EPISODIC LOGIC: NATURAL LOGIC + REASONING

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Abstract: There are two extreme stances in mechanizing natural language inference. One seeks to reformulate a raw message so as to conform with the syntax and semantics of some formal logical system (such as FOL) suited for reliable, potentially deep general reasoning. The other uses what has become known as Natural Logic—an easy but shallow way of treating natural language itself as logic and reasoning directly on this level. Finding the right balance between these opposing stances is one of the key tasks in advancing the ability of machines to understand human language, and thus, for example, make inferences from text. In this paper, we provide arguments and evidence that EPILOG, a general reasoner for the natural language–like Episodic Logic, can be equipped with the knowledge needed for effective Natural Logic–like inference while also providing greater generality.

1 INTRODUCTION

The beauty of Natural Logic (NLog) lies in its ability to make simple, intuitively natural inferences by looking at the surface structure of a sentence and exploiting linguistic properties such as polarity, implicativity, and factivity. Polarity refers to the fact that certain linguistic environments are upward entailing (positive), allowing truth-preserving substitution of more general terms, while others are downward entailing (negative), allowing substitution of more specific terms. For example, a majority of predicates as well as conjunction and disjunction pass the polarity of the environment in which they occur to their operands, while negation, conditional antecedents, and restrictors of universal quantifiers induce the opposite polarity in their operands. Implicativity (typically involving verbs with infinitive complements) and factivity (typically involving verbs with subordinate-clause complements) interact with polarity but arise in intensional contexts. For example, consider the following news headlines[1]:

1. Vatican refused to engage with child sex abuse inquiry.
2. A homeless Irish man was forced to eat part of his ear.
3. Oprah is shocked that President Obama gets no respect.
4. Meza Lopez confessed to dissolving 300 bodies in acid.

[1]From the *Guardian*, 11 Dec. 2010; *The Huffington Post*, 18 Feb. 2011; Fox News, 15 Feb. 2011; and Examiner.com, 22 Feb. 2011.

While such headlines may deliver messages at multiple levels, including insinuated appraisals (e.g., Oprah is wrong), they certainly purport to provide *facts* concerning the current state of the world. Thus, a crucial part of understanding these headlines is making the inferences that (1) The Vatican did *not* engage with the child sex abuse inquiry, (2) An Irish man *did* eat part of his ear, (3) President Obama gets no respect, and (4) Meza Lopez dissolved 300 bodies in acid.

These facts can be directly established by exploiting the implication signatures a/b of the main verbs in these headlines, where $a, b \in \{+, -, \circ\}$. For example, an implicative verb like 'refuse (to)' has an implication signature $-/+$, indicating that in a positive environment, 'x refuse to y' carries the negative implication 'not x y', and in a negative environment it carries the positive implication 'x y'. Similarly a factive verb like 'is shocked (that)' has an implication signature $+/+$, indicating that in both positive and negative environments, 'x is shocked that y' implies 'y'. The signatures of 'be forced (to)' and 'confess (to something)' are both $+/\circ$, indicating that these verbs carry an implication only in positive environments. Note that the uniform signatures $+/+$ and $-/-$, corresponding to factives and antifactives, indicate *presuppositional* predicates. We also occasionally use bracketing, e.g., $+/(+)$, to indicate weak or cancelable implications.

The shortcoming of this approach is that it obtains little more than superficial inferences. MacCart-

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ney demonstrated that their NATLOG system, an entailment verifier based on NLog, makes surprisingly accurate judgments on FraCaS test instances,[2] but it can only *verify* the given entailment; one has to specify both the premise and the conclusion (MacCartney and Manning, 2008). Moreover, inferences are limited to single premise sentences and have to result from "aligning" the premise with the hypothesis and then judging whether a sequence of "edits" (substitutions, insertions, deletions) leading from the premise to the hypothesis makes it likely that the premise entails the hypothesis. Hence NATLOG can verify the correctness of the entailment

$$\frac{\text{Jimmy Dean refused to move without his jeans}}{\text{James Dean didn't dance without pants}},$$

but it would not be able, for example, to use a second premise, 'Jimmy Dean could not find his jeans' to conclude that 'Jimmy Dean did not dance'. (Assume that not being able to do something entails not doing it, and not finding something entails not having it.)

We show that Episodic Logic (EL), a very natural representation of human language, has the potential to overcome the inherent shallowness of the NLog scheme. To demonstrate this potential, we supply EL axioms, meta-axioms, and inference rules to EPILOG, a general EL reasoner that has been shown to hold its own in scalable first-order reasoning against the best current FOL theorem provers, even though its natural language–like expressive devices go well beyond FOL. It has been used to solve problems in self-aware and commonsense reasoning and some challenge problems in theorem proving (Morbini and Schubert, 2007; Morbini and Schubert, 2008; Schubert and Hwang, 2000). Once a sentence is in EL form, we only need a KB that contains axioms and inference rules specifying what conclusions can be drawn from predicates with particular signatures. The result is a reasoning system that can not only handle the dual-premise example above but can also perform general logical reasoning not directly related to natural language. We point out the benefits of our approach over ones based only on NLog or FOL—and also provide an evaluation on 108 sentences randomly sampled from the Brown corpus—in Section 4.

2 PREVIOUS WORK

In the linguistics community, a tremendous amount of effort has been invested in the study of presupposition, implicativity, and polarity. We do not intend to cover all the subtleties involved in this field of study, but we give a brief discussion of the aspects directly relevant to our work.

[2] See MacCartney's site http://www-nlp.stanford.edu/∼wcmac/downloads/

Table 1: The typical behavior of E, P, and I.

	E	P	I
Project from embeddings	no	yes	no
Cancelable when embedded	–	yes	–
Cancelable when unembedded	no	no	yes

The Strawsonian definition of presupposition (relevant to factives and antifactives) is

One sentence presupposes another iff whenever the first is true or false, the second is true.

This provides a nice logical characterization that covers the case of lexically "triggered" presuppositions—in particular, the polarity-independent existence of the presupposed content (Strawson, 1952). As we will see in Section 3, this rules out an axiomatic approach to presupposition inference.

Other important aspects of implicativity and presupposition are cancelability and projection. The implications of an implicative such as 'refuse' can be canceled in a negative context ('John didn't *refuse* to fight, but simply had no occasion to fight'), and do not survive an embedding ('John probably refused to fight'). In contrast, a presupposition typically cannot be canceled (#'John doesn't know that he snores, and in fact he doesn't'), and typically projects when embedded ('John probably knows that he snores'), but not in all cases ('I said to Mary that John knows that he snores'). The typical behavior of entailments (E), presuppositions (P), and implicatures (I) are summarized in Table 1 (Beaver and Geurts, 2011). A notable attempt to regulate presupposition projection is the classification of embedding constructions into *plugs*, *filters*, and *holes* (Karttunen, 1973). Plugs (e.g., 'say' above) block all projections, filters (e.g., 'if–then') allow only certain ones, and holes (e.g., 'probably' above) allow all.

There have also been many efforts to computationally process these linguistic phenomena. They tend to focus on handling monotonicity properties of quantifiers and other argument-taking lexical items, which ultimately determine the polarity of arbitrarily embedded constituents. For instance, (Nairn et al., 2006) proposed a polarity propagation algorithm that accommodates entailment and contradiction in linguistically-based representations. MacCartney and Manning's NATLOG and its success on FraCaS examples showed the potential effectiveness of a NLog-based system that leverages these linguistic properties (MacCartney and Manning, 2008). (Clausen and Manning, 2009) further showed how to project presuppositions in NLog in accord with the plug–hole–filter scheme. (Danescu-Niculescu-Mizil et al., 2009) exploited Ladusaw's hypothesis—that negative polarity items only appear within the scope of downward-entailing operators—for unsupervised discovery of downward-entailing operators (DEOs): lexical items with negative polarity in their argument scope.

The main focus of this paper is not on handling all the linguistic subtleties examined in the literature (in particular, the projection problem of presuppositions). Rather, it is to show how NLog-like reasoning based on implicatives, factives and attitudinal verbs can be incorporated into a formal reasoner, to come to grips with some interesting problems that arise in the process, and to argue that our approach ultimately enjoys advantages over other approaches to inference in language understanding.

EPILOG's capability in NLog-like entailment inference has already been partially demonstrated by (Schubert et al., 2010). EPILOG's inference mechanism is polarity-centered, in the sense that much of its reasoning consists of substituting consequences of subformulas in positive environments and anti-consequences in negative environments. In that respect it rather closely matches NLog inference. For instance, having inferred that Jimmy did not move from 'Jimmy refused to move', it easily makes the further inference that Jimmy did not dance (knowing that dancing entails moving). But our focus here is not on these natural entailment inferences, but on building a lexical knowledge base that will permit us to obtain NLog-like inferences on a wide variety of text examples involving implicatives, factives, and attitudinal verbs.

3 METHOD

We have manually constructed a list of around 250 implicatives, factives, and attitudinal verbs with their semantics. About half of the items come from (Nairn et al., 2006) via personal correspondence with Cleo Condoravdi at PARC. We have further expanded them by considering their synonyms and antonyms, as well as entirely novel items. The attitudinal verbs were separately collected, with the goal of enabling inferences of beliefs and desires. For example, if John *thinks* that Bin Laden is alive, then we may reasonably infer that John *believes* that Bin Laden is *probably* alive; if Mary *struggles* to get an A, then Mary surely *wants* to get an A; etc. We have also collected a list of around 80 DEOs such as 'doubt (that)', which preserve truth under specialization of the complement. Around 60 of them came from those obtained by (Danescu-Niculescu-Mizil et al., 2009).

We can encode lexical items into a semantic database for EPILOG by declaring the types of the predicates and stating axioms or inference rules. In this seemingly straightforward process, we encounter both implementation issues and interesting linguistic issues.

Table 2: Some simplified axiom templates.

x dare to $p \Rightarrow x$ p
x not dare to $p \Rightarrow x$ not p
x decline to $p \Rightarrow x$ not p
x not decline to $p \Rightarrow$ probably x p
x is delighted that $w \Rightarrow w$
x is not delighted that $w \Rightarrow w$
x doubts that $w \Rightarrow x$ believes probably not w

3.1 Axiomatizing Implicatives

EPILOG allows expression of very general axiom schemas through syntactic quantification (e.g., the quantifier 'all_pred') and quotation (transparent to syntactic metavariables). Thus, we could formalize the implications of verbs like 'manage' or 'dare' in a positive environment as follows:

(all_pred p ('p imp+p)
  (all_pred q
    (all x ((x p (ka q)) ⇒ (x q)))))).

This says that if a predicate p (e.g., 'dare') has positive implicativity in a positive environment (denoted by `('p imp+p)`), then whenever a subject x stands in relation p to a kind of action (ka q) (e.g., 'to dance'; the 'ka' operator reifies an action or attribute predicate into a kind of action or attribute), then x does the action q. If we now add the axiom `(s '('dare imp+p))`, we will in principle enable the desired positive inference for 'dare'.

This approach may be elegant, but it suffers from $O(n^k)$ runtime with respect to proofs of length n for a KB of size k in the current implementation of EPILOG, since it may retrieve and attempt to match numerous formulas containing matchable variables and metavariables at *every* step in backward chaining. (Inferential retrieval is geared toward completeness rather than efficiency). A solution is to expand general schemas like the above into verb-specific ones, like the following for *dare*:

(all_pred p (all x ((x dare (ka p)) ⇒ (x p))))),
(all_pred p (all x ((not (x dare (ka p))) ⇒ (not (x p)))))).

A partial list of informal English templates for such logical axioms is shown in Table 2.

3.2 The Presupposition Problem

As noted in Section 2, presuppositional inferences can be made without regard to the polarity of the antecedent. Now suppose that we try to capture this behavior for a presuppositional verb like 'know', via meta-axioms stating that both knowing *w* and not knowing *w* entail *w*:

(all_wff w (all x ((x know (that w)) ⇒ w)))),
(all_wff w (all x ((not (x know (that w))) ⇒ w)))).

But this is absurd, because if both the truth and the falsity of a premise lead to the conclusion that *w* holds, then *w* simply holds unconditionally, and we will be able to derive it even if no specific "knowing that" premises are available. Similar comments apply in the case of antifactives such as "pretending that" (which in combination with axioms for factives makes EPILOG conclude that any claim is both true and false).

What this indicates is that we need to carefully distinguish the assertion of a proposition in a given context from its truth. It is the *assertion* of a "knowing that" proposition or its negation in a context, that justifies adding the object of "knowing that" to the context. The truth or falsity of a "knowing that" proposition—one of which always obtains for *any* proposition in a bivalent semantics—is no basis for inferring its presuppositions.

In Natural Logic, this particular issue does not arise, because conclusions are always based on explicitly available sentences, not on general logical considerations. (For example, we cannot derive 'John is alive or he is not alive' from an empty KB in NLog.) But in EL, we need to avoid the above pitfall. We do so here in a way that is adequate for top-level occurrences of (anti)factives or their negations by formulating implicative rules as *inference rules* rather than axioms, where the premises must be explicitly present for the conclusion to be drawn. (Note that the above issue is analogous to the fact that in logics of necessity (Hughes and Cresswell, 1996), the necessitation rule $p/\Box p$, with the premise p restricted to being a theorem of the logic, cannot be recast as an axiom $p \Rightarrow \Box p$, as this would trivialize the logic, rendering all true formulas necessarily true.) Fabrizio Morbini, the designer of the current EPILOG, implemented a facility with which one can easily create such inference rules. In particular the rule for *know* can be written with the function `store-prs-ir`, which takes a list of arguments, the premise, and the conclusion to generate an inference rule at compilation[3].

(store-prs-ir '(((w_wff) (x)) (x know (that w)) w)),
(store-prs-ir '(((w_wff) (x)) (not (x know (that w))) w)).

[3]These rules are insufficient for arbitrarily embedded occurrences of 'know', such as 'John probably does not know that he snores'. What we need more generally is a projection mechanism; this could in principle be expressed with a meta-axiom concerning embedded occurrences of 'know' (etc.): `(((w_wff v_wff x_term)) ('(x know (that v)) projectibly-embedded-in 'w) v)`, where `projectibly-embedded-in` is procedurally decidable.

One fortuitous side effect is that the use of *store-prs-ir* leads to faster inference than would be obtained with axioms with similar content, because it reduces the amount of work by blocking one direction of reasoning.

4 SOME RHETORIC AND SOME RESULTS

Having created a lexical knowledge base as described above, we can perform the top-level inferences allowed by our implicatives, factives, and attitudinal verbs. In particular, we can go back to the opening examples in this paper. Given the following EL-approximations to the news headlines for use in EPILOG (where we have ignored the role of episodes, among some other details),

```
(s '(Vatican refuse
        (ka (engage-with Child-sex-abuse-inquiry)))),
(s '(some x (x (attr homeless (attr Irish man)))
     (x (pasv force)
       (ka (l y (some r (r ear-of y)
                 (some s (s part-of r) (y eat s)))))))),
(s '(Oprah (pasv shock)
        (that (not (Obama get (k respect)))))),
(s '(Meza-Lopez confess
        (ka (l x (some y (y ((num 300) (plur body)))
                   (x dissolve y)))))).
```

EPILOG returns the correct answers to each of the following queries in a small fraction of a second:

```
(Vatican engage-with Child-sex-abuse-inquiry), [NO]
(some x (x (attr homeless (attr Irish man1)))
  (some r (r ear-of y) (some s (s part-of r) (x eat s)))) [YES]
(Obama get (k respect)), [NO]
(some y (y ((num 300) (plur body)))
  (Meza-Lopez dissolve y)) [YES]
```

Note the conformity of these LFs with surface semantic structure. They are also close to the outputs of an existing parser/interpreter—*when* it works correctly, which is not very often, mostly because of parser errors and the lack of a coreference module. The greatest shortcoming of the current work remains that we cannot yet fully automate the conversion of natural language into EL. Does this defeat the whole purpose of our approach—easy and effective inferences on the lexical level, within a more general inference framework? We argue that it does not by highlighting the advantages of our approach over purely FOL- or NLog-based reasoners.

4.1 Advantages Vis-à-Vis FOL

The weaknesses of FOL as a representation for natural language are well-known. In particular intensionality (including, but not limited to, attitudes), generalized quantification ('most people who own cars'), modification ('unusually talented'), and reification ('his absentmindedness', 'the fact that he snores') can at best be handled with complex circumlocutions. It is often claimed that a more expressive logic suffers from higher computational complexity. But this is false, in the sense that any inference that is straightforward in FOL is just as straightforward in a superset of FOL (as was shown in the EPILOG references cited earlier). In fact, a richer, language-like representation can facilitate many inferences that are straightforwardly expressible in words, but circuitous in a more restrictive representation.

Another common misunderstanding is that *any* logical representation demands absolute precision and disambiguation to be usable. However, it should be emphasized that we can be just as tolerant of imprecision and ambiguity in EL as in NLog (although in both cases there are limits to how much can be tolerated without adverse effects; when told that John had gerbils as a child, we probably do not wish to conclude that he ate, or gave birth to, small rodents). The language-like syntax and tolerance of imprecision of EL allow us to easily handle modality and vague, generalized quantifiers. At the same time, it supplies a solid framework for accumulation of context-independent, modular knowledge, which can then be used for both superficial and deep reasoning.

4.2 Advantages Vis-à-Vis NLog

4.2.1 Multiple Premises

Because EPILOG is a logical system that stores its knowledge in a KB available throughout its lifespan, it can trivially handle inferences requiring multiple premises. Consider the following contrived, but illustrative inference example. From the sentence 'John is surprised that Mary declines to contribute to charity', we wish to be able to derive that 'Mary is probably not very altruistic' based on the world knowledge 'If someone declines to donate to charity, that person is probably not very altruistic.' Given the premises in the EL-approximations,

(John surprised
(that (Mary decline (ka (contribute-to (k charity)))))),
(all x ((x decline (ka (donate-to (k charity)))) ⇒
(probably (not (x (very altruistic)))))),

and also the knowledge

(all x (all y ((x donate-to y) ⇒ (x contribute-to y)))),

EPILOG correctly answers the query:

(probably (not (Mary (very altruistic)))) [YES].

This kind of reasoning, requiring both the NLog-style superficial inference and multiple-premise derivations beyond the scope of NLog verifiers, is at the heart of commonsense reasoning in our daily lives.

We know that we have hydrogen in water.
→ We have hydrogen in water.

The second of the above pair of sentences is a reasonably clear and plausible conclusion from the first sentence.

1. I agree
2. I lean towards agreement
3. I'm not sure
4. I learn toward disagreement
5. I disagree

Figure 1: The survey on the Brown corpus inferences.

Table 3: The frequency of the ratings. Lower numbers are better; see Figure 1.

Rating	Frequency Count	Percent
1	502	75%
2	114	17%
3	31	5%
4	14	2%
5	3	0%

Table 4: The frequency of words in the sampling.

Word	Count	Word	Count
think	25	suppose	4
know	15	appear	3
say	9	show	3
guess	7	tend	3
try	4	20 others	27

4.2.2 "Anywhere, Anytime"

After temporal deindexing and author/addressee deindexing, EL formulas are usable for inference "anywhere, anytime", whereas English sentences are not. For instance, the deindexed form of John's assertion 'Yesterday I managed to propose to Mary' would be that 'John asserted at about 1pm June 14/11 that John managed to propose to Mary on June 13/11'. This fact could be used in any context, at any time, e.g., to make the implicativity-based inference that 'John conversationally implied at about 1pm June 14/11 that John proposed to Mary on June 13/11'. By contrast, the English sentence is false from virtually anyone's perspective but John's (because of the use of 'I'), and even for John will become false by June 15/11 (because John didn't propose to Mary 'yesterday' relative to June 15); likewise a conclusion like 'I conversationally imply that I proposed to Mary yesterday' becomes false, even from John's perspective, very shortly after John's utterance (because he has moved on to saying and implying other things).

Table 5: Average score of each judge on the inferences. "Corr." is the average pairwise Pearson correlation.

Judge 1	Judge 2	Judge 3	Judge 4	Judge 5	Corr.
1.33	1.21	1.56	1.40	1.23	0.13

Automatic deindexing of tense and temporal adverbials is quite well-understood in EL (Schubert and Hwang, 2000), and tense deindexing (as well as quantifier scoping) are performed in the existing parser/interpreter. Speaker/addressee deindexing is also handled in a limited way. However, adverbial deindexing remains unimplemented, and in any case improving statistical parser performance and implementing coreference resolution are more urgent needs. Despite this incompleteness in the implementation work, it is clear that systematic deindexing is feasible, and that only deindexed formulas (or else ones permanently tagged with their utterance contexts) are usable "anywhere, anytime".

4.3 Evaluation on the Brown Corpus

We have randomly sampled 108 sentences from the Brown corpus containing the relevant implicative, presuppositional, and attitude predicates in our KB, and run forward inferences on their EL approximations. The NL-to-EL conversion was done by manually correcting the flawed outputs from the current EL interpreter. EPILOG produces 133 distinct premise-conclusion pairs when the approximated EL formulas are loaded. The EL-to-NL (verbalization) direction is completely automated. To evaluate the plausibility/usefulness of the inferences, five people (students and researchers at two sites) judged their quality on a 1–5 scale; the survey question is shown in Figure 1.

As seen in Tables 3 and 5, the ratings are very high overall, affirming the robustness of inferences rooted in the well-studied linguistic properties we made use of. The highest-rated inferences tend to be those where the premise and conclusion are contentful and easily understood, and of course the conclusion is viewed as obvious from the premise; e.g., 'The soldiers struggle to keep open a road to the future in their hearts' ⇒ 'The soldiers want to keep open a road to the future in their hearts' (mean: 1, median: 1). The lowest rated inferences are either trivial or too vague to be useful, e.g., 'The little problems help me to do so' ⇒ 'I do so' (mean: 2.75, median: 2.5). The low correlation among judges can be attributed to differing interpretations as to how seriously sentence content and quality should be taken. But this is a minor concern, given the generally high scores.

Some of the chained-forward inferences illustrate the need to attend to the projection problem. For instance, the inference 'They refuse to mention that they're not there' ⇒ 'They don't mention that they're not there' is obtained by the negative implication of 'refuse'. EPILOG then infers from this conclusion that 'They're not there' by the presuppositional nature of 'mention'. However, it is dubious if this latter inference projects from the initial embedding.

It is also interesting to note the frequency of the words in the sampled sentences (Table 4); a vast majority are attitude verbs like 'think', illustrating our tendency to express personal opinion—and thereby the importance of extracting information from them.

5 CONCLUSIONS

We have taken a step toward combining "shallow" and "deep" linguistic inference methodologies by equipping a general reasoner with NLog-like inference capabilities. In addition to laying out some important implementation issues and addressing relevant linguistic phenomena, we have argued that our approach has specific advantages over ones based on less expressive logics or on shallow, indexical NLog reasoning alone. Though the work is far from complete (with regard to automatic processing of NL sentences, efficient inference, and the handling of the projection problem), our evaluation on the Brown corpus indicates that this is a promising direction for further advancing language understanding and, thereby, the acquisition of inference-capable knowledge from language.

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