Ontological Primitives for Visual Knowledge

Alexandre Lorenzatti[1], Mara Abel[1], Sandro Rama Fiorini[1],
Ariane Kravczyk Bernardes[2], and Claiton Marion dos Santos Scherer[2]

[1] Instituto Informática – Universidade Federal do Rio Grande do Sul
{alorenzatti,marabel,srfiorini}@inf.ufrgs.br
[2] Instituto Geociências – Universidade Federal do Rio Grande do Sul
claiton.scherer@ufrgs.br

Abstract. In the last few years, we have analyzed the best alternatives for acquiring and processing visual knowledge with the goal of supporting problem solving. We call *visual knowledge* the set of mental models that support the process of reasoning over information that comes from the spatial arrangement and visual aspects of entities. Also, visual knowledge is implicit, meaning that it is difficult to be explicitly represented solely with propositional constructs. In this paper, we describe a representational approach that helps geologists in capturing and applying this kind of knowledge, in order to support software development applied to interpretation tasks in Petroleum Geology applications. Our approach combines propositional constructs with visual pictorial constructs in order to model visual knowledge of geologists. These constructs are proposed in a strong formal model, founded by Formal Ontology concepts. Based on these constructs, we develop a full ontology for stratigraphic description of sedimentary facies. The Formal Ontology background and the approach are detailed and evaluated through the paper.

1 Introduction

Imagistic domains are those in which the problem-solving process starts with a visual pattern-matching process that captures the information, which will further support the abstract inference process of interpretation. Image-based diagnosis in Medicine, biological analysis and Geological interpretation are common examples of tasks that are based on visual interpretation. Moreover, the decrease in the price of image-capturing devices has caused a quick dissemination of the use of images as complement of information register in general: reports, sites, databases. Otherwise, the indexing, searching and retrieving of content from images has shown a difficult task that is far of getting an adequate solution. Ontologies have been shown the more promising alternative to face this challenge.

We focus this paper on the needs of representation primitives for capturing content from images and scenes in order to build domain ontologies that provide support to storing, indexing and processing visual information. We present a revision on visual-knowledge representation approaches that are being studied around the world and propose some directives to develop ontologies in imagistic domains. Our contribution is the representational approach to capture visual knowledge and the domain ontology for sedimentary facies, which was validated with the community of Stratigraphy in Geology.

A.C. da Rocha Costa, R.M. Vicari, F. Tonidandel (Eds.): SBIA 2010, LNAI 6404, pp. 1–10, 2010.

Several approaches for developing ontologies in visual domains described in the literature have tried to translate the visual concepts into a propositional representation and deal with the semantic gap found between some pictorial representation (such as digital files that represent pictures, maps or graphs) and the semantic content expressed in a symbolic representation. Hudelot and colleagues in [1] have tried to automatic extract objects from image and to associate them to a knowledge model for shapes and, in another level, to a domain model to diagnose diseases in rose leafs. Liu, Zhang et al. [2] defined an ontology of bird anatomy shapes (body, beak and wing shapes), which is used to recognize bird species. An image processing algorithm segments bird pictures and matches them against the shapes in the library and a domain ontology of Ornithology helps in defining the specific bird. Bertini [3] uses a domain ontology and a set of visual concepts that are used to represent the visual counterpart of abstract linguistic concepts enriching ontologies with pictorial content. It is applied for digital video libraries annotation in the soccer domain. Our approach extends the previous proposal by defining domain-independent primitives – the *PictorialConcept* and *PictorialAttribute* – that expand the expressivity of pictorial representations and are possible of being processed by knowledge systems. These primitives are instantiated here in the domain of Geology.

2 Visual Knowledge

Even though they seem intrinsically connected, *visual knowledge* and *image* are disjointed concepts. In order to understand the distinction, we will start for referring the Ullmann triangle [4] that describes the relation among an *Object* in the reality, a *Concept* in some conceptualization and a *Symbol* in some language (A modified version is shown in Figure 1). An *Object* is supposed to be a real or concrete object, although its existence only can be referred through the process of perception and abstraction by someone. *Concepts*, by their side, are the way in which the human being deals with the external world, creating and manipulating mental internal representations of it in order to reason about and to act upon the environment. *Symbols* are one of the many possibilities in which concepts can be *externalized* in the process of communication in order to share the conceptualization among the community. It will depend on the language chosen by the person that should preserve some *ontological commitment* [5] with the conceptualization. One concept may have many alternative external representations in different languages for distinct purposes. The term *image*, by its side, is usually referred as a pictorial representation of an object, and should be situated in the lower side of the Ullmann triangle.

Based on these assumptions, we define visual knowledge as follows:

"Visual knowledge is the set of mental models (concepts) of real or imaginary scenes manipulated by the brain in order to deal with image-based tasks, such as, image interpretation or pattern or shape recognition in the reality."

Consequently, when we mention *visual knowledge,* we are referring to the *conceptualization* vertex of the Ullmann triangle in the human mind scope. A pictorial representation of a *scene*, like a picture, a map or a draw, is related to the language vertex, i.e., it refers to some external representation of the internal conceptualization. Propositional and visual concepts are both part of the conceptualization and appear to be manipulated in mind in some indistinct way. The choice of one instead of other are defined by their use, for example, spatial, location problems that demand visual representation or communication problems that require shared concepts. Pictorial representations of visual knowledge are, then, produced by people in order to express the visual knowledge. They are symbols that can not be translated to propositional representations. Thus, we add a new dimension to the Ullmann triangle (the new vertex: "Pictorial representation in a Visualization", in the base of the triangle in Figure 1) in order to separate the symbolic representations of propositional and visual concepts and their visualizations. The representation of a concept is its name in some language, while the same concept can be depicted as an image, a draw, a graphic or an icon. The correspondence between the pictorial representation and the symbol in a language, when both refer to the same concept is called *anchoring*.

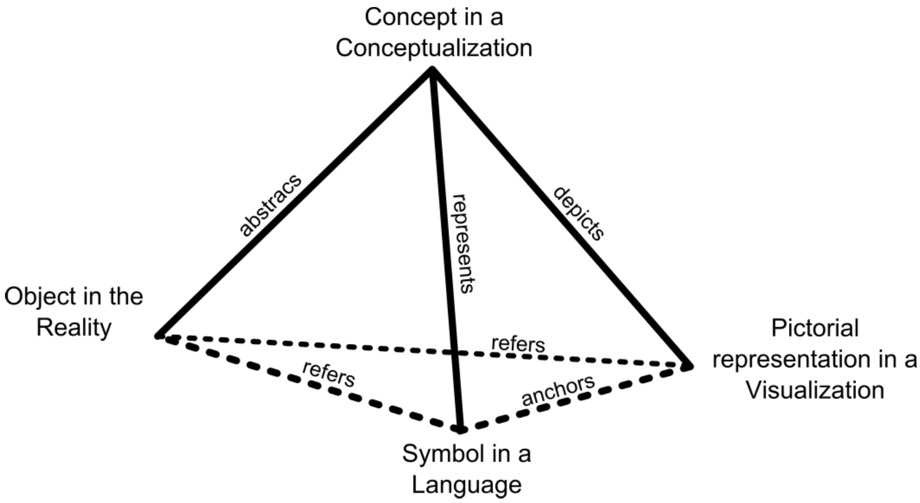


Fig. 1. The extension of the Ullmann triangle considers *visual knowledge* as a special kind of conceptualization in mind that can have either symbolic or pictorial representation

3 Conceptual Modeling Foundation

Concepts are the way in which people capture identifiable portions of reality with the purpose of understanding and knowing how to deal with them. A conceptualization is the whole set of knowledge a person has about his/her world, what was referred by Alan Newell as the *knowledge level* [6]. In order to share this conceptualization with other people or systems, someone will express it through an external representation artifact in the *symbolic level*. When a community agreed about the meaning and formalization of some representation, we call this an *ontology* [7]. More specifically, *domain ontologies* are those developed for formalizing technical vocabulary in some domain, with the intention of making communication more efficient and support problem solving [8].

The main intention of our work is developing domain ontologies for imagistic domains, especially in Geology for supporting petroleum exploration. In order to achieve this goal, we have studied and proposed primitives that are capable to capture both the visual and propositional part of the concept. The demand for ontological definition in petroleum geology is mainly motivated by the need of terminological definition and development of interpretation systems based on symbolic information.

We have carried on knowledge acquisition and built our model based on the theoretical framework of meta-properties and meta-types proposed by Nicola Guarino [7, 9] and Giancarlo Guizzardi [5], in the context of Formal Ontology. Specially, we will mention here the notions of rigid sortals, properties, quality domains, partonomic relations and hierarchical relations, which are being used through this text. A rigid sortal is a concept whose definition requires that their instances cannot stop being an instance of this concept in any possible world. This means that if the *essential properties* chosen to define the concept cease to be recognized in the way they were defined, the instance will cease to exist too, because it looses its identity criterion.

A person is a rigid sortal while a student is not, since there are instances of it that can stop being a student without losing its identity. These are important constructs for ontological models, given that they allow producing trustful mappings among different domain ontologies that support interoperability.

A sortal is defined by its (essential) properties. In the framework defined by Guizzardi, each property is associated with a *quality domain*, which defines the set of possible values the property can assume. A quality domain can also be shared by more than one property. A value in a quality domain is called *quale*, having its own independent existence. Taking, for instance, the sortals *apple* and *car* and the quality domain *color*, both sortals have a property (e.g., *skin color* and *exterior color*) related to the same quality domain *color*. Eventually, two individuals, a red apple and a red car, will have the same *quale* as color. In this case, both individuals will be linked to the same *quale* in the *color* quality domain.

Relations represent the associative links between the objects of the domain and will define the organization and possibilities of inference in that domain. Further details of these definitions can be found in [5].

4 Sedimentary Facies Ontology

The studies on [10, 11] have proved that the expertise in Geology is mainly supported by visual information that cannot be described symbolically through geometric components, such as size and format, alone, which limits the application of machine learning or image processing algorithms. Stratigraphy is the study of sedimentary terrains in surface or subsurface, in order to define the geological history of their formation based on the description of well cores and outcrops. The main object of study and description is the *sedimentary structure*. Sedimentary structure is the external visual aspect of some internal spatial arrangement of the rock grains that, along with the preserved fossil content and the rock type, identifies the depositional environment in which the existent sediment has been deposited and consolidated in that rock. It is the more striking visual object recognized in the domain and the first one to be used in raising interpretation hypotheses. The sedimentary structure concept comprises a challenge for ontology engineering, because of the incapability of the geologists in defining a sedimentary structure in a pure verbal (propositional) way, requiring a drawing or a picture to completely express the idea.

In order to represent that implicit part of knowledge we have developed some meta-constructs inspired in the idea of inferential *free-rides*. Atsushi Shimojima [12] formally defines inferential free-rides as the possibility of capturing semantic information through the direct correspondence among the properties of visual representations and the concepts' properties, i.e. the visual representations are built in order to express the semantic information. We have proposed two kinds of icons based on the idea of free-rides: one to represent *visual kinds* and other to represent values (*qualia*) in a *quality domain*. The method for defining the representation from the original structures is showed in [13]. We use, for example, the qualia to define the quality domain for the properties of the class sedimentary structures, and the visual kinds to define iconic representations for their subkinds. For each defined icon we associate a formal definition in a propositional form, intended to be used by reasoning methods, querying and also to produce exported reports. The propositional form is associated with the iconic representations through the proposed meta-constructs *PictorialConcept* and *PictorialAttribute*, described in the sequence.

The meta-construct *PictorialConcept* is used to represent sortals, i.e. visual kinds which instances must be so in any possible world. It is defined as the tuple

$$PC = \{V_{S_c}, V_{P_c}, A_c, i_{S_c}, i_{P_c}\}. \quad (1)$$

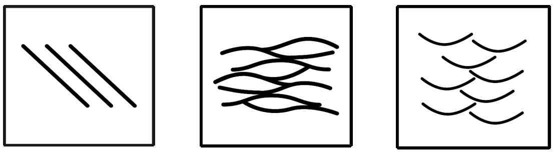
The sets V_{S_c} and V_{P_c} contains respectively the symbolic (propositional) and pictorial vocabulary to represent concepts. In our proposal, the pictorial vocabulary is constituted by icons. The grounding relation A_c maps elements in $V_{P_c}$to elements in V_{S_c}, representing the *anchor* axis from the extended Ullmann triangle. The relation is also total and injective, since every pictorial concept is grounded in one distinct symbolic concept. The interpretation functions i_{S_c} and i_{P_c} establish the mapping relation from the symbolic and pictorial vocabulary to the concept they represent (here representing respectively the *represents* and *depicts* axes from the Ullmann extended triangle).

The meta-construct *PictorialAttribute* is used to represent the *qualia* from the quality domains, i.e., possible values that can be assumed by a property. It is defined as the tuple

$$PA = \{V_{S_a}, V_{P_a}, A_a, i_{S_a}, i_{P_a}\}. \quad (2)$$

The sets V_{S_a} and V_{P_a} are respectively the symbolic (propositional) and pictorial vocabularies used to *represent values inside a quality domain*. In our proposal, the elements in the pictorial vocabulary are icons as well. The grounding relation A_a maps elements in V_{P_a} to elements in V_{S_a}, representing the *anchor* axis from the extended Ullmann triangle. The relation A_a is also total and injective. The interpretation functions i_{S_a} and i_{P_a} define the mapping relation from the symbolic and pictorial representations to the concept they represent (here also representing respectively the *represents* and *depicts* axes from the Ullmann extended triangle).

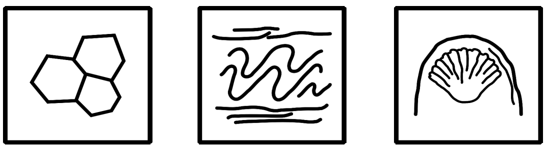
In our study of stratigraphy, we elicited a set of 28 stratigraphic structures and a set of 32 qualia. They have been acquired in both propositional ($V_{S_c}$and V_{S_a}) and pictorial form. Then we defined 32 icons that describe property values (V_{P_a}) and 28 visual kinds of sedimentary structures in siliciclastic rocks (V_{P_c}). The completeness of the terminology is being tested by the geological community. Figure 2 shows a set of icons for a subset of values of the property *lamina-shape* of the concept Sedimentary structure.



(a) (b) (c)

Fig. 2. Three of the seven possible values of lamina-shape property of sedimentary structure. (a) planar, (b) trough cross strata, and (c) truncated wavy lamination.

Figure 3 presents three among a hundred of defined subkind icons of sedimentary structures.



(a) (b) (c)

Fig. 3. Subkinds of sedimentary structure. (a) Top or base structures of mud crack, (b) deformation structure of convolute lamination, and (c) deformation structure of tool mark.

Figure 4 describes the propositional model of a subtype of the rigid sortal *sedimentary structure* defined in the ontology. Every value on the quality domain of properties (*high angle, planar and medium*) has an equivalent value in the visual qualia.

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Concept Cross_stratification
 Sub-type of: Traction and fallout Structure
Angularity: high angle
LaminaShape: planar
Thickness: medium
End_concept Cross_stratification
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Fig. 4. Propositional definition of sedimentary structure

The knowledge acquisition carried on with the expert geologist let us to organize the sedimentary structures based on visual criteria, differently of the most common organization found in literature, which is based on environment interpretation criteria. Since the intention of the ontology is to help non-experts in the task of description, a pure descriptive organization was required to make the search of a particular sedimentary structure easy for the users.

Other important concept in our ontology is the sedimentary facies concept. Sedimentary facies group together a set of diagnostic visual aspects of sedimentary rocks strongly connected with the depositional conditions in which this rock was created. The interpretation of a facies requires the identification of the attributes Sphericity, Roundness, Geometry and Sorting, the lithotype and, if found, the fossil content. Figure 5 depicts the modeling of the sedimentary facies concept.

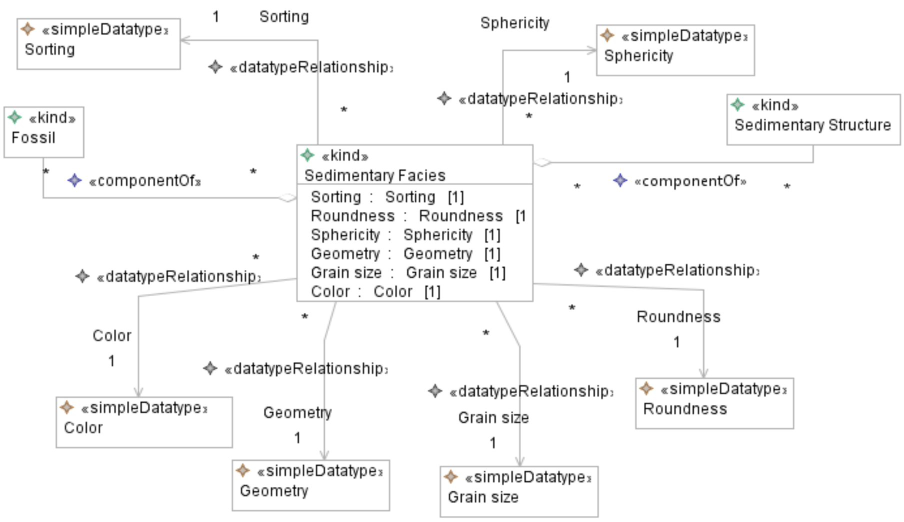

Fig. 5. Sedimentary Facies' main attributes and its relation with the Sedimentary Structure and Fossil concepts

5 Preliminary Validation of the Ontology in the Geology Community

In order to validate the method for defining icons, we carried out an empirical experiment that measured the expressiveness of the iconic representations proposed by the geologist expert. The number of participants, 21, was not statistically significant, but it was enough for a preliminary evaluation. The selected sample to be interviewed has different levels of expertise in Geology: 16 undergraduate students, 3 master students and one Ph.D. geologist. The sample was also grouped according to the amount of hours per month (in the last 12 months) that was dedicated to professional or academic activities related to the Sedimentary Stratigraphy, such as, description of cores and outcrops or interpretation.

The experiment consisted in showing to the participants a list of geological terms, assumed to be known by them, and the list of iconic representations defined in this work, which were unknown to them. Each geological term refers to only one iconic representation. The objective of the experiment was to verify if the iconic representations are expressive enough, to the point that a geologist were able to associate it with the right geological term, even without any previous training effort.

We applied a total of 64 geological terms, divided in two parts. The first part contained the terms related to attributes of sedimentary facies (34 terms) while the second part contained the terms related to sedimentary structures (30 terms). The geological terms (offered both in English and Brazilian Portuguese) were disposed in one column, while the iconic representations were disposed in a second column. The pictorial content was presented without any subtitles that could help the participants in identifying the corresponding geological term. Icons that represented values from a single quality domain were grouped. The objective of the participant is to associate the unknown icons with the geological known terms. The participants were allowed to let the answer blank in the case they didn't know the meaning of a geological term, reducing the chance in the choice of an icon.

The media of correct associations between geological terms and icons were 70.84% for sedimentary facies icons and 66.45% for sedimentary structure icons. Considering that it was the first contact with the proposed representation, the results confirm that the icons were quite intuitive and expressive as a representation of the geological features. The difference between the indexes can be explained by the different nature of facies and structures in terms of knowledge. Sedimentary facies are a formal knowledge, whose vocabulary is learnt through expository classes and immersion in the literature, while sedimentary structures are strongly visual knowledge that are learnt along the experience in the domain. Since the sample has more students than experienced geologists, the association between sedimentary structures and icons (that are, in the end, visual representations of the objects) was less effective.

The analyses of the results considered the level of formation of the participants that were grouped in three sets: undergraduate, Master and Ph.D. geologists. The undergraduate participants obtained 67.86% and 72%, Master participants obtained 70.59% and 86.36% and the PHD participant obtained 76.47% and 83.33% of correct associations for sedimentary facies and sedimentary structures terms, respectively. These results indicate that participants with a better formation could make a higher number of correct associations.

The relation between the amount of time applied in daily basis dealing with tasks of sedimentary Stratigraphy and the level of correct associations was also significant. The participants were grouped in three sets: the first one contains participants who spent less than 11 hours per month; the second one contains participant who spent 11 or more hours and less than 40 hours per month; the third one contains participants who spent 40 or more hours per month in professional and/or academic activities related to the domain in the last 12 months. Participants belonging to the first group obtained 70% and 61.11% of right associations for terms related to sedimentary facies and sedimentary structures, respectively. The second group of participants obtained indexes of 67.86% and 80%, while the third 85.29% and 83.33% of right associations between icons and the geological terms. The results corroborated what was expecting:

the more they work in recognizing facies, the better they identify the correct icon for the geological feature.

The evaluation (all indexes over 60%) showed that the proposed iconic representations have a high level of expressiveness of their meanings. It was detected also a convergence on the errors, showing that some of the chosen representations were not adequate to represent the geological feature. Those icons were further replaced in the ontology.

The results of our experiment corroborate those described in [10] that demonstrated that individuals with higher levels of expertise (formation and experience in the domain) capture and store their acquired knowledge through visual concepts and establish more associations within their mental models. The results observed in our experiment also show that participants with higher levels of expertise (formation and experience in the domain) could establish more associations among the proposed iconic representations and their mental models, thus giving an elevated number of correct associations among the icons and the geological terms.

6 Conclusion

Ontology, by its nature, is a propositional conceptual model, since it is basically constructed for communication and people are mainly verbal when exchange messages. The better a community understand the domain, the more effective will be the ontology in translating the conceptualization of the domain. In the frontiers of Science, however, a domain ontology may miss in providing adequate vocabulary that allows people to exchange their knowledge. This is especially true in imagistic domains, where the problem solver will drive his/her reasoning mainly supported by the visually collected knowledge over the domain.

We understand that the visual content of a conceptualization is an inherent part of it, and it is naturally used by people. The first step, showed in this work, was given in order to formally capture and represent the visual content into a domain ontology using special constructs. A second step is to develop a visual theory, exploring the characteristics of the human visual perceptual system and the visual properties of the representations. That theory will be focused in creating visual representations according to the ontological analysis of the nature from concept represented, providing and adequate language to capture the visual content.

The validation of the set of icons was carried on through a group of 21 geologists requested to associate each icon with its corresponding geological term without the support of the icons' labels. The results of the experiment showed that the proposed icons were able to express the concepts in the conceptualization and the participants were able to comprehend them in most of the associations.

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