Digital Libraries, Conceptual Knowledge Systems, and the Nebula Interface

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Abstract

Concept Analysis [12] provides a principled approach to effective management of wide area information systems, such as the Nebula File System and Interface [1]. This not only offers evidence to support the assertion [8] that a digital library is a bounded collection of incommensurate information sources in a logical space, but also sheds light on techniques for collaboration through coordinated access to the shared organization of knowledge [3].

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Introduction

In their lead-off paper for last year's Digital Library' 94 conference [8], Francis Miksa and Philip Doty ask the question “Why should a digital library be called a ‘library’?” They examine three aspects of the traditional library which may reveal the meaning of a digital library. These three aspects were highlighted in their statement (our emphases) that

“a library is a collection of information sources in a place.”

• A collection consists of objects gathered and assembled together with boundaries based upon pragmatic considerations and purpose.

• Information sources are separate and unique intellectual and artistic entities, which inform the user by highly incommensurate methods, purposes, and intensions.

• A place is an intellectual construct, a logical or intellectual space, with location of place meaning “a rationalized set of relationships” which structure the members of a collection.

In the announcement for this year’s Digital Library’ 95 conference [3], Richard Furuta directs our attention to a further collaborative aspect of digital libraries, which was highlighted in his statement (our emphases) that

“scholarly work in the digital library of the future will be mediated through coordinated access to shared information spaces. Patrons will organize their own private digital libraries, collaborate with colleagues through shared digital libraries, and have access to huge amounts of multimedia information in global, public digital libraries”.

In this paper we describe a mathematical framework, Concept Analysis and conceptual knowledge systems, and an implementation prototype in the areas of resource discovery and wide area information management, the Nebula File System and Interface, which potentially satisfy all four of these criteria.

• The bounded collection is represented by the notions of many-valued context and formal context in Concept Analysis or context in Nebula.

• The information source is represented by an object in Concept Analysis or a file object in Nebula. The incommensurability of information sources is represented by the typing of synoptic information which has been abstracted from objects, and afterward is associated with them.

• The place, or logical space, is represented by the notion of a concept lattice in Concept Analysis or a view taxonomy in Nebula.

• Collaboration through coordinated access to the organization of shared information spaces, is provided in Nebula by the specification of connectivity between information spaces via scoping, and is represented in Concept Analysis in terms of elaboration of the notion of a conceptual knowledge system as a constrained sum of formal contexts.
Table 1: Analogies

Table 1 summarizes the analogies between these four aspects of Digital Libraries and various notions in Concept Analysis and the Nebula Interface. Since libraries function as shared repositories of information, their contents must be classified and catalogued for easy access by patrons. Classification is a common technique for organizing information [10]. A taxonomy or classification scheme is an orderly arrangement of items into classes according to shared characteristics [14]. There is a strong and useful analogy displayed in Table 2 between classification in Library Science and classification in Network Information Discovery and Retrieval (NIDR) systems such as Nebula. The Nebula File System [1] and Interface [9] is a prototype wide area information system [2], which offers a new model for the organization and coordinated access of information spaces. The Nebula system integrates information management with traditional file system operations. In Nebula, resource meta-information is classified by collocation in views. Views are conceptual classes which organize resource meta-information into dynamically customizable information spaces.

Concept Analysis [12] provides a principled approach to the effective management of wide area information systems such as Nebula. It is a new approach to the analysis of information, which provides the mathematical foundation for faceted, synthetic classification. This is the appropriate model for the organization of knowledge in dynamic view-oriented NIDR systems. Conceptual scaling [4] provides the mathematical foundation for faceted analysis via the user’s view and interpretation of information. A flexible dynamic organizing/browsing mechanism, based on ideas from conceptual scaling, is important as publishing moves from a “push” model, where an editor determines what readers see, to a “pull” model, where users decide for themselves what to read by selecting from a variety of information sources. Conceptual knowledge systems [13] provide an adequate theory of knowledge consisting of: knowledge representation, knowledge inferencing, knowledge acquisition, and knowledge communication tools. Shared access to information spaces, as specified by Nebula scoping, can be formally represent by conceptual knowledge systems.

Table 2: Analogies
The paper is organized as follows. Section 1 discusses the nature and benefits of the data abstraction known as meta-information. It is also concerned with the interpretation of such data by faceted analysis. Interpreted meta-information is modeled by formal contexts in Concept Analysis. Such contexts correspond to the idea that digital libraries are “collections” with boundaries. In Section 2 the organization of knowledge through synthetic classification is described in terms of the notion of conceptual knowledge systems from Concept Analysis. An instance of conceptual knowledge systems called view taxonomy is constructed in Nebula by the specification of views as descriptive names within scoped indexes. The conceptual space of such organized knowledge corresponds to the notion of digital libraries as collections of information resources “in a place.” Section 3 is concerned with the management of information. It discusses the twin paradigms of searching and browsing, and introduces the idea of concept neighborhood navigation. Section 4 indicates how collaboration between digital libraries, small local conceptual spaces (private or group) and large global conceptual spaces, can be defined via shared organization. Finally, Section 5 summarizes what we have accomplished in this paper and briefly describes some future work.

1 Abstracting Meta-Information

In the universe of all knowledge, both verbal knowledge and the non-verbal knowledge in music and art, there is a certain amount of summarization or synoptic knowledge that has been recorded \[14\]. This knowledge is called meta-information, and is referred to as the bibliographic universe in Library Science. This meta-information often consists of a set of tag/value attributes or elements. The Nebula File System abstracts from files various elements of meta-information such as filename, size, date created, owner, etc. Nebula refers to such meta-information as a file object. A file object consists of a collection of attributes which the represented file possesses or has. Nebula file objects are gathered together into contexts. A Nebula context stores not only file objects, but also views and a collection of binary index relations that connect attribute values to file objects. There is one index relation for each attribute tag. Table 3 displays a Nebula context of documents (see Figure 2 in \[1\]).

Nebula contexts are instances of the Concept Analysis notion of a many-valued context. The unanalyzed and uninterpreted data of many application domains can often be conceptualized as a constrained collection of many-valued contexts. A many-valued context \[4\] is a quadruple \(\langle G, N, D, \phi \rangle\), where: \(G\) is a set of objects, which models the set of file objects and views in Nebula; \(N\) is a set of sorts, which model attribute-tags in Nebula (and database or entity/relationship attributes); \(D = \{D_a \mid a \in N\}\) is an \(N\)-indexed collection of domains of values, corresponding to the attribute-values in Nebula; and \(\phi = \{G \xrightarrow{\phi} D_a \mid a \in N\}\) is an \(N\)-indexed collection of functions, called an information function, whose inverses correspond to the index relations in a Nebula context. The Nebula context of documents in Table 3 is a many-valued context. The set of sorts is \(N = \{\text{project, format}\}\), the set of objects is \(G = \{\text{plan1.ps, plan2.ps, plan2.doc, notes1.txt, notes2.txt}\}\), the domains are \(D_{\text{project}} = \{\text{plan1, plan2}\}\) and \(D_{\text{format}} = \{\text{postscript, text}\}\), and the information function \(\phi_{\text{project}}(\text{plan1.ps}) = \text{plan1}\), \(\phi_{\text{project}}(\text{notes1.txt}) = \text{plan2}\), etc.

The has relationship between Nebula file objects and attributes is an instance of the binary incidence matrix of a formal context. A (formal) context is a triple \(\langle G, M, I \rangle\) consisting of two sets \(G\) and \(M\) and a binary incidence relation \(I \subseteq G \times M\) between \(G\) and \(M\). Intuitively, the
elements of $G$ are thought of as entities or objects, the elements of $M$ are thought of as properties, characteristics or attributes that the entities might have, and $gIm$ asserts that “object $g$ has attribute $m$.” Table 4 displays a formal context obtained by nominal conceptual scaling of the attributes from the multi-valued context displayed in Table 3.

| objects       | incidence | attributes          |
|---------------|-----------|---------------------|
| 1 plan1.ps    | 1 2 3 4   | 1 project=plan1     |
| 2 plan2.ps    | 1 × ×     | 2 project=plan2     |
| 3 plan2.doc   | 2 × ×     | 3 format=postscript |
| 4 notes1.txt  | 3 ×       | 4 format=text       |
| 5 notes2.txt  | 4 × ×     |                     |
|               | 5 × ×     |                     |

Table 3: Many-Valued Context for Documents

Table 4: Formal Context for Documents

2 Organizing Conceptual Space

Nebula identifies resources through descriptive names [9, 2]. A descriptive name is an expression which selects objects based upon their registered attributes. A basic form of descriptive name is just a conjunction of attributes, such as

format=text & project=plan2 & name=notes2.txt.

Descriptive names provide file name resolution through associative access. They are particularly important for finding resources in very large information spaces when the resource location is unknown. A set of functions for resolving descriptive names exists in each Nebula context. These include attribute domain operations such as equality and order, and regular expression matching.

Nebula replaces the directories in traditional file systems with database views. The directory structure of traditional file systems is a static organization, which “reflects the requirements of the system designer, not the varied requirements of a diverse user-base” [1]. Nebula views provide a powerful and flexible mechanism for the logical and dynamic organization of an information space, which allows user customization. In Nebula a view is a query which by using a descriptive name selects file objects from within a scope index. Views relate file objects by containment and scope.
Containment defines an abstraction relationship over the file objects contain in a view. The properties shared by those objects are abstracted in the descriptive name in the containment attribute of the view. The view serves as the conceptual class for the objects it contains. Scope defines a generalization-specialization relationship between the conceptual classes denoted by the views. By using views the Nebula File System provides a classification scheme which is both synthetic and faceted: synthetic, because it generates conceptual categorizations “on the fly”; faceted, because it uses atomic units of information known as facets to accomplish this categorization.

Nebula views are instances of the notion of a formal concept in Concept Analysis, used within the confines of a conceptual knowledge system. A formal concept or conceptual class consists of any group of entities or objects exhibiting one or more common characteristics, traits or attributes. Conceptual classes are logically characterized by their extension and intension. The extension of a class is the aggregate of entities or objects which it includes or denotes. The intension of a class is the sum of its unique characteristics, traits or attributes, which, taken together, imply the concept signified by the conceptual class. The process of subordination of conceptual classes and collocation of objects exhibits a natural order, proceeding top-down from the more general classes with larger extension and smaller intension to the more specialized classes with smaller extension and larger intension. This isa relationship is a partial order called generalization-specialization. Conceptual classes with this generalization-specialization ordering form a class hierarchy for the context, which mathematically is a complete lattice, Figure 1 displays the lattice of conceptual classes associated with the formal context of documents displayed in Table 4.

According to Concept Analysis, in addition to modeling knowledge representation in file systems, with the notion of a conceptual knowledge system we will be able to do knowledge inferencing, knowledge acquisition, and knowledge communication. There are 3 basic notions in conceptual knowledge systems: objects, attributes, and concepts. In Nebula, these correspond to: file objects, attributes, and views, respectively. There are 4 basic relationships in conceptual knowledge systems: an object has an attribute, an object belongs to a concept, an attribute abstracts from a concept, and a concept is a subconcept of another concept. In Nebula, these correspond to: has, containment, constructor, and scope relationships, respectively. These notions and relationships partition the frame of a conceptual knowledge system as in Table 5.

Table represents a conceptual knowledge system within the conceptual universe of all documents in an information system and their properties (see Figure 2 in ). The conceptual knowledge system in Table extends the formal context of documents represented by Table. It consists of
Table 5: Conceptual Knowledge System Relationships

a set $B$ of five concepts of $D$ defined as views, in addition to the set of objects and attributes in Table 4. For convenience of illustration, we have added an additional object “notes0.txt”. The crosses in Table 6 represent four relations (Boolean matrices): the organization submatrix is the order relation on the 5 classes, and the having submatrix is identical to the incidence matrix in Table 4. Figure 2 represents the lattice of conceptual classes for the conceptual knowledge system displayed in Table 6. The set of concepts $B = \{\text{objs, docs, postscript, plan1, plan2}\}$, which were added to the document space to form the conceptual knowledge system, are each represent by a node at the top of the line diagram in Figure 2.

Table 6: Conceptual Knowledge System in the Document Universe

3 Managing Information

In Library Science only the bibliographic universe can be controlled. Such control is performed by means of bibliographic tools. Catalogs are bibliographic tools, which exercise bibliographic control through three basic functions: identification, collocation, and evaluation. A user, who has a citation or bibliographic item in mind, should be able to match or identify or find a bibliographic entry for that item. This is the searching paradigm. A user, based upon various bibliographic data and connecting references, should be able to bring together in one place or collocate bibliographic entries for similar and closely related material. This is part of the browsing paradigm. A user should be able to choose by evaluation from among many bibliographic entries the one that best represents the knowledge, information or specific item desired. This also is part of the browsing paradigm.

Wide area information systems provide access to networked information resources through many
different application interfaces: WWW hypertext, Gopher menus, and Archie search. File management systems, such as Archie, Gopher, Prospero, WAIS, and WWW, use an existing file system as a storage repository. Resource discovery systems, such as Harvest and Whois++, effectively manipulate the tremendous amount of heterogeneous information in wide area information systems and wide area file systems, by using the uniform, logical interface provided by the resource meta-information in bibliographic records: Harvest defines its Summary Object Interchange Format (SOIF) and Whois++ can use the resource description called the Uniform Resource Characteristic (URC) currently being developed by the Internet Engineering Task Force (IETF) working group on uniform resource identifiers. Just as the ISBD in Library Science, this meta-information is typed in order to represent the heterogeneity of networked information resources. Resource discovery systems use two paradigms for managing information: searching and organizing/browsing.

Searching is the process of locating resources. The user provides a description or query of the resources being sought. The resource discovery system resolves the query and returns to the user a list of resources which match the description. Archie is the canonical example of an information system based upon the search paradigm. To search for a file the user must possess enough information about the file to formulate a query. Searching is most effective when a user can formulate a precise query from attributes that are indexed for efficient lookup. The main weakness of searching is that formation of good queries can be a difficult task, especially in an information space unfamiliar to the user.

Organizing is the human-guided process (on the server side) of deciding how to interrelate information, usually by placing it into some sort of hierarchy (for example, the hierarchy of directories in an FTP file system). Browsing is the corresponding human-guided process (on the client side) of exploring the organization and contents of a resource space. The main weakness of organizing/browsing is that (1) it is done by someone else, (2) it is not easy to change (for example, in Library Science the standard classification systems of Dewey and the Library of Congress are fixed and possibly not relevant to the present-day patron), and (3) it is difficult to keep a large amount of data “well organized”. For effective browsing the system does not resolve queries, but instead it organizes the information space so that the user can navigate it easily. The key to effective browsing is a well-organized, flexible, dynamic information space. Classification is a common technique for organizing information. A taxonomy or classification scheme is an orderly arrangement of terms or classes. Such a scheme arranges a set of objects into classes with shared characteristics.

Figure 2: Lattice for Document Conceptual Knowledge System
Concept Analysis defines a navigation method called *concept neighborhood navigation*, which moves between local conceptual neighborhoods. This allows for an interactive exploration of information spaces, individual or shared. A subset of facets can be chosen and starting from these, a local environment of related items can be explored. When browsing a very large data repository, it can be desirable to select a set of starting objects and to interactively explore their neighborhood. This process consists of the following steps:

**Initialization**  The facets are evaluated with respect to the uninterpreted data and transformed into binary relations (formal contexts). The evaluated facets are composed into a single formal context using the operation of *apposition* (this operation requires the contexts to share a common object set). A global analysis is performed on the total context, chiefly in terms of the collection of local neighborhood lattices.

**Browse Loop**  A new seed is chosen. This may be either an object or an attribute. The local neighborhood of a given seed object is analyzed and previewed. To simplify the visualization data to be presented to the user (and possibly reach an acceptable number of conceptual classes), the local neighborhood is modified using various means: raising the connectivity threshold, rank-ordering the attributes and restricting to the most important ones, restricting to a ball around the seed induced by a similarity metric, etc. The local neighborhood is visualized. At this time the user may want to visualize the union context of the local neighborhoods for the old seed and the new seed — this allows comparison of “distance” moved and classes in common.

### 4 Sharing Organization

Scoping in Nebula can provide coordinated access and efficient sharing of the organization of separate, sharable information spaces [9]. Comparison of the private individual information spaces of experts in the context of psychoanalysis has been discussed in Concept Analysis [11]. The mathematical foundations, for collaboration by coordinated access to the knowledge organized in logical spaces, is defined in terms of constrained sums of formal contexts [5] applied to conceptual knowledge systems. The sharing of knowledge organization can be accomplished with the specification of connectivity between logical information spaces. Sharing organization between two logical spaces is visualize in Table 7 in terms of elaborated conceptual knowledge systems. The first logical space makes use of the organization of the second logical space by specifying the link connectivity sharing\(_{1,2}\). These links represent scoping the first logical space conceptual classes on appropriate classes in the second logical space. So with links in sharing\(_{1,2}\) the second logical space shares its organization with the first logical space. The linked connectivity in sharing\(_{2,1}\) represent the dual situation — the sharing of the first by the second. The cross-linked instantiation in blocks instantiation\(_{1,2}\) and instantiation\(_{2,1}\) is derived connectivity defined by incidence matrix closure.

As Francis Miksa and Philip Doty have pointed out [8], the Internet Gopher space today is not a digital library — it contains a huge variety of useful sources, but these are “not tied together as a single intellectual construct, neither in the sense of structure nor in the sense of access methods.” We contend that such legacy information can be augmented and organized by coordinated access into a collection of collaborating digital libraries. The following example, which is part of the LC Marvel Gopher space at the Library of Congress, describes how this can be done.

The Library of Congress Machine-Assisted Realization of the Virtual Electronic Library (LC Marvel located at gopher://marvel.loc.gov/) classifies government publications. The conceptual
space defined includes government publications as objects and abstracted content as attributes. Table 7 shows attributes registered for three documents in the conceptual space defined by Marvel. The conceptual space is structured according to government branch, office, and project. Table 8 shows several document classes that exist. When implemented in Nebula, each publication is a file object with attributes registered for relevant properties. In practice, these attributes are collected by textual summarizers that process the typical structure of government documents such as press releases, newsletters, and BAA’s. A special “class” attribute is registered for a document that corresponds to the path of Gopher menus traversed to retrieve the document. The “class” attribute provides some additional information about the content of the document.

Nebula represents each class as a view that contains all objects in the corresponding menu or in any submenu. That is, the “Executive” view contains all publications for the White House, the Department of Agriculture, and any other Executive branch department or committee. In addition to the conceptual space of government publications, each user defines a “reader” space that augments the structure of the conceptual space defined by Marvel. The user space represents a profile of information the user finds interesting. For example, a user may consider interesting the class of documents regarding nuclear waste disposal. This class of documents crosses the boundaries of classes defined by Marvel. In fact it might include publications by the Judicial branch, executive orders and press releases from the White House and the Department of Energy, and legislative actions from Congress.

Intuitively, the reason for constructing user classes is that formal, organizational classification of government publications is too general. While the general classification is useful for browsing the collection of documents, it is not sufficient for issue-specific location of publications. Nebula accommodates user classes by layering them on top of the more general structure. The formal structure is available globally. In a separate user space, an issue-specific view is constructed by scoping it on the appropriate organizational classes. In this way, the formal structure provides a reasonable first approximation on which users can construct a customized structure.

5 Conclusions & Future Work

In this paper we have demonstrated in a very real sense how the Nebula prototype and Concept Analysis articulate the idea of digital libraries as bounded collections of typed information sources in conceptual spaces with collaboration defined by coordinated access to the shared organization of knowledge.

In particular, we have shown how Concept Analysis provides a principled foundation for the Nebula Interface, by giving it a mathematically rigorous base, which fits well with the intuitions
behind Nebula. For example, the notion of a concept lattice provides an explicit mathematical structure for Nebula view taxonomies. In addition, Concept Analysis reveals the composite nature of view specification. The first step is the explicit specification of the lattice join of the superordinate views in the scope component. The second step is the specialization of the superordinate join view via the conceptually scaled attributes in the constructor component.

The Concept Analysis foundation should allow us to apply the same extensions to Nebula which have been given to Concept Analysis: the Fuzzy Logic extension of Concept Analysis [7] will allow us to define rough Nebula views. Concept Analysis strongly suggests the use of faceted analysis via conceptual scaling, along with the current awareness ideas of SDI and continuous queries, to serve as a basis for the descriptive name component in the specification of views. It suggests the importance of “implications” and expert system type rules as an augmented means for analyzing taxonomic structures in Nebula.

A formal basis for describing views in terms of objects and a more expressive environment for
analyzing the relationships between views may make it possible to simplify a collection of views, thus providing query/space optimization. In the simple case, two views could be collapsed into one if they always contains the same set of objects. This is a straightforward application of the Concept Analysis optimization technique of “purification”. Also applicable is the optimization technique of “reduction”, which eliminates objects and attributes which are not irreducible.

More generally, a “cluster” of similar (but not identical) views might be abstracted into a more general view that many would find interesting. In Concept Analysis this kind of clustering has been captured by the notion of a rough concept in the Rough Set extension, which is based upon an indiscernibility relation on objects (which could dually be on attributes). It can also be realized by the notion of a generalized metric over conceptual classes (views), which would cluster views by a tolerance setting (a ball around a view of a certain small radius).

Traditional browsing systems, such as Gopher and the World Wide Web, define browsing transitions along the physical links of the knowledge organization, whether these are hierarchical as in Gopher-space or cross-referential as in the Web. Concept Analysis offers a more flexible and logical alternative. By introducing the idea of a concept neighborhood, it defines browsing transitions along conceptual links of the knowledge organization. The knowledge organization here consists of the whole information space, which would normally be only virtually represented. One travels from the local concept neighborhood of one object to the local concept neighborhood of a neighboring object. The transition can be pictured by the union neighborhood.

Future work will include: the incorporation into Nebula of Fuzzy Logic and Rough Set extensions; application of conceptual scaling techniques from Concept Analysis to provide for a rigorous foundation and elaboration of the associative access in Nebula view specification; realization of a testbed for collaborative studies; and development of client software for analysis and browsing by concept neighborhood navigation.

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