

# Forest: A Language and Toolkit For Programming with Filestores

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## Abstract

Many applications use the file system as a simple persistent data store. This approach is expedient, but not robust. The correctness of such an application depends on the collection of files, directories, and symbolic links having a precise organization. Furthermore these components must have acceptable values for a variety of file system attributes such as ownership, permissions, and timestamps. Unfortunately, current programming languages do not support documenting assumptions about the file system. In addition, actually loading data from disk requires writing tedious boilerplate code.

This paper describes Forest, a new domain-specific language embedded in Haskell for describing directory structures. Forest descriptions use a type-based metaphor to specify portions of the file system in a simple, declarative manner. Forest makes it easy to connect data on disk to an isomorphic representation in memory that can be manipulated by programmers as if it were any other data structure in their program. Forest generates metadata that describes to what degree the files on disk conform to the specification, making error detection easy. As a result, the system greatly lowers the divide between on-disk and in-memory representations of data. Forest leverages Haskell's powerful generic programming infrastructure to make it easy for third-party developers to build tools that work for any Forest description. We illustrate the use of this infrastructure to build a number of useful tools, including a visualizer, permission checker, and description-specific replacements for a number of standard shell tools. Forest has a formal semantics based on classical tree logics.

## 1. Introduction

Databases are an effective, time-tested technology for storing structured and semi-structured data. Nevertheless, many computer users eschew the benefits of structured databases and store important semi-structured information in collections of conventional files scattered across a conventional file system instead. For example, the Princeton Computer Science Department stores records of undergraduate student grades in a structured set of directories and uses scripts to compute averages and study grading trends. Similarly, Michael Freedman collects sets of log files from CoralCDN, a distributed content distribution network [5, 6]. The logs are organized in hierarchical directory structures based on machine name, time and date. Freedman mines the logs for information on system security, health and performance. At Harvard, Vinodhan Manoharan, a physics professor, stores his experimental data in sets of files and extracts information using python scripts. At AT&T, vast structured repositories contain networking information, phone call detail and billing data. And there are many other examples across the computational sciences and social sciences, in computer systems research, in computer systems administration, and in industry.

Users choose to implement ad hoc databases in this manner for a number of reasons. A key factor is that using databases often requires paying substantial up-front costs such as: (1) finding and evaluating the appropriate database software (and possibly paying

for it); (2) learning how to load data into the database; (3) possibly writing programs that transform raw data so it may be loaded; (4) learning how to access the data once it is in the database; and (5) interfacing the database with a conventional programming language to support applications that use the data. Finally, it may be the case that the database optimizes for a pattern of use not suited to the actual application, which makes paying the overhead of the database system even less desirable.

Rather than paying these costs, programmers often store data in the file system, using a combination of directory structure, file names and file contents to organize the data. We will call such a representation of a coherent set of data a *filestore*. The “query language” for a filestore is often a shell script or conventional programming language.

Unfortunately, the informality of filestores can have negative consequences. First, there is generally no documentation, which means it can be hard to understand the data and its organization. New users struggle to learn the structure, and if the system administrator leaves, knowledge of the data organization may be lost. Second, the structure of the filestore tends to evolve: new elements are added and old formats are changed, sometimes accidentally. Such evolution can cause hacked-up data processing tools to break or return erroneous results; it also further complicates understanding the data. Third, there is often no systematic means for detecting data errors even though data errors can be immensely important. For example, for filestores containing monitoring information, errors can signal that some portion of the monitored system is broken. Fourth, analyses tend to be built from scratch. There is no auxiliary query or tool support and no help with debugging. Tools tend to be “one-off” efforts that are not reuseable. Fifth, dealing with large data sets, which are common in this setting, imposes extra difficulties. For example, standard tools such as `ls` fail when more than 256 files appear on the command line. Hence, programmers must break up their data and process it in smaller sets, a tedious task.

In this paper, we propose a better way: A novel type-based specification language, programming environment and toolkit for managing filestores. This language, called Forest, is an embedded domain-specific language in Haskell. Forest allows programmers to describe the expected shape of a filestore and to lazily materialize it as format-specific Haskell data structures with the goal of making programming with filestores as easy and robust as programming with any other Haskell data structure. Furthermore, Forest leverages Haskell's support for generic programming to make it easy to define tools that work for any filestore with a Forest description.

Forest descriptions provide *executable documentation* that can be used to check whether a given filestore conforms to its specification. For example, Unix file systems should be laid out as described by the Filesystem Hierarchy Standard Group in an informal standards document [2]. In addition, the standard requires that certain directories contain *only* the specified files, presumably for security reasons. Forest provides a language for writing such standards precisely and a checker that allows users to verify that their installation conforms to the standard. As another example, the Pads

website [16] contains a complex set of scripts and data files to implement an online demo. Unless all of the required data files, directories, and symbolic links are configured correctly, the web demo fails with an inscrutable error message. Forest allows the Pads webmaster to precisely document all of these requirements and to detect specification violations, making it easy to find and repair errors.

In exchange for writing a Forest specification, programmers obtain a number of benefits. These benefits include (1) a set of type declarations to represent the filestore in memory, (2) a set of type declarations that capture errors and file system attributes for the filestore, (3) a loading function to populate these in-memory structures, and (4) type class instance declarations that make it possible for programmers to query, analyze, and transform filestore data using generic functions.

To illustrate the power of the generic programming infrastructure and to increase the value of writing a Forest specification, we built a number of tools that work for any filestore with a Forest specification. These tools include a filestore visualizer, a permission checker, and filestore-specific versions of standard command-line tools such as `grep` and `tar`. Using this same infrastructure, we built a tool to infer a Forest specification for the directory structure starting at a given path, which means programmers do not have to start from scratch when writing a specification for their filestores.

In summary, this paper makes the following contributions.

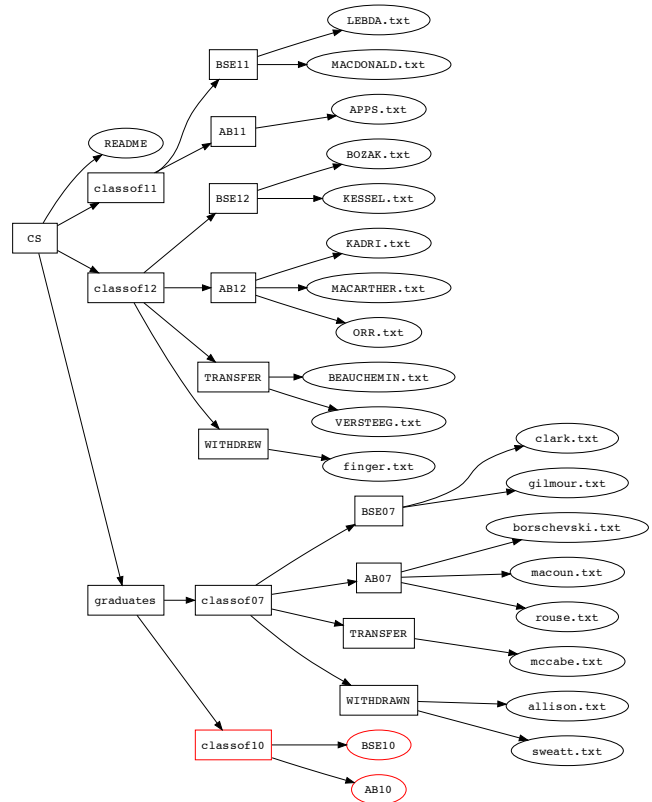
- **Conceptual:** We propose the *idea* of extending a modern programming language with *tightly integrated linguistic features for describing filestores* and for automatically generating programming infrastructure from such descriptions.
- **Language Design:** We present the design of Forest and illustrate its use on real-world examples. The design is expressive, concise and smoothly integrated into Haskell. It is supported by a formal semantics inspired by classical tree logics.
- **Tool Generation:** We describe how third-party developers can use Haskell’s generic programming infrastructure to generate filestore-specific tools generically.
- **Case Study in Domain-Specific Language Design:** Forest is fully implemented and its design serves as a case study in extensive, practical, domain-specific language design in modern languages by combining a number of experimental features of Haskell such as quasi-quoting and Template Haskell. Moreover, our Forest design and implementation experience has had practical impact on the Haskell implementation itself: the Haskell team modified and extended Template Haskell and the quasi-quoting mechanism in response to our needs. These modifications are available in the most recent release of Haskell.

## 2. Example Filestores

In this section, we present two example filestores. We will use these examples to motivate and explain the design of Forest.

The first filestore contains information about students in Princeton’s undergraduate computer science program. The faculty use the information in the filestore to decide on undergraduate awards and to track grading trends. As it has evolved over time, there have been a few slight changes in format – typical for ad hoc filestores. Naturally, any description needs to cope with the variation.

Figure 1 shows a snippet of the (anonymized) student filestore designed to illustrate its structure. At the top level, there are three directories: `classof11` (seniors), `classof12` (juniors) and `graduates` (students who have graduated). There is also a `README` file containing a collection of notes. Inside `graduates`, there is set of directories named `classofYY` where `YY` dates back to 92. Inside each `classofYY` directory, there are at least the two degree subdirectories `ABYY` and `BSEYY` as the computer sci-



**Figure 1.** Anonymized snippet of Princeton computer science undergraduate data. Red notes denotes an error—i.e., missing files.

ence department gives out both Arts and Science and Engineering degrees. Optionally, there are also subdirectories for students who withdrew from Princeton or transferred to another program. Within any degree subdirectory, there is one text file per student that records the courses taken and the corresponding grades. Each such directory can also contain a template file named `sss.txt` (or something similar) for creating new students.

The second filestore contains log files for CoralCDN [5, 6]. To monitor the performance, health, and security of the system, the hosts participating in CoralCDN periodically send usage statistics back to a central server. These statistics are collected in a filestore with a top-level `logs` directory containing a set of subdirectories, one for each host. Each such host directory contains another set of directories, labeled by date and time. Finally, each of these directories contains one or more compressed log files. For the purposes of this example, we will focus on the `coralwebserv.log.gz` log file, which contains detailed information about the web requests made on the host during the preceding time period.

## 3. Forest Design

Forest is a domain-specific language embedded within Haskell using the Quasiquote mechanism [14]. In a typical Forest description, Forest declarations are interleaved with ordinary Haskell declarations. To introduce new Forest declarations, the programmer simply opens the Forest sublanguage scope:

```
[forest| ... forest declarations ... ]
```

Forest uses a type-based metaphor to describe directory structures, so once within the Forest sublanguage, the programmer writes declarations that look and feel very much like extended

```

data Forest_md = Forest_md
  { numErrors :: Int
  , errorMsg  :: Maybe ErrMsg
  , fileInfo  :: FileInfo
  }

data FileInfo = FileInfo
  { fullpath   :: FilePath
  , owner      :: String
  , group      :: String
  , size       :: COff
  , access_time :: EpochTime
  , mod_time   :: EpochTime
  , read_time  :: EpochTime
  , mode       :: FileMode
  , isSymLink  :: Bool
  , kind       :: FileType
  }

```

**Figure 2.** Forest metadata types.

Haskell type declarations. Each such type declaration serves three purposes: (1) it describes a fragment of the file system, (2) it specifies the structure of the in-memory *representation* that will be constructed when the fragment is (lazily) loaded into a Haskell program, and (3) it specifies the structure of the in-memory *metadata* that will be generated when the fragment loaded. Such metadata includes error information (missing file, insufficient permissions, *etc.*) as well as file system attributes (owner, size, *etc.*). As we explain the design of Forest, readers should keep these three different aspects in mind. The effectiveness of the Forest language comes in part from the fact that these three elements can all be specified in a single compact description.

Every Forest description is defined relative to a *current path* within the file system. As Forest matches a description against the file system, it adjusts the current path to reflect its navigation.

At its core, Forest is a simple dependent type system in which base types denote files of various flavors and record types describe directories. Forest also includes a list type to describe collections of files that all share some type. We use a variety of other type constructors to build more refined structures from these basic building blocks. We discuss each of these constructs in turn in the remainder of this section. A note on terminology: we use the term “file system object” or more simply “object” to denote either a file, or a directory, or a symbolic link.

### 3.1 Files

Forest provides a small collection of base types for describing files: `Text` for ASCII files, `Binary` for binary files, and `Any` for arbitrary files. As with all Forest types, each of these types specifies a representation type, a metadata type, and a loading function. The in-memory representation for an ASCII file is a Haskell `String`; for binary and arbitrary files, it is a `ByteString`. For all three file types, the metadata type pairs file-system metadata with metadata describing properties of the file contents. The file-system metadata has type `Forest_md`, shown in Figure 2. This structure stores two kinds of information: (1) the number and kind of any errors that occurred while loading the file and (2) the attributes associated with the file. File-content metadata typically describes errors within the file, but can be used for other purposes. For these three file types, there is no meaningful content metadata and so this type is the unit type. Leveraging Haskell’s laziness, the loading functions create the in-memory representations and set the metadata on demand.

Of course, there are many kinds of files, and the appropriate representation and content metadata type for each such file varies. Possible examples include XML documents, Makefiles, source files

in various languages, shell scripts, *etc.* To support such files, Forest provides a plug-in architecture, allowing third party users to define new file base types by specifying a representation type, a metadata type, and a corresponding loading function.

A common class of files are *ad hoc data files* containing semi-structured information, an example of which is the Princeton student record file format. In such cases, Forest can leverage the Pads/Haskell data description language to define format-specific in-memory representations, content metadata, and loading functions. Pads/Haskell is a recently developed version of Pads [3, 4, 15]. Like Forest, Pads/Haskell is embedded in Haskell using quasiquotation. For example, the following code snippet begins the Pads specification of the Princeton student record format:

```

[ pads |
  data Student (name :: String) = < pads decl >
]

```

This description is parameterized by the name of the student whose data is in the file; the complete description appears in the appendix. From this specification, the Pads compiler generates an in-memory representation type `Student`, a content metadata type `Student_md`, and a parsing function.

Forest provides the `File` type constructor to lift Pads types to Forest file types. For example, the declaration

```

[ forest |
  type SFile (n :: String) = File (Student n)
]

```

introduces a new file type named `SFile` whose format is given by the Pads type `Student`. As with the Pads type, `SFile` is parameterized by the name of the student.

Using Pads/Haskell descriptions in Forest not only helps specify the structure of ad hoc data files, but it also generates a structured in-memory representation of the data, allowing Haskell programmers to traverse, query and otherwise manipulate such data. Indeed, Pads/Haskell and Forest were designed to work seamlessly together. From the perspective of the Haskell programmer traversing a resulting in-memory data structure, there is effectively no difference between iterating over files in a directory or structured sequences of lines or tokens within a file.

While Pads/Haskell is independently interesting, the rest of this paper focuses on Forest. Henceforth, any unadorned declarations occur within the Forest scope `[ forest | . . . ]` unless otherwise noted. Any declarations prefixed by `>` are ordinary Haskell declarations.

### 3.2 Optional Files

Sometimes, a given file (or directory or symbolic link) may or may not be present in the file system, and either situation is valid. Forest provides the `Maybe` type constructor for this situation. If `T` is a Forest type, then `Maybe T` is the Forest type denoting an optional `T`. In particular, `Maybe T` succeeds and returns representation `None` when the current path does not exist in the file system. `Maybe T` also succeeds and returns `Just v` for some `v` of type `T` when the current path exists and matches `T`. `Maybe T` registers an error in the metadata when the current path exists but the corresponding object does not match `T`.

### 3.3 Symbolic Links

When symbolic links occur in a described file system fragment, Forest follows the symbolic link to its target, mimicking standard shell behavior. In addition, however, it is possible for programmers to specify explicitly that a particular file is a symbolic link using the base type `SymLink`. The in-memory representation for an explicit symbolic link is the path that is the target of the link. It is possible

to use constraints (Section 3.6) to specify desired properties of the link target, such as requiring it to be to a specific file.

In Forest, any file system object may be described in multiple ways. Hence, in the case of a symbolic link, it is possible to use one declaration to specify that the object is a symbolic link and a second to specify the type of the link target. We will see such a specification in the next subsection.

### 3.4 Directories

Forest directories are record-like datatype constructors that allow users to specify directory structures. For example, to specify the root directory of the student repository in Figure 1, we might use the following declaration. This declaration assumes that we have already defined `Class y`, a parameterized description that specifies the structure of a directory holding data for the class of year `y`, and `Grads`, a description that specifies the structure of the directory holding all graduated classes.

```
type PrincetonCS_1 = Directory
  { notes   is "README"   :: Text
  , seniors is "classof11" :: Class 11
  , juniors is "classof12" :: Class 12
  , grads   is "graduates" :: Grads
  }
```

Each field of the record describes a single file system object. It has three components: (1) an internal name (e.g., `notes` or `seniors`) that must be a valid Haskell record label, (2) an external name specified as a value of type `String` (e.g., "README" or "classof11") that gives the name of the object on disk, and (3) a Forest description of the object (e.g., `Text` or `Class 11`).

When the external name is itself a valid Haskell label, users may omit it, in which case Forest uses the label as the on-disk name:

```
type PrincetonCS_2 = Directory
  { notes   is "README"   :: Text
  , classof11 :: Class 11
  , classof12 :: Class 12
  , graduates :: Grads
  }
```

We could not abbreviate the `notes` field because labels must start with a lowercase letter in Haskell.

**Matching.** For a file system object to match a directory description, the object must be a directory and each field of the record must match. A field `f` matches when the object whose path is the concatenation of the current path and the external name of `f` matches the type of `f`.

It is possible for the same file system object to match multiple fields in a directory description at the same time. For example, if "README" were actually a symbolic link, it is possible to document that fact by mentioning it twice in the directory description, once as a text file and once as a symbolic link:

```
type PrincetonCS_3 = Directory
  { link   is "README"   :: SymLink
  , notes is "README"   :: Text
  , ...   }
```

It is also possible for a directory to contain objects that are unmatched by a description. We allow extra items because it is common for directories to contain objects that users do not care about. For example, a directory structure may contain extra files or directories related to a version control system, and a description writer may not want to clutter the Forest specification with that information. As we will see shortly, it is possible to specify the absence of file system objects using constraints.

As suggested by the syntax, the in-memory representation of a directory is a Haskell record with the corresponding labels. The

type of each field is the representation type of the Forest type for the field. The metadata has a similar structure. The metadata for each field has two components: file-system attribute information of type `Forest_md` and field-specific metadata whose type is derived from the Forest type for the field. In addition, the directory metadata contains an additional value of type `Forest_md` that summarizes the errors occurring in directory components and stores the `FileInfo` structure for the directory itself. When loading a directory, Forest constructs the appropriate in-memory representation for each field that matches and puts the corresponding metadata in the metadata structure. For fields that do not match, Forest constructs default values and marks the metadata with suitable error information.

**Computed Paths** The above descriptions are a good start for our application, but neither is ideal. Every year, the directory for graduating seniors (i.e., `classof11`) is moved into the graduates directory, the juniors are promoted to seniors and a new junior class is created. As it stands, we would have to edit the description every year. An alternative is to parameterize the description with the current year and to *construct* the appropriate file names using Haskell functions:

```
> toStrN i n = (replicate(n - length(show i)) '0')
              ++ (show i)
> mkClass y = "classof" ++ (toStrN y 2)
```

```
type PrincetonCS (y::Integer) = Directory
  { notes   is "README"   :: Text
  , seniors is <|mkClass y |> :: Class y
  , juniors is <|mkClass (y+1)|> :: Class <|y+1|>
  , graduates :: Grads
  }
```

The bracket syntax `<|...|>` provides an escape so that we may use Haskell within Forest code to specify arbitrary computations. This example also illustrates abstraction: any Forest declaration may be parameterized by specifying a legal Haskell expression identifier and its type. The types of the fields for `seniors` and `juniors` illustrate the use of parameterized descriptions. When an argument is a constant or variable, it may be supplied directly. When an argument is more complex, however, it must be written in brackets to escape to Haskell.

**Approximate Paths** As filestores evolve, naming conventions may change. Additionally, directory structures with multiple instances may have minor variations in the names of individual files across instances. For example, in each Princeton class directory, there may (or may not) be some number of students that have withdrawn from the program, transferred to a different program, or gone on leave. Over the years, slightly different directory names have been used to represent these situations.

To accommodate this variation, Forest includes the matching construct to approximate file names. We can use this mechanism to describe the class directory:

```
> transRE = RE "TRANSFER|Transfer"
> leaveRE = RE "LEAVE|Leave"
> wdRE    = RE "WITHDRAWN|WITHDRAWAL|Withdrawn"
```

```
type Class (y::Integer) = Directory
  { bse is <|"BSE" ++ (toString y)|> :: Major
  , ab  is <|"AB"  ++ (toString y)|> :: Major
  , trans matches transRE :: Maybe Major
  , withd matches wdRE    :: Maybe Major
  , leave matches leaveRE :: Maybe Major
  }
```

A field with the form `<label> matches <regex> :: T` finds the set of paths in the files system that match `currentPath/`

<regex>. If there are zero or one such files, the matches form acts just as the is form. If more than one file matches, one of the matches is selected non-deterministically, a multiple match error is registered in the metadata, and matching continues as it would with the is form. In addition to regular expressions, the matching construct also allows *glob patterns*, (i.e., patterns such as \*.txt), to specify the names of files on disk.

### 3.5 List Comprehensions

Record directories allow programmers to specify a fixed number of file system objects, each with its own type. List comprehensions, on the other hand, allow programmers to specify an arbitrary number of file system objects, each with the same type. As an example, we can use a list comprehension to specify the Grads directory from Figure 1:

```
> getYear s =
>   toInteger (reverse (take 2 (reverse s)))
> cRE = RE "classof[0-9][0-9]"

type Grads =
  [c :: Class <|getYear c|> | c <- matches cRE]
```

In this specification, Grads is a directory fragment containing a number of Class subdirectories with names c that match the regular expression cRE. The Haskell function getYear extracts the last two digits from the name of the directory, converts the string digits to an integer year, and passes the year to the underlying Class specification. More generally, comprehensions have the following form.

```
[path :: T | id <- gen, pred]
```

Here, id is bound in turn to each of the file names generated by gen, which may be a matches clause (used to match against the files at the current path as in the previous section) or a list computed in Haskell. These generated ids are filtered by the optional predicate pred. For each such legal id, there is a corresponding expression path, which Forest interprets as extending the current path. The object at each such path should have the Forest type T. The identifier id is in scope in pred, path, and T.

The in-memory representation of a comprehension is a list containing pairs of the name of a matching object and its representation. The metadata is a list of the metadata of the matching objects paired with a summary metadata structure of type Forest\_md.

**Representation Transformations** Although the list representation for comprehensions is useful, it can be desirable to use a more sophisticated data structure to represent such collections. To support this usage, Forest allows programmers to prefix a list comprehension with any type constructor that belongs to a container type class that supports operations to convert between the list representation and the desired container representation.

As an example, consider the specification of the Major directory. Each such directory contains a list of student files and an additional template file named either sss.txt or sxx.txt. The declaration below specifies the collection of student files by matching with a glob pattern and filtering to exclude template files. It uses the Map type constructor to specify that the data and metadata should be collected in a Map rather than a list.

```
> template s = s `elem` ["sss.txt", "sxx.txt"]
> txt = GL "*.txt"

type Major = Map
  [ s :: File (Student <|dropExtension s|>)
  | s <- matches txt, <|not (template s)|>]
```

```
[forest|
data PrincetonCS (y::Integer) = Directory
  { notes is "README" :: Text
  , seniors is <|mkClass y |> :: Class y
  , juniors is <|mkClass (y+1)|> :: Class <|y+1|>
  , graduates :: Grads
  }

data Class (y::Integer) = Directory
  { bse is <|"BSE" ++ (toString y)|> :: Major
  , ab is <|"AB" ++ (toString y)|> :: Major
  , trans matches transRE :: Maybe Major
  , withd matches wdRE :: Maybe Major
  , leave matches leaveRE :: Maybe Major
  }

type Grads =
  [c :: Class <|getYear c|> | c <- matches cRE]

type Major = Map
  [ s :: File (Student <|dropExtension s|>)
  | s <- matches txt, <|not (template s)|>]
|]
```

**Figure 3.** Forest description of Princeton filestore. (Associated Haskell and Pads code appears in the appendix.)

### 3.6 Attributes and Constraints

Every file system object has a number of attributes associated with it, such as the file owner and size. In general, if a Forest identifier id refers to a path, the attributes for the object at that path are available through the identifier id\_att, which has type Forest\_md (Figure 2). Forest defines accessor functions such as get\_modes (get permissions), get\_kind (get ascii/binary/directory characteristics) and others to inspect these attributes.

*Constrained types* make use of attributes. For example, the type PrivateText specifies a text file accessible only by its owner.

```
type PrivateFile =
  Text where <|get_modes this_att == "-rw-----"|>
```

The keyword **where** introduces a constraint on the underlying type. If a constraint is false, an error is registered in the metadata. Within the constraint, this refers to the representation of the underlying object, this\_att refers to its attributes and this\_md to its complete metadata.

Using attributes, we can write a *universal directory description*, which is sufficiently general to describe any directory:

```
type Universal = Directory
  { asc is [ f :: Text
           | f <- matches (GL "*"),
           <| get_kind f_att == AsciiK |> ]
  , bin is [ b :: Binary
           | b <- matches (GL "*"),
           <| get_kind b_att == BinaryK |> ]
  , dir is [ d :: Universal
           | d <- matches (GL "*"),
           <| get_kind d_att == DirectoryK |> ]
  , sym is [ s :: SymLink
           | s <- matches (GL "*"),
           <| get_sym s_att == True |> ]
  }
```

The description requires recursion to describe the directory case, which Forest supports. In the case that a symbolic link creates a cycle in the file system by pointing to a parent directory, the Haskell in-memory representation is a (lazy) infinite data structure.

We can also use constraints to specify that certain files do not appear in certain places. As an example, we might want to require

```
[forest]
data Log = Directory
  { log is coralwebsrv :: Gzip (File CoralLog) }
type Site = [ d :: Log | d <- matches time ]
type Coral = [ s :: Site | s <- matches site ]
]
```

**Figure 4.** Forest CoralCDN description. Associated Haskell and Pads code appears in the appendix.

Load Functions:

```
log_load    :: FilePath -> IO (Log, Log_md),
site_load   :: FilePath -> IO (Site, Site_md)
coral_load  :: FilePath -> IO (Top, Top_md),
```

Representation Types:

```
data Log    = Log    {log :: CoralLog}
newtype Site = Site [(String, Log)]
newtype Coral = Coral [(String, Site)]
```

Metadata Types:

```
data Log_inner_md =
  Log_inner_md {log_md :: (Forest_md, CoralLog_md)}
type Log_md       = (Forest_md, Log_inner_md)
type Site_md      = (Forest_md, [(String, Log_md)])
type Coral_md     = (Forest_md, [(String, Site_md)])
```

**Figure 5.** Coral load functions, representation and metadata types

that no binaries appear in a directory given to an untrusted user as scratch space. The description below flags an error if a binary file exists in the directory.

```
type NoBin =
  [ b :: Binary | b <- matches (GL "+"),
    <| get_kind b_att == BinaryK |> ]
where <|length this == 0|>
```

### 3.7 Gzip and Tar Type Constructors

Some files need to be processed before they can be used. A typical example is a compressed file such as the gzipped log files in CoralCDN. Forest provides processing-specific type constructors to describe such files. For example, if `CoralInfo` is a Pads/Haskell description of a CoralCDN log file then

```
type CoralLog = Gzip (File CoralInfo)
```

describes a gzipped log file. Likewise, suppose `logs.tar.gz` is a gzipped tar file and that the type `Coral` describes the directory of log files that `logs.tar` expands to when untarred. Such a situation can be described using a combination of the `Tar` and `Gzip` type constructors:

```
type Coral = Gzip (Tar Coral)
```

### 3.8 Putting it all together

The previous subsections give an overview of the Forest design. Figures 3 and 4 show Forest specifications for our two running examples, minus the associated Pads/Haskell and Haskell declarations. The complete descriptions of these filestores and additional descriptions are available in the appendix, including descriptions of the Pads website, a Gene Ontology filestore, and the CVS repository structure.

## 4. Programming with Forest

Most Forest programs work in two phases. In the first phase they use Forest to load relevant portions of the file system into memory, and in the second phase they use an ordinary Haskell function to traverse the in-memory representation of the data (or its associated metadata) and compute the desired result.

To facilitate this style of programming, the Forest compiler generates several Haskell functions and types from every Forest description. It generates a *load function*, which traverses the file system and reads the files, directories, and symbolic links mentioned in the description into a structured object in memory; it generates a Haskell type for the in-memory *representation* of the data produced by the load function; and it generates a Haskell type for the *metadata* associated with the representation. For example, from the descriptions for CoralCDN logs in Figure 4, the compiler generates the load functions, the representation types, and the metadata types presented in Figure 5. Note that the structure of each of these artifacts mirrors the structure of the Forest description that generated them. This close correspondence makes it easy for programmers to write programs using these Forest-generated artifacts.

As a simple example, consider the `Coral` description in Figure 4. The `coral_load` function takes a path as an argument and produces the representation and metadata obtained by loading each of the site directories contained in the directory at that path:

```
(rep,md) <- coral_load "/var/log/coral1"
```

Because `Coral` is a comprehension, both `rep` and `md` are lists. More specifically, `rep` has the form

```
Coral [ ("planetab2.eecs.wsu.edu", Site [...]),
        ("planetlab3.williams.edu", Site [...]), ... ]
```

where the list contains pairs of names of subdirectories and representations for the data loaded from those directories. The metadata is a pair consisting of a generic header of type `Forest_md` and a list of pairs of names of subdirectories and their associated metadata. The header records aggregate information about any errors encountered during loading as well as the file system attributes of each file, directory, or symbolic link loaded from the file system:

```
Forest_md
  { numErrors = 0,
    errorMsg = Nothing,
    fileInfo = FileInfo
      { fullpath = /var/log/coral,
        owner = alice, group = staff, size = 102,
        access_time = Fri Nov 19 01:47:09 2010,
        mod_time = Thu Nov 18 20:42:37 2010,
        read_time = Fri Nov 19 01:47:28 2010,
        mode = drwxr-xr-x, isSymLink = False,
        kind = Directory } },
  [ ("planetlab2.eecs.wsu.edu", Forest_md {...}),
    ("planetlab3.williams.edu", Forest_md {...}), ... ]
```

Using these functions and types, it is easy to formulate many useful queries as simple Haskell programs. For instance, to count the number of sites we can simply compute the length of the nested list in `rep`:

```
num_sites = case rep of Coral l -> List.length l
```

More interestingly, since the internals of the web log are specified using Pads/Haskell (see the appendix for details), it is straightforward to dig in to the file data and combine it with file metadata or attributes in queries. For example, to calculate the time when statistics were last reported for each site, we can zip the lists in `rep` and `md` together and project out the site name and the `mod_time` field from each element in the resulting list of pairs:

```

get_site = fst
get_mod (_, (f,_)) = mod_time . fileInfo $ f
sites_mod () =
  case (rep,md) of (Coral rs, (_,ms)) ->
    map (get_site *** get_mod) (zip rs ms)

```

These simple examples show how Forest blurs the distinction between data represented on disk and in memory. After writing a suitable Forest description, programmers can write programs that work on file system data as if it were in memory. Moreover, because Forest uses lazy I/O operations, many simple programs do not require constructing an explicit representation of the entire directory being loaded in memory—a good thing as the directory of CoralCDN logs contains approximately 1GB of data! Instead, the load functions only read the portions of the file system that are needed to compute the result—in this case, only the site directories and not the gzipped log files contained within them.

As a final example, consider a program that computes the top- $k$  requested URLs from all CoralCDN nodes by size. The CoralCDN administrators compute this statistic periodically to help monitor and tune the performance of the system [5]. We define the analogous function in Haskell using helper functions such as `get_sites` to project out components of `rep`:

```

topk k =
  take k $ sortBy descBytes $ toList $
    fromListWith (+)
      [ (get_url e, get_total e)
      | (site,sdir) <- get_sites rep,
        (datetime,ldir) <- get_dates sdir,
        e <- get_entries ldir,
        is_in e ]

```

Reading this program inside-out, we see that it first uses a list comprehension to iterate through `rep`, collecting the individual log entries in the `coralwebserv.log.gz` file for incoming requests and projecting out the URL requested and the total size of the request. It then sums the sizes of all requests for the same URL using the `fromListWith` function from the `Data.Map` module. Next, it sorts the entries in descending order. Finally, it returns the first  $k$  entries of the list as the final result.

Overall, the main take-away from this section is how the Forest-generated infrastructure and tight coupling to Haskell facilitates construction of remarkably terse queries over the combination of file contents, file attributes and directory structure. Exploratory data analysis in this new programming paradigm is light-weight, easy and highly effective.

## 5. Tools

Third-party developers can use generic programming [11] to generate tools that will work for any file system structure that has a Forest description. As a proof of concept, we have written a number of such tools, which we describe in this section.

### 5.1 Generic Querying

One simple application of generic programming is querying metadata to find files with a particular collection of attributes. The `findFiles` function

```

findFiles :: (ForestMD md) =>
  md -> (FileInfo -> Bool) -> [FilePath]

```

takes as input any Forest metadata value (*i.e.*, any value of type `md` where `md` belongs to the Forest metadata class `ForestMD`) and a predicate on `FileInfo` structures, and returns the list of all `FilePath`s anywhere in the input metadata whose associated `FileInfo` satisfies the predicate. For example, if `cs_md` is the metadata associated with the Princeton computer science department filestore, then the code

```

dirs = findFiles cs_md \(r::FileInfo) ->
      (kind r) == DirectoryK)
other = findFiles cs_md \(r::FileInfo) ->
      (owner r) /= "bwk")

```

binds `dirs` to the list of all directories in the data set and `other` to all the directories and files not owned by user "bwk".

To implement the `findFiles` function, we use the generic Haskell function `listify`:

```

findFiles md pred = map fullpath (listify pred md)

```

The return type of the polymorphic `listify` function is instantiated to match the argument type of its predicate argument. We map the `fullpath` function over the resulting list of `FileInfo` structures to return only the `FilePath`s.

### 5.2 File System Visualization

`ForestGraph` generates a graphical representation of any directory structure that matches a Forest specification. We generated the graph in Figure 1 using this tool. In the default configuration, `ForestGraph` uses boxes to denote directories and ovals to denote files. Borders of varying thickness distinguish between ASCII and binary files. Dashed node boundaries indicate symbolic links and red nodes flag errors.

The core functionality of `ForestGraph` lies in the Haskell function `mdToPDF`:

```

mdToPDF :: ForestMD md =>
  md -> FilePath -> IO (Maybe String)

```

The function takes as input any metadata value and a filepath that specifies where to put the generated PDF file. It optionally returns a string (`Maybe String`); if the option is present, the string contains an error message. The `IO` type constructor indicates that there can be side effects during the execution of the function. A use of this function to generate the graph for the Princeton computer science department filestore looks like:

```

do { (cs_rep,cs_md) <- CS_load "facadm"
      ; mdToPDF cs_md "Output/CS.pdf" }

```

Note that this code needs only the metadata to generate the graph; laziness means Forest will not load the representation in this case.

The related function `mdToPDFWithParams` takes an additional argument that allows the user to specify how to draw the nodes and edges in the output graph. Among other things, this parameter specifies how to map a value of type `Forest_md` into `GRAPHVIZ` [7, 8] attributes. By appropriately setting the parameter, a user can customize the formatting of each node according to its owner, group, or permissions, *etc.*, as well as specify global properties of the graph such as its orientation and size. `ForestGraph` uses the Haskell binding of the `GRAPHVIZ` library to layout and render the graphs, so all customizations provided by `GRAPHVIZ` are available.

The `listify` function is at the heart of the implementation of this tool; we use it to convert the input metadata to the list of `FileInfos` in the metadata. We then convert this list into a graph data structure suitable for use with the `GRAPHVIZ` library.

### 5.3 Permission Checker

The permission tool is designed to check the permissions on the files and directories in a Forest description on a multi-user machine. In particular, it enables one user to determine which files a second user can read, write, or execute. If the second user cannot access a file in a particular way, the tool also reports the names of the files and directories whose permissions have to change to allow the access. The tool is useful when trying to share files with a colleague. It helps the first user ensure that all the necessary permissions have

been set properly to allow the second user access. The key to the implementation of this tool is again applying the `listify` function to the metadata for the Forest description.

#### 5.4 Shell Tools

We have implemented analogs of many shell tools that work over a file system fragment defined by a Forest description:

```
ls      :: (ForestMD md) => md -> String -> IO String
grep    :: (ForestMD md) => md -> String -> IO String
tar     :: (ForestMD md) => md -> FilePath -> IO ()
cp      :: (ForestMD md) => md -> FilePath -> IO ()
```

All of these functions work by extracting the relevant file names from the argument metadata structure using `listify` and then calling out to a shell tool to do the work. For `ls`, the second argument gives the command-line arguments to pass to the shell version of `ls`, and the result is the resulting output. The implementation uses `xarg` to lift the restriction on the number of files that can be passed to `ls`. For `grep`, the second argument is the search string and result is the output of the shell version of `grep`. For `tar`, the second argument specifies the location for the resulting tarball. The implementation uses a file manifest to allow `tar` to work regardless of the number of files involved. The `cp` tool uses the `tar` tool to move the files mentioned in the metadata to the location specified by the second argument *while retaining the same directory structure*. The module that implements these tools is 80 lines of Haskell code.

#### 5.5 Description Inference Tool

This tool allows the user to generate a Forest description from the contents of the file system. The function

```
getDesc :: FilePath -> IO String
```

takes as an argument the path to the root of the directory structure to infer. It returns a string containing the generated representation. For example, below we show a fragment of the results when `getDesc` is invoked on the `classof11` directory:

```
data classof11 = Directory {
  aB11 is "AB11" :: aB11,
  bSE11 is "BSE11" :: bSE11,
  tTRANSFER is "TRANSFER" :: tTRANSFER,
  WITHDREW is "WITHDREW" :: WITHDREW
}
data tTRANSFER = Directory {
  BEAUCHEMINtxt is "BEAUCHEMIN.txt" :: File Ptext,
  VERSTEEGtxt is "VERSTEEG.txt" :: File Ptext
}
...
```

The description is not perfect: the label names are generated from the file name, for example. Nevertheless, the tool improves programmer productivity as it is easier for a programmer to edit a generated description than to start from scratch. Our first tool in this vein is simple; a more sophisticated variant would collapse records of files into comprehensions when a width limit was exceeded or other criteria were met. Another variant might collapse deeply nested directories into a universal directory description when a depth limit was exceeded. The `getDesc` function works by using the universal description to load the contents of the file system starting from the supplied path. It then walks over the resulting metadata to generate a Forest parse tree, which it then pretty prints.

## 6. Implementation

We have fully implemented the Forest language and anticipate making it publicly available within the next few months. Haskell

provides powerful language features and libraries that greatly facilitated the implementation of Forest. The most obvious of these features is the quasi-quoting [14] mechanism that we used to embed Forest into Haskell. This mechanism allowed us to enjoy the benefits of being an embedded domain-specific language without having to sacrifice the flexibility of defining our own syntax. To use quasi-quoting, we defined a Haskell value `forest` of type `QuasiQuoter` which specifies how to convert an input string representing a Forest declaration into the Template Haskell [17] data structures that represent the syntax of the corresponding collection of Haskell declarations. The quasi-quoting syntax `[forest| <input> |]` is legal anywhere the identifier `forest` is in scope. When the Haskell compiler processes this declaration, it first passes `<input>` as a string to the `forest` quasi-quoter, and then it compiles the resulting Template Haskell data structures as if the corresponding Haskell code had appeared in the input at the location of the quasi-quote. Early versions of quasi-quoting supported quoting only expression and pattern forms. Simon Peyton Jones extended the mechanism to permit declaration and type quasi-quoting partly to enable the Forest implementation. We used this same approach to implement Pads/Haskell, which we built concomitantly.

**Parsing.** We used the `parsec 3.1.0` parser combinator library [12] to implement the Forest parser. One key element of the Forest design is to allow arbitrary Haskell expressions in various places inside Forest descriptions. We did not want to reimplement the grammar for Haskell expressions, which is quite complicated. Instead, we structured the Forest grammar so we could always determine the extent of any embedded Haskell code. We then used the Haskell Source Extension package [9] to parse these fragments. The data structure that this library returns is unfortunately not the data structure that Template Haskell requires, so we used yet another library, the Haskell Source Meta package [10], that provides this translation.

**Type checking.** We would like to give users high-quality error messages if there are type errors in their Forest declarations. At the moment, typechecking occurs, but only after the Forest declarations have been expanded to the corresponding Haskell code. Although these error messages can be quite informative, it is sub-optimal to report errors in terms of generated code. Type checking the Forest source is complicated by the embedded fragments of Haskell. As with the syntax, we do not want to reimplement the Haskell type-checker! There is an active proposal [19] to extend the Template Haskell infrastructure with functions that would enable us to ask the native Haskell typechecker for the types of embedded expressions and to extend the current type environment with type bindings for new identifiers. With this combination of features, we will be able to type check Forest sources directly.

## 7. A Core Calculus for Forest

We have defined an idealized core calculus that captures the essence of Forest. This calculus helped us to design various aspects of the language and provides a compact way of describing the central features of the language in a precise way. It is inspired by classical (*i.e.*, not separating, substructural or ambient) unordered tree logics, customized slightly to our application domain.

**File system model and specification syntax.** Figure 6 presents the formal file system model. File paths  $r$  are sequences of string names<sup>1</sup> and file systems  $F$  are finite partial maps from paths to

<sup>1</sup>For simplicity, we ignore the special path elements “.” and “..”. It is easy to add these features, although the semantics becomes more complicated because path expressions must be normalized.



Strings	$n \in \Sigma^*$
Paths	$r, s ::= \bullet \mid r/n$
Attributes	$\mathbf{a} ::= \dots$
Filesystem	$T ::= \text{File}(n)$
Contents	$\mid \text{Dir}(\{n_1, \dots, n_k\})$
	$\mid \text{Link}(r)$
Filesystems	$F ::= \{ \{ r_1 \mapsto (\mathbf{a}_1, T_1), \dots, r_k \mapsto (\mathbf{a}_k, T_k) \} \}$
Values	$v ::= \mathbf{a} \mid n \mid r \mid \text{True} \mid \text{False} \mid () \mid (v_1, v_2)$
	$\mid \text{Just}(v) \mid \text{Nothing} \mid \{v_1, \dots, v_k\}$
Expressions	$e ::= x \mid v \mid \dots$
Environments	$\mathcal{E} ::= \bullet \mid E, x \mapsto v$
Specifications	$s ::= k_{\tau_r}^{\tau_m} \mid \text{Adhoc}(b_{\tau_r}^{\tau_m}) \mid e :: s \mid \langle x:s_1, s_2 \rangle$
	$\mid \{s \mid x \in e\} \mid \text{Pred}(e) \mid s?$

**Figure 6.** File systems and their specifications

pairs of file attributes  $\mathbf{a}$  and file system contents  $T$ . We leave the attribute records abstract; they should include the usual fields: owner, group, date modified, *etc.* We write  $\mathbf{a}_{\text{default}}$  for a default attribute record where necessary. The contents  $T$  of a node in the file system may be a file  $\text{File}(n)$  (with underlying string contents  $n$ ), a directory  $\text{Dir}(\{n_1, \dots, n_k\})$  (with contents named  $n_1, \dots, n_k$ ) or a symbolic link  $\text{Link}(r)$  (where  $r$  is the path pointed to by the link).

A file system model  $F$  is *well-formed* if it is tree-shaped, with directories forming internal nodes and files and symbolic links at the leaves. In addition, these conditions must hold:

- The domain of  $F$  must be prefix-closed.
- If  $F(r) = (\mathbf{a}, \text{Dir}(\{n_1, \dots, n_k\}))$  then for  $i = 1, \dots, k$ ,  $r/n_i \in \text{dom}(F)$ .
- If  $F(r) = (\mathbf{a}, \text{File}(n_r))$  or  $(\mathbf{a}, \text{Link}(r'))$  then there does not exist  $n$  such that  $r/n \in \text{dom}(F)$ .

Figure 6 also presents the syntax of a simple computation language  $e$  and our file system specifications  $s$ . The computation language  $e$  contains values  $v$ , variables  $x$ , and other operators, which we leave unspecified. An environment  $\mathcal{E}$  maps variables to values. The semantic function  $\text{eval}_\tau(\mathcal{E}, F, r, e)$  evaluates an expression  $e$  in an environment  $\mathcal{E}$  and file system  $F$  with respect to a current path  $r$ , yielding a value  $v$  of type  $\tau$ .

The simplest file system specifications are constants  $k$ , which range over basic specifications such as those for files (F), text files (T), binary files (B), or any file system contents at all (A).

Pads/Haskell specifications are modeled as  $\text{Adhoc}(b_{\tau_r}^{\tau_m})$  where  $b_{\tau_r}^{\tau_m}$  is a parser—i.e., a total function from pairs of environments and strings to pairs of type  $\tau_r \times \tau_m$ , where the first element is the representation for the parsed data and the second element is its metadata.

Forest’s surface syntax combines specifications for records and paths into a single construct (and similarly for comprehensions and paths). The calculus models (dependent) records, paths, and comprehensions as independent, orthogonal constructs. Record specifications are written  $\langle x:s_1, s_2 \rangle$ , where  $x$  may appear in  $s_2$ . Path specifications are written  $e :: s$ , where  $e$  is a path name (to be appended to the current path) and  $s$  specifies a fragment of the file system at that path. Comprehension specifications are written  $\{s \mid x \in e\}$ , where  $e$  is a set of values,  $x$  is a variable, and  $s$ , which may depend on  $x$ , specifies a fragment of the file system for each value of  $x$ . Forest’s combined record-and-path construct  $\{c \text{ is } "c.txt" :: C, d \text{ is } "d.txt" :: D c\}$  is en-

$\mathcal{E}; F; r \models k_{\tau_r}^{\tau_m} \rightsquigarrow ck(k_{\tau_r}^{\tau_m}, F, r)$
$\frac{F(r) = (\mathbf{a}, \text{File}(n)) \quad b_{\tau_r}^{\tau_m}(E, n) = v, d}{\mathcal{E}; F; r \models \text{Adhoc}(b_{\tau_r}^{\tau_m}) \rightsquigarrow v, (\text{valid}(d), (d, \mathbf{a}))}$
$\frac{F(r) = (\mathbf{a}, T) \quad T \neq \text{File}(n) \quad b_{\tau_r}^{\tau_m}(E, \epsilon) = (v, d)}{\mathcal{E}; F; r \models \text{Adhoc}(b_{\tau_r}^{\tau_m}) \rightsquigarrow v, (\text{False}, (d, \mathbf{a}))}$
$\frac{r \notin \text{dom}(F) \quad b(E, \epsilon) = (v, d)}{\mathcal{E}; F; r \models \text{Adhoc}(b_{\tau_r}^{\tau_m}) \rightsquigarrow v, (\text{False}, (d, \mathbf{a}_{\text{default}}))}$
$\frac{\mathcal{E}; F; \text{eval}_{\text{path}}(E, F, r, r/e) \models s \rightsquigarrow v, d}{\mathcal{E}; F; r \models e :: s \rightsquigarrow v, d}$
$\frac{\mathcal{E}; F; r \models s_1 \rightsquigarrow v_1, d_1 \quad \mathcal{E}[x \mapsto v_1, x_d \mapsto d_1]; F; r \models s_2 \rightsquigarrow v_2, d_2}{\mathcal{E}; F; r \models \langle x:s_1, s_2 \rangle \rightsquigarrow (v_1, v_2), (\text{valid}(d_1) \wedge \text{valid}(d_2), (d_1, d_2))}$
$\frac{\text{eval}_{(\tau \text{ set})}(\mathcal{E}, F, r, e) = \{v_1, \dots, v_k\} \quad S = \{(v, d) \mid v' \in \{v_1, \dots, v_k\} \text{ and } \mathcal{E}[x \mapsto v']; F; r \models s \rightsquigarrow v, d\}}{\mathcal{E}; F; r \models \{s \mid x \in e\} \rightsquigarrow \pi_1 S, (\bigwedge \text{valid}(\pi_2 S), \pi_2 S)}$
$\frac{}{\mathcal{E}; F; r \models \text{Pred}(e) \rightsquigarrow (), (\text{eval}_{\text{bool}}(E, F, r, e), ())}$
$\frac{r \notin \text{dom}(F)}{\mathcal{E}; F; r \models s? \rightsquigarrow \text{Nothing}, (\text{False}, \text{Nothing})}$
$\frac{r \in \text{dom}(F) \quad \mathcal{E}; F; r \models s \rightsquigarrow v, d}{\mathcal{E}; F; r \models s? \rightsquigarrow \text{Just}(v), (\text{valid}(d), \text{Just}(d))}$

**Figure 7.** Forest calculus semantics

coded in the calculus as  $\langle x:("c.txt" :: C), ("d.txt" :: D x) \rangle$ . Similarly, Forest’s comprehension  $[x :: s \mid x <- e]$  is encoded as the composition of the calculus constructors  $\{s_1 \mid x \in e\}$  and  $s_1 = x :: s$ .

Predicate specifications  $\text{Pred}(e)$  succeed when  $e$  evaluates to True and fail when  $e$  evaluates to False under the current environment. A Forest constraint of the form  $s$  **where**  $e$  is encoded in the calculus as a dependent pair with a predicate:  $\langle x:s, \text{Pred}(e[x/\text{this}]) \rangle$

Finally, maybe specifications are written as  $s?$  in the calculus.

**Calculus Semantics.** The semantics of the calculus is organized into three separate definitions, one for each of the three artifacts generated by the Forest compiler. These definitions are spelled out in Figures 7 and 8.

The first semantic judgement has the form  $\mathcal{E}; F; r \models s \rightsquigarrow v, d$ . This judgement captures the behavior of the load function. Intuitively, it states that in environment  $\mathcal{E}$  and file system  $F$ , specification  $s$  matches the file system fragment at current path  $r$  and produces the representation  $v$  and metadata  $d$ . This judgement may also be viewed as a total function from  $\mathcal{E}, F, r$  and  $s$  to the pair  $v$  and  $d$ . The judgement is total because when file system fragments fail to match the given specification, defaults are generated for the representation  $v$  and errors are recorded in the metadata  $d$ . This design is preferable to failing as it allows a programmer to explore a file system fragment even when it contains errors, as is common in filestores.

$s$	$\mathcal{R}[s] =$	$\mathcal{M}[s] =$
$k_{\tau_r}^{\tau_m}$	$\tau_r$	$\tau_m \text{ } md$
$\text{Adhoc}(b_{\tau_r}^{\tau_m})$	$\tau_r$	$(\tau_m \times att) \text{ } md$
$e :: s$	$\mathcal{R}[s]$	$\mathcal{M}[s]$
$\langle x:s_1, s_2 \rangle$	$\mathcal{R}[s_1] \times \mathcal{R}[s_2]$	$(\mathcal{M}[s_1] \times \mathcal{M}[s_2]) \text{ } md$
$\{s \mid x \in e\}$	$\mathcal{R}[s] \text{ } list$	$(\mathcal{M}[s] \text{ } list) \text{ } md$
$\text{Pred}(e)$	$unit$	$unit \text{ } md$
$s?$	$\mathcal{R}[s] \text{ } option$	$(\mathcal{M}[s] \text{ } option) \text{ } md$

**Figure 8.** Forest calculus data and metadata types

The rule for constants depends upon an auxiliary function  $ck$  (pronounced “check”) that interprets the constants. For example, the  $ck$  function for the (F) construct, which describes any file (but not symbolic links or directories), is defined as follows:

$$\begin{aligned}
ck(\mathbf{F}_{string}^{att}, F, r) &= (n, (\text{True}, \mathbf{a})), \text{ if } F(r) = (\mathbf{a}, \text{File}(n)) \\
ck(\mathbf{F}_{string}^{att}, F, r) &= (" ", (\text{False}, \mathbf{a})), \text{ if } F(r) = (\mathbf{a}, T), T \neq \text{File}(n) \\
ck(\mathbf{F}_{string}^{att}, F, r) &= (" ", (\text{False}, \mathbf{a}_{\text{default}})), \text{ otherwise}
\end{aligned}$$

The rule for Pads/Haskell parsers, and several of the other rules, use the function  $valid(d)$ . This function extracts a boolean from the metadata structure  $d$ , returning True if there are no errors in the structure and False otherwise.

The second and third semantic judgements specify the representation and metadata types for a given specification. They have the form  $\mathcal{R}[s] = \tau$  and  $\mathcal{M}[s] = \tau$ , respectively. Note here that  $att$  is the type for file attribute records and the  $md$  type is defined as follows.

$$\begin{aligned}
\tau \text{ } md &= header \times \tau \\
header &= bool
\end{aligned}$$

The three sets of definitions obey the following basic coherence property, where  $\vdash v : \tau$  states that the value  $v$  has type  $\tau$ .

### Proposition 1

If  $\mathcal{E}; F; r \models s \rightsquigarrow v, d$  and  $\mathcal{R}[s] = \tau_{\mathcal{R}}$  and  $\mathcal{M}[s] = \tau_{\mathcal{M}}$  then  $\vdash v : \tau_{\mathcal{R}}$  and  $\vdash d : \tau_{\mathcal{M}}$

## 8. Related Work

The work in this paper builds upon ideas developed in the Pads project [3, 4]. Pads uses extended type declarations to describe the grammar of a document and simultaneously to generate types for parsed data and a suite of data-processing tools. The obvious difference between Pads (and other parser generators) and Forest is that Pads generates infrastructure for processing strings (the insides of a single file) whereas Forest generates infrastructure for processing entire file systems. Forest (and Pads/Haskell) is architecturally superior to previous versions of Pads in the tight integration with its host language and in its support for third-party generic programming and tool construction.

More generally, Forest shares high-level goals with other systems that seek to make data-oriented programming simpler and more productive. For example, Microsoft’s LINQ [13] extends the .NET languages to enable querying any data source that supports the `IEnumerable` interface using a simple, convenient syntax. LINQ differs in that it does not provide support for declaratively specifying the structure of, and then ingesting, filestores. *Type Providers* [18], an experimental feature of F#, help programmers materialize standard data sources equipped with predefined schema (such as XML documents or databases) in memory in an F# program. Type Providers and Forest descriptions are complementary language features. In fact, it may be possible to define a new F# Type Provider capable of interpreting Forest file system schema and

ingesting the described data, thereby making any Forest-described data available in F#.

In the databases community, a number of XML-based description languages have been defined for specifying file formats, file organization and file locations. One example of such a language is XFiles [1]. XFiles has many features in common with Forest. It can describe file locations, permissions, ownership and other attributes. It can also specify the name of an application capable of parsing the files in question. The main difference between a language like XFiles and Forest is that Forest is tightly integrated into a general-purpose, conventional programming language. Forest declarations generate types, functions and data structures that materialize the data within a surrounding Haskell program. XFiles does not inter-operate directly with conventional programming languages.

## 9. Conclusions

In this paper, we present the design of Forest, an embedded domain-specific language for describing filestores. A Forest description concisely specifies a collection of files, directories, and symbolic links as well as expected file system attributes such as owners and permissions. From a description, the Forest compiler generates code to lazily load the on-disk data into an isomorphic in-memory representation, lowering the divide between on-disk and in-memory data. Forest also generates type class instances that make it easy for third-party tool developers to use Haskell’s generic programming infrastructure. We have used this infrastructure ourselves to define a number of useful tools. In addition, the language has a formal semantics based on classical tree logics and is fully implemented. On the latter point, our work serves as an extensive case study in domain-specific language design, and, as such, has inspired changes in the design of Template Haskell. We anticipate releasing the source code for Forest shortly.

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## A. Appendix

This appendix contains contains Forest descriptions of a variety of different filestores. Please note that this appendix is best viewed electronically. Some of the graphs generated are very large, but shrunk down to fit on a single page. They will not display well when printed. However, reviewers may zoom in electronically on the PDF to view the details.

## B. Pads Web Site Description

This Forest description describes the Pads web site. The description starts with Pads descriptions of files that contain information that impacts the directory structure. The configuration file supplies the paths where various components of the website should be located. The SourceNames file lists the names of the data files available for the demo. Each user directory will have a subdirectory for each file listed in SourceNames. Each user is logged in the file UserEntries. For each user in this file, there is a directory with a corresponding name containing all of the information relevant to that user. A graph of the Pads website, generated using the ForestGraph tool follows the description.

```
[pads|
-- Configuration file for learning demo web site; contains paths to various web site components.
data Config_f = {
  header      :: [Pstringln] with term length of 13,
  "$host_name =", host_name  :: Config_entry_t,  --Name of machine hosting web site
  "$static_path =", static_path :: Config_entry_t, --URL prefix for static content
  "$cgi_path =", cgi_path  :: Config_entry_t,    --URL prefix for cgi content
  "$script_path =", script_path :: Config_entry_t, --Path to directory of scripts in live web site
  "$tmp_root =", tmp_root  :: Config_entry_t,    --Path to directory for demo user data
  "$pads_home =", pads_home  :: Config_entry_t,  --Path to directory containing pads system
  "$learn_home =", learn_home :: Config_entry_t, --Path to directory containing learning system
  "$sml_home =", sml_home   :: Config_entry_t,  --Path to directory containing SML executable
  "$install_src =", install_src :: Config_entry_t, --Path to directory containing learning demo website source
  "$static_dst =", static_dst :: Config_entry_t, --Path to directory for static content in live web site
  "$cgi_dst =", cgi_dst    :: Config_entry_t,   --Path to directory for cgi content in live web site site
  trailer     :: [Pstringln]
}

type Config_entry_t = Line (" \"", Pstring '\", "\";")
type Header_t = [Pstringln] with term length of 13

{- File listing data sources for web site -}
type SourceNames_f = [Pstringln]

{- Information related to a single user's use of the web site -}
type UserEntries_f = [Line UserEntry_t] with term Eor

{- Each visitor gets assigned a userId that is passed as a ? parameter in URL.
Security considerations preclude using user-modifiable values as part of file paths.
Thus, we map each userId to a corresponding dirId.
The dirId names the directory containing the associated user's data.
A userEntry_t contains a single such mapping.
A file with type userEntries_t describes a collection of such mappings.
-}
data UserEntry_t = {
  "id.",  usrId :: Pint,
  "id.",  dirId :: (Pint, '.', Pint)   where <| usrId == fst dirId |>
}

{- Log of requests. Used to prevent denial of service attacks. -}
type LogFile_f = [LogEntry_t]

{- Request entry. -}
data LogEntry_t = {
  userId :: Pint,           --user making request
  ip     :: IP_t,          --IP address of requestor
  script :: Pstring ' ', ' ', --script to be executed
  userDir :: Pstring ' ', ' ', --directory to put results, corresponds to user
  padsv  :: Pstring ' ', ' ', --version of PADS used
  sml    :: PstringSE(RE " "), --version of SML used
  msg    :: Maybe Pstringln  --optional message
}

type IP_t = (Pint, '.', Pint, '.', Pint, '.', Pint)
|]
```

```

[forest]
{- Files with various permission settings. -}
type BinaryRO      = Binary      where <| get_modes this_att == "-rw-r--r--" |>
type BinaryRX     = Binary      where <| get_modes this_att == "-rwxr-xr-x" |>
type TextRX       = Text        where <| get_modes this_att == "-rwxr-xr-x" |>
type TextRO       = Text        where <| get_modes this_att == "-rw-r--r--" |>

{- Optional binary file with read/execute permission. -}
type OptBinaryRX = Maybe BinaryRX

{- Files with PADS descriptions -}
type Config       = File Config_f   where <| get_modes this_att == "-rw-r--r--" |>
type SourceNames = File SourceNames_f where <| isReadOnly this_att |>
type UserEntries = File UserEntries_f where <| isReadOnly this_att |>
type LogFile      = File LogFile_f   where <| isReadOnly this_att |>

{- Directory of image files -}
type Imgs_d = Directory {
  logo   is "pads_small.jpg" :: BinaryRO,
  favicon is "favicon.ico"   :: BinaryRO
}

{- Directory of static content -}
type Static_d = Directory {
  style_sheet is "pads.css"           :: TextRO,
  intro_redir is "learning-demo.html" :: TextRO,
  title_frame is "atitle.html"       :: TextRO,
  logo_frame  is "top-left.html"     :: TextRO,
  top_frame   is "banner.html"       :: TextRO,
  empty_frame is "nothing.html"     :: TextRO,
  images      is "images"            :: Imgs_d where <| get_modes images_md == "drwxr-xr-x" |>
}

{- Directory of dynamic content -}
type Cgi_d = Directory {
  config'   is "PLConfig.pm"           :: TextRO,
  perl_utils is "PLUtilities.pm"      :: TextRO,
  intro     is "learning-demo.cgi"     :: TextRX,
  intro_nav is "navbar-orig.cgi"      :: TextRX,
  select_data is "pads.cgi"           :: TextRX,
  result_nav is "navbar.cgi"          :: TextRX,
  format_chosen is "data-results.cgi" :: TextRX,
  gen_desc   is "build-description.cgi" :: TextRX,
  get_user_data is "build-roll-your-own.cgi" :: TextRX,
  gen_desc_usr is "genData.cgi"       :: TextRX,
  build_lib  is "build-library.cgi"    :: TextRX,
  build_accum is "build-accum.cgi"     :: TextRX,
  build_xml  is "build-xml.cgi"       :: TextRX,
  build_fmt  is "build-fmt.cgi"       :: TextRX
}

```

```

{- Directory of shell scripts invoked by CGI to run learning system -}
type Scripts_d = Directory {
  rlearn      :: TextRX,           --Shell script for running PADS comiler on stock format
  rlearnown  is "rlearn-own" :: TextRX, --Shell script for running PADS compiler on user format
  raccum    is "r-accum"   :: TextRX, --Shell script to generate and run accumulator
  rxml       is "r-xml"    :: TextRX, --Shell script to generate and run XML converter
  rfmt       is "r-fmt"    :: TextRX, --Shell script to generate and run formatting program
  rlibrary   :: TextRX           --Shell script to build PADS library
}

{- Directory containing administrative files used by demo web site -}
type Info_d = Directory {
  sources is "sampleFiles" :: SourceNames, --List of source data files whose formats can be learned
  users   is "userFile"    :: UserEntries, --Mapping from userIDs to associated directory names
  logfile is "logfile"     :: LogFile      --Log of server actions
}

{- Collection of files named by sources containing actual data. -}
type DataSource_d(sources :: [String]) = [ s :: Text | s <- sources ]

{- Type of a symbolic link with pointing to source-}
type SymLink_f (path :: FilePath) = SymLink where <| this == path |>

{- Directory of optional links to source data files -}
type Data_d ((root,sources) :: (FilePath, [String])) = Directory {
  datareps is [s :: Maybe Text | s <- sources],
  datalinks is [s :: Maybe (SymLink_f <| root++"/"++ s |>) | s <- sources]
}

{- Directory that stores the generated machine-dependent output for data source named source -}
type MachineDep_d (source :: String) = Directory {
  pads_c   is <| source ++ ".c" |> :: TextRO,           --Generated C source for PADS description
  pads_h   is <| source ++ ".h" |> :: TextRO,           --Generated C header for PADS description
  pads_o   is <| source ++ ".o" |> :: BinaryRO,         --Compiled library for PADS description
  pads_pxml is <| source ++ ".pxml" |> :: TextRO,        --PADS description in xml syntax
  pads_xsd is <| source ++ ".xsd" |> :: TextRO,         --Xschema of XML syntax for source description
  pads_acc is <| source ++ "-accum" |> :: OptBinaryRX,   --Optional generated accumulator program
  pads_fmt is <| source ++ "-fmt" |> :: OptBinaryRX,    --Optional generated formatting program
  pads_xml is <| source ++ "-xml" |> :: OptBinaryRX     --Optional generated XML conversion program
}

{- Directory that stores the generated output for data source named "source". -}
type Example_d (source :: String) = Directory {
  pads_p      is <| source ++ ".p" |> :: TextRO,           --PADS/C description of data source
  pads_pml    is <| source ++ ".pml" |> :: Maybe TextRO,  --PADS/ML description of data source
  vanilla     is "vanilla.p" :: TextRO,                 --input tokenization
  makefile    is "GNUmakefile" :: Text,                --Makefile
  machine     is <| envVar "AST_ARCH" |> :: Maybe (MachineDep_d source), --Platform dependent files
  accum_c     is <| source ++ "-accum.c" |> :: Maybe TextRO, --Template for accumulator program
  accum_out   is <| source ++ "-accum.out" |> :: Maybe TextRO, --ASCII Accumulator output
  accum_xml_out is <| source ++ "-accum_xml.out" |> :: Maybe TextRO, --XML Accumulator output
  xml_c       is <| source ++ "-xml.c" |> :: Maybe TextRO, --Template for XML converter
  xml_out     is <| source ++ "-xml.out" |> :: Maybe TextRO, --XML representation of source
  xml_xsd     is <| source ++ ".xsd" |> :: Maybe TextRO, --Xschema for XML representation of source
  fmt_c       is <| source ++ "-fmt.c" |> :: Maybe TextRO, --Template for formatting program
  fmt_out     is <| source ++ "-fmt.out" |> :: Maybe TextRO --Formatted representation of source
}

{- Directory that stores all information for one user. -}
type User_d(arg@ (r, sources) :: (FilePath, [String])) = Directory {
  dataSets is "data" :: Maybe (Data_d arg),
  runExamples is [ s :: Maybe (Example_d s) | s <- sources ]
}

```

```

{- Collection of directories containing temporary information for all users. -}
type Users_d((r,info) :: (FilePath, Info_d)) =
  [userDir :: User_d <|(r, getSources info) |> | userDir <- <| userNames info |> ]

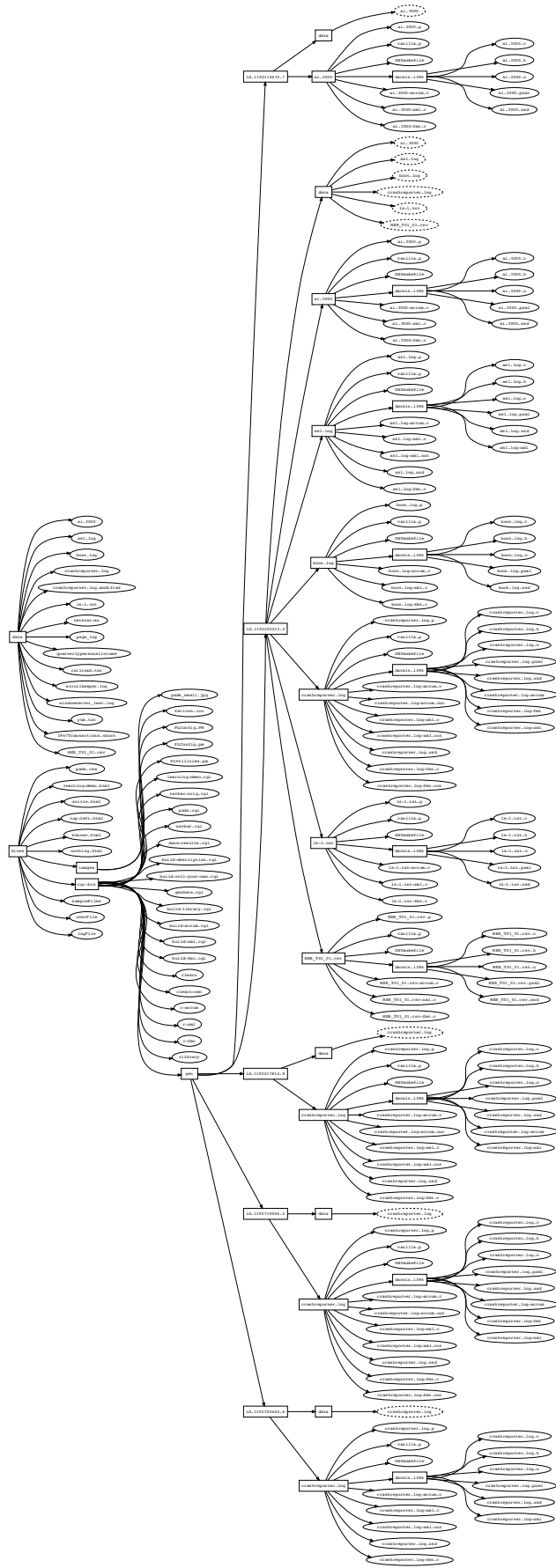
{- Top-level of PADS website. -}
type Website_d(config::FilePath) = Directory {
  c
  static_content is <| gstatic_dst c |> :: Static_d,      --Configuration file with locations of other components
  dynamic_content is <| gcgi_path c |> :: Cgi_d,           --Static web site content
  scripts        is <| gscript_path c |> :: Scripts_d,    --Dynamic web site content
  admin_info     is <| gstatic_dst c |> :: Info_d,        --Shell scripts invoked by cgi to run learning system
  data_dir       is <| (glearn_home c)++"/examples/data" |> --Administrative information about website
  usr_data       is <| gtmp_root c |> :: DataSource_d <|(getSources admin_info)|>, --Stock data files for website
}
  : Users_d <|(get_fullpath data_dir_md, admin_info)|> --User info
}
[]

{- HASKELL HELPER FUNCTIONS -}
isReadOnly md = get_modes md == "-rw-r--r--"

{- Function userName gets the list of user directorn names from an info structure. -}
userNames info = getUserEntries (users info)
getUserEntries (UserEntries (UserEntries_f users)) = map userEntryToFileName users
userEntryToFileName userEntry = pairToFileName (dirId userEntry)
pairToFileName (Pint n1, Pint n2) = "id."++(show n1)++"."++(show n2)

{- Helper functions to convert a Config entry to a FilePath -}
cToS (Config_entry_t (Pstring s)) = s
ghost_name (Config c) = cToS $ host_name c
gstatic_path (Config c) = cToS $ static_path c
gcgi_path (Config c) = cToS $ cgi_path c
gscript_path (Config c) = cToS $ script_path c
glearn_home (Config c) = cToS $ learn_home c
gtmp_root (Config c) = cToS $ tmp_root c
gstatic_dst (Config c) = cToS $ static_dst c

```





## C. Students.hs Description

This section includes the Forest description of the Princeton Computer Science Department filestore. The following is the initial portion of a student record, shown here to illustrate the format.

```
KESSEL, PHIL          BSE  '11
-----
Type   Yr  Course      Grade
      1
      2      A+ to F
d      2      P ( Pass )
t D p  3      INC
o . .  4 Dept xxx N (Not Avail)
-----
d . .  1 COS   101  C
o . .  1 HOC   101  A
o . .  1 GOL   599  A+
...
```

```
-- Auxiliary Haskell functions for PADS description
```

```
ws  = RE "[ ]+"
ows = RE "[ ]*"
junk = RE ".*"
space = ' '
quote = ''
comma = ','
```

```
-- PADS description of Princeton CS Student Record Format
```

```
[pads|
type Grade = Pre "[ABCD][+-]?|F|AUD|N|INC|P"

data Course =
  { sort          :: Pre "[dto]",          ws
  , departmental :: Pre "[.D]",          ws
  , passfail     :: Pre "[.p]",          ws
  , level        :: Pre "[1234]",        ws
  , department   :: Pre "[A-Z][A-Z][A-Z]", ws
  , number       :: Pint where <| 100 <= number && number < 600 |>, ws
  , grade        :: Grade,                junk
  }

data Middle_name = {space, middle :: Pre "[a-zA-Z][.]" }

data Student_Name(myname::String) =
  { lastname      :: Pre "[a-zA-Z]*" where <| toString lastname == myname |>, comma, ows
  , firstname    :: Pre "[a-zA-Z]*"
  , middlename   :: Maybe Middle_name
  }

data School = AB | BSE

data Person (myname::String) =
  { fullname     :: Student_Name myname,    ws
  , school       :: School,                 ws, quote
  , year         :: Pre "[0-9][0-9]"
  }

type Header = [Line (Pre ".*")] with term length of 7
type Trailer = [Line (Pre ".*")] with term Eof
data Student (name::String) =
  { person      :: Line (Person name)
  , Header
  , courses    :: [Line Course]
  , Trailer
  }
|]
```

```

-- Auxiliary Haskell functions for Forest description
template s = s `elem` ["SSSS.txt", "SSS.txt", "sxx.txt", "sss.txt", "ssss.txt"]
not_template = not . template

getYear :: String -> Integer
getYear s = read (reverse (take 2 (reverse s)))
toStrN i n = (replicate (n - length (show i)) '0') ++ (show i)
mkClass y = "classof" ++ (toStrN y 2)

transferRE = RE "TRANSFER|Transfer"
leaveRE    = RE "LEAVE|Leave"
withdrawnRE = RE "WITHDRAWN|WITHDRAWAL|Withdrawn|Withdrawal|WITHDREW"
cRE        = RE "classof[0-9][0-9]"
txt         = GL "*.txt"

-- FOREST description of Princeton CS Department Database
[forest]
-- Root of the hierarchy
type PrincetonCS (y::Integer) = Directory
  { notes is "README" :: Text
  , seniors is <|mkClass y |> :: Class y
  , juniors is <|mkClass (y + 1)|> :: Class <| y + 1 |>
  , graduates :: Grads
  }

-- Collection of directories containing graduated students
type Grads =
  Map [ c :: Class <| getYear c |> | c <- matches cRE ]

-- Directory containing all students in a particular year
type Class (y :: Integer) = Directory
  { bse is <|"BSE" ++ (toStrN y 2)|> :: Major
  , ab is <|"AB" ++ (toStrN y 2)|> :: Major
  , transfer matches transferRE :: Maybe Major
  , withdrawn matches withdrawnRE :: Maybe Major
  , leave matches leaveRE :: Maybe Major
  }

-- Collection of files containing all students in a particular major.
type Major = Map
  [ s :: File (Student <| dropExtension s |>)
  | s <- matches txt, <| (not . template) s |> ]
[]

```

## C.1 Generated Description

Here follows a description generated from a small sample of the student directory data using the description inference tool.

```
data transfer = Directory {
}
data WITHDREW = Directory {
  fingertxt is "finger.txt" :: File Ptext
}
data tTRANSFER = Directory {
  BEAUCHEMINtxt is "BEAUCHEMIN.txt" :: File Ptext,
  VERSTEEGtxt is "VERSTEEG.txt" :: File Ptext
}
data bSE11 = Directory {
  transfer is "transfer" :: transfer,
  BOZAKtxt is "BOZAK.txt" :: File Ptext,
  KESSELTtxt is "KESSEL.txt" :: File Ptext,
  sstxt is "sss.txt" :: File Ptext
}
data aB11 = Directory {
  KADRItxt is "KADRI.txt" :: File Ptext,
  MACARTHERtxt is "MACARTHER.txt" :: File Ptext,
  ORRtxt is "ORR.txt" :: File Ptext,
  SSSStxt is "SSSS.txt" :: File Ptext
}
data classof11 = Directory {
  aB11 is "AB11" :: aB11,
  bSE11 is "BSE11" :: bSE11,
  tTRANSFER is "TRANSFER" :: tTRANSFER,
  WITHDREW is "WITHDREW" :: WITHDREW
}
```

## D. Coral.hs Description

This section gives the PADS and Forest descriptions for the CoralCDN Log repository. A graph of the CoralCDN repository, generated like the graph above using the ForestGraph tool from the description and (a subset of) the actual repository follows.

```
-- Auxiliary Haskell definitions for PADS description
comma_ws = RE ", [ ]*"
status_re = RE "[0-9]+"

-- PADS description of CoralCDN Webserver Log Format
[pads|
type Time = (Pint, ".", Pint)

type Byte = constrain x :: Pint where <| 0 <= x && x <= 256 |>

type IP_Port =
  { "",
    ip :: (Byte, '.', Byte, '.', Byte, '.', Byte), ":",
    port :: Pint, "" }

type Status = PstringME(status_re)

type Statistics =
  { stats_size      :: Pint,      comma_ws
  , stats_proxy    :: Pre "[01]", comma_ws
  , stats_level    :: Pint,      comma_ws
  , stats_lookup   :: Pint,      comma_ws
  , stats_xfer     :: Pint,      comma_ws
  , stats_total    :: Pint }

type NoQuote = PstringME (RE "[^\\"]*")

type Generic = ('"', NoQuote, "'")

type Url = Generic

data Header =
  { version      :: Maybe (Pre "[12],[ \\t]*")
  , time        :: Time      }

data Request =
  { src          :: IP_Port, comma_ws
  , dst         :: IP_Port, comma_ws
  , url         :: Url    }

data InData =
  { "\\IN\\",      comma_ws
  , in_req       :: Request, comma_ws
  , in_status1  :: Status,  comma_ws
  , in_status2  :: Status,  comma_ws
  , in_stats    :: Statistics }

data OutData =
  { "\\OUT\\",      comma_ws
  , out_remote  :: Pre "\\(REM|LOC)\\", comma_ws
  , out_req     :: Request,  comma_ws
  , out_referrer :: Url,     comma_ws
  , out_status  :: Status,   comma_ws
  , out_stats   :: Statistics, comma_ws
  , out_forwarded :: Generic, comma_ws
  , out_via     :: Generic   }

data InOut = In InData | Out OutData

data Entry =
  { header      :: Header,  comma_ws
  , payload     :: InOut
  , Eor        }

type Entries = [Entry] with term Eor

type Coral = (Entries, Eof)
|]
```

```

-- Forest description of CoralCDN Log Repository
[forest]
  -- Directory containing log files
  type Log = Directory
    { web is "coralwebsrv.log.gz" :: Gzip (File Coral),
      dns is "coraldnsrv.log.gz"  :: Maybe (Gzip (File Ptext)),
      prb is "probed.log.gz"      :: Maybe (Gzip (File Ptext)),
      dmn is "corald.log.gz"      :: Maybe (Gzip (File Ptext)) }

  -- Directory containing dates
  type Site = [ d :: Log | d <- matches (RE "[0-9]{4}_[0-9]{2}_[0-9]{2}-[0-9]{2}_[0-9]{2}") ]

  -- Directory containing sites
  type Top = [ s :: Site | s <- matches (RE "[^.]\\.*)" ]
]

```

```

-- Load function for CoralCDN description
(rep,md) = unsafePerformIO $ top_load "/var/log/coral"

-- Helpers: deconstruct representations
get_sites :: Top -> [(String,Site)]
get_dates :: Site -> [(String,Log)]
get_entries :: Log -> [Entry]

-- Helpers: project fields
get_stats :: Entry -> Statistics
get_total :: Entry -> Int
get_date :: String -> String
get_url::Entry -> String
string_of_url :: Url -> String
is_in :: Entry -> Bool
is_out :: Entry -> Bool

-- Helper: builds an association list
lmap f p tdir =
  [ f host datetime e | (host,hdir) <- get_sites tdir,
                        (datetime,ldir) <- get_dates hdir,
                        e <- get_entries ldir,
                        p e ]

-- Uses of lmap
by_date = lmap (\h d e -> (get_date d, get_total e))
by_host = lmap (\h d e -> (h, get_total e))
by_url_bytes = lmap (\h d e -> (get_url e, get_total e))
by_url_counts = lmap (\h d e -> (get_url e, 1))

-- Helpers: fold down an association list
go_bins m p = fromListWith (+) (m p rep)

count_bins m = fromListWith (+) (fold (\ c l -> (c,l):l) [] m)

go_flat p =
  sum [ (get_total e) | (host,hdir) <- get_sites tdir,
                       (datetime,ldir) <- get_dates hdir,
                       e <- get_entries ldir,
                       p e ]

-- Several useful queries
in_total = go_flat is_in
out_total = go_flat is_out
in_by_host = go_bins by_host is_in
out_by_host = go_bins by_host is_out
in_by_date = go_bins by_date is_in
out_by_date = go_bins by_date is_out
in_url_bytes = go_bins by_url_bytes is_in
out_url_bytes = go_bins by_url_bytes is_out
in_url_counts = go_bins by_url_counts is_in
out_url_counts = go_bins by_url_counts is_out
in_counts_urls = count_bins $ go_bins by_url_counts is_in
out_counts_urls = count_bins $ go_bins by_url_counts is_out
num_sites () = case load_logs () of Top l -> List.length l

-- Top-k URLs
topk k =
  take k $ sortBy sortDown $ toList $
  fromListWith (+)
  [ (get_url e, get_total e)
  | (site,sdir) <- get_sites rep,
    (datetime,ldir) <- get_dates sdir,
    e <- get_entries ldir,
    is_in e ]

```



## E. Gene Ontology

This section presents a description of gene ontology data found here: <http://www.geneontology.org/gene-associations/>. A graph generated using ForestGraph on a subset of the data follows the description.

This filestore is a web directory of gene association data files. The root directory contains a number of .gz files, a readme directory and a submission directory. Each .gz file is the gene ontology (GO) data of the genes in one or more organism, and the file names have the format "gene\_association.XXX\_YYY.gz", where XXX represents the name of the institute that provides the data and YYY is the name of the organism. YYY is optional because some institute provides the data for only one organism.

The readme directory contains a set of .README files for a subset of the GO data in the root.

The submission directory contains a set of .gz files, their corresponding .conf files, and a paint sub-directory. The .gz files are similar to the ones in root except they are older. The .conf file summarizes some attributes of the .gz file such as "the name of the project", "contact email", etc. The paint sub-directory contains a further set of subdirectories of the form PTHRXXXXXX, where XXXXX is a 5-digit number. These subdirectories each contain six text files and an XML file. These are the annotation inference of the gene ontology using phylogenetic trees and the PAINT tool.

```
-- PADS descriptions of data file format.
[ pads |
  type Pfloat          = (Pint, '.', Pint)
  type Pdate           = {mon :: Pint, '/', day :: Pint, '/', year :: Pint}
  type Purl            = ("http://", Pstringln)
  type Version_t       = ("!CVS Version: Revision: ", Pfloat, ws, '$')
  type Valid_date_t    = ("!GOC Validation Date: ", Pdate, ws, '$')
  type Sub_date_t      = ("!Submission Date: ", Pdate)
  type Project_name_t  = ("!Project_name: ", Pstringln)
  type URL_t           = ("!URL: ", Purl)
  type Email_t         = ("!Contact Email: ", Pstringln)
  type Funding_t       = ("!Funding: ", Pstringln)
  type Gaf_ver_t       = ("!gaf-version: ", Pfloat)
  type Organism_t      = ("!organism:", ws, Pstringln)
  type Date_t          = ("date:", ws, Pdate)
  type Note_t          = ('!', ws, Pstringln)

  data Header_line_t =
    Version Version_t
    | Valid_date Valid_date_t
    | Sub_date Sub_date_t
    | Project_name Project_name_t
    | URL URL_t
    | Email Email_t
    | Funding Funding_t
    | Gaf_ver Gaf_ver_t
    | Organism Organism_t
    | Date Date_t
    | Note Note_t
    | Other ('!', Pstringln)

  type Other_line_t = Pstringln

  type GA_f = ([Line Header_line_t], [Line Other_line_t] with term Eof)
]

[ pads |
  data Pair_t = {key::Pstring '=', '=', val::Pstringln}
  type Conf_f = [Line Pair_t] with term Eof
]

[ pads |
  type Xml_header = ("<?xml ", Pstringln)
  type XML_f = (Line Xml_header, [Line Pstringln])
]
```



```

-- Forest description of Gene Ontology filestore
[forest]
  type Readme_d = Directory {
    readmes is [rm :: Maybe Text | rm <- <|map get_readme_file (comb_source sources)|>]
  }

  type PTHR_d (name :: String) = Directory {
    attr is <| name ++ ".save.attr" |> :: Text,
    gaf is <| name ++ ".save.gaf" |> :: Text,
    msa is <| name ++ ".save.msa" |> :: Text,
    paint is <| name ++ ".save.paint" |> :: File XML_f,
    sfan is <| name ++ ".save.sfan" |> :: Text,
    tree is <| name ++ ".save.tree" |> :: Text,
    txt is <| name ++ ".save.txt" |> :: Text,
    wts is <| name ++ ".save.txt" |> :: Text
  }

  type Pre_sub_d = Directory {
    pre_gz_files is [gz :: Maybe (Gzip (File GA_f)) | gz <- <|map get_gz_file (comb_source sources)|>],
    pre_conf_files is [conf :: Maybe (File Conf_f) | conf <- <|map get_conf_file (comb_source sources)|>]
  }

  type Paint_d = Directory {
    pthr_dirs is [dir_name :: PTHR_d (dir_name) | dir_name <- matches RE "PTHR[0-9]+"],
    pre_sub is "pre-submission" :: Pre_sub_d
  }

  type Submission_d = Directory {
    gz_files is [gz :: Maybe (Gzip (File GA_f)) | gz <- <|map get_gz_file (comb_source sources)|>],
    conf_files is [conf :: Maybe (File Conf_f) | conf <- <|map get_conf_file (comb_source sources)|>],
    paint_files is [cs :: Maybe (File Conf_f) | cs <- <|map (\x -> get_conf_file ("paint" ++ x)) (comb_source sources)|>],
    paint_d is "paint" :: Paint_d
  }

  type Top_d = Directory {
    data_files is [gz :: Maybe (Gzip (File GA_f)) | gz <- <|map get_gz_file (comb_source sources)|>],
    readme is "readme" :: Readme_d,
    sub is "submission" :: Submission_d
  }
[]

-- Haskell code to generate graph corresponding to sample data set in filestore "Data/ga"
doImg = do
  (rep,md) <- top_d_load "Data/ga"
  ; mdToPDF md "Examples/ga.pdf"

```

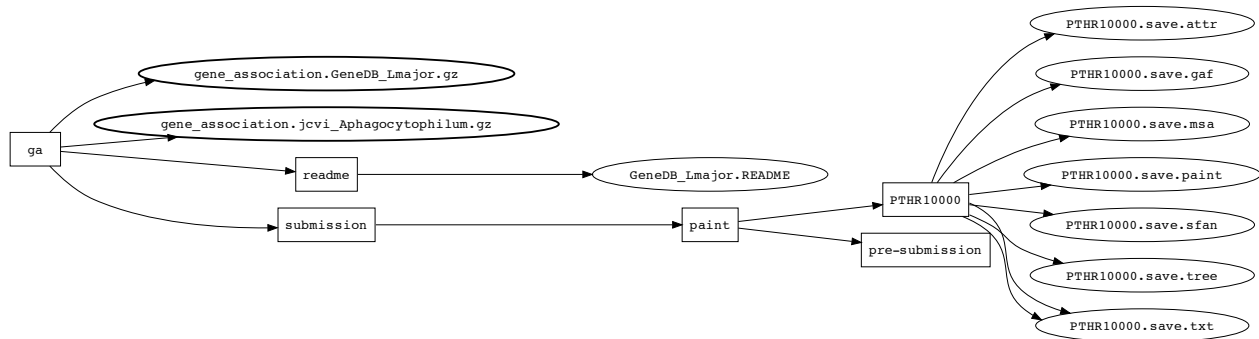
```

-- Auxiliary Haskell Definitions
ws = RE "[ ]+"
title = "gene_association"
get_gz_file f = title ++ "." ++ f ++ ".gz"
get_readme_file f = f ++ ".README"
get_conf_file f = title ++ "." ++ f ++ ".conf"

{- each source is a pair (institute name, list of organisms the institute provides) -}
sources = [
  ("Compugen", [])
  , ("GeneDB", ["Lmajor", "Pfalciparum", "Spombe", "Tbrucei", "tsetse"])
  , ("PAMGO", ["Atumefaciens", "Ddadantii", "Mgrisea", "Oomycetes"])
  , ("aspgd", [])
  , ("cgd", [])
  , ("dictyBase", [])
  , ("ecocyc", [])
  , ("fb", [])
  , ("goa", ["arabidopsis", "chicken", "cow", "human", "mouse", "pdb", "rat",
            "uniprot", "uniprot_noiea", "zebrafish"])
  , ("gramene", ["oryza"])
  , ("jvci", ["Aphagocytophilum", "Banthraxis", "Cburnetii", "Chydrogenoformans",
            "Cjejuni", "Cperfringens", "Cpsychrerythraea", "Dethenogenes", "Echaffeensis",
            "Gsulfurreducens", "Hneptunium", "Lmonocytogenes", "Mcapsulatus", "Nsennetsu",
            "Pfluorescens", "Psyringae", "phaseolicola", "Soneidensis", "Spomeroyi",
            "Vcholerae"])
  , ("mgi", [])
  , ("pseudocap", [])
  , ("reactome", [])
  , ("rgd", [])
  , ("sgd", [])
  , ("sgn", [])
  , ("tair", [])
  , ("wb", [])
  , ("zfin", []) ]
comb_source [] = []
comb_source ((inst, organs):sources) =
  let cl = case organs of
        [] -> [inst]
        _ -> map (\organism -> inst ++ "_" ++ organism) organs
  in cl ++ (comb_source sources)

{- the GO files, when unzipped, contain a header like the following:
!CVS Version: Revision: 1.19 $
!GOC Validation Date: 01/27/2007 $
!Submission Date: 1/15/2007
-}

```



## F. CVS.hs Description

This section provides a generic description for CVS repositories.

```
-- PADS description of CVS file formats
[getpads| type Repository_f = Line Pstringln
data Mode_t = Ext ":ext:" | Local ":local:" | Server ":server:"
data Root_t = { cvs_mode :: Maybe Mode_t
               , machine  :: Pstring ':', ':'
               , path     :: Pstringln
               }
type Root_f = Line Root_t
data Dentry_t = { "D/"
                , dirname :: Pstring '/'
                , "////"
                }

data Revision_t = Version (Pint, '.', Pint) | Added '0' | Removed '-'
data TimeStamp_t = { ts          :: PstringSE (RE "[+]" )
                    , conflict  :: Maybe ('+', Pstring '/') }

type Fentry_t = {
                , filename  :: Pstring '/',
                , revision  :: Revision_t,
                , timestamp :: TimeStamp_t,
                , options   :: Pstring '/',
                , tagdate   :: Pstringln
                }

data Entry_t = Dir Dentry_t | File Fentry_t | NoDir 'D'
type Entries_f = [Line Entry_t] with term Eof
]

-- Auxiliary Haskell functions
getEntries cvs = let (Entries_f l) = entries cvs in l
getDirName d = let (Pstring s) = dirname d in s
getFileName f = let (Pstring s) = filename f in s

isDir entry = case entry of Dir _ -> True; otherwise -> False
isFile entry = case entry of File _ -> True; otherwise -> False

getDirs cvs = map (\(Dir d) -> d) (filter isDir (getEntries cvs))
getFiles cvs = map (\(File f) -> f) (filter isFile (getEntries cvs))

-- FOREST description of CVS directory structure
-- Note that this description is recursive.
-- Note also that the collection of dirs and the
-- collection of files are determined from information in the cvs
-- directory.
[forest| type CVS_d = Directory
        { repository is "Repository" :: File Repository_f
        , root       is "Root"       :: File Root_f
        , entries    is "Entries"    :: File Entries_f
        }

        type CVS_Repository_d = Directory
        { cvs          is "CVS"          :: CVS_d
        , dirs        is [ n as <| getDirName d |> :: CVS_Repository_d | d <- <| getDirs cvs |> ]
        , files       is [ <| getFileName f |> :: Text | f <- <| getFiles cvs |> ]
        } |]

-- Sample use of PADS and FOREST descriptions
meta_dir = "Examples/ CVS"
entries_file = meta_dir ++ "/Entries"
doParseEntries = do {
  (rep, md) <- parseFile entries_file
}

doLoadCVS = do {
  (meta_rep, meta_md) <- cvs_d_load meta_dir
}
```

## G. Universal.hs Description

This section includes a universal data description. This universal description is used to drive some of our generic tools.

```
-- Universal Forest Directory Description
```

```
[forest|
  type Universal_d = Directory
  { ascii_files  is [ f :: Text          | f <- matches (GL "*"), <| get_kind f_att == AsciiK    |> ]
  , binary_files is [ b :: Binary        | b <- matches (GL "*"), <| get_kind b_att == BinaryK   |> ]
  , directories  is [ d :: Universal_d   | d <- matches (GL "*"), <| get_kind d_att == DirectoryK |> ]
  , symLinks     is [ s :: SymLink       | s <- matches (GL "*"), <| get_isSym s_att == True    |> ]
  }
|]
```

```
-- Use of Universal directory
```

```
universal_dir = "Examples/data/universal"
doLoadUniverse = do {
  (rep, md) <- universal_d_load universal_dir
}
```