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Stevenson, M. and Wilks, Y. (2001) The interaction of knowledge sources in word sense disambiguation. *Computational Linguistics*, 27 (3). pp. 321-349. ISSN 0891-2017

<https://doi.org/10.1162/089120101317066104>

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The Interaction of Knowledge Sources in Word Sense Disambiguation

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Word sense disambiguation (WSD) is a computational linguistics task likely to benefit from the tradition of combining different knowledge sources in artificial intelligence research. An important step in the exploration of this hypothesis is to determine which linguistic knowledge sources are most useful and whether their combination leads to improved results. We present a sense tagger which uses several knowledge sources. Tested accuracy exceeds 94% on our evaluation corpus.

Our system attempts to disambiguate all content words in running text rather than limiting itself to treating a restricted vocabulary of words. It is argued that this approach is more likely to assist the creation of practical systems.

1. Introduction

Word sense disambiguation (WSD) is a problem long recognised in computational linguistics (Yngve 1955) and there has been a recent resurgence of interest, including a special issue of this journal devoted to the topic (Ide and Véronis 1998). Despite this there is still a considerable diversity of methods employed by researchers, as well as differences in the definition of the problems to be tackled. The SENSEVAL evaluation framework (Kilgarriff 1998) was a DARPA-style competition designed to bring some conformity to the field of WSD, although it has yet to achieve that aim completely. The main sources of divergence are the choice of computational paradigm, the proportion of text words disambiguated, the granularity of the meanings assigned to them, and the knowledge sources used. We will discuss each in turn.

Resnik and Yarowsky (1997) noted that, for the most part, part-of-speech tagging is tackled using the noisy channel model, although transformation rules and grammatico-statistical methods have also had some success. There has been far less consensus as to the best approach to WSD. Currently, machine learning methods (Yarowsky 1995; Rigau, Atserias, and Agirre 1997) and combinations of classifiers (McRoy 1992) have been popular. This paper reports a WSD system employing elements of both approaches.

Another source of difference in approach is the proportion of the vocabulary disambiguated. Some researchers have concentrated on producing WSD systems that base results on a limited number of words, for example Yarowsky (1995) and Schütze (1992) who quoted results for 12 words, and a second group, including Leacock, Towell, and Voorhees (1993) and Bruce and Wiebe (1994), who gave results for just one, namely *interest*. But limiting the vocabulary on which a system is evaluated can have two serious drawbacks. First, the words used were not chosen by frequency-based sampling techniques and so we have no way of knowing whether or not they are special cases, a point emphasised by Kilgarriff (1997). Secondly, there is no guarantee

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that the techniques employed will be applicable when a larger vocabulary is tackled. However it is likely that mark-up for a restricted vocabulary can be carried out more rapidly since the subject has to learn the possible senses of fewer words.

Among the researchers mentioned above, one must distinguish between, on the one hand, supervised approaches that are inherently limited in performance to the words over which they evaluate because of limited training data and, on the other hand, approaches whose unsupervised learning methodology is applied to only small numbers of words for evaluation, but which could in principle have been used to tag all content words in a text. Others, such as Harley and Glennon (1997) and ourselves Wilks and Stevenson (1998a, 1998b; Stevenson and Wilks 1999), have concentrated on approaches that disambiguate all content words.¹ In addition to avoiding the problems inherent in restricted vocabulary systems, wide coverage systems are more likely to be useful for NLP applications, as discussed by Wilks et al. (1990).

A third difference concerns the granularity of WSD attempted, which one can illustrate in terms of the two levels of semantic distinctions found in many dictionaries: homograph and sense (see Section 3.1). Like Cowie, Guthrie, and Guthrie (1992), we shall give results at both levels, but it is worth pointing out that the targets of, say, work using translation equivalents (e.g., Brown et al. 1991; Gale, Church, and Yarowsky 1992c; and see Section 2.3) and Roget categories (Yarowsky 1992; Masterman 1957) correspond broadly to the wider, homograph, distinctions.

In this paper we attempt to show that the high level of results more typical of systems trained on many instances of a restricted vocabulary can also be obtained by large vocabulary systems, and that the best results are to be obtained from an optimization of a combination of types of lexical knowledge (see Section 2).

1.1 Lexical Knowledge and WSD

Syntactic, semantic, and pragmatic information are all potentially useful for WSD, as can be demonstrated by considering the following sentences:

- (1) John did not feel *well*.
- (2) John tripped near the *well*.
- (3) The *bat* slept.
- (4) He bought a *bat* from the sports shop.

The first two sentences contain the ambiguous word *well*; as an adjective in (1) where it is used in its “state of health” sense, and as a noun in (2), meaning “water supply”. Since the two usages are different parts of speech they can be disambiguated by this syntactic property.

Sentence (3) contains the word *bat*, whose nominal readings are ambiguous between the “creature” and “sports equipment” meanings. Part-of-speech information cannot disambiguate the senses since both are nominal usages. However, this sentence can be disambiguated using semantic information, such as preference restrictions. The verb *sleep* prefers an animate subject and only the “creature” sense of *bat* is animate. So Sentence (3) can be effectively disambiguated by its semantic behaviour but not by its syntax.

¹ In this paper we define content words as nouns, verbs, adjectives, and adverbs, although others have included other part-of-speech categories (Hirst 1995).

A preference restriction will not disambiguate Sentence (4) since the direct object preference will be at least as general as physical object, and any restriction on the direct object slot of the verb *sell* would cover both senses. The sentence can be disambiguated on pragmatic grounds because it is far more likely that sports equipment will be bought in a sports shop. Thus pragmatic information can be used to disambiguate *bat* to its “sports equipment” sense.

Each of these knowledge sources has been used for WSD and in Section 3 we describe a method which performs rough-grained disambiguation using part-of-speech information. Wilks (1975) describes a system which performs WSD using semantic information in the form of preference restrictions. Lesk (1986) also used semantic information for WSD in the form of textual definitions from dictionaries. Pragmatic information was used by Yarowsky (1992) whose approach relied upon statistical models of categories from Roget’s Thesaurus (Chapman, 1977), a resource that had been used in much earlier approaches to WSD such as Masterman (1957).

The remainder of this paper is organised as follows: Section 2 reviews some systems which have combined knowledge sources for WSD. In Section 3 we discuss the relationship between semantic disambiguation and part-of-speech tagging, reporting an experiment which quantifies the connection. A general WSD system is presented in Section 4. In Section 5 we explain the strategy used to evaluate this system, and we report the results in Section 6.

2. Background

A comprehensive review of WSD is beyond the scope of this paper but may be found in Ide and Véronis (1998). Combining knowledge sources for WSD is not a new idea; in this section we will review some of the systems which have tried to do that.

2.1 McRoy’s System

Early work on coarse-grained WSD based on combining knowledge sources was undertaken by McRoy (1992). Her work was carried out without the use of machine-readable dictionaries (MRD), necessitating the manual creation of the complex set of lexicons this system requires. There was a lexicon of 8,775 unique roots, a hierarchy of 1,000 concepts, and a set of 1,400 collocational patterns. The collocational patterns are automatically extracted from a corpus of text in the same domain as the text being disambiguated and senses are manually assigned to each. If the collocation occurs in the text being disambiguated, then it is assumed that the words it contains are being used in the same senses as were assigned manually.

Disambiguation makes use of several knowledge sources: frequency information, syntactic tags, morphological information, semantic context (clusters), collocations and word associations, role-related expectations, and selectional restrictions. The knowledge sources are combined by adding their results. Each knowledge source assigns a (possibly negative) numeric value to each of the possible senses. The numerical value depends upon the type of knowledge source. Some knowledge sources have only two possible values, for example the frequency information has one value for frequent senses and another for infrequent ones. The numerical values assigned for each were determined manually. The selectional restrictions knowledge source assigns scores in the range -10 to $+10$, with higher scores being assigned to senses that are more specific (according to the concept hierarchy). Disambiguation is carried out by summing the scores from each knowledge source for all candidate senses and choosing the one with the highest overall score.

In a sample of 25,000 words from the *Wall Street Journal*, the system covered 98% of word-occurrences that were not proper nouns and were not abbreviated, demonstrating the impressive coverage of the hand-crafted lexicons. No quantitative evaluation of the disambiguation quality was carried out due to the difficulty in obtaining annotated test data, a problem made more acute by the use of a custom-built lexicon. In addition, comparison of system output against manually annotated text had yet to become a standard evaluation strategy in WSD research.

2.2 The Cambridge Language Survey System

The *Cambridge International Dictionary of English* (CIDE) (Procter 1995) is a learners' dictionary which consists of definitions written using a 2,000 word controlled vocabulary. (This lexicon is similar to LDOCE, which we use for experiments presented later in this paper; it is described in Section 3.1.) The senses in CIDE are grouped by **guidewords**, similar to homographs in LDOCE. It was produced using a large corpus of English created by the Cambridge Language Survey (CLS).

The CLS also produced a semantic tagger (Harley and Glennon 1997), a commercial product that tags words in text with senses from their MRD. The tagger consists of four sub-taggers running in parallel, with their results being combined after all have run. The first tagger uses collocations derived from the CIDE example sentences. The second examines the subject codes for all words in a particular sentence and the number of matches with other words is calculated. A part-of-speech tagger produced in-house by CUP is run over the text and high scores are assigned to senses that agree with the syntactic tag assigned. Finally, the selectional restrictions of verbs and adjectives are examined. The results of these processes are combined using a simple weighting scheme (similar to McRoy's; see Section 2.1). This weighting scheme, inspired by those used in computer chess programs, assigns each sub-process a weight in the range -100 to +100 before summing. Unlike McRoy, this approach does not consider the specificity of a knowledge source in a particular instance but always assigns the same overall weight to each.

Harley and Glennon report 78% correct tagging of all content words at the CIDE guideword level (which they equate to the LDOCE sense level) and 73% at the sub-sense level, as compared to a hand-tagged corpus of 4,000 words.

2.3 Machine Learning applied to WSD

An early application of machine learning to the WSD problem was carried out by Brown et al. (1991). Several different disambiguation cues, such as first noun to the left/right and second word to the left/right, were extracted from parallel text. Translation differences were used to define the senses, as this approach was used in an English-French machine translation system. The parallel text effectively provided supervised training examples for this algorithm. Nadas et al. (1991) used the flip-flop algorithm to decide which of the cues was most important for each word by maximizing mutual information scores between words. Yarowsky (1996) used an extremely rich features set by expanding this set with syntactic relations such as subject-verb, verb-object and adjective-noun relations, part-of-speech n -grams and others. The approach was based on the hypothesis that words exhibited "one sense per collocation" (Yarowsky 1993). A large corpus was examined to compute the probability of a particular collocate occurring with a certain sense and the discriminatory power of each was calculated using the log-likelihood ratio. These ratios were used to create a decision list, with the most discriminating collocations being preferred. This approach has the benefit that it does not combine the probabilities of the collocates, which are highly non-independent knowledge sources.

Yarowsky (1993) also examined the discriminatory power of the individual knowledge sources. It was found that each collocation indicated a particular sense with a very high degree of reliability, with the most successful—the first word to the left of a noun—achieving 99% precision. Yet collocates have limited applicability; although precise, they can only be applied to a limited number of tokens. Yarowsky (1995) dealt with this problem largely by producing an unsupervised learning algorithm that generates probabilistic decision list models of word senses from seed collocates. This algorithm achieves 97% correct disambiguation. In these experiments Yarowsky deals exclusively with binary sense distinctions and evaluates his highly effective algorithms on small samples of word tokens.

Ng and Lee (1996) explored an approach to WSD in which a word is assigned the sense of the most similar example already seen. They describe this approach as “exemplar-based learning” although it is also known as k -nearest neighbor learning. Their system is known as LEXAS (LEXical Ambiguity-resolving System), a supervised learning approach which requires disambiguated training text. LEXAS was based on PEBLS, a publically available exemplar-based learning algorithm.

A set of features is extracted from disambiguated example sentences, including part-of-speech information, morphological form, surrounding words, local collocates, and words in verb-object syntactic relations. When a new, untagged, usage is encountered, it is compared with each of the training examples and the distance from each is calculated using a metric adopted from Cost and Salzberg (1993). This is calculated as the sum of the differences between each pair of features in the two vectors. The differences between two values v_1 and v_2 is calculated according to (5), where $C_{1,i}$ represents the number of training examples with value v_1 that are classified with sense i in the training corpus, and C_1 the number with value v_1 in any sense. $C_{2,i}$ and C_2 denote similar values and n denotes the total number of senses for the word under consideration. The sense of the example with the minimum distance from the untagged usage is chosen: if there is more than one with the same distance, one is chosen at random to break the tie.

$$\delta(v_1, v_2) = \sum_{i=1}^n \left| \frac{C_{1,i}}{C_1} - \frac{C_{2,i}}{C_2} \right| \quad (5)$$

Ng and Lee tested LEXAS on two separate data sets: one used previously in WSD research, the other a new, manually tagged, corpus. The common data set was the *interest* corpus constructed by Bruce and Wiebe (1994) consisting of 2,639 sentences from the *Wall Street Journal*, each containing an occurrence of the noun *interest*. Each occurrence is tagged with one of its six possible senses from LDOCE. Evaluation is carried out through 100 random trials, each trained on 1,769 sentences and tested on the 600 remaining sentences. The average accuracy was 87.4%, significantly higher than the figure of 78% reported by Bruce and Wiebe.

Further evaluation was carried out on a larger data set constructed by Ng and Lee. This consisted of 192,800 occurrences of the 121 nouns and 70 verbs that are “the most frequently occurring and ambiguous words in English” (Ng and Lee 1996, 44). The corpus was made up from the Brown Corpus (Kučera and Francis 1967) and the Wall Street Journal Corpus and was tagged with the correct senses from WordNet by university undergraduates specializing in linguistics. Before training, two subsets of the corpus were put aside as test sets: the first (BC50) contains 7,119 occurrences of the ambiguous words from the Brown Corpus, while the second (WSJ6) contained 14,139 from the Wall Street Journal Corpus. LEXAS correctly disambiguated 54% of words in BC50 and 68.6% in WSJ6. Ng and Lee point out that both results are higher than choosing the first, or most frequent, sense in each of the corpora. The authors

Table 1
Relative contribution of knowledge sources in LEXAS.

Knowledge Source	Accuracy
Collocations	80.2%
PoS and Morphology	77.2%
Surrounding words	62.0%
Verb-object	43.5%

attribute the lower performance on the Brown Corpus to the wider variety of text types it contains.

Ng and Lee attempted to determine the relative contribution of each knowledge source. This was carried out by re-running the data from the “*interest*” corpus through the learning algorithm, this time removing all but one set of features. The results are shown in Table 1. They found that the local collocations were the most useful knowledge source in their system. However, it must be remembered that this experiment was carried out on a data set consisting of a single word and may, therefore, not be generalizable.

2.4 Discussion

This review has been extremely brief and has not covered large areas of research into WSD. For example, we have not discussed connectionist approaches, as used by Waltz and Pollack (1985), Véronis and Ide (1990), Hirst (1987), and Cottrell (1984). However, we have attempted to discuss some of the approaches to combining diverse types of linguistic knowledge for WSD and have concentrated on those which are related to the techniques used in our own disambiguation system.

Of central interest to our research is the relative contribution of the various knowledge sources which have been applied to the WSD problem. Both Ng and Lee (1996) and Yarowsky (1993) reported some results in the area. However, Ng and Lee reported results for only a single word and Yarowsky considers only words with two possible senses. This paper is an attempt to increase the scope of this research by discussing a disambiguation algorithm which operates over all content words and combines a varied set of linguistic knowledge sources. In addition, we examine the relative effect of each knowledge source to gauge which are the most important, and under what circumstances.

We first report an in-depth study of a particular knowledge source, namely part-of-speech tags.

3. Part of Speech and Word Senses

3.1 LDOCE

The experiments described in this section use the *Longman Dictionary of Contemporary English* (LDOCE) (Procter 1978). LDOCE is a learners’ dictionary, designed for students of English, containing roughly 36,000 word types. LDOCE was innovative in its use of a defining vocabulary of 2,000 words with which the definitions were written. If a learner of English could master this small core then, it was assumed, they could understand every entry in the dictionary.

In LDOCE, the senses for each word type are grouped into **homographs**: sets of senses with related meanings. For example, one of the homographs of *bank* means

bank¹ *n* 1 land along the side of a river, lake, etc. 2 earth which is heaped up in a field or a garden, often making a border or division 3 a mass of snow, mud, clouds, etc.: *The banks of dark cloud promised a heavy storm* 4 a slope made at bends in a road or race-track, so that they are safer for cars to go round 5 SANDBANK: *The Dogger Bank in the North Sea can be dangerous for ships*

bank² *v* [IØ] (of a car or aircraft) to move with one side higher than the other, esp. when making a turn – see also BANK UP

bank³ *n* 1 a row, esp. of OARs in an ancient boat or KEYS on a TYPEWRITER

bank⁴ *n* 1 a place where money is kept and paid out on demand, and where related activities go on – see picture at STREET 2 (*usu. in comb.*) a place where something is held ready for use, esp. ORGANIC product of human origin for medical use: *Hospital bloodbanks have saved many lives* 3 (a person who keeps) a supply of money or pieces for payment or use in a game of chance 4 **break the bank** to win all the money that the BANK⁴(3) has in a game of chance

bank⁵ *v* 1[T1] to put or keep (money) in a bank 2[L9, esp. *with*] to keep one's money (esp. in the stated bank): *Where do you bank?*

Figure 1

The entry for *bank* in LDOCE (slightly simplified for clarity).

roughly “things piled up”, with different senses distinguishing exactly what is piled (see Figure 1). If the senses are sufficiently close together in meaning there will be only one homograph for that word, which we then call *monohomographic*. However, if the senses are far enough apart, as in the *bank* case, they will be grouped into separate homographs, which we call *polyhomographic*.

As can be seen from the example entry, each LDOCE homograph includes information about the part of speech with which the homograph is marked and that applies to each of the senses within that homograph. The vast majority of homographs in LDOCE are marked with a single part of speech; however, about 2% of word types in the dictionary contain a homograph that is marked with more than one part of speech (e.g., noun or verb), meaning that either part of speech may apply.

Although the granularity of the distinction between homographs in LDOCE is rather coarse-grained, they are, as we noted at the beginning of this paper, an appropriate level for many practical computational linguistic applications. For example, *bank* in the sense of “financial institution” translates to *banque* in French, but when used in the “edge of river” sense it translates as *bord*. This level of semantic disambiguation is frequently sufficient for choosing the correct target word in an English-to-French Machine Translation system and is at a similar level of granularity to the sense distinctions explored by other researchers in WSD, for example Brown et al. (1991), Yarowsky (1996), and McRoy (1992) (see Section 2).

3.2 Using Part-of-Speech Information to Resolve Senses

We began by examining the potential usefulness of part-of-speech information for sense resolution. It was found that 34% of the content-word types in LDOCE were polysemous, and 12% polyhomographic. (Polyhomographic words are necessarily polysemous since each homograph is a non-empty set of senses.) If we assume that the part of speech of each polyhomographic word in context is known, then 88% of word types would be disambiguated to the homograph level. (In other words, 88% do not have two homographs with the same part of speech.) Some words will be disambiguated to the homograph level if they are used in a certain part of speech but not others. For example, *beam* has 3 homographs in LDOCE; the first two are marked as nouns while the third is marked as verb. This word would be disambiguated if used as a verb but not if used as a noun. If we assume that every word of this type is assigned a part of speech which disambiguates it (i.e., verb in the case of *beam*), then an additional 7% of words in LDOCE could, potentially, be disambiguated. Therefore, up to 95% of word types in LDOCE can be disambiguated to the homograph level by part-of-speech information alone. However, these figures do not take into account either errors in part-of-speech tagging or the corpus distribution of tokens, since each word type is counted exactly once.

The next stage in our analysis was to attempt to disambiguate some texts using the information obtained from part-of-speech tags. We took five articles from the *Wall Street Journal*, containing 391 polyhomographic content words. These articles were manually tagged with the most appropriate LDOCE homograph by one of the authors. The texts were then part-of-speech tagged using Brill's transformation-based learning tagger (Brill, 1995). The tags assigned by the Brill tagger were manually mapped onto the simpler part-of-speech tag set used in LDOCE.² If a word has more than one homograph with the same part of speech, then part-of-speech tags alone cannot always identify a single homograph; in such cases we chose the first sense listed in LDOCE since this is the one which occurs most frequently.³

It was found that 87.4% of the polyhomographic content words were assigned the correct homograph. A baseline for this task can be calculated by computing the number of tokens that would be correctly disambiguated if the first homograph for each was chosen regardless of part of speech. 78% of polyhomographic tokens were correctly disambiguated this way using this approach.

These results show there is a clear advantage to be gained (over 42% reduction in error rate) by using the very simple part-of-speech-based method described compared with simply choosing the first homograph. However, we felt that it would be useful to carry out some further analysis of the data. To do this, it is useful to divide the polyhomographic words into four classes, all based on the assumption that a part-of-speech tagger has been run over the text and that homographs which do not correspond to the grammatical category assigned have been removed.

Full disambiguation (by part of speech): If only a single homograph with the correct part of speech remains, that word has been fully disambiguated by the tagger.

2 The Brill tagger uses the 48-tag set from the Penn Tree Bank (Marcus, Santorini, and Marcinkiewicz 1993), while LDOCE uses a set of 17 more general tags. Brill's tagger has a reported error rate of around 3%, although we found that mapping the Penn TreeBank tags used by Brill onto the simpler LDOCE tag set led to a lower error rate.

3 In the 3rd Edition of LDOCE the publishers claim that the senses are indeed ordered by frequency, although they make no such claim in the 1st Edition used here. However, Guo (1989) found evidence that there is a correspondence between the order in which senses are listed and the frequency of occurrence in the 1st Edition.

Partial disambiguation (by part of speech): If there is more than one possible homograph with the correct part of speech but some have been removed from consideration, that word has been partially disambiguated by part of speech.

No disambiguation (by part of speech): If all the homographs of a word have the same part of speech, which is then assigned by the tagger, then none can be removed and no disambiguation has been carried out.

Part-of-speech error: It is possible for the part-of-speech tagger to assign an incorrect part of speech, leading to the correct homograph being removed from consideration. It is worth mentioning that this situation has two possible outcomes: first, some homographs, with incorrect parts of speech, may remain; or second, all homographs may have been removed from consideration.

In Table 3 we show in the column labelled Count the number of words in our five articles which fall into each of the four categories. The relative performance of the baseline method (choosing the first sense) compared to the reported algorithm (removing homographs using part-of-speech tags) are shown in the rightmost two columns. The figures in brackets indicate the percentage of polyhomographic words correctly disambiguated by each method on a per-class basis. It can be seen that the majority of the polyhomographic words (297 of 342) fall into the “Full disambiguation” category, all of which are correctly disambiguated by the method reported here. When no disambiguation is carried out, the algorithm described simply chooses the first sense and so the results are the same for both methods. The only condition under which choosing the first sense is more effective than using part-of-speech information is when the part-of-speech tagger makes an error and all the homographs with the correct part of speech are removed from consideration. In most cases this means that the correct homograph cannot be chosen; however, in a small number of cases, this is equivalent to choosing the most frequent sense, since if all possible homographs have been removed from consideration, the algorithm reverts to using the simpler heuristic of choosing the word’s first homograph.⁴

Although this result may seem intuitively obvious, there have, we believe, been no other attempts to quantify the benefit to be gained from the application of a part-of-speech tagger in WSD (see Wilks and Stevenson 1998a). The method described here is effective in removing incorrect senses from consideration, thereby reducing the search space if combined with other WSD methods.

In the experiments reported in this section we made use of the particular structure of LDOCE, which assigns each sense to a homograph from which its part of speech information is inherited. However, there is no reason to believe that the method reported here is limited to lexicons with this structure. In fact this approach can be applied to any lexicon which assigns part-of-speech information to senses, although it would not always be possible to evaluate at the homograph level as we do here.

In the remainder of this paper we go on to describe a sense tagger that assigns senses from LDOCE using a combination of classifiers. The set of senses considered by the classifiers is first filtered using part-of-speech tags.

⁴ An example of this situation is shown in the bottom row of Table 2.

Table 2

Examples of the four word types introduced in Section 3.2. The leftmost column indicates the full set of homographs for the example words, with upper case indicating the correct homograph. The remaining columns show (respectively) the part-of-speech assigned by the tagger, the resulting set of senses after filtering, and the type of the word.

All Homographs	PoS Tag	After tagging	Word type
N, v, v	n	N	Full disambiguation
n, adj, V	v	V	Full disambiguation
n, V, v	v	V, v	Partial disambiguation
n, N, v	n	n, N	Partial disambiguation
N, n	n	N, n	No disambiguation
v, V	v	v, V	No disambiguation
N, v, v	v	v v	PoS error
N, v, v	adj	N, v, v	PoS error

Table 3

Error analysis for the experiment on WSD by part of speech alone.

Word Type	Count	Correctly disambiguated by:	
		Baseline method	PoS method
Full disambiguation	297	268 (90%)	297 (100%)
Partial disambiguation	58	22 (38%)	32 (55%)
No disambiguation	23	10 (43%)	10 (43%)
Part-of-speech error	13	5 (38%)	3 (23%)
All polyhomographic	391	305 (78%)	342 (87%)

4. A Sense Tagger which Combines Knowledge Sources

We adopt a framework in which different knowledge sources are applied as separate modules. One type of module, a **filter**, can be used to remove senses from consideration when a knowledge source identifies them as unlikely in context. Another type can be used when a knowledge source provides evidence for a sense but cannot identify it confidently; we call these **partial taggers** (in the spirit of McCarthy's notion of "partial information" [McCarthy and Hayes, 1969]). The choice of whether to apply a knowledge source as either a filter or a partial tagger depends on whether it is likely to rule out correct senses. If a knowledge source is unlikely to reject the correct sense, then it can be safely implemented as a filter; otherwise implementation as a partial tagger would be more appropriate. In addition, it is necessary to represent the context of ambiguous words so that this information can be used in the disambiguation process. In the system described here these modules are referred to as **feature extractors**.

Our sense tagger is implemented within this modular architecture, one where each module is a filter, partial tagger, or feature extractor. The architecture of the system is represented in Figure 2. This system currently incorporates a single filter (part-of-speech filter), three partial taggers (simulated annealing, subject codes, selectional restrictions) and a single feature extractor (collocation extractor).

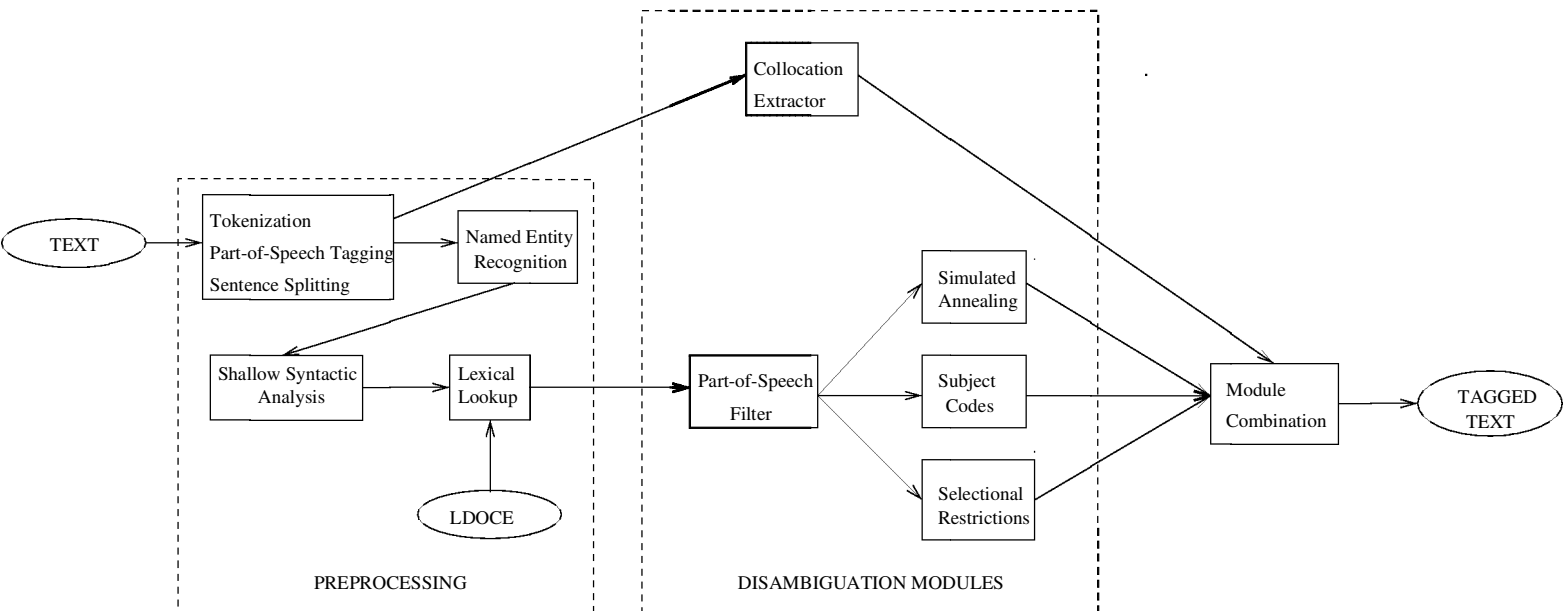


Figure 2
Sense tagger architecture.

4.1 Preprocessing

Before the filters or partial taggers are applied, the text is tokenized, lemmatized, split into sentences, and part-of-speech tagged, again using Brill's tagger. A named entity identifier is then run over the text to mark and categorize proper names, which will provide information for the selectional restrictions partial tagger (see Section 4.4). These preprocessing stages are carried out by modules from Sheffield University's Information Extraction system, LaSIE, and are described in more detail by Gaizauskas et al. (1996).

Our system disambiguates only the content words in the text, and the part-of-speech tags are used to decide which are content words. There is no attempt to disambiguate any of the words identified as part of a named entity. These are excluded because they have already been analyzed semantically by means of the classification added by the named entity identifier (see Section 4.4). Another reason for not attempting WSD on named entities is that when words are used as names they are not being used in any of the senses listed in a dictionary. For example, *Rose* and *May* are names but there are no senses in LDOCE for this usage. It may be possible to create a dummy entry in the set of LDOCE senses indicating that the word is being used as a name, but then the sense tagger would simply repeat work carried out by the named entity identifier.

4.2 Part-of-Speech filtering

We take the part-of-speech tags assigned by the Brill tagger and use a manually created mapping to translate these to the corresponding LDOCE grammatical category (see Section 3.2). Any senses which do not correspond to the category returned are removed from consideration. In practice, the filtering is carried out at the same time as the lexical lookup phase and the senses whose grammatical categories do not correspond to the tag assigned are never attached to the ambiguous word. There is also an option of turning off filtering so that all senses are attached regardless of the part-of-speech tag. If none of the dictionary senses for a given word agree with the part-of-speech tag then all are kept.

It could be reasonably argued that removing senses is a dangerous strategy since, if the part-of-speech tagger made an error, the correct sense could be removed from consideration. However, the experiments described in Section 3.2 indicate that part-of-speech information is unlikely to reject the correct sense and can be safely implemented as a filter.

4.3 Optimizing Dictionary Definition Overlap

Lesk (1986) proposed that WSD could be carried out using an overlap count of content words in dictionary definitions as a measure of semantic closeness. This method would tag all content words in a sentence with their senses from a dictionary that contains textual definitions. However, it was found that the computations which would be necessary to test every combination of senses, even for a sentence of modest length, was prohibitive.

The approach was made practical by Cowie, Guthrie, and Guthrie (1992) (see also (Wilks, Slator, and Guthrie 1996)). Rather than computing the overlap for all possible combinations of senses, an approximate solution is identified by the simulated annealing optimization algorithm (Metropolis et al. 1953). Although this algorithm is not guaranteed to find the global solution to an optimization problem, it has been shown to find solutions that are not significantly different from the optimal one (Press et al. 1988). Cowie et al. used LDOCE for their implementation and found it correctly disambiguated 47% of words to the sense level and 72% to the homograph level

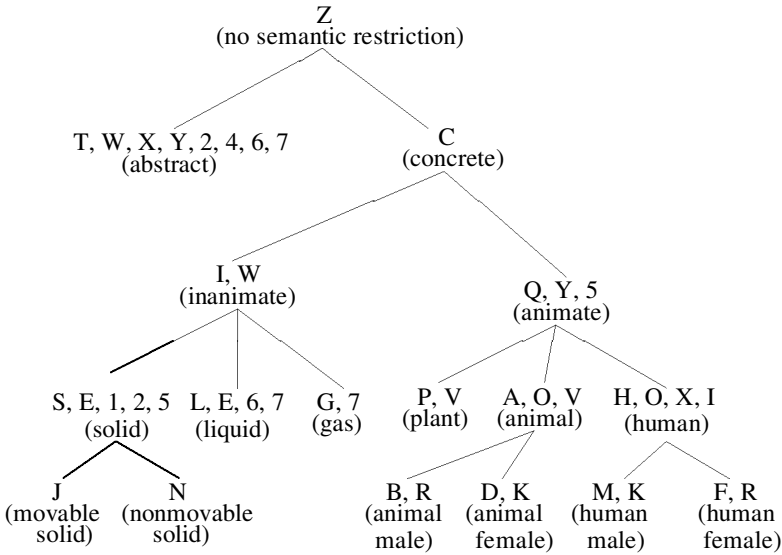


Figure 3
Bruce and Guthrie's hierarchy of LDOCE semantic codes.

when compared with manually assigned senses. The optimization must be carried out relative to a function that evaluates the suitability of a particular choice of senses. In the Cowie et al. implementation this was done using a simple count of the number of words (tokens) in common between all the definitions for a given choice of senses. However, this method prefers longer definitions, since they have more words that can contribute to the overlap, and short definitions or definitions by synonym are correspondingly penalized. We addressed this problem by computing the overlap in a different way: instead of each word contributing one, we normalized its contribution by the number of words in the definition it came from. In their implementation Cowie et al. also added pragmatic codes to the overlap computation; however, we prefer to keep different knowledge sources separate and use this information in another partial tagger (see Section 4.5). The Cowie et al. implementation returned one sense for each ambiguous word in the sentence without any indication of the system's confidence in its choice, but we adapted the system to return a set of suggested senses for each ambiguous word in the sentence.

4.4 Selectional Preferences

Our next partial tagger returns the set of senses for each word that is licensed by selectional preferences (in the sense of Wilks 1975). LDOCE senses are marked with selectional restrictions expressed by 36 semantic codes not ordered in a hierarchy. However, the codes are clearly not of equal levels of generality; for example, the code H is used to represent all humans, while M represents human males. Thus for a restriction with type H , we would want to allow words with the more specific semantic class M to meet it. This can be computed if the semantic categories are organized into a hierarchy. Then all categories subsumed by another category will be regarded as satisfying the restriction. Bruce and Guthrie (1992) manually identified relations between the LDOCE semantic classes, grouping the codes into small sets with roughly the same meaning and attached descriptions; for example M , K are grouped as a pair described as "human male". The hierarchy produced is shown in Figure 3.

Table 4

Mapping of named entities onto LDOCE semantic codes. The named entities can be mapped to any semantic code within a particular node of the hierarchy since the disambiguation algorithm treats all codes in the same node as equivalent.

Named Entity Type	LDOCE code
PERSON	H (= Human)
ORGANIZATION	T (= Abstract)
LOCATION	N (= Non-movable solid)
DATE	T (= Abstract)
TIME	T (= Abstract)
MONEY	T (= Abstract)
PERCENT	T (= Abstract)
UNKNOWN	Z (= No semantic restriction)

The named entities identified as part of the preprocessing phase (Section 4.1) are used by this module, which requires first a mapping between the name types and LDOCE semantic codes, shown in Table 4.

Any use of preferences for sense selection requires prior identification of the site in the sentence where such a relationship holds. Although prior identification was not done by syntactic methods in Wilks (1975), it is often easiest to think of the relationships as specified in grammatical terms, e.g., as subject-verb, verb-object, adjective-noun etc. We perform this step by means of a shallow syntactic analyzer (Stevenson 1998) which finds the following grammatical relations: the subject, direct and indirect object of each verb (if any), and the noun modified by an adjective. Stevenson (1998) describes an evaluation of this system in which the relations identified were compared with those derived from Penn TreeBank parses (Marcus, Santorini, and Marcinkiewicz 1993). It was found that the parser achieved 51% precision and 69% recall.

The preference resolution algorithm begins by examining a verb and the nouns it dominates. Each sense of the verb applies a preference to those nouns such that some of their senses may be disallowed. Some verb senses will disallow all senses for a particular noun it dominates and these senses of the verb are immediately rejected. This process leaves us with a set of verb senses that do not conflict with the nouns that verb governs, and a set of noun senses licensed by at least one of those verb senses. For each noun, we then check whether it is modified by an adjective. If it is, we reject any senses of the adjectives which do not agree with any of the remaining noun senses. This approach is rather conservative in that it does not reject a sense unless it is impossible for it to fit into the preference pattern of the sentence.

In order to explain this process more fully we provide a walk-through explanation of the procedure applied to a toy example shown in Table 5. It is assumed that the named-entity identifier has correctly identified *John* as a person and that the shallow parser has found the correct syntactic relations. In order to make this example as straightforward as possible, we consider only the case in which the ambiguous words have few senses. The disambiguation process operates by considering the relations between the words in known grammatical relations, and before it begins we have essentially a set of possible senses for each word related via their syntax. This situation is represented by the topmost tree in Figure 4.

Disambiguation is carried out by considering each verb sense in turn, beginning with *run*(1). As *run* is being used transitively, it places two restrictions on the sentence: first, the subject must satisfy the restriction *human* and the object *abstract*. In this

Table 5
Sentence and lexicon for toy example of selectional preference resolution algorithm.

Example sentence: <i>John ran the hilly course.</i>		
Sense	Definition and Example	Restriction
John	proper name	type:human
ran (1)	to control an organisation <i>run IBM</i>	subject:human object:abstract
ran (2)	to move quickly by foot <i>run a marathon</i>	subject:human object:inanimate
hilly (1)	undulating terrain <i>hilly road</i>	modifies:nonmovable solid
course (1)	route <i>race course</i>	type:nonmovable solid
course (2)	programme of study <i>physics course</i>	type:abstract

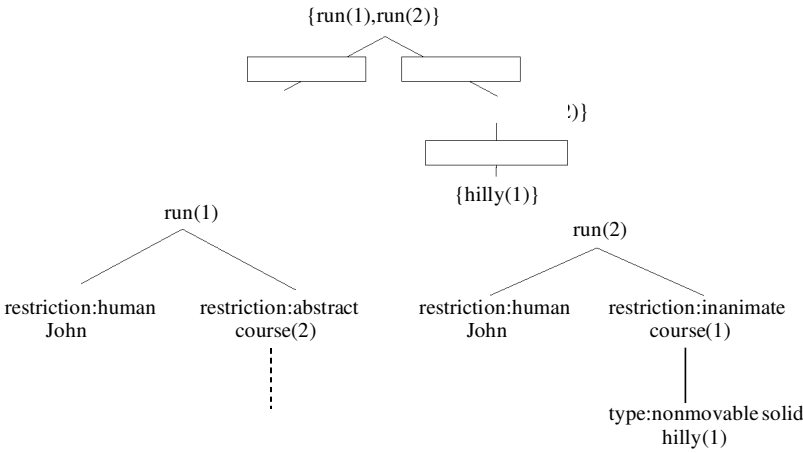


Figure 4
Restriction resolution in toy example.

example, *John* has been identified as a named entity and marked as `human`, so the subject restriction is not broken. Note that, if the restriction were broken, then the verb sense *run(1)* would be marked as incorrect by this partial tagger and no further attempt would be made to resolve its restrictions. As this was not the case, we consider the direct-object slot, which places the restriction `abstract` on the noun which fills it. *course(2)* fulfils this criterion. *course* is modified by *hilly* which expects a noun of type `nonmovable solid`. However, *course(2)* is marked `abstract`, which does not comply with this restriction. Therefore, assuming that *run* is being used in its second sense leads to a situation in which there is no set of senses which comply with all the restrictions placed on them; therefore *run(1)* is not the correct sense of *run* and the partial tagger marks this sense as wrong. This situation is represented by the tree at the bottom left of Figure 4. The sense *course(2)* is not rejected at this point since it may be found to be acceptable in the configuration of senses of another sense of *run*.

The algorithm now assumes that *run(2)* is the correct sense. This implies that *course(1)* is the correct sense as it complies with the `inanimate` restriction that that verb sense places on the direct object. As well as complying with the restriction imposed by *run(2)*, *course(1)* also complies with the one imposed by *hilly(1)*, since `nonmovable solid` is subsumed by `inanimate`. Therefore, assuming that the senses *run(2)* and

course(1) are being used does not lead to any restrictions being broken and the algorithm marks these as correct.

Before leaving this example it is worth discussing a few additional points. The sense *course*(2) is marked as incorrect because there is no sense of *run* with which an interpretation of the sentence can be constructed using *course*(2). If there were further senses of *run* in our example, and *course*(2) was found to be suitable for those extra senses, then the algorithm would mark the second sense of *course* as correct. There is, however, no condition under which *run*(1) could be considered as correct through the consideration of further verb senses. Also, although *John* and *hilly* are not ambiguous in this example, they still participate in the disambiguation process. In fact they are vital to its success, as the correct senses could not have been identified without considering the restrictions placed by the adjective *hilly*.

This partial tagger returns, for all ambiguous noun, verb, and adjective occurrences in the text, the set of senses which satisfy the preferences imposed on those words. Adverbs do not have any selectional preferences in LDOCE and so are ignored by this partial tagger.

4.5 Subject Codes

Our final partial tagger is a re-implementation of the algorithm developed by Yarowsky (1992). This algorithm is dependent upon a categorization of words in the lexicon into subject areas—Yarowsky used the Roget large categories. In LDOCE, primary pragmatic codes indicate the general topic of a text in which a sense is likely to be used. For example, LN means “Linguistics and Grammar” and this code is assigned to some senses of words such as “ellipsis”, “ablative”, “bilingual” and “intransitive”. Roget is a thesaurus, so each entry in the lexicon belongs to one of the large categories; but over half (56%) of the senses in LDOCE are not assigned a primary code. We therefore created a dummy category, denoted by --, used to indicate a sense which is not associated with any specific subject area and this category is assigned to all senses without a primary pragmatic code. These differences between the structures of LDOCE and Roget meant that we had to adapt the original algorithm reported in Yarowsky (1992).

In Yarowsky’s implementation, the correct subject category is estimated by applying (6), which maximizes the sum of a Bayesian term (the fraction on the right) over all possible subject categories (*SCat*) for the ambiguous word over the words in its context (*w*). A context of 50 words on either side of the ambiguous word is used.

$$\underset{SCat}{\text{ARGMAX}} \sum_{w \in \text{context}} \log \frac{\Pr(w|SCat) \Pr(SCat)}{\Pr(w)} \quad (6)$$

Yarowsky assumed the prior probability of each subject category to be constant, so the value $\Pr(SCat)$ has no effect on the maximization in (6), and (7) was in effect being maximized.

$$\underset{SCat}{\text{ARGMAX}} \sum_{w \in \text{context}} \log \frac{\Pr(w|SCat)}{\Pr(w)} \quad (7)$$

By including a general pragmatic code to deal with the lack of coverage, we created an extremely skewed distribution of codes across senses and Yarowsky’s assumption that subject codes occur with equal probability is unlikely to be useful in this application. We gained a rough estimate of the probability of each subject category by determining the proportion of senses in LDOCE to which it was assigned and applying the maximum likelihood estimate. It was found that results improved when the

rough estimate of the likelihood of pragmatic codes was used. This procedure generates estimates based on counts of types and it is possible that this estimate could be improved by counting tokens, although the problem of polysemy in the training data would have to be overcome in some way.

The algorithm relies upon the calculation of probabilities gained from corpus statistics: Yarowsky used the Grolier's Encyclopaedia, which comprised a 10 million word corpus. Our implementation used nearly 14 million words from the non-dialogue portion of the British National Corpus (Burnard 1995). Yarowsky used smoothing procedures to compensate for data sparseness in the training corpus (detailed in Gale, Church, and Yarowsky [1992b]), which we did not implement. Instead, we attempted to avoid this problem by considering only words which appeared at least 10 times in the training contexts of a particular word. A context model is created for each pragmatic code by examining 50 words on either side of any word in the corpus containing a sense marked with that code. Disambiguation is carried out by examining the same 100 word context window for an ambiguous word and comparing it against the models for each of its possible categories. Further details may be found in Yarowsky (1992).

Yarowsky reports 92% correct disambiguation over 12 test words, with an average of three possible Roget large categories. However, LDOCE has a higher level of average ambiguity and does not contain as complete a thesaural hierarchy as Roget, so we would not expect such good results when the algorithm is adapted to LDOCE. Consequently, we implemented the approach as a partial tagger. The algorithm identifies the most likely pragmatic code and returns the set of senses which are marked with that code. In LDOCE, several senses of a word may be marked with the same pragmatic code, so this partial tagger may return more than one sense for an ambiguous word.

4.6 Collocation Extractor

The final disambiguation module is the only feature-extractor in our system and is based on collocations. A set of 10 collocates are extracted for each ambiguous word in the text: first word to the left, first word to the right, second word to the left, second word to the right, first noun to the left, first noun to the right, first verb to the left, first verb to the right, first adjective to the left, and first adjective to the right. Some of these types of collocation were also used by Brown et al. (1991) and Yarowsky (1993) (see Section 2.3). All collocates are searched for within the sentence which contains the ambiguous word. If some particular collocation does not exist for an ambiguous word, for example if it is the first or last word in a sentence, then a null value (NoColl) is stored instead. Rather than storing the surface form of the co-occurrence, morphological roots are stored instead, as this allows for a smaller set of collocations, helping to cope with data sparseness. The surface form of the ambiguous word is also extracted from the text and stored. The extracted collocations and surface form combine to represent the context of each ambiguous word.

4.7 Combining Disambiguation Modules

The results from the disambiguation modules (filter, partial taggers, and feature extractor) are then presented to a machine learning algorithm to combine their results. The algorithm we chose was the **TiMBL memory-based learning** algorithm (Daelemans et al. 1999). Memory-based learning is another name for exemplar-based learning, as employed by Ng and Lee (Section 2.3). The **TiMBL** algorithm has already been used for various NLP tasks including part-of-speech tagging and PP-attachment (Daelemans et al. 1996; Zavrel, Daelemans, and Veenstra 1997).

Like PEBLS, which formed the core of Ng and Lee's LEXAS system, TiMBL classifies new examples by comparing them against previously seen cases. The class of the most similar example is assigned. At the heart of this approach is the distance metric $\Delta(X, Y)$ which computes the similarity between instances X and Y . This measure is calculated using the weighted overlap metric shown in (8), which calculates the total distance by computing the sum of the distance between each position in the feature vector.

$$\Delta(X, Y) = \sum_{i=1}^n w_i \delta(x_i, y_i) \quad (8)$$

where:

$$\delta(x_i, y_i) = \begin{cases} \frac{x_i - y_i}{\max_i - \min_i} & \text{if numeric, else} \\ 0 & \text{if } x_i = y_i \\ 1 & \text{if } x_i \neq y_i \end{cases} \quad (9)$$

From (9) we can see that TiMBL treats numeric and symbolic features differently. For numeric features, the unweighted distance is computed as the difference between the values for that feature in each instance, divided by the maximum possible distance computed over all pairs of instances in the database.⁵ For symbolic features, the unweighted distance is 0 if they are identical, and 1 otherwise. For both numeric and symbolic features, this distance is multiplied by the weight for the particular feature, based on the Gain Ratio measure introduced by Quinlan (1993). This is a measure of the difference in uncertainty between the situations with and without knowledge of the value of that feature, as in (10).

$$w_i = \frac{H(C) - \sum_v \Pr(v) \times H(C|v)}{H(v)} \quad (10)$$

Where C is the set of classifications, v ranges over all values of the feature i and $H(C)$ is the entropy of the class labels. Probabilities are estimated from frequency of occurrence in the training data. The numerator of this formula determines the knowledge about the distribution of classes that is added by knowing the value of feature i . However, this measure can overestimate the value of features with large numbers of possible values. To compensate, it is divided by $H(v)$, the entropy of the feature values.

Word senses are presented to TiMBL in a feature-vector representation, with each sense which was not removed by the part of speech filter being represented by a separate vector. The vectors are formed from the following pieces of information in order: headword, homograph number, sense number, rank of sense (the order of the sense in the lexicon), part of speech from lexicon, output from the three partial taggers (simulated annealing, subject codes, and selectional restrictions), surface form of headword from the text, the ten collocates, and an indicator of whether the sense is appropriate or not in the context (correct or incorrect).

Figure 5 shows the feature vectors generated for the word *influence* in the context shown. The final value in the feature vector shows whether the sense is correct or not in the particular context. We can see that, in this case, there is one correct sense, *influence_1_1a*, the definition of which is "power to gain an effect on the mind of

⁵ An earlier version of this system (Stevenson and Wilks 1999) used TiMBL version 1.0 (Daelemans et al. 1998), which supports only symbolic features.

Context	
Regarding Atlanta's new million dollar airport, the jury recommended "that when the new management take charge Jan. 1 the airport be operated in a manner that will eliminate political influences ".	
Feature Vectors	
Learning features	Truth
influence 1 1a 1 n influences 1 12.03 y NoColl manner NoColl eliminate NoColl in NoColl political NoColl eliminate	correct
influence 1 1b 2 n influences 0 12.03 y NoColl manner NoColl eliminate NoColl in NoColl political NoColl eliminate	incorrect
influence 1 2 3 n influences 0 12.03 y NoColl manner NoColl eliminate NoColl in NoColl political NoColl eliminate	incorrect
influence 1 3 4 n influences 0 12.03 y NoColl manner NoColl eliminate NoColl in NoColl political NoColl eliminate	incorrect
influence 1 4 5 n influences 0 12.03 n NoColl manner NoColl eliminate NoColl in NoColl political NoColl eliminate	incorrect
influence 1 5 6 n influences 0 12.03 n NoColl manner NoColl eliminate NoColl in NoColl political NoColl eliminate	incorrect
influence 1 6 7 n influences 0 12.03 n NoColl manner NoColl eliminate NoColl in NoColl political NoColl eliminate	incorrect

Figure 5
Example feature-vector representation.

or get results from, without asking or doing anything". Features 10–19 are produced by the collocation extractor, and these are identical since each vector is taken from the same content. Features 7–9 show the results of the partial taggers. The first is the output from *simulated annealing*, the second the *subject code*, and the third the *selectional restrictions*. All noun senses of *influence* share the same pragmatic code (--), and consequently this partial tagger returns the same score for each sense. A final point worth noting is that in LDOCE, *influence* has a verb sense which the part-of-speech filter removed from consideration, and consequently this sense is not included in the feature-vector representation.

The TiMBL algorithm is trained on tokens presented in this format. When disambiguating unannotated text, the algorithm is applied to data presented in the same format without the classification. The unclassified vectors are then compared with all the training examples, and it is assigned the class of the closest one.

5. Evaluation Strategy

5.1 Evaluation Corpus

The evaluation of WSD algorithms has recently become a much-studied area. Gale, Church, and Yarowsky (1992a), Resnik and Yarowsky (1997), and Melamed and Resnik (2000) each presented arguments for adopting various evaluation strategies, with Resnik and Yarowsky's proposal directly influencing the set-up of SENSEVAL (Kilgarriff 1998). At the heart of their proposals is the ability of human subjects to mark up text with the phenomenon in question (WSD in this case) and evaluate the results of computation. This linguistic phenomenon has proved to be far more elusive and complex than many others. We have discussed this at length elsewhere (Wilks 1997) and will assume here that humans can mark up text for senses to a sufficient degree. Kilgarriff (1993) questioned the possibility of creating sense-tagged texts, claiming the task to be impossible. However, it should be borne in mind that no alternative has yet been widely accepted and that Kilgarriff himself used the markup-and-test model for SENSEVAL. In the following discussion we compare the evaluation methodology adopted here with those proposed by others.

The standard evaluation procedure for WSD is to compare the output of the system against gold standard texts, but these are very labor-intensive to obtain; lexical semantic markup is generally considered to be a more difficult and time-consuming task than part-of-speech markup (Fellbaum et al. 1998). Rather than expend a vast amount of effort on manual tagging we decided to combine two existing resources: SEMCOR (Landes, Leacock, and Tengi 1998), and SENSUS (Knight and Luk 1994). SEMCOR is a 200,000 word corpus with the content words manually tagged as part of the WordNet project. The semantic tagging was carried out by trained lexicographers under disciplined conditions that attempted to keep tagging inconsistencies to a minimum. SENSUS is a large-scale ontology designed for machine-translation and was itself produced by merging the ontological hierarchies of WordNet, LDOCE (as derived by Bruce and Guthrie, see Section 4.4), and the Penman Upper Model (Bateman et al., 1990) from ISI. To facilitate the merging of these three resources to produce SENSUS, Knight and Luk were required to derive a mapping between the senses in the two lexical resources. We used this mapping to translate the WordNet-tagged content words in SEMCOR to LDOCE tags.

The mapping of senses is not one-to-one, and some WordNet synsets are mapped onto two or three LDOCE senses when WordNet does not distinguish between them. The mapping also contained significant gaps, chiefly words and senses not in the translation scheme. SEMCOR contains 91,808 words tagged with WordNet synsets, 6,071 of which are proper names, which we ignored, leaving 85,737 words which could potentially be translated. The translation contains only 36,869 words tagged with LDOCE senses; however, this is a reasonable size for an evaluation corpus for the task, and it is several orders of magnitude larger than those used by other researchers working in large vocabulary WSD, for example Cowie, Guthrie, and Guthrie (1992), Harley and Glennon (1997), and Mahesh et al. (1997). This corpus was also constructed without the excessive cost of additional hand-tagging and does not introduce any of the inconsistencies that can occur with a poorly controlled tagging strategy.

Resnik and Yarowsky (1997) proposed to evaluate large vocabulary WSD systems by choosing a set of test words and providing annotated test and training examples for just these words, allowing supervised and unsupervised algorithms to be tested on the same vocabulary. This model was implemented in SENSEVAL (Kilgariff 1998). However, for the evaluation of the system presented here, there would have been no benefit from using this strategy since it still involves the manual tagging of large amounts of data and this effort could be used to create a gold standard corpus in which all content words are disambiguated. It is possible that some computational techniques may evaluate well over a small vocabulary but may not work for a large set of words, and the evaluation strategy proposed by Resnik and Yarowsky will not discriminate between these cases.

In our evaluation corpus, the most frequent ambiguous type is *have*, which appears 604 times. A large number of words (2407) occur only once, and nearly 95% have 25 occurrences or less. Table 6 shows the distribution of ambiguous types by number of corpus tokens. It is worth noting that, as would be expected, the observed distribution is highly Zipfian (Zipf 1935).

Differences in evaluation corpora makes comparison difficult. However, some idea of the difficulty of WSD can be gained by calculating properties of the evaluation corpus. Gale, Church, and Yarowsky (1992a) suggest that the lowest level of performance which can be reasonably expected from a WSD system is that achieved by assigning the most likely sense in all cases. Since the first sense in LDOCE is usually the most frequent, we calculate this baseline figure using a heuristic which assumes the first sense is always correct. This is the same baseline heuristic we used for the experiments

Table 6
Occurrence of ambiguous words in the evaluation corpus.

Occurrence Range	Count
1–25	5488 (94.6%)
26–50	202 (3.5%)
51–75	67 (1.2%)
76–100	21 (0.04%)
100–604	26 (0.4%)

reported in Section 3, although those were for the homograph level. We applied the naive heuristic of always choosing the first sense in our corpus and found that 30.9% of senses were correctly disambiguated.

Another measure that gives insight into an evaluation corpus is to count the average polysemy, i.e., the number of possible senses we can expect for each ambiguous word in the corpus. The average polysemy is calculated by counting the sum of possible senses for each ambiguous token and dividing by the number of tokens. This is represented by (11), where w ranges over all ambiguous tokens in the corpus, $S(w)$ is the number of possible senses for word w , and N is the number of ambiguous tokens. The average polysemy for our evaluation corpus is 14.62.

$$\text{Average polysemy} = \frac{\sum_{w \text{ in text}} S(w)}{N} \quad (11)$$

Our annotated corpus has the unusual property that more than one sense may be marked as correct for a particular token. This is an unavoidable side-effect of a mapping between lexicon senses which is not one-to-one. However, it does not imply that WSD is easier in this corpus than one in which only a single sense is marked for each token, as can be shown from an imaginary example. The worst case for a WSD algorithm is when each of the possible semantic tags for a given word occurs with equal frequency in a corpus, and so the prior probabilities exhibit a uniform, uninformative distribution. Then a corpus with an average polysemy of 5, and 2 senses marked correct on each ambiguous token, will have a baseline not less than 40%. However, one with an average polysemy of 2, and only a single sense on each, will have a baseline of at least 50%. Test corpora in which each ambiguous token has exactly two senses were used by Brown et al. (1991), Yarowsky (1995) and others.

Our system was tested using a technique known as **10-fold cross validation**. This process is carried out by splitting the available data into ten roughly equal subsets. One of the subsets is chosen as the test data and the TiMBL algorithm is trained on the remainder. This is repeated ten times, so that each subset is used as test data exactly once, and results are averaged across all of the test runs. This technique provides two advantages: first, the best use can be made of the available data, and secondly, the computed results are more statistically reliable than those obtained by simply setting aside a single portion of the data for testing.

5.2 Evaluation Metrics

The choice of scoring metric is an important one in the evaluation of WSD algorithms. The most commonly used metric is the ratio of words for which the system has assigned the correct sense compared to those which it attempted to disambiguate. Resnik and Yarowsky (1997) dubbed this the **exact match metric**, which is usually expressed

as a percentage calculated according to the formula in (12).

$$\text{Exact match} = \frac{\text{Number of correctly assigned senses}}{\text{Number of senses assigned}} \times 100\% \quad (12)$$

Resnik and Yarowsky criticize this metric because it assumes a WSD system commits to a particular sense. They propose an alternative metric based on cross-entropy that compares the probabilities for each sense as assigned by a WSD system against those in the gold standard text. The formula in (13) shows the method for computing this metric, where the WSD system has processed N words and $\Pr(cs_i)$ is the probability assigned to the correct sense of word i .

$$-\frac{1}{N} \sum_{i=1}^N \log_2 \Pr(cs_i) \quad (13)$$

This evaluation metric may be useful for disambiguation systems that assign probabilities to each sense, such as those developed by Resnik and Yarowsky, since it provides more information than the exact match metric. However, for systems which simply choose a single sense and do not measure confidence, it provides far less information. When a WSD assigns only one sense to a word and that sense is incorrect, that word is scored as ∞ . Consequently, the formula in (13) returns ∞ if there is at least one word in the test set for which the tagger assigns a zero probability to the correct sense. For WSD systems which assign exactly one sense to each word, this metric returns 0 if all words are tagged correctly, and ∞ otherwise. This metric is potentially very useful for the evaluation of WSD systems that return non-zero probabilities for each possible sense; however, it is not useful for the metric presented in this paper and others that are not based on probabilistic models.

Melamed and Resnik (2000) propose a metric for scoring WSD output when there may be more than one correct sense in the gold standard text, as with the evaluation corpus we use. They mention that when a WSD system returns more than one sense it is difficult to tell if they are intended to be disjunctive or conjunctive. The score for a token is computed by dividing the number of correct senses identified by the algorithm by the total it returns, making the metric equivalent to precision in information retrieval (van Rijsbergen 1979).⁶ For systems which return exactly one sense for each word, this equates to scoring a token as 1 if the sense returned is correct, and 0 otherwise. For the evaluation of the system presented here, the metric proposed by Melamed and Resnik is then equivalent to the exact match metric.

The exact match metric has the advantage of being widely used in the WSD literature. In our experiments the exact match figure is computed at the LDOCE sense level, where the number of tokens correctly disambiguated to the sense level is divided by the number ambiguous at that level. At the homograph level, the number correctly disambiguated to the homograph is divided by the number which are polyhomographic.

6. Performance

Using the evaluation procedure described in the previous section, it was found that the system correctly disambiguated 90% of the ambiguous instances to the fine-grained sense level, and in excess of 94% to the homograph level.

⁶ The metric operates slightly differently for systems that assign probabilities to senses.

Table 7

System results, baselines, and corpus characteristics. Sense level results are calculated over all polysemous words in the evaluation corpus while those reported for the homograph level are calculated only over polyhomographic ones.

		Entire Corpus	Noun	Subcorpora Verb	Subcorpora Adjective	Adverb
Sense level	Accuracy	90.37%	91.24%	88.38%	91.09%	70.61%
	Baseline	30.90%	34.56%	18.46%	25.76%	36.73%
Tokens		36,774	26,091	6,465	3,310	908
Types		5,804	4,041	1,021	1,006	125
Average Polysemy		14.62	13.65	24.35	6.07	4.43
Homograph level	Accuracy	94.65%	94.63%	95.26%	96.89%	90.67%
	Baseline	71.24%	73.47%	60.72%	87.10%	86.87%
Tokens		18,219	11,380	5,194	1,326	319
Types		1,683	1,264	709	201	34
Average Polysemy		2.52	2.32	2.81	2.95	3.13

In order to analyze the effectiveness of our tagger in more detail, we split the main corpus into sub-corpora by grammatical category. In other words, we created four individual sub-corpora containing the ambiguous words which had been part-of-speech tagged as nouns, verbs, adjectives, and adverbs. The figures characterizing each of these corpora are shown in Table 7. The majority of the ambiguous words were nouns, with far fewer verbs and adjectives, and less than one thousand adverbs. The average polysemy for nouns, at both sense and homograph levels, is roughly the same as the overall corpus average although it is noticeably higher for verbs at the sense level. At the sense level the average polysemy figures are much lower for adjectives and adverbs. This is because it is common for English words to act as either a noun or a verb and, since these are the most polysemous grammatical categories, the average polysemy count becomes large due to the cumulative effect of polysemy across grammatical categories. However, words that can act as adjectives or adverbs are unlikely to be nouns or verbs. This, plus the fact that adjectives and adverbs are generally less polysemous in LDOCE, means that their average polysemy in text is far lower than it is for nouns or verbs.

Table 7 shows the accuracy of our system over the four subcorpora. We can see that the tagger achieves higher results at the homograph level than the sense level on each of the four subcorpora, which is consistent with the result over the whole corpus.

There is quite a difference in the tagger's results across the different subcorpora—91% for nouns and 70% for adverbs. Perhaps the learning algorithm does not perform as well on adverbs because that corpus is significantly smaller than the other three. This hypothesis was checked by testing our system on portions of each of the three subcorpora that were roughly equal in size to the adverb subcorpus. We found that the reduced data caused a slight loss of accuracy on each of the three subcorpora; however, there was still a marked difference between the results for the adverb subcorpus and the other three. Further analysis showed that the differences in performance over different subcorpora seem linked to the behavior of different partial taggers when used in combination. In the following section we describe this behavior in more detail.

6.1 Interaction of Knowledge Sources

In order to gauge the contribution of each knowledge source separately, we implemented a set of simple disambiguation algorithms, each of which uses the output from a single partial tagger. Each algorithm takes the result of its partial tagger and checks it against the disambiguated text to see if it is correct. If the partial tagger returns more than one sense, as do the `simulated_annealing`, `subject_code` and `selectional_preference` taggers, the first sense is taken to break the tie. For the partial tagger based on Yarowsky's subject-code algorithm, we choose the sense with the highest saliency value. If more than one sense has been assigned the maximum value, the tie is again broken by choosing the first sense. Therefore, each partial tagger returns a single sense and the exact match metric is used to determine the proportion of tokens for which that tagger returns the correct sense. The part-of-speech filter is run before the partial taggers make their decision and so they only consider the set of senses it did not remove. The results of each tagger, computed at both sense and homograph levels over the evaluation corpus and four subcorpora, are shown in Table 7.

We can see that the partial taggers that are most effective are those based on the simulated annealing algorithm and Yarowsky's subject code approach. The success of these modules supports our decision to use existing disambiguation algorithms that have already been developed rather than creating new ones.

The most successful of the partial taggers is the one based on Yarowsky's algorithm for modelling thesaural categories by wide contexts. This consistently achieves over 70% correct disambiguation and seems particularly successful when disambiguating adverbs (over 85% correct). It is quite surprising that this algorithm is so successful for adverbs, since it would seem quite reasonable to expect an algorithm based on subject codes to be more successful on nouns and less so on modifiers such as adjectives and adverbs.

Yarowsky (1992) reports that his algorithm achieves 92% correct disambiguation, which is nearly 13% higher than achieved in our implementation. However, Yarowsky tested his implementation on a restricted vocabulary of 12 words, the majority of which were nouns, and used Roget large categories as senses. The baseline performance for this corpus is 66.5%, considerably higher than the 30.9% computed for the corpus used in our experiments. Another possible reason for the difference in results is the fact that Yarowsky used smoothing algorithms to avoid problems with the probability estimates caused by data sparseness. We did not employ these procedures and used simple corpus frequency counts when calculating the probabilities (see Section 4.5). It is not possible to say for sure that the differences between implementations did not lead to the differences in results, but it seems likely that the difference in the semantic granularity of LDOCE subject codes and Roget categories was an important factor.

The second partial tagger based on an existing approach is the one which uses simulated annealing to optimize the overlap of words shared by the dictionary definitions for a set of senses. In Section 4.3 we noted that Cowie et al. (1992) reported 47% correct disambiguation to the sense level using this technique, while in our adaptation over 17% more words are correctly disambiguated. Our application filtered out senses with the incorrect part of speech in addition to using a different method to calculate overlap that takes account of short definitions. It seems likely that these changes are the source of the improved results.

Our least successful partial tagger is the one based on selectional preferences. Although its overall result is slightly below the overall corpus baseline, it is very successful at disambiguating verbs. This is consistent with the work of Resnik (1997), who reported that many words do not have strong enough selectional restrictions to carry out WSD. We expected preferences to be successful for adjectives as well, although

Table 8
Performance of individual partial taggers (at sense level).

	All	Nouns	Verbs	Adjectives	Adverbs
simulated annealing (1)	65.24%	66.50%	67.51%	49.02%	50.61%
selectional preferences (2)	44.85%	40.73%	75.80%	27.56%	0%
subject codes (3)	79.41%	79.18%	72.75%	73.73%	85.50%

this is not the case in our evaluation. This is because the sense discrimination of adjectives is carried out after that for nouns in our algorithm (see Section 4.4), and the former is hindered by the low results of the latter. Adverbs cannot be disambiguated by preference methods against LDOCE because it does not contain the appropriate information.

Our analysis of the behavior of the individual partial taggers provides some clues to the behavior of the overall system, consisting of all taggers, on the different sub-corpora, as shown in Table 7. The system performs to roughly the same level over the noun, verb, and adjective sub-corpora with only a 3% difference between the best and worst performance. The system's worst performance is on the adverb sub-corpus, where it disambiguates only slightly more than 70% of tokens successfully. This may be due to the fact that only two partial taggers provide evidence for this grammatical category. However, the system still manages to disambiguate most of the adverbs to the homograph level successfully, and this is probably because the part-of-speech filter has ruled out the incorrect homographs, not because the partial taggers performed well.

One can legitimately wonder whether in fact the different knowledge sources for WSD are all ways of encoding the same semantic information, in a similar way that one might suspect transformation rules and statistics encode the same information about part-of-speech tag sequences in different formats. However, the fact that an optimized combination of our partial taggers yields a significantly higher figure than any one tagger operating independently, shows that they must be orthogonal information sources.

6.2 The overall value of the part-of-speech filter

We have already examined the usefulness of part-of-speech tags for semantic disambiguation in Section 3. However, we now want to know the effect it has within a system consisting of several disambiguation modules. It was found that accuracy at the sense level reduced to 87.87% and to 93.36% at the homograph level when the filter was removed. Although the system's performance did not decrease by a large amount, the part-of-speech filter brings the additional benefit of reducing the search space for the three partial taggers. In addition, the fact that these results are not affected much by the removal of the part-of-speech filter, shows that the WSD modules alone do a reasonable job of resolving part-of-speech ambiguity as a side-effect of semantic disambiguation.

7. Conclusion

Previously reported WSD systems that enjoyed a high level of accuracy have often operated on restricted vocabularies and employed a single WSD methodology. These methods have often been pursued for sound reasons to do with evaluation, but have been limited in their applicability and also in their persuasiveness regarding the scal-

ability and interaction of the various WSD partial methods. This paper reported a system which disambiguated all content words in a text, as defined by a standard machine readable dictionary, with a high degree of accuracy.

Our evaluation shows that disambiguation can be carried out with more accurate results when several knowledge sources are combined. It remains unclear exactly what it means to optimize the combination of modules within a learning system like TiMBL: we could, in further work, treat the part-of-speech tagger as a partial tagger and not a filter, and we could allow the system to learn some “optimal” weighting of all the partial taggers. It also remains an interesting question whether, because of the undoubted existence of novel senses in text, a sense tagger can ever reach the level that part-of-speech tagging has. However, we believe we have shown that interesting combinations of WSD methods on a substantial training corpus are possible, and that this can show, among other things, the relative independence of the types of semantic information expressed by the various forms of lexical input.

Acknowledgments

The work described here was supported by the European Union Language Engineering project ECRAN – Extraction of Content: Research at Near-market (LE-2110). One of the authors was also supported by the EPSRC grant MALT (GR/M73521) while writing this paper. We are grateful for the feedback from many colleagues in Sheffield, especially Mark Hepple, and for the detailed comments from the anonymous reviewers of an earlier version of this paper. Gillian Callaghan was extremely helpful in the preparation of the final version of this paper. Any errors are our own.

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