

```
# Please do not change this cell because some hidden tests might depend on it.
import os

# Otter grader does not handle ! commands well, so we define and use our
# own function to execute shell commands.
def shell(commands, warn=True):
    """Executes the string `commands` as a sequence of shell commands.

    Prints the result to stdout and returns the exit status.
    Provides a printed warning on non-zero exit status unless `warn`
    flag is unset.
    """
    file = os.popen(commands)
    print (file.read().rstrip('\n'))
    exit_status = file.close()
    if warn and exit_status != None:
        print(f"Completed with errors. Exit status: {exit_status}\n")
    return exit_status

shell("""
ls requirements.txt >/dev/null 2>&1
if [ ! $? = 0 ]; then
    rm -rf .tmp
    git clone git@github.com:cs236299-2023-spring/lab4-4.git .tmp
    mv .tmp/tests ./
    mv .tmp/requirements.txt ./
    rm -rf .tmp
fi
pip install -q -r requirements.txt
""")
```

```
# Initialize Otter
import otter
grader = otter.Notebook()
```

Unsupported Cell Type. Double-Click to inspect/edit the content.

▼ Course 236299

Lab 4-4 - Sequence-to-sequence models

In lab 4-2, we used a syntactic-semantic grammar for semantic parsing to convert natural language to meaning representations in SQL. In this lab, we consider an alternative approach, sequence-to-sequence models, which can solve this task by directly learning the mapping from a sequence of inputs to a sequence of outputs. Since sequence-to-sequence models make few assumptions about the data, they can be applied to a variety of tasks, including machine translation, document summarization, and speech recognition.

In this lab, we will implement a sequence-to-sequence model in its most basic form (as in [this seminal paper](#)), and apply it to the task of converting English number phrases to numbers, as exemplified in the table below.

Input	Output
seven thousand nine hundred and twenty nine	7929
eight hundred and forty two thousand two hundred and fifty nine	842259
five hundred and eight thousand two hundred and seventeen	508217

For this simple task, it is possible to write a rule-based program to do the conversion. However, here we take a learning-based approach and learn the mapping from demonstrations, with the benefit that the system we implement here can be applied to other sequence-to-sequence tasks as well (including the ATIS-to-SQL problem in project segment 4).

New bits of Pytorch used in this lab, and which you may find useful include:

- [torch.transpose](#): Swaps two dimensions of a tensor.
- [torch.reshape](#): Redistributes the elements of a tensor to form a tensor of a different shape, e.g., from 3 x 4 to 6 x 2.
- [torch.nn.utils.rnn.pack_padded_sequence](#) (imported as `pack`): Handles paddings. A more detailed explanation can be found [here](#).

▼ Preparation - Loading data

```
import copy
import math
import os
import wget

import torch
import torch.nn as nn

from datasets import load_dataset
from tokenizers import Tokenizer
from tokenizers.pre_tokenizers import WhitespaceSplit
from tokenizers.processors import TemplateProcessing
from tokenizers import normalizers
from tokenizers.models import WordLevel
from tokenizers.trainers import WordLevelTrainer
from transformers import PreTrainedTokenizerFast

from tqdm import tqdm
import csv

from torch.nn.utils.rnn import pack_padded_sequence as pack

# GPU check, make sure to use GPU where available
device = torch.device("cuda" if torch.cuda.is_available() else "cpu")
print (device)

cuda
```

```
# Download data
def download_if_needed(source, dest, filename):
    os.makedirs(dest, exist_ok=True) # ensure destination
    os.path.exists(f"{dest}/{filename}") or wget.download(source + filename, out=dest)

local_dir = "data/"
remote_dir = "https://github.com/nlp-236299/data/raw/master/Words2Num/"
os.makedirs(local_dir, exist_ok=True)

for filename in [
    "train.src",
    "train.tgt",
    "dev.src",
    "dev.tgt",
    "test.src",
    "test.tgt",
]:
    download_if_needed(remote_dir, local_dir, filename)
```

Next, we process the dataset by extracting the sequences and their corresponding labels and save it in CSV format.

```
# Process data
for split in ['train', 'dev', 'test']:
    src_in_file = f'{local_dir}{split}.src'
    tgt_in_file = f'{local_dir}{split}.tgt'
    out_file = f'{local_dir}{split}.csv'

    with open(src_in_file, 'r') as f_src_in, open(tgt_in_file, 'r') as f_tgt_in:
        with open(out_file, 'w') as f_out:
            src, tgt= [], []
            writer = csv.writer(f_out)
            writer.writerow(('src','tgt'))
            for src_line, tgt_line in zip(f_src_in, f_tgt_in):
                writer.writerow((src_line.strip(), tgt_line.strip()))
```

Let's take a look at what each data file looks like.

```
shell('head "data/train.csv"')

src,tgt
five million eight hundred and seventy nine thousand four hundred and sixty four,5 8 7 9 4 6 4
twenty thousand eight hundred and eighty five,2 0 8 8 5
one thousand five hundred and ten,1 5 1 0
fifty nine thousand one hundred and six,5 9 1 0 6
forty three thousand one hundred and forty six,4 3 1 4 6
three hundred and fifty five million four hundred and fifty eight thousand six hundred and eighty six,3 5 5 4 5 8 6 8 6
```

five billion eight hundred and sixty three million sixty five thousand six hundred and seventy three,5 8 6 3 0 6 5 6 7 3
two hundred and forty six thousand four hundred and seventy one,2 4 6 4 7 1
eight hundred and twenty nine thousand eight hundred and one,8 2 9 8 0 1

▼ The dataset

Let's take a first look at the dataset of English number phrases and their translations into digit-sequence form.

```
with open(local_dir + "dev.csv") as f:
    for line, _ in zip(f, range(3)):
        src, tgt = line.split(',')
        print (f'{src.strip():70s} {tgt.strip():>12s}')
```

src	tgt
seven thousand nine hundred and twenty nine	7 9 2 9
eight hundred and forty two thousand two hundred and fifty nine	8 4 2 2 5 9

As before, we use datasets to load data.

```
dataset = load_dataset('csv', data_files={'train':f'{local_dir}train.csv', \
                                          'val': f'{local_dir}dev.csv', \
                                          'test': f'{local_dir}test.csv'})

dataset
```

```
WARNING:datasets.builder:Using custom data configuration default-0d8534ee189bd400
Downloading and preparing dataset csv/default to /root/.cache/huggingface/datasets/csv/default-0d8534ee189bd400/0
Downloading data files: 100% 3/3 [00:00<00:00, 57.26it/s]

Extracting data files: 100% 3/3 [00:00<00:00, 93.87it/s]

/usr/local/lib/python3.10/dist-packages/datasets/download/streaming_download_manager.py:776: FutureWarning: the '
return pd.read_csv(xopen(filepath_or_buffer, "rb", use_auth_token=use_auth_token), **kwargs)
/usr/local/lib/python3.10/dist-packages/datasets/download/streaming_download_manager.py:776: FutureWarning: the '
return pd.read_csv(xopen(filepath_or_buffer, "rb", use_auth_token=use_auth_token), **kwargs)
Dataset csv downloaded and prepared to /root/.cache/huggingface/datasets/csv/default-0d8534ee189bd400/0.0.0/6b34f
/usr/local/lib/python3.10/dist-packages/datasets/download/streaming_download_manager.py:776: FutureWarning: the '
return pd.read_csv(xopen(filepath_or_buffer, "rb", use_auth_token=use_auth_token), **kwargs)

100% 3/3 [00:00<00:00, 90.79it/s]

DatasetDict({
  train: Dataset({
    features: ['src', 'tgt'],
    num_rows: 65022
  })
  val: Dataset({
    features: ['src', 'tgt'],
    num_rows: 700
  })
  test: Dataset({
    features: ['src', 'tgt'],
    num_rows: 700
  })
})
```

```
train_data = dataset['train']
val_data = dataset['val']
test_data = dataset['test']
```

We build tokenizers from the training data to tokenize the source and target sequnces and convert them into word ids.

```

unk_token = '[UNK]'
pad_token = '[PAD]'
bos_token = '<bos>'
eos_token = '<eos>'
src_tokenizer = Tokenizer(WordLevel(unk_token=unk_token))
src_tokenizer.pre_tokenizer = WhitespaceSplit()

src_trainer = WordLevelTrainer(special_tokens=[pad_token, unk_token])
src_tokenizer.train_from_iterator(train_data['src'], trainer=src_trainer)

tgt_tokenizer = Tokenizer(WordLevel(unk_token=unk_token))
tgt_tokenizer.pre_tokenizer = WhitespaceSplit()

tgt_trainer = WordLevelTrainer(special_tokens=[pad_token, unk_token, bos_token, eos_token])

tgt_tokenizer.train_from_iterator(train_data['tgt'], trainer=tgt_trainer)

tgt_tokenizer.post_processor = TemplateProcessing(single=f"{bos_token} $A {eos_token}", special_tokens=[(bos_token, tgt_tokenizer.token_t

```

Note that we prepended `<bos>` and appended `<eos>` to target sentences. The purpose for introducing them will become clear in later parts of this lab.

We use `datasets.Dataset.map` to convert text into word ids. As shown in lab 1-5, first we need to wrap `tokenizer` with the `transformers.PreTrainedTokenizerFast` class to be compatible with the `datasets` library.

```

hf_src_tokenizer = PreTrainedTokenizerFast(tokenizer_object=src_tokenizer, pad_token=pad_token, unk_token=unk_token)
hf_tgt_tokenizer = PreTrainedTokenizerFast(tokenizer_object=tgt_tokenizer, pad_token=pad_token, unk_token=unk_token, bos_token=bos_token,

```

```

def encode(example):
    example['src_ids'] = hf_src_tokenizer(example['src']).input_ids
    example['tgt_ids'] = hf_tgt_tokenizer(example['tgt']).input_ids
    return example

```

```

train_data = train_data.map(encode)
val_data = val_data.map(encode)
test_data = test_data.map(encode)

```

100%	65022/65022 [00:20<00:00, 2030.95ex/s]
100%	700/700 [00:00<00:00, 1585.71ex/s]
100%	700/700 [00:00<00:00, 1429.70ex/s]

```

# Compute size of vocabulary
src_vocab = hf_src_tokenizer.get_vocab()
tgt_vocab = hf_tgt_tokenizer.get_vocab()

print(f"Size of src vocab: {len(src_vocab)}")
print(f"Size of tgt vocab: {len(tgt_vocab)}")
print(f"Index for src padding: {src_vocab[pad_token]}")
print(f"Index for tgt padding: {tgt_vocab[pad_token]}")
print(f"Index for start of sequence token: {tgt_vocab[bos_token]}")
print(f"Index for end of sequence token: {tgt_vocab[eos_token]}")

```

```

Size of src vocab: 34
Size of tgt vocab: 14
Index for src padding: 0
Index for tgt padding: 0
Index for start of sequence token: 2
Index for end of sequence token: 3

```

To load data in batched tensors, we use `torch.utils.data.DataLoader` for data splits, which enables us to iterate over the dataset under a given `BATCH_SIZE`. For the test set, we use a batch size of 1, to make the decoding implementation easier.

```

BATCH_SIZE = 32      # batch size for training and validation
TEST_BATCH_SIZE = 1  # batch size for test; we use 1 to make implementation easier

```

Defines how to batch a list of examples together

```

def collate_fn(examples):
    batch = {}
    bsz = len(examples)
    src_ids, tgt_ids = [], []
    for example in examples:
        src_ids.append(example['src_ids'])
        tgt_ids.append(example['tgt_ids'])

    src_len = torch.LongTensor([len(word_ids) for word_ids in src_ids]).to(device)

```

```

src_max_length = max(src_len)
tgt_max_length = max([len(word_ids) for word_ids in tgt_ids])

src_batch = torch.zeros(bsz, src_max_length).long().fill_(src_vocab[pad_token]).to(device)
tgt_batch = torch.zeros(bsz, tgt_max_length).long().fill_(tgt_vocab[pad_token]).to(device)
for b in range(bsz):
    src_batch[b][:len(src_ids[b])] = torch.LongTensor(src_ids[b]).to(device)
    tgt_batch[b][:len(tgt_ids[b])] = torch.LongTensor(tgt_ids[b]).to(device)

batch['src_lengths'] = src_len
batch['src_ids'] = src_batch
batch['tgt_ids'] = tgt_batch
return batch

train_iter = torch.utils.data.DataLoader(train_data,
                                         batch_size=BATCH_SIZE,
                                         shuffle=True,
                                         collate_fn=collate_fn)
val_iter = torch.utils.data.DataLoader(val_data,
                                       batch_size=BATCH_SIZE,
                                       shuffle=False,
                                       collate_fn=collate_fn)
test_iter = torch.utils.data.DataLoader(test_data,
                                       batch_size=TEST_BATCH_SIZE,
                                       shuffle=False,
                                       collate_fn=collate_fn)

```

Let's take a look at a batch from these iterators.

```

batch = next(iter(train_iter))
src_ids = batch['src_ids']
src_example = src_ids[2]
print(f"Size of src batch: {src_ids.size()}")
print(f"Third src sentence in batch: {src_example}")
print(f"Length of the third src sentence in batch: {len(src_example)}")
print(f"Converted back to string: {hf_src_tokenizer.decode(src_example)}")

tgt_ids = batch['tgt_ids']
tgt_example = tgt_ids[2]
print(f"Size of tgt batch: {tgt_ids.size()}")
print(f"Third tgt sentence in batch: {tgt_example}")
print(f"Converted back to string: {hf_tgt_tokenizer.decode(tgt_example)}")

```

Size of src batch: torch.Size([32, 19])
Third src sentence in batch: tensor([7, 3, 2, 17, 9, 4, 10, 3, 2, 18, 13, 0, 0, 0, 0, 0, 0, 0, 0], device='cuda:0')
Length of the third src sentence in batch: 19
Converted back to string: seven hundred and forty three thousand nine hundred and sixty eight [PAD] [PAD] [PAD] [PAD] [PAD] [PAD] [PAD] [PAD]
Size of tgt batch: torch.Size([32, 12])
Third tgt sentence in batch: tensor([2, 6, 10, 4, 5, 8, 11, 3, 0, 0, 0, 0], device='cuda:0')
Converted back to string: <bos> 7 4 3 9 6 8 <eos> [PAD] [PAD] [PAD] [PAD]

▼ Neural Encoder-Decoder Models

Sequence-to-sequence models are sometimes called neural encoder-decoder models, as they consist of an encoder, which maps a sequence of source tokens into some vector representations, and a decoder, which generates a sequence of output words from those encoded vectors.

Formally, given a sequence of source tokens $\mathbf{x} = x_1, \dots, x_S$, the goal is to map it to a sequence of target tokens $\mathbf{y} = y_1, \dots, y_T$.

In practice, we prepend a special beginning-of-sequence symbol $y_0 = \text{<bos>}$ to the target sequence. Further, in order to provide a way of knowing when to stop generating \mathbf{y} , we append a special end-of-sequence symbol $y_{T+1} = \text{<eos>}$ to the target sequence, such that when it is produced by the model, the generation process stops.

The generation process is structured as a generative model:

$$\Pr(y_0, \dots, y_{T+1} \mid x_1, \dots, x_S) = \prod_{t=1}^{T+1} \Pr(y_t \mid y_{<t}, x_1, \dots, x_S),$$

where $y_{<t}$ denotes the tokens before y_t (that is, y_0, \dots, y_{t-1}).

We use a recurrent neural network with parameters θ to parameterize $\Pr(y_t \mid y_{<t}, x_1, \dots, x_S)$:

$$\Pr(y_t \mid y_{<t}, x_1, \dots, x_S) \approx \Pr_{\theta}(y_t \mid y_{<t}, x_1, \dots, x_S),$$

or equivalently,

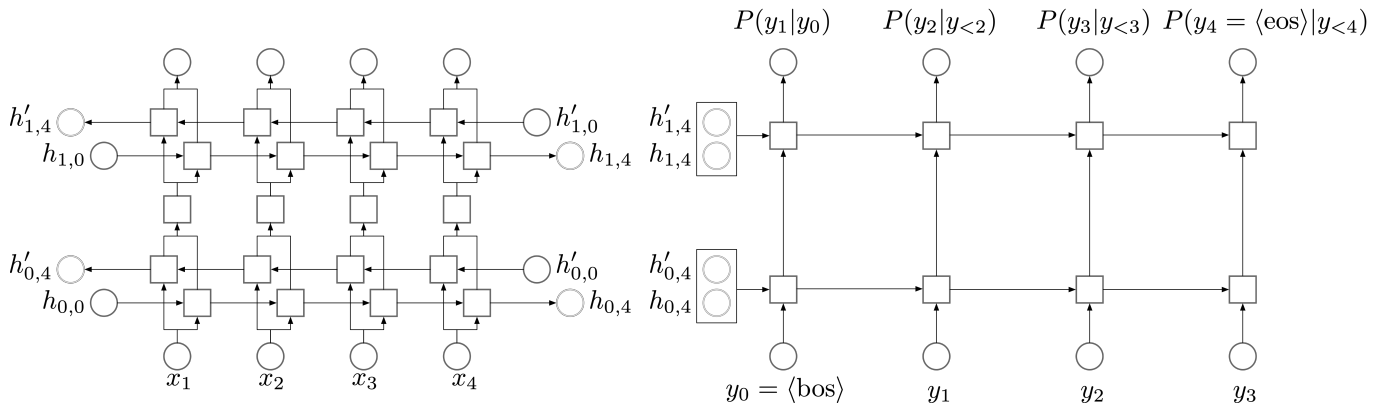
$$\Pr_{\theta}(y_1, \dots, y_T \mid x_1, \dots, x_S) = \prod_{t=1}^{T+1} \Pr_{\theta}(y_t \mid y_{<t}, x_1, \dots, x_S)$$

In neural encoder-decoder models, we first use an encoder to encode \mathbf{x} into some vectors (either of fixed length as we'll see in this lab, or of varying length as we'll see in the next lab). Based on the encoded vectors, we use a decoder to generate \mathbf{y} :

$$\Pr_{\theta}(y_t \mid y_{<t}, x_1, \dots, x_S) = \text{decode}(\text{encode}(x_1, \dots, x_S), y_{<t})$$

▼ RNN Encoder-Decoders

We can use any recurrent neural networks such as LSTMs as encoders and decoders. In this lab, we will use a bidirectional LSTM as the encoder, and a unidirectional LSTM as the decoder, as shown in the illustration below.



In the above illustration, $S = 4$, $T = 3$, and there are two encoder/decoder layers. Since we are using a bidirectional encoder, for each layer there are two final states, one for the cell running from left to right (such as $h_{0,4}$), and the other for the cell running from right to left (such as $h'_{0,4}$). We concatenate these two states and use the result to initialize the corresponding layer of the decoder. (In the example, we concatenate $h_{0,4}$ and $h'_{0,4}$ to initialize layer 0, and we concatenate $h_{1,4}$ and $h'_{1,4}$ to initialize layer 1.) Therefore, to make the sizes match, we set the hidden state size of the encoder to be half of that of the decoder.

Note that in PyTorch's LSTM implementation, the final hidden state is represented as a tuple (h, c) ([documentation here](#)), so we want to apply the same operations to c to initialize the decoder.

You'll implement `forward_encoder` and `forward_decoder` in the code below. The `forward_encoder` function will be reminiscent of a sequence model from labs 2-* and project segment 2. It operates on a batch of source examples and proceeds as follows:

1. Map the input words to some word embeddings. You'll notice that the embedding size is an argument to the model.
2. Optionally "pack" the sequences to save some computation using `torch.nn.utils.rnn.pack_padded_sequence`, imported above as `pack`.
3. Run the encoder RNN (a bidirectional LSTM) over the batch, generating a batch of output states.
4. Reshape the final state information (which will have h and c components each of half the size needed to initialize the decoder) so that it is appropriate to initialize the decoder with.

The `forward_decoder` function takes the reshaped encoder final state information and the ground truth target sequences and returns logits (unnormalized log probs) for each target word. (These are ready to be converted to probability distributions via a softmax.)

The steps in decoding are:

1. Map the target words to word embeddings.
2. Run the decoder RNN (a unidirectional LSTM) over the batch, initializing the hidden units from the encoder final states, generating a batch of output states.
3. Map the RNN outputs to vectors of vocabulary size (so that they could be softmaxed into a distribution over the vocabulary).

The components that you'll be plugging together to do all this are already established in the `__init__` method.

The major exception is the reshaping of the encoder output h and c to form the decoder input h and c . **This is the trickiest part.** As usual, your best strategy is to keep careful track of the shapes of each input and output of a layer or operation. We recommend that you try out just the reshaping code on small sample data to test it out before running any encodings or decodings.

Hint #1: The total number of `for` loops in our solution code for the parts you are to write is...zero.

Hint #2: According to the documentation of [torch.nn.LSTM](#), its outputs are: `outputs, (h, c)`. `outputs` contains all the intermediate states, which you don't need in this lab. You will need h and c , both of them have the shape: `(num_layers * num_directions, batch_size, hidden_size)`.

```

# TODO - finish implementing the `forward_encoder` and `forward_decoder` methods
class EncoderDecoder(nn.Module):
    def __init__(self, hf_src_tokenizer, hf_tgt_tokenizer, embedding_size=64, hidden_size=64, layers=3):
        """
        Initializer. Creates network modules and loss function.
        Arguments:
            hf_src_tokenizer: hf src tokenizer
            hf_tgt_tokenizer: hf tgt tokenizer
            embedding_size: word embedding size
            hidden_size: hidden layer size of both encoder and decoder
            layers: number of layers of both encoder and decoder
        """
        super(EncoderDecoder, self).__init__()
        self.hf_src_tokenizer = hf_src_tokenizer
        self.hf_tgt_tokenizer = hf_tgt_tokenizer

        # Keep the vocabulary sizes available
        self.V_src = len(self.hf_src_tokenizer)
        self.V_tgt = len(self.hf_tgt_tokenizer)

        # Get special word ids or tokens
        self.padding_id_src = self.hf_src_tokenizer.pad_token_id
        self.padding_id_tgt = self.hf_tgt_tokenizer.pad_token_id
        self.bos_id = self.hf_tgt_tokenizer.bos_token_id
        self.eos_id = self.hf_tgt_tokenizer.eos_token_id

        # Keep hyper-parameters available
        self.embedding_size = embedding_size
        self.hidden_size = hidden_size
        self.layers = layers

        # Create essential modules
        self.word_embeddings_src = nn.Embedding(self.V_src, embedding_size)
        self.word_embeddings_tgt = nn.Embedding(self.V_tgt, embedding_size)

        # RNN cells
        self.encoder_rnn = nn.LSTM(
            input_size=embedding_size,
            hidden_size=hidden_size // 2, # to match decoder hidden size
            num_layers=layers,
            batch_first=True,
            bidirectional=True, # bidirectional encoder
        )
        self.decoder_rnn = nn.LSTM(
            input_size=embedding_size,
            hidden_size=hidden_size,
            num_layers=layers,
            batch_first=True,
            bidirectional=False, # unidirectional decoder
        )

        # Final projection layer
        self.hidden2output = nn.Linear(hidden_size, self.V_tgt)

        # Create loss function
        self.loss_function = nn.CrossEntropyLoss(
            reduction="sum", ignore_index=self.padding_id_tgt
        )

    def forward_encoder(self, src, src_lengths):
        """
        Encodes source words `src`.
        Arguments:
            src: src batch of size (batch_size, max_src_len)
            src_lengths: src lengths of size (batch_size)
        Returns:
            a tuple (h, c) where h/c is of size (layers, bsz, hidden_size)
        """
        # TODO - implement this function
        # Optional: use `pack` to deal with paddings (https://discuss.pytorch.org/t/simple-working-example-how-to-use-packing-for-variabl
        # note that the batch size is the first dimension, and the sequences are not sorted.

        # print('\n\n\n\n\n')
        # print(f'batch_size={src.shape[0]} max_src_len={src.shape[1]=} {self.embedding_size=}')
        emb = self.word_embeddings_src(src) # batch_size, max_src_len, embedding_size
        # print(f'{emb.shape=}')
        pack = torch.nn.utils.rnn.pack_padded_sequence(emb, src_lengths.cpu().numpy(), batch_first=True, enforce_sorted=False)

        _, (h, c) = self.encoder_rnn(pack)
        # print(f'{h.shape=}') # (layers, bsz, hidden_size)
        # print(f'{c.shape=}') # (layers, bsz, hidden_size)
        bs = src.shape[0]

```

```

h = h.view(2,self.layers, bs, int(self.hidden_size/2)) #creates a torch of size (layers, bs, hidden_size/2)
h = torch.cat((h[0],h[1]), 2)
c = c.view(2,self.layers, bs, int(self.hidden_size/2)) #creates a torch of size (layers, bs, hidden_size/2)
c = torch.cat((c[0],c[1]), 2)
# h = torch.reshape(h, (self.layers, bs, self.hidden_size))
# c = torch.reshape(c, (self.layers, bs, self.hidden_size))

# print(f'{h.shape}') # (layers, bsz, hidden_size)
# print(f'{c.shape}') # (layers, bsz, hidden_size)
return h, c

def forward_decoder(self, encoder_final_state, tgt_in):
    """
    Decodes based on encoder final state and ground truth target words.
    Arguments:
        encoder_final_state: a tuple (h, c) where h/c is of size (layers, bsz, hidden_size)
        tgt_in: a tensor of size (bsz, tgt_len)
    Returns:
        Logits of size (bsz, tgt_len, V_tgt) (before the softmax operation)
    """
    # TODO - implement this function
    emb = self.word_embeddings_tgt(tgt_in) # batch_size, max_src_len, embedding_size
    # print(f'{emb.shape=}')

    outputs, _ = self.decoder_rnn(emb, encoder_final_state)
    # print(f'{logits.shape=}')
    # print(f'{h.shape=}')
    logits = self.hidden2output(outputs)
    # print(f'{logits.shape=}')
    # print(self.V_tgt)
    # print(tgt_in.shape[1])
    return logits

def forward(self, src, src_lengths, tgt_in):
    """
    Performs forward computation, returns logits.
    Arguments:
        src: src batch of size (bsz, max_src_len)
        src_lengths: src lengths of size (bsz)
        tgt_in: a tensor of size (bsz, tgt_len)
    """
    # Forward encoder
    encoder_final_state = self.forward_encoder(src, src_lengths) # tuple (h, c)
    # Forward decoder
    logits = self.forward_decoder(encoder_final_state, tgt_in) # bsz, tgt_len, V_tgt
    return logits

def forward_decoder_incrementally(self, decoder_state, tgt_in_token):
    """
    Forward the decoder at `decoder_state` for a single step with token `tgt_in_token`.
    This function will only be used in the beam search section.
    Arguments:
        decoder_state: a tuple (h, c) where h/c is of size (layers, 1, hidden_size)
        tgt_in_token: a tensor of size (1), a single token
    Returns:
        `logits`: Log probabilities for `tgt_in_token` of size (V_tgt)
        `decoder_state`: updated decoder state, ready for next incremental update
    """
    bsz = decoder_state[0].size(1)
    assert bsz == 1, "forward_decoder_incrementally only supports batch size 1!"
    # Compute word embeddings
    tgt_embeddings = self.word_embeddings_tgt(
        tgt_in_token.view(1, 1)
    ) # bsz, tgt_len, hidden
    # Forward decoder RNN and return all hidden states
    decoder_outs, decoder_state = self.decoder_rnn(tgt_embeddings, decoder_state)
    # Project to get logits
    logits = self.hidden2output(decoder_outs) # bsz, tgt_len, V_tgt
    # Get log probabilities
    logits = torch.log_softmax(logits, -1)
    return logits.view(-1), decoder_state

def evaluate_ppl(self, iterator):
    """Returns the model's perplexity on a given dataset `iterator`."""
    # Switch to eval mode
    self.eval()
    total_loss = 0
    total_words = 0
    for batch in iterator:
        # Input and target
        src = batch['src_ids'] # bsz, max_src_len
        src_lengths = batch['src_lengths'] # bsz

```



```

tgt_in = batch['tgt_ids'][:, :-1].contiguous() # Remove <eos> for decode input (y_0=<bos>, y_1, y_2)
tgt_out = batch['tgt_ids'][:, 1:].contiguous() # Remove <bos> as target (y_1, y_2, y_3=<eos>)
# Forward to get logits
logits = self.forward(src, src_lengths, tgt_in) # bsz, tgt_len, V_tgt
# Compute cross entropy loss
loss = self.loss_function(logits.view(-1, self.V_tgt), tgt_out.view(-1))
total_loss += loss.item()
total_words += tgt_out.ne(self.padding_id_tgt).float().sum().item()
return math.exp(total_loss / total_words)

```

```

def train_all(self, train_iter, val_iter, epochs=10, learning_rate=0.001):
    """Train the model."""
    # Switch the module to training mode
    self.train()
    # Use Adam to optimize the parameters
    optim = torch.optim.Adam(self.parameters(), lr=learning_rate)
    best_validation_ppl = float("inf")
    best_model = None
    # Run the optimization for multiple epochs
    for epoch in range(epochs):
        total_words = 0
        total_loss = 0.0
        for batch in tqdm(train_iter):
            # Zero the parameter gradients
            self.zero_grad()
            # Input and target
            tgt = batch['tgt_ids'] # bsz, max_tgt_len
            src = batch['src_ids'] # bsz, max_src_len
            src_lengths = batch['src_lengths'] # bsz
            tgt_in = tgt[:, :-1] # Remove <eos> for decode input (y_0=<bos>, y_1, y_2)
            tgt_out = tgt[:, 1:] # Remove <bos> as target (y_1, y_2, y_3=<eos>)
            batch_size = src.size(0)
            # Run forward pass and compute loss along the way.
            logits = self.forward(src, src_lengths, tgt_in) # bsz, tgt_len, V_tgt
            loss = self.loss_function(logits.reshape(-1, self.V_tgt), tgt_out.reshape(-1))
            # Training stats
            num_tgt_words = tgt_out.ne(self.padding_id_tgt).float().sum().item()
            total_words += num_tgt_words
            total_loss += loss.item()
            # Perform backpropagation
            loss.div(batch_size).backward()
            optim.step()

        # Evaluate and track improvements on the validation dataset
        validation_ppl = self.evaluate_ppl(val_iter)
        self.train()
        if validation_ppl < best_validation_ppl:
            best_validation_ppl = validation_ppl
            self.best_model = copy.deepcopy(self.state_dict())
        epoch_loss = total_loss / total_words
        print(f"Epoch: {epoch} Training Perplexity: {math.exp(epoch_loss):.4f} "
              f"Validation Perplexity: {validation_ppl:.4f}")

```

```

EPOCHS = 2 # epochs, we highly recommend starting with a smaller number like 1
LEARNING_RATE = 2e-3 # learning rate

```

```
# Instantiate and train classifier
```

```

model = EncoderDecoder(
    hf_src_tokenizer,
    hf_tgt_tokenizer,
    embedding_size=64,
    hidden_size=64,
    layers=3,
).to(device)

```

```

model.train_all(train_iter, val_iter, epochs=EPOCHS, learning_rate=LEARNING_RATE)
model.load_state_dict(model.best_model)

```

```

100%|██████████| 2032/2032 [00:40<00:00, 50.54it/s]
Epoch: 0 Training Perplexity: 1.5980 Validation Perplexity: 1.0821
100%|██████████| 2032/2032 [00:37<00:00, 53.52it/s]
Epoch: 1 Training Perplexity: 1.0410 Validation Perplexity: 1.0225
<All keys matched successfully>

```

Since the task we consider here is very simple, we should expect a perplexity very close to 1.

```

# Evaluate model performance
print (f'Test perplexity: {model.evaluate_ppl(test_iter):.3f}')

```

```
Test perplexity: 1.020
```

```
grader.check("encoder_decoder_pp1")
```

All tests passed!

▼ Decoding

Now that we have a well-trained model, we need to consider how to use it to do the actual conversion. At decoding time, given a source sequence x_1, \dots, x_S , we want to find the target sequence $y_1^*, \dots, y_T^*, y_{T+1}^*$ (recall that $y_{T+1} = \langle \text{eos} \rangle$) such that the conditional likelihood is maximized:

$$\begin{aligned} y_1^*, \dots, y_T^*, y_{T+1}^* &= \operatorname{argmax}_{y_1, \dots, y_T, y_{T+1}} \Pr_{\theta}(y_1, \dots, y_T \mid x_1, \dots, x_S) \\ &= \operatorname{argmax}_{y_1, \dots, y_T, y_{T+1}} \prod_{t=1}^{T+1} \Pr_{\theta}(y_t \mid y_{<t}, x_1, \dots, x_S) \end{aligned}$$

In previous labs and project segments, we used *greedy decoding*, i.e., taking $\hat{y}_1 = \operatorname{argmax}_{y_1} \Pr_{\theta}(y_1 \mid y_0, x_1, \dots, x_S)$,

$\hat{y}_2 = \operatorname{argmax}_{y_2} \Pr_{\theta}(y_2 \mid y_0, \hat{y}_1, x_1, \dots, x_S), \dots, \hat{y}_{T+1} = \operatorname{argmax}_{y_{T+1}} \Pr_{\theta}(y_{T+1} \mid y_0, \hat{y}_1, \dots, \hat{y}_T, x_1, \dots, x_S)$, until $\hat{y}_{T+1} = \langle \text{eos} \rangle$.

Question: Does greedy decoding guarantee finding the optimal sequence (the sequence with the highest conditional likelihood)? Why or why not?

No, greedy decoding does not guarantee finding the optimal sequence. The reason for this is that greedy decoding makes locally optimal choices at each step in the sequence generation process. At each time step, it selects the option with the highest probability and then moves on to the next step, completely disregarding the rest of the options.

the problem with locally optimal choice is that it does not necessarily lead to a globally optimal solution.

Meaning the choice with the highest probability at a certain step might lead us down a path that results in a lower probability overall for the entire sequence compared to some other paths.

▼ Beam search decoding

Beam search decoding is the most commonly used decoding method in sequence-to-sequence approaches. Like greedy decoding, it uses a left-to-right search process. But instead of only keeping the single argmax at each position, beam search maintains the K best partial hypotheses $H_t = \{(y_1^{(k)}, \dots, y_t^{(k)}) : k \in \{1, \dots, K\}\}$ at every step t . To proceed to $t+1$, we compute the scores of sequences $y_1^{(k)}, \dots, y_t^{(k)}, y_{t+1}$ for every possible extension $y_{t+1} \in \mathcal{V}$ and every possible prefix $(y_1^{(k)}, \dots, y_t^{(k)}) \in H_t$, where \mathcal{V} is the vocabulary. Among these $K \times |\mathcal{V}|$ sequences, we only keep the top K sequences with the best partial scores, and that becomes $H_{t+1} = \{(y_1^{(k)}, \dots, y_{t+1}^{(k)}) : k \in \{1, \dots, K\}\}$. To start at $t=1$, $H_1 = \{(y) : y \in \operatorname{K-argmax}_{y_1 \in \mathcal{V}} \log P(y_1 | y_0 = \text{bos})\}$. Here K is called the beam size.

To summarize,

$$\begin{aligned} H_1 &= \{(y) : y \in \operatorname{K-argmax}_{y_1 \in \mathcal{V}} \log P(y_1 | y_0 = \text{bos})\} \\ H_{t+1} &= \operatorname{K-argmax}_{\{(y_1, y_2, \dots, y_{t+1}) \in \mathcal{V}^{t+1} : (y_1, \dots, y_t) \in H_t\}} \log P(y_1, \dots, y_{t+1} | x) \end{aligned}$$

until we reach a pre-specified maximum search length, and we collect the completed hypotheses along the way. (By completed we mean ending with $\langle \text{eos} \rangle$.) The finished hypothesis with the best score will then be returned.

Question: Is beam search better than greedy search when $K=1$? Is it better when $K>1$? Why? How big a K value do we need to get a guarantee that we can find the globally best sequence (assuming a maximum sequence length T and vocabulary size $|\mathcal{V}|$).

When $K=1$, beam search becomes equivalent to the greedy search, as it only keeps the single most probable sequence at each step. Thus, there's no benefit to using beam search over greedy search when $K=1$.

When the beam size is greater than 1, beam search is generally superior to a greedy search. The reason is that it allows the model to maintain multiple hypotheses (K of them) at each time step, rather than committing to a single path. This improves the likelihood of finding a higher-quality output sequence overall.

The drawback, however, is that it also increases computation and memory usage, as it needs to evaluate and store more options at each step. While beam search can result in better sequences than greedy search, it still doesn't guarantee finding the optimal sequence. This is because it only keeps the top K sequences at each step, and there might be a lower-scoring sequence at an early step that could lead to the highest-scoring sequence overall if fully followed.

therefore to guarantee that we can find the globally best sequence $K = |\mathcal{V}|$.

Under the probabilistic formulation of sequence-to-sequence models, the partial scores are decomposable over time steps:

$\log \Pr_{\theta}(y_1, \dots, y_T | x) = \sum_{t=1}^T \log \Pr_{\theta}(y_t | y_{<t}, x)$. Therefore, we can save computation in the above process by maintaining the partial sums $\sum_{t'=1}^t \log \Pr_{\theta}(y_{t'}^{(k)} | y_{<t'}^{(k)}, x)$, such that we only need to compute $\log \Pr_{\theta}(y_{t+1}^{(k)} | y_{<t+1}^{(k)})$ when we want to go from t to $t+1$.

Here is pseudo-code for the beam search algorithm to decode a single example x of maximum length max_T using a beam size of K .

```

1. def beam_search(x, K, max_T):
2.     finished = [] # for storing completed hypotheses
   # Initialize the beam
3.     beams = [Beam(hyp=(bos), score=0)] # initial hypothesis: bos, initial score: 0

4.     for t in [1..max_T] # main body of search over time steps
5.         hypotheses = []

           # Expand each beam by all possible tokens y_{t+1}
6.         for beam in beams:
7.             y_{1:t}, score = beam.hyp, beam.score
8.             for y_{t+1} in V:
9.                 y_{1:t+1} = y_{1:t} + [y_{t+1}]
10.                new_score = score + log P(y_{t+1} | y_{1:t}, x)
11.                hypotheses.append(Beam(hyp=y_{1:t+1}, score=new_score))

           # Find K best next beams
12.        beams = sorted(hypotheses, key=lambda beam: -beam.score)[:K]

           # Set aside finished beams (those that end in <eos>)
13.        for beam in beams:
14.            y_{t+1} = beam.hyp[-1]
15.            if y_{t+1} == eos:
16.                finished.append(beam)
17.                beams.remove(beam)

           # Break the loop if everything is finished
18.        if len(beams) == 0:
19.            break
20.        return sorted(finished, key=lambda beam: -beam.score)[0] # return the best finished hypothesis

```

Implement function `beam_search` in the below code. Note that there are some differences from the pseudo-code: first, we maintained a `decoder_state` in addition to $y_{1:t}$ and score such that we can compute $P(y_{t+1} | y_{<t+1}, x)$ efficiently; second, instead of creating a list of actual hypotheses as in lines 8-11, we use tensors to get pointers to the beam id and y_{t+1} that are among the best K next beams.

```

MAX_T = 15 # max target length

class Beam():
    """Helper class for storing a hypothesis, its score and its decoder hidden state."""
    def __init__(self, decoder_state, tokens, score):
        self.decoder_state = decoder_state
        self.tokens = tokens
        self.score = score

class BeamSearcher():
    """Main class for beam search."""
    def __init__(self, model):
        self.model = model
        self.bos_id = model.bos_id
        self.eos_id = model.eos_id
        self.V = model.V_tgt

    def beam_search(self, src, src_lengths, K, max_T=MAX_T):
        """Performs beam search decoding.

        Arguments:
            src: src batch of size (1, max_src_len)
            src_lengths: src lengths of size (1)
            K: beam size
            max_T: max possible target length considered

        Returns:
            a list of token ids
        """
        finished = []

```

```

# Initialize the beam
self.model.eval()
#TODO - fill in encoder_final_state and init_beam below
encoder_final_state = self.model.forward_encoder(src, src_lengths)
init_beam = Beam(encoder_final_state, torch.tensor([[self.bos_id]], device=device), 0)
beams = [init_beam]

for t in range(max_T): # main body of search over time steps

    # Expand each beam by all possible tokens y_{t+1}
    all_total_scores = []
    for beam in beams:
        y_1_to_t, score, decoder_state = beam.tokens, beam.score, beam.decoder_state
        y_t = y_1_to_t[-1]
        #TODO - finish the code below
        # Hint: you might want to use `model.forward_decoder_incrementally`
        total_scores, decoder_state = self.model.forward_decoder_incrementally(decoder_state, y_t)
        all_total_scores.append(total_scores)
        beam.decoder_state = decoder_state # update decoder state in the beam
    all_total_scores = torch.stack(all_total_scores) # (K, V) when t>0, (1, V) when t=0

    # Find K best next beams
    # The below code has the same functionality as line 6-12, but is more efficient
    all_scores_flattened = all_total_scores.view(-1) # K*V when t>0, 1*V when t=0
    topk_scores, topk_ids = all_scores_flattened.topk(K, 0)
    beam_ids = topk_ids.div(self.V, rounding_mode='floor')
    next_tokens = topk_ids - beam_ids * self.V
    new_beams = []
    for k in range(K):
        beam_id = beam_ids[k] # which beam it comes from
        y_t_plus_1 = next_tokens[k] # which y_{t+1}
        score = topk_scores[k]
        beam = beams[beam_id]
        decoder_state = beam.decoder_state
        y_1_to_t = beam.tokens
        #TODO
        y_1_to_t_plus_1 = torch.cat((y_1_to_t, y_t_plus_1.view(1,1)))
        new_beam = Beam(decoder_state, y_1_to_t_plus_1, beam.score+score)
        new_beams.append(new_beam)
    beams = new_beams

    # Set aside completed beams
    # TODO - move completed beams to `finished` (and remove them from `beams`)
    new_beams = []
    for beam in beams:
        y_1_to_t, score, decoder_state = beam.tokens, beam.score, beam.decoder_state
        y_t = y_1_to_t[-1]
        if y_t.view(1) == self.model.eos_id:
            finished.append(beam)
        else:
            new_beams.append(beam)
    beams = new_beams

    # Break the loop if everything is completed
    if len(beams) == 0:
        break

# Return the best hypothesis
if len(finished) > 0:
    finished = sorted(finished, key=lambda beam: -beam.score)
    return [token.item() for token in finished[0].tokens]
else: # when nothing is finished, return an unfinished hypothesis
    return [token.item() for token in beams[0].tokens]

```

```
grader.check("beam_search")
```

All tests passed!

Now we can use beam search decoding to predict the outputs for the test set inputs using the trained model.

```

DEBUG_FIRST = 10 # set to 0 to disable printing predictions
K = 5 # beam size 5

correct = 0
total = 0

# create beam searcher
beam_searcher = BeamSearcher(model)

for index, batch in enumerate(test_iter, start=1):

```

```
# Input and output
src = batch['src_ids']
src_lengths = batch['src_lengths']
# Predict
prediction = beam_searcher.beam_search(src, src_lengths, K)
# Convert to string
prediction = hf_tgt_tokenizer.decode(prediction, skip_special_tokens=True)
ground_truth = hf_tgt_tokenizer.decode(batch['tgt_ids'][0], skip_special_tokens=True)
# Print out the first few examples
if DEBUG_FIRST >= index :
    src = hf_src_tokenizer.decode(src[0], skip_special_tokens=True)
    print (f'Source:      {index}. {src}\n'
          f'Prediction:    {prediction}\n'
          f'Ground truth: {ground_truth}\n')
if ground_truth == prediction:
    correct += 1
total += 1

print (f'Accuracy: {correct/total:.2f}')
```

```
Source:      1. sixteen thousand eight hundred and thirty two
Prediction:   1 6 8 3 2
Ground truth: 1 6 8 3 2

Source:      2. sixty seven million six hundred and eighty five thousand two hundred and thirty
Prediction:   6 7 6 8 5 2 3 0
Ground truth: 6 7 6 8 5 2 3 0

Source:      3. six thousand two hundred and twelve
Prediction:   6 2 1 2
Ground truth: 6 2 1 2

Source:      4. seven hundred and ninety eight million three hundred and thirty one thousand eight hundred and eighteen
Prediction:   7 9 8 3 3 1 8 1 8
Ground truth: 7 9 8 3 3 1 8 1 8

Source:      5. eighty eight million four hundred and thirteen thousand nine hundred and eighteen
Prediction:   8 8 4 1 3 8 1 9
Ground truth: 8 8 4 1 3 9 1 8

Source:      6. three hundred and seventy four thousand two hundred and seventy
Prediction:   3 7 4 2 7 0
Ground truth: 3 7 4 2 7 0

Source:      7. ninety eight million three hundred and seventy thousand five hundred and forty five
Prediction:   9 8 3 7 0 5 4 5
Ground truth: 9 8 3 7 0 5 4 5

Source:      8. ninety seven thousand seven hundred and sixty two
Prediction:   9 7 7 6 2
Ground truth: 9 7 7 6 2

Source:      9. four hundred and ten thousand two hundred and three
Prediction:   4 1 0 0 2 3
Ground truth: 4 1 0 2 0 3

Source:     10. five hundred and ninety eight thousand three hundred and ninety seven
Prediction:   5 9 8 3 9 7
Ground truth: 5 9 8 3 9 7

Accuracy: 0.95
```

You might have noticed that using a larger K might lead to very similar performance as using $K = 1$ (greedy decoding). This is largely due to the fact that there are no dependencies among target tokens in our dataset (e.g., knowing that y_1 is 1 does not affect our prediction on y_2 conditioned on the source). In real world applications, people usually find using a fixed value of $K > 1$ (such as $K = 5$) performs better than greedy decoding.

Question: Can we use beam search decoding to decode an HMM? For state space Q , sequence length T , what is the complexity of beam search with beam size K ? What is the complexity of Viterbi decoding? What are their pros and cons?

Yes, we can use beam search decoding for a Hidden Markov Model (HMM). The beam search and Viterbi algorithm, both, work by determining the sequence of states that maximizes the joint probability of the observations and states. They have different time complexities, though, and this influences their applicability.

cons of Beam search: as mentioned in the previous question beam search the main flaw in beam search that it doesn't guarantee finding the optimal sequence.

pros of Beam search: However the advantage of beam search is that it is more computationally efficient when $K < N$. This makes it particularly useful when we have a large state space but we're only interested in a few of the most likely paths.

cons of Viterbi: Viterbi can be more computationally expensive than beam search, especially when the state space is large.

pros of Viterbi: Viterbi algorithm is guaranteed to find the most likely sequence of states, it provides the globally optimal solution.

The complexity of the Viterbi algorithm is $O(TN^2)$, and the The complexity of beam search is $O(KTN)$, where: K is the beam size, T is the length of the sequence, and N is the number of states in the state space.

▼ Lab debrief

Question: We're interested in any thoughts your group has about this lab so that we can improve this lab for later years, and to inform later labs for this year. Please list any issues that arose or comments you have to improve the lab. Useful things to comment on might include the following:

- Was the lab too long or too short?
- Were the readings appropriate for the lab?
- Was it clear (at least after you completed the lab) what the points of the exercises were?
- Are there additions or changes you think would make the lab better?

but you should comment on whatever aspects you found especially positive or negative.

Type your answer here, replacing this text.

▼ End of Lab 4-4

To double-check your work, the cell below will rerun all of the autograder tests.

```
grader.check_all()
```

beam_search:

All tests passed!

✓ 21s completed at 9:39 PM

