# Higher Order Uncertainty and Evidential Ontologies

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***Abstract*—The uncertainties implicit in intelligence gathering are not only about the state of the world, but also about the ways in which varying contexts should affect the degree to which a proposition is believed. We call this latter form of uncertainty *higher order uncertainty*, and argue that the introduction of a logical operator to K. Laskey's MEBN specification can allow for learning about such uncertainty to occur.**

## I. Introduction

In [1], Laskey et. al proposed the creation of ontologies of evidence as a way of facilitating intelligence gathering. Their proposal envisioned such ontologies as represented by Bayesian belief networks. In particular, the proposal of [1] and the similar proposal in [3] envisioned a network in which various assertions about the world were assigned degrees of belief. The relationships between such beliefs and pertinent facts were encoded in the structure of the network, and the impact of new facts on the degrees of belief were updated via Bayesian learning. While a great deal of the relational structure pertinent to reasoning in a specific scenario can be captured in the structure of a pure Bayesian network, an extra level of expressivity will be represented by an implementation done in MEBN [2], Laskey's fusion of Bayesian networks with first-order logic. The introduction of logical formalism allows an ontology to represent and learn more general structure than would otherwise be allowed. Laskey has shown that for any logical consequence of a MEBN theory, the associated learning algorithm will derive that consequence in the limit.

It is worth noting that the expressivity of first-order logic is likely to be crucial when working with human intelligence sources. While a source may make quantifier-free assertions (such as "bin Laden is Kandahar"), he or she is also likely to make assertions whose content necessarily uses quantifiers. For example, a highly credible source might make the following assertions:

1) "bin Laden is somewhere in Afghanistan"
2) "the only luxury cars used by al-Qaeda are in Kandahar, Parachinar, or Islamabad"
3) "bin Laden was recently seen in an al-Qaeda owned luxury car"

To conclude from this information that bin Laden is (probably) in Kandahar requires the deductive power of first-order logic.

One feature which will not automatically be present in such a scheme is the ability to robustly code and learn the ways in which contextual factors affect the manner in which evidence determines the appropriate confidence for a particular assertion. For example, the credibility of a particular source is not likely to be a static property of that source, but rather a parameter which changes based on circumstances ( for example, if a source is the subject of physical or financial distress ). While the proposal in [3] allows for a complex network of reasoning to support the determination of any one particular credibility distribution, and further allows for a source's credibility to be indexed by the context in which the assertion is made, it does not allow for a general mechanism which would decrease any source's credibility if that source is under duress. Rather, it relies on the knowledge engineer to make a determination of how credibility should be affected by duress. Furthermore, it does not allow the network to learn about the complex ways in which several factors such as age, constitution, family status, etc. might influence the effect of duress on credibility. The immense complexity of human psychology makes such a determination highly non-trivial, and equally as wanting of computational assistance as many of the assertions such networks are designed for. [1]

I will argue in this paper that extending MEBN to allow for a new operator will mitigate some of these problems. While passing to a full-blown higher order implementation is fraught with difficulties (lack of deductive completeness, for example), an implementation in which a single operator is introduced can add the requisite expressivity while preserving fundamental meta-logical properties.

## II. Higher Order Uncertainty

Let us consider a situation in which the human source $X$ makes assertions 1-3 above. We would want to represent his assertions, but we would also want to include information about the credibility of his assertions, as discussed in [1] and [3]. In particular, we would want to have an assessment of $X$'s credibility in making his assertion, which would include information about his deceptiveness, competence and opportunity to judge the situation [3]. These are all factors which would be subject to varying contextual conditions, rather than being static properties of $X$. As such, they seem to be best coded either as joint properties of the source and the assertion, or else single properties of the assertion (the latter being a form

[1] One question that is immediately raised in this context is that of determining what the most important factors in determining a source's credibility are. While this is an important question, its answer is best determined by experts in the appropriate fields (e.g. psychology for human sources, or engineering for mechanical ones)

of short-hand for the former, since (tokens of) assertions are associated with unique sources).

As a particular case, let us suppose that $X$ makes his assertions while under some form of duress. It is clear that the duress should have some effect on the credibility of $X$'s assertion, but it is not clear what precisely that effect should be (in fact there are cases in which duress would conceivably *increase* the credibility of an assertion, while one would expect the credibility to decrease under most circumstances). It will apparently depend on a number of factors, including the nature of the duress, various facts about $X$, and the nature of the statement being made. In fact, it doesn't take very long to realize that the number of factors and potential ways they can interact quickly defies any easy analysis. This complexity creates a new form of uncertainty. Noting that this is about the network structure rather than about what the network represents, we term this uncertainty *higher order*.

One might certainly treat each assertion individually, and [3] suggests the possibility of having a complex network behind the credibility distribution of any source's assertion of any particular statement. However this misses an opportunity to discover general truths about the structure of the higher order uncertainty, and a universal mechanism for coding hypotheses about that structure would be beneficial.

One obvious way of implementing this would be to allow complex parameter based statements to be made about a source's assertion. For example, a partial rule for determining the effect of duress on the credibility of an assertion of $a$ by $X$ might encode the following:

- If the assertion is inconsequential, then the credibility is unaltered
- Otherwise, monetary duress combined with a belief by $X$ that he will be paid for his information should result in the credibility of the assertion being decreased by some parameter $\alpha$
- A consequential assertion made while under physical duress should result in a decrease by the parameter $\beta$ if $X$ is deemed insufficiently competent to judge $a$.

Formally, this might be written as:

$$\begin{aligned}
&\forall a \forall X \\
&\Big[\big(\mathrm{Source}(X) \wedge \mathrm{Asserts}(X,a) \wedge \mathrm{UnderDuress}(X)\big)\Big] \rightarrow \\
&\big(\mathrm{Consequential}(a) < \chi\big) \rightarrow \Delta(\mathrm{Cred}(a)) = 0\big) \bigwedge \\
&\big((\mathrm{Consequential}(a) \geq \chi) \wedge \\
&\quad (\mathrm{DuressType}(X) = \mathrm{Monetary}) \wedge \\
&\quad (\mathrm{Believes}(X, \text{``WillBePaidFor}(X, \mathrm{Asserts}(X,a)\text{''})) > \xi) \\
&\quad \rightarrow \quad (\Delta(\mathrm{Cred}(a)) = -\alpha)\big) \bigwedge \\
&\big((\mathrm{Consequential}(a) \geq \chi) \wedge \\
&\quad (\mathrm{DuressType}(X) = \mathrm{Physical}) \wedge \\
&\quad (\mathrm{CompetenceToJudge}(X,a) < \theta) \\
&\quad \rightarrow (\Delta(\mathrm{Cred}(a)) = -\beta)\big)
\end{aligned}$$

In this coding, $\chi, \xi$ and $\theta$ represent threshold parameters which determine whether or not a variable is strong enough to have an impact. The function $\Delta$ represents the change in the credibility of a given assertion, and $\alpha, \beta$ are parameters as described above. One advantage of coding with parameters is that they are subject to machine learning rather than being completely determined by the judgement of a knowledge engineer.

It is notable that many of these predicates (for example $\mathrm{Asserts}(X, a)$ and $\mathrm{Believes}(X, b)$) take propositions as parameters. As such they do not necessarily lie within the scope of first order logic. [2] One is left with the question of how to represent such statements in an ontology of evidence. A natural solution is provided by the work of Neuhaus and Andersen in [4]. In their paper on speech acts and ontologies, these authors have suggested encoding speech acts by introducing an $\mathrm{AssertiveSpeechAct}$ predicate along with a $\mathrm{PropositionalContent}$ operator; the role of the latter is to refer to the content of a given speech act. Introducing such an operator into MEBN would allow for universal statements about assertions; the semantics could be defined in such a way that any instantiation of a speech act would come attached with a default network structure, which would be modified as learning (for example of the parameters $\alpha, \beta$) occurred.

## III. Nesting Speech Acts

Another scenario which is worth considering is one in which a source makes an assertion *about* another assertion. For example, $X$ might say that $Y$ told him that bin Laden was in Kandahar. An implementation of the $\mathrm{AssertiveSpeechAct}$ mechanism described above would allow such structured assertions to be represented quite naturally.

Such nested speech acts are likely to occur, and any ontology of evidence must be prepared to deal with them. As a simple example, one would be inclined to give less credence to an assertion heard third-hand than the same assertion given first-hand.

## IV. Certain Knowledge

A final benefit of this proposal is possibly of greater theoretical than practical value. Following the example of the axiomatic method in mathematics, one can argue that the findings in any knowledge base should be certain and uncontroversial (this is analogous to the fact that the axioms of a mathematical theory are normally taken to be self-evident.) Any knowledge which is controversial should be generated rather than assumed.

By allowing speech acts to be encapsulated within higher order structures, we are able to do away with some of the ambiguity that might otherwise be inherent in working with ontology of evidence. For example, rather than assigning a credibility score to a particular act or actor, we can merely record which facts pertain to credibility, and have the actual score calculated by the network. In particular, in the previously described example there would no controversy in recording that $Y$ asserted that bin Laden is in Kandahar and that $Y$ was under physical duress at the time of the assertion. To assign a

[2] There are first order theories in which propositions can be meaningfully thought of as parameters for predicates, a natural example being Robinson's $Q$ (via Gödel coding). This is an exceptional theory however, and many theories exist in which no such coding is possible.

credibility of 0.67, on the other hand, is very much a matter of judgement and open to question. A scheme which records the former rather than the latter may have an arbitrariness in our choice of network structure and parameters, but at least the latter are subject to being updated. Further, the arbitrariness of structure and parameters arguably corresponds to the arbitrary choice of a non-logical language and way of expressing a set of first order axioms (in that they represent representational rather than semantic choices).

## V. Future Work

While the value of the expressivity contemplated is clear, there are still many questions that need to be answered. Amongst these, the question of what the added computational cost would be seems to be foremost. While the case of modal logic offers reasonable hope that this proposal might be implemented in a way which preserves soundness and completeness of the logical formalism, one would like to know that the added complexity isn't practically prohibitive.

A related question that would be interesting to explore is that of what level of quantifier complexity is actually necessary. It is noteworthy that the immediate examples of "higher order" statements that come to mind seem to be universal (with respect to "higher order" predicates). A bound on the required quantifier complexity could significantly ease the computational cost of an implementation.

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