CS378: Natural Language Processing
Lecture 17: Transformers for Language Modeling, Implementation

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Transformers
Dimensions

- Vectors: $d_{model}$
- Queries/keys: $d_k$, always smaller than $d_{model}$
- Values: separate dimension $d_v$, output is multiplied by $W^0$ which is $d_v \times d_{model}$ so we can get back to $d_{model}$ before the residual
- FFN can explode the dimension with $W_1$ and collapse it back with $W_2$

$$\text{FFN}(x) = \max(0, xW_1 + b_1)W_2 + b_2$$

Vaswani et al. (2017)
Transformers: Position Sensitivity

The ballerina is very excited that she will dance in the show.

- If this is in a longer context, we want words to attend locally
- But transformers have no notion of position by default
Transformers: Position Sensitivity

- Encode each sequence position as an integer, add it to the word embedding vector
- Why does this work?
Transformers

Alammar, *The Illustrated Transformer*

- Alternative from Vaswani et al.: sines/cosines of different frequencies (closer words get higher dot products by default)
Transformers: Complete Model

- Original Transformer paper presents an encoder-decoder model
- Right now we don’t need to think about both of these parts — will return in the context of MT
- Decoder differs because each token only attends to those coming before it. Can do this with an attention mask

Vaswani et al. (2017)
Attention Maps

- Example visualization of attention matrix A (from assignment)
- Each row: distribution over what that token attends to. E.g., the first “v” attends very heavily to itself (bright yellow box)
- Your task on the HW: assess if the attentions make sense
Using Transformers
What do Transformers produce?

- **Encoding of each word** — can pass this to another layer to make a prediction (like predicting the next word for language modeling)

- Like RNNs, Transformers can be viewed as a transformation of a sequence of vectors into a sequence of context-dependent vectors
Transformer Uses

- **Transducer**: make some prediction for each element in a sequence

  ![Diagram of Transducer]
  
  Output $y = \text{score for each tag, then softmax}$

  - `DT`  `NN`  `VBD`  `JJ`
  - `the movie was great`

- **Classifier**: encode a sequence into a fixed-sized vector and classify that

  ![Diagram of Classifier]
  
  Predict sentiment (matmul + softmax)
  
  Translate
  
  Paraphrase/Compress

  - `the movie was great`
Transformer Uses

- predict sentiment (matmul + softmax)
- translate
- paraphrase/compress

Alternative: use a placeholder [CLS] token at the start of the sequence. Because [CLS] attends to everything with self-attention, it can do the pooling for you!

encoding of [CLS token] → matmul + softmax → predict sentiment
Transformer Uses

- Sentence *pair* classifier: feed in two sentences and classify something about their relationship

Contradiction

[CLS] The woman is driving a car [SEP] The woman is walking.

- Why might Transformers be particularly good at sentence *pair* tasks compared to something like a DAN?
Transformer Language Modeling

\[ P(w|\text{context}) = \frac{\exp(w \cdot h_i)}{\sum_{w'} \exp(w' \cdot h_i)} \]

equivalent to

\[ P(w|\text{context}) = \text{softmax}(Wh_i) \]

- \( W \) is a (vocab size) x (hidden size) matrix; linear layer in PyTorch (rows are word embeddings)
Training Transformer LMs

I saw the dog running

- Input is a sequence of words, output is those words shifted by one,
- Allows us to train on predictions across several timesteps simultaneously (similar to batching but this is NOT what we refer to as batching)
Training Transformer LMs

$P(w|\text{context})$

loss = $-\log P(w^*|\text{context})$

Total loss = sum of negative log likelihoods at each position

```
loss_fcn = nn.NLLLoss()
loss += loss_fcn(log_probs, ex.output_tensor)
```

- Batching is a little tricky with NLLLoss: need to collapse [batch, seq len, num classes] to [batch * seq len, num classes]. You do not need to batch
I saw the dog running in the park and it looked very excited to be there.

- Batch dim
- Multiple sequences and multiple timesteps per sequence
A Small Problem with Transformer LMs

- This Transformer LM as we’ve described it will *easily* achieve perfect accuracy. Why?

- With standard self-attention: “I” attends to “saw” and the model is “cheating”. How do we ensure that this doesn’t happen?
Attention Masking

- We want to prohibit

\[
<s> \quad \text{I saw the dog}
\]

Key words

- We want to mask out everything in red (an upper triangular matrix)

Query words

- I
- saw
- the
- dog
Implementing in PyTorch

- nn.TransformerEncoder can be built out of nn.TransformerEncoderLayers, can accept an input and a mask for language modeling:

```python
# Inside the module; need to fill in size parameters
layers = nn.TransformerEncoderLayer([...])
transformer_encoder = nn.TransformerEncoder(encoder_layers, num_layers=[...])

# Inside forward(): puts negative infinities in the red part
mask = torch.triu(torch.ones(len, len) * float('-inf'), diagonal=1)
output = transformer_encoder(input, mask=mask)
```

- You cannot use these for Part 1, only for Part 2
LM Evaluation

- Accuracy doesn’t make sense — predicting the next word is generally impossible so accuracy values would be very low

- Evaluate LMs on the likelihood of held-out data (averaged to normalize for length)

\[
\frac{1}{n} \sum_{i=1}^{n} \log P(w_i|w_1, \ldots, w_{i-1})
\]

- Perplexity: \(\exp(\text{average negative log likelihood})\). Lower is better
  
  - Suppose we have probs 1/4, 1/3, 1/4, 1/3 for 4 predictions
  
  - Avg NLL (base e) = 1.242 \quad \text{Perplexity} = 3.464 \leq \text{geometric mean of denominators}
Transformers are usually large and you don’t want to train them for each new task.

Train on language modeling... then “fine-tune” that model on your target task with a new classification layer.
Transformer Extensions
Scaling Laws

Figure 1  Language modeling performance improves smoothly as we increase the model size, dataset size, and amount of compute used for training. For optimal performance all three factors must be scaled up in tandem. Empirical performance has a power-law relationship with each individual factor when not bottlenecked by the other two.

‣ Transformers scale really well!

Kaplan et al. (2020)
Even though most parameters and FLOPs are in feedforward layers, Transformers are still limited by quadratic complexity of self-attention.

Many ways proposed to handle this
Performers

Figure 1: Approximation of the regular attention mechanism $AV$ (before $D^{-1}$-renormalization) via (random) feature maps. Dashed-blocks indicate order of computation with corresponding time complexities attached.

- No more $len^2$ term, but we are fundamentally approximating the self-attention mechanism (cannot form $A$ and take the softmax)

Choromanski et al. (2020)
Longformer

(a) Full $n^2$ attention  (b) Sliding window attention  (c) Dilated sliding window  (d) Global+sliding window

Figure 2: Comparing the full self-attention pattern and the configuration of attention patterns in our Longformer.

- Use several pre-specified self-attention patterns that limit the number of operations while still allowing for attention over a reasonable set of things
- Scales to 4096-length sequences

Beltagy et al. (2021)
Vision and RL

- DALL-E 1: learns a discrete “codebook” and treats an image as a sequence of visual tokens which can be modeled autoregressively, then decoded back to an image

- Decision Transformer: does reinforcement learning by Transformer-based modeling over a series of actions

- Transformers are now being used all over AI

Ramesh et al. (2021), Chen et al. (2021)
Takeaways

‣ Transformers are going to be the foundation for the much of the rest of this class and are a ubiquitous architecture nowadays

‣ Many details to get right, many ways to tweak and extend them, but core idea is the multi-head self attention and their ability to contextualize items in sequences

‣ Next: machine translation and seq2seq models (conditional language modeling)