Incremental structured prediction

L101: Machine Learning for Language Processing
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Structured prediction reminder

Given an input $x$ (e.g. a sentence) predict $y$ (e.g. a PoS tag sequence, cf lecture 6):

$$\hat{y} = \arg\max_{y \in \mathcal{Y}} \text{score}(x, y)$$

Where $\mathcal{Y}$ is rather large and often depends on the input (e.g. $L^{|x|}$ in PoS tagging)

Various approaches:
- Linear models (structured perceptron)
- Probabilistic linear models (conditional random fields)
- Non-linear models
Decoding

Assuming we have a trained model, decode/predict/solve the argmax/inference:

\[ \hat{y} = \arg \max_{y \in \mathcal{Y}} \text{score}(x, y; \theta) \]

Dynamic programming to the rescue?

Yes! But we need to make assumptions on the structure:

- 1st order Markov assumption (linear chains), rarely more than 2nd
- The scoring function must decompose over the output structure

What if we need greater flexibility?
Incremental structured prediction

A classifier $f$ predicting actions to construct the output:

$$\hat{\alpha}_1 = \underset{\alpha \in \mathcal{A}}{\text{arg max}} f(\alpha, x),$$

$$\hat{\mathbf{y}} = \text{output} \left( \begin{array}{c} \hat{\alpha}_2 = \underset{\alpha \in \mathcal{A}}{\text{arg max}} f(\alpha, x, \hat{\alpha}_1), \\ \hat{\alpha}_N = \underset{\alpha \in \mathcal{A}}{\text{arg max}} f(\alpha, x, \hat{\alpha}_1 \ldots \hat{\alpha}_{N-1}) \end{array} \right)$$

Examples:

- Predicting the PoS tags word-by-word (MEMM without Viterbi)
- Building a syntax tree by shifting items to and reducing a stack
- Generating a sentence word-by-word (these days with seq2seq)
Incremental structured prediction

Pros:
✓ No need to enumerate all possible outputs
✓ No modelling restrictions on features

Cons:
✗ Prone to error propagation
✗ Classifier not trained w.r.t. task-level loss
Error propagation

We do not score complete outputs:

- early predictions do not know what follows
- cannot be undone if purely incremental/monotonic
  (doesn’t need to be)
- we are training with gold standard predictions for previous predictions, but test with predicted ones (exposure bias)

Ranzato et al. (ICLR2016)
Incremental basics: Greedy and Beam search

**Greedy:** pick the most likely action (“the nice woman”)

**Beam:** keep the top-k paths alive (“the dog has” with k=2)

Overcome locally optimal decisions that are not globally optimal according to the model

https://huggingface.co/blog/how-to-generate
Beam search algorithm

**Input:** word sequence $x = [x_1, \ldots, x_N]$, tags $\mathcal{Y}$, parameters $\theta$

Initialize beam $B = \{y_{\text{temp}} = ([\text{START}], \text{score} = 0)\}$, size $k$

for $n = 1 \ldots N$ do

\[ B' = \{\} \]

for $b \in B$ do

for $y \in \mathcal{Y}$ do

\[ s = \text{score}(x, [b.y_{\text{temp}}; y]; \theta) \]

\[ B' = B' \cup ([b.y_{\text{temp}}; y], s) \]

end for

end for

\[ B = B'[1 : k] \]

end for

return $B[1]$
Beam search in practice

- It works, but **implementation matters**
  - Feature decomposability is key to reuse previously computed scores
  - Sanity check: on small/toy instances large enough beam should find the exact argmax

- Take care of bias due to **action types with different score ranges**: picking among all English words is not comparable with picking among PoS tags
Beam search extensions

Reranking:
- Adjust probabilities to normalise for sentence length
- Model to pick outputs that are likely to have better global score (e.g. BLEU)
- Re-rank intermediate beams, a.k.a. incremental beam manipulation

We still rely on beam search to generate good hypotheses

Training decoders for beam search:
- Penalize the model when the correct hypothesis falls of the beam (beam search optimization, beam-aware training)
- Train a greedy decoder to approximate beam search to maximize a sentence-level score
Being less exact helps?

- In **Neural Machine Translation** performance degrades with larger beams...
- **Search errors save us from model errors!**
  - Also MAP decoding does not always do justice to our models
- Part of the problem at least is that we train word-level models but the task makes (a lot more!) sense at the sentence-level really...

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Table 1: NMT with exact inference. In the absence of search errors, NMT often prefers the empty translation, causing a dramatic drop in length ratio and BLEU.

<table>
<thead>
<tr>
<th>Search</th>
<th>BLEU</th>
<th>Ratio</th>
<th>#Search errors</th>
<th>#Empty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greedy</td>
<td>29.3</td>
<td>1.02</td>
<td>73.6%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Beam-10</td>
<td>30.3</td>
<td>1.00</td>
<td>57.7%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Exact</td>
<td>2.1</td>
<td>0.06</td>
<td>0.0%</td>
<td>51.8%</td>
</tr>
</tbody>
</table>
Training for incremental structured prediction

In supervised training we assume a loss function e.g. negative log likelihood against gold labels in classification with logistic regression/ feedforward NNs.

In incremental structured prediction, what do we train our classifier to do?

Predict the action leading the correct output. Losses over **structured outputs**:

- Hamming loss: number of incorrect part of speech tags in a sentence
- False positives and false negatives: e.g. named entity recognition
- Reduction in BLEU score (n-gram overlap) in generation tasks, e.g. machine translation
Can we assess the goodness of each action?

- In PoS tagging, predicting a tag at a time with Hamming loss?
  - YES
- In machine translation predicting a word at a time with BLEU score?
  - NO

BLEU score doesn’t decompose over the actions defined by the transition system.
Incremental structured prediction can be viewed as (degenerate) RL: 

- No environment dynamics
- No need to worry about physical costs (e.g. robots damaged)

Sutton and Barto (2018)
Policy gradient

Learn the parameters $\theta$ of policy/classifier $\pi$ that optimize rewards/task loss $v$:

$$J(\theta) = \sum_{s \in S} d^{\pi_\theta}(s) v^{\pi_\theta}(s)$$

$$= \sum_{s \in S} d^{\pi_\theta}(s) \sum_{\alpha \in A} \pi_\theta(\alpha|s) Q^{\pi_\theta}(s, \alpha)$$

- on-policy learning: the policy affects the distributions of states visited $d$
- the reward from reaching a state $s$ is its expectation according to the policy

We can now do our stochastic gradient (ascent) updates:

$$\theta_{t+1} = \theta + \alpha \nabla J(\theta_t)$$

What could go wrong?
Reinforcement learning is hard...

See Choshen et al. (2020), and Kiegeland and Kreutzer (2021) for a recent debate

To obtain training signal we need complete trajectories
- Can sample (REINFORCE) but inefficient in large search spaces
- High variance when many actions are needed to reach the end (credit assignment problem)
- Can learn $Q$ to evaluate the outcome of the action (actor-critic)

In NLP, often the models are trained initially in the standard supervised way and then fine-tuned with RL (e.g. for summarization)
- Hard to tune the balance between the two
- Constrains the benefits of RL
Imitation learning

- Both reinforcement and imitation learning learn a classifier/policy to maximize reward
- Learning in imitation learning is facilitated by an expert
- Basic form: supervised learning using expert demonstrations, a.k.a. behavioural cloning; IL algorithms go beyond this
Train without assuming that all previous words are correctly predicted.

This idea was first introduced as the **DAgger algorithm** in robotics.
Imitation learning in a nutshell

- Rollins-rollouts mix model and expert predictions
- First iteration trained on expert, later ones increasingly use the trained model
- Exploring one-step deviations from the rollin of the classifier

Chang et al. (2015)
Imitation learning is hard too!

- **Defining a good expert is difficult**
  - How to know all possible correct next words to add given a partial translation and a gold standard?
  - Without a better than random expert, we are back to RL

- While expert demonstrations make learning more efficient, it is still difficult to handle large numbers of actions

- The interaction between learning the feature extraction and learning the policy/classifier is not well understood in the context of RNNs
Bibliography

- Kai Zhao’s survey
- Noah Smith’s book
- Sutton and Barton Reinforcement learning book
- This blog on policy gradient methods
- Imitation learning tutorials:
  - structured prediction
  - natural language generation
  - ML-oriented