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Do You See What I Mean?

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> "When I use a word," Humpty Dumpty said, in a rather scornful tone, "it means just what I choose it to mean, neither more nor less."
>
> From *Through the Looking Glass*, L. Carroll

Visualizers, like logicians, have long been concerned with meaning. Generalizing from MacEachren's overview of cartography,[1] visualizers have to think about how people extract meaning from pictures (psychophysics), what people understand from a picture (cognition), how pictures are imbued with meaning (semiotics), and how in some cases that meaning arises within a social and/or cultural context. If we think of the communication acts carried out in the visualization process (see Figure 1), further levels of meaning are suggested. In the figure, visualization begins when someone has data that they wish to explore and interpret; the data are encoded as input to a visualization system, which may in its turn interact with other systems to produce a representation. This is communicated back to the user(s), who have to assess this against their goals and knowledge, possibly leading to further cycles of activity.

Each phase of this process involves communication between two parties. For this to succeed, those parties must share a common language with an agreed meaning. For example, when someone passes a data set to a visualization tool, it is with some understanding of how the tool will interpret content of the data set, and how to interpret the output of algorithms that the tool might apply to the data. This agreed meaning can arise and be expressed in many different ways. We offer the following three steps, in increasing order of formality:

1. terminology (jargon),
2. taxonomy (vocabulary), and
3. ontology.

The terminology level introduces the meaning of concepts and expresses them informally through, for example, a glossary or published papers. The organization of concepts is ad hoc and not in itself machine processable. This step includes concepts where the concept itself might be given a precise mathematical definition; although the definition is precise within the body of theory in which it is located, shared meaning of the concept relies on social and cultural mechanisms.

In the taxonomy level, a definition of concepts remains informal, but the concepts themselves are organized in some structured way. The organization of the concept provides some context in which concepts can be related and compared. However, because the organization itself need not follow any particular set of rules, the taxonomy is not machine processable, and operations on multiple taxonomies (for example, comparison, union, and so on) require understanding and interpretation of the basis on which the taxa are formed.

The ontology level describes concepts using a set of constructors with a preagreed meaning, for example, through a set of relationships that can be asserted between primitives. Because there is a fixed way of defining new concepts, it's possible for an ontology to be made machine processable. This extends to operations across multiple ontologies.

To date, much of the knowledge about visualization data, processes, and representations is at level 1 (terminology)—for example, in the definition of data sets, documentation of procedural interfaces, and theories from cognate disciplines. However, there has been work to organize this knowledge, resulting in a number of taxonomies and models that formalize aspects of the visualization process (at level 2, or taxonomy). Our argument in this article is that it's time to begin synthesizing these fragments and views into a level 3 model, an ontology of visualization. We also address why this should happen, what is already in place, how such an ontology might be constructed, and why now.

Motivation

We give four reasons for seeking a more rigorous foundation for visualization:

- collaboration,
- composition,
- preservation (curation), and
- education.

We now expand each of these points.

Visualization is a collaborative activity involving domain and system experts, and sometimes multiple visualization systems. A shared vocabulary might be sufficient for human-to-human collaboration, but if we want to support remote collaboration via software tools, a greater level of formalization is required.

Developments in the Web services, Semantic Web, and Grid communities, of which we will have more to say

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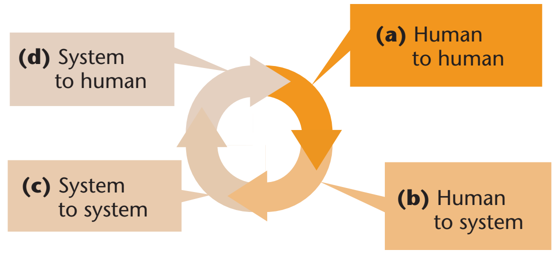
later, make possible the provision of visualization services. Mechanisms for the discovery and composition of such services rely on a precisely agreed meaning.

Visual analysis, like any kind of experimental protocol, should be repeatable. There is a growing interest in the ability to preserve the process and parameters by which visualization was performed.

Visualization is both a research discipline and a commodity. What concepts should users of visualization systems understand (for visual literacy)? What are the important concepts to cover in a visualization curriculum? Given the plethora of systems and vocabularies, there is a need to at least understand what different courses are covering and where they overlap. Education remains a core motivation for work that surveys and defines visualization terminology. Books in the field have set out personal views of its foundations and core concepts, though these are aimed at specialized audiences.

A resource intended for wider access is an outline of statistical methods and visualization techniques provided by Canada's national statistics agency (http://www.statcan.ca/english/edu/power/toc/contents.htm). However, while books and online resources document a level of consensus and definition, they do so via unstructured and informal text; even if you can find a definition of a term, there is no basis for using machine processing to work with that definition or to compare it with others. The challenge of locating a definition can be ameliorated by a glossary that structures the presentation of terminology, but the underlying meaning remains informal.



1 **Visualization cycle: (a) human to human, dialogue between domain and/or visualization experts to explore the problem requirements; (b) human to system, data to be visualized, required representation, and/or the process to be used; (c) system to system, specification of services including data models and functional behavior; and (d) system to human, visualization product output to user for inspection.**

Taxonomies

A more structured definition of concepts comes from the presentation of a taxonomy, in which concepts that are alike in some way are organized into groups, and/or a small number of dimensions that characterizes and differentiates them. The visualization community has produced a number of taxonomies, one of the most recent being the work of Tory and Möller.[2] These works vary from broad overviews of the whole field[2] to deep descriptions of specific areas or problems, for example layout techniques in graph visualization.[3] Interestingly, some systems also provide a form of taxonomy. For example, Microsoft Excel has a built-in classification of representation techniques (such as various forms of chart and business graphics), and modular visualization tools such as those from AVS extend this classification to algorithms. These classifications capture a limited domain of meaning about what makes sense as a representation, or at least what can be built in that specific system. However, the underlying model is of a limited domain; it's not intended for sharing beyond the specific tool, or in particular for integration with other models; and although the classification is coded within a machine, it's not necessarily encoded in a way that allows search, interchange, or reasoning.

Toward a formal approach

One step toward a more formal (level 3) approach is to restrict the language used to define the underlying concepts. The E- and O-notations developed by Brodlie, for example, model the structure of a data field and data representations.[4] Like the work of Keller and Keller, it supports a taxonomy of representation techniques.[5] These notations, like any formal representation, require informal text to ground the meaning of the primitives for human readers. However, in principle at least, the language is sufficiently formal that descriptions could be machine processed, for example, as a basis for type-checking data connections in a modular visualization environment.

Although sometimes overlooked, visualization systems and tools also embody and promulgate a range of core concepts. For example, while the ubiquitous phrase *visualization pipeline* originated in the work of Haber and McNabb on visualization idioms,[6] it has gained widespread currency through its implementation within environments such as AVS tools. Software tools are by necessity based on explicit, formal models of data and processes. As tools become adopted by a community, these models too are adopted, sometimes becoming de facto standards—OpenGL is a well known example. Popular geometry formats have influenced the way we think of data representation; consider, for example, how the vocabulary used to describe scenes has been influenced by file formats such as BYU, OBJ, and from OpenInventor, and how these continue to impact thinking in this area (the legacy of the Inventor format, for example, is manifest, through VRML in X3D; see http://www.web3d.org).

Tools have an impact above the format level; VTK (http://www.vtk.org), for example, defines a hierarchy of types that represents one way of classifying a significant range of scientific data sets. Other systems—for example, IBM's Visualization Data Explorer (now OpenDX; http://www.opendx.org)—provide a quite different set of data types. Each technology has a community of practice built up around it, within which the models and concepts underlying these tools have wider use. In the case of the Data Explorer, Treinish's paper[7] gives a nice overview of the model that it contributes, as well as being an early note on the importance of metadata. On the positive side, the insight embodied within systems design gives us a major pool of knowledge, backed by practice, on which to build an ontology. The difficulty is that there are subtle differences in how systems (and their communities) interpret even apparently common concepts: for example, points and cells.

Five years ago, the prospects for capturing the meaning of the visualization field, or indeed that of other fields, was limited; specific approaches such as the E- and O-notations could clarify the meaning of a compact set of concepts, but there was little prospect of linking such descriptions into a more comprehensive model. Nor, pedagogical reasons aside, was there strong motivation. Recently, however, initiatives from within the Semantic Web community have entered the mainstream of practice, and technologies for representing and processing semantic content are being adopted as practical tools for industrial use. Defined by the World Wide Web Consortium (W3C; see http://www.w3.org/2001/sw), Resource Description Framework (RDF) and Web Ontology Language (OWL) are models and languages that provide a small set of concepts and relationships for describing the meaning of entities within some domain.

RDF provides a standard model to define and exchange metadata; OWL makes it possible to build ontologies and corresponding inference systems using well understood principles (with roots in the research results of the knowledge representation communities). A number of communities have already used these tools to develop ontologies. One of the earliest and most widely known is Dublin Core (http://www.dublincore.org), an ontology for the metadata that can be associated with documents and other online resources; many digital libraries use this ontology. An example closer to the discussion here is the gene ontologies that a consortium (see http://www.geneontology.org) is developing to provide a common vocabulary for researchers in genetics. Further examples of consortia-led efforts to develop ontologies can be found at http://www.semanticweb.org. The life sciences industry has been particularly active in this area, as it recognizes that progress in the field is now highly contingent on sharing and integrating disparate sources of data. A report on the 2004 W3C Workshop on the Semantic Web for Life Sciences (http://www.w3.org/2004/10/swls-workshop-report.html) contains evidence of the extent to which the Semantic Web technologies have entered industrial practice in the biosciences domain.

The right time

We believe that now is the right time to consider an ontology for visualization. There is renewed interest within the community on foundational issues, in part reflecting the maturity of the community, and in response to new challenges—for example, understanding what is common to scientific and information visualization (a significant discussion topic at IEEE Visualization 2004).

Technology is also acting as a driver; development of the Semantic Web, Web services, and the Grid enables the creation of visualization services, which as noted earlier will require precise semantic description to enable discovery and composition. In the UK, for example, a national program for e-Science (large-scale collaborative science supported by high-performance networks and computing) includes visualization as a significant activity, and a number of visualization projects are experimenting with Semantic Web/Grid technologies (for example, the OpenOverlays project[8]).

A robust framework is also needed to document and relate the models derived from specific technologies; this would be beneficial both in supporting visualization services built from heterogenous systems, and in providing the communities involved with a "Rosetta Stone" to aid interpretation of models and results.

Finally, the need to share and integrate a wide range of data resources is not unique to the life sciences or the physical sciences; the integration of visualization with other data analysis tools is contingent on ways of aligning multiple vocabularies and on documenting the provenance of data sources and analysis products.

If it is sensible to move toward a visualization ontology, it's important for the community to be aware of what is happening within W3C: the technologies for supporting ontology development, the process involved, and lessons learned from early experiences. An important aspect that emerged from the discussions at W3C is that ontologies should be shared and combined. Indeed, an ontology is not a monolithic edifice defined in isolation, but is rather something that can be developed through a community process. The developers of OWL specifically included features that let one ontology include or refer to other ontologies, allow the equivalence of terms to be defined, and provide for version management.

Also, ontologies can be developed via a seeding process, starting with small components that are formalized separately. Support for this process has been proposed, in the form of a peer-to-peer infrastructure that uses mappings to reconcile operations over simple, distributed ontologies.[9] We can think of the results as a collection of ontology islands; apart from addressing expressive and computational issues of ontology languages, it allows for different rates and levels of development across the constituents. For example, within a sea of visualization ontologies, there may be well defined islands corresponding to certain data representation(s), but formalization of process or task knowledge may be more skeletal (perhaps closer to a coral atoll, by analogy).

Expanding these points further, for many subdomains it would be difficult or inadvisable to develop an ontology as a single step; expressing an ontology in a language such as OWL requires significant effort and requires a level of consensus within the relevant community that may take time to develop. As an example for an intermediate step, Simple Knowledge Organization Systems (SKOS, http://www.w3.org/2001/sw/Europe/reports/thes/1.0/guide/) provides a simpler RDF schema for representing thesauri and similar types of knowledge organization, using only a few simple elements of OWL. This could be used initially as a tool or an example to collect and structure knowledge about some subdomain. The thesaurus itself could then exist as one island providing an opportunity for debate and discussion within the community. Other efforts are directed at techniques that will harvest an ontology from semistructured or even informal models. SKOS and ontology islands are the result of ongoing work within the Semantic Web community. While these efforts are motivated by practical examples, it's too early to say how well these tools will work across other domains.

Given the importance of the Semantic Web technologies to visualization, the visualization community needs to become involved in the Semantic Web community. A more general point for discussion is on how to generate a community process to oversee the design, acceptance, and maintenance of an ontology. For example, there is a tension between maintaining an open process that encourages a wide range of contributions, while providing some form of quality assurance and oversight that gives users (in a particular industry) confidence in the content's consistency and interpretation. Rather than think of a visualization ontology as the product of a standardization effort (such as within ISO or ANSI), a better model would be as a kind of open source project. Although these efforts are open to contributions, there is always a core team with a mandate to accept and audit changes and to issue updates. An open question is what kind of body would carry the confidence of the visualization community in fulfilling this role.

As visualization problems move from just a private enterprise involving data and tools owned by a research team into a public activity using shared data repositories, computational grids, and distributed collaboration, Humpty Dumpty's position quoted in the introduction becomes untenable. Meaning becomes a shared responsibility and resource. Through the Semantic Web, there is both the means and motivation to develop a shared picture of what we see when we turn and look within our own field. ■

Acknowledgment

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