TECHNISCHE
UNIVERSITÄT
DRESDEN

Fakultät Informatik

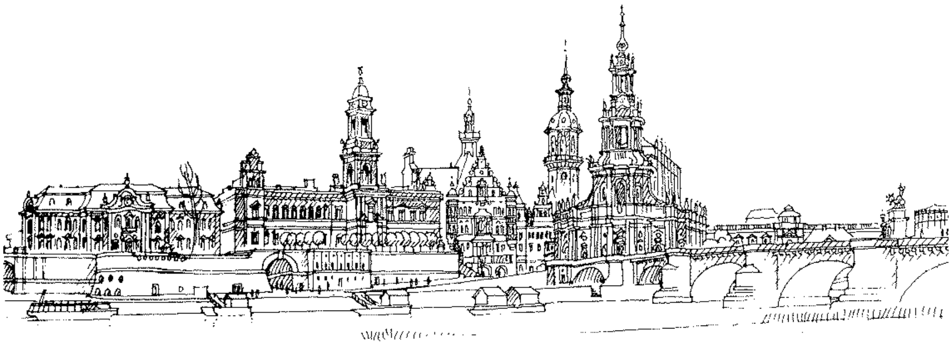
Technische Berichte
Technical Reports
ISSN 1430-211X

TUD-FI11-01 März 2011

M. Voigt, J. Polowinski

Institut für Software und Multimediatechnik

Towards a Unifying Visualization Ontology



Technische Universität Dresden
Fakultät Informatik
D−01062 Dresden
Germany
URL: http://www.inf.tu−dresden.de/

Towards a Unifying Visualization Ontology

M. Voigt[1] and J. Polowinski[1]

[1]Technische Universität Dresden, Germany

Abstract

Although many terminologies, taxonomies and also first ontologies for visualization have been suggested, there is still no unified and formal knowledge representation including the various fields of this interdisciplinary domain. We moved a step towards such an ontology by systematically reviewing existing models and classifications, identifying important fields and discussing inconsistently used terms. Finally, we specified an initial visualization ontology which can be used for both classification and synthesis of graphical representations. Our ontology can also serve the visualization community as a foundation to further formalize, align and unify its existing and future knowledge.

Keywords: Visualization, Graphics, Formalization, Ontology, Standardization, Knowledge

---

1. Introduction

Numerous models and classifications have been developed in the field of visualization with different goals, e. g., to allow for systematic reviews of existing techniques, to clarify concepts of the domain or to model knowledge for visualization systems. However, the existing work is still hard to compare, since a common meaning of visualization-related terms is missing. The contained knowledge is also not machine-process- and understandable because of its informal character. First approaches of visualization ontologies (VO) emerged trying to tackle the problems [DBD04,SAR08]. But we argue that these do not sufficiently build on the knowledge contained in existing models and classifications which is underpinned in Sect. 2. Furthermore, the VOs are not available, thus, they can not be discussed, reused or extended by the community.

We aim at developing a unifying ontology which is applicable in visualization systems. Using a VO with a visualization system means for us that it allows reasoning which graphic representation needs to be reused or synthesized in a special situation. Therefore, the data as well as the user, task, and system context need to be describable using our formal visualization vocabulary. As an example consider the following visualization scenario: A novice user has the task to survey the governmental budget distribution using a device that has a small display. He has to identify and compare the hierarchical data.

In this paper, we present how we extracted and aligned visualization knowledge from existing work to formalize it and build the vocabulary. The VO could also be beneficial to classify new work or identify research directions that received little attention in the past.

The remainder of the paper is structured as follows. In Sect. 2, our survey on well-known models and classifications illustrates the work we, considered to model the ontology. There, we are the first giving an overview on existing visualization ontologies including their intents and drawbacks. In Sect. 3, we discuss the visualization vocabulary used in the related work, point to differences and contradictions and show which important terms are formalized in our ontology. In Sect. 4, we showcase how to describe a visualization scenario with our formal vocabulary. Finally, in Sect. 5, we summarize our results and give an outlook on possible future work based on the ontology.

2. Related Work

During knowledge gathering, we studied both visualization models and classifications, which are both valuable source for revealing new insights in the area of visualization theory since years. The objective was to identify important work to build on, to comprehend which areas of visualization knowledge are covered and what are the drawbacks of existing models and classifications.

Technical Report – Technische Universität Dresden (3/2011).

2.1. Visualization Models

The process of creating suitable graphic representations to foster knowledge extraction from data by means of visualization is a complex procedure involving many steps. Therefore, several abstract models with different focuses were developed to allow for a better understanding of this process. The pipeline model, first published by Haber and McNabb [HM90], is the most prominent example. It describes visualization as a process consisting of a series of transformation steps that convert data into a displayable image. Other researchers adopted this model and extended it, e. g., with human interaction and tasks [CMS99], focused on data transformation [Chi00] or coordination of different views [BRR03]. Van Wijk [vW05] established a model to calculate the value of visualization. Tory and Möller [TM04] proposed a high-level, model-based taxonomy which unifies scientific and information visualization. Finally, the model of Brodlie and Noor [BN07] should be mentioned here which combines a set of aspects from other existing models. We observed that all models relate to the fields of *data* and *graphic representation*. As some are modeling also the *user* [vW05] or their *tasks* [BN07] we identified the first areas to formalize knowledge from.

2.2. Visualization Classifications

Several types of classifications exist. Since we require one that can be equally processed and understood by humans and machines, a high level of formalization is a critical factor to our work. Duke et al. [DBDH05] distinguish the following three levels of formalization for classifications: **Terminologies** introduce concepts in a less structured, informal way. **Taxonomies** define concepts in a hierarchically structured but mostly informal way. **Ontologies** are the most formal approach where concepts and their relations are based on a preagreed, shared meaning.

In the following, a brief overview of existing terminologies, taxonomies as well as on VO is given to identify which areas of research need be discovered for our work.

2.2.1. Terminologies and Taxonomies

In the domain of visualization and related areas, numerous terminologies and taxonomies have been developed with different goals, e.g. to allow for systematic reviews of existing techniques and ideas. It is not possible to discuss them all in depth in this work, hence, Fig. 1 illustrates the overall results of surveying 53 terminologies and taxonomies. An extensive comparison can be found at our website[1]. Similar to the models mentioned above, we identified different areas, all the work done is associated with. We distinguish between the area of *data* and their *domain*. Further, we refer to *graphic representation* as the result of the visualization process which is synthesized using a *graphical vocabulary*. We subsume the topics *task and interaction* because a clear separation between both concerns is not yet given (cf. Sect. 3.3). The fields *user* and *system* is about user/system modeling and how this benefits the visualization process.

From our survey we discovered three findings. In Fig.1-a one can observe that most classifications concentrate on data, the graphical representation and task/interaction. The other fields got less attention and, thus, seem to be good future directions of research. Further, only few work tries to *unify* a broader spectrum of concepts of this interdisciplinary domain because in most cases only 1 or 2 sometime three areas are tackled by a single work (cf. Fig. 1-b). Finally, about 90% of the reviewed literature deal with terminologies or taxonomies.

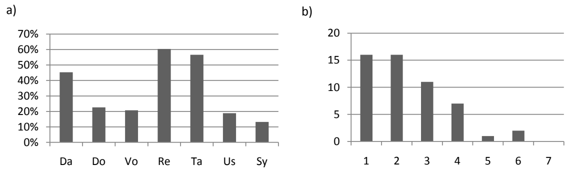


Figure 1: *Statistical overview of reviewed literature (a) by fields they focus in general [Data (Da), Domain (Do), Graphical Vocabulary (Vo), Graphic Representation (Re), Task and Interaction (Ta), User (Us) and System (Sy)] and (b) by how many areas are covered within a single work*

2.2.2. Overview on Existing Visualization Ontologies

In the following, we give an overview on existing VOs and relate them to our objectives. Gruber defines an ontology as an "explicit specification of a conceptualization" [Gru93]. Based on a workshop held at the National e-Science Centre in 2004 [BDD04], Duke et al. advise to merge the existing visualization knowledge fragments by means of an ontology [DBD04]. They provide a vocabulary by which users and system can communicate. It comprises only a small set of concepts and relations like data, visual representation and task. Unfortunately, an implemented or even a more detailed version of the sketch is missing. Potter and Wright [PW06] grabbed the idea for the description of visualization resources with focus on hard- and software requirements. Their specified ontology is not accessible and also misses a comprehensive overview. Rhodes et al. [RKR06] worked on an application to categorize and store information about software visualization systems. Although they state to incorporate the concepts of Duke et al. [DBD04], the paper lacks a clear description of this fusion. Further, the developed ontology schema is tailored to software visualization, thus, the work does not directly contribute to a domain independent VO. Gilson et al. [GSGC08] propose a *Visual Representation Ontology* as part of a tool for automatic visualization. Their ontology comprises properties of an entire

---

[1] http://mmt.inf.tu-dresden.de/VO

graphic representation as well as attributes of single graphical objects contained in it. While this work is promising in terms of formalization, its focus is narrowed. Neither interaction or tasks nor the user are considered in this ontology. Finally, Shu et al. [SAR08] created an ontology for visualization, intended for the semantic description of visualization services. Based on the initial VO [DBD04] as well as on taxonomies proposed in [Bro92] and [TM04] their VO mainly comprises classes for modeling data and visualization techniques. However, they did not consider concepts like user, tasks or interaction. In the end, the names of numerous classes (e. g. “EnS3” or “A3_3T3”) are readable for machines but hard to understand for humans working with the VO and hard to map to concepts from existing ontologies.

The brief survey shows that existing approaches lack subsumption and alignment of established models and classifications. Some of them are not implemented [DBD04], comprise only high-level concepts [PW06, RKR06], have a narrowed focus [GSGC08, SAR08], one is hard to interpret for both humans and computers [SAR08] and they are not *accessible* and so not *reusable* by the community. Hence, unifying visualization knowledge in a formal manner is still pending.

3. Formalization of Visualization Knowledge

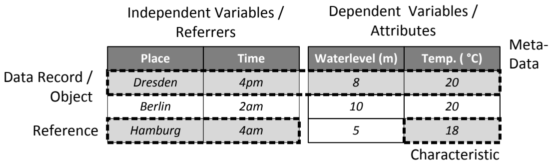
In this section, for each field related to visualization, we will point to contradicting terms, homonyms and synonyms and present the concepts that we chose in order to align and formalize these terms.

3.1. Data

Using the well-known tabular data model as an example, we will introduce some basic terms related to data (cf. Fig. 2) that we adopted for the VO. The table (in general a *data set*) is a set of rows (in general *data records*) in turns consisting of cells (the *data values*). It has columns that we varied, the *independent variables*, and columns that we measured, the *dependent variables*. All variables together are part of the *data-structure*. A data value, e.g. gained by observation, generally complies to a scale of measurement. If a *unit* belongs to this scale it becomes inherently connected to the values. This extrinsic information on units and scales of measurement can be stored as *meta-data*. We will now discuss the field of data in more detail, first focusing on data structure and then on properties of the single data variables. Finally, we will present data-related ontologies that have been integrated with the VO.

3.1.1. Properties of Data Structure

Independent and Dependent Variables The term variable is used differently in computer science, statistics and general mathematics. In mathematics variables are considered input to functions. In-line with this view, Andrienko and Andrienko [AA06] see the whole data set as a function between *independent variables*, the input that is varied when we measure, and *dependent variables*, the output that is measured. Independent variables, are also called referrers [AA06] or variables of the domain [KV98]. The combination of all values of the independent variables is called a reference. Dependent variables are also called attributes [AA06] or variables of the range [KV98]. Two variables (dependent or not) may correlate, e. g. foot-size will correlate shoe-size. Variables that have formerly been varied can also be interpreted as dependent and the other way round [AA06]. Therefore, we modelled dependency as an exchangeable role (cf. Fig. 5).



Place	Time	Waterlevel (m)	Temp. (°C)
Dresden	4pm	8	20
Berlin	2am	10	20
Hamburg	4am	5	18

Figure 2: *Overview of data terms (tabular data)*

Dimensionality Dimensionality is often seen as the number of variables (both independent and dependent) since the term *dimension* is used synonymously with variable/attribute [Kei02,TM04,Maz09]. Similarly the term *multi-dimensional* is sometimes used synonymously with the term *multivariate* [YWR03]. However, for Santos [San04] dimensionality refers only to independent variables, not to all the variables — consequently he differentiates multi-dimensional and multivariate data. Multi-dimensional data has multiple *independent* variables [San04,AA06] while multivariate data has multiple *dependent* variables [San04]. A varying meaning of dimensionality has also been noticed by Tory and Möller [TM04]: They realized that, in their own taxonomy, *dimensionality* means “number of independent variables” when used in the context of continuous models while for discrete models it means “number of dimensions in total”. To shift around these different interpretations we speak of *dimensionality of independent variables* vs. *dimensionality of dependent variables* similar to Kemp and Vckovski [KV98].

Linked Data Structures or Graphs This concerns the relations linking the records, not the records itself. These relations form a topology that might be a sequence, a tree (cf. Fig. 3) or another possibly cyclic un-/directed graph. More characteristics include planarity, average degree of fan-in and fan-out and the existence of disconnected subsets [Spe07]. Besides the topology of the relation other characteristics can be described such as whether the relation is reflexive, symmetric or transitive and whether it is a weighted relation. Linked data structures can be represented by *Triples*, *Matrices*, or other *Tables* with references.

3.1.2. Properties of Data Variables

Scales of Measurement Data can be characterized by the applied scale of measurement. Wilkinson [Wil05] distinguishes two possible approaches of classifying scales: The first classification is based on Stevens' basic work on axiomatic scale theory [Ste46]. He defined four different types of scales based on the operations that are allowed on the values. These types are *nominal*, *ordinal*, *interval* and *ratio*. Combining the latter, Ware [War04] and Mazza [Maz09] are considering *categorical*, *ordinal* and *quantitative* data values. Stevens scales were detailed again by Card [CMS99] who added *spatial* (Q_s), *similarity* (Q_m), *geographic* (Q_g) and *time* (Q_t) *quantitative* scales. When he calls them time or spatial quantitative, Card describes the domain of the scales of measurement. Also Engelhardt [Eng02] does this when he considers *relations of physical order* and *physical distance*. The need for more than Stevens' scale types has been realized in the field of geography [Chr95] and by Marks [Mar74] who defined many more scale types. Prytulak [Pry75] criticizes that every operation introduced, leads to another scale type and consequently the number of scale types is arbitrary. However, the general usefulness of scale types to classify variables is mostly not doubted [KS93]. As a second classification Wilkinson differentiates base unit classes (e.g., *length, mass, time, temperature*) following *The International System of Units* (SI) [TT01], secondary unit classes that are derived (e.g., *area*, *volume*, *density*; also SI) and dimensionless scales of measurement. While adopting Steven's well known scale types, we modeled the domain of the data separately as an orthogonal concern. Base unit classes could be integrated from existing vocabulary (cf. Sect. 3.1.3).

Continuous vs. Discrete Andrienko and Andrienko [AA06] distinguish continuous and discrete referrers and attributes. However, they do not state that a variable is continuous per se, but that an attribute is continuous with respect to some referrer. As a prerequisite for a continuous attribute this referrer has to be continuous as well. An attribute is discrete if there are only characteristics for a countable number of references possible, otherwise it is continuous. This can be aligned with Tory and Möller's [TM04] view who understand continuity as a property of the model of data in the users mind, not as an intrinsic property of data itself. We would like to adapt this notion of continuity; however this is not yet implemented.

3.1.3. Integration of Data-Related Ontologies

Ontologies on data partly exist and have partly been integrated: The XML Schema Part 2 [BM04] defines primitive data types (e.g., byte, data, integer, sequence) and gives a mechanism for deriving further user-defined types. Beyond that, as early as in 1994 Gruber and Olsen [GO94] worked on the EngMath ontology, a shared notation for mathematics to allow a formal notation of physical quantities and dimensions. Multiple ontologies exist that are concerned with units — we will only consider two recent ones from 2009 in more detail: The first is the *Quantities and Units of Measure Ontology Standard* (QUOMOS) by OASIS [TC09b] that aims at specifying the basic concepts of quantities, systems of measurement units and scales based on the SI [TT01]. The other, the *Quantities, Units, Dimensions and Data Types in OWL and XML* Ontologies (QUDT) by TopQuadrant and NASA [MHK10] follows similar goals and is already fully specified in OWL, therefore it could be well integrated with the VO.

3.2. Graphic

In this section we discuss terms that emerged in the context of graphical grammars and languages as suggested by Mackinlay [Mac86], Engelhardt [Eng02], Wilkinson [Wil05] and Andrienko and Andrienko [AA06]. Figure 3 shows some of the terms and relations that we finally formalized.

Graphic Representation A *graphic representation* is the result of visualization, when visualization is seen as a process as we do. Engelhardt distinguishes *primary graphic representations* (e.g. *map*, *table*, *link diagram*) and *hybrid graphic representations* (e.g. *chronological link diagram*) [Eng02]. We consider primary graphic representations to be useful concepts that should appear in a VO because users are comfortable with these terms and will watch out for common terms like *map*. However, it is not clear if further named classes, such as those described by Engelhardt's hybrid graphic representations, make sense since a combinatorial explosion of such types will obviously happen for further specializations. Following Mackinlay [Mac86], we allow graphic representations to be assigned a value of *expressiveness* and *effectiveness* with regard to a certain datatype.

Graphic Object Following the composite pattern, a *graphic object* may be an *elementary graphic object* or a *composite graphic object*, according to Engelhardt [Eng02]. A *composite graphic object* is defined as "a graphic object that consists of a graphic space, a set of graphic objects that are contained in this graphic space, and a set of graphic relations in which these contained graphic objects are involved". Engelhardt further states that graphic objects carry the visual attributes such as *size*, *shape* and *color*. He sees graphic representations as special composite graphic objects that allow recursion. Bertin uses the term *marks* [Ber83], however, this term seems to refer rather to the *role* that an object plays in a diagram.

3.2.1. Visual Means

We use the term *visual means* to refer to the things that we can vary in a visualization. Bertin used the term *visual variable* for this [Ber83]. Mackinlay puts a *basis set of primitive graphical languages* that consists of positional language categories such as *single position* and *apposed position* and the

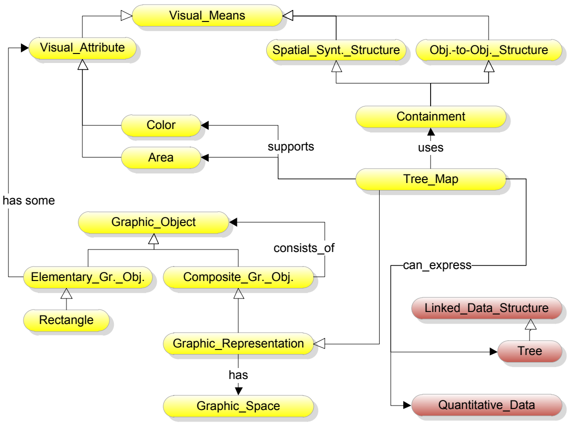


Figure 3: *Concepts in the field of graphic and data*

retinal variables list, but also of the categories *map*, *connection* (trees, networks) and *misc* (pie charts, venn diagrams). However, when we consider that both attributes and complex structures can be used to visualize data, terms like *variable* or *language* seem misleading to us. *Visual variable* could also be confused with *visual attribute*. We therefore use *visual means* instead as a term for this upper concept.

Visual Attributes Visual attributes are properties of graphical objects. Bertin introduced the term *retinal variables* for properties to which the retina is sensitive independent of the movement of the eye: *size*, *saturation*, *texture*, *color*, *orientation*, *shape*. Other categories of Bertin are *positional* and *temporal variables*. Later authors reused this classification [Mac86, Maz09]. Similarly Engelhardt classifies visual attributes into two groups: spatial attributes and area-fill attributes [Eng02]. He describes the difference as follows: “If we would regard every point of a graphic object as being anchored to its location in graphic space, then varying a spatial attribute of the object would alter this anchoring, while varying an area-fill attribute of the object would not alter this anchoring.”

Andrienko and Andrienko also use the term *retinal variables* that they see as “internal, individual properties of marks” and distinguish *dimensions* which they describe as “containers for marks”.

Both time and space, as physical dimensions, play an extra role. Although time is often less discussed, already Bertin introduced *temporal relationships* and gave *animation* as an example. Besides using time as another physical dimension, it can also be used in visual attributes such as *flicker frequency*.

Syntactic Structures We will now have a close look at the aforementioned “set of graphic relations” and the resulting *graphical syntactic structures*, as Engelhardt calls them [Eng02]. Since he distinguishes spatial and area-fill attributes, he introduces *spatial syntactic structures* and *attribute-based syntactic structures*. He further differentiates structures of relations inbetween graphical objects and between graphical objects and graphical space. Structures involving object-to-object relations are for example *spatial clustering*, *linking*, *containment* and *superimposition*. Card calls them *topological structures* [CMS09]. A structure involving object-to-space relations is for example a coordinate system that spans a metric space.

Andrienko and Andrienko’s *dimensions* are similar to Engelhardt’s spatial syntactic structures. They are concerned with everything that provides a position. This includes physical dimensions, but also *various arrangements of the display space*. Examples for arrangements are node-link-structures and discontinuous tables that resemble Engelhardt’s spatial object-to-object structures.

The treatment of visual means, especially spatial structures, is the field where we encountered the most alternative approaches. Engelhardt’s description of object-to-object and object-to-space structures as well as the consideration of both attribute- and spatial-relationships covers all our use cases and uses coherent terms. For this reason, we basically picked his terms for reuse in the VO (cf. Fig 3).

3.2.2. Relations between Visual Means

Two relations between visual means can be distinguished, *dependency* and *interaction*, that have to be considered when using multiple visual means at the same time. Instead of using them only for visual attributes, we extended the usage to describe relations of all visual means.

Dependency Visual attributes are *independent* if it is possible to set them to any value without changing the values of other variables, e.g. color and shape can be varied independently. Visual attributes are *dependent* if one variable is composed from the others, for example $area = height * width$. As a consequence it is not possible to use all involved attributes at the same time. Dependency is closely related to the observations of Wilkinson who notes that attributes can be bundled and describes color as a bundle of *hue, saturation* and *brightness* [Wil05]. Although not speaking of bundles, Engelhardt calls *size* a versatile attribute and notes that variations of size can either be homegeneous or “restricted to height, length or width of an object” [Eng02].

Interaction Interaction between two visual attributes may cause difficulties in interpreting a value encoded by one attribute when the other takes certain values, such as extreme ones. As an example Mackinlay [Mac86] describes the perceptual problem that occurs when *shape* and *size* of a visual object both encode information and *size* takes very low values. Interaction between syntactic structures occurs, for example, between *lineup* and *connection* when we try to avoid crossing connectors. Currently our VO is only able to describe which properties depend on each other or interact, but not *how* they do.

3.3. Human Activity

The modeling and classification of tasks has a long tradition in the interdisciplinary domain of the user-centered design “to improve the understanding of how a user interacts with a user interface to accomplish a given interactive task” [LV03]. Thus, human *tasks* and *interaction techniques* are not only dealt with the domain of visualization (e. g. [ZF98]) but also in other fields of research such as HCI (e. g. [Nor88]), cognitive science (e. g. [Zha97]) or business processes ([TC09a]).

However, a closer reflection of the existing models and taxonomies of human activity exposes many differences which makes it hard to unify the existing knowledge into a formal model. Yi et al. [YKSJ07] state that they are different levels of granularity which reach from low-level interaction techniques to high-level user tasks. As the terms interaction and task are used synonymously a proper separation between them is missing. The survey of Limbourg and Vanderdonckt [LV03] depicts that also diverse concepts relate to tasks which are not common at all, e. g. data, roles, events, plans or system operations. Furthermore, task taxonomies can be divided into data-/question-oriented (e. g. [AA06]) and operation-oriented approaches (e. g. [AES05]).

After considering different models and taxonomies about structuring human doing, the *Activity Theory*, which is well-established in the domain of HCI [Nar96], is a good foundation for structuring terms and relations in this field. Bardram [Bar97] gives a concisely subsumption of this theory where the *three-level hierarchy* is the most valuable characteristic for our work. The level of *activity* describes **why** a person accomplishes an activity which consists of one or more actions. The level of *action* explains **what** a person does. An action is a conscious goal-directed process performed by an actor and contains a set of operations. The level of *operation* embodies **how** a person realizes an action. An operation is an unconscious process that is determined by the current conditions in the context of an activity.

The purpose of the activity theory in HCI is to get an understanding of “the use of technology in human activity” [Bar97]. That fits our goal of modeling tasks and interaction to effectively support users of visualization systems. Taking into account for example the matured GOMS model [CNM83] which is designed to measure human performance in interactive systems, some parallels can be identified. A task (activity) is operationalized by methods (action) which have goals to accomplish. Further, a method describes a procedure of elementary acts called operators (operation). Recent work in characterizing the users’ visual analytic activity [GZ08] takes the activity theory into account where it offers a clear separation of concerns using the proposed three-level hierarchy. Using this, existing task and interaction knowledge from literature can be aligned as follows and is modeled in the VO as illustrated in Fig. 4.

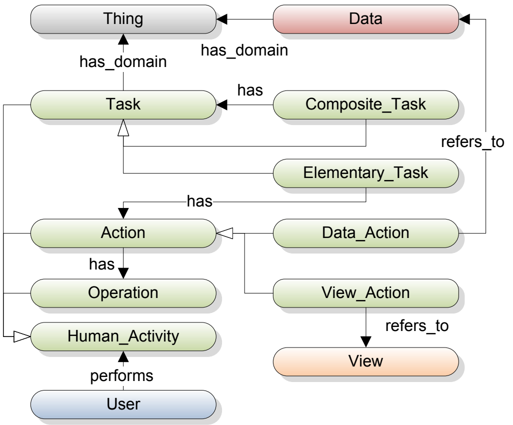


Figure 4: *Concepts in the field of human activity*

Task At the highest level in this hierarchy, “tasks are activities that have to be performed to reach a goal.” [Pat01] Only a few taxonomies relate to this level which should answer **why** a user is acting somehow. For example, Amar and Stasko [AS04] propose a taxonomy of high-level tasks based on the identification of analytical gaps. They define rationale-based tasks and worldview-based tasks. Further, Amar et al. [AES05] as well as Yi et al. [YKSJ07] ascertain low-level tasks but also admit that some existing high-level task are not covered through their taxonomies. An example task taken from existing work is “*Identify key market insights to generate investment recommendations*” [GZ08]. According to Nigay et al. [NV98] tasks are domain-dependent which is confirmed in [GZ08]. Thus, the mentioned example belongs to finance domain. Furthermore, tasks have a composite character which is not part of the activity theory but rather element of most of the task models [LV03]. Sub-tasks correspond to a more concrete motive but are still coupled to a domain, e.g. ‘*Characterize the overall 52-week market trend in the technology sector*’ [GZ08]. Such a more concrete level is parallel to the understanding of tasks from data-oriented approaches (e. g. [AA06]) which define them as questions relating to the underlying components of the data. Finally, sub-tasks which cannot be decomposed (cf. *elementary task* in Fig. 4) are the bridge to the level of actions which is verified, e. g., by Bezold [Bez09] “Tasks describe the users activity by combining user actions hierarchically.”

Action An action explains **what** a person does towards consciously fulfilling a concrete goal. Zhang refers to an action as “basic unit in problem solving" [Zha97] what matches the understanding of an atomic analytical step [GZ08]. Opposite to the higher level of tasks, actions are domain and application independent, thus, they could be performed across different systems supporting varying tasks in diverse domains. The term action is almost always unused in existing taxonomies in visualization domain although they

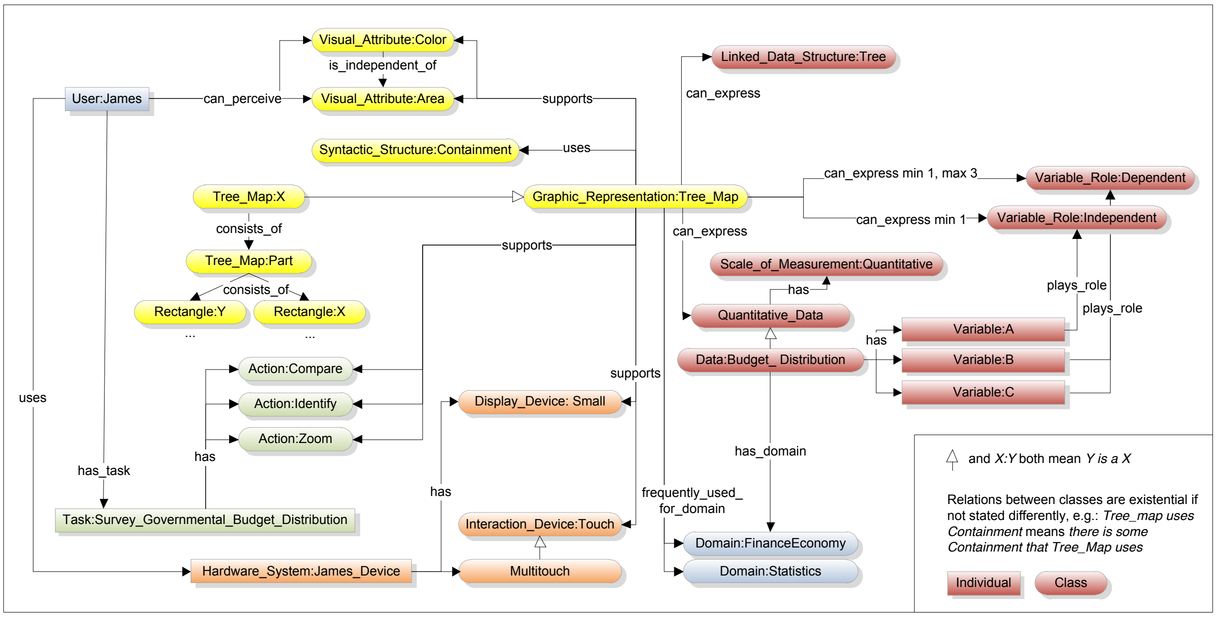


Figure 5: *Instantiating the ontology with data from an exemplary visualization scenario*

mostly characterize what users consciously do while working with visualizations systems. Thus, we have the opinion that most of them relate to the action level. As we refer the data-oriented approaches to the level of sub-tasks, the user-/operation-oriented taxonomies (e. g. [YKSJ07]) can be assigned to the action level as they comprise actions describing what a user does. While actions are domain-independent they have a relation to the data or the view representing the data. That means with an action the user can e. g. *query*, *filter* or *create* data as well as he can modify the user interface by e. g. *zooming*, *panning* or *reordering* views [GZ08]. User actions consist of sub-sequences of events which are generated using operations.

Finally, some well-known taxonomies do not fit nicely to the level of actions as we have an user-centered point of view. They focus more on the classification and description of the underlying techniques using a more technical standpoint (e. g. [Kei02]) or define requirements (e. g. [Shn96]) "that an information visualization application should support" [KHL*07].

Operation The lowest level in our hierarchy is formed by operations which are executed by the user to directly manipulate the visualization system (**how**). This understanding goes along with existing definitions like "By operation, we mean all user interactions" [CR98] or "Interaction is the way in which communication between the user(s) and the machine(s) takes place" [FDBJK07]. For an effective communication, different media could be used to capture the input (e. g. mouse, keyboard,and microphone) but also to present the feedback (e. g. different scales of displays) at which the way of communicating expresses the modality (e. g. hand gestures or speech). The interaction of a user is represented by a series of low-level events inside the system which contain only little semantics and could be traced to conclude actions executed [GZ08, Bez09]. Most of the visualization research has not yet addressed the field of interaction [YKSJ07], however, we recommend e. g. Fikkert et al. [FDBJK07] who link both research areas in detail.

3.4. Integrating User-, System- and Domain Ontologies

Pursuing the idea of creating a unified VO we also need to pay attention on the knowledge of other visualization related fields not considered previously. We identified that the areas like user, system and domain modeling are also relevant (cf. Sect. 2.2) which are enabling visualization systems to provide situational adequate graphic representations to overcome existing barriers in users visual data exploration process [GTS10]. As we see the VO as evolving prototype which both grows on its needs and integrates in best-case already modeled knowledge, in following, we consider resources to build on.

User Over the past decades research on user models has matured, for instances, due to the fields of HCI (e. g. [Nor88, All97]) or adaptive web systems (e. g. [BM07]). Reviewing existing work in this areas we identified different terms concerning user modeling like *user*, *design*, *mental* or *cognitive* model. The most fundamental distinction between the terms is that a *mental model* is inside a user's head containing the expectations he has about systems's behavior. In contrast, *user models* appear in the computer comprising information about the user [All97]. Unfortunately, the latter is not consequently used in literature (e. g. [TM04]).

While modeling concepts of mental models within the VO is possible and helps to formalize existing knowledge, in our work we will focus on user models to support personalization of our visualization systems at first. There are different scopes for characterizing user models (e. g. [Ric83]), from our perspective the level of formalization is most interesting. Thus, we can reuse existing concepts e. g. from “Friend of a Friend” (FOAF) [2] which already contains relevant user properties and relates to concepts like organizations. Furthermore, we model concepts (cf. Fig. 6) to express a persons preferences, abilities and knowledge like proposed in [GKV*07] or [PMWM08].

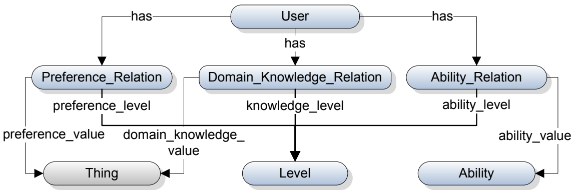


Figure 6: *Concepts and relations for user modelling*

System Modeling the system context has also a long tradition e. g. in the domains of adaptive web systems [BM07] or ubiquitous computing [SO09] and often goes along with the use of user models [BM07, PMWM08]. But in contrast to user models, formal and open classifications about computational system to build on are rare. Therefore, we began to model concepts based on CroCo [PMWM08] and the System Information API[3] to describe input and output devices as well as user interface components with its API and required libraries.

Domain The user with his domain knowledge solves domain specific tasks (cf. Sec. 3.3) using graphic representations. As many domain ontologies but also upper ontologies like UMBEL[4] exist in the Semantic Web we do not want to develop our own concepts for the different domains. We create relations with an untyped range to link from VO to their concepts. (cf. Fig. 4 and 6)

4. A Scenario Using the Unified Ontology

In the last section, we exhaustively analyzed the identified visualization-related areas and formalized the interrelated concepts we found. For this purpose, we first and foremost built on the existing body of literature. Additionally, we verified our conclusions by first specifying exemplary visualization scenarios using our ontology, and then checking, if we are able to reason answers to different questions that need to be solved by our future visualization systems. Examples are “Which combinations of visual attributes do interact?” or “Which graphic representation can be chosen to express a data structure with two independent variables?” In the following we briefly introduce one of our scenarios. For the most part it is illustrated in Fig. 5.

The user James has the task to “survey the governmental budget distribution” with his smartphone having a small touch display. He has to compare objects from his quantitative data set which is tree-structured, relates to the financial domain and contains three in-/dependent variables. Also graphical representations like a tree map are described, with its syntactic structure, their contained rectangles as well as color and area as supported visual attributes. Having formalized this scenario using the VO, humans but also visualization system have a base to reason that, e. g. a tree map is a suitable graphic representation for visualizing a quantitative data set from the financial domain, comprising one independent and two dependent variables.

5. Conclusion and Further Work

We found that most visualization knowledge is stored informally in terminologies and taxonomies and is not directly usable for computational reasoning. Further, we distinguished seven fields the existing work can be associated with. Most of this work focuses only on few of these fields while there is little work that tries to unify all of them. The few existing visualization ontologies do not sufficiently subsume existing domain knowledge. Furthermore, they are not accessible to public.

Trying to tackle these shortcomings, we systematically surveyed the broad corpus of visualization literature and discussed existing concepts and relations used by different authors. During this “manual pattern matching” only few, mostly basic, entities, e. g., *color*, had the same meaning in all cases. In contrast, many terms had multiple meanings and also their relationships were not always in-line. An example is the dichotomy of *continuous* and *discrete*. Although many authors see this difference, the involved concepts are often slightly different — while Andrienko and Andrienko [AA06] speak of continuous vs. discrete attributes, referrers and phenomenons, Wilkinson [Wil05] differentiates continuous vs. categorical variables and scales. Finally, we specified a visualization ontology, containing and aligning the terms we chose from literature and gave an idea of its usage by example. An initial version of this ontology, written in the Web Ontology Language *OWL 2*[5], is published at

---

[2] http://xmlns.com/foaf/spec/

[3] http://www.w3.org/TR/system-info-api/

[4] http://umbel.org/

[5] http://www.w3.org/TR/owl2-overview/

the url *http://purl.org/viso/* to allow for discussion within the community. We also consider to allow editing of a simplified view of the ontology through a web platform.

Although the concepts that we want to formalize have been identified, the actual implementation requires completion, e. g. the modeling of concepts such as roles. Furthermore, existing ontologies need to be better integrated and, as an extension to the presented ontology, facts and constraints will be added to allow for e. g. rankings of visualizations. We will evaluate the ontology in different academical prototypes, for example as semantic foundation for the description of UI components for the UI mashup platform *CRUISe* [Pie10] or as background of a faceted classification of graphic representations in *DelViz* [KKW*10].

References

[AA06] ANDRIENKO N., ANDRIENKO G.: *Exploratory Analysis of Spatial and Temporal Data: A Systematic Approach*. Springer, 2006.

[AES05] AMAR R., EAGAN J., STASKO J.: Low-level components of analytic activity in information visualization. In *Proc. of IEEE Symposium on Information Visualization* (2005), pp. 111–117.

[All97] ALLEN R. B.: *Handbook of Human-Computer Interaction*. Elsevier Science Inc., New York, NY, USA, 1997, ch. Mental Models and User Models, pp. 49–63.

[AS04] AMAR R., STASKO J.: A knowledge task-based framework for design and evaluation of information visualizations. In *Proc. of IEEE Symposium on Information Visualization* (2004), pp. 143–150.

[Bar97] BARDRAM J. E.: I love the system — I just don't use it! In *Proc. of the international ACM SIGGROUP conference on supporting group work* (New York, NY, USA, 1997), ACM, pp. 251–260.

[BDD04] BRODLIE K., DUCE D., DUKE D.: Visualization ontologies - report of a workshop held at the national e-science centre. Online, July 2004.

[Ber83] BERTIN J.: *Semiology of graphics*. University of Wisconsin Press, 1983.

[Bez09] BEZOLD M.: Describing user interactions in adaptive interactive systems. In *User Modeling, Adaptation, and Personalization* (2009), vol. 5535 of *LNCS*, Springer, pp. 150–161.

[BM04] BIRON P. V., MALHOTRA A.: XML schema part 2: Datatypes second edition. http://www.w3.org/TR/xmlschema-2, 2004.

[BM07] BRUSILOVSKY P., MILLÁN E.: User models for adaptive hypermedia and adaptive educational systems. *The adaptive web: methods and strategies of web personalization* (2007), 3–53.

[BN07] BRODLIE K., NOOR N. M.: Visualization notations, models and taxonomies. In *Theory and Practice of Computer Graphics* (2007), Lim I. S., Duce D., (Eds.), Eurographics Association, pp. 207–212.

[Bro92] BRODLIE K. W.: *Scientific Visualization - Techniques and Applications*. Springer, 1992, ch. Visualization Techniques, pp. 37–86.

[BRR03] BOUKHELIFA N., ROBERTS J., RODGERS P.: A coordination model for exploratory multiview visualization. In *Coordinated and Multiple Views in Exploratory Visualization* (2003), pp. 76–85.

[Chi00] CHI E.: A taxonomy of visualization techniques using the data state reference model. In *Proc. of IEEE Symposium on Information Visualization* (2000), pp. 69–75.

[Chr95] CHRISMAN N. R.: Beyond stevens: a revised approach to measurement for geographic information. In *Proc. of the International Symposium on Computer-Assisted Cartography* (1995).

[CMS99] CARD S. K., MACKINLAY J. D., SHNEIDERMAN B.: *Readings in information visualization: using vision to think*. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, 1999.

[CMS09] CARD S., MACKINLAY J. D., SHNEIDERMAN B.: Information visualization. *Human-Computer Interaction: Design Issues, Solutions, and Applications* (2009), 181.

[CNM83] CARD S. K., NEWELL A., MORAN T. P.: *The Psychology of Human-Computer Interaction*. Lawrence Erlbaum Associates Inc., Hillsdale, NJ, USA, 1983.

[CR98] CHI E. H.-H., RIEDL J.: An operator interaction framework for visualization systems. In *Proc. of IEEE Symposium on Information Visualization* (1998), pp. 63–70.

[DBD04] DUKE D., BRODLIE K., DUCE D.: Building an ontology of visualization. In *Proc. of the conference on Visualization* [BDD04].

[DBDH05] DUKE D., BRODLIE K., DUCE D., HERMAN I.: Do you see what I mean? *Computer Graphics and Applications, IEEE 25*, 3 (2005), 6–9.

[Eng02] ENGELHARDT V. J.: *The Language of Graphics*. PhD thesis, Universiteit van Amsterdam, Institute for Logic, Language and Computation, Sept. 2002.

[FDBJK07] FIKKERT W., D'AMBROS M., BIERZ T., JANKUN-KELLY T. J.: Interacting with visualizations. In *Human-Centered Visualization Environments*, vol. 4417 of *LNCS*. Springer, 2007, pp. 77–162.

[GKV*07] GOLEMATI M., KATIFORI A., VASSILAKIS C., LEPOURAS G., HALATSIS C.: Creating an ontology for the user profile: Method and applications. In *Proc. of the First International Conference on Research Challenges in Information Science* (2007).

[GO94] GRUBER T. R., OLSEN G. R.: An ontology for engineering mathematics. In *Proc. of 4th International Conference on Principles of Knowledge Representation and Reasoning* (1994).

[Gru93] GRUBER T.: A translation approach to portable ontology specifications. *Knowledge Acquisition 5*, 2 (1993), 199–220.

[GSGC08] GILSON O., SILVA N., GRANT P., CHEN M.: From web data to visualization via ontology mapping. *Computer Graphics Forum 27*, 3 (2008), 959–966.

[GTS10] GRAMMEL L., TORY M., STOREY M.-A.: How information visualization novices construct visualizations. In *Proc. of IEEE Symposium on Information Visualization* (2010).

[GZ08] GOTZ D., ZHOU M.: Characterizing users' visual analytic activity for insight provenance. In *Proc. of IEEE Symposium on Visual Analytics Science and Technology* (2008), pp. 123 –130.

[HM90] HABER R., MCNABB D. A.: Visualization idioms: A conceptual model for scientific visualization systems. *Visualization in Scientific Computing* (1990), 74–93.

[Kei02] KEIM D. A.: Information visualization and visual data mining. *IEEE Transactions on Visualization and Computer Graphics, 8*, 1 (2002), 1–8.

[KHL*07] KATIFORI A., HALATSIS C., LEPOURAS G., VASSILAKIS C., GIANNOPOULOU E.: Ontology visualization methods—a survey. *ACM Comput. Surv. 39*, 4 (2007), 10.

[KKW*10] KECK M., KAMMER D., WOJDZIAK J., TARANKO S., GROH R.: DelViz: Untersuchen von Visualisierungsformen durch eine Klassifizierung beruhend auf Social Tagging. In *Proc. of GeNeMe10* (2010), Meissner K., Engelien M., (Eds.).

[KS93] KHURSHID A., SAHAI H.: Scales of measurements: an introduction and a selected bibliography. *Quality and Quantity 27*, 3 (1993), 303–324.

[KV98] KEMP K., VCKOVSKI A.: Towards an ontology of fields. In *3rd International Conference on GeoComputation* (1998).

[LV03] LIMBOURG Q., VANDERDONCKT J.: Comparing task models for user interface design. In *The handbook of task analysis for human-computer interaction*, Diaper D., Stanton N., (Eds.). Lawrence Erlbaum Associates, 2003, ch. Comparing Task Models for User Interface Design, pp. 135–154.

[Mac86] MACKINLAY J.: Automating the design of graphical presentations of relational information. *ACM Trans. Graph. 5*, 2 (1986), 110–141.

[Mar74] MARKS L. E.: *Sensory processes: The new psychophysics*. Academic Press, New York, 1974.

[Maz09] MAZZA R.: *Introduction to Information Visualization*. Springer, 2009.

[MHK10] MASTERS J., HODGSON R., KELLER P. J.: QUDT - quantities, units, dimensions and types. http://www.qudt.org/, Feb. 2010.

[Nar96] NARDI B. A.: *Context and consciousness: activity theory and human-computer interaction*. The MIT Press, 1996.

[Nor88] NORMAN D. A.: *The Psychology Of Everyday Things*. Doubleday, New York, 1988.

[NV98] NIGAY L., VERNIER F.: Design method of interaction techniques for large information spaces. In *Proc. of the working conference on Advanced visual interfaces* (1998), pp. 37–46.

[Pat01] PATERNO F.: Task models in interactive software systems. In *Handbook of Software Engineering and Knowledge Engineering* (2001), Chang S., (Ed.), vol. 1, World Scientific Publishing Company.

[Pie10] PIETSCHMANN S.: Model-driven development and runtime platform for adaptive composite web applications. *International Journal on Advances in Internet Technology 4*, 1 (February 2010), 277–288.

[PMWM08] PIETSCHMANN S., MITSCHICK A., WINKLER R., MEISSNER K.: CroCo: Ontology-Based, Cross-Application Context Management. In *Proc. of the 3rd International Workshop on Semantic Media Adaptation and Personalization (SMAP 2008)* (2008).

[Pry75] PRYTULAK L. S.: Critique of SS stevens' theory of measurement scale classification. *Perceptual and Motor Skills 41* (1975), 3–28.

[PW06] POTTER R., WRIGHT H.: An ontological approach to visualization resource management. In *DSV-IS* (2006), pp. 151–156.

[Ric83] RICH E.: Users are individuals: individualizing user models. *International Journal of Man-Machine Studies 18*, 3 (1983), 199 - 214.

[RKR06] RHODES P., KRAEMER E., REED B.: Vision: an interactive visualization ontology. In *Proc. of the 44th annual Southeast regional conference* (2006), pp. 405–410.

[San04] SANTOS S. R. D.: *A Framework for the Visualization of Multidimensional and Multivariate Data*. PhD thesis, University of Leeds, 2004.

[SAR08] SHU G., AVIS N., RANA O.: Bringing semantics to visualization services. *Advances in Engineering Software 39*, 6 (2008), 514–520.

[Shn96] SHNEIDERMAN B.: The eyes have it: a task by data type taxonomy for information visualizations. In *Proc. of IEEE Symposium on Visual Languages* (1996), pp. 336–343.

[SO09] STRASSNER J., O'SULLIVAN D.: Knowledge management for context-aware, policy-based ubiquitous computing systems. In *Proc. of the 6th international workshop on Managing ubiquitous communications and services* (2009), pp. 67–76.

[Spe07] SPENCE R.: *Information Visualization: Design for Interaction*, 2nd ed. Prentice-Hall, Inc., 2007.

[Ste46] STEVENS S. S.: On the theory of scales of measurement. *Science 103*, 2684 (Jun 1946), 677–680.

[TC09a] TC O. B.: *Web Services - Human Task (WS-HumanTask) Specification Version*. OASIS, Nov. 2009.

[TC09b] TC O. Q.: *OASIS Quantities and Units of Measure Ontology Standard (QUOMOS) TC*. OASIS, 2009.

[TM04] TORY M., MÖLLER T.: Rethinking visualization: A high-level taxonomy. In *Proc. of IEEE Symposium on Information Visualization* (2004), pp. 151–158.

[TT01] TAYLOR B. N., THOMPSON A.: *The international system of units (SI)*. US Dept. of Commerce, Technology Administration, National Institute of Standards and Technology, 2001.

[vW05] VAN WIJK J. J.: The value of visualization. In *Proc. of IEEE Visualization* (2005), pp. 79–86.

[War04] WARE C.: *Information Visualization: Perception for Design*, vol. 2. Morgan Kaufmann Publishers Inc., 2004.

[Wil05] WILKINSON L.: *The grammar of graphics*. Springer, 2005.

[YKSJ07] YI J. S., KANG Y. A., STASKO J., JACKO J.: Toward a deeper understanding of the role of interaction in information visualization. *IEEE Transactions on Visualization and Computer Graphics 13*, 6 (2007), 1224–1231.

[YWR03] YANG J., WARD M., RUNDENSTEINER E.: Hierarchical exploration of large multivariate data sets. *Data visualization: The state of the art 2003* (2003), 201–212.

[ZF98] ZHOU M. X., FEINER S. K.: Visual task characterization for automated visual discourse synthesis. In *Proc. of the SIGCHI conference on Human factors in computing systems* (1998), pp. 392–399.

[Zha97] ZHANG J.: The nature of external representations in problem solving. *Cognitive Science 21*, 2 (1997), 179–217.