9. Postscript – Additional Research Topics

Given the vast amount of research on artificial intelligence and natural language, it was inevitable some relevant research would not be discussed in this Ph.D. thesis, though it addressed a wide range of previous research. So, there are some additional topics appropriate to discuss in this postscript, drafted as a future Chapter 9 of the thesis. These discussions do not change Chapter 7's findings about novelty and plausibility of the TalaMind approach. The previous research is not identical, and indicates TalaMind can be successful, since research in similar directions has been somewhat successful.

9.1 Natural Logic

Natural logic research[1] has studied how natural language syntax can be analyzed directly to support logically valid reasoning. It is an exception allowed by §1.2's statement that almost all AI research on natural language understanding has attempted to translate natural language into a formal language and perform reasoning with expressions in the formal language. It does not appear natural logic research has studied use of natural language syntax in a language of thought for an AI system.

9.1.1 Natural Logic According to Lakoff

Lakoff (1970) defined a 'natural logic' as a logic that would account for inferences made in natural language, and in which non-synonymous sentences would have different logical forms.[2] He argued such a logic would need to satisfy a 'generative semantics' hypothesis that "the rules of grammar are just the rules relating logical forms to surface forms of sentences." From this he concluded "the underlying grammatical structure of each sentence would be identical with its logical form" and "the logical forms of sentences are to be represented in terms of phrase structure trees."

Thus, he argued for an approach consistent with Hypothesis II of this thesis, and consistent with the design of the Tala mentalese, which were developed without recalling his paper.

Lakoff wrote that words used in logical forms need additional axioms or "meaning postulates" to characterize their interrelationships and provide models in terms of which logical forms can represent meanings. This corresponds to the ability of words and expressions at the TalaMind linguistic level to refer to concepts and encyclopedic knowledge at the archetype level, or to perceptions at the associative level of Figure 1-1.

However, there are several points of difference between Lakoff (1970) and this thesis.

[1] Distinct from 'natural deduction', a proof-theory approach to logic (Prawitz, 1965).

[2] This is a summary of five goals for natural logic stated by Lakoff (1970, p.195).

For instance, Lakoff's arguments were based on a linguistic analysis of grammaticality and logical sense or nonsense for various English sentences. In contrast, per §3.4.1 the Tala syntax is not limited to expressions people might consider perfectly grammatical English. Per §1.2, this thesis advances Hypothesis II from a strategic perspective, not based on arguments about natural language grammaticality and logical sense or nonsense.

Lakoff (1970) did not discuss many of the topics related to the design of Tala and the TalaMind approach discussed in the Chapters 3, 5, and 6. His paper was concerned with issues related to human logic and natural language, not with artificial intelligence. Indeed, as §2.3.2 notes, Lakoff has been very skeptical about the prospects for human-level AI. It is not clear he would agree the TalaMind approach can succeed, even though it incorporates ideas from cognitive linguistics, supports embodiment, etc. Lakoff (1970) was also very cautious about prospects for developing a natural logic comprehensive for English grammar, suggesting this would take centuries, if possible at all. However, §5.3 notes a comprehensive syntax for English is not required for TalaMind's success.

Likewise, this thesis need not fully subscribe to the generative semantics hypothesis, nor to other hypotheses in Lakoff's 1970 paper. Though Tala has a generative grammar, it also supports composable constructions that can transform Tala sentences, effectively extending the grammar. And per §3.2.1 the TalaMind approach is open to use of formal languages such as predicate calculus and conceptual graphs, to support understanding natural language, and logical reasoning in general. TalaMind does not require that the only logical forms used to represent semantics be phrase structure trees.

9.1.2 Monotonicity-Based Natural Logic

Van Benthem (2008) gives an overview of the history of natural logic research. He describes the theoretical background starting with Montague's (1973) analysis of natural language quantifiers. This was followed by analysis of generalized quantifiers (Barwise & Cooper, 1981); analysis of monotonicity for generalized quantifiers (van Benthem, 1986 *et seq.*; Sánchez-Valencia, 1991); and more recently, analysis of semantic relations for containment and exclusion (MacCartney & Manning, 2008 *et seq.*), to give a few highlights of this research. Systems leveraging these theoretical analyses will here be called 'monotonicity-based natural logic' systems.

Such systems can compute many entailments of natural language sentences by analyzing parse trees for natural language sentences, for instance the following example from MacCartney & Manning (2009):

> "Every firm polled saw costs grow more than expected, even after adjusting for inflation."
> =>
> "Every big company in the poll reported cost increases."

Monotonicity-based natural logic has been somewhat successful, in comparison with other approaches to natural language understanding. MacCartney (2009) reports that a natural logic system called NatLog achieved 70% accuracy (and 89% precision) on a subset of the FraCaS test suite[3] containing 183 single-premise natural language entailment problems. On the RTE3 test suite[4] of 800 problems, NatLog achieved 59% accuracy and 70% precision. In comparison, MacCartney notes a system based on first order logic (Bos & Markert, 2006) achieved 76% precision on the RTE2 test suite[5] but could only answer about 4% of the problems. NatLog achieved 70% precision answering about 25% of the RTE2 problems.

However, monotonicity-based natural logic has had several limitations. MacCartney (2009) writes that NatLog cannot combine information from multiple premises, and this is a limitation for all other natural logic systems of which he is aware.[6] Because NatLog has a weaker proof theory than first order logic, it cannot perform some inferences, such as those involving De Morgan's laws for quantifiers, e.g. "Not all birds fly ⇔ Some birds don't fly." MacCartney & Manning (2008) note that many types of inference are not addressed by natural logic, listing examples such as paraphrase, verb alteration, relation extraction, and commonsense reasoning.

In contrast, the TalaMind approach does not have these limitations, though it could also be considered a kind of natural logic since it involves reasoning directly with natural language syntax. Tala sentences can use pattern-matching to perform inference with multiple premises; perform translations supporting De Morgan's laws for quantifiers; support paraphrase, verb alteration, and relation extraction; and perform commonsense reasoning, if supported by encyclopedic knowledge (§3.6.7.4) in the TalaMind architecture. (Schubert (2013) discusses how natural logic-like inference can be performed by a formal logic system, EL/EPILOG, also without such limitations.)

The TalaMind approach is open to use of monotonicity-based natural logic, as it is to formal logic methods. The success of monotonicity-based natural logic supports the plausibility of Hypothesis II. TalaMind may provide an answer to van Benthem's (2008) question, Can we find a more "surfacy" natural logic?

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[3] Viz. Cooper *et al.* (1996).

[4] Viz. Giampiccolo *et al.* (2007).

[5] Viz. Bar-Haim *et al.* (2006).

[6] It does not appear that supporting multiple premises is impossible in principle for monotonicity-based natural logic. Thus, van Benthem (2008) gives an example involving multiple premises to illustrate how anaphora resolution can be important for monotonicity inferences. MacCartney (2009) notes multiple premises can be supported if combined in a single sentence.

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