

Parallel Sentence Discovery for Low-Resource Languages

by

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Chapter 1

Introduction

Almost all modern SMT systems are trained using a large collection of translated sentence pairs known as a parallel corpus. Sources of parallel data include parliament proceedings, books, and news articles. While this data may be abundant for some language pairs, such as French/English, it is scarce for most others. In addition, even when parallel data is available, it may not match the domain of the data you wish to translate, and this can have a large effect on performance (Munteanu and Marcu, 2005).

The creation of new parallel corpora can be expensive, especially when bilingual speakers are rare for the language pair of interest. In order to acquire more parallel data without costly human annotation, researchers have looked to corpora which may contain some parallel sentences, but are not completely parallel. Such corpora are referred to as comparable corpora, and examples include multilingual news feeds

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(Munteanu and Marcu, 2005) and Wikipedia articles (Adafre and de Rijke, 2006; Smith et al., 2010). Most work in extracting parallel sentences from these corpora assumes an initial bilingual dictionary or an existing parallel corpus.

On the other hand, there has also been work on aligning sentences in parallel corpora where the documents may contain 2 : 1 or 1 : 2 sentence alignments, or there may be large insertions or deletions of sentences (Gale and Church, 1993; Chen, 1993; Moore, 2002). This work, by contrast, does not require existing parallel data or a bilingual dictionary for the language pair of interest. Instead, the structure of the documents and the lengths of the sentences are used to determine the sentence alignment. Any information about bilingual word correspondence comes from the parallel data that is being aligned.

In this work, we aim to combine techniques from both parallel and comparable sentence alignment to improve the state of the art for parallel sentence extraction from comparable corpora. First, we will describe a novel discriminative model for aligning sentences in comparable documents. We will also describe a model for aligning comparable documents which needs only a minimal amount of supervision. Similar to how unsupervised word alignment models can learn their parameters from unlabeled data, we aim to learn parameters for a sentence alignment model from comparable unaligned documents.

1.1 Sentence Alignment

In this section, we will describe our task and notation. We will view both parallel corpora alignment and the extraction of parallel sentences from comparable corpora as an alignment task. In either type of alignment we are given a set of bilingual document pairs in *source* and *target* languages. When performing parallel corpora alignment, these document pairs will correspond to each other very strongly, while in the case of comparable corpora, some these document pairs may contain no parallel sentences. Munteanu and Marcu (2005) take their document pairs from news stories published at roughly the same time, while Adafre and de Rijke (2006); Smith et al. (2010) use entries from Wikipedia that are on the same topic (Figure 1.1 gives an example). The task of finding comparable document pairs is not addressed in this work.

Antipartícula

A cada una de las **partículas** de la naturaleza le corresponde una **antipartícula** que posee la misma **masa**, el mismo **espín**, pero distinta **carga eléctrica**. Algunas partículas son idénticas a su antipartícula, como por ejemplo el **fotón**, que no tiene carga. Pero no todas las partículas de carga neutra son idénticas a su antipartícula.

Antiparticle

From Wikipedia, the free encyclopedia

Corresponding to most kinds of **particles**, there is an associated **antiparticle** with the same **mass** and opposite **electric charge**. For example, the antiparticle of the electron is the positively charged antielectron, or **positron**, which is produced naturally in certain types of **radioactive decay**.

Figure 1.1: An example of a Spanish/English document pair from Wikipedia.

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Each document pair contains a sequence of source sentences (denoted by \mathbf{S}) and target sentences (denoted by \mathbf{T}). Individual source and target sentences are referred to by S and T respectively. Similarly, we refer to the words within source and target sentences with the lowercase s and t . We borrow the notation of (Och and Ney, 2003) for describing alignments between sentences as subsets of the Cartesian product of sentence positions. Sentence alignments are referred to with the uppercase A , and word alignments with the lowercase a .

The goal of sentence alignment is to identify which sentence pairs in the bilingual document pairs are parallel. We view this as a retrieval task for parallel sentence pairs, and so when annotated sentence alignments are present, we can compute precision, recall, and F-measure.

Chapter 2

Discriminative Sentence Alignment

In this chapter we will describe a discriminative models for performing sentence alignment on comparable document pairs. We use Wikipedia as our first source for comparable documents, and use a conditional random field (Lafferty et al., 2001) as the sentence alignment model. We also apply a discriminative monotonic alignment model to comparable documents mined from the Web as described by Uszkoreit et al. (2010).

2.1 Wikipedia as a Comparable Corpus

Wikipedia (Wikipedia, 2004) is an online collaborative encyclopedia available in a wide variety of languages. While the English Wikipedia is the largest, with over 3 million articles, there are 24 language editions with at least 100,000 articles.

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French 496K	German 488K	Polish 384K	Italian 380K	Dutch 357K	Portuguese 323K	Spanish 311K	Japanese 252K
Russian 232K	Swedish 197K	Finnish 146K	Chinese 142K	Norwegian 141K	Volapük 106K	Catalan 103K	Czech 87K

Table 2.1: Number of aligned bilingual articles in Wikipedia by language (paired with English).

Articles on the same topic in different languages are also connected via “interwiki” links, which are annotated by users. This is an extremely valuable resource when extracting parallel sentences, as the document alignment is already provided. Table 2.1 shows how many of these “interwiki” links are present between the English Wikipedia and the 16 largest non-English Wikipedias.

Wikipedia’s markup contains other useful indicators for parallel sentence extraction. The many hyperlinks found in articles have previously been used as a valuable source of information. (Adafre and de Rijke, 2006) use matching hyperlinks to identify similar sentences. Two links match if the articles they refer to are connected by an “interwiki” link. Also, images in Wikipedia are often stored in a central source across different languages; this allows identification of captions which may be parallel. Finally, there are other minor forms of markup which may be useful for finding similar content across languages, such as lists and section headings. In Section 2.2.3, we will explain how features are derived from this markup.

2.2 Models for Parallel Sentence Extraction

In this section, we will focus on methods for extracting parallel sentences from aligned, comparable documents. The related problem of automatic document alignment in news and web corpora has been explored by a number of researchers, including Resnik and Smith (2003), Munteanu and Marcu (2005), Tillmann (2009), and Tillmann and Xu (2009). Since our corpus already contains document alignments, we sidestep this problem, and will not discuss further details of this issue. That said, we believe that our methods will be effective in corpora without document alignments when combined with one of the aforementioned algorithms.

2.2.1 Binary Classifiers and Rankers

Much of the previous work involves building a binary classifier for sentence pairs to determine whether or not they are parallel (Munteanu and Marcu, 2005; Tillmann, 2009). The training data usually comes from a standard parallel corpus. There is a substantial class imbalance ($O(n)$ positive examples, and $O(n^2)$ negative examples), and various heuristics are used to mitigate this problem. Munteanu and Marcu (2005) filter out negative examples with high length difference or low word overlap (based on a bilingual dictionary).

We propose an alternative approach: we learn a ranking model, which, for each

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sentence in the *source* document, selects either a sentence in the *target* document that it is parallel to, or “null”. This formulation of the problem avoids the class imbalance issue of the binary classifier.

In both the binary classifier approach and the ranking approach, we use a Maximum Entropy classifier, following Munteanu and Marcu (2005).

2.2.2 Sequence Models

In Wikipedia article pairs, it is common for parallel sentences to occur in clusters. A global sentence alignment model is able to capture this phenomenon. For both parallel and comparable corpora, global sentence alignments have been used, though the alignments were monotonic (Gale and Church, 1993; Moore, 2002; Zhao and Vogel, 2002). Our model is a first order linear chain conditional random field (CRF) (Lafferty et al., 2001). The set of source and target sentences are observed. For each *source* sentence, we have a hidden variable indicating the corresponding *target* sentence to which it is aligned (or null). The model is similar to the discriminative CRF-based word alignment model of (Blunsom and Cohn, 2006).

2.2.3 Features

Our features can be grouped into four categories.

2.2.3.1 Features derived from word alignments

We use a feature set inspired by (Munteanu and Marcu, 2005), who defined features primarily based on IBM Model 1 alignments (Brown et al., 1993). We also use HMM word alignments (Vogel et al., 1996) in both directions (*source* to *target* and *target* to *source*), and extract the following features based on these four alignments:¹

1. Log probability of the alignment
2. Number of aligned/unaligned words
3. Longest aligned/unaligned sequence of words
4. Number of words with fertility 1, 2, and 3+

We also define two more features which are independent of word alignment models. One is a sentence length feature taken from (Moore, 2002), which models the length ratio between the *source* and *target* sentences with a Poisson distribution. The other feature is the difference in relative document position of the two sentences, capturing the idea that the aligned articles have a similar topic progression.

The above features are all defined on sentence pairs, and are included in the binary classifier and ranking model.

¹These are all derived from the one best alignment, and normalized by sentence length.

2.2.3.2 Distortion features

In the sequence model, we use additional distortion features, which only look at the difference between the position of the previous and current aligned sentences. One set of features bins these distances; another looks at the absolute difference between the expected position (one after the previous aligned sentence) and the actual position.

2.2.3.3 Features derived from Wikipedia markup

Three features are derived from Wikipedia’s markup. The first is the number of matching links in the sentence pair. The links are weighted by their inverse frequency in the document, so a link that appears often does not contribute much to this feature’s value. The image feature fires whenever two sentences are captions of the same image, and the list feature fires when two sentences are both items in a list. These last two indicator features fire with a negative value when the feature matches on one sentence and not the other.

None of the above features fire on a null alignment, in either the ranker or CRF. There is also a bias feature for these two models, which fires on all non-null alignments.

2.2.3.4 Word-level induced lexicon features

In order to address sparsity issues in our seed parallel corpora, we introduce a bilingual lexicon model which learns word translation probabilities from the linked Wikipedia articles. The details of this model and the features derived from it can be

found in (Smith et al., 2010).

2.3 Experiments

2.3.1 Data

We annotated twenty Wikipedia article pairs for three language pairs: Spanish-English, Bulgarian-English, and German-English. Each sentence in the *source* language was annotated with possible parallel sentences in the *target* language (the target language was English in all experiments). The pairs were annotated with a quality level: **1** if the sentences contained some parallel fragments, **2** if the sentences were mostly parallel with some missing words, and **3** if the sentences appeared to be direct translations. In all experiments, sentence pairs with quality **2** or **3** were taken as positive examples.

Language Pair	Binary Classifier			Ranker			CRF	
	Avg Prec	R@90	R@80	Avg Prec	R@90	R@80	Avg Prec	R@90
English-Bulgarian	75.7	33.9	56.2	76.3	38.8	57.0	80.6	52.9
English-Spanish	90.4	81.3	87.6	93.4	81.0	84.5	94.7	87.6
English-German	61.8	9.4	27.5	66.4	25.7	42.4	78.9	52.2

Table 2.2: Average precision, recall at 90% precision, and recall at 80% precision for each model in all three language pairs. In these experiments, the Wikipedia features and lexicon features are omitted.

For our seed parallel data, we used the Europarl corpus (Koehn, 2005) for Spanish and German and the JRC-Aquis corpus for Bulgarian, plus the article titles for parallel

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Setting	Ranker			CRF		
	Avg Prec	R@90	R@80	Avg Prec	R@90	R@80
English-Bulgarian						
One Direction	76.3	38.8	57.0	80.6	52.9	59.5
Intersected	78.2	47.9	60.3	79.9	38.8	57.0
Intersected +Wiki	80.8	39.7	68.6	82.1	53.7	62.8
Intersected +Wiki +Lex	89.3	64.4	79.3	90.9	72.0	81.8
English-Spanish						
One Direction	93.4	81.0	84.5	94.7	87.6	90.2
Intersected	94.3	82.4	89.0	95.4	88.5	91.8
Intersected +Wiki	94.5	82.4	89.0	95.6	89.2	92.7
Intersected +Wiki +Lex	95.8	87.4	91.1	96.4	90.4	93.7
English-German						
One Direction	66.4	25.7	42.4	78.9	52.2	54.7
Intersected	71.9	36.2	43.8	80.9	54.0	67.0
Intersected +Wiki	74.0	38.8	45.3	82.4	56.9	71.0
Intersected +Wiki +Lex	78.7	46.4	59.1	83.9	58.7	68.8

Table 2.3: Average precision, recall at 90% precision, and recall at 80% precision for the Ranker and CRF in all three language pairs. “+Wiki” indicates that Wikipedia features were used, and “+Lex” means the lexicon features were used.

Wikipedia documents, and translations available from Wiktionary entries.²

2.3.2 Intrinsic Evaluation

Using 5-fold cross-validation on the 20 document pairs for each language condition, we compared the binary classifier, ranker, and CRF models for parallel sentence extraction. To tune for precision/recall, we used minimum Bayes risk decoding. We define the loss $L(\tau, \mu)$ of picking target sentence τ when the correct target sentence is μ as 0 if $\tau = \mu$, λ if $\tau = \text{NULL}$ and $\mu \neq \text{NULL}$, and 1 otherwise. By modifying the null

²Wiktionary is an online collaborative dictionary, similar to Wikipedia.

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loss λ , the precision/recall trade-off can be adjusted. For the CRF model, we used posterior decoding to make the minimum risk decision rule tractable. As a summary measure of the performance of the models at different levels of recall we use average precision as defined in (Ido et al., 2006). We also report recall at precision of 90 and 80 percent. Table 2.2 compares the different models in all three language pairs.

In our next set of experiments, we looked at the effects of the Wikipedia specific features. Since the ranker and CRF are asymmetric models, we also experimented with running the models in both directions and combining their outputs by intersection. These results are shown in Table 2.3.

Identifying the agreement between two asymmetric models is a commonly exploited trick elsewhere in machine translation. It is mostly effective here as well, improving all cases except for the Bulgarian-English CRF where the regression is slight. More successful are the Wikipedia features, which provide an auxiliary signal of potential parallelism.

The gains from adding the lexicon-based features can be dramatic as in the case of Bulgarian (the CRF model average precision increased by nearly 9 points). The lower gains on Spanish and German may be due in part to the lack of language-specific training data. These results are very promising and motivate further exploration. We also note that this is perhaps the first successful practical application of an automatically induced word translation lexicon.

2.3.3 SMT Evaluation

We also present results in the context of a full machine translation system to evaluate the potential utility of this data. A standard phrasal SMT system (Koehn et al., 2003) serves as our testbed, using a conventional set of models: phrasal models of source given target and target given source; lexical weighting models in both directions, language model, word count, phrase count, distortion penalty, and a lexicalized reordering model. Given that the extracted Wikipedia data takes the standard form of parallel sentences, it would be easy to exploit this same data in a number of systems.

		German	English	Spanish	English	Bulgarian	
Medium	sentences	924,416	924,416	957,884	957,884	413,514	
	types	351,411	320,597	272,139	247,465	115,756	
	tokens	11,556,988	11,751,138	18,229,085	17,184,070	10,207,565	10,207,565
Large	sentences	6,693,568	6,693,568	7,727,256	7,727,256	1,459,900	1,459,900
	types	1,050,832	875,041	1,024,793	952,161	239,076	239,076
	tokens	100,456,622	96,035,475	155,626,085	137,559,844	29,741,936	29,741,936
Wiki	sentences	1,694,595	1,694,595	1,914,978	1,914,978	146,465	146,465
	types	578,371	525,617	569,518	498,765	107,690	107,690
	tokens	21,991,377	23,290,765	29,859,332	28,270,223	1,455,458	1,455,458

Table 2.4: Statistics of the training data size in all three language pairs.

For each language pair we explored two training conditions. The “Medium” data condition used easily downloadable corpora: Europarl for German-English and Spanish-English, and JRC/Acquis for Bulgarian-English. Additionally we included titles of all linked Wikipedia articles as parallel sentences in the medium data con-

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		German	English	Spanish	English	Bulgarian	English
Dev A	sentences	2,000	2,000	2,000	2,000	2,000	2,000
	tokens	16,367	16,903	24,571	21,493	39,796	40,503
Test A	sentences	5,000	5,000	5,000	5,000	2,473	2,473
	tokens	42,766	43,929	68,036	60,380	52,370	52,343
Wikitest	sentences	500	500	500	500	516	516
	tokens	8,235	9,176	10,446	9,701	7,300	7,701

Table 2.5: Statistics of the test data sets.

dition. The “Large” data condition includes all the medium data, and also includes using a broad range of available sources such as data scraped from the web (Resnik and Smith, 2003), data from the United Nations, phrase books, software documentation, and more.

In each condition, we explored the impact of including additional parallel sentences automatically extracted from Wikipedia in the system training data. For German-English and Spanish-English, we extracted data with the null loss adjusted to achieve an estimated precision of 95 percent, and for English-Bulgarian a precision of 90 percent. Table 2.4 summarizes the characteristics of these data sets. We were pleasantly surprised at the amount of parallel sentences extracted from such a varied comparable corpus. Apparently the average Wikipedia article contains at least a handful of parallel sentences, suggesting this is a very fertile ground for training MT systems.

The extracted Wikipedia data is likely to make the greatest impact on broad domain test sets – indeed, initial experimentation showed little BLEU gain on in-

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domain test sets such as Europarl, where out-of-domain training data is unlikely to provide appropriate phrasal translations. Therefore, we experimented with two broad domain test sets.

First, Bing Translator provided a sample of translation requests along with translations in German-English and Spanish-English – this constituted our standard development and test set for those language pairs. Unfortunately no such tagged set was available in Bulgarian-English, so we held out a portion of the large system’s training data to use for development and test. In each language pair, the test set was split into a development portion (“Dev A”) used for minimum error rate training (Och, 2003) and a test set (“Test A”) used for final evaluation.

Language pair	Training data	Dev A	Test A	Wikitest
Spanish-English	Medium	32.6	30.5	33.0
	Medium+Wiki	36.7 (+4.1)	33.8 (+3.3)	39.1 (+6.1)
	Large	39.2	37.4	38.9
	Large+Wiki	39.5 (+0.3)	37.3 (-0.1)	41.1 (+2.2)
German-English	Medium	28.7	26.6	13.0
	Medium+Wiki	31.5 (+2.8)	29.6 (+3.0)	18.2 (+5.2)
	Large	35.0	33.7	17.1
	Large+Wiki	34.8 (-0.2)	33.9 (+0.2)	20.2 (+3.1)
Bulgarian-English	Medium	36.9	26.0	27.8
	Medium+Wiki	37.9 (+1.0)	27.6 (+1.6)	37.9 (+10.1)
	Large	51.7	49.6	36.0
	Large+Wiki	51.7 (+0.0)	49.4 (-0.2)	39.5 (+3.5)

Table 2.6: BLEU scores of MT systems under various training and test conditions. The final BLEU score from minimum error rate training is in the first column; two additional columns are BLEU scores on held-out test sets. For training data conditions including the extracted Wikipedia sentences, the parenthesized values indicate the absolute BLEU difference against the corresponding system without Wikipedia extracts.

Second, we created new test sets in each of the three language pairs by sampling parallel sentences from held out Wikipedia articles. To ensure that this test data was clean, we manually filtered the sentence pairs that were not truly parallel and edited them as necessary to improve adequacy. We called this “Wikitest”. Characteristics of these test sets are summarized in Table 2.5.

We evaluated the resulting systems using BLEU-4 (Papineni et al., 2002); the results are presented in Table 2.6. First we note that the extracted Wikipedia data are very helpful in medium data conditions, significantly improving translation performance in all conditions. Furthermore we found that the extracted Wikipedia sentences substantially improved translation quality on held-out Wikipedia articles. In every case, training on medium data plus Wikipedia extracts led to equal or better translation quality than the large system alone. Furthermore, adding the Wikipedia data to the large data condition still made substantial improvements.

2.4 Comparable documents from the Web

Multilingual websites have often been used as a source of parallel data (Resnik and Smith, 2003; Huang et al., 2005; Shi et al., 2006). Most approaches for finding potential parallel documents rely on metadata rather than the content of the websites. This metadata may include links which appear to point to alternate versions of the same page in another language, the URLs of the websites, or their HTML

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structure. Another approach for finding multilingual websites is given by Uszkoreit et al. (2010), who translate all non-English web pages into English using their MT system and then use monolingual document similarity measures to find comparable document pairs. Uszkoreit et al. (2010) also describe a sentence alignment model which is applied to the comparable document pairs. In this work, we will instead use a discriminative, monotonic alignment model to align these document pairs. As this requires labeled sentence alignment data for both training and evaluation, we also describe an annotation tool for monotonic alignments which allows $m : n$ sentence matchings.

2.4.1 Data collection

2.4.1.1 Annotation Tool

We obtain a set of Japanese-English document pairs using the method described by Uszkoreit et al. (2010). From this set, we randomly selected roughly 1000 document pairs to be annotated. The annotators were presented with the interface shown in Figure 2.1. For each document pair we asked if the two documents are in the correct language pair, and if one of the documents appeared to be machine translated. If the language pair was correct and the documents appeared to be translated by a human, then the annotators aligned the sentences in the document.

The annotation tool is closely related to the monotonic alignment model in how

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Instructions: Annotate the Japanese/English document pair with sentence alignments. If the two selected sentences are translations of each other, click "Match". Use the "Skip Left" and "Skip Right" buttons to skip sentences that do not have translations in the other document.

Is this a Japanese/English document pair? ☒ Yes ☐ No

Is translation quality too poor to be written by a human? ☐ Yes ☒ No

CINii - CT 読解 洲綾 オ 綾玖 " オ 語音 キ 食 聊 綾 ヨ 退皮 ッ カ : CT 読解 洲綾 ヨ 語 " 閑陸 オ 語	<input type="button" value="Skip Left"/> <input type="button" value="Match"/> <input type="button" value="Skip Right"/> <input type="button" value="Merge Left"/> <input type="button" value="Undo"/> <input type="button" value="Merge Right"/>	CINii - Study for Exposure of CT Examinations : Patient Exposure for CT Examinations
CINii 蝗 ス 逸区 ュ 遊 ア 塾 フ 退皮 ッ カ 寒 隅 久 枚 語 遊 ア 網 凱 ン 綾 イ 網 シ 綾 ソ [綾 オ 綾 , 網 九 う]	<input type="button" value="Skip to here"/>	CINii National Institute of Informatics Scholarly and Academic Information Navigator
諄 一 閑 冗 匿 軒 イ	<input type="button" value="Skip to here"/>	Sign Up
網 ュ 綾 一 綾 , 網 ウ	<input type="button" value="Skip to here"/>	Login

Figure 2.1: The annotation interface for sentence alignment.

it operates. The user is asked whether or not the first sentences in each document are parallel. If they are, the user selects “Match”, the sentences are aligned, and the user is then prompted about the next two sentences. If the sentence pair presented to the annotator is not parallel, they will select either “Skip Left” or “Skip Right”, which advance the current sentence in the document on the left or right. These three operations correspond to the operations used in the monotonic alignment model, and the annotator’s sequence of operations can be directly used as training data.

The tool also allows the annotator to specify arbitrary $n : m$ sentence alignments through the “Merge Left” and “Merge Right” buttons. The merge actions append the immediately following sentences to the currently selected sentences, which can then be aligned.

2.4.1.2 Data Collection Results

Since the data we have annotated using this tool is taken from the HTML source of webpages, and converted to plain text and segmented into sentences automatically, the “Merge” buttons are often used to correct errors in sentence segmentation. This results in a few large $n : m$ alignments, though most alignments are still 1 : 1. Table 2.7 breaks down the alignments that the annotators have provided.

Alignment Type	1:1	2:1	1:2	2:2	Other
Percentage	95.8%	1.70%	1.28%	0.159%	1.12%

Table 2.7: Statistics on the types of $n : m$ alignments found in the annotated data.

2.4.2 Monotonic alignment model

Our sentence alignment model is a discriminatively trained monotonic alignment model. An illustration of this model is given in Figure 2.2. Formally, we represent the model as a weighted finite-state automata (WFSA) with features that fire on each arc as described in Eisner (2002). Specifically, in this work we use a weighted finite-state transducer (WFST) to describe our alignment model. A WFST includes a set of states \mathbb{Q} , source and target alphabets Σ_S and Σ_T , transition function $\delta : \mathbb{Q} \times \Sigma_S \times \Sigma_T \longrightarrow \mathbb{Q} \times W$, and start and end states \mathbb{S} and \mathbb{F} .

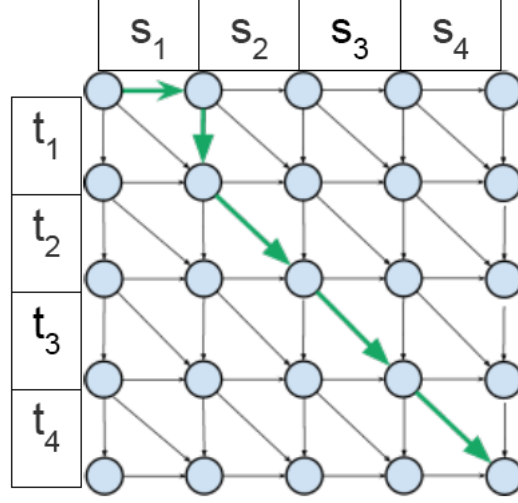


Figure 2.2: The discriminative model for monotonic sentence alignment. The highlighted path represents a possible alignment between the two documents.

$$\begin{aligned}
 \mathbb{Q} &= \{q_{i,j} \mid 0 \leq i \leq |\vec{S}|, 0 \leq j \leq |\vec{T}|\} \\
 \Sigma_S &= \{\epsilon\} \cup \{S_i \mid 0 \leq i < |\vec{S}|\} \\
 \Sigma_T &= \{\epsilon\} \cup \{T_j \mid 0 \leq j < |\vec{T}|\} \\
 \delta(q_{i,j}) &= \{(q_{i+1,j}, (S_i, \epsilon), \vec{f}(S_i, \epsilon) \cdot \vec{w}), \\
 &\quad (q_{i,j+1}, (\epsilon, T_j), \vec{f}(\epsilon, T_j) \cdot \vec{w}), \\
 &\quad (q_{i+1,j+1}, (S_i, T_j), \vec{f}(S_i, T_j) \cdot \vec{w})\} \\
 \mathbb{S} &= q_{0,0} \\
 \mathbb{F} &= q_{|\vec{S}|, |\vec{T}|}
 \end{aligned}$$

The FSM representing the set of possible alignments for a document pair (\vec{S}, \vec{T}) has $(|\vec{S}| + 1) \cdot (|\vec{T}| + 1)$ states. These states correspond to positions in the source and

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target documents. Each state has at most three transitions, which either skip the current source sentence, skip the current target sentence, or align the current source and target sentences. Note that these operations directly match the actions used by the annotators to generate the labeled alignments, so they may be directly used as an observed path through the WFSA. This automata only contains 1 : 1 alignments, though $n : m$ alignments could be added to this machine through additional arcs on each state.

The weights on each of the arcs a come from the dot product of the features which fire on that arc and the weight vector \vec{w} . The total weight of a path $\pi = a_0, a_1, \dots, a_n$ is the dot product of all features firing on each arc and the weight vector. Using this property we can now define a probability distribution over paths through this WFST:

$$p(\pi | \vec{S}, \vec{T}) = \frac{\sum_{a \in \pi} \exp \vec{f}(a) \cdot \vec{w}}{\sum_{\pi'} \sum_{a \in \pi'} \exp \vec{f}(a) \cdot \vec{w}}$$

The denominator is the sum of the weights of all paths through the WFST. We train our model to maximize the probability of the observed training data:

$$\operatorname{argmax}_{\vec{w}} \sum_{(\pi, \vec{S}, \vec{T})} p(\pi | \vec{S}, \vec{T})$$

The gradient of this objective can be computed using standard finite-state algorithms (Eisner, 2002).

2.4.2.1 Features

We chose to use a simple set of features which are mostly based on bag-of-words similarity measures. First, we have bias features which fire on all “matching” and “mismatching” arcs (arcs which emit (S_i, T_j) are matching arcs, and the mismatching arcs emit either (ϵ, T_j) or (S_i, ϵ)). For the matching arcs, we project the source sentence through a weighted bilingual dictionary and compute cosine similarity with the target sentence (and the same is done in reverse).

We also experimented with a set of first-order features, which look at the previous arc taken in the WFST. This is made possible by splitting each state $q_{i,j}$ into $q_{i,j,+}$ and $q_{i,j,-}$. “Match” transitions lead to $q_{i,j,+}$ while “mismatch” transitions lead to $q_{i,j,-}$. Since the states are now recording the last operation, the arcs leaving these states have features which fire on two matches in a row, for example. The intuition behind adding these features is that matches often follow other matches, and a similar trend is present for mismatches.

2.4.3 Results

We compare our discriminatively trained model against a hand-tuned monotonic alignment model. Our results are shown in Table 2.8.

CHAPTER 2. DISCRIMINATIVE SENTENCE ALIGNMENT

Model	Precision	Recall	F1
Baseline	63.9%	95.0%	76.4%
Discriminative Aligner	66.0%	94.4%	77.7%
+First Order Features	65.1%	95.2%	77.3%

Table 2.8: Precision, recall and F1 score measured on a held out set of aligned Japanese-English document pairs.

Chapter 3

Unsupervised Parallel Sentence Extraction from Comparable Corpora

3.1 Unsupervised Sentence Alignment

In most previous work on finding parallel sentences in comparable corpora, some initial parallel data (parallel sentences or bilingual dictionary entries) is used as a starting point. This data is used to extract parallel sentences, with the hope that the bilingual word correspondences from the initial data are enough to determine whether or not two sentences are parallel. The obvious drawback is the reliance on the initial data, which may be small. Ideally, one would learn additional word correspondences

CHAPTER 3. UNSUPERVISED PARALLEL SENTENCE EXTRACTION FROM COMPARABLE CORPORA

from parallel sentences that were extracted, and this information could be used to find more parallel sentences. In fact, this bootstrapping method has been used in previous work (Fung and Cheung, 2004a,b; Wu and Fung, 2005).

We will explore a novel way of using semi-supervised learning to find parallel sentences: by including sentence and word alignment in a single model. Much like the IBM word alignment models (Brown et al., 1993) which can be trained on sentence pairs without word alignment data, our model can be trained on document pairs without sentence or word alignment data, and can similarly be trained using the expectation-maximization (EM) algorithm (Dempster et al., 1977).

3.1.1 Model

First we must define a generative model of a bilingual (possibly) parallel document pair. We will use a joint model of the source and target documents based on stochastic edit distance (Ristad and Yianilos, 1998). Document pairs are generated by a memoryless transducer which generates substitution pairs (S, T) , insertion pairs (ϵ, T) , deletion pairs (S, ϵ) , and the termination pair (ϵ, ϵ) , borrowing the convention used by (Oncina and Sebban, 2006) for simplicity. Substitution pairs correspond to parallel source and target sentences, while the insertion and deletion pairs are monolingually generated. For this model to be properly defined, the probability of generating all pairs must sum to one:

CHAPTER 3. UNSUPERVISED PARALLEL SENTENCE EXTRACTION FROM COMPARABLE CORPORA

$$\sum_{x \in S \cup \{\epsilon\}, y \in T \cup \{\epsilon\}} p(x, y) = 1 \quad (3.1)$$

Since the insertion and deletion operations are monolingual generation of sentences, we use a standard n -gram language model for their probabilities. For the probability of a substitution pair, we decompose $p(S, T)$ into $p(T|S)p(S)$. $p(T|S)$ is defined by an IBM word alignment model (Brown et al., 1993) (Model 1 in this preliminary work), and $p(S)$ is given by the same language model used to generate deletion pairs $((S, \epsilon))$. Since $p(S, T)$, $p(S, \epsilon)$ and $p(\epsilon, T)$ all individually sum to one, they must be weighted to ensure that $p(\mathbf{S}, \mathbf{T})$ is properly normalized.¹ In this work, we will use a single parameter to weight these pairs:

$$\begin{aligned} p(S, T) &= \lambda p_{Model1}(T|S) p_{LM}(S) \\ p(S, \epsilon) &= \frac{1 - \lambda}{2} p_{LM}(S) \\ p(\epsilon, T) &= \frac{1 - \lambda}{2} p_{LM}(T) \end{aligned}$$

p_{Model1} and p_{LM} refer to the IBM Model 1 and a unigram language model, respectively. The parameter λ roughly controls how eager the model is to label sentence pairs as parallel. This can be set based on some prior knowledge about the corpus.

p_{Model1} is given by the following equation from (Brown et al., 1993):

¹Since our document pairs are always observed, we can safely ignore the stopping cost $p(\epsilon, \epsilon)$ by assuming it to be some small constant.

CHAPTER 3. UNSUPERVISED PARALLEL SENTENCE EXTRACTION FROM COMPARABLE CORPORA

$$p(T|S) = p(|T|||S|) \frac{1}{|S|^{|T|}} \prod_{j=1}^{|T|} \sum_{i=1}^{|S|} p(t_j|s_i) \quad (3.2)$$

For simplicity, we assume the source sentence S contains the null word. The term $\frac{1}{|S|^{|T|}}$ is the uniform alignment probability. The length distribution, $p(|T|||S|)$, was originally described as a uniform distribution over a large finite set of lengths. Since Model 1 is usually applied to parallel corpora with observed sentence alignments, and the goal of using Model 1 is to find word translation probabilities ($p(t|s)$), it is unnecessary to find an accurate model of sentence length. However, when the sentence alignments are being learned, it is important to have an accurate model of the length of the target sentence given the source sentence. In this work, we use a Poisson distribution to model the target sentence length, following Moore (2002).

The probability for generating sentences monolingually, $p_{LM}(S)$, is a unigram model estimated from the source language documents in the corpus. Similarly, $p_{LM}(T)$ is estimated from the target language documents. While a higher order language model could be learned, we use a unigram model to more closely match IBM Model 1, which can be thought of as a mixture of unigram models (one for each source word and one for the null word) that generate the target sentence. We also use a Poisson distribution to model the lengths of monolingually generated sentences, rather than generating a special end-of-sentence token.

3.2 Data Collection

In order to evaluate the unsupervised sentence alignment model that we are proposing, we must have bilingual document pairs with an annotated sentence alignment. While existing parallel corpora may be used for this, the document pairs in these corpora are highly parallel and would not resemble the alignments found in Wikipedia articles on the same topic, or comparable news articles. We will instead annotate comparable document pairs with their sentence alignment using Amazon’s Mechanical Turk (MTurk).

3.2.1 Mechanical Turk

MTurk is an online marketplace where people may post collections of tasks that workers may choose to complete for small amounts of money. These tasks are referred to as Human Intelligence Tasks (or HITs) because they are intended to be easy for humans to complete but difficult to automate. Examples of HITs include the identification of offensive images, moderation of forum posts or blog comments, and finding the contact information of a business. The workers on MTurk are referred to as “Turkers”. MTurk has also been used for several natural language tasks (Snow et al., 2008), including the evaluation of machine translation output (Callison-Burch, 2009) and even translation itself (Zaidan and Callison-Burch, 2011). The greatest concern when using MTurk for annotation is ensuring that the results are reliable.

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There are many ways in which sentence alignment of bilingual comparable documents could be organized into HITs on MTurk. The simplest way would be to take all possible sentence pairs in the document pair, and ask the Turkers to decide whether or not they are parallel. Unfortunately, this will result in far too many tasks to be affordable, as some Wikipedia articles have over a thousand sentences. In order to cut down on the number of tasks, we applied pruning to the candidate sentence pairs.

3.2.2 Pruning and Data Selection

Our pruning strategy is roughly based on that of Munteanu and Marcu (2005). Sentence pairs are filtered by two criteria. **Length ratio:** The ratio between the lengths (in words) of the two sentences must be below a threshold in each direction. **Coverage:** The percentage of target words t which either have an exact string match with a source word, or have $p(t|s)$ (under IBM Model 1) greater than a threshold for some s in the source sentence. We obtain the Model 1 probabilities by training on existing parallel data and bilingual dictionary entries for the language pair. Coverage is computed on both the source and target sentences, and a sentence pair is filtered if the average coverage falls below a threshold.

This pruning strategy requires three thresholds to be set: a maximum length ratio, a minimum average source/target coverage, and a minimum Model 1 probability for determining whether or not a word is covered. We tune these thresholds on existing parallel data to ensure that the filter has high recall (90%) while still removing many

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non-parallel sentence pairs. For our Urdu/English experiments, the thresholds we used were 2.5 for the maximum length ratio, 0.01 for the minimum average coverage, and 0.575 for the Model 1 word coverage threshold. We take our parallel data for training Model 1 parameters from the NIST MT09 Urdu-English training set and the bilingual dictionaries and sentences gathered by Post et al. (2012).

In addition to pruning sentence pairs which are not likely parallel, we also remove any pairs containing sentences with less than five tokens. Wikipedia articles include section headings lists of names (such as an actor’s filmography), and links to other articles or external websites. Since our goal is to find parallel sentences, we do not ask Turkers to annotate these very short segments.

Since we are not asking Turkers to annotate all possible sentence pairs from an article pair, evaluation becomes more difficult. We will discuss how we use our partial annotation in Section 3.2.5.

3.2.3 Task Design

Our strategy for designing the HITs on MTurk was to give the user an Urdu sentence and a list of up to ten English sentences. The Turker is asked to select which of the English sentences is parallel to the Urdu sentence, or select “None of the above” if none of the English sentences are parallel. We also ask if the sentence pair they find is a partial or full match, and give some examples of each in the instructions. Figure 3.1 shows an example of one of these questions.

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جنوری - باراک حسین اوباما نے نئے امریکی صدر کا حلد اٹھایا۔20

- ☐ april 14 - vaisakhi in sikhism
- ☐ chemistry - ada yonath , venkatraman ramakrishnan , and thomas a. steitz
- ☐ None of the above
- *Is this match full or partial?* ☐ Full ☐ Partial

جنوری - روس نے یورپ کو سپلائی کی جانے گیس بند کر دی۔7

- ☐ russia 's foreign ministry criticises the expulsions .
- ☐ january 7 - russia shuts off all gas supplies to europe through ukraine .
- ☐ chemistry - ada yonath , venkatraman ramakrishnan , and thomas a. steitz
- ☐ april 14 - vaisakhi in sikhism
- ☐ economics - clinor ostrom and oliver e. williamson
- ☐ physics - charles k. kao , willard boyle , and george e .
- ☐ None of the above
- *Is this match full or partial?* ☐ Full ☐ Partial

Figure 3.1: The MTurk annotation interface for finding Urdu-English parallel sentences.

Our method of pruning potential sentence pairs may leave us with more than ten candidate English sentences for some Urdu sentences. When this happens, we make additional questions about these Urdu sentences to ensure all candidate pairs are accounted for in the annotation.

In each HIT, we ask the Turkers to annotate up to ten Urdu sentences with their English counterpart (if any), including two control questions with sentences taken from the parallel data described in Section 3.2.2. There is one positive and one negative control in each HIT. We also request that each HIT be done by three Turkers.

3.2.4 Data Collection Results

In our first large-scale experiment, we took 92 Urdu-English article pairs, applied our filters as described in Section 3.2.2, and uploaded our task to MTurk. While there were over 8 million possible sentence pairs in these articles before pruning, we ended up with 785,000 sentence pairs to be annotated at a total cost of \$726.80 (this cost includes the duplicate annotations).

Agreement among the Turkers was high ($\kappa = 0.84$). While the most common answer was “None of the above”, there were a substantial number of Urdu sentences which the Turkers found some English counterpart for. For 21.4% of Urdu sentences, at least one Turker found one of the English sentences to be parallel, and in 44.8% of Urdu sentences, at least two Turkers identified a match.

3.2.5 Evaluation Using Partial Alignments

When we evaluate our sentence pair alignment model, we would like to compute the precision and recall of the proposed sentence alignments. However, since we prune many possible sentence pairs before asking the Turkers for annotation, we cannot be sure whether or not some sentence pairs are parallel. In this section, we will outline a scheme for evaluating sentence alignments using our partially annotated data.

Our primary intrinsic evaluation metric is alignment F-measure on sentence alignments. This metric could also be seen as F-measure on a parallel sentence pair re-

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trieval task. Let T be the set of true positives (sentence pairs that are truly parallel), and P be the set of predicted positives (sentence pairs identified by our model as parallel). Precision, recall, and F-measure are defined as follows:

$$\begin{aligned} \text{Precision} &= \frac{|T \cap P|}{|P|} \\ \text{Recall} &= \frac{|T \cap P|}{|T|} \\ \text{F-measure} &= \frac{2 \cdot \text{Precision} \cdot \text{Recall}}{\text{Precision} + \text{Recall}} \end{aligned}$$

When our document pairs are only partially annotated, we will use modified definitions of precision, recall, and F-measure. Let U be the set of sentence pairs which were not annotated as parallel or non-parallel.

$$\begin{aligned} \text{Precision} &= \frac{|T \cap P|}{|P \setminus U|} \\ \text{Recall} &= \frac{|T \cap P|}{|T|} \\ \text{F-measure} &= \frac{2 \cdot \text{Precision} \cdot \text{Recall}}{\text{Precision} + \text{Recall}} \end{aligned}$$

Since T and U are disjoint, only the definition of precision needs to be modified.

Given the annotations we gathered from MTurk, it is possible to define U in multiple ways. The most conservative method would be to take U to be all sentence pairs not presented to the Turkers. However, if we make the assumption that sentence alignments of the document pairs are 1 : 1, then when a Turker annotates a sentence

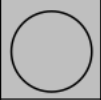

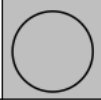



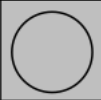

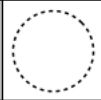
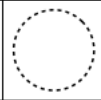


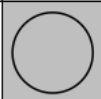
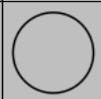

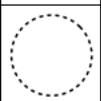

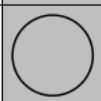

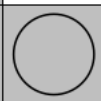
	S_1	S_2	S_3	S_4	S_5
T_1					
T_2					
T_3					
T_4					

Figure 3.2: A partial alignment grid for a comparable document pair. The shaded cells in the grid represent the sentence pairs which were presented to the Turkers for annotation. A filled circle indicates the Turker found the sentence pair to be parallel, and an empty circle means the pair is not parallel. The dashed circles represent the sentence pairs we infer to be non-parallel by assuming the sentence alignments are 1 : 1.

pair (S, T) as parallel, it follows that all (S, T') pairs with $T' \neq T$ and (S', T) pairs with $S' \neq S$ are not parallel. Since the alignments we found were mostly 1 : 1, we decided to go with this option.² Figure 3.2 illustrates this method.

3.2.6 Alternate Evaluation Strategies

Section 3.2.5 describes a method for using Turkers' partial annotation of a document pair's sentence alignment for intrinsic evaluation of a sentence alignment model. In this section, we will explore other strategies for using the Turkers' output for evaluation.

²There were a small number of alignments which were not 1 : 1, most of which were image captions.

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In our MTurk task setup (see Section 3.2.3), we collect redundant annotations for each HIT. While this was done primarily for quality control, and it is more convenient to use a single judgement for each sentence pair, we can perform a more fine-grained analysis by looking at the individual Turkers’ judgements. Also, we gave the option of labeling a parallel sentence pair as a “partial” or “full” match.

3.3 Experiments

Our first set of experiments uses a semi-supervised setting. We have both parallel sentences (labeled data) and comparable document pairs (unlabeled data), and learn our model’s parameters from both of these resources.

Our parallel corpus is taken from the NIST MT09 Urdu-English training set and the bilingual dictionaries and sentences gathered by Post et al. (2012).³ The parallel sentences from this corpus are treated as single sentence document pairs. Alternatively, the entire training set could be seen as a single document pair whose sentence alignment lies completely on the diagonal. The model described in 3.1 does not differentiate between these two ways of viewing the corpus. In either case, learning from the parallel sentences is identical to IBM Model 1 training.

The comparable document pairs are a subset of the Wikipedia article pairs that we annotated using MTurk as described in Section 3.2. 60% of this data was taken

³This is the same parallel corpus used to create the sentence pair filters used in collecting the annotated sentence alignments.

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as a development set. The remaining 40% of the annotated document pairs was split into two equal sized test sets.⁴

In the following experiments the setup is as follows: We initialize our parameters by running five iterations of EM on the parallel sentences from our labeled data. Then we run several iterations of EM on both the labeled data and unlabeled data, measuring performance after each iteration.

3.3.1 Results

3.4 Experiments (Alternate)

In this section, we explore the relationship between the amount of initial parallel data, the quality of the extracted parallel data, and the end-to-end machine translation quality. We start with Spanish-English as our language pair, since this is a high resource language pair, and we can always simulate a low resource setting by restricting the amount of data used.

3.4.1 Datasets

For our initial parallel data, we use the parallel and monolingual corpora available for the 2010 Machine Translation Workshop’s shared task (WMT10). For the Spanish-

⁴This split was done in order to have training, development, and test sets for supervised sentence alignment models.

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English task, the WMT10 data includes Europarl version 5 (we use version 6 in our experiments) (Koehn, 2005), the United Nations parallel text, and parallel and monolingual news corpora. Table 3.1 lists the corpora used in detail.

		Spanish	English	English (Monolingual)
Europarl	Sentences	1.79M	1.79M	1.79M
	Tokens	46.8M	44.7M	44.7M
United Nations	Sentences	6.22M	6.22M	6.22M
	Tokens	191M	164M	164M
News Commentary	Sentences	98.6K	98.6K	126K
	Tokens	2.45M	2.10M	261M
News	Sentences	N/A	N/A	48.7M
	Tokens	N/A	N/A	989M

Table 3.1: Statistics for the initial parallel/monolingual data used in training baseline MT systems and for extracting new parallel data. The monolingual data is only used for language modeling, not for extracting parallel sentences.

This data is used both for training the parallel sentence extractor, and as the initial data in the MT system.

3.4.2 Supervised Parallel Sentence Extraction

In order to extract parallel sentence pairs from Wikipedia, we used a simplified version of the approach described in Smith et al. (2010).

Using the initial parallel data and a small amount of annotated Spanish-English Wikipedia articles, we extracted sentence pairs from all of the Spanish-English Wikipedia articles which were identified as sharing a topic through Wikipedia’s Interwiki link system. This gave us a set of 433 thousand comparable document pairs. For all

CHAPTER 3. UNSUPERVISED PARALLEL SENTENCE EXTRACTION FROM COMPARABLE CORPORA

pairs of sentences in each document pair, we applied a binary classifier to determine whether or not the sentence pair was parallel.

Table 3.2 lists the parallel corpora extracted from Spanish-English article pairs from Wikipedia. “Wiki@X” refers to the parallel sentences extracted with a classification threshold of X (a lower classification threshold will allow more sentences to be extracted). The monolingual data was taken from the English side of all Spanish-English document pairs, making it consistent across conditions.

		Spanish	English	English (Monolingual)
Wiki@0.75	Sentences	—	—	14.8M
	Tokens	—	—	286M
Wiki@0.5	Sentences	1.60M	1.60M	14.8M
	Tokens	44.8M	51.0M	286M
Wiki@0.25	Sentences	—	—	14.8M
	Tokens	—	—	286M

Table 3.2: Statistics for parallel corpora extracted from Wikipedia.

3.4.3 Results

We report end-to-end MT results using the initial parallel data and the extracted parallel data from Wikipedia. For our baseline MT system we used the phrase-based model included in the Moses toolkit Koehn et al. (2007) with all options set to the default.

We used two test sets to evaluate the end-to-end MT performance: the test set from WMT10 which was taken from the news domain, and a set of parallel sentences

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from Wikipedia gathered by (Smith et al., 2010).

	WMT10	Wikipedia
Europarl Only	24.75	—
+Wiki LM	26.91	—
+Wiki Parallel (@0.75)	—	—
+Wiki Parallel (@0.5)	27.41	—
+Wiki Parallel (@0.25)	—	—
All Initial Corpora	28.51	—
+Wiki LM	28.55	—
+Wiki Parallel (@0.75)	—	—
+Wiki Parallel (@0.5)	29.23	—
+Wiki Parallel (@0.25)	—	—

Table 3.3: BLEU scores for systems trained on different sets of parallel and monolingual data before and after adding data from Wikipedia.

3.5 Conclusions

Chapter 4

Related Work

Research in statistical machine translation (SMT) began as large parallel corpora became available. These corpora include the Canadian Hansards (French-English parliament proceedings) and the Hong Kong Laws Corpus, among many others. While these corpora were parallel in the sense that they were created by directly translating text in one language, they were not sentence aligned. Noise in the form of missing data or sentences without a 1 : 1 correspondence made alignment a non-trivial problem. This led to the development of several approaches for aligning parallel corpora in the early 1990s. We will give an overview of these approaches in Section 4.1.

In addition to aligning parallel texts, there has also been a considerable amount of work done on finding parallel sentence pairs in comparable corpora. A comparable corpus is a multilingual collection of documents which may contain parallel sentences, but is not completely parallel. This broad definition includes both weakly aligned data

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such as timestamped multilingual news feeds, and Wikipedia articles linked at the document level. Depending on the type of comparable corpus, different methods may be more or less effective for finding parallel sentences. We will split our review of comparable corpora mining methods into two categories. In Section 4.2.1, we will examine methods used on closely aligned comparable corpora, and in Section 4.2.2 we will review work on extracting parallel sentences from less related multilingual documents.

4.1 Parallel Corpus Alignment

Perhaps the most well known work on parallel corpus alignment is Gale and Church (1991, 1993). The authors described a sentence alignment method based on dynamic programming which used only sentence length to determine whether or not two sentences were parallel. This method is widely applicable since it assumes almost no linguistic knowledge.¹ Despite this, it achieved very high accuracy on a corpus of economic reports from the Union Bank of Switzerland in English, French and German. Brown et al. (1991) had a similar approach, using only sentence lengths to align parallel corpora, but they measured length in words rather than characters.

Even when there is no bilingual lexicon available for a language pair, if the source and target languages are similar enough it may be possible to use the surface similarity

¹The only bit of information about the language pair required is a ratio of sentence lengths in characters.

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of words to infer cognates. Simard et al. (1993) made use of this by replacing the length based alignment scoring of Gale and Church (1993) with a cognate based scoring method using a simple method for identifying cognates. Church (1993) made use of cognates with a radically different approach: creating a dotplot of character n -gram matches weighted by inverse frequency, and then finding an alignment which best matches the dots. While this cognate based approach was intended to work for similar languages, the authors noted that even in language pairs like Japanese-English, matches can be found on technical terms and markup.

The sentence alignment approach of Kay and Röscheisen (1993) also used little linguistic knowledge, though they build a bilingual dictionary from the parallel text to facilitate alignment. Beginning with an initial set of sentence alignments, they iteratively update the bilingual dictionary and the sentence alignments in a manner similar to Viterbi EM, though no explicit probability model is given. Chen (1993) had a similar approach, except he incorporated the learning of both sentence and word alignments into a probabilistic model. While this is similar to our work in that there is a generative story of document pairs used to infer sentence alignments, Chen (1993) used a joint probability distribution of source/target sentence pairs which must be approximated for efficient inference, and several choices are made in the inference strategy which assume a strongly monotonic sentence alignment. Stochastic Viterbi EM is used to find the best sentence alignment.

As an alternative method for creating a bilingual dictionary, Fung and Church

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(1994) built a vector for each source/target word representing how it is distributed in the parallel corpus. The intuition was that since the alignment between the source and target data was strongly monotonic, so words that appear in the same relative positions in the source/target corpora are likely to be translations of one another.

Moore (2002) builds off of the length based alignment approach of Gale and Church (1993) by adding a bootstrapping step after the initial alignment. First, a length based sentence alignment is done on the parallel corpus. Then, the sentences found to be parallel are used to train a word alignment model (IBM Model 1), and the sentence alignment dynamic program is repeated using the word alignment scores in addition to length based scores. This bootstrapping approach is popular in work on mining noisy parallel/comparable corpora (see Section 4.2).

4.2 Comparable Corpus Mining

4.2.1 Noisy Parallel Corpora

The first category of work on comparable corpora mining that we will review is on noisy parallel data. While even corpora called “parallel” contain some noise, we are referring to corpora which the methods in Section 4.1 would fail on.

Similar to the dynamic programming approaches explored in Section 4.1, Zhao and Vogel (2002) used a dynamic programming strategy for aligning parallel sentences in a document pair. They create a probabilistic model of a comparable doc-

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ument pair $P(S, T, A)$ and choose an alignment to maximize the probability of the observed source and target documents. To estimate the probability of two sentences being aligned, they used IBM-style word alignment models (Model 3, specifically) which were estimated on existing parallel data. Zhao and Vogel (2002) also describes a bootstrapping approach where high confidence sentence alignments are added to the training data for the word alignment model, and then sentence alignments are re-computed. Much of the work on noisy parallel/comparable corpora mining used this technique (Fung and Cheung, 2004a,b; Wu and Fung, 2005; Munteanu and Marcu, 2005).

4.2.2 Comparable Corpora

In comparable corpora such as bilingual news feeds or websites, the document alignment is often not given.² First, we will review methods for finding comparable document pairs in a comparable corpus, and then methods for identifying parallel sentence pairs within these documents.

4.2.2.1 Finding Comparable Document Pairs

The Gigaword corpus contains news feeds in multiple languages, and is annotated with the date of publication. Since these news articles are potentially on the same topic, there are potentially parallel sentence pairs in these articles. Munteanu et al.

²A notable exception to this is Wikipedia

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(2004); Munteanu and Marcu (2005); Fung and Cheung (2004a,b) make use of this information to find comparable document pairs. The basic strategy is to first consider all bilingual article pairs published within a time window to be potentially comparable. Then, documents in one language are projected through a bilingual dictionary, and bag-of-words based document similarity measures are used to prune this large set of document pairs. This requires either existing parallel data or at least a bilingual dictionary. Document pairs that pass through these filter are then mined for parallel sentences.

Multilingual websites are another potential source for comparable or parallel document pairs. STRAND (Resnik and Smith, 2003) used some heuristics for identifying links between versions of the same website in different languages. This provides a candidate set of document pairs, which are further filtered by looking at their HTML structure. Each website is converted into a list of start tags, end tags, and “chunks” (text within a tag), and these lists are aligned using standard dynamic programming techniques. This alignment is not only used to determine whether a pair of websites is comparable, but it also gives an alignment of text chunks which greatly narrows down the space of possible sentence alignments

A drastically different approach for finding parallel web pages is given by Uszko-reit et al. (2010). Using an existing language identification and translation systems, they identify the language of all webpages and translate the non-English ones into English. Since all documents are now in the same language, the problem of identifying

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comparable webpages is treated as near-duplicate detection. An index is built mapping n -grams to documents, and this index is used to find a bag-of- n -grams score for potentially comparable documents. The computation is kept feasible by only creating index entries for rare n -grams.

4.2.2.2 Finding Parallel Sentences

Once comparable document pairs have been identified, most comparable corpora extraction methods will independently judge each sentence pair as parallel or non-parallel. Since there is often a very large amount of document pairs and thus potential sentence pairs, filters are used to prune out sentence pairs that are highly unlikely to be parallel. For example, Munteanu and Marcu (2005) used a sentence length filter to remove sentence pairs where one sentence was more than twice as long as the other. In addition, they used a word overlap filter based on the bilingual dictionary used to find candidate document pairs.

Given a filtered set of sentence pairs, more expensive methods of scoring sentence pairs can be used. Munteanu and Marcu (2005) use a MaxEnt binary MaxEnt classifier to ultimately determine whether or not a sentence pair is parallel. The classifier is trained on parallel data and makes use of features which are mostly based on word alignments. Others Fung and Cheung (2004a,b); Tillmann (2009); Tillmann and Xu (2009) use a single score for sentence pairs based on either a word alignment model or bag-of-words similarity after projection through a bilingual lexicon, and tune a

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threshold on held out data.

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