Using AutoMed Metadata in Data Warehousing Environments

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ABSTRACT
What kind of metadata can be used for expressing the multiplicity of data models and the data transformation and integration processes in data warehousing environments? How can this metadata be further used for supporting other data warehouse activities? We examine how these questions are addressed by AutoMed, a system for expressing data transformation and integration processes in heterogeneous database environments.

Categories and Subject Descriptors
H.2.1 [Logical Design]: Data models, Normal forms, Schema and subschema

General Terms
Design

Keywords
Metadata, Data warehouse, Data integration

1. INTRODUCTION
Metadata is essential in data warehouse environments since it enables activities such as data integration, data transformation, OLAP and data mining. Typically, the metadata in a data warehouse includes information about both data and data processing. The former includes the schemas of the data sources, warehouse and data marts, ownership of the data, time information etc. The latter includes rules for data extraction, cleansing and transformation, data refresh and purging policies, the lineage of migrated and transformed data etc.

Up to now, in order to transform and integrate data from heterogeneous data sources, a conceptual data model (CDM) has been used. For example, [16, 5] use a dimensional model; [4, 1, 19, 12] use an ER model, or extensions of it; [20] uses a multidimensional CDM called MAC; [10] describes a framework for data warehouse design based on its Dimensional Fact Model; [21] presents a conceptual model and a set of abstract transformations for data extraction-transformation-loading (ETL); and [11] adopts the relational data model as the CDM. All these approaches assume a single CDM for the data transformation/integration — see Figure 1(a). Each source data has a wrapper for translating its schema and data into the CDM. The integrated schema is then derived from these CDM schemas by means of view definitions, and is expressed in the same modelling language as them.

AutoMed is a data transformation and integration system which adopts a low-level hypergraph-based data model (HDM) as its common data model [14, 15]. So far, research has focused on using AutoMed for virtual data integration. This paper describes how AutoMed can also be used for materialized data integration.

Using AutoMed for materialised data integration, the data source wrappers translate the source schemas into their equivalent specification in terms of AutoMed’s low-level HDM — see Figure 1(b). AutoMed’s schema transformation facilities can then be used to incrementally transform and integrate the source schemas into an integrated schema. The integrated schema can be defined in any modelling language which has been specified in terms of AutoMed’s HDM. We will examine in this paper the benefits of this alternative approach to data transformation/integration in data warehousing environments.

Section 2 gives an overview of the AutoMed framework, to the level of detail necessary for our purposes here. Section 3 shows how AutoMed metadata has enough expressivity to describe the data integration and transformation processes in a data warehouse. Section 4 discusses how the AutoMed metadata can be used for some key data warehousing activities. Section 5 discusses the benefits of our approach.

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Section 6 gives our concluding remarks and directions of further work.

An earlier paper [18] proposed using the HDM as the common data model for both virtual and materialised integration, and a hypergraph-based query language for defining views of derived constructs in terms of source constructs. However, that paper did not focus on expressing data warehouse metadata, or on warehouse activities such as data cleansing or populating and maintaining the warehouse.

2. AUTOMED

The basis of AutoMed is the HDM data model. An HDM schema consists of a set of nodes, edges and constraints, and so each modelling construct of a higher-level modelling language is specified as some combination of HDM nodes, edges and constraints. For any modelling language M specified in this way (via the API of AutoMed’s Model Definitions Repository), AutoMed automatically provides a set of primitive schema transformations that can be applied to schema constructs expressed in M. In particular, for every construct of M there is an add and a delete primitive transformation which (conceptually) add to, or delete from, the underlying HDM schema the corresponding set of nodes, edges and constraints. For those constructs of M which have textual names, there is also a rename primitive transformation.

In AutoMed, schemas are incrementally transformed by applying to them a sequence of primitive transformations \( t_1, \ldots, t_n \). Each primitive transformation \( t_i \) makes a ‘delta’ change to the schema by adding, deleting or renaming just one schema construct. Thus, intermediate schemas may contain constructs of more than one modelling language.

Each add or delete transformation is accompanied by a query specifying the extent of the new or deleted construct in terms of the rest of the constructs in the schema. This query is expressed in a functional query language, IQL

\(^2\)

Also available are contract and extend transformations which behave in the same way as add and delete except that they indicate that their accompanying query may only partially construct the extent of the new/removed schema construct. Moreover, their query may just be the constant \( \top \), indicating that the extent of the new/removed construct cannot be derived even partially, in which case the query can be omitted.

We term a sequence of primitive schema transformations from one schema \( S_1 \) to another schema \( S_2 \) a transformation pathway from \( S_1 \) to \( S_2 \), denoted \( S_1 \rightarrow S_2 \). All source, intermediate and integrated schemas, and the pathways between them, are stored in AutoMed’s Schemas & Transformations Repository. The queries present within transformations that add or delete schema constructs mean that each primitive transformation has an automatically derivable reverse transformation. In particular, each add/extend transformation is reversed by a delete/contract transformation with the same arguments, while each rename transformation is reversed by swapping its two arguments.

Once a set of source schemas \( S_1, \ldots, S_n \) have been integrated into an integrated schema \( S \) by means of a set of pathways, we will see in Section 4.1 how these pathways can be used for populating \( S \) if it is going to be a materialised schema.

If \( S \) is a virtual schema, then view definitions defining its constructs in terms of the constructs of \( S_1, \ldots, S_n \) can automatically be derived from the pathways, and in particular, from the add, extend and rename steps within them. This is done by traversing the pathways \( S_1 \rightarrow S_\ldots \rightarrow S \) backwards from \( S \) down to each \( S_i \) (see [13]). These view definitions can then be used for global query processing by substituting them into queries expressed over the integrated schema in order to reformulate them into queries expressed on the source schemas.

2.1 Representing a Multidimensional Model

Previous work has shown how conceptual modelling languages such as relational, ER, UML and XML can be represented in terms of the HDM. Here we illustrate how a simple multidimensional data model can be represented.

An HDM schema is a triple \((\text{Nodes}, \text{Edges}, \text{Constraints})\). Nodes and Edges define a labelled, directed, nested hypergraph. It may be ‘nested’ in the sense that edges can link any number of both nodes and other edges. A query over a schema is an expression whose variables are members of \( \text{Nodes} \cup \text{Edges} \). Constraints is a set of boolean-valued queries over the schema which are satisfied by all instances of the schema. Nodes are uniquely identified by their names. Edges and constraints have an optional name associated with them. Edges need not be uniquely named within an HDM schema but are uniquely identified by the combination of their name and the components they link.

The constructs of any higher-level modelling language \( M \) may be nodal, linking, nodal-linking or constraint constructs (see [14]), or possibly a combination of these. The scheme of a construct (delimited by double chevrons) uniquely identifies it within a schema. Our simple multidimensional data model has four basic modelling constructs: Fact, Dim (dimension), Att (non-key attribute) and Hierarchy; for simplicity, we model a measure as any other non-key attribute. Fact and Dim are nodal, Att is nodal-linking, and Hierarchy is a constraint:

<table>
<thead>
<tr>
<th>Dimensional Construct</th>
<th>HDM Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>construct: Fact</td>
<td>node: ( \langle R \rangle )</td>
</tr>
<tr>
<td>class: nodal</td>
<td></td>
</tr>
<tr>
<td>scheme: ( \ll R, k_1, \ldots, k_n \gg )</td>
<td></td>
</tr>
<tr>
<td>construct: Dim</td>
<td>node: ( \langle R \rangle )</td>
</tr>
<tr>
<td>class: nodal</td>
<td></td>
</tr>
<tr>
<td>scheme: ( \ll R, k_1, \ldots, k_n \gg )</td>
<td></td>
</tr>
<tr>
<td>construct: Att</td>
<td>node: ( \langle R : a \rangle )</td>
</tr>
<tr>
<td>class: nodal-linking</td>
<td>edge: ( \ll R : a \gg )</td>
</tr>
<tr>
<td>scheme: ( \ll R, a \gg )</td>
<td></td>
</tr>
<tr>
<td>construct: Hierarchy</td>
<td>constraint:</td>
</tr>
<tr>
<td>class: constraint</td>
<td>( [x_i]([x_1, \ldots, x_n]) )</td>
</tr>
<tr>
<td>scheme: ( \ll R, k_1, k_1' \gg )</td>
<td>( \subseteq )</td>
</tr>
<tr>
<td></td>
<td>( [y_j][y_1, \ldots, y_m] )</td>
</tr>
<tr>
<td></td>
<td>( \ll R', k_1', \ldots, k_m' \gg )</td>
</tr>
</tbody>
</table>

We see that a fact or dimension table \( R \) with primary attributes \( k_1, \ldots, k_n \) is uniquely identified by the scheme \( \ll R, k_1, \ldots, k_n \gg \). This translates in the HDM to a nodal construct \( \ll R \gg \) the extent of which is the projection of the table \( R \) onto its primary key attributes \( k_1, \ldots, k_n \). Each non-key attribute \( a \) of a fact or dimension table \( R \) is

\(^2\)IQL is a comprehensions-based functional query language. Such languages subsume query languages such as SQL and OQL in expressiveness [9].
uniquely identified by the scheme \( \ll R, a \gg \). This translates in the HDM into a nodal-linking construct comprising a new node \( \ll R : a \gg \) and an edge \( \ll R, R : a \gg \). The extent of the edge is the projection of table \( R \) onto \( k_1, \ldots, k_n, a \).

Hierarchy constructs reflect the relationship between a primary key attribute \( k_i \) in a fact table \( R \) and its referenced foreign key attribute \( k'_i \) in a dimension table \( R' \), or between a primary key attribute in a dimension table \( R \) and its referenced foreign key attribute in a sub-dimension table \( R' \).

3. EXPRESSING DATA WAREHOUSE SCHEMAS AND TRANSFORMATIONS

Figure 2 illustrates the data transformation and integration process in a typical data warehouse. Generally, the ETL process includes extracting and transforming data from the data sources, and loading the transformed data into the warehouse schema. In this paper we assume that data extraction has already happened, i.e., that all the ‘data sources’ are local copies of data extracted from remote data sources. Thus, the data transformation/integration process is divided into the six stages shown in Figure 2: transforming, single-source cleansing, multi-source cleansing, integrating, summarising, and creating data marts.

In Figure 2, the data source schemas (DSS) may be expressed in any modelling language that has been specified in AutoMed. The transformation process translates each DSS into a transformed schema TS. Each TS may be defined in the same, or a different, modelling language as DSS, and other TSs. The translation from a DSS to a TS is expressed as a transformation pathway DSS \( \rightarrow \) TS. Such translation may not be necessary if the data cleansing tools to be employed can be applied directly to DSS, in which case TS and DSS are identical.

The single-source data cleansing process transforms each TS into a single-source-cleansed schema SS, which is defined in the same modellling language as TS, but may be a different from it. The single-source cleansing process is expressed as a transformation pathway TS \( \rightarrow \) SS. Multi-source data cleansing removes conflicts between sets of single-source-cleansed schemas and creates a multi-source-cleansed schema MS, from them. Between the single-source-cleansed schemas and the detailed schema (DS) of the data warehouse there may be several stages of MSs, possibly represented in different modelling languages.

In general, if during multi-source data cleansing, \( n \) schemas \( S_1, \ldots, S_n \) need to be transformed and integrated into one schema \( S \), we can first automatically create a ‘union’ schema \( S_1 \cup \ldots \cup S_n \) (after first undertaking any renaming of constructs necessary to avoid any naming ambiguities). We can then express the transformation/integration process as a pathway \( S_i \cup \ldots \cup S_n \rightarrow S \).

After multi-source data cleansing, the resulting MSs are then transformed and integrated into a detailed schema, DS, expressed in the data model supported by the data warehouse. The DS can then be enriched with summary views by means of a pathway from DS to the final data warehouse schema DWS.

Data mart schemas (DMS) can subsequently be derived from the DWS and these may be expressed in the same, or a different, modelling language as the DWS. Again, the derivation is expressed as a pathway DWS \( \rightarrow \) DMS.

Using AutoMed, four steps are needed in order to create the metadata expressing the above schemas and pathways:

1. **Create AutoMed repositories**: AutoMed metadata is stored in the Model Definitions Repository (MDR) and the Schemas & Transformations Repository (STR). The API to these repositories uses JDBC to access an underlying relational database. Thus, these repositories can be implemented using any DBMS supporting JDBC. If the DBMS of the data warehouse supports JDBC, then the AutoMed repositories can be part of the data warehouse itself.

2. **Specify data models**: All the data models that will be required for expressing the various schemas of Figure 2 need to be specified in terms of AutoMed’s HDM, via the API of the MDR (if they are not already specified within the MDR).

3. **Extract data source schemas**: Each data source schema is automatically extracted and translated into its equivalent AutoMed representation using the appropriate wrapper for that data source.

4. **Define transformation pathways**: The remaining schemas of Figure 2 and the pathways between them can now be defined, via the API of the STR. After any primitive transformation is applied to a schema, a new schema results. After any \( \text{add}(c,q) \) transformation step, it is possible to materialise the new construct \( c \) by creating, externally to AutoMed, a new local data source whose local schema includes \( c \) and populating this data source by the result of evaluating the query \( q \) (we discuss this process in more detail in Section 4.1 below). Thus, in general, a schema may be a materialised schema (all its constructs are materialised) or a virtual schema (none of its constructs are materialised) or partially materialised.

In the following sections, we discuss in more detail how AutoMed transformation pathways can be used for describing the data transformation/integration process of Figure 2. We firstly give a simple example, assuming that no data cleansing is necessary.

3.1 An Example

Figure 3 shows a multi-dimensional schema consisting of a fact table **Salary** and two dimension tables **Person** and **Job**: an HDM schema consisting of two nodes **Dept_id** and **name**
and an (un-named) edge between them; and a relational schema consisting of a single table Dept into which the other two schemas need to be transformed and integrated.

We discussed in Section 2.1 how a multidimensional model can be represented in AutoMed. For the HDM itself, the modelling constructs are Node, Edge and Constraint. We assume here a simple relational model which is represented similarly to our multidimensional model: each relation R with key attributes k₁,...,kₙ and non-key attributes a₁,...,aₘ is represented by a Rel construct ≪ R, k₁,...,kₙ ≫ whose extent is the projection of R onto k₁,...,kₙ, plus a set of Att constructs ≪ R, a₁ ≫, ..., ≪ R, aₘ ≫, where the extent of each ≪ R, aᵢ ≫ is the projection of R onto k₁,...,kₙ, aᵢ (we refer the reader to [14] for an encoding of the full relational model in the HDM).

In order to integrate the two source schemas into the target schema we first form their union schema. The following three primitive transformations are then applied to this schema in order to add the Dept relation to it, defining the extent of its id key attribute to be the same as the extent of the Dept_id HDM node, the extent of its name attribute to be the same as that of the Dept_id HDM edge from Dept to name, and the extent of its total_salary attribute to be obtained by summing the salaries for each department in the Salary table. In the last step, the IQL function gc is a higher-order function that takes as its first argument an aggregation function and as its second argument a bag of pairs; it groups the pairs on their first component, and then applies the aggregation function to each bag of values formed from the second components.

\begin{align*}
\text{addRel} & (\langle\text{Dept}_{-}\text{id}\rangle,\langle\text{Dept}_{-}\text{id}\rangle); \\
\text{addAtt} & (\langle\text{Dept},\text{name}\rangle,\langle\_,\text{Dept}_{-}\text{id}\rangle); \\
\text{addAtt} & (\langle\text{Dept},\text{total}_{-}\text{salary}\rangle, \\
& \text{gc sum} \ [(d,s)|(i,j,s)<-\langle\text{Salary},\text{salary}\rangle; \\
& (i',j',d)<-\langle\text{Salary}_{-}\text{id}\rangle; \\
& i=i'; j=j')] \\
\end{align*}

The following transformations can then be applied to the current schema to remove the HDM constructs from it — the queries show how the extents of these constructs could be reconstructed from the remaining schema constructs:

\begin{align*}
\text{delEdge} & (\langle\_,\text{Dept}_{-}\text{id}\rangle,\langle\_,\text{Dept}_{-}\text{name}\rangle); \\
\text{delNode} & (\langle\name\rangle,\langle a_{|d,n}\rangle-\langle\_,\text{Dept}_{-}\text{name}\rangle); \\
\text{delNode} & (\langle\text{Dept}_{-}\text{id}\rangle,\langle\_,\text{id}\rangle); \\
\end{align*}

Finally, the following transformations remove the multi-dimensional schema constructs — note that contract rather than delete transformations are used since their extents cannot be reconstructed from the remaining schema constructs:

\begin{align*}
\text{contractHierarchy} & (\langle\text{Salary},\text{Person}_{-}\text{id}\rangle); \\
\text{contractHierarchy} & (\langle\text{Salary},\text{Job}_{-}\text{job}\_id\rangle); \\
\text{contractAtt} & (\langle\text{Salary}\rangle,\langle\text{Salary}_{-}\text{id}\rangle); \\
\text{contractAtt} & (\langle\text{Salary}_{-}\text{id}\rangle,\langle\_,\text{Dept}_{-}\text{id}\rangle); \\
\text{contractFact} & (\langle\text{Salary}_{-}\text{id}\rangle,\langle\_,\text{Job}_{-}\text{job}\_id\rangle); \\
\text{contractAtt} & (\langle\text{Job}_{-}\text{job}\_descr\rangle); \\
\text{contractDim} & (\langle\text{Job}_{-}\text{job}\_id\rangle); \\
\text{contractAtt} & (\langle\text{Person}_{-}\text{name}\rangle); \\
\text{contractDim} & (\langle\text{Person}_{-}\text{id}\rangle); \\
\end{align*}

3.2 Transforming
The above example illustrates how a schema expressed in one data model can be transformed into a schema expressed in another. The general approach is to first add the new schema constructs in the target data model (relational in the above example) and then to delete or contract the schema constructs expressed in the original data model(s) (HDM and multi-dimensional in the above example).

3.3 Data Cleansing
Data cleansing deals with detecting and removing errors and inconsistencies from data in order to improve its quality, and is typically required before loading the transformed data into the data warehouse. In [17], the data cleansing problem is classified into two aspects, single-source and multisource. For each of these, there are two levels of problems, schema-level and instance-level. Schema-level problems can be addressed by evolving the schema as necessary. Instance-level problems refer to errors and inconsistencies in the actual data which are not visible at the schema level. In this section, we describe how AutoMed metadata can be used for expressing the data cleansing process, for both single and multiple data sources, and for both schema-level and instance-level problems.

Single-Source Cleansing. Schema-level single-source problems may arise within a transformed schema TS in Figure 2 and they can be resolved by means of an AutoMed transformation pathway that evolves TS, as necessary. Single-source instance-level problems include value, attribute and record problems. Value problems occur within a single value and include problems such as a missing value, a mis-spelled value, a mis-fielded value (e.g. putting a city name in a country attribute), embedded values (putting multiple values into one attribute value), using an abbreviation, or a mis-expressed value (e.g. using the wrong order of first name and family name within a name attribute). Attribute problems relate to multiple attributes in one record and include problems such as dependence violation (e.g. between city and zip, or between birth-date and age). Record problems relate to multiple records in the data source, and include problems such as duplicate records or contradictory records.

Some instance-level problems do not require the schema to be evolved, only the extent of one or more schema constructs to be corrected. In general, suppose that the extent of a schema construct c needs to be replaced by a new, cleaned, extent. We can do this using an AutoMed pathway by following these steps:

1. Add a new temporary construct temp to the schema, whose extent consists of the ‘clean’ data that is needed to generate the new extent of c. This clean data is derived from the extents of the existing schema constructs. This derivation may be expressed as an IQL query, or as a call to an ‘external’ function or, more generally, as an IQL query with embedded calls to external functions. The IQL interpreter is easily extensible with new built-in functions, implemented in Java, and these may themselves call out to other external functions. If the extent of a new schema construct depends on calls to one or more external functions, then the new construct must be materialised. Otherwise, if the extent of a new construct is defined purely in terms of IQL and its own built-in functions then the new construct need not be materialised.

2. Contract the construct c from the schema.
3. Add a new construct c whose extent is derived from temp.
attribute in different schemas (e.g. for a maritalStatus attribute) or a different interpretations of the values of an attribute in different schemas (e.g. US Dollar vs Euro in a currency attribute).

Such problems can be resolved by generating a new extent for the attribute in one of the schemas by applying an appropriate conversion function to each its values. In general, suppose we wish to convert each of the values within the extent of a construct c in a schema S by applying a function f to it. First a new construct c_new is added to S, whose extent is populated by iterating over the extent of c and applying f to each of its values. Then, the old construct c is deleted or contracted from the schema, and finally c_new is renamed to c. For example, the following pathway converts a 'M'/S' representation for the maritalStatus attribute in the above Person table into a 'Y'/N' representation, assuming the availability of a built-in function convertMS which maps 'M' to 'Y' and 'S' to 'N':

```prolog
addAtt (<<Person,maritalStatus_new>>, [(i,convertMS s) | (i,s)<-<<Person,maritalStatus>>]);
contractAtt (<<Person,maritalStatus>>);
renameAtt (<<Person,maritalStatus_new>>, <<Person,maritalStatus>>);
```

Note that if there is also available an inverse function convertMSinv which maps 'Y' to 'M' and 'N' to 'S', then a delete transformation could have been used in the second step above instead of a contract:

```prolog
deleteAtt (<<Person,maritalStatus>>, [(i,convertMSinv s) | (i,s)<-<<Person,maritalStatus_new>>]);
```

Record problems include duplicate records or contradictory records among different data sources. For duplicate records, suppose that constructs c and c' from different schemas are to be integrated into a single construct within some multi-source cleaned schema. Then, prior to the integration, we can create a new extent for c comprising only those values not present in the extent of c':

```prolog
add (c_new, [v|v<-c; not (member c' v)]);
contract (c);
rename (c_new, c)
```

For contradictory records, we can similarly create a new extent for c comprising only those values which do not contradict values in the extent of c'. For example, suppose we have tables Person and Emp in different schemas, both with key id, and the attributes <<Person,maritalStatus>> and <<Emp,maritalStatus>> are going to be integrated into a single attribute of a single table within some multi-source cleaned schema. Then the following transformation removes values from <<Person,maritalStatus>> which contradict values in <<Emp,maritalStatus>> (assuming that the latter is the more reliable source — the opposite choice would also of course be possible):

```prolog
addAtt (<<Person,maritalStatus_new>>, [[(i,s)|(i,s)<-<<Person,maritalStatus>>; (i',s)<-<<Emp,maritalStatus>>; i = i' & not (s = s')]])
contractAtt (<<Person,maritalStatus>>);
```

For illustrative purposes, suppose we have available a built-in function toolCall which allows a specified external data cleansing tool to be invoked with specified input data. Then, we can invoke the QuickAddress Batch tool3 to correct the zip and address attributes of a table Person(id, name, address, zip, city, country, phoneAndFax, maritalStatus) by re-generating these attributes given the combination of address, zip and city information:

```
addRel (<Temp, id, address, zip>>, toolCall 'QuickAddress Batch'
     '<<Person,address>>'
     '<<Person,zip>' '<<Person,city>>');
contractAtt (<<Person,zip>>);
contractAtt (<<Person,address>>);
addAtt (<<Person,zip>>, [(i,z)|(i,a,z)<-<<Temp, id, address, zip>>]);
addAtt (<<Person,address>>, [(i,a)|(i,a,z)<-<<Temp, id, address, zip>>]);
deleteRel (<<Temp, id, address, zip>>, [(i',z)<-<<Person,zip>>; i=i']);
```

Some instance-level problems will also require the schema to be evolved e.g. if we have available a built-in function split_phone_fax which splits a string comprising a phone number followed by one or more spaces followed by a fax number into a pair of numbers, then the following AutoMed pathway converts the attribute phoneAndFax of the Person table above into two new attributes phone and fax:

```
addRel (<<Temp, id, phone, fax>>, [i,p,f]<-split_phone_fax pf>);
addAtt (<<Person,phone>>, [(i,pf)<-<<Temp, id, phone, fax>>]);
addAtt (<<Person,fax>>, [(i,f)<-<<Temp, id, phone, fax>>]);
contractAtt (<<Person,phoneAndFax>>);
deRel (<Temp, id, phone, fax>>, [(i',p,f)<-<<Person,phone,fax>>; i=i']);
```

Multi-Source Cleansing. After single-source data cleaning, there may still exist conflicts between different single-source cleaned schemas in Figure 2, leading to the process of multi-source cleaning.

Schema-level problems in multi-source cleaning include attribute and structure conflicts. Attribute conflicts arise when different sources use the same name for different constructs (homonynms) or different names for the same construct (synonyms), and they can be resolved by applying appropriate rename transformations to one of the schemas. Structure conflicts arise when the same information is modelled in different ways in different schemas, and they can be resolved by evolving one or more of the schemas using appropriate AutoMed pathways.

Instance-level problems in multi-source cleaning include attribute, record, reference, and data source problems. Attribute problems include different representations of the same
renameAtt (<<Person,maritalStatus_new>>, <<Person,maritalStatus>>);

taining both sets of source data within the target multi-
data source). Such conflicts can be resolved either by re-
Struct in one data source and per product category in another
different data sources (e.g. sales may be recorded per prod-
for example, aggregation at different levels of detail in dif-
ferent techniques. If a materialised construct has new data inserted into it (an increment) or data deleted from it (a decrement). We actually do not use the whole view definition $g$ generated for $c$, but instead track the changes from $c^n$ through each step of the pathway. In particular, at each add or rename step we use the set of increments and decrements computed so far to compute the increment and decrement for the construct $c$ being generated by this step of the pathway.

4.3 Tracing the Lineage of DW Data

The lineage of a data item $t$ in the extent of a materialised
construct $c$ of a schema $S$ is a set of source data items from
which $t$ was derived. The fundamental definitions regarding
data lineage were developed in [7], including the concept of a
derivation pool for tracing the data lineage of a tuple in a ma-
terialised view. Another fundamental concept was addressed
in [2], namely the difference between ‘why-provenance’ and
‘where-provenance’. Why-provenance refers to the source
data that had some influence on the existence of the inte-
grated data. Where-provenance refers to the actual data in
the sources from which the integrated data was extracted.
The problem of why-provenance has been studied for rela-
tional databases in [7, 22, 6].

We have developed definitions for data lineage in Au-
otoMed based on both why-provenance and where-provenance,
which we term affect-pool and origin-pool. In [9] we give
formulæ for deriving the affect-pool and origin-pool of a
data item \( t \) in the extent of a materialised construct \( c \)
created by a transformation step of the form \( \text{add}(c,q) \) applied
to a schema \( S \). These formulæ generate derivation tracing
queries \( [7] q^{\text{DP}}(t) \) and \( q^{\text{SP}}(t) \) which can be applied to \( S \) in
order to respectively obtain the affect-pool and origin-pool
of the data item \( t \).

In [9] we give an algorithm for tracing the affect-pool and
origin-pool of a materialised data item \( t \) all the way back
to the data sources by using the AutoMed pathways from
the data source schemas \( DSS_1, \ldots, DSS_n \) to the warehouse
schema. This algorithm traverses a pathway backwards, and
incrementally computes new affect- and origin-pools when-
ever an \( \text{add} \) or \( \text{rename} \) step is encountered, finally ending
with the required affect- and origin-pools for \( t \) from within
\( DSS_1, \ldots, DSS_n \).

5. DISCUSSION

We have shown how AutoMed metadata can be used to
express the ETL process in a data warehouse and how the resulting
transformation pathways can be used for some key
warehouse activities. There are three main differences be-
tween this approach and the traditional data warehousing
approach based on a single conceptual data model (CDM):

1. In the CDM approach, each data source wrapper trans-
lates the data source model into the CDM. Since both are
likely to be high-level conceptual models, semantic mismatch-
es may exist between the CDM and the source data model,
and there may be a loss of information between them. In
contrast, with the AutoMed approach the data source wrap-
ers translate each data source schema into its equivalent
AutoMed representation, without loss of information. Any
necessary inter-model translation then happens explicitly
within the AutoMed transformation pathways, under the control
of the data warehouse designer.

2. In the CDM approach, the data transformation and in-
tegration metadata is tightly coupled with the CDM of the
particular data warehouse. If the data warehouse is to be re-
deployed on a platform with a different CDM, it is not easy
to reuse the previous data transformation and implementa-
tion effort. In contrast, with the AutoMed approach it is
possible to extend the existing pathways from the data
source schemas \( DSS_1, \ldots, DSS_n \) to the current detailed
data warehouse schema, DS, with extra transformation steps
that evolve DS into a new schema \( DSS_n^{\text{new}} \), expressed in the
data model of the new data warehouse implementation. The
pathway \( DS \rightarrow DSS_n^{\text{new}} \) can be used to populate the detailed
schema of the new data warehouse from the current ware-
house. The downstream schemas from \( DSS_n^{\text{new}} \) (i.e. the sum-
mary views and the data mart schemas) do still have to be
defined again by means of new pathways from \( DSS_n^{\text{new}} \), but
all the upstream data transformation/integration metadata
can be reused. In particular, the pathways from \( DSS_1, \ldots,
DSS_n \) to \( DSS_n^{\text{new}} \) (via DS) can be used to maintain the new
data warehouse.

3. In the CDM approach, if a data source schema changes
it is not straightforward to evolve the view definitions of the
data warehouse constructs. With the AutoMed approach,
a change of a data source schema \( DSS_i \) into a new schema
\( DSS_i^{\text{new}} \) can be expressed as a pathway \( DSS_i \rightarrow DSS_i^{\text{new}} \).
The (automatically derivable) reverse pathway \( DSS_i^{\text{new}} \rightarrow
DSS_i \) can then be prefixed to the original pathway \( DSS_i \rightarrow
TS_i \), to give a pathway \( DSS_i^{\text{new}} \rightarrow TS_i \), thus extending the
transformation network of Figure 2 to encompass the new
schema. Let us examine the impact of this extension. Sup-
pose that the pathway \( DSS_i \rightarrow DSS_i^{\text{new}} \) consists of a single
primitive transformation \( t \) (longer pathways can be treated
as a sequence of single-step pathways). There are three cases
to consider for \( t \), the first two of which can be handled totally
automatically and the third semi-automatically.

(i) If \( t \) is an \( \text{add} \), \( \text{delete} \) or \( \text{rename} \) transformation, then
\( DSS_i^{\text{new}} \) is semantically equivalent to \( DSS_i \), and no fur-
ther change to the transformation network is needed. When new data is extracted from \( DSS_i^{\text{new}} \), the new
pathway \( DSS_i^{\text{new}} \rightarrow TS_i \) can be used to transmit the
new data to \( TS_i \).

(ii) If \( t \) is of the form \( \text{contract}(c) \) then construct \( c \) will
no longer be available from \( DSS_i^{\text{new}} \). The transforma-
tion network needs to be modified to remove all down-
stream constructs directly or indirectly dependent on
\( c \) (and their underlying extents, if they have been ma-
terialised). This is done by first removing the initial
\( \text{extend}(c) \) step from \( DSS_i^{\text{new}} \) to \( DSS_i \), (and as a result
removing also \( DSS_i \)) and then examining the query
accompanying each subsequent \( \text{add} \) step and the con-
structs referenced in each subsequent \( \text{rename} \) step.

(iii) If \( t \) is of the form \( \text{extend}(c) \) then there will be new data
available from \( DSS_i^{\text{new}} \) that was not available before. If
the transformation network remains as it is, then the first
step from \( DSS_i^{\text{new}} \) to \( DSS_i \), is \( \text{contract}(c) \) which
removes \( c \). Thus, the transformation network is still
consistent, but it does not utilise the new data.

It may be the case that we want to evolve the ware-
house detailed schema, DS, to include this new data.
In this case, we can simply remove the \( \text{contract}(c) \)
step (and hence also \( DSS_i \)) from the transformation
network. This has the effect of automatically propa-
gating the construct \( c \) to all the downstream schemas
in the transformation network. Some further man-
ual modification of the network may also be neces-
sary e.g. removing \( c \) from the data mart schemas by
inserting a \( \text{contract}(c) \) step in the pathway from
the DWS to a data mart schema; ‘cleaning’ \( c \) by inserting
extra transformation steps before \( SS \), and/or before
the appropriate multi-source cleaned schemas; seman-
tically integrating \( c \) with existing data by inserting ex-
tra transformation steps before the detailed schema,
DS; utilising \( c \) in new view definitions etc.

6. CONCLUDING REMARKS

In this paper we have discussed the use of AutoMed meta-
data in data warehousing environments. We have shown
how AutoMed metadata can be used to express the data
schemas, and the data cleansing, transformation, and in-
tegration processes. We have shown how this metadata can
then be used for populating the data warehouse, increment-
ally maintaining the warehouse data after data source up-
dates, and tracing the lineage of warehouse data.

In contrast to the traditional data warehousing approach
which adopts a single conceptual data model to transform
and integrate data from multiple heterogeneous data sources
we use a low-level common data model, the HDM. Data

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source wrappers first translate the source schemas into their equivalent HDM specification. AutoMed’s transformation pathways are then used to incrementally transform and integrate the source schemas into an integrated schema. The integrated schema can be defined in any modelling language which has been specified in terms of AutoMed’s HDM. We discussed in Section 5 how several benefits result: no semantic mismatch between the data source schemas and their representation in the HDM; support of evolution of the data source schemas; and reuse of much of the transformation/integration effort if the data warehouse is redeveloped on a platform supporting a different data model.

In contrast to commercial ETL tools, AutoMed metadata provides sufficient information to support activities such as data lineage tracing and incremental view maintenance. Furthermore, AutoMed’s HDM provides a unifying semantics for higher-level modelling constructs and hence a basis for automatically or semi-automatically generating the semantic links between them — this is ongoing work being undertaken by other members of the AutoMed project.

So far, our incremental view maintenance and data lineage tracing algorithms have used only the add and rename transformation steps from the data sources to the integrated schema. We are now looking at how to also make use of the information imparted by the queries within delete and contract transformation steps. We are also looking at the impact of calls to external functions on our incremental view maintenance and data lineage tracing algorithms.

Clearly, not all data warehouse metadata can be captured by AutoMed e.g. information about physical organisation of the data, ownership of the data, access control, temporal information, and data refresh and purging policies. Thus, we envisage AutoMed being used alongside an existing DBMS supporting such facilities. We are currently investigating this interaction of AutoMed with existing data warehousing functionality in the context of a data warehousing project in the bioinformatics domain. This project is creating an integrated data warehouse in Oracle from the CATH database and other specialist data sources. It is also extracting specialist data marts from this warehouse, tailored for individual researchers’ needs and deployed in lightweight DBMSs such as Postgres or MySQL. The data sources are evolving over time, as are the researchers’ requirements for their data marts. Thus, this application is well-suited to the functionality that AutoMed offers.

7. REFERENCES