Semantic Web – Interoperability, Usability, Applicability 0 (0) 1
IOS Press

The Role of Space and Time For Knowledge Organization on the Semantic Web

Editor(s): Pascal Hitzler, Wright State University, USA
Solicited review(s): Christoph Schlieder, University of Bamberg, Germany
Open review(s): Pascal Hitzler, Wright State University, USA

Krzysztof Janowicz
jano@psu.edu
GeoVISTA Center, Department of Geography,
The Pennsylvania State University, USA

Abstract. Space and time have not received much attention on the Semantic Web so far. While their importance has been recognized recently, existing work reduces them to simple latitude-longitude pairs and time stamps. In contrast, we argue that space and time are fundamental ordering relations for knowledge organization, representation, and reasoning. While most research on Semantic Web reasoning has focused on thematic aspects, this paper argues for a unified view combining a spatial, temporal, and thematic component. Besides their impact on the representation of and reasoning about individuals and classes, we outline the role of space and time for ontology modularization, evolution, and the handling of vague and contradictory knowledge. Instead of proposing yet another specific methodology, the presented work illustrates the relevance of space and time using various examples from the geo-sciences.

Keywords: Semantic Heterogeneity, Ontologies, Context, Space and Time, Sensors and Observations, Geospatial Semantics.

1. The Beauty of Semantic Heterogeneity

Overcoming semantic heterogeneity is a core topic of many contributions to such diverse research fields as semantic interoperability, semantics-based information retrieval, service composition, the Sensor Web, and ontology engineering. But do we really want to *overcome* or *resolve* semantic heterogeneity and what would this mean for the Semantic Web?

In contrast to syntactic heterogeneities caused by differences in data types, signatures, and protocols, semantic heterogeneity refers to differences in the intended interpretation, i.e., meaning, of information. While homonyms or polysemes are classical linguistic examples, semantic heterogeneities in information science tend to be more subtle. Web service interfaces to weather stations offer an impressive example. Two services can return a string called *wind direction* as output and even specify that the results are numerical values ranging from 0 - 360° but still have a contradicting interpretation of *wind direction*. For instance, one service refers to *wind blows to* while the other adapts a *wind blows from* semantics. Combining the results to compute the dispersion of a toxic gas plume would lead to meaningless and potentially dangerous results [1]. It seems obvious that such incompatibilities need to be resolved by overcoming semantic heterogeneity. While this is true in many cases and at the core of classical data integration, it may not be the most appropriate solution for a Web following the AAA slogan[1].

Consider the following simple, yet entertaining example of potholes in the UK [3]. Due to a severe winter millions of potholes need to be repaired by the local councils that are legally responsible for the maintenance of roads within their administrative boundaries. While potholes are defined as cracks of more than 30mm depth in North East Somerset, they must be of the width of a ’large dinner plate’ (300mm) and the depth of a ’golf ball’ (40mm) in Gloucestershire. Worcestershire, in contrast, defines potholes by the width of a smaller ’dinner plate’ (200mm) with a minimum depth of a ’fist’ (40mm). In Coventry, a pothole can be reported by citizens if its depth is ’a pound coin and a 1p coin side by side’. These, and many other,

---

[1] **A**nyone can say **A**nything about **A**ny topic [2].

councils have different conceptualizations of the term *pothole* for good reasons - probably because of the budget they would need to invest in fixing them. Consequently, it is unlikely that they want to resolve semantic heterogeneity in the first place.

Assuming one knows all local definitions of pothole and all potential cracks in roads, answering the question how many potholes are there in Britain becomes a complex, yet feasible task. In contrast, the question of how many lakes are there in Minnesota, USA cannot be answered this way. While the Department of Natural Resources lists 11,842 lakes over 10 acres, *lake* is a vague concept by nature. Its intended interpretation is not restricted to a degree which would allow to decide whether a water body is a single lake or two lakes connected by a watercourse, or how to distinguish them from ponds [4]. In fact, many size-based definitions take 5 acres as criterion [5]. One could argue that the size of a lake is all it needs for its definitions, but a flooded grassland is not a lake while a temporarily dry basin may still count as lake.

What appears to be an academic exercise only is, in fact, a common problem in cross-border Spatial Data Infrastructures (SDI). To query and exchange data between administrative units or states requires to take local conceptualizations into account. Similarly, in most cases the reuse of sensor data fails due to different measuring practices and requirements and, hence, data is collected again and again. One approach to ensure that, e.g., a forest does not stop at a state's border and continues as (wood) pasture on the other side just because of varying definitions of *forest*[2] is top-down standardization. The Infrastructure for Spatial Information in the European Community INSPIRE is such a large scale standardization endeavor aiming at cross-scale, cross-language, and cross-border interoperability and access to geo-data.

However, creating top-down definitions of geographic feature types bears the danger of excluding local definitions [7]. To take yet another example from geography, the European Water Framework Directive defines *river* as '[a] body of inland water flowing for the most part on the surface of the land but which may flow underground for part of its course'. Simplifying, European member states have to encode their data according to such global schemata. Nevertheless, rivers in Southern Europe may lack any flowing water for long parts of the year. Therefore, the local definitions may contradict with the global schemata.

While the previous examples involved space as a criterion for their variety, the following example also involves time as driving force. One key concept in ecology is *succession*. It describes the ordered, sometimes cyclic sequence of changes resulting in transitions between ecological communities within the same geographic location. An often cited, cyclic example are beaver dams. By changing the water flow of streams they create ponds in forested areas. These ponds repress the trees, hence, change the composition of the habitat and, therefore, may not offer the right food sources for beavers anymore. Such ponds will then be abandoned by the beavers and dry out again. The resulting meadows form yet another habitat with optimal conditions for plants requiring more direct light. However, they will turn back into forested areas on the long term and serve as beaver habitats again. From an ontological point of view, this raises several questions about how to define identity criteria for such places and how to model them. We can define the state before the stream is dammed and after the pond is replaced by a meadow; the question from which point in time a stream *segment* becomes a pond and how much water is required to distinguish the pond from a meadow is more difficult. Finally, if the cyclic succession at the same location creates ponds again and again, are these ponds the same entity[3]?

Summing up, one reason for the success of Semantic Web technologies in life sciences such as medicine is based on canonical definitions. While we can define a human hand as having five distinguishable fingers in a specific order[4], the above examples illustrate that there is no context free definitions of lakes, forests, and many other geographic feature types. Context however, as will be discussed in the following, is largely determined by space and time. With respect to the question of overcoming semantic heterogeneity, the introduced examples illustrate the need for a change in perspective. Namely, shifting from resolving heterogeneity to accounting for it and acknowledging the importance of local conceptualizations by focusing on negotiation and semantic translation. In previous work, we have discussed how semantic similar-

---

[2] and there are, for various reasons, several hundred local definitions of forest [6].

[3] This argument should also be kept in mind when arguing for *Web of Things* related approaches to grounding, e.g., by assigning URIs to real world entities.

[4] and we consider deviations such as caused by Polydaktylie, i.e., having supernumerary fingers, as deformities.

ity can be used to estimate how accurately an ontology captures the user's initial conceptualization [8]. Such work could also be used for the negotiation of semantics on the Web.

2. Contexts and Concepts

Categorization is an essential prerequisite for interacting with and reasoning about our environment. Nevertheless, there is no a priori conceptualization of the world and the creation of entities and types is an act of cognition and social convention [9,10]. The decision of how to carve out fields of sensory input depends on context, i.e., factors such as cultural background, previous knowledge, language, personal goals, the current situation, and especially also on space and time. What is a *deep lake* for recreation may be a *shallow pond* for navigation purposes; see also [11]. In fact, conceptualization is the act of introducing distinctions for certain needs – making these decisions explicit in a formal way, i.e., constraining their interpretation, is what ontology engineering should be about. Concepts and relations between them are not fixed but emerge from the context [12].

The importance of contextual information has been widely recognized in information retrieval; which role does it play for the Semantic Web? Today, the Web is essentially still about documents and fixed links between them. These documents encapsulate information by providing structure and context for the inherent data and, hence, support their interpretation. The forthcoming Data Web, however, is about linking data, not documents. Data sets are not bound to a particular document but can be freely combined outside of their original creation context. In theory, users can query the Linked Data cloud to answer complex queries spanning multiple sources and establish new links between data on-the-fly. However, retrieving meaningful results is more difficult than one may expect. While uncoupling data from documents eases their accessibility it puts the burden on their interpretation.

Data is always created for a particular purpose, even if it may be as broad as the creation of a free and collaborative encyclopedia such as the Wikipedia. Consider the following gedankenexperiment as illustration: do all appearances of a particular term in the Wikipedia conform with its definition in the according Wikipedia main article? For instance, the article about *time* is based on modern physics, while the term is used in a colloquial way throughout hundreds of thousands of Wikipedia articles. If a future DBpedia version would capture more data from Wikipedia then it does so far, would it assign the same ontological concept *time* to all of them? To a certain degree DBpedia already faces such problems. For instance, searching for actors may be done using rdf:type 'Actor' or by the relation 'occupation' with the filler 'actor' – both SPARQL queries produce overlapping but different result sets.

Revisiting the examples in the previous section also illustrates that similar difficulties arise for the creation of meaningful URIs for Linked Data. Entities are often constructed based on social convention and differ between information communities or even individuals. *Downtown* or other vague regions may act as examples [13]. If we do not want to end up in assigning URIs to single pixels of raster data or the whole swath width of sensors, we need to make some choices about how to extract entities, e.g., points of interest, from datasets. These choices are arbitrary to a certain degree and should therefore be encoded in the URI. As recently discussed by Halpin and Hayes, using *owl:sameAs* for identity links is not sufficient and may be even misleading [14].

How do humans establish communication if the meaning of terms is influenced or even determined by local contexts? Leaving the physical layer, e.g., the cortex and the role of mirror neurons aside, substantial work from cognitive science argues for a situated nature of categorization [15]; see also [16]. Instead of rigid and pre-defined conceptualizations with clear boundaries, many concepts arise by simulating situations. A classical example are so-called ad-hoc categories such as *things-to-extinguish-a-fire* which include such diverse entities as bed sheets and water. The function of artifacts, for instance, may be best understood in terms of the HIPE theory, i.e., by their History, Intentional perspective, the Physical environment, and Event sequences [17].

Humans can interact not because they share the same conceptualizations but because they can make sense of each other's statements by putting them into context. Meaningful communication, i.e., semantic interoperability in terms of the Web, can be established as long as the consequences, e.g., actions, of our counterpart are consistent and meet our expectations [18,19]. For instance, while *hill* and *mountain* may have clearly defined distinctions of social importance[5],

---

[5] Cineastes are referred to the movie *The Englishman Who Went Up a Hill But Came Down a Mountain* for an example.

they are irrelevant for many everyday situations such as agreeing to climb its peak. The reason why we are not confused when our counterpart uses the term *mountain* for what we would call a *hill* is that the potential interpretations of the terms are sufficiently restricted by the sentence or the context, e.g., the surrounding landscape. Where and when we use a term restricts its interpretation towards the intended model. Consequently when describing the nature of the Web, the AAA slogan may be more appropriately described as AAAAA slogan – **A**nyone can say **A**nything about **A**ny topic at **A**ny time and **A**nywhere.

Acknowledging the role of context for conceptualization and the importance of the resulting heterogeneities sheds new light on the vision of establishing ontologies for the Web. Learning from the success of user generated content on the social Web, a promising approach would be to support users in becoming active knowledge engineers instead of trying to develop de-contextualized ontologies top-down. A set of building blocks and tools could support information communities in specifying their local conceptualizations. Semantic annotations should connect local ontologies with Linked Data on-the-fly.

How to define such building blocks without falling into the symbol grounding trap, i.e., how to avoid an endless regress? While this topic is too complex to be discussed here, embodiment seems to be a crucial part of potential solutions [20]. Humans do not share the same conceptualization of the world but commonalities can be established by fundamental properties of our bodies and sensor systems. Experiences of surfaces, containment, paths, center-periphery, blockage, and many more are shared as they are directly observable based on our bodily interaction with the environment [21,22]. It is interesting to note how many of these so called *image schema* have spatial roots. A prominent linguistic examples illustrating the same argumentation are spatial and temporal metaphors [23]. Gibson's notion of Affordances [24], i.e., action possibilities arising from the combination of the actor's physical properties and those of the environment is another approach, and has been recently used to demonstrate how to ground geographic categories in observations [25] as well as for robot control. Strictly speaking, one may object that the argumentation provided above requires an inter-subjective *stimulus meaning* and a similar sensory reception. However, as argued by Quine, we can stay with private stimulus meanings as the inter-subjectivity is provided by the use of language [19].

The ontological question of *what is there* bears the danger of introducing entities and fixed types in an early stage instead of focusing on *observation categoricals* [19]; see also [26] for the construction of bodies from observations. Ontologies should act as bridges between the continuous fields of sensor-based observations, numerical models, and the rather entity-centric use of language. Highlighting the importance of observations does not exclude social aspect of semantics. With respect to the pothole example, all local definitions share an observable component - a depression in the road - while the required size is a matter of social convention and negotiation.

Space and time are two of the most fundamental ordering relations used in human cognition, language, and even on the physical level in the formation of patterns inside the human cortex. While we may not agree on the definition of *chair* by referring to shape, size, the number of legs, or the existence of a backrest - we can reach agreement in stating that their surfaces offer support and hence *sitability*. To demonstrate the impact of space on categorization[6], another approach to understand whether a visually perceived object is a chair is via its *position* relative to a table, bin, or other objects. Context and categorization influence each other mutually. While entering an unfamiliar building we constantly make predictions on what we expect to encounter [27]. Once we have identified a room as office by recognizing tables though stacks of paper *placed on* them, a partially visible gray box positioned *under* a table (that could not be categorized before) is likely to be a computer. In other words, unfamiliar objects can be categorized based on their *place* and at the same time give feedback about whether our assumptions about the current context were appropriate. If we cannot identify chairs in the room, the office hypothesis may need to be revised. This could also affect the interpretation of other objects categorized before. Personal information managers (PIMs) use this fact to split to-do lists based on contexts such things to do *at* the office, home, or during travel.

Summing up, to ensure the meaningful usage of (linked) data requires to restrict their potential interpretations. Ontologies are one method to make the underlying distinctions explicit but depend on context themselves. The attempt to develop stable and global ontologies contradicts with the nature of the Web. While this section illustrates the role of context

---

[6] Marked *italic* in the following sentences.

and situated concepts, various approaches have been proposed in the knowledge representation and reasoning literature within the last decades – recent examples include C-OWL [28] or Bennett's notion of standpoint semantics [29]. Embodiment, sensors, and observations are crucial elements for establishing common building blocks to align or translate between user-contributed ontologies. To combine two buzzwords: a promising approach for the future may be to ground the Semantic Web in the Sensor Web.

3. Giving Order by Space and Time

While the previous section focused on knowledge representation, this section describes how to structure and organize concepts and ontologies. Since the impact of context is not random, reasoning about and building bridges between local ontologies requires a meta-theory explaining which kind of contextual information matters, which refines, and how context causes diversification. In contrast to Semantic Web research, understanding the user's context and trying to infer implicit information out of it is a central task in information retrieval and related areas.

The challenge of handling local conceptualizations at a global level is a prominent topic in artificial intelligence research since decades. One core idea is to be consistent at the local level but allow contradicting conceptualizations within the global knowledge base. One approach is to organize knowledge in domain specific *microtheories* (also called contexts) and has been used in OpenCyC. Each microtheory is developed as a coherent set of statements and can be thought of as a single ontology; see also work on ontology modularization [30]. Separate microtheories may hold information about the same concept but contain incompatible facts. Using the time example introduced above, one microtheory may be more precise and rigid with respect to physical properties and laws of nature, while another microtheory may be based on weaker constraints to support *naïve physics* [31]

Microtheories are organized in subsumption hierarchies, i.e., facts specified in the super-microtheory must also hold in each of its sub-theories. In contrast, sibling-theories can store contradicting facts. More formally, the hierarchy of microtheories is established through the generalization relationship *genlMt* [32]. Given $ist(mt, p)$ is the *is true in* relation between a microtheory mt and a predicate p, then $genlMt$ is the anti-symmetric, reflexive, and transitive binary predicate by which the theory hierarchy is constructed by adding axioms of the form

$$mt_0 : \forall p \; ist(mt_g, p) \wedge genlMt(mt_g, mt_s) \longrightarrow ist(mt_s, p)$$

to the topmost theory mt_0; where mt_g is the more general and mt_s the more specific theory; see also [33] for details.

Surprisingly, alternative ordering principles based on space, time, or cultural background have not been discussed so far. While the previous sections illustrate the impact of climatic, geological, ecological, administrative, and further factors on the categorization of geographic feature into types, this impact does not occur randomly but follows gradually changing patterns[7]. In other terms, using Tobler's famous First Law of Geography: 'Everything is related to everything else, but near things are more related than distant things' [34]. For instance, the definition of *river* changes gradually from northern to southern European countries. Similarly, temporal examples can be found in the domain of cultural heritage research which has to deal with incomplete, biased, and contradicting information. For instance, beliefs about the solar system from the Middle Ages may be organized in a different branch of a knowledge base than microtheories describing beliefs from the age of industrialization. To structure microtheories by spatial (or administrative) containment $genlMt$ can be enriched.

$$\begin{aligned} mt_0 : \; & \forall p \; ist(mt_g, p) \wedge genlMtC(mt_g, mt_s) \\ & \longrightarrow genlMt(mt_g, mt_s) \wedge \circledcirc(mt_g, mt_s) \end{aligned}$$

Hence, $genlMtC(mt_g, mt_s)$ holds if mt_s is a subtheory of mt_g and all footprints of individuals of geographic feature types specified in mt_s are (spatially or administratively) contained in mt_g; see [7] for more details. This containment predicate ($\circledcirc$) requires a spatial footprint for the individuals as well as for the spatial scope of the theory; a formal semantics including the Region Connection Calculus (RCC) is left for further work.

The usefulness of this approach can be demonstrated by the INSPIRE example. Adding $genlMtC$ to the meta-theory structuring local ontologies ensures that geographic feature types defined by states that are administratively contained by the European Union must be sub-types of the EU wide definition. Based on this requirement, instead of developing common schemata for all European member states top-

---

[7] Which does not exclude crisp borders between them as in case of some administrative factors.

down, local conceptualizations and non-standard inference such as computing the Least Common Subsumer (LCS) [35] and similarity reasoning [36] can be employed to automatically infer an appropriate top-level which does not violate local definitions. Consequently, if Spanish rivers do not necessarily contain flowing water but rivers in Germany do, the computed top-level for the EU should not define rivers based on the feature of flowing water; see [7] for details.

Summing up, besides subsumption hierarchies ontologies can be organized using space and time. Understanding and modeling the relation and interaction between ontologies will support the development of and reasoning about user-centric ontologies for the Web.

4. Towards an Ecology of Concepts

The previous sections argue that conceptualization is influenced by spatial and temporal factors, and that these factors can be used on a higher abstraction level to establish structure between different conceptualizations. Consequently, if concepts are not static, how to study their evolution [37] and diversification in space and time? Since shifts in conceptualization are difficult to detect and quantify, one may search for an analogy to a well known process. An interesting approach would be to study how species evolve and what factors drive their diversification. One promising candidate may be the process of *adaptive radiation*. In short, it described the evolutionary diversification of a single ancestor into several species each adapted to a particular ecological niche; Darwin's finches are a classical example. Simplifying, the process is caused by some (sudden) change in the environment, e.g., the volcanic creation of an isolated island. To construct a meaningful analogy requires to establish partial mappings between the evolution of concepts and biological evolution. While concepts and emerging new sub-concepts can be mapped to the radiation of species, the changing environmental, e.g., spatial, aspects can be mapped to a semantic space [38], distance to semantic distance, i.e., similarity, and so forth. The sudden diversification of *pothole* definitions caused by climatic and economic conditions may serve as a first example. An alternative approach based on time-geography was recently presented by Raubal [38] arguing for a time-indexed representation of concepts in GIScience. Schlieder discusses the related notion of *semantic ageing* for the long-term preservation of digital data [39].

For an impressive example on how theories from ecology and evolutionary biology can explain human strategies in gathering information, see Pirolli's Information Foraging Theory [40].

5. Conclusions

In this work we discussed the role of space and time for knowledge engineering and organization from three distinct perspectives: (1) their role for the definition of individual concepts, (2) their role for the organization of these concepts, and (3) their role for understanding their mutual interaction. We illustrated the need for semantic heterogeneity and the situated nature of conceptualization using various examples from the geo-sciences, outlined how space and time can act as structuring principles between local ontologies, and sketched an approach to model how concepts evolve in space and time. To create and maintain such local ontologies, we have to raise the user from a content creator to an active knowledge engineer. Citizens as sensors [41] and the Sensor Web may serve as a foundation for Semantic Web ontologies based on observation categoricals.

6. Acknowledgments

The comments from the reviewers and discussions with Werner Kuhn, Martin Raubal, and Simon Scheider provided useful suggestions to improve the content and clarity of this paper.

References

[1] F. Probst and M. Lutz. Giving Meaning to GI Web Service Descriptions. In *International Workshop on Web Services: Modeling, Architecture and Infrastructure (WSMAI 2004)*, 2004.

[2] D. Allemang and J. Hendler. *Semantic Web for the Working Ontologist: Effective Modeling in RDFS and OWL.* Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, 2008.

[3] R. Lefort. Telegraph.co.uk: Pothole britain: councils disagree about when hole becomes a pothole. http://www.telegraph.co.uk/motoring/news/7436237/Pothole-Britain-councils-disagree-about-when-hole-becomes-a-pothole.html, Published: 13.03.2010.

[4] D. R. Montello and P. C. Sutton. *An introduction to scientific research methods in geography.* Sage Publications, 2006.

[5] P. Williams, M. Whitfield, J. Biggs, S. Bray, G. Fox, P. Nicolet, and D.A. Sear. Comparative biodiversity of rivers, streams, ditches and ponds in an agricultural landscape in southern england. *Biological Conservation*, 115(2):329–341, 2004.

[6] G. Lund. Definitions of forest, deforestation, afforestation, and reforestation. Technical report, Forest Information Services, 03/22/2010.

[7] S. Duce and K. Janowicz. Microtheories for spatial data infrastructures - accounting for diversity of local conceptualizations at a global level. In *6th International Conference on Geographic Information Science (GIScience 2010)*, 2010; forthcoming.

[8] K. Janowicz, P. Maué, M. Wilkes, S. Schade, F. Scherer, M. Braun, S. Dupke, and W. Kuhn. Similarity as a quality indicator in ontology engineering. In C. Eschenbach and M. Grüninger, editors, *5th International Conference on Formal Ontology in Information Systems*, volume 183, pages 92–105. IOS Pres, October 2008.

[9] David M. Mark. Toward a theoretical framework for geographic entity types. In *Spatial Information Theory: A Theoretical Basis for GIS, International Conference COSIT '93*, pages 270–283, 1993.

[10] S. Lehar. *The World in Your Head: A Gestalt View of the Mechanism of Conscious Experience*. Lawrence Erlbaum, 2003.

[11] M. Raubal and A. Adams. The semantic web needs more cognition. *Semantic Web – Interoperability, Usability, Applicability*, 2010; in this issue.

[12] L. Gabora, E. Rosch, and D. Aerts. Toward an ecological theory of concepts. *Ecological Psychology*, 20(1):84–116, 2008.

[13] Daniel R. Montello, Michael F. Goodchild, Jonathon Gottsegen, and Peter Fohl. Where's downtown?: Behavioral methods for determining referents of vague spatial queries. *Spatial Cognition & Computation*, 3(2):185–204, 2003.

[14] H. Halpin and P. Hayes. When owl:sameas isn't the same: An analysis of identity links on the semantic web. In *Linked Data on the Web (LDOW2010)*, 2010.

[15] L. Barsalou. Situated simulation in the human conceptual system. *Language and Cognitive Processes*, 5(6):513–562, 2003.

[16] B. Brodaric and M. Gahegan. Experiments to Examine the Situated Nature of Geoscientific Concepts. *Spatial Cognition and Computation*, 7(1):61–95.

[17] L. Barsalou, S.A. Sloman, and S.E. Chaigneau. *Representing functional features for language and space: Insights from perception, categorization and development*, chapter The HIPE theory of function, pages 131–147. Oxford Univ. Press, 2005.

[18] H. P. Grice. Logic and conversation. In Peter Cole and Jerry L. Morgan, editors, *Syntax and semantics*, volume 3. New York: Academic Press, 1975.

[19] W. V. O. Quine. *Pursuit of Truth; revised edition*. Cambridge, MA: Harvard University Press., 1992.

[20] L. Steels and T. Belpaeme. Coordinating perceptually grounded categories through language: A case study for colour. *Behavioral and Brain Sciences*, 28:469–529, 2005.

[21] M. Johnson. *The Body in the Mind: The Bodily Basis of Meaning, Imagination, and Reason*. Univ. of Chicago Press, 1987.

[22] W. Kuhn. An image-schematic account of spatial categories. In S. Winter, M. Duckham, L. Kulik, and B. Kuipers, editors, *Spatial Information Theory, 8th International Conference (COSIT 2007)*, volume 4736 of *LNCS*, pages 152–168. Springer, 2007.

[23] G. Lakoff and M. Johnson. *Metaphors We Live By*. University Of Chicago Press, 1980.

[24] J. Gibson. The theory of affordances. In R. Shaw and J. Bransford, editors, *Perceiving, Acting, and Knowing - Toward an Ecological Psychology*, pages 67–82. Lawrence Erlbaum Ass., Hillsdale, New Jersey, 1977.

[25] S. Scheider, K. Janowicz, and W. Kuhn. Grounding geographic categories in the meaningful environment. In K. Hornsby, C. Claramunt, M. Denis, and G. Ligozat, editors, *Conference on Spatial Information Theory (COSIT 2009)*, volume 5756 of *LNCS*, pages 69–87. Springer, 2009.

[26] S. Scheider, F. Probst, and K. Janowicz. Constructing bodies and their qualities from observations. In *Proceeding of the 2010 Conference on Formal Ontology in Information Systems (FOIS 2010)*, pages 131–144. IOS Press, 2010.

[27] J. Hawkins and S. Blakeslee. *On Intelligence*. Times Books, 2004.

[28] Paolo Bouquet, Fausto Giunchiglia, Frank van Harmelen, Luciano Serafini, and Heiner Stuckenschmidt. C-owl: Contextualizing ontologies. In D. Fensel, K. Sycara, and J. Mylopoulos, editors, *The Semantic Web - ISWC 2003, Second International Semantic Web Conference*, pages 164–179, 2003.

[29] B. Bennett, D. Mallenby, and A. Third. An ontology for grounding vague geographic terms. In *Formal Ontology in Information Systems - Proceedings of the Fifth International Conference (FOIS 2008)*, volume 183, pages 280–293. IOS Press, 2008.

[30] B. C. Grau, I. Horrocks, Y. Kazakov, and U. Sattler. Modular reuse of ontologies: theory and practice. *Journal of Artificial Intelligence Research*, 31(1):273–318, 2008.

[31] P. J. Hayes. The naive physics manifesto. In D. Michie, editor, *Expert Systems in the Micro Electronic Age*, pages 242–270. Edinburgh University Press, 1979.

[32] J. McCarthy and S. Buvac. Formalizing context (expanded notes), 1996.

[33] R. Guha, R. Mccool, and R. Fikes. Contexts for the semantic web. In *International Semantic Web Conference (ISWC 2004)*, number 3298 in Lecture Notes in Computer Science, pages 32–46. Springer, 2004.

[34] W. Tobler. A computer model simulating urban growth in the detroit region. *Economic Geography*, 46(2):234–240, 1970.

[35] W. Cohen, A. Borgida, and H. Hirsh. Computing least common subsumers in description logics. In *10th National Conference on Artificial Intelligence*, pages 754–760. MIT Press, 1992.

[36] K. Janowicz and M. Wilkes. $SIM - DL_A$: A Novel Semantic Similarity Measure for Description Logics Reducing Inter-concept to Inter-instance Similarity. In L. Aroyo, P. Traverso, F. Ciravegna, P. Cimiano, T. Heath, E. Hyvoenen, R. Mizoguchi, E. Oren, M. Sabou, and E. Simperl, editors, *6th Annual European Semantic Web Conference (ESWC2009)*, volume 5554 of *LNCS*, pages 353–367. Springer, 2009.

[37] N. Noy and M. Klein. Ontology evolution: Not the same as schema evolution. *Knowledge and Information Systems*, 6(4):428–440, 2004.

[38] M. Raubal. Representing concepts in time. In C. Freksa, N.Newcombe, P. Gärdenfors, and S. Wölfl, editors, *International Conference on Spatial Cognition*, volume 5248 of *LNCS*, pages 328–343. Springer, 2008.

[39] C. Schlieder. Digital heritage: Semantic challenges of long-term preservation. *Semantic Web – Interoperability, Usability, Applicability*, 2010; in this issue.

[40] P. Pirolli. *Information Foraging Theory: Adaptive Interaction with Information*. Oxford University Press, Inc., New York, NY, USA, 2007.

[41] M. Goodchild. Citizens as Sensors: the World of Volunteered Geography. *GeoJournal*, 69(4):211–221, 2007.