

On the Equivalence between Deep NADE and Generative Stochastic Networks

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Abstract. Neural Autoregressive Distribution Estimators (NADEs) have recently been shown as successful alternatives for modeling high dimensional multimodal distributions. One issue associated with NADEs is that they rely on a particular order of factorization for $P(\mathbf{x})$. This issue has been recently addressed by a variant of NADE called Orderless NADEs and its deeper version, Deep Orderless NADE. Orderless NADEs are trained based on a criterion that stochastically maximizes $P(\mathbf{x})$ with all possible orders of factorizations. Unfortunately, ancestral sampling from deep NADE is very expensive, corresponding to running through a neural net separately predicting each of the visible variables given some others. This work makes a connection between this criterion and the training criterion for Generative Stochastic Networks (GSNs). It shows that training NADEs in this way also trains a GSN, which defines a Markov chain associated with the NADE model. Based on this connection, we show an alternative way to sample from a trained Orderless NADE that allows to trade-off computing time and quality of the samples: a 3 to 10-fold speedup (taking into account the waste due to correlations between consecutive samples of the chain) can be obtained without noticeably reducing the quality of the samples. This is achieved using a novel sampling procedure for GSNs called annealed GSN sampling, similar to tempering methods that combines fast mixing (obtained thanks to steps at high noise levels) with accurate samples (obtained thanks to steps at low noise levels).

1 Introduction

Unsupervised representation learning and deep learning have progressed rapidly in recent years [5]. On one hand, supervised deep learning algorithms have achieved great success. The authors of [15], for instance, claimed the state-of-the-art recognition performance in a challenging object recognition task using a deep convolutional neural network. Despite the promise given by supervised deep learning, its unsupervised counterpart is still facing several challenges [3]. A large proportion of popular unsupervised deep learning models are based on either directed or undirected graphical models with latent variables [12, 13, 20]. One problem of these unsupervised models is that it is often intractable to compute the likelihood of a model exactly.

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The Neural Autoregressive Distribution Estimator (NADE) was proposed in [16] to avoid this problem of computational intractability. It was inspired by the early work in [4], which like NADE modeled a binary distribution by decomposing it into a product of multiple conditional distributions of which each is implemented by a neural network, with parameters, representations and computations shared across all these networks. These kinds of models therefore implement a fully connected directed graphical model, in which ancestral sampling of the joint distribution is simple (but not necessarily efficient when the number of variables, e.g., pixel images, is large). Consequently, unlike many other latent variable models, it is possible with such directed graphical models to compute the exact probability of an observation tractably. NADEs have since been extended to model distributions of continuous variables in [23], called a real-valued NADE (RNADE) which replaces a Bernoulli distribution with a mixture of Gaussian distributions for each conditional probability (see, e.g., [9]). The authors of [22] proposes yet another variant of NADE, called a Deep NADE, that uses a *deep* neural network to compute the conditional probability of each variable. In order to make learning tractable, they proposed a modified training procedure that effectively trains an ensemble of multiple NADEs.

Another thread of unsupervised deep learning is based on the family of autoencoders (see, e.g., [25]). The autoencoder has recently begun to be understood as a density estimator [1, 7]. These works suggest that an autoencoder trained with some arbitrary noise in the input is able to learn the distribution of either continuous or discrete random variables. This perspective on autoencoders has been further extended to a generative stochastic network (GSN) proposed in [6].

Unlike a more conventional approach of directly estimating the probability distribution of data, a GSN aims to learn a transition probability of a Markov Chain Monte Carlo (MCMC) sampler whose stationary distribution estimates the data generating distribution. The authors of [6] were able to show that it is possible to learn the distribution of data with a GSN having a network structure inspired by a deep Boltzmann machine (DBM) [21] using this approach. Furthermore, a recently proposed multi-prediction DBM (MP-DBM) [11], which models the joint distribution of data instance and its label, can be considered a special case of a GSN and achieves state-of-the-art classification performance on several datasets.

In this paper, we find a close relationship between the deep NADE and the GSN. We show that training a deep NADE with the order-agnostic (OA) training procedure [22] can be cast as GSN training. This equivalence allows us to have an alternative theoretical explanation of the OA training procedure. Also, this allows an alternative sampling procedure for a deep NADE based on a MCMC method, rather than ancestral sampling.

In Sec. 2.1 and Sec. 3, we describe both NADE and GSN in detail. Based on these descriptions we establish the connection between the order-agnostic training procedure for NADE and the training criterion of GSN in Sec. 4 and propose a novel sampling algorithm for deep NADE. In Sec. 5, we introduce a novel sampling strategy for GSN called annealed GSN sampling, which is inspired

by tempering methods and does a good trade-off between computing time and accuracy. We empirically investigate the effect of the proposed GSN sampling procedure for deep NADE models in Sec. 6.

2 Deep NADE and Order-Agnostic Training

In this section we describe the deep NADE and its training criterion, closely following [22].

2.1 NADE

NADE [16] models a joint distribution $p(\mathbf{x})$ where $\mathbf{x} \in \mathbb{R}^D$. D is the dimensionality of \mathbf{x} . NADE factorizes $p(\mathbf{x})$ into

$$p(\mathbf{x}) = \prod_{d=1}^D p(x_{o_d} | \mathbf{x}_{o_{<d}}) \quad (1)$$

where o is a predefined ordering of D indices. $o_{<d}$ denotes the first $d - 1$ indices of the ordering o .

The NADE then models each factor in Eq. (1) with a neural network having a single hidden layer H . That is,

$$p(x_{o_d} = 1 | \mathbf{x}_{o_{<d}}) = \sigma(\mathbf{V}_{\cdot, o_d} \mathbf{h}_d + b_{o_d}),$$

where

$$\mathbf{h}_d = \phi(\mathbf{W}_{\cdot, o_{<d}} + \mathbf{c}).$$

$\mathbf{V} \in \mathbb{R}^{H \times D}$, $b \in \mathbb{R}^D$, $\mathbf{W} \in \mathbb{R}^{H \times D}$ and $\mathbf{c} \in \mathcal{R}^H$ are the output weights, the output biases, the input weights and the hidden biases, respectively. σ is a logistic sigmoid function, and ϕ can be any nonlinear activation function.

To train such a model, one maximizes the log-likelihood function of the training set

$$\theta^* = \arg \max_{\theta} \mathcal{L}_o(\theta) = \arg \max_{\theta} \frac{1}{N} \sum_{n=1}^N \sum_{d=1}^D \log p(x_{o_d}^n | \mathbf{x}_{o_{<d}}^n, o), \quad (2)$$

where θ denotes all the parameters of the model.

2.2 Deep NADE

One issue with the original formulation of the NADE is that the ordering of variables needs to be predefined and fixed. Potentially, this limits the inference capability of a trained model such that when the model is asked to infer the conditional probability which is not one of the factors in the predefined factorization (See Eq. (1)). For instance, a NADE trained with D visible variables with

an ordering $(1, 2, \dots, D)$, one cannot easily infer $x_2 \| x_1, x_D$ except by expensive (and intractable) marginalization over all the other variables.

Another issue is that it is not possible to build a deeper architecture for NADE with the original formulation without losing a lot in efficiency. When there is only a single hidden layer with H units in the neural network modeling each conditional probability of a NADE, it is possible to share the parameters (the input weights and the hidden biases) to keep the computational complexity linear with respect to the number of parameters, i.e., $O(DH)$. However, if there are more than one hidden layers, it is not possible to re-use computations in the same way. In this case, the computational complexity is $O(DH + DH^2L)$ where L is the number of hidden layers. Notice the extra D factor in front, compared to the number of parameters which is $O(DH + H^2L)$. This comes about because we cannot re-use the computations performed after the first hidden layer for predicting the i -th variable, when predicting the following ones. In the one-layer case, this sharing is possible because the hidden units weighted sums needed when predicting the $i + 1$ -th variable are the same as the weighted sums needed when predicting the i -th variable, plus the scalar contributions w_{ki} associated with the k -th hidden unit and the extra input x_i that is now available when predicting x_{i+1} but was not available when predicting x_i .

To resolve those two issues, the authors of [22] proposed the order-agnostic (OA) training procedure that trains a factorial number of NADEs with shared parameters. In this case, the following objective function is maximized, instead of \mathcal{L}_o in Eq. (2):

$$\mathcal{L}(\theta) = \mathbb{E}_{\mathbf{x}^n} \sum_{d=1}^D \mathbb{E}_{o < d} \mathbb{E}_{o_d} \log p(x_{o_d}^n | \mathbf{x}_{o < d}^n, \theta, o). \quad (3)$$

This objective function is, however, intractable, since it involves the factorial number of summations. Instead, in practice, when training, we use a stochastic approximation $\widehat{\mathcal{L}}$ by sampling an ordering o , the index of predicted variable d and a training sample \mathbf{x}^n at each time:

$$\widehat{\mathcal{L}}(\theta) = \frac{D}{D-d+1} \sum_{i \notin o < d} \log p(x_i^n | \mathbf{x}_{o < d}^n, \theta, o). \quad (4)$$

Computing $\widehat{\mathcal{L}}$ is identical to a forward computation in a regular feedforward neural network except for two differences. Firstly, according to the sampled ordering o , the input variables of indices $o > d$ are set to 0, and the identity of the zeroed indices is provided as extra inputs (through a binary vector of length D). Secondly, the conditional probabilities of only those variables of indices $o > d$ are used to compute the objective function $\widehat{\mathcal{L}}$.

This order-agnostic procedure solves the previously raised issues of the original NADE. Since the model is optimized for all possible orderings, it does not suffer from being inefficient at inferring any conditional probability. Furthermore, the lack of predefined ordering makes it possible to use a single set of parameters for modeling all conditional distributions. Thus, the computational cost of training

a deep NADE with the OA procedure is linear with respect to the number of parameters, regardless of the depth of each neural network.

From here on, we call a NADE trained with the OA procedure simply a deep NADE to distinguish it from a NADE trained with a usual training algorithm other than the OA procedure.

3 Generative Stochastic Networks

In [6, 7] a new family of models called generative stochastic networks (GSN) was proposed, which tackles the problem of modeling a data distribution, $p(\mathbf{x})$, although without providing a tractable expression for it.

The underlying idea is to learn a transition operator of a Markov Chain Monte Carlo (MCMC) sampler that samples from the distribution $p(\mathbf{x})$, instead of learning the whole distribution directly. If we let $p(\mathbf{x}' | \mathbf{x})$ be the transition operator, then we may rewrite it by introducing a latent variable h into

$$p(\mathbf{x}' | \mathbf{x}) = \sum_{\forall \mathbf{h}} p(\mathbf{x}' | \mathbf{h})p(\mathbf{h} | \mathbf{x}). \quad (5)$$

In other words, two separate conditional distributions $p(\mathbf{x}' | \mathbf{h})$ and $p(\mathbf{h} | \mathbf{x})$ jointly define the transition operator. In [6, 7] it is argued that it is easier to learn these simpler conditional distributions because they have less modes (they only consider small changes from the previous state), meaning that the associated normalization constants can be estimated more easily (either by an approximate parametrization, e.g., a single or few component mixture, or by MCMC on a more powerful parametrization, which will have less variance if the number of modes is small).

A special form of GSN also found with denoising auto-encoders predefines $p(\mathbf{h} | \mathbf{x})$ such that it does not require learning from data. Then, we only learn $p(\mathbf{x}' | \mathbf{h})$. This is the case in [7], where they proposed to use a user-defined corruption process, such as randomly masking out some variables with a fixed probability, for $p(\mathbf{h} | \mathbf{x})$. They, then, estimated $p(\mathbf{x}' | \mathbf{h})$ as a denoising auto-encoder f_θ , parameterized with θ , that reverses the corruption process $p(\mathbf{h} | \mathbf{x})$ [24].

It was shown in [7] that if the denoising process f_θ is a consistent estimator of $p(\mathbf{x}' | \mathbf{h})$, this leads to consistency of the Markov chain's stationary distribution as an estimator of the data generating distribution. This is under some conditions ensuring the irreducibility, ergodicity and aperiodicity of the Markov chain, i.e., that it mixes. In other words, training f_θ to match $p(\mathbf{x}' | \mathbf{h})$ is enough to learn implicitly the whole distribution $p(\mathbf{x})$, albeit indirectly, i.e., through the definition of a Markov chain transition operator. The result from [6] further suggests that it is possible to also parameterize the corruption process $p(\mathbf{h} | \mathbf{x})$ and learn both $p(\mathbf{h} | \mathbf{x})$ and $p(\mathbf{x}' | \mathbf{h})$ together.

From the qualitative observation on some of the learned transition operators of GSNs (see, e.g., [6]), it is clear that the learned transition operator quickly finds a plausible mode in the whole distribution, even when the Markov chain

was started from a random configuration of \mathbf{x} . This is because the GSN reconstruction criterion encourages the learner to quickly move from low probability configurations to high-probability ones, i.e., to burn-in quickly. This is in contrast to using a Gibbs sampler to generate samples from other generative models that explicitly model the whole distribution $p(\mathbf{x})$, which requires often many more *burn-in* steps before the Markov chain finds a plausible mode of the distribution.

4 Equivalence between Deep NADE and GSN

Having described both deep NADE and GSN, we now establish the relationship, or even equivalence, between them. In particular, we show in this section that the order-agnostic (OA) training procedure for NADE is one special case of GSN learning.

We start from the stochastic approximation to the objective function of the OA training procedure for deep NADE in Eq. (4). We notice that the sampled ordering o in the objective function $\hat{\mathcal{L}}$ can be replaced with another random variable $\mathbf{m} \in \{0, 1\}^D$, where D is the dimensionality of an observation x . The binary mask \mathbf{m} is constructed such that

$$m_i = \begin{cases} 1, & \text{if } i \in o_{<d} \\ 0, & \text{otherwise} \end{cases}$$

Then, we rewrite Eq. (4) by

$$\begin{aligned} \hat{\mathcal{L}}(\theta) &\propto \sum_{i=1}^D (1 - m_i) \log p(x_i^n \mid \mathbf{m} \odot \mathbf{x}^n, \theta, \mathbf{m}) \\ &= \sum_{i=1}^D \log (m_i + (1 - m_i)p(x_i^n \mid \mathbf{m} \odot \mathbf{x}^n, \theta, \mathbf{m})) \\ &= \sum_{i=1}^D \log (m_i + (1 - m_i)p(x_i^n \mid \mathbf{h}^{(n)}, \theta)) \end{aligned} \tag{6}$$

where m_i is the i -th element of the binary mask \mathbf{m} , and \odot is an element-wise multiplication. We introduced a new variable $\mathbf{h} = [\mathbf{m}, \mathbf{m} \odot \mathbf{x}^n] \in \mathbb{R}^{2D}$ which is a concatenation of the corrupted copy (some variables masked out) of \mathbf{x}^n and the sampled mask \mathbf{m} .

It is now easy to see the connection between the objective function of the OA training procedure in Eq. (6) to a GSN training criterion using a user-defined (not learned) corruption process which we described in the earlier section.

In this case, the corruption process $p(\mathbf{h} \mid \mathbf{x})$ (Eq. (5)) is

$$p(\mathbf{h} \mid \mathbf{x}) = p([\mathbf{m}, \mathbf{m} \odot \mathbf{x}] \mid \mathbf{x}) = \prod_{i=1}^D k \prod_{j=1}^D \delta_{m_j x_j}(h_{j+D}), \tag{7}$$

where k is a random number sampled uniformly between 0 and 1, and $\delta_\mu(a)$ is a shifted Dirac delta function which is 1 only when $a = \mu$ and 0 otherwise. This means that sampling is done by first generating an uniformly random binary mask \mathbf{m} and then taking $\mathbf{m} \odot \mathbf{x}$ as the corrupted version of \mathbf{x} .

The conditional probability of \mathbf{x}' given \mathbf{h} is

$$p(\mathbf{x}' | \mathbf{h}) = \prod_{i=1}^D [m_i \delta_{x_i}(x'_i) + (1 - m_i) p(x'_i | r_i(\mathbf{x} \odot \mathbf{m} | \theta))], \quad (8)$$

where r_i is a parametric function (neural network) that models the conditional probability.

If we view the estimation of $p(\mathbf{x}' | \mathbf{h})$ in Eq. (8) as a denoising autoencoder, one effectively ignores each variable x'_i with its mask m_i set to 1, since the sample of x'_i from Eq. (8) is always x_i due to $\delta_{x_i}(x'_i)$. A high-capacity auto-encoder could learn that when $m_i = 1$, it can just copy the i -th input to the i -th output. On the other hand, when m_i is 0, training this denoising autoencoder would maximize $\log p(x'_i | r_i(\mathbf{x} \odot \mathbf{m} | \theta))$, making it assign high probability to the original x_i given the non-missing inputs. Therefore, maximizing the logarithm of $p(\mathbf{x}' | \mathbf{h})$ in Eq. (8) is equivalent to maximizing \widehat{L} in Eqs. (6) and (4) up to a constant.

In essence, maximizing \widehat{L} in Eq. (4) is equivalent to training a GSN with the conditional distributions defined in Eqs. (7)–(8). Furthermore, the chain defined in this way is ergodic as every state \mathbf{x} has a non-zero probability at each step ($\mathbf{x} \rightarrow \mathbf{x}'$), making this GSN chain a valid MCMC sampler.

4.1 Alternative Sampling Method for NADE

Although the training procedure of the deep NADE introduced in [22] is order-agnostic, sampling from the deep NADE is not.

The authors of [22] proposed an ancestral sampling method for a deep NADE. Firstly, one randomly selects an ordering uniformly from all possible orderings. One generates a sample of each variable from its conditional distribution following the selected ordering. When D , H and L are respectively the dimensionality of the observation variable, the number of hidden units in each hidden layer and the number of layers, the time complexity of sampling a single sample using this ancestral approach is $O(DLH^2)$.

We propose here an alternative sampling strategy based on our observation of the equivalence between the deep NADE and GSN. The new strategy is simply to alternating between sampling from $p(\mathbf{h} | \mathbf{x})$ in Eq. (7) and $p(\mathbf{x}' | \mathbf{h})$ in Eq. (8), which corresponds to performing Markov Chain Monte Carlo (MCMC) sampling on $p(\mathbf{x})$. The computational complexity of a single step ($\mathbf{x} \rightarrow \mathbf{h} \rightarrow \mathbf{x}'$) in this case is $O(DH + LH^2)$.

Unlike the original ancestral strategy, the proposed approach does not generate an exact sample in a single step. Instead, one often needs to run the chain K steps until the exact, independent sample from the stationary distribution of

the chain is collected, which we call *burn-in*. In other words, the new approach requires $O(KDH + KLH^2)$ to collect a single sample in the worst case.¹

If we assume that H is not too larger than D ($H = O(D)$ or $H = \Theta(D)$), which is an usual practice, the time complexity of the ancestral approach is $O(D^3)$, and that of the proposed GSN approach is $O(KD^2)$, where we further assume that L is a small constant. Effectively, if the MCMC method used in the latter strategy requires only a small, controllable number K of steps to generate a single exact, independent sample such that $K \ll D$, the new approach is more efficient in collecting samples from a trained deep NADE. Importantly, as we have already mentioned earlier, a GSN has been shown to learn a transition operator of an MCMC method that requires only a small number of burn-in steps.

In the experiments, we investigate empirically whether this new sampling strategy is computationally more efficient than the original ancestral approach in a realistic setting.

4.2 The GSN Chain Averages an Ensemble of Density Estimators

As discussed in [22], maximizing $\widehat{\mathcal{L}}$ in Eq. (3) can be considered as training a factorial number of different NADEs with shared parameters. Each NADE differs from each other by the choice of the ordering of variables and may assign a different probability to the same observation.² Based on this observation, it is suggested in [22] to use the average of the assigned probabilities by all these NADE, or a small randomly chosen subset of them, as the actual probability.

This interpretation of seeing the deep NADE as an ensemble of multiple NADEs and our earlier argument showing that the deep NADE training is special case of GSN training naturally leads to a question: *does the GSN Markov chain average an ensemble of density/distribution estimators?*

We claim that the answer is yes. From the equivalence we showed in this paper, it is clear that a GSN trained with a criterion such as the NADE criterion *learns* an ensemble of density/distribution estimators (in this case, masking noise with the reconstruction conditional distribution in Eq. (8)). Furthermore, when one samples from the associated GSN Markov chain, one is averaging the contributions associated with different orders. So, although each of these conditionals (predicting a subset given another subset) may not be consistent with a single joint distribution, the associated GSN Markov chain which combines them randomly does define a clear joint distribution: the stationary distribution of the Markov chain. Clearly, this stationary distribution is an ensemble average over all the possible orderings.

¹ Since it is a usual practice to collect every t -th samples from the same chain, where $t \ll K$, we often do not need KN steps to collect N samples.

² The fact that all ensembles share the exact same parameters makes it similar to the recently proposed technique of dropout [14].

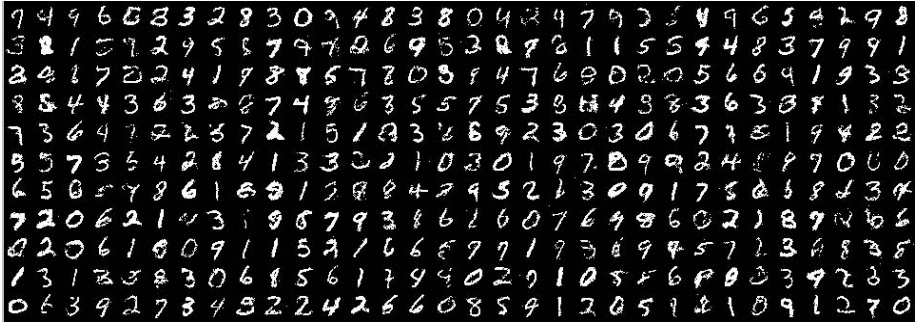


Fig. 1. Independent samples generated by the ancestral sampling procedure from the deep NADE

5 Annealed GSN Sampling

With the above proposal for GSN-style sampling of a Deep NADE model, one can view the average fraction p of input variables that are resampled at each step as a kind of noise level, or the probability of resampling any particular visible variable x_i . With uniform sampling of subsets, we obtain $p = 0.5$, but both higher and lower values are possible. When $p = 1$, all variables are resampled independently and the resulting samples are coming from the marginal distributions of each variable, which would be a very poor rendering of the Deep NADE distribution, but would mix very well. With p as small as possible (or more precisely, resampling only one randomly chosen variable given the others), we obtain a *Gibbs sampler* associated with the Deep NADE distribution, which we know has the same stationary distribution as Deep NADE itself. However, this would mix very slowly and would not bring any computational gain over ancestral sampling in the Deep NADE model (in fact it would be considerably worse because the correlation between consecutive samples would reduce the usefulness of the Markov chain samples, compared to ancestral sampling that provides i.i.d. samples). With intermediate values of p , we obtain a compromise between the fast computation and the quality of samples.

However, an even better trade-off can be reached by adopting a form of annealed sampling for GSNs, a general recipe for improving the compromise between accuracy of the sampling distribution and mixing for GSNs. For this purpose we talk about a generic noise level, although in this paper we refer to p , the probability of resampling any particular visible variable.

The idea is inspired by annealing and tempering methods that have been useful for undirected graphical models [18, 19]: *before sampling from the low-noise regime, we run the high-noise version of the transition operator and gradually reduce the noise level over a sequence of steps*. The steps taken at high noise allow to mix quickly while the steps taken at low noise allow to burn-in near high probability samples. Therefore we consider an approximation of the GSN transition operator which consists of the successive application of a sequence of

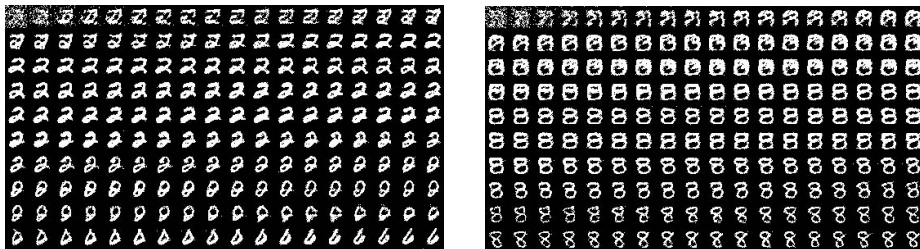


Fig. 2. The consecutive samples from the two independent GSN sampling chains without any annealing strategy. Both chains started from uniformly random configurations. Note the few spurious samples which can be avoided with the annealing strategy (see Figure 3).

instances of the operator associated with gradually reduced noise levels, ending at the target noise level. Conceptually, it is as if the overall Markov chain was composed, for each of its steps, by a short chain of steps with gradually decreasing noise levels. By making the annealing schedule have several steps at or near the target low noise level, and by controlling the lengths of these annealing runs, we can trade-off between accuracy of the samples (improved by a longer annealing run length) and speed of computation.

In the experiments, we used the following annealing schedule:

$$p_t = \max(p_{\min}, p_{\max} - (t - 1) * (p_{\max} - p_{\min}) / (\alpha * (T - 1)))$$

where p_{\max} is the high noise level, p_{\min} is the low (target) noise level, T is the length of the annealing run, and $\alpha \geq 1$ controls which fraction of the run is spent in annealing vs doing burn-in at the low noise level.

6 Experiments

6.1 Settings: Dataset and Model

We run experiments using the handwritten digits dataset (MNIST, [17]) which has 60,000 training samples and 10,000 test samples. Each sample has 784 dimensions, and we binarized each variable by thresholding at 0.5. The training set is split into two so that the first set of 50,000 samples is used to train a model and the other set of 10,000 samples is used for validation.

Using MNIST we trained deep NADE with various architectures and sets of hyperparameters using the order-agnostic (OA) training procedure (see Sec. 2.2). The best deep NADE model according to the validation performance has two hidden layers with size 2000 and was trained with a linearly decaying learning rate schedule (from 0.001 to 0) for 1000 epochs. We use this model to evaluate the two sampling strategies described and proposed earlier in this paper.



Fig. 3. Samples generated by the annealed GSN sampling procedure for the same deep NADE model. Visually the quality is comparable to the ancestral samples, and mixing is very fast. This is obtained with $p_{\max} = 0.9$, $p_{\min} = 0.1$, $\alpha = 0.7$ and $T = 20$.

6.2 Qualitative Analysis

Fig. 1 shows a subset of 10,000 samples collected from the deep NADE using the conventional ancestral sampling. The average log-probability of the samples is -70.36 according to the deep NADE. As each sample by the ancestral sampling is exact and independent from others, we use these samples and their log-probability as a baseline for assessing the proposed GSN sampling procedure.

We first generate samples from the deep NADE using the GSN sampling procedure without any annealing strategy. A sampling chain is initialized with a uniformly random configuration, and a sample is collected at each step. The purpose of this sampling is to empirically confirm that the GSN sampling does not require many steps for burn-in. We ran two independent chains and visualize the initial 240 samples from each of them in Fig. 2, which clearly demonstrates that the chain rapidly finds a plausible mode in only a few steps.

Although this visualization suggests a faster burn-in, one weakness is clearly visible from these figures (Fig. 2). The chain generates many consecutive samples of a single digit before it starts generating samples of another digit. That is, the samples are highly correlated temporally, suggesting potentially slow convergence to the stationary distribution.

We then tried sampling from the deep NADE using the novel annealed GSN sampling proposed in Sec. 5. Fig. 3 visualizes the collected, samples over the *consecutive* annealing runs. Compared to the samples generated using the ordinary GSN sampling method, the chain clearly mixes well. One can hardly notice a case where a successive sample is a realization of the same digit from the previous sample. Furthermore, the samples are qualitatively comparable to those exact samples collected with the ancestral sampling (see Fig. 1).

In the following section, we further investigate the proposed annealed GSN sampling in a more quantitative way, in comparison to the ancestral sampling.

6.3 Quantitative Results

We first evaluate the effect of using a user-defined noise level in $p(\mathbf{h} | \mathbf{x})$ (Eq. (7)). We generated 1000 samples from GSN chains with five different noise levels; 0.1, 0.3, 0.4, 0.5 and 0.6. For each noise level, we ran 100 independent chains and collected every 200-th sample from each chain. As a comparison, we also generated 1000 samples from a chain with the proposed annealed GSN sampling with $p_{\max} = 0.9$, $p_{\min} = 0.1$ and $\alpha = 0.7$.

We computed the log-probability of the set of samples collected from each chain with the deep NADE to evaluate the quality of the samples. Tab. 1 lists the log-probabilities of the sets of samples, which clearly shows that as the noise level increases the quality of the samples degrades. Importantly, none of the chains were able to generate samples from the model that are close to those generated by the ancestral sampling. However, the annealed GSN sampling was able to generate samples that are quantitatively as good as those from the ancestral sampling.

Noise	Log-Probability
0.1	-77.1
0.3	-78.93
0.4	-77.9
0.5	-81.1
0.6	-88.1
Annealed	-69.72
Ancestral	-70.36

Table 1. Log-probability of 1000 samples when annealing is not used. To collect samples, 100 parallel chains are run and 10 samples are taken from each chain and combined together. The noise level is fixed at a particular level during the sampling. We also report the best log-probability of samples generated with an annealed GSN sampling.

We also perform quantitative analysis to measure the computational gain when using the GSN sampling procedure to generate samples. The speedup by using annealed GSN sampling instead of ancestral sampling is shown in Figure 4. To compute the speedup factor, we timed both the ancestral NADE sampling and GSN sampling on the same machine running single process. NADE sampling takes 3.32 seconds per sample and GSN sampling takes 0.009 seconds. That means the time to get one sample in ancestral sampling can get 369 samples in GSN sampling. Although the the direct speedup factor is 369, it must be discounted because of the autocorrelation of successive samples in the GSN chain. Then we perform different GSN sampling runs with different settings of α . Figure 4 shows the results with different α . For each α , a GSN sampling starting at random is run and we collect one out of every K samples till 1000 samples are collected. The effective sample size [10] is then estimated based on the sum of the autocorrelations in the autocorrelation factor. The speedup factor is discounted accordingly.

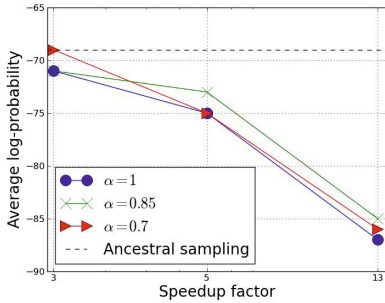


Fig. 4. The annealed GSN sampling procedure is compared against NADE ancestral sampling, trading off the computational cost (computational wrt to ancestral sampling on x-axis) against log-likelihood of the generated samples (y-axis). The computational cost discards the effect of the Markov chain autocorrelation by estimating the effective number of samples and increasing the computational cost accordingly.

7 Conclusions

This paper introduced a new view of the orderless NADE training procedure as a GSN training procedure, which yields several interesting conclusions:

- The orderless NADE training procedure also trains a GSN model, where the transition operator randomly selects a subset of input variables to be resampled given the others.
- Whereas orderless NADE models really represent an ensemble of conditionals that are not all compatible, the GSN interpretation provides a coherent interpretation of the estimated distribution through the stationary distribution of the associated Markov chain.
- Whereas ancestral sampling in NADE is exact, it is very expensive for deep NADE models, multiplying computing cost (of running once through the neural network to make a prediction) by the number of visible variables. On the other hand, each step of the associated GSN Markov chain only costs running once through the predictor, but because each prediction is made in parallel for all the resampled variables, each such step is also less accurate, unless very few variables are resampled. This introduces a trade-off between accuracy and computation time that can be controlled. This was validated experimentally.
- A novel sampling procedure for GSNs was introduced, called annealed GSN sampling, which permits a better trade-off by combining high-noise steps with a sequence of gradually lower noise steps, as shown experimentally.

Acknowledgments. We would like to thank the developers of Theano [2, 8]. We would also like to thank CIFAR, and Canada Research Chairs for funding, and Compute Canada, and Calcul Québec for providing computational resources.

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