

**Learning word meaning by inferring speakers' intentions:
An incremental approach to socially-guided statistical learning**

Michael C. Frank, Molly L. Lewis, Mika Braginsky, & Noah D. Goodman
Department of Psychology, Stanford University

Many thanks to ...

Please address correspondence to Michael C. Frank, Department of Psychology, Stanford University, 450 Serra Mall (Jordan Hall), Stanford, CA, 94305, tel: (650) 724-4003, email: mcfrank@stanford.edu.

Abstract

How do children learn the meanings of words? While some accounts suggest that word learning happens in a single moment, others privilege the gradual accumulation of information across time. Previous modeling work has attempted to unify these viewpoints in a single framework that allows for both in-the-moment interpretation and gradual statistical accumulation, but at the cost of substantial computational complexity. We describe a new, incremental model of this interaction, in which statistical associations are the product of in-the-moment interpretations. This process-level model successfully captures a number of experimental findings and suggests a number of extensions.

Introduction

Word learning is a fundamental part of language acquisition. Starting slowly in late infancy and speeding up after their first birthday, children accumulate a vocabulary of words that they can reliably recognize and produce (Bergelson & Swingley, 2012; Bloom, 2002). The exact timing of this process is highly variable across children, but generally by the end of the second year, children can produce several hundred words and are well on their way to combining these to express complex and novel propositions (R. Brown, 1973; Fenson et al., 1994). How are these early words learned?

In this paper, we elaborate an answer to this question that combines children’s statistical learning abilities (Saffran, Newport, & Aslin, 1996; Aslin & Newport, 2012) with their emerging competence in social interaction (Carpenter, Nagell, Tomasello, Butterworth, & Moore, 1998). Our proposal is that vocabulary is accumulated via a process in which children attempt to interpret the language they hear, and then retain guesses about the meanings of words based on these interpretations. Building on a previous model of joint interpretation and language learning (Frank, Goodman, & Tenenbaum, 2009), we implement this proposal in the language of probabilistic modeling. Our model instantiates the idea that there are two timescales involved in word learning (cf. McMurray, Horst, & Samuelson, 2012): in-the-moment interpretation, and cross-situational mapping.

Our model constitutes an incremental approach to integrating across timescales: For each utterance, it proposes a possible referential interpretation, then updates a graded lexicon accordingly. Although the model is incremental, it nevertheless instantiates normative Bayesian inferences; in this respect it is a “rational process model” that makes normative probabilistic inferences under cognitive resource constraints (Griffiths, Vul, & Sanborn, 2012; Sanborn, Griffiths, & Navarro, 2010). We compare this incremental, process-level inference algorithm with

a batch inference algorithm that considers all the available data and find that they are surprisingly similar to one another. One radical consequence of this approach is that there is no separate process of “word learning”; instead word learning is what falls out of learners remembering their best guesses about what a particular piece of language meant in the contexts of its use.

In what follows, we briefly motivate our proposal with respect to the previous literature on children’s word learning. We then review prior computational models of word learning with the goal of grounding and highlighting our conceptual contributions. We then present our model and show that it can be both applied to annotated corpora of child language and can be used to simulate individual experiments. We end by considering open questions for the field of early language learning.

Mechanisms of early word learning

One clue to the mechanisms of early vocabulary learning comes from the makeup of children’s early vocabulary. Although children produce words of all different types, certain kinds of words are nevertheless overrepresented in early vocabulary. Names for things make up a substantially larger proportion of children’s early vocabulary than they do later (Tardif et al., 2008; Caselli et al., 1995), alongside names for people and words used in simple social routines (e.g., “hi” and “bye”). Many observers have suggested that these kinds of words—especially basic-level nouns—are learned early because of the ease with which the linguistic form can be mapped to a particular observable referent (Locke, 1700; Bloom, 2002; Clark, 2003). From there, generalizing particular referents to a broader class of referents is relatively trivial, given that the relevant concepts are typically at the basic-level and typically represent whole objects rather than parts (Markman, 1991).

A single learning instance can in principle provide strong evidence for a particular word meaning. For example, imagine that a parent points to a ball and says “ball!” An observer with an

understanding of pointing can infer that the speaker is referring to the ball, infer that the concurrently uttered word refers to it, and generalize to the broader concept of balls in general. In practice, however, very young children typically require several exposures to a word before they recognize it and retain it for future use, even when the context of naming is unambiguous (Woodward, Markman, & Fitzsimmons, 1994).

In addition, many learning situations range from slightly to substantially more ambiguous. Imagine that the parent had uttered the phrase “look at that nice, round ball!”—this phrase has a number of competing words that might be candidates for the object name (though perhaps worse candidates by virtue of sentential position, stress, or phonological structure). Or the parent might not have pointed but instead relied on the fact that the child was playing with the ball. Perhaps there might have been other toys present competing for the child’s attention. In each of these cases, the child might be able to guess that the word “ball” referred to the ball, but with less certainty than in the simplest case (Yurovsky, Smith, & Yu, 2013, gives a concrete instantiation of such differences in certainty in naturalistic play session videos).

While such ambiguous cases might not license strong inferences about word meaning, many theorists have noted that learners in principle could accumulate information across instances (Pinker, 1984; Gleitman, 1990; Siskind, 1996; Yu & Ballard, 2007). This strategy, dubbed *cross-situational learning*, has now been demonstrated in a number of small-scale laboratory experiments with both adults and children (Yu & Ballard, 2007; L. Smith & Yu, 2008). In addition, a number of computational demonstrations suggest that this kind of strategy could be effective for learning in social situations (Yu & Smith, 2007; Frank et al., 2009; Johnson, Demuth, & Frank, 2012), with realistic vocabulary sizes and levels of ambiguity (Blythe, Smith, & Smith, 2010), and even with more complex propositional meanings (Siskind, 1996). In fact, a growing literature in natural language processing implements precisely this strategy for a variety of what

are known as “grounded language learning” tasks (e.g. Zettlemoyer & Collins, 2005; Wong & Mooney, 2007; Artzi & Zettlemoyer, 2013; Liang, Jordan, & Klein, 2011; Kim & Mooney, 2013).

Nevertheless, the existence of such an uncertainty-reduction strategy does not necessarily imply that learners make use of it. Indeed, there has been substantial debate about the degree to which learners represent cross-situational statistics (Medina, Snedeker, Trueswell, & Gleitman, 2011; Yu & Smith, 2012; Yurovsky et al., 2013; Trueswell, Medina, Hafri, & Gleitman, 2013; K. Smith, Smith, & Blythe, 2011; Yurovsky & Frank, under review). On some accounts, learners encode only a single hypothesis at a time; on others, learners maintain some representation of all of the data that they have access to. But regardless of the specific representation and algorithm that learners use for this process, all accounts of cross-situational learning posit *consistency* across situations, which even single-hypothesis learners exploit by checking their hypotheses across situations (Trueswell et al., 2013; Yu & Smith, 2012). To understand the range of possible theories of cross-situational learning, we next turn to the modeling literature.

Prior modeling work

Although a number of theorists had discussed cross-situational strategies for learning word meanings (Pinker, 1984; Gleitman, 1990), an important early instantiation of this idea came from a model by Siskind (1996). This model used a propositional representation of meaning in combination with a set of deductive rules to infer word-meaning mappings from artificial data. This ambitious model provided a powerful proof-of-concept, but was limited by the assumption that the propositional structure of meanings was observed by the learner.

An alternate, more graded, view of word learning came from the connectionist tradition. Plunkett, Sinha, Møller, and Strandsby (1992) described a graded word-image mapping model that reproduced a number of category generalization and vocabulary growth phenomena. This basic model type has been followed by a number of related models that capture phenomena like

mutual exclusivity (Regier, 2005), the phonological dynamics of the mono- and bilingual lexicon (Li & Farkas, 2002; Li, Farkas, & MacWhinney, 2004; Li, Zhao, & Whinney, 2007), and the emergence of categorization principles (Mayor & Plunkett, 2010). Nevertheless, none of these models focused specifically on the challenge of disambiguating reference in ambiguous contexts.

The problem of referential uncertainty played a more central role in a number of other models that emerged from the machine learning tradition. In a series of systems, Yu and colleagues developed a model stemming from classic machine translation systems (P. Brown, Pietra, Pietra, & Mercer, 1993). This model looked for correspondences between words and their referents that was consistent across situations; these mappings could be biased by a number of perceptual and social aspects of the learning scenario (Yu, Ballard, & Aslin, 2005; Yu & Ballard, 2007). Critically, these models could be applied to annotated corpora of child-directed speech, a major advance over previous work that had only been applied to artificial corpora.

A complementary probabilistic model considered how generalization biases could emerge from statistical inferences under ambiguity across situations (Xu & Tenenbaum, 2007). This model was able to predict adults' and children's patterns of taxonomic generalization by reference to general principles of probabilistic inference. Although it did not specifically apply to the problem of referential uncertainty across situations, it nevertheless aggregated information across exposures to make graded inferences about word meaning.

Building on these two lines of work, we proposed a probabilistic treatment of referential uncertainty in Frank et al. (2009). This model differed from earlier approaches in that it explicitly assumed that in any individual situation, speakers have an intention to refer to a particular object or objects and that the labels they utter correspond to these words. In contrast, previous models had computed associations directly between words and referents, without considering that some of these associations were not relevant because the speaker might not be trying to refer to some

objects. This “intentional” assumption led to an increase in accuracy in learning from corpus data relative to previous work, and also allowed the model to capture a number of experimental findings. A number of related pieces of work have extended this model to incorporate word segmentation (Johnson, Demuth, Frank, & Jones, 2010), social cues (Frank, Ichinco, & Tenenbaum, 2008; Johnson et al., 2012), conceptual generalization (Lewis & Frank, 2013a), lexical constraints (Lewis & Frank, 2013b), some basic aspects of grammatical structure (Johnson et al., 2010), and even pragmatic inference (N. J. Smith, Goodman, & Frank, 2013).

The basic framework described in Frank et al. (2009) nevertheless suffered from a number of weaknesses. First, it posited a discrete lexicon represented by a bipartite graph linking words and object concepts. While this representation was technically convenient, it seemed at odds with the conception of graded, uncertain mappings implied by the experimental literature.¹ In addition, the model was posed at Marr’s (1982) “computational theory” level; as such, it considered all the available data in its computation. This “batch” inference was of course unrealistic in terms of the memory constraints on learners; in addition, practically speaking it kept the model from considering phenomena that involved the gradual accumulation of data about a particular inference. Finally, because of technical limitations, the inference scheme in this model was not fully Bayesian: It did not recover the posterior probability distribution on lexicons given a particular exposure. Instead, it only searched for the single best lexicon.

One important parallel development has come from expansions of the Yu and Ballard (2007) translation model. Fazly, Alishahi, and Stevenson (2010) described an incremental version

¹Although there is debate about the uncertainty implied by adult cross-situational learning experiments (e.g. C. Smith & Frank, 2012; Trueswell et al., 2013), many experiments with children imply increases in word recognition accuracy with greater experience (e.g. Fernald, Pinto, Swingley, Weinberg, & McRoberts, 1998; Bergelson & Swingley, 2012). Thus, some sort of graded conception of the lexicon appears to be an important aspect of models that hope to capture such findings.

of this model, which they applied to meaning representations derived from speech in CHILDES. This model reproduced a number of empirical findings in the incremental context. In addition, the meaning representations were graded distributions over the full inventory of lexical elements. Both of these desirable features point the way towards applications of this model; indeed, it has been extended to simulate cognitive constraints (Nematzadeh, Fazly, & Stevenson, 2012), individual differences in acquisition (Nematzadeh, Fazly, & Stevenson, 2011), and the effects of syntactic structure (Alishahi & Fazly, 2010). Nevertheless, this model has no obvious route for the accommodation of social information.

A second important development in incremental modeling of cross-situational learning is the model described by McMurray et al. (2012). These authors introduce a connectionist model that—like the Frank et al. (2009) model—explicitly operates at two timescales: the timescale of language interpretation in the moment and the timescale of cross-situational mapping. Because of the incremental nature of this model, however, it is able to simulate the dynamics of reference resolution in the moment. In addition, the exhaustive set of simulations using this model suggests that the combination of graded representation, incremental processing, and multi-timescale inference allows this model to capture most of the relevant data points. Similar to the Fazly et al. (2010) model, however, the one major lacuna in this set of simulations is social learning phenomena.

The current model

Taken together, the models presented by Frank et al. (2009), Fazly et al. (2010), and McMurray et al. (2012) synthesize and unify a striking amount of work on the mechanisms and dynamics of early word learning. Each of these has some features that could be improved upon, however. In particular, the Frank et al. (2009) model is non-incremental, while the Fazly et al. (2010), and McMurray et al. (2012) models fail to consider social information. Our goal in the

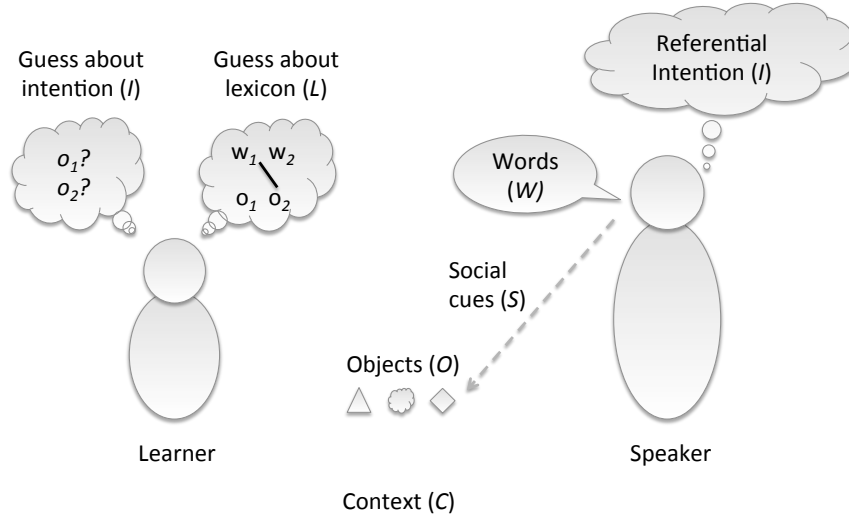


Figure 1. A schematic depiction of the learning situation, with the relevant variables marked for ease of interpretation. The learner faces a joint inference problem: inferring what the speaker is talking about and learning the consistent meanings of words. Reprinted from ? (?).

current work is thus to provide an incremental interpretation of the Frank et al. (2009) model, which would serve to unify the social framework in that work with the findings of these other incremental models.

Model

In the sections that follow, we describe the formal specification of our model as well as two inference algorithms—a batch Gibbs sampler and an incremental particle filter—that are focused around referential interpretation. As will become clear, these two inference algorithms are deeply related to one another. All code and data for the model and simulations reported below are available at <http://github.com/mcfrank/dmww>.

The schematic word learning situation is shown in Figure 1. The learner is hypothesized to jointly infer the speaker’s referential intention, I , and the lexicon of their language, L . These

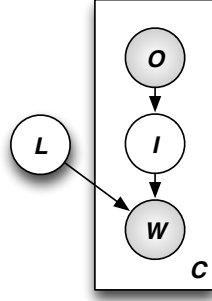


Figure 2. The generative model assumed in our current work, similar to Frank et al. (2009). The plate over contexts indicates that objects, words, and referential intentions are present in each context, while the lexicon stays constant across contexts. [should update this fig with reference variables... also not currently mentioned in main text.]

inferences are informed by the elements of the context, C : the words, W , that the speaker utters, the relevant referents (objects O) that are present in the situation, and potentially auxiliary social cues.

The generative model

A sketch of the generative model is shown in Figure 2. We will write \vec{W} for all utterances across contexts, W^i for the utterance in the i th context, and W_j^i for its j th word; similar for other variables.

Our primary departure from (Frank et al., 2009) is to assume that the lexicon places a distribution over all words for each object, rather than being a discrete association from objects to words. That is, we smooth the previous model by allowing some probability that an unusual word is used to refer to an object. Formally we assume each the lexical entry for each object (type) is a distribution over words drawn from a symmetric Dirichlet distribution:

$$L_{ob} \sim \text{Dirichlet}(\alpha) \quad (1)$$

Where *ob* can be any object in the world and can also be the special “object” *NR*, which accounts for all non-referential words. [should we talk about them as objects or categories?] The words themselves will be drawn below from multinomial distributions with parameters determined by L_{ob} .

Following (Frank et al., 2009) we assume that speakers have simple intentions to refer to objects in the context. For current purposes we simplify by assuming speakers intend to refer to only one object, and that they will refer to each possible object with equal probability. Thus $I^i \in O^i$ and $P(I^i|O^i) = \frac{1}{|O^i|}$. [This is where we put social cues.. either intention directly depends on social cues, $P(I^i|O^i, S^i)$, or social cues depend on intention, which still leads to a distribution on intentions that depends on social cues.]

We next assume that speakers realize their intention by deciding which word in the utterance should be the referring word, generating this word appropriately using the lexicon, and then generating “non-referring” words for the remainder of the utterance.² That is, for an utterance of N_i words there is a variable $r^i \in \{1, \dots, N_i, \emptyset\}$ that determines which word realizes the referential intention. The probability that $r^i = \emptyset$ (i.e. no word realizes the referential intention) is a fixed constant, and r^i has equal probability for the other words. Words are then drawn from either the distribution specified by the lexicon for the intention object or the *NR* non-referential item:

$$W_j^i \sim \begin{cases} \text{Multinomial}(L_{I^i}) & \text{if } r^i = j \\ \text{Multinomial}(L_{NR}) & \text{else} \end{cases} \quad (2)$$

Note that for any j , $\emptyset \neq j$ and as a result *no* word in the utterance is referring when $r^i = \emptyset$. [do we need to give $P(W_j^i|...)$ or is the stats notation enough?]

²This is a departure from (Frank et al., 2009) where it was assumed that each word might refer to an object independent of whether another word also referred to that object. That is, here we assume that the pressure to refer can be “satisfied” by one word, leaving the other words to play other (non-referential) roles.

The words in the utterance are independent given r^i , I^i , and L , hence:

$$P(W^i|r^i, I^i, L) = \prod_{j=1..N} P(W_j^i|r^i, I^i, L) \quad (3)$$

Learning at the computational level

We assume that the words, \vec{W} , and objects, \vec{O} , are fully observed in the learning contexts, and hence the problem for the learner is to infer the lexicon, L , and the intentions and referential words, \vec{I} and \vec{r} . By Bayes' rule:

$$P(\vec{I}, \vec{r}, L | \vec{W}, \vec{O}) \propto P(\vec{W} | \vec{I}, \vec{r}, L, \vec{O}) P(\vec{I}, \vec{r}, L | \vec{O}).$$

By assumption \vec{W} depends on the context only through the intention, \vec{I} , while \vec{r} and L are a priori independent of the other variables. In addition, inferences in different contexts are independent, given L , hence:

$$P(\vec{I}, \vec{r}, L | \vec{W}, \vec{O}) \propto P(\vec{W} | \vec{I}, \vec{r}, L) P(\vec{I} | \vec{O}) P(\vec{r}) P(L) \quad (4)$$

$$\propto P(L) \prod_i P(W^i | I^i, r^i, L) P(I^i | O^i) P(r^i) \quad (5)$$

While the learner must jointly consider intentions and lexical meanings, it is only the posterior on lexica, $P(L | \vec{W}, \vec{O})$, that impacts future language use or learning (that is, L screens off previous contextual variables from future). Thus, the task of the learner in the moment can be seen as integrating out the contextual variables (and then updating lexicon beliefs):

$P(L | \vec{W}, \vec{O}) = \sum_{\vec{I}, \vec{r}} P(\vec{I}, \vec{r}, L | \vec{W}, \vec{O})$. We next describe two algorithmic, sampling-based strategies for integrating the context variables.

Sequential learning

Imagine that we know the posterior on lexica for some amount of learning data, $P(L | \vec{W}, \vec{O})$, and then observe an additional context, w and o . The full posterior can be written as:

$$P(L | \vec{W}, \vec{O}, w, o) \propto P(w | o, L) P(L | \vec{W}, \vec{O}).$$

[ok, now we need to talk about sampling... where does conjugacy go?]

Thus, we construct a learner who focusses on interpreting the intention, I , and it's realization, r , in the moment, but uses these inferences to update beliefs about the lexicon, L , and it is these updated lexical beliefs that get carried forward into the future.

Batch learning

In the full generative model the contexts are exchangeable: the order of contexts doesn't impact the overall probability. This means that we could always pretend a particular context was the last one. This idea gives rise to the *Gibbs sampling* strategy: rather than building a sample incrementally as above, start with any assignment of context variables and then update by selecting a context, pretending it is the last, and sampling using Equation XX.

Simulations

Corpus simulations

Cross-situational word learning with adults

Yu & Smith (2007).

Experiments with children

Disambiguation.

Dewar & Xu (2007).

Discussion

Open questions for the cross-situational, social viewpoint

Synergies with other problems.

Extensions to other parts of the vocabulary.

Representations supporting cross-situational word learning. (Yurovsky & Frank, under review)

Conclusions

References

- Alishahi, A., & Fazly, A. (2010). Integrating syntactic knowledge into a model of cross-situational word learning. In *Proc. of cogsci* (Vol. 10).
- Artzi, Y., & Zettlemoyer, L. S. (2013). Weakly supervised learning of semantic parsers for mapping instructions to actions. *Transactions of the Association for Computational Linguistics, 1*, 49–62.
- Aslin, R. N., & Newport, E. L. (2012). Statistical learning from acquiring specific items to forming general rules. *Current directions in psychological science, 21*, 170–176.
- Bergelson, E., & Swingley, D. (2012). At 6–9 months, human infants know the meanings of many common nouns. *Proceedings of the National Academy of Sciences, 109*, 3253–3258.
- Bloom, P. (2002). *How children learn the meanings of words*. Cambridge, MA: MIT Press.
- Blythe, R. A., Smith, K., & Smith, A. D. (2010). Learning times for large lexicons through cross-situational learning. *Cognitive Science, 34*, 620–642.
- Brown, P., Pietra, V., Pietra, S., & Mercer, R. (1993). The mathematics of statistical machine translation: Parameter estimation. *Computational linguistics, 19*, 263–311.
- Brown, R. (1973). *A first language: The early stages*. Harvard U. Press.
- Carpenter, M., Nagell, K., Tomasello, M., Butterworth, G., & Moore, C. (1998). Social cognition, joint attention, and communicative competence from 9 to 15 months of age. *Monographs of the society for research in child development, 63*.
- Caselli, M., Bates, E., Casadio, P., Fenson, J., Fenson, L., Sanderl, L., & Weir, J. (1995). A cross-linguistic study of early lexical development. *Cognitive Development, 10*, 159–199.
- Clark, E. (2003). *First language acquisition*. Cambridge, UK: Cambridge University Press.
- Fazly, A., Alishahi, A., & Stevenson, S. (2010). A probabilistic computational model of cross-situational word learning. *Cognitive Science, 34*, 1017–1063.

- Fenson, L., Dale, P., Reznick, J., Bates, E., Thal, D., Pethick, S., . . . Stiles, J. (1994). Variability in early communicative development. *Monographs of the society for research in child development*, 59.
- Fernald, A., Pinto, J., Swingley, D., Weinberg, A., & McRoberts, G. (1998). Rapid gains in speed of verbal processing by infants in the 2nd year. *Psychological Science*, 9, 228.
- Frank, M. C., Goodman, N. D., & Tenenbaum, J. B. (2009). Using speakers' referential intentions to model early cross-situational word learning. *Psychological Science*, 20, 578–585.
- Frank, M. C., Ichinco, D., & Tenenbaum, J. B. (2008). Principles of generalization for learning sequential structure in language. In *Proceedings of the 30th annual meeting of the cognitive science society*.
- Gleitman, L. (1990). The structural sources of verb meanings. *Language Acquisition*, 3–55.
- Griffiths, T. L., Vul, E., & Sanborn, A. N. (2012). Bridging levels of analysis for probabilistic models of cognition. *Current Directions in Psychological Science*, 21, 263–268.
- Johnson, M., Demuth, K., & Frank, M. (2012). Exploiting social information in grounded language learning via grammatical reduction. In *Acl*. Retrieved from <http://www.aclweb.org/anthology/P12-1093>
- Johnson, M., Demuth, K., Frank, M., & Jones, B. (2010). Synergies in learning words and their referents. *Advances in Neural Information Processing Systems*.
- Kim, J., & Mooney, R. J. (2013). Adapting discriminative reranking to grounded language learning. In *Acl*. Retrieved from <http://www.cs.utexas.edu/users/ml/papers/kim.acl13.pdf>
- Lewis, M., & Frank, M. C. (2013a). An integrated model of concept learning and word-concept mapping. In *Proceedings of the 35th Annual Conference of the Cognitive Science Society*.
- Lewis, M., & Frank, M. C. (2013b). Modeling disambiguation in word learning via multiple

- probabilistic constraints. In *Proceedings of the 35th Annual Conference of the Cognitive Science Society*.
- Li, P., & Farkas, I. (2002). A self-organizing connectionist model of bilingual processing. *Bilingual sentence processing*, 59–85.
- Li, P., Farkas, I., & MacWhinney, B. (2004). Early lexical development in a self-organizing neural network. *Neural Networks*, 17, 1345–1362.
- Li, P., Zhao, X., & Whinney, B. (2007). Dynamic self-organization and early lexical development in children. *Cognitive Science: A Multidisciplinary Journal*, 31, 581–612.
- Liang, P., Jordan, M. I., & Klein, D. (2011). Learning dependency-based compositional semantics. In *Association for computational linguistics (acl)*.
- Locke, J. (1700). *An essay concerning human understanding*.
- Markman, E. M. (1991). *Categorization and naming in children: Problems of induction*. The MIT Press.
- Marr, D. (1982). *Vision: A computational investigation into the human representation and processing of visual information*. New York, NY: Henry Holt and Co.
- Mayor, J., & Plunkett, K. (2010). A neurocomputational account of taxonomic responding and fast mapping in early word learning. *Psychological review*, 117, 1.
- McMurray, B., Horst, J., & Samuelson, L. (2012). Using your lexicon at two timescales: Investigating the interplay of word learning and recognition. *Psychological Review*, 119, 831–877.
- Medina, T., Snedeker, J., Trueswell, J., & Gleitman, L. (2011). How words can and cannot be learned by observation. *Proceedings of the National Academy of Sciences*, 108, 9014.
- Nematzadeh, A., Fazly, A., & Stevenson, S. (2011). A computational study of late talking in word-meaning acquisition. In *Proceedings of the 33rd annual conference of the cognitive*

- science society* (pp. 705–710).
- Nematzadeh, A., Fazly, A., & Stevenson, S. (2012). A computational model of memory, attention, and word learning. In *Proceedings of the 3rd workshop on cognitive modeling and computational linguistics* (pp. 80–89).
- Pinker, S. (1984). *Language learnability and language development*. Cambridge, MA: Harvard University Press.
- Plunkett, K., Sinha, C., Møller, M., & Strandsby, O. (1992). Symbol grounding or the emergence of symbols? vocabulary growth in children and a connectionist net. *Connection Science*, 4, 293–312.
- Regier, T. (2005). The emergence of words: Attentional learning in form and meaning. *Cognitive Science: A Multidisciplinary Journal*, 29, 819–865.
- Saffran, J. R., Newport, E., & Aslin, R. (1996). Word segmentation: The role of distributional cues. *Journal of memory and language*, 35, 606–621.
- Sanborn, A. N., Griffiths, T. L., & Navarro, D. J. (2010). Rational approximations to rational models: alternative algorithms for category learning. *Psychological review*, 117, 1144.
- Siskind, J. M. (1996). A computational study of cross-situational techniques for learning word-to-meaning mappings. *Cognition*, 61, 39-91.
- Smith, C., & Frank, M. (2012). Zero anaphora and object reference in japanese child-directed speech. In *Proceedings of the 33rd Annual Meeting of the Cognitive Science Society*.
- Smith, K., Smith, A. D., & Blythe, R. A. (2011). Cross-situational learning: An experimental study of word-learning mechanisms. *Cognitive Science*, 35, 480–498.
- Smith, L., & Yu, C. (2008). Infants rapidly learn word-referent mappings via cross-situational statistics. *Cognition*, 106, 1558–1568.
- Smith, N. J., Goodman, N., & Frank, M. (2013). Learning and using language via recursive

- pragmatic reasoning about other agents. In *Advances in neural information processing systems* (pp. 3039–3047).
- Tardif, T., Fletcher, P., Liang, W., Zhang, Z., Kaciroti, N., & Marchman, V. A. (2008). Baby's first 10 words. *Developmental Psychology*, *44*, 929.
- Trueswell, J. C., Medina, T. N., Hafri, A., & Gleitman, L. R. (2013). Propose but verify: Fast mapping meets cross-situational word learning. *Cognitive psychology*, *66*, 126–156.
- Wong, Y. W., & Mooney, R. J. (2007). Learning synchronous grammars for semantic parsing with lambda calculus. In *Acl*. Retrieved from <http://www.cs.utexas.edu/users/ai-lab/?wong:acl07>
- Woodward, A., Markman, E., & Fitzsimmons, C. (1994). Rapid word learning in 13-and 18-month-olds. *Developmental Psychology*, *30*, 553–566.
- Xu, F., & Tenenbaum, J. (2007). Word Learning as Bayesian Inference. *Psychological Review*, *114*, 245.
- Yu, C., & Ballard, D. (2007). A unified model of early word learning: Integrating statistical and social cues. *Neurocomputing*, *70*, 2149–2165. Retrieved from <http://linkinghub.elsevier.com/retrieve/pii/S092523120600508X>
- Yu, C., Ballard, D., & Aslin, R. (2005). The role of embodied intention in early lexical acquisition. *Cognitive Science: A Multidisciplinary Journal*, *29*, 961–1005.
- Yu, C., & Smith, L. (2007). Rapid word learning under uncertainty via cross-situational statistics. *Psychological Science*, *18*, 414–420.
- Yu, C., & Smith, L. B. (2012). Modeling cross-situational word–referent learning: Prior questions. *Psychological review*, *119*, 21.
- Yurovsky, D., & Frank, M. C. (under review). An integrative account of constraints on cross-situational word learning.

- Yurovsky, D., Smith, L. B., & Yu, C. (2013). Statistical word learning at scale: the baby's view is better. *Developmental science*, 16, 959–966.
- Zettlemoyer, L. S., & Collins, M. (2005). Learning to Map Sentences to Logical Form: Structured Classification with Probabilistic Categorical Grammars. In *Uai*.

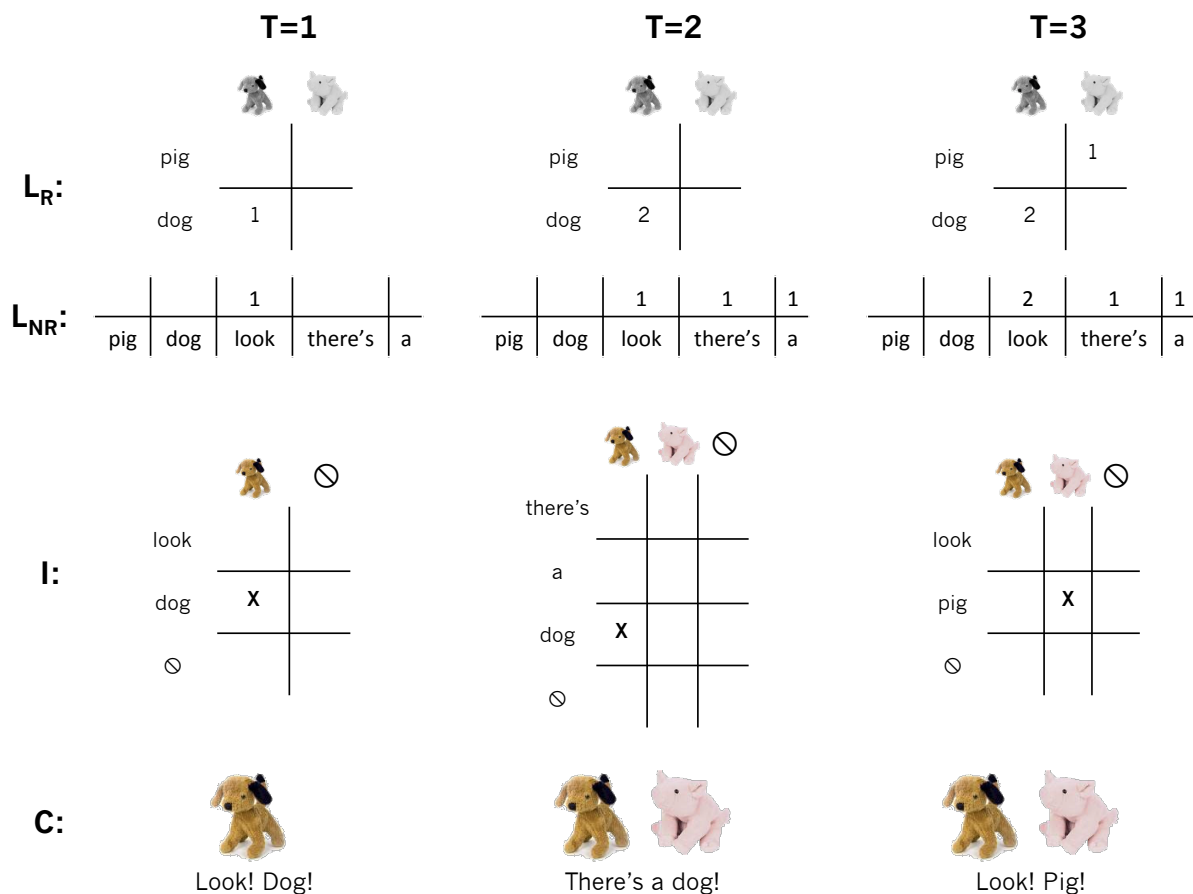


Figure 3. A schematic of the model’s evolving internal states when applied to a simple corpus with three contexts (marked $T = 1, 2, 3$). States are shown for the particle filter inference algorithm with a single particle. Show at the top are the referential and non-referential lexicons (for simplicity, only the words “pig” and “dog” are shown in the referential lexicon). In the middle, the model’s guesses about the referential correspondence between words and objects are shown for each situation.