hyper MEDIA

Design

ISSUES

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This article discusses experiences and lessons learned from the design of an open hypermedia system, one that integrates applications and data not "owned" by the hypermedia. The work was conducted under the auspices of the DeVise project at the computer science department of Aarhus University, Denmark [5]. The DeVise project is developing general tools to support experimental system development and cooperative design in a variety of application areas including large engineering projects. The intensely collaborative, open-ended work characteristics of such settings make demands beyond the cross linking traditionally supported by hypermedia. These include a shared database, access from multiple platforms, portability, extensibility and tailorability. (For a detailed discussion of our engineering project use setting and its CSCW and hypermedia requirements, see [3, 4].)

FOR A DEXTER-BASED HYPERMEDIA SYSTEM

No hypermedia system to our knowledge meets these requirements on the platforms we need to support. Having to build our own, we nonetheless wanted to benefit from the experience and expertise of past and present hypermedia designers. Thus, we decided to use the *Dexter Hypertext Reference Model* [9, 10] (called Dexter throughout this article) as our platform. Dexter attempts to capture the best design ideas from a group of "classic" hypertext systems, in a single overarching *data* and *process* model. Although these systems have differing design goals and address a variety of application areas, Dexter managed to combine and generalize many of their best features.

We took the Dexter reference model as the starting point and turned it into an object-oriented design and prototype implementation (called DeVise hypermedia, or "DHM"), running on the Apple Macintosh. As a programming environment, we chose the Mjølner Beta System supporting the object-oriented programming language BETA [13]. The Mjølner Beta System includes an object-oriented database [11], in which our hypermedia structures are stored. Among the media supported by DHM are text, graphics, and video, using a styled text editor, a simple drawing editor, and a QuickTime movie player, respectively. DHM also supports link and atomic component browser composites, and a composite to capture screen configurations of open components (modeled on the NoteCards *TableTop* [18]). In addition to traversing links (including multiheaded ones), users can edit link end points using a graphical interface. Components can also be retrieved and presented via title search. Dexter's model of anchoring is extended to include a distinction between *marked* and *unmarked* anchors. Finally, in contrast to Dexter, DHM explicitly supports dangling links.

In short, our attempt to directly "implement" Dexter was largely successful. We were surprised at the robustness of the resulting design—it met several of our goals not explicitly identified in the Dexter paper. At the same time, we uncovered holes in the model, areas where further development is needed. For some of these, we now feel prepared to offer proposals for other hypermedia designers.

This article briefly reviews the Dexter model before discussing our experiences in applying it. Our focus here is on links, anchors, composites and cross-layer interfaces. For each of these, we comment on the utility and applicability of Dexter, identify the implementation choices made in our prototype, and make recommendations for designers of future systems and standards. We close with research issues and open questions.

The Dexter Model

The Dexter Hypertext Reference Model [9, 10] separates a hypertext system into three layers with well-defined interfaces (see Figure 1). The *storage layer* captures the persistent, storable objects making up the hypertext which consists of a set of components. *Component* is the basic object provided in the storage layer. As shown in Figure 2, the component includes a *contents specification,* a general-purpose set of *attributes,* a *presentation specification* and a set of *anchors*. The *atomic component* is an abstraction replacing the widely used but weakly defined concept of 'node' in a hypertext. *Composite components* provide a hierarchical structuring mechanism. The contents of a link

component is a list of *specifiers,* each including a presentation specification as well as component and anchor identifiers.

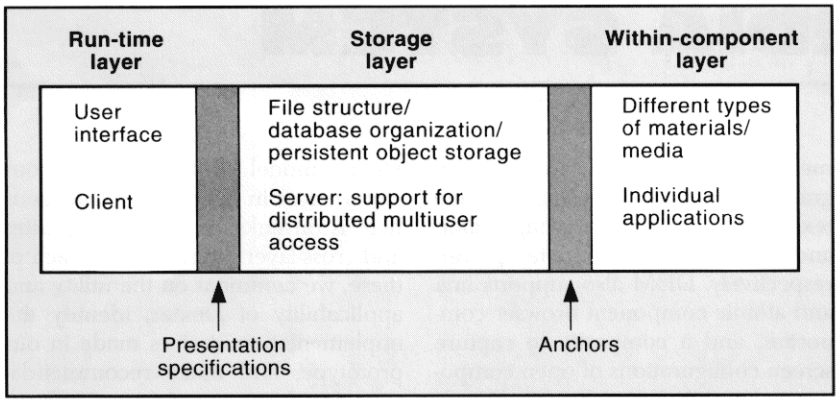
The *within-component layer* corresponds to individual applications. The applications are responsible, for example, for supporting content selections for link anchoring. The interface between the storage and within-component layers is based on the notion of anchors. Anchors consist of an identifier that can be referred to by links and a value that picks out the anchored part of the material.

The *run-time* layer is responsible for handling links, anchors, and components at run time. Objects in the run-time layer include *session,* managing interaction with particular hypertexts, and *instantiation,* managing interaction with particular components. The run-time layer provides tool-independent user interface facilities. The interface between the storage layer and the run-time layer includes presentation specifications that determine how components are presented at run time. Presentation specifications might include information on screen location and size of a presentation window, as well as a "mode" for presenting a component. Halasz and Schwartz [9, 10] use the example of an animation component that can be opened in either run mode or edit mode.

Links

Links have traditionally formed the heart of hypertext systems. Indeed, the traversable network structures formed by links distinguish hypertext from other means of organizing information. Hypertext systems have implemented links in several ways, many of which are unified by Dexter's notion of *link component.* In addition to the typical source/destination links, Dexter can model multiheaded links. Furthermore, because links are components, they can be the endpoints of other links. The Dexter model supports computed as well as static links through the use of specifiers. Simple "typing" can be supported by adding attributes to the link component. But DHM also supports full-fledged typing of links due to its object-oriented component design.

Though in principle a Dexter link could have fewer than two endpoints, this is expressly forbidden by the model's semantics. In DHM, we have relaxed this constraint; that is, "dangling" links having zero or one endpoint are perfectly legal. This means we can avoid the modal "start link/end link" link creation style of many hypertext interfaces. In DHM's user interface (UI) links can be created in two ways: (1) a "New Link" operation creating a link having one end point based on the current selection in the active editor (Figure 3); in this case no instantiation or link editor is opened. And, (2) via a new component operation creating a link with an open instantiation and link editor. In this case the link has no end points (see the 'Link 78' link instantiation in Figure 4). End points can be added to the link at any time and as shown in Figure 4, links can have other links as end points. In our implementation of links, we confronted two problems with Dexter's model: 1) its aversion to dangling links, and 2) its notion of link directionality.



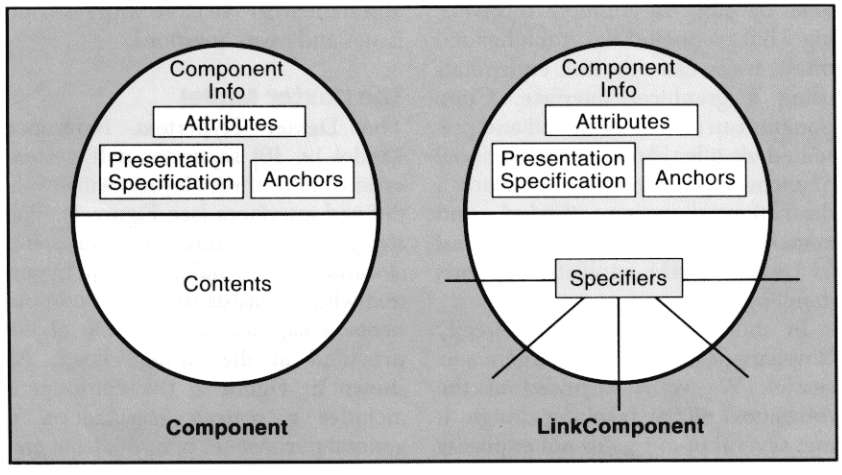


Figure 1. The Dexter model layers and interfaces. (Some of the text appearing in the figure is the authors'.)

Figure 2. Component structure in the storage layer

Dangling Links

In spite of Dexter's explicit aversion to dangling links, we chose to support them for several reasons: First, they allow lazy updating and garbage collection following component and anchor deletion. This is useful when the link to be deleted (or modified) lives on another machine or is currently locked by another user. A second, related situation involves data objects outside the control of the hypermedia (for example, files with

component data needing to be moved or deleted). Third, the dangling end point can be "relinked" or reconnected to another component or anchor without having to rebuild the entire link (especially useful for multiheaded links). Finally, dangling links can be created intentionally as placeholders when the desired end point component or anchor does not yet exist.[1] The presence of such dangling links could be monitored by the system either on command or automatically. Users could then be prompted to reconnect "missing" link end points.

We imagine four different dangling-link situations arising in an integrated Dexter-based hypermedia system: 1) the end point's component has been deleted, 2) its anchor has been deleted, 3) relevant data objects referred to by the component's contents are unavailable, and 4) the anchor value is invalid. In the first two cases, the deletion operation modifies the objects so that later calls to followLink raise exceptions. Component deletion is implemented by clearing the anchors list and component contents, and setting a "deleted" flag. Anchor deletion is carried out similarly.

Cases 3 and 4 described in the preceding paragraph usually result from actions outside the control of the hypermedia. For example, data objects making up a component's contents can become unavailable if the content is a file identifier, and the file has been moved or deleted independent of the hypermedia (case 3). In this case the followLink operation should catch the file system exception and pass it along as a dangling exception to the user.

In case 4, the data specified by the anchor value becomes invalid when relevant parts of the component's contents are modified with editors outside the hypermedia. This situation is impossible to detect in general during a CreateLinkMarker or a followLink operation, since the lookup/computation of anchor value may not raise an exception. An example is when the anchor value is still legal but out of date, as a result of "unauthorized" editing of the surrounding text. Currently in DHM, we have implemented detection and relink options for case 1.

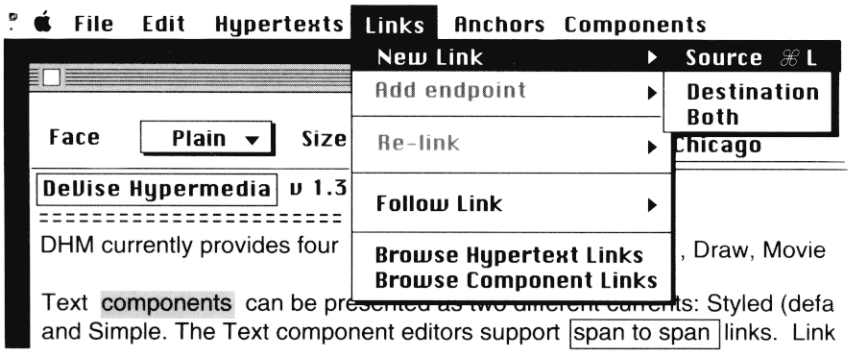


Figure 3. Creating a link with one source end point, anchored in the currently selected text "components"

Link Directionality

The Dexter model includes only minimal motivation for its notion of link directionality. We are told that each link specifier indicates a directionality using one of the constants FROM, TO, BIDIRECT, or NONE, depending on whether the end point is to be interpreted as a source, destination, both source and destination or neither, respectively. Furthermore, every link must have at least one TO specifier.[2] Such directionality constants are used to model the

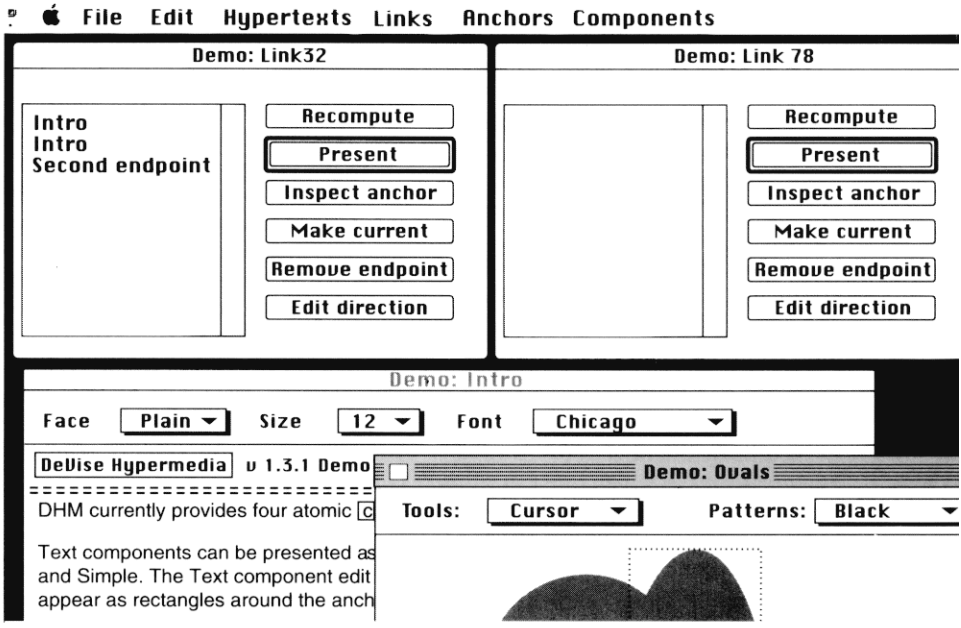


Figure 4. Two open link instantiations. Link32 has three endpoints, two in the 'Intro' text component, the third in the 'Ovals' component. Link 78 has no endpoints.

[1] An anonymous reviewer mentioned an example from asynchronous collaborative writing: When checking out parts of a hypertext, the links should dangle but be reattached when the structures are returned to the larger hypertext.

link semantics of existing hypermedia systems. For example, Intermedia links are modeled with BIDIRECT directionality on all specifiers. This is because the end points of an Intermedia link are directionally interchangeable [6].[3] In NoteCards, on the other hand, links have a definite source and destination [8].

This scheme seems insufficient, however, to model the ways people interpret link direction in practice. Consider the following three notions of directionality:

- *Semantic direction.* This concerns the semantic relationship between the components represented by the link. For example, a "supports" link connecting components A and B has a direction in which it normally "reads"; the argument in component A "supports" the claim in component B [18, Chap. 4].
- *Creation direction.* This direction corresponds to the order in which the link end points were created: the source of the link is the first end point created while the destination is the last.
- *Traversal direction.* This direction specifies how the link can be traversed. HyperCard links, for example, can only be traversed from source to destination.[4] NoteCards links can be traversed in both directions, although the interface style is different. When moving from source to destination, one clicks on the source anchor's icon. To move from destination to source, a menu of "backlinks" is opened in the destination component and the appropriate link icon is chosen.

These senses of link direction are in principle orthogonal. For example, the directions in which one can physically traverse a link in a particular system need not depend on the link's semantic direction. Nonetheless, many systems enforce dependencies. In NoteCards, for example, the creation direction corresponds to the traversal direction.

Selection of creation and traversal directions in the UI is supported in DHM, based in part on the Dexter proposal for direction attributes on link specifiers. When *creating* a link the user can choose the first end point to be either source, destination or both (see Figure 3). This corresponds to setting either FROM, TO or BIDIRECT, respectively, as the value of the direction attribute on the corresponding specifier. Similar choices are available when adding end points to a link with the add end point operation. By default, end points created using new link are sources and those created with add end point are destinations.

The direction values recorded in the specifiers support the user's choice of *traversal* direction. As shown in Figure 5, the follow link operation can be invoked with a direction parameter. When following a link in the forward direction, endpoints with direction value TO or BIDIRECT are presented. In the backward direction, end points with direction value FROM or BIDIRECT are presented. When following a link in all directions, all end points are presented.

As previously described, the Dexter direction values were originally introduced to model directionality in existing systems. Designers of systems based on the model need to make operational interpretations of the values. This is straightforward for the TO and FROM values, though less clear for NONE and BIDIRECT. In DHM we use BIDIRECT for endpoints that are conceived of as both source and destination. Currently, we have not chosen a semantics for the NONE value, but it could be used to mark endpoints that (temporarily) should not be presented when following a link. Such end points would still be accessible, however, through a link instantiation (see Figure 4). Link instantiations also allow the user to change the direction values of the individual end points.

Semantic direction is not explicitly supported in DHM (or in Dexter), but the general attribute mechanism that allows creation of different link types could also support assigning semantic directions to links.

Anchors

One of Dexter's major contributions is its explicit identification of anchors as the "glue" connecting network structures to the contents of particular components. Anchors are a controlled means of referring to the "within-component" layer. Without them, links connect only whole components.

Dexter's anchors are defined relative to a component and have an identification (id), that is unique within that component. Link specifiers must identify both the component id and the anchor id. Explicit mention of the ids can be avoided, however, by use of the resolver function. Thus the component appearing at a link's end point can be computed dynamically at run time.

The biggest problem with Dexter's model of anchors is that they are not properly related to composites. That is, although the contents of a composite (a list of baseComponents) is "visible" (i.e., explicitly represented) in Dexter, no mention is made of how anchors should refer to baseComponents within a parent composite. In DHM we allow composites to include full-fledged components (see the following discussion on structures), adding further problems. For example, can an anchor in the parent composite be tied to an anchor in one of its components? That is, can a link "indirect" through a composite's anchor, to an enclosed component's anchor?

There are other anchor-related issues not discussed in the Dexter model. Consider, for example, links to whole components. Should they have an empty anchor reference in the specifier or should there be a "whole-component" anchor type? In that case, should all whole-component links share a single whole-component anchor, or should there be one anchor for each link endpoint? Indeed the general issue of sharing vs. multiplying anchors is left open in Dexter. When creating a new link, should one always try to reuse any existing applicable anchor? Suppose there is more than one?

[2] An anonymous reviewer informs us that the wording of the constraint should have been, "at least one TO or BIDIRECT specifier."

[3] Intermedia anchor attributes can, however, be notated with directionality information.

[4] This is because HyperCard links are implemented as "GO" statements in a script in the link's source component. This also means that links cannot normally be seen from their destination cards.

DHM extends Dexter's model of anchors in several ways. First, we use dynamic references ("pointers") instead of anchor ids.[5] This means that link specifiers point directly at component anchors avoiding the need for an accessor function. Similar benefits accrue from our block-structured type definitions. For example, a component need not include an explicit reference to its enclosing hypertext, since the component definition is nested within the definition of a hypertext. Likewise, an anchor need not include an explicit reference to its enclosing component.

DHM distinguishes three high-level anchor types which are independent of the type of the enclosing component. *Whole-component* anchors support the degenerate case of link end points not anchored within a component's contents.[6]

A *marked* anchor is one for which an object is directly embedded in the component's contents. This object is called a *link marker* in Dexter. It may or may not be visible—indeed, some link markers (e.g., an Emacs "mark") may never be made visible as such. Link markers can be implemented in a variety of ways depending on the medium and the application. Visible icons inserted in text or graphic windows can serve as link markers (e.g., NoteCards link icons). But a link marker can also correspond to what Meyrowitz [15] calls a "permanent tie." Such an object can "track" editing changes to the component's contents, including changes to the selection itself. The instantiation may or may not choose to make the link marker visible (see, for example, Intermedia's arrow icon registering the presence of a permanent selection). DHM supports link markers in text components by maintaining outlined regions around the anchored text selections (see, for example, Figure 5). A command-click within the link marker region invokes a follow on the corresponding marked anchor's links.

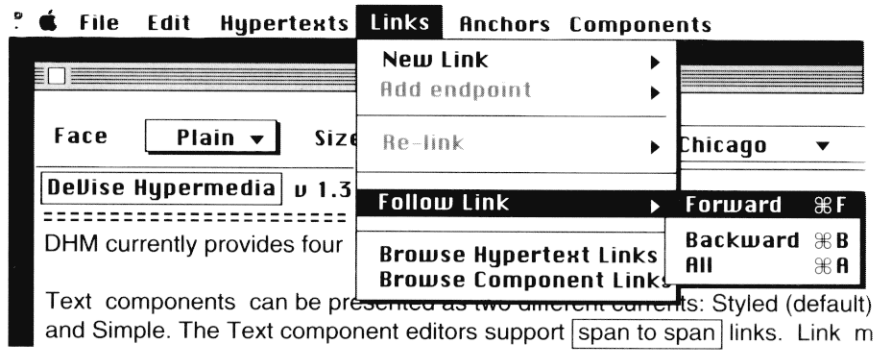


Figure 5. FollowLink invoked with a direction parameter

Unmarked anchors have no link markers. Normally their location within a component must be computed. Text components in DHM support a particular kind of unmarked anchor called *keyword* anchor, resembling the end points of HyperTies text links [17]. As an example, consider the situation of creating a new link shown in Figure 3. Assume that creating this new link requires creating a new anchor (as opposed to reusing an existing one), and that the anchor is to be a keyword anchor. In that case, a copy of the selected text string "components" is saved as the anchor's *value*. If we later invoke followLink from this component (assuming we have not selected some marked anchor), the values of all keyword anchors will be checked against the currently selected text. In particular, if the current selection's text matches the string "components," then the link created earlier in Figure 3 will be followed.

What sets a marked anchor apart from an unmarked one is the ability to retrieve the anchor directly from a selection in the component's editor. If a link marker is currently selected (or clicked on) in an active instantiation, then the instantiation is able to directly access the corresponding marked anchor. This is in contrast to unmarked anchors, where a search is required. In general, each unmarked anchor must be asked whether it is currently "selected" (or perhaps more descriptively, "applicable"). The operation of following a link from a marked anchor takes constant time, whereas following a link from an unmarked anchor requires in the worst-case time proportional to the total number of unmarked anchors in the component.[7]

Structures

The notion of structure (usually hierarchical) has been a part of most hypertext systems since the time of NLS/Augment in the 1960s [2]. In KMS, for example, (as well as its ancestor ZOG), a hierarchical structuring capability is built in to every node [1]. That is, all nodes (called "frames" in ZOG/KMS) can act as containers for other nodes. Usually, however, hierarchical structuring (and on rare occasions, nonhierarchical structuring), is supported through separate mechanisms.

In his article "Reflections on NoteCards: Seven Issues for the Next Generation of Hypermedia Systems," Halasz proposed that the *composite* be elevated to peer status with atomic nodes and links [7]. Composites would provide a means of capturing nonlink-based organizations of information, making structuring beyond pure networks an explicit part of hypertext functionality.[8] Halasz also argued for the related notions of computed and virtual composites. The contents of a computed composite might be, say, the result of a structural query over the hypertext returning sets of nodes and links as "hits." A virtual composite is created on demand at run time, but not saved in the database. Later, in Aquanet [14], the composite idea was used to capture slot-based struc-

[5]Utilizing an OODB makes our pointers persistent. We nonetheless maintain component and anchor ids in order to be able to generate transportable interchange formats for the hypermedia structure.

[6]In DHM, all links with whole-component endpoints in a component share a single whole-component anchor.

[7]This can be improved using hash tables and the like.

[8]A similar appeal was made by van Dam in his attack on links as "GOTO" statements [20].

tures consisting of nodes and *relations*, multiheaded variants of links.

Halasz [7] also criticized purely link-based structures, arguing that they lack a single node capturing the overall structure. The Dexter model's composite addresses this critique. As an aggregation of base components, it acts both as a full-fledged node in the network, and as container for the structure. In particular, such a composite can contain link components (in addition to atomic components and other composites) and thus capture complex nonhierarchical network structures (like Aquanet relations [14]). Furthermore, because of Dexter's clean separation of storage and run-time environments, virtual composites are a simple variant.

Though Dexter's notion of composite is a significant step forward, it is only one point in a spectrum of possible designs, each having certain advantages and meeting certain needs. Our architecture extends some of the features of composites to all components and supports tailoring for particular applications. Users adding a new component type to our framework make choices along several dimensions:

- *Virtual/nonvirtual components.* Any component type (not just composites) can be made virtual by setting a flag. Such components resemble normal components, but are only saved in the database if pointed at by another component (say, a link). Virtual components resemble objects in a dynamic programming environment—if they are not pointed at, then garbage collection reclaims them. For example, a virtual component might be created automatically to display the results of a user-instigated search over the components in the hypertext. Such a component persists beyond the current session only if the user creates a link to (or from) it, or adds it to an existing nonvirtual composite.
- *Computed/static components.* Any component type (again, not just composites) can be the result of a computation rather than manually created by the user. A typical example is a component created on the basis of executing a query. An attribute contains the information used to perform the computation. The component's contents can later be recomputed, either on demand or automatically. Some computed components (like browsers) reflect the contents or structure of parts of the network. In such cases, recomputation can be based on periodic checks of the relevant subnet, or be forced by changes to the relevant components or structures.
- *Component contents.* Typically, the contents of a component in a hypermedia system is not simply a flat set of enclosed data objects as suggested by the Dexter model. The contents are often structured and can include external data objects or references to other components. Figure 6 shows an example of a composite type supporting link browsing in DHM. The link browsers are implemented as virtual, computed composites with contents consisting of lists of references to LinkComponents. Though not anticipated by the Dexter model, this kind of component was fairly easy to implement using the framework described.

Integration and Component Contents

The phenomenon of system developers "owning the world" is becoming increasingly rare. Today, most practical computer environments consist of several third-party applications, perhaps customized for particular work settings by local programmers or user "tailors". Unfortunately, the application's inner workings and structures are rarely open to the developer trying to integrate them into a larger environment. The problem is exacerbated if the environment includes a variety of platforms.

In the last few years, researchers and developers have tried to use hypermedia to address this integration problem [6, 12, 15, 16]. They argue that rather than build a hypermedia system that includes all the applications needed in the work setting, one should employ hypermedia as a linking architecture, "connecting" the world rather than "owning" it.

The Dexter reference model makes certain important contributions to this effort. At the architectural level, Dexter distinguishes between objects belonging to the hypermedia (both run-time and storage objects), and the "within-component layer" belonging to an application. In addition to describing the hypermedia data model, Dexter offers two important concepts that help cross the boundary: anchors and presentation specifications (or "pspecs"). Anchors support linking to and from points within the contents of an application document. Pspecs provide a means of storing information with a Dexter component on how to start and configure the appropriate application.

In this way, Dexter opens the possibility of integrating third-party applications into a linked hypermedia environment. But it leaves unaddressed at least two important integration-related questions. First, Dexter does not distinguish between components whose contents are managed (in particular, stored) by the hypermedia and those whose contents are managed by third-party applications.

The second problem involves application documents having internal structure. Such documents can be integrated as a single unit into the hypermedia using a component "wrapper," but often the document's internal structure needs to be "exposed" for link anchoring. Dexter suggests using composite components, but says almost nothing about how to anchor within the subcomponents of a composite. It also does not discuss whether or how a composite component's structure should model the internal structure of an application document.

Various possibilities for storing and structuring component contents are discussed in the following subsections.

Atomic Components

Figure 7 shows two possible relations between an atomic component and an anchored data object. In part (a) of Figure 7, a traditional situation in which an application and its data objects are built into the hypermedia system is shown. DrawComponents in DHM, for example, encapsulate lists of graphical objects stored in the object-oriented database (OODB)

together with the components.

In part (b) of Figure 7, on the other hand, data objects wrapped by a component are stored separately and only referenced by the contents of the component. In DHM such a component/data object relationship characterizes *FileComponents* and *MovieComponents*. FileComponents are used to wrap arbitrary files in the file system, using file ids stored in the component contents. In this way, DHM supports linking (using WholeComponent anchors) to documents created with applications like Microsoft Word or Excel. The followLink operation automatically launches the appropriate applications on the files.

MovieComponents "wrap" QuickTime movies,[9] large multimedia data objects (from five to several hundred MB) too complex to be easily stored in the hypermedia's OODB. Hence, they are better handled using MovieFiles referred to by the component contents.[10] In this case, the component contents is again a file identification object.

Typically, an atomic data object belongs to exactly one atomic component. But there are cases in which two or more components need to share data. Here the components could have different types and/or different sets of anchors. Such multiple "views" can be supported by the containment style shown in part (b) of Figure 7. An example is the sharing of movie files across several hypertexts.

Composite Components

With regard to more complex structures of components and data objects, we found Dexter's notion of composite too narrow. According to Dexter, a composite may only contain encapsulated data objects (for example, see the bottom-left composite in Figure 8). As noted by Halasz and Schwartz [9] this kind of composite can model structures like graphical canvases. For other applications, however, composites need to refer to external data objects or other components. In the following paragraphs we discuss examples of such composite types.

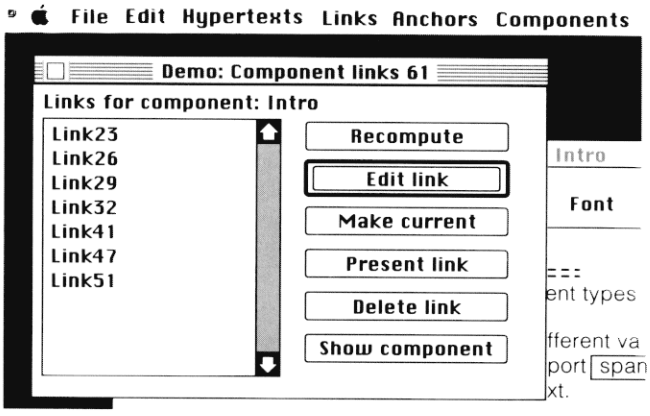


Figure 6. A link browser composite in DHM; lists all links to and from the 'Introduction' node.

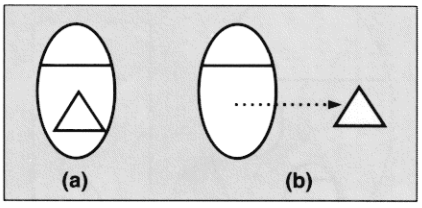


Figure 7. Data is either part of an atomic component's contents or referenced by it. Dotted arrows denote references out of the hypermedia structure (e.g., file structures).

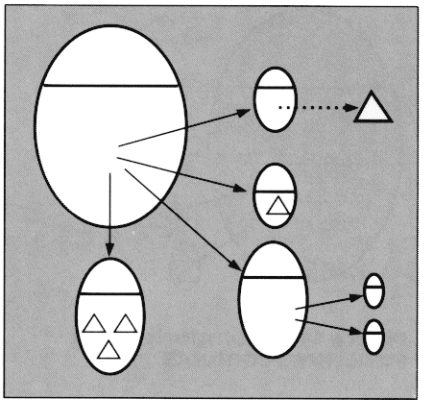


Figure 8. A composite refering to components of arbitrary type. Solid arrows denote internal pointers to hypermedia components.

Composites "containing" components. We first consider composites that refer to other *components* as shown in Figure 8. One example is the TableTopComposite used to save configurations of components presented together on the screen [19]. The contents of a TableTopComposite in DHM is a list of "pointers" to components of arbitrary type (including links and other composites); the composite does not directly contain or wrap the data objects. Another example is a *search* composite. Here the contents is a list of components (again of arbitrary type) resulting from a title search or a query over component attributes. In DHM, such search composites are implemented as virtuals (see the discussion on structures).

Figure 9 shows a slightly different kind of composite also used to group components. In this case, the composite is both virtual and has contents restricted to certain component types. The VirtualLinkComposite shown in Figure 9 is used in DHM to implement a variety of link browsers. VirtualLinkComposites are "computed" composites; their creation requires collecting a set of links for an entire hypertext, a specific component, or a specific anchor, depending on the kind of link browser.

When appropriate, restricting the component types pointed at by a composite allows customization of the composite's interface. For example, the VirtualLinkComposite interface supports inspecting individual link specifiers. A nontyped compos-

[9]QuickTime™ by Apple Computer Inc. implements a format for storing/compressing digitized video.

[10]In the current version of DHM, we support only one movie per MovieFile (and thus, one per component).

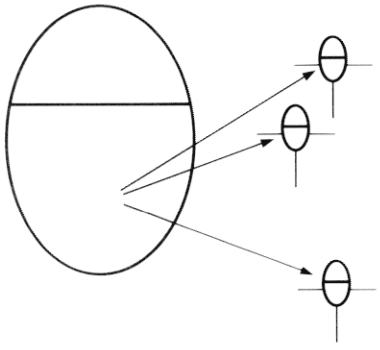


Figure 9. A virtual composite restricted to refer to LinkComponents. Shading indicates that the composite is virtual.

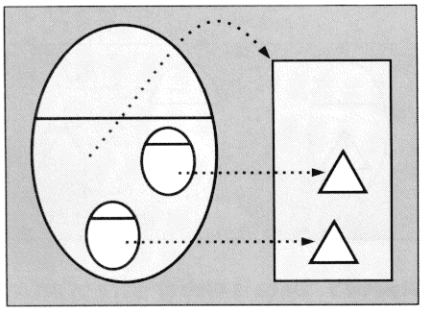


Figure 10. Typed composite with nested components points at encapsulated data objects

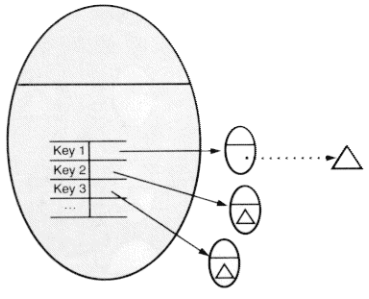


Figure 11. A composite with structured contents

ite would require run-time checking of the types of contained objects.

Encapsulated data objects. Up to this point we have focused on composites referring to other components. We now turn to composites referring directly to data objects. In Figure 10, the data objects depicted as triangles are encapsulated in a "container" object (drawn as a rectangle). In this case, the internal structure of the rectangular object is visible to the hypermedia system. Hence the composite and its nested components can refer both to the enclosing object and to its internal structure.[11]

An example of such a composite is used to represent modules in the Mjølner Beta programming environment [13]. Mjølner supports fine-grained modularization of programs using atomic modules called 'fragments' contained in parent 'fragment groups.' Each fragment group is stored in a file. To represent such structures in DHM, we use a FragmentGroupComposite whose contents includes a reference to a fragment group file and a list of references to atomic FragmentComponents, declared inside the block structure of the FragmentGroupComposite. The nested structure of the 'real world' data objects (fragments and fragment groups) is mapped directly onto the nested structure of the representing components. Hence, we can link both to the composite and to the nested atomic components representing individual fragments.

We provide anchors at the FragmentGroupComposite level to comments made at the group level, and at the FragmentGroupComposite level to comments and source code belonging to individual fragments.

Structured composites. An Aquanet *relation* [14], is an example of a hypermedia composite with structured contents. A fundamental feature of an Aquanet relation is that it resembles a multiheaded link with named end points.

We suggest implementing such relations as composites with contents consisting of a keyed table of component references (see Figure 11). Such a composite can refer to basic objects (atomic components) as well as to other relations (structured composite components). In addition, instantiations of such composites can support link-like "end-point" presentation. Here "end points" refers to the components pointed at by the composite's encapsulated structure.

Summary

The preceding examples show the need to support a broad view of component contents when developing open Dexter-based hypermedia systems. Integrating components of the storage layer with data objects of the within-component layer is one important aspect (as illustrated by the difference between a DrawComponent and a MovieComponent). Another is the internal integration of components and composites as illustrated by the cases of TableTopComposite and VirtualLinkComposite. Table 1 summarizes the discussion in this section along three dimensions.

[11] A nested component is one whose definition lies within the block structure of the parent component and thus can only be seen in the context of the parent component. (The block structure of DHM's object-oriented component definitions is similar to the block structure found in procedural programming languages like Pascal.)

Table 1. Three aspects of component contents

Structure of Contents	Type/Location of Contents	Definition of Contents
• Atomic • Unstructured collection • Structured collection – sorted list – keyed table – tree – ...	• Data objects – within component – outside component • Components – restricted types – unrestricted	• Encapsulated in this component • Globally visible

Conclusion

The Dexter-based hypermedia development in the DeVise project at Aarhus University was the foundation for this work, which has lead to clarifications and extensions to the Dexter model. The topics discussed in this article concern integration issues and the design of central object classes like links, anchors, and composites.

Our work on Dexter-based hypermedia contributes to the Esprit III project, EuroCODE, aimed at developing a CSCW Open Development Environment, a so-called "CSCW shell." One of the EuroCODE activities involves extending our Dexter-based hypermedia architecture to support cooperation via long-term transactions, flexible locking and event notifications. The open, extensible architecture we are developing comprises an object-oriented framework for developing multiuser hypermedia applications [3]. ◘

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This article discusses experiences and lessons learned from the design of an open hypermedia system, one that integrates applications and data not "owned" by the hypermedia. The work was conducted under the auspices of the DeVise project at the computer science department of Aarhus University, Denmark [5]. The DeVise project is developing general tools to support experimental system development and cooperative design in a variety of application areas including large engineering projects. The intensely collaborative, open-ended work characteristics of such settings make demands beyond the cross linking traditionally supported by hypermedia. These include a shared database, access from multiple platforms, portability, extensibility and tailorability. (For a detailed discussion of our engineering project use setting and its CSCW and hypermedia requirements, see [3, 4].)

FOR A DEXTER-BASED HYPERMEDIA SYSTEM

No hypermedia system to our knowledge meets these requirements on the platforms we need to support. Having to build our own, we nonetheless wanted to benefit from the experience and expertise of past and present hypermedia designers. Thus, we decided to use the *Dexter Hypertext Reference Model* [9, 10] (called Dexter throughout this article) as our platform. Dexter attempts to capture the best design ideas from a group of "classic" hypertext systems, in a single overarching *data* and *process* model. Although these systems have differing design goals and address a variety of application areas, Dexter managed to combine and generalize many of their best features.

We took the Dexter reference model as the starting point and turned it into an object-oriented design and prototype implementation (called DeVise hypermedia, or "DHM"), running on the Apple Macintosh. As a programming environment, we chose the Mjølner Beta System supporting the object-oriented programming language BETA [13]. The Mjølner Beta System includes an object-oriented database [11], in which our hypermedia structures are stored. Among the media supported by DHM are text, graphics, and video, using a styled text editor, a simple drawing editor, and a QuickTime movie player, respectively. DHM also supports link and atomic component browser composites, and a composite to capture screen configurations of open components (modeled on the NoteCards *TableTop* [18]). In addition to traversing links (including multiheaded ones), users can edit link end points using a graphical interface. Components can also be retrieved and presented via title search. Dexter's model of anchoring is extended to include a distinction between *marked* and *unmarked* anchors. Finally, in contrast to Dexter, DHM explicitly supports dangling links.

In short, our attempt to directly "implement" Dexter was largely successful. We were surprised at the robustness of the resulting design—it met several of our goals not explicitly identified in the Dexter paper. At the same time, we uncovered holes in the model, areas where further development is needed. For some of these, we now feel prepared to offer proposals for other hypermedia designers.

This article briefly reviews the Dexter model before discussing our experiences in applying it. Our focus here is on links, anchors, composites and cross-layer interfaces. For each of these, we comment on the utility and applicability of Dexter, identify the implementation choices made in our prototype, and make recommendations for designers of future systems and standards. We close with research issues and open questions.

The Dexter Model

The Dexter Hypertext Reference Model [9, 10] separates a hypertext system into three layers with well-defined interfaces (see Figure 1). The *storage layer* captures the persistent, storable objects making up the hypertext which consists of a set of components. *Component* is the basic object provided in the storage layer. As shown in Figure 2, the component includes a *contents specification*, a general-purpose set of *attributes*, a *presentation specification* and a set of *anchors*. The *atomic component* is an abstraction replacing the widely used but weakly defined concept of 'node' in a hypertext. *Composite components* provide a hierarchical structuring mechanism. The contents of a link