

# Toward Conditional Models of Identity Uncertainty with Application to Proper Noun Coreference

Andrew McCallum<sup>†</sup>

<sup>†</sup>Department of Computer Science  
University of Massachusetts Amherst  
Amherst, MA 01003 USA  
mccallum@cs.umass.edu

Ben Wellner<sup>†\*</sup>

<sup>\*</sup>The MITRE Corporation  
202 Burlington Road  
Bedford, MA 01730 USA  
wellner@cs.umass.edu

## Abstract

Coreference analysis, also known as record linkage or identity uncertainty, is a difficult and important problem in natural language processing, databases, citation matching and many other tasks. This paper introduces several discriminative, conditional-probability models for coreference analysis, all examples of undirected graphical models. Unlike many historical approaches to coreference, the models presented here are relational—they do not assume that pairwise coreference decisions should be made independently from each other. Unlike other relational models of coreference that are generative, the conditional model here can incorporate a great variety of features of the input without having to be concerned about their dependencies—paralleling the advantages of conditional random fields over hidden Markov models. We present experiments on proper noun coreference in two text data sets, showing results in which we reduce error by nearly 28% or more over traditional thresholded record-linkage, and by up to 33% over an alternative coreference technique previously used in natural language processing.

## 1 Introduction

In many domains—including computer vision, databases and natural language processing—we find multiple views, descriptions, or names for the same underlying object. Correctly resolving these references is a necessary precursor to further processing and understanding of the data. In computer vision, solving object correspondence is necessary for counting or tracking. In databases, performing record linkage or de-duplication creates a clean set of data that can be accurately mined. In natural language processing, coreference analysis finds the nouns, pronouns and phrases that refer to the same entity, enabling the extraction of relations among entities as well as more complex propositions.

Consider, for example, the text in a news article; it may discuss the entities *George Bush*, *Colin Powell*, and *Donald Rumsfeld*. The article would contain multiple mentions of Colin Powell by different strings—“Secretary of State Colin Powell,” “he,” “Mr. Powell,” “the Secretary”—and would

also refer to the other two entities with sometimes overlapping strings. The coreference task is to use content and context of all the mentions to determine how many entities are discussed in the article, and which mention corresponds to which entity.

This task is most frequently solved by examining individual pair-wise distance measures between mentions independently of each other. For example, database record-linkage and citation reference matching has been performed by learning a pairwise distance metric between records, and setting a distance threshold below which records are merged [Monge and Elkan, 1997; Borthwick *et al.*, 2000; McCallum *et al.*, 2000b; Bilenko and Mooney, 2002; Cohen and Richman, 2002]. Coreference in NLP has also been performed with distance thresholds or pairwise classifiers [McCarthy and Lehnert, 1995; Ge *et al.*, 1998; Soon *et al.*, 2001; Ng and Cardie, 2002].

But these distance measures are inherently noisy and the answer to one pair-wise coreference decision may not be independent of another. For example, if we measure the distance between all of the three possible pairs among three mentions, two of the distances may be below threshold, but one above—an inconsistency due to noise and imperfect measurement. For example, “Mr. Powell” may be correctly coresolved with “Powell,” but particular grammatical circumstances may make the model incorrectly believe that “Powell” is coreferent with a nearby occurrence of “she”. Inconsistencies might be better resolved if the coreference decisions are made in *dependent relation* to each other, and in a way that accounts for the values of the multiple distances, instead of a threshold on single pairs independently. Valuable distinctions in real data are also often even more subtle. For example in noun coreference, the gender attribute of one mention might combine with the job-title attribute of another coreferent mention, and this combination, in turn, might help coresolve a third mention. This has been recognized, and there are some examples of techniques that use heuristic feature merging [Morton, 1997].

Recently Pasula *et al.* [2003] have proposed a formal, relational approach to the problem of identity uncertainty using a type of Bayesian network called a Relational Probabilistic Model [Friedman *et al.*, 1999]. A great strength of this model is that it explicitly captures the dependence among multiple coreference decisions.

However, it is a generative model of the entities, mentions and all their features, and thus has difficulty using many features that are highly overlapping, non-independent, at varying levels of granularity, and with long-range dependencies. For example, we might wish to use features that capture the phrases, words and character n-grams in the mentions, the appearance of keywords anywhere in the document, the parse-tree of the current, preceding and following sentences, as well as 2-d layout information. To produce accurate generative probability distributions, the dependencies between these features should be captured in the model; but doing so can lead to extremely complex models in which parameter estimation is nearly impossible.

Similar issues arise in sequence modeling problems. In this area significant recent success has been achieved by replacing a generative model—hidden Markov models—with a conditional model—conditional random fields (CRFs) [Lafferty *et al.*, 2001]. CRFs have reduced part-of-speech tagging errors by 50% on out-of-vocabulary words in comparison with HMMs [Ibid.], matched champion noun phrase segmentation results [Sha and Pereira, 2003], and significantly improved the segmentation of tables in government reports [Pinto *et al.*, 2003]. Relational Markov networks [Taskar *et al.*, 2002] are similar models, and have been shown to significantly improve classification of Web pages.

This paper introduces three conditional undirected graphical models for identity uncertainty. The models condition on the mentions, and generate the coreference decisions, (and in some cases also generate attributes of the entities). Clique potential functions can measure, for example, the degree of consistency between “Mr. Powell”, “he” and our assignment of the attribute MALE to their common entity. In the first most general model, the dependency structure is unrestricted, and the number of underlying entities explicitly appears in the model structure. The second model the third models have no structural dependence on the number of entities, and fall into a class of Markov random fields in which inference exactly corresponds to graph partitioning [Boykov *et al.*, 1999].

We show preliminary experimental results using the third model on a proper noun coreference problem two different newswire text domains: broadcast news stories from the DARPA Automatic Content Extraction (ACE) program, and newswire articles from the DARPA MUC corpus. In both domains we take advantage of the ability to use arbitrary, overlapping features of the input, including string equality, substring, and acronym matches. Using the same features, in comparison with an alternative natural language processing technique, we reduce error by 33% and 28% in the two domains.

There are a wide variety of choices for addressing coreference using conditionally-trained undirected graphical models. This paper aims to describe part of that landscape, and present some preliminary experimental results. The progression of the three models show the trajectory of our thinking, as well as some more flexible models to which one could return in further experiments. Conditionally-trained identity uncertainty models are a topic with much promise for additional future work.

## 2 Three Conditional Models of Identity Uncertainty

We now describe three possible configurations for conditional models of identity uncertainty, each progressively simpler and more specific than its predecessor. All three are based on conditionally-trained, undirected graphical models.

Undirected graphical models, also known as Markov networks or Markov random fields, are a type of probabilistic model that excels at capturing interdependent data in which causality among attributes is not apparent. We begin by introducing notation for mentions, entities and attributes of entities, then in the following subsections describe the likelihood, inference and estimation procedures for the specific undirected graphical models.

Let  $\mathbf{E} = (E_1, \dots, E_m)$  be a collection of classes or “entities”. Let  $\mathbf{X} = (X_1, \dots, X_n)$  be a collection of random variables over observations or “mentions”; and let  $\mathbf{Y} = (Y_1, \dots, Y_n)$  be a collection of random variables over integer identifiers, unique to each entity, specifying to which entity a mention refers. Thus the  $y$ ’s are integers ranging from 1 to  $m$ , and if  $Y_i = Y_j$ , then mention  $X_i$  is said to refer to the same underlying entity as  $X_j$ . For example, some particular entity  $e_4$ , *U.S. Secretary of State, Colin L. Powell*, may be mentioned multiple times in a news article that also contains mentions of other entities:  $x_6$  may be “Colin Powell”;  $x_9$  may be “Powell”;  $x_{17}$  may be “the Secretary of State.” In this case, the unique integer identifier for this entity,  $e_4$ , is 4, and  $y_6 = y_9 = y_{17} = 4$ .

Furthermore, entities may have attributes. Let  $\mathbf{A}$  be a random variable over the collection of all attributes for all entities. Borrowing the notation of Relational Markov Networks [Taskar *et al.*, 2002], we write the random variable over the attributes of entity  $E_s$  as  $E_s.\mathbf{A} = \{E_s.A_1, E_s.A_2, E_s.A_3, \dots\}$ . For example, these three attributes may be *gender*, *birth year*, and *surname*. Continuing the above example, then  $e_4.a_1 = \text{MALE}$ ,  $e_4.a_2 = 1937$ , and  $e_4.a_3 = \text{Powell}$ . One can interpret the attributes as the values that should appear in the fields of a database record for the given entity. Attributes such as *surname* may take on one of the finite number of values that appear in the data set.

We may examine many features of the mentions,  $\mathbf{x}$ , but since a conditional model doesn’t generate them, we don’t need random variable notation for them. Separate measured features of the mentions and entity-assignments,  $\mathbf{y}$ , are captured in different feature functions,  $f(\cdot)$ , over cliques in the graphical model. Although the functions may be real-valued, typically they are binary. The parameters of the model are associated with these different feature functions. Details and example feature functions and parameterizations are given for the three specific models below.

The task is then to find the most likely collection of entity-assignments,  $\mathbf{y}$ , (and optionally also the most likely entity attributes,  $\mathbf{a}$ ), given a collection of mentions and their context,  $\mathbf{x}$ . A generative probabilistic model of identity uncertainty is trained to maximize  $P(\mathbf{Y}, \mathbf{A}, \mathbf{X})$ . A conditional probabilistic model of identity uncertainty is instead trained to maximize  $P(\mathbf{Y}, \mathbf{A}|\mathbf{X})$ , or simply  $P(\mathbf{Y}|\mathbf{X})$ .

## 2.1 Model 1: Groups of nodes for entities

First we consider an extremely general undirected graphical model in which there is a node for the mentions,  $\mathbf{x}$ ,<sup>1</sup> a node for the entity-assignment of each mention,  $y$ , and a node for each of the attributes of each entity, *e.a.* These nodes are connected by edges in some unspecified structure, where an edge indicates that the values of the two connected random variables are dependent on each the other.

The parameters of the model are defined over cliques in this graph. Typically the parameters on many different cliques would be tied in patterns that reflect the nature of the repeated relational structure in the data. Patterns of tied parameters are common in many graphical models, including HMMs and other finite state machines [McCallum *et al.*, 2000a; Lafferty *et al.*, 2001], where they are tied across different positions in the input sequence, and by more complex patterns based on SQL-like queries, as in Markov Relational Networks [Taskar *et al.*, 2002]. Following the nomenclature of the later, these parameter-tying-patterns are called *clique templates*; each particular instance a template in the graph we call a *hit*.

For example, one clique template may specify a pattern of consisting of two mentions, their entity-assignment nodes, and an entity’s *surname* attribute node. The hits would consist of all possible combinations of such nodes. Multiple feature functions could then be run over each hit. One feature function might have value 1 if, for example, both mentions were assigned to the same entity as the surname node, and if the surname value appears as a substring in both mention strings (and value 0 otherwise). Another feature function might be 1 if and only if both the mention strings and the surname value are identical.

The Hammersley-Clifford theorem stipulates that the probability of a particular set of values on the random variables in an undirected graphical model is a product of potential functions over cliques of the graph. Our cliques will be the hits,  $\mathbf{h} = \{h, \dots\}$ , resulting from a set of clique templates,  $\mathbf{t} = \{t, \dots\}$ . In typical fashion, we will write the probability distribution in exponential form, with each potential function calculated as a dot-product of feature functions,  $f$ , and learned parameters,  $\lambda$ ,

$$P(\mathbf{y}, \mathbf{a}, \mathbf{x}) = \frac{1}{Z_{\mathbf{x}}} \exp \left( \sum_{t \in \mathbf{t}} \sum_{h_t \in \mathbf{h}_t} \sum_l \lambda_l f_l(\mathbf{y}, \mathbf{a}, \mathbf{x} : h_t) \right),$$

where  $(\mathbf{y}, \mathbf{a}, \mathbf{x} : h_t)$  indicates the subset of the entity-assignment, attribute, and mention nodes selected by the clique template hit  $h_t$ ; and  $Z_{\mathbf{x}}$  is simply a normalizer to make the probabilities over all  $\mathbf{y}$  sum to one (also known as the partition function).

Being a conditional model allows great flexibility in the features used. They can be overlapping and inter-dependent without requiring model structure to capture the dependencies; they can be a varying levels of granularity—for example, questions about the entire document, context around the

<sup>1</sup>Even though there are many mentions in  $\mathbf{x}$ , because we are not generating them, we can represent them as a single node. This helps show that feature functions can ask arbitrary questions about various large and small subsets of the mentions and their context. We will still use  $x_i$  to refer to the content and context of the  $i$ th mention.

mention, the words in the mention, and character-sequences in the mention.

The parameters,  $\lambda$ , can be learned by maximum likelihood from labeled training data. Calculating the partition function is problematic because there are a very large number of possible  $\mathbf{y}$ ’s and  $\mathbf{a}$ ’s. Loopy belief propagation or Gibbs sampling have been used successfully in other similar situations, *e.g.* [Taskar *et al.*, 2002]. One may refer to these sources for more details about the training procedure.

However, note that both loopy belief propagation and Gibbs sampling only work over a graph with fixed structure. But in our problem the number of entities (and thus number of attribute nodes, and the domain of the entity-assignment nodes) is unknown. Inference in these models must determine for us the highest-probability number of entities.

In related work on a generative probabilistic model of identity uncertainty, Pasula *et al.* [2003], solve this problem by alternating rounds of Metropolis-Hastings sampling on a given model structure with rounds of Metropolis-Hastings to explore the space of new graph structures. Our desire to avoid the complexity and lack of scalability of this approach motivates our Model 2.

## 2.2 Model 2: Nodes for mention pairs, with attributes on mentions

To avoid the need to change the graphical model structure during inference, we now remove any parts of the graph that depend on the number of entities,  $m$ : (1) The per-mention entity-assignment nodes,  $Y_i$ , are random variables whose domain is over the integers 0 through  $m$ ; we remove these nodes, replacing them with binary-valued random variables,  $Y_{ij}$ , over each pair of mentions,  $(X_i, X_j)$  (indicating whether or not the two mentions are coreferent); although it is not strictly necessary, we also restrict the clique templates to operate over no more than two mentions (for efficiency). (2) The per-entity attribute nodes  $A$  are removed and replaced with attribute nodes associated with each mention; we write  $x_i.\mathbf{a}$  for the set of attributes on mention  $x_i$ .

Even though the clique templates are now restricted to pairs of mentions, this does not imply that pairwise coreference decisions are made independently of each other—they are still highly dependent. Many pairs will overlap with each other, and constraints will flow through these overlaps. This point is reiterated with an example in the next subsection.

Notice, however, that it is possible for the model as thus far described to assign non-zero probability to an inconsistent set of entity-assignments,  $\mathbf{y}$ . For example, we may have an “inconsistent triangle” of coreference decisions in which  $y_{ij}$  and  $y_{jk}$  are 1, while  $y_{ik}$  is 0. We can enforce the impossibility of all inconsistent configurations with the introduction of some additional clique potentials. We add inconsistency-checking functions  $f_{i'j'}(y_{ij}, y_{jk}, y_{ik})$  for all mention triples, with the corresponding  $\lambda_{i'j'}$ ’s fixed at negative infinity—thus assigning zero probability to them. (Note that this is simply a notational trick; in practice the inference implementation simply avoids any configurations of  $\mathbf{y}$  that are inconsistent—a check that is simple to perform.) Thus we have

$$P(\mathbf{y}, \mathbf{a}|\mathbf{x}) = \frac{1}{Z_{\mathbf{x}}} \exp \left( \sum_{i,j,l} \lambda_l f_l(x_i, x_j, y_{ij}, x_i \cdot \mathbf{a}, x_j \cdot \mathbf{a}) + \sum_{i,j,k,l'} \lambda_{l'} f_{l'}(y_{ij}, y_{jk}, y_{ik}) \right).$$

We can also enforce consistency among the attributes of coreferent mentions by similar means, either sharply (as with entity-assignments), or more softly using non-infinite  $\lambda$ 's. Consistent attribute values will propagate around the network, behaving much like the analogous propagation of region identifiers in Markov random fields used for segmentation in computer vision.

Since this model can hypothesize different numbers of entities without changing the model structure, we can avoid Metropolis-Hastings, and simply use the more standard and efficient inference procedures mentioned above. The price we have paid is the  $O(n^2)$  binary mention-coreference variables,  $y_{ij}$ ; however, there are many widely-used techniques for efficiently and drastically reducing the number of pairwise comparisons, e.g. [Monge and Elkan, 1997; McCallum *et al.*, 2000b]. In this case, we could also restrict  $f_l(x_i, x_j, y_{ij}) \equiv 0, \forall y_{ij} = 0$ .

The main purpose of the attributes is to obtain values for filling the fields of a proposition or database, and they are not needed for when the task is solely coreference. This case motivates our next model.

### 2.3 Model 3: Nodes for mention pairs, graph partitioning with learned distance metric

When gathering attributes of entities is not necessary, we can avoid the extra complication of attributes by removing them from the model. What results is a straightforward, yet highly expressive, discriminatively-trained, undirected graphical model that can use rich feature sets and relational inference to solve identity uncertainty tasks. Determining the most likely number of entities falls naturally out of inference. The model is

$$P(\mathbf{y}|\mathbf{x}) = \frac{1}{Z_{\mathbf{x}}} \exp \left( \sum_{i,j,l} \lambda_l f_l(x_i, x_j, y_{ij}) + \sum_{i,j,k,l'} \lambda_{l'} f_{l'}(y_{ij}, y_{jk}, y_{ik}) \right). \quad (1)$$

Recently there has been increasing interest in study of the equivalence between graph partitioning algorithms and inference in certain kinds of undirected graphical models, e.g. [Boykov *et al.*, 1999]. This graphical model is an example of such a case. With some thought, one can straightforwardly see that finding the highest probability coreference solution,  $\mathbf{y}^* = \arg \max_{\mathbf{y}} P(\mathbf{y}|\mathbf{x})$ , exactly corresponds to finding the graph partitioning of a (different) graph in which the entities are the nodes and the edge weights are the (log) clique potentials on the pair of nodes  $\langle x_i, x_j \rangle$  involved in their edge:  $\sum_l \lambda_l f_l(x_i, x_j, y_{ij})$ , where  $f_l(x_i, x_j, 1) = -f_l(x_i, x_j, 0)$ ,

and edge weights range from  $-\infty$  to  $+\infty$ . Unlike classic mincut/maxflow binary partitioning, here the number partitions (corresponding to entities) is unknown, but a single optimal number of partitions exists; negative edge weights encourage more partitions.

Graph partitioning with negative edge weights is NP-hard, but it has a history of good approximations, and several efficient algorithms to choose from. Our current experiments use an instantiation of the minimizing-disagreements Correlational Clustering algorithm in [Bansal *et al.*, 2002]. This approach is a simple yet effective partitioning scheme. It works by measuring the degree of inconsistency incurred by including a node in a partition, and making repairs. Due to space constraints we refer the reader to Bansal *et al.* [2002] for further details.

The resulting solution does not make pairwise coreference decisions independently of each other. It has a significant “relational” nature because the assignment of a node to a partition (or, mention to an entity) depends not just on a single low distance measurement to one other node, but on its low distance measurement to all nodes in the partition (and furthermore on its high distance measurement to all nodes of all other partitions). For example, the “Mr. Powell”-“Powell”-“she” problem discussed in the introduction would be prevented by this model because, although the distance between “Powell” and “she” might grammatically look low, the distance from “she” to another member of the same partition, (“Mr. Powell”) is very high (due to a highly-weighted feature function that checks for gender-consistency).

Interestingly, in our model, the distance measure between nodes is learned from labeled training data. That is, we use data,  $\mathcal{D}$ , in which the correct coreference partitions are known in order to learn a distance metric such that, when the same data is clustered, the correct partitions emerge. This is accomplished by maximum likelihood—adjusting the weights,  $\lambda$ , to maximize the product of Equation 1 over all instances  $\langle \mathbf{x}, \mathbf{y} \rangle$  in the training set. Fortunately this objective function is concave—it has a single global maximum—and there are several applicable optimization methods to choose from, including gradient ascent, stochastic gradient ascent and conjugate gradient; all simply require the derivative of the objective function. The derivative of the log-likelihood,  $L$ , with respect to weight  $\lambda_l$  has a quite intuitive meaning. It is the expected value of feature  $f_l$  given the correct partitions  $\mathbf{y}$  in the labeled training data, minus the expected value of feature  $f_l$  given the probability distribution over partitions given by the current model,

$$\frac{\partial L}{\partial \lambda_l} = \sum_{\langle \mathbf{x}, \mathbf{y} \rangle \in \mathcal{D}} \left( \sum_{i,j,l} f_l(x_i, x_j, y_{ij}) - \sum_{\mathbf{y}'} P_{\Lambda}(\mathbf{y}'|\mathbf{x}) \sum_{i,j,l} f_l(x_i, x_j, y'_{ij}) \right),$$

where  $P_{\Lambda}(\mathbf{y}'|\mathbf{x})$  is defined by Equation 1, using the current set of  $\lambda$  parameters,  $\Lambda$ , and  $\sum_{\mathbf{y}'}$  is a sum over all possible partitionings.

The number of possible partitionings is exponential in the number of mentions, so for any reasonably-sized problem, we

obviously must resort to approximate inference for the second expectation. A simple option is stochastic gradient ascent in the form of a voted perceptron [Collins, 2002]. Here we calculate the gradient for a single training instance at a time, and rather than use a full expectation in the second line, simply using the single most likely (or nearly most likely) partitioning as found by a graph partitioning algorithm, and make progressively smaller steps in the direction of these gradients while cycling through the instances,  $\langle \mathbf{x}, \mathbf{y} \rangle$  in the training data. Neither the full sum,  $\sum_{\mathbf{y}'}$ , or the partition function,  $Z_{\mathbf{x}}$ , need to be calculated in this case. Further details are given in [Collins, 2002].

### 3 Experiments with Proper Noun Coreference

We test our approach to identity uncertainty without attributes (Model 3) on natural language proper noun coreference, using two different data sets: 30 newswire articles from the MUC-6 corpus, and a set of 117 stories from the broadcast news portion of the DARPA ACE data set. Both data sets had annotated coreferences; annotated *non-proper* nouns are ignored in these first experiments. We pre-processed both data sets with the Brill part-of-speech tagger.

We compare our Model 3 against two other techniques representing typical approaches to the problem of identity uncertainty. The first is single-link clustering with a threshold, (*single-link-threshold*), which is universally used in database record-linkage and citation reference matching [Monge and Elkan, 1997; Borthwick *et al.*, 2000; Bilenko and Mooney, 2002; McCallum *et al.*, 2000b; Cohen and Richman, 2002]. It forms partitions by simply collapsing the spanning trees of all mentions with pairwise distances below some threshold. Our threshold of 0.6 was selected by cross validation.

The second technique, which we call *best-previous-match*, has been used in natural language processing applications [Morton, 1997; Ge *et al.*, 1998; Ng and Cardie, 2002]. It works by scanning linearly through a document, and associating each mention with its best-matching predecessor—best as measured with a single pairwise distance. For each mention there is also the option to match against the null predecessor.

In our experiments, both single-link-threshold and best-previous-match implementations use a distance measure based on a binary maximum entropy classifier—matching the practice of Morton [1997], Borthwick *et al.* [2000] and Cohen and Richman [2002]. We also tested the heuristic feature merging of Morton [1997], but found it to make no difference on these data sets.

We use an identical feature set for all techniques, including our Method 3. The features are described in Table 3. They are quite non-independent, and operate at multiple levels of granularity. They are typical of features used in several other NLP coreference systems.

Table 2 shows the average of five-fold cross-validation for all three models on the ACE and MUC data sets. Evaluation was performed using the MUC-6 coreference algorithm for both data sets. Model 3 out-performs both the single-link-threshold and the best-previous-match technique. Model 3 reduces the error by 28% over single-link-threshold on the ACE data, and by 24% on the MUC-6 data set. All differences from Model 3 are statistically significant.

**Normalized substring** non-zero when one string is a substring of another string, after both strings are normalized. Normalization consists of removing words from the phrase that do not have the part of speech NNP or NNPS and words that contain no vowels or that end in a period. This effectively removes honorifics and non proper noun modifiers.

**Un-normalized substring** non-zero when one string is a substring of the other.

**Acronym** non-zero when the sequence of capital letters derived from one string is a substring of the other string.

**Identical** non-zero when the two mentions are identical.

**Head Identical** non-zero when the last tokens of each mention are identical.

**Modifier words and part-of-speech** non-zero features for the words and their parts of speech that appear to the left of the head word in both mentions.

Figure 1: The binary features over pairs of mentions used in the experiments

	ACE	MUC-6
best-previous-match	90.98	88.83
single-link-threshold	91.65	88.90
Model 3	93.96	91.59

Figure 2: MUC F1 results on two data sets, showing 28% reduction and a 24% reduction in error over single-link on the ACE and MUC-6 data sets, respectively.

There are some differences between the data sets. We used a noun phrase tagger to identify noun phrases in the MUC-6 data. The MUC-6 coreference annotations do not include singletons (i.e. there is no annotation if a phrase is non-coreferential), thus we identified these additional noun phrases automatically—introducing an extra element of noise into the MUC-6 data. By contrast, in the ACE data, all candidate noun phrases are hand-annotated. There are also differences in the annotation guidelines between the two data sets.

In preliminary experiments with coreference analysis of *all* nouns (including pronouns and common nouns), we reach 60% on the ACE data set, which compares favorably with the state-of-the-art.

We expect that switching to more robust clustering algorithms, and using a better estimate of our model’s posterior distribution (sampling of partitions instead of voted perceptron) may further improve our model’s accuracy, especially on small, noisy data sets.

Analysis of several individual coreference outputs bears out the intuition discussed earlier: making coreference decisions in dependent relation to each other results in more accurate decisions.

### 4 Related Work and Conclusions

There has been much related work on identity uncertainty in various specific fields. Traditional work in de-duplication for databases or reference-matching for citations measure the distance between two records by some metric, and then collapse all records at a distance below a threshold, *e.g.* [Monge and Elkan, 1997; McCallum *et al.*, 2000b]. This method is not relational, that is, it does not account for the inter-dependent

relations among multiple decisions to collapse. Most recent work in the area has focused on learning the distance metric [Bilenko and Mooney, 2002; Cohen and Richman, 2002] not the clustering method.

Natural language processing has had similar emphasis and lack of emphasis respectively. Pairwise coreference learned distance measures have used decision trees [McCarthy and Lehnert, 1995; Ng and Cardie, 2002], SVMs [Zelenko *et al.*, 2003], maximum entropy classifiers [Morton, 1997], and generative probabilistic models [Ge *et al.*, 1998]. But all use thresholds on a single pairwise distance, or the maximum of a single pairwise distance to determine if or where a coreference merge should occur.

Pasula *et al.* [2003] introduce a generative probability model for identity uncertainty based on Probabilistic Relational Networks networks [Friedman *et al.*, 1999]. Our work is an attempt to gain some of the same advantages that CRFs have over HMMs by creating conditional models of identity uncertainty. The models presented here, as instances of conditionally-trained undirected graphical models, are also instances of relational Markov networks [Taskar *et al.*, 2002] and conditional Random fields [Lafferty *et al.*, 2001]. Taskar *et al.* [2002] briefly discuss clustering of dyadic data, such as people and their movie preferences, but not identity uncertainty or inference by graph partitioning.

The ties between inference in our model and graph partitioning [Boykov *et al.*, 1999] are not only interesting, but particularly helpful in that they provide concrete and efficient algorithms for finding the highest probability solution, and for fruitful Gibbs sampling. The possible use of spectral clustering, *e.g.* [Ng *et al.*, 2001], is an area of future work.

Identity uncertainty is a significant problem in many fields. In natural language processing, it is not only especially difficult, but also extremely important, since improved coreference resolution is one of the chief barriers to effective data mining of text data. Natural language data is a domain that has particularly benefited from rich and overlapping feature representations—representations that lend themselves better to conditional probability models than generative ones [Lafferty *et al.*, 2001; Collins, 2002; Morton, 1997]. Hence our interest in conditional models of identity uncertainty.

## Acknowledgments

We would like to thank Andrew Ng, Jon Kleinberg, David Karger, Avrim Blum and Fernando Pereira for helpful and insightful discussions. This work was supported in part by the Center for Intelligent Information Retrieval and in part by SPAWARSYSCEN-SD grant numbers N66001-99-1-8912 and N66001-02-1-8903, and DARPA under contract number F30602-01-2-0566.

## References

[Bansal *et al.*, 2002] Nikhil Bansal, Shuchi Chawla, and Avrim Blum. Correlation clustering. In *The 43rd Annual Symposium on Foundations of Computer Science (FOCS)*, pages 238–247, 2002.

[Bilenko and Mooney, 2002] Mikhail Bilenko and Raymond J. Mooney. Learning to combine trained distance metrics for duplicate detection in databases. Technical Report Technical Report AI 02-296, Artificial Intelligence Laboratory, University of Texas at Austin, Austin, TX, February 2002.

[Borthwick *et al.*, 2000] Andrew Borthwick, Vikki Papadouka, and Deborah Walker. The MEDD de-duplication project. In *Immunization Registry Conference*, 2000.

[Boykov *et al.*, 1999] Yuri Boykov, Olga Veksler, and Ramin Zabih. Fast approximate energy minimization via graph cuts. In *ICCV (1)*, pages 377–384, 1999.

[Cohen and Richman, 2002] William Cohen and Jacob Richman. Learning to match and cluster entity names. In *Proceedings of KDD-2002, 8th International Conference on Knowledge Discovery and Data Mining*, 2002.

[Collins, 2002] Michael Collins. Discriminative training methods for hidden markov models: Theory and experiments with perceptron algorithms, 2002.

[Friedman *et al.*, 1999] Nir Friedman, Lise Getoor, Daphne Koller, and Avi Pfeffer. Learning probabilistic relational models. In *IJ-CAI*, pages 1300–1309, 1999.

[Ge *et al.*, 1998] N. Ge, J. Hale, and E. Charniak. A statistical approach to anaphora resolution. In *Proceedings of the Sixth Workshop on Very Large Corpora*, pages 161–171, 1998.

[Lafferty *et al.*, 2001] John Lafferty, Andrew McCallum, and Fernando Pereira. Conditional random fields: Probabilistic models for segmenting and labeling sequence data. In *Proc. ICML*, pages 282–289, 2001.

[McCallum *et al.*, 2000a] Andrew McCallum, Dayne Freitag, and Fernando Pereira. Maximum entropy Markov models for information extraction and segmentation. In *Proceedings of ICML*, pages 591–598, 2000.

[McCallum *et al.*, 2000b] Andrew McCallum, Kamal Nigam, and Lyle H. Ungar. Efficient clustering of high-dimensional data sets with application to reference matching. In *Knowledge Discovery and Data Mining*, pages 169–178, 2000.

[McCarthy and Lehnert, 1995] Joseph F. McCarthy and Wendy G. Lehnert. Using decision trees for coreference resolution. In *IJ-CAI*, pages 1050–1055, 1995.

[Monge and Elkan, 1997] Alvaro E. Monge and Charles Elkan. An efficient domain-independent algorithm for detecting approximately duplicate database records. In *Research Issues on Data Mining and Knowledge Discovery*, 1997.

[Morton, 1997] Thomas Morton. Coreference for NLP applications. In *Proceedings ACL*, 1997.

[Ng and Cardie, 2002] Vincent Ng and Claire Cardie. Improving machine learning approaches to coreference resolution. In *Fortieth Anniversary Meeting of the Association for Computational Linguistics (ACL-02)*, 2002.

[Ng *et al.*, 2001] A. Ng, M. Jordan, and Y. Weiss. On spectral clustering: Analysis and an algorithm. In *Advances in Neural Information Processing (NIPS)*, 2001.

[Pasula *et al.*, 2003] Hanna Pasula, Bhaskara Marthi, Brian Milch, Stuart Russell, and Ilya Shpitser. Identity uncertainty and citation matching. In *Advances in Neural Information Processing (NIPS)*, 2003.

[Pinto *et al.*, 2003] David Pinto, Andrew McCallum, Xen Lee, and W. Bruce Croft. Table extraction using conditional random fields. In *Proceedings of the 26th ACM SIGIR*, 2003.

[Sha and Pereira, 2003] Fei Sha and Fernando Pereira. Shallow parsing with conditional random fields. Technical Report CIS TR MS-CIS-02-35, University of Pennsylvania, 2003.

[Soon *et al.*, 2001] W. M. Soon, H. T. Ng, and D. C. Y. Lim. A machine learning approach to coreference resolution of noun phrases. *Computational Linguistics*, 27(4):521–544, 2001.

[Taskar *et al.*, 2002] B. Taskar, P. Abbeel, and D. Koller. Discriminative probabilistic models for relational data. In *Eighteenth Conference on Uncertainty in Artificial Intelligence (UAI02)*, 2002.

[Zelenko *et al.*, 2003] Dmitry Zelenko, Chinatsu Aone, and Anthony Richardella. Kernel methods for relation extraction. *Journal of Machine Learning Research (submitted)*, 2003.