Introductions to Description Logics – A Guided Tour

Anni-Yasmin Turhan

Theoretical Computer Science,
TU Dresden, Germany
turhan@tcs.inf.tu-dresden.de

Abstract. Description Logics (DLs) are the logical formalism underlying the standard web ontology language OWL 2. DLs have formal semantics which are the basis for many powerful reasoning services. This paper provides an overview of basic topics in the field of Description Logics by surveying the introductory literature and course material with a focus on DL reasoning services. The resulting compilation also gives a historical perspective on DLs as a research area.

1 Introduction

Description Logics (DLs) are a family of knowledge representation formalisms that have formal semantics. This family of logics is designed towards representing terminological knowledge of an application domain in a structured and formally well-understood way. DLs allow users to define important notions, such as classes or relations of their application domain in terms of concepts and roles. *Concepts* correspond to unary predicates and *roles* correspond to binary predicates in First Order Logic (FOL). They restrict the interpretations of the classes and relations, respectively.

Starting from a set of concept names and role names, complex concept descriptions can be built by means of *concept constructors*. For instance, expressive DLs offer the Boolean connectors as concept constructors. Concept descriptions are the main building blocks for capturing information in the *knowledge base* (or *ontology*). Typically, a DL knowledge base consists of two parts:

- the *TBox*, which contains the terminological knowledge, i.e., the knowledge on the categories and relations relevant in the application domain and
- the *ABox*, which contains the assertional knowledge, i.e., the knowledge on individual facts.

Knowledge that is captured only implicitly in the ontology can be *inferred* from the given descriptions of concepts and roles and also from the information on the individuals in the ABox, as for instance, sub-class or instance relationships.

DLs have been investigated and used since the late eighties. Of main interest are the reasoning problems defined for DLs and the corresponding reasoning algorithms. Many courses and tutorials have been given on the subject since. Here, instead of providing yet another standard introduction on this branch of logics, we rather survey existing course material. Mostly, these courses were designed and held by people, who are active in research on the subjects covered in those courses. The set of papers, tutorials

S. Rudolph et al. (Eds.): Reasoning Web 2013, LNCS 8067, pp. 150–161, 2013.

and courses covered here is certainly only a part of the existing material. We focus on material that is available on-line at the time of writing.

This paper is structured as follows. In the next section we give an overview of introductory literature and tutorials on Description Logics in general. In Section 3 we give short historic overview, followed by a commented list of course material on basic reasoning and newer reasoning services in DLs in Section 4. The last section provides references to material on application areas of DLs.

2 Introductory Material to DLs in General

Introductory readings. The standard reference for DLs is certainly the DL handbook [5]. For the DL novice with a bit of a background in logics, the two introductory chapters [22] and [10] are a good starting point to get a detailed and slow paced introduction to the basic notions of DLs. For a short reference of basic DL terms see [1].

The chapters on DLs in the *Handbook of Modal Logic* [9] and in the *Handbook on Ontologies* [8] provide also detailed and self-contained introductions. While the first emphasizes more the theoretical aspects of DLs, the latter rather highlights practical aspects of using DLs. A more recent and comprehensive introduction is given in [2]. For readers who are more interested in what current DL systems can do and how to employ them (and not so much in the theoretical foundations) [50] is a good reference. The most up-to-date 'all purpose' beginner's introduction is the *DL primer* [64].

Introductory courses. Probably the most detailed on-line course on DLs are the slides from Enrico Franconi's course [40] from 2002. This course lays the foundations by giving an introduction to Computational Logics in general in Module 1 and provides an introduction to simple, i.e., rather inexpressive DLs (with only a few concept constructors) in the Modules 2, 3 and 4. Other classic courses on introductions to DLs that are rather suitable for the reader with a little knowledge on logics, are [67,90].

2.1 Relation to Other Logics

DL are logics and as such closely related to other formal logics. In particular, most DLs are a fragment of First Order Logic. Concepts are simply FOL formulas with one free variable. Some DLs are simply syntactic variants of Hybrid Logics or Modal Logics, see [87]. The correspondences between DLs and other logics are explained in detail in the DL handbook chapter dedicated to this topic [86] and in the already mentioned online course by Franconi [40](Module 5). Most introductory tutorials provide translation functions from DL knowledge bases into FOL, such as [2].

3 A Short Historical Overview

In this section we give an overview over the main developments of the DL research. The papers cited here are mainly the original research papers (and rather of interest for readers with DL background). Typically, the following historical phases of DL research are distinguished:

Early knowledge representation systems. Historically, DLs originate from knowledge representation systems such as *semantic networks* [82,93] or *frame systems* [72]. Despite the fact that these systems lacked formal semantics, they offered methods to compute inheritance relations between the specified notions.

Early DL systems. In the late eighties, reasoning algorithms for DL systems were mostly sound, but incomplete, i.e., they would compute correct answers, but not necessarily all correct answers. At this time the belief was held that terminological reasoning is inherently intractable [76,77], and thus completeness was traded for tractability. These reasoning algorithms have been implemented in systems such as Back [76,78] and Classic [19,18,21].

DLs in the nineties. During the nineties, sound and complete reasoning methods were investigated for the core inferences of DL systems: consistency and subsumption. *Consistency* assures that the specification of the concepts, roles and individuals are free of contradictions. For *subsumption* one computes super- and sub-concept relations from the given specifications of concepts (and roles).

The underlying technique for computing the basic DL inferences is the tableau method [39,89]. The core idea of the tableau method is to construct a model, which then gives evidence that a particular knowledge base has a model. The tableau method was extended to more and more expressive DLs ([12,31]). The gain in expressiveness came at the cost of higher complexity for the reasoning procedures—reasoning for the DLs investigated is PSpace-complete or even ExpTime-complete [31]).

Despite the high complexity, highly optimized DL reasoning systems—most prominently the FaCT system [48]—were implemented based on the tableau method [74]. In fact, it turned out that these highly optimized implementations of the reasoning methods do perform surprisingly well on DL knowledge bases from practical applications.

DLs in the new millennium. The quest for more expressive DLs with decidable reasoning procedures for standard reasoning continued–allowing for more information that can be stated on roles, such as inverse of roles, for instance, see [55,56,52,57]. Around that time first initiatives emerged for standardizing DLs (such as DAML+OIL, see [33]) and the reasoner interfaces (such as the on from the DL implementers group [16,98]). Based on these initiatives, the development of a variety of ontology tools started. Early ontology editors such as OilEd [15], OntoTrack [65] Protégé [41,61] or Swoop [59] were developed and user communities of DL systems started to grow.

In the last decade there were two main trends in DL research. First, the investigation of so-called ‘light-weight’ DLs, i.e., DL that are of fairly low expressivity, but have good computational complexity for reasoning. There are two ‘families’ of lightweight DLs: the $\mathcal{EL}$ family [23,3,4], for which the subsumption and the instance problem are polynomial, and the DL Lite family [27,29], for which the instance problem and the answering of (unions of) conjunctive queries are polynomial[1]. A member of each of

[1] If measured in the size of the data alone the complexity is even LogSpace.

these two families is the DL corresponding to one of the profiles of the OWL 2 standard [99]. The second trend is, that various new, so-called non-standard inferences are investigated for DLs. For instance,

- the generation of *explanations* of unexpected consequences that the DL reasoner detected [88,81,11,58,46],
- *answering of conjunctive queries* as a means to access the instance data of an ontology, [75,28,29,43,79,38,66],
- support for building ontologies by computing *generalizations* [24,13,37,101], and
- computing *modularizations* of ontologies to facilitate their reuse [42,69,35,71,62].

4 DL Reasoning

4.1 Standard DL Reasoning

The standard reasoning problems for DLs, such as satisfiability or subsumption are discussed in the introductions to DLs mentioned in Section 2. A rather detailed discussion of the model theoretic properties of basic DLs (such as the moderately expressive DL $\mathcal{ALC}$) were recently given in [68,90].

Solutions to DL reasoning problems are computed by different reasoning procedures. As mentioned earlier, for expressive DLs tableaux-based procedures are common, see [31,12,67]. Reasoning in the $\mathcal{EL}$-family underlying the OWL 2 EL profile is realized by *completion-based* or *consequence-driven* approaches, which are covered in the courses [96,63].

Another approach to obtain decision procedures for DL reasoning problems is the *automata-based* approach. Automata-based approaches are often more convenient for showing ExpTime complexity upper-bounds than tableau-based approaches. This approach is described in detail in [6,67,2].

The computational complexity of deciding standard reasoning problems is discussed in [36] and more recently in [67,2,90].

The reader interested in the implementations of DL systems is referred to [74] for an early—by now almost historic—overview. Fairly recent accounts on this ever changing subject can be found in [73,51].

4.2 On Non-standard Reasoning Tasks

Building DL ontologies. The subject of ontology engineering is addressed, for example, in [60]. However, reasoning based approaches that either employ standard reasoning [73] or inferences that compute generalizations of either collections of (complex) concept descriptions or of an individual are described in [9,95].

Explanation and Repair. When a reasoner computes a consequence of information represented in the ontology, the result might be un-intuitive to the user. Thus computing explanations of (or even plans how to repair) such unexpected consequences are helpful. Both tasks have been discussed in the tutorial [47]. The first task is described for the $\mathcal{EL}$-family in [14] and the course [96]. Implementations for this task are described in [47,51].

Modularity. Re-using a part of an ontology requires to identify that part of the ontology that does not 'interact' with the rest of the ontology when computing a given reasoning task. Furthermore, it should be ensured that the importing ontology does not entail unwanted consequences w.r.t. the given reasoning task when importing the new ontology module. These tasks are topics of the course material provided in [47] (with an emphasis on tool support) and in [68,91] with an emphasis on the theoretical background.

Answering Conjunctive Queries. As mentioned earlier, answering conjunctive queries allows for a much more expressive query language than concept-based querying, i.e., instance queries. This reasoning task is currently a very active research area of DLs. The DL Lite family of DLs is designed such that conjunctive query answering can be performed efficiently. Query answering in DL Lite is covered in [26]. Methods for query answering for both families of light-weight DLs is described in the course slides [32]. In addition to query answering for the light-weight DLs, [80] explains also the methods for expressive DLs.

5 Application Areas of DLs

This section gives pointers introductory reading and course material on prominent application areas for DLs.

Data integration. Since DLs can represent information on different levels of detail they are a good candidate for data integration. The core of the data integration approach via DLs is their ability to capture other modeling languages frequently used to specify database schemas—such as entity relationship diagrams (ER), see [40], module 2 or UML, see [25].

Biomedical ontologies. An account on the early use of DLs in the medical field is given in [83]. In [100] an application in protein classifications described.

As a matter of FaCT, the medical ontology Galen [84] was the prime motivation for the development of highly optimized reasoners [49]. Since then large biomedical ontologies [94,34,85,92] have been valuable benchmarks for DL reasoners. More recent overviews on medical ontologies written in DLs is given in [70,50].

Semantic Web. The semantic web was early spotted as a potential application area of DLs, since they allow to write ontologies in order to annotate web resources, see [7,45]. More importantly, the reasoning services defined and investigated for DLs support the querying of these ontologies. From the plethora of course material on DLs and the semantic web, we recommend to the reader [7,45] for early views on the subject and [54,53] for more recent and technical ones.

The potential application of the semantic web facilitated the standardization of DLs. An introduction to the original OWL standard can be found in [54] and OWL 2 and its profiles is covered in [63,44,97].

Ontology-based data access. Ontology-based data access (ODBA) exploits DLs to enrich the data in a database by information from the DL ontology. The initial ideas were described in [17]. The key idea is to employ query answering for this task. In the last years the topic received more attention due to low complexity for DL Lite for this task. An early course on this subject is [30], which includes descriptions of first tools. Recent courses on the topic [26,32] focus more on the algorithms behind ODBA. The most up-to-date resource for a course on ODBA is the one in this Reasoning Web summer School.

References

1. Baader, F.: Description logic terminology. In: [5], pp. 485–495. Cambridge University Press (2003)
2. Baader, F.: Description logics. In: Tessaris, S., Franconi, E., Eiter, T., Gutierrez, C., Handschuh, S., Rousset, M.-C., Schmidt, R.A. (eds.) Reasoning Web. LNCS, vol. 5689, pp. 1–39. Springer, Heidelberg (2009)
3. Baader, F., Brandt, S., Lutz, C.: Pushing the $\mathcal{EL}$ envelope. In: Proc. of the 19th Int. Joint Conf. on Artificial Intelligence (IJCAI 2005). Morgan-Kaufmann Publishers, Edinburgh (2005)
4. Baader, F., Brandt, S., Lutz, C.: Pushing the $\mathcal{EL}$ envelope further. In: Clark, K., Patel-Schneider, P.F. (eds.) Proc. of the OWLED Workshop (2008)
5. Baader, F., Calvanese, D., McGuinness, D., Nardi, D., Patel-Schneider, P.F. (eds.): The Description Logic Handbook: Theory, Implementation, and Applications. Cambridge University Press (2003)
6. Baader, F., Hladik, J., Lutz, C., Wolter, F.: From tableaux to automata for description logics. In: Vardi, M.Y., Voronkov, A. (eds.) LPAR 2003. LNCS, vol. 2850, pp. 1–32. Springer, Heidelberg (2003), Slides of the talk are available from `http://lat.inf.tu-dresden.de/~baader/Talks/LPAR03.pdf`
7. Baader, F., Horrocks, I., Sattler, U.: Description logics for the semantic web. KI 16(4), 57–59 (2002)
8. Baader, F., Horrocks, I., Sattler, U.: Description logics. In: Staab, S., Studer, R. (eds.) Handbook on Ontologies. International Handbooks on Information Systems, pp. 3–28. Springer (2004), `http://www.cs.ox.ac.uk/people/ian.horrocks/Publications/download/2004/BaHS04a.pdf`
9. Baader, F., Lutz, C.: Description logic. In: Blackburn, P., van Benthem, J., Wolter, F. (eds.) The Handbook of Modal Logic, pp. 757–820. Elsevier (2006)
10. Baader, F., Nutt, W.: Basic description logics. In: [5], ch. 2, pp. 43–96. Cambridge University Press (2003)
11. Baader, F., Peñaloza, R., Suntisrivaraporn, B.: Pinpointing in the description logic $\mathcal{EL}$. In: Calvanese, D., Franconi, E., Haarslev, V., Lembo, D., Motik, B., Tessaris, S., Turhan, A.-Y. (eds.) Proc. of the 2007 Description Logic Workshop (DL 2007), CEUR-WS (2007)
12. Baader, F., Sattler, U.: An overview of tableau algorithms for description logics. Studia Logica 69, 5–40 (2001)
13. Baader, F., Sertkaya, B., Turhan, A.-Y.: Computing the least common subsumer w.r.t. a background terminology. Journal of Applied Logics (2007)
14. Baader, F., Suntisrivaraporn, B.: Debugging SNOMED CT using axiom pinpointing in the description logic $\mathcal{EL}^+$. In: Proceedings of the International Conference on Representing and Sharing Knowledge Using SNOMED (KR-MED 2008), Phoenix, Arizona (2008)

15. Bechhofer, S., Horrocks, I., Goble, C.A., Stevens, R.: OilEd: a Reason-able Ontology Editor for the Semantic Web. In: Baader, F., Brewka, G., Eiter, T. (eds.) KI 2001. LNCS (LNAI), vol. 2174, pp. 396–408. Springer, Heidelberg (2001), OilEd download page http://oiled.man.ac.uk
16. Bechhofer, S., Möller, R., Crowther, P.: The DIG Description Logic Interface. In: Proc. of the 2003 Description Logic Workshop (DL 2003), Rome, Italy (2003)
17. Borgida, A., Lenzerini, M., Rosati, R.: Description logics for databases. In: [5], pp. 462–484. Cambridge University Press (2003)
18. Borgida, A., Patel-Schneider, P.F.: A semantics and complete algorithm for subsumption in the CLASSIC description logic. Journal of Artificial Intelligence Research 1, 277–308 (1994)
19. Brachman, R.J., Borgida, A., McGuinness, D.L., Alperin Resnick, L.: The CLASSIC knowledge representation system, or, KL-ONE: the next generation. Preprints of the Workshop on Formal Aspects of Semantic Networks, Two Harbors, Cal. (1989)
20. Brachman, R.J., Levesque, H.J.: Readings in Knowledge Representation. Morgan Kaufmann, Los Altos (1985)
21. Brachman, R.J., McGuinness, D.L., Patel-Schneider, P.F., Resnick, L.A., Borgida, A.: Living with classic: When and how to use a kl-one-like language. In: Principles of Semantic Networks, pp. 401–456. Morgan Kaufmann (1991)
22. Brachman, R.J., Nardi, D.: An introduction to description logics. In: [5], ch. 1, pp. 1–40. Cambridge University Press (2003)
23. Brandt, S.: Polynomial time reasoning in a description logic with existential restrictions, GCI axioms, and—what else? In: de Mantáras, R.L., Saitta, L. (eds.) Proc. of the 16th European Conf. on Artificial Intelligence (ECAI 2004), pp. 298–302. IOS Press (2004)
24. Brandt, S., Küsters, R., Turhan, A.-Y.: Approximation and difference in description logics. In: Fensel, D., McGuinness, D., Williams, M.-A. (eds.) Proc. of the 8th Int. Conf. on the Principles of Knowledge Representation and Reasoning (KR 2002). Morgan Kaufmann Publishers, San Francisco (2002)
25. Calvanese, D., De Giacomo, G.: Description logics for conceptual data modeling in uml. Course held at ESSLLI 2003 (2003), http://www.inf.unibz.it/~calvanese/teaching/2003-08-ESSLLI-UML
26. Calvanese, D., De Giacomo, G., Lembo, D., Lenzerini, M., Poggi, A., Rodriguez-Muro, M., Rosati, R.: Ontologies and databases: The *DL-lite* approach. In: Tessaris, S., Franconi, E., Eiter, T., Gutierrez, C., Handschuh, S., Rousset, M.-C., Schmidt, R.A. (eds.) Reasoning Web. LNCS, vol. 5689, pp. 255–356. Springer, Heidelberg (2009), Course slides available from http://www.inf.unibz.it/ calvanese/teaching/2009-09-ReasoningWeb-school-ontologies-dbs/ReasoningWeb-2009-ontologies-dbs.pdf
27. Calvanese, D., De Giacomo, G., Lembo, D., Lenzerini, M., Rosati, R.: DL-Lite: Tractable description logics for ontologies. In: Veloso, M.M., Kambhampati, S. (eds.) Proc. of the 20th Nat. Conf. on Artificial Intelligence (AAAI 2005), pp. 602–607. AAAI Press/The MIT Press (2005)
28. Calvanese, D., De Giacomo, G., Lembo, D., Lenzerini, M., Rosati, R.: Data complexity of query answering in description logics. In: Proc. of the 10th Int. Conf. on the Principles of Knowledge Representation and Reasoning (KR 2006), pp. 260–270 (2006)
29. Calvanese, D., De Giacomo, G., Lembo, D., Lenzerini, M., Rosati, R.: Tractable reasoning and efficient query answering in description logics: The DL-Lite family. Journal of Automated Reasoning 39(3), 385–429 (2007)

30. Calvanese, D., De Giacomo, G., Rodriguez-Muro, M.: Integrating data into ontologies. Part of the ISWC 2008 tutorial 'Reasoning for Ontology Engineering and Usage' (2008), http://www.inf.unibz.it/ calvanese/teaching/2008-10-ISWC-tutorial-tones/TonesTutorial08-4.pdf
31. Calvanese, D., Giacomo, G.D.: Expressive description logics. In: [5], ch. 5, pp. 178–218. Cambridge University Press (2003)
32. Calvanese, D., Zakharyaschev, M.: Answering queries in description logics: Theory and applications to data management. Course held at ESSLLI 2010 (2010), http://www.inf.unibz.it/ calvanese/teaching/2010-08-ESSLLI-DL-QA/
33. Connolly, D., van Harmelen, F., Horrocks, I., McGuinness, D.L., Patel-Schneider, P.F., Stein, L.A.: DAML+OIL reference description. W3C Note (March 2001), http://www.w3.org/TR/daml+oil-reference
34. Consortium, T.G.O.: Gene Ontology: Tool for the unification of biology. Nature Genetics 25, 25–29 (2000)
35. Cuenca Grau, B., Horrocks, I., Kazakov, Y., Sattler, U.: Modular reuse of ontologies: Theory and practice. Journal of Artificial Intelligence Research 31, 273–318 (2008)
36. Donini, F.M.: Complexity of reasoning. In: [5], ch. 3, pp. 96–136. Cambridge University Press (2003)
37. Donini, F.M., Colucci, S., Di Noia, T., Di Sciascio, E.: A tableaux-based method for computing least common subsumers for expressive description logics. In: Proc. of the Twenty-First International Joint Conference on Artificial Intelligence (IJCAI 2009), pp. 739–745. AAAI (July 2009)
38. Eiter, T., Lutz, C., Ortiz, M., Simkus, M.: Query answering in description logics with transitive roles. In: Proceedings of the 21st International Joint Conference on Artificial Intelligence (IJCAI 2009). AAAI Press (2009)
39. Fitting, M.: Basic modal logic. In: Handbook of Logic in Artificial Intelligence and Logic Programming, vol. 1, pp. 365–448. Oxford Science Publications (1993)
40. Franconi, E.: Description logics – tutorial course information (2002), http://www.inf.unibz.it/~franconi/dl/course
41. Gennari, J., Musen, M., Fergerson, R., Grosso, W., Crubézy, M., Eriksson, H., Noy, N., Tu, S.: The evolution of PROTÉGÉ-2000: An environment for knowledge-based system development. International Journal of Human-Computer Studies 58, 89–123 (2003)
42. Ghilardi, S., Lutz, C., Wolter, F.: Did I damage my ontology? a case for conservative extensions in description logics. In: Doherty, P., Mylopoulos, J., Welty, C. (eds.) Proc. of the 10th Int. Conf. on the Principles of Knowledge Representation and Reasoning (KR 2006), pp. 187–197. AAAI Press (2006)
43. Glimm, B., Horrocks, I., Lutz, C., Sattler, U.: Conjunctive query answering for the description logic $\mathcal{SHIQ}$. In: Veloso, M.M. (ed.) Proc. of the 20th Int. Joint Conf. on Artificial Intelligence (IJCAI 2007), Hyderabad, India, pp. 399–404 (2007)
44. Hitzler, P., Krötzsch, M., Parsia, B., Patel-Schneider, P.F., Rudolph, S.: OWL 2 Web Ontology Language: Primer (October 27, 2009), http://www.w3.org/TR/owl2-primer/
45. Horrcks, I., Sattler, U.: Logical foundations for the semantic web. Slides of the ESSLI 2003 tutorial (2003), http://www.cs.man.ac.uk/~horrocks/ESSLLI2003
46. Horridge, M., Parsia, B., Sattler, U.: Laconic and precise justifications in OWL. In: Sheth, A.P., Staab, S., Dean, M., Paolucci, M., Maynard, D., Finin, T., Thirunarayan, K. (eds.) ISWC 2008. LNCS, vol. 5318, pp. 323–338. Springer, Heidelberg (2008)

47. Horridge, M., Sattler, U.: Understanding and repairing inferences (includes modularisation). Part of the ISWC 2008 tutorial 'Reasoning for Ontology Engineering and Usage' (2008), http://www.inf.unibz.it/ calvanese/teaching/2008-10-ISWC-tutorial-tones/TonesTutorial08-3.pdf
48. Horrocks, I.: Using an expressive description logic: FaCT or fiction? In: Cohn, A., Schubert, L., Shapiro, S. (eds.) Proc. of the 6th Int. Conf. on the Principles of Knowledge Representation and Reasoning (KR 1998), pp. 636–647 (1998)
49. Horrocks, I.: Ontology engineering: Tools and methodologies. Slides from the tutorial at the Norwegian Semantic Days (April 2007), http://www.cs.ox.ac.uk/people/ian.horrocks/Seminars/download/SemanticDays07-tutorial.ppt
50. Horrocks, I.: Description logic: a formal foundation for languages and tools. Slides from the tutorial at the Semantic Technology Conference (SemTech) (2010), http://www.cs.ox.ac.uk/people/ian.horrocks/Publications/download/2010/HoPa10a.pdf
51. Horrocks, I.: Tool support for ontology engineering. In: Fensel, D. (ed.) Foundations for the Web of Information and Services, pp. 103–112. Springer (2011)
52. Horrocks, I., Kutz, O., Sattler, U.: The even more irresistible $\mathcal{SROIQ}$. In: Doherty, P., Mylopoulos, J., Welty, C. (eds.) Proc. of the 10th Int. Conf. on the Principles of Knowledge Representation and Reasoning (KR 2006), pp. 57–67. AAAI Press (2006)
53. Horrocks, I., Patel-Schneider, P.F.: KR and reasoning on the semantic web: OWL. In: Domingue, J., Fensel, D., Hendler, J.A. (eds.) Handbook of Semantic Web Technologies, ch. 9, pp. 365–398. Springer (2011), http://www.cs.ox.ac.uk/people/ian.horrocks/Publications/download/2010/HoPa10a.pdf
54. Horrocks, I., Patel-Schneider, P.F., McGuinness, D.L., Welty, C.A.: OWL: a Description Logic Based Ontology Language for the Semantic Web. In: Baader, F., Calvanese, D., McGuinness, D., Nardi, D., Patel-Schneider, P.F. (eds.) The Description Logic Handbook: Theory, Implementation, and Applications, ch. 14, 2nd edn., Cambridge University Press (2007), http://www.cs.ox.ac.uk/people/ian.horrocks/Publications/download/2003/HPMW07.pdf
55. Horrocks, I., Sattler, U.: Optimised reasoning for $\mathcal{SHIQ}$. In: Proc. of the 15th European Conference on Artificial Intelligence (2002)
56. Horrocks, I., Sattler, U.: A tableaux decision procedure for $\mathcal{SHOIQ}$. In: Proc. of the 19th Int. Joint Conf. on Artificial Intelligence (IJCAI 2005). Morgan Kaufmann (January 2005)
57. Horrocks, I., Sattler, U.: A tableau decision procedure for $\mathcal{SHOIQ}$. J. of Automated Reasoning 39(3), 249–276 (2007)
58. Kalyanpur, A., Parsia, B., Horridge, M., Sirin, E.: Finding all justifications of OWL DL entailments. In: Aberer, K., Choi, K.-S., Noy, N., Allemang, D., Lee, K.-I., Nixon, L.J.B., Golbeck, J., Mika, P., Maynard, D., Mizoguchi, R., Schreiber, G., Cudré-Mauroux, P. (eds.) ISWC/ASWC 2007. LNCS, vol. 4825, pp. 267–280. Springer, Heidelberg (2007)
59. Kalyanpur, A., Parsia, B., Sirin, E., Cuenca Grau, B., Hendler, J.: Swoop: A web ontology editing browser. J. Web Sem. 4(2), 144–153 (2006)
60. Keet, M.: Introduction to ontology engineering, with emphasis on semantic web technologies. Meraka Institute, South Africa. Course in the Masters Ontology Winter School 2010 (2010), http://www.meteck.org/teaching/SA/MOWS10OntoEngCouse.html
61. Knublauch, H., Horridge, M., Musen, M.A., Rector, A.L., Stevens, R., Drummond, N., Lord, P.W., Noy, N.F., Seidenberg, J., Wang, H.: The protege owl experience. In: Grau, B.C., Horrocks, I., Parsia, B., Patel-Schneider, P.F. (eds.) Proceedings of the OWLED Workshop. CEUR Workshop Proceedings, vol. 188, CEUR-WS.org. (2005)

62. Konev, B., Ludwig, M., Walther, D., Wolter, F.: The logical difference for the lightweight description logic $\mathcal{EL}$. J. Artif. Intell. Res. (JAIR) 44, 633–708 (2012)
63. Krötzsch, M.: OWL 2 Profiles: An introduction to lightweight ontology languages. In: Eiter, T., Krennwallner, T. (eds.) Reasoning Web 2012. LNCS, vol. 7487, pp. 112–183. Springer, Heidelberg (2012), Course slides available from http://korrekt.org/talks/2012/OWL_2_Profiles_Reasoning-Web-2012.pdf
64. Krötzsch, M., Simančík, F., Horrocks, I.: A description logic primer. CoRR, abs/1201.4089 (2012), http://arxiv.org/abs/1201.4089
65. Liebig, T., Noppens, O.: ONTOTRACK: Combining browsing and editing with reasoning and explaining for OWL lite ontologies. In: McIlraith, S.A., Plexousakis, D., van Harmelen, F. (eds.) ISWC 2004. LNCS, vol. 3298, pp. 244–258. Springer, Heidelberg (2004), OntoTrack download page http://www.informatik.uni-ulm.de/ki/ontotrack/
66. Lutz, C.: The complexity of conjunctive query answering in expressive description logics. In: Armando, A., Baumgartner, P., Dowek, G. (eds.) IJCAR 2008. LNCS (LNAI), vol. 5195, pp. 179–193. Springer, Heidelberg (2008)
67. Lutz, C., Sattler, U.: Description logics (2005), Slides are available from http://www.computational-logic.org/content/events/iccl-ss-2005/lectures/lutz/index.php?id=24
68. Lutz, C., Sattler, U., Wolter, F.: Modularity in logical theories and ontologies. Slides of the ESSLI 2008 tutorial (2008), http://cgi.csc.liv.ac.uk/~frank/publ/esslli08.html
69. Lutz, C., Walther, D., Wolter, F.: Conservative extensions in expressive description logics. In: Proc. of the 20th Int. Joint Conf. on Artificial Intelligence (IJCAI 2007). AAAI Press (2007)
70. Lutz, C., Wolter, F.: Mathematical logic for life science ontologies. In: Ono, H., Kanazawa, M., de Queiroz, R. (eds.) WoLLIC 2009. LNCS, vol. 5514, pp. 37–47. Springer, Heidelberg (2009)
71. Lutz, C., Wolter, F.: Deciding inseparability and conservative extensions in the description logic $\mathcal{EL}$. Journal of Symbolic Computation 45(2), 194–228 (2010)
72. Minsky, M.: A framework for representing knowledge. Technical report, MIT-AI Laboratory, Cambridge, MA, USA (1974)
73. Möller, R.: Introduction to standard reasoning. Part of the ISWC 2008 tutorial 'Reasoning for Ontology Engineering and Usage' (2008), http://www.inf.unibz.it/ calvanese/teaching/2008-10-ISWC-tutorial-tones/TonesTutorial08-1.pdf
74. Möller, R., Haarslev, V.: Description logic systems. In: [5], pp. 282–305. Cambridge University Press (2003)
75. Motik, B., Sattler, U.: A Comparison of Reasoning Techniques for Querying Large Description Logic ABoxes. In: Hermann, M., Voronkov, A. (eds.) LPAR 2006. LNCS (LNAI), vol. 4246, pp. 227–241. Springer, Heidelberg (2006), KAON2 download page http://kaon2.semanticweb.org/
76. Nebel, B.: Computational complexity of terminological reasoning in BACK. Artificial Intelligence Journal 34(3), 371–383 (1988)
77. Nebel, B.: Terminological reasoning is inherently intractable. Artificial Intelligence Journal 43, 235–249 (1990)
78. Nebel, B., von Luck, K.: Hybrid reasoning in BACK. In: Proc. of the 3rd Int. Sym. on Methodologies for Intelligent Systems (ISMIS 1988), pp. 260–269. North-Holland Publ. Co., Amsterdam (1988)

79. Ortiz, M., Calvanese, D., Eiter, T.: Data complexity of query answering in expressive description logics via tableaux. Journal of Automated Reasoning 41(1), 61–98 (2008)
80. Ortiz, M., Šimkus, M.: Reasoning and query answering in description logics. In: Eiter, T., Krennwallner, T. (eds.) Reasoning Web 2012. LNCS, vol. 7487, pp. 1–53. Springer, Heidelberg (2012), Course slides available from http://www.kr.tuwien.ac.at/events/rw2012/teaching-material/RW12-Tutorial-Ortiz-Simkus-1p.pdf
81. Parsia, B., Sirin, E., Kalyanpur, A.: Debugging OWL Ontologies. In: Ellis, A., Hagino, T. (eds.) Proc. of the 14th Int. World Wide Web Conference (WWW 2005), Chiba, Japan, pp. 633–640 (May 2005)
82. Quillian, M.R.: Word concepts: A theory and simulation of some basic capabilities. Behavioral Science 12, 410–430 (1967), Republished in [20]
83. Rector, A.: Medical informatics. In: [5], pp. 406–426. Cambridge University Press (2003)
84. Rector, A.L., Rogers, J.: Ontological and practical issues in using a description logic to represent medical concept systems: Experience from GALEN. In: Barahona, P., Bry, F., Franconi, E., Henze, N., Sattler, U. (eds.) Reasoning Web 2006. LNCS, vol. 4126, pp. 197–231. Springer, Heidelberg (2006)
85. Rosse, C., Mejino, J.L.V.: A reference ontology for biomedical informatics: the foundational model of anatomy. Journal of Biomedical Informatics 36, 478–500 (2003)
86. Sattler, U., Calvanese, D., Molitor, R.: Relationships with other formalisms. In: [5], ch. 4, pp. 137–177. Cambridge University Press (2003)
87. Schild, K.: A correspondence theory for terminological logics: preliminary report. In: Mylopoulos, J., Reiter, R. (eds.) Proc. of the 12th Int. Joint Conf. on Artificial Intelligence (IJCAI 1991), Sydney, Australia (1991)
88. Schlobach, S., Cornet, R.: Non-standard reasoning services for the debugging of description logic terminologies. In: Gottlob, G., Walsh, T. (eds.) Proc. of the 18th Int. Joint Conf. on Artificial Intelligence (IJCAI 2003), Acapulco, Mexico, pp. 355–362. Morgan Kaufmann, Los Altos (2003)
89. Schmidt-Schauß, M., Smolka, G.: Attributive concept descriptions with unions and complements. Technical Report SR-88-21, Deutsches Forschungszentrum für Künstliche Intelligenz (DFKI), Kaiserslautern, Germany (1988)
90. Schneider, T., Sattler, U.: Description logics: an introductory course on a nice family of logics. Course held at ESSLLI 2012 (August 2012), http://www.informatik.uni-bremen.de/~ts/teaching/2012_dl
91. Schneider, T., Walther, D.: Modularity in ontologies. Course held at ESSLLI 2011 (August 2011), http://www.informatik.uni-bremen.de/˜ts/teaching/2011_modularity
92. Sioutos, N., de Coronado, S., Haber, M.W., Hartel, F.W., Shaiu, W.-L., Wright, L.W.: NCI thesaurus: A semantic model integrating cancer-related clinical and molecular information. J. of Biomedical Informatics 40(1), 30–43 (2007)
93. Sowa, J.F. (ed.): Principles of Semantic Networks. Morgan Kaufmann, Los Altos (1991)
94. Spackman, K.: Managing clinical terminology hierarchies using algorithmic calculation of subsumption: Experience with SNOMED-RT. Journal of the American Medical Informatics Assoc. (2000) (Fall Symposium Special Issue)
95. Turhan, A.-Y.: Bottom-up contruction of ontologies. Part of the ISWC 2008 tutorial 'Reasoning for Ontology Engineering and Usage' (2008), http://www.inf.unibz.it/ calvanese/teaching/2008-10-ISWC-tutorial-tones/TonesTutorial08-2.pdf
96. Turhan, A.-Y.: Reasoning and explanation in $\mathcal{EL}$ and in expressive description logics. In: Aßmann, U., Bartho, A., Wende, C. (eds.) Reasoning Web. LNCS, vol. 6325, pp. 1–27. Springer, Heidelberg (2010)

97. Turhan, A.-Y.: Description logic reasoning for semantic web ontologies. In: Akerkar, R. (ed.) Proc. of the International Conference on Web Intelligence, Mining and Semantics, WIMS 2011, p. 6. ACM (2011)
98. Turhan, A.-Y., Bechhofer, S., Kaplunova, A., Liebig, T., Luther, M., Möller, R., Noppens, O., Patel-Schneider, P., Suntisrivaraporn, B., Weithöner, T.: DIG 2.0 – Towards a flexible interface for description logic reasoners. In: Cuenca Grau, B., Hitzler, P., Shankey, C., Wallace, E. (eds.) Proceedings of the Second International Workshop OWL: Experiences and Directions (November 2006)
99. W3C OWL Working Group. OWL 2 web ontology language document overview. W3C Recommendation (October 27, 2009), `http://www.w3.org/TR/2009/REC-owl2-overview-20091027/`
100. Wolstencroft, K., Brass, A., Horrocks, I., Lord, P., Sattler, U., Turi, D., Stevens, R.: A little semantic web goes a long way in biology. In: Gil, Y., Motta, E., Benjamins, V.R., Musen, M.A. (eds.) ISWC 2005. LNCS, vol. 3729, pp. 786–800. Springer, Heidelberg (2005)
101. Zarrieß, B., Turhan, A.-Y.: Most specific generalizations w.r.t. general $\mathcal{EL}$-TBoxes. In: Proceedings of the 23rd International Joint Conference on Artificial Intelligence (IJCAI 2013). AAAI Press, Beijing (to appear, 2013)