Adversarial Autoencoders (AAE)

Adapted from Makhzani et al., 2015

Giovanni Papini

Universitá degli Studi di Firenze

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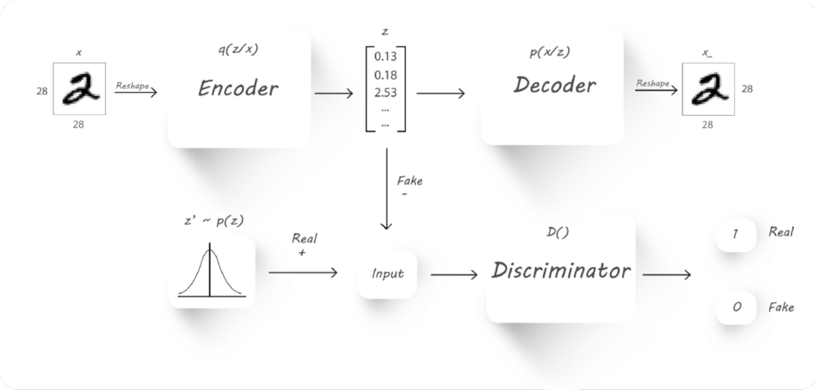
Context

- Scalable generative models to capture rich distributions
- Graphical models such as RBMs , DBNs, DBMs are based on MCMC algorithms for doing inference
- VAE [Kingma and Welling, 2013], GAN [Goodfellow et al., 2014], GMMN [Li, Swersky, and Zemel, 2015] are trained via direct back-propagation
- The AAE is trained via back-propagation with dual objectives:
  - **minimizing the reconstruction error** — $||\boldsymbol{x} - \hat{\boldsymbol{x}}||^2$
  - **adversarial training criterion** — matching the aggregated posterior distribution of the latent representation to an arbitrary prior

The AAE architecture



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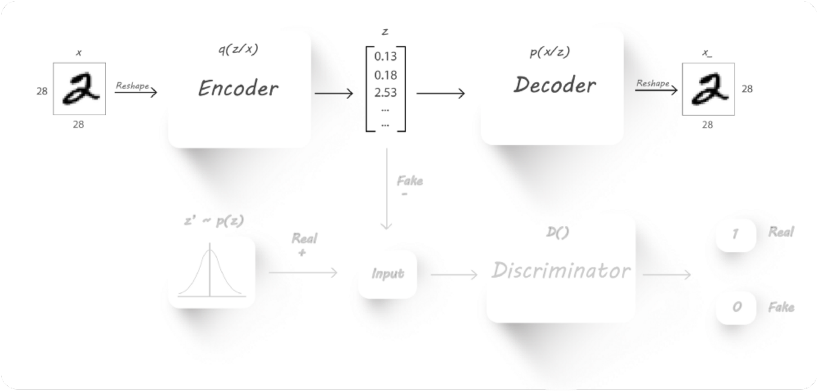

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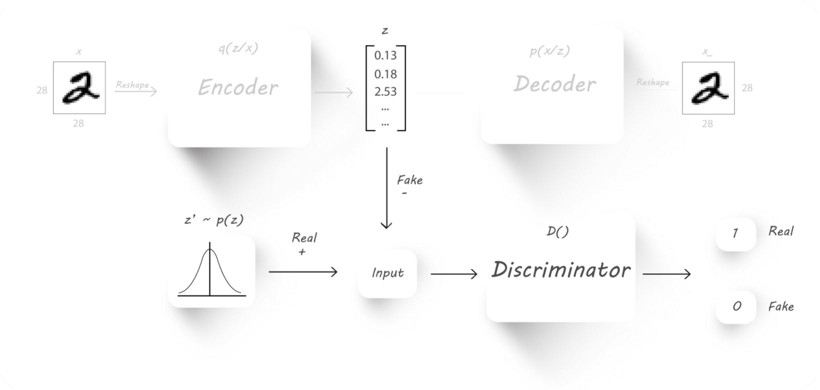

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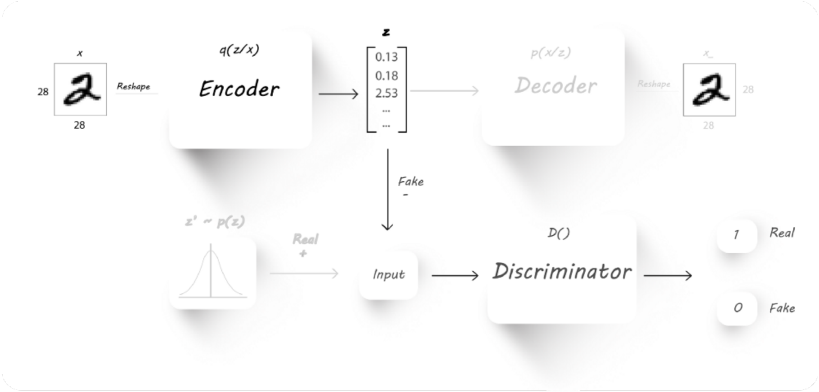


The encoder

$$q(\boldsymbol{z}) = \int_{\Omega_x} q(\boldsymbol{z}|\boldsymbol{x}) p_d(\boldsymbol{x}) \mathrm{d}\boldsymbol{x} \to p(\boldsymbol{z})$$

- **Deterministic —** (used in the paper)
- **Gaussian posterior —** $z_i|\boldsymbol{x} \sim \mathcal{N}(\mu_i(\boldsymbol{x}), \sigma_i(\boldsymbol{x}))$
- **Universal approximator posterior —** $\boldsymbol{z}|\boldsymbol{x}, \boldsymbol{\eta} \sim \delta(\boldsymbol{z} - f(\boldsymbol{x}, \boldsymbol{\eta}))$
  where $\boldsymbol{\eta}$ is random noise with a fixed distribution

$$q(\boldsymbol{z}|\boldsymbol{x}) = \int_{\Omega_\eta} q(\boldsymbol{z}|\boldsymbol{x}, \boldsymbol{\eta}) p_\eta(\boldsymbol{\eta}) \mathrm{d}\boldsymbol{\eta}$$

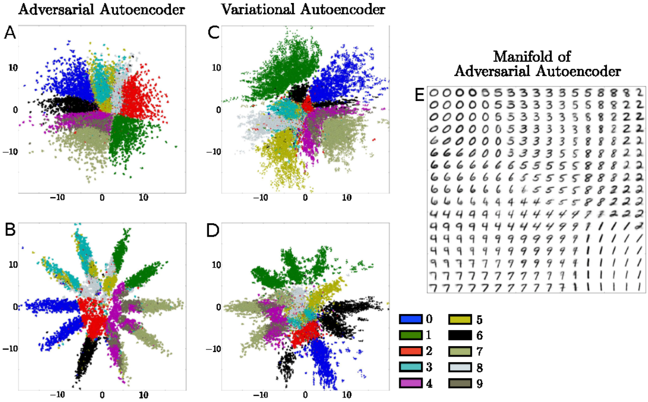
Relationship with VAEs

VAE aims to minimize the negative ELBO:

$$
\begin{aligned}
-\log p(\boldsymbol{x}) &< \mathbb{E}_{\boldsymbol{z}\sim q(\boldsymbol{z}|\boldsymbol{x})}[-\log p(\boldsymbol{x}|\boldsymbol{z})] + \mathbb{KL}(q(\boldsymbol{z}|\boldsymbol{x})||p(\boldsymbol{z})) \\
&= \mathbb{E}_{\boldsymbol{z}}[-\log p(\boldsymbol{x}|\boldsymbol{z})] - H(q(\boldsymbol{z}|\boldsymbol{x})) + \mathbb{E}_{\boldsymbol{z}\sim q(\boldsymbol{z}|\boldsymbol{x})}[-\log p(\boldsymbol{z})] \\
&= \text{Reconstr. Err.} - \text{Entropy} + \text{Crossentropy}
\end{aligned}
$$

VAE	**AAE**
◦ encourages $q(\boldsymbol{z})$ to match $p(\boldsymbol{z})$ modes because of crossentropy penalty ◦ needs the exact functional form of the prior distribution in order to back-propagate through KL divergence	◦ encourages $q(\boldsymbol{z})$ to match the *whole* $p(\boldsymbol{z})$ because of the adversarial training ◦ can impose even complicated distributions just through the capability of sampling from them

Relationship with VAE



Relationship with GAN and GMMN

GAN	AAE
◦ imposes the data distribution to the output of a neural network	◦ relies on the autoencoder to capture the data distribution ◦ shapes a much lower dimensional space into a much simpler distribution

GMMN	AAE
◦ (first) trains a dropout autoencoder (then) fits a distribution in the code-space of the pretrained network	◦ uses adversarial training as a regularizer that shapes the code distribution while training the autoencoder from scratch

Likelihood analysis

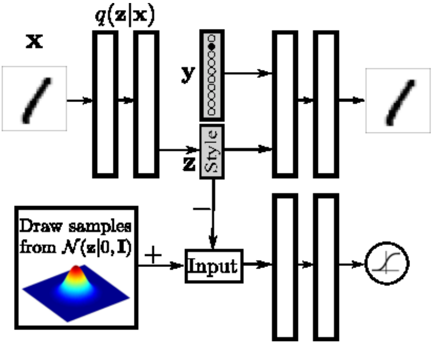
- Benchmarks on: MNIST, Toronto Face Dataset (TFD)
- Not direct likelihood measure, but lower bound approximation (KDE using Gaussian Parzen window, σ selected by cross-validation)
- Samples of 10K and 10M units to estimate the test set log-likelihood

	MNIST(10K)	MNIST(10M)	TFD(10K)	TFD(10M)
DBN	138 ± 2.0	-	1909 ± 66	-
Stacked CAE	121 ± 1.6	-	2110 ± 50	-
Deep GSN	214 ± 1.1	-	2890 ± 29	-
GAN	225 ± 2.0	386	2057 ± 26	-
GMMN + AE	282 ± 2.0	-	2204 ± 20	-
AAE	340 ± 2.0	427	2252 ± 16	2522

Semi-supervised approach

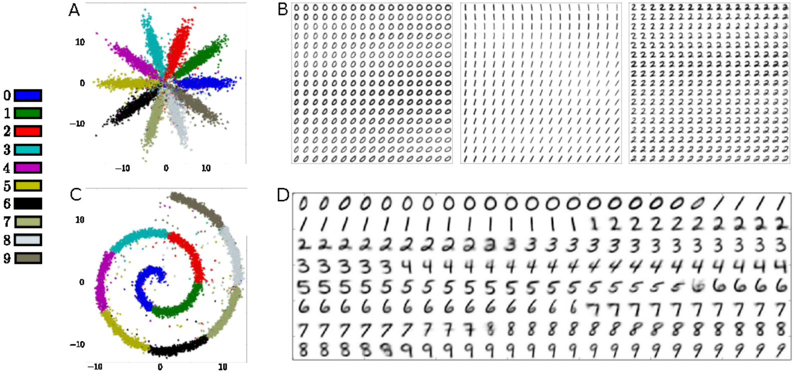
Incorporating label information

- Incorporate one-hot vector in the latent representation



Semi-supervised approach

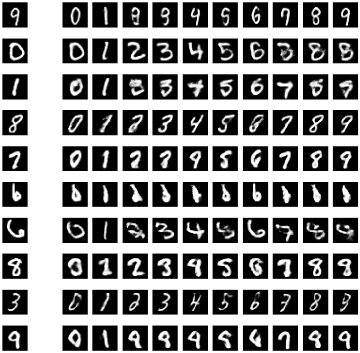
Incorporating label information



Semi-supervised approach

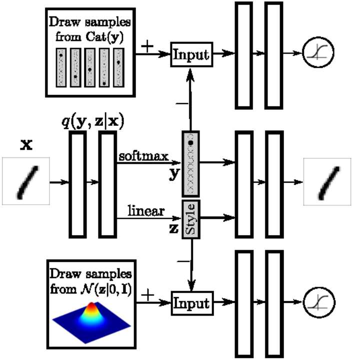
Incorporating label information

- The AAE disentangles *style* features from *content/semantic* features
- Experiments on MNIST and Street View House Number dataset (SVHN)



Semi-supervised classification

Architecture



- Improve classification performance using both labeled and unlabeled data
- Assume the latent space is a mixed Categorical and Gaussian distribution

$$p(\boldsymbol{y}) = \mathrm{Cat}(\boldsymbol{y}) \quad p(\boldsymbol{z}) = \mathcal{N}(\boldsymbol{z}; 0, \mathbf{I})$$

- For each distribution a different adversarial network regularizes the latent representation

Semi-supervised classification

Training

3-phase training, all with SGD:

1. *reconstruction* — the AE updates the encoder $q(\boldsymbol{z}, \boldsymbol{y}|\boldsymbol{x})$ to minimize the reconstruction error
2. *regularization* — each adversarial network
   - first updates the discriminative network to distinguish true samples from the generated samples
   - then update the encoder to confuse the discriminative networks
3. *semi-supervised classification* — the AE updates $q(\boldsymbol{z}, \boldsymbol{y}|\boldsymbol{x})$ to minimize the cross-entropy cost on a labeled minibatch

Semi-supervised classification

Results

	MNIST(100)	MNIST(1000)	MNIST(All)	SVHN(1000)
NN Baseline	25.80	8.73	1.25	47.5
VAE (M1) + TSVM	11.82 ± 0.03	4.24 ± 0.07	-	55.33 ± 0.11
VAE (M2)	11.97 ± 1.71	3.60 ± 0.56	-	36.02 ± 0.10
VAE (M1 + M2)	3.33 ± 0.14	2.40 ± 0.02	0.96	24.63
CatGAN	1.91 ± 0.10	1.73 ± 0.18	0.91	-
Ladder Networks	1.06 ± 0.37	0.84 ± 0.08	0.57 ± 0.02	-
ADGM	0.96 ± 0.10	-	-	16.61 ± 0.24
AAE	1.90 ± 0.10	1.60 ± 0.08	0.85 ± 0.02	17.70 ± 0.30

Table: Error rate on semi-supervised classification.

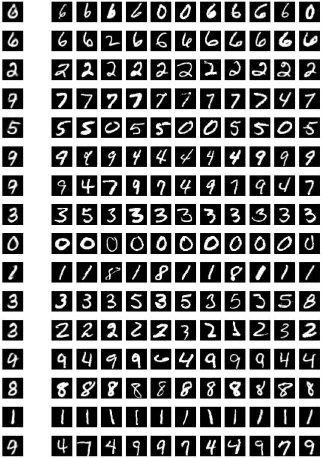
Unsupervised clustering

- Similar to the semi-supervised architecture, but without the semi-supervised training stage
- Not necessarily 10 classes, arbitrary number of clusters
- Benchmark criterion: find $\arg\max_{\boldsymbol{x}_n} q(y_i|\boldsymbol{x}_n)$ and assign label of x_n to all elements of i-th cluster, then compute error rate based on the assigned class labels

	MNIST (Unsupervised)
CatGAN (20 clusters)	9.70
AAE (16 clusters)	9.55 ± 2.05
AAE (30 clusters)	4.10 ± 1.13

Table: Error-rate on unsupervised clustering

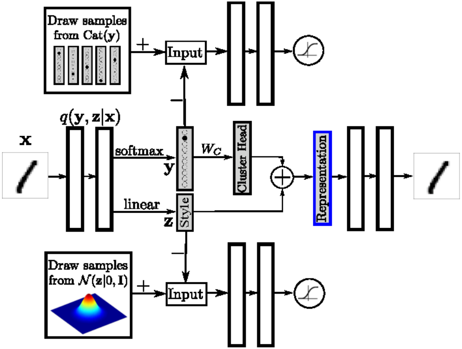
Unsupervised clustering



Dimensionality reduction

Architecture

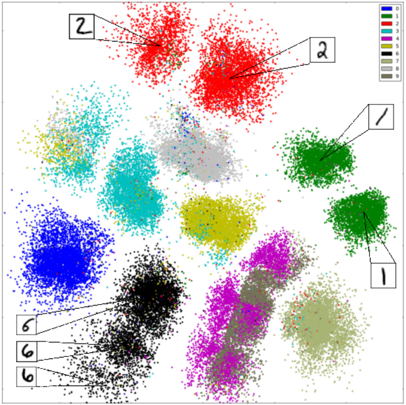
- Typically, non-regularized autoencoders fracture the manifolds $\Rightarrow$ very different codes for similar images
- Little modification label-integrated AAE architecture

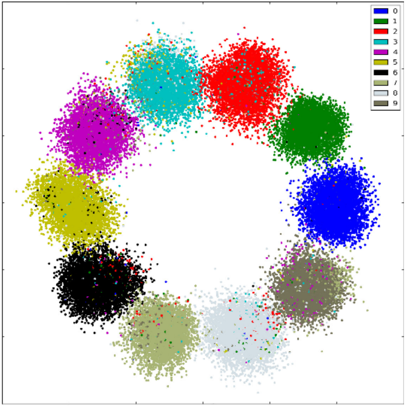


- Additional cost to penalize euclidean distance between cluster heads

Dimensionality reduction

- Reducing the dimensionality of the hidden space (from 10 to 2) can impact on the predictive power of the whole network
- Ad hoc tricks can balance this trade-off





Conclusions

Pros

- it is framework capable of modeling complex distributions only requiring to be able to sample from it
- the AAE is highly flexible, could be combined with variational objectives (see Rosca et al., 2017)

Cons

- like GANs, it requires much hyper-parameter tuning to perform at the top
- it could suffer from complex adversarial game dynamics
- it could be an overkill just to treat Gaussian/Gaussian-mixture distributions

* It would need some real-world testing.

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