Title
Lineage in GIS: The Problem and a Solution (90-6)

Author
Lanter, David P.

Publication Date
1990-09-01

National Center for Geographic Information and Analysis

LINEAGE IN GIS:

THE PROBLEM AND A SOLUTION

David P. Lanter
NCGIA Fellow, Department of Geography
University of California at Santa Barbara
Santa Barbara, CA 93106

NCGIA Technical Paper 90-6
Sept. 1990

THE PROBLEM OF LINEAGE IN GIS

David P. Lanter
Department of Geography
University of California
Santa Barbara, California 93106
(805) 961-8616

ABSTRACT. This paper focuses attention on a fundamental geographic structure: the GIS application. Lineage documentation specifies an application's source data, transformations, and input/output specifications. Such information is inherently causal, communicating the theory embodied in a GIS application and the meaning of its product. A number of techniques for automating lineage information are examined. None are found to be capable of documenting data lineage.

KEYWORDS: GIS, Application, Automated documentation, Spatial data quality, Spatial data transfer standards, Geographic structure.

A geographic information system (GIS) is computer software designed to collect, store, retrieve, manipulate, and display objects defined as points, lines, or areas (Tomlinson et al. 1976; Marble 1984; Clarke 1986; and Dueker 1987). The GISs unique ability to manipulate existing data and "synthesize" new spatial entities separates it from other information processing technologies (Burrough 1986; Cowmen 1988). This ability to create new entities results from programmed code for making explicit features from implicitly expressed spatial relations between data stored in the GIS database. Goodchild refers to this process as spatial analysis (Goodchild 1987). Transforming existing data into new data is a double-edged sword. The resulting database may have more information than the old one. The meaning of the new information, however, is exogenous and not found in the data (Tobler 1979).

To address the problem of interpreting the meaning of derived spatial data the National Committee for Digital Cartographic Data Standards (NCDCDS) has proposed that exchanged cartographic data be accompanied by a ‘lineage' statement within a formal quality report (Morrison 1988). The committee's definition of lineage is information describing source materials and transformations used to derive final digital cartographic data files (Chrisman 1983a; Morrison 1988). The lineage report is intended to serve as a communication mechanism between data producers and users. It is a "truth in labeling" approach to cartographic data quality reporting (Moellering 1987). The producer's responsibility is to label the GIS derived data product with information concerning its source materials and processing history. The user's responsibility is to interpret such information and determine the data’s fitness for use (Chrisman 1983; Grady 1988).

This paper focuses attention on the structure of spatial data lineage. A number of automated systems are examined, including history files, version control systems, map librarians, and polygon attributes. A critical review illustrates that none of these methods are capable of fulfilling the informational requirements of a lineage report. A system that would meet such requirements would detail the characteristics of cartographic sources, the topologic relationships between source, intermediate and product layers, and the transformations applied to sources to derive GIS applications output products.

The Temporal Topology Component

Langran and Chrisman differentiate between two temporal axes relating to cartographic change (Langran and Chrisman 1988). World time' tracks changes to geographic features occurring on the surface of the Earth. Tagging each feature with a time-stamp marks time on this axis and facilitates tracking it as it changes over many dates (Basoglu and Morrison 1977; Armstrong 1988; Langran 1988; Langran, 1989). The world time axis is important to producers of map products having strict requirements for currency and historical accountability (Hunter 1988; Vrana 1989).

'Database time' differs from 'world time', according to Langran and Chrisman, in that its concern is for tracking entry of spatial entities into a geographic database (Langran and Chrisman 1988). This begins, they argue, when the first data is entered into the database and ends on the last data entry. Langran and Chrisman's, definition of database time, however, cuts short the length of the axis. From the view of a GIS, database time extends beyond the phase of data collection and storage and continues through phases of retrieval, manipulation, and display. It marks not only the changing nature of geographic entities as they are stored within a database, but also the derivation of new ones as they are derived by geographic information processing. Lengthening the 'database time' axis thus makes it useful for structuring transformations recorded within lineage documentation of a GIS application.

Langran and Chrisman suggest that topologies are useful not only for organizing spatial data, but for structuring the cartographic time axes to track changing cartographic features in a geographic database (Langran and Chrisman 1988). They instruct,

> ... just as the spatial topological data structure would provide a means of navigating from an object to its neighbor in space, the corresponding temporal data structure would provide a means of navigating from a state or a version to its neighbor in time. (p. 7)

Tomlin's cartographic model (Tomlin 1990) is useful for focusing attention on such topologies taking place within GIS applications. The cartographic model’s diagrammatic specification explicitly records the flow of maps through transformations applied throughout the course of geographic information processing (Tomlin and Berry 1979; Tomlin 1983). The model records the sequence of transformations thematic layers undergo from source materials through intermediate processes to final products. It is a special form of data flow diagram depicting layers as nodes and transformations as labeled directed links. The resulting network representation specifies an application's processes and data interfaces between them (Martin and McClure 1985). Its graphical representation expresses the morphology of a GIS application. An example cartographic model is illustrated in Figure 1.

Recording processing steps applied to geographic data in a cartographic model provides a powerful mechanism for documenting input/output relationships inherent in a GIS application. Examining the cartographic model reveals the entire history of transformations applied to source materials throughout the course of a GIS application. It captures two of three important aspects of lineage information: input/output

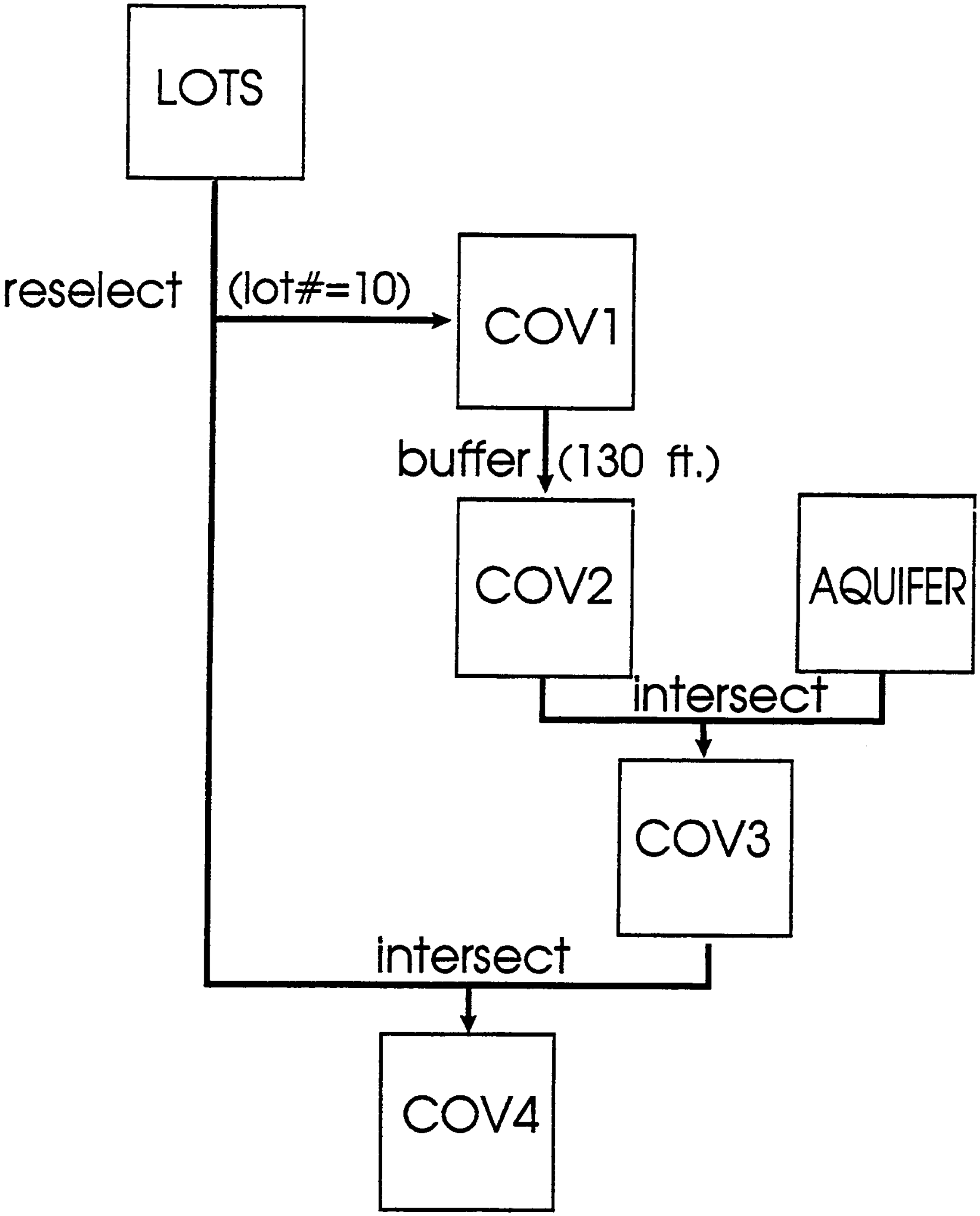


Figure 1. Cartographic model of application to determine parcels at risk of pollution by discharge from lot# 10.

relationships and transformations. This information when combined with descriptions of source materials is lineage documentation.

Lineage Documentation As Geographical Structure

Tobler suggests, "a geographic structure is a transformation of geographic data, a theory, or model of reality" (Tobler 1979, 105). Lineage information is such a geographic structure. It documents source data, transformations, and input/output specifications illustrating the derivation of cartographic products within a GIS application. By representing causal structure, cartographic lineage can be viewed as a theory or model of geographic reality. This structure communicates the meaning of the derived map.

Analysis of a derived map's lineage provides understanding of the geographic reality it represents. It also makes obvious when a GIS application is based on flawed logic. This is important. If the theory encoded in a GIS application is not clearly understood, then a correct interpretation of the resulting map is not possible. Recording this information along with documenting sources has critical relevance to decision makers using information derived by GIS applications.

By representing structure, lineage documentation transforms the GIS application into material reality. It expresses the nature of source data, input/output relationships, and transformations. Documentation of sources and sequences of transformations expressed in terms of commands and command modifier values has the potential of simultaneously reflecting and reinforcing the world view and spatial thought of the institution applying them to analyze digital representations of the world. As a result, lineage documentation provides cultural cartographers with material necessary to study the cultural context of GIS-based decision making (Rundstrom 1990).

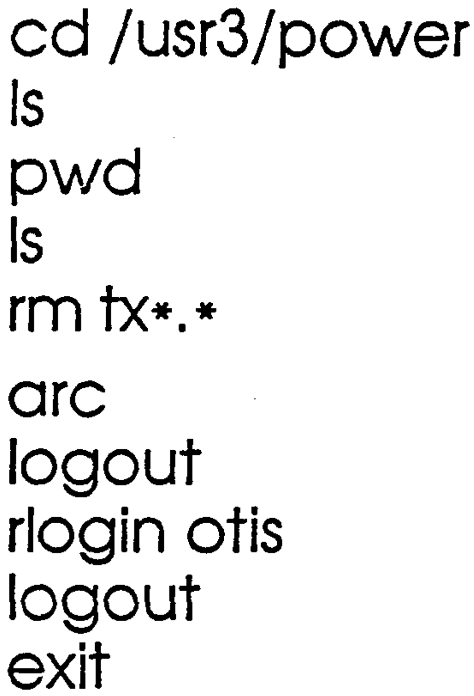
The Problem of Lineage In GIS

Lineage documentation is important to interpreting the nature and quality of a GIS derived map products. However, it is used rarely if at all. Vonderohe and Chrisman (1989) report that of six interrelated spatial data quality components: lineage, positional accuracy, attribute accuracy, logical completeness and currency, lineage is the only one that is "not testable" in the course of spatial data processing (Vonderohe and Chrisman 1985). This is because no technique for automatically creating and manipulating lineage information has been suggested in the geographic literature. The sections that follow review existing aspatial and spatial methods for tracking lineage in various information systems.

Tracking Lineage in Aspatial Systems

Systems for documenting and tracking changes to data files within an information system are common in computer environments. These methods range from simple history files, log files and audit files to more complicated schemes of tracking updates to programmed source code and text documents.

History Files. The most basic form of documenting changes to a data file is through use of a "history file" (Figure 2). This capability is often part of a computer's operating system and provides a way for the system administrator to keep track of commands given to the system by users. An examination of a history file will yield commands used and subsequent changes made to various files by users. An example of such a history can be found in the UNIX operating system (McGilton and Morgan 1983).



```
cd /usr3/power
ls
pwd
ls
rm tx*.*
arc
logout
rlogin otis
logout
exit
```

Figure 2. Unix history file.

Audit and Log Files. Variations on the history approach include the 'audit' and 'log' files. These systems provide detailed listings of user commands and system output (Figures 3 and 4). Audit or 'watch' files typically record the entry and system responses for each given command. In addition, log files record date, elapsed time, and amount of system resources used during execution of each command. Examples of such facilities can be found in the ERDAS and ARC/INFO systems.

Each of the history, audit, and log files has serious short comings related to lineage documentation. They do not document the nature of data sources input into the GIS database. Nor do they provide any connectivity to specific data layers within the database. As a result, many pages of output or CRT screens of data must be reviewed to determine what transformations were made to specific maps by user entered commands. While they are able to capture commands as typed by users, these facilities are unable to explicitly represent topological input/output relationships between sources and derived spatial data products. Due to the dynamic nature of spatial information systems such manual approaches to determining all the source data and transformations resulting in a given map are inadequate.

Version Control Systems. Version Control Systems track revisions made to documents and program source code. They are software engineering tools often supplied along with hardware by computer manufactures such as Control Data Corporation, IBM,

```
> ERDAS:NOMENU
  ERD>
> read
  READ -- Multichannel Image Display
  Version 7.3.00.82
  Display file FOREST again?
? No
  Enter Image filename: (FOREST)
        :
? master
# 1
# 1
  Select Band to Color assignment (R,G,B)  (-1 = do
  not use this color)
? 4,3,2
  Enter the number of standard deviations to use
? 2
  Data limits for the RED image  (Band 4)
? 10,109
  Data limits for the GREEN image  (Band 3)
? 10,48
  Use the Function Memories for Image Scaling?
? Yes
  Enter coordinates for center of image
? 368,276

  Use Magnification, Reduction, or No change?

? No change
  Use the Box or the Keyboard?
? Keyboard
  Enter desired coordinates for display center
? 256,256
```

Figure 3. ERDAS audit file.

```
198923021442   1    3    OARCPLOT
198923021442   0    10   OBUILD NISLAND POLY
198923021442   0    1    OEXTERNAL NISLAND
198923021503   20   44   OARCPLOT
198923021505   0    3    OPOLYGRID NISLAND
198923021512   2    15   Opolygrid nisland
198923021514   1    24   Ogridpoly nisland.svf nigrid 662795 680175 30 30
198923021516   2    6    Oarcplot
198923021520   2    4    Oarcplot
198923021520   0    2    Oarcplot
198923021520   0    0    Oexternal nisland
198923021520   0    1    Oexternal nigrid
198923021520   0    3    Oarcplot
198923021526   5    71   Oarcedit
198923021530   0    1    ORENAME NIGRID NIG30
198923021533   3    72   OPOLYGRID NISLAND GR10.SVF
198923021536   3    85   OGRIDPOLY GR10.SVF NI10 662795 680175 10 10
```

Figure 4. ARC/INFO log file.

SUN, Univac, and others. One example is the Source Control and Configuration System ('SCCS') originally part of the Berkeley UNIX operating system. SCCS is a library of operating system functions enabling users to maintain a file of revisions to source code documents created in the course of software development (Allman 1984).

The SCCS stores the initial document and file of changes ('deltas') to that document associated with each revision (Figure 5). The delta is the set of differences between each revision and the previous revision. Each delta is accompanied by a time and date-stamp and an optional user comment. Using this file of deltas, a user can start with an initial document and more forward in time recreating any subsequent version. Alternatively, other version control systems store the complete current versions of a document together with a series of deltas containing the history of revisions made over time. This allows the user to move backward in time to recreate any previous version. Polytron's PVCS is an example of this latter type (Kinzer and Kinnaird 1987).

Version control systems provide a mechanisms for both documenting sources and explicitly representing input/output relationships. Their major limitation results from their inability to create meaningful deltas from spatial data. In addition, they lack an automated capability for documenting the transformations applied to input layers used to derive a product. Users of version control systems tracking changes to aspatial data could cope with this limitation by manually keying in text to describe each transformation and its associated parameters.

```
     mn.c_v Rev 1.0 (20 Nov 1988 20:57:50)
                  mn.c_v Rev 1.1 (30 Jan 1989 15:40:32)
====================
        13    13   :     int path=0,  count, c, oldcount;
        14    14   :     static char  font0()        ="HAL0104.FNT";
-       15         :     static char  display0()     ="DISPLAY";
-       16         :     static char  digitize0()    ="DIGITIZE";
-       17         :     static char  delete0()      ="DELETE";
-       18         :     static char  quit0()        ="QUIT";
        19    15   :
        20    16   :     int one=2;
====================
        45    41   :     /* Place test */
        46    42   :     count=1;
-       47         :     display0();
        48    43   :
        49    44   : do(  /* readlocator, exit if both mouse keys pressed. */
====================
        67    62   :                      • mnucntr12(what.t.w,s,z,sc,ia,ib);
        68    63   :                        break;
+             64   :                     case 4:
+             65   :
+             66   :                        break;
+             67   :                     case 5:
+             68   :
+             69   :                        break;
+             70   :                             case 6:   /* quit */
-       69         :                             case 4:   /* quit */
        70    72   :                        c=ESCAPE;
        71    72   :                        break;
====================
```

\- indicates lines deleted
\+ indicates lines added

Figure 5. POLYTRON's delta file.

Tracking Lineage in GIS

Consumers taking advantage of a growing range of source materials and automated map derivation tools feel the need for lineage information. GIS users participating in even small projects are quickly realize their ability to create new maps exceeds their ability to track the processes used to create them (Moore 1983).

To address the problem of lineage in GIS, Krogulecki and Parks have proposed a system of standard forms to manually document digital map creation (Krogulecki and Parks 1988). Information concerning source digitized materials are entered by GIS users into a log book along with specific transformations applied in the course of file creation. This information can then be typed into a computer file and exchanged as a file header field of free text with an associated layer (Guptill 1987; Cooper 1989). One problem with the manual approach to lineage reporting is that it requires a conscientious effort on the part of all users to fill out forms at each step of a spatial application. A means for automatically creating lineage documentation and associating it with a derived GIS data product is clearly preferable.

A review of various commercial geographic information system manuals (from ESRI, ERDAS, Geobased, and IIBM) and telephone interviews with technical staff of other GIS vendors and systems integrators (Anderson Consulting, Deltasystems, GeoVision, Intergraph, Kork, McDonald Douglas, Software-AG, Synercom, USA-CERL, and Wild Heerbrug) reveals many systems have capabilities for maintaining history, log, and audit files, but all lack an automated lineage tracing capability. Some vendors argue that their systems maintained critical data management information within "map librarians", or as "polygon overlay attributes".

Map Librarians. In general, map librarians are a series of tools for partitioning and organizing a geographic database by location and theme (Aronson and Morehouse 1984). They provide a spatial and thematic framework for organizing a cartographic database. This framework is a basis for establishing checking-in and checking-out procedures. Such procedures are useful for controlling the process of data archival. This ability to control a data archive facilitates implementing standards of data content consistency (ESRI 1989).

Map librarians, however, are not intended to record the lineage of derived maps. While data sources may be stored as layers within a map library, the sources are not documented with attributes concerning date (in world time), scale, projection, agency, and accuracy. In addition, librarians are not equipped to record the dynamic nature of database structure with temporal topology as new layers are created, nor the history of transformations applied when various layers are used to produce a product.

Polygon Overlay Attributes. Of the various families of spatial analytic functions polygon overlay is one of the most powerful. Polygon overlay functions are set theoretic operations. Such operations involve the superimposition of spatially registered thematic map layers. The result is a composite representation exhaustively specifying the spatial interaction of thematically differentiated geographic features contained within input layers.

Systems supporting spatially topological polygon overlay often handle spatial and aspatial data separately. In topological polygon overlay the newly derived geographic features inherit their aspatial attributes from input features. The aspatial attributes may be organized as attribute tables transferred from sources and merged as annotation of the derived features. Often the new attributes maintain a symbolic connection to their ‘parental' input layers. In these cases database time topology is maintained as attributes of the layer created by the overlay. This is illustrated in Figure 6.

Examination of the attributes inherited by a new feature reveals a lack of documentation concerning the type of overlay (e.g. union or intersection) and command modifiers (e.g. tolerances) used to derive the resulting map. Thus, critical information for determining the lineage of a product derived by topological overly is missing.

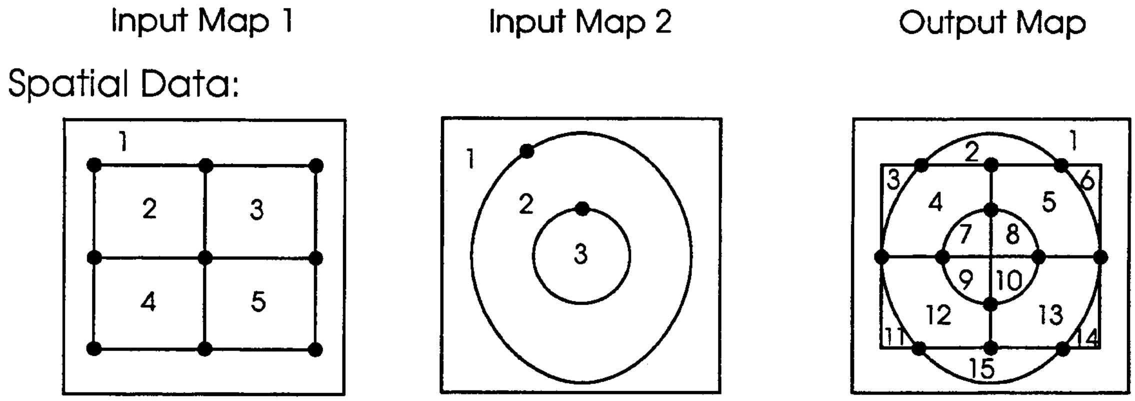
In addition to neglecting documentation of transformations, such systems often lack annotation concerning the nature of imported or digitized source layers. Such systems also often lack documenting imported or digitized source layers with lineage attributes. Another problem concerns the fact that many GIS applications are not based solely on map overlay. GIS applications often use other types of transformations (e.g. buffer generation, aspatial attribute selection, contiguity or connectivity determination). In contrast to those derived by polygon overlay, features and layers resulting from these operations are not connected to their inputs. In summary, systems supporting topologic polygon overlay often lack documentation concerning data sources, transformations and associated parameters. While they do document inputs related to features derived by polygon overlay, they do not document input/output relationships between a number of other important GIS operators.

Conclusion

Lineage information has been defined as consisting of three components. These components are: source data description, transformation documentation, and input/output specifications. The combination of the three is a complete description of the structure of a GIS application. As such, lineage information expresses the logic resulting in derived data. It is a model useful for communicating the theory embodied in a GIS application and the meaning of its derived data product.

A number of automated techniques were examined and found to be ill-equipped for creating or maintaining such critical lineage information. History lists, log and audit files document transformations and parameters lack source description and input/output specifications. Map librarians lack all three components of lineage information: source description, transformation documentation, and input/output specification. Polygon overlay attributes maintain input/output specifications but neglect source description and transformation documentation. While such systems do document the use of data sources used in deriving layers by topologic polygon overlay, they do so for a limited number of transformations.

The only systems found to have the potential to include the three informational components of lineage are manual ones. Combining source descriptions with the application detailing of a cartographic model is a useful method of specifying a lineage report for a GIS application’s product. Automating this information will insure systematic documentation of the lineage qualities of derived GIS data products.



Aspatial Attributes:

Input Map 1	
id#	Attribute
1	
2	A
3	B
4	C
5	D

Input Map 2	
id#	Attribute
1	
2	102
3	103

Output Map	Input Map 1		Input Map 2	
id#	id#	Attribute	id#	Attribute
1	1		1	
2	1		2	102
3	2	A	1	
4	2	A	2	102
5	3	B	2	102
6	3	B	1	
7	2	A	3	103
8	3	B	3	103
9	4	C	3	103
10	5	D	3	
11	4	C	1	
12	4	C	2	102
13	5	D	2	102
14	5	D	1	
15	1		2	102

Figure 6. In topological polygon overlay the output map is connected to its inputs by aspatial attributes.

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DESIGN OF A LINEAGE-BASED META-DATABASE FOR GIS

David P. Lanter
Department of Geography
University of California
Santa Barbara, California 93106
(805) 961-8616

ABSTRACT. This paper presents the conceptual design of a meta-database system for documenting data sources and GIS transformations applied to derive cartographic products. Artificial intelligence techniques of semantic networks are used to organize input-output relationships between map layers and frames to organize lineage attributes characterizing source, intermediate, and product layers. An illustrative example indicates that a lineage meta-database enables GIS users to engage in source assessment throughout their analysis of spatial data sets.

KEYWORDS: GIS database management, Spatial data lineage, artificial intelligence, semantic networks, frames, source assessment

One reason GIS data lineage documentation has not been automated in geographic information systems is that its structure has not been well understood. Lineage documentation is based on three components. These components are: source description, details of transformations, and input/output relationships between layers. When the three are combined they model the structure of a GIS application. Study of a lineage model documenting the structure of a GIS application makes possible an understanding of a derived cartographic data product. This paper presents a technique for automating lineage information and documenting the content and structure of a GIS database.

A system design capable of acquiring and manipulating cartographic data lineage information is based on two levels: a geographic level and a 'meta-data’ level (Smith and Pazner 1984; Abler 1987; Gahegan and Roberts 1988; Salge' and Sclafer 1989; Feuchtwanger 1989). The geographic level contains spatial and aspatial information stored in traditional GIS data structures. The meta-data level contains abstract information describing data stored in the geographic level. Therefore, implementing the meta-data level creates an information system about the GIS's database.

Salge' and Sclafer suggest that the meta-data level contain quality and genealogical specifications for the geographic data (Figure 1). This concept is useful for automating and manipulating lineage information. The result is a lineage meta-database system for tracking data entering the GIS and the transformations applied once they are there.

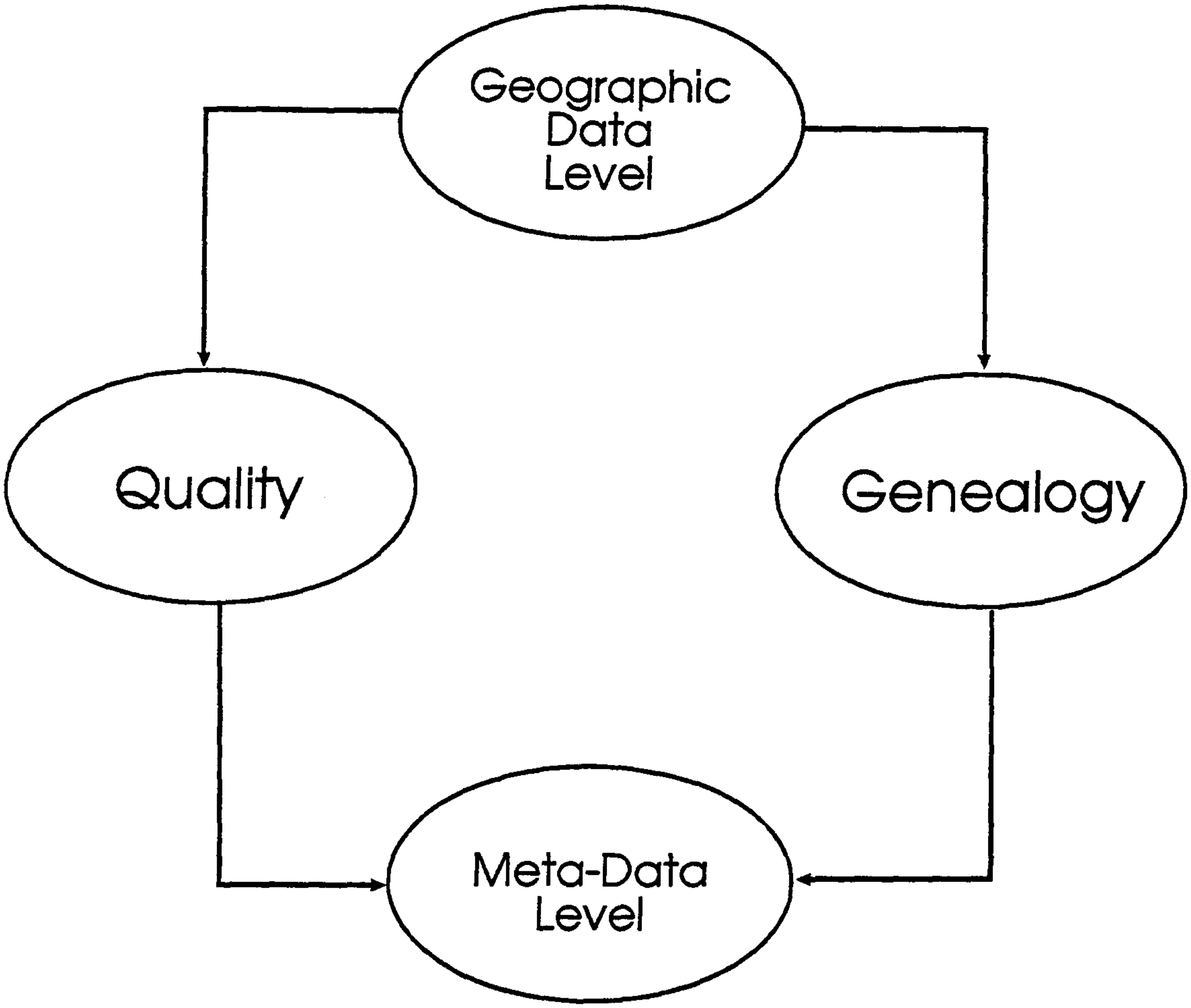


Figure 1. Relationship between geographic and meta-data levels. (After Salge and Sclafer, 1989)

Conceptual Design

There are many approaches to organizing spatial data in geographic information systems including the 'Least Common' or 'Integrated Geographical Unit' (Chrisman, 1975), and object-oriented models (Kjerne and Dueker 1986; Charlwood et al. 1987; Herring 1987; Gahegan and Roberts 1988; Egenhofer and Frank 1989). The automated lineage meta-database system presented in this study is oriented towards layer-based geographic information systems. The layer-based GIS model, illustrated in Figure 2, separates individual themes of data into a set of registered overlays (Chrisman and Niemann 1985; Kjerne and Dueker 1986; Aronson 1987; Bracken and Webster 1989). Layer-based geographic information systems are chosen because they are commonly available and well understood. Examples of layer-based GIS include the vector-based ARC/INFO and the raster-based Map Analysis Package.

In a companion article it was suggested that the relationships between derived maps and their sources is topological. Such connectivity between an application's layers is readily represented with Tomlin and Berry's cartographic model (Tomlin and Berry 1979). The cartographic model is a diagramming convention for representing map data flowing through a GIS application as they undergo transformations from source material through intermediate states to final products. The model's three basic building blocks are: thematic layers, processes, and data flows. From a pictorial standpoint, these transformations are documented by arrows representing data flows between layers. Processes transforming layers are documented as annotations along flow arrows. The result is a flowchart illustrating a sequence of data transformations necessary to achieve the desired map product.

Tomlin and Berry suggest cartographic modeling is a means of sequentially ordering GIS operators as if they were mathematical functions in a conventional algebraic expression (Tomlin and Berry 1979; Berry 1987)." An illustration of cartographic modeling in an application to determine parcels over an aquifer at risk from a discharge of hazardous pesticides.

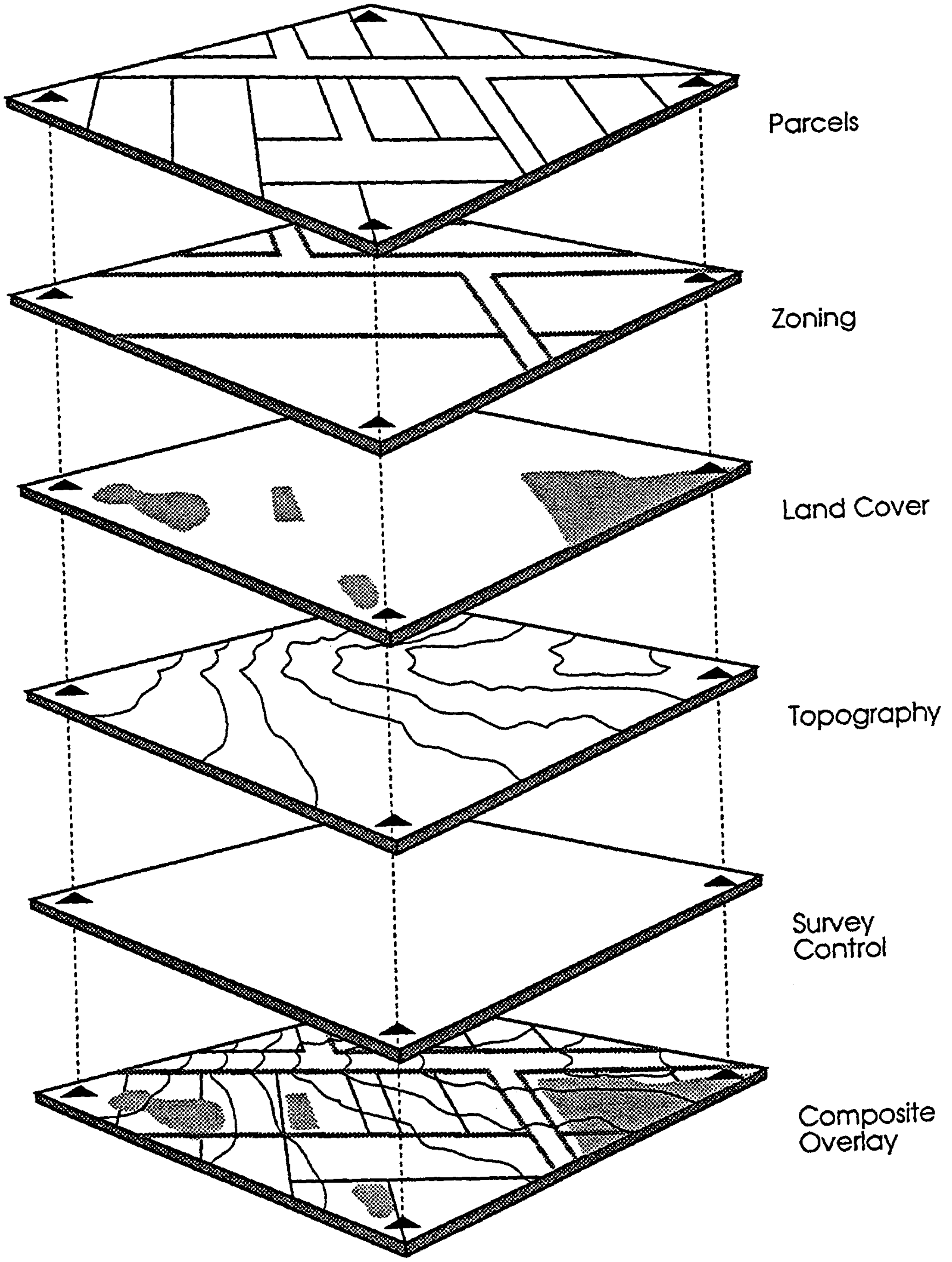


Figure 2. Conceptual model of a GIS databases as a set of spatially registered thematic layers.

The application begins with: a parcel map (LOTS), an underground water aquifer map (ZONE), and a lot from parcel map having a hazardous discharge of pesticides. The pesticides may have a horizontal range of flow of a certain distance (130 ft.). The task is to find where a buffer zone of pollution threatens the aquifer, and inform owners of parcels at risk of tainted water. A simplified cartographic model for this application is diagrammed in Figure 3.

The cartographic model is an elegant approach that helps potential users to understand how a GIS derived data product was produced. For example, the complete cartographic model illustrated in Figure 3 shows COW is derived from several intermediate layers, all tracing their lineage back to LOTS and ZONES. Questions concerning the processing required to create COW can also be answered by examination of the cartographic model.

Thus, in layer-based geographic information systems: maps are layers, GIS operations transform individual or combinations of layers to derive new layers. The cartographic model is a powerful mechanism for documenting the temporal topology of spatial data lineage inherent in GIS applications. However, it is typically used informally if it is used at all.

Missing from the cartographic model, however, is documentation of the source layers. If either are the output of some other application, then that application's cartographic model would reveal its lineage and point to the original data sources contributing to a produc (e.g. COW). Questions concerning the original input scale, source agencies, projection, etc. can only be answered with documentation of those layers (e.g. LOTS and ZONES). For the cartographic model to be useful for automated lineage tracing it must be adapted to include attributes of three layer types within GIS applications.

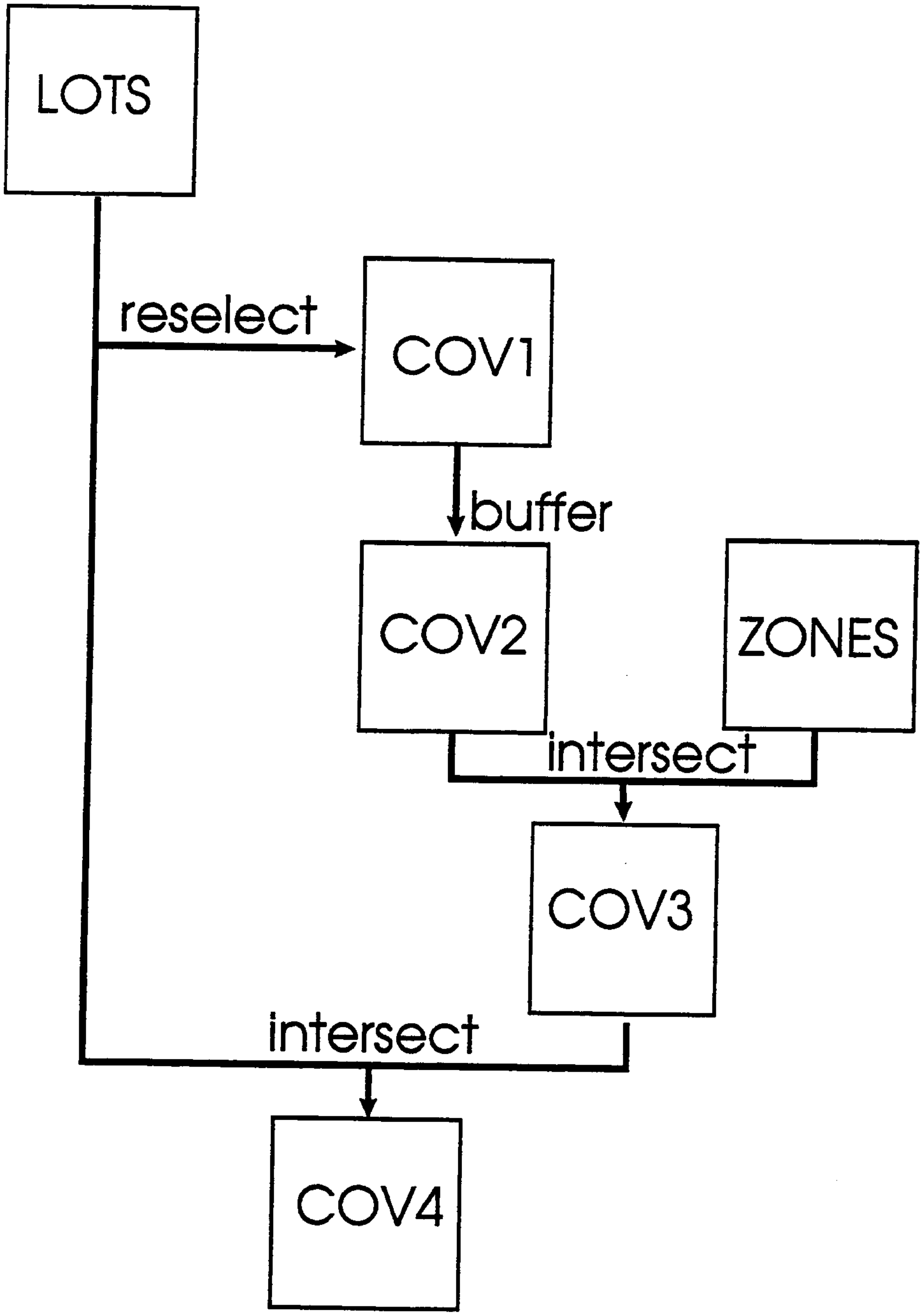


Figure 3. Cartographic model of application to determine parcels at risk.

A taxonomy of source, intermediate, and product layers serves as a basis for structuring layer attributes needed to trace spatial data lineage. These attributes are needed to encode the conditions of the steps of a geographic algorithm (e.g. parameters, algorithms, mathematical transformations, etc.), characteristics of the map layers inherent in them (e.g. source, data, scale, use, responsibility etc.), as wen as their uses in decision making. This information is critical to an understanding of derived maps resulting from spatial information processing.

Source layers are original inputs to a spatial database. The National Committee for Digital Cartographic Data Standards (Morrison 1988) suggest source documentation includes lineage information concerning name, feature types, date, responsible agency, scale, projection, and accuracy. Documenting database sources with this kind of information is fundamental to determining their utility and their "offspring's" utility for GIS-based spatial analysis.

Intermediate layers bridge the gap between source and final products. Therefore, they require documentation concerning the nature of the transformation used in their derivation. Products layers output from the system for use in decision making. Their existence does not indicate any finality in terms of their use in subsequent processing. Rather, they record a pause in a continuing GIS database life cycle. Products are intermediate layers requiring documentation of the transformation used for their creation. In addition, products may be documented with information concerning their use in decision making. Such information might include the decision makers using them, their role in decision making, release dates, and those responsible for their maintenance.

Design Considerations

A design of a lineage information program ('LIP') capable of creating and managing a lineage meta-database is based upon a set of general assumptions. The design presented here assumes the following: a layer-based geographic information system, the temporal topology of lineage between database layers inherent in spatial applications, and computer programming techniques of semantic networks and frames. As shall be demonstrated knowledge-based techniques of semantic networks and frames serve as building blocks for creating a lineage meta-database.

Knowledge representations are data structures in which knowledge about a particular problem domain is stored. Such structures are important because they are useful for representing information about recurring patterns extracted from our experience (Rich 1983). A semantic network is a general framework in which knowledge is organized as a set of nodes connected by labeled links. Since relationships are explicitly represented as links in a graph, a semantic network traversal algorithm could make relevant associations by simply following links (Luger and Stubblefield 1989).

Semantic network representation of a domain, such as a geographic application, assigns semantic meaning to nodes and links. Parent and child relationships are useful metaphors for describing the order found in the graph structure of GIS applications. Nodes represent map layers within a GIS database. Links denote semantic parent and child relationships between layers. These relationships connect input and output maps of spatial transformation processes within GIS applications.

Parent links indicate which output layers are the direct result of processing a particular input layer. They answer the genealogical question: Who are my descendants? Child links indicate which input layers a particular output layer was derived from. They answer the lineage question: From whom am I derived? In Figure 4, Map-1 has one parent link pointing to MAP-2. Map-2 has one child link pointing to MAP- 1.

Semantic networks can serve as a basis for differentiating layers within geographic applications. Figure 5 illustrates the semantic network representation of an application to create the final product layer COW from sources LOTS and ZONES. The properties made clear from the semantic network of parent/child relationships relate to source layers intermediate layers, and final products. If a layer lacks child links it must be a source layer within the horizon of the GIS database. In Figure 5, LOTS and ZONES lack such links.

The fact that a layer lacks links pointing to input data layers indicates it was obtained from data originating outside the database. If child links exist, then the spatial data layer is an intermediate layer. In the Figure 5 it can be observed that COV1, COV2, COV3, and COV4 are intermediate layers having child links. AR intermediate layers are associated with parent layers from which they are derived. These parent layers are accessible through child links. If an intermediate layer's parent links are empty, then it is an application's final product. COW is a final product because it is an intermediate layer that lacks parent links.

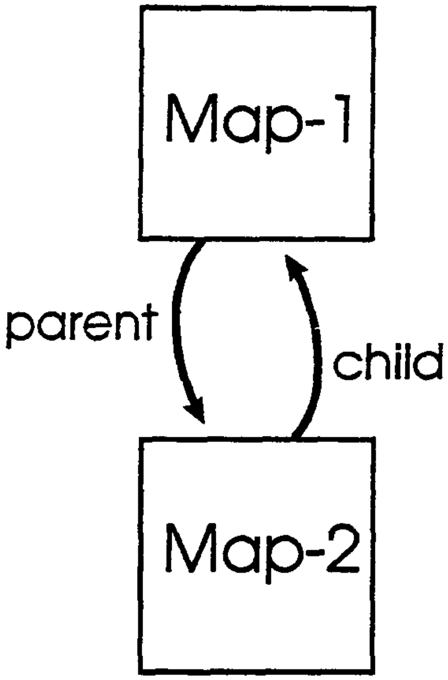


Figure 4. Semantic links between layers.

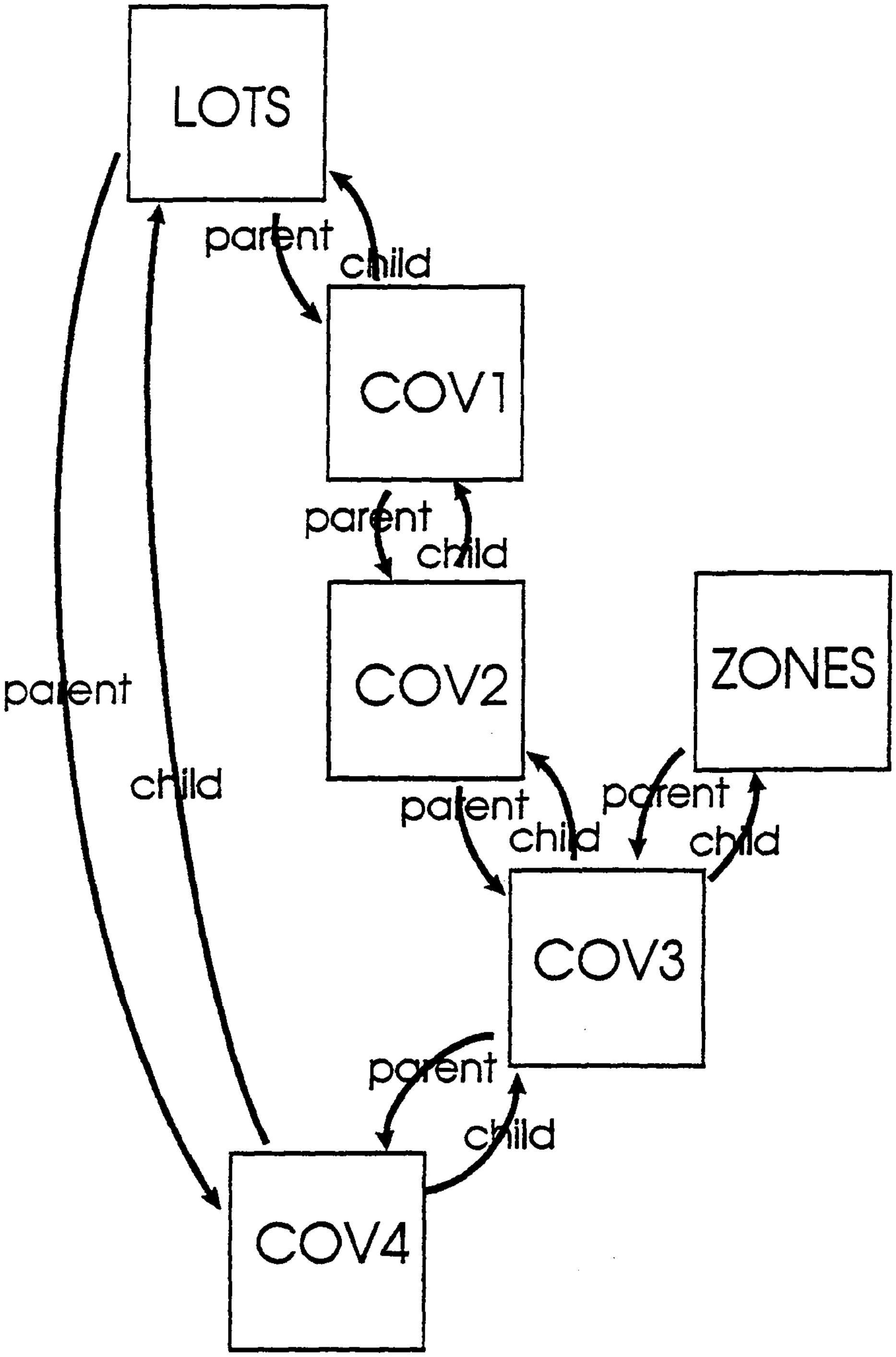


Figure 5. Semantic links between source, intermediate, and product layers.

Thus, transforming a geographic application into a semantic network of parent/child links makes it possible to distinguish different types of geographic data layers. Source layers have parent but lack child links. Intermediate layers have child links and may or may not have parent links. An application's product layer is an intermediate layer that has child but no parent links.

The use of frames embodies the concept that knowledge relevant to a particular phenomenon can be represented (Minsky, 1975). Frames usually consist of a name of a phenomenon and a listing of attributes that describe it. These attributes are usually called "slots" and the values documenting instances of the phenomena fill the slots.

Frames serve as structures to store attributes of entities. Therefore, they are useful in organizing lineage attributes of layers within GIS applications. One frame is designed to store documentation about such things as a layers date, scale, and projection. Another stores information about the command used to transform a layer's inputs. A third handles attributes that document a layer's use in decision making.

Source layers are documented typically with quality information attributes concerning such characteristics as: layer name, source agency, feature types, date of source, responsible agency, scale, projection, and accuracy. Such information is stored in a Source Description Frame (Figure 6).

All intermediate layers are identified with the command attributes associated with its creation. The command, its modifiers, and the modifier values (if any) are stored in appropriate command attribute slots in the Command Frame (Figure 7).

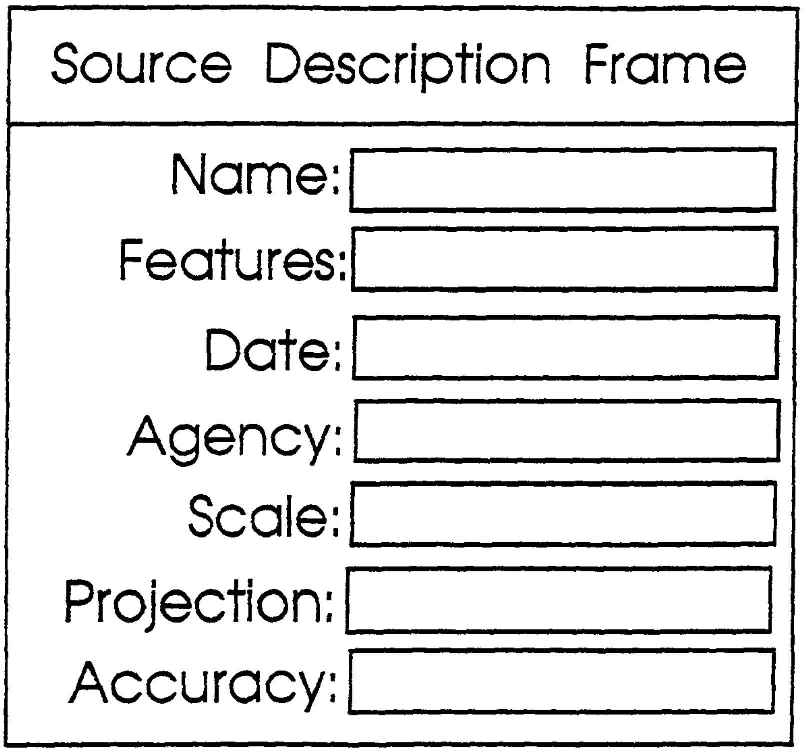


Figure 6. Source Description Frame with slot definitions.

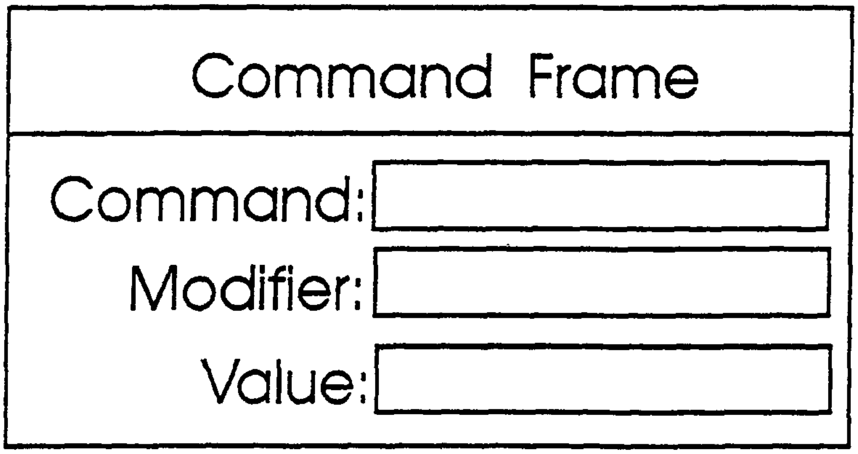


Figure 7. Command Frame with slot definitions.

An application's product is typically used in a decision making process. Each Product, therefore, is documented with attributes concerning: to what use it Win be applied, who the users are, who is the person responsible for creating it, what is that person's affiliation (department or agency), and the product's release date. This information is contained in a Product Frame (Figure 8).

The lineage knowledge representation is a hybrid data structure consisting of semantic parent/child links between three types of layers with their associated source, command, and product frames. Figure 9 illustrates that source layers have a Source Description Frame. Intermediate layers created from the sources have their own Command Frames documenting the command that created it. An application's product has a Product Frame documenting its use in decision making. Thus, original inputs, intermediate layer and final product are linked by parent links pointing from input layers to derived layers, and child links pointing from outputs to inputs they were derived from.

The hybrid semantic network/frame structure models the theory implicit in the GIS application. It supports the design of functions capable of lineage deduction by navigating links and accessing frame slots. Encoding this information in a separate lineage meta-database makes it possible for the lineage information program (LIP) to report on the sources and transformations used in spatial applications.

Functional Design

The structure of the LEP/GIS relationship is shown in Figure 10. User entered GIS commands are first processed by the LIP then passed to the GIS which executes them to derive new information or query the GIS database. As data manipulation commands are executed the LIP creates a knowledge representation of the relationships between input map layers and output map layers stored within the GIS database. As the knowledge representation evolves, the transformational relationship between input and output layers is modeled. The LIP not only keeps track of the geographic information system commands as history, log, and audit files do, but creates an explicit record of how individual layers are related to one another.

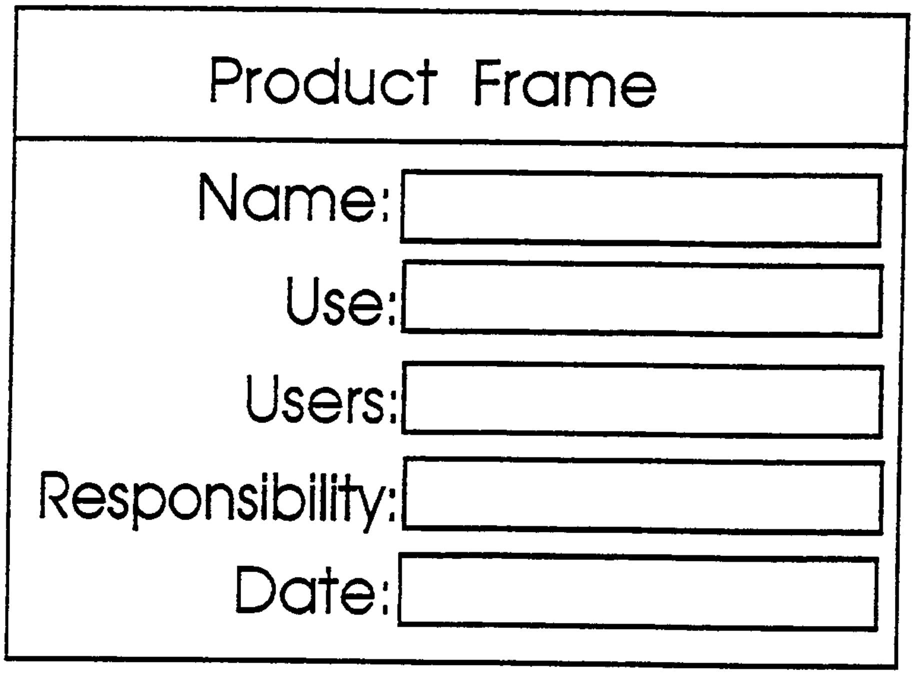


Figure 8. Product Frame with slot definitions.

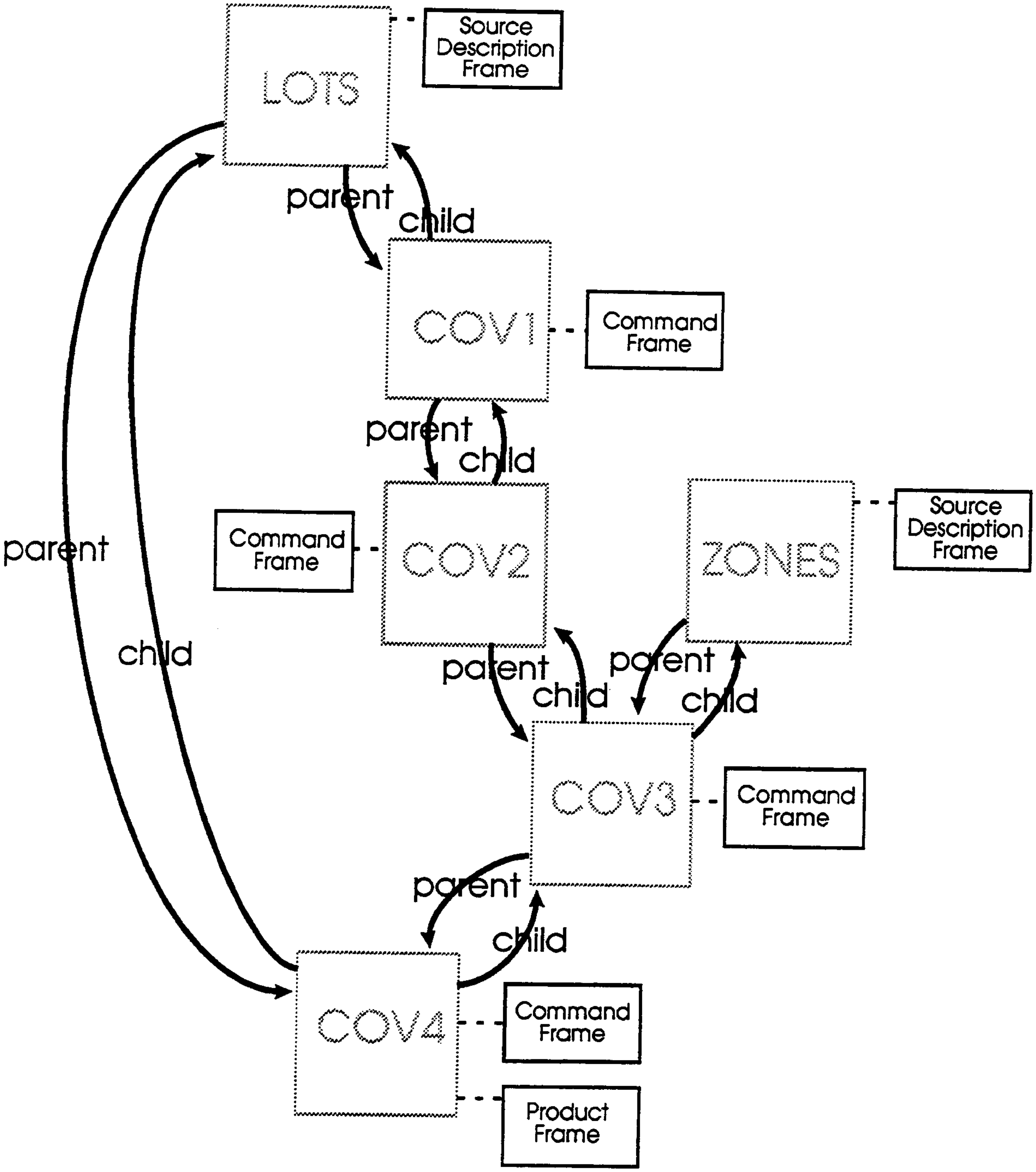


Figure 9. Lineage knowledge representation.

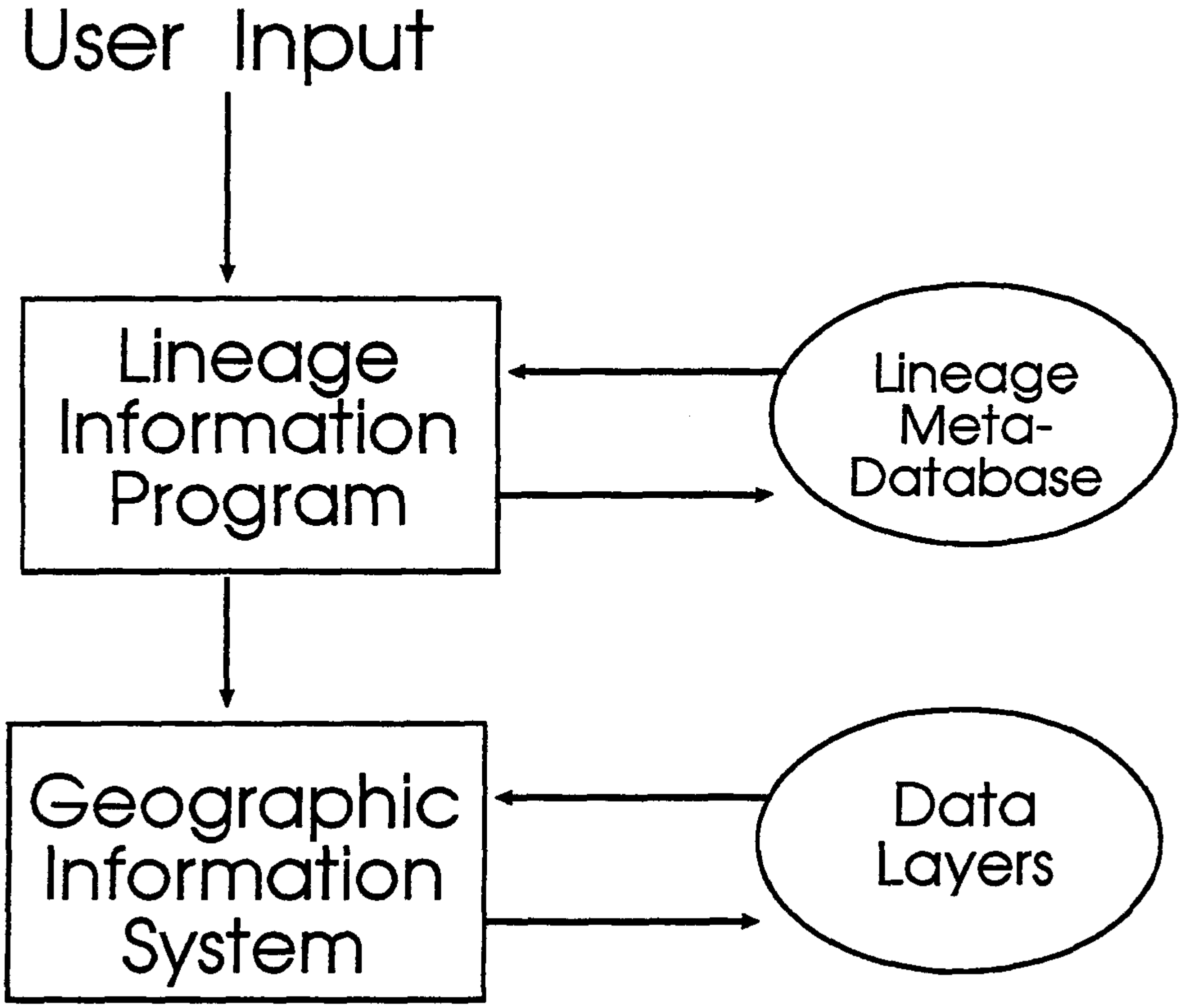


Figure 10. The GIS/LIP relationship.

The LIP utilizes building blocks depicted in Figure 11: parser, knowledge representer, and knowledge representation interrogator. Each consists of software modules coded in LISP. GIS commands presented to the parser which extracts input/output relationships, commands and command modifiers. This information is passed from parser to knowledge representer for update of the knowledge representation. The evolving lineage knowledge representation is stored in the meta-database to model the GIS application. Subsequently, the knowledge interrogator provides a mechanism for manipulating the meta-database to answer questions concerning lineage.

The creation of the lineage knowledge representation begins with a user command for loading a data layer into the GIS. During the initialization process, the knowledge representer creates a representation in the meta-database of the data layer. The LIP then calls the Source Description Frame creation routine which requests documentation of the name of the data file, features contained within the data layer, date of the source, agency responsible for the source, scale of the source, projection of the source, and a measure of accuracy of the source. The Source Description Frame creation routine fills the frame slots with associated lineage attributes input by the user (Figure 12).

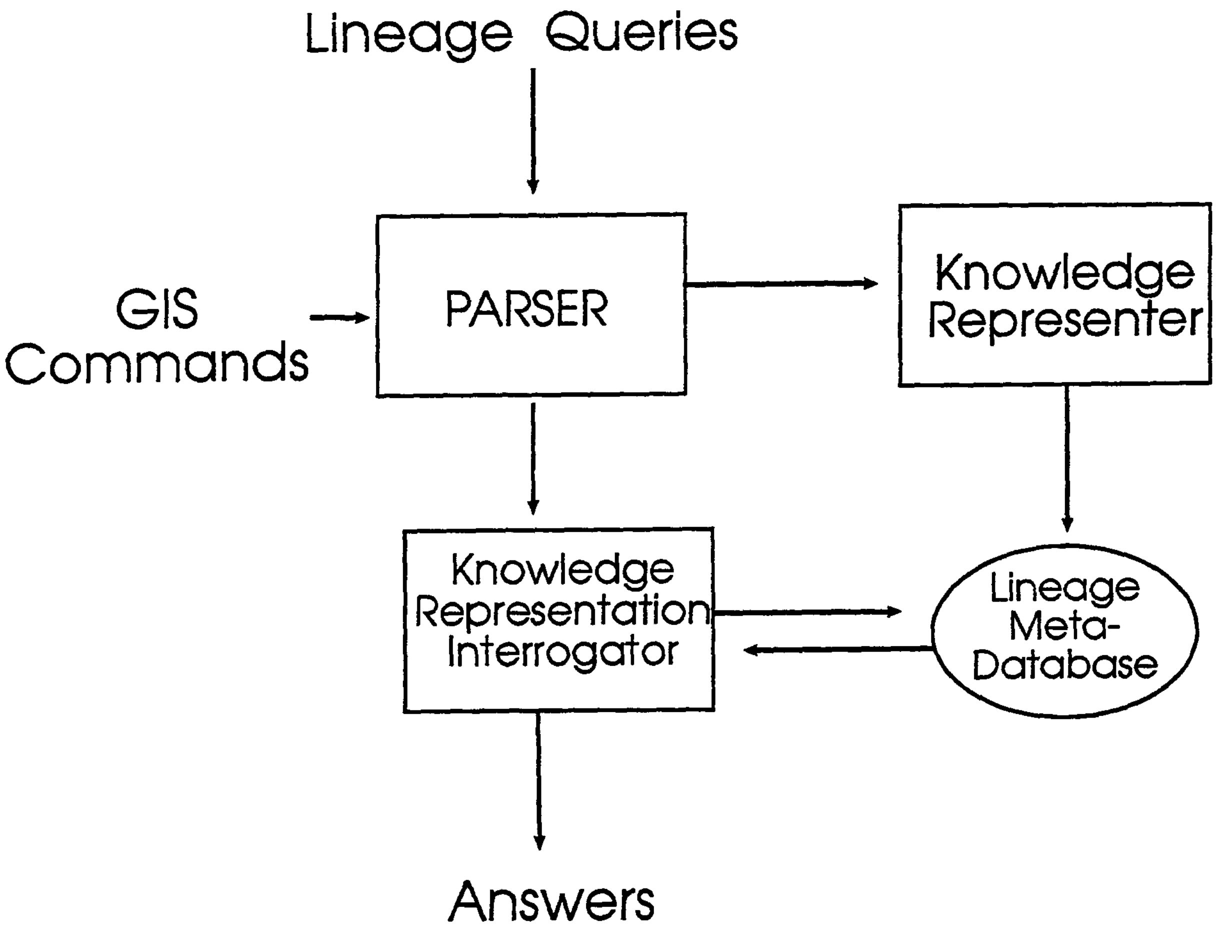


Figure 11. Building blocks of the LIP.

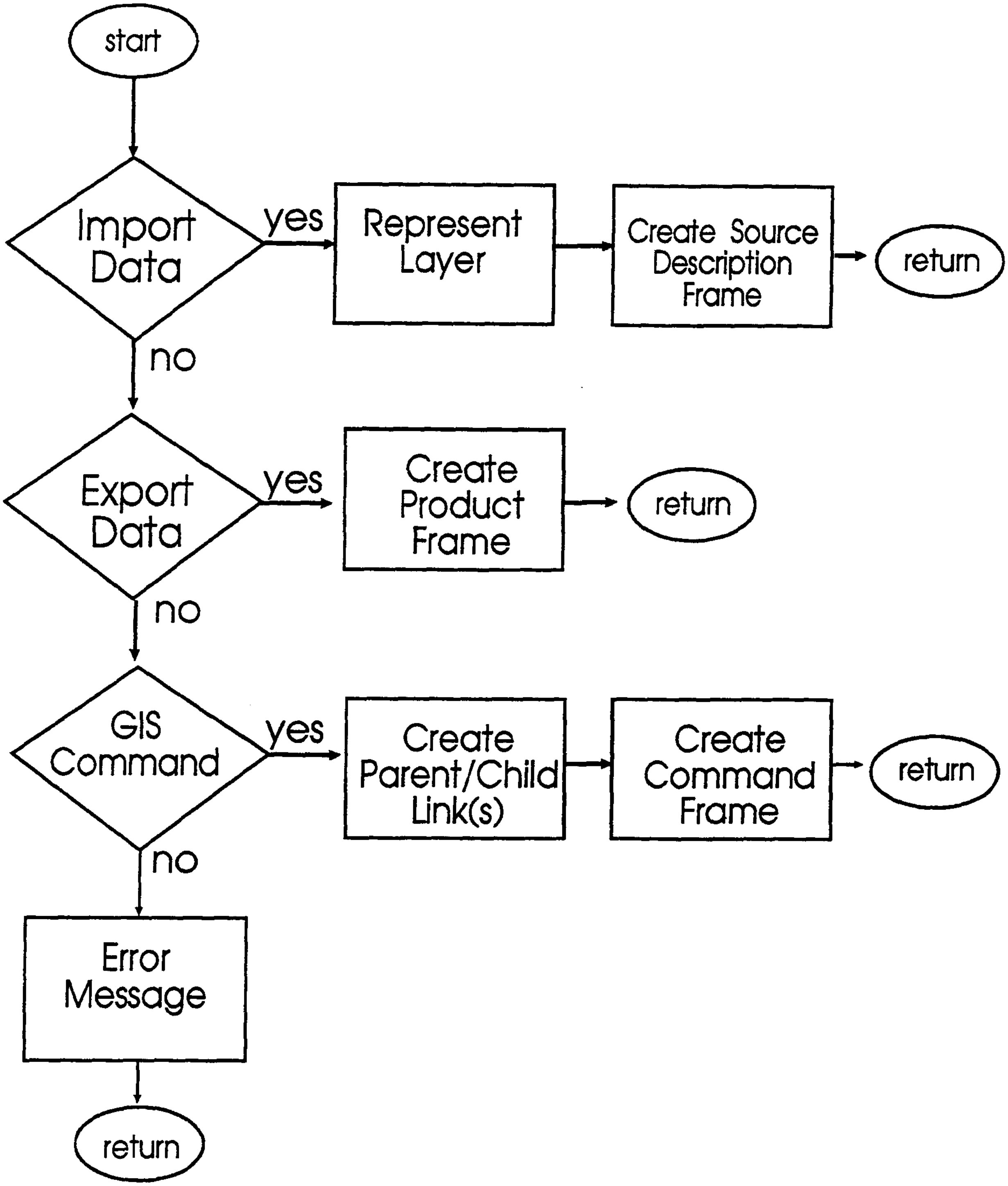


Figure 12. Functional design of the Knowledge Representer.

As the user enters subsequent commands to the GIS the LIP's parser intercepts it and extracts information concerning each transformation. If each subsequent GIS data transformation command is valid, and the initial layers are properly entered along with their source description attributes, the parsed representation of the GIS command (i.e. the input/output layers, and command and command modifiers) is presented to the knowledge representer by the parser. The knowledge representer uses this information to update the knowledge representation by adding a node, links, and frames concerning the newly created GIS layer. In this fashion, a new transformation is added to the lineage knowledge representation (Figure 12).

If the users command is one that exports a layer from the spatial database or plots it on a graphic output device, the parser signals the knowledge representer to prompt the user for information to be included in the slots of the Product Frame. This information includes: to what use will the product be applied, who the users are, who is the responsible person for creating the map product, what is the person! s affiliation (department or agency) and date of release of the product. This information is then placed into the layer's product frame (Figure 12).

The knowledge representation interrogator allows a user to request information found during search of the lineage knowledge representation stored in the meta-database. Such requests are answered by functions that traverse child and parent links and access attribute information stored in the various frames. These functions determine answers to queries concerning lineage or genealogy of maps stored in the GIS database.

In lineage search, child links are followed to determine the ancestry of a particular layer in the database. During the course of such a query, the contents of intermediate layer command frames can be viewed to determine the transformations used to create a particular layer. When a source layer is found at the end of a child link, the Source Description Frame is accessed to retrieve attributes concerning the data sources. Thus, the knowledge representation interrogator may be used to trace the lineage of any final output product back to source layers. Further, determinations concerning sources are made by analysis of the slots of the Source Description Frame.

Genealogy questions determine the layers a particular source contributed to. For example, the effect of updates to a particular source input layer can be traced through the lineage knowledge representation to determine which intermediate layers to recreate in the course of updating an affected output product. In such a case, parent links of the updated source are queried to determine descendents affected by the change. Accessing the command frame of each child provides the material needed (i.e. commands and modifiers) to apply to layers of the previous 'generation' to recreate and update the layer in question. In this case, beginning with source layers, each child layer is visited in turn, and command and command modifiers extracted from the command frames. The commands that transformed parent layers into child layer are applied to update the corresponding layer in the spatial database. When this is done the child's parent links are followed and the updating process is applied until the product is finally recreated. In this way, an updated product can be created.

Evaluation

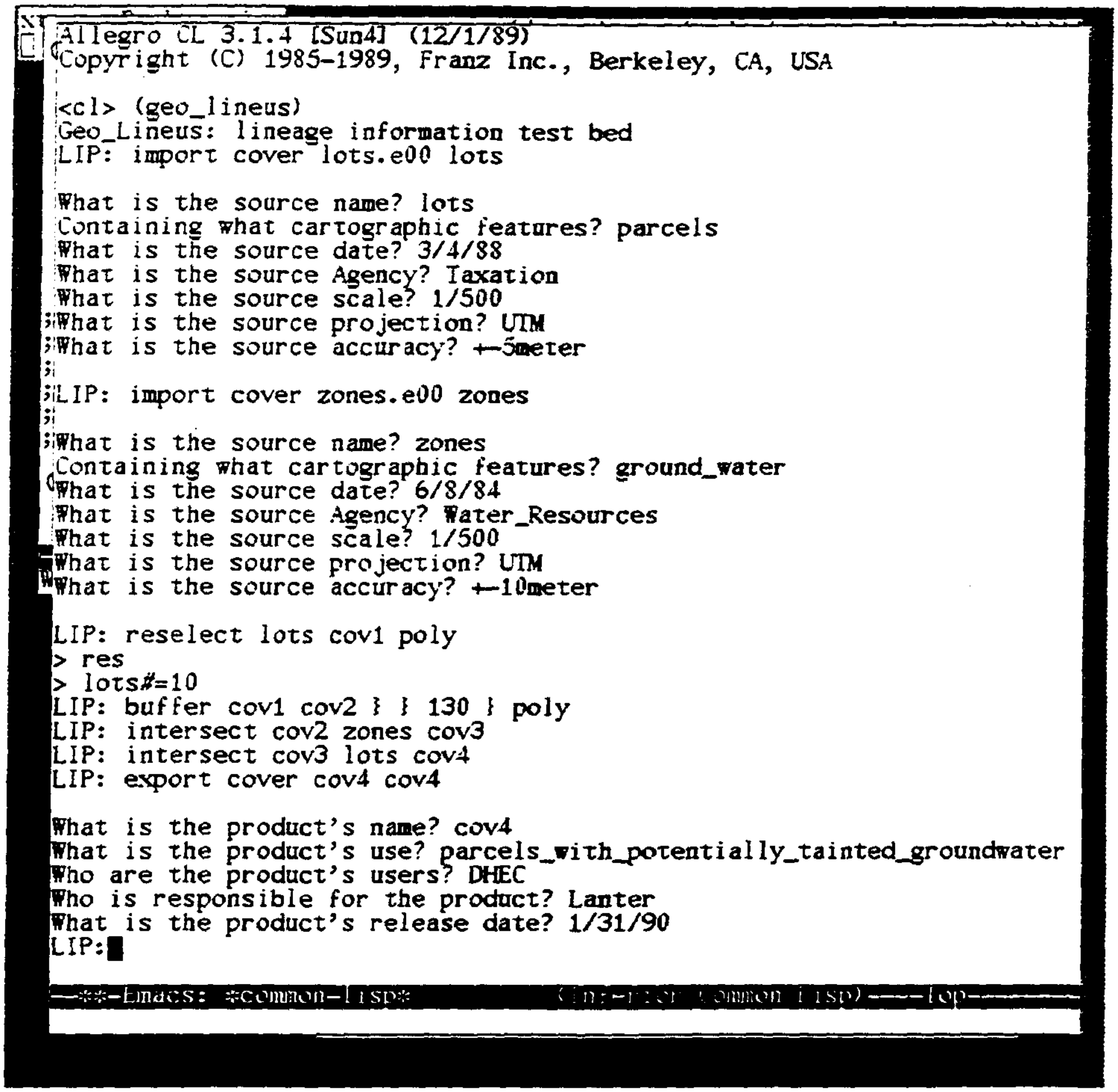
An illustrative example serves as a basis for evaluating the lineage meta-database concept. the application begins with: a parcel map (LOTS), an underground water aquifer map (ZONE), and a lot from parcel map that has a hazardous discharge of pesticides that can flow through the ground (The lot with discharge has a polygon ID# = 10). We assume that pesticides have a range of flow of a certain distance (130 ft.) The task is to find where a buffer zone of pollution overlaps the aquifer, and inform the land owners whose parcels might have tainted water that their portion of the aquifer overlaps the pollution buffer zone.

ARC/INFO commands to execute the task:

```
1.    reselect lots cov1 poly
           res lots# = 10
2.    buffer cov 1 cov2 # # 130 # poly
3.    intersect zones cov2 cov3
4.    intersect lots cov3 cov4
```

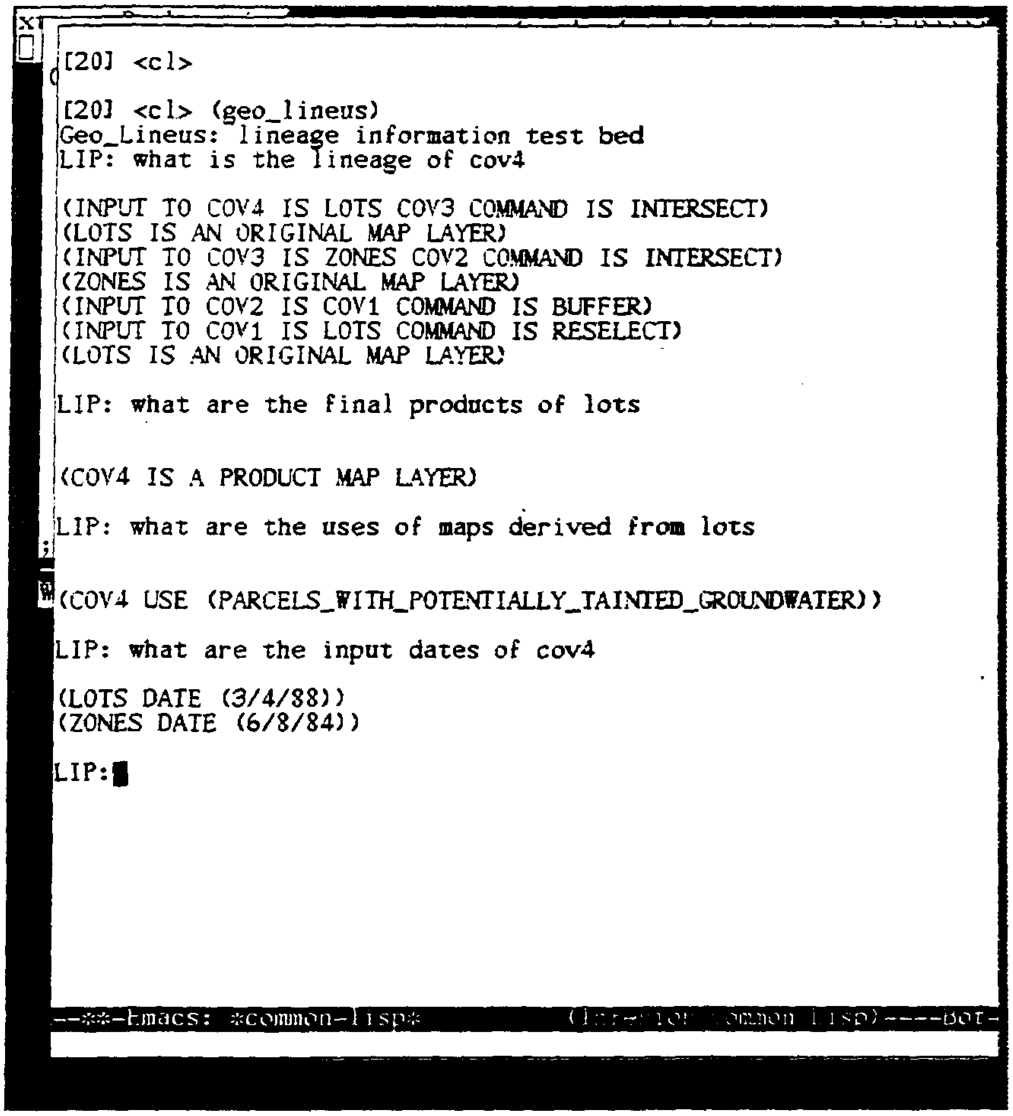
The user-LIP interaction is illustrated in the following figures. The user enters a command, and the lineage meta-database system parses it (Figure 13). The LIP then updates its knowledge representation. As sources are entered into the database the LIP requests quality information that is not normally part of the GIS data entry process. Subsequent processing of the sources finds the LIP extracting and storing input output relationships between layers, commands, and command modifiers. At any time the user can query the lineage information program and retrieve information concerning sources, transformations, or data products (Figure 14).

The interaction between a user and a GIS with a lineage meta-database stands in sharp contrast to the application run without the benefit of a lineage meta-database. The only information available to the user concerning the relationships between layers in the spatial database are the time/date stamps associated with them in the directory listings. At any time throughout the course of the application the user can request a listing of the contents of the directory from the operating system and see the order in which the layers were created.



```
Allegro CL 3.1.4 [Sun4] (12/1/89)
Copyright (C) 1985-1989, Franz Inc., Berkeley, CA, USA

<cl> (geo_lineus)
Geo_Lineus: lineage information test bed
LIP: import cover lots.e00 lots

What is the source name? lots
Containing what cartographic features? parcels
What is the source date? 3/4/88
What is the source Agency? Taxation
What is the source scale? 1/500
What is the source projection? UTM
What is the source accuracy? +-5meter

LIP: import cover zones.e00 zones

What is the source name? zones
Containing what cartographic features? ground_water
What is the source date? 6/8/84
What is the source Agency? Water_Resources
What is the source scale? 1/500
What is the source projection? UTM
What is the source accuracy? +-10meter

LIP: reselect lots cov1 poly
> res
> lots#=10
LIP: buffer cov1 cov2 } } 130 } poly
LIP: intersect cov2 zones cov3
LIP: intersect cov3 lots cov4
LIP: export cover cov4 cov4

What is the product's name? cov4
What is the product's use? parcels_with_potentially_tainted_groundwater
Who are the product's users? DHEC
Who is responsible for the product? Lanter
What is the product's release date? 1/31/90
LIP:█
```

Figure 13. User-LIP/GIS interaction.



```
[20] <cl>

[20] <cl> (geo_lineus)
Geo_Lineus: lineage information test bed
LIP: what is the lineage of cov4

(INPUT TO COV4 IS LOTS COV3 COMMAND IS INTERSECT)
(LOTS IS AN ORIGINAL MAP LAYER)
(INPUT TO COV3 IS ZONES COV2 COMMAND IS INTERSECT)
(ZONES IS AN ORIGINAL MAP LAYER)
(INPUT TO COV2 IS COV1 COMMAND IS BUFFER)
(INPUT TO COV1 IS LOTS COMMAND IS RESELECT)
(LOTS IS AN ORIGINAL MAP LAYER)

LIP: what are the final products of lots


(COV4 IS A PRODUCT MAP LAYER)

LIP: what are the uses of maps derived from lots


(COV4 USE (PARCELS_WITH_POTENTIALLY_TAINTED_GROUNDWATER))

LIP: what are the input dates of cov4

(LOTS DATE (3/4/88))
(ZONES DATE (6/8/84))

LIP:█








--**-Emacs: *common-lisp*             (Inferior Common Lisp)----Bot-
```

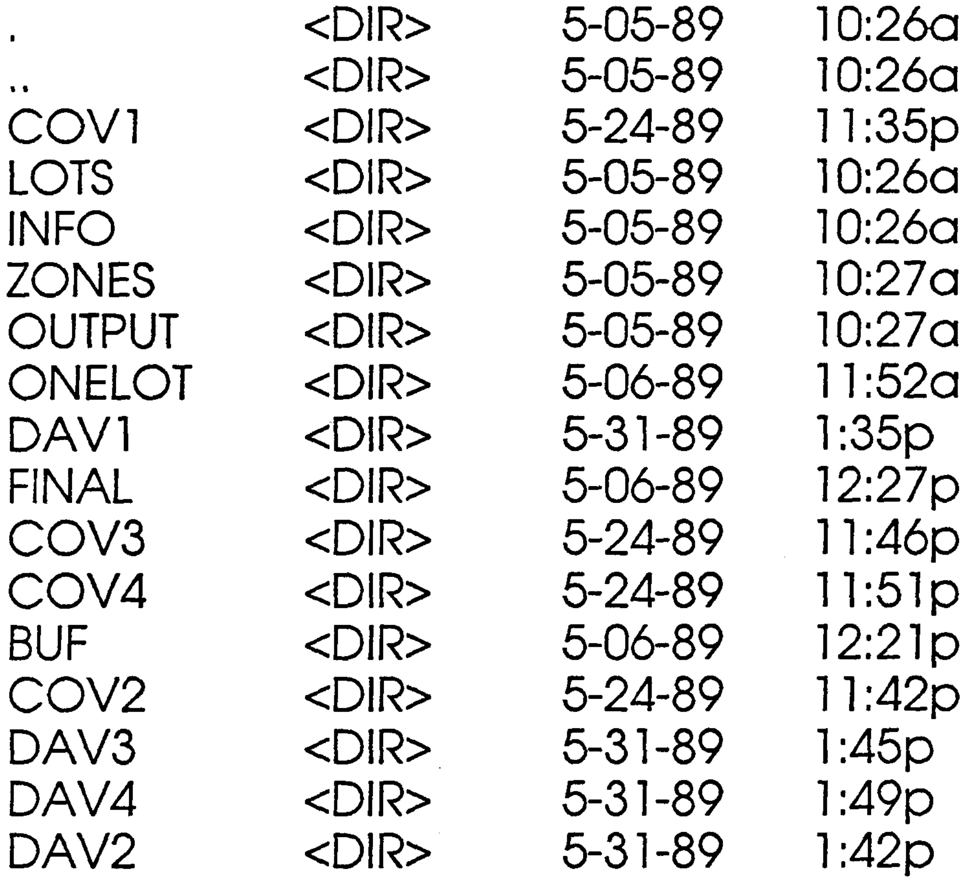
Figure 14. Lineage Queries.

Figure 15 illustrates the directory at the end of the application. After COW was created, the directory contains among other records: LOTS, ZONES, COV1, COV2, COV3, and COV4. What is lacking is information concerning the connectivity between the layers. That is, after the application is over, it is not clear which layers were sources, which were intermediate layers used as steps toward the final product, and which layer (if any) was an application product.

Conclusion

The node and pointer representations of semantic networks provide a basis for structuring input-output relationships between map layers. Frames serve to organize lineage attributes characterizing source layers in Source Description Frames, transformations in Command Frames associated with intermediate layers, and uses of product maps in Product Frames. Thus, a hybrid knowledge representation of semantic networks and frames has been demonstrated as a useful means of structuring lineage information.

The lineage meta-database concept and the functional design of the lineage information program presented in this study is a step toward more powerful and intelligent geographical tools. The example demonstrates that a GIS/LIP combination is an ’interesting’ alternative to a GIS alone. Creating and providing access to lineage information embodied in hybrid semantic network./frame knowledge representations opens up the possibility of engaging in source assessment throughout the manipulation of GIS data sets.



```
.            <DIR>     5-05-89    10:26a
..           <DIR>     5-05-89    10:26a
COV1         <DIR>     5-24-89    11:35p
LOTS         <DIR>     5-05-89    10:26a
INFO         <DIR>     5-05-89    10:26a
ZONES        <DIR>     5-05-89    10:27a
OUTPUT       <DIR>     5-05-89    10:27a
ONELOT       <DIR>     5-06-89    11:52a
DAV1         <DIR>     5-31-89    1:35p
FINAL        <DIR>     5-06-89    12:27p
COV3         <DIR>     5-24-89    11:46p
COV4         <DIR>     5-24-89    11:51p
BUF          <DIR>     5-06-89    12:21p
COV2         <DIR>     5-24-89    11:42p
DAV3         <DIR>     5-31-89    1:45p
DAV4         <DIR>     5-31-89    1:49p
DAV2         <DIR>     5-31-89    1:42p
```

Figure 15. Directory of GIS database layers.

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