

Neural Sequence Models

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Logistics

- ▶ Tutorial on HW4 (constituent parsing) by Udit Arora (TBA)
- ▶ Next three weeks: deep learning methods and applications
- ▶ Guest lecture on 12/1:
How far have we come in giving our NLU systems common sense?



technical team. [Apply here.](#)

I'm co-founder of [Verneek](#), a new deep-tech AI startup based in NYC with the mission of enabling anyone to make data-informed decisions. [We are now hiring for various roles. It's the best time to join us as we are putting together our core](#)



I work on building AI systems that can **comprehend human language**, in a deep manner, where they can show basic **commonsense reasoning** capabilities and **"explain"** themselves! I mainly model language in terms of 'events' and their temporal and **causal** relations, through which we can build causal networks that predict **what happens next!** The applications of my work range from **storytelling** to **vision & language**.

- ▶ Project presentation on 12/8: 3 minutes + 1 minute Q&A (10%)

Modular approaches to NLP

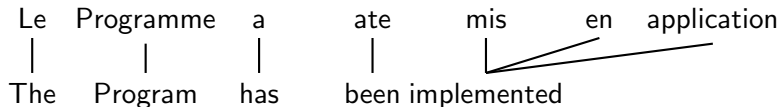
Example: **phrase-based machine translation**

When I look at an article in Russian, I say: This is really written in English, but it has been coded in some strange symbols. I will now proceed to decode. —Warren Weaver

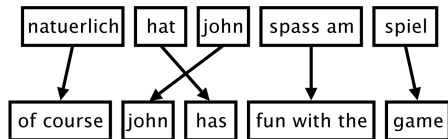
Noisy-channel model:

$$p(y | x) = \frac{p(y)p(x | y)}{\sum_y p(y)p(x | y)}$$

Word alignment: $p(x | y) = \sum_a p(x, a | y)$



Example: phrase-based MT pipeline



1. Preprocessing: tokenization, truecasing, cleaning
2. Train a (n-gram) language model on the target data
3. Train the translation model
 - 3.1 Estimate word alignment using EM
 - 3.2 Extract and score phrase pairs from aligned examples
 - 3.3 Learn the reordering model
4. Learn a linear model to score hypothesis: features include translation score, LM score, reordering score etc.

Where do we use domain-specific knowledge?

End-to-end approaches to NLP

Sequence-to-sequence models (aka encoder-decoder models):

- ▶ Directly model $p(y \mid x)$ with minimal assumption on the sequence structure
- ▶ Encoder: $\phi_{\text{enc}}: \mathcal{X} \rightarrow \mathbb{R}^d$
- ▶ Decoder: $\phi_{\text{dec}}: \mathbb{R}^d \rightarrow \mathcal{Y}$

Extremely flexible framework:

- ▶ Summarization: document to summary
- ▶ Open-domain dialogue: context to response
- ▶ Parsing: sentence to linearized trees
- ▶ In general: text to text

A simple implementation of seq2seq

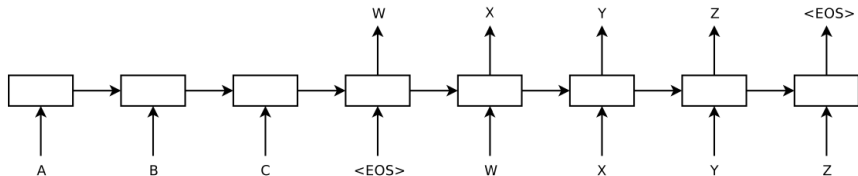


Figure: Sequence to Sequence Learning with Neural Networks [Sutskever+ 2014]

- ▶ Encoder/decoder: uni-directional multi-layer LSTM
- ▶ Large improvement when the input sequence is reversed
- ▶ Outperforms phrase-based MT systems: 34.8 vs 33.3 (on WMT'14 En-Fr)

Seq2seq for constituent parsing

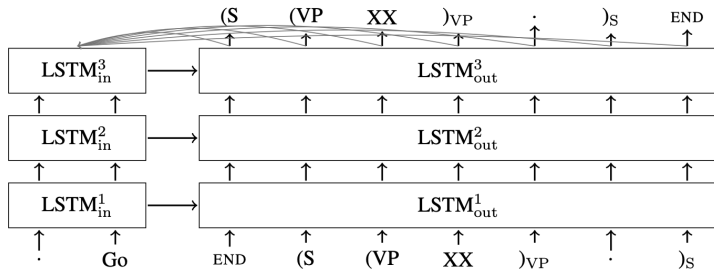


Figure: Grammar as a Foreign Language [Vinyals+ 2015]

- ▶ Text to linearized parse trees (no binarization)
- ▶ Seq2seq enhanced with attention mechanism (later)
- ▶ Matches result from BerkelyParser

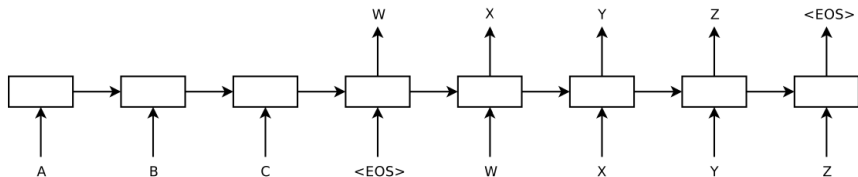
Table of Contents

Encoder-decoder models

Training and inference

Application and evaluation

Variants of RNN-based seq2seq architectures

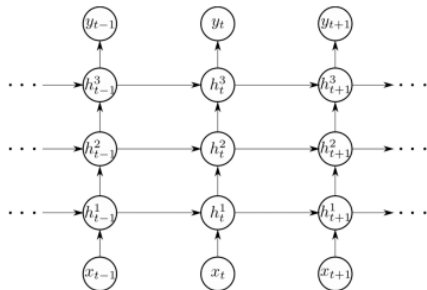


- ▶ Basic recurrent unit: vanilla RNN, LSTM, GRU
- ▶ Number of layers
- ▶ Uni-directional / bi-directional
- ▶ Decoder input/output embedding sharing
- ▶ Attention mechanism

Multiple layers

Multi-layer RNN (aka stacked RNN):

- ▶ Previous layer's outputs are inputs to the next layer
- ▶ Use the last layer's output as the input embedding



Pros: “deep” models work better in practice

Cons: longer runtime

Decoder embedding sharing

Input layer: embed previous word y_{i-1}

$$y_{i-1} \mapsto W_{\text{in}} \phi_{\text{one-hot}}(y_{i-1})$$

Output layer: distribution over the next word y_i

$$h_i \mapsto \text{softmax}(W_{\text{out}} h_i + b)$$

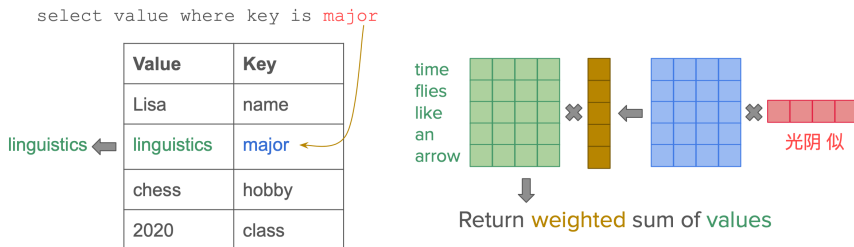
Decoder input/output embedding sharing (aka weight tying)

- ▶ $W_{\text{in}} = W_{\text{out}}$ (what is the implicit constraint?)
- ▶ Intuition: the inner product of h_i and the word embedding of y_i indicates how likely y_i is.
- ▶ Worth considering if you don't have lots of data or want to reduce model size

Attention mechanism

Motivation: different target words may depend on different parts of the source input

Select **content** (referenced by a **key**) relevant to a **query**

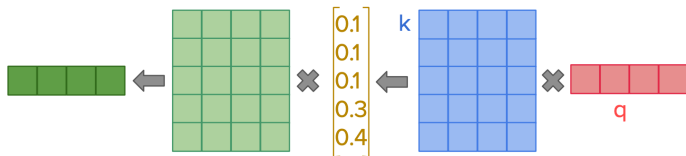


Attention is a pooling/aggregation mechanism:

- ▶ Encoder states: a memory of *key-value* pairs $(k_1, v_1), \dots, (k_n, v_n)$.
- ▶ Decoder states: a *query* to retrieve from the memory by matching the *keys*.
- ▶ Output from the memory: a weighted combination of the *values*.

Attention mechanism

- **Query** / **Values**: sentence or word embeddings
- **Keys**: projections of values



- ▶ How likely is q matched to k_i : score $a_i = \alpha(q, k_i)$
- ▶ Normalize scores to get attention weights: $b_i = \text{softmax}(a)[i]$
- ▶ Output weight combination of values in the memory: $o_i = \sum_{i=1}^n b_i v_i$
- ▶ In matrix form: $\text{attention}(Q, K, V)$ (rows are corresponding vectors)

Common attentions

Design the similarity function between queries and keys: $a_i = \alpha(q, k_i)$

Dot-product attention

$$\alpha(q, k) = q \cdot k$$

MLP attention

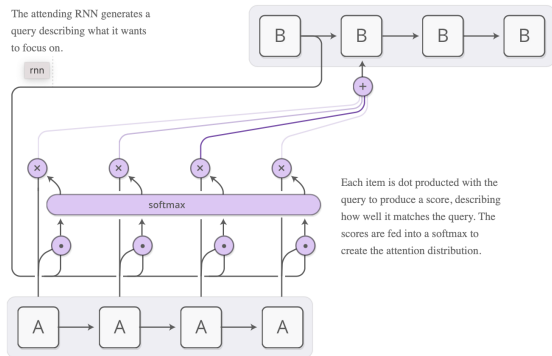
$$\alpha(q, k) = u^T \tanh(W[q; k])$$

Multi-head attention

$$\begin{aligned} \text{head}_i &= \text{attention}(Q W_i^Q, K W_i^K, V W_i^V) \\ \text{output} &= [\text{head}_1; \dots; \text{head}_h] W^O \end{aligned}$$

Compute attention with h linear projections of (Q, K, V) .

Attention in encoder-decoder models



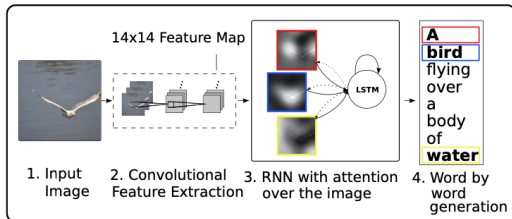
Without attention: $p(y_i \mid y_{<i}, x) \propto f(y_{i-1}, h_{i-1})$

With attention: $p(y_i \mid y_{<i}, x) \propto f(y_{i-1}, h_{i-1}, c_{i-1})$

Applications of attention

In general, adding attention often improves results in encoder-decoder models.

Visual attention:



Use caution with interpretation

Attention is not Explanation [Jain+ 2019]

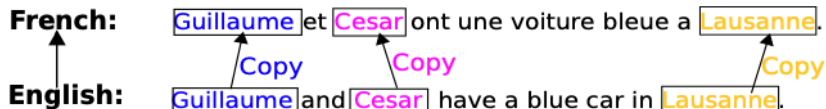
Attention is not not Explanation [Wiegrefe+ 2019]

Learning to Deceive with Attention-Based Explanations [Pruthi+ 2020]

Copy mechanism

Motivation: reuse words in the source

Unknown words in MT:



Dialogue, summarization:

I: Hello Jack, my name is Chandralekha.

R: Nice to meet you, Chandralekha.

I: This new guy doesn't perform exactly as we expected.

R: What do you mean by "doesn't perform exactly as we expected"?

Copy mechanism

Interpolate two distributions:

$$p(y_i \mid x, y_{<i}) = \lambda_{\text{gen}} p_{\text{gen}}(y_i \mid x, y_{<i}) + (1 - \lambda_{\text{gen}}) p_{\text{copy}}(y_i \mid x, y_{<i})$$

- ▶ p_{gen} : distribution over words in the vocabulary
- ▶ p_{copy} : distribution over words in the source

Design decisions:

- ▶ Learned (function of the input) vs fixed λ_{gen}
- ▶ p_{copy} : use attention weights or compute from a separate model

Application of the copy mechanism

Most successful in abstractive summarization

Extractive Summarization

Select parts (typically sentences) of the original text to form a summary.



- Easier
- Too restrictive (no paraphrasing)
- Most past work is extractive

Abstractive Summarization

Generate novel sentences using natural language generation techniques.



- More difficult
- More flexible and human
- Necessary for future progress

Figure: Slides from Abigail See

Application of the copy mechanism

Most successful in abstractive summarization

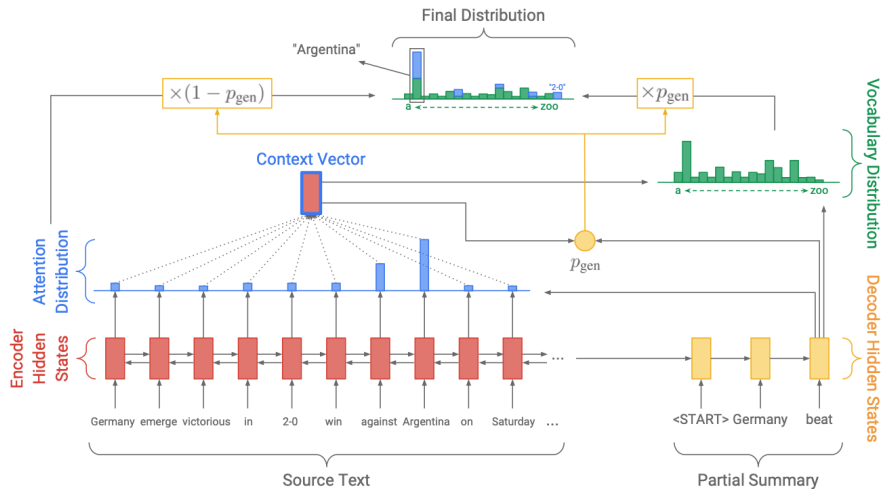


Figure: Pointer-Generator network [See+ 2016]

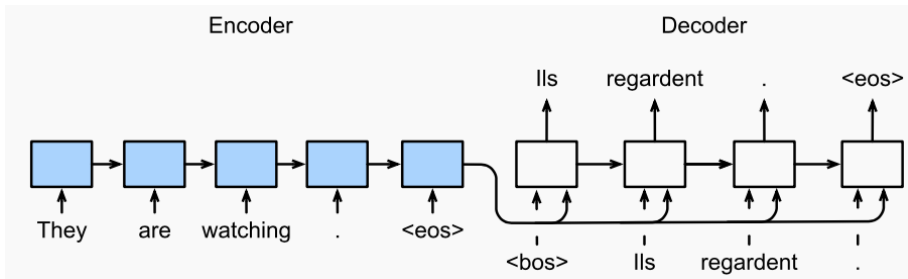
Table of Contents

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Training



MLE:

$$\begin{aligned} & \max_{\theta} \sum_{i=1}^N \log p(y^{(i)} \mid x^{(i)}; \theta) \\ &= \max_{\theta} \sum_{i=1}^N \sum_{t=1}^T \underbrace{\log p(y_t^{(i)} \mid x^{(i)}, y_{1:t-1}^{(i)}; \theta)}_{\text{decoder output}} \end{aligned} \quad \text{auto-regressive model}$$

Argmax decoding

Argmax decoding (aka MAP decoding):

$$\hat{y} = \arg \max_{y \in \mathcal{Y}^n} p(y \mid x; \theta)$$

- ▶ Return the most likely sequence
- ▶ \mathcal{Y} is the vocabulary size for text generation
- ▶ Exact search is intractable when scores aren't locally decomposable

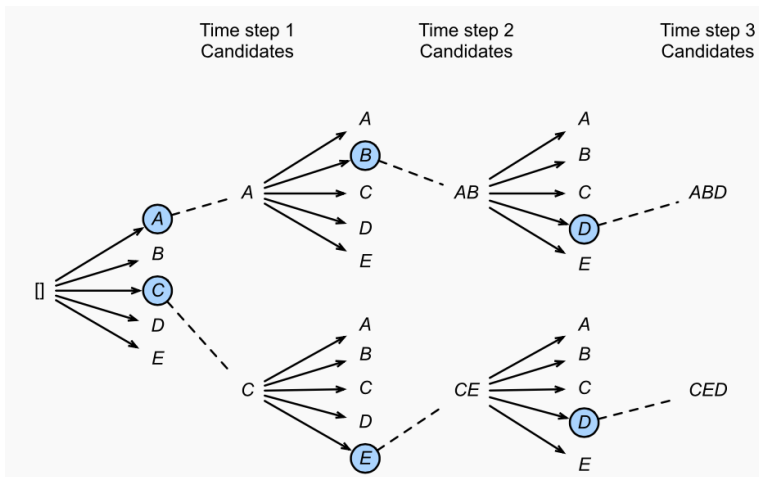
Approximate search:

- ▶ **Greedy decoding**: return the most likely symbol at each step

$$y_t = \arg \max_{y \in \mathcal{Y}} p(y \mid x, y_{1:t-1}; \theta)$$

Approximate MAP decoding: beam search

Beam search: maintain k highest-scored *partial* solutions at any time



Is MAP the right decoding objective?

High likelihood can be correlated with low quality outputs.

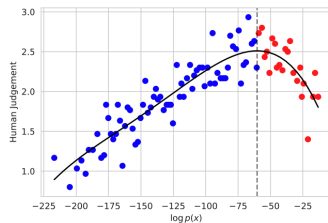


Figure: Samples from an LM [Zhang+ 2020]

In practice, argmax decoding has been observed to lead to

- ▶ Repetitive generations, e.g.
“..., was conducted by researchers from the Universidad Nacional Autonoma de Mexico (UNAM) and the Universidad Nacional Autonoma de Mexico (UNAM/Universidad Nacional Autonoma de Mexico/Universidad Nacional Autonoma de Mexico/Universidad Nacional Autonoma...”
- ▶ Degraded generations with large beam size in MT

Sampling-based decoding

Directly sampling from $p(y \mid x; \theta)$ often produces non-sensical sentences:

They were cattle called Bolivian Cavalleros; they live in a remote desert uninterrupted by town,
and they speak huge, beautiful, paradisiacal Bolivian linguistic thing.

Tempered sampling: change the concentration of the distribution

$$p(y_t \mid x, y_{1:t-1}; \theta) \propto \exp \underbrace{(s_\theta(y_t, x, y_{1:t-1}))}_{\text{score of } y_t}$$

$$q(y_t \mid x, y_{1:t-1}) \propto \exp (s_\theta(y_t, x, y_{1:t-1}) / T) \quad \text{where } T \in (0, +\infty)$$

- ▶ What happens when $T \rightarrow 0$ and $T \rightarrow +\infty$?
- ▶ Does it change the rank of y according to likelihood?
- ▶ Typically we choose $T \in (0, 1)$.

Sampling-based decoding

Truncated sampling: truncate the tail of the distribution

Top-k sampling:

$$q(y_t \mid x, y_{1:t-1}) \propto p(y_t \mid x, y_{1:t-1}; \theta) \mathbb{I}(r(y_t) \leq k)$$

where $r(y)$ for $y \in \mathcal{Y}$ returns the rank of y by $p(y_t \mid x, y_{1:t-1}; \theta)$ in descending order.

Top-p sampling (aka nucleus sampling):

$$q(y_t \mid x, y_{1:t-1}) \propto p(y_t \mid x, y_{1:t-1}; \theta) \mathbb{I}\left(\sum_{i=1}^{r(y_t)} f(i) \leq p\right)$$

where $f(i)$ for $i \in |\mathcal{Y}|$ returns i -th highest $p(y_t \mid x, y_{1:t-1}; \theta)$.

Decoding in practice

Rule of thumb:

- ▶ Use beam search with small beam size for tasks where there exists a correct answer, e.g. machine translation, summarization
- ▶ Use top- k or top- p for open-ended generation, e.g. story generation, chit-chat dialogue, continuation from a prompt

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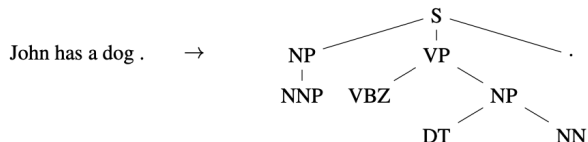
Application and evaluation

Applications

Text generation: MT, summarization, chit-chat dialogue, image caption, story generation etc.

Structured prediction:

► Parsing



John has a dog . → (S (NP NNP)_{NP} (VP VBZ (NP DT NN)_{NP})_{VP} .)_S

► Text-to-SQL

Evaluation

Evaluate translations:

Reference 1 It is a guide to action that ensures that the military will forever heed Party commands.

Reference 2 It is the guiding principle which guarantees the military forces always being under the command of the Party.

Candidate 1 It is a guide to action which ensures that the military always obeys the commands of the party.

Candidate 2 It is to insure the troops forever hearing the activity guidebook that party direct.

Task: given the reference(s) of each source sentence, evaluate the quality of the generated sequences.

Main idea: good generations should have high overlap with the reference.

BLEU: n-gram precision

First try: n-gram precision (x : input, c : candidate, r : reference)

$$p_n = \frac{\sum_{(x,c,r)} \sum_{s \in \text{n-gram}(c)} \mathbb{I}[s \text{ in } r]}{\sum_{(x,c,r)} \sum_{s \in \text{n-gram}(c)} \mathbb{I}[s \text{ in } c]}$$

BLEU: n-gram precision

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Problem: matching only a few words in the reference(s)

Candidate the the the the the the

Reference 1 The cat is on the mat

Reference 2 There is a cat on the mat

unigram precision = ?

Solution: clip counts to maximum count in the reference(s)

BLEU: n-gram precision

Given p_n 's, we need to combine n-gram precisions.

Weighted average? Problem: precision decreases roughly exponentially with n .

Solution: geometric mean (when $w_n = 1/n$)

$$\exp \left(\sum_{i=1}^n w_n \log p_n \right)$$

Problem with precision:

Candidate of the

Reference 1 It is the guiding principle which guarantees the military forces always being under the command of the Party.

Reference 2 It is the practical guide for the army always to heed the directions of the party.

What are problems with recall with *multiple* references?

BLEU: brevity penalty

A good translation must match the reference in:

word choice captured by precision

word order capture by n-gram

length ?

candidate length $C = \sum_{(x,c,r)} \text{len}(c)$

reference length $R = \sum_{(x,c,r)} \arg \min_{a \in \{\text{len}(r_1), \dots, \text{len}(r_k)\}} |a - \text{len}(c)|$

► Use the reference whose length is closest to the candidate

Brevity penalty $BP = \begin{cases} 1 & \text{if } c > r \\ e^{1-R/C} & \text{if } c \leq r \end{cases}$

► No penalty if $r \leq c$

BLEU

Putting everything together:

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

$$\log \text{BLEU} = \min(1 - \frac{R}{C}, 0) + \sum_{n=1}^N w_n \log p_n$$

- ▶ Both precision and the brevity penalty are computed at the *corpus level*.
- ▶ Need smoothing for sentence-level BLEU.
- ▶ Good correlation with human evaluation for MT (typically $n = 4$).

ROUGE

Task: given a candidate summary and a set of reference summaries, evaluate the quality of the candidate.

ROUGE-n: n-gram recall

- ▶ Encourage content coverage

ROUGE-L: measures longest common subsequence between a candidate and a reference

- ▶ Precision = $LCS(c, r) / \text{len}(c)$
- ▶ Recall = $LCS(c, r) / \text{len}(r)$
- ▶ F-measure = $\frac{(1+\beta^2)RR}{R+\beta^2P}$
- ▶ Doesn't require consecutive match.

Often used for summarization, but human evaluation is still needed.

Automatic evaluation metrics for sequence generation

n-gram matching metrics (e.g. BLEU, ROUGE)

- ▶ Measures exact match with reference; interpretable.
- ▶ Do not consider semantics.

Embedding-based metrics (e.g. BERTScore)

- ▶ Measures similarity to the reference in an embedding space.
- ▶ Captures synonyms and simple paraphrases.

However, we also want to measure

- ▶ Is the generation correct? e.g. faithfulness (summarization), adequacy (MT).
- ▶ Open-ended generation: is the story/dialogue interesting, informative, engaging?

Automatic evaluation metrics for sequence generation

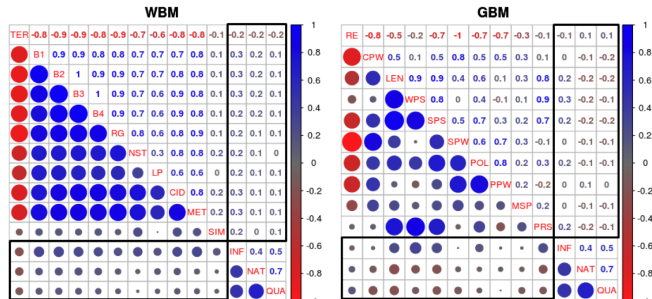


Figure: [Novikova+ 2017]

- ▶ Correlation between automatic metrics and human ratings on generation quality
- ▶ Left: word-overlap metrics; right: grammar-based metrics
- ▶ Overall, low correlation with human ratings

Human Evaluation

- ▶ Human or machine generated?

Once upon a time, there lived a pirate. He was the sort of pirate who would rather spend his time chasing away the sharks swimming around his ship than sail to foreign ports in search of booty. He was a good pirate, a noble pirate, an honest pirate. He was a pirate who would rather be at home with his wife and son than out on a ship in the middle of the ocean.

Human Evaluation

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- ▶ Human evaluation can be tricky as the models gets better!
- ▶ Pros: more reliable, multifaceted evaluation
- ▶ Cons: high variance, misalignment

Evaluation in practice

Evaluation is a key blocker to progress in text generation.

In practice, multiple evaluation methods are needed for reliable results:

- ▶ Held-out NLL/perplexity: how close are $p_{\theta}(y \mid x)$ and $p(y \mid x)$?
- ▶ Automatic evaluation: how close are the candidate generation and the reference(s)?
- ▶ Human evaluation: task-specific criteria, e.g. grammaticality, coherence, correctness etc.
 - ▶ Annotator may need to be trained
 - ▶ Need to report annotator agreement
- ▶ *Show the outputs!*