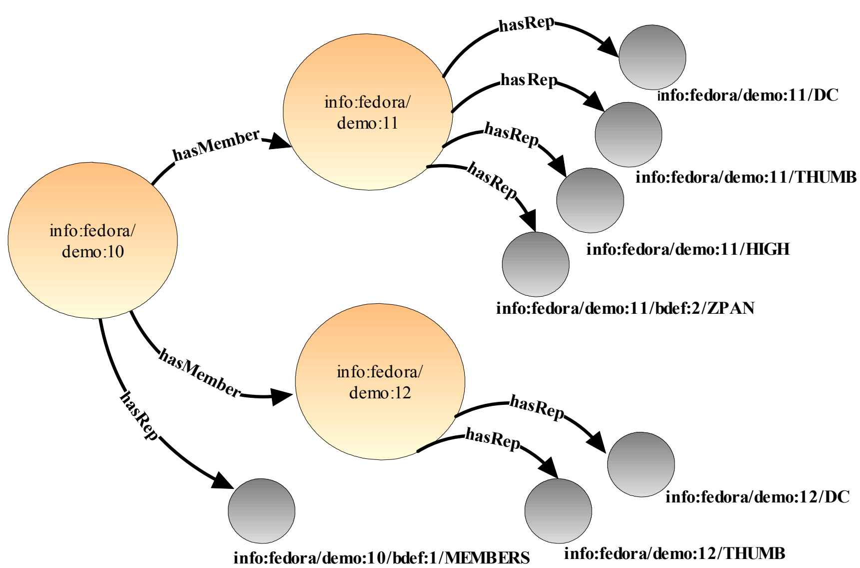

Figure 1: Representational View of Fedora Objects

Figure 1 depicts the representational view of three inter-related Fedora objects. The diagram shows a directed graph, where the larger nodes are digital objects, and the smaller nodes are representations of the digital objects[1]. These nodes are linked by two types of arcs – relationship arcs connect digital objects, and representation arcs connect digital objects to their respective representations. This graph can be expressed as RDF, stored in a triple store, and queried. This is discussed later Section 4.

Each digital object in the diagram has at least one representation, related to its originating digital object by a "hasRep" arc. For example, the node labeled info:fedora/demo:11 is an image digital object with four representations, identified by their respective URIs:

- Dublin Core record, identified as info:fedora/demo:11/DC
- High-resolution image, identified as info:fedora/demo:11/HIGH
- Thumbnail image, identified as info:fedora/demo:11/THUMB
- Image with zoom/pan utility, as info:fedora/demo:11/bdef:2/ZPAN

We have yet to define the underlying source of these representations. In fact, in this view of the architecture such details are hidden from the client application concerned with access to these representations.

Figure 1 also demonstrates an example of inter-object relationships. In this example, the node labeled info:fedora/demo:10 is a "collection" with two "items", the nodes labeled info:fedora/demo:11 and info:fedora/demo:12. These collection-item relationships are expressed by the "hasMember" arc that emanates from the collection object. The inverse "isMemberOf" relationships are not shown in the diagram for simplification.

This simple representational view forms the basis of Fedora's REST-based access service (i.e., API-A-LITE), whereby digital object URIs and representation URIs can be easily converted to service request URLs upon Fedora repositories.

While the representational perspective of the Fedora object model provides a simple, access-oriented overlay for digital resources and collections, the functional perspective, described next, provides a view of the core underlying data model for Fedora. In the following sections, we take one of the digital object nodes depicted in Figure 1, and drill down to unveil the specific components of a Fedora digital object that enable access to representations. We start with the digital object as a container with a persistent unique identifier (i.e., PID). From there, we unveil the components incrementally, first focusing on components that enable simple content aggregation,

---

[1] This graph-based overlay model can form the basis for interoperability among heterogeneous object models and repositories. This concept is currently being explored as part of a new NSF-funded research project, Pathways, which is a collaboration between the authors of this paper and colleagues at Cornell, LANL, and others [12] Pathways: Lifecycles for Information Integration in Distributed Scholarly Communication, , [50] Van de Sompel, H., Payette, S., Erickson, J., Lagoze, C. and Warner, S. Rethinking Scholarly Communication: Building the System that Scholars Deserve. *D-Lib Magazine* (September).

then on components that enable dynamic and computed content, and finally on components related to digital object integrity. We note again that these underlying details are invisible to clients concerned only with information access.

2.2 Functional View I - Datastreams

In its simplest form a Fedora object is an aggregation of content items, where each content item maps to a representation. The Fedora object model defines a component known as a Datastream to represent a content item. A datastream component either encapsulates bytestream content internally or references it externally. In either case that content may be in any media type. Figure 2 shows a digital object as an aggregation of datastreams and the one-to-one correspondence of those datastreams to the representations of the digital object that are exposed to accessing clients. In this simple case, each representation of a Fedora object is a simple transcription of the content that lies behind a datastream component.

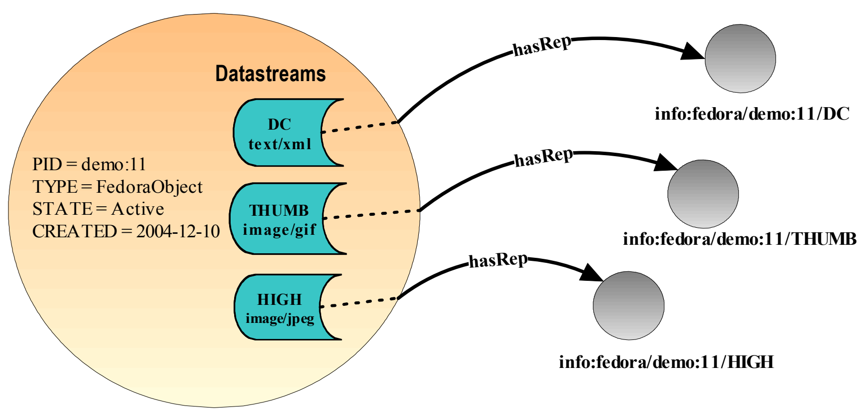

Figure 2: Fedora Object with PID, Properties, and Datastreams

As seen in the above diagram, a digital object has a unique identifier (PID) and a set of key descriptive properties. Each datastream contains information necessary to manage a content item in a Fedora repository. These are stored as properties of the datastream as shown in Figure 3.

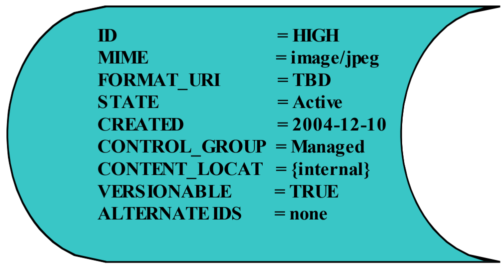

Figure 3: Properties of a Datastream Component

Three datastream properties deserve special attention. The Format URI refines the media type definition and anticipates the emergence of a global digital format registry such as the GDFR [7]. Control group defines whether the datastream represents either local or remote content. Datastreams with a control group of "Managed" are internal content bytestreams that are under the direct custodianship of the Fedora repository. Datastreams, whose control group is "External" or "Redirected" (the difference between these is outside the scope of this paper) represent content that is stored outside the repository. These datastreams have a content location property that is a URL pointing to a service point outside the repository that is responsible for providing the content. The ability to create digital objects that aggregate locally managed content with external content is a powerful feature of Fedora, and is useful in a variety of contexts. A good example of a hybrid local/remote object is an educational object where local content is the instructor's syllabus, lecture notes, and exams, and remote content are primary resources included by-reference from other sites.

2.3 Functional View II - Disseminators

In addition to the representations described in the previous section, which are direct transcriptions of datastreams, the Fedora object model enables the definition of *virtual representations* of a digital object. A virtual representation is a view of an object that is produced by a service operation (i.e., a method invocation) that can take as input one or more of the datastreams of the respective digital object. As such, it is a means to deliver dynamic or computed content from a Fedora object.

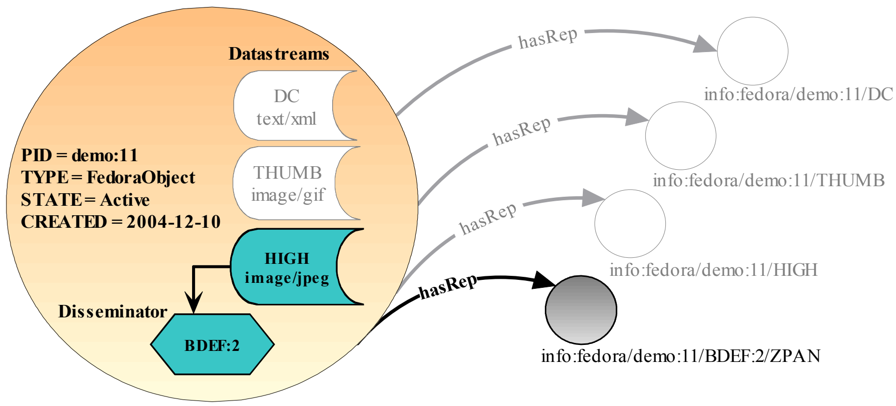

Figure 4: Fedora Object with Disseminator Added

This is illustrated in Figure 4, where a virtual representation labeled `info:fedora/demo:11/BDEF:2/ZPAN` is highlighted. From the access perspective this representation is an image wrapped in a java application that provides image zoom and pan functions. Note that this representation is not a direct transcription of any Datastream in the object. Instead, it is the result of a service operation defined in the Disseminator component labeled "`BDEF:2`" inside the object that uses the datastream labeled "`HIGH`" as input.

To enable such behavior, a Disseminator must contain three pieces of information: (1) a reference to a description of service operation(s) in an abstract syntax, (2) a reference to a WSDL service description [14] that defines bindings to concrete web service to run operation(s), and (3) the identifiers of any Datastreams in the object that should be used as input to the service operation(s).

Fedora stores the service operation description and the WSDL service description within special digital objects, respectively known as BDefs (behavior definitions) and BMechs (behavior mechanisms). Figure 5 depicts a Fedora BDef object and BMech object along with object-to-object relationships that exist due to the presence of the Disseminator component in the main object (demo:11).

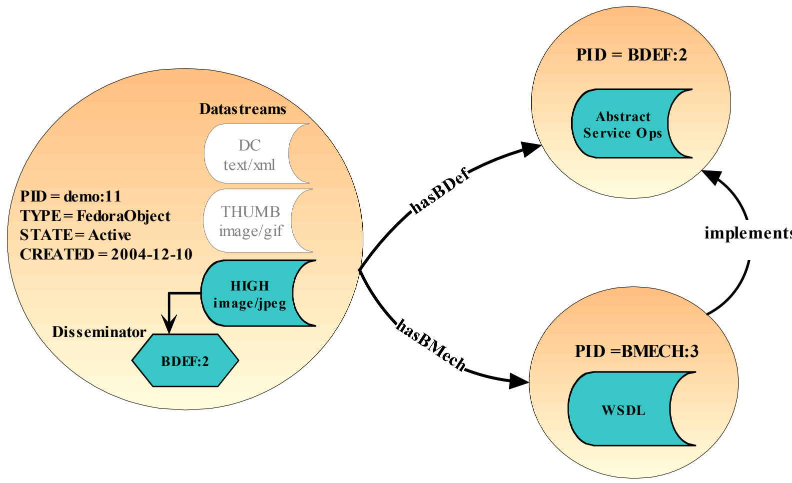

Figure 5: Disseminators establish relationships to service definition objects

Disseminators are effectively metadata that the Fedora repository uses at run time to construct and dispatch service requests and produce one or more virtual representations of the digital object. From a client perspective this is transparent since virtual representations look just like other representations of the object.

Disseminators are a powerful feature in the Fedora object model. They can be used to create common representational access points for digital objects that have different underlying structure or format. For example, an institutional repository might contain scholarly documents in a variety of root formats (e.g., Word, HTML, TeX), where the root format is stored as a datastream in a Fedora digital object. For interoperability purposes, a virtual representation can be defined on each object that converts the datastream containing the root format to a common format (e.g., PDF). Similarly, a repository manager can decide for archival purposes to convert all documents in a repository to a canonical preservation format without disrupting the manner in which clients access documents for browsing, viewing, etc. Finally, disseminators can add utility operations to digital objects. For example, a Disseminator can be defined for a digital object that provides parameterized query access to the relationships defined for that object. Such a query might return the "members of a collection" or, in the case of an educational digital library such as the NSDL [52], the set of resources that are appropriate for K-12 mathematics education. The implementation of these queries is described in Section 4.

2.4 Functional View III – Object Integrity Components

The Fedora object model defines several metadata entities that pertain to managing the integrity of digital objects. These entities are the object's relationship metadata, access control policy, and audit trail. To keep the Fedora model simple and consistent, integrity entities are modeled as datastream components with reserved identifiers. As such, the integrity entities are stored like other datastreams, however the Fedora Repository system recognizes them as special and asserts constraints over how they are created and modified. Figure 6 depicts these integrity-oriented entities as special datastreams in a digital object, identified as Relations, Policy, and Audit Trail.

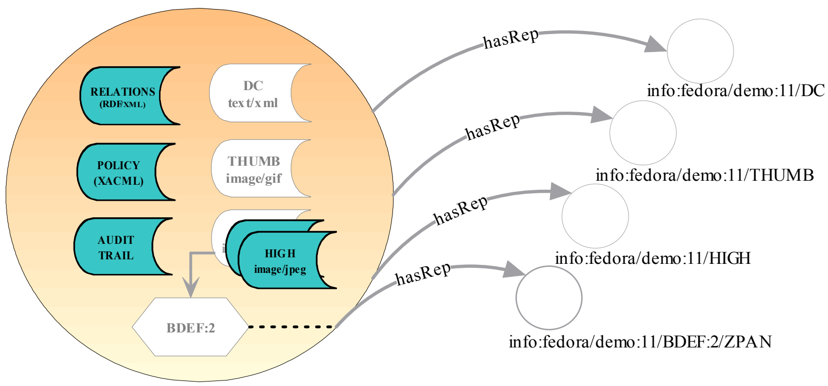

Figure 6: Integrity Datastreams - Relationships, Policy, and Audit Trail

A Relations datastream is used to assert object-to-object relationships such as collection/member, part/whole, equivalence, "aboutness," and more. The previously discussed "hasMember" relationship is an example of the type of assertion that can be managed via the Relations datastream, described in Section 4.

A Policy datastream is used to express authorization policies for digital objects, both to protect the integrity of an object and to enable fine-grained access controls on an object's content. In Fedora objects, a policy is expressed using the eXtensible Access Control Markup Language (XACML) [3], which is a flexible XML-based language used to assert statements about who can do what with an object, and when they can do it. Object policies are enforced by the authorization module (i.e., AuthZ) implemented within the Fedora Repository Service.

The Audit Trail is a system-controlled datastream that keeps a record of all changes to an object during its lifetime. The Fedora Repository Service automatically creates an audit record for every operation upon an object, detailing who, what, when, where, and why an object was changed. This information is important to support preservation and archiving of digital objects.

Another feature for managing the lifecycle of objects is versioning. Versioning is important for applications where change tracking is essential, as well as for preservation and archiving systems that must be able to recover historical views of digital objects. The Fedora object model supports component-level versioning, meaning that datastreams and disseminators can be changed without losing their former instantiations. Fedora automatically creates a new version of these components whenever they are modified.

This is depicted in Figure 6, which shows a digital object with multiple versions of a datastream (see component labeled "HIGH"). Also, the versioned datastream is input to the disseminator labeled "BDEF:2." Requests for representations of this digital object can be date-time stamped and the Fedora Repository Service will ensure that the appropriate component version is returned. This feature applies for representations that are direct transcriptions of datastream content, as well as for virtual representation where datastream content is mediated via a Disseminator.

2.5 XML Serialization of Fedora Objects

The Fedora object model has been discussed from both the representational and functional perspectives. These provide an understanding of the abstractions that form the basis of a Fedora digital object. From an implementation perspective, Fedora digital objects can be serialized and stored as XML. The Fedora object model is directly expressed using XML Schema language in a format known as Fedora Object XML (FOXML)[2]. FOXML defines a <digitalObject> root element that contains as set of <objectProperties>, one or more <datastream> components, and one or more <disseminator> components. Appendix A contains the XML serialization of the digital object info:fedora/demo:11 that corresponds to the example discussed above.

Although FOXML is the preferred XML serialization format for storing objects in a Fedora repository, Fedora supports ingest and export of digital objects in other XML formats. Currently, the system supports a Fedora profile of the Metadata Encoding and Transmission Format (METS) [11] and it will soon support the OAI-PMH harvesting [49] of objects encoded in MPEG21 Digital Object Description Language (DIDL) [26].

3 A service-based architecture for complex objects

The digital object model described in the previous section exists within the context of a broader server architecture. The remainder of this section describes that architecture. Further details are documented at the Fedora open-source project web site [4].

3.1 The Fedora Service Framework

Fedora digital objects are managed within the Fedora Service Framework which consists of a set of loosely coupled services that interact and collaborate with each other. At the core of the framework is the Fedora Repository Service, as depicted in Figure 7. Other services exist around the core to provide additional functionality that is not considered a fundamental function of a repository. Any number of services can

---

[2] The FOXML schema is available at http://www.fedora.info/definitions/1/0/foxml1-0.xsd.

be developed to collaborate with the core Fedora Repository Service. In the diagram, there are three collaborating services around the core: the Fedora OAI provider, a Fedora Search service, and a Fedora Preservation Monitoring Service. The framework approach anticipates that new services will be added over time.

Outside of the boundaries of the Fedora framework are external services that can either call upon Fedora services, or that Fedora can leverage in some way. The distinction between services within the Fedora Service Framework, and those outside, is that those within the framework are in a trusted relationship with the Fedora Repository Service, and are designed to specifically interact with Fedora repositories. Services outside the framework are typically general-purpose services, or organization-specific services that call upon Fedora as an underlying repository for digital content.

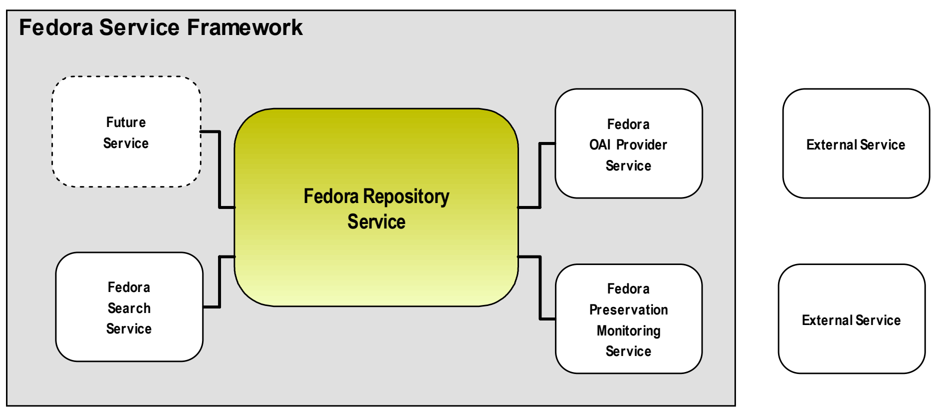

Figure 7: Core Fedora Repository Service with Collaborating Services

Prior to version 2.0 of Fedora, all Fedora-related functionality was built into the core Fedora Repository Service. As of version 2.0, the Fedora Service Framework was defined to move the Fedora architecture in a direction where new services can easily be developed and plugged into the Framework. This is consistent with general trends developing in web services technology and enterprise application architectures in which formerly tightly-integrated systems are broken apart into atomic, modular services that can be flexibility aggregated into different multi-service compositions.

At the time of writing, Fedora is migrating to the new service framework approach. Version 2.1 of Fedora will include a new OAI Provider and a new Search service as part of the Fedora open-source distribution. These functions were previously built into the core repository. The Fedora Preservation Monitoring Service will be developed as part of the new Phase II Fedora project. Other services are being developed by members of the Fedora user community and will be contributed back to the open source project.

3.2 The Fedora Repository Service

At the core of the Fedora Service Framework is the Fedora Repository Service which exposes interfaces for managing and accessing digital objects in a repository. In Figure 8, the repository service is deconstructed so that its internal modules and public service interfaces are visible.

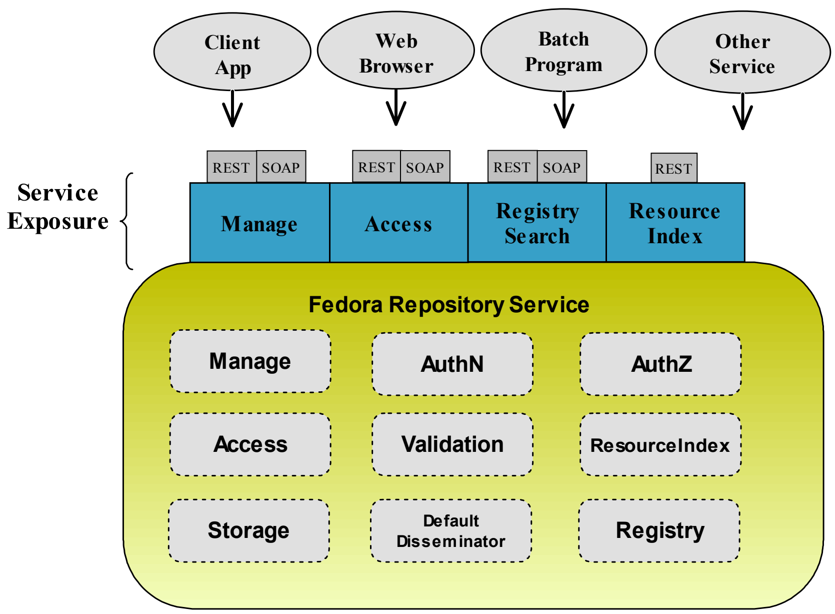

Figure 8: Fedora Repository Internal Modules and Service Interfaces

At the top of Figure 8, there are alternative client scenarios for accessing the Fedora repository through its four web service interfaces. Each service interface is defined using the Web Service Description Language (WSDL) [14], with both SOAP and REST bindings. The internal implementation of the Fedora Repository Service consists of a set of internal java modules that can be configured, and optionally replaced with alternative implementations. The internal modules are not directly exposed to accessing clients; instead clients interact with the repository only through the defined web service interfaces.

The Manage(ment) service interface (API-M) contains read/write operations necessary to managed a repository of digital objects. API-M operations exist for ingesting and exporting digital objects in an XML format, either Fedora's FOXML, or alternatively METS or MPEG21/DIDL. Also, objects can be created and modified using component-level operations that reflect the functional view of the Fedora object model described earlier. The major management operations are:

- set/get/removeObjectProperty
- set/get/removePolicy
- add/modify/purgeDatastream
- add/modify/purgeDisseminator
- ingest/export/purgeObject

The Access service interface (API-A) contains read-only operations for accessing digital objects. The two main purpose of the Access interface is to (1) introspect on a digital object (i.e., to discover what datastreams and disseminator methods are available) and (2) request disseminations on an object (i.e., access particular representations of the object's content). The major Access operations are:

- getObjectProfile
- getObjectHistory
- listDatastreams
- listMethods
- getDatastreamDissemination
- getDissemination

In addition to the SOAP-based Access bindings, all Access operations can be invoked with a simple URL syntax via a light-weight, REST-based interface (API-A-LITE). This interface can be used to access digital objects from the representational perspective described earlier. The graph node URIs for Fedora objects and their representations can be easily converted to Fedora API-A-LITE request URLs by replacing the "info:fedora" URI scheme with the base URL for the repository as follows:

info:fedora/demo:11 →	http://myfedora.edu:8080/fedora/get/demo:11
info:fedora/demo:11/HIGH →	http://repo.edu:8080/fedora/get/demo:11/HIGH

The final two access points to the Fedora Repository Service are the Registry Search and Resource Index interfaces. These provide discovery capabilities to locate digital objects. The Registry Search interface exposes service operations to perform a simple search of the digital object registry based on object properties. The Resource Index interface is the service entry point to an RDF-based index of the entire repository. The Resource Index is an expanded version of the representational view of digital objects described earlier. As such it contains all representations and relationships of objects, plus object properties and Dublin Core metadata elements. The Resource Index and its uses are discussed in detail in the next section.

4 Relationships in Fedora

As described in Section 2.1, the Fedora object model can be abstractly viewed as a directed graph, consisting of *internal* arcs that relate digital objects nodes to their representation nodes and *external* arcs between digital objects. In this section we focus on that relationship graph and describe a Fedora service, the *Resource Index,* which allows storage and query of the graph. This architecture builds on the RDF (Resource Description Framework) [30] primitives developed within the semantic web community. The Fedora system supplies a base relationship ontology (defining a core of internal and external relationships) that, in the fashion of any RDF properties, can co-exist with domain-specific relationship ontologies from other namespaces. Each digital object's external relationships to other digital objects are expressed in RDF/XML [16] within a reserved datastream in the respective object. A relationship graph over the digital objects in the repository can then be derived by merging the internal relationships implied by the Fedora object model with the external relationships explicitly stated in their relationship datastreams. The triples representing this graph are then stored in the Kowari [45] triple-store providing the capability for searches over the graph.

4.1 Representing object-to-object relationships

A number of efforts have developed standards for representing the structure complex object. For example, the Making of America [22] project formalized structural metadata and defined a set of templates that correspond to well-known physical artifacts such as a book composed of chapters and diaries consisting of entries.

The expression of structural relationships within a single digital object is useful for a variety of applications. However, there are other types of non-structural relationships such as:

- The organization of individual resources into larger *collection* units, for the purpose of management, OAI-PMH harvesting [29], user browsing, and other uses.
- The relationships among *bibliographic* entities such as those described in the Functional Requirements for Bibliographic Relationships [6].
- *Semantic* relationships among resources such as their relevance to state educational standards or curricula in an educational digital library like the National Science Digital Library [52].
- Modeling more complex forms of *network overlays* over the resources in a content repository such as citation links [23, 25], link structure, friend of a friend [5], etc.

All of these relationships, including structural relationships, should be expressible both within individual digital objects and among multiple digital objects. For example breaking the components of a structural entity, such as the chapters of a book, into separate digital objects provides the flexibility for reuse of those individual components into other structural units. This is even more important for the other forms of relationships. For example, a single resource may be part of multiple collections or may be relevant for multiple state standards.

The expression of arbitrary, inter-object relationships in Fedora is enabled by a reserved datastream known as the Relations datastream. This datastream allows for a restricted subset of RDF/XML where the subject of each statement must be the digital object within which the datastream is defined and the object of each statement must be another Fedora digital object.

```
<rdf:RDF
   xmlns:rdf ="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
   xmlns:nsdl=”http://nsdl.org/std#”
   xmlns:rel="http://example.org/rel#"
   xmlns:frbr="http://example.org/frbr#">
     <rdf:Description rdf:about="info:fedora/demo:11">
       <rel:isMemberOf  rdf:resource="info:fedora/demo:10"/>
       <std:fulfillsStandard rdf:resource="info:fedora/demo:Standard5"/>
       <frbr:isManifestionOf rdf:resource=
             "info:fedora/demo:Expression2"/>
    </rdf:Description>
</rdf:RDF>
```

Table 1 - Example Relations datastream

Since predicates from any vocabulary can be used in Relations, the repository manager has considerable flexibility in the kinds of relationships that can be asserted. Table 1 shows an example Relations datastream in a Fedora digital object identified by the URI, info:fedora/demo:11. The RDF/XML refers to three different relationship vocabularies (hypothetical for the purpose of this example) and asserts the following relationships:

- demo:11 is a member of the collection represented by the object demo:10,
- demo:11 fulfills the state educational standard represented by the object demo:Standard5,
- demo:11 is a manifestation of the expression represented by the object demo:Expression2.

4.2 Representing object representations and properties in the Resource Index

As described earlier, a Fedora digital object consists of a number of core components such as datastreams and disseminators, which bind to BDefs and BMechs. In addition each Fedora digital object has system metadata or properties. The architecture provides a system-defined ontology to represent the relationships among these core components. For example, the relationships of an object to its representations is expressed using the <fedora-model:disseminates> predicate as shown in the triple in Table 2.

```
<info:fedora/demo:11>
  <fedora-model:disseminates>
     <info:fedora/demo:11/HIGH>
```

Table 2 - Object-represenation relationship

In addition to these relationships, the system-defined ontology also represents object data properties whose range contains date and boolean datatypes, as shown in the triple in Table 3.

```
<info:fedora/demo:11/HIGH>
   <fedora-view:lastModifiedDate>
      "2004-12-12T00:22:00"^^xsd:dateTime
```

Table 3 - Data type properties

Unlike the relationships expressed in the Relations datastream, these relationships are not explicitly asserted within the digital object. Instead they are derived from the object structure itself and mapped into the Resource Index, alongside the relationships represented in the Relations datastreams. This is described in the next section.

4.3 Storing and querying the relationship graph

All these relationships – the relationships explicitly stated in the Relations datastream, the relationships implied by the object structure, and the data relationships contained in the object properties – are stored in the resource index. This index is automatically updated by the system whenever an object structure is modified or its Relations datastream is changed.

The Resource Index handles queries over these relationships. The combination of all relationships into a single graph, and the automated management of that combined graph, enables a powerful and flexible service model. External services may issue queries combining relationships from different name spaces, since they are all RDF properties. For example, Table 4 shows a query listing all the representations of all objects that are members of a particular collection.

```
select $dissemination
from <#ri>
where ($object <fedora-view:disseminates> $dissemination)
    and $object <rel:isMemberOf> <demo:10>
```

Table 4 - Sample RDF query using iTQL

An early design goal of the Resource Index was to allow the use of different triplestores and thus allow the Fedora repository administrator to choose the most appropriate underlying store. To that end, the Resource Index employs a triplestore API similar in spirit to JDBC, to provide a consistent update and query interface to a variety of triplestores. Extensive testing of both query performance time and query language features ultimately led to the selection of Kowari as the default triplestore.

The query interface to the relationship graph currently supports three RDF query languages, RDQL [39], iTQL [44], and SPO [38][3]. Both RDQL and iTQL share a superficially similar syntax to SQL, with RDQL enjoying broader implementation support, but iTQL providing a richer feature set [24].

The RDF query results naturally take the form of rows of key-value pairs, again similar to the result sets returned by a SQL query. However, it is often useful to work with a sub-graph or a constructed graph based on the original. To this end, the query API may also return *triples* instead of *tuples*.

4.4 Using the relationship graph

The Resource Index is exposed as one of the interfaces of the core Fedora Repository Service that was discussed earlier. This facilitates the development of other services in the Fedora Service Framework. The Resource Index interface is exposed in a REST architectural style to provide a stateless query interface that accepts queries by value or by reference. The service has been implemented with an eye toward eventual conformance to the W3C Data Access Working Group's SPARQL protocol for RDF[19], as it matures.

One example of a new service exploiting the Resource Index is a new OAI Provider Service that exposes metadata about resources in a repository. The interaction of this service with the Resource Index is as follows. An external OAI harvester requests Dublin Core records of members for a particular set of resources from the repository. The OAI Provider service processes this by issuing the query to the Resource Index listed in Table 5. This query effectively requests "all OAI Dublin Core records of resources that are members of the collection identified as 'demo:10'". This would return the tuples shown in Table 6 that can provide the basis of an OAI response. Note that the OAI representations were not shown earlier in Figure 1.

```
select $member $collection $dissemination
from <#ri>
where $member <rel:isMemberOf> <info:fedora/demo:10>
    and $member <rel:isMemberOf> $collection
    and $member <rel:isMemberOf> $dissemination
    and $member <fedora-view:disseminates> $dissemination
    and $dissemination <fedora-view:disseminationType>
<info:fedora/*/bdef:OAI/getDC>
```

Table 5 - A query to build an OAI response

---

[3] Future releases will also support SPARQL [37] Prud'Hommeaux, E. and Seaborne, A. SPARQL Query Language for RDF, W3C, 2004..

member	collection	dissemination
info:fedora/ demo:11	info:fedora/ demo:10	info:fedora/ demo:11/ bdef:OAI/getDC
info:fedora/ demo:12	info:fedora/ demo:10	info:fedora/ demo:12/ bdef:OAI/getDC

Table 6 - The query response as tuples

We envision a variety of other applications that exploit the features of the Resource Index. One developing application exists in the NSDL [52], where Fedora is being used to represent the relationships among learning objects, standards, reviewers, and metadata from various sources. The Resource Index will provide the foundation for higher level NSDL services that expose this rich information to users and clients.

5 Conclusion and Future Work

As mentioned previously, the Fedora project is now in its second phase of funding from the Andrew W. Mellon Foundation. This phase extends through 2007. This work addresses a number of areas including adding new services, tools, and utilities; optimizing for scale and performance; adding new integrity and preservation features; and enabling the creation of peer-to-peer networks of repositories ("Fedorations"). This work will be motivated by the specific requirements of institutional repositories, extremely large digital collections and archives, and distributed educational applications. The phase 2 development plan is prioritized to first focus on functionality that will make it easier for institutions to get a jump start in using Fedora – specifically by easily loading heterogeneous digital collections into Fedora repositories. Later work we will add functionality that helps Fedora users move towards building large-scale, highly dependable repositories. This will provide the basis for a shared, seamless information space in which virtual collections and networked objects can be fully realized.

In addition to this core development work by Cornell and the University of Virginia teams, a number of other parties have joined in a Fedora Development Consortium[4]. The purpose of this group is to provide a framework for collective knowledge sharing and collaboration for developers working within the Fedora Service Framework, described earlier. At the time of writing this paper, the Consortium has met for

[4] Details on members of the consortium are at the Fedora Open Source Project web site – http://www.fedora.info.

the first time, with follow-on meetings planned. We anticipate that the Consortium will augment the core Fedora system with additional value-added open-source software, and eventually produce a number of vertical "Fedora-inside" applications.

Fedora has been designed from the beginning for extensibility. A key aspect of its basic design is the existence of a well-defined object model and the exposure of the model through programmatic interfaces. A powerful feature of this model is the notion of an object having multiple representations, including virtual representations that involve the interaction of data and services. Another important feature of the model is the extensible relationship architecture that allows content managers to model within Fedora complex networks of information. Finally, the Fedora Service Framework, which is the implementation context for this object model, is the foundation for the deployment of extended services and user/client applications that apply Fedora in a variety of domains.

Increasingly rich digital content is placing greater demands on the institutions responsible for the creation, storage, management, and preservation of that content. Fedora is well-positioned to meet those demands and its open architecture provides the basis for meeting new requirements as they develop in the future.

Acknowledgments

The Fedora Open Source Project is currently funded by the Andrew W. Mellon Foundation. The authors express gratitude to Mellon for their long-term support of this project. Prior support came from the National Science Foundation and DARPA. The authors acknowledge the significant contributions of the Fedora project team at the University of Virginia led by co-PI Thornton Staples. The team members include Ross Wayland and Ronda Grizzle from the University Library and Tim Sigmon and Bill Niebel from Information Technology and Communication. The Fedora project has also benefited from the collaboration and contributions of members of the Fedora Development Consortium. The authors also express gratitude to Michael Nelson and Herbert Van de Sompel for their on-going collaboration and their encouragement in writing this paper.

References

[1] arXiv.org e-Print archive, http://arXiv.org

[2] eprints.org, http://www.eprints.org

[3] eXtensible Access Control Markup Language (XACML), http://www.oasis-open.org/committees/tc_home.php?wg_abbrev=xacml

[4] The Fedora™ Project: An Open-Source Digital Repository Management System, http://www.fedora.info

[5] The Friend of a Friend (FOAF) Project, http://www.foaf-project.org/

[6] Functional Requirements for Bibliographic Records, International Federation of Library Associations and Institutions, 1998.

[7] Global Digital Format Registry (GDFR), http://hul.harvard.edu/gdfr/

[8] IEEE P1484.12 Learning Object Metadata Working Group, http://ltsc.ieee.org/wg12/

[9] "info" URI Scheme, http://info-uri.info/registry/OAIHandler?verb=ListRecords&metadataPrefix=oai_dc

[10] Metadata Encoding and Transmission Standard (METS), http://www.loc.gov/standards/mets/

[11] METS, Metadata Encoding and Transmission Standard, http://www.loc.gov/standards/mets/>

[12] Pathways: Lifecycles for Information Integration in Distributed Scholarly Communication,

[13] Reference Model for an Open Archival Information System (OAIS), Consultative Committee for Space Data Systems, 1999.

[14] Web Services Description Language (WSDL) 1.1, http://www.w3.org/TR/wsdl

[15] Cornell Project Prism, http://www.prism.cornell.edu/main.htm

[16] Beckett, D. and McBride, B., RDF/XML Syntax Specification (Revised), http://www.w3.org/TR/rdf-syntax-grammar/

[17] Bekaert, J., Hochstenbach, P. and Van de Sompel, H. Using MPEG-21 DIDL to Represent Complex Digital Objects in the Los Alamos National Laboratory Digital Library. *D-Lib Magazine*, *9* (11).

[18] Brickley, D. and Guha, R.V. RDF Vocabulary Description Language 1.0: RDF Schema. McBride, B. ed., W3C, 2004.

[19] Clark, K.G., SPARQL Protocol for RDF, http://monkeyfist.com/kendall/sparql-protocol/

[20] Daniel Jr., R. and Lagoze, C., Distributed Active Relationships in the Warwick Framework. in *IEEE Metadata Conference*, (Bethesda, 1997).

[21] Daniel Jr., R. and Lagoze, C. Extending the Warwick Framework: From Metadata Containers to Active Digital Objects. *D-Lib Magazine*.

[22] Digital Library Federation (DLF). The Making of America II Testbed Project White Paper, Digital Library Federation, 1998.

[23] Garfield, E. *Citation indexing: Its theory and application in science, technology, and humanities*. John Wiley, New York, NY, 1979.

[24] Haase, P., Broekstra, Egerhart, A. and Volz, R., A comparison of RDF query languages. in *Third International Semantic Web Conference*, (Hiroshima, Japan, 2004).

[25] Hitchcock, S., Bergmark, D., Brody, T., Gutteridge, C., Carr, L., Hall, W. and Lagoze, C. Open Citation Linking. *D-Lib Magazine*, *8* (10).

[26] Iverson, V., Song, Y.-W., Van de Walle, R., Rowe, M., Doim Chang, Santos, E. and Schwartz, T. MPEG-21 Digital Item Declaration, International Organization for Standardization, 2000.

[27] Kahn, R. and Wilensky, R. A Framework for Distributed Digital Object Services, Corporation for National Research Initiatives, Reston, 1995.

[28] Lagoze, C. and Davis, J.R. Dienst - An Architecture for Distributed Document Libraries. *Communications of the ACM*, *38* (4). 47.

[29] Lagoze, C., Van de Sompel, H., Nelson, M. and Warner, S., The Open Archives Initiative Protocol for Metadata Harvesting - Version 2.0, http://www.openarchives.org/OAI_protocol/openarchivesprotocol.html

[30] Manola, F. and Miller, E. RDF Primer, W3C, 2003.

[31] National information Standards Organization (U.S.), The OpenURL Framework for Context-Sensitive Services, http://www.niso.org/committees/committee_ax.html

[32] Payette, S., Blanchi, C., Lagoze, C. and Overly, E. Interoperability for Digital Objects and Repositories: The Cornell/CNRI Experiments. *D-Lib Magazine*, *May*.

[33] Payette, S. and Lagoze, C., Flexible and Extensible Digital Object and Repository Architecture (FEDORA). in *Second European Conference on Research and Advanced Technology for Digital Libraries*, (Heraklion, Crete, 1998).

[34] Payette, S. and Lagoze, C., Policy-Enforcing, Policy-Carrying Digital Objects. in *Fourth European Conference on Research and Advanced Technology for Digital Libraries*, (Lisbon, Portugal, 2000).

[35] Payette, S. and Lagoze, C. Value-Added Surrogates for Distributed Content: Establishing a Virtual Control Zone. *D-Lib Magazine*, *6* (6).

[36] Payette, S. and Staples, T., The Mellon Fedora Project: Digital Library Architecture Meets XML and Web Services. in *European Conference on Research and Advanced Technology for Digital Libraries*, (Rome, 2002).

[37] Prud'Hommeaux, E. and Seaborne, A. SPARQL Query Language for RDF, W3C, 2004.

[38] Seaborne, A., Joseki: Query Languages,

[39] Seaborne, A., RDQL - A Query Language for RDF, http://www.w3.org/Submission/2004/SUBM-RDQL-20040109/

[40] Smith, M., Bass, M., McClellan, G., Tansley, R., Barton, M., Branschofsky, M., Stuve, D. and Walker, J.H. DSpace: An Open Source Dynamic Digital Repository. *D-Lib Magazine*, *9* (1).

[41] Staples, T. and Wayland, R. Virginia Dons FEDORA: A Prototype for a Digital Object Repository. *D-Lib Magazine*, *July*.

[42] Staples, T., Wayland, R. and Payette, S. The Fedora Project. *D-Lib Magazine*, *9* (4).

[43] Treloar, A., Building an Institutional Research Repository from the Ground Up: The ARROW Experience. in *AusWeb04*, (Gold Coast, Australia, 2003).

[44] Tucana Technologies, iTQL Commands, http://kowari.org/271.htm

[45] Tucana Technologies, Kowari metastore, http://www.kowari.org/

[46] Tufts University, VUE: Visual Understanding Environment, http://vue.tccs.tufts.edu/

[47] Unsworth, J., Suporting Digital Scholarship: a project funded by the Andrew W. Mellon Foundation, http://www.iath.virginia.edu/sds/proposal.html

[48] Van de Sompel, H., Bekaert, J., Liu, X., Balakireva, L. and Schwander, T., aDORe: a modular, standard-based Digital Object Repository, http://www.arxiv.org/abs/cs.DL/0502028

[49] Van de Sompel, H., Nelson, M., Lagoze, C. and Warner, S. Resource Harvesting within the OAI-PMH Framework. *D-Lib Magazine*, *10* (12).

[50] Van de Sompel, H., Payette, S., Erickson, J., Lagoze, C. and Warner, S. Rethinking Scholarly Communication: Building the System that Scholars Deserve. *D-Lib Magazine* (September).

[51] VTLS, VITAL, http://www.vtls.com/Products/vital.shtml

[52] Zia, L.L. The NSF National Science, Technology, Engineering, and Mathematics Education Digital Library (NSDL) Program. *D-Lib Magazine*, *8* (11).

Appendix A

Example Digital Object Encoded in FOXML

```xml
<?xml version="1.0" encoding="UTF-8"?>
<foxml:digitalObject PID="demo:11"
   xmlns:foxml="info:fedora/fedora-system:def/foxml#"
   xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
   xsi:schemaLocation="info:fedora/fedora-system:def/foxml#
   http://www.fedora.info/definitions/1/0/foxml1-0.xsd">
<!-- ********************************************************************** -->
<!-- OBJECT PROPERTIES -->
<!-- ********************************************************************** -->
<foxml:objectProperties>
  <foxml:property NAME="http://www.w3.org/1999/02/22-rdf-syntax-ns#type"
                  VALUE="FedoraObject"/>
  <foxml:property NAME="info:fedora/fedora-system:def/model#state"
                  VALUE="A"/>
  <foxml:property NAME="info:fedora/fedora-system:def/model#label"
                  VALUE="Image Object – UVA Pavilion"/>
  <foxml:property NAME="info:fedora/fedora-system:def/model#createdDate"
                  VALUE="2004-12-10T00:21:57Z"/>
  <foxml:property NAME="info:fedora/fedora-system:def/view#lastModifiedDate"
                  VALUE="2004-12-23T00:20:00Z"/>
  <foxml:property NAME="info:fedora/fedora-system:def/model#contentModel"
                  VALUE="UVA_STD_IMG"/>
</foxml:objectProperties>
<!-- ********************************************************************** -->
<!-- DATASTREAMS -->
<!-- ********************************************************************** -->
<foxml:datastream ID="THUMB" CONTROL_GROUP="E" MIMETYPE="image/jpg"
                  STATE="A" VERSIONABLE="true">
    <foxml:datastreamVersion ID="THUMB.0" LABEL="Preview Pavilion III"
                             CREATED="2004-12-10T00:21:57Z">
        <foxml:contentLocation TYPE="URL"
            REF="http://icarus.lib.virginia.edu/images/iva/archerd05small.jpg" />
        </foxml:datastreamVersion>
</foxml:datastream>
<foxml:datastream ID="HIGH" CONTROL_GROUP="M" MIMETYPE="image/jpeg"
                  STATE="A" VERSIONABLE="true">
    <foxml:datastreamVersion ID="HIGH.0" LABEL="Drawing Pavilion III"
                             CREATED="2004-12-10T00:21:57Z">
        <foxml:contentLocation TYPE="INTERNAL_ID"
                              REF="demo:11:HIGH:HIGH.0"/>
    </foxml:datastreamVersion>
    <foxml:datastreamVersion ID="HIGH.1" LABEL="Drawing Pavilion III"
                             CREATED="2004-12-12T00:22:00Z">
        <foxml:contentLocation TYPE="INTERNAL_ID"
                              REF="demo:11:HIGH:HIGH.1"/></foxml:datastreamVersion>
    <foxml:datastreamVersion ID="HIGH.2" LABEL="Drawing Pavilion III"
                             CREATED="2004-12-23T00:20:00Z">
        <foxml:contentLocation TYPE="INTERNAL_ID"
```

```xml
                    REF="demo:11:HIGH:HIGH.2"/></foxml:datastreamVersion>
</foxml:datastream>
<!-- ************************************************************************ -->
<!-- INTEGRITY DATASTREAMS -->
<!-- ************************************************************************ -->
<foxml:datastream ID="DC" CONTROL_GROUP="X"  MIMETYPE="text/xml"
                STATE="A" VERSIONABLE="true">
    <foxml:datastreamVersion ID="DC.0" LABEL="Dublin Core Record"
                    CREATED="2004-12-10T00:21:57Z">
        <foxml:xmlContent>
        <oai_dc:dc xmlns:oai_dc="http://www.openarchives.org/OAI/2.0/oai_dc/"
        xmlns:dc="http://purl.org/dc/elements/1.1/">
                <dc:title>Image of UVA Pavilion - Drawing</dc:title>
                <dc:subject>Architectural drawings</dc:subject>
                <dc:publisher>University of Virginia</dc:publisher>
                <dc:identifier>demo:11</dc:identifier>
        </oai_dc:dc>
        </foxml:xmlContent>
    </foxml:datastreamVersion>
</foxml:datastream>
<foxml:datastream ID="RELS-EXT" CONTROL_GROUP="X" MIMETYPE="text/xml"
                STATE="A" VERSIONABLE="true">
        <foxml:datastreamVersion ID="RELS-EXT.0" LABEL="Relationships"
                    CREATED="2004-12-10T00:21:57Z">
            <foxml:xmlContent>
                <rdf:RDF xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
              xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
              xmlns:fedora="info:fedora/fedora-system:def/relations-external#"
              xmlns:myns="http://www.nsdl.org/ontologies/relationships#"
              xmlns:dc="http://purl.org/dc/elements/1.1/"
              xmlns:oai_dc="http://www.openarchives.org/OAI/2.0/oai_dc/">
                    <rdf:Description rdf:about="info:fedora/demo:11">
                        <fedora:isMemberOf rdf:resource="info:fedora/demo:10"/>
                    </rdf:Description>
                </rdf:RDF>
            </foxml:xmlContent>
        </foxml:datastreamVersion>
    </foxml:datastream>
<foxml:datastream ID="AUDIT" CONTROL_GROUP="M" MIMETYPE="text/xml"
                STATE="A" VERSIONABLE="false">
        <foxml:datastreamVersion ID="AUDIT.0" LABEL="Object Audit Trail"
                    CREATED="2004-12-12T00:22:00Z">
    <foxml:xmlContent>
                <audit:auditTrail xmlns:audit="info:fedora/def:audit/">
                    <audit:record ID="AUDREC1">
                        <audit:process type="Fedora API-M"/>
                        <audit:action>modifyDatastreamByRef</audit:action>
                        <audit:componentID>HIGH</audit:componentID>
                        <audit:responsibility>fedoraAdmin</audit:responsibility>
                        <audit:date>2004-12-12T00:22:00Z </audit:date>
                        <audit:justification></audit:justification>
                    </audit:record>
                    <audit:record ID="AUDREC2">
                        <audit:process type="Fedora API-M"/>
```

```
                        <audit:action>modifyDatastreamByRef</audit:action>
                        <audit:componentID>HIGH</audit:componentID>
                        <audit:responsibility>fedoraAdmin</audit:responsibility>
                        <audit:date>2004-12-23T00:20:00Z</audit:date>
                        <audit:justification></audit:justification>
                    </audit:record>
                </audit:auditTrail>
            </foxml:xmlContent>
        </foxml:datastreamVersion>
    </foxml:datastream>
<!-- ********************************************************************** -->
<!-- DISSEMINATOR(S) -->
<!-- ********************************************************************** -->
<foxml:disseminator ID="DISS1" BDEF_CONTRACT_PID="BDEF:2" STATE="A"
                  VERSIONABLE="true">
        <foxml:disseminatorVersion ID="DISS1.0"
                  BMECH_SERVICE_PID="BMECH:3"
                  LABEL="UVA Simple Image Behaviors"
                  CREATED="2004-12-10T00:21:57Z">>
            <foxml:serviceInputMap>
                <foxml:datastreamBinding KEY="HIGHRES_IMG"
                  DATASTREAM_ID="HIGH" LABEL="Input Image"/>
            </foxml:serviceInputMap>
        </foxml:disseminatorVersion>
</foxml:disseminator>
</foxml:digitalObject>
```