An Annotated Bibliography on Temporal and Evolution Aspects in the Semantic Web

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The TIMECENTER icon on the cover combines two "arrows." These "arrows" are letters in the so-called *Rune* alphabet used one millennium ago by the Vikings, as well as by their precedessors and successors. The Rune alphabet (second phase) has 16 letters, all of which have angular shapes and lack horizontal lines because the primary storage medium was wood. Runes may also be found on jewelry, tools, and weapons and were perceived by many as having magic, hidden powers.

The two Rune arrows in the icon denote "T" and "C," respectively.

An Annotated Bibliography on Temporal and Evolution Aspects in the Semantic Web

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1 Introduction

Time is a pervasive dimension of reality as everything evolves as time elapses. Therefore, Web-based information systems and knowledge representation tools at least mirror, and often have to capture, the time-varying and evolutionary nature of the phenomena they model and of the activities they support. This aspect has been acknowledged and long studied in the field of temporal databases [JeSn09] but it truly applies also to the World Wide Web and Semantic Web in particular.

Several papers addressing, in an explicit or implicit way, the representation and management of time and evolution in the Semantic Web appeared recently and, on some aspects, showed a clear upward trend in last years, witnessing a sustained and/or growing research interest. Reflecting and acknowledging such interest, we started in 2011 to collect references concerning the handling of time and evolution issues in Semantic Web research. As it was for [Gra03], the purpose of this collection was to compile a bibliography which could be of help, in particular, to students and young researchers. As a result of such endless work, we wrote the present bibliography, whose latest version will be available on the Web at URL:

http://www-db.deis.unibo.it/~fgrandi/TWbib/TSWbib.html

This follows several fortunate bibliographies on time-varying information management, including seven ones on temporal databases [BAD+83, McK86, StSn88, Soo91, Kli93, TsKu96, WJS88], two ones on spatio-temporal databases [ASM93, ASM94], two ones on spatio-temporal data mining [RoSp99, RHS00], one on schema evolution [Rod92], one on (temporal) indeterminacy [Dyr96], and one on temporal and evolution aspects in the World Wide Web [Gra03] also advertised on Sigmod Record [Gra04]. Notice that the bibliography we gathered in 2003, already contained the embryo of the present work, with 16 papers dealing with temporal and evolution aspects in the Semantic Web [Gra03, Sec. 2.8].

The collected references, which amount to nearly 650 as of August 2012, are partitioned into two main sections, where they are further organized according to some similarity criterion introduced by brief notes. The former main section (Sec. 2) contains papers explicitly dealing with time or temporal aspects represented in Semantic Web resources or involved in their modelling and management. The latter main section (Sec. 3) contains papers dealing with dynamic aspects of the Semantic Web without explicit reference to any temporal dimension. We apologize in advance (with the readers and especially with the authors) for any

errors, **misclassifications** and **omissions** may result from the collected entries. Additions, corrections and comments are obviously welcome. Papers that could have been classified as belonging to more than one section of this bibliography, have actually been assigned to the most representative one, although sometimes such a choice could seem in part arbitrary.

2 Time and Temporal Aspects

This first group of collected references is devoted to time and temporal aspects in the Semantic Web. In this collection of 219 papers, we can make a first partition between 116 works properly dealing with modelling and management of temporal Semantic Web resources (in Sec. 2.1 and Sec. 2.2), and 103 works focusing on the study of the semantic and ontological aspects of time itself (in Sec. 2.3 and Sec. 2.4). Within each of the two partitions, we separated papers dealing with time alone (in Sec. 2.1 and Sec. 2.3, respectively) from papers dealing with either time and space (in Sec. 2.2 and Sec. 2.4, respectively).

2.1 Temporal Extensions of Semantic Web

With an approach similar to that employed in temporal database [JeSn09] and temporal XML [DyGr09] research, time dimension(s) are explicitly added to Semantic Web languages and formalisms (e.g., RDF, OWL and SPARQL) in order to represent time in semantic annotations, to build temporal ontologies and to support temporal querying and reasoning. The considered time dimension is usually *valid time* [JDB+98], which represents the time when some fact is true in the real world, although other time dimensions have also been considered in some approaches. A number of 79 references has been gathered in this group, where space dimensions have not been considered.

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2.2 Spatio-temporal Extensions of Semantic Web

Among the papers belonging to the temporal extensions group, we can evidence a specific subset of 37 works dealing with time in addition to space dimensions in the Semantic Web. The addition of the space dimension(s) is aimed at supporting spatio-temporal or geospatial knowledge representation and reasoning.

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2.3 Towards an Ontology of Time

In this subsection, we can found papers concerning the definition of an ontology of time and temporal phenomena. Whereas this problem can sometimes be seen as an application of Semantic Web techniques to the universe of time, it also has a deeper theoretical side which crosses over the boundaries of Semantic Web studies to meet with linguistics and ontological research as philosophical discipline. In this respect, we also included some "classic" studies not belonging to the Semantic Web literature.

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2.4 Towards an Ontology of Time and Space

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3 Evolution and Versioning Aspects

In the second main group of collected references we put the studies devoted to dynamic aspects in the realm of Semantic Web without an explicit interest in time and temporal aspects involved in the evolution. In this collection of 428 papers, we can make a main partition between papers dealing with evolution aspects (from Sec. 3.1 to Sec. 3.4) and papers dealing with versioning issues (in Sec. 3.5). In this respect, we follow the conceptual distinction between *evolution* and *versioning* formalized in the temporal database field [JDB$^+$98] for the maintenance of a database schema [Rod09a, Rod09b]. Hence, considering for instance the management of an ontology in the Semantic Web, to support evolution means to permit modifications of the ontology and adaptation of the related resources without requiring maintenance of the previous versions (i.e., the changes are effected by overwriting modified elements and deletions are destructive). On the other hand, supporting versioning means to permit modifications while retaining the previous versions. The maintenance of the whole modification history of the ontology through all its subsequent versions is aimed at continuing the support of legacy applications developed to work with one of the past versions, which is an important requirement in some application fields (e.g., in the legal domain).

The partition of papers dealing with evolution aspects is the most crowded section of the whole bibliography, with a total number of 371 papers. Most of them actually consider *evolution of ontologies*, even if evolution support for other kinds of Semantic Web resources (e.g., services) has sometimes been considered. In order to highlight the papers dealing with more specific aspects in the context of evolution, we made separate groups of papers specifically dealing with formalization and execution of changes (in Sec. 3.2), design and implementation of editors (in Sec. 3.3) and detection and reasoning about changes (in Sec. 3.4).

3.1 Evolution Issues

In this subsection, all the papers generically dealing with evolution of ontologies and Semantic Web resources find place. Although more specific references have been excerpted in subsections from 3.2 to 3.3, with its 212 entries this is still the more crowded collection, witnessing how the dynamic aspects and evolution problems are outstanding in this field and have received a lot of attention by Semantic Web researchers.

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3.2 Management of Changes

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3.3 Editors for Semantic Web

Conceptually belonging to the evolution group, we made a separate list in this subsection for the papers describing the design, implementation and usage functionalities of editors for the Semantic Web. Such list consists of the collection of 47 entries which which follows. In particular, nearly all describe *ontology editors*.

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3.4 Detection and Analysis of Changes

Another subset of papers dealing with management of changes in the context of Semantic Web evolution is even more focused on change detection and analysis. In particular, several works are devoted to detection, mining, reasoning and evaluation of ontology changes or of differences between ontology versions. The resulting selection of 51 bibliographic entries follows.

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3.5 Versioning Issues

This subsection is devoted to the 57 papers most specifically dealing with versioning and management of multiple versions of resources (e.g., of ontologies and RDF graphs, in particular) in the Semantic Web. In such a framework, multi-version settings also include the management of multi-contextual, multidimensional and multi-perspective semantic resources, without an explicit reference to time as a versioning dimension.

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