Decipherment with Word Embeddings through Multinomial Regression

Abstract

We introduce into Bayesian decipherment a base distribution derived from similarities of word embeddings. We integrate learning of embedding similarities with decipherment in a stochastic EM process. Experimental results show that the base distribution is highly beneficial to decipherment, improving the state-of-the-art decipherment accuracy from 29.0% to 59.0% for Spanish/English, 5.1% to 11.2% for Malagasy/English.

1 Introduction

Tremendous advances in Machine Translation (MT) have been made since we began applying automatic learning techniques to learn translation rules automatically from parallel data. However, the reliance on parallel data also limits development and application of high-quality MT systems, as the amount of parallel data is far from adequate in low-density languages and domains.

In general, it is easier to obtain non-parallel monolingual data. The ability to learn translations from monolingual data can alleviate obstacles caused by insufficient parallel data. Motivated by this idea, researchers have proposed different approaches to tackle this problem, which can be largely divided into two groups. The first group is based on the idea proposed by Rapp (1995), where words are represented as context vectors, and two words are likely to be translations if their context vectors are similar. Initially, the vectors contained only context words. Later extensions introduced more features (Haghighi et al., 2008; Garera et al., 2009; Bergsma and Van Durme, 2011; Daumé and Jagarlamudi, 2011; Irvine and Callison-Burch, 2013b; Irvine and Callison-Burch, 2013a), and used more abstract representation such as word embeddings (Klementiev et al., 2012).

Another promising approach to solve this problem is through decipherment. It has drawn significant amounts of interest in the past few years (Ravi and Knight, 2011; Nuhn et al., 2012; Dou and Knight, 2013; Ravi, 2013) and has been shown to improve end-to-end translation. Decipherment views a foreign language as a cipher for English and finds a translation table that converts foreign texts into sensible English.

Both approaches have been shown to improve quality of MT systems for domain adaptation (Daumé and Jagarlamudi, 2011; Dou and Knight, 2012; Irvine et al., 2013) and low density languages (Irvine and Callison-Burch, 2013a; Dou et al., 2014). Meanwhile, they have their own advantages and disadvantages. While the former can take larger context into account, it requires high quality seed lexicons to learn a mapping between two vector spaces. In contrast, the latter does not depend on any seed lexicon, but only looks at a limited n-gram context.

In this work, we take advantages of both approaches and combine them in a joint inference process. More specifically, we extend previous work in large scale Bayesian decipherment by introducing a better base distribution derived from similarities of word embedding vectors. The main contributions of this work are:

- We propose a new framework that combines the two main approaches to finding translations from monolingual data.
- We develop a new base-distribution technique that improves state-of-the art decipherment accuracy by a factor of two for Spanish/English and Malagasy/English.

- We make our software available for future research, functioning as a kind of GIZA for non-parallel data.

2 Decipherment Model

In this section, we describe the previous decipherment framework that we build on. This framework follows Ravi and Knight (2011), who built an MT system using only non-parallel data for translating movie subtitles; Dou and Knight (2012) and Nuhn et al. (2012), who scaled decipherment to larger vocabularies; and Dou and Knight (2013), who improved decipherment accuracy with dependency relations between words.

Throughout this paper, we use f to denote target language or ciphertext tokens, and e to denote source language or plaintext tokens. Given ciphertext $\mathbf{f} : f_1 ... f_n$, the task of decipherment is to find a set of parameters $P(f_i|e_i)$ that convert F to sensible plaintext. The ciphertext $\mathbf{f}$ can either be full sentences (Ravi and Knight, 2011; Nuhn et al., 2012) or simply bigrams (Dou and Knight, 2013). Since using bigrams and their counts speeds up decipherment, in this work, we treat $\mathbf{f}$ as bigrams, where $\mathbf{f} = \{\mathbf{f}^n\}_{n=1}^N = \{f_1^n, f_2^n\}_{n=1}^N$.

Motivated by the idea from Weaver (1955), we model an observed cipher bigram $\mathbf{f}^n$ with the following generative story:

- First, a language model $P(\mathbf{e})$ generates a sequence of two plaintext tokens e_1^n, e_2^n with probability $P(e_1^n, e_2^n)$.
- Then, substitute e_1^n with f_1^n and e_2^n with f_2^n with probability $P(f_1^n \mid e_1^n) \cdot P(f_2^n \mid e_2^n)$.

Based on the above generative story, the probability of any cipher bigram $\mathbf{f^n}$ is:

$$P(\mathbf{f}^n) = \sum_{e_1 e_2} P(e_1 e_2) \prod_{i=1}^{2} P(f_i^n \mid e_i)$$

If the entire ciphertext corpus contains N such bigrams $F_1 ... F_N$, we write down the probability of the ciphertext corpus as:

$$P(\{\mathbf{f}^n\}_{n=1}^N) = \prod_{n=1}^{N} P(\mathbf{f}^n)$$

There are two sets of parameters in the model: the channel probabilities, $\{\ P(f \mid e)\}$, and the bigram language model probabilities $\{P(e' \mid e)\}$, where f ranges over the ciphertext vocabulary and e, e' range over the plaintext vocabulary. Given a plaintext bigram language model, the training objective is to learn $P(f \mid e)$ that maximize $P(\{\mathbf{f}^n\}_{n=1}^N)$. When formulated like this, one can directly apply EM to solve the problem (Knight et al., 2006). However, EM has time complexity $O(N \cdot V_e^2)$ and space complexity $O(V_f \cdot V_e)$, where V_f, V_e are the sizes of ciphertext and plaintext vocabularies respectively, and N is the number of cipher bigrams. This makes the EM approach unable to handle long ciphertexts with large vocabulary size.

An alternative approach is Bayesian inference (Ravi and Knight, 2011). We assume that $P(f \mid e)$ and $P(e' \mid e)$ are drawn from a Dirichet distribution with hyper-parameters $\alpha_{f,e}$ and $\alpha_{e,e'}$, that is:

$$\begin{aligned} P(f \mid e) &\sim Dirichlet(\alpha_{f,e}) \\ P(e \mid e') &\sim Dirichlet(\alpha_{e,e'}). \end{aligned}$$

The remainder of the generative story is the same as the noisy channel model for decipherment. In the next section, we describe how we learn the hyper parameters of the Dirichlet prior. Given $\alpha_{f,e}$ and $\alpha_{e,e'}$, The joint likelihood of the complete data and the parameters,

$$\begin{aligned} &P(\{\mathbf{f}^n, \mathbf{e}^n\}_{n=1}^N, \{P(f \mid e)\}, \{P(e \mid e')\}) \\ &= P(\{\mathbf{f}^n \mid \mathbf{e}^n\}_{n=1}^N, \{P(f \mid e)\}) \\ &P(\{\mathbf{e}^n\}_{n=1}^N, P(e \mid e')) \\ &= \prod_e \frac{\Gamma\left(\sum_f \alpha_{f,e}\right)}{\prod_f \Gamma\left(\alpha_{e,f}\right)} \prod_f P(f \mid e)^{\#(e,f)+\alpha_{e,f}-1} \\ &\prod_e \frac{\Gamma\left(\sum_{e'} \alpha_{e,e'}\right)}{\prod_{e'} \Gamma\left(\alpha_{e,e'}\right)} \prod_f P(e \mid e')^{\#(e,e')+\alpha_{e,e'}-1}, \end{aligned} \tag{1}$$

where $\#(e, f)$ and $\#(e, e')$ are the counts of the translated word pairs and plaintext bigram pairs in the complete data, and $\Gamma(\cdot)$ is the Gamma function. Unlike EM, in Bayesian decipherment, we no longer search for parameters $P(f \mid e)$ that maximize the likelihood of the observed ciphertext. Instead, we draw samples from posterior distribution of the plaintext sequences given the ciphertext. Under the above Bayesian decipherment model, it turns out that the probability of a particular cipher word f_j having a value k, given the current plaintext word e_j, and the samples for all the other ciphertext and plaintext words, $\mathbf{f}_{-j}$ and $\mathbf{e}_{-j}$, is:

$$P(f_j = k \mid e_j, \mathbf{f}_{-j}, \mathbf{e}_{-j}) = \frac{\#(k, e_j)_{-j} + \alpha_{e_j,k}}{\#(e_j)_{-j} + \sum_f \alpha_{e_j,f}}. \quad (2)$$

Where, $\#(k, e_j)_{-j}$ and $\#(e_j)_{-j}$ are the counts of the ciphertext, plaintext word pair and plaintext word in the samples excluding f_j and e_j. Similarly, the probability of a plaintext word e_j taking a value l given samples for all other plaintext words,

$$P(e_j = l \mid \mathbf{e}_{-j}) = \frac{\#(l, e_{j-1})_{-j} + \alpha_{l,e_{j-1}}}{\#(e_{j-1})_{-j} + \sum_e \alpha_{e,e_{j-1}}}. \quad (3)$$

Since we have large amounts of plaintext data, we can train a high-quality dependency-bigram language model, $P_{LM}(e \mid e')$ and use it to guide our samples and learn a better posterior distribution. For that, we define $\alpha_{e,e'} = \alpha P_{LM}(e \mid e')$, and set α to be very high. The probability of a plaintext word (Equation 3) is now

$$P(e_j = l \mid \mathbf{e}_{-j}) \approx P_{LM}(l \mid e_{j-1}). \quad (4)$$

We have to say that in previous work , $\alpha_{e,f}$ has been set to $\alpha * uniform$

. To sample from the posterior, we iterate over the observed ciphertext bigram tokens and use equations 2 and 4 to sample a plaintext token with probability

$$P(e_j \mid \mathbf{e}_{-j}, \mathbf{f}) \propto P_{LM}(e_j \mid e_{j-1}) \times \quad (5)$$
$$P(f_j \mid e_j, \mathbf{f}_{-j}, \mathbf{e}_{-j}). \quad (6)$$

At the end of sampling, we compute $P(f \mid e)$ from ciphertext and its plaintext samples using maximum likelihood estimation:

$$P(f \mid e) = \frac{\#(f, e)}{\#(e)}.$$

In the next section, we will describe how we model and learn an improved base distribution for $P(f \mid e)$.

3 Base Distribution with Cross-Lingual Word Similarities

As shown in the previous section, the base distribution in Bayesian decipherment is given independent of the inference process. A better base distribution can improve decipherment accuracy. Ideally, we should assign higher base distribution probabilities to word pairs that are similar.

One straightforward way is to consider orthographic similarities. This works for close related languages, e.g., the English word "new" is translated as "neu" in German and "nueva" in Spanish. However, this fails when two languages are not closely related, e.g., Chinese/English. Previous work aims to discover translations from comparable data based on word context similarities. This is based on the assumption that words appearing in similar contexts have similar meanings. The approach straightforwardly discovers monolingual synonyms. However, when it comes to finding translations, one challenge is to draw a mapping between the different context spaces of the two languages. In previous work, the mapping is usually learned from a seed lexicon.

Recently work learns distributional vectors (embeddings) for words. The most popular among these is learned by the skip-gram and continuous-bag-of-words models (Mikolov et al., 2013a). In (Mikolov et al., 2013b), the authors are able to successfully learn word translations using *linear transformations* between the source and target word vector-spaces. However, unlike our learning setting, their approach relied on large amounts of translation pairs learned from *parallel* data to train their linear transformations. Inspired by these approaches, we aim to exploit high-quality monolingual word embeddings to help learn better posterior distributions in unsupervised decipherment, without any parallel data.

In the previous section, we incorporated our pre-trained language model in $\alpha_{e,e'}$ to steer our sampling. In the same vein, we model $\alpha_{e,f}$ using pre-trained word embeddings, enabling us to improve our estimate of the posterior distribution. In (Mimno and McCallum, 2012), the authors develop topic models where the base distribution over topics is a log-linear model of observed document features, which permits learning better priors over topic distributions for each document. Similarly, we introduce a latent cross-lingual linear mapping M and define:

$$\alpha_{f,e} = \exp\{v_e M v_f^T\}, \quad (7)$$

where v_e and v_f are the pre-trained plaintext word and ciphertext word embeddings. M is the similarity matrix between the two embedding spaces. $\alpha_{f,e}$ can be thought of as the affinity of a plaintext word to be mapped to a ciphertext word. Rewriting the channel part of the joint likelihood in equation 1,

$$P(\{\mathbf{f}^n \mid \mathbf{e}^n\}_{n=1}^N, \{P(f \mid e)\})$$
$$= \prod_e \frac{\Gamma\left(\sum_f \exp\{v_e M v_f^T\}\right)}{\prod_f \Gamma\left(\exp\{v_e M v_f^T\}\right)}$$
$$\prod_f P(f \mid e)^{\#(e,f)+\exp\{v_e M v_f^T\}-1}$$

Integrating out the channel probabilities, the complete data log-likelihood of the observed ciphertext bigrams and the sampled plaintext bigrams,

$$P(\{\mathbf{f}^n \mid \mathbf{e}^n\} \tag{8}$$
$$= \prod_e \frac{\Gamma\left(\sum_f \exp\{v_e M v_f^T\}\right)}{\prod_f \Gamma\left(\exp\{v_e M v_f^T\}\right)} \tag{9}$$
$$\prod_e \frac{\prod_f \Gamma\left(\exp\{v_e M v_f^T\} + \#(e,f)\right)}{\Gamma\left(\sum_f \exp\{v_e M v_f^T\} + \#(e)\right)}. \tag{10}$$

The derivative of the log of $P(\{\mathbf{f}^n \mid \mathbf{e}^n\}$ with respect to M,

$$\frac{\partial \log P(\{\mathbf{f}^n \mid \mathbf{e}^n\}}{\partial M} \tag{11}$$
$$= \sum_e \sum_f \exp\{v_e M v_f^T\} v_f v_e^T (\tag{12}$$
$$\Psi\left(\sum_{f'} \exp\{v_e M v_{f'}^T\}\right) - \tag{13}$$
$$\Psi\left(\sum_{f'} \exp\{v_e M v_{f'}^T\} + \#(e)\right) + \tag{14}$$
$$+ \Psi\left(\exp\{v_e M v_f^T\} + \#(e,f)\right) - \tag{15}$$
$$\Psi\left(exp\{v_e M v_f^T\}\right), \tag{16}$$

where $\Psi(\cdot)$ is the Digamma function, the derivative of the $\log\Gamma(\cdot)$. Again, following (Mimno and McCallum, 2012), we train the similarity matrix M with stochastic EM. In the E-step, we sample plaintext words for the observed ciphertext using equation 5 and in the M-step, we learn M that maximizes $\log P(\{\mathbf{f}^n \mid \mathbf{e}^n\}$ with stochastic gradient descent.

4 Deciphering Spanish Gigaword

In this section, we describe our data and experimental conditions for deciphering Spanish into English.

	Spanish	English
Training	992 million (Gigaword)	940 million (Gigaword)
Evaluation	1.1 million (Europarl)	1.0 million (Europarl)

Table 1: Size of data in tokens used in Spanish-English decipherment experiment

4.1 Data

In our Spanish-English decipherment experiments, we use half of the Gigaword corpus as monolingual data, and a small amount of parallel data from Europarl *only for evaluation*. We keep only the 10k most frequent word types for both languages and replace all other word types with "UNK". We also exclude sentences longer than 40 tokens, which significantly slow down our parser. After preprocessing, the size of data for each language is shown in Table 1. While we use all the monolingual data shown in Table 1 to learn word embeddings, we only parse the AFP (Agence France-Presse) section of the Gigaword corpus to extract cipher dependency bigrams and build a plaintext language model. We also use GIZA (Och and Ney, 2003) to align Europarl parallel data to build a dictionary for evaluating our decipherment.

4.2 Systems

We implement a baseline system based on the work described in Dou and Knight (2013). The baseline system carries out decipherment on dependency bigrams. Therefore, we use the Bohnet parser (Bohnet, 2010) to parse the AFP section of both Spanish and English versions of the Gigaword corpus. Since not all dependency relations are shared across the two languages, we do not extract all dependency bigrams. Instead, we only use bigrams with dependency relations from the following list:

- Verb / Subject
- Verb / Object
- Preposition / Object
- Noun / Noun-Modifier

The baseline uses slice sampling with a uniform base distribution.

We denote the system that uses our new method as **DMRE** (Dirichlet Multinomial Regression). The system is the same as the baseline except that it uses a base distribution derived from word context similarities. Word embeddings are learned using word2vec (Mikolov et al., 2013a).

For all the systems, language models are built using the SRILM toolkit (Stolcke, 2002). We use the modified Kneser-Ney (Kneser and Ney, 1995) algorithm for smoothing.

4.3 Sampling Procedure

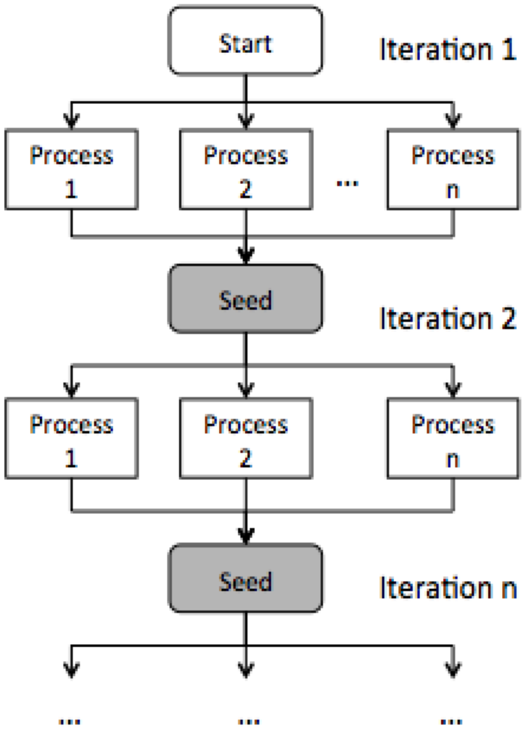

Figure 1: Iterative sampling procedures

Motivated by the previous work, we use multiple random restarts and an iterative sampling process to improve decipherment (Dou and Knight, 2012), as shown in Figure 1. The idea is to start a few sampling processes each with a different random sample. Then we combine the results from different runs and use the combined results to initiate the next sampling iteration. The details of the sampling procedure are listed below:

- Extract dependency bigrams from parsing outputs and collect their counts.
- Keep bigrams whose counts are greater than a threshold t. Then start N different randomly seeded and initialized sampling processes. Perform sampling.
- At the end of sampling, extract word translation pairs (f, e) from the final sample. Estimate translation probabilities $P(e|f)$ for each pair. Then construct a translation table by keeping translation pairs (f, e) seen in more than one decipherment and use the average $P(e|f)$ as the new translation probability.
- Lower the threshold t to include more bigrams into the sampling process. Start N different sampling processes again and initialize the first sample using the translation pairs obtained from the previous step (for each dependency bigram f_1, f_2, find an English sequence e_1, e_2, whose $P(e_1|f_1) \cdot P(e_2|f_2) \cdot P(e_1, e_2)$is the highest). Perform sampling again.
- Repeat until $t = 1$.

In our Spanish-English decipherment experiments, we use 10 different random starts. In experiments, we also use a higher base distribution weight as more ciphtertext becomes available. We set the weight to 2, 10, and 50 for ciphertexts with 100k, 1 million, and 10 million tokens respectively.

4.4 Evaluation Metrics

We use top-5 type accuracy as our evaluation metric. Given a word type f in Spanish, we find top-5 translation pairs (f, e) ranked by $P(e|f)$ from the learned decipherent translation table. If any pair (f, e) can also be found in a gold translation lexicon T_{gold}, we treat the word type f as correctly deciphered. Let $|C|$ be the number of word types correctly deciphered, and $|V|$ be the total number of word types evaluated. We define type accuracy as $\frac{|C|}{|V|}$.

To create T_{gold}, we use GIZA to align a small amount of Spanish-English parallel text (1 million tokens for each language), and use the lexicon derived from the alignment as our gold translation lexicon. T_{gold} contains a subset of 4233 word types in the top 5000 frequent word types, and 7479 word types in the top 10k frequent word types. We decipher the 10k most frequent Spanish word types to the 10k most frequent English word types, and evaluate decipherment accuracy on both the 5k most frequent word types as well as the full 10k word types.

5 Deciphering Malagasy

Malagasy belongs to the Malayo-Polynesian branch of the Austronesian language family. Malagasy and English have very different word order, starting with VOS versus SVO. Generally,

	Malagasy	English
Training	16 million (Web)	1.2 billion (Gigaword and Web)
Evaluation	2.0 million (GlobalVoices)	1.8 million (GlobalVoices)

Table 2: Size of data in tokens used in Malagasy-English decipherment experiment. GlobalVoices is parallel data.

Malagasy is a typical head-initial language: Determiners precede nouns, while other modifiers and relative clauses follow nouns (e.g. ny "the" boky "book" mena "red"). The significant differences in word order pose great challenges for decipherment.

5.1 Data

Table 2 lists the sizes of monolingual and parallel data used in this experiment, released by Dou et al. (2014). The monolingual data in Malagasy contains news text collected from Madagascar websites. The English monolingual data contains Gigaword and additional 300 million tokens of African news. Parallel data (used for evaluation only) is collected from GlobalVoices, a multilingual news website, where volunteers translate news into different languages.

5.2 Systems

The baseline system is the same as the baseline used in Spanish-English decipherment experiments. We use data provided in previous work (Dou et al., 2014) to build a Malagasy dependency parser. For English, we use the Turbo parser, trained on the Penn Treebank (Martins et al., 2013).

Because the Malagasy parser does not predict dependency relation types, we use head-child part-of-speech (POS) tag patterns to select a subset of dependency bigrams for decipherment:

- Verb / Noun
- Verb / Proper Noun
- Verb / Personal Pronoun
- Preposition / Noun
- Preposision / Proper Noun
- Noun / Adjective
- Noun / Determiner
- Noun / Verb Particle
- Noun / Verb Noun
- Noun / Cardinal
- Noun / Noun

5.3 Sampling Procedure

We use the same sampling protocol designed for Spanish-English decipherment. However, in experiments, we find that simply using Viterbi decoding to initialize the first sample does not work as well. Therefore, in addition to using Viterbi decoding, we also initialize the base distribution to the base distribution of the previous decipherment that produces highest accuracy.

Compared with Spanish-English decipherment, we find the base distribution plays a more important role in achieving higher decipherment accuracy for Malagasy-English. Therefore, we set weight to 10, 100, and 500 when deciphering 100k, 1 million, and 20 million token ciphtertexts, respectively.

6 Results

In experiments, we compare decipherment accuracy of the baseline with our new approach, at various ciphertext sizes. We evaluate accuracy for the 5k and 10k most frequent word types for each language pair, and present them in Table 3.

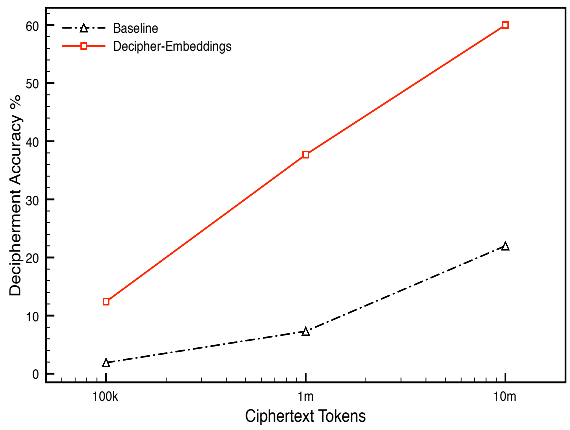

Figure 2: Learning curves of top-5 accuracy evaluated on 5k most frequent word types for Spanish-English decipherment.

We also present the learning curves of decipherment accuracy for 5k most frequent word types. Figure 2 compares the baseline with **DMRE** in deciphering Spanish into English. Performance of the baseline is in line with previous work (Dou and Knight, 2013). (The accuracy reported here is higher as we evaluate top 5 accuracy for each word

	Spanish-English				Malagasy-English			
Top	5k		10k		5k		10k	
System	Baseline	DMRE	Baseline	DMRE	Baseline	DMRE	Baseline	DMRE
100k	1.9	12.4	1.1	7.1	1.2	2.7	0.6	1.4
1 million	7.3	37.7	4.2	23.6	2.5	5.8	1.3	3.2
10 million	26.0	59.0	15.9	43.7	5.4	11.2	3.0	6.9

Table 3: Spanish-English and Malagasy-English decipherment top-5 accuracy (%) of 5k and 10k most frequent word types

type.) With 100k tokens of Spanish text, the baseline achieves 1.9% accuracy, while the new system achieves 12.4% accuracy, which improves the baseline by over 6 times. The improvement holds consistently throughout the experiment. In the end, the baseline achieves 26.0% accuracy, while the new system achieves 59.1% accuracy, over 2 times higher.

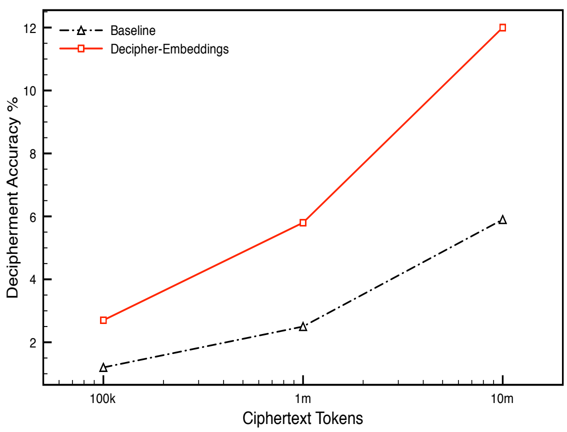

Figure 3: Learning curves of top-5 accuracy evaluated on 5k most frequent word types for Malagasy-English decipherment.

Figure 3 compares the baseline with our new approach in deciphering Malagasy into English. With 100k tokens of data, the baseline achieves 1.2% accuracy, while the new system achieves 2.4% accuracy. We observe consistent improvement throughout the experiment. In the end, the baseline accuracy climbs to 5.8%, while the new system improves it to 11.2%.

Overall, the improvement we achieved is solid, and is observed across different language pairs. When we examine the base distribution, we find that the correct translations have higher probability. This helps prevent the language model driving deicpherment to a wrong direction.

7 Conclusion and Future Work

We propose a new framework that simultaneously performs decipherment and learns a cross-lingual mapping of word embeddings. The mapping is used to give decipherment a better base distribution.

Experimental results show that our new algorithm improves the state-of-the-art decipherment accuracy significantly: from 22% to 60% for Spanish-English, and 5.8% to 12.0% for Malagasy-English. This improvement could lead to further advances in using monolingual data for to improve end-to-end MT. In the future, we will work on making the new method scale to much larger vocabulary sizes, and apply it to improve MT systems.

Acknowledgments

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