Transformer and Unsupervised NMT
Erweiterungsmodul: Machine Translation

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Slides originally from Dario Stojanovski, errors are mine
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Outline

1. Transformer
   - Self-attention
   - Transformer building blocks

2. Document-Level Neural Machine Translation
   - Discourse-level phenomena
   - Models

3. Unsupervised Neural Machine Translation
   - Initialization
   - Denoising auto-encoding
   - Iterative backtranslation
   - Combining the techniques
1. Transformer
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A Brief History

- Machine translation: the task of receiving a sentence in the source language and outputting a translation in the target language

- RNN encoder-decoder proved that this is possible with neural networks (Sutskever, Vinyals, and Le 2014)

- Attention-based encoder-decoder provided state-of-the-art performance (Bahdanau, Cho, and Bengio 2015)

- Convolutional encoder-decoder (Gehring et al. 2017)

- Transformer - Attention is all you need (Vaswani et al. 2017)
Why Not RNN Encoder-Decoder

- Up to Transformer, most models implemented with attention-based RNN encoder-decoder
- RNNs process words sequentially
- They do not lend themselves to parallelization
- Difficult to model long-term dependencies
Bidirectional RNN enable more meaningful modeling of words near the end

Attention enables direct access to all hidden states

Still not a fundamental solution to the problem, the interplay between hidden states of arbitrary words is limited
Parallelization

- Very important in the big data era
- Robust MT requires millions of parallel sentences
- Convolutional encoder-decoder helps with parallelization, but requires many layers to be able to model long-term dependencies
Transformer

- First purely self-attention-based encoder-decoder model - all hidden states interact with each other
- Can easily be parallelized
- State-of-the-art model architecture for MT and most NLP tasks
- Used for training large Language Models (BERT, GPT-2) which provide large improvements in many NLP tasks by making use of transfer learning
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Attention in RNN Encoder-Decoder

- Hidden states computed with an RNN
- Attention computed at each decoder step
- Attention over encoder hidden states
- Computed “context” vector integrated into decoder hidden state

Figure from Bahdanau, Cho, and Bengio 2015
Attention in RNN Encoder-Decoder

- Motivation: do not summarize the whole sentence in a single vector.

- Variable length representation - keep RNN hidden states for each word.

- Pay more attention to more relevant hidden states (words).

- Attention determines what source words are important for predicting the next target word.

Figure from Bahdanau, Cho, and Bengio 2015
Self-Attention


- Self-attention is also called intra-attention - it relates different positions of the same input sequence

- All hidden states are computed using only attention!
  - No recurrence - all recurrent connections replaced with attention
  - Self-attention replaces the RNN

- A given hidden state is a weighted linear combination of all hidden states
  - A given word interacts with all other words, including itself
The cat chased the mouse

Self-Attention

The cat chased the mouse

w_{11} w_{21} w_{31} w_{41} w_{51}
Self-Attention

The cat chased the mouse

The cat chased the mouse

w_{12} w_{22} w_{32} w_{42} w_{52}
The cat chased the mouse.

Diagram:

- `w_{13}`
- `w_{23}`
- `w_{33}`
- `w_{43}`
- `w_{53}`
The cat chased the mouse.
Self-Attention

The cat chased the mouse

w_15, w_25, w_35, w_45, w_55
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Queries $Q$, Keys $K$, Values $V$

The interaction between $Q$ and $K$ determines how to score $V$ (how important certain values are).

In Bahdanau, Cho, and Bengio 2015, $Q$ is the current decoder state, $K$ and $V$ are all encoder states.
Computing Attention

Bahdanau, Cho, and Bengio 2015 used multi-layer perceptron for the attention in their LSTM (RNN) translation model:

\[ c_j = \sum_{i}^{T_x} \alpha_{ij} h_i \]

\[ \alpha_{ij} = \frac{\exp(e_{ij})}{\sum_{k=1}^{T_x} \exp(e_{kj})} \]

\[ e_{ij} = v_a^T \tanh(U_a s_j' + W_a h_i) \]

But this requires additional parameters \( U_a, W_a \) and \( v_a \)

\( s_j \) - decoder hidden state, \( h_i \) - encoder hidden state
Dot-product attention does not require parameters

$$a(q, k) = qk^T$$

Dimensionality of $q$ and $k$ has to be the same.

The scale of the dot product depends on the dimensionality of the vectors. Scale grows as dimensionality grows. Can be fixed by scaling proportionally to the dimensionality:

$$a(q, k) = \frac{qk^T}{\sqrt{|k|}}$$
Scaled Dot-Product Attention in Transformer

\[
\text{Attention}(Q, K, V) = \text{softmax}\left(\frac{QK^T}{\sqrt{d_K}}\right)V
\]

Vaswani et al. 2017
for self-attention, the input is Q, K and V at the same time

At Transformer encoder layer 1 (E is token embedding)

In practice, the Transformer learns 3 separate projection layers at each encoder or decoder layer for Q, K and V.

\[ Q = EW_1^Q, \quad K = EW_1^K, \quad V = EW_1^V \]
Multi-Head Attention

- Computing one attention may be too brittle

- Separation of concerns - learn multiple separate attentions.

- Intuition is that different attention heads learn different things and are allowed to focus on different things in the input

- Conceptually, one head may learn to incorporate local information for each token representation and another may learn to look for potential long-term dependencies

- Many works try to interpret attention, but it is not clear if strong conclusions can be made by looking at attention scores
Transformer learns \( h \) attention heads (initially 8, but lots of other values have been tried)

Linear projection layers \( W \) project the input to dimensionality \( d/h \). Separate linear layers for each head.

Output of all attention heads is later concatenated and an additional linear layer is applied.

Computational overhead of multiple attention heads compensated by applying attention over smaller parameter spaces.

Vaswani et al. 2017
One attention head is focusing most on "the animal", while another is focusing on "tired".

http://jalammar.github.io/illustrated-transformer/
One attention head is focusing most on "the animal", while another is focusing on "tired"

http://jalammar.github.io/illustrated-transformer/
Multi-Head Attention - Visualizations

It is harder to interpret the other 6 attention heads. (Visualizations from great tutorial, highly recommended (see video too)!)  
http://jalammar.github.io/illustrated-transformer/
Positional Information

- Positional information is built-in in RNN encoder-decoder by way of processing the input sequentially.

- Self-attention is ignorant of any positional information and therefore it has to be explicitly provided.

- Learns separate embeddings for positional information - maximum length has to be specified.

- Transformer introduced sinusoidal positional embeddings - may allow for easier learning of relative position information and extrapolation to unseen sequence lengths.
Transformer

- Multiple encoder and decoder layers
- Token-level and positional embeddings
- Multi-head attention
  - Self-Attention
  - Encoder attention
- Feed-forward networks
- Residual connections (Add)
- Layer normalization (Norm)
- Final linear projection to size of vocabulary and softmax to determine most probable next output token

Vaswani et al. 2017
Transformer Encoder

- Apply multi-head self-attention to input as we talked about before.
- Residual connection, add the input to multi-head attention to its output.
- Apply layer normalization.
- Apply a feed-forward neural network.
- Residual connection + layer normalization.

Vaswani et al. 2017
Transformer Decoder

- Masked multi-head self-attention
- Attention over encoder hidden states
- Remaining components used as before

Vaswani et al. 2017
Residual Connections, Layer Norm, Position-wise
Feed-Forward NN

- Deep neural networks can be difficult to train - gradients may explode or vanish
- Residual connections and layer normalization address these issues
- Feed-forward neural network is applied to each position separately and identically

He et al. 2016
Masking

Self-Attention

Masked Self-Attention

http://jalammar.github.io/illustrated-gpt2/
## Comparison to RNN and Convolution

<table>
<thead>
<tr>
<th>Layer Type</th>
<th>Complexity per Layer</th>
<th>Sequential Operations</th>
<th>Maximum Path Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self-Attention</td>
<td>$O(n^2 \cdot d)$</td>
<td>$O(1)$</td>
<td>$O(1)$</td>
</tr>
<tr>
<td>Recurrent</td>
<td>$O(n \cdot d^2)$</td>
<td>$O(n)$</td>
<td>$O(n)$</td>
</tr>
<tr>
<td>Convolutional</td>
<td>$O(k \cdot n \cdot d^2)$</td>
<td>$O(1)$</td>
<td>$O(\log_k(n))$</td>
</tr>
<tr>
<td>Self-Attention (restricted)</td>
<td>$O(r \cdot n \cdot d)$</td>
<td>$O(1)$</td>
<td>$O(n/r)$</td>
</tr>
</tbody>
</table>

Vaswani et al. 2017, Table 1

- $n$ - sequence length, $d$ - representation dimension, $k$ - kernel size of convolutions
- Sequential operations - how much can be parallelized
- Maximum Path Length: path length between long-range dependencies
Conclusion

- Self-attention - a powerful mechanism
- Multi-head attention
- Parallelizable, instant access to all inputs, less complexity
- Transformers are ubiquitous in NMT and NLP
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Traditionally MT works on the sentence-level - single sentence input and output

Phrase-based and Neural MT are both largely ignorant of broader discourse-level phenomena
Why do we do sentence-level NMT?

- Resource limitations - memory requirements

- Document-level models may be challenging to train

- Document-aligned data is scarce

- A high portion of publicly available datasets either do not preserve the sequential order or lack document boundaries

- Why is this the case? - most of textual data is part of some document in one form or another

- Likely because of historical reasons - small number of works on document-level MT
Claims of human parity

- Some works have claimed that they have achieved human parity in MT (Hassan et al. 2018)

- These claims have been challenged by Läubli, Sennrich, and Volk 2018; Toral et al. 2018

- Among other remarks, both works note that the manual evaluation was done in a context-agnostic way
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Discourse-level phenomena

- Coreference (anaphora) resolution
  - Important for gender and number pronoun agreement
  - *It presents a problem.* $\rightarrow$ *Er [masculine] präsentiert ein Problem.*
  - Context: *Let me summarize the novel for you.*

- Coherence - consistency to concepts and world knowledge

- Cohesion - consistency to surface formulations

- Deixis - words and phrases that cannot be understood without context (time and place dependent), formality

- Style - “is anybody hurt” and “is someone wounded”

- Domain - important for domain-dependent ambiguous translations
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Document-level NMT

- Also referred to as context-aware NMT
- Using contextual (document) information
- Main questions:
  - How do we process/model the context?
  - How do we integrate contextual information in our models?
How do context-aware (document-level) models differ?

Source-Target
- Do they use source or target side contextual information?

Fine-grained vs. coarse-grained
- Do they aim to obtain a fine-grained or coarse-grained document representation?

Input-Output
- Do they only input large pieces of text or do they output them as well?

Previous-Subsequent context

Many methods are a mix of different types.
Concatenation models

- First work by Tiedemann and Scherrer 2017
- Concatenate consecutive sentences on the input side
  - And optionally on the output side as well

*Input*
Let me summarize the novel for you. [SEP] It presents a problem.

*Output*
Ich fasse den Roman für dich zusammen. [SEP] Er präsentiert ein Problem.

- No need to modify the baseline NMT architecture or to come up with a context integration scheme
- Works fine with a limited number of contextual sentences, but some effort is required to scale to a somewhat larger context. Straightforward application to very large sequences almost impossible.
Context-aware Transformer

Stojanovski and Fraser 2019
Context integration

- **Gating**

  - $dm_i$ - main sentence representation in decoder (after dec-to-enc attention)

  - $dc_i$ - context sentence representation in decoder

- Compute a gate $z_i$

- Control how much contextual information is needed for the prediction of the next word

  \[
  z_i = \sigma(U_z dm_i + W_z dc_i)
  \]

  \[
  d_i = z_i \ast dm_i + (1 - z_i) \ast dc_i
  \]
Hierarchical attention

Miculicich et al. 2018 - attention over tokens followed by attention over sentences
Are context-aware models going to be more widely used by the MT community?

The potential benefits from contextual information are clear

Flexible, simple and scalable models

Transformer LM capable of large input modeling - adaptation to NMT?
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Unsupervised Neural Machine Translation

- NMT models require parallel data to be efficiently trained
- Parallel data is scarce across many language pairs and domains
- Monolingual data on the other hand is prevalent
- There are works making use of monolingual data, but still need parallel data as well
- Unsupervised NMT uses monolingual data only
Critical Components of Unsupervised MT

- **Meaningful initialization:**
  - random initialization works for models trained on parallel data, but it is useless for UMT

- Unsupervised Bilingual Word Embeddings

- **Iterative improvement**
  - Denoising auto-encoding

  - Iterative backtranslation
Unsupervised NMT - Important Ingredients

- Proper initialization - unsupervised BWEs
- Learn to generate proper language
  - Denoising auto-encoding
- Enable continuous improvement
  - Iterative backtranslation
- One model for both translation directions
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Unsupervised Bilingual Word Embeddings

- Works well for closely related languages, less so for distant languages
- Use unsupervised BWEs to initialize the NMT embeddings
- Use the unsupervised BWEs to do bilingual lexicon induction
- Use induced lexicon to create word-by-word translation
  - Not appropriate for: reordering, compound words, phrases

Lample et al. 2018c
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Denoising Auto-Encoding

- How can we make the model generate proper target language sentences?
- Reconstruct the input - a trivial task because it only involves copying
- What if we add noise to the input and try to reconstruct the original?

Vincent et al. 2010,
https://predictivehacks.com/autoencoders-for-dimensionality-reduction/
Denoising Auto-Encoding - Noise

- Randomly drop words

\[ X = \text{I am tired because I went on a run} \]
\[ \text{Drop}(X) = \text{I am because I went on run} \]

\[
\text{Denoising auto-encoding} \\
\text{Drop}(X) \rightarrow X \\
\text{I am because I went on run} \rightarrow \text{I am tired because I went on a run}
\]

- a word is dropped with a certain probability \( p_{wd} \)

- the model learns important properties about the language

- word insertions: a run

- perhaps something about semantics as well: tired - run
Permute words within a certain neighborhood

\[ X = \text{I want to play tennis on Friday} \]
\[ \text{Shuffle}(X) = \text{I want to on Friday tennis play} \]

Denoising auto-encoding
\[ \text{Shuffle}(X) \rightarrow X \]
I want to on Friday tennis play → I want to play tennis on Friday

In German
Ich möchte am Freitag Tennis spielen

- the model can learn to do word reordering
- important when word order between the 2 languages is not the same, e.g. English and German
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Backtranslation

- Effective way to integrate monolingual data

Steps:

- Find target language monolingual data $M_t$
- Train a reverse NMT model - if we care about English to German translation, we will train an additional German to English model $NMT_{de-en}$
- Use the trained reverse model $NMT_{de-en}$ to translate the monolingual data $M_t$
- Create a pseudo parallel corpus: pair the corresponding monolingual sentences with the obtained translations
- Translations on the source side, monolingual data on the target
- Fine-tune the $NMT_{en-de}$ model with the new pseudo parallel corpus
Ich denke, also bin ich
Wesenheiten dürfen nicht über das Notwendige hinaus vermehrt werden
Die Grenzen meiner Sprache bedeuten die Grenzen meiner Welt

I think, therefore I am
Entities should not be multiplied unnecessarily
The limits of my language mean the limits of my world

I think, therefore I am
Ich denke, also bin ich
Wesenheiten dürfen nicht über das Notwendige hinaus vermehrt werden
Die Grenzen meiner Sprache bedeuten die Grenzen meiner Welt

Source /// Target
I think, therefore I am /// Ich denke, also bin ich
Entities should not... /// Wesenheiten dürfen nicht...
The limits of my language... /// Die Grenzen meiner Sprache...

Fine-tune
NMT
EN->DE
Iterative Backtranslation

- Backtranslation improves performances
  - Translations are noisy - encoder learns to deal with noise better
  - Almost arbitrary amount of pseudo parallel data

- But why should we do it only once?

- If the model improves, we can use the improved model to generate new backtranslations and repeat the process - iterative backtranslation

- On-the-fly iterative backtranslation
  - For UNMT, one model can do both translation directions
  - No need to backtranslate the whole corpus before fine-tuning
  - Backtranslate and fine-tune alternately
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The same model must be used for:
- $L_1 \rightarrow L_1$ and $L_2 \rightarrow L_2$ (denoising auto-encoding)
- $L_1 \rightarrow L_2$ and $L_2 \rightarrow L_1$ (translation)

Encoder representation should be language-agnostic

Lample et al. 2018b use adversarial training

Artetxe et al. 2018
Unsupervised NMT Lample et al. 2018a

- BPE-level model
  - Previously word-level models

- Single unified model
  - Single encoder, single decoder

- No adversarial training
Shared BPEs

- Take L1 and L2 monolingual corpora and split on BPE-level
  - Jointly learn on both languages to enable more frequent BPE sharing

- Train fasttext word embeddings

- Initialize NMT embeddings

- Embeddings are shown to be a useful initialization for UNMT

- Caveat: L1 and L2 need to share surface forms. Works well for English and German, not for English and Nepali.
Unified Model

- Single encoder and decoder (no discriminator or adversarial training)

- How do we deal with encoder language representation?

- Special language tag in decoder &lt;2en&gt;, &lt;2de&gt;

- Encoder has to learn a language-agnostic representation because the same representation can be used for denoising auto-encoding or translation

- Decoder is forced fed the language tag and knows what language to generate
Conclusion

- Most of the basic techniques explained here are still used

- Most works use pretrained LMs as initialization (next lecture)

- UNMT does not work:
  - for distant languages
  - when the source and target domain are not comparable
  - when there is insufficient monolingual corpora available for at least one of the languages
Summary

- **Transformer**
  - State-of-the-art NMT architecture

- **Document-level NMT**
  - Important for coherent translations across a document

- **Unsupervised NMT**
  - Important for enabling translation across a wide range of language pairs
Thank you for your attention


