Managing Multiple Representations of "Base Carto" Features: A Data Modeling Approach

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Abstract. The demand for a single, detailed cartographic database that supports map representations at multiple scales and for multiple purposes continues to challenge the discipline. Throughout the database life cycle, derived representations intermix with original compilation, making it difficult to distinguish data capture from data abstraction. As a consequence, database features that persist across compilation scales may vary in geometry, dimensionality, and singularity. Currently, most GIS and map production systems offer only minimal software support for linked multi-scale data management. Linkages between complex data representations can be established only on simple attributes (e.g., object IDs or timestamps). This paper presents relational database architecture to link representations and unify mapping at multiple scales and for multiple purposes. The architecture is being developed by empirical investigation and comparison of existing federal agency map series databases, and by systematic experimentation with cartographic abstraction and generalization applied to these data. Current work involves DLG and DIGEST data dictionaries for geographical footprints in Texas and in California. The separation of captured and derived data follows European work practice that captures data within Digital Landscape Models (DLM), and derives data from the DLM to a series of Digital Cartographic Model (DCM) databases for targeted scales and purposes.

1.0 Introduction

Characteristics about geographic landscapes can be communicated in many ways within a geospatial database or on a map. Data capture involves measurements, observation and inference to acquire information. Data representation involves a suite of procedures that abstract characteristics and distinguish features and attributes. (For purposes of this paper, the term *abstraction* refers to a (set of) geoprocessing procedures that change the existence, geometry, dimensionality, symbolization or prominence of a feature in a data representation.) The landscape comprises a continuous fabric within which all scales of process are embedded. It is the spatial resolution at which a measurement or observation takes place that largely determines if evidence of a process is captured or missed. In contrast, maps and GIS databases contain isolated representations that are meaningful within a finite range of map scale or modeling resolution. The challenge is to create, manage and publish geospatial data representations for a range of scales and mapping purposes. To do this efficiently and effectively, the need exists to link multiple representations in the database.

The demand for a single, detailed cartographic database that supports data representations at multiple scales and for multiple purposes continues to challenge the discipline. National mapping agencies compile geospatial data to standardized map scale specifications. This requires managing multiple databases for different scales and purposes. Compilation rules are based in a paper map legacy that targets graphical appearance and sometimes neglects real form and process in the landscape. Throughout the database life cycle, derived representations intermix with original compilation, making it difficult to distinguish data capture from data abstraction. We know that database features that persist across compilation scales may vary in geometry, dimensionality, and singularity. For example, a city may be modeled in one database representation as a point, in another as a polygon boundary, in a third as a compound object. Similarly a stream may be modeled as a single channel in one database and as a braided channel in another. Currently, most GIS and map production systems offer only minimal software support for linked multi-scale data management. Linkages between complex data representations can be established only on simple attributes (e.g., object IDs or timestamps). As a consequence, features that persist at multiple scales may confound efficient update.

This paper presents relational database architecture to link data representations and unify mapping at multiple scales and for multiple purposes. The architecture is being developed by empirical comparison among existing federal agency map series databases, and by systematic experimentation with cartographic abstraction and generalization. Current work involves DLG and DIGEST data dictionaries for a common geographical footprint in southern California. A dual strategy separates captured data from data modeled within the database, and derives data and map products through conditional abstraction and rendering. The paper describes the relational architecture and situates it within established principles of cartographic abstraction, generalization and symbolization. At the end of the paper, we present results of initial experiments with multi-purpose mapping, and propose a plan for continuing investigation across map scales.

2.0 Relating Scale to Resolution

At the outset, it is important to clarify the distinction between two concepts that are often (and incorrectly) interchanged. *Scale* in this paper refers to the ratio between distance among map or database coordinates, and Earth (ground) distance (Robinson et al 1995). It indicates the amount of reduction that takes place on a map (Slocum et al, 2005). It relates the size of a study area to the level of precision and generalization of detail (Dent, 1999). *Resolution* on the other hand relates more to data acquisition and storage than to data display. The term refers to the size of the smallest item that can be isolated in the data (Lillesand et al 2004), or the smallest enumeration unit one can expect to encounter in a dataset (Wiens, 1989), or conversely the smallest distance that can be measured between individual items (Jensen, 2000).

Tobler (1987) draws upon Sampling Theory (e.g., Benedetto and Ferreira, 2001) when he notes that the detection of a feature is only possible if sampling rate is half the size of the feature. Otherwise the feature could slip between observations. He concludes that one must know in advance the size of features of interest before acquiring data. In adopting the National Map Accuracy Standard, one assumes that the smallest graphical mark that can be made on a page is 1/2 mm (1/50 inch) at scale. Tobler provides example conversions between a scale's Representative Fraction (RF) and corresponding resolution values:

Scale	Resolution (1/2mm)	Detection (+/- 1/2mm)
1: 10,000	5 m	10 m
1: 24,000	12 m	24 m
1:100,000	25 m	50 m

Inspection of these conversions gives the general rules:

- Detection = RF denominator / 1000 (answer in meters)
- Resolution = 1/2 Detection

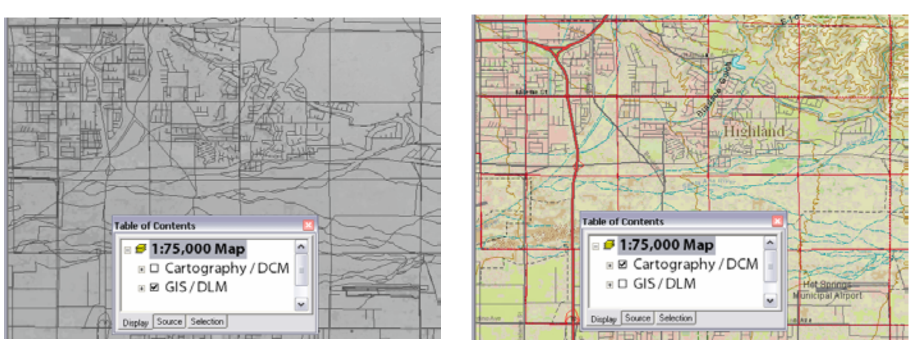
The distinction between resolution and scale becomes important as one considers the dual strategy adopted in the relational architecture proposed here. As described above, the dual strategy separates data capture from derived data products.

3.0 A flexible architecture for multiple cartographic representations

The separation of captured and derived data follows European work practice that captures data within Digital Landscape Models (DLM) databases, and derives data from the DLM to a series of Digital Cartographic Model (DCM) databases for targeted scales and purposes. (http://www.eurogeographics.org/) Concepts underlying DLM and DCM have been adopted widely by the European cartography community (see for example Burghardt, 2004; Golucke 2004; Hardy, 2004). DLM database layers including topography, transportation, hydrography, vegetation, and administrative boundaries are currently distributed by seventeen national mapping agencies (http://www.eurogeographics.org/gddd/lists/sp_54.htm). The ATKIS website lists a partial data dictionary (http://www.atkis.de/dstinfo/dstinfo2.dst_gliederung) planned for English language translation in the near future (Meng, 2004).

A Digital Landscape Model (DLM) is a database containing topographic features as captured or compiled. The geometric form of the DLM contains explicit or implicit topological information. Database objects, their attributes and the relations between the objects are referred to in terms of real world entities. A Digital Cartographic Model (DCM) is derived from a DLM by abstraction, generalization and data modeling procedures (what a GIS analyst would call geoprocessing). DCMs are suitable for specialized mapping purposes. In the context of GIS, the DCM may be used as "base carto" information. The geometric form of the DCM is often primarily vector, although raster layers such as digital terrain may form a component.

A DLM differs from a DCM in several ways. In addition to features, the DLM will incorporate scale-independent data, such as names, descriptive and analytical attributes, revision information, and important boundary and control points. However, the DLM incorporates no symbolic representation or text placement rules. As such, it is a wireframe data model of a landscape (Figure 1). Items within the DLM carry a referent resolution, that is, the granularity with which features were captured.



Digital Landscape Model (DLM) Digital Cartographic Model (DCM)

Figure 1

In contrast, the DCM incorporates features specific to a given scale limit and given map purpose (that may be general or specific). The DCM may also incorporate symbolization rules or symbol palettes appropriate to develop particular map and atlas products. The DCM carries a referent of a Representative Fraction (RF) denominator. In Figure 2, the data production sequence shows the capture of data into three DLMs at resolutions of 5 meters, 25 meters and 1,000 meters; derivation of DCMs from specific DLMs, and the types and scales of map products that can be appropriately generated at specific display scales. For example, DCMs for products ranging from 1:50,000 – 1:250,000 could be generated from a 25 meter DLM.

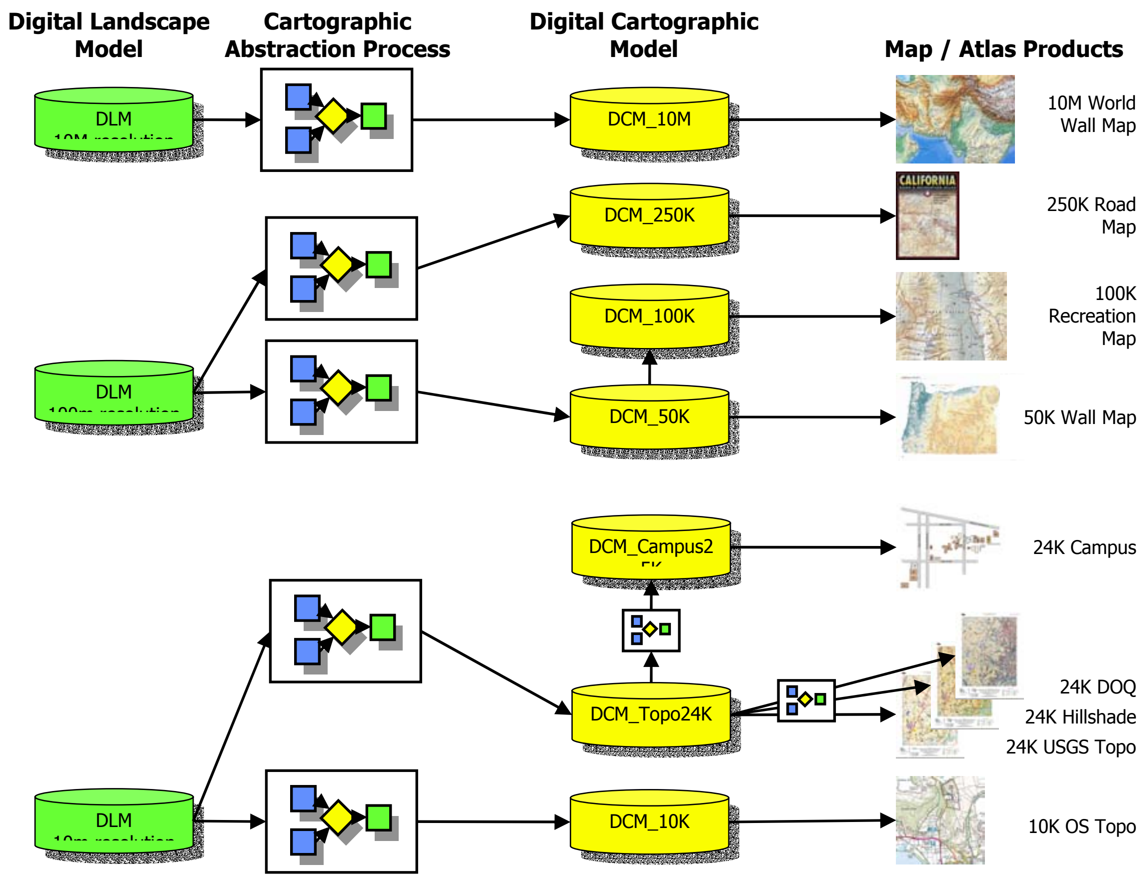


Figure 2
Architecture for multi-scale, multipurpose basemap products
(Illustration courtesy of Aileen Buckley, ESRI)

It is possible of course to derive DCM databases from DCMs, as in the example in Figure 2 of a 1:25,000 campus database from a 1:24,000 topographic database. The procedure involves geoprocessing and data modeling that could be thought of as functional rather than scale-based generalization. Icons in Figure 2 in the column headed “Cartographic Abstraction” indicate geoprocessing tools used to abstract DLM data in several ways: simplification (detail reduction), classification (changing feature code or attribute category taxonomies) or enhancement (interpolation, exaggeration, or other data modeling procedures that systematically introduce detail) (Buttenfield and Mark, 1989).

3.1 DLM-DCM architecture in practice

The question of determining appropriate scales for a particular map purpose is unresolved, and remains a particular research challenge. It's neither feasible nor accurate to derive DLM and DCM representations from a single detailed DLM feature set. Nonetheless it is possible to guide data capture and data use protocols for broad feature domains. We know for example that some data domains (e.g., terrain) are more sensitive to scale than others (e.g., transportation) because highways are built to a fixed radius of curvature and their shape is not modified by erosion and deposition (except in extreme circumstance).

In Figure 3, one sees a range of data product scales. Each bar in the figure represents either creation of a database either by compilation, in the case of a DLM, or by a geoprocessing sequence for the DCM. In the leftmost column, terrain, hydrography and image base data would be captured for DLMs at each resolution, to generate DCMs, using Tobler's 1987 formulae to create data at the corresponding scale. Transportation and settlement features might need to be compiled at only three DLM resolutions to generalize DCM representations across a similar range of scales, while land use data might need two additional DLM compilations at finer resolutions. Administrative boundaries, land records and place names might need only a single compilation in order to geoprocess DCM representations at all map scales.

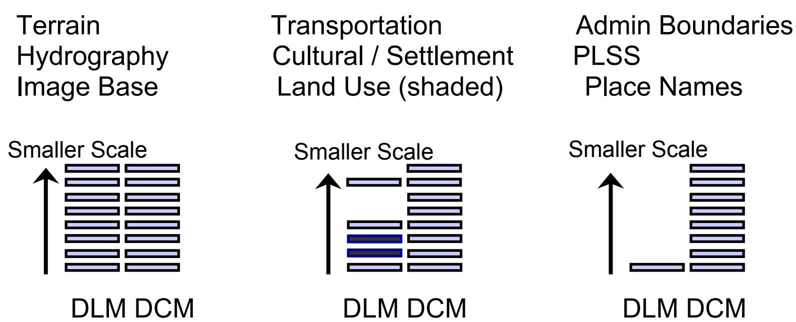


Figure 3
Synchronizing data compilation (DLM) with
data modeling / generalization (DCM) for various data domains

Software support for data modeling and management differs with DLM and DCM representations. In particular, compilation rules in the DLM dictate what feature types are captured, and identify feature sensitivities to capture resolution. Examples of compilation rules can be found in any National Mapping Agency data dictionary, as for example "Capture perennial streams from the downstream tributary junction to the next junction upstream, and continue to the source point". In contrast, the DCM contains relational tables that manage symbology and associate specific feature types with map representation rules. These rules might govern what level of land use is displayed by default (Anderson Level 1 or Level 2, for example). Alternatively the rules might guide predicate refinements (figure/ground and visual hierarchy), such as the USGS prioritization of naturally occurring features at 1:24,000 versus the prominence of transportation / settlement features at 1:100,000.

Software tools for data abstraction and geoprocessing (specifically, reduction of detail, typification, and enhancement) provide a process by which DCM data is derived from DLMs. In a GIS scripting environment, geoprocessing tools are coded as modular scripts that can be sequenced or combined according to map purpose. Geoprocessing parameters provide flexibility to modify the level of abstraction for target scales.

3.2 A "solution space" for multiple representations

Within a mapping agency, development of an architecture integrating DLM representations (R1, R3, R7) at multiple levels of resolution will provide compiled data across a range of levels of abstraction that can be distributed to other organizations for multiple purposes (Figure 4).

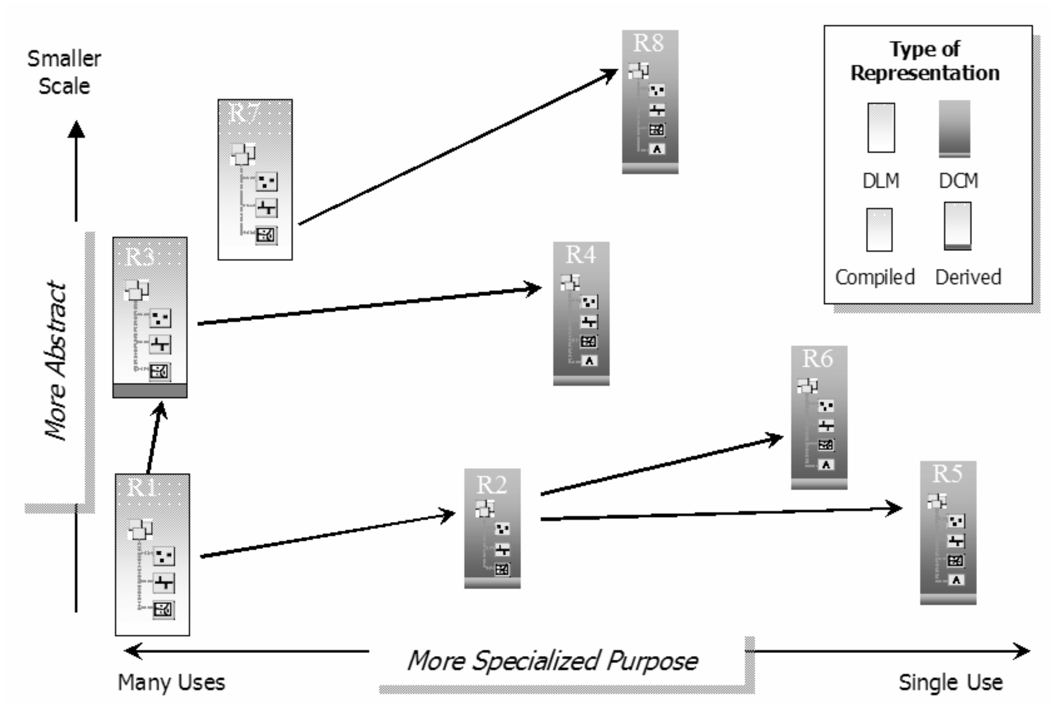


Figure 4
A multi-scale multi-purpose data architecture in practice
(Designed in collaboration with Charlie Frye, ESRI)

The DLM representations are considered general purpose because each database can be used to generate a range of databases for map products. Geoprocessing sequences generalize DLM data according to agency data dictionary specifications to create DCM representations (R2, R4, R8) that are in each case more abstract than their DLM source, and at the same time are tailored more closely to particular data product purposes. For example, a large scale road DCM (R2) for a State Highway Department, or a medium scale regional Land Use DCM (R4) for a tri-county Planning Board. An independent compilation (R7) can guide creation of a small scale reference DCM (R8) for use in creating a multi-state recreational atlas for hiking, biking and fishing.

Figure 4 provides a "solution space" in which the agency can plan, generate and maintain data products. The space is two-dimensional. One axis aligns a continuum of increasing abstraction, with an implication that more abstract representations will be produced at smaller scales. DLM databases can be derived anywhere along the axis, and there is an implicit assumption that deriving a DLM from another DLM must increase the level of abstraction somehow. That is, one can derive R3 from R1 in Figure 4, but not vice versa. It would be inaccurate and cartographically inappropriate to derive a 5 meter DLM from a 50 m DLM.

Similarly, the horizontal axis of this solution space provides a range of general purpose to special purpose data and map products; the implication is that geoprocessing transforms data towards more specialized purposes. Although the two axes appear at right angles in the Figure, they are not unrelated: generalization and abstraction tend to result in data that is appropriately used at an equal or smaller scale. The arrows in the solution space follow this premise, and interpretations about the slope of geoprocessing arrows are probably valid. That is to say, aggressive generalization (steep arrows) is required for large jumps in scale. Moreover, larger scale jumps are more easily achieved from smaller scales: it is more straightforward to generalize 1:1million data to 1:10million, than to transform 1:100,000 to 1:1,000,000, which could require creation of intermediate representations (at say 1:250,000).

A national mapping agency should be able to define and bound a solution space for creating a multi-scale, multi-purpose geospatial data architecture based on its mission, the size of its nation's geographic footprint, and understanding the diversity of data products it needs to market. The solution space should facilitate planning and efficient strategies for building DLMs, DCMs and data/map products, and for identifying bottlenecks and potential problems in agency-wide production flows. An agency in practice would need to populate some parts of a solution space with a higher concentration of products depending on its mission. Likewise, a decision to expand operations by creating a new line of data products can be discussed in the context of how much new data compilation activity would be required.

In the scenario, a single DCM can generate multiple products tied to specific purposes. For example, the Land Use Planning DCM (R4 in the figure above) could be used to generate terrain analysis maps, maps for planning infrastructure developments, and to run a suitability analysis for anticipated land use changes (Figure 5).

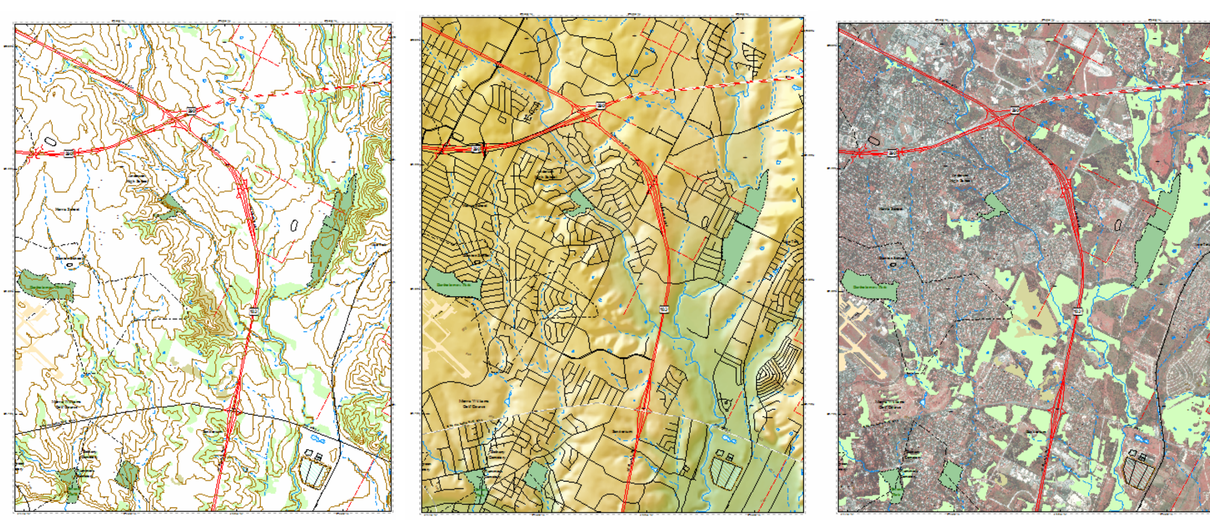


Figure 5

Multi-purpose map products generated from DCM R4 in Figure 4.

4.0 Ongoing Experiments

In work last fall, the authors focused on how to streamline creation of DCMs given an existing data dictionary. The issue relates to either creating a database schema, if no data product specification exists; or (more likely the case) correcting an existing schema to separate data compilation rules from data representation rules, basing distinctions upon an existing schema. Representation rules include database representation (semantic hierarchy, dimensionality, continuity, feature code assignments and taxonomy) as well as graphic representation (symbology, name placement if relevant, and graphical defaults). Focusing here on feature code hierarchy and assignments, the authors undertook the exercise of building a DCM schema for a 1:250,000 VMAP database. The objectives of the experiment were to gain insights about DCM schema construction for an existing general purpose data set; to extend work begun at ESRI (Buckley, 2004) on DCM construction at larger scales (1:24,000, 1:100,000), and to establish the feasibility of utilizing DCM schema comparison as a method for comparing database semantics.

VMAP stands for Vector Map. Its data schema is compliant with DIGEST, an international data standard that has been applied in military data representation and mapping applications. Formerly known as Digital Chart of the World (DCW), the schema has a legacy derived from hardcopy maps, many of which were compiled prior to 1992. VMAP was developed by agencies subsequently integrated into NIMA, a USA military mapping agency conglomerate. The data schema is currently maintained by NGA. Additional information and a VMAP data dictionary are available at http://geoengine.nga.mil.

Using a manual reverse engineering process, we manually extracted unique feature codes from a VMAP dataset for southern California. Beginning with VMAP geodatabases and associated feature code libraries, we opened each feature class (.dbf) file in Excel, using the advanced filer to isolate unique records. On the first pass, we collected combinations for all attributes, compiling these into a single spreadsheet comprising multiple tables for each feature dataset. Figure 7 (next page) shows an excerpt from the hydrography tables. It should be clear from this table that the data are not in normal form.

Figure 6
Advanced Filtering in Excel

Constructing a schema table directly from the data would have accomplished the first objective (examining the schema creation process) but we were also interested in the second (comparing schemas across scales) and the third (comparing the VMAP schema to another DCM). We utilized an existing DCM schema based on DLG data at 1;24,000, and matched feature types using semantic rather than cartographic rationale. The intention was not to create a USGS topographic map from VMAP data, but rather to compare the two database schema. Where the two feature schemas are the same, we attached DLG schema identifiers. We note schema categories where the feature code taxonomy or hierarchy differ and discuss these below.

Feature Class	Feature Type	f_code	f_code_description
damc	point	BI020	Dam/Weir

Feature Class	Feature Type	f_code	f_code_description	exs	exs_description	hyc	hyc_description
lakesresa	area	BH080	Lake/Pond			6	Non-Perennial/Intermittent/Fluctuating
lakesresa	area	BH080	Lake/Pond			8	Perennial/Permanent
lakesresa	area	BH080	Lake/Pond			3	Dry
lakesresa	area	BH130	Reservoir	1	Definite		
lakesresa	area	BH080	Lake/Pond			3	Dry

Feature Class	Feature Type	f_code	f_code_description	exs	exs_description	hyc	hyc_description
watrcrsl	line	BH030	Ditch			8	Perennial/Permanent
watrcrsl	line	BH020	Canal	32	Navigable	8	Perennial/Permanent
watrcrsl	line	BH140	River/Stream			6	Non-Perennial/Intermittent/Fluctuating
watrcrsl	line	BH140	River/Stream			8	Perennial/Permanent
watrcrsl	line	BH020	Canal	32	Navigable	3	Dry
watrcrsl	line	BH020	Canal	6	Abandoned/Disused	8	Perennial/Permanent
watrcrsl	line	BH030	Ditch			6	Non-Perennial/Intermittent/Fluctuating

Feature Class	Feature Type	f_code	f_code_description	exs	exs_description	hyc	hyc_description
wellsprp	point	AA050	Well (Water)	28	Operational	8	Perennial/Permanent
wellsprp	point	BI010	Cistern	61	Not Isolated		
wellsprp	point	BH170	Spring/Water-Hole			8	Perennial/Permanent
wellsprp	point	BH170	Spring/Water-Hole			6	Non-Perennial/Intermittent/Fluctuating
wellsprp	point	AA050	Well (Water)	28	Operational	6	Non-Perennial/Intermittent/Fluctuating
wellsprp	point	AA050	Well (Water)	28	Operational	8	Perennial/Permanent
wellsprp	point	AA050	Well (Water)	28	Operational	8	Perennial/Permanent
wellsprp	point	AA050	Well (Water)	28	Operational	3	Dry
wellsprp	point	AA050	Well (Water)	6	Abandoned/Disused	8	Perennial/Permanent
wellsprp	point	BH170	Spring/Water-Hole			8	Perennial/Permanent

Feature Class	Feature Type	f_code	f_code_description
damc	point	BI020	Dam/Weir

Feature Class	Feature Type	f_code	f_code_description	scc	scc_description
lakesresa	area	BH080	Lake/Pond	11	Fresh
lakesresa	area	BH080	Lake/Pond	11	Fresh
lakesresa	area	BH080	Lake/Pond	11	Fresh
lakesresa	area	BH130	Reservoir		
lakesresa	area	BH080	Lake/Pond	10	Salt

Feature Class	Feature Type	f_code	f_code_description	tid	tid_description
watrcrsl	line	BH030	Ditch		
watrcrsl	line	BH020	Canal		
watrcrsl	line	BH140	River/Stream	1	Non-Tidal
watrcrsl	line	BH140	River/Stream	1	Non-Tidal
watrcrsl	line	BH020	Canal		
watrcrsl	line	BH020	Canal		
watrcrsl	line	BH030	Ditch		

Feature Class	Feature Type	f_code	f_code_description	pro	pro_description	scc	scc_description	wft	wft_description
wellsprp	point	AA050	Well (Water)	116	Water	9	Freshwater/Potable	5	Dug or Drilled Well
wellsprp	point	BI010	Cistern						
wellsprp	point	BH170	Spring/Water-Hole			9	Freshwater/Potable		
wellsprp	point	BH170	Spring/Water-Hole			9	Freshwater/Potable		
wellsprp	point	AA050	Well (Water)	116	Water	9	Freshwater/Potable	5	Dug or Drilled Well
wellsprp	point	AA050	Well (Water)	116	Water	9	Freshwater/Potable	3	Artesian Well
wellsprp	point	AA050	Well (Water)	116	Water	4	Mineral	5	Dug or Drilled Well
wellsprp	point	AA050	Well (Water)	116	Water	9	Freshwater/Potable	5	Dug or Drilled Well
wellsprp	point	AA050	Well (Water)	116	Water	9	Freshwater/Potable	5	Dug or Drilled Well
wellsprp	point	BH170	Spring/Water-Hole			4	Mineral		

Figure 7

Excerpt from extracted VMAP data schema

5.0 Discussion

Two summary tables show (respectively) the differences between the two DCM. In some cases, the differences are likely due to scale; consider that the DLG schema is for a representation of landscape processes operating at 10 times finer resolution. In other cases the issue is more just as likely related to agency mission. This is true for example of DLG hydrography, whose DCM schema shows 8-10 times the number of hydrographic feature codes as VMAP. Conversely, the VMAP schema for industrial feature categories (and particularly refinery and manufacturing features) proved much richer than DLG. We presume this is for strategic reasons.

DLG Summary Table				
		Data		
Feature_dataset	Feature_class	DLG Features	VMAP Matches	Difference
hydrography	hydro_arcs	100	13	87
	hydro_nodes	2		2
	hydro_polys	117	9	108
	hydro_pts	67	8	59
hydrography Total		286	30	256
manmade_features	manmade_polys	2		2
manmade_features Total		2		2
(blank)	(blank)	3	9	-6
(blank) Total		3	9	-6
Grand Total		291	39	252

Interestingly, several hydrographic features in VMAP are listed under DLG settlement categories, for example several types of dams, canals, dykes and other human-made water features. Our work was cut short by unexpected failures in Python scripts. We intend to correct these and present a more complete comparison at the conference. We are continuing investigation of taxonomic categories that appear to 'jump' levels and classes in the hierarchy and will report on these as well. We argue that in addition to providing systematic comparisons between agency DCMs, discrepancies in a data schema can tell a lot about the agency view of a real world landscape as reflected in its mission and its work practice. Extracting schemas is a reasonable undertaking with a limited dataset. In the long run, insights would be maximized with a comprehensive exercise spanning the entire data dictionary. More importantly, the most relevant comparisons will be afforded by comparing DCMs at a common or similar scale.

6.0 Summary

To summarize the multiple representations problem in cartography, we note that map features represented in databases at different scales and for varying purposes tend to differ in level of abstraction (again, that term refers to changes in feature existence, geometry, dimensionality, symbolization or prominence within a data representation). Currently, map production systems and GIS environments offer only minimal support for linking database features that are described by multiple representations in geospatial databases. Because rules for capture and compilation are confounded with symbology rules it becomes difficult to distinguish compiled from derived data, and this has important implications for preserving database integrity and semantics across a range of mapping scales.

We propose a data architecture to accommodate multiple representations based on a DLM/DCM strategy in emerging use in Europe. Our proposal is to implement the DLM/DCM architecture as relational tables, as for example in a geodatabase. The lack of need for pointers means that performance will not be slowed regardless of how many multiple representations are created. The architecture separates data as originally acquired from derivations produced by geoprocessing. Once compiled in the base data model, a feature becomes available for multiple scales and multiple purposes of representation. Changes to symbolization are implemented in the DCM. The creation of a DCM is tied to purpose and to map scale, thus preserving cartographic integrity. Changes to the DLM can be readily propagated to subsequent DCM representations, and this should lead to improvements in data integrity.

Impediments to adoption of this architecture include a lack of cartographic geoprocessing tools available in GIS environments. Conditional rendering tools and symbolization strategies that are sensitive to graphical context are being developed at national mapping agencies in France, Switzerland, and UK. These tools remain isolated from commercially available GIS platforms. Another related issue is a lack of understanding about the limits of data at a particular resolution to be transformed to another resolution, or mapped to the limits of scale. This problem is complex because different data domains have differing sensitivities to resolution, and this forms an important area for future research.

One possible institutional impediment to adoption of the DLM-DCM architecture is the time required to build a database schema. The truth of the matter is that most data managers intermix compiled with derived data, and over the life cycle of many data products it becomes impossible to distinguish between items that rightfully belong to the DLM and derived products that should reside in a DCM. In some cases (and particularly for smaller data management operations), metadata about the chronology of geoprocessing has become separated from the data. It is likely that unless an organization is specifically in the business of data acquisition or primary feature extraction, the only avenue towards a multi-scale multi-purpose DLM-based architecture is for a national mapping agency to initiate compilation of DLMs and propagate DCMs throughout the user community.

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