“Deep” Learning
Big picture: natural language analyzers

Natural language input signal:
- Web page
- Question
- Search query
- Tweet
- Voice command

natural language analyzer

Output analysis:
- Question
- Answer
- Command to a robot
- Trending topics
Big picture: natural language analyzers

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Today: deep learning for NLP components

Natural language input signal:
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- Tweet
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- Answer
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Agenda

• Big picture

• Why deep learning?

• Building blocks of a deep neural network

• How to train deep neural networks

• Important results
Running example: document classification
Running example: document classification

output = arg\max_l f(l, d)

- Politics
- Business
- Science
- Sports
- Health

Barcelona lost to Real Madrid

Sports
How to define $f(l, d)$: linear models

Linear models: $f(l, d) = w \cdot g(l, d)$

$l = \text{Sports}$

$d = \text{Barcelona lost to Real Madrid}$

Number of times $\text{Lost}$ appears in a document labeled $\text{Sports}$

Number of times $\text{Barcelona}$ appears in a document labeled $\text{Sports}$
How to define $f(l, d)$: linear models

Linear models: $f(l, d) = w \cdot g(l,d)$

- Easy to implement
- Easy to optimize $w$

Two possible improvements:
- Define more complex functions
- Find better representations of $(l,d)$

Figure credits: Barbara Rosario
Agenda

• Big picture

• Why deep learning?

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• Important results
neural network v1.0: linear model

Linear models: \( f(l, d) = w \cdot g(l, d) = w(l) \cdot x(d) \)
e.g., \( y_1 = x_1 w_{1,1} + x_2 w_{2,1} + x_3 w_{3,1} + x_4 w_{4,1} + x_5 w_{5,1} = w(1) \cdot x(d) \)
neural network v1.0: linear model

Linear models: $f(l, d) = w \cdot g(l, d) = w(l) \cdot x(d)$
e.g., $y_1 = x_1 w_{1,1} + x_2 w_{2,1} + x_3 w_{3,1} + x_4 w_{4,1} + x_5 w_{5,1} = w(1) \cdot x(d)$

similar words still share no parameters!
neural network v2.0: representation learning

Big idea: induce low-dimensional dense feature representations of high-dimensional objects
neural network v2.1: representation learning

Big idea: embed words in a dense vector space and use the word embeddings as dense features

Did this really solve the problem?
neural network v3.0: complex functions

Big idea: define more complex functions by adding a hidden layer

\[ y = W x \]
neural network v3.0: complex functions

Big idea: define more complex functions by adding a hidden layer

\[ y = W_2 h_1 = W_2 (W_1 x) = W x \]

Wait! Is that true?!
neural network v3.0: complex functions

Big idea: define more complex functions by adding a hidden layer

\[ y = W_2 h_1 = W_2 a_1(W_1 x) \]

non-linear functions, e.g., logistic function
\[ a_1(z) = \frac{1}{1 + e^{-z}} \]

Universal approximation theorem
# neural network v3.0: complex functions

## Popular activation/transfer/non-linear functions:

<table>
<thead>
<tr>
<th>Name</th>
<th>Plot</th>
<th>Equation</th>
<th>Derivative</th>
<th>Range</th>
<th>Order of continuity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identity</td>
<td></td>
<td>$f(x) = x$</td>
<td>$f'(x) = 1$</td>
<td>$(-\infty, \infty)$</td>
<td>$C^\infty$</td>
</tr>
<tr>
<td>Binary step</td>
<td></td>
<td>$f(x) = \begin{cases} 0 &amp; \text{for } x &lt; 0 \ 1 &amp; \text{for } x \geq 0 \end{cases}$</td>
<td>$f'(x) = \begin{cases} 0 &amp; \text{for } x \neq 0 \ ? &amp; \text{for } x = 0 \end{cases}$</td>
<td>${0, 1}$</td>
<td>$C^{-1}$</td>
</tr>
<tr>
<td>Logistic (a.k.a Soft step)</td>
<td></td>
<td>$f(x) = \frac{1}{1 + e^{-x}}$</td>
<td>$f'(x) = f(x)(1 - f(x))$</td>
<td>$(0, 1)$</td>
<td>$C^\infty$</td>
</tr>
<tr>
<td>TanH</td>
<td></td>
<td>$f(x) = \tanh(x) = \frac{2}{1 + e^{-2x}} - 1$</td>
<td>$f'(x) = 1 - f(x)^2$</td>
<td>$(-1, 1)$</td>
<td>$C^\infty$</td>
</tr>
<tr>
<td>ArcTan</td>
<td></td>
<td>$f(x) = \tan^{-1}(x)$</td>
<td>$f'(x) = \frac{1}{x^2 + 1}$</td>
<td>$(-\frac{\pi}{2}, \frac{\pi}{2})$</td>
<td>$C^\infty$</td>
</tr>
<tr>
<td>Softsign (^7)</td>
<td></td>
<td>$f(x) = \frac{x}{1 +</td>
<td>x</td>
<td>}$</td>
<td>$f'(x) = \frac{1}{(1 +</td>
</tr>
<tr>
<td>Rectified Linear Unit (ReLU)(^8)</td>
<td></td>
<td>$f(x) = \begin{cases} 0 &amp; \text{for } x &lt; 0 \ x &amp; \text{for } x \geq 0 \end{cases}$</td>
<td>$f'(x) = \begin{cases} 0 &amp; \text{for } x &lt; 0 \ 1 &amp; \text{for } x \geq 0 \end{cases}$</td>
<td>$[0, \infty)$</td>
<td>$C^0$</td>
</tr>
</tbody>
</table>


[Source: en.wikipedia.org/wiki/Activation_function]
neural network v3.5: “deeper” networks

Wait but why do we need more layers?

\[
y = W_3 \, h_2 = W_3 \, a_2(\ W_2 \, a_1(W_1 \, x) )
\]
neural network v3.5: “deeper” networks
neural network v4.0: recurrent neural networks

Big idea: use hidden layers to represent sequential state

How did we represent x for document classification?

Real …. Madrid = Real Madrid

Do we share parameters across states?

Figure credits: Andrej Karpathy
neural network v4.0: recurrent neural networks

How to compute the hidden layers?

Figure credits: Christopher Olah
neural network v4.1: output sequences

Figure credits: Andrej Karpathy
neural network v4.1: output sequences

Example:

Character-level language models

Figure credits: Andrej Karpathy
neural network v4.1: output sequences

Sample output:

Copyright was the succession of independence in the slop of Syrian influence that was a famous German movement based on a more popular servicious, non-doctrinal and sexual power post. Many governments recognize the military housing of the [[Civil Liberalization and Infantry Resolution 265 National Party in Hungary]], that is sympathetic to be to the [[Punjab Resolution]] (PJS)[http://www.humah.yahoo.com/guardian.cfm/7754800786d17551963s89.htm]

Official economics Adjoint for the Nazism, Montgomery was swear to advance to the resources for those Socialism's rule, was starting to signing a major tripad of aid exile.]]
neural network v4.2: Long-Short Term Memory

Figure credits: Christopher Olah http://colah.github.io/posts/2015-08-Understanding-LSTMs/
neural network v4.2: Long-Short Term Memory

Figure credits: Christopher Olah http://colah.github.io/posts/2015-08-Understanding-LSTMs/
neural network v4.3: bidirectional RNNs

Unidirectional RNNs

Bidirectional RNNs

Figure credits: Christopher Olah
neural network v4.4: attention models

Figure 1: The graphical illustration of the proposed model trying to generate the $t$-th target word $y_t$ given a source sentence $(x_1, x_2, \ldots, x_T)$. 

Bahdanau et al. (2015)
neural network v5: convolutional NN

Figure credits: Christopher Olah
neural network v5: convolutional NN

Feed-forward NN

Convolutional NN

Figure credits: Christopher Olah
neural network v5: convolutional NN

Do we share parameters of different convolutions? In the same layer? In different layers?

Figure credits: Christopher Olah
neural network v5: convolutional NN

convolutional layer 2

convolutional layer 1

2D convolutions

Figure credits: Christopher Olah
neural network v5.1: recursive NNs

(From Bottou (2011))
neural network v6: dropout
Agenda

- Big picture
- Why deep learning?
- Building blocks of a deep neural network
- How to train deep neural networks
- Important results
How to train NN models?

- \( \text{argmax}_l f(d, l) \) only tells us which label to predict.
- Supervised learning (need input/output pairs)
- Loss function: e.g., cross-entropy between empirical distribution and model distribution

\[
- \log p(l^* | d) = - \log \left( \frac{e^{f(d, l^*)}}{\sum_l e^{f(d, l)}} \right)
\]

Regression problems?
Mean square error
\[
E[(y - y^*)^2]
\]
How to optimize the loss?

- Stochastic gradient descent

for $i = 1, 2, \ldots$

Pick random training example $t$ and compute:

$$g^{(i)} = \left\{ \frac{\partial L(x_t, y_t)}{\partial \theta} \right\}_{\theta=\theta^{(i)}}$$

$$\theta^{(i+1)} = \theta^{(i)} - \eta g^{(i)}$$
How to optimize the loss?

• Parameter initialization
  – Break the symmetry
  – Use small values
  – Random restarts
  – Popular choice: uniform with mean=zero and variance = 1 / size of previous layer

How to optimize the loss?

• Other optimization methods
  – Variants of stochastic gradient descent (e.g., averaged SGD, SGD with momentum)
  – Adagrad
  – Adam
  – Adadelta
How to optimize the loss?

- Computing gradients: the hard way
  - Analytically derive the expression that represents the gradient with respect to each input.
  - Compute that expression.

- Computing gradients: automatic differentiation
  - Translate the loss function into a sequence of *atomic operations*
  - Hard-code the differentiation of each atomic operation with respect to its parameters is hard-coded.
  - Recursively compute the gradient of the loss function with respect to model parameters using chain rule.
How to optimize the loss: automatic differentiation

\[ y = \log \sin^2 x \]

**What is the derivative at** \( x_0 \)?

<table>
<thead>
<tr>
<th>components</th>
<th>range</th>
<th>differential</th>
<th>d-range</th>
</tr>
</thead>
<tbody>
<tr>
<td>( y = f(u) = \log u )</td>
<td>( \mathbb{R} )</td>
<td>( \frac{dy}{du} = \frac{1}{u} )</td>
<td>( \mathbb{R} )</td>
</tr>
<tr>
<td>( u = g(v) = v^2 )</td>
<td>( \mathbb{R} )</td>
<td>( \frac{du}{dv} = 2v )</td>
<td>( \mathbb{R} )</td>
</tr>
<tr>
<td>( v = h(x) = \sin x )</td>
<td>( \mathbb{R} )</td>
<td>( \frac{dv}{dx} = \cos x )</td>
<td>( \mathbb{R} )</td>
</tr>
</tbody>
</table>

\[
\frac{dy}{dx}\bigg|_{x=x_0} = \frac{dy}{du}\bigg|_{u=g(h(x_0))} \cdot \frac{du}{dv}\bigg|_{v=h(x_0)} \cdot \frac{dv}{dx}\bigg|_{x=x_0}
\]
How to optimize the loss: automatic differentiation

\[
y = \sum_{i=1}^{n} (W \exp x)_i \quad \text{where} \quad x \in \mathbb{R}^d \quad \text{and} \quad W \in \mathbb{R}^{n \times d}
\]

<table>
<thead>
<tr>
<th>components</th>
<th>range</th>
<th>differential</th>
<th>d-range</th>
</tr>
</thead>
<tbody>
<tr>
<td>( y = f(u) = \sum_{i=1}^{n} u_i )</td>
<td>( \mathbb{R} )</td>
<td>( \frac{\partial y}{\partial u} = 1 )</td>
<td>( \mathbb{R}^{1 \times n} )</td>
</tr>
<tr>
<td>( u = g(v) = Wv )</td>
<td>( \mathbb{R}^n )</td>
<td>( \frac{\partial u}{\partial v} = W )</td>
<td>( \mathbb{R}^{n \times d} )</td>
</tr>
<tr>
<td>( v = h(x) = \exp x )</td>
<td>( \mathbb{R}^d )</td>
<td>( \frac{\partial v}{\partial x} = \text{diag}(\exp x) )</td>
<td>( \mathbb{R}^{d \times d} )</td>
</tr>
</tbody>
</table>

\[
\frac{dy}{dx} \bigg|_{x=x_0} = \frac{dy}{du} \bigg|_{u=g(h(x_0))} \cdot \frac{du}{dv} \bigg|_{v=h(x_0)} \cdot \frac{dv}{dx} \bigg|_{x=x_0}
\]

\[
\begin{align*}
\mathbb{R}^{1 \times n} & \quad \mathbb{R}^{n \times d} & \quad \mathbb{R}^{d \times d}
\end{align*}
\]
How to optimize the loss: deep learning libraries

<table>
<thead>
<tr>
<th>Library</th>
<th>Class</th>
<th>Time (ms)</th>
<th>forward (ms)</th>
<th>backward (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nervana-neon-fp16</td>
<td>ConvLayer</td>
<td>176</td>
<td>58</td>
<td>118</td>
</tr>
<tr>
<td>Nervana-neon-fp32</td>
<td>ConvLayer</td>
<td>211</td>
<td>69</td>
<td>141</td>
</tr>
<tr>
<td>CuDNN[R4]-fp16 (Torch)</td>
<td>cudnn.SpatialConvolution</td>
<td>242</td>
<td>86</td>
<td>156</td>
</tr>
<tr>
<td>CuDNN[R4]-fp32 (Torch)</td>
<td>cudnn.SpatialConvolution</td>
<td>268</td>
<td>94</td>
<td>174</td>
</tr>
<tr>
<td>fbfft (Torch)</td>
<td>SpatialConvolutionCuFFT</td>
<td>342</td>
<td>114</td>
<td>227</td>
</tr>
<tr>
<td>TensorFlow</td>
<td>conv2d</td>
<td>349</td>
<td>101</td>
<td>248</td>
</tr>
<tr>
<td>Chainer</td>
<td>Convolution2D</td>
<td>620</td>
<td>135</td>
<td>484</td>
</tr>
<tr>
<td>cudaconvnet2*</td>
<td>ConvLayer</td>
<td>723</td>
<td>176</td>
<td>547</td>
</tr>
<tr>
<td>CuDNN[R2] *</td>
<td>cudnn.SpatialConvolution</td>
<td>810</td>
<td>234</td>
<td>576</td>
</tr>
<tr>
<td>Caffe</td>
<td>ConvolutionLayer</td>
<td>823</td>
<td>355</td>
<td>468</td>
</tr>
<tr>
<td>Torch-7 (native)</td>
<td>SpatialConvolutionMM</td>
<td>878</td>
<td>379</td>
<td>499</td>
</tr>
<tr>
<td>CL-nn (Torch)</td>
<td>SpatialConvolutionMM</td>
<td>963</td>
<td>388</td>
<td>574</td>
</tr>
<tr>
<td>Caffe-CLGreenTea</td>
<td>ConvolutionLayer</td>
<td>2857</td>
<td>616</td>
<td>2240</td>
</tr>
</tbody>
</table>

[https://github.com/soumith/convnet-benchmarks/](https://github.com/soumith/convnet-benchmarks/)
Also see: CMU’s locally grown library at [https://github.com/clab/cnn](https://github.com/clab/cnn)
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• Important results
Major results: language modeling

Neural Language Model
[Mikolov et al. Interspeech 2011]

MSR MAVIS Speech System
[Dahl et al. 2012; Seide et al. 2011; following Mohamed et al. 2011]

“The algorithms represent the first time a company has released a deep-neural-networks (DNN)-based speech-recognition algorithm in a commercial product.”

Slide credit: Richard Socher
Major results: image classification

Krizehvsky et al. (2012)

Table 1: Comparison of results on ILSVRC-2010 test set. In *italics* are best results achieved by others. Models with an asterisk* were “pre-trained” to classify the entire ImageNet 2011 Fall release. See Section 6 for details.

<table>
<thead>
<tr>
<th>Model</th>
<th>Top-1</th>
<th>Top-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sparse coding [2]</td>
<td>47.1%</td>
<td>28.2%</td>
</tr>
<tr>
<td>SIFT + FVs [24]</td>
<td>45.7%</td>
<td>25.7%</td>
</tr>
<tr>
<td>CNN</td>
<td>37.5%</td>
<td>17.0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model</th>
<th>Top-1 (val)</th>
<th>Top-5 (val)</th>
<th>Top-5 (test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIFT + FVs</td>
<td>—</td>
<td>—</td>
<td>26.2%</td>
</tr>
<tr>
<td>1 CNN</td>
<td>40.7%</td>
<td>18.2%</td>
<td>—</td>
</tr>
<tr>
<td>5 CNNs</td>
<td>38.1%</td>
<td>16.4%</td>
<td>16.4%</td>
</tr>
<tr>
<td>1 CNN*</td>
<td>39.0%</td>
<td>16.6%</td>
<td>—</td>
</tr>
<tr>
<td>7 CNNs*</td>
<td>36.7%</td>
<td>15.4%</td>
<td>15.3%</td>
</tr>
</tbody>
</table>

Table 2: Comparison of error rates on ILSVRC-2012 validation and test sets. In *italics* are best results achieved by others. Models with an asterisk* were “pre-trained” to classify the entire ImageNet 2011 Fall release. See Section 6 for details.
Major results: ImageNet

Krizehovsky et al. (2012): positive and negative examples
Major results: ImageNet

Krizehovsky et al. (2012): sample convolution filters
Major results: speech recognition

Graves et al. (2013)

Table 1. TIMIT Phoneme Recognition Results. ‘Epochs’ is the number of passes through the training set before convergence. ‘PER’ is the phoneme error rate on the core test set.

<table>
<thead>
<tr>
<th>NETWORK</th>
<th>WEIGHTS</th>
<th>EPOCHS</th>
<th>PER</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTC-3L-500H-TANH</td>
<td>3.7M</td>
<td>107</td>
<td>37.6%</td>
</tr>
<tr>
<td>CTC-1L-250H</td>
<td>0.8M</td>
<td>82</td>
<td>23.9%</td>
</tr>
<tr>
<td>CTC-1L-622H</td>
<td>3.8M</td>
<td>87</td>
<td>23.0%</td>
</tr>
<tr>
<td>CTC-2L-250H</td>
<td>2.3M</td>
<td>55</td>
<td>21.0%</td>
</tr>
<tr>
<td>CTC-3L-421H-UNI</td>
<td>3.8M</td>
<td>115</td>
<td>19.6%</td>
</tr>
<tr>
<td>CTC-3L-250H</td>
<td>3.8M</td>
<td>124</td>
<td>18.6%</td>
</tr>
<tr>
<td>CTC-5L-250H</td>
<td>6.8M</td>
<td>150</td>
<td>18.4%</td>
</tr>
<tr>
<td>TRANS-3L-250H</td>
<td>4.3M</td>
<td>112</td>
<td>18.3%</td>
</tr>
<tr>
<td>PRETRANS-3L-250H</td>
<td>4.3M</td>
<td>144</td>
<td>17.7%</td>
</tr>
</tbody>
</table>
Major results: translation

Sutskever et al. (2014)

Table 1: The performance of the LSTM on WMT’14 English to French test set (ntst14). Note that an ensemble of 5 LSTMs with a beam of size 2 is cheaper than of a single LSTM with a beam of size 12.

<table>
<thead>
<tr>
<th>Method</th>
<th>test BLEU score (ntst14)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bahdanau et al. [2]</td>
<td>28.45</td>
</tr>
<tr>
<td>Baseline System [29]</td>
<td>33.30</td>
</tr>
<tr>
<td>Single forward LSTM, beam size 12</td>
<td>26.17</td>
</tr>
<tr>
<td>Single reversed LSTM, beam size 12</td>
<td>30.59</td>
</tr>
<tr>
<td>Ensemble of 5 reversed LSTMs, beam size 1</td>
<td>33.00</td>
</tr>
<tr>
<td>Ensemble of 2 reversed LSTMs, beam size 12</td>
<td>33.27</td>
</tr>
<tr>
<td>Ensemble of 5 reversed LSTMs, beam size 2</td>
<td>34.50</td>
</tr>
<tr>
<td>Ensemble of 5 reversed LSTMs, beam size 12</td>
<td>34.81</td>
</tr>
</tbody>
</table>

Table 2: Methods that use neural networks together with an SMT system on the WMT’14 English to French test set (ntst14).

<table>
<thead>
<tr>
<th>Method</th>
<th>test BLEU score (ntst14)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline System [29]</td>
<td>33.30</td>
</tr>
<tr>
<td>Cho et al. [5]</td>
<td>34.54</td>
</tr>
<tr>
<td>State of the art [9]</td>
<td>37.0</td>
</tr>
<tr>
<td>Rescoring the baseline 1000-best with a single forward LSTM</td>
<td>35.61</td>
</tr>
<tr>
<td>Rescoring the baseline 1000-best with a single reversed LSTM</td>
<td>35.85</td>
</tr>
<tr>
<td>Rescoring the baseline 1000-best with an ensemble of 5 reversed LSTMs</td>
<td><strong>36.5</strong></td>
</tr>
<tr>
<td>Oracle Rescoring of the Baseline 1000-best lists</td>
<td>~45</td>
</tr>
</tbody>
</table>
Major results: translation

Bahdanau et al. (2015)

Table 1: BLEU scores of the trained models computed on the test set. The second and third columns show respectively the scores on all the sentences and on the sentences without any unknown word in themselves and in the reference translations. Note that RNNsearch-50* was trained much longer until the performance on the development set stopped improving. (∗) We disallowed the models to generate [UNK] tokens when only the sentences having no unknown words were evaluated (last column).
Major results: dependency parsing

Chen and Manning (2014)

![Neural network architecture diagram]

**Figure 2: Our neural network architecture.**

<table>
<thead>
<tr>
<th>Parser</th>
<th>Dev UAS</th>
<th>Dev LAS</th>
<th>Test UAS</th>
<th>Test LAS</th>
<th>Speed (sent/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>standard</td>
<td>90.2</td>
<td>87.8</td>
<td>89.4</td>
<td>87.3</td>
<td>26</td>
</tr>
<tr>
<td>eager</td>
<td>89.8</td>
<td>87.4</td>
<td>89.6</td>
<td>87.4</td>
<td>34</td>
</tr>
<tr>
<td>Malt:sp</td>
<td>89.8</td>
<td>87.2</td>
<td>89.3</td>
<td>86.9</td>
<td>469</td>
</tr>
<tr>
<td>Malt:eager</td>
<td>89.6</td>
<td>86.9</td>
<td>89.4</td>
<td>86.8</td>
<td>448</td>
</tr>
<tr>
<td>MSTParser</td>
<td>91.4</td>
<td>88.1</td>
<td>90.7</td>
<td>87.6</td>
<td>10</td>
</tr>
<tr>
<td>Our parser</td>
<td><strong>92.0</strong></td>
<td><strong>89.7</strong></td>
<td><strong>91.8</strong></td>
<td><strong>89.6</strong></td>
<td><strong>654</strong></td>
</tr>
</tbody>
</table>

Table 5: Accuracy and parsing speed on PTB + Stanford dependencies.

<table>
<thead>
<tr>
<th>Parser</th>
<th>Dev UAS</th>
<th>Dev LAS</th>
<th>Test UAS</th>
<th>Test LAS</th>
<th>Speed (sent/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>standard</td>
<td>82.4</td>
<td>80.9</td>
<td>82.7</td>
<td>81.2</td>
<td>72</td>
</tr>
<tr>
<td>eager</td>
<td>81.1</td>
<td>79.7</td>
<td>80.3</td>
<td>78.7</td>
<td>80</td>
</tr>
<tr>
<td>Malt:sp</td>
<td>82.4</td>
<td>80.5</td>
<td>82.4</td>
<td>80.6</td>
<td>420</td>
</tr>
<tr>
<td>Malt:eager</td>
<td>81.2</td>
<td>79.3</td>
<td>80.2</td>
<td>78.4</td>
<td>393</td>
</tr>
<tr>
<td>MSTParser</td>
<td><strong>84.0</strong></td>
<td><strong>82.1</strong></td>
<td>83.0</td>
<td>81.2</td>
<td><strong>6</strong></td>
</tr>
<tr>
<td>Our parser</td>
<td><strong>84.0</strong></td>
<td><strong>82.4</strong></td>
<td><strong>83.9</strong></td>
<td><strong>82.4</strong></td>
<td><strong>936</strong></td>
</tr>
</tbody>
</table>

Table 6: Accuracy and parsing speed on CTB.
Major results: dependency parsing

Dyer et al. (2015)

Table 1: English parsing results (SD)

<table>
<thead>
<tr>
<th>Development</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UAS</td>
</tr>
<tr>
<td>S-LSTM</td>
<td>93.2</td>
</tr>
<tr>
<td>–POS</td>
<td>93.1</td>
</tr>
<tr>
<td>–pretraining</td>
<td>92.7</td>
</tr>
<tr>
<td>–composition</td>
<td>92.7</td>
</tr>
<tr>
<td>S-RNN</td>
<td>92.8</td>
</tr>
<tr>
<td>C&amp;M (2014)</td>
<td>92.2</td>
</tr>
</tbody>
</table>

Table 2: Chinese parsing results (CTB5)

<table>
<thead>
<tr>
<th>Development</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UAS</td>
</tr>
<tr>
<td>S-LSTM</td>
<td>87.2</td>
</tr>
<tr>
<td>–POS</td>
<td>82.8</td>
</tr>
<tr>
<td>–pretraining</td>
<td>86.3</td>
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<tr>
<td>–composition</td>
<td>85.8</td>
</tr>
<tr>
<td>S-RNN</td>
<td>86.3</td>
</tr>
<tr>
<td>C&amp;M (2014)</td>
<td>84.0</td>
</tr>
</tbody>
</table>

Figure 1: A stack LSTM extends a conventional left-to-right LSTM with the addition of a stack pointer (notated as TOP in the figure). This figure shows three configurations: a stack with a single element (left), the result of a pop operation to this (middle), and then the result of applying a push operation (right). The boxes in the lowest rows represent stack contents, which are the inputs to the LSTM, the upper rows are the outputs of the LSTM (in this paper, only the output pointed to by TOP is ever accessed), and the middle rows are the memory cells (the c_i’s and h_i’s) and gates. Arrows represent function applications (usually affine transformations followed by a nonlinearity), refer to §2.1 for specifics.

Figure 2: Parser state computation encountered while parsing the sentence “an overhasty decision was made.” Here S designates the stack of partially constructed dependency subtrees and its LSTM encoding; B is the buffer of words remaining to be processed and its LSTM encoding; and A is the stack representing the history of actions taken by the parser. These are linearly transformed, passed through a ReLU nonlinearity to produce the parser state embedding p. An affine transformation of this embedding is passed to a softmax layer to give a distribution over parsing decisions that can be taken.
Important things we didn’t cover

• Dark knowledge
• Connection to graphical models
• Alternatives to the softmax output layer
Agenda

• Big picture

• Why deep learning?

• Building blocks of a deep neural network

• How to train deep neural networks

• Important results
Open question: can we do without the intermediate linguistic abstractions?

Natural language input signal:
- Web page
- Question
- Search query
- Tweet
- Voice command

Output analysis:
- Question
- Answer
- Command to a robot
- Trending topics