Generating Sequences with Recurrent Neural Networks

Alex Graves
CIFAR Global Scholar
University of Toronto
Why Generate Sequences?

• To improve classification?
• To create synthetic training data?
• Practical tasks like speech synthesis?
• To simulate situations?
• To understand the data
Generation and Prediction

• Obvious way to generate a sequence: repeatedly predict what will happen next

\[
Pr(x) = \prod_t Pr(x_t|x_{1:t-1})
\]

• Best to split into smallest chunks possible: more flexible, fewer parameters, avoids ‘blurred edges’
The Role of Memory

• Need to remember the past to predict the future

• Having a longer memory has several advantages:
  • can store and generate longer range patterns
  • especially ‘disconnected’ patterns like balanced quotes and brackets
  • more robust to ‘mistakes’
Long Short-Term Memory

- **LSTM** is an RNN architecture designed to have a better memory. It uses linear memory cells surrounded by multiplicative gate units to store read, write and reset information.

  - **Input gate**: scales input to cell (write)
  - **Output gate**: scales output from cell (read)
  - **Forget gate**: scales old cell value (reset)

Basic Architecture

- Deep recurrent LSTM net with skip connections
- Inputs arrive one at a time, outputs determine predictive distribution over next input
- Train by minimising log-loss:
  \[
  \sum_{t=1}^{T} -\log \Pr(x_t | x_{1:t-1})
  \]
- Generate by sampling from output distribution and feeding into input
Text Generation

• Task: generate text sequences one character at a time
• Data: raw wikipedia markup from Hutter challenge (100 MB)
• 205 inputs (unicode bytes), 205 way softmax output layer, 5 hidden layers of 700 LSTM cells, ~21M weights
• Split into length 100 sequences, no resets in between
• Trained with SGD, learn rate 0.0001, momentum 0.9
• Took forever!
## Compression Results

<table>
<thead>
<tr>
<th>Method</th>
<th>Bits per Character</th>
</tr>
</thead>
<tbody>
<tr>
<td>bzip2</td>
<td>2.32</td>
</tr>
<tr>
<td>M-RNN(^1)</td>
<td>1.6 (text only)</td>
</tr>
<tr>
<td><strong>deep LSTM</strong></td>
<td><strong>1.42</strong> (1.33 validation)</td>
</tr>
<tr>
<td>PAQ-8(^2)</td>
<td>1.28</td>
</tr>
</tbody>
</table>

1) I. Sutskever et. al. “Generating Text with Recurrent Neural Networks” ICML, 2011
Handwriting Generation

• Task: generate pen trajectories by predicting one (x,y) point at a time

• Data: IAM online handwriting, 10K training sequences, many writers, unconstrained style, captured from whiteboard

So you say to your neighbour,
would find the bus safe and sound
would be the vineyards

• First problem: how to predict real-valued coordinates?
Recurrent Mixture Density Networks

- Can model continuous sequences with RMDNs
- Suitably squashed output units parameterise a mixture distribution (usually Gaussian)
- Not just fitting Gaussians to data: every output distribution conditioned on all inputs so far

\[
Pr(o_t) = \sum_i w_i(x_{1:t}) N(o_t \mid \sigma_i(x_{1:t}), \Sigma_i(x_{1:t}))
\]

- For prediction, number of components is number of choices for what comes next

Network Details

- 3 inputs: $\Delta x$, $\Delta y$, pen up/down
- 121 output units
  - 20 two dimensional Gaussians for $x,y = 40$ means (linear) + 40 std. devs (exp) + 20 correlations (tanh) + 20 weights (softmax)
  - 1 sigmoid for up/down
- 3 hidden Layers, 400 LSTM cells in each
- 3.6M weights total
- Trained with RMSprop, learn rate 0.0001, momentum 0.9
- Error clipped during backward pass (lots of numerical problems)
- Trained overnight on fast multicore CPU
Samples
Handwriting Synthesis

• Want to tell the network *what* to write without losing the distribution over *how* it writes

• Can do this by conditioning the predictions on a text sequence

• **Problem**: alignment between text and writing unknown

• **Solution**: before each prediction, let the network decide *where* it is in the text sequence
Soft Windows

window vector (input to net)

\[ v^{t+1} = \sum_{i=1}^{S} w^t_i s_i \]

kernel weights (net outputs for a,b,c)

\[ w^t_i = \sum_{k=1}^{K} a^t_k \exp \left( -b^t_k [c^t_k - i]^2 \right) \]

input vectors (text)

\((s_1, \ldots, s_S)\)
Network Architecture
Alignment

Thought that the muster from
Which is Real?

that a doctor should be

that a doctor should be

that a doctor should be

that a doctor should be
Which is Real?

of present reality in remembering
of present reality in remembering
of present reality in remembering
of present reality in remembering
of present reality in remembering
Which is Real?

was an occasion worthy of his
was an occasion worthy of his
was an occasion worthy of his
was an occasion worthy of his
was an occasion worthy of his
was an occasion worthy of his
was an occasion worthy of his
was an occasion worthy of his
Unbiased Sampling

These sequences were generated by picking samples at every star. Every line is a different style. Yes, real people write this badly.
Biased Sampling

when the samples are biased towards more probable sequences they get easier to read but less interesting to look at.
Primed Sampling

when the sample study with real data
(prison welfare Officers complement)
if continues in the same style
(He dismissed the idea)
Synthesis Output Density
## Some Numbers

<table>
<thead>
<tr>
<th>Network</th>
<th>Δ Nats</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 layer tanh prediction</td>
<td>+1139(!)</td>
</tr>
<tr>
<td>1 layer prediction</td>
<td>+15</td>
</tr>
<tr>
<td>3 layer prediction (baseline)</td>
<td>0</td>
</tr>
<tr>
<td>3 layer synthesis</td>
<td>-56</td>
</tr>
<tr>
<td>3 layer synthesis + var. Bayes</td>
<td>-86</td>
</tr>
<tr>
<td>3 layer synthesis + text</td>
<td>-25</td>
</tr>
</tbody>
</table>
Where Next?

• Speech synthesis
• Better understanding of internal representation
• Learn high level features (strokes, letters, words...) rather than adding them manually
Thank You!