Hybrid-Search and Storage of Semi-structured Information

by

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Submitted to the Department of Electrical Engineering and Computer Science
in partial fulfillment of the requirements for the degree of
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Abstract

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Many different solutions have been proposed to the general information seeking task of users, but few if any have addressed the needs of individuals or have leveraged the benefit of single-user interaction. The Haystack project is an attempt to answer the needs of the individual user. Once the user's information is represented in Haystack, the types of questions users may ask are highly varied. In this thesis we will propose a means of representing information in a robust framework within Haystack. Once the information is represented we describe a mechanism by which the diverse questions of the individual can be answered. This novel method functions by using a combination of existing information systems. We will call this combined system a hybrid-search system.

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Chapter 1

Introduction

Given today's tangle of digital information, one of the hardest tasks for computer users of information systems is finding anything in the mess. For a number of well documented reasons including the amazing growth in the Internet's popularity and the drop in the cost of storage, the amount of information on the net as well as on a user's local computer, has increased dramatically in recent years. Although this readily available information should be extremely beneficial for computer users, paradoxically it is now much harder to find anything.

Many different solutions have been proposed to the general information seeking task of users, but few if any have addressed the needs of individuals or have leveraged the benefit of single-user interaction. The Haystack project is an attempt to answer the needs of the individual user. Once the user's information is represented in Haystack, the types of questions users may ask are highly varied. In this thesis we will propose a means of representing information in a robust framework within Haystack. Once the information is represented we describe a mechanism by which the diverse questions of the individual can be answered. This novel method functions by using a combination of existing information systems. We will call this combined system, a hybrid-search system.
1.1 The Problem

There are two different but related search tasks in the digital domain. The first is exemplified by a search in a large digital library. The user only has awareness of the existence of a small set of items and does not necessarily grasp the full nature of the corpus\(^1\) (just as a library patron doesn’t know the full set of books the library has). The second type of search task is much more constrained in nature and answers the user’s need to find things in their own information space (i.e. his/her own bookshelf, rather than the library).

Until recently this second type of search task has not been a real problem. Users were constrained to limited disk space and limited bandwidth. Both factors contributed to limitations in the amount of information a user would ever be exposed to. Most systems were therefore designed for the first task. This approach generated two types of systems. One deals with the very general class of users (i.e. the Internet user base). The other deals with a very small number of specialized users (i.e. librarians or researchers). Unfortunately, neither approach completely satisfies, nor takes advantage of, information specific to a single user.

Today, we are rapidly approaching the end of the limits to personal disk space and bandwidth. Information is making its way quickly to, and residing permanently, on the user’s desktop. The non-problem of yesterday is becoming a real problem today. In this thesis we will concentrate on this rapidly worsening problem: finding information on the personal level. For our purposes, personal information corresponds to things that a user possesses in some form. The information can exist as physical paper, as digital bits, in the user’s memory, or any combination of these forms. What kind of questions might we ask about this type of information?

- *Where is the file that David sent me last week?*

- *Which e-mails did I get last month from Lynn that I didn’t respond to?*

- *What web pages did I see about “semantic association networks?”*

\(^1\)Corpus is an Information Retrieval (IR) term generally referring to a collection of documents.
• Who wrote this document and when did I get it?

These questions are a small sample of what a user may ask when trying to make sense of, organize, or find something in, their personal information space. We can now ask ourselves whether previous methods of approaching the search problem are applicable to the personal situation. Section 1.1.1 will describe a model for querying an information system to find something in a collection of data. In section 1.1.2 we develop categories for the different components in this model. We then extend the model in section 1.2. Finally, in section 1.3 we will summarize the goals of this thesis.

1.1.1 A Model for Searches

Figure 1-1 illustrates our view of the query process. This feedback system model will allow us to properly analyze different aspects of current search mechanisms, and where this work hopes to improve on them. Formally, our system looks like this:

- Initial query function: \( Q_1(i, c, \Delta) \rightarrow q^i \), where \( i \) is the information need, \( c \) is a set of constraints, and \( q^i \) some intermediate description of the desired information (we will return to the \( \Delta \) shortly).

- Secondary query function: \( Q_2(q^i, G) \rightarrow q^f \), where \( G \) is some grammar associated with the search tool, and \( q^f \) a formal query expressed in the grammar.

Figure 1-1: The query model
• Information system core function: \( I(q^f, D) \rightarrow r_1 \), where \( D \) is the corpus (data) we are querying against, and \( r_1 \) some intermediate set of matches.

• Information system “post-processing” function: \( C(r_1, q^f) \rightarrow r_2 \), where \( C \) performs some post-processing on \( r_1 \) to generate some \( r_2 \).

• Human evaluation function: \( R(r_2, q^i) \rightarrow \begin{cases} \text{generate } \Delta \text{ if result unsatisfactory} \\ \text{output } r_2 \text{ otherwise} \end{cases} \)

Let’s look at this system qualitatively for a minute. We start off with a data corpus (the data in the figure) which contains some information the user would like to find. The first task a user performs is to combine their information need (i.e. what they are searching for), with any constraints they may have. For example, if the user is searching for some document (their information need), they may also remember that Bob wrote it last year and that it was about “apples” (the constraints). The user combines the information need with the constraints to form (possibly just in their minds) some informal query in \( Q_1 \): “I want the document that Bob wrote last year about apples.”

Unfortunately, systems today are incapable of handling arbitrary natural language queries, so it is necessary for the user to generate some formal query based on the language specification of the information system. This corresponds to the function \( Q_2 \).

The previous query may then become (if our information system was a SQL database), “SELECT * FROM docbase WHERE author = 'Bob’ AND date > 01/01/97 AND date < 01/01/98 AND topic = 'apples'.”

The user then passes this formal query to the information system, \( I \). The information system in turn generates a set of responses that satisfy the user’s formal query. If it is capable of doing so, the system may also rank the responses as to the likelihood of satisfying the query (we’ll get back to this). This primary result set is then passed to a post-processing function, \( C \). This function acts as an additional level of computation on the initial result set as specified by the formal query. The general idea is that sometimes a user wants a single top matching response, or alternatively sometimes they want a summarization of all the responses, or possibly some
other representation (sorted by date, for example). Portions of the formal query that correspond to these “instructions” are passed to $C$ for evaluation.

Finally, once we have this secondary result set it is necessary to turn again to the input of the user. The user must evaluate what was returned by the system based on their informal query. If the information satisfies their need we’re done. Otherwise, the user must form what we will call the $\Delta$ (the mathematical symbol for change). This $\Delta$ corresponds to some additional restrictions or modifications the user will apply to his original informal query function, $Q_1$. Let’s go back to the initial query for an example. If Bob wrote many papers last year with a majority being about “apples” and “oranges” the system will return many matches. If the user is only interested in the documents that are exclusively about apples, they will have to revise their query to reflect this need. The user can now say that they are interested in all documents Bob wrote last year about “apples” but not “oranges.” With a new informal query in hand, the user will now repeat the previous walk through the system. What we would like to do is minimize the number of iterations so that a user gets what they want much more quickly. However, before discussing our particular solution it would be valuable to understand how current solutions map to our model.

1.1.2 Query Model System Components

In discussing the system components we can follow the same route as a human would, and consider the query formulation process first (functions $Q_1$ and $Q_2$). Abstractly, there are many different kinds of searches users perform for different information needs. These include searches for data for analytical needs, searches for documents that the user created, and searches for documents related to a current research thread. Different information systems are designed to handle different types of queries. We will call the query that the system can handle the computable input.

Functionally, we can distinguish between two extremes of input into the system. The first of these we will call the exploratory or browsing search tools. This type

---

2Ordinarily, the need of a user will fall somewhere between these extremes.
of search involves the use of a “probe” into the information followed by an iterative refinement of the search until satisfying information is found. An example of this type of search is, “find some documents about the crime rates in northern California cities.” The second type of search we will call the explicit search. Users will perform an explicit search when they are aware of the existence of some document or object and wish to locate it. An example of this is, “find the web page on the MIT site dealing with patent licensing.” Between these two extremes of exploratory and explicit lies the information spectrum [11]. What distinguishes one end from the other is the size of the constraint set the user applies to the query. Users of information systems begin to formulate better constraint either by becoming adept users of the systems or using the feedback loop from the result sets.

Just as we categorized the types of input into the system, we can do the same for different $I$ functions. We will call the $I$ function, the implementation of the information system, and devise three categories for it. The first form can be classified under the heading of associative search tools. For the most part, these correspond to hypertext systems, and allow for explicit, sometimes non-trivial\textsuperscript{3}, connections to be made between documents. The second category is the unstructured or fuzzy search tools. The unstructured search refers to the questions a user has about the (generally) textual contents of a document. These tools generally correspond to information retrieval (IR) systems. IR systems were designed to work well with the operations of indexing and searching among text based collections. The last category consists of structured or deterministic search tools. Traditionally, these have been database systems. Structured search does not necessarily have to do with the structure of the document, but is usually about querying some data in a predefined schema. An example of this type of query is, “return all documents that are of type e-mail.” or, “return all documents that are dated 9/9/97”

Are all information systems $I$ capable of handling all input queries? To some extent this is true. Figure 1-2 maps input to form, and as we shall discuss in chapter 2

\textsuperscript{3}By non-trivial we mean that current computer technology could not have created the links automatically.
there exist systems that satisfy any of the lines in the figure (occasionally even more than one). However, what will become evident shortly is the need to satisfy all the input → form mappings, not just a subset.

The final component that requires some discussion is the post-processing function, $C$. Imagine a query, “find the average grade for student $x$ for this year,” applied to database of student records. This can be broken down into two tasks: “final all the grades for student $x$ for this year,” and, “average the result set.” The first task we have already solved through function $I$. The second task, which involves some post-processing, must now be applied to the result set. This is where the compression function comes in. There are a variety of compression functions we may wish to see implemented. We can design $C$ to allow all documents to pass through. Borrowing from linear algebra, we will call this the identity function. Alternatively, we can build some functional summary of the data. We call this function the aggregate. Various database technologies provide this facility as a feature of their system and for certain applications this serves a very practical purpose.

Finally, we categorize the complete system $(Q + I + C)$ as the class of the system. What will become apparent is that different classes of systems will be better suited for different types of problems. The intuition is that different systems are designed and optimized for different problems. Systems with an Information Retrieval core are generally intended for full-text fuzzy matching. Databases are (usually) intended for highly constrained, exact searches. Hypertext systems are (usually) intended for browsing. Because these different systems have different properties, each is well suited towards different tasks. We believe that at different times, users have different information needs and constraints, and will require different types of systems to satisfy those needs. So while one unified solution would be optimal, this may not be possible.

In chapter 2 we will review why current systems that fit our search model all
have useful and negative characteristics. What would be ideal is to augment the variety of information systems with the features of other information systems. A system composed of complementary sub-systems, is in our opinion, a much more ideal solution that satisfies the full spectrum of user needs. We call this system, the *Hybrid-Search*.

### 1.2 Better living through Hybrid-Search

Let's back up for a moment and look at our problem from one level higher. What we would like to accomplish in general terms is a system that assists users remember and organize. Additionally (and optimally), we are not interested in having the user think in the constrained grammar rules we set for our system. Rather we would like our system to act within the rules and models a human would apply to finding information.

The tool we would like to provide to users is one that is flexible and robust enough to handle the user's internal methods of recall. This means that we would like to provide users with a set of tools that allows a diverse set of queries in which the user may express the same set of constraints that occur in their own minds. We call this tool *hybrid-search*.

This thesis was proposed within the context of the Haystack project[23], as a means to extend the functionality of this adaptive personal information repository system. Details of Haystack's core implementation, which have made this thesis possible, will be discussed in great details in chapters 4 and 5.

The Haystack architecture provides the means to rapidly integrate a variety of information systems into the general Haystack implementation. From the query perspective, it possible through Haystack to build a "multiplexer" that selects information systems that directly match the users needs, and a method of combining the results. From the indexing side, we can build tools to centrally maintaining a data repository. This functionality will allow for the hybrid-search mechanism we are aiming for. Figure 1-3 reflects the goal of breaking up a query into different components
Figure 1-3: The Hybrid-Search query model
for processing by the optimal information system.

This revised model splits the information system into three parts: $I_1 + C_1$ (the IR system), $I_2 + C_2$ (the database), and $I_3 + C_3$ (the hypertext system). Additionally, the model creates two new functions:

- A Multiplexing function, $M(q^f) \rightarrow q^f_1, q^f_2, q^f_3$ which routes different parts of the original query to the information system(s) best suited to deal with it.
- A combination function, $\Sigma(r_{21}, r_{22}, r_{21}) \rightarrow r_2$ which merges the results of the different compression functions into one result set.

If it is not entirely clear yet what type of query a user could issue to such a system it may be helpful, in conclusion, to provide some examples of hybrid-search type queries (which independent information systems would not be able to answer):

- Which documents do I have about four legged animals that I wrote last year?
- Which web pages did I visit after looking at the MIT homepage last week?
- Which email did I send to David in regards to his request for clarification on Lore?

1.3 Thesis Overview

This thesis proposes that:

1. The hybrid-search system should map well to how we believe individual humans want to query.

2. Our hybrid-search system should provide more efficient query mechanisms then hybrid-search emulation on any one of the other tools independently.

3. Our system should demonstrate an efficient mechanism for storing the semistructured information used in our system.
4. The system should demonstrate an efficient mechanism for extracting this information.

The next chapter reviews previous efforts and a general overview the technologies used in this thesis. Chapter 3 describes the mapping between human memory, documents, and why we believe hybrid-search will work in this domain. Chapter 4 and 5 respectively cover the implementation of the Haystack system. The data model and service model architectures are discussed respectively. Chapter 6 details the Haystack → Lore interface. Finally, chapter 7 discusses some conclusions and describes some future directions for Haystack.
Chapter 2

Background

In this chapter we will review previous efforts in information system research that may prove useful for the type of hybrid-search capabilities we will attempt in Haystack. Specifically, we will approach the previous work from four directions: unstructured search technologies, structured search technology, associative search technology, and current hybrid solutions. Finally, in Section 2.2 we will discuss the two primary building blocks for this thesis, Haystack and Lore.

2.1 Previous Work

2.1.1 Structured Search

The major contrast between unstructured and structured search is the items we are trying to categorize and index. While the unstructured IR system concentrates on the act of “indexing” across one dimension (language features), structured systems tend to index across multiple dimensions. Traditionally, unstructured search tools fall into the domain of database technology. A very good introduction to database technologies is [12].

What kind of information is structured? The easiest way to think of structured information is something one could put in a table. For example, if someone had a large compact disk (CD) collection, and wanted to be able to find certain CDs easily,
they might create a database based on a number of different dimensions: CD title, performer’s name, date released, date purchased, number of songs, song titles, etc. In setting up the database, the user would specify the dimensions\(^1\) and the data types of each dimension. Most databases provide a number of different data types for indexing. These can include, strings, characters, real numbers, integers, and esoteric multimedia and BLOB types.

Another way to look at structured search applications is in terms of metadata. Metadata, for our purposes, is information about information. That is, if the CD in the previous example is the “information” we are looking for, the dimensions by which we categorize the CD (title, performer, etc.) is the metadata. In the structured search a user generally does not know anything about the data itself, but understands (or at least has access to) the metadata. Because databases understand data types, it is possible to formulate powerful queries on information other than text. An example of this type of search is, “give me all the names of employees who make more than $30,000 a year.” Equivalently in SQL (a very structured database query language) this could be, “SELECT name FROM employees WHERE salary > 30000.” Notice that it is now possible for us to ask questions about numerical values and > sign has a significance when applied to numerical dimensions.

While it was possible to test certain mathematical predicates, most databases are incapable of judging between the semantic similarity of two items. For example, while they can tell you that “1 < 2” is true, they can’t decide if “MIT is near Harvard.” A notable exception to this are systems such as VAGUE [34] that allow for extensions to the notion of similarity by allowing additional domain and rule knowledge to be added to the database schema. Unfortunately, querying such a system is tedious and requires much interaction as the system attempts to understand what the user meant. If we look for an Italian restaurant near our house, the system will try to understand the concept of “near” and how important certain portions of the query are (i.e. is it more important that the restaurant is “near” us, or that it serves Italian food?).

\(^1\)If we look at the database as a table, the dimensions are generally the columns (i.e. title, performer, date, etc. in this case)
To take full advantage of database systems a user has to have a very good understanding of the structure of the search space as well as the query language. On the other hand, if the user does understand both the structure of the data and the structure of the query language, information can be found in fewer iterations of searching.

An additional constraint of most database systems is their inability to extend past their original schema\textsuperscript{2} definitions. That is, once a user describes the dimensions of his data this is more or less set in stone.

In summary:

- Database systems are able to generically deal with many data types.
- Database are good at deciding equality between queries,
- But they have no sense of similarity at the semantic level.
- Databases define constrained information spaces (schemes or dimensions).

\textbf{2.1.2 Unstructured Search}

The unstructured search task refers to the needs of a user when they know or believe some piece of information to exist within an object. We can also think of this type of textual search. Alternatively, we can refer to this type of search in terms of the tools intended as a solution, the Information Retrieval (IR) problem.

An example of this type of search is the case where a user may know, or at least think, that the words “Apple pie” (or some variant) exists in the object they are looking for. The user may or may not have ideas on how to find this particular piece of information. Regardless, they will generally approach the task in the same manner. The first step is to start with some textual search engine, and submit some free-text query. The query is an indication of what the user thinks the document should/will contain or more generally, what he hopes it will contain. Depending on the quality of

\textsuperscript{2}The schema is essentially the model of the data in the database (i.e. the dimensions upon which we categorize the data).
the query, the experience of the user, and the capabilities of the information retrieval (IR) system, a useful result may be returned to the user.

IR research has a long history in computer science. Starting in 1950 with H.P. Luhn’s KWIC indexing system[28], researchers have endeavored to create computerized retrieval systems for bibliographic and “full text” applications. A very good general overview of IR technology is available in [41]. What will prove to be both a boon and a problem for IR systems is the intense efforts made by the research community to address issues of textual indexing.

The general idea behind trivial IR systems is the use of an inverted file index which maps words to their source documents. Much experimentation has been done to provide optimal data structures for this task. These include anything from hashtables, to B-trees, to more esoteric structures. The goal, of course, is to provide an efficient (i.e. $O(1)$ or some other low order) lookup operation. When a user issues a query for $word_1 \cap 1word_2$, the IR system will look up the set of documents containing the word $word_1$ and then the set of $word_2$, and find the intersection of the two sets. This type of fairly simplistic IR system is called a boolean IR system. Boolean systems generally have a number of operators based on their namesake, Boolean logic (i.e. ANDs, ORs, NOT, etc.).

Other systems, which are of more interest to us, are the “fuzzy” IR systems. A fairly simple example is a boolean system with ranking. Essentially, when the IR system evaluates the boolean query, it will rank the returned documents based on the number of conditionals the document satisfies. A much more powerful ranking system is the vector-based IR system. In very simple terms, documents are projected into $n$-dimensional\(^3\) vector space. When a query is issued a vector corresponding to the query terms is created and thrown into the document vector space. The IR system then uses a metric to find the vectors that are the closest to the query vector. These metrics include cosine measures (angle between the query vector and document vectors) and Euclidean distance among others. The theory behind this approach is

\(^3\)Where $n$ corresponds to some subset of words in the given language (i.e. “Apple” is one dimension, “Bowl” another, etc.)
that documents with high co-occurrence of words cluster together, and queries that share terms with those documents imply that the documents are related to the query. The exact methodology for this approach is not necessarily the driving factor for its discussion. Rather, the general concept, that IR systems produce fuzzy matches is of greatest importance. IR systems, being oriented towards the indexing language features, have evolved to capture semantic information about documents.

IR systems are judged by a precision-recall metric. Precision is simply:

\[
\frac{\text{The number of correct answers returned}}{\text{The total number of answers returned}}
\]

Recall is defined as:

\[
\frac{\text{The number of correct answers returned}}{\text{The number of correct answers in the system}}
\]

Correct implies that something, or more precisely someone, has made the judgment that a certain document matches a certain query. A human will inevitably have a different view of “correctness” of a certain document based on a semantic understanding of the material. It is therefore necessary for IR systems to contain the ability to work “fuzzily” in a way that creates some semantic, rather than purely syntactic, understanding.

The semantic information derived by IR systems is by no means “intelligent.” For the most part it has some statistical basis or was derived by some rule based heuristic. Statistical mechanisms include the elimination of low entropy words (i.e. words that are not useful in distinguishing between documents). Additionally, IR systems have been developed that provide relevance feedback and machine learning functionality that allow the system to improve its results over time. These algorithms create the appearance of semantic understanding by observing human operation. In the rule based algorithm tool kit, IR systems hold thesauri (for indexing not only the word, but its synonyms) and stemming algorithms (for breaking a word down into its root and indexing by the root).

The unfortunate side effect of complex IR system behavior is the inability to handle certain queries. For example, what can we do if we wanted to index a document by
add additional features such as author, or date? We can of course emulate this behavior to some extent. We can place the phrases “author: David” and “date: 01/01/99” at the beginning (or end) of the document, and allow the IR system to index the terms. Furthermore if we wanted to have one document imply a relation to another, say a citation to a document name document1, we can add the text “cites: document1.”

We call the concept of implementing one information system on top of another (in this case database and hypertext on top of IR) an emulation system. When we want to find all papers written by David about “oranges” we could make the query: “author: David’ AND ’oranges’.” The IR system (assuming it is capable of finding phrases and not just words) will quite possibly return the right thing. Such a query works for the reason that an IR system is capable of matching text to text. However, what happens when we want to find all documents about oranges written between 12/15/98 and 1/13/99? We are no longer able postulate such a query. Even though the IR system can provide us with fuzzy answers, these are fuzzy in terms of text and not numerical values. Searching against different data types is not a forte of IR systems.

In summary:

- IR systems are oriented towards language features
- IR systems have a refined sense of similarity between queries and text documents (i.e. they have some sense of language semantics).
- IR algorithms are optimized for text indexing.
- IR system responses are fuzzy. They return probable matches based on some heuristic.

2.1.3 Associative “Search”

Interestingly the first attempt to describe a personal information assistant described what would later lead to the large body of hypertext research [9]. In his essay, As We May Think, Vannevar Bush asked his readers to
Consider a future device for individual use, which is a sort of mechanized private file and library. It needs a name, and to coin one at random, "memex" will do. A memex is a device in which an individual stores all his books, records, and communications, and which is mechanized so that it may be consulted with exceeding speed and flexibility. It is an enlarged intimate supplement to his memory.

The memex Bush describes is a mechanical device for building associations between "documents." Subsequently a number of efforts were made to produce such as system in the digital domain, most notably, Douglas Engelbart's system AUGMENT/NLS (oN Line System)[14]. Although both Bush's and Engelbart's visions were for the individual human, Hypertext developed in a different direction. As explained previously disk space and bandwidth were a commodity, and systems built tended to have an emphasis on institutional knowledge representation. To this day, especially with the advent of the WWW, hypertext systems tend to be used to display one specific view that is produced by the hypertext creator. The associations created between objects generally satisfies the author's agenda, and not necessarily anything the reader could conceive.

So what exactly do hypertext systems do for us? Most systems allow for the creation of named "links" between documents. These links imply relationships between the documents that a user may traverse to get from one document to another. The claim is that associations would seem to be more valuable than mere indexing because humans think in terms of associations [9]. Hypertext systems therefore allow humans to explicitly describe relationships between documents that may not have been derived by a machine. In the case where the hypertext system is in fact entirely text (rather than hypermedia) a number of proposals [2] [4] devise a method for generating links on-the-fly.

However, while hypertext systems are good for browsing, on their own, they are usually ill equipped for searching purposes.

In summary:
Hypertext systems are good for explicitly defining connections between documents.

Hypertext systems are good for browsing a document corpus from a certain perspective.

Hypertext systems would seem to replicate the same type of model humans use for remembering.

Hypertext systems are not necessarily useful for easily finding things (unless the path is known).

2.1.4 Hybrid-Search

Hybrid Emulation

A number of previous efforts have endeavoured to create a hybrid-search solution by emulating one type of system on top of another. In [38] and later in [17] a model is described to extend standard relational algebra to allow Non First Normal Form ($NF^2$) relations. Such a system allows for nested information in a relational databases and the necessary power to emulate some IR behavior need more info on $nf2$. This approach is however limited to the expressiveness of relational databases and requires new implementations and new query languages to function. Some databases allow for extension by the user and in [30] a database is extended using abstract datatype (ADT) to allow for textual indexing. However, this system only provided boolean queries to be performed against the data.

In [21] a method is described for using standard SQL to emulate a ranking IR system. This is achieved by creating additional database tables holding TFIDF$^4$ tables. The argument is that such a solution is more efficient and cost effective than either creating a new type of database or utilizing both an IR and database system

$^4$TFIDF is $\frac{term\_frequency}{document\_frequency}$ and is simply a way to measure the number of times a word appears in a document vs. in all the documents. This measure is then used to judge relevance of a document to a query.
separately. Such a system, unfortunately, suffers from the limitation of the database in handling text specific heuristics (stemming, thesaurus) as well as IR system features such as relevance feedback, and vector based indexing/retrieval.

A similar, albeit Oracle\(^5\) specific, experiment is described in [13]. Most databases will endevour to satisfy a set of so called ACID\(^6\) properties. By utilizing an ACID satisfying database (i.e. Oracle), a consistency is ensured between the text of the database and other structured information. Although in this specific case the database emulates an IR system (rather than using IR heuristics and algorithms), such an approach is generally refered to as a tight coupling. Tight coupling implies that the consistency is maintained between the IR and database systems.

Although tight coupling is achievable even when the IR and Database systems are separate there is a cost in efficiency. The hybrid-search model we propose will be loosely-coupled and we will not enforce atomic transactions on both the database and IR systems. Rather, a lazy updating scheme ensures that the information represented by the two information systems will converge over time for any given document.

**Loosely-coupled Hybrid-Search Solutions**

Although in some cases it is attractive to emulate an IR system through a database, generally an approach that links two independent systems proves to be the more popular choice.

A number of systems have approached the query and data fusion problem between disparate information systems using centrally managed domain knowledge. Systems such as [5] utilize domain knowledge to dispatch queries to the appropriate destination and merge the results. This assumes a formal specification of the properties of different systems.

Researchers at the University of Massachusetts, Amherst have perviously suggested a model for intergrating the INQUERY IR system with an Object Oriented database (OODB) in [10] and with a relation database [42]. Another attempt was also

---

\(^5\)A commercial database manufacturer, see [http://www.oracle.com](http://www.oracle.com).

\(^6\)(A)tomicity, (C)onsistency, (I)solation, and (D)urability
made by a different group [22] to integrate INQUERY with the Sybase SQL database. All three approaches relied on a specialized query language that was preprocessed by a mediator and submitted to either the IR system or the database. Unfortunately, all three database systems require a pre-defined schema for the database and are not readily extensible. The combination we propose will allow for dynamic shifts in the structure of the database.

2.2 Technologies

2.2.1 Haystack

Over the past two years our research group has worked to implement the first version of the Haystack personal information repository system [2]. As of August, 1997 the first version, written in Perl, was released for public review. The system implemented a number of our design goals, the most abstract of which was to provide the users of our system with a repository that implements both intelligent storage and retrieval of arbitrary data. Although we are currently limited to textual representations of the data, anything on the user’s hard drive or on the Internet should be fair game for becoming an entry in the user’s Haystack repository. A user can easily organize and find information in their repository at a later time. To facilitate these operations, Haystack will make an effort to extract a textual representation of the data object, object metadata, and allow users to annotate the object. In the future, we hope that we will not need to be reliant on “textual representations” and be able query images or sounds. However, for the most part, we are dependent on the technologies of today.

At a more detailed level, Haystack consists of a number of core modules. User interface modules (which currently include a personal web server, command line, and Emacs) provide access to the system. Textifiers provide the machinery to extract text from a variety of file formats. Field finders extract metadata information about a given object. Finally, Haystack provides modules that interact bi-directionally with information retrieval (IR) systems. If any textual information is derived from the
object, Haystack can index this information in any basic information retrieval system. We want this abstraction because different IR systems will represent their data differently and present different query options to users. This includes anything from basic Boolean operations (such as “all documents that contain ‘MIT’ and ‘Artificial Intelligence’”), to more complicated relevance ranked schemes (i.e. “documents that are most strongly related to MIT and Artificial Intelligence”).

As noted above, Haystack extracts both text (through textifiers) and metadata (through field finders) from data objects it encounters. Metadata includes anything from the automatically generated checksum field, to the user generated comment field.

2.2.2 Lore

Although Haystack provides us with the interface to a variety of information retrieval systems, it is necessary to find a suitable database and hypertext system. We were lucky to discover a system that would provide us with a capability for both built-in. The Lightweight Object REpository (Lore) system from Stanford’s database group [32] is a DBMS capable of querying and indexing semi-structured information. This ability satisfies our need to store objects that do not have a pre-defined schema. Lore is an extension to the Object Database Management Groups (ODMG) database standard. The language used to interact with Lore is known as Lorel (Lore language) [1] and extends the Object Query Language (OQL) language (which in turn extends the SQL standard).

Lore data structures are based entirely Object Exchange Model (OEM) objects. These data structures can take on atomic values such as integer, real, string, etc. OEM objects can also be complex. Complex OEM objects contain named links to other OEM objects. Additionally, all OEM values carry a unique ID (OID). The structure formed by a Lore database can therefore be an arbitrarily complex graph structure.

We will return to the specifics of Lore when discussing its integration into Haystack (see Chapter 6). However, as some basic knowledge of Lore is required for the next chapter, some examples may help. Figure 2-1 is a sample graph of a Lore database.
Figure 2-1: A Sample OEM Graph
The text on the connections between OEM nodes indicate the named relationship between the parent (the higher node) to the child (the lower node). The number inside the nodes is the OID of the object. The atomic values for those OEM that have them are shown below the node in italics.

There are a number of important things to note about the graph structure we generated. The first thing to notice is the ability of OEM objects to hold any number of “children” of a given type. By not pre-defining a schema we can connect any number of named links to an object (Address for example). Additionally, it is the link which is named (i.e. is of a specific type) rather than the object it points at. This gives us the ability to connect to a number of objects with the same link name regardless of how the objects are represented. For example, one of the Address nodes for the “Eytan” object is a complex OEM object pointing at three other OEM objects: Street, City, and Zip. The other Address object is an atomic object with a string component. Finally, we note the ability to explicitly name objects, and to set points to those objects.

Figure 2-2 is the corresponding textual OEM model that is used to generated the graph. An OEM “object” consists of a link name followed by some value, between the signs < and >. For example, we create the Name node by specifying: <Name ‘‘Eytan’’>. To create a complex object, we place the “children” in braces: <linkName {oemObject1, oemObject2, ...}>. Finally, we can name objects by using placing a name followed by a colon in the OEM “constructor.” For example: <AD1: Address ‘‘NE43-309’’> binds the name AD1 to the object pointed at by the Address link (i.e. NE43-309). To point at a named object we use the ampersand followed by the name of the object. For example, in the “Mark” object, we point the Address at AD1 by using: <Address &AD1>. It is not necessary to use the same link name in pointing to the same object. We could have, for example, said: <Office &AD1>. This would have created an Office link pointing at the NE43-309 object.

Now that an OEM representation has been created, it is possible to start asking Lore for information about this structure. The Lorel query syntax looks surprisingly like SQL.
<HaystackPeople::HaystackPeople {
   <GroupMember {
      <Name 'Eytan'>
      <AD1: Address 'NE43-309'>
      <Address {
         <Street 'Freeman St.'>
         <City 'Brookline'>
         <Zip 02146>
      }
      <Supervisor &Lynn>
      <Supervisor &David>
   }
   <GroupMember {
      <Name 'Mark'>
      <Address &AD1>
   }
   <Lynn: GroupMember {
      <Name 'Lynn'>
      <Phone 2663>
   }
   <David: GroupMember {
      <Name 'David'>
      <PhoneNumber '6167'>
   }
}

Figure 2-2: A textual representation of the OEM graph
The variable $a$ is the view we want to take of the returned data (i.e. how much of the data we want to see). The data we query against is limited to the set $b$, and we impose additional constraints with the predicates $c_1$. For example we can issue the query:

\begin{verbatim}
select X.PhoneNumber from HaystackPeople.GroupMember X
where X.Name = 'David'
\end{verbatim}

This statement creates a set $X$ of $GroupMembers$, we then constrain the set to those group members whose $Name$ is David. Out of the result set, we select the object pointed at by the $PhoneNumber$ link. In this case, we return “6167.” A slightly more complex example is:

\begin{verbatim}
select X.#.Phone% from HaystackPeople X
where X.GroupMember.Name = 'David'
\end{verbatim}

The two characters # and % are wildcard characters. The # is a path wildcard character which will match any link name. In the above examples the # evaluates to: $GroupMember$ (only a single path in this example). The Phone% means that we are looking for links starting with the string Phone. In this case, Phone and PhoneNumber both satisfy the requirement. However, the where clause limits us to the “David” $GroupMember$, and we again return “6167.” A complete specification of Lorel is available in [1].

The final aspect of Lore that requires some discussion is the concept of DataGuides [19]. Lore has the built in ability to take a snapshot of the current database and produce a new database representing the schema of the original. Such a tool is highly useful for visualizing the domain in which a user can query. A user can, for example, fill in different fields within the graph in order to perform a query against the
database. This would allow a user to perform queries without necessarily understanding the structure of the database. A DataGuide for the graph before is represented in Figure 2-3.
Chapter 3

A Tale of Paper and Straw

Before we can continue with a discussion of the implementation of hybrid-search in Haystack, it would be advantageous to understand exactly why hybrid-search is an appropriate method for representing documents. This chapter will create a model based on document state. By analyzing the structure of this model, and the type of queries a user may invoke against it, a data model for Haystack will be developed.

3.1 Documents

To understand the purpose of this thesis, it is important to understand the information we are trying to operate against. While we call these objects simply documents, the term is loaded with meaning. This chapter, among other things, will discuss the philosophical (as well as more reality-grounded) aspects of documents[7].

There has been much research of the nature of documents, and an all encompassing study of these definitions is well beyond the scope of this thesis. For our purposes we can condense a number of definitions to give documents following definition: “A source of information in any form which is archivable.” This broad definition applies, therefore, to all media formats as long as they maintain some sort of persistence. It is notable, however, that Haystack functions best on documents with some text form.

With this definition of documents it is now possible to explore the nature of documents. We make the additional argument that documents are composed of stateful
properties and relations. We can then leverage this state represent documents within Haystack in a manner that allows for improved searches.

**Document State**

We are now ready to define a new model for documents, which will be called the *document state model*. A document can be seen as an entity present at some point in time. The document as a unit has some state within that instant of time. This document will also have some properties and relations. The properties of the document and its relationship to other documents can also be seen as units of information with state.

![Figure 3-1: A breakdown of document state](image)

Figure 3-1 illustrates this model of document state. Some portions of the document state can be derived automatically, others by semantic interpretation of a user when reading the document. We can separate the document state into three constituent parts (based on properties and relations):

- **Internal State** Properties that are of this type generally refer to the content or internal representation of the document. For example we can say that a document *contains* the word “apple.” Generally, things that are part of the internal state of the document are properties we can define by looking inside the document. These properties may be non-obvious, and may be derived by some semantic understanding of the document\(^1\).

\(^1\)We make this claim even though semantic understanding is partially based on comprehending
• **External State** Properties that can be considered meta-data are generally held as part of external state. The author, date of publication, and date are good examples of external state. However, it is important to note that properties are not necessarily exclusive (i.e. a property can be part of more than one state). For example, the author of a document can be “David” by virtue of the fact that we know that David wrote it and emailed it to us. This knowledge is part of some external state. By reading the document we can find that it is “by: David.” So we have derived an authorship relation by Semantic understanding, and so the author being “David” is also part of the internal state.

• **Relative State** There are a set of fuzzy properties of a document that encapsulate relationships between one document and another. One document can cite another or link to it. These relationships can be derived automatically by scanning through a document (i.e. find all hyperlinks). However, the relationships can also be semantically derived by a user observing the object. For example, one document can be related to another by virtue of the fact that the reader read both while eating a chocolate ice cream cone. As stated before, we will place non-trivial properties in this category.

The final important idea to consider is that state of a document may change. We will make the claim that documents present state is also a function of its previous states. For example, while a document (call it *myThesis*) may have been located on goose.lcs.mit.edu, it may have subsequently moved to haystack.lcs.mit.edu. A user looking for document *myThesis* by constraining his search system to the previous location may come up empty handed if the system does not remember that the document used to be on goose.lcs.mit.edu. Any piece of state that has previously existed may be of importance to the user who will later look for the document based on this previous state. Additionally, the more expressive an implemented system can be in maintaining all the state information of a given document, the better it will be

the document in terms of other documents or concepts. If a property is semantically non-trivial (i.e. different readers of a document can conclude different values of the same property) we can add this information to the relative state information.
able to respond to user queries.

### 3.2 Straw

Now that we have a basic understanding of the document domain, we can turn our attention to developing a model for data in Haystack. Abstractly, our goal is to map what we have learned from memory and document models into usable data structures.

When discussing the query model previously (see Section 1.1.1, we found two components that were part of every query, the information need, and hints. These hints were used by the person to narrow down the results produced by the Information system to match the information need. In Haystack we would like to be able to handle three distinct types of hints:

- Hints based on document content
- Hints based on document metadata
- Hints based on relationship between documents

These of course map to the three components of document state described above. Alternatively, they also map to the three information system types: information retrieval, databases, and hypertext, respectively. Table 3.1 describes the relationships between all the models we are trying to describe. From left to right, the models described become increasingly concrete. The document model represents ideas that will become instantiated in the Straw model we will presently describe. Our motivation is to build an efficient and useful implementation that most accurately maps our abstract models into reality.

Now that we have a goal in mind, it is possible to begin to build a model representation. First, it is important to note that we are working in an object-oriented environment. We define objects to be instantiation of a particular class. A class is a definition of an object containing both data members and methods. Data members and methods simply correspond to variables and functions. Classes can be extended
Table 3.1: The relationship between the different models in a hierarchical fashion, where an extension inherits certain public data members and methods of its ancestors. The Haystack data model is essentially a graph structure where the nodes (vertices) and ties are first-class objects\(^3\). Both ties and nodes extend a specific class. In adherence to our namesake we call this class Straw. Straw will be discussed in great detail in Chapter 4, but for now regarding Straw objects as nodes will suffice.

\(^3\)First-class can be named, exist on their own, and be passed to, and returned by functions.
The graph structure in Figure 3-3 is a possible (but simplistic) representation of Straws. This model shows Document straws connected to a variety of other objects: publisher, title, author, date, as well as other documents. We will also make the claim that there are three types of connections between straws: *inter-document ties*, *intra-document ties*, and *term ties*\(^4\).

Intra-document ties represent a mapping to what we have previously called the external state or metadata of an object. For example, we can connect an author node to the document node by means of an intra-document tie. To partition different documents we will also draw a virtual foundry around clusters of straws connected by intra-document ties and call this a *document cluster*. In the figure we see one central document node for each document cluster. In Haystack we call this document node a *HaystackDocument* object. The nodes that have some associated data with them we will call a *Needle*\(^5\). For example, we can have an author node/Noodle which contains the data “David” (with the obvious implication that David is the author). We’ll return to both of these objects in Chapter 4 when we describe the implementation of Haystack data model in full.

Inter-document ties represent associations between different document clusters. For example, if one document cites another, we can draw the cites connection between the two. Alternatively, if one document is a web page that ties to another, we can use the relation “ties to.” This, of course represents the hypertext aspect of the system.

Finally, term ties allow us to connect terms held within the document to the document cluster. That is, if the word “dog” appears in a document, we connect a node holding the word dog to to the document by means of a term tie.

With this model, we are now capable of describing documents in a way that appropriately maps the memory and document models. We propose that it is now possible to both describe objects and to query for them in a powerful manner that is consistent with the way humans think and represent information in mental models.

---

\(^4\)As stated before, ties are first class objects defined by the class Tie, but we’ll ignore that for now to keep the model simple.

\(^5\)Needle in a haystack, get it?
as well as in the "real" world.

Hybrid-Search

Although the straw model described above is a powerful one, querying it is an inefficient and difficult process. Queries to this type of network structure are a complex graph-isomorphism problem. Essentially, when a user makes a query they are trying to map a sub-graph they construct mentally to the full graph structure. For example looking for a document by Bob written in January about Apples is the graph consisting of a document node connected to an author node (with the content Bob), a date node (with the content January) and a term node (with the content apples).

However, we need not despair. It is now time to re-introduce the specialized information systems described previously, and begin to build efficiency into the system.

The first task is to combine the term nodes into an efficient data structure. It is here that IR systems come to the rescue. With an IR system in hand it is now possible to take the term nodes and merge them into the inverted file hash table which full-text IR systems are famous for. This shift is described in Figure 3-3. In this figure we see all the term nodes merged into an inverted file, with the appropriate pointers from the file to the remaining document clusters.

The second task involves the optimization of the remaining ties into a queryable structure. The two types of information systems, databases and hypertext systems, would seem to be the best answer. However, we recall that Lore allows us to build both types of systems into one. Figure 3-4 shows this final transformation between the abstract Straw structure to the concrete Lore model described previously.
<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Computer</td>
<td>1.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dog</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fruit</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Inverted File

**Figure 3-3: The Implemented Straw Model I**

**Figure 3-4: The Implemented Straw Model II**
Chapter 4

The Haystack Data Model

This chapter describes the general system architecture of the Haystack Data Model. Although we will try to avoid it, this chapter will make some references to Java specific constructs. There are a number of good references that may be of assistance to the reader.

4.1 General Overview

The Haystack architecture can be described in two distinct parts, a Haystack Data Model (HDM) and a Haystack Service Model (HSM). The data model is the means by which we represent the user’s information space, and the services (for the most part) append or process the data in some fashion. This chapter discusses in great detail the building blocks of the Haystack system. Specific details on issues such as persistent storage and object creation will be touched upon briefly here, but will be discussed fully in Chapter 5.

As described in Chapter 3 the abstract representation of the Haystack data model (HDM) is that of a directed graph with first class edges and vertices. Vertices and edges are typed, and the typing information also semantic information about the

\footnote{Specifically, Sun’s Java Web site, at \url{http://java.sun.com}, contains a number of useful references.}
structure. For example, we can have a \texttt{bale.HaystackDocument} \footnote{\texttt{bale.HaystackDocument} is a special node type that is an anchor for any objects a user adds to Haystack (see section 4.6).} node attached to a \texttt{needle.Location.URL} \footnote{The naming convention we will use in referring to specific Straw types is: \texttt{strawGeneralClass.strawSpecificInformation}, where \texttt{strawGeneralClass} will be \texttt{needle}, \texttt{bale}, or \texttt{tie}. There is also an implicit \texttt{haystack.object} Java package prefix appended to all the objects. For example, the full path for the class \texttt{needle.Author} is \texttt{haystack.object.needle.Author}.} node. The \texttt{needle.Location.URL} has some content associated with it (let's say http://web.mit.edu/). The implication then is that the URL of this particular \texttt{bale.HaystackDocument} is http://goose.lcs.mit.edu/. Nodes in Haystack are called Straws. All Straws are created with a unique identifier associated with them (see \texttt{HaystackID} below). The way to think about this model is in terms of associations. As discussed previously, we are attempting to model the same type of associations that correspond naturally to the document state model. With the HDM it is then possible to represent both the metadata associations between objects (i.e. the URL of a document, the author of a thesis, the date the picture was deleted), as well as the associations between documents (i.e. the two documents that I wrote about oranges). Figure 4-1 illustrates some of these relationships.

The HDM sample structure illustrates the use of the three main Straw components: bales, ties, and needles. Recall the Straw model described in the previous chapter depended on three types of ties connecting nodes. In implementing Straws in Java these tie types are created implicitly by the objects the connect. For example, to bind Straws to one document cluster (i.e. by an \textit{intra-document tie}) a \texttt{bale.HaystackDocument} object is created, and all Straws associated with the same document cluster are attached to that \texttt{bale.HaystackDocument}. \textit{Inter-document ties} are created simply by attaching two \texttt{bale.HaystackDocuments} together. To create the \textit{term ties} a \texttt{Needle} \footnote{Recall, a \texttt{Needle} is content bearing Straw} with text is attached to the Bale.

As stated previously, ties (or as implemented: Ties) are also first class objects. Specifically, Ties are an extension of Straws with a number of extra features (discussed in section 4.4). Additionally, because Ties are first class, we can apply metadata and relations to links and not just nodes. In the figure above the \texttt{tie.Filetype}
Figure 4-1: A sample Straw structure
was created (specifically a FileTypeGuessService). To make this fact obvious a 
**tie.Creator** is attached to the **tie.Filetype** object with the creator’s name at-
tached to that.

It is important to note that all objects are derived from a primary interface. A 
Java interface contains the method signatures of all functions that are required to be 
declared by any class that implements that interface. The particular primary interface 
in Haystack is known as **haystack.object.Weavable**. All Haystack data objects are 
defined within the Java package **haystack.object**. Other defined interfaces include 
**TieWeavable**, **NeedleWeavable**, and **BaleWeavable**. This chapter will discuss each 
of these interfaces in turn as well as their basic implementations. We will also discuss 
the model by which we add new nodes to the HDM.

### 4.2 The Mile High View

Before we begin the discussion of specific interfaces and class implementations, it is 
important to have a high level view of the different objects in the HDM. We also wish 
to describe the naming convention for HDM objects more fully. Figure 4-2 represents 
the package hierarchy for HDM objects. There are 4 important interfaces in the 
HDM:

- **haystack.object.Weavable**: The basic interface which all other HDM objects 
  implement or extend. (see section 4.3). Classes that implement this object 
  directly usually reside in the **haystack.object** package.
- **haystack.object.TieWeavable**: This is the interface for HDM link objects. 
  (see section 4.4). Classes that implement this object reside in the **haystack.object.tie** package.
- **haystack.object.NeedleWeavable**: This is the interface for HDM primitive 
  objects (see section 4.5). Classes that implement this object reside in the 
  **haystack.object.needle** package.
- `haystack.object.BaleWeavable`: This is the interface for HDM collection objects (see section 4.6). Classes that implement this object reside in the `haystack.object.bale` package.

![UML diagram of the Haystack object package structure](image)

Figure 4-2: A UML diagram of the Haystack object package structure.

It is possible that in the future new core packages will defined to encapsulate other functionality. However, the framework defined for Haystack Data Model Objects makes this a trivial step.

**Object Typing**

As stated previously, the type of the object carries information that implies relationships between Straws. For example, given a `bale.HaystackDocument` connected to a `needle.Filetype.Postscript`, the data associated with the `bale.HaystackDocument` is assumed to be of type “postscript.”
Originally, Haystack was designed with a mechanism for dynamically adding new object types to the HDM. If there was not a class definition (in the Java sense) for an object, a “generic” Straw would be created with the appropriate type field set to the new value. This approach unfortunately caused a breach of abstraction barriers and the strong typing enforced by Java. Until a Haystack type checking mechanism is implemented, a more modest approach was necessary.

All objects defined within the HDM models have an associated Java implementation. The Java implementation can be a simple stub, and does not need to provide any additional functionality. It is not necessary to recompile any portions of Haystack to add new Straw sub-types, but it is necessary to compile the stub.

The other fundamental invariant of the HDM model is the package/class hierarchy. To extend one Straw class, a package is created with the Straw name in all lower case letters. All extensions to the original Straw are placed within that package. For example, in Haystack we have a generic needle.Filetype object (notice the upper case). Let us also assume that we have some agent (human or computer) that is interested in all Postscript files that enter into a Haystack. If needle.Filetype was the “deepest” we went, the agent would have to check inside every single needle.Filetype to decide which are Postscript and which aren’t. This would seem to be a waste as we’ve already decided which documents are Postscript and which can make this more obvious to interested agents. This is achieved by creating the package, needle.filetype (notice the lowercase). We can then create the class, needle.filetype.Postscript, which will reside in this package and “extend” the needle.Filetype object. The Postscript specific Needle can still be casted (i.e. converted) to a needle.Filetype, but it is now possible to tell what the Needle will contain by just looking at the type information of the object.

The only other requirement for extensions of the HDM is that all Straws must extend an object residing one level higher in the package hierarchy. Formally: ∀ classes a.b...i.j.K ∃ class a.b...i.J, where {a,b,c,...,z} are parts of a package path and {A,B,C,...,Z} are class names. In our previous example, for needle.filetype:

5With the exception of the base classes, Bale, Tie and Needle

54
type.Postscript to exist, needle.Filetype had to exist.

The StrawType Class

To simplify the handling of type information, Haystack includes the haystack.object.StrawType class. This class includes a variety of static utility functions that make conversion between types and traversal of Straw hierarchies a trivial operation.

The main functions provided by StrawType are provided in Appendix B. StrawType also provides a list of some of the predefined Straws available in Haystack in a compact representation. Haystack provides a service for creating objects dynamically. To invoke the create operation the programmer must pass in the full classname for the object he wishes to create. However, as the class names for Straws tend to be long, StrawTypes ease the programmers job by creating obvious shortcuts. So for example, instead of passing in “haystack.object.needle.filetype.Postscript”, the static value StrawType.PostscriptTypeNeedle is passed. The shortcuts currently defined within StrawType are described in Table 4.1 (more will very likely be added in the future).

<table>
<thead>
<tr>
<th>AdditionalLocationTie</th>
<th>Bale</th>
<th>BodyNeedle</th>
<th>BodyTie</th>
</tr>
</thead>
<tbody>
<tr>
<td>CausalTie</td>
<td>CcFieldNeedle</td>
<td>ChecksumNeedle</td>
<td>ChecksumTie</td>
</tr>
<tr>
<td>DateFieldNeedle</td>
<td>Directory</td>
<td>DirectoryNeedle</td>
<td>DirectoryTypeNeedle</td>
</tr>
<tr>
<td>DviTypeNeedle</td>
<td>EmailTypeNeedle</td>
<td>FileTypeNeedle</td>
<td>FileTypeTie</td>
</tr>
<tr>
<td>FromFieldNeedle</td>
<td>FrommailTypeNeedle</td>
<td>GifTypeNeedle</td>
<td>GZipTypeNeedle</td>
</tr>
<tr>
<td>HaystackDocument</td>
<td>HTMLTypeNeedle</td>
<td>LastArchiveNeedle</td>
<td>LastArchiveTie</td>
</tr>
<tr>
<td>LastIndexNeedle</td>
<td>LastIndexTie</td>
<td>LatexTypeNeedle</td>
<td>LocationNeedle</td>
</tr>
<tr>
<td>LocationTie</td>
<td>MailfieldNeedle</td>
<td>MailfieldTie</td>
<td>MessageIDFieldNeedle</td>
</tr>
<tr>
<td>MessageIDNeedle</td>
<td>Needle</td>
<td>PostscriptTypeNeedle</td>
<td>RMAILNeedle</td>
</tr>
<tr>
<td>RmailTypeNeedle</td>
<td>SubjectFieldNeedle</td>
<td>SummaryNeedle</td>
<td>SummaryTie</td>
</tr>
<tr>
<td>TextNeedle</td>
<td>TextTie</td>
<td>TextTypeNeedle</td>
<td>Tie</td>
</tr>
<tr>
<td>ToFieldNeedle</td>
<td>UnknownTypeNeedle</td>
<td>URLNeedle</td>
<td>UUETypeNeedle</td>
</tr>
</tbody>
</table>

Table 4.1: Shortcuts available within StrawType.
4.3 The Weavable Interface and the Straw Class

Every node and link type in our system originates from the Weavable interface. By providing one default interface and implementation it is possible to design components of the system that will accept arbitrary node and link types. Additionally, the Weavable interface provides a number of vital methods including the usual constructors, accessors and modifiers for efficiently dealing with our object model.

The primary implementation (in Java terminology) of the Weavable interface is the haystack.object.Straw class. All derivative nodes and links extend (again, Java terminology) the Straw class. The Straw class contains two important data members, two StrawTies objects and a HaystackID object. One of the StrawTies objects maintains the pointers in the forward direction (i.e. Straws pointed at). The other maintains pointers to the back objects (i.e. Straws pointing to). We’ll return to this shortly.

The Straw class is extended in a variety of ways, but is never instantiated on its own (that is, we never have an object of type Straw in a HDM graph). The key methods provided by the Weavable interface and implemented by Straw are described in the subsequent sections. StrawTies are also important in understanding Straw structure so I short overview is provide here.

StrawTies

The two StrawTies objects provide a one-to-many mapping between keys, and other Haystack objects. This essentially provides us with a method to maintain the list of “edges” that any vertex is attached to. StrawTies therefore represent the function \( f \), where \( f(s) = \{\text{TieWeavable objects}\} \), where \( s \) is a string label.

StrawTies are internally implemented as two Hashtables. One table maps a key to set of pointers (in the Java sense), and the other contains the mapping between a key and the HaystackIDs (see below) of the objects. In order to save the HDM structure persistently we serialize\(^6\) (see Section 5.3.5 each Straw object to save on

\(^6\)Java serialization allows for an object, and its state, to be converted into a byte stream which
disk. Because the Java serialization mechanism will save not only the object being serialized but any objects that the serialized object points at, it is necessary to break apart **Straws** before saving them. Maintaining the two **Hashtables** is an optimization that allows us to break apart and reassemble **Straws** easily.

We enforce the following invariant: let each vertex of the HDM graph (the **Straw**) possess a function, $f_1$ which accept as input some key, $k$ and produce a set of connected edges, $A$, labeled $k$. Let $f_2$ map some key $j$ to a set of identifiers, $B$. Then $\forall$ keys $k, j, k = j$, $\exists$ $a$ in $A$ and $b$ in $B$, s.t. $a.getID() = b$.

**StrawTies** provide a subset of the features of the Java Hashtable. The function `getVal(label)` returns the Vector of values with the given label. To place a new element into the table, `put(key,value)` is used. Alternatively, `remove(...) ` and `removeKey(...)` allow for pointers (i.e. edges) to be removed. `getAllLinks()`, `getIDs()`, `isEmpty()`, and `toString()` perform obvious functions.

### 4.3.1 Straw Constructors

Straws are created by one central process (**HsObjectCreatorService**, see Section 5.3.1). This process ensures that the constructor for Straws is invoked properly. Specifically, this means generating a unique identifier for the Straw in the form of a **HaystackID**.

**The HaystackID Class**

When deciding on the specifics of the HDM, it was clear that a method to uniquely identify nodes within the graph would be highly useful. By tagging Straws with a unique identifier services could quickly access different portions of the graph and the keeping track of the state of the special **Straws** within Haystack would be easier.

In order to guarantee that our identification scheme was scalable enough, the actual identity information is encapsulated inside a **HaystackID** object. Currently, the internal representation for **HaystackIDs** is the `java.math.BigInteger` class. `BigInteger` allows for arbitrarily large integer values, which is sufficient for maintaining
uniqueness within a given Haystack. In the future, when Haystacks interact together, additional user-specific information will need to be added.

The HaystackID class currently provides for a number of operations to extract the "low level" representation of the identifier, but use of these should be limited, and possibly prohibited in the future. The class also defines a number of comparison operators for judging equality between two identifiers. Because each Straw is assumed to be unique, the test for equality between two Straws is done simply by comparing the two HaystackIDs.

4.3.2 Straw Modifiers

The main modifier operations provided by Weavable are systematic methods of connecting and disconnecting objects.

When directly connecting a Straw to a Tie, the Straw class provides methods to attachForwardLink(...) and attachBackLink(...). These functions directly add the pointer to the appropriate StrawTies object.

When connecting two objects that have some relationship to each other, say a bale.HaystackDocument and a needle.Title, the HDM model calls for the connection to be done by means of a Tie. This is true for a connection between a Bale and a Needle, between two Needles or two Bales. When attaching a Needle (say a comment about a Tie) to a Tie, this is done by means of a third Tie. This is due to the first class nature of edges in the HDM graph.

In designing an interface for dealing with the HDM objects it became obvious that a substantial amount of the time a programmer wants to connect two objects directly without concern for the intermediate Tie. To facilitate this, Straw provides two functions attachForwardObject(...) and attachBackObject(...). Both functions generate the intermediate Tie object and perform all the necessary adjustments to connect the two Straws. Ties are generated in a somewhat "intelligent" fashion. That is, a Tie is selected that most closely matches the object it is connecting. For example, if a needle.filetype.Mail object is to be attached to a bale.HaystackDocument, the attachForwardObject() operation will find the first valid object in the
tie package that most accurately represents the needle. The first thing the function checks is if there exists a `tie.filetype.Mail`. If that fails, the function attempts to create a `tie.Filetype`. If after crawling up the hierarchy, no match is found, a basic Tie object is created to connect the two Straws.

Straws also provide a mechanism to detach links (`detachForwardLink(...), detachBackLink(...)`). Use of these should be avoided as the HDM so reflect changes over time, but they are provided for adept programmers who require such modifications to the HDM graph.

### 4.3.3 Straw Accessors

The Straw class provides numerous functions to traverse the HDM graph space. `forwardLinksOf()` and `backLinksOf()` return all edges propagating from the current Straw in the forward and backward directions respectively. Similarly `getForwardLinks(label)` and `getBackLinks(label)` return the links under a given label. For example, in Figure 4-1, invoking `forwardLinksOf()` on the topmost `bale.HaystackDocument`, the set: `{tie.Body, tie.Text, tie.Author, tie.Title, tie.Location, tie.Filetype}` is returned, or more specifically, the set of pointers to these objects is returned.

The functions `getAllForwardObjects()` and `getAllBackObjects()` skip the intermediate Tie objects between the current Straw and what is attached to it and returns all the “destination objects.” `getAllBackFilteredObjects(label)` and `getAllForwardFilteredObjects(label)`, filter the `getAll...Objects()` function and return only objects with the given label. `getLastForwardObject(label)` and `getLastBackObject(label)` filter the edge names and return most recent (i.e. the last) edge with the given label. The function `depthFirstSearch()` returns a list of objects traversed in a depth first search originating at the current Straw up to a given depth. In figure 4-1, `getAllBackObjects()` invoked on the needle.filetype.Postscript node will return the set: `bale.HaystackDocument,needle.Text`.

Straws also provide methods to access the ID of the object (`getID()`), get the “supertypes” of the Straw (`getSupertypes()`), and to get the “type” of the current
Straw (getTypeString()).

Finally, Straws provide functions to generate a string representation of the object (toString()), as well as a method of generating a text representation (toText()) that we will index in the Information Retrieval System. So for a needle.mailfield.Tofield containing “eytan@mit.edu,” toText() will simply return “eytan@mit.edu.” On bale.HaystackDocument objects we don’t necessarily have text of their own we can call getIndexable() which will get the text of objects we point at.

4.4 The TieWeavable Interface and Tie Class

The basic link interface is defined in TieWeavable, and implemented in the haystack.object.Tie class. The Tie class extends the Straw class. This means that some functions are overridden and functions unique to links are implemented.

TieWeavable provides the following methods: setForward, setBack, getForward, and getBack. Ties are different than standard Straws in one major way: in their jobs as links they connect two, and only two nodes. While it is possible to add fields to Ties (such as needle.Creator, or needle.Comment), Ties maintain a single back pointer and forward pointer that is separate from the StrawTie objects. This idea is represented in Figure 4-3. It is noteable, however, that Ties override the get...Links() functions so that they will not only include the links held within their StrawTies but also the link held within their “specialty” pointer field. In the sample figure, a Straw (1) points another Straw (3) by means of a Tie (2). The label used within the two Straws matches the type of the Tie. Similarly, the Tie (2) is connected to another Straw (5) by means of yet another Tie (4).

The benefit of the single back/forward pointer property is that it disambiguates the intention of the Tie. It is easy to determine what nodes the link connects and what nodes are associated with the link in some other way (as before, the example is a comment on the link).
Figure 4-3: A sample Tie cluster.
The tie.Causal Class

There are a number of special Ties extensions implemented within Haystack, the most important of which is tie.Causal. The class tie.Causal does not implement any additional functionality, but we are interested in its use for the sake of the implicit information it provides in its type.

The use of tie.Causal is fairly simple. If a Straw A was created because of a Straw B, then we connect the two (starting at A) with a tie.Causal. For example, if we have a needle.Location that points at some file somewhere, and we retrieve the file and create a needle.Body to hold the bits, we draw a tie.Causal connection between needle.Body and needle.Location. This shows that the text exists because of the needle.Location. More examples of this are illustrated in Figure 4-1.

4.5 The NeedleWeavable Interface and Needle Class

An important issue that we have so far glossed over involves the content of Straws. NeedleWeavable and their implementation Needle provide us with the mechanism for holding actual "data." One could say that these Needles represent atomic values within the Haystack graph. However, calling them "atomic" is slightly misleading. Needles have the same functionality as Straws in their ability to be linked from and to by other Straws. They are atomic in that they provide wrappers around pre-existing data (such as files, database entries, web pages, etc).

This difference should be obvious to those with knowledge of database systems. However, we extend the concept of database primitive from the usual set of strings, ints, reals, etc. The Haystack data model primitive provides a wrapper around any conceivable data type. For example a needle.Text represents a wrapping around a particular bit of digital text. An needle.Date may wrap around a long representation of the date.

To access this information, NeedleWeavable defines the getData method. The return type of getData is of the Java Object class. Therefore it is up to the programmer to cast the Object to a more specific type. So for example, postscript-
Needle.getData() may return a String, or an integer, or some other primitive type. The setData(...) operation of the Needle will also take as argument an Object. However, the Needle programmer may throw a NeedleDataException if the data is not castable to the required format. For example, if the Needle is supposed to hold a long, and is passed a String: “foo bar mumble,” a NeedleDataException is throw.

It is our hope that this flexibility will not cause great difficulties to the programmers and users of our system. By properly specifying the behavior of all nodes we hope that the added functionality will allow for a richer set of services and applications.

The Promise Class

Because the data of the Needle is also loaded into memory at the same time as the Needle, we do not want (for example) a 10Mb+ Postscript file loaded into memory. Instead we create a Promise class. The Promise class holds one function, fulfill() which returns a Reader (a Java stream type). It is the programmers job to implement the details of the fulfill() class for their particular “promise.”

As an example, consider the case of some user creating a needle.Body that is supposed to hold a large Postscript file. The file resides on disk somewhere. Instead of setting the data field within the needle.Body to the bits of the Postscript file, we can set it to a special Promise class that holds the name of the file location. WhengetData() is invoked on the needle, the Promise is returned, and when fulfill() is invoked on the Promise the bits of the Postscript file are dynamically loaded from disk.

Some Promises are designed to do “actual” work. For example, a Promise held within a needle.Text may actually extract the text from some other location on-the-fly. Re-running the Promise is highly inefficient, so in Haystack we provide the means for caching promises (see Section 5.3.6).
4.6 The BaleWeavable Interface and Bale Class

In the initial design of the Haystack data model we have made the decision to include an interface for nodes that represent collections. The only obvious use for this Straw extension (aside from the implicit typing information) is the ability to override certain Straw functions to provide ordering. For example, in Haystack, when a query is invoked a `bale.QueryResult` object can be generated pointing at the Straws that satisfy the query. What we note, however, is that query results are usually ordered based on some relevance metric. In invoking the `getAllForwardObjects()` for the `bale.QueryResult` object, we want the ordering maintained. This is achieved by overriding the `getAllForwardObjects()` to order the data based on some other information (i.e. a list of results and scores).

The `bale.HaystackDocument` Class

There is one Bale extension that is truly a vital building block for the HDM graph. As stated previously, we would like to group all the properties of a given document inside some “cluster.” This is achieved by the use of the `bale.HaystackDocument`. This class does not implement any additional functionality beyond Straws, but serves the important purpose of marking document clusters in Haystack.
Chapter 5

The Haystack Service Model
Architecture

The bulk of functionality within Haystack is done by objects in the Haystack Service Model (HSM). Abstractly, Haystack can be viewed as standard three-tiered architecture consisting of three different layers, a user interface layer (the client), a server/service layer, and a database. Figure 5-1 represented the layers (and components within the layers) graphically.

This chapter primarily concerns itself with components of the service layer. The Haystack service layer consists of a number of services and the Haystack Data Model (HDM) objects running within the context of one HaystackRootServer.

Figure 5-1 illustrates some of the relationships between services in Haystack. As stated previously, services run within the context of one HaystackRootServer. There are services that provide interfaces between the user and the indexing and archiving subsystems. There are services that provide utility functions for other services. For example, a name service allows for communication between services, and a resource control service provides the mechanism for the locking of arbitrary named resources. There are services within the HaystackRootServer that "listen" for changes in the HDM. When those changes happen, the services are notified and they act upon the data.
Figure 5-1: Abstract inter-service communication model
5.1 Service Architecture

For those with an understanding of CORBA[31] the internals of the service layer should be fairly straightforward. The Haystack service model utilizes an architectural framework that borrows a number of important ideas from the OMG specifications for CORBA.

In the Haystack notation, just as in CORBA, services are merely objects that act as clients, servers, or even peers. A service encapsulates a specific functionality behind a well defined interface. This functionality can be readily invoked from any other service. A session can be represented as follows (see figure 5-2):

1. In the first step, service A and B are both loaded (i.e. they are instantiated) in the HaystackRootServer (see below). In this case it is the same HaystackRootServer, but as we shall see, this isn’t necessary. Both services invoke the register() method of the HsNameService (see below), with an abstract version of their name (represented by the ServiceName class).

2. In the second step, service A wishes to communicate with service B, so A will generate the ServiceName object for B, and submit a getService() request to the HsNameService. The HsNameService will respond with a pointer to the instantiated version of B running within the HaystackRootServer.

3. In the final step service A can now communicate with B. For now, it is assumed that A knows which methods B has made public. In the future services will be implemented as JavaBean objects [25] that define an introspection method (so that A can dynamically decide how to call B).

5.1.1 Service Types

The services loaded into the HaystackRootServer (discussed in Section 5.2) fall into a number of categories:

- Basic services (Section 5.3) provide a number of vital functions necessary for maintaining the basic functionality of the Haystack. These include:
Figure 5-2: Abstract inter-service communication model
- **HsNameService** (Section 5.2.2) a built-in naming service to initiate inter-service communication.

- **HsObjectCreatorService** (Section 5.3.1) a service that dynamically creates new Haystack data objects.

- **HsDispatcher** (Section 5.3.2) a service that defines relationships between Haystack data objects and services that are interested in them.

- **HsConfigService** (Section 5.3.3) a service that loads other services based on some user configured options.

- **HsResourceControlService** (Section 5.3.4) a service to provide locking on VM external objects

- **HsPersistentObjectService** (Section 5.3.5) a service to provide permanent storage of HDM objects

- **HsCache** (Section 5.3.6) implements the mechanism for Promise caching described in the previous chapter.

- Other base services (Section 5.3.7) are included for debugging and logging a variety of messages (these include **HsDebug**, **HsMessage**, and **HsError**).

*Interface services* (Section 5.4) provide the mechanisms for external processes to talk to Haystack. These include: socket/stream communication services, an RPC service, and a WWW server.

- **Middleman** (Section 5.4.1) This is slightly different service as it does not extend the **HsService** class. It provides an RPC communication for inter-VM communication.

- **HsCommandAPI** (Section 5.4.2) A service to allow dynamic loading of “commands” that are exposed to external processes.

- **HsCommunicator** (Section 5.4.3) In order to communicate with Haystack from a non-Java program we provide a socket based protocol for communicating (on a limited basis) with Haystack services.
- **HsCommandLine** (Section 5.4.4) A simple interactive command line into Haystack

- **Event driven services** (Section 5.5) provide the import function of responding to data as it enters a user’s Haystack. By expressing interest in specific graph structures these services are notified of changes to those graph structures. Once invoked they are free to augment the Haystack data structure in some fashion. Examples of this type of service are the text convertors and field extractors.

- **“Data manipulation” services** (Section 5.6) include services to general control services that allow for archiving and querying.
  - **HsArchive** (Section 5.6.1) allows new documents to enter into Haystack.
  - **HsIndex** (Section 5.6.2) derives textual information for documents and “pushes” the information into an Information Retrieval system.
  - **HsQuery** (Section 5.6.3) facilitates queries between user interface components and Information Retrieval system.

- **Data layer (interface) services** provide the interfaces necessary to communicate with the variety of information sources Haystack uses (currently IR systems and Lore). A sample IR interface is described in the context of HsIndex (Section 5.6.2). The interface to Lore is described in Chapter 6.

- **Automatic services** work in their own thread space within the HaystackRoot-Server doing pre-programmed tasks. These include services that pre-fetch new documents, or recreate the Haystack indices. Currently, there are no services that qualify as automatic services, but facilities for their creation have been included in the Haystack code (including timer objects that “wake up” automatic services at specified intervals).

- **Proxy services** actively attempt to watch the user interact with various external processes. For example a WWW proxy will observe the user’s interactions with
their web through their web browser.\footnote{At the time of this writing a WWW proxy service was in the process of being developed, but formal specifications are not yet available}

\section{The HaystackRootServer}

The Haystack system depends on the instantiation of the \texttt{HaystackRootServer} object. This object performs much the same functionality as the object request broker (ORB) does in CORBA. The \texttt{HaystackRootServer} object automatically starts itself with a number of services.

The \texttt{HaystackRootServer} is instantiated in one of two modes, root, and non-root. A user is always assumed to be running one \texttt{HaystackRootServer} running in root mode. The server running in “root” mode causes a number of event driven services and the HDM objects to be loaded into the VM’s memory space. HDM objects are currently loaded only into a root \texttt{HaystackRootServer} as Haystack does not currently support a concurrency model robust enough to allow for manipulation of HDM structures outside of the main \texttt{HaystackRootServer}’s scope. However, in Section 7.1 we recommend a method that will allow the active transfer of HDM objects between VMs.

A non-root \texttt{HaystackRootServer} is used for the purposes of loading services that need to run outside the root-VM. For example, if a user has multiple computers and wishes to archive the files on both into one Haystack, they can run a non-root \texttt{HaystackRootServer} with an archiver service. All data then gets aggregated to the root \texttt{HaystackRootServer} and indexed with the data from the other computer. For services that need to decide if they are running under a root or non-root context, \texttt{HaystackRootServer} provides a static method, \texttt{amIRoot()} to answer that question.

To successfully create a \texttt{HaystackRootServer}, a user must both instantiate and initialize the \texttt{HaystackRootServer} object. Instantiation is done through the standard \texttt{new} operator, and initialization through the \texttt{init()} procedure of the \texttt{HaystackRootServer}. It is important to note that the \texttt{HaystackRootServer} utilizes the singleton
pattern[18] to insure that only one copy of the server is running in a given VM. The init() method takes a configuration file, and an optional port as arguments. The port is used for binding the Middleman service, and the configuration file is routed to the HsConfigService for further processing. The HaystackRootServer, furthermore, will invoke the init() procedure on the HsNameService as well as the HsConfigService (these are the two essential services we need to bootstrap). Additionally, we can terminate the HaystackRootServer by calling the close() method which will close the HsNameService.

The only other vital function of the HaystackRootServer is the ability to statically call for a number of the bootstrap services. Table 5.1 shows the static data member in the HaystackRootServer and its corresponding value.

<table>
<thead>
<tr>
<th>Static variable</th>
<th>Points at</th>
</tr>
</thead>
<tbody>
<tr>
<td>myNameService</td>
<td>The HsNameService running under this HaystackRootServer. This allows us to lookup any service not in this table.</td>
</tr>
<tr>
<td>myConfigService</td>
<td>The HsConfigService, holds global settings</td>
</tr>
<tr>
<td>myDebugger</td>
<td>HsDebug, a tool for debugging Haystack</td>
</tr>
<tr>
<td>myErrLogger</td>
<td>HsError, a tool to deal gracefully with errors</td>
</tr>
<tr>
<td>myPersistentStore</td>
<td>The HsPersistentObjectService</td>
</tr>
<tr>
<td>myObjCreator</td>
<td>The HsObjectCreatorService</td>
</tr>
<tr>
<td>myMsgLogger</td>
<td>HsMessage, for non-error messages</td>
</tr>
<tr>
<td>myDispatcher</td>
<td>The HsDispatcher, so that new services can register themselves.</td>
</tr>
<tr>
<td>myCounter</td>
<td>The HsCounter service generates unique IDs</td>
</tr>
<tr>
<td>mySendable</td>
<td>The appropriate Middleman object for this root server.</td>
</tr>
</tbody>
</table>

Table 5.1: Static variables within HaystackRootServer

5.2.1 The HsService Class

All services, except the Middleman, extend the HsService class. This is necessary in order to guarantee some interface for all services. Since we are not as flexible about modeling our services in IDL (as in CORBA) we need to ensure some sort of base behavior that will allow us to dynamically load services. All services are implemented within the haystack.service package.
On instantiation, the HsService class will register its ServiceName (see Section 5.2.2) with the name service. Furthermore, as we have stated above, HsService guarantees the existence of the init() and close() operations for loading and unloading. All services that need to provide some sort of startup and/or shutdown operations can overload these methods.

5.2.2 The HsNameService

The first important bootstrap service, beyond the HaystackRootServer object is the HsNameService which is loaded on initialization of HaystackRootServer. The idea is that one service can ask the HsNameService for a pointer to another service. The returned pointer can be "cached" by the querying service (so that calls to the HsNameService are at a minimum). The HsNameService maintains essentially one table. The table contains two fields: name, and service pointer.

The ServiceName field refers to the name of the service. This name is unique to the Haystack in question, and is persistently maintained with the service. So if there are two services that load information from the Internet (so-called fetch services), they can be named fetch1 and fetch2, and the names will be bound to the particular code. If there is a collision between two names, the second service with the same name will not be loaded and the user of the system will be notified of the failure. It is therefore the programmer’s responsibility to insure that names for services are unique. Naming is an issue elaborated on below.

The service pointer field simply contains a pointer to an instantiated (in the Java sense) version of the service object. The table entry for this fetch service would therefore look like:

Service Naming

The naming scheme described above is unfortunately incomplete. It does not address a number of problems arising from the application of the design to the implicit goals of Haystack. Specifically, it becomes difficult to ensure that new services can be
created, or existing services are optimized in a dynamic function. This is due to the inflexible nature of "naming" services. What we would like instead is to be able to "describe" services.

The reasoning for this extended definition is as follows. Within the context of a single user Haystack system, if a certain service serviceFoo is upgraded in such a way that the results from version 1 of the service are not the same as version 2. It would therefore seem that we should maintain both versions of the service, in which case what do we mean when we talk about serviceFoo? the new or the old? Our concept of flat naming breaks in this case. A quick fix is changing the way in which we assign names. The original serviceFoo is called (from creation on) "serviceFoo v1.0," and the new version is "serviceFoo v2.0."

Unfortunately, as soon as we switch to a multi-user environment we get a different flavor of the same problem. Specifically in dealing with services created by different users but having the same local name, say “serviceFoo v1.0.”

To solve the more general problem we introduce the notion that an object’s name is actually a set of metadata that define the characteristics of the object. This metadata is in no way as complicated as the Haystack object model, and is constrained to a given set of properties. Currently we believe the properties that are formally attached to the object’s “name” are:

- **name**: This is the general, human readable name of the service (i.e. serviceFoo).

- **version**: The version of the service (i.e. “v1.0”). There is no specified format for this. Each service can maintain it’s own numbering scheme as this will increase the likelihood that collisions will not occur between like-named services.

- **creator**: The exact syntax of this is an open issue, but a possible option in the first implementation is the email address of the service implementer. If the service is part of the core Haystack package, the creator field will state “system.” To preserve our ability to add additional packages to Haystack at a later time, “system” and any strings derived from it (i.e. “system.foo”) are reserved creator names.
In addition there are a set of metadata items that are important or useful, but are not important for naming (in its pure definition). These as well as other fields can be added to future versions of Haystack:

- **service type:** this is the fuzzy notion of what function the service performs. For example we can have a number of services that serve as interfaces to IR systems. Therefore the type of these objects is "IR system interface." The exact method of classification is an open issue.

- **function signature:** This describes the input/output behavior of the "main" function of the service. With the function signature, we can ask for all services that have a certain function and invoke them. For example, if the services have a cleanup() procedure, a cleanup daemon can collect all services that have this procedure and invoke them.

- **cost:** the monetary cost of using the service, usually 0.

- **trust:** a value assigned by the user as to the trustworthiness of information returned by the service.

- **reliability:** a value assigned by the user to indicate the reliability of the service in responding (i.e. how reliable the network connection is to the service).

It is very likely that we will find more features that we want to describe services by, but for now these will suffice.

What we implicitly achieved by introducing the service metadata concept is the ability to map a description to a service rather than a name. We argue that the three primary fields for service naming partition the set of all services into single service sets. That is, there will most likely be only one service that maps to a given name, version, and creator. Beyond this, we have made our HsNameService a powerful system. It is now able to ask questions such as: "give me all services that are of type 'IR interface service' and cost 0."

We can also improve our quality of service when answering user's queries to information needs. For example, if a user makes a query for an object that has two
needle. TypeNeedle attached to it, one saying “this object is of type Postscript” and the other saying “this object is of type Text.” We can check to see which service created these TypeNeedles, then check the trust value of these services, and use these values in displaying the results in a fashion that is more useful to the user. In this example, if the service that created the “Postscript” guess is more trustworthy Haystack could pull up a postscript viewer instead of a text viewer.

The functionality we describe above provides us with a mechanism to do two types of nameservice resolution. The first, is the use of a name that is guaranteed to be unique (with high probability), primarily the “[name] [version] [creator]” triplet.

The second resolution is a “query” for services. We define a specific kind of object called a ServiceName. This class encapsulates all of the metadata characteristics of services as described above. To perform a query we create a new ServiceName and fill in the fields we know. For example, if we know that we want a query service (HsQuery) but know nothing else about it, we fill in the name field of the ServiceName with HsQuery and submit it to the HsNameService which returns a list (a Vector, specifically) of matching services. It is then up to the programmer to decide which service they want to use. It may be possible in the future to implement filters that provide some default decisions for choosing between services. For example, a filter could decide which was the newest version of the service, and return only that one.

We recommend that the HsNameService be implemented in two stages. The first utilizes the triplet naming scheme (name, version, creator) for naming and lookup. Lookups are done explicitly rather than in the database fashion described above. The second stage can complete the implementation as described above.

5.3 The Basic Services

5.3.1 The HsObjectCreatorService

One of the basic functions of Haystack is to dynamically create new straws. This task is handled by the HsObjectCreatorService service. The interface for the HsObj-
ectCreatorService is fairly straight-forward. One function, newObject(n) generates a new straw of type n (where n is a string of the fully qualified class name of the Straw, see section 4.2). The HsObjectCreatorService then uses the Java reflection API to dynamically load and create the desired object. If the class for a certain straw does does not exist, or for some reason can not be created, a NoSuchStrawException is thrown. By using the fully qualified class name HsObjectCreatorService allows for the loading of objects not directly in the haystack.object package. This is valuable as it may be desirable to keep one Haystack installation on a machine intended for multiple users. However, as users may want to generate new object types, these will necessarily sit outside the haystack.object package.

HsObjectCreatorService also serves two other important functions. First, it will contact the HsCounter to get a unique ID for the new straw. Second, it will contact the HsPersistentObjectService to register the newly created object so that storage is guaranteed when the HDM data is flushed to disk.

Future Improvements

Although it is not the direct responsibility of the HsObjectCreatorService, for reasons we shall discuss below, adding functions to dynamically generate new class files for new Straw types would be an extremely valuable addition to Haystack. This functionality can be achieved in one of two ways. Either the HsObjectCreatorService will generate the java code for the new Straw types or directly act as the bytecode generator and create the class file for the new Straw.

5.3.2 The HsDispatcher Service

A full description of the HsDispatcher is available in [6], but a general design overview is provided here. It is our intent that the HDM be expanded dynamically by a variety of tools. Essentially, we would like to implement services that express interest in some HDM sub-graph and are notified when new instances of the sub-graph come into existence, or old instances change.
We could of course engineer the services to merely listen for any event in the HDM and then decide whether or not to act on it. However, this model is highly painful for the programmer who must decide if the object that triggered the event is one of interest. It would be much more preferable to describe interest in a sub-graph. To facilitate this, Haystack includes the HsDispatcher service. HsDispatcher acts as an intermediary between event driven services and the data model.

There are two orthogonal aspects of the HsDispatcher’s job. The first is to distinguish between the events triggered in the HDM. The second is to distinguish between structures in HDM. Events can be enumerated (as we do below), but the general graph isomorphism problem is NP-hard\(^2\). Therefore, allowing services to express interest in arbitrary graph structures would prove infeasible. Rather we concentrate on what we call star graphs.

**The StarGraph Class**

In order to express interest in a specific subgraph, a service instantiates a StarGraph object with information about the desired structure. Star graphs in Haystack are much more limited that a standard “star graph.” Within Haystack, we define a star graph to consists of a central node. To the central node we can have any number of Tie objects, and to each of these Tie objects we specify to which Straw they connect to.

An example may help in understanding this. The HsTypeGuesser service has the task of deciding the type of an object. Type can be guessed by two methods, heuristic methods that analyze the file name or Uniform Resource Location (URL) or heuristic methods that analyze the content of the document\(^3\). The HsTypeGuesser is then interested in a bale.HaystackDocument object connected to a needle.Location.URL and a needle.Body object. Graphically, this corresponds to Figure 5-3.

In this case, we don’t actually care what the two type of the two Ties are.

---

\(^2\) Graph isomorphism corresponds to the problem of verifying that one graph is contained in another.

\(^3\) For example, we can guess a file is Postscript if it starts with “%!.” We can also guess it is Postscript if the suffix of the file name is “.ps.”
The graph is still of interest whether the `needle.Location.URL` is connected by a `tie.Location.URL`, a `tie.Location`, or just a `Tie`. Additionally, we may wish to ask for any extension of `needle.Location` type (i.e. `needle.Location*`, where * is a wildcard character). To allow for this behaviour, the StarGraph object is instantiated not with an explicit description of the sub-graph, but rather a regular expression that models all acceptable matches. Figure 5-4 represents this graphically. Note also that we are assuming a case insensitive regular expression (i.e. `tie*` matches both `Tie` and `tie.Location`). The complete definition of the StarGraph regular expression syntax is available in [6].

---

**The HDM Event Model**

Now that we have an understanding of the type of structures we are trying to observe, what type of events are we waiting for? The following are the events generated by the HDM and their meaning:

---

\(^4\)When specifying a regular expression \(s^*\) means we want a string \(s\) followed by 0 or more characters
A HaystackEvent is generated for changes in the structure of the graph. Specifically, there are two extensions to HaystackEvent:

- Whenever a change in graph structure happens (as indicated by the setting of both the “forward” and “back” pointers of a Tie) a HaystackCreateEvent is issued.
- When a Needle that is connected to at least one other Straw has it’s data changed (by means of a setData(...) invocation) a HaystackChangeEvent is generated.

An ObjectEvent is generated for changes and creations in any independent Straw (regardless of what it is connected to). This is useful for services that are interested in keeping track of all object changes in the HDM (for example the HsLore service will want to update each Straw entered in the database as it happens). There are three types of ObjectEvents:

- An ObjectCreateEvent is generated whenever a new HDM object is created.
- An objectDeleteEvent is generated whenever an HDM object is deleted.
- Finally, Haystack defines an abstract (i.e. non-instantiatable) ObjectChangeEvent class. This class is extended by two specific implementations:
  * An ObjectChangeLinkEvent is generated when any pointer (i.e. the pointers in Ties as well as the StrawTies in Straw) are changed.
  * An ObjectChangeDataEvent is generated when a Needle’s data is changed.

5.3.3 The HsConfigService

One of the most important design concerns for Haystack is the customizability of the system for the preferences of a given user. It is important to provide a single point of entry for configuration of a wide variety of services. To this end, Haystack
includes a configuration service, \texttt{HsConfigService}. A baseline implementation of the \texttt{HsConfigService} is discussed below, as well as possible improvements for added flexibility and scaleability.

Currently, Haystack defines the following format for configuration files:

\begin{verbatim}
  Key, Val_1 Val_2 Val_3 ... Val_n
\end{verbatim}

This format is \textit{very} simplistic, and does not allow for any comments or repetition of keys. Each \texttt{key \rightarrow value(s)} mapping must reside on a separate line. Values are assumed to be separated by single spaces. Examples of keys are: \texttt{HAYLOFT} (the location of the user’s Haystack repository), \texttt{ObjectStore} (the file used by the persistent object store), and \texttt{CacheDirectory} (the directory in which to maintain cached information).

\texttt{HsConfigService} currently provides only two interesting interfaces: \texttt{getVal(n)} and \texttt{getVal(n,i)}. The first returns the Vector of values corresponding to the key \texttt{n}. The second returns the String corresponding to the \texttt{i}th value for key \texttt{n}. Both return exceptions if the key is not found (see appendix C).

The only other functional part of \texttt{HsConfigService} is the initialization routine which ensures that the user’s Hayloft directory exists. If not \texttt{HsConfigService} will create it, and check for read/write permissions.

\textbf{Future Improvements}

As the \texttt{HsConfigService} is currently implemented in the most simplistic functional model possible, some future improvements are discussed below. The first major improvement would be in the format of the configuration file. This file should allow for added robustness (in terms of allowed keys and values). Ideally, services in Haystack should be able to construct a set of rules for configuration items they will require. This rule could then be passed to the \texttt{HsConfigService} and it, in turn, would confirm that the key/value mappings it has loaded from disk adhere to the restrictions of the rules.
An example rule would be (as proposed by the HsPersistentObjectService to
the HsConfigService): “Make sure the ObjectStore key exists, and has one textual
value.” Another example may be: “make sure that key foo can be read as an integer,
and that it has one of the following values: 1,5,7.” Once Haystack has a wide variety
of services, the exact scope of the rules will become evident. It should then be possible
to formulate a rule language for services.

Finally, a user interface that allows for changes and explains the properties of
different keys would also be invaluable.

5.3.4 The HsResourceControlService

Although it is possible to implement synchronized methods within the context of a
single Java VM by means of the synchronized key word, it is impossible to guarantee
locks outside that scope. To allow for locking Haystack includes a resource control
service, HsResourceControlService. This service allows for locking and unlocking
of arbitrarily named resources. Locks are held maintained for a certain amount of
time (currently 5 minutes).

The methods currently implemented by HsResourceControlService are:

* testResource(n) which returns true if the resource n is locked, and false oth-
erwise.

* unlockResource(n) forces an unlock of the resource n. HsResourceControl-
Service doesn’t verify that the caller has the “right” to do this.

* lockResource(n) tries to lock the resource n. If the lock was successful it
returns true, if the attempt to lock timesout, false is returned.

* nonBlockLock(n) tries to lock the resource, and immediately returns (i.e. there
is no timeout).

The HsResourceControlService internally maintains an extension to the Hash-
table class called ResourceControlHash. The ResourceControlHash maintains a
list of current resources as well as a list of their timeouts. The ResourceControlHash maintains the synchronization necessary to ensure atomic lock functionality.

Future Improvements

As with most of the Haystack services, a number of improvements can be made to increase the functionality of the HsResourceControlService. Specifically, it would be value to provide some sort of deadlock detection or two-stage locking. The HsResourceControlService could easily maintain some sort of ordering on the resources.

By holding some function \( r \) mapping resource names uniquely to some sortable value (i.e. \( r(name) = i_{name} \), where \( name \) is the resource name, and \( i_{name} \) is the unique value for that \( name \)). Instead of merely invoking the above functions with the a resource name, services would also send a pointer to themselves. The HsResourceControlService could then maintain a list of resources held by each service, and only allow a new lock to be allocated if \( r(newName) > r(mostRecentLock) \). Releases are done in reverse. The function \( r \) would, of course, need to be predefined.

5.3.5 The HsPersistentObjectService

Once we have created HDM objects it is vital that we be able to save them persistently to disk and reload them between Haystack sessions. To this end, Haystack provides a HsPersistentObjectService class.

HsPersistentObjectService is built using a very simple model. Within the service a Hashtable is maintained mapping HaystackIDs to Straws. When a new object is created, the method register(...) is invoked by the HsObjectCreatorService. The new Straw is placed in the Hashtable. To save the Straw to disk HsPersistentObjectService makes use of a Java implementation of a standard DBM package developed by the WWW Consortium for a Java based web server[44]. In Haystack we extend the DBM functionality to a handle the serialization of Java objects. HsPersistentObjectService will pass the (key,value) pair of (HaystackID, Straw) to the
DBM package. The DBM will serialize the Straw (i.e. transform it into bytes), and save it to disk keyed on the HaystackID. Recall from the discussion of the StrawTies implementation that the Straws “break” apart from the HDM structure on serialization. This ensures that objects are saved and loaded independently (rather than in complex subgraphs).

If a service requests an object from the HsPersistentObjectService by means of the `getObject(...)` method, the HsPersistentObjectService will first check in its cache for the object. If the Straw exists in the Hashtable it is immediately returned. Otherwise, an attempt is made to retrieve the object from the DBM database. If that fails, an exception is thrown (ObjectNotFoundException). If the object is loaded from disk and reconstructed, it is placed in the cache and returned to the requesting service.

Because Straws are “disassembled” for saving, it is necessary to reconstruct all the pointers once the object is loaded from disk. To do this, Straws contain a boolean variable called loaded. If loaded is set to false, the Straw will repeatedly call the HsPersistentObjectService to obtain all the pointers to its outgoing edges. Recall, this is achievable because Straws always retain the HaystackIDs for outgoing edges.

**Future Improvements**

One of the fundamental problems of the HsPersistentObjectService is its inability to clean its cache. This leads to the constant growth of the memory requirements of any running Haystack session. As it is impossible to count the number of services holding a pointer to any particular Straw we can never be certain if it is safe to remove the Straw from the cache. If we removed the Straw and someone modifies it at some later point, the change will not be saved. The simple solution is to rely on the Java garbage collection mechanism which will eventually remove a Straw that nobody is holding from memory. Unfortunately, as long as the cache holds the Straw, it will never be garbage collected.

Fortunately, Java 1.2 provides a new type of object reference (pointer). These references are known as “weak references.” Weak reference objects maintain a pointer to an object. If nothing else has a strong reference (i.e. is holding a pointer) to
the object, the garbage collector can remove the object from memory. If the HsPersistentObjectService cache maintained only weak references to the Straws the garbage collector could still remove the object from memory and allow the Haystack memory footprint to remain manageable.

5.3.6 The HsCache Service

As discussed in Chapter 4, the HDM at times makes reference to external sources of information. This allows the HDM to remain compact in size, but still robust enough to handle the variety of objects that a user may want to archive.

Recall, that the Promise classes provide the mechanism for “re-generating” Needle data dynamically. This is inefficient, however, if the the same Promise is repeatedly asked to generate the same data. As a solution, Haystack provides a mechanism for caching data created by a Promise. Optionally, a programmer may modify the getData() operation for a Needle so that as data is being generated by the Promise it is simulatenously being sent to disk for temporary caching. The Needle requests this disk space by calling the allocateCache(key) command on the HsCache, where key is the Needle’s ID.

When HsCache receives a request it returns a special extension of the Java stream Writer class, CacheFileWriter. This extension overrides a number of the Writer’s functions so that the HsCache can check to see if the cache space is in use.

After the Needle has placed the data in the cache, it can request that the HsCache open a Reader to that cache space (a Promise holding Needle returns a Reader when getData() is invoked). This reader is also an extension to the standarad Reader class and is called CacheFileReader. As data is read using the CacheFileReader the “life” of the item in the cache is extended. As soon as data is not being actively read, the file will be removed after a period of five to ten minutes.
5.3.7 Other Base Services

The HsDebug, HsMessage, and HsError Services

As the HaystackRootServer allows for a multitude of services to run concurrently, it was necessary for us to create a mechanism by which we could log errors and messages. This would prevent the user from being barraged with a variety of status and error messages that might be a normal part of the system’s function. The three services, HsDebug, HsMessage, and HsError provide this functionality through a very clean interface.

All three of these services extend the LoggerService (in the haystack.service.misc package). This service provides the basic functionality which allows messages to be printed to any arbitrary location (i.e. file, screen, etc.). Every time the print() command is invoked on any of the three services above (with the invoker and message as arguments), the LoggerService pretty prints the message to the appropriate location. Both HsMessage and HsError are trivial extensions to this. HsDebug, on the other hand, provides a slightly more complex set of functions.

The customary way to debug an application has usually consisted of setting some boolean value (call it debug). When you want to debug your application you set the value to true. Inside your code, the programmer ordinarily places conditionals: if (debug) then print out some stuff to STDERR or STDOUT. HsDebug provides a much more refined debugging manager. A user can set debugging on for anything as fine grained as a class. Within a class, the class developer can call the function print() on the HsDebug service. The arguments to print() are the reference to the object being debugged (i.e. the this in Java), and the message to print. Someone who is debugging the system can tell HsDebug, by means of the debugClass() method which classes they are interested in debugging (to turn this off you would use the method unDebugClass() with the class name as an argument).

Now, whenever print() is invoked, the HsDebug service checks to see if debugging is turned on for the invoking class. If it is, the debugging message is printed. HsDebug also allows the programmer to set where the debug messages are printed to. The
method toScreen() resets messages to System.err (i.e. STDERR).

5.4 The Interface Services

5.4.1 The Middleman

This section provides a very basic introduction to communication between two HaystackRootServers. The full implementation details for the Middleman are available in [6].

When initially selecting to work in Java it was necessary to decide how inter-process communication was to work in Haystack. Specifically, because Java processes run within the context of a Virtual Machine (VM), some mechanism is needed to communicate between processes running in separate VMs. For example, Haystack specifies that a user always have one central HaystackRootServer. Perhaps this HaystackRootServer is running on the user’s computer at home. If the user needs to query his Haystack from work, it is necessary to be able to interact with the main HaystackRootServer remotely. Additionally, as Haystack begins to support collaboration inter-VM communication will become a vital necessity.

The Middleman technology facilitates this inter-VM communication by implementing a form of remote procedure call (RPC). Java provides a built in method called Remote Method Invocation (RMI) for inter-VM communication. However, this implementation was evaluated to be too slow and extreme for our purposes. Additionally, RMI is only provided in some implementations of Java and may not be used in the future. Other solutions, such as CORBA and ILU[24] were too complex for our needs.

In implementing Haystack we wanted to provide a very simplistic mechanism for exporting the functions of one service so that a process running in a separate VM would be able to invoke these functions as if they were in the local VM.

The general process for this communication model is fairly simple. When implementing a service that is to have exportable functions, three versions of the service are created. The first is the interface of the service. For example if we want to have
an exportable service \texttt{HsFoo}, the interface will exist \texttt{haystack.service.HsFoo}. The implementation that does all the work will exist in \texttt{haystack.service.real.HsFoo}. The "stub" (or skeleton) implementation exists in \texttt{haystack.service.virtual.HsFoo}.

When the "root" \texttt{HaystackRootServer} is created it will load a copy of the \texttt{real.HsFoo} service and a \texttt{MiddlemanServer}. Figure 5-5 describes a simplified interaction between a service \texttt{A} running in a non-root VM with \texttt{HsFoo}.

- In step A of the interaction, the \texttt{real.HsFoo} service registers itself with the \texttt{HsNameService}. At the same time, the \texttt{HsNameService} running in the context of the second \texttt{HaystackRootServer} connects to the "root" \texttt{HsNameService} by means of a \texttt{Middleman} service. \texttt{Middleman} interaction involve the setting up of TCP socket over which serialized Java objects are passed (i.e we convert Java objects into a byte stream, send it over the TCP connection, and reassemble the bytes into the Java object on the other end).

- In step B, Service \texttt{A} asks it's local \texttt{HsNameService} for a pointer to \texttt{HsFoo}. \texttt{HsNameService}, after deciding that \texttt{real.HsFoo} object is running in the root \texttt{HaystackRootServer}, will instantiate a \texttt{virtual.HsFoo} object.

- The \texttt{HsNameService} will pass the pointer to the \texttt{virtual.HsFoo} object back to Service \texttt{A} in step C.

- In step B, Service \texttt{A} can now call the functions of \texttt{virtual.HsFoo} just as it would when communicating with the \texttt{real.HsFoo} object. The \texttt{virtual.HsFoo} object will then pass the method name and arguments it receives to the \texttt{Middleman} which in turn will pass the arguments to the \texttt{MiddlemanServer}, and these get applied to the \texttt{real.HsFoo} objet. The results are passed in the reverse direction.

The actual model for the \texttt{Middleman} is much more complex and allows for multiple connections between VMs and a more complex method for passig "packets" between the VMs.
Figure 5-5: Abstract inter-service communication model
5.4.2 The HsCommandAPI Service

Because we would like to see Haystack extended and used by non-Java systems the Middleman is not a perfect solution. In addition to the Middleman we introduce the HsCommandAPI service. This service allows users to create a set of "scripts" (in Java) that are invokable from external processes by means of a textual command. The command scripts (which are of type Command) reside in the haystack.object.command package.

At any point after instantiation, it is possible to call the register() method on the HsCommandAPI with a Command object as an argument. Once an object is registered it is possible to invoke it through the HsCommandAPI. Abstractly, what we now have is a service to allow for virtual method invocations. This invocation is done by means of the invoke() method which accepts a string as an argument. The string is usually in the form (optionally with a new line at the end):

```
Functioni Arg1 Arg2 Arg3 ... Argn
```

Arguments are seperated by a white space character. For multi-word arguments, HsCommandAPI allows for the use of either quote or doublequote characters to specify the beginning and end of a multi-word string (i.e. 'this is a multi-word argument'). Additionally, HsCommandAPI handles a number of special characters:

<table>
<thead>
<tr>
<th>Character</th>
<th>Evaluates to:</th>
</tr>
</thead>
<tbody>
<tr>
<td>\t</td>
<td>tab</td>
</tr>
<tr>
<td>\n</td>
<td>new line</td>
</tr>
<tr>
<td>\r</td>
<td>return</td>
</tr>
<tr>
<td>\f</td>
<td>form feed</td>
</tr>
<tr>
<td>\x</td>
<td>x (i.e. any other character)</td>
</tr>
</tbody>
</table>

Table 5.2: The interpretation of special characters within the HsCommandAPI

This leads the HsCommandAPI to invoke the Command object corresponding to the name Functioni with the set of parsed arguments. Additonally, HsCommandAPI is able to understand the special "help [functionName]" command which returns the
set of functions it is capable of handling or the usage information for a particular function (with the optional functionName argument).

The invoke() command will return the string response generated by the invocation of the specific function. If there was an error in handling the function an exception (BadCommandException) is thrown with details of the error.

The Command Class

The Command interface is fairly straightforward. It contains a limited set of methods that allow for the basic abstracted functionality necessary to fulfill their task. Currently, classes that implement Command provide:

- A name() method which returns the string name by which the specific command should be invoked.

- A commandSig() method which returns the “signature” of the command (i.e. how it should be used.

- A help() method which returns some textual information on the intent and usage of the command.

- And a fulfill() method which takes the arguments as parsed by the HsCommandAPI and either processes them or returns an error.

Haystack currently supports the following commands:

- AttachCommand (usage: attach [forward|back] HaystackID1 HaystackID2, returns: boolean) Attach allows us to connect to objects (with IDs HaystackID1 and HaystackID2 respectively). The forward/back relationship indicates the direction we want the link to take (i.e. object1 → object2 or object1 ← object2).

- **SetCommand** (usage: `set HaystackID value_to_set`, returns: boolean), this command allows you to set the values of any Needle (indicated by HaystackID) to some value (specifically, `value_to_set`). It returns 1 on success, 0 on failure.

- **TerminateCommand** (usage: `terminate`, returns: boolean) This command causes the HaystackRootServer to shut down. This is a "clean" shutdown and the `close()` function on all services gets called.

- **ViewCommand** (usage: `view HaystackID`, returns: string) View returns the string representation of the Straw with the given HaystackID.

**Future Improvements**

There are a number of obvious improvements to be made to the HsCommandAPI service. Specifically, it would be nice if commands could generate a grammar that could be compared by the HsCommandAPI to the incoming commands. That is, a Command should be able to specify it's function signature in such a way that the HsCommandAPI could perform the necessary type checking and argument checking for the Command.

**5.4.3 The HsCommunicator Service**

Now that we have a method of processing different types of external commands within Haystack we should briefly discuss the two services within Haystack that currently use the HsCommandAPI. We can view these two services as handling the "transport" layer between outside functions and the HsCommandAPI.

The first, the HsCommunicator service, acts as a network socket based interface. The service starts up within its own thread space and listens to incoming connections on a given port (5776 as the default). These connections are passed off to CommunicatorThread objects (in the haystack.service.misc package). The CommunicatorThread objects are themselves threads which allows the HsCommunicator to handle multiple calls simultaneously. The CommunicatorThread objects simply read the input from the socket and submit that to the HsCommandAPI.
There are a number of utility functions within the HsCommunicator that allow for the cleaning up of all CommunicatorThread objects. We would like Haystack to shut down when the close() operation is invoked on the HsCommunicator it will run through the CommunicatorThreads it knows about and shuts them down.

Future Improvements

The one significant improvement that should be included in future releases is the addition of a security protocol for the HsCommunicator. There is currently no way of knowing who the remote caller is. This may lead to abuse and destruction of a person's Haystack by a malicious user. When an appropriate security protocol is designed it should be fairly trivial to incorporate into the HsCommunicator.

5.4.4 The HsCommandLine Service

As not all commands need to be executed over a socket connection, Haystack provides the HsCommandLine service. This service simply sits and listens to the System.in InputStream (same as STDIN). Whenever the user types a command and hits enter, the string is sent off to the HsCommandAPI.

The only two important functions of this service are: run() which starts the service listenting, and setPrompt() which the user to change the prompt that is visible on the command line (default: "Haystack> ").

5.5 Event Driven Services

A number of event driven services are described in the next sections However, a brief summary of their design is provided here. Services interested in listening for events (i.e. changes in the HDM) extend the class haystack.service.events.HaystackEventService. This class provides the basic functionality necessary to register the service with the HsDispatcher to be notified of specific events (HaystackEvents and/or ObjectEvents).
Event driven services are different than other Haystack services in two ways. Services that extend the \texttt{HaystackEventService} class will also implement the interface \texttt{HaystackEventListener} and \texttt{ObjectEventListener}. The functions defined by each of these "handle" the events generated by the HDM. We also impose the invariant that any service modifying a piece of data in HDM lock the data first in the \texttt{HsResourceControlService}. This prevents a number of race conditions, and allows us to decide when an object has reached stable state (when it hasn’t been locked for a long time).

5.6 "Data manipulation" Services

In [6] Mark Asdoorian defines the implementation of the services necessary to archive, index, and query documents in Haystack. A full description of the implementation is beyond the scope of this thesis, but a description of the general design of these important components is provided below.

5.6.1 The \texttt{HsArchive} Service

In order to initially "introduce" documents into a user's Haystack a basic service is necessary to create a kernel of an HDM subgraph. From this kernel Haystack services can begin the process of assembling a representation of the document in the HDM. \texttt{HsArchive} serves in this capacity by instantiating the "kernel" composed of a \texttt{bale.HaystackDocument} and a \texttt{needle.Location}.

Once the \texttt{bale.HaystackDocument} and \texttt{needle.Location} have been created, the event based service, \texttt{haystack.service.fetch.FetchService} (or a more specialized fetch service\footnote{As we have different Location types it may be useful to provide different fetch services to obtain the different pieces of data.}) is informed of a new event in the HDM. It will subsequently try to retrieve the data being pointed at by the \texttt{needle.Location}. When this data is obtained a \texttt{needle.Body} is attached to the \texttt{bale.HaystackDocument}. Additionally, the \texttt{FetchService} will also calculate the MD5 checksum and generate a checksum \texttt{needle} to attach to the \texttt{bale.HaystackDocument}. 
**HsArchive** is invoked with a variety of options that indicate how the kernel should be constructed. A document's uniqueness is measured by two values: its location and its checksum. HsArchive maintains two tables, one mapping locations to needle.Location objects with that location, and a table mapping checksums to the needle.Body objects that produced the checksum value. In invoking the archive() method in HsArchive, a user may specify Haystack's behavior in dealing with the four possible cases: location and checksum match, one of the two matches (2 cases), and neither matches. The user's specification for archiving behavior for a specific document are retained in a table.

After the FetchService obtains the object and makes the appropriate connections, another event-driven service is invoked. This service, the HsFileChecker, awaits the appearance of a bale.HaystackDocument attached to a location and checksum. The HsFileChecker will lookup the user specified archive options described above. It will also check to see if the location and checksum are already in the HsArchive's databases. If both the url and checksum match implication is that the user asked for the same document to be archived twice. The default behavior is to removed this HDM cluster and abort. However, the user may specify that a new cluster is to be created. The last case (neither match) is similarly trivial, as we know the object is entirely new, the cluster is left alone and archiving continues.

If the location matched but the checksum did not, the implication is that the document has changed. The default behavior is to connect the new needle.Body object to the old bale.HaystackDocument and in effect supercede the previous body. Alternatively, a user may specify that the HDM cluster continue to exist seperately. Finally, if the checksum matched but the location did not, one of two things may have happened, the document was copied or the document was moved. This is easily testable by looking at the old location and determining if the document is still there. The options available to the user in this state would be to merge, supercede, or abort the archive.

If the HDM cluster has survived the HsFileChecker, other services may begin to act on it. The HsTypeGuesser can decide type type of the object and attached
the appropriate needle.Filetype object. Once a type is guessed, field finders and
textifiers can start their work on the cluster. A field finder can parse through the
needle.Body of a file, finding relevant pieces of data corresponding to the document
state previously discussed. Trivially, a HsMailFieldFinder service can extract the
to, from, subject, date, and id lines for an e-mail document and generate the appro-
priate needle.Mailfield objects. Finally, a textifier service specific to the type of
document may extract the text form the document. This extraction does not need
to be done immediately and the textifier may leave a Promise in the needle.Text
object. At the time of this writing methods have been implemented to extract text
from Postscript and PDF files as well as some trivial ascii based file formats.

5.6.2 The HsIndex Service

The HsIndex service is an event driven service that is set to wait for a user config-
urable star graph. The most frequently used star graph for HsIndex is a bale.Hay-
stackDocument attached to a needle.Text. When the HsIndex service is noti-
fied of the existence of such a sub-graph it will ad a pointer to the subgraph in a
queue. Periodically it will test to see if the cluster is in stable state\textsuperscript{6}. Once the
bale.HaystackDocument has arrived in stable state, the HsIndex service invokes the
getIndexable() method. The result of this call is some text.

HsIndex will check to see which IR systems the Haystack is configured to use,
and will pass the text to that IR system for indexing. Currently the only de-

defined IR system interface in Haystack is to the Isearch system [16], which is defined
in haystack.service.ir.HsIsearch. HsIsearch extends the class haystack.ser-
vice.ir.IRSystemService which has a large set of utility functions for taking the
text generated by HsIndex and generating something that IR systems can index.

\textsuperscript{6}Recall from above that stable state is implied when the object is not locked
5.6.3 The HsQuery Service

Now that we have a number of indexed documents we would like to allow users to doc-
uments within the index. HsQuery is a simple service that provides this functionality. 
HsQuery accepts a string query and routes that query to the IR system currently 
being used. The match objects (generally of the type bale.HaystackDocument) are 
encapsulated in a QueryResults object and passed back.
Chapter 6

Haystack and Lore Integration

Now that the core frameworks with Haystack have been established, we can describe the mechanisms by which the HDM can be held within Lore.

6.1 Representing HDM objects in Lore

There are a number of ways in which we can represent the HDM inside the OEM model. A simple variation is provided here. It is sufficiently expressive and concise to efficiently described the HDM graph inside the Lore OEM model.

Figure 6-1 is a small OEM representation of an bale.HaystackDocument connected to a needle.Body by means of a tie.Body object. Although the figure looks unnecessarily complex, it is in fact a very compact representation.

The Lore OEM structure created for Haystack starts with a single pointer into a complex object. The label for this pointer is Haystack\(^1\). The generated OEM file begins with: "<Haystack::Haystack {" and ends with: "}". Because the period character has significance in Lore files, the OEMStrawType for any Straw is modified to use the "_" character. For example, bale.HaystackDocument becomes bale.HaystackDocument. The HaystackID corresponds to the Straw's ID, and BackPointerID\(_n\) and ForwardPointerID\(_n\) correspond to the HaystackID of the

\(^1\)What we depict here is the process of generating a complete OEM structure from an existing HDM graph. Incremental modifications to an existing Lore structure are described in Section 6.3
Figure 6-1: An OEM diagram for a small portion of an HDM cluster

```
<IDHaystackID:: OEMStrawType {
  <HID "HaystackID">
  <HTYPE "StrawType">
  <FPOINTERS {
    <&IDForwardPointerID1 >
    <&IDForwardPointerID2 >
    ...
    <&IDForwardPointerIDn >
  }>
  <BPOINTERS {
    <&IDBackPointerID1 >
    <&IDBackPointerID2 >
    ...
    <&IDBackPointerIDn >
  }>
  ...additional Tie/Needle information...
}
```

Figure 6-2: An OEM representation of a Straw.
nth back and forward pointers held within the Straw's StrawTies.

The first line of the code creates two pointers to a complex object. The first pointer is the globally named pointer “IDHaystackID” (i.e. ID followed by the Straw’s HaystackID value). The second pointer emanates from the Haystack complex OEM object (see Figure 6-1) and is labeled with the type of the object. From this complex node we draw four additional pointers: HID which connects to an atomic object holding the HaystackID for the Straw. The HTYPE label points at a node holding the type of the Straw. The two pointers FPOINTERS and BPOINTERS are created if there are any backward or forward pointers emanating from the Straw. These objects are complex and point at other named Straw objects in the OEM graph.

When creating the OEM data for a Tie, two additional lines are added to the Straw definition in Figure 6-2 (in the space for additional information):

```
<TIEBPOINTER &ID TieBackPointerID>
<TIEFPOINTER &ID TieForwardPointerID>
```

TieBackPointerID corresponds to the HaystackID of the back pointer of the Tie (i.e. what is obtained by calling getBack()). TieForwardPointerID is the same thing in the forward direction.

For a Needle we replace add the following to the Straw OEM code:

```
<Data needleData>
```

The needleData field simply corresponds to the data held by the Needle. If the data held by a Needle is a String, the needleData is encapsulated in a quotation marks (so that Lore knows the data is a string). If the data is some number, it does not need to be enapsulated in quotes.

The Straw class in Haystack implements the basic functionality that generates the code specified in 6-2. To obtain the OEM representation of a Straw, the generateOEM() method is called on the Straw. The Tie class extends the code generated by Straw and adds the appropriate fields specific to objects in the tie package (i.e. TIEBPOINTER and TIEFPOINTER). Similarly, The Needle class extends the code generated by Straw by adding the correct DATA information. By default the data is assumed
to be text. Specific Needles can override the code generation method to produce an OEM field of the appropriate type (for example, a needle.Date will produce an integer DATA field).

6.2 The HsOEMGenerator Class

In theory if a user has always had Lore attached to their Haystack it should never be necessary to regenerate the OEM graph. However, in the case where the data either becomes corrupt, or the Lore is added to Haystack at some later time, a service is provided to regenerate the OEM graph from scratch. HsOEMGenerator is a simple utility service that is invoked with the generateOEM() procedure. This procedure checks to see which location is specified for the OEM file in the HsConfigService. It then creates the necessary header information and iteratively retrieves all Straws in the HsPersistentObjectService. For each of these Straws, the HsOEMGenerator invokes the generateOEM() method and saves the resulting OEM structure to disk.

A user may then use the OEM loading facility in Lore to reload the new data into the Haystack Lore database.

6.3 The HsLore Class

The HsLore class is a simple event listener class that expresses interest in ObjectEvents. This implies that any change in the HDM triggers an event. Once HsLore is notified of an event, it will invoke the generateLore() method of the Straw that caused the event. The generated string corresponds to the Lore query that will update the database to the new state of the object.

Upon initialization HsLore opens a stream connection to the Lore process executing either locally on a remote machine\(^2\). Once the Lore update code has been generated by the Straw, HsLore will pass the query into Lore.

---

\(^2\)This is necessary as Lore is not currently portable to all machines
Unfortunately, at the time of this writing the Lorel update language has not been completely defined. The following is the current Lorel syntax for updating the Lore database for Straws, Ties, and Needles.

Lore allows us to refer to the globally named pointer directed at the current Straw by means of the Global! Identifier argument. For example, if a Straw with the HaystackID 253 is loaded into Lore, the Lore OEM object corresponding to that Straw can be accessed by Global! ID253. The Lorel to update a generic Straw with HaystackID x and type y is of the form:

\[
\text{Global!ID}_x := \text{oem}(\text{HID:''x''}, \text{HTYPE:''y''}, \\
\text{FPOINTERS:}\text{oem}(\text{ID}_{f1}, \text{ID}_{f2}, \ldots, \text{ID}_{fn}), \\
\text{BPOINTERS:}\text{oem}(\text{ID}_{b1}, \text{ID}_{b2}, \ldots, \text{ID}_{bn}));
\]

The values of ID$_{f1}$ - ID$_{fn}$ are simply the names of the global Lore pointers to the the forward objects of the Straw. For example, if the Straw has a forward pointer to some object with the HaystackID 494, then one of the ID$_{fi}$ values would be replaced with the string ID494.

For a Tie, the form of the Lorel query is very similar:

\[
\text{Global!ID}_x := \text{oem}(\text{HID:''x''}, \text{HTYPE:''y''}, \\
\text{FPOINTERS:}\text{oem}(\text{ID}_{f1}, \text{ID}_{f2}, \ldots, \text{ID}_{fn}), \\
\text{BPOINTERS:}\text{oem}(\text{ID}_{b1}, \text{ID}_{b2}, \ldots, \text{ID}_{bn}), \\
\text{TIEFPOINTER:}\text{ID}_{tfp}, \text{TIEBPOINTER:}\text{ID}_{tbp});
\]

Where ID$_{tfp}$ and ID$_{tbp}$ are the global OEM identifiers for the forward and backward pointers of the Tie respectively. Finally, an update for a Needle object is of the form:

\[
\text{Global!ID}_x := \text{oem}(\text{HID:''x''}, \text{HTYPE:''y''}, \\
\text{FPOINTERS:}\text{oem}(\text{ID}_{f1}, \text{ID}_{f2}, \ldots, \text{ID}_{fn}), \\
\text{BPOINTERS:}\text{oem}(\text{ID}_{b1}, \text{ID}_{b2}, \ldots, \text{ID}_{bn}), \text{DATA:''data''});
\]

Currently, we do not provide a simple method for the deletion of objects as Lore does not provide a mechanism to delete a global name. However, it is possible to disconnect the Straw from the total OEM graph. If we desire, for example, to remove the Straw with ID 4565, the following query would work: Haystack =- ID4656.
Chapter 7

Conclusions

In this thesis we have created a mechanism by which users can represent documents in a natural and expandable fashion. We have determined the nature of documents in terms of document state, and creating a data model to represent this state within Haystack. Furthermore we have shown the system context in which this data model resides.

Through Haystack a user is now capable of indexing documents in a powerful fashion. Haystack heuristically extracts a variety of information properties from the document and indexes those through a number of means.

We have also shown that information systems individually are incapable of answering the full set of questions a user may ask. Databases provide us with “what you ask for is what you get” functionality. Information Retrieval systems attempt to extract semantic meaning in textual documents. Finally, associative information systems facilitate the creation (both manual and automatic) of associations between documents. In combination these information systems are capable of handling the full spectrum of user queries.

In this thesis we have described mechanism to convert Haystack’s internal data model to each of these systems.
7.1 Future Work

The one important aspect of functionality within Haystack that we have failed to address is the actual mechanism by which queries are made. Although there are independent methods to query each information system there is currently no uniform method to simultaneously query all of them.

Ideally, a natural language solution will one day exist that will be able to dispatch different aspects of the query to different information systems. For example, the question, “What documents about apples that I read yesterday?” would be split into two different questions: “find me all documents about apple” and “find all documents read yesterday.” The first question is obviously based on some semantic considerations and so it will be dispatched to an IR system. On the other hand, the other question is inherently a database type question and can be dispatched to Lore. Result combination is also an open issue. Ideally, the user should be able to scale the results of the different information systems in some way.

The second alternative for querying utilizes the Lore DataGuide model. By taking a snapshot of the current database schema and representing it graphically a user’s can simply fill in different parts of the graph and the appropriate query will be generated. A special box can hold free text queries (those intended for an IR system).

Regardless of the exact query mechanism, the hybrid-search system proposed here has the potential to solve a much greater variety of problems than any independent information system.
Appendix A

UML model of Straw

Figure A-1 is a UML class diagram for the primary interfaces and implementations of objects in the HDM.
Figure A-1: A UML diagram of the core Haystack object interfaces/classes.
Appendix B

Functions of StrawType

These are some of the useful functions provided (statically) within the StrawType object.

<table>
<thead>
<tr>
<th>Function</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>string2Vector(...)</td>
<td>Breaks apart a string representation of a class name (with an optional delimiter, &quot;.” by default).</td>
</tr>
<tr>
<td>class2Vector(...)</td>
<td>Breaks apart the name of the Class object into a Vector.</td>
</tr>
<tr>
<td>vector2String(...)</td>
<td>Merges a Vector into a String representation. For example: {a b C} becomes a.b.C. (the delimiter can be specified).</td>
</tr>
<tr>
<td>vector2Class(...)</td>
<td>Generates a Class object for the given Vector of Strings. So {a b C} will generate a class object for a.b.C. This will generate an exception if Java can’t find the class file for the object.</td>
</tr>
<tr>
<td>straw2Package(...)</td>
<td>Generates the name of the package that holds extensions to the Straw. For example, if the argument is a.b.C, the function returns a.b.c.</td>
</tr>
<tr>
<td>getPackageOf(...)</td>
<td>Returns the package that this object is part of. So if the Straw is {a.b.C}, the function returns a.b.</td>
</tr>
<tr>
<td><strong>Function</strong></td>
<td><strong>Description</strong></td>
</tr>
<tr>
<td>---------------------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><code>package2Straw(...)</code></td>
<td>Returns the super-type of all objects in the package. For example, given <code>{a.b.c}</code>, the function returns <code>a.b.C</code>.</td>
</tr>
<tr>
<td><code>package2Class(...)</code></td>
<td>Same as above, but returns the <code>Class</code> object rather than a <code>String</code>. Throws an exception if Java can’t find the class for the specific <code>Straw</code>.</td>
</tr>
<tr>
<td><code>toTie(...)</code></td>
<td>Returns the equivalent “tie” name for a <code>Class</code> or the <code>String</code> name of the object. For example, if the object is <code>bale.C</code>, the function returns: <code>tie.C</code>.</td>
</tr>
<tr>
<td><code>toTieClass(...)</code></td>
<td>Same as above but returns a <code>Class</code> representations. Exceptions as above.</td>
</tr>
<tr>
<td><code>toValidTie(...)</code></td>
<td>Same as above but will walk back through a <code>Straw</code>'s hierarchy until it finds a valid (i.e. Java recognizable) <code>Tie</code> extension. For example, submitting <code>needle.filetype.Postscript</code>, will return <code>tie.Filetype</code> (because <code>tie.filetype.Postscript</code> doesn’t exist).</td>
</tr>
<tr>
<td><code>toBale(...)</code></td>
<td>Same as <code>toTie</code> above but generates a bale.</td>
</tr>
<tr>
<td><code>toBaleClass(...)</code></td>
<td>Same as <code>toTieClass</code> above but generates a bale <code>Class</code>.</td>
</tr>
<tr>
<td><code>toNeedle(...)</code></td>
<td>Same as <code>toTie</code> above but generates a needle.</td>
</tr>
<tr>
<td><code>toNeedleClass(...)</code></td>
<td>Same as <code>toTieClass</code> above but generates a needle <code>Class</code>.</td>
</tr>
<tr>
<td><code>getSupertypes(...)</code></td>
<td>Finds all <code>valid</code> supertypes of a given <code>Straw</code>.</td>
</tr>
<tr>
<td><code>isValid(...)</code></td>
<td>Verify that Java can load an object with the given name.</td>
</tr>
</tbody>
</table>
Appendix C

Exceptions

There are a number of exceptions issued by the Haystack implementation. They are provided here in table form as reference.

<table>
<thead>
<tr>
<th>Exception</th>
<th>Extends</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BadQueryException</td>
<td>Exception</td>
<td>An exception for a malformed query expression.</td>
</tr>
<tr>
<td>CannotFindOpenPortException</td>
<td>IOException</td>
<td>When any service attempting to grab a port for communication can't find one.</td>
</tr>
<tr>
<td>CommunicationException</td>
<td>IOException</td>
<td>When the Middleman can't find an open port.</td>
</tr>
<tr>
<td>DotfileException</td>
<td>Exception</td>
<td>Exception when trying to archive a dotfile.</td>
</tr>
<tr>
<td>DuplicateNameException</td>
<td>Exception</td>
<td>HsNameService and HsCommanddAPI exception when someone tries to register the same named object.</td>
</tr>
<tr>
<td>DuplicateURLException</td>
<td>Exception</td>
<td>Exception by the archive process when the user tries to archive the same object.</td>
</tr>
<tr>
<td>Exception Class</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>-----------------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>HsServiceCloseException</td>
<td>If any service can’t close properly it describes the problem through the HsServiceCloseException.</td>
<td></td>
</tr>
<tr>
<td>HsServiceCriticalInitException</td>
<td>A critical service initialization error. The HaystackRootServer will shut down.</td>
<td></td>
</tr>
<tr>
<td>HsServiceInitException</td>
<td>A service initialization error.</td>
<td></td>
</tr>
<tr>
<td>KeyNotFoundException</td>
<td>Used when a database type service can’t find a certain key.</td>
<td></td>
</tr>
<tr>
<td>NameNotFoundException</td>
<td>Used by HsNameService on a getService() request if it can’t find the service.</td>
<td></td>
</tr>
<tr>
<td>NeedleDataException</td>
<td>If someone tries to place the wrong type of data into a Needle and casting can’t fix it.</td>
<td></td>
</tr>
<tr>
<td>NoSuchStrawException</td>
<td>If the HsObjectCreatorService can’t create the requested Straw because it doesn’t exist.</td>
<td></td>
</tr>
<tr>
<td>OEMGenerateException</td>
<td>If the HsOEMGenerator gets errors while generating the OEM file.</td>
<td></td>
</tr>
<tr>
<td>ObjectNotFoundException</td>
<td>If HsPersistentObjectService doesn’t have a specific Straw.</td>
<td></td>
</tr>
<tr>
<td>SoftlinkException</td>
<td>If the user tries to archive a soft-linked file.</td>
<td></td>
</tr>
</tbody>
</table>

Table C.1: Exceptions generated by Haystack
Bibliography


[18] Erich Gamma, Richard Helm, Ralph Johnson, and John Vlissides. Design Patterns: Elements of Reusable Object-Oriented Software. Addison-Wesley, Reading, Massachusetts, 1995.


