A compositional semantics-pragmatics model for coordination of generic sentences

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Probabilistic models of pragmatic reasoning have achieved tremendous success in recent years in accounting for a wide range of empirical phenomena surrounding understanding meaning in context [1]. Despite their successes, these models (e.g., Rational Speech Act models) largely operate at the level of comprehending whole utterances, ignoring the structure and compositionality of language. Understanding the interplay between syntax, semantics, and pragmatics is key to understanding human language, and we examine a quirky phenomenon with generic sentences [2] as a case study:

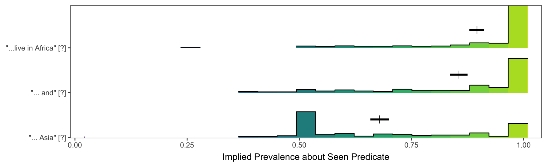
(1) Elephants live in Africa. (2) Elephants live in Africa and Asia.

Intuitively, (1) means that most elephants live in Africa, while (2) means that some (perhaps half) of elephants live in Africa and some (perhaps half) of elephants live in Asia, due to the mutual exclusivity (ME) of the conjuncts. A model that treats a generic as a flexible-threshold quantifier can derive this inference [3] by treating (2) as an instance of sentential conjunction, proposed by [2]. This interpretive difference (verified empirically by [4]) suggests that while hearing (2), a belief-change occurs concerning how many elephants live in Africa. Consistent with this conjecture, [4] also observed an *incremental updating effect* such that listeners interpret the fragment "Elephants live in Africa and" in a gradient manner intermediate between the interpretations of (1) and (2). However, in [4], participants were asked about the prevalence of the seen property (e.g. "living in Africa") and an alternative (e.g. "living on some other continent"), and so it is possible that listeners do not update their beliefs spontaneously, but only when suggested by the experimenter through this prompt. We thus replicated the incremental updating effect while asking only about the seen property. Participants ($n = 200$) read a story book where each critical chapter ended with a novel conjunctive generic (e.g. "Dorbs live in Caro and Este") that was interrupted with a page break either after the first conjunct, after the conjunction, or after the second conjunct. The participant was then asked what percentage of the kind (e.g. "dorbs") possessed the seen conjunct (e.g. "live in Caro"). We successfully replicated the incremental updating effect of [4] (Fig. 1a; $\beta_{\text{conj}-\text{pred}_1} = [-0.13, -0.04], \beta_{\text{pred}_2-\text{conj}} = [-0.22, -0.12]$).

In order to account for the incremental updating effect, we modify the model of [3] to include a compositional semantics which builds a truth value up from a syntactic tree generated by a probabilistic context-free grammar (PCFG). The semantics are continuized [5], which allows the generic to scope above or below conjunction, yielding the intuitive ambiguity in which (2) could mean that generically many individual elephants live in Africa and generically many individual elephants live in Asia, or (though not true) that generically many individual elephants live on both continents. The model can, upon encountering a sentence fragment, infer the intended syntactic tree by comparing a possible tree's linearization to the observed fragment, yielding an interpretation that is a mixture of interpretations of all possible completions, which may be either ME or non-ME. This model accounts for the pattern of data observed in the replication.

The assumption by [2] and [4] that (2) is an instance of sentential conjunction suggests that there will be no effect of coordination level on interpretations; sentential conjunction would require the mechanism of generalized coordination in which the level of coordination does not affect the truth value of the utterance. To test this assumption, we asked participants for prevalence estimates after observing generics under different levels of conjunction, using the same materials as [4]. Pilot data (Fig. 1b, $n = 51$) suggest that there may be an effect of coordination level on ME interpretation. If coordination level does have an effect on interpretation, it would suggest that other mechanisms besides generalized conjunction influence interpretation of coordinated utterances. This work highlights the utility of integrating theories of compositional semantics with probabilistic semantics and pragmatics, yielding new insights into the interface between the structure and function of language.

(a) Results for replication of incremental updating effect [4]. Histograms of prevalence estimates after observing the generic interrupted at various points (y-axis). Horizontal bars show 95% bootstrapped confidence intervals, with the empirical mean shown as a vertical line.



(b) Pilot data for variable coordination experiment. Histograms of prevalence estimates after observing complete generics under differing levels of coordination (y-axis). Horizontal bars show 95% bootstrapped confidence intervals, with the empirical mean shown as a vertical line.

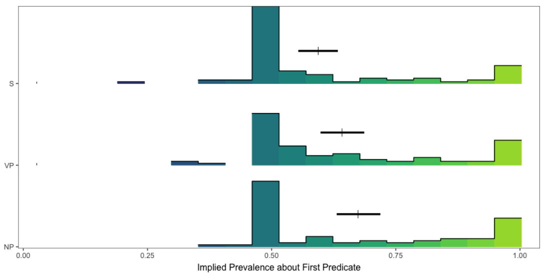


Figure 1

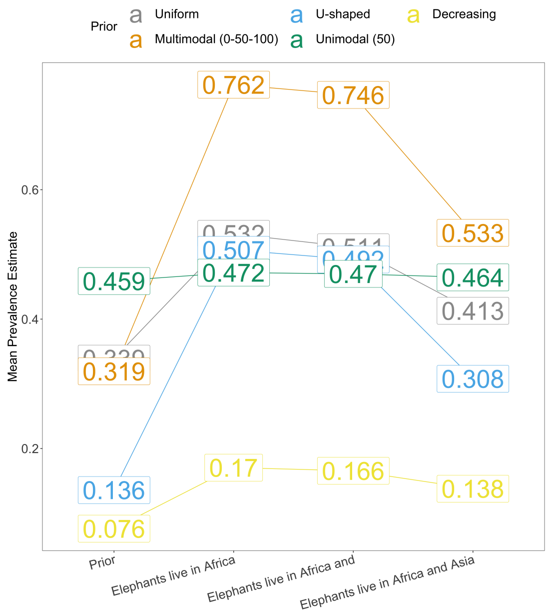


Figure 2: Model predicted prevalence over the course of a conjunctive generic sentence. An incremental updating effect appears numerically for many different shapes of the prior (color). Predictions obtained by setting the probability of mutual exclusivity to .99, the probability of coordination to .1, the probability of the Gen > And scope to .6, and the probability of lexical entries (i.e. Africa vs. Asia) to uniform.

Table 1: Composition rules for branching nodes in the PCFG, accompanied by their node annotations, which are slightly different from those suggested by previous work [5] in order to simplify the model. **VP** and **PP** nodes are simply annotated with the identity function.

Composition Rule	Node Annotation
S $\rightarrow$ **QP VP**	**VP**(λ P: **QP**(λ x: P(x)))
S $\rightarrow$ **QP VP**	**QP**(λ x: **VP**(λ P: P(x)))
QP $\rightarrow$ **Q NP**	**Q**(**NP**)
XP $\rightarrow$ **X and X**	λ c: c(**X**) $\wedge$ c(**X**)

[1] Noah D. Goodman and Michael C. Frank. Pragmatic language interpretation as probabilistic inference. *Trends in Cognitive Sciences*, 20:818–829, 2016.

[2] Bernhard Nickel. Generics and the ways of normality. *Linguistics and Philosophy*, 2008.

[3] Michael Henry Tessler and Noah D. Goodman. The language of generalization. *Psychological Review*, 126(3):395–436, 2019.

[4] Michael Henry Tessler, K Gu, and R Levy. Incremental understanding of conjunctive generic sentences. In *Proceedings of the 41st Annual Meeting of the Cognitive Science Society*, 2019.

[5] Chris Barker. Introducing continuations. In *Proceedings of the 11th Conference on Semantics and Linguistic Theory*. Linguistic Society of America, 2001.

[6] Richard Montague. The proper treatment of quantification in ordinary english. In Patrick Suppes, Julius Moravcsik, and Jaakko Hintikka, editors, *Approaches to Natural Language*, pages 221–242. Dordrecht, 1973.

The model of [3] cannot account for the empirical data obtained by [4], who obtain model predictions qualitatively. We extend the uncertain threshold model to take advantage of the compositionality of language, enabling us to derive quantitative predictions. The incremental updating effect is robust for a variety of prior shapes (Figure 2).

The model was implemented in the probabilistic programming language `webppl` (webppl.org). A working version of the model can be found at forestdb.org/models/elephants.html. Following [3], the model defines a representation of the world in the form of a prior probability distribution over the prevalence of features x such as `living in Africa` (relativized to a category such as `elephants`). Upon encountering an utterance string U, the model infers the intended syntactic tree S and its associated truth value. Crucially, the truth value is dependent upon the world state. The model then performs a Bayesian belief update, assuming that the observation was true, to obtain a posterior belief:

$$P(x, \theta, S \mid U) \propto \mathcal{L}(S, x, \theta)P(U \mid S)P(S)P(\theta)P(x)$$

where $P(U \mid S)$ is given by the linearization of the syntactic structure, $P(S)$ is the distribution of such structures given by the PCFG, $\mathcal{L}$ is the lexicon function which filters worlds according to the semantics of S (for the generic, the semantics are : $x > \theta$), $P(\theta)$ is the prior distribution of the generic threshold (assumed to be uniform), and $P(x)$ is the prior distribution of prevalence.

We model the distribution of prevalence $P(x)$ as a multivariate Beta distribution. To create the joint probability distributions that comprise the world knowledge, we first assume that the prevalence of each feature is independent from the prevalence of all other features. To model mutual exclusivity, if for a given state the total prevalence over two properties (e.g., the % of elephants that live in Africa $+$ % elephants that live in Asia) exceeds 100% (which is impossible for mutually exclusive features), then we decrease the probability of that state. Properties are mutually exclusive with some probability, set to $.99$ for model predictions shown in Figure 2.

The semantic interpretation function takes in a syntactic-semantic representation of a declarative utterance and returns its truth value under the given world state. The truth value is computed using functional application [6], with annotations at branching nodes specifying the composition rule. We adopt a continuized grammar to generate quantifier scope ambiguity [5] (Table 1). The syntactic-semantic representations are generated by a PCFG. The PCFG's lexical frequencies and rewrite rule probabilities are given for the model predictions in Figure 2. Following previous work on the computational modeling of generics [3], we express the generic quantifier with an uncertain threshold, which is jointly inferred with the world state.

Scope ambiguity arises in the continuized grammar because there are two ways to continuize the **S** node (Table 1), with either the Gen>And scope or the And>Gen scope. We can then obtain an effect on ME interpretation of different levels of coordination by modifying the PCFG such that one continuization of **S** favors certain levels of coordination (e.g. **VP**), while the other continuization favors other levels (e.g., **NP**). Generalized conjunction arises naturally from adopting the theory of continuations [5]. This means that generalized coordinators have the same meaning that they do in traditional logical systems: `and` simply means logical conjunction. The model can thus also account for disjunction easily.

The model jointly infers the values of three variables: the world state, the underspecified threshold of generics, and the syntactic structure of the observed sentence. We marginalize to obtain the variable of interest: world state (prevalence). Since the model does not know the actual syntactic structure, it obtains the meaning of a full sentence (possibly ambiguous) by inferring over all possible syntactic structures that would produce the observed string. Similarly, it obtains the meaning of an incomplete sentence by inferring over all possible syntactic structures that would, when pronounced, begin with the observed fragment.