

## Final Project: Character-Level Language Modeling for Text Generation via Deep Markov Models

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### Remarks

We attempted to use a deep markov model (DMM) to make a character-level language model. This work is based on recent developments in the understanding of discrete time series, such as MIDI, as well as natural language processing. Using a DMM, we were able to generate text that yielded quantitative performance approaching state of the art for character-based language models. However, training remains unstable and more research into DMMs is likely required for their performance for language models to improve.

### Deep Markov Models

Traditional markov models are a method representing complex temporal dependencies in observed data. A markov model has a chain of latent variables, with each latent (or hidden) variable in the chain is conditioned on the previous latent variable. This is a useful approach, but if we want to represent complex data with complex dynamics, such as text, we would like to be able to model dynamics that are potentially highly non-linear.

This brings forth the idea of a deep markov model, wherein we allow the transition probabilities governing the dynamics of the latent variables as well as the emission probabilities that govern how the observations are generated by the latent dynamics to be parametrized by (non-linear) neural networks. DMMs were first used in the setting of polyphonic music generation. Using a MIDI representation of musical notes, Krishnan et. al were able to generate high-quality songs and learn a representation of electronic health record data [2].

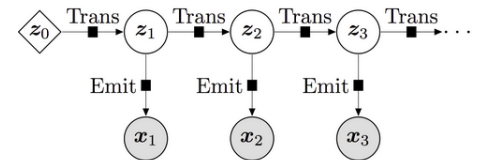


Figure 1: An illustration of a DMM. Each of the black squares represent an RNNs that determine the probability of emission or transmission. Image replicated from Pyro documentation [1]

Even though this method was originally designed for music generation, character-level language models can be thought of in a similar way. At each time step, music can be represented by an 88-dimensional binary vector. Similarly, characters in a phrase can be represented by a one-hot vector with a dimension given by the size of the learned dictionary. Research by the Harvard Intelligent Probabilistic Systems (HIPS) group takes a similar approach, using a neural network for both polyphonic music generation and character-level language modeling, the only change being the distribution from which the data is drawn from, the observation likelihood (Bernoulli vs categorical) [3]. HIPS uses a generative flow model for character-level language modelling as opposed to a DMM, however. The inference strategy we're going to use called variational inference (VI), which requires specifying a parametrized family of distributions that can be used to approximate the posterior distribution over the latent random variables. Due to the complex temporal relations we seek to model, we can expect the posterior distribution to be highly non-trivial, necessitating a probabilistic approach. Thus, we use PyTorch as

our choice of deep learning framework, as well as Pyro, a probabilistic programming language integrated into PyTorch to effectively sample and perform VI on our model.

### Implementation Details

We use a single-layer RNN for our emission and transmission probabilities. Our objective function is the ELBO (evidence-based lower bound) with a KL-annealing term  $\beta$ , inspired by [4].

$$\mathcal{F}(\theta, \phi, \beta; \mathbf{x}, \mathbf{z}) \geq \mathcal{L}(\theta, \phi; \mathbf{x}, \mathbf{z}) = \mathbb{E}_{q_{\phi}(\mathbf{z}|\mathbf{x})}[\log p_{\theta}(\mathbf{x}|\mathbf{z})] - \beta D_{KL}(q_{\phi}(\mathbf{z}|\mathbf{x})||p(\mathbf{z})) \quad (1)$$

We use Monte Carlo estimates of the KL divergence term.

We train the language model using the Penn Treebank (PTB) corpus. We perform treat every line in the corpus as a distinct sequence, or sentence, and tokenize each character in each sentence, adding the <unk> token for low-frequency or unknown words, and <eos> to demarcate the end of a sentence. The size of the dictionary was 52. In order to generate a character embedding, we simply encoded our character dictionary as a one-hot 52-dimensional vector. This was an appropriate choice due to the small dictionary size. We opt for a batch size of 16. For full details see [github.com/armaank/textDMM](https://github.com/armaank/textDMM) for the full codebase and the parameters used to train the network.

We found that using the entirety of the PTB dataset to be challenging for our language model. The longer the sentence used in the character level language model, the more difficult the model was to optimize. We found that limiting ourselves to sentences shorter than 50 characters significantly improved results. However, this would mean that the semantic quality of generated sentences would be reduced as the length of the sentence increases.

### Results & Discussion

Figure illustrates the negative log likelihood learning curve, showing that the model converges.



In order to see if our implementation is reasonable we compared our results to the numbers reported in [3] in Table 1

NLL Validation/Test Loss	
LSTM	1.38
AWD-LSTM	1.18
IAF	1.42
DMM	6.82

Table 1: This table compares the various results of state of the art character level language models. The results for the LSTM, AWD-LSTM and IAF come from [3]

The LSTM, AWD-LSTM and IAF are state of the art language models. These language models were able to train for much longer durations and were able to use a larger portion of the PTB dataset because they could use long sentences. Our results are fairly close to the others in terms of NLL loss, which appears to be the standard performance metric in character-level language modelling tasks.

Performance of the DMM might be improve by using a different method for KL annealing, which can improve stability during training. Furthermore, we use a Monte Carlo estimate of the KL divergence, leading to higher variance gradient estimates of the ELBO loss, which can also destabilize performance during early training periods. We might also trying using an LSTM architecture to parametrize our transmission and emission probabilities over the so-called ‘vanilla’ RNN. On a related note, one possibility is that exploding gradients are caused by lengthy input sequences, so one way to resolve this issue would be to only train on shorter sequences of characters.

## Conclusion

In conclusion, we were able to successfully train a DMM as a character-level language model and achieve strong performance. However, though more research is needed to improve DMMs for NLP tasks.

## References

- [1] “Deep markov model.” [Online]. Available: <https://pyro.ai/examples/dmm.html>
- [2] R. G. Krishnan, U. Shalit, and D. Sontag, “Structured inference networks for nonlinear state space models,” 2016.
- [3] Z. M. Ziegler and A. M. Rush, “Latent normalizing flows for discrete sequences,” 2019.
- [4] I. Higgins, L. Matthey, A. Pal, C. Burgess, X. Glorot, M. M. Botvinick, S. Mohamed, and A. Lerchner, “beta-vae: Learning basic visual concepts with a constrained variational framework,” in *ICLR*, 2017.

## Appendix A: Code

The code below is dmm.py, the main model code.

```

1  """dmm
2  """
3  import argparse
4  import os
5
6  import numpy as np
7  import torch
8  import torchtext
9  import pyro
10
11 import torch.nn as nn
12 import pyro.distributions as dist
13 import pyro.poutine as poutine
14
15 from torch.autograd import Variable
16 from pyro.distributions import TransformedDistribution
17
18 import utils
19
20
21 class Emitter(nn.Module):
22     """
23     parameterizes the categorical observation likelihood  $p(x_t|z_t)$ 
24     """
25
26     def __init__(self, input_dim, z_dim, emission_dim):
27         super().__init__()
28         """
29         initilize the fcns used in the network
30         """
31         self.lin_z_to_hidden = nn.Linear(z_dim, emission_dim)
32         self.lin_hidden_to_hidden = nn.Linear(emission_dim, emission_dim)
33         self.lin_hidden_to_input = nn.Linear(emission_dim, input_dim)
34         self.relu = nn.ReLU()
35
36         pass
37
38     def forward(self, z_t):
39         """
40         given  $z_t$ , compute the probabilities that parameterizes the categorical distribution  $p(x_t|z_t)$ 
41         """
42         h1 = self.relu(self.lin_z_to_hidden(z_t))
43         h2 = self.relu(self.lin_hidden_to_hidden(h1))
44         probs = torch.sigmoid(
45             self.lin_hidden_to_input(h2)
46         ) # might need to change to argmax, max?, softmax?
47

```

```

48     return probs
49
50
51 class GatedTransition(nn.Module):
52     """
53     parameterizes the gaussian latent transition probability  $p(z_t | z_{t-1})$ 
54     """
55
56     def __init__(self, z_dim, transition_dim):
57         super().__init__()
58         """
59         initilize the fcns used in the network
60         """
61         self.lin_gate_z_to_hidden = nn.Linear(z_dim, transition_dim)
62         self.lin_gate_hidden_to_z = nn.Linear(transition_dim, z_dim)
63         self.lin_proposed_mean_z_to_hidden = nn.Linear(z_dim, transition_dim)
64         self.lin_proposed_mean_hidden_to_z = nn.Linear(transition_dim, z_dim)
65         self.lin_sig = nn.Linear(z_dim, z_dim)
66         self.lin_z_to_loc = nn.Linear(z_dim, z_dim)
67
68         self.lin_z_to_loc.weight.data = torch.eye(z_dim)
69         self.lin_z_to_loc.bias.data = torch.zeros(z_dim)
70
71         self.relu = nn.ReLU()
72         self.softplus = nn.Softplus()
73
74     pass
75
76     def forward(self, z_t_1):
77         """
78         Given the latent  $z_{t-1}$  we return the mean and scale vectors that parameterize the
79         (diagonal) gaussian distribution  $p(z_t | z_{t-1})$ 
80         """
81         # compute the gating function
82         _gate = self.relu(self.lin_gate_z_to_hidden(z_t_1))
83         gate = torch.sigmoid(self.lin_gate_hidden_to_z(_gate))
84         # compute the 'proposed mean'
85         _proposed_mean = self.relu(self.lin_proposed_mean_z_to_hidden(z_t_1))
86         proposed_mean = self.lin_proposed_mean_hidden_to_z(_proposed_mean)
87         # assemble the actual mean used to sample  $z_t$ , which mixes a linear transformation
88         # of  $z_{t-1}$  with the proposed mean modulated by the gating function
89         loc = (1 - gate) * self.lin_z_to_loc(z_t_1) + gate * proposed_mean
90         # compute the scale used to sample  $z_t$ , using the proposed mean from
91         # above as input the softplus ensures that scale is positive
92         scale = self.softplus(self.lin_sig(self.relu(proposed_mean)))
93         # return loc, scale which can be fed into Normal
94         return loc, scale
95
96
97 class Combiner(nn.Module):
98     """

```

parameterizes  $q(z_t | z_{t-1}, x_{t:T})$ , which is the basic building block of the guide (i.e. the variational distribution). The dependence on  $x_{t:T}$  is through the hidden state of the RNN

"""

**def** \_\_init\_\_(self, z\_dim, rnn\_dim):

**super().\_\_init\_\_()**

    """

    initilize the fcns used in the network

    """

    self.lin\_z\_to\_hidden = nn.Linear(z\_dim, rnn\_dim)

    self.lin\_hidden\_to\_loc = nn.Linear(rnn\_dim, z\_dim)

    self.lin\_hidden\_to\_scale = nn.Linear(rnn\_dim, z\_dim)

    self.tanh = nn.Tanh()

    self.softplus = nn.Softplus()

**pass**

**def** forward(self, z\_t\_1, h\_rnn):

    """

    Given the latent  $z_{t-1}$  at a particular time as well as the hidden state of the RNN  $h(x_{t:T})$  we return the mean and scale vectors that parameterize the (diagonal) gaussian distribution  $q(z_t | z_{t-1}, x_{t:T})$

    """

    # combine the rnn hidden state with a transformed version of  $z_{t-1}$

    h\_combined = 0.5 \* (self.tanh(self.lin\_z\_to\_hidden(z\_t\_1)) + h\_rnn)

    # use the combined hidden state to compute the mean used to sample  $z_t$

    loc = self.lin\_hidden\_to\_loc(h\_combined)

    # use the combined hidden state to compute the scale used to sample  $z_t$

    scale = self.softplus(self.lin\_hidden\_to\_scale(h\_combined))

    # return loc, scale which can be fed into Normal

**return** loc, scale

**class** DMM(nn.Module):

    """

    module for the model and the guide (variational distribution) for the DMM

    """

**def** \_\_init\_\_(

    self,

    input\_dim=52,

    z\_dim=100,

    emission\_dim=100,

    transition\_dim=200,

    rnn\_dim=600,

    num\_layers=1,

    dropout=0.0,

):

**super().\_\_init\_\_()**

    """

```

150     instantiate modules used in the model and guide
151     """
152     self.emitter = Emitter(input_dim, z_dim, emission_dim)
153     self.transition = GatedTransition(z_dim, transition_dim)
154     self.combiner = Combiner(z_dim, rnn_dim)
155
156     if num_layers == 1:
157         rnn_dropout = 0.0
158     else:
159         rnn_dropout = dropout
160
161     self.rnn = nn.RNN(
162         input_size=input_dim,
163         hidden_size=rnn_dim,
164         nonlinearity="relu",
165         batch_first=True,
166         bidirectional=False,
167         num_layers=num_layers,
168         dropout=rnn_dropout,
169     )
170     """
171     define learned parameters that define the probability distributions  $P(z_{1:T})$  and  $q(z_{1:T})$  and hidden
state of rnn
172     """
173     self.z_0 = nn.Parameter(torch.zeros(z_dim))
174     self.z_q_0 = nn.Parameter(torch.zeros(z_dim))
175     self.h_0 = nn.Parameter(torch.zeros(1, 1, rnn_dim))
176
177     self.cuda()
178
179     pass
180
181 def model(self, batch, reversed_batch, batch_mask, batch_seqLens, kl_anneal=1.0):
182     """
183     the model defines  $p(x_{1:T}|z_{1:T})$  and  $p(z_{1:T})$ 
184     """
185     # maximum duration of batch
186     Tmax = batch.size(1)
187
188     # register torch submodules w/ pyro
189     pyro.module("dmm", self)
190
191     # setup recursive conditioning for  $p(z_t|z_{1:t-1})$ 
192     z_prev = self.z_0.expand(batch.size(0), self.z_0.size(0))
193
194     # sample conditionally independent text across the batch
195     with pyro.plate("z_batch", len(batch)):
196         # sample latent vars z and observed x w/ multiple samples from the guide for each z
197         for t in pyro.markov(range(1, Tmax + 1)):
198
199             # compute params of diagonal gaussian  $p(z_t|z_{1:t-1})$ 

```

```

200         z_loc, z_scale = self.transition(z_prev)
201
202         # sample latent variable
203         with poutine.scale(scale=kl_anneal):
204             z_t = pyro.sample(
205                 "z_%d" % t,
206                 dist.Normal(z_loc, z_scale)
207                 .mask(batch_mask[:, t - 1 : t])
208                 .to_event(1),
209             )
210
211         # compute emission probability from latent variable
212         emission_prob = self.emitter(z_t)
213
214         # observe x_t according to the Categorical distribution defined by the emitter
215         probability
216         pyro.sample(
217             "obs_x_%d" % t,
218             dist.OneHotCategorical(emission_prob)
219             .mask(batch_mask[:, t - 1 : t])
220             .to_event(1),
221             obs=batch[:, t - 1, :],
222         )
223
224         # set conditional var for next time step
225         z_prev = z_t
226     pass
227
228 def guide(self, batch, reversed_batch, batch_mask, batch_seqlens, kl_anneal=1.0):
229     """
230     the guide defines the variational distribution  $q(z_{1:T}|x_{1:T})$ 
231     """
232     # maximum duration of batch
233     Tmax = batch.size(1)
234
235     # register torch submodules w/ pyro
236     pyro.module("dmm", self)
237
238     # to parallelize, we broadcast rnn into contiguous gpu memory
239     h_0_contig = self.h_0.expand(
240         1, batch.size(0), self.rnn.hidden_size
241     ).contiguous()
242
243     # push observed sequence through rnn
244     rnn_output, _ = self.rnn(reversed_batch, h_0_contig)
245
246     # reverse and unpack rnn output
247     rnn_output = utils.pad_and_reverse(rnn_output, batch_seqlens)
248
249     # setup recursive conditioning
250     z_prev = self.z_q_0.expand(batch.size(0), self.z_q_0.size(0))

```



```
250
251 with pyro.plate("z_batch", len(batch)):
252
253     for t in pyro.markov(range(1, Tmax + 1)):
254
255         z_loc, z_scale = self.combiner(z_prev, rnn_output[:, t - 1, :])
256
257         z_dist = dist.Normal(z_loc, z_scale)
258         assert z_dist.event_shape == ()
259         assert z_dist.batch_shape[-2:] == (len(batch), self.z_q_0.size(0))
260
261         # sample z_t from distribution z_dist
262         with pyro.poutine.scale(scale=kl_anneal):
263             z_t = pyro.sample(
264                 "z_%d" % t, z_dist.mask(batch_mask[:, t - 1 : t]).to_event(1)
265             )
266
267         # set conditional var for next time step
268         z_prev = z_t
269
270     pass
```

The code below is train.py, the main code used to perform training and evaluation.

```

1  """train
2  """
3  import os
4  import random
5  import time
6
7  import numpy as np
8  import pyro
9  import torch
10
11 import torchtext
12
13 from torch import nn
14
15 from pyro.infer import SVI, Trace_ELBO
16 from pyro.optim import ClippedAdam
17 from torch.autograd import Variable
18
19 import utils
20 import datahandler
21 from dmm import DMM
22
23
24 class Trainer(object):
25     """
26     trainer class used to instantiate, train and validate a network
27     """
28
29     def __init__(self, args):
30
31         # argument gathering
32         self.rand_seed = args.rand_seed
33         self.dev_num = args.dev_num
34         self.cuda = args.cuda
35         self.n_epoch = args.n_epoch
36         self.batch_size = args.batch_size
37         self.lr = args.lr
38         self.beta1 = args.beta1
39         self.beta2 = args.beta2
40         self.wd = args.wd
41         self.cn = args.cn
42         self.lr_decay = args.lr_decay
43         self.kl_ae = args.kl_ae
44         self.maf = args.maf
45         self.dropout = args.dropout
46         self.ckpt_f = args.ckpt_f
47         self.load_opt = args.load_opt
48         self.load_model = args.load_model
49         self.save_opt = args.save_opt
50         self.save_model = args.save_model

```

```

51     self.maxlen = args.maxlen
52     # setup logging
53     self.log = utils.get_logger(args.log)
54     self.log(args)
55
56     def _validate(self, val_iter):
57         """
58         freezes training and validates on the network with a validation set
59         """
60         # freeze training
61         self.dmm.rnn.eval()
62         val_nll = 0
63         for ii, batch in enumerate(iter(val_iter)):
64
65             batch_data = Variable(batch.text[0].to(self.device))
66             seqLens = Variable(batch.text[1].to(self.device))
67
68             # transpose to [B, seqLen, vocab_size] shape
69             batch_data = torch.t(batch_data)
70             # compute one hot character embedding
71             batch_onehot = nn.functional.one_hot(batch_data, self.vocab_size).float()
72             # flip sequence for rnn
73             batch_reversed = utils.reverse_seq(batch_onehot, seqLens)
74             batch_reversed = nn.utils.rnn.pack_padded_sequence(
75                 batch_reversed, seqLens, batch_first=True
76             )
77             # compute temporal mask
78             batch_mask = utils.generate_batch_mask(batch_onehot, seqLens).cuda()
79             # perform evaluation
80             val_nll += self.svi.evaluate_loss(
81                 batch_onehot, batch_reversed, batch_mask, seqLens
82             )
83
84             # resume training
85             self.dmm.rnn.train()
86
87             loss = val_nll / self.N_val_data
88
89             return loss
90
91     def _train_batch(self, train_iter, epoch):
92         """
93         process a batch (single epoch)
94         """
95         batch_loss = 0
96         epoch_loss = 0
97         for ii, batch in enumerate(iter(train_iter)):
98
99             batch_data = Variable(batch.text[0].to(self.device))
100             seqLens = Variable(batch.text[1].to(self.device))
101

```

```

102     # transpose to [B, seqlen, vocab_size] shape
103     batch_data = torch.t(batch_data)
104     # compute one hot character embedding
105     batch_onehot = nn.functional.one_hot(batch_data, self.vocab_size).float()
106     # flip sequence for rnn
107     batch_reversed = utils.reverse_seq(batch_onehot, seqLens)
108     batch_reversed = nn.utils.rnn.pack_padded_sequence(
109         batch_reversed, seqLens, batch_first=True
110     )
111     # compute temporal mask
112     batch_mask = utils.generate_batch_mask(batch_onehot, seqLens).cuda()
113
114     # compute kl-div annealing factor
115     if self.kl_ae > 0 and epoch < self.kl_ae:
116         min_af = self.maf
117         kl_anneal = min_af + (1 - min_af) * (
118             float(ii + epoch * self.N_batches + 1)
119             / float(self.kl_ae * self.N_batches)
120         )
121     else:
122         # default kl-div annealing factor is unity
123         kl_anneal = 1.0
124
125     # take gradient step
126     batch_loss = self.svi.step(
127         batch_onehot, batch_reversed, batch_mask, seqLens, kl_anneal
128     )
129     batch_loss = batch_loss / (torch.sum(seqLens).float())
130     print("loss at iteration {0} is {1}".format(ii, batch_loss))
131     epoch_loss = epoch_loss + batch_loss
132
133     return epoch_loss
134
135 def train(self):
136     """
137     trains a network with a given training set
138     """
139     self.device = torch.device("cuda")
140     np.random.seed(self.rand_seed)
141     torch.manual_seed(self.rand_seed)
142
143     train, val, test, vocab = datahandler.load_data("./data/ptb", self.maxlen)
144
145     self.vocab_size = len(vocab)
146
147     # make iterable dataset object
148     train_iter, val_iter, test_iter = torchtext.data.BucketIterator.splits(
149         (train, val, test),
150         batch_sizes=[self.batch_size, 1, 1],
151         device=self.device,
152         repeat=False,

```

```

153         sort_key=lambda x: len(x.text),
154         sort_within_batch=True,
155     )
156     self.N_train_data = len(train)
157     self.N_val_data = len(val)
158     self.N_batches = int(
159         self.N_train_data / self.batch_size
160         + int(self.N_train_data % self.batch_size > 0)
161     )
162
163     self.N_train_data = len(train)
164     self.N_val_data = len(val)
165     self.N_batches = int(
166         self.N_train_data / self.batch_size
167         + int(self.N_train_data % self.batch_size > 0)
168     )
169     self.log("N_train_data: %d N_mini_batches: %d" % (self.N_train_data, self.N_batches) )
170
171
172     # instantiate the dmm
173     self.dmm = DMM(input_dim=self.vocab_size, dropout=self.dropout)
174
175     # setup optimizer
176     opt_params = {
177         "lr": self.lr,
178         "betas": (self.beta1, self.beta2),
179         "clip_norm": self.cn,
180         "lrd": self.lr_decay,
181         "weight_decay": self.wd,
182     }
183     self.adam = ClippedAdam(opt_params)
184     # set up inference algorithm
185     self.elbo = Trace_ELBO()
186     self.svi = SVI(self.dmm.model, self.dmm.guide, self.adam, loss=self.elbo)
187
188     val_f = 10
189
190     print("training dmm")
191     times = [time.time()]
192     for epoch in range(self.n_epoch):
193
194         if self.ckpt_f > 0 and epoch > 0 and epoch % self.ckpt_f == 0:
195             self.save_ckpt()
196
197         # train and report metrics
198         train_nll = self._train_batch(train_iter, epoch,)
199
200         times.append(time.time())
201         t_elps = times[-1] - times[-2]
202         self.log(
203             "epoch %04d -> train nll: %.4f \t t_elps=%.3f sec"

```

```

204         % (epoch, train_nll, t_elps)
205     )
206
207     if epoch % val_f == 0:
208         val_nll = self._validate(val_iter)
209     pass
210
211 def save_ckpt(self):
212     """
213     saves the state of the network and optimizer for later
214     """
215     self.log("saving model to %s" % self.save_model)
216     torch.save(self.dmm.state_dict(), self.save_model)
217     self.log("saving optimizer states to %s" % self.save_opt)
218     self.adam.save(self.save_opt)
219
220     pass
221
222 def load_ckpt(self):
223     """
224     loads a saved checkpoint
225     """
226     assert exists(args.load_opt) and exists(
227         args.load_model
228     ), "--load-model and/or --load-opt misspecified"
229     self.log("loading model from %s..." % self.load_model)
230     self.dmm.load_state_dict(torch.load(self.load_model))
231     self.log("loading optimizer states from %s..." % self.load_opt)
232     self.adam.load(self.load_opt)
233
234     pass

```