TIL as Hyperintensional Logic for Natural Language Analysis

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Abstract. In the paper, we introduce the main ideas of a new scientific project devoted to new methods of computer-aided linguistic and logical analysis of natural language, in particular English and Czech.
The presented project started in 2015 and its main aims lead to the research of the Transparent Intensional Logic (TIL) as a framework for analysis of natural language communication and reasoning. The project follows up the previous successful cooperation between the teams involved and builds new findings on both developed linguistic and logical resources and tools as well as new methods of analysis regarding phenomena such as individual attitudes, dynamic discourse, or tenses and events.

Keywords: Transparent intensional logic; TIL; hyperintensional logic; semantic analysis of natural language

1 Introduction and Related Works

In the area of natural language analysis and knowledge representation much has been done, but even more still needs to be done. Historically, Frege was (to the best of our knowledge) the first to develop a formal semantics. In [1] Frege introduced the well-known semantic schema assigning to expressions their sense (Sinn) and denotation (Bedeutung). Wishing to save compositionality, Frege made the semantics of an expression depend on the linguistic context in which it is embedded. According to Frege an expression names its Bedeutung (extension) in ordinary contexts and Sinn (intension) in oblique contexts. Frege, in an attempt to save compositionality, had recourse to contextualism. The price he paid is too high, though. No expression can, according to Frege, denote an object, unless a particular kind of context is provided. Yet such a solution is far from being natural. There are cases of real ambiguity, witness homonymous expressions. But would anybody say that 'The author of Waverley' were

Aleš Horák, Pavel Rychlý, Adam Rambousek (Eds.): Proceedings of Recent Advances in Slavonic Natural Language Processing, RASLAN 2015, pp. 113–124, 2015.

another such a case of homonymy? Hardly. Furthermore, expressions can be embedded within other expressions to various degrees; consider the sentence

"Charles knows that Tom believes that the author of *Waverley* is a poet."

The expression 'The author of *Waverley*' should now denote the 'normal' sense of the 'normal sense' of itself. Adding still further layers of embedding sets off an infinite hierarchy of senses, which is to say that 'The author of *Waverley*' has the potential of being infinitely ambiguous. This seems plain wrong, and is first and foremost an awkward artefact of Fregean semantics (see [8, §1.5]).

The second half of the last century can be characterized as a syntactic turn in semantics. We were developing systems of particular logics which are characterized by a language with a precisely defined syntax and a model set-theoretic semantics. The main goal of building such a system is to find a subset of sentences of the language, axioms of the theory, in fact, which characterize a given area under scrutiny, and then apply proper rules of inference in order to mechanically derive consequences from the axioms. If the system has a model, then it is consistent, and all we are interested in is manipulating symbols. Hence *syntactic turn.*

The mainstream in this direction was *Possible World Semantics* (PWS). Possible-world intensions are extensionally individuated and the PWS semantics is a *logic of intensions*, in particular the *model-theoretic* (hence set-theoretic) *theory of modalities*. Yet its individuation of meaning is too crude (up to logical equivalence only), and thus it is not apt to solve the notoriously well-known problem of the analysis of belief and other attitude sentences. Carnap in [3] says that modal sentences like "It is necessary that P" are intensional with respect to the clause P. However, sentences about belief like "John believes that P" are *neither intensional nor extensional* with respect to P. He also criticises Frege's 'naming method' (nowadays we would say 'denotational semantics'), because then we multiply the names *ad infinitum*, and we end up with the antinomy of naming. For Carnap, extensions are not a matter of *logical semantics* because it is a matter of empirical facts and factual knowledge. Prior to the meaning of a term is an *intension* independent of contingent facts that uniquely determines the extension (if any), but not *vice versa*.

In order to solve the problem of belief sentences, Carnap tried to define a stronger relation between expressions than L-equivalence that might rightly calibrate the identity of meaning (i.e. *synonymy*). He defined inductively the relation of *intensional isomorphism* on the set of sentences. Roughly, two sentences S and P are intensionally isomorphic if they are L-equivalent and each designator (either simple or composed) that is a constituent of S is L-equivalent to the respective designator of P. Thus sentences S and P have the same intensional structure if they are composed in the same way from designators with the same intensions. In our opinion, all these tenets and philosophical desiderata of Carnap are plausible and it might seem that he succeeded in analyzing the subjects of beliefs, knowledge, convictions, etc. Moreover, his definition is independent of the language being applied and the syntactic structure in which the clause is encoded. So far, so good; yet Carnap's method was criticized by

Alonzo Church [4]. Church's argument is based on two principles. First, it is Carnap's principle of tolerance (which itself is, of course, desirable), and second, which is less desirable, this principle makes it possible to introduce into a language *syntactically simple* expressions as definitional abbreviations of *semantically complex* expressions. As a result, Carnap's method can yield expressions P and Q intensionally isomorphic though they obviously have different meanings.

Church proposes *synonymous isomorphism*: all the mutually corresponding designators must be not only L-equivalent but also synonymous, where the synonymy of syntactically simple designators must be *postulated* as a semantic base of a language. We can postulate any convention for introducing these synonymous abbreviations, but as soon as we postulate the meaning of a constant it becomes valid and cannot be changed by another convention. The definition of synonymy occupied Church for many years, which resulted in his Alternatives (0) up to (1). Yet, he was not fully content with any of these proposals.

Since the late 60s of the last century many logicians have strived for *hyperintensional semantics* and *structured meanings* (see, for instance [16]). The structured character of meaning was urged by David Lewis in [23], where non-structured intensions are generated by finite, ordered trees. This idea of 'tree-like' meanings obviously influenced George Bealer's idea of 'intensions of the second kind' in his [1]. The idea of structured meanings was propagated also by M.J. Cresswell who defines structured meanings as ordered n-tuples (see [5,6]). That this is far from being a satisfactory solution is shown in Tichý [30], Jespersen [20] and also Bealer [2]. In brief, tuples are set-theoretic entities that are not structured. Besides, tuples are of the wrong making to serve as truth-bearers and objects of attitudes, since a tuple cannot be true or be known, hoped, etc., to be true.

In [25] Moschovakis comes with the idea of *meaning as algorithm*. The meaning of a term A is "an (abstract, not necessarily implementable) algorithm which computes the denotation of A" ([26, 27]; see also [25]). Yet much earlier, in [27] and [28], Pavel Tichý formulated the idea of *procedural semantics*. Thus, for instance, a sentence encodes an *instruction* how in any possible world at any time to execute the abstract *procedure* expressed by the sentence as its meaning, i.e., to evaluate the truth-conditions of the sentence. He developed a logical framework known today as *Transparent Intensional Logic* (TIL). In modern jargon, TIL belongs to the paradigm of *structured meaning*. However, Tichý does not reduce structure to set-theoretic sequences, as do Kaplan and Cresswell. Nor does Tichý fail to explain how the sense of a molecular term is determined by the senses of its atoms and their syntactic arrangement, as Moschovakis objects to 'structural' approaches in [26, 27].

Tichý's TIL is an overarching logical framework apt for the analysis of all sorts of discourse, whether colloquial, scientific, mathematical or logical. The theory is a *procedural* (as opposed to denotational) one, according to which the meaning of an expression is an abstract, extra-linguistic procedure detailing

what operations to apply to what procedural constituents to arrive at the product (if any) of the procedure that is the object denoted by the expression. Such procedures are rigorously defined as TIL *constructions*. TIL proceeds top-down from structured meanings to the entities that these meanings are modes of presentation of. It is a theory that, on the one hand, develops syntax and semantics in tandem while, on the other hand, keeps pragmatics and semantics separate. It disowns *possibilia*; instead the theory operates with a constant domain of individuals for all worlds and times. What vary are the values that (non-constant) intensions have in different worlds and at different times, and not the domains that different worlds and times have. It rejects individual essentialism without quarter, yet subscribes wholeheartedly to intensional essentialism. It denies that the actual and present satisfiers of empirical conditions (possible-world intensions) are ever semantically and logically relevant, and instead replaces the widespread semantic actualism (that the actual of all the possible worlds plays a privileged semantic role) by a thoroughgoing anti-actualism. And most importantly, it unifies unrestricted referential transparency, unrestricted compositionality of sense, and hyperintensional individuation of senses in one theory.

In 2010, the book by Duží, Jespersen and Materna *Procedural Semantics for Hyperintensional Logic* [8] was published in Springer. The book provides an exposition of TIL and its applications as of 2010. Logical semantics is a field progressing by leaps and bounds, and much has happened since Tichý put out his first and only book in 1988 [29]. The 2010 book assembles in one place the most important extensions, improvements and applications stemming from the last several years that address issues not dealt with either at all or only cursorily by Tichý. The book devotes special attention to some topics that generally tend to be dealt with only in passing by contemporary formal semantics. They include, *inter alia*, procedural isomorphism, notional attitudes, knowing whether, concepts (understood rigorously and non-mentalistically), attitudes *de re* and anaphora in hyperintensional contexts. Besides, the extensive treatment of anaphora represents a major step forward for the development of TIL, which had so far barely dealt with this linguistic device. The addition opens up new fragments of natural language to analysis. Another vastly developed notion is *requisite*, which underpins our intensional essentialism (in terms of *a priori* relations-in-extension between intensions). The crown in the jewel is the extremely detailed and principled elaboration of the *de dicto*/*de re* dichotomy. The dichotomy is at the heart of TIL, because it pretty much does the work that is done by reference shift in most other theories.

From the formal point of view, TIL is a hyperintensional, partial, typed lambda calculus. The main feature of lambda calculi is their ability to distinguish between functions and functional values. An additional feature of TIL is its ability to distinguish between functions and *modes of presentation* of functions and their values. We explicate these modes of presentation as abstract *procedures* rigorously defined as TIL *constructions*. Constructions are arranged in a ramified, higher-order type theory that is based on a simple type theory of first-order objects that are non-procedural. The simple type theory, when used for natural-

language analysis, spans four ground types (individuals, truth-values, possible worlds, and reals doubling as times) and types of partial functions defined over them. The ramified type theory extends the base of ground types with the types of constructions and types of partial functions defined over them. The typing does not apply to linguistic entities, as in categorial grammar (cf. Montague, Leśniewski, Ajdukiewicz, Cresswell), but to abstract objects such as functions, truth-values, and higher-order entities, as in the constructivist type theory of Martin-Löf. Our bi-dimensional type theory fixes the objective relations among this multi-layered multitude of abstract entities. It thus enables the semanticist to control whether the input is type-theoretically internally coherent and whether the right type of output follows, so as to prevent categorial mismatches.

2 Objectives of the project

This project is interdisciplinary in the sense that the goals we want to achieve concern two closely interrelated areas, viz. computational linguistics and logic.

2.1 Linguistic and logical analysis

The first goal in this area is to make improvements to the *Normal Translation Algorithm*, which is a method that integrates *logical analysis of sentences* with the *linguistic approach* to semantics. The algorithm has been implemented within the previous project. It exploits *complex valency frames (CVF*s) in the *VerbaLex* lexicon of verb valencies (see [17]). The logical analysis module is based on the syntactic analysis result provided by *Synt* module; as a final product, it converts syntactic analyses into formulae in the TIL formalism. To this end we make use of the most important information conveyed by a simple sentence, viz. the verb phrase and its arguments. For the translation of a sentence into a TIL formula, we thus need a wide-coverage lexicon of TIL types assigned to verbs and their arguments. As a result of our intensive work, the TIL type lexicon has been extended up to 10,500 verb-type assignments and about 30 thousands of logical schemata for verbs that serve for assigning correct types to verb arguments thus making it possible to create a proper TIL construction. We make use of VerbaLex lexicon of Czech verb valencies containing deep verb frames. These frames are then used to propose TIL types assigned to verbs and verb logical schemata. In order to assign types to verb arguments, we exploit the links to Princeton WordNet. Finally, the resulting lexicons are manually checked and edited. Currently we have got the corpus of 6,000 TIL constructions that serve for computer-aided analysis of language.

Yet we are still not fully satisfied with the accuracy of the translation. Some sentences are translated into a number of TIL constructions that sometimes differ significantly. Hence we will investigate the causes of these inaccuracies, correct the analyses and erase those that do not match the meaning of a sentence. To this end we must also improve typing in order that it is fully

compatible with TIL theory. Here we will make use of the theoretical results in the area of logic and philosophy, in particular of the definition of the three kinds of context, to wit extensional, intensional and hyperintensional, in which the meaning of an expression can occur. The adequacy of the analysis will also be checked by automatically deriving relevant consequences which will be checked manually as for their adequacy. This double checking will yield improvements of the translation algorithm.

The other goal is *bi-lingual analysis*. Here we make use of the definition of procedural isomorphism. Since we explicate structured meanings procedurally, our basic idea is that any two terms or expressions, even in different languages, are synonymous whenever their respective meanings are *procedurally isomorphic*. The notion of procedural isomorphism helps TIL to a principled account of hyperintensional individuation. This is a major issue, because only expressions with procedurally isomorphic meanings are synonymous and can be mutually substituted in hyperintensional contexts.

Yet the synonymy of semantically simple expressions must be established linguistically. To this end we make use of two *very large web corpora*, namely *czTenTen* (for Czech, 5.5 billion tokens) and *enTenTen* (for English, 13 billion tokens). We have designed and developed new tools that are published and publicly used by hundreds of users all over the world – Chared, Onion, JusText and SpiderLing. For an efficient management of such very large corpora, we use the Manatee/Bonito corpus manager developed at the NLP Centre FI MU. Testing on these data showed sufficient speed, coverage and precision of the parsers on general texts from the Internet domain for the Czech language. What remains to be done is transferring the syntactic analysis and logical analysis rules to the English language in order to propose a bi-lingual analysis of general texts in the form of the resulting TIL constructions.

2.2 Logical semantics

First, we plan to improve the analysis of *tenses* as compared to temporal logics, the analysis of *epistemic verbs* and *events*, and the analysis of *ambiguities* in natural language. The foundations of these analyses have been laid down in the previous project No. 401/10/0792 "Temporal Aspects of Knowledge and Information", see [10]. Yet the results deserve to be spelt out further.

Second, we will pursue research on the problem of *synonymy* in natural language. To this end we have defined three variants of *procedural isomorphism* that slightly differ in the degree of individuation of hyperintensions. The first takes only α- and η-equivalent constructions as procedurally isomorphic; the second includes also restricted β-conversion 'by name', and finally the third proposal encompasses α- and β-conversion 'by value' equivalency. Yet we admit that slightly different definitions of procedural isomorphism are still thinkable. What appears to be synonymous in an ordinary vernacular might not be synonymous in a professional language like the language of, for instance, logic, mathematics or physics. Thus we are also considering whether it is philosophically wise to adopt several notions of procedural isomorphism. It

is not improbable that several degrees of hyperintensional individuation are called for, depending on which sort of discourse happens to be analysed. Thus the problem of synonymy is still very much an open issue.

Third, we will accomplish the definition of TIL as an extensional logic of hyperintensions (see [9,11,12]). Though TIL's analytical potential is very large, deduction in TIL remains underdeveloped. Tichý defined a sequent calculus for pre-1988 TIL, that is TIL based on the simple theory of types. Since then no other attempt to define a proof calculus for TIL has been presented. The goal is to propose a generalization and adjustment of Tichý's calculus to TIL as per the 2010 book [8]. The adjustments of the calculus concern in particular extensions to the three kinds of context such that it be applicable to hyperintensions within the ramified hierarchy of types. TIL operates with a single procedural semantics for all kinds of logical-semantic context, be it extensional, intensional or hyperintensional. Though operating in a hyperintensional context is far from being technically trivial, it is feasible. To this end we introduce a substitution method that operates on hyperintensions. It makes use of a four-place substitution function (called *Sub*) defined over hyperintensions.

2.3 Communication system

The goal is to apply our analytic methods and application modules so that an interactive *intelligent system* of computer-aided, bi-lingual *communication* is created. To this end we have been developing a computational variant of TIL, viz. the functional programming language *TIL-Script*. The first attempt at a prototype system was accomplished within the five-year (2004–2008) project "Logic and Artificial Intelligence for Multi-agent Systems" that was supported by the Czech Academy of Science. As one of the results of this project, our autonomous intelligent agents can communicate by messaging. The content of messages is encoded in TIL. We developed a small domain ontology of a traffic system both in Czech and English. A noteworthy result was this. Using the common bilingual ontology we could smoothly switch between Czech and English without any programming-code adjustments. Due to hyperintensional features of TIL the agents were able to learn by experience and even recognize ambiguous messages. In such a case the receiver asks the sender for refinement of the message content. The goal of this project is to improve and further develop the system in order to make it compatible with the corpora developed in the NLP Centre FI MU. Moreover, we will improve the analysis of questions so that the system will take into account the fact that questions often come attached with a presupposition. If the presupposition is not valid, the agent replies by a negated presupposition so that the sender can react adequately.

TIL-Script fully complies with TIL, but it is adjusted to the needs of computers. The adjustments concern in particular the syntax of the TIL 'language of constructions'. In TIL-Script we use TeX-like syntax rather than Greek letters, subscripts and superscripts in order to make the language easier to use in computational practice. Moreover, in the interest of better applicability we

introduced separate atomic types of real numbers, natural numbers and times, and the types of lists and tuples, though the lists and tuples can be defined as molecular types mapping natural numbers to a particular TIL type. Within the previous projects we implemented syntactic analysis and parsing for TIL-Script and began to build the TIL *inference machine*. The first version of this machine was based on Prolog. In order to extend the calculus to hyperintensional logic of partial functions, we will implement the TIL sequent calculus, which is another goal of this project. At this moment it is an open issue whether we will make use of the general resolution method or implement the calculus directly.

2.4 Summary

In summary, the goals of the project are these.

a) *Logical theory*; further development of TIL, in particular research on
   - the analysis of *tenses*, *presuppositions*, *epistemic verbs*, *events* and *ambiguities* in natural language;
   - procedural isomorphism and the problem of synonymy;
   - TIL sequent calculus

b) *Linguistic and logical analysis*;
   - improvement of the *Normal Translation Algorithm* in order to increase its preciseness and accuracy
   - *bi-lingual analysis* for Czech and English

c) *Communication and agents' attitudes*
   - transformation of a *dialogue* into the *knowledge base*
   - the TIL *inference machine*, the *TIL-Script* functional programming language

3 Methodology and project planning

The project work will run in parallel in three closely cooperating and partly overlapping groups:

- *TIL natural-language processing* group
- *TIL theoretical backgrounds* group
- *TIL inference machine* group

As mentioned above, our theoretical background is Transparent Intensional Logic (TIL) with its procedural semantics. The main tenets of our logical framework are these:

- *Semantic transparency*. We assign TIL constructions to natural language expressions as their context- invariant meanings.
- *Procedural semantics*. TIL constructions are abstract procedures. Thus natural-language expressions encode instructions how, in any state-of-affairs at any time, to evaluate these procedures in order to obtain their product, if any.

Milestones	Theoretical results	Applications	
		Logical analysis	Inference
1st year (2015)	Study of procedural isomorphism and synonymy; questions and answers with presupposition; logic of dynamic discourse, tenses and events	Computer-aided analysis of individual attitudes in present, future and past tenses and their representation in the knowledge base	Substitution and existential generalization into the three kinds of context while respecting partiality
2nd year (2016)	Resolving ambiguities in natural language; specification of the algorithm of anaphora resolution	Computer-aided analysis of dynamic dialogue based on knowledge bases and ontologies of autonomous agents	Implementation of the algorithm of anaphora resolution in dynamic discourse
3rd year (2017)	Definition of TIL proof calculus; TIL vs. intuitionistic proofs and epsilon calculus	Effective methods of question answering based on knowledge bases and ontologies of autonomous agents	Implementation of the TIL calculus as specified by the theoretical group

Fig. 1. Summary of the project plan.

– *Compositionality*. This principle is closely connected with semantic transparency and Carnap's principle of subject matter. The latter says in principle the following. The constituents of the meaning of an expression can be only constructions of those objects that are explicitly mentioned by the expression. TIL constructions are procedures that spell out how these constituents are unified together into a structured whole.
– *Hyperintensionality*. In TIL ramified theory of types we can easily distinguish three kinds of context, namely extensional, intensional and hyperintensional ones. Yet due to semantic transparency, the meaning of an unambiguous expression is context-invariant. What does depend on a particular context are the objects on which our constructions operate rather than the construction/meaning assignment. In the hyperintensional contexts constructions themselves are objects of predication (though a higher-order construction must be used to produce this lower-order argument construction). In the intensional contexts the products of constructions, that is set-theoretical functions, are the objects of predication. And in the exten-

sional contexts functional values are the objects of predication that get operated on.
– *Extensional logic of hyperintensions*. The above principles altogether make it possible to develop an extensional calculus of hyperintensions in which the extensional principles like existential generalisation and substitution of identicals are valid.

Logical analysis of natural language will adhere to these principals. Moreover, we aim to integrate computer-aided linguistic analysis with logical analysis. In particular, we must still improve the products of linguistic typing in order to match them with logical typing. We will improve the Normal Translation Algorithm, a method that integrates *logical analysis of sentences* with the *linguistic approach* to semantics. The algorithm exploits *complex valency frames* in the VerbaLex lexicon of verb valencies.

Concerning the development of TIL inference machine, much has been done yet still more remains to be done. The results have been presented at respectable international conferences and published in journals. What remains is the specification of the rigorous extensional calculus of hyperintensions and its implementation in the computational variant of TIL, viz. the *TIL-Script* language.

4 Conclusions

We have presented the main ideas of a just started research project that aims to built on the logical framework of the Transparent Intensional Logic (TIL) as a basis for complex analysis of higher-order semantic phenomena of natural languages. As a subject study, the project will verify all findings on at least two representatives of a range of natural languages, namely Czech, as a morphology-rich free-word-order language, and English, as a mainstream example of analytical language.

We believe that fulfilling the project goals will move the research in natural language processing beyond the well-known shortcomings of set-theoretical natural-language semantics. Moreover, computer-aided analysis of natural language will make it possible to develop an intelligent system of communication both in Czech and English.

Acknowledgements This work has been partly supported by the Ministry of Education of CR within the LINDAT-Clarin project LM2010013 and the research leading to these results has received funding from the Norwegian Financial Mechanism 2009–2014 and the Ministry of Education, Youth and Sports under Project Contract no. MSMT-28477/2014 within the HaBiT Project 7F14047.

References

1. Bealer, G. (1982): *Quality and concept*. Oxford: Clarendon Press.

2. Bealer, G. (2004): An inconsistency in direct reference theory. *Journal of Philosophy* 101: 574–593.
3. Carnap, R. (1947): *Meaning and necessity*. Chicago: Chicago University Press.
4. Church, A. (1954): Intensional isomorphism and identity of belief. *Philosophical Studies* 5: 65–73.
5. Cresswell, M.J. (1975): Hyperintensional logic. *Studia Logica* 34: 25–38.
6. Cresswell, M.J. (1985): *Structured meanings*. Cambridge: MIT Press.
7. Duží M. (2008): TIL as the Logic of Communication in a Multi-Agent System. *Research in Computing Science*, 2008, vol. 33, special issue Advances in Natural Language Processing and Applications, pp. 27–40. ISSN 1870-4069.
8. Duží M., Jespersen B. and Materna P. (2010): *Procedural Semantics for Hyperintensional Logic. Foundations and Applications of Transparent Intensional Logic*. First edition. Berlin: Springer, series Logic, Epistemology, and the Unity of Science, vol. 17, ISBN 978-90-481-8811-6, 550 pp.
9. Duží, M. (2012a): Extensional logic of hyperintensions, in *Conceptual Modelling and its Theoretical Foundations*, A. Duesterhoeft, M. Klettke and K.-D. Schewe (eds.), LNCS 7260, Berlin-Heidelberg: Springer 2012, pp. 268–290, ISBN 978-3-642-28278-9.
10. Duží, M. (2012b): Resolving topic-focus ambiguities in natural language. In *Semantics in Action – Applications and Scenarios*. Ed. Muhammad Tanvir Afzal, Croatia: In-Tech Europe, 2012, pp. 239–266, ISBN 978-953-51-0536-7.
11. Duží, M. (2012c): Towards an extensional calculus of hyperintensions. *Organon F*, Vol. 19, supplementary issue 1, pp. 20–45.
12. Duží, M. (2013): Deduction in TIL: From simple to ramified hierarchy of types. *Organon F*, vol. 20, supplementary issue 2, pp. 5–36.
13. Duží, M., Jespersen, B. (2012): Transparent quantification into hyperpropositional contexts *de re. Logique and Analyse*, vol. 220, pp. 513–554.
14. Duží, M., Jespersen, B. (2013): Procedural isomorphism, analytic information and beta-conversion by value. *Logic Journal of the IGPL*, vol. 21, pp. 291–308.
15. Fellbaum, Ch. (1998, ed.): *WordNet: An Electronic Lexical Database*. Cambridge, MA: MIT Press.
16. Fox, Ch. and Lappin, S. (2010): Expressiveness and complexity in underspecified semantics, *Linguistic Analysis*, vol.36.
17. Hlaváčková, D., Horák, A. (2006): VerbaLex - New Comprehensive Lexicon of Verb Valencies for Czech. In: *Computer Treatment of Slavic and East European Languages*. Bratislava, Slovakia: Slovenský národný korpus, 2006. pp. 107–115.
18. Horák, A. (2008): *Computer Processing of Czech Syntax and Semantics*. Brno, Czech Republic: Librix.eu, 241 pp.
19. Horák, A., Pala, K., Materna, P., Duží, M. (2007): Verb Valency Semantic Representation for Deep Linguistic Processing. In *ACL 2007, Proceedings of the Workshop on Deep Linguistic Processing*. Praha: The Association for Computational Linguistics (ACL), 2007. pp. 97–104.
20. Jespersen, B. (2003): Significant sententialism in Transparent Intensional Logic and Martin-Löf's type theory, in: *The Logica Yearbook 2002*, T. Childers, O. Majer (eds.), Czech Academy of Sciences, Prague (2003), 117–31.
21. Jespersen, B. and G. Primiero (2010): Two kinds of procedural semantics for privative modification, *Lecture Notes in Artificial Intelligence*, vol. 6284 (2010), 252–271.
22. Jespersen, B. and G. Primiero (2013): Alleged assassins: realist and constructivist semantics for modal modification. *Lecture Notes in Computer Science*, vol. 7758 (2013), 94–114 (Revised Selected Papers).

23. Lewis, D. (1972): General semantics. In *Semantics of Natural Language*, eds. D. Davidson and G. Harman, 169–218. Dordrecht: Reidel.
24. Martin-Löf, P. (1984): *Intuitionistic Type Theory*. Bibliopolis, Naples.
25. Moschovakis, Y.N. (1994): Sense and denotation as algorithm and value. In *Lecture Notes in Logic*, eds. J. Väänänen and J. Oikkonen, vol. 2, 210–249. Berlin: Springer.
26. Moschovakis, Y.N. (2006): A logical calculus of meaning and synonymy. *Linguistics and Philosophy* 29: 27–89.
27. Tichý, P. (1968): Smysl a procedura. *Filosofický časopis* 16: 222–232. Translated as 'Sense and procedure' in [31, 77–92].
28. Tichý, P. (1969): Intensions in terms of Turing machines. *Studia Logica* 26: 7–25. Reprinted in [31, 93–109].
29. Tichý, P. (1988): *The Foundations of Frege's Logic*. Berlin, New York: De Gruyter.
30. Tichý, P. (1994): The analysis of natural language. *From the logical point of view* 3: 42–80. Reprinted in [31, 801–841].
31. Tichý, P. (2004): *Collected Papers in Logic and Philosophy*, eds. V. Svoboda, B. Jespersen, C. Cheyne. Prague: Filosofia, Czech Academy of Sciences, and Dunedin: University of Otago Press.