

Natural Language Understanding, Generation, and Machine Translation (2020–2021)

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Coursework 2: Neural Machine Translation

This assignment is due on Friday, the 5th of March 2021, at 4PM, UTC.

Deadline for choosing partners: Monday, the 15th of February at 12PM, UTC.

Executive Summary Your task will be to work with a simple baseline NMT model for German to English, analysing its code and evaluating its performance. To improve over the baseline NMT model, you will implement the lexical attention model as described in Nguyen and Chiang (2017). Finally, you will analyse a basic implementation of the Transformer architecture and implement the multi-head attention mechanism according to Vaswani *et al.* (2017) to complete the model.

IMPORTANT: While modifying the baseline code may only take you a few minutes or hours, training the extended models will take you **A LOT OF TIME**. You might implement something in thirty minutes and leave it to train overnight. Imagine that you return the next morning to find it has a bug! If the next morning is the due date, then you'll be in a pickle, but if it's a week before the due date, you have time to recover. So, if you want to complete this coursework on time, **start early**.

Submission Deadline and Pacing You may work with a partner, but it is not required to do so. If you do want to work with a partner, you have an earlier deadline to relate this to us, on **Monday, the 15th of February at 12PM, UTC**. i.e., 21 days before the coursework due date. The coursework is due on **5th March 2021 at 4PM UTC**.

There are seven questions in total, divided into four areas of interest. Part 1 asks you to analyse the code and train an improvement to the baseline without modifying the code. This part should not be too time consuming. However, (re-)training the model can take up to 10 hours, so make sure to plan accordingly. Part 2 asks you to consider extensions to the baseline already supported in the code. Part 3 considers the lexical attention model and you will have to implement this in code, train a new model and discuss your results. Part 4 asks you to consider the Transformer model and requires

you to add the Multi-Head attention code to complete the model. Make sure to allocate sufficient time to implement, train, and evaluate your model extensions.

Pair work policy. You are *strongly* encouraged to work with a partner on this assignment. When you work with another person, you learn more, because you need to explain things to each other as you pool your collective expertise to solve problems. Explaining something to another person helps you debug your own thinking, and their questions help you overcome your own blind spots—something you cannot do on your own by staring at maths, code, or data. For this reason, it is best to seek partners with complementary skills to your own. You may not work in teams of three or more.

If you work with a partner, only one of you should submit your completed work. But we need to know that the submission represents the work of two people, and we need to know that reliably in advance in order to estimate marking hours. So, **you must do the following to ensure that both of you receive credit:**

1. Find a partner and confirm which one of you will submit the partnering form. If this is you, **confirm you have correctly recorded your partner's student number (UUN)**.
2. Submit your names and UUNs using the following form: [Link to form](#)
This form is only accessible when you are logged into your University email account, so you may have to enter your password. You can also notify us here if you want to be randomly paired with a partner in your timezone.

You must do this by **Monday, the 15th of February at 12PM (UTC)**. You may not change partners after you have done this, so take this commitment seriously. If we do not receive a submission from you or your partner by the deadline, we will assume that you are working alone. Either way, we will confirm your choice with you shortly after the deadline to avoid later confusion. **We advise you to choose your partner now and get to work.** Piazza offers a feature that allows you to search for a partner, and you are welcome to use this. We can also assign you a partner in your timezone if you need one. You can select that option in the partnering form.

Submission You will submit **two** items for assessment for this coursework. You will deliver a document detailing your answers to all questions, including code sections where appropriate, and also a ZIP archive containing the files specified below. Your solution should be delivered in two parts and uploaded to Blackboard Learn. **Do not include any names in either the code or the write-up.** The coursework will be marked anonymously since this has been empirically shown to reduce bias. For your writeup you must do the following:

- Write up your answers in a file titled `<UUN>.pdf`. For example, if your UUN is S1234567, your corresponding PDF should be named `S1234567.pdf`.
- The answers should be clearly numbered and can contain text, diagrams, graphs, formulas, where appropriate. Do not repeat the question text. If you are not comfortable with writing maths on L^AT_EX/Word you are allowed to include scanned handwritten answers in your submitted PDF. You will lose marks if your handwritten answers are illegible.
- On Blackboard Learn, select the Turnitin Assignment “Coursework 2 REPORT”. Upload your `<UUN>.pdf` to this assignment, and use the submission title `<UUN>`. So, for above example, you should enter the submission title S123456.
- Please make sure you have submitted the right file. We cannot make concessions for students who turn in incomplete or incorrect files by accident.

For your code and parameter files:

- Compress your code for `lstm.py`, `train.py`, `transformer.py` and `transformer_helper.py` into a ZIP file named `<UUN>.zip`. For example, if your UUN is S1234567, your corresponding ZIP should be named `S1234567.zip`.
- On Blackboard Learn, select the Turnitin Assignment “Coursework 2 CODE”. Upload your `<UUN>.zip` to this assignment, and use the submission title `<UUN>`. So, for above example, you should enter the submission title S123456.

Good Scholarly Practice Please remember the University requirement as regards all assessed work for credit. Details and advice about this can be found at:

<http://web.inf.ed.ac.uk/infweb/admin/policies/academic-misconduct>

and links from there. Note that you are required to take reasonable measures to protect your assessed work from unauthorised access. For example, if you put your work in a public repository then you must restrict access only to yourself and your partner. **You are not permitted to publish your code solution online.**

For your write-up, and particularly on the final questions, you should pay close attention to the guidance on plagiarism. Your instructors are **very good** at detecting plagiarism that even Turnitin can’t spot. In short: the litmus test for plagiarism is not the Turnitin check—that is simply an automated assistant. If you have borrowed or lightly edited someone else’s words, you have plagiarised. We are fully aware of what code examples and tutorials are on the Internet. Write your report in your own words. We will not mark for eloquence—as long as we can clearly understand what you did, that is fine.

Python Virtual Environment For this assignment you will be using Python 3.7 along with a few open-source packages. If you installed a Conda environment for CW1 – you will likely need to update it for CW2.

The instructions below are for DICE. You are free to use your own machine, but we cannot offer support for non-DICE machines. Similarly, this installation is for the CPU version of PyTorch and we cannot offer support for GPU programming or any attempts to execute the assignment on a cluster such as `mlp.inf.ed.ac.uk`. The package specification file (`requirements.txt`) will only work for Linux based systems.

Open a terminal on a DICE machine and follow these instructions. We are expecting you to enter these commands in **one-by-one**. Waiting for each command to complete will help catch any unexpected warnings and errors. The total installation is about 4.33GB, please ensure you have sufficient space using the `freespace` command on DICE.

First install Miniconda from the home directory of your DICE user space (respond yes to all prompts). *You can skip this stage if you already have Miniconda installed.*

```
$> wget https://repo.continuum.io/miniconda/Miniconda3-latest-Linux-x86_64.sh
$> bash ./Miniconda3-latest-Linux-x86_64.sh
$> rm ./Miniconda3-latest-Linux-x86_64.sh
$> source ~/.bashrc
```

Now, your default Python version should be Python 3.7 or newer. Confirm with `python3 --version`. Having ensured you have a right version of Python, proceed to create a new environment called `nlu`. We will use the file `requirements.txt`, **which has been updated since CW1**, to generate this environment.

1. Clone the GitHub repository to an appropriate location in your workspace

You must do this even if you have the environment set up:

```
$> git clone https://github.com/tomsherborne/nlu_cw2
$> cd nlu_cw2
```

2. Create an environment using the provided `requirements.txt` file:
`conda create -n nlu --file ./requirements.txt -c pytorch`

3. Activate the `nlu` virtual environment:

```
$> conda activate nlu
```

4. **Optional** Clean your workspace to free up space:

```
$> conda clean --all
```

* **Alternative** Update your existing NLU environment from CW1:

```
$> conda activate nlu
$> conda install --file ./requirements.txt
```

You should now have all the required packages installed. You only need to create the virtual environment and perform the package installations (step 1-4) **once**. However, make sure you activate your virtual environment (step 3) **every time** you open a new terminal to work on your assignment. Remember to use the `conda deactivate` command to disable the virtual environment when you don't need it.

1. Activate the environment:

```
$> conda activate nlu # Ready for working
```

2. Deactivate the environment (if you want to work on something else):

```
$> conda deactivate nlu
```

Additionally, learning to use UNIX tools such as `screen` and DICE tools like `longjob` will make running code for this assignment much easier. Run `man screen` or `man longjob` for guidance with this.

Using a different machine The above installation is designed for usage on DICE, but will also work for other Linux machines. If you are using Mac or Windows, you will have difficulty installing the required packages using the `requirements.txt` file as they are not designed for your computer. You can replace commands 3 & 4 using the following commands:

1.

```
$> conda create -n nlu python=3.7
```
2.

```
$> conda activate nlu
```
3.

```
$> conda install pytorch=1.7.1 torchvision torchaudio cpuonly -c pytorch
```
4.

```
$> conda install tqdm=4.56 pandas=1.2.1 seaborn=0.11.1
```

Baseline NMT model To download the baseline code, open the terminal and type:

```
git clone https://github.com/tomsherborne/nlu_cw2
```

You'll find several directories inside the downloaded `nlu_cw2` folder, including `europarl_raw` containing raw English and German parallel data, `europarl_prepared` containing the pre-processed data your models will be trained on, and `seq2seq` containing the code you will be asked to extend. Moreover, you will find several python files of importance to the assignment (**DO NOT MODIFY FILES MARKED WITH ***):

- `train.py*` is used to train the translation models.
- `translate.py*` translates the test-set greedily using model parameters restored from the best checkpoint file and saves the output to `model_translations.txt`.

- `example.sh`. This is a suggested outline of a single experiment run to train a model, generate translations and then find the test-set BLEU score.

To train a baseline model, follow `example.sh` without modifying any lines. This script includes training and inference and is designed to help you get started, but you can modify it for later parts of the coursework. You can specify the hyper-parameters for the training using the appropriate argument flags, but **we strongly recommend training with the default settings**. Run this script directly by running `bash example.sh` in the directory downloaded from GitHub. You can also just train a model by running: `python train.py`.

After calling the training script, you should see a progress bar denoting the training progress for the current epoch. Training will continue until no improvement can be observed on the development set for 10 consecutive epochs. After each epoch, the latest model file is saved to disk as `checkpoint_last.pt`. If the model achieved a lower dev-set perplexity in the concluded epoch than in the previous epochs, a ‘best’ model file is saved to disk, as well, as `checkpoint_best.pt`. You can find the checkpoint files in the `checkpoints` directory or the location you specify using the `--save-dir` argument to the training script. After your model has finished training, use it to translate the test set by running: `python translate.py`.

The translations will be output to the file `model_translations.txt`. Next, use the `multi-bleu.perl` script to calculate the test-BLEU score of the baseline model:

```
perl multi-bleu.perl -lc europarl_raw/test.en < model_translations.txt
```

To report your results, note the BLEU score and the validation-set perplexity and training loss from the final epoch. Then back up the checkpoints directory (e.g. by renaming it to `checkpoints_baseline` but `example.sh` does this automatically). This model is still quite basic and trained on a small dataset, so the quality of translations will be (very) poor. Your goal will be to see if you can improve it.

The current translation model implementation in `seq2seq/models/lstm.py` encodes the sentence using a bidirectional LSTM: one LSTM passing over the input sentence from left-to-right, the other from right-to-left. The final states of these LSTMs are concatenated and attended over by the decoder, using global attention with the general scoring function as described in Luong *et al.* (2015). While the encoder is implemented as a single-layer bidirectional RNN equipped with the LSTM cell, the decoder is a single-layer unidirectional RNN, also equipped with the LSTM cell. The file `seq2seq/models/transformer.py` defines an implementation of the Transformer architecture from Vaswani *et al.* (2017). The layers, positional embeddings and attention mechanism (that you must complete) are contained in `seq2seq/models/transformer_helper.py`.

Part 1: Getting Started

Question 1: Understanding the Baseline Model [10 marks]

Before we go deeply into modifications to the translation model, it is important to understand the baseline implementation, the data we run it on, and some of the techniques that are used to make the model run on this data.

The file `seq2seq/models/lstm.py` contains explanatory comments to step you through the code. Five of these comments (A-E) are missing, but they are easy to find: search for the string `__QUESTION` in the file. A sixth comment (F) is missing from `train.py`. For each of these cases:

1. Add explanatory comments to the code
2. Copy your comments to your report (we will mark the comments in your report, not the code, so it is vital that they appear there)

If you aren't certain what a particular function does, refer to the PyTorch documentation: <https://pytorch.org/docs/stable/index.html>. (However, explain the code in terms of its effect on the MT model; don't simply copy and paste function descriptions from the documentation).

Before you continue to improve the model, validate that you can train the baseline model by training the LSTM with default arguments (given in `lstm.py`). The script `example.sh` shows you how to do this. Confirm that you can train this model and your results look similar to these metrics (your baseline performance may vary slightly due to the random nature of model parameter initialisation):

- `training loss during last epoch: 2.145`
- `validation set perplexity during last epoch: 26.8`
- `test set BLEU: 11.03`

If your model performs similarly to the baseline, proceed with the rest of the assignment. Training the model may take between 4-6 hours depending on your CPU capability.

Question 2: Understanding the Data [10 marks]

The dataset we provide is a small sample of the Europarl Corpus (Koehn, 2005), which is a transcription of proceedings from the European Parliament. We will focus on parallel German and English data, providing 10,000 sentence pairs for training, and 500 pairs for validation and testing. In preparing the training data, word types that appear only

once are replaced by a special token, `<UNK>`. This prevents the vocabulary from growing out of hand, and enables the model to handle unknown words in new test sentences (which may be addressed by post-processing). **Note that the data has already been tokenised for you, so you do not need to use further tokenisation software.**

Examine the parallel training data located in the `europarl_raw` directory (`train.en` and `train.de`) and answer the following questions in your report.

1. How many word tokens are in the English data? In the German data? Give both the total count and the number of word types in each language.
2. How many word tokens will be replaced by `<UNK>` in English? In German? Subsequently, what will the total vocabulary size be?
3. Inspect the words which will be replaced by `<UNK>`. Is there a specific type of word which will be commonly replaced? Give an example of this type of word from English and German. How will this affect the test set? What ‘type’ could refer to here could be a specific POS tag or entity class, but you are free to come up with another idea based upon your understanding of the data.
4. How many unique vocabulary tokens are the same between both languages? How could we exploit this similarity in our model? You don’t have to consider false friends such as the English verb ‘die’ and German article ‘die’, just treat them as the same.
5. Given the observations above, how do you think the NMT system will be affected by differences in sentence length, token ratios, and unknown word handling?

Part 2: Exploring the Model

Let’s explore the decoder. It makes predictions one word at a time from left-to-right, as you can see by examining the decoder module in the file `seq2seq/models/lstm.py` and the greedy decoding script in `translate.py`. Prediction works by first computing a distribution over all possible tokens conditioned on the input sentence. We then choose the most probable token, output it, add it to the conditioning context, and repeat until the end-of-sentence token (`<EOS>`) is predicted.

Question 3: Improved Decoding [10 marks]

1. Currently, the model uses greedy decoding, which simply chooses the maximum-probability token at each time step. Can you explain why this might be problematic? Give language specific examples as part of your answer.

2. How would you modify this decoder to do beam search - that is, to consider multiple possible translations at each time step. **NOTE:** You don't need to implement beam search. The purpose of this question is simply for you to think through and clearly explain how you would do it. Try and be as mathematically descriptive as possible in your explanation.
3. Often with beam search (and greedy decoding), the decoder will output translations which are shorter than one would expect. As such, length normalisation is often used to fix this. Why does the decoder favour short sentences? What is a problem that length normalisation can introduce?

Question 4: Adding Layers [5 marks]

1. Change the number of layers in the encoder = 2, decoder = 3. You don't need to modify the codebase to train a deeper model - this is already supported by the provided code. Inspect the source code to find out how you can control the number of encoder and decoder layers via command line arguments. Train a system with this deeper architecture, and report the command that you used in your write up.
2. What effect does this change have on dev-set perplexity, test BLEU score and the training loss (all in comparison to the baseline metrics given in Q1)? Can you explain why it does worse/better on the training, dev, and test sets than the baseline single layer model? Is there a difference between the training set, dev set, and test set performance? Why is this the case?

Part 3: Lexical Attention

Question 5: Implementing the Lexical Model [30 marks]

In this part of the assignment, we ask you to augment the encoder-decoder with the lexical model defined in Section 4 of Nguyen and Chiang (2017). For this task, your primary guidance should be the descriptions provided in the paper. Moreover, we have marked the different points in the encoder-decoder implementation where you are strongly encouraged to insert your code (marked as `__QUESTION-5`).

Implementing the lexical model can be roughly subdivided into three steps:

1. Compute the weighted sum of source embeddings using weights extracted from the decoder-to-encoder attention mechanism.
2. Define the feed-forward layers used to project the weighted sum of source language embeddings.

3. Incorporate the lexical context tensor into the calculation of the predictive distribution over output words.

To accomplish this, **you only need to modify** `lstm.py` and **nothing else**. Implementing the modifications should not take you very long, but retraining the model will.

NOTE: We recommend that test your modifications by retraining on a small subset of the data (e.g. a thousand sentences). To do that, you should add the flag `--train-on-tiny` to the set of arguments when executing `train.py`, i.e.:

```
python train.py --train-on-tiny
```

The results will not be very good; your goal is simply to confirm that the change does not break the code and that it appears to behave sensibly. This is simply a sanity check, and a useful time-saving engineering test when you're working with computationally expensive models like neural MT. For your final models, you should train on the entire training set.

Implement lexical model as described above, all changes to the baseline implementation **must be done in the decoder**. You should be able to easily access both source embeddings (assigned to the `src_embeddings` variable) as well as attention weights specific to each decoding step (assigned to the `step_attn_weights` variable). Adding your code to the specified positions within the decoder architecture will help ensure that everything works correctly.

When you have completed your implementation and you are sure that it doesn't break your model: retrain your translation model after augmenting it with the lexical model by running the following command:

```
python train.py --decoder-use-lexical-model True
```

Again, explain how the change affects results compared to the baseline in terms training set loss, dev perplexity, and test BLEU scores. Consider whether the addition of lexical translation is beneficial or detrimental to performance on these automatic metrics.

Optionally, you can also examine the output translations – using translations that differ between models as motivating examples in your explanation of the effects of lexical attention. You do not need to exhaustively examine every output – but consider if you can find any trends in improvement between models (there may be none). In your report, you can discuss a trend you identify with a maximum of **five example output pairs**. Do not include all your model outputs in the report.

Part 4: Transformers

Modern NMT systems rely heavily on the Transformer architecture (Vaswani *et al.*, 2017), which has emerged in recent years as a viable competitor to the more established LSTM-based approach to sequence transduction. Transformers are a non-recurrent architecture which has set state-of-the-art performance in many areas of MT. We recommend you start this section using the reading for Lecture 10 (Vaswani *et al.* (2017) and the blog post).

Question 6: Understanding the Transformer Model [10 marks]

This question asks you to similarly complete five explanatory comments (6A-6E) in `seq2seq/models/transformer.py` (6A-6C) and `seq2seq/models/transformer_helper.py` (6D, 6E). Find these again by searching for the string `__QUESTION-6` in the file.

1. Add explanatory comments to the code.
2. Copy your comments to your report (we will mark the comments in your report, not the code, so it is vital that they appear there).

Again, you can use the PyTorch documentation if you don't understand a function. You must still explain each function in the model in your own words.

Question 7: Implementing Multi-Head Attention [25 marks]

In the final section of the coursework, we ask you to implement Multi-Head attention from Section 3.2 of Vaswani *et al.* (2017). As before, your main guidance should be the equations in the paper itself. If you use external resources, you **must** cite these.

Implementing multi-head attention can be roughly subdivided into three steps:

1. Linear projection of Query, Key and Value.
2. Computing scaled dot-product attention for h attention heads.
3. Concatenation of heads and output projection.

To accomplish this, you need to modify the `forward` method in the `MultiHeadAttention` class in `transformer_helper.py` and nothing else (marked as `__QUESTION-7`). This is a larger task than the lexical model and may take you some time to develop and test this function. There are some comments and checks to guide you about the required shape of the output tensors. We discourage you from trying to solve this using a series of obscure tensor transformations. A few more lines of readable code is easier to understand than one line which does everything. We **strongly** encourage you to add descriptive comments to your code so we can understand your implementation in your

words. Copy **only** your forward function from the `MultiHeadAttention` into your report, as we will mark this first.

As before, we recommend that you test the modifications by retraining on a small subset of the data. To do this for the Transformer, add the following arguments to `train.py`, i.e.:

```
python train.py --train-on-tiny --arch transformer
```

When you have completed multi-head attention, train a transformer model with the default arguments on the full dataset. Report your test-set BLEU and the final epoch training loss and validation-set perplexity as you did for the baseline models. Similar to before, this might take **a long time (5 hours)**. Can you explain why it does worse/better on the development and test sets than the previous LSTM-based models? Is there a difference between the training set, dev set, and test set performance? You should compare to the previous models you have trained.

You might notice that the quality of outputs is poor and the model converges quickly. Considering the dataset and the model size, give **two reasons** why this may be the case? How could we possibly improve performance? Note you do not have to retrain this model. You can answer without having a functioning model if you compare between the literature and the provided code.

Acknowledgements

The baseline NMT implementation is based on the following codebase: <https://github.com/tangbinh/machine-translation>

References

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