

Word alignment with multilingual BERT: from subwords to lexicons

Multilingual NLP – Lab 2

Philippos Triantafyllou

Table of contents

1 Selecting languages	2
2 Obtaining embeddings with mBERT	5
3 First alignment method: argmax over cosine similarities	8
4 Second alignment method: Competitive linking using the Hungarian algorithm	17
5 Third alignment method: CCA-based mapping	21

1 Selecting languages

We will load data from `sentence-transformers/parallel-sentences-jw300` and bilingual pairs from `MUSE`.

We select 5 languages that are well represented in the training of mBERT and 5 others that are either less represented or absent (the only language that is completely absent from mBERT is Kurdish). All the languages also have a bilingual lexicon from MUSE that we will use for the CCA.

```
# (language, code, link_to_MUSE)
langs = [
    ("albanian", "sq", "https://dl.fbaipublicfiles.com/arrival/dictionaries/en-sq.0-5000.txt"),
    ("arabic", "ar", "https://dl.fbaipublicfiles.com/arrival/dictionaries/en-ar.0-5000.txt"),
    ("french", "fr", "https://dl.fbaipublicfiles.com/arrival/dictionaries/en-fr.0-5000.txt"),
    ("german", "de", "https://dl.fbaipublicfiles.com/arrival/dictionaries/en-de.0-5000.txt"),
    ("greek", "el", "https://dl.fbaipublicfiles.com/arrival/dictionaries/en-el.0-5000.txt"),
    ("hindi", "hi", "https://dl.fbaipublicfiles.com/arrival/dictionaries/en-hi.0-5000.txt"),
    ("japanese", "ja", "https://dl.fbaipublicfiles.com/arrival/dictionaries/en-ja.0-5000.txt"),
    ("macedonian", "mk", "https://dl.fbaipublicfiles.com/arrival/dictionaries/en-mk.0-5000.txt"),
    ("persian", "fa", "https://dl.fbaipublicfiles.com/arrival/dictionaries/en-fa.0-5000.txt"),
    ("thai", "th", "https://dl.fbaipublicfiles.com/arrival/dictionaries/en-th.0-5000.txt")
]
```

Loading the datasets.

```
import requests
from datasets import load_dataset

def install_datasets(langs):
    corpora = {}

    # Iterate through each language definition (name, ISO code, lexicon URL)
    for lang, code, links in langs:
        print(f"Processing {lang}...")
        corpora[lang] = {}
        print(f"\tLoading pairs...")

        # Load parallel English-target-language sentence pairs from JW300
        data = load_dataset(
            "sentence-transformers/parallel-sentences-jw300",
            f"en-{code}",
            split="train"
        )
        print(f"\tLoaded JW300 for {lang}")

        corpora[lang]['pairs'] = (
            data
            # Load up to 5,000 parallel sentence pairs
            .take(5000) # type: ignore
            .map(
                # Clean zero-width Unicode chars
                lambda x: {
                    'english': x['english'].replace('\u200b', '').replace('\u200f', '').replace('\u200c',
                        ''),
                    'non_english': x['non_english'].replace('\u200b', '').replace('\u200f',
                        '').replace('\u200c', '')
                }
            )
            # Drop any pair where either side becomes empty after cleaning
            .filter(
                lambda x: x['english'].strip() and x['non_english'].strip()
            )
        )
```

```
# Report how many valid parallel pairs remain after filtering
print(f"\tKept {len(corpora[lang]['pairs'])} aligned sentence pairs")

print("\tLoading lexicons...")

# Download and decode the lexicon text file
text = requests.get(links).content.decode("utf-8", errors="ignore")

# Parse tab-separated lexicons if tabs are present
if '\t' in text:
    lexicon = [
        tuple(line.split('\t', 1))
        for line in text.splitlines()
        if line.strip() and '\t' in line
    ]
# Otherwise parse whitespace-separated lexicons (French and German)
else:
    lexicon = [
        tuple(line.split(None, 1))
        for line in text.splitlines()
        if line.strip()
    ]

    corpora[lang]["lexicon"] = lexicon
return corpora
```

```
Processing albanian...
    Loading pairs...
```

```
README.md: 0.00B [00:00, ?B/s]
```

```
en-sq/train-00000-of-00001.parquet: 0% | 0.00/83.8M [00:00<?, ?B/s]
```

```
Loaded JW300 for albanian
Kept 4928 aligned sentence pairs
Loading lexicons...
Processing arabic...
    Loading pairs...
```

```
en-ar/train-00000-of-00001.parquet: 0% | 0.00/71.7M [00:00<?, ?B/s]
```

```
Loaded JW300 for arabic
Kept 4844 aligned sentence pairs
Loading lexicons...
Processing french...
    Loading pairs...
```

```
en-fr/train-00000-of-00001.parquet: 0% | 0.00/297M [00:00<?, ?B/s]
```

```
Loaded JW300 for french
Kept 4773 aligned sentence pairs
Loading lexicons...
Processing german...
    Loading pairs...
```

```
en-de/train-00000-of-00001.parquet: 0% | 0.00/268M [00:00<?, ?B/s]
```

```
Loaded JW300 for german
Kept 4942 aligned sentence pairs
Loading lexicons...
Processing greek...
Loading pairs...
```

```
en-el/train-00000-of-00002.parquet: 0%| 0.00/173M [00:00<?, ?B/s]
```

```
en-el/train-00001-of-00002.parquet: 0%| 0.00/174M [00:00<?, ?B/s]
```

```
Loaded JW300 for greek
Kept 4618 aligned sentence pairs
Loading lexicons...
Processing hindi...
Loading pairs...
```

```
en-hi/train-00000-of-00001.parquet: 0%| 0.00/86.8M [00:00<?, ?B/s]
```

```
Loaded JW300 for hindi
Kept 4053 aligned sentence pairs
Loading lexicons...
Processing japanese...
Loading pairs...
```

```
en-ja/train-00000-of-00002.parquet: 0%| 0.00/142M [00:00<?, ?B/s]
```

```
en-ja/train-00001-of-00002.parquet: 0%| 0.00/136M [00:00<?, ?B/s]
```

```
Loaded JW300 for japanese
Kept 4557 aligned sentence pairs
Loading lexicons...
Processing macedonian...
Loading pairs...
```

```
en-mk/train-00000-of-00001.parquet: 0%| 0.00/66.7M [00:00<?, ?B/s]
```

```
Loaded JW300 for macedonian
Kept 4890 aligned sentence pairs
Loading lexicons...
Processing persian...
Loading pairs...
```

```
en-fa/train-00000-of-00001.parquet: 0%| 0.00/40.4M [00:00<?, ?B/s]
```

```
Loaded JW300 for persian
Kept 4511 aligned sentence pairs
Loading lexicons...
Processing thai...
Loading pairs...
```

```
en-th/train-00000-of-00001.parquet: 0%| 0.00/135M [00:00<?, ?B/s]
```

```
Loaded JW300 for thai
Kept 4167 aligned sentence pairs
Loading lexicons...
```

2 Obtaining embeddings with mBERT

For the selected languages, obtain the mBERT representations for all these sentences, aggregating subword embeddings in order to reconstruct word-level vectors.

```
from transformers import AutoTokenizer, AutoModel

tokenizer = AutoTokenizer.from_pretrained("google-bert/bert-base-multilingual-cased")
model = AutoModel.from_pretrained("google-bert/bert-base-multilingual-cased")
```

The pipeline is as follows:

- A function takes care to extract the embeddings for a list of sentences in a given language.
- A second function iterates over all languages in the dataset, calling the first function for each language and storing the results.
- Finally, we save the extracted embeddings to disk for later use.

Function to extract embeddings.

```
import torch

def get_word_embeddings(sentences, tokenizer, model, batch_size=16, device=None):
    # Device detection
    if device is None:
        device = torch.device('cuda' if torch.cuda.is_available() else 'cpu')

    model.to(device)
    model.eval()

    all_results = []
    total_sentences = len(sentences)

    # Process in batches
    for batch_idx in range(0, total_sentences, batch_size):
        batch = sentences[batch_idx:batch_idx + batch_size]

        # Tokenize batch
        encoded = tokenizer(
            list(batch),
            return_tensors='pt',
            padding=True,
            truncation=True,
            max_length=512,
            add_special_tokens=True
        )

        # Move to device
        input_ids = encoded['input_ids'].to(device)
        attention_mask = encoded['attention_mask'].to(device)

        # Get embeddings
        with torch.no_grad():
            outputs = model(input_ids=input_ids, attention_mask=attention_mask)
            embeddings = outputs.last_hidden_state # [batch_size, seq_len, hidden_size]
```

```
# Process each sentence in the batch
for idx_in_batch, sentence in enumerate(batch):
    word_ids = encoded.word_ids(batch_index=idx_in_batch)
    sent_embeddings = embeddings[idx_in_batch]

    # Group tokens by word_id
    word_to_token_indices = {}
    for token_idx, word_id in enumerate(word_ids):
        if word_id is not None:
            if word_id not in word_to_token_indices:
                word_to_token_indices[word_id] = []
            word_to_token_indices[word_id].append(token_idx)

    # Aggregate embeddings (mean)
    word_embeddings = []
    for word_id in sorted(word_to_token_indices.keys()):
        token_indices = word_to_token_indices[word_id]
        token_embs = sent_embeddings[token_indices]
        word_emb = token_embs.mean(dim=0)

        word_embeddings.append({
            'word_id': word_id,
            'embedding': word_emb.cpu().numpy(),
            'num_tokens': len(token_indices)
        })

    all_results.append({
        'sentence': sentence,
        'word_embeddings': word_embeddings,
        'num_words': len(word_embeddings)
    })

# Progress
processed = min(batch_idx + batch_size, total_sentences)
progress_pct = (processed / total_sentences) * 100
print(f"\tProgress: {processed}/{total_sentences} ({progress_pct:.1f}%)", end='\r')

# Memory management
if device.type == 'cpu' and batch_idx % (batch_size * 20) == 0:
    import gc
    gc.collect()

if device.type == 'cuda' and batch_idx % (batch_size * 10) == 0:
    torch.cuda.empty_cache()

print()
return all_results
```

Function to process all languages in the dataset.

```
def process_all_languages(data, tokenizer, model, batch_size=16, device=None, save_dir=None):
    import time

    embeddings_by_language = {}
    total_start_time = time.time()

    for lang_idx, (lang, corpora) in enumerate(data.items(), 1):
        print(f"\n{'='*70}")
        print(f"[{lang_idx}/{len(data)}] Processing {lang.upper()}")
        print('='*70)

        embeddings_by_language[lang] = {}

        if 'pairs' in corpora:
            english_sentences = corpora['pairs']['english']
            non_english_sentences = corpora['pairs']['non_english']
```

```

# Process English
print(f"\nProcessing English sentences ({len(english_sentences)} total)...")
start_time = time.time()
embeddings_by_language[lang]['english'] = get_word_embeddings(
    english_sentences, tokenizer, model,
    batch_size=batch_size, device=device
)
english_time = time.time() - start_time
print(f"\tCompleted in {english_time:.2f} seconds")

# Process non-English
print(f"\nProcessing {lang.capitalize()} sentences ({len(non_english_sentences)} total)...")
start_time = time.time()
embeddings_by_language[lang]['non_english'] = get_word_embeddings(
    non_english_sentences, tokenizer, model,
    batch_size=batch_size, device=device
)
non_english_time = time.time() - start_time
print(f"\tCompleted in {non_english_time:.2f} seconds")

# Summary
print(f"\n{lang.upper()} Summary:")
print(f"\tEnglish: {len(embeddings_by_language[lang]['english'])} sentences")
print(f"\t{lang.capitalize()}: {len(embeddings_by_language[lang]['non_english'])} sentences")
print(f"\tTotal time: {english_time + non_english_time:.2f} seconds")

# Save intermediate results
if save_dir:
    import pickle
    import os
    os.makedirs(save_dir, exist_ok=True)

    filepath = os.path.join(save_dir, f'embeddings_{lang}.pkl')
    with open(filepath, 'wb') as f:
        pickle.dump(embeddings_by_language[lang], f)
    print(f"\tSaved to {filepath}")

total_time = time.time() - total_start_time
print(f"\n{'='*70}")
print("ALL LANGUAGES PROCESSED!")
print(f"Total time: {total_time:.2f} seconds ({total_time/60:.2f} minutes)")
print('='*70)

return embeddings_by_language

```

```

embeddings_by_language = process_all_languages(
    data,
    tokenizer,
    model,
    batch_size=16,
    device=None,
    save_dir='./embeddings'
)

```

Checking that all embeddings have been extracted correctly.

```

def validate_word_embeddings(data, embeddings_by_language):
    for lang in data.keys():
        english_embeddings = embeddings_by_language[lang]['english']
        non_english_embeddings = embeddings_by_language[lang]['non_english']

        # Sanity check: sentence-level alignment
        if len(english_embeddings) != len(non_english_embeddings):
            print("FAILED")
            return False

    # Check all sentence embeddings

```

```
for en_sent, non_en_sent in zip(english_embeddings, non_english_embeddings):
    if len(en_sent['word_embeddings']) != en_sent['num_words']:
        return False
    if len(non_en_sent['word_embeddings']) != non_en_sent['num_words']:
        return False

    return print("All embeddings validated successfully.")

validate_word_embeddings(data, embeddings_by_language)
```

All embeddings validated successfully.

3 First alignment method: argmax over cosine similarities

Right now we have one embedding per word. That is, for each example, we have computed a contextualised embedding. Since our goal is to build a lexicon, we need to aggregate these embeddings across all examples.

The simplest way to do this is to average the embeddings for each word in the vocabulary. This way, we obtain a single embedding per word type. But this approach has some drawbacks:

- It ignores the fact that words can have multiple meanings (polysemy).
- It treats all occurrences of a word equally, regardless of context.
- It can be sensitive to outliers, as rare contexts can skew the average.
- It does not capture the full distribution of meanings a word can have.
- It assumes that the average embedding is a good representation of the word's meaning!

The “correct” way to take into account multiple meanings would be to use a sense inventory and cluster the embeddings based on these senses. However, this requires external resources that we currently do not have. Furthermore, even if we had such inventories, how would we know for each occurrence which sense is being used? The contextualised embeddings already capture some of this information, but we would need a way to link them to the senses. For example we could compute the average embedding for each sense from the inventory and then assign each occurrence to the closest sense embedding...

A “better” way to do this given our resources is to use clustering. For each word, we can cluster its contextualised embeddings and then use the centroids of these clusters as the word’s representations. This way, we can capture multiple meanings of a word and reduce the impact of outliers. But this approach also has its challenges. For example, choosing the right number of clusters can be tricky, how can we decide how many senses a word has?

For this exercise, we will stick to the simple averaging method. Either way, it is a good step to start with the simplest method and see if it works well enough for our purposes.

For each language, we will build a lexicon by word type, averaging the embeddings for each word across all its occurrences.

- One function to build the lexicon for a given language.
- A loop to build lexicons for all languages.

We also want to drop all invalid words (punctuation, special tokens, numbers, etc.). We can use a simple regex to do this. We can take advantage of python's `str.isalpha()` method, which checks if a character is alphabetic in any script.

```
import numpy as np
from collections import defaultdict

def build_lexicon_for_language(embeddings):
    word_to_embeddings = defaultdict(list)

    for sent in embeddings:
        words = sent['sentence'].split()
        word_embs = sent['word_embeddings']

        for w, w_emb in zip(words, word_embs):
            if not w.isalpha():
                continue
            w = w.lower()
            word_to_embeddings[w].append(w_emb['embedding'])

    return {
        word: np.mean(np.stack(embs), axis=0)
        for word, embs in word_to_embeddings.items()
    }
```

```
def build_lexicons_for_all_languages(embeddings_by_language):
    lexicons_by_language = {}

    for lang in embeddings_by_language.keys():
        print(f"\nLanguage: {lang}")

        english_lexicon = build_lexicon_for_language(
            embeddings_by_language[lang]['english']
        )
        non_english_lexicon = build_lexicon_for_language(
            embeddings_by_language[lang]['non_english']
        )

        lexicons_by_language[lang] = {
            'english': english_lexicon,
            'non_english': non_english_lexicon
        }

        # Print unique word types
        print(f"English word types ({len(english_lexicon)}):")

        print(f"Non-English word types ({len(non_english_lexicon)}):")

    return lexicons_by_language
```

```
Language: albanian
English word types (13906):
Non-English word types (17797):

Language: arabic
English word types (13483):
Non-English word types (18304):

Language: french
English word types (14164):
Non-English word types (16312):

Language: german
English word types (13717):
Non-English word types (17397):
```

```
Language: greek
English word types (14163):
Non-English word types (18510):
```

```
Language: hindi
English word types (13702):
Non-English word types (9297):
```

```
Language: japanese
English word types (13482):
Non-English word types (9682):
```

```
Language: macedonian
English word types (12985):
Non-English word types (17234):
```

```
Language: persian
English word types (10663):
Non-English word types (8414):
```

```
Language: thai
English word types (14605):
Non-English word types (5754):
```

```
def validate_lexicons(embeddings_by_language, lexicons_by_language):
    for lang in embeddings_by_language.keys():
        for side in ['english', 'non_english']:
            lexicon = lexicons_by_language[lang][side]

            # Check dimensional consistency
            dims = {v.shape for v in lexicon.values()}
            if len(dims) != 1:
                return False

            # Check lexicon size vs total tokens
            total_tokens = sum(
                len(s['word_embeddings'])
                for s in embeddings_by_language[lang][side]
            )
            if len(lexicon) > total_tokens:
                return False

    return True

validate_lexicons(embeddings_by_language, emb_lexicons_by_language)
```

```
True
```

Right now we have embeddings for each “word type” in each language, but we have included whole sentences that also contain punctuation marks and special tokens. We need to filter these out to keep only valid words. We can use a simple regex to do this.

Now we can build a cosine similarity matrix for each language between the English and non-English lexicons.

```
import numpy as np
from sklearn.metrics.pairwise import cosine_similarity

def build_cosine_similarity_matrix(lexicon_non_english, lexicon_english):
    # Extract word lists
    non_en_words = list(lexicon_non_english.keys())
    en_words = list(lexicon_english.keys())
```

```
# Stack embeddings into matrices
non_en_vectors = np.stack([lexicon_non_english[w] for w in non_en_words])
en_vectors = np.stack([lexicon_english[w] for w in en_words])

# Cosine similarity: rows = non-English, columns = English
sim_matrix = cosine_similarity(non_en_vectors, en_vectors)

return sim_matrix, non_en_words, en_words
```

```
similarity_matrices = {}

for lang, lexicons in emb_lexicons_by_language.items():
    sim_matrix, non_en_words, en_words = build_cosine_similarity_matrix(
        lexicons['non_english'],
        lexicons['english']
    )

    similarity_matrices[lang] = {
        'matrix': sim_matrix,
        'non_english_words': non_en_words,
        'english_words': en_words
    }
```

We can now build lexicons for all languages.

```
def build_lexicon(similarity_matrices, k=1):
    lexicons = {}

    for lang, sim_data in similarity_matrices.items():
        sim_matrix = sim_data['matrix']
        non_en_words = sim_data['non_english_words']
        en_words = sim_data['english_words']

        lexicon = {}
        for i, non_en_word in enumerate(non_en_words):
            sims = sim_matrix[i]

            if k == 1:
                best_idx = int(np.argmax(sims))
                lexicon[non_en_word] = [en_words[best_idx]]
            else:
                topk_idx = np.argsort(sims)[-k:][::-1]
                lexicon[non_en_word] = [en_words[j] for j in topk_idx]

        lexicons[lang] = lexicon

    return lexicons
```

Note

There might be a slight encoding problem, the print statements show empty strings for some languages but this is only a problem for latex. The actual strings are there.

```
Language: albanian
Sample lexicon entries:
faqja -> ['photo']
dy -> ['two']
çfarë -> ['how']
kemi -> ['to']
mësuar? -> ['up.']
kanë -> ['have']
kaluar -> ['over']
pesëdhjetë -> ['four']
```

```
vjet -> ['years']
q  -> ['which']
```

Language: arabic
Sample lexicon entries:

```
-> ['what']
-> ['others']
-> ['that']
-> ['addicted']
-> ['habits']
-> ['recordings']
-> ['radio']
-> ['day']
-> ['concluded:']
-> ['on']
```

Language: french

Sample lexicon entries:

```
 l oge -> ['mystery']
des -> ['of']
t moins -> ['whom']
l' uvre -> ['which']
de -> ['of']
pr dication -> ['efforts']
j hovah -> ['jehovah']
s' tend -> ['which']
rapidement. -> ['run']
cette -> ['this']
```

Language: german

Sample lexicon entries:

```
ein -> ['a']
wort -> ['word']
zugunsten -> ['against']
der -> ['the']
zeugen -> ['witnesses']
jehovas -> ['jehovah's']
das -> ['is']
predigtwerk -> ['worldwide']
dehnt -> ['changed']
sich -> ['while']
```

Language: greek

Sample lexicon entries:

```
 n c -> ['one']
k l c -> ['than']
 y c -> ['which']
 l a -> ['for']
t u c -> ['them']
 p t r c -> ['four']
  -> ['the']
 p s c -> ['paraguay']
 p y t c -> ['testimony']
 w  -> ['of']
```

Language: hindi

Sample lexicon entries:

```
-> ['large']
-> ['military']
-> ['and']
-> ['against']
! -> ['fascinating, ']
-> ['us']
-> ['all']
-> ['on']
-> ['its']
-> ['effect']
```

Language: japanese

Sample lexicon entries:

```

-> ['other']
-> ['and']
-> ['witnesses,']
-> ['and']
-> ['scribes,']
-> ['and']
-> ['ps.']
-> ['and']
-> ['and']
-> ['and']

Language: macedonian
Sample lexicon entries:
младите -> ['young']
прашуваат... -> ['walk']
како -> ['as']
можам -> ['could']
да -> ['to']
се -> ['known']
справам -> ['cope']
со -> ['with']
неправдата? -> ['injustice']
ги -> ['them']

Language: persian
Sample lexicon entries:
international -> ['society']
bible -> ['bible']
students -> ['society']
association -> ['society']
-> ['this']
-> ['publication']
-> ['for']
-> ['sale.']
-> ['is']
-> ['and']

Language: thai
Sample lexicon entries:
-> ['near']
-> ['where']
-> ['from']
. -> ['year']
. -> ['c.e.,']
-> ['once']
-> ['state']
-> ['mixed']
-> ['enough']
-> ['mixed']

```

The first results are not great... we can also create “top-k” lexicons to see if the correct translation is among the top candidates. For example k=5.

```
top5_lexicons = build_lexicon(similarity_matrices, k=5)
```

```

Language: albanian
Sample lexicon entries:
faqja -> ['photo', 'perhaps.', 'mirror', 'ela', 'falter']
dy -> ['two', 'three', 'four', 'third', 'second']
çfarë -> ['how', 'did', 'what', 'whether', 'then']
kemi -> ['to', 'which', 'them', 'and', 'they']
mësuar? -> ['up.', 'them', 'to', 'it.', 'them.']
kanë -> ['have', 'least', 'been', 'they', 'had']
kaluar -> ['over', 'before', 'period', 'long', 'last']
pesëdhjetë -> ['four', 'five', 'half', 'years', 'ten']
vjet -> ['years', 'year', 'years.', 'years,', 'ago.']

```

```

që -> ['which', 'that', 'and', 'as', 'they']

Language: arabic
Sample lexicon entries:
-> ['what', 'how', 'why', 'whether', 'what,']
-> ['others', 'lead', 'learn', 'avoid', 'could']
-> ['that', 'it', 'leave', 'purpose', 'last']
-> ['addicted', 'recklessly', 'again', 'addiction', 'raising']
-> ['habits', 'behavior', 'known', 'hours,', 'them']
-> ['recordings', 'reports', 'between', 'friends', 'their']
-> ['radio', 'middle', 'over', 'and', 'reports']
-> ['day', 'perhaps', 'often', 'may', 'times']
-> ['concluded:', 'set', 'evolution', 'yourself', 'thought']
-> ['on', 'off', 'at', 'over', 'place']

Language: french
Sample lexicon entries:
éloge -> ['mystery', '"the', '"life', 'isa.', 'matt.']
des -> ['of', 'or', 'and', 'which', 'some']
témoins -> ['whom', 'which', 'witnesses.', 'witnesses,', 'and']
l'œuvre -> ['which', 'on', 'the', 'an', 'and']
de -> ['of', 'which', 'and', 'or', 'less']
prédication -> ['efforts', 'work', 'purpose', 'work,', 'service']
jéhovah -> ['jehovah', 'jehovah's', 'witnesses', 'john', 'god,']
s'étend -> ['which', 'of', 'and', 'second', 'wide']
rapidement. -> ['run', 'it.', 'long', 'along', 'hard']
cette -> ['this', 'these', 'which', 'such', 'the']

Language: german
Sample lexicon entries:
ein -> ['a', 'an', 'and', 'while', 'or']
wort -> ['word', 'god,', 'god.', 'holy', 'things.']
zugunsten -> ['against', 'toward', 'instead', 'bringing', 'taken']
der -> ['the', 'of', 'which', 'that', 'and']
zeugen -> ['witnesses', 'jehovah's', 'persons', 'jehovah', 'members']
jehovas -> ['jehovah's', 'jehovah', 'witnesses', 'jehovah.', 'god,']
das -> ['is', 'is,', 'that', 'and', 'it']
predigtwerk -> ['worldwide', 'holy', 'matt.', 'preaching', 'gigantic']
dehnt -> ['changed', 'further', 'of', 'second', 'increased']
sich -> ['while', 'and', 'was', 'become', 'them']

Language: greek
Sample lexicon entries:
ἕνας -> ['one', 'another', 'a', 'an', 'other']
καλός -> ['than', 'national', 'for', 'four', 'a']
λόγος -> ['which', 'the', 'of', 'on', 'law']
για -> ['for', 'which', 'hold', 'and', 'it.']
τους -> ['them', 'whom', 'them.', 'their', 'them,']
μάρτυρας -> ['four', 'whom', 'three', 'matt.', 'and']
η -> ['the', 'which', 'is', 'it', 'and']
δραστης -> ['paraguay', 'rectifier', 'stitch', 'argentina', 'condenser']
κηρύγματος -> ['testimony', 'clergy', 'second', 'matt.', 'book']
των -> ['of', 'which', 'them', 'those', 'whom']

Language: hindi
Sample lexicon entries:
-> ['large', 'great', 'more', 'small', 'up']
-> ['military', 'which', 'great', 'toxic', 'major']
-> ['and', 'which', 'or', 'as', 'more']
-> ['against', 'threat', 'act', 'or', 'which']
! -> ['fascinating', 'great', 'big', 'awake!', 'success']
-> ['us', 'others', 'clearly', 'must', 'there']
-> ['all', 'its', 'them', 'most', 'and']
-> ['on', 'of', 'for', 'against', 'which']
-> ['its', 'it', 'which', 'this', 'makes']
-> ['effect', 'causes', 'of', 'effects', 'on']

Language: japanese
Sample lexicon entries:
-> ['other', 'prov.', 'further', 'bible', 'national']

```

```

-> ['and', 'of', 'which', 'or', 'neither']
-> ['witnesses', 'witnesses', 'neither', 'whom', 'and']
-> ['and', 'kingdom', 'from', 'his', 'whom']
-> ['scribes', 'servant', 'teaching', 'welcome', 'glad']
-> ['and', 'father', 'his', 'witnesses', 'kingdom']
-> ['ps.', 'of', 'and', 'peaceful', 'national']
-> ['and', 'which', 'kingdom', 'ps.', 'purpose']
-> ['and', 'of', 'or', 'neither', 'which']
-> ['and', 'of', 'on', 'it.', 'less']

Language: macedonian
Sample lexicon entries:
младите -> ['young', 'children', 'old', 'youngsters', 'men']
прашувала... -> ['walk', 'known', 'observe', 'isaiah', 'they']
како -> ['as', 'which', 'known', 'and', 'well']
можам -> ['could', 'can', 'able', 'ever', 'known']
да -> ['to', 'make', 'known', 'them', 'until']
се -> ['known', 'are', 'as', 'well', 'were']
справам -> ['cope', 'well', 'and', 'known', 'doing']
со -> ['with', 'and', 'including', 'which', 'whom']
неправдата? -> ['injustice', 'what', 'contact', 'discouraged', 'exceeded']
ги -> ['them', 'known', 'they', 'and', 'were']

```

```

Language: persian
Sample lexicon entries:
international -> ['society', 'assembly', 'watch', 'tower', 'bible']
bible -> ['bible', 'society', 'bible', 'bible?', 'bible's']
students -> ['society', 'york', 'tower', 'tract', 'pennsylvania']
association -> ['society', 'pennsylvania', 'watch', 'york', 'tower']
-> ['this', 'these', 'the', 'such', 'other']
-> ['publication', 'published', 'publications', 'article', 'distribution.']
-> ['for', 'form', 'family.', 'purpose', 'perhaps']
-> ['sale.', 'publication', 'distribution.', 'publications', 'download']
-> ['is', 'not', 'no', 'only', 'simply']
-> ['and', 'thick', 'which', 'or', 'of']

```

```

Language: thai
Sample lexicon entries:
-> ['near', 'before', 'revelation', 'special', 'or']
-> ['where', 'once', 'at', 'which', 'when']
-> ['from', 'into', 'per', 'revelation', 'through']
.-> ['year', 'state', 'new', 'kingdom', 'world']
.-> ['c.e.', 'c.e.', 's.', 'south', 'u.s.']
-> ['once', 'finest', 'a', '"there', 'was']
-> ['state', 'or', 'back', 'world', 'once']
-> ['mixed', 'state', 'once', 'great', 'new']
-> ['enough', 'his', 'mixed', 'once', 'time']
-> ['mixed', 'once', 'near', 'which', 'never']

```

Looking at the first entries (I consider only the languages I can speak, French, Greek and German), there seems to be an ever so slight improvement when considering the top-5 candidates. What seems to me the case more often than not is that functional words are translated correctly more often than content words. Furthermore, there seems to be a “pooling” effect, where functional words get high similarity scores with content words and thus appear in the top translation-candidate position.

```

def sentence_level_hit_at_k(src_sentences, tgt_sentences, lexicon):
    tgt_word_sets = [set(sent.split()) for sent in tgt_sentences]
    accuracies = []

    for src_sent, tgt_word_set in zip(src_sentences, tgt_word_sets):
        hits = 0
        total = 0

        for w in src_sent.split():
            if w not in lexicon:

```

```

    continue

predicted_words = set(lexicon[w])

if predicted_words & tgt_word_set:
    hits += 1

total += 1

accuracies.append(hits / total if total > 0 else 0.0)

return accuracies

```

```

import pandas as pd

def evaluate_all_languages(data, translation_lexicons):
    rows = []

    for lang, lexicon in translation_lexicons.items():
        accuracies = sentence_level_hit_at_k(
            src_sentences=data[lang]['pairs']['non_english'],
            tgt_sentences=data[lang]['pairs']['english'],
            lexicon=lexicon
        )

        rows.append({
            "language": lang,
            "hit": float(np.mean(accuracies))
        })

    return pd.DataFrame(rows)

```

Table 1: Results for argmax evaluation across all languages.

language	hit
albanian	0.275912
arabic	0.173384
french	0.307206
german	0.362282
greek	0.313626
hindi	0.194358
japanese	0.245503
macedonian	0.336152
persian	0.156475
thai	0.0587208

Table 2: Results for top 5 evaluation across all languages.

language	hit
albanian	0.493644
arabic	0.341002
french	0.525088
german	0.585316
greek	0.530915
hindi	0.410893

language	hit
japanese	0.512551
macedonian	0.551903
persian	0.304214
thai	0.20467

Our evaluation method is “hit at k”, meaning that we check if the correct translation is among the top k candidates.

Concretely, we have build lexicons for each language, where each source word is mapped to its top k most similar target words based on cosine similarity of the mean of their contextualized embeddings. One manual way to evaluate is to simply look at those lexicons and see if the translations make sense, but of course, this is not very informative...

What we want to do is to look at the pairs of sentences in our dataset, and for each source word in the sentence, check if its translation (or set of candidate translations) is present in the target sentence. This approach can at least inform us if on the sentence level, our lexicon is able to capture some of the correct translations. This of course completely ignores the alignment, but either way, since languages have different word orders, this is a reasonable first step.

More importantly, this evaluation is flawed in that it does not account for the errors introduced by the alignment method itself. For example, if a source word is aligned to an incorrect target word, say a functional word, if that functional word happens to be present in the target sentence, we would count that as a hit, even though the alignment was incorrect. This means that our evaluation might overestimate the quality of our lexicon.

When we look at the results across all languages, the performance is quite low, with hit@1 scores around 10-30% and hit@5 scores around 20-60%. It is not surprising that the performance increases when considering the top 5 candidates instead of just the top 1, but it can also overestimate the lexicon quality due to the reasons mentioned above.

4 Second alignment method: Competitive linking using the Hungarian algorithm

```
from scipy.optimize import linear_sum_assignment

def build_lexicon_competitive_linking(similarity_matrices):
    lexicons = {}

    for lang, sim_data in similarity_matrices.items():
        print(f"Building competitive lexicon for language: {lang}")

        sim_matrix = sim_data["matrix"]
        non_en_words = sim_data["non_english_words"]
        en_words = sim_data["english_words"]

        # Hungarian algorithm minimizes cost, so negate similarities
        cost_matrix = -sim_matrix
```

```
row_idx, col_idx = linear_sum_assignment(cost_matrix)

lexicon = {}
for i, j in zip(row_idx, col_idx):
    lexicon[non_en_words[i]] = en_words[j]

lexicons[lang] = lexicon
print(f"Linked {len(lexicon)} word pairs\n")

return lexicons
```

Language: albanian

Sample lexicon entries:

```
faqja -> falter
dy -> two
çfarë -> did
kemi -> we
mësuar? -> learned?
kanë -> have
kaluar -> leaving
pesëdhjetë -> fifty
vjet -> years
që -> that
```

Language: arabic

Sample lexicon entries:

```
-> learning.
-> fidgeting,
-> complaining
-> manners
-> media
-> watcher.
-> occasionally
-> mainland.
-> "every
-> ritual?
```

Language: french

Sample lexicon entries:

```
éloge -> deluge
des -> perhaps
témoins -> congregations
l'œuvre -> upbuilding
de -> of
prédication -> work,
jéhovah -> jehovah's
s'étend -> watchtower
rapidement. -> masse.
cette -> this
```

Language: german

Sample lexicon entries:

```
ein -> inexperienced
wort -> word
der -> the
zeugen -> witnesses,
jehovas -> witnesses
das -> provides
predigtwerk -> work:
sich -> kept
sehr -> very
schnell -> fast
```

Language: greek

Sample lexicon entries:

```
ένας -> one
καλός -> simpler
λόγος -> account
```

για -> for
τους -> them
μάρτυρας -> did:
η -> everyday
των -> prophecies
μαρτύρων -> relics
του -> of

Language: hindi
Sample lexicon entries:

-> huge
-> business.
-> and
-> illegal
! -> fascinating,
-> we
-> all,
-> on
-> makes
-> effect

Language: japanese

Sample lexicon entries:

-> james
-> the
-> witness
-> back
-> scribes,
-> witnesses
-> preaching
-> purpose
-> was
-> produce

Language: macedonian

Sample lexicon entries:

младите -> youths
прашываат... -> drama
како -> as
можам -> can't
да -> to
се -> being
справам -> calm
со -> with
неправдата? -> misread
ги -> them

Language: persian

Sample lexicon entries:

international -> tower
bible -> bible?
students -> york,
association -> society
-> this
-> publication
-> for
-> sale.
-> wise,
-> going.

Language: thai

Sample lexicon entries:

-> threats
-> environment
-> internal
. -> antioch,
. -> c.e.,
-> finest
-> respective
-> preparing

-> caused
-> always

We can then evaluate the same way as before.

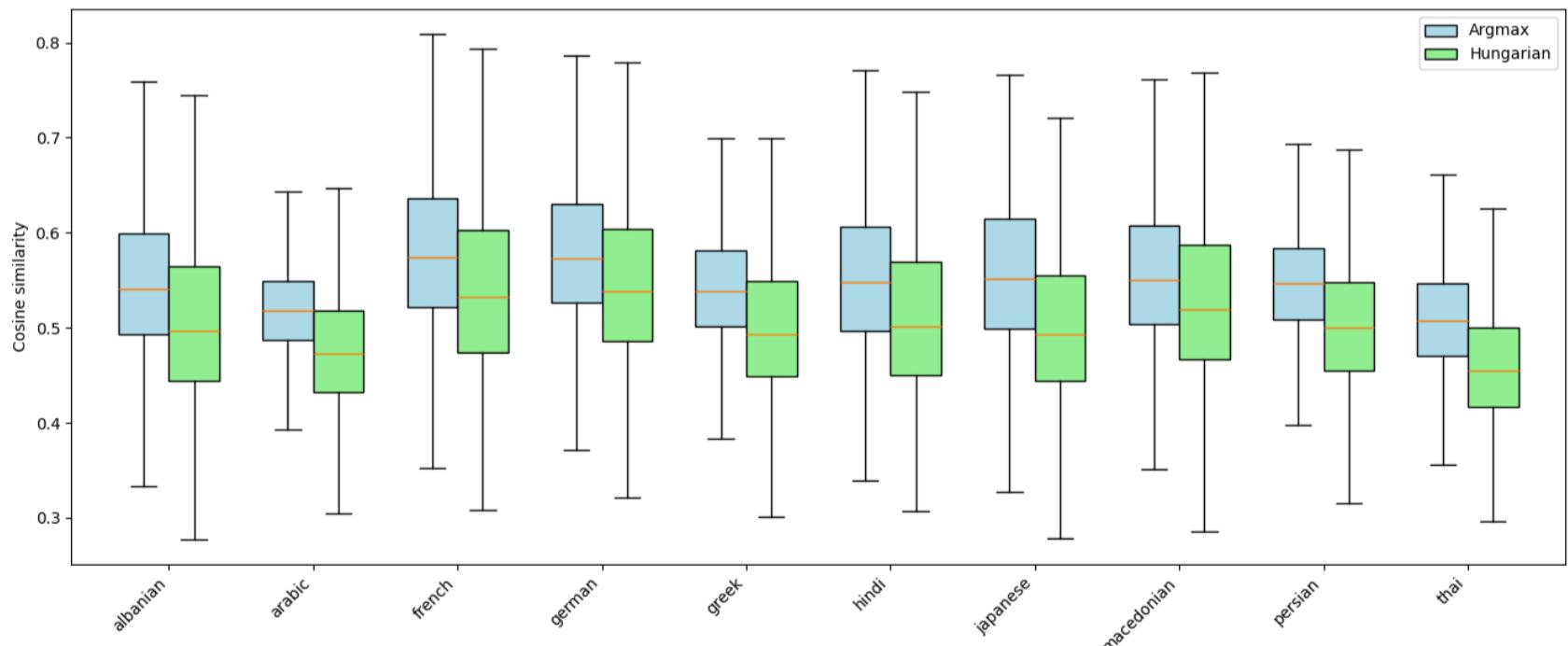
Table 3: Results for competitive linking evaluation across all languages.

language	hit
albanian	0.0892302
arabic	0.142443
french	0.11539
german	0.0888936
greek	0.111314
hindi	0.11673
japanese	0.111532
macedonian	0.0868781
persian	0.0777913
thai	0.114054

The results are considerably worse, but they have curiously improved for Thai. With a one-to-one alignment, we avoid the “pooling” effect where functional words get aligned to multiple content words, which was leading to many false positives in the previous evaluation.

We can also have a look at the distribution of similarity scores for both methods.

Figure 1: Box plots comparing similarity distributions for Argmax and Competitive Linking methods across languages.



Across all languages, argmax consistently yields higher median and upper-range similarities, reflecting its greedy nature: it selects the strongest possible match for each source word, often

reusing frequent English words. Competitive linking shows lower medians, confirming that enforcing one-to-one alignments limits the maximum achievable similarity scores ,as “hub” words cannot be reused. There seems not to be a significant difference between languages, the median values for both methods (around 0.5-0.6) are relatively consistent.

5 Third alignment method: CCA-based mapping

The starting point is to load the bilingual lexicons from MUSE as well as the previously computed embeddings from mBERT. We will describe the pipeline for one language.

- Load the bilingual lexicon from MUSE.
- Filter to pairs covered by the precomputed mBERT word-type lexicons, and extract the corresponding embeddings to form aligned training matrices.
- Train a CCA model to learn linear projections for the two languages.
- Project all source and target word embeddings into the shared CCA space.
- Compute cosine similarity matrix in the CCA space.
- Repeat for all languages.

Building the aligned training matrices.

```
def build_cca_training_data(src_lex, tgt_lex, gold_pairs):
    X, Y = [], []
    for src_w, tgt_w in gold_pairs:
        if src_w in src_lex and tgt_w in tgt_lex:
            X.append(src_lex[src_w])
            Y.append(tgt_lex[tgt_w])
    return np.array(X), np.array(Y)
```

Compute the CCA projections. Concerning the components, the documentation says: “number of components to keep. Should be in [1, min(n_samples, n_features, n_targets)]”. So we do something similar by setting a fixed upper bound of 50 components and then clamping the actual number of components to the maximum value allowed by the data, namely the minimum of the number of gold pairs minus one and the embedding dimensionality.

```
def train_cca(X, Y, max_components=50):
    n_pairs, dim = X.shape
    n_components = min(max_components, n_pairs - 1, dim)
    cca = CCA(n_components=n_components, max_iter=2000)
    cca.fit(X, Y)
    return cca
```

```
def build_cca_similarity_matrix(src_lex, tgt_lex, cca):
    src_words = list(src_lex.keys())
    tgt_words = list(tgt_lex.keys())

    X = np.stack([src_lex[w] for w in src_words])
    Y = np.stack([tgt_lex[w] for w in tgt_words])

    # Project both vocabularies jointly into the CCA space
    Xp, Yp = cca.transform(X, Y)

    sim = cosine_similarity(Xp, Yp)
```

```
    return sim, src_words, tgt_words
```

Apply the pipeline for one language.

```
def cca_align_language(lang, lexicons_by_language, data, max_components=50, min_pairs=100):
    src_lex = lexicons_by_language[lang]["non_english"]
    tgt_lex = lexicons_by_language[lang]["english"]
    gold_pairs = data[lang]["lexicon"]

    X, Y = build_cca_training_data(src_lex, tgt_lex, gold_pairs)

    if X.shape[0] < min_pairs:
        print(f"Skipping {lang}: only {X.shape[0]} gold pairs")
        return None

    cca = train_cca(X, Y, max_components)
    return build_cca_similarity_matrix(src_lex, tgt_lex, cca)
```

... and for all languages.

```
def cca_align_all_languages(lexicons_by_language, data, max_components=50, min_pairs=100):
    cca_similarity_matrices = {}

    for lang in lexicons_by_language:
        print(f"Training CCA for {lang}")
        results = cca_align_language(
            lang,
            lexicons_by_language,
            data,
            max_components=max_components,
            min_pairs=min_pairs
        )

        if results is None:
            continue

        sim, src_words, tgt_words = results
        cca_similarity_matrices[lang] = {
            "matrix": sim,
            "non_english_words": src_words,
            "english_words": tgt_words
        }

    return cca_similarity_matrices
```

Now we can build the lexicons in the CCA space and evaluate them using the same hit@k method as before.

```
argmax_caa_lexicons = build_lexicon(cca_similarity_matrices)
```

Table 4: Results for CCA argmax evaluation across all languages.

language	hit
albanian	0.00322573
french	0.00987898
german	0.00315783

The results are pretty terrible, but this has certainly to do with the very poor evaluation we have been using so far. We can perhaps use the MUSE lexicons as a gold standard for

evaluation instead of the sentence-level co-occurrence method.

```

def evaluate_lexicon_hit_at_k(induced_lexicon, muse_pairs, k=1):
    # Build gold lookup since MUSE may have multiple targets per source
    gold_lookup = {}
    for src, tgt in muse_pairs:
        gold_lookup.setdefault(src, set()).add(tgt)

    hits = 0
    total = 0

    for src_word, gold_targets in gold_lookup.items():
        if src_word not in induced_lexicon:
            continue

        predicted = induced_lexicon[src_word] [:k]

        if any(tgt in gold_targets for tgt in predicted):
            hits += 1

        total += 1

    return hits / total if total > 0 else 0.0

```

Table 5: Detailed results for CCA argmax evaluation across all languages.

language	hit@1	n_gold
albanian	0.553191	11491
french	0.698189	10872
german	0.651899	14677

Yes, this is actually much better! Lets see with k=5.

Table 6: Detailed results for CCA top 5 evaluation across all languages.

language	hit@5	n_gold
albanian	0.553191	11491
french	0.700201	10872
german	0.651899	14677

There is only an improvement for French.