

API4KP Metamodel: a Meta-API for Heterogeneous Knowledge Platforms

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Abstract. API4KP target the basic administration services as well as the retrieval, modification and processing of expressions in machine-readable languages, including but not limited to knowledge representation and reasoning (KRR) languages, within heterogeneous (multi-language, multi-nature) knowledge platforms. KRR languages of concern in this paper include but are not limited to RDF(S), OWL, RuleML and Common Logic, and the knowledge platforms may support one or several of these. Additional languages, e.g. SQL, XMPP, are integrated using mappings into KRR languages. A general notion of structure for knowledge sources is developed using monads. The presented API4KB metamodel, in the form of an OWL ontology, provides an abstract syntax for communications about knowledge sources and environments, including a classification of knowledge source by mutability, structure, and an abstraction hierarchy as well as the use of performatives (inform, query, ...), languages, logics, dialects, formats and lineage. Finally, a framework is provided for describing operations on knowledge sources and environments and their execution, which may be used for requests (message-passing).

1 Introduction

The inherent complexity of many application domains - including but not limited to finance, healthcare, law, telecom and enviromental protection - paired with the fast pace of innovation, requires increasingly robust, scalable and maintainable software solutions. Design patterns have shifted from monolithic applications towards distribution and service-orientation. Standards have been published to improve interoperability. Model driven architectures (MDA) have been adopted to support declarative, platform-independent specifications of an application's business logic [11]. A special type of MDA, Knowledge Driven Architectures (KDA) [15], rely on models such as ontologies that are not only standard, but also have a formal grounding in KRR.

KDA, while not yet ubiquitous, have a variety of applications. We consider as a running example a usecase from the healthcare domain.

A “connected patient” system gathers input from biomedical devices, part of a publish-subscribe architecture, which post observations including physical quantities, spatio-temporal coordinates and other context information. The data can be represented in a device-specific format (e.g. using XMPP [2]) or as streams of RDF graphs over time. The vocabularies referenced in the streams include units of measure, time, geospatial and biomedical ontologies, expressed in RDF(S), OWL or Common Logic (CL). Healthcare providers will submit SPARQL queries and receive incremental streams as new data becomes available. A Clinical Decision Support System (CDS), implemented using event-condition-action (ECA) rules, will also react to events simple (e.g. a vital parameter exceeding a threshold) and complex (e.g. a decreasing trend in the average daily physical activity) and intervene with alerts and reminders. If an alert is not addressed in a timely fashion, it will escalate to another designated recipient. Some patients will qualify for clinical pathways and the system will maintain a stateful representation of their cases, allowing clinicians to check for compliance with the planned orders (e.g. drug administrations, tests, procedures, ...). As medical guidelines evolve, the logic of the pathway may need revision: queries to the patient’s history should be contextualized to whatever logic was valid at the time orders were placed.

From a systems-oriented perspective communicating entities in distributed systems are processes (or simple nodes in primitive environments without further abstractions) and from a programming perspective they are objects, components or services/agents. They may be single-sorted or many-sorted, with sorts being characterized by the kind of communications that may be initiated, forwarded or received, and by the kind of entity that may be received or forwarded from or sent to. Communication channels may in general be many-to-many and uni- or -bidirectional. Each communication has a unique source; multi-source communications are not modelled directly, but are emulated by knowledge sources that publish streams that may be merged to give the appearance of multiple sources. We will allow for failure, either in communication or in execution, but do not specify any particular failure recovery strategy. Various types of communication paradigms are supported from strongly-coupled communication via low-level inter-process communication with ad-hoc network programming, loosely coupled remote invocation in a two-way exchange via interfaces (RPC/RMI/Component/Agent) between communicating entities, to decoupled indirect communication, where sender and receiver are time and space uncoupled via an intermediary such as a publish-subscribe and event processing middleware. The communication entities fulfill different roles and responsibilities (client, server, peer, agent) in typical architectural styles such as client-server, peer-to-peer and multi-agent systems. Their placement (mapping) on the physical distributed infrastructure allows many variations (partitioning, replication, caching and proxying, mobile) such as deployment on multiple servers and caches

to increase performance and resilience, use of low cost computer resources with limited hardware resources or adding/removing mobile computers/devices.

Given this variety of architectural requirements, an abstraction is required to facilitate the interchange, deployment, revision and ultimately consumption of formal, declarative pieces of knowledge within a knowledge-driven application. In 2010 the OMG published the first formalized set of KDA requirements in an RFP titled "the API for Knowledge Bases (API4KB)". In 2014 the OMG published a second RFP titled "Ontology, Model, and Specification Integration and Interoperability (OntoIOP)" [13]. This second RFP contains the requirements for a substantial part of the API4KB, and a submission, called DOL [1] is near completion. To address the remaining aspects of the API4KB RFP, a multi-disciplinary working group is creating a standard meta-API, called API4KP, for interaction with the Knowledge Platforms at the core of KDAs.

To provide a semantic foundation for the operations and their arguments, we have created a metamodel of knowledge sources and expressed it as an OWL ontology⁶. The primary concepts of the metamodel are described in Sec. 2, with details for structured knowledge resource in Sec. 3. In Sec. 4 we provide a proof-of-concept based on application to the usecase, identification of existing implementations, and prototypical implementation of monadic tree structures.

2 API4KP Metamodel

The API4KP metamodel is hierarchical, with a few under-specified concepts at the upper levels, and more precisely defined concepts as subclasses. The principle upper-level concepts in the API4KP metamodel are

Knowledge Source: source of machine-readable information with semantics.

Examples: a stream of RDF graphs, a stateful representation with OWL snapshots, or a database with a mapping to an ontology.

Environment: mathematical structure of mappings and members, where the domain and codomains of the mappings are members of the environment. Example: a KRR language environment containing semantics-preserving translations from RDF and OWL into Common Logic.

Knowledge Operation: function (possibly with side-effects. i.e. effects beyond the output value returned) having a knowledge source, environment or operation type in its signature. Examples: creating, modifying, deleting, parsing, translating, querying, downloading, or reasoning about a knowledge source.

Knowledge Event: successful evaluation or execution of a knowledge operation by a particular application at a particular time.

These definitions are intentionally vague so as to be adaptable to a variety of implementation paradigms.

We have developed a hierarchy of *knowledge source level* of abstraction that is a generalization of the FRBR [8] Work-Expression-Manifestation-Item (WEMI)

⁶ <https://github.com/API4KBs/api4kbs>

hierarchy of abstraction tailored for machine-readable KRR languages. The fundamental building blocks of knowledge sources are *basic knowledge resources*, which are immutable knowledge sources without structure. Subclasses of basic knowledge resources are defined according to their knowledge source level.

Basic Knowledge Expression: well-formed formula in the abstract syntax of a machine-readable language.⁷ Example KE1: the instance of the OWL 2 DL abstract syntax for a version of biomedical ontology from an ontology series KA1, differing from other versions of the series only in the natural language definitions.

Basic Knowledge Manifestation: character-based embodiment of a basic knowledge expression in a concrete dialect. Example KM1: the OWL/RDF XML abstract DOM instance of example KE1.

Basic Knowledge Item: single exemplar of a basic knowledge manifestation in a particular location. Example KI1: a file on a network server embodying example KM1.

Basic Knowledge Asset: equivalence class of basic expressions determined by the equivalence relation of an asset environment (see Sec. 2.2.) Example KA1: an OWL2 DL series for a biomedical ontology, viewed as an equivalence class of basic knowledge expressions in OWL2 DL, including example KE1, according to a semantics-preserving environment for the OWL2 DL language where the mapping to the focus language strips the natural language definitions from the axioms.

API4KP lifting/lowering operations (see 2.4) provide transformations from one level to another complying with the following relations:

exemplify: to instantiate (a knowledge manifestation) in particular format(s) and at particular location(s) (address in some virtual address space). Example: KI1 exemplifies KM1, KM1 prototypes KI1.

Inverse: *prototype*

embody: to represent (a knowledge expression) in concrete syntax(es) (dialects) of particular KRR language(s). Example: KM1 embodies KE1, KE1 parses KM1.

Inverse: *parse*

express: to represent (a knowledge asset) in abstract syntax(es) of particular KRR language(s). Example: KE1 expresses KA1, KA1 conceptualizes KE1.

Inverse: *conceptualize*

Note that plurality in the above definitions corresponds to heterogeneous knowledge sources, not non-determinism.

2.1 Mutability

Following RDF concepts [4], knowledge sources are characterized as mutable or immutable, and immutable knowledge sources are called *knowledge resources*. In

⁷ The use of "basic" in API4KP differs from its usage in DOL - a DOL basic OMS is a set, and corresponds to a Set-structured knowledge asset in API4KP.

this context, immutable does not necessarily mean static; a stream of knowledge, e.g. a feed from a biomedical device, may be considered an *observable* knowledge resource that is revealed over time, as described further in Sec. 3. A *mutable knowledge source* is a container that has, at any point in time, an explicit state that is fully represented by a knowledge resource, e.g. the snapshot of a patient's current condition (with timestamp). The language, structure and content of a mutable knowledge source may change over time; however, the abstraction level is unchanging.

We distinguish between the *implicit* state that a mutable knowledge source holds indirectly when operators such as actions, complex event patterns or aggregations are computed on it, and the explicit state that evolves with time and that can be managed explicitly by an additional state transformer component responsible for *explicit* state management, concurrency control, reasoning (specifically, inference of state deltas), and state updates. There are various ways to manage explicit state, e.g. embedded inside the processors of the knowledge source in global variables or state accumulating variables or tuples that are available either locally to an individual operator or across the operators as a shared storage, or with explicit state and concurrency control which lies outside of knowledge resource processors, e.g. by threading the variables holding state through a functional state transformer and by using State monads (see 3), which exist within the context of another computation or transformation, thus allowing to attach state information to any kind of functional expression.

2.2 Environments

In DOL, a concept of heterogeneous logical environment is defined as "environment for the expression of homogeneous and heterogeneous OMS, comprising a logic graph, an OMS language graph and a supports relation". In API4KP, we generalize this concept of environment as follows.

Categorical Environment: environment with an associative composition operation for mappings, that is closed under composition and contains an identity mapping for every member

Language Environment: environment whose members are languages

Focused Environment: nonempty environment which has a member F (called the focus or focus member) such that for every other member A, there is a mapping in the environment from A to F

Preserving Environment: environment where every mapping preserves a specified property

Asset Environment: focused, categorical, preserving language environment where the focus is a KRR language

The special case where all languages in an asset environment are KRR languages supporting model-theoretic semantics without side-effects (logics), and the preserving property is characterized by a logical graph reduces to a heterogeneous logical environment as defined in DOL.

The Knowledge Query and Manipulation Language [6] introduced the concept of *performatives*, which was later extended by FIPA-ACL [7]. The KRR Languages covered by API4KP include ontology languages (e.g. OWL), query languages (e.g. SPARQL), languages that describe the results of queries, events and actions (e.g. KR RuleML), and declarative executable languages (e.g. Prolog, ECA RuleML). In the latter case, the languages typically includes syntactic constructs for performatives, e.g. *inform*, *query*, and the description of a knowledge resource may include a list of the performatives that are used within it. Performatives will be modelled as *operations* as defined in Sec. 2.4.

2.3 Descriptions

As stated above, we do not make assumptions regarding the drivers for communications, e.g. an implementation may be message-driven, event-driven, or a combination of both. However, our metamodel takes a message-centric perspective, with the message body typically being a description of a knowledge source or a knowledge operation.

A *knowledge source description* is a knowledge resource whose subject matter is another knowledge source, which may be expressed, e.g., as an OWL ontology of individuals or an RDF graph. The properties and classes in the API4KP namespace that may be employed in knowledge source descriptions are listed in the following tables and formalized in the API4KP OWL ontologies. Further, IRIs in other namespaces may be used to express metadata within a knowledge source description. A description about the description itself may be referenced through an IRI, or included within the description explicitly through the `:has-Description` property, OWL annotations, or as an RDF dataset [5].

Key	Value
Y	exactly 1
Y+	1 or more
Y?	0 or 1
Y*	0 or more
N	exactly 0
I[+?]*]	indirect

Table 1. Legend

Prefix	Expansion
:	http://www.omg.org/spec/API4KP/API4KPTerminology/
ks:	:KnowledgeSource/
kr:	:KnowledgeResource/
ka:	kr:Asset/
ke:	kr:Expression/
km:	kr:Manifestation/
ki:	kr:Item/
lang:	:Language/
map:	:Mapping/
xsd:	http://www.w3.org/2001/XMLSchema#

Table 2. Prefix Mappings

2.4 Operations and Events

In the API4KP framework, the building blocks for all knowledge operations are *actions* – unary functions, possibly with side-effects and possibly of higher-order.

Property	Range	ka:	ke:	km:	ki:
:hasIdentifier	:Identifier	Y?	Y?	Y?	Y?
:level	ks:Level	Y	Y	Y	Y
:usesPerformative	:Operation	I*	Y*	I*	I*
:hasLocator	:Address	Y?	Y?	Y?	Y
:usesLanguage	:Language	I*	Y*	I*	I*
:usesDialect	km:Dialect	N	N	Y*	I*
:usesConfiguration	ki:Configuration	N	N	N	Y*
:accordingTo	lang:Environment	Y	N	N	N
:isBasic	xsd:boolean	Y	Y	Y	Y
:isOutputOf	ev:	Y?	Y?	Y?	Y?
:hasMetaData	:KnowledgeResource	Y*	Y*	Y*	Y*
:hasDescription	:KnowledgeResource	Y*	Y*	Y*	Y*

Table 3. Knowledge Resource Metamodel

Property	Domain	Range	Inverse
:exemplify (?)	ki:	km:	:prototype (*)
:embody (?)	km:	ke:	:parse (*)
:express (*)	ke:	ka:	:conceptualize (*)

Table 4. Knowledge Resource Elevation Properties

Actions are defined in terms of their possible events. To maintain a separation of concerns, side-effectful actions are assumed to be void, with no significant return value. Particular kinds of actions include:

Lifting Action: side-effect-free action whose output is at a higher knowledge source level than the input

Lowering Action: side-effect-free action whose output is at a lower knowledge source level than the input

Horizontal Action: side-effect-free action whose output is at the same knowledge source level as the input

Idempotent Action: side-effect free action that is equal to its composition with itself ($A = A \circ A$)

Higher-Order Action: side-effect-free action whose input or output (or both) is an action

Lifting and lowering are utility actions for changing the knowledge source level, e.g. parsing and IO. Horizontal actions are useful e.g. for constructing structured knowledge sources, while higher-order actions are needed to specify more complex operations e.g. querying.

In this framework, we define two void actions that have side-effects on the state of mutable knowledge resources:

Put: void action whose input is a mutable knowledge source and has the side-effect of setting the mutable knowledge source to a particular, fully-specified state

Property	Range	ke:Language	km:Dialect	ki:Configuration
:hasIdentifier	:Identifier	Y	Y	Y
:hasLocator	:Address	N	N	Y?
:supports	:Logic	Y	I	I
:usesLanguage	ke:Language	N	Y	I
:usesDialect	km:Dialect	N	N	Y
:usesFormat	ki:Format	N	N	Y
:location	:Address	N	N	Y

Table 5. Knowledge Resource Configuration Metamodel

Property	Range	T:Environment
:hasIdentifier	:Identifier	Y?
:mapping	T:Mapping	Y*
:focus	T:	Y?
:preserves	T:EquivalenceRelation	Y*
:isOutputOf	ev:	Y?

Table 6. Generic Environment Metamodel. The generic prefix T: specifies the member type. Specific environments include lang:Environment (a system of mappings between the abstract syntax of languages) .

Update: void action whose input is a mutable knowledge source and has the side-effect of setting the mutable knowledge to a new state that is the result of applying a side-effect-free action to the current state

A side-effectful operation can be considered idempotent if its successful execution multiple times (synchronously) leads to no additional detectable side-effects beyond that of the first execution. Note that this is a different, but related, concept of idempotence than that for side-effect-free actions. An Update action based on an idempotent side-effect-free action is idempotent in this sense, an important factor in failure recovery.

3 Structured Knowledge Resources

We generalize the DOL concept for structured OMS (ontologies, models and specifications) to define a concept of structured knowledge resource for each level of abstraction. In DOL, a structured OMS "results from other basic and structured OMS by import, union, combination, ... or other structuring operations". In API4KP, A *structured knowledge resource* is a collection whose components are knowledge resources of the same level of abstraction; structuring knowledge operations are provided in Sec. 2.4.

Structured Knowledge Expression: collection of knowledge expressions (either structured or basic), which are not necessarily in the same language and may themselves have structure. ExampleKE2: a heterogeneous collection of streaming data and RDF graphs, together with static OWL ontologies and

Property	Range	T:Mapping
:hasIdentifier	:Identifier	Y?
:location	:Address	Y?
:start	T:	Y
:end	T:	Y
:preserves	:EquivalenceRelation	Y*
:usesLanguage	map:Language	Y*
:isBasic	xsd:boolean	Y
:components	T:MappingList	Y?

Table 7. Generic Mapping Metamodel

Property	Domain	Range	Inverse
:hasEvent (*)	op:	ev:	:isEventOf (1)
:executes (*)	:Application	ev:	:isExecutedBy (1)
:input (?)	ev:ActionEvent	:	:isInputOf (*)
:output (?)	ev:	:	:isOutputOf (?)
:atTime (1)	ev:	xsd:dateTime	

Table 8. Knowledge Resource Operation and Event Properties

Common Logic texts, and ECA rules describing actions of a CDS. Example KE3: the OWL 2 DL ontology series KA1, viewed as a collection of expressions rather than an equivalence class.

Structured Knowledge Manifestation: collection of knowledge manifestations (either structured or basic), which are not necessarily in the same language or dialect and may themselves have structure. Example KM2: a heterogeneous structure of RDF Turtle, OWL Manchester as sequences of string tokens, and XMPP, OWL/XML, ECA RuleML and Common Logic XCL2 as XML abstract DOM documents embodying example KE2.

Structured Knowledge Item: collection of knowledge items (either structured or basic), which are not necessarily in the same language, dialect, format or location, and may themselves have structure. Example KI2: a heterogeneous structure of an RDF triple store, network connections to binary input streams cached in a MySQL database, RuleML XML files on a local hard drive and Common Logic XCL2 files on a network server in a content management system, exemplifying example KM2.

Structured Knowledge Asset: collection of knowledge assets (either structured or basic), which are not necessarily according to the same environment, but where there is a unique language that is the focus of the environment of each component. Example KA2: a heterogeneous structure of assets conceptualized from the RDF, OWL and Common Logic expressions of example KE2 according to an environment that provides translations from RDF or OWL into Common Logic, and an ontology-based data access (OBDA) source schema providing a mapping from XMPP schemas to OWL.

To assist in defining operations on structured knowledge sources while still maintaining generality, the collection structure of a structured knowledge re-

source is required to arise from a monadic functor (monad). Collection structures that satisfy these requirements include sets, bags and sequences, but other useful structures also meet these requirements.

3.1 Monads

In seminal work that established a theoretical foundation for proving the equivalence of programs, Moggi [12] applied the notion of monad from category theory [10] to computation. As defined in category theory, a monad is an endofunctor on a category C (a kind of mapping from C into itself) which additionally satisfies some requirements (the monad laws). In functional programming, monads on the category with types as objects and programs as arrows are employed. For example, the `List[_]` typeclass is a monad, e.g. `List[Int]` is a type that is a member of `List[_]`.

Each monad has the following transformations (exemplified for the `List` monad where lists are denoted with angle brackets)

- `unit`: $A \Rightarrow M[A]$ lifts the input into the monad (e.g. `unit(2) = <2>`)
- `join`: $M[M[A]] \Rightarrow M[A]$ collapses nested monad instances by one level (e.g. `join(<<1, 2>, <3, 4>)<1, 2, 3, 4>`)
- `map`: $(A \Rightarrow B) \Rightarrow (M[A] \Rightarrow M[B])$ takes a function between two generic types and returns a function relating the corresponding monadic types (e.g. `map(s => 2*s)(<1, 2>) = <2, 4>`)

Note that we choose the `unit`, `join` and `map` transformations [16] as fundamental in this development of the monad laws because it is useful for later discussion on tree structures, whereas the usual theoretical treatment, based on `unit` and `bind = join o map`, is more concise.

Monads of relevance to API4KP include, but are not limited to

- Try**: handles exceptions, has subclasses `Success`, which wraps a knowledge resource, and `Failure`, which wraps a (non-fatal) exception
- IO**: handles IO side-effects, wraps a knowledge resource and an *item configuration*
- Task**: handles general side-effects, wraps a knowledge resource and a description of a side-effectful task
- Observable**: handles concurrent streams, wraps a sequence of knowledge resources that become available over time
- State**: handles state, wraps a knowledge resource (the state) and implements state transitions

These monad functors may be composed; for example, given a basic knowledge expression type E , the type $(\text{State} \circ \text{Try} \circ \text{List}) [E] = \text{State}[\text{Try}[\text{List}[E]]]$ may be defined. In general, the composition of monads is not necessarily a monad.

3.2 Monadic Tree Structures

The monad structures needed for API4KP are a restricted form of the monads seen in functional programming - rather than applying to category of all types,

these monads are functors on a smaller category of knowledge resource types. In DOL, the concept of structured expression using sets is introduced. For example, let B be the category of (basic) Common Logic text expressions, and $Q[B] = B$ or $\text{SetTree}[B]$, where $\text{SetTree}[B] = \text{Set}[Q[B]] = \text{Set}[B \text{ or } \text{SetTree}[B]]$ is the typeclass of SetTree -structured Common Logic expressions. In particular, a member of type $\text{SetTree}[B]$ is specified by a Set whose members are either basic leaves (of type B) or structured branches (of type $\text{SetTree}[B]$).

The Set monad is appropriate for defining structured expressions in monotonic logics, like Common Logic, because the order and multiplicity of expressions in a collection has no effect on semantics. The semantics of CL is provided by the CL interpretation structure that assigns a truth-value to each basic CL text expression. The truth-value of a set of CL text expressions is true in an interpretation I if each member of the set maps to true in I . The truth value $I(y)$ of a SetTree -structured CL expression y is defined to be $I(\text{flatten}(y))$, where $\text{flatten}(y)$ is the set of leaves of y .

We generalize this approach for defining the semantics of structured expressions to an arbitrary language L with basic expressions E and M -tree structured expressions. We assume that

- M is a monad on the category of types,
- model-theoretic semantics is supplied through an interpretation structure I defined for basic expressions in E and simply-structured expressions $M[E]$,
- a post-condition contract for side-effects is specified by a truth-valued function $P(F, y)$ for all supported void knowledge actions F and all y in E or $M[E]$.

Let $N[_]$ be the M -tree monad corresponding to the minimal (finite) fixed point of $N[E] = M[E \text{ or } M[N[E]]]$, where " A or B " is used as an abbreviation for an unbiased $\text{Either}[A, B]$ bifunctor. The unit function for N is the same as the unit function for M . The map and join functions for N are defined from a straight-forward recursive application of the map and join functions for M . The proof⁸ of the satisfaction of the monad laws is dependent on the use of the Either bifunctor to handle the union types, so that the left or right intention is preserved even in the case when the types are not disjoint.

If E is a type of basic knowledge resources, then $N[E]$ is the type of M -tree-structured knowledge resources, and $Q[E] = E$ or $N[E]$ is the corresponding type of knowledge resources (either basic or structured). By convention, the M -tree monad is named by appending "Tree" to the name of the underlying monad; thus, $\text{SetTree}[E] = \text{Set}[E \text{ or } \text{SetTree}[E]]$.

For all $x, y \in Q[E]$, we define⁸ a flatten transformation. Informally

level: $Q[E] \Rightarrow N[E] \ni \text{level}(x) \doteq \text{unit}(x)$ if $x \in E$, x otherwise
flatten: $Q[E] \Rightarrow E \text{ or } M[E] \ni \text{flatten}(y) \doteq y$ if $y \in E$ or $M[E]$,
 $\text{flatten}(\text{join}_N(\text{map}_M(\text{level})(y)))$ otherwise

⁸ https://github.com/API4KBs/api4kbs/blob/currying/Monad_Trees.pdf

Then for all $y \in Q[E]$, we may define the interpretation $I(y) = I(\text{flatten}(y))$, with entailments defined accordingly. Implementations that honor the semantics must satisfy $P(F)(y) = P(F)(\text{flatten}(y))$, where $P(F)$ is a function representing the post-conditions after execution of side-effectful knowledge operation F on the knowledge resource y .

3.3 Heterogeneous Structures

Suppose A and B are expression types of two languages where an environment provides a semantics-preserving transformation T from B to A . Further suppose that an interpretation mapping I is defined on A or $M[A]$. The Either type $E = A$ or B defines the basic knowledge expressions in this environment, while structured expressions are $N[E]$ where N is the M-tree monad $N[E]$. The Either type $Q[E] = E$ or $N[E]$ contains all expressions in this environment, basic or structured.

Using the transformation T from the environment, we may define the interpretation of the M-tree structured expressions in terms of the interpretations of basic expressions in A and operations on monads. In particular,

$$\begin{aligned} S(x) &\doteq T(x) \text{ if } x \in B, x \text{ otherwise} \\ I(x) &\doteq I(\text{map}(S)(\text{flatten}(x))) \equiv I(\text{flatten}(\text{map}(S)(x))) \end{aligned}$$

Notice that the expressions of type B are not required to be in a knowledge representation language. They could be in a domain-specific data model based on XML, JSON or SQL. The semantics of expressions of type B are derived from the transformation to type A , the focus knowledge representation language of the environment. API4KP employs this feature to model ontology-based data access (OBDA) and rule-based data access (RBDA).

Structured expressions can always be constructed in a monad that has more structure than necessary for compatibility with the semantics of a given language. For example, List and Stream monads can be used for monotonic, effect-free languages even though the Set monad has sufficient structure for these languages; a forgetful functor is used to define the semantics in the monad with greater structure in terms of the monad of lesser structure. A heterogeneous structure of languages containing some languages with effects and others without effects (e.g. an ECA rulebase supported by ontologies) could thus make primary use of an M-tree monad that preserves order, such as ListTree or StreamTree, while permitting some members of the collection to have a SetTree structure.

While an immutable knowledge source (i.e. a knowledge resource) has a specific structure, as discussed above, a mutable knowledge source has structure only indirectly through the structure of its state. In general, the structure of a mutable knowledge source's state changes arbitrarily over time, but could be restricted in order to emulate common dynamic patterns. Simple examples include state as a basic knowledge resource (linear history without caching), a key-value map with values that are basic knowledge resources (branching history without caching), or a sequence of basic knowledge resources (linear cached history).

4 Proof-of-Concept

An RDF stream from a biomedical device can be modelled using a Stream monad (also called Observable). A query registered against this RDF Stream will generate another Stream, with each item containing additions (if any) to the query result due to the assertion of the newly-arrived graph. Because RDF has monotonic semantics, the accumulated query results will always be equivalent to the result of the query applied to the accumulated graphs of the stream. Cumulative queries and other cumulative operations on Streams may be implemented through *fold* operations, while windowing and filtering are implemented through *map*.

The connected-patient system uses a heterogeneous language environment to map input XMPP data from biomedical devices into a KRR language, e.g. RDF, employing terms from a vocabulary defined in a common ontology. Thus streaming data may be transformed into streaming knowledge which is queryable as discussed in the previous item. The structure of this system may be modelled as a SetTree of Streams, since each device streams its output asynchronously.

State, Task and IO monads are appropriate to the use case of an active knowledge base where evaluation of an operation leads to side-effects; the choice of monad depends on the nature of the side-effects and the implementation. Equivalence of such knowledge resources requires not only the same entailments, but also side-effects that are equivalent. The CDS monitoring our connected patient may be modelled using a State monad, where the sending of a message is a side-effect.

The connected patient's case history may be modelled as a mutable knowledge asset because of the possibility of correction of the history without a change of case identifier. The modular nature of medical records is amenable to SetTree (a set of laboratory test results) or ListTree (a procedure performed) structures. Although some aspects, such as the addition of new medical orders, would fit with the Stream structure, queries of the case history are not expected to produce streaming results, and so the mutable asset model is a better fit than a Stream-based model.

Failure recovery in the CDS alert system may be modelled using the Try monad, so that results can be reported as Success or Failure. A Success response is a wrapper around a result from the successful execution of a request. A Failure response includes information about the nature of the failure (e.g. timeout exception) so that the system can recover appropriately, e.g. by escalating to another recipient.

A possible extension of the CDS which allows a streaming model in combination with explicit state management and concurrency follows an implementation [9] that was demonstrated for sports competitions using the Prova rule engine [14].

The monad laws have been verified experimentally for SetTree and ListTree monads by implementation in Java8 together with the Functional Java [3] li-

baries, with the source available on Github⁹. Informal tests confirm that the map and join operations are linear in the size of the collection, as expected.

5 Related Work and Discussion

The API4KP metamodel introduces the following generalizations of DOL concepts:

- Knowledge sources can have different levels of abstraction. DOL’s OMS concept correspond to knowledge expressions, while we consider also the levels of asset, manifestation and item.
- Knowledge sources can be mutable or immutable. DOL’s OMS correspond to immutable knowledge expressions.
- Each API4KP knowledge asset is conceptualized according to a customizable environment, instead of assuming a single logical environment in which all OMS are interpreted.
- Environment members can be any language with an abstract syntax, instead of requiring each member to have a specific semantics. Only the focus of the environment is required to have its own semantics.
- Semantics is generalized to include side-effects as well as logical entailment.
- Structured knowledge resources may have structures other than nested sets.

The variety of monad structures necessary to model the diversity of usecases demonstrates that a high level of abstraction is needed to define operations for modifying knowledge resources - adding, subtracting or modifying. Category theory provides the tools for these abstractions, through applicative functors (a generalization of monads having a binary operator allowing a structure of functions to be applied to another structure), catamorphisms (generalization of aggregation over a list to other monads) and anamorphisms (e.g. generation of a list from a seed and recursion formula).

6 Conclusion and Future Work

The primary contributions of this paper are two-fold:

- a metamodel of heterogeneous knowledge sources, environments, operations and events, providing an abstract syntax for interaction with the Knowledge Platforms at the core of KDAs
- a monadic tree structure derived from other monads, as the conceptual basis of structured knowledge resources, providing a framework that supports modularity, state management, concurrency and exception handling

We have provided a proof-of-concept of this conceptual framework by application to a usecase from healthcare, identification of implementations employing this approach, as well as mathematical proofs of the monadic character and prototypical implementations of the tree structures.

Future work on API4KP may include:

⁹ <https://github.com/ag-csw/Java4CL>

- generalization of approach to include structures based on applicative functors, and operations in terms of catamorphisms and anamorphisms
- population of the ontology with specifications of additional operations, especially querying and life-cycle management

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