

DL Project Final Report: Shakespeare - English Sequence to Sequence Modeling

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Abstract

We present our attempt to create an English-Shakespeare Sequence to Sequence Model, and its application to create a pseudo supervised style transfer system for text. We experimented with different Encoder-Decoder Architectures with and without Attention Mechanisms. We discuss our data procurement and processing to help facilitate learning, and present our experimental results.

1 Introduction

We applied a suite of Encoder-Decoder models with varying attention mechanisms (and lack of attention mechanisms) along with teacher forcing rates to a corpus of Modern English - Original Shakespeare data. Discussion of our data is in Section 2, our processing methods are described in Section 3. We used our neural machine translation systems to apply a supervised style transfer between the two forms of writing. More specifically, we tested models currently used in decoding languages (Section 4) and how they can be used in this capacity. We provide results for several model combinations and discuss the successes and failures of each system (Section 6.5). We also describe important implementation details in Section 5. Diagrams for our models can be found in the appendix.

2 Data

Most of our data came from previous alignment work by Xu et al.[9], in which two aligned corpora were procured from Sparknotes and Enotes. Both datasets, deriving from different websites, differed drastically. Sparknotes

was more liberal in its translations, opting for reordering that differed drastically from the original plays, and was harder to learn. Enotes was a smaller corpus of 8 plays, but had less reordering, and was easier to train on. The data was aligned, and not all of the original lines from the plays are included (i.e. the sentences could not be aligned properly).¹

Play	Line Count
Hamlet	2,010
Julius Caesar	1,201
Macbeth	1,085
Merchant of Venice	831
A Midsummer Night's Dream	833
Othello	1,893
Romeo and Juliet	1,743
Tempest	769
Total	10,365

Figure 1: Line Counts for Shakespeare-English Corpus per Play (Enotes)

The vocabulary sizes are 9,004 source (original) words and 7,497 target (modern) words for the Sparknotes set. We had a total of 10,365 lines of Shakespeare plays to train on. There is a total word count of 233,282 words for the entire corpus (unprocessed). Sample data pairs (processed) are provided in Figure 2.

BLEU scores (discussed in Section 5.3.2) for Original to Modern is 0.4455, and Modern to Original is 0.4465, indicating strong correlation between the two corpora.

¹<https://github.com/cocoxu/Shakespeare>

#	Original Sentence	Modern Sentence
1	take me with you , take me with you , wife .	catch me , catch me , wife .
2	that 's fouler .	that 's even more evil .
3	perchance till after propn ' wedding - day .	maybe until after propn ' wedding - day .
4	propn truly knows that thou art false as hell .	propn truly knows that you are as false as hell .
5	then weep no more .	so stop crying .
6	of propn , a n't please your mastership .	of propn , if it pleases you , sir .
7	how ill this taper burns !	how badly this candle burns !
8	the charm 's wound up .	the charm 's going to bring things to a head .
9	before the time be out ?	before the debt is paid ?
10	but soft !	quiet !

Figure 2: Sample Original-Modern Sentence Pairs, Processed

3 Preprocessing

We applied several techniques to improve the quality of our data and reduce the vocabulary size to train on.

3.1 Proper Nouns

Proper nouns are unique in both corpus, and have direct translations. In order to reduce vocabulary size and aggregate the learning of all proper nouns, we replace all proper nouns with the following token: propn. Thus our model should learn to map propn to propn, and can utilize the encoding to learn the most likely token following its usage. We use SpaCy's² nlp models to identify proper nouns in each sentence, and replace the tokens.

3.2 NLTK Tokenization

We use NLTK's `tokenize` module to further process our text data. We can use this module to split our strings into its component words, punctuation, contractions, etc.

For instance, the modern sentence from Hamlet *there's rue for you, and here's some for me.* will be tokenized into: *there 's rue for you , and here 's some for me .*

Additionally, contractions are split: *isn't he honest?* tokenizes to *is n ' t he honest ?*

We can use this to easily split words and train on each token. We lower case all input before tokenizing.

3.3 SOS/EOS Tokens

During runtime, we encapsulate every sentence with two special tokens: SOS and EOS. The Start of Sentence token (SOS) signals the start of a sequence, and allows us to map our first real word to one that most likely starts a sentence, given the current hidden state from the encoder (and encoder outputs if attention is used).

We use the End of Sentence (EOS) token to signal the end of the sequence, i.e. when to stop the decoding process. In the batched version, the EOS token signals which tokens should be counted in the loss, while everything after EOS is masked (see Section 5.3.1).

3.4 Data Split

We randomly shuffle and split the combined preprocessed dataset into three sets: Train, Dev, and Test. We opted for a 87.5/10/2.5 split to reduce the appearance of unknown tokens (UNK). This gives us a sizable training corpus to actually learn, and a reasonable validation set to measure BLEU scores and loss. The small test set allows us to digest our results. Since the amount of Shakespeare data is limited, and will not increase in size, we can have small test sets and seek to overtrain the model.

File	Line Count
train.snt.aligned	9,069
dev.snt.aligned	1,036
test.snt.aligned	260
Total	10,365

Figure 3: Data Split for Shakespeare-English Corpus (Enotes)

²<https://spacy.io>

4 Model Architecture

We developed several models to create our pseudo style-transfer system, incorporating context, attention, and training methods. It incorporates an encoder-decoder style model as used in Cho et al. [3] and Sutskever et al. [8].

4.1 Overview

Our idea is inspired by reducing our style-transfer system to a translation problem. Hence our approach to provide state of the art neural MT systems to provide a reasonable transfer of the target styling for a given source sequence.

NMT systems are comprised of two sub models: an Encoder and Decoder. The encoder is known as the *inference network* and encodes the input sequence to provide context to the decoder, or *generative network*. The decoder then uses the encoder's output to generate tokens corresponding to words in the target language. Attention mechanisms have shown to improve the generative network, as detailed in Bahdanau et al. [1], and further work from Luong et al. [5].

We describe the underlying components used to build these sub-networks, and their advantages and disadvantages.

4.2 Encoders

The encoder, or *inference network*, receives an input token sequence $\vec{x} = [x_1, \dots, x_n]$ of length n and processes this to create an output encoding. The result is a sequence $\vec{h} = [h_1, \dots, h_n]$ that maps to the input sequence \vec{x} . The final hidden state is h_n .

Encoders share the same architecture except for the recurrent layer. For each input word x_j , the encoder looks up the associated word embedding, and runs the sequence through the recurrent layer. We define W_e as the word embedding, with each row corresponding to an input token.

$$\vec{h} = \begin{cases} \text{RNN}(W_e[\vec{x}]) \\ \text{GRU}(W_e[\vec{x}]) \\ \text{BiGRU}(W_e[\vec{x}]) \end{cases} \quad (1)$$

The output of the recurrent layer is our encodings, and we propagate the layer's last hidden state to the decoder. Theoretically, the hidden state should encode all the important information from the input sequence and pass it along to the decoder, but the encodings can

be used with attention to provide better models. If the encoder type is bidirectional, then we return only the forward hidden state.

We use three types of encoders: RNN, GRU, and the Bidirectional GRU (BiGRU).

4.3 Decoders

The decoder, or *generative network*, receives the encoder outputs, the model's hidden state, and the last input token. On the first pass of the decoder, the hidden state is the encoder's final hidden state, and the input token is SOS.

We can describe our decoders in two ways: with and without attention. For our recurrent layers, we use the RNN and GRU layers. We cannot use a Bidirectional GRU because we do not know the full decoded sequence (and hence why we are decoding).

$$\tau_i = \begin{cases} W_e[t_i] & \text{No Attention} \\ W_e[t_i] \parallel c_i & \text{With Attention} \end{cases} \quad (2)$$

In the case of attention, we apply one of the attention schemes (described in the next section) to the encoder output, given our current decoder's hidden state. We concatenate the attention results, known as a context vector c_i with our input embedding for an input token t_i .

Without attention, we just use the input embedding and ignore the encoder outputs.

$$\mathbf{y} = W_d \cdot \begin{cases} \text{RNN}(\tau_i, s_{i-1}) \\ \text{GRU}(\tau_i, s_{i-1}) \end{cases} \quad (3)$$

We apply a recurrent layer to the attended tensor, using the hidden state provided. After applying a linear layer with weights W_d and applying a log softmax, we output our result for evaluation, which is the log probability distribution across the target vocabulary.

$$\log \sigma(\mathbf{y}) = \log \frac{\exp(y_i)}{\sum_j \exp(y_j)} \quad (4)$$

4.4 Attention

Attention mechanisms have been shown to improve sequence to sequence translations from Bahdanau et al. [1], and further work from Luong et al. [5] examines global vs local approaches to attention-based encoder-

Encoder	Decoder	Attention	Model Parameters
RNN	RNN	None	6,414,153
GRU	GRU	None	6,940,489
BiGRU	GRU	None	7,335,241
BiGRU	GRU	General	7,859,530
BiGRU	GRU	Concat	7,925,578

Figure 4: Total Model Parameters (for Enote dataset)

decoders. Common attention mechanisms are:

$$score(s_{i-1}, h_j) = \begin{cases} v_a^T \cdot \tanh(W_a[s_{i-1} || h_j]) & \text{concat} \\ s_{i-1}^T \cdot W_a \cdot h_j & \text{general} \\ s_{i-1}^T \cdot h_j & \text{dot} \end{cases} \quad (5)$$

where s_{i-1} is the previous decoder hidden state, and h_j is the j th encoder output. To compute scores, which are used to create attention weights, we apply a softmax:

$$a(s_{i-1}, h_j) = \frac{\exp(score(s_{i-1}, h_j))}{\sum_{j'} \exp(score(s_{i-1}, h_{j'}))} \quad (6)$$

Using these scores, we create a context vector c_i , which is just the batch matrix multiplication between our attention weights and the encoder outputs (i.e. a weighted sum of the encoder outputs).

$$c_i = \sum_{j'} a(s_{i-1}, h_{j'}) \cdot h_{j'} \quad (7)$$

We will focus on general attention and concat attention in our experiments.

4.5 Teacher-Forcing

In terms of training, an encoder-decoder system can either accept the target token or the model's prediction as the next input during the decoding step. When we use the target token, this is known as teacher forcing, and is shown to be favored during initial training iterations but should be backed off to use the model's own predictions. Continuous use of teacher forcing without backing off to the model's own decoded tokens will exhibit instability in the translations as shown in Lamb et al. [4]

During training, we randomly determine whether to feed in the true target token instead of the generated token to the decoder. This is a configurable parameter that determines the threshold to allow teacher forcing, where 0 means no teacher forcing and 1 is constant teacher forcing.

5 Implementation

5.1 Batching

In order to improve training speed and prevent noisy gradients, we introduced batching for our model. As recommended by Morishita et al. [6], we batch by the sorting the source sequences by size in ascending order, and grouping sequences of equivalent sizes together. We have the option to limit the maximum size of the batches, which is currently defaulted to 128. For batching the target sequences, we pad each sequence with the EOS token, up to the maximum target sequence length in the set.

This allows us to run multiple sequences through the model simultaneously, and build up decoded sequences for many sentences at a time. This also improves learning by averaging the gradients as they are backpropagated.

For our dataset, at a maximum batch size of 128, we created 151 training batches and 65 dev batches.

5.2 GPU/CPU

Standard training can be done on a CPU, but neural networks have been shown to gain massive speedups. In order to improve training time, we have allowed an optional parameter to use a gpu, if system capable.

Our group has 3 GPUs (Morris: 1; Riley: 2). We distributed our tests across multiple GPUs for faster experimentation.

5.3 Metrics

Our model uses two main metrics to describe the quality of our system.

5.3.1 Masked NLL Loss

While we would normally use the *Negative Log Likelihood Loss* (NLL) to measure our error to backpropagate on, because of batching we must modify this loss

to mask tokens that are past the target length for a decoded sequence.

$$NLL(x_n, y_n) = -x_{n, y_n} \quad (8)$$

Hence we define a mask m such that for a target token index t_{ni} for the i th decoded token of the n th sequence in the batch:

$$m_{t_{ni}} = \begin{cases} 1 & \text{if } i < \text{target length} \\ 0 & \text{otherwise} \end{cases} \quad (9)$$

We describe the masked loss for an input log probability vector x_n and true target token index t_{ni} as:

$$NLL(x_n, t_{ni}) = -x_{n, t_{ni}} \cdot m_{t_{ni}} \quad (10)$$

We average our loss across the batch

5.3.2 BLEU Scores

We use the Bilingual Evaluation Understudy (BLEU) score as one of our criteria for the quality of model translations. Outputs are in the range $[0, 1]$, and a BLEU score of 1 indicates a perfect translation to the reference texts. We do not need not obtain a perfect score in order to have a good translation model.

BLEU scores are calculated for individual sentences and averaged across the whole corpus. Intelligibility and grammatical correctness are not taken into account when calculating BLEU scores. A full description of how BLEU scores are calculated from Papineni et al. [7] can be found in Appendix A.4

6 Results: Shakespeare-English

Our results demonstrate how different models and teaching methods affect the final translations. In Figure 5 below, we can see the final BLEU scores for our models.

6.1 RNN

The bare bones RNN had almost no capacity to learn and suffers from issues such as the vanishing gradient problem and long term dependencies. Since many of our sentences were long, this was problematic. The most distinguishing feature of the RNN translations is the overuse of repeated punctuation.

6.2 GRU and Bidirectional GRU

The GRU showed better promise in achieving higher BLEU scores, as seen in Figure 5, since GRUs mitigate the vanishing gradient problem and have a higher capacity.

The Bidirectional GRU achieved slightly better results, most likely from incorporating both a forward and backward context to the sequence. In addition, the bidirectional has two sublayers, thus doubling the GRU capacity to learn.

6.3 Attention Mechanisms

Although our best results were from a model trained with concat attention, we can see that the model trained with general attention actually worked well on shorter sentences. An explanation for this is that Luong et al. [5] attention mechanisms work best in a local setting. This means that either the sentence is short, or the model only looks at a small window of the full sequence. It is reasonable to assume that since we looked at the global context of our source encodings, the general attention failed whereas the Bahdanau [1] concat attention performed better overall.

6.4 Teacher Forcing

The 'best model' score came from our BiGRU architecture with concat attention and 100% teacher forcing. Looking at the scores, we can actually see that our model trained with 50% teacher forcing did better than the one with 100%, but our final best results were from the one with 100% and after many iterations with random initializations and keeping the trained model that worked best. This is important to note as well, because it demonstrates how randomness and initializations can greatly affect the final outcome. If we had more time and resources, we would train a model that starts with 100% teacher forcing and slowly back it down as training progresses.

6.5 Best Model

Our best model, as selected by test BLEU score, was the BiGRU architecture with concat attention and 100% teacher forcing, after training for 500 iterations. This model achieved a target BLEU score of 0.1450. The next best model was the BiGRU with concat attention and 50% teacher forcing, with target BLEU score of 0.1349.

Model	Source BLEU	Target BLEU
RNN	0.0000	0.0000
GRU	0.0237	0.0238
BiGRU	0.0297	0.0336
BiGRU + General	0.0291	0.0333
BiGRU + General + 50% TF	0.0264	0.0330
BiGRU + General + 100% TF	0.0348	0.0395
BiGRU + Concat	0.0953	0.0842
BiGRU + Concat + 50% TF	0.1505	0.1349
BiGRU + Concat + 100% TF	0.1153	0.1042
Best Model	0.1647	0.1450
Original-Modern	0.4465	0.4455

Figure 5: Model BLEU Results for Experiments. Source BLEU compares results to the source (original) sentences. Target BLEU compares results to the target (modern) sentences. We aim for high Target BLEUs.

This shows that attention is necessary for good results, and that teacher forcing helps the model achieve better translations by feeding in the true target tokens. However, these models can be trained longer, and the effects of random initialization is not clear. In addition, more training dynamics can be incorporated to provide deeper insight into this problem.

7 Key Takeaways

We detail several key takeaways from our experiments on training a Shakespeare-English sequence to sequence model.

7.1 General vs Local Attention

Our attention models use the *global* approach which attends to all the source embeddings at once. However, Luong et al. [5] showed that by using a *local* approach that attends to only a subset of the encodings, a neural encoder-decoder system could make effective gains in BLEU scores.

In our experiments, both attention models used the *global* approach, and it is clear why general failed to do well compared to the Bahdanau concat attention. Luong states that global attention fails on long sequences whereas a local approach is more effective. The *local* approach takes source embeddings within a window, computes the attention, and weights the attention probabilities by a gaussian distribution.

7.2 Teacher Forcing Impact

Teacher Forcing was required to make effective gains in our attention models. However, our results are inconclusive on how much teacher forcing should be applied. According to Lamb et al. [4], teacher forcing acts as a regularizer for these systems. In addition, Bengio et al. [2] describes an annealing process, changing the task from an easy one with target tokens, to a more realistic approach of feeding in the model’s prediction.

7.3 Random Initialization

As our results show, different initializations can lead to different BLEU scores, and different generalization performance. We saw this between our concat models that used teacher forcing. We believe that random initialization had a role to play in how these models performed.

7.4 GPU vs CPU Training Times

Training on a GPU yielded significant performance increases, allowing us to train multiple models quickly. Our model with the largest capacity took 11-13 minutes on a standard CPU, but only 111 seconds on a GPU for 2 full epochs.

8 Conclusion & Future Work

If given more time, obvious extensions to our existing experiments would included: batch annealing, reverse training a English to Shakespeare model, and implementing local attention with a window.

Model	Sentence
Source	double , double , toil and trouble ; fire burn and cauldron bubble .
RNN	damned as you are , you have cast the spell , the [followed by 490 commas]
GRU	double , double , toil and ; ; and burn burn burn burn cauldron bubble .
BiGRU	double , double , toil and ; ; burn , , , and cauldron bubble . .
BiGRU + General	double , double , toil , and ; , , burn , , bubble bubble .
BiGRU + General + 50% TF	double , double , toil and trouble ; fire , burn ; and cauldron , bubble .
BiGRU + General + 100% TF	double , double , toil and trouble ; fire , burn ; and cauldron , bubble .
BiGRU + Concat	double , double , toil and trouble ; , fire burn ; and cauldron bubble bubble .
BiGRU + Concat + 50% TF	double , double , toil and trouble ; fire , burn ; and cauldron , bubble .
BiGRU + Concat + 100% TF	double , double , toil and trouble ; fire , burn ; and cauldron , bubble .
Best Model	double , double , toil and trouble ; fire , burn ; and cauldron , bubble .
Target	double , double , toil and trouble ; fire , burn ; and cauldron , bubble .

Figure 6: Model Results for Selected Source-Target Pair: #1

Model	Sentence
Source	tonight , my lord ?
RNN	what you you ,
GRU	how , my lord ?
BiGRU	my , my lord ?
BiGRU + General	, my lord lord ?
BiGRU + General + 50% TF	my lord lord ?
BiGRU + General + 100% TF	brother , my lord ?
BiGRU + Concat	tonight , my lord ?
BiGRU + Concat + 50% TF	three , , my lord ?
BiGRU + Concat + 100% TF	tonight , my lord ?
Best Model	tonight , my lord ?
Target	tonight , my lord ?

Figure 7: Model Results for Selected Source-Target Pair: #1

Model	Sentence
Source	what say you , propn ?
RNN	what , you ,
GRU	what do you , propn propn ?
BiGRU	what do you say , propn ?
BiGRU + General	what do you say , propn ?
BiGRU + General + 50% TF	what do you say , propn ?
BiGRU + General + 100% TF	what do you say , propn ?
BiGRU + Concat	what did you say , propn ?
BiGRU + Concat + 50% TF	what do you say , propn ?
BiGRU + Concat + 100% TF	what do you say , propn propn ?
Best Model	what do you say , propn ?
Target	what do you say , propn ?

Figure 8: Model Results for Selected Source-Target Pair: #1

Model	Sentence
Source	propn thou not see her paddle with the palm of his hand ?
RNN	do n ' t
GRU	will n ' t storms ; his his his the ? ?
BiGRU	propn ' n ' t with you like the the the the hand hand ?
BiGRU + General	does ' ' t you ' t his his his his his all ?
BiGRU + General + 50% TF	propn , remember you in the hand of night of great hand ?
BiGRU + General + 100% TF	might do n ' t see the his dying hand , might see about the ?
BiGRU + Concat	do you ' t that you speak with the with such of of hand hand ?
BiGRU + Concat + 50% TF	have n ' t see her with the same of of his his hand ?
BiGRU + Concat + 100% TF	do n ' t you see her for the scripture of his body ?
Best Model	did n ' t go see her close with the same of his hand ?
Target	did n ' t you see her play with the palm of his hand ?

Figure 9: Model Results for Selected Source-Target Pair: #1

Model	Sentence
Source	some wine , ho !
RNN	what , ho !
GRU	what , , , !
BiGRU	and , ho !
BiGRU + General	give , oh ! !
BiGRU + General + 50% TF	oh , oh , hello !
BiGRU + General + 100% TF	some three , a blessing in like a !
BiGRU + Concat	some ! , ho !
BiGRU + Concat + 50% TF	let me fight !
BiGRU + Concat + 100% TF	some whiskey , hello !
Best Model	some wine , ho !
Target	some wine , ho !

Figure 10: Model Results for Selected Source-Target Pair: #1

Model	Sentence
Source	src sent
RNN	RNN
GRU	GRU
BiGRU	GRU
BiGRU + General	GRU
BiGRU + General + 50% TF	GRU
BiGRU + General + 100% TF	GRU
BiGRU + Concat	GRU
BiGRU + Concat + 50% TF	GRU
BiGRU + Concat + 100% TF	GRU
Best Model	GRU
Target	tgt sent

Figure 11: Model Results for Selected Source-Target Pair: #1

Source Shakespeare Sentence	General Attention Output	Target
i am much bound to you .	i am to you .	thank you so much .
o propn , they fight !	o propn , listen !	o lord , they ' re fighting !
do you like this haste ?	honestly must hurry ?	do you like this speed ?
wilt thou provoke me ?	you wilt make me ?	will you still provoke me ?
give me your neaf , propn propn .	let me your hand propn .	give me your hand , propn propn .

Figure 12: This demonstrates that general attention can work well on shorter sentences.

8.1 Batch Annealing

We wanted to study the effects of adaptive batch sizes, where training would begin with a small batch size and progressively increase to very large sizes. This would allow for stochastic updates in the beginning before approximating full gradient in later iterations. We think that this would have improved training and provided better results.

8.2 English to Shakespeare Modeling

We wanted to also train a reverse model for English to Shakespeare, to apply a translation between english sentences and turn it into Shakespeare. This is a weak form of style transfer masked as a translation problem. However, more work needs to be done improving the quality of our Shakespeare to English models before we find the best architecture.

8.3 Local Attention with Window

As discussed in Section 7.1, incorporating a window to allow for true *local* attention over *global* could results in better models. General might perform better in a *local* context over a global approach.

9 Advice to Future Students

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A Additional Information

A.1 RNN

The simplest way to process sequences of inputs is to use recurrent layers, which accept an input and previous hidden state to update its output. Our baseline models incorporate the *Elman RNN*, the simplest recurrent layer.

$$h_t = \tanh(W_{ih}x_t + b_{ih} + W_{hh}h_{t-1} + b_{hh}) \quad (11)$$

However, the layer is prone to the vanishing gradient problem on large sequences. In addition, *Elman RNNs* have the lowest capacity to learn.

A.2 GRU

Improvements have been made to the baseline RNN to increase capacity and improve gradient flow over long sequences. *Long Short-Term Memory* (LSTM) and *Gated Recurrent Units* (GRU) are two of the most popular improvements to recurrent networks. Both solve the vanishing gradient problem found in traditional RNN layers, and improve a model's capacity to learn.

$$\begin{aligned} r_t &= \sigma(W_{ir}x_t + b_{ir} + W_{hr}h_{t-1} + b_{hr}) \\ z_t &= \sigma(W_{iz}x_t + b_{iz} + W_{hz}h_{t-1} + b_{hz}) \\ n_t &= \tanh(W_{in}x_t + b_{in} + r_t \circ (W_{hn}h_{t-1} + b_{hn})) \\ h_t &= (1 - z_t) \circ n_t + z_t \circ h_{t-1} \end{aligned} \quad (12)$$

For our models, we use GRUs, as they have been shown to perform as well as LSTMs but with less parameters.

A.3 Bidirectional GRU

GRUs, and RNNs in general, only process sequences in a forward direction. However, encoding both the preceding and succeeding input would be beneficial to learning the context of a word in its local vicinity. Bidirectional layers allow models to encode inputs in both the forward and reverse direction. This is a simple, yet powerful, extension to uni-directional recurrent layers.

$$\begin{aligned} \vec{h}_f &= \text{GRU}(\overrightarrow{\text{input}}) \\ \overleftarrow{h}_b &= \text{GRU}(\overleftarrow{\text{input}}) \\ h_o &= \vec{h}_f \parallel \overleftarrow{h}_b \end{aligned} \quad (13)$$

Bidirectional layers run two separate recurrent layers, one on the forward input sequence; the other on the reversed input. Thus we get two output tensors, one for each direction. We reverse the backward tensor, and stack the two output tensors together. Thus our final tensor encodes the forward and backward context.

A.4 BLEU Scores

We use the Bilingual Evaluation Understudy (BLEU) score as one of our criteria for the quality of model translations. Outputs are in the range $[0, 1]$, and a BLEU score of 1 indicates a perfect translation to the reference texts. We do not need not obtain a perfect score in order to have a good translation model. BLEU scores are calculated for individual sentences and averaged across the whole corpus. Intelligibility and grammatical correctness are not taken into account when calculating BLEU scores. According to the original paper by Papineni et al. [7], BLEU scores are computed as follows:

$$\text{BLEU} = \text{BP} \cdot \exp \left(\sum_{n=1}^N w_n \log p_n \right) \quad (14)$$

where p_n is the geometric average of the modified n -gram precisions and BP is the brevity penalty, explained below. ([7] uses $N = 4$, uniform weights $w_n = \frac{1}{N}$.) The brevity penalty BP is used for translations that are too short compared to the reference. BP is defined as:

$$\text{BP} = \begin{cases} 1 & \text{if } c > r \\ e^{(1-r/c)} & \text{if } c \leq r \end{cases} \quad (15)$$

with effective reference corpus length r and candidate translation length c . BLEU scores are non-differentiable, and therefore we cannot directly optimize on this metric, but can use it to enhance our understanding regarding the quality of our models given the data.

B Model Architecture Diagrams

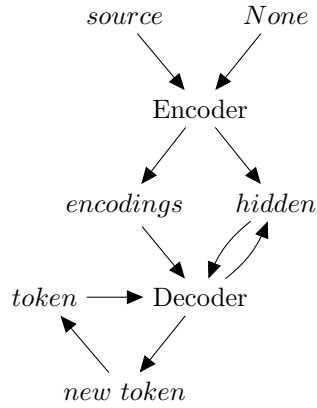


Figure 13: Model Architecture Overview for Encoder-Decoder.

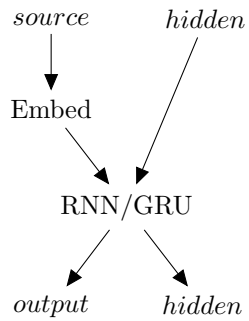


Figure 14: Model Architecture for Encoder.

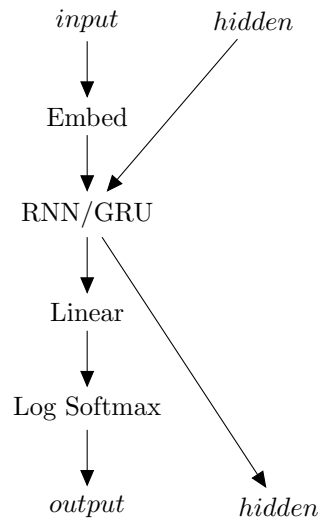


Figure 15: Decoder with No Attention.

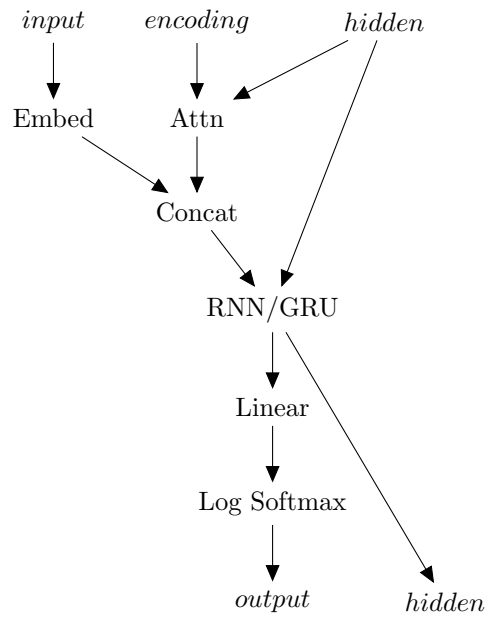


Figure 16: Decoder with Attention.

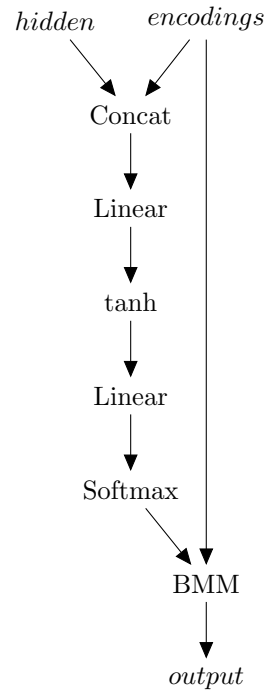


Figure 17: Concat (Bahdanau) Attention Layer.

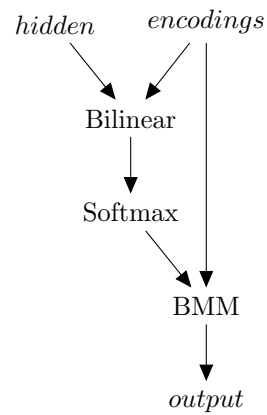


Figure 18: General Attention Layer.