



## Citation:

DOI:  
<http://dx.doi.org/>Supplemental Materials:  
<http://dx.doi.org/10.1098/rsif.2013.0969>

Received:

Accepted:

Published:

Competing Interests: The  
authors have declared that no  
competing interests exist.

Corresponding Author:

Author Name

Corresponding author email address

Copyright: © 2019  
Massachusetts Institute of Technology  
Published under a Creative Commons  
Attribution 4.0 International  
(CC BY 4.0) license

The MIT Press

Interpreting Metaphor: Distributional Semantics  
for Bayesian Pragmatics

1

2

Keywords: metaphor, informativity, Bayesian pragmatics, distributional semantics

## ABSTRACT

Humans interpret metaphors, like *Life is a journey* or *My lawyer is a shark*, with relative ease, incorporating contextual knowledge to determine which aspects of the predicate (*journey, shark*) are true of the subject (*life, my lawyer*). One theory of the process underlying metaphor interpretation, proposed by Grice (1975), is that a listener reasons about an informative speaker (who in turn reasons about the listener) to update their beliefs about the subject and the relevant dimensional of meaning.

This reasoning process can be modeled probabilistically in the *Rational Speech Acts framework* (Frank & Goodman, 2012). However, previous instantiations of these models have required a hand-specified semantics, restricting the generality of the model and the scope of empirical investigation into the effectiveness of pragmatic reasoning for metaphor interpretation.

We present a method to combine empirically learned word embeddings with a Rational Speech Acts model of metaphor. This allows us to interpret arbitrary predicative and adjectival metaphors without manually stipulating the denotations of the words they contain. We find a significant preference in human judgments for our model over a comparable word embedding model without explicit pragmatic reasoning.

## INTRODUCTION

Metaphor presents a compelling theoretical challenge for the understanding of meaning in natural language. On hearing (1) in a context where the subject, Jane, is known to be a consultant, a listener might infer that Jane is not literally a soldier, but rather that she shares certain attributes with soldiers (perhaps determination, endurance, or ruthlessness).

(1) Jane is a soldier

The Gricean view of metaphor takes the meaning conveyed by (1) in a given context to be the result of a process of *pragmatic reasoning*, about a speaker who is trying to communicate truthfully, informatively, and relevantly. That is, the listener attempts to jointly deduce what Jane must be like and what aspect of Jane is plausibly relevant, such that the speaker would have chosen the predicate *soldier* over other alternatives.

**Modeling metaphor** Obtaining metaphorical interpretations for utterances like (1) is within the scope of a formalization of Gricean reasoning, the *Rational Speech Acts framework* (Frank & Goodman, 2012). This framework models pragmatic interpretation and produc-

tion of language via probabilistic models of speakers and listeners, who reason about each other in a nested fashion, with the assumption of cooperativity and a shared semantics.

Kao, Bergen, and Goodman (2014) extend the framework by introducing a new model,  $L_1^Q$ , which is able to interpret metaphors. It does so by the mechanism of *projection functions*<sup>1</sup> which dictate the dimension of the world that the speaker cares about communicating. This, in turn, allows for a model of a listener which jointly determines the state of the world (e.g. what Jane is like) and the aspect of the world the speaker cares to communicate (e.g. Jane's determination). Crucially, this listener assumes an informative speaker: one whose choice of utterance maximizes the probability of communicating the world  $w$  to the speaker's model of the listener, up to the projection  $q$ .

This model provides an account of predicative metaphors (those of the form *A is a B*) and adjective-noun (AN) metaphors (like *fiery temper*). However, in order to generate predictions from the model, previous instantiations of the model have required the manual construction of a semantics for the words involved, restricting the model's scalability.

**Our contribution** We adapt  $L_1^Q$  to a setting where the denotations of words are points in an abstract, and empirically determined, vector space. Such *word embedding* spaces are a core NLP tool, and have been shown to represent various notions of semantic similarity via the geometry of the space (Pennington, Socher, & Manning, 2014). This adaption requires a new semantics, as well as a generalization of projection functions to the vectorial setting, and an inference algorithm to calculate the now continuous posterior distribution of  $L_1^Q$ .

By doing so, we obtain a model capable of interpreting arbitrary predicative and adjectival metaphors, without the need for a hand-specified semantics. We show that our model significantly outperforms a baseline which uses a distributional semantics without explicit pragmatic reasoning.

### OVERVIEW OF METAPHOR

Metaphor exists in many syntactic forms. For present purposes, we focus on copular predicates (e.g. *Jane is a soldier*) and AN noun phrases (e.g. *fiery temper*). We refer to the predicated or modified noun (*Jane*, *temper*) as the *target* of the metaphor and the predicate or adjective (*soldier*, *fiery*) as the *source* (see (Lakoff & Johnson, 1980) for the more general sense of these terms).

For a given metaphor, only certain properties of the target are described by the source, and which these are depend on the metaphor and the context. For instance, (2), said of a sleeping dog, could convey that it is unresponsive, but said of a large alert dog, could convey that it is heavy.

- (2) The dog is a rock.

While certain metaphors are conventional - comparing someone to a lion tends to connote bravery - examples like (2) suggest that the interpretation of a metaphor is contextually dependent. The benefit of the Gricean view of metaphor is the ability to explain this

---

<sup>1</sup> These are often referred to in RSA literature as *Questions under Discussion*.

dependence on context, in a way which takes into account an underlying semantics (e.g. the conventional meanings of *dog* and *rock*).

### A BAYESIAN MODEL OF METAPHOR INTERPRETATION

The Rational Speech Acts framework (RSA) provides an elegant and practical way of formalizing Gricean pragmatics as nested Bayesian inference (Frank & Goodman, 2012).

In this framework, listeners and speakers are represented as conditional probability distributions. Speakers are distributions  $P(U|W)$  over possible utterances given worlds, and listeners distributions  $P(W|U)$  over possible worlds given utterances, where  $W$  is the set of possible states, and  $U$  is the set of utterances available to a speaker. The most basic version of RSA (Frank & Goodman, 2012) is incapable of interpreting metaphors, due to the strict adherence to truth observed by the speaker. To address this, Kao et al. (2014) proposes a model  $L_1^Q$ , defined in (5).

$$\begin{aligned} (3) \quad L_0(w|u) &\propto \llbracket u \rrbracket(w) \cdot P_L(w) \\ (4) \quad S_1(u|w, q) &\propto \sum_{w'} \delta_{q(w)=q(w')} \cdot L_0(w'|u) \\ (5) \quad L_1^Q(w, q|u) &\propto S_1(u|q, w) \cdot P_L(w) \cdot P_{L_Q}(q) \end{aligned}$$

**The literal listener**  $L_0$  represents a model of a listener that, given an utterance  $u \in U$  updates their belief about the world  $w \in W$  in accordance with the semantics  $\llbracket \cdot \rrbracket$  and their prior  $P_L$ . This semantics, usually a function  $U \rightarrow (W \rightarrow \{0, 1\})$ , represents the conventional association between states  $w$  and utterances  $u$  which the speaker and listener take as given.

**Projections** Functions  $q \in Q$  formalize the notion of picking a particular *aspect* or *dimension* of  $w$ . Formally, they are surjective functions out of  $W$ .

**The informative speaker**  $S_1$  has a state  $w$  they want to communicate, and reasons about  $L_0$ , preferring utterances  $u$  which maximize the  $L_0$  posterior probability on  $w$ , up to the aspect of  $w$  specified by  $q$ . If  $q$  is the identity function,  $S_1(u|w) \propto L_0(w|u)$ , and is thus a model of a speaker who prefers to choose the most informative utterance available.

**The pragmatic listener**  $L_1^Q$  jointly infers values for  $w$  and  $q$ . The key dynamic is that the listener may hear an utterance  $u$  and infer a pair  $(w, q)$  where  $u$  is semantically incompatible with  $w$  (i.e.  $\llbracket u \rrbracket(w) = 0$ ) but where  $u$  conveys some aspect of  $w$  as determined by  $q$ .

We can view  $L_1^Q$  as a model of metaphor interpretation as follows, with the example of (6). Suppose that the goal of the speaker is to communicate a state  $w$ , representing what John is like. To this end, they choose a predicate  $u$ , here *shark*. Conversely, the goal of the listener on hearing (6) is to infer  $w$  as well as the *aspect* of  $w$  that the speaker cares about.

(6) John is a shark.

To make this precise, and derive predictions from  $L_1^Q$ , five things must be provided: a set  $W$  of states, a set  $U$  of utterances, a set  $Q$  of projections, a prior  $P_L$  representing the listener's uncertainty over  $W$ , and a semantics  $\llbracket \cdot \rrbracket$ . (We assume throughout that the prior  $P_{L_Q}$  over  $Q$  is uniform.) Jointly, we say that these determine an *interpretation* of  $L_1^Q$ .

One possible interpretation, similar to what is provided by Kao et al. (2014), treats points in the state space  $W$  as n-tuples of truth values, corresponding to Boolean properties  $w \in P$ . We refer to this as a *set theoretic* interpretation of  $L_1^Q$ . We give a very simple example below, for  $P = \{\text{vicious}, \text{non-human}\}$ :

- $P_L = \{(\text{vicious} = T, \text{non-human} = T) : 0.075,$   
 $(\text{vicious} = T, \text{non-human} = F) : 0.675,$   
 $(\text{vicious} = F, \text{non-human} = T) : 0.025,$   
 $(\text{vicious} = F, \text{non-human} = F) : 0.225\}$
- $U = \{\text{shark}, \text{silence}\}$
- $Q = \{q_{\text{vicious}}(\lambda(x, y) : x), \quad q_{\text{non-human}}(\lambda(x, y) : y)\}$

We assume a semantics  $\llbracket \cdot \rrbracket$  in which *shark* is compatible only with (vicious, non-human), and *silence* is compatible with every state. Note that the projections map each tuple to its value at a single property.

The results of  $L_1^Q$  hearing *shark* are shown in figure 1. The key fact to note is that the prior belief that John is not literally an animal leads  $L_1^Q$  to conclude that the speaker cares about conveying the viciousness dimension (i.e. projection  $q_{\text{vicious}}$ ), and that John is vicious.

Importantly,  $L_1^Q$  can do more than simply using prior knowledge to interpret literally false statements in a flexible way. It is also capable of reasoning about alternative utterances: for instance, suppose we add a third property, *quickness*, so that *shark* is compatible only with (vicious = T, non-human = T, quick = T), and also add a third utterance, *hummingbird*, compatible with only (vicious = F, non-human = T, quick = T).

In this second example, when  $L_1^Q$  hears *shark*, it infers that John is more likely vicious than quick. This is because a speaker who wanted to communicate that John is vicious would only be able to use the utterance *shark*, whereas a speaker who wanted to communicate that John is quick would be able to choose between either *shark* or *hummingbird*. The utterance *shark* is therefore more likely to have been produced by the speaker trying to communicate John's viciousness.

$L_1^Q$  can also model AN metaphors in a similar way. For instance, for a phrase like *fiery temper*, we say that the goal of a listener is to decide what is true of the temper in question given that the speaker has modified it with *fiery*.

## DISTRIBUTIONAL SEMANTICS

From a linguistic corpus, it is possible to obtain a mapping from words to points in a high-dimensional vector space that has the property that semantic similarity of a pair of words  $a$  and  $b$  corresponds to a metric, such as cosine distance, between the vectors  $\vec{a}$  and  $\vec{b}$ .

Mappings of this sort, commonly referred to as *word embeddings* or *distributional models of word meaning*, can be obtained either by dimensionality reduction of a co-occurrence matrix (Pennington et al., 2014), or by extracting the weights of a statistical model (Devlin, Chang, Lee, & Toutanova, 2018; Mikolov, Sutskever, Chen, Corrado, & Dean, 2013; Peters et al., 2018) trained on a separate task.

In either case, word embeddings provide a way to empirically obtain fine grained connotations of lexical items (Mikolov et al., 2013), and have been used effectively in a number of NLP tasks (Dai & Le, 2015; Radford, Narasimhan, Salimans, & Sutskever, 2018).

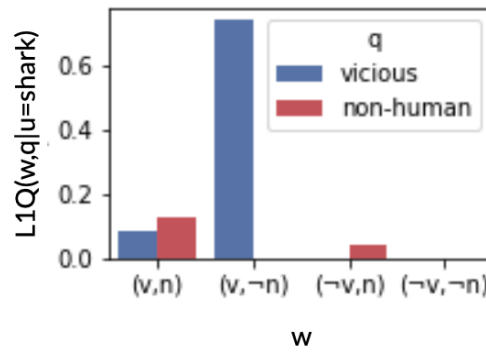


Figure 1: Figure showing the posterior distribution of  $L_1^Q$  on hearing *shark*.  $v$  and  $n$  abbreviate the Boolean variables *vicious* and *non-human* respectively.

They have also been used to compute vectorial representations of phrases and sentences (Coecke, Sadrzadeh, & Clark, 2010; Socher et al., 2013).

Metaphor is an obvious candidate for approaches that use distributional semantics: a wide variety of attempts have been made to leverage the information inherent in pre-trained word vectors for the detection, interpretation and paraphrase of metaphor (see Shutova (2016) for an overview of proposed systems.).

Our hypothesis is that, while the information in high quality word embeddings captures important aspects of meaning, a cognitively realistic model of metaphor interpretation should also incorporate Gricean reasoning, of the sort formalized in the RSA framework. We now explain how  $L_1^Q$  can be combined with a distributional model of word meaning.

### BAYESIAN PRAGMATICS WITH A DISTRIBUTIONAL SEMANTICS

The set-theoretic interpretation of  $L_1^Q$  takes states  $w \in W$  to be sets of properties describing the source of the given metaphor, and a semantics to be a function  $U \rightarrow (W \rightarrow \{0, 1\})$ .

We now introduce a *vectorial* interpretation of  $L_1^Q$ . Importantly, this requires no modification to equations (3-5). The crucial difference is that our state space  $W$  is now not just a set, but a vector space determined by a word embedding  $E : U \rightarrow W$ , so that elements  $\vec{w} \in W$  are vectors.<sup>2</sup> As before,  $U$  is a set of adjectives.

**The listener's prior** In the set-theoretic interpretation of  $L_1^Q$ , with finite  $W$ , a discrete prior  $P_L$  over  $W$  sufficed. In the present case, where  $W$  is necessarily infinite (ranging continuously over real-valued vectors), we use a multivariate spherical Gaussian distribution, which can be parametrized by a vector  $\vec{\mu}$  for the mean and a single scalar  $\sigma$  (the value of

<sup>2</sup> We note that this generalization is natural, since the set-theoretic interpretation of  $L_1^Q$  can be viewed as a special case of the vectorial interpretation, for a vector space over the Boolean field (rather than the real field). That is, consider an  $n$ -tuple of Booleans  $w$  as a vector of 0s and 1s, with  $P$  providing the basis of the space.

every diagonal entry of the covariance matrix). We define the prior over projections  $P_{L_Q}$  to be uniform.

$$(7) \quad P_L(w) = P_{\mathcal{N}}(w|\mu = E(\text{target}), \sigma = \sigma_1)$$

We can view  $P_L$  as representing uncertainty over the position of the entity or concept that the target noun (e.g. *man* in “The man is a shark”) represents.<sup>3</sup> The goal of the speaker is to convey a position in the space to the listener, and the goal of the listener is to infer what this position is. In this sense, a spatial reference game is being played (Golland, Liang, & Klein, 2010), in an abstract word embedding space.

The multidimensional Gaussian distribution weights most heavily those points nearest to its mean. By setting the mean of the prior as  $E(\text{target})$ , we encode the listener’s assumption that the meaning the speaker wishes to communicate is in the neighborhood of the source noun.  $\sigma_1$  is a hyperparameter of the model.

**The semantics** A word embedding space has no explicit representation of truth. That is to say, while we can compare the similarity of a noun and an adjective according to a variety of metrics, we do not have a means of categorically determining the compatibility of that adjective and noun.

As far as our model is concerned, this is not a problem since the definition of  $L_0$  in (3) requires only that the semantics  $\llbracket \cdot \rrbracket$  be a function  $U \rightarrow (W \rightarrow \mathbb{R})$ . We can define such a function as follows, with  $\sigma_2$  as a hyperparameter:

$$(8) \quad \llbracket u \rrbracket(w) = P_{\mathcal{N}}(w|\mu = E(\text{source}), \sigma = \sigma_2)$$

The result of this definition is that the value of  $\llbracket u \rrbracket(w)$  is a real number which decreases with the Euclidean distance between  $u$  and  $w$ . The advantage of defining a semantics in this way is that both the prior of  $L_0$ , shown in (7) and the likelihood, namely the semantics shown in (8), have the form of Gaussian distributions, which allows for a closed form solution of  $L_0$ .

**Projections** Finally, we need to supply an notion of a projection function  $q$  that is defined on our vector space, and to specify a set  $Q$  of such projections. For this, we use linear projections<sup>4</sup> along a vector (or hyperplane)  $\vec{v}$  capturing the degree to which each  $\vec{w}$  extends along  $\vec{v}$ , ignoring orthogonal dimensions. Geometrically, it can be thought of as dropping a line from an input vector  $\vec{w}$  at a right angle onto  $\vec{u}$ , as depicted in figure 2.

In practice, we restrict ourselves to projections along a vector, rather than a larger subspace. To obtain a set  $Q$  of projections, we first note that since the denotations of words are vectors in  $W$ , any word parametrizes a linear projection  $q$ . For instance, we can think of the word *vicious* as parameterizing a *viciousness* projection, which measures how far the denotations of all other points in the space fall along *vicious*. We choose  $Q$  as a set of gradable adjectives, so that the projection of a noun  $n$  onto  $\vec{v}$  amounts to asking: to what extent is  $n$   $v$ ?

<sup>3</sup> This bears comparison to the *conceptual space* semantics of Gärdenfors (2004).

<sup>4</sup> To see why this is the natural analogue of the projection functions used in the set-theoretic interpretation of  $L_1^Q$ , note that when viewed as vectors in a vector space over the Boolean field, projection functions are precisely linear projections. Alternatively, note that in either case, projections  $q$  are idempotent maps ( $W \rightarrow W$ ).

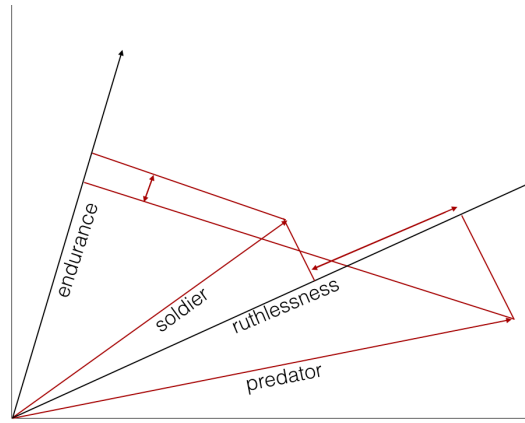


Figure 2: In this hand-constructed 2D example, vectors for  $\overrightarrow{\text{soldier}}$  and  $\overrightarrow{\text{predator}}$  are mapped onto subspaces given by  $\overrightarrow{\text{endurance}}$  and  $\overrightarrow{\text{ruthlessness}}$ .

### INFERENCE

Because  $P_L(w)$  is a continuous distribution in the vectorial interpretation of  $L_1^Q$ , inference by enumeration is no longer possible, and either analytic or approximate methods are required. We employ a mix of the two; the  $L_0$  and  $S_1$  posteriors can be calculated analytically, while  $L_1^Q$  requires us to develop an approximate inference algorithm.<sup>5</sup> We describe this algorithm in parts, working up from the  $L_0$ .

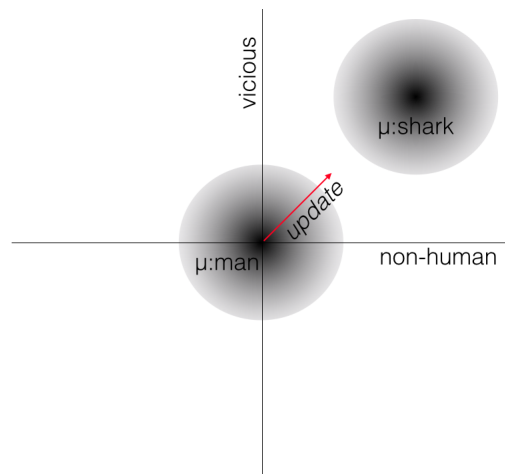


Figure 3: 2D depiction of vectorial  $L_0$ , for  $\overrightarrow{\text{man}} = (0,0)$  and  $\overrightarrow{\text{shark}} = (1,1)$ .

<sup>5</sup> Inference for all our models is implemented in Tensorflow, and will be made publicly available.



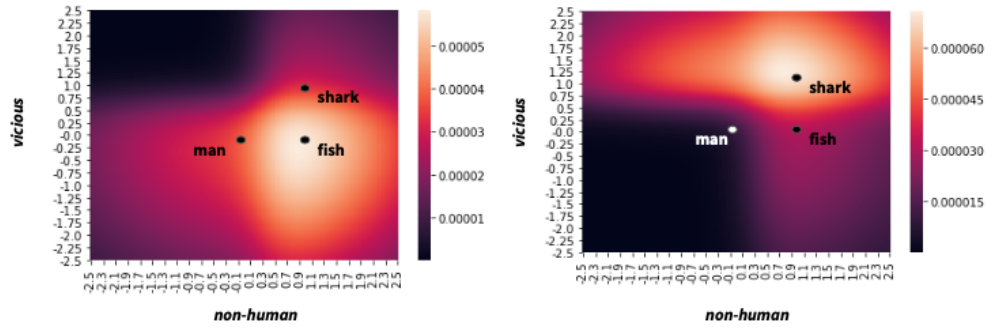


Figure 4: Heatmaps visualizing the inferred  $L_1^Q$  marginal posterior over worlds given *fish* (left) and *shark* (right), with  $U = \{man, shark, fish\}$ , hand-chosen denotations overlaid, and  $\sigma_1 = 5.0, \sigma_2 = 0.5$ .

**$L_0$  Inference** Intuitively, the vectorial interpretation of  $L_0$  amounts to the process shown in figure 3, where a ball, corresponding to the prior, is moved in the direction of the point corresponding to the received utterance. To calculate  $L_0$  analytically, we make use of Gaussian conjugacy. When the prior  $P_L$  is defined as in Equation 7, and the semantic interpretation is defined as in Equation 8, then conjugacy implies that the listener posterior is given by:

$$(9) \quad L_0(w|u) = P_{\mathcal{N}}(w|\mu = \frac{\sigma_1^2 \sigma_2^2}{\sigma_1^2 + \sigma_2^2} \cdot (\frac{E(target)}{\sigma_1^2} + \frac{E(source)}{\sigma_2^2}), \sigma = \frac{\sigma_1^2 \sigma_2^2}{\sigma_1^2 + \sigma_2^2})$$

**$S_1$  Inference** The speaker is defined by Equation 4, which in the continuous case can be rewritten as:

$$(10) \quad S_1(u|w, q) \propto \int_{w'} \delta_{q(w)=q(w')} \cdot L_0(w'|u)$$

This integral is computing the marginal probability of  $w_q$ , the projection of world  $w$  onto QUD vector  $q$ . From Equation 9,  $L_0(\cdot|u)$  is a normally distributed random variable, and therefore projection of this random variable is also normally distributed, providing a closed-form solution to  $S_1$ .

**$L_1$  Inference** The  $L_1$  posterior is a joint distribution over one continuous and one discrete random variable. Because of the linear structure of the problem, we are able to devise a near-exact inference algorithm for the marginal distribution over  $Q$ , derived as follows:

$$\begin{aligned} L_1(q|u) &= \int_w L_1(w, q|u) = \frac{1}{K} P(q) \int_w P(w) S_1(u|w, q) \\ &= \frac{1}{K} P(q) \int_w P(w_q, w^\perp) S_1(u|w_q, q) = \frac{1}{K} P(q) \int_w P(w_q) P(w^\perp) S_1(u|w_q, q) \\ &= \frac{1}{K} P(q) \int_{w^\perp \in Q^\perp} P(w^\perp) \int_{w_q \in Q} P(w_q) S_1(u|w_q, q) \\ &= \frac{1}{K} P(q) \int_{w_q \in Q} P(w_q) S_1(u|w_q, q) \end{aligned}$$



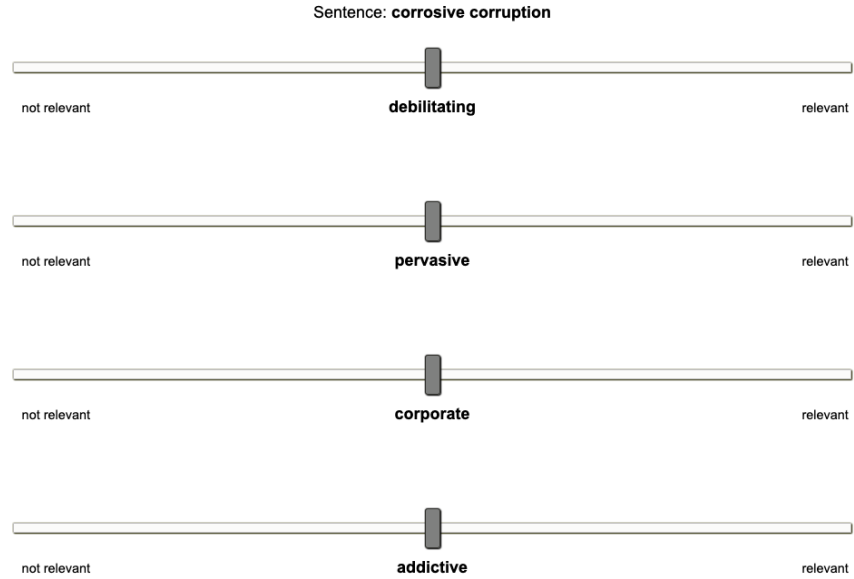


Figure 5: An item in the experiment. Item order, and in-item order of the 4 adjectives from  $L_1^Q$  and baseline models is randomized.

Here  $K = \sum_{q'} \int_{w'} P(w')P(q')S_1(u|w', q')$ .  $w, q \in \mathbb{R}^n$ , and  $w_q$  is the projection of  $w$  onto the vector  $q$ .  $Q$  is the subspace of  $\mathbb{R}^n$  spanned by the vector  $q$ , and  $Q^\perp$  is the orthogonal complement of  $Q$ . The vector  $w^\perp$  is the projection of vector  $w$  onto the subspace  $Q^\perp$ . The final equation is a one-dimensional integral, and can be computed using a discrete approximation. The constant  $K$  can be found from the constraint  $\sum_q L_1(q|u) = 1$ .

Figure 4 provides a visualization of the  $L_1^Q$  posterior in a simple 2D case corresponding to the example used for the set-theoretic example in figure 1.

#### Interpreting results from $L_1^Q$

We now have an algorithm for approximating the posterior distribution of  $L_1^Q$  after hearing a metaphor  $u$ . We convert this into an interpretable prediction by selecting the adjectives  $q \in Q$  which have high probability under the marginal posterior distribution over  $Q$  as interpretations of the metaphor.

### EXPERIMENTAL VALIDATION

In order to test our model on human judgments, we design an experiment which compares the  $L_1^Q$  interpretations of metaphors to a baseline model which uses word embeddings but no pragmatic reasoning.

**Experimental Design** (Tsvetkov, Boytsov, Gershman, Nyberg, & Dyer, 2014) provides a corpus of  $\sim 800$  AN metaphors, gathered by human annotators, of which we select  $\sim 100$  of

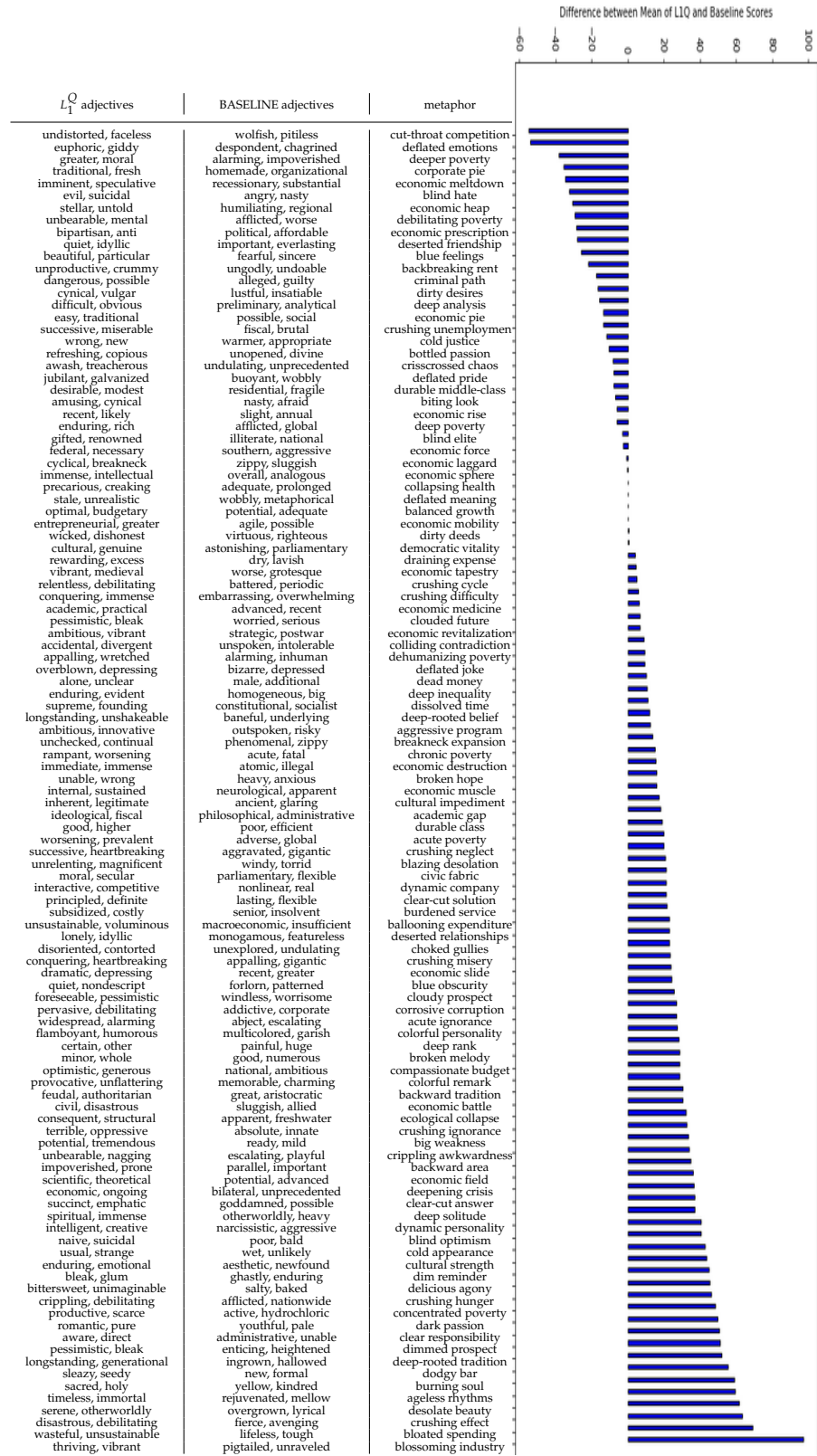


Figure 6: The 109 metaphors used in the experiment, and corresponding baseline and  $L_1^Q$  proposals, plotted against mean rating given to that metaphor under these two models.

the least frequent by bigram count<sup>6</sup> for our experiment, in order to filter out conventionalized metaphors. Our full set of 109 metaphors is shown in figure 6.

In our experiment, each participant is shown a series of 12 metaphors, selected randomly from the total 109. For each metaphor, they are asked to rate on a slider four adjectives representing interpretations of the metaphor, of which two are selected by  $L_1^Q$  and two from a baseline model (details below). An example is shown in figure 5.

The experiment was run on Mechanical Turk, with 99 participants, all of whom are native English speakers. Participants who failed to follow instructions on a test item were excluded, leaving 60 participants (although this affects results very little, which remain significant without the exclusion).

**Baseline model** The aim of our experiment is to determine whether pragmatic reasoning results in better interpretations of metaphors, according to human judgments. As such, a natural baseline model to compare against is a model with a distributional semantics that does not make use of the pragmatic reasoning process inherent in  $L_1^Q$ .

Our baseline model is defined as follows: for a given metaphor of the form  $(a\ n)$ , we take the mean of the adjective  $a$  and noun  $n$ . The two nearest adjectives  $q$  to this mean are our baseline interpretations for the metaphor. We use the mean (a weighted sum) in light of the effectiveness of vector addition in deriving representations of phrasal and sentence meanings from constituent words, see (Grefenstette, 2013; Mitchell & Lapata, 2010; Socher et al., 2013). Cosine distance is a standard metric of similarity used for word embeddings (Pennington et al., 2014).

**$L_1^Q$  hyperparameters** We use the largest available (300 dimensional) GloVe vectors, as our word embedding  $E$ . For each AN metaphor  $(a\ n)$ , we specify  $U$  as a set of 101 alternative utterances, consisting of  $a$  and 100 of the nearest adjectives (by cosine distance) to  $n$ . These adjectives are chosen from the set of the 1425 adjectives with concreteness ranking  $> 3.0$  in the concreteness corpus of (Brysbaert, Warriner, & Kuperman, 2014), to exclude abstract nouns.

Similarly, we select a set  $Q$  of projections corresponding to the hundred closest adjectives to the mean of the subject and predicate (the method of adjective choice in the baseline model), and take  $P_{L_Q}$  to be a uniform distribution over  $Q$ .

By tuning on a validation set of hand-selected metaphors, we choose  $\sigma_1 = \sigma_2 = 0.1$ . We select the adjectives corresponding to the two projections with highest marginal posterior mass under  $L_1^Q$  as the interpretations provided from our model in the experiment.

**Analysis** The data, shown in figure 6, were analyzed using a mixed-effects model with random slopes and intercepts for items and participants. The target interpretations were rated significantly higher than the baseline interpretations ( $\beta=13.8$ ,  $t=5.3$ ,  $p<0.001$ ).

## DISCUSSION

<sup>6</sup> N-grams data from the Corpus of Contemporary American English (Davies, 2011).

The significant improvement of  $L_1^Q$  over a model with the same semantics but no pragmatic reasoning provides evidence that this reasoning is key to obtaining human-like interpretations of metaphors.

In building a tractable inference algorithm for  $L_1^Q$ , we have also shown that the technical challenges in adapting a nested Bayesian model of pragmatics to a continuous setting are not insurmountable. We see this as an important step towards an open domain model of pragmatic language interpretation and production.

## REFERENCES

- Brysbaert, M., Warriner, A. B., & Kuperman, V. (2014). Concrete-ness ratings for 40 thousand generally known english word lemmas. *Behavior research methods*, 46(3), 904–911.
- Coecke, B., Sadrzadeh, M., & Clark, S. (2010). Mathematical foundations for a compositional distributional model of meaning. *arXiv preprint arXiv:1003.4394*.
- Dai, A. M., & Le, Q. V. (2015). Semi-supervised sequence learning. In *Advances in neural information processing systems* (pp. 3079–3087).
- Davies, M. (2011). Word frequency data: Corpus of contemporary american english. *Provo, UT: COCA*.
- Devlin, J., Chang, M.-W., Lee, K., & Toutanova, K. (2018). Bert: Pre-training of deep bidirectional transformers for language understanding. *arXiv preprint arXiv:1810.04805*.
- Frank, M. C., & Goodman, N. D. (2012). Predicting pragmatic reasoning in language games. *Science*, 336(6084), 998–998.
- Gärdenfors, P. (2004). *Conceptual spaces: The geometry of thought*. MIT press.
- Golland, D., Liang, P., & Klein, D. (2010). A game-theoretic approach to generating spatial descriptions. In *Proceedings of the 2010 conference on empirical methods in natural language processing* (pp. 410–419).
- Grefenstette, E. (2013). Category-theoretic quantitative compositional distributional models of natural language semantics. *arXiv preprint arXiv:1311.1539*.
- Grice, H. P. (1975). Logic and conversation. 1975, 41–58.
- Kao, J. T., Bergen, L., & Goodman, N. (2014). Formalizing the pragmatics of metaphor understanding. In *Cogsci*.
- Lakoff, G., & Johnson, M. (1980). *Metaphors we live by*. Chicago, IL: University of.
- Mikolov, T., Sutskever, I., Chen, K., Corrado, G. S., & Dean, J. (2013). Distributed representations of words and phrases and their compositionality. In *Advances in neural information processing systems* (pp. 3111–3119).
- Mitchell, J., & Lapata, M. (2010). Composition in distributional models of semantics. *Cognitive science*, 34(8), 1388–1429.
- Pennington, J., Socher, R., & Manning, C. D. (2014). Glove: Global vectors for word representation. In *Emnlp* (Vol. 14, pp. 1532–1543).
- Peters, M. E., Neumann, M., Iyyer, M., Gardner, M., Clark, C., Lee, K., & Zettlemoyer, L. (2018). Deep contextualized word representations. *arXiv preprint arXiv:1802.05365*.
- Radford, A., Narasimhan, K., Salimans, T., & Sutskever, I. (2018). *Improving language understanding with unsupervised learning* (Tech. Rep.). Technical report, OpenAI.
- Shutova, E. (2016). Design and evaluation of metaphor processing systems. *Computational Linguistics*.
- Socher, R., Perelygin, A., Wu, J., Chuang, J., Manning, C. D., Ng, A., & Potts, C. (2013). Recursive deep models for semantic compositionality over a sentiment treebank. In *Proceedings of the 2013 conference on empirical methods in natural language processing* (pp. 1631–1642).
- Tsvetkov, Y., Boytsov, L., Gershman, A., Nyberg, E., & Dyer, C. (2014). Metaphor detection with cross-lingual model transfer. In *Proceedings of the 52nd annual meeting of the association for computational linguistics (volume 1: Long papers)* (Vol. 1, pp. 248–258).