

# EE-559 – Deep learning

## 9.2. Autoencoders

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<https://fleuret.org/ee559/>

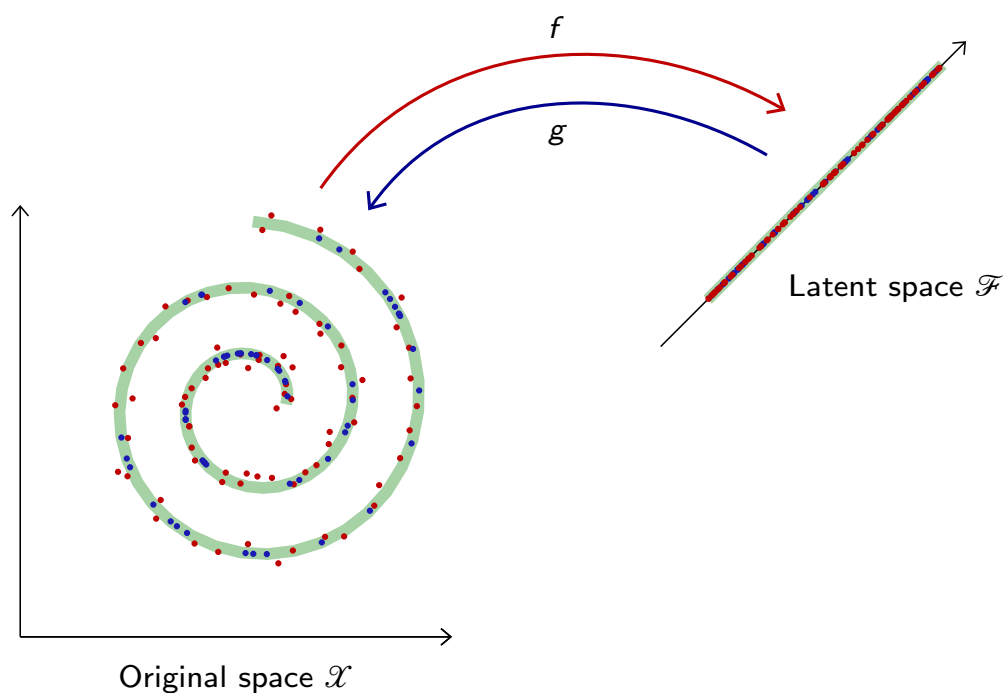
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## Embeddings and generative models

Many applications such as image synthesis, denoising, super-resolution, speech synthesis, compression, etc. require to go beyond classification and regression, and model explicitly a high dimension signal.

This modeling consists of finding “meaningful degrees of freedom” that describe the signal, and are of lesser dimension.

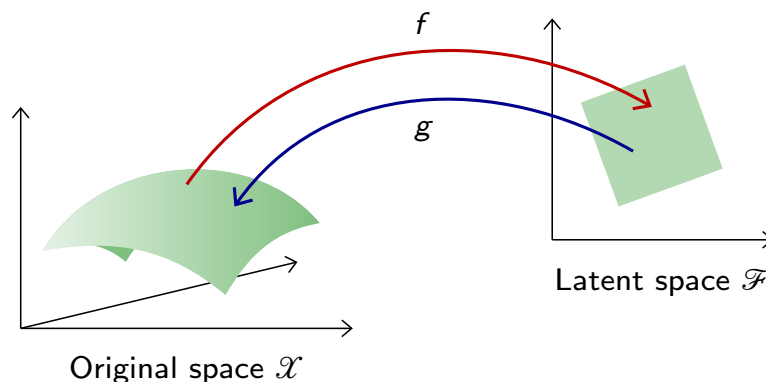


When dealing with real-world signals, this objective involves the same theoretical and practical issues as for classification or regression: defining the right class of high-dimension models, and optimizing them.

Regarding synthesis, we saw that deep feed-forward architectures exhibit good generative properties, which motivates their use explicitly for that purpose.

## Autoencoders

An autoencoder (Bourlard and Kamp, 1988; Hinton and Zemel, 1994) combines an **encoder**  $f$  from the original space  $\mathcal{X}$  to a **latent space**  $\mathcal{F}$ , and a **decoder**  $g$  to map back to  $\mathcal{X}$ , such that  $g \circ f$  is [close to] the identity on the data.



A proper autoencoder has to capture a “good” parametrization of the signal, and in particular the statistical dependencies between the signal components.

Let  $q$  be the data distribution over  $\mathcal{X}$ . A good autoencoder could be characterized with the quadratic loss

$$\mathbb{E}_{X \sim q} [\|X - g \circ f(X)\|^2] \simeq 0.$$

Given two parametrized mappings  $f(\cdot; w)$  and  $g(\cdot; w)$ , training consists of minimizing an empirical estimate of that loss

$$\hat{w}_f, \hat{w}_g = \operatorname{argmin}_{w_f, w_g} \frac{1}{N} \sum_{n=1}^N \|x_n - g(f(x_n; w_f); w_g)\|^2.$$

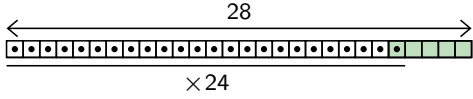
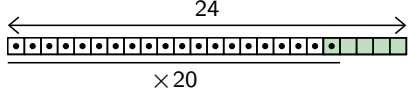
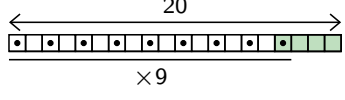
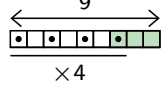

A simple example of such an autoencoder would be with both  $f$  and  $g$  linear, in which case the optimal solution is given by PCA. Better results can be achieved with more sophisticated classes of mappings, in particular deep architectures.

## Deep Autoencoders


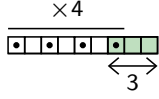
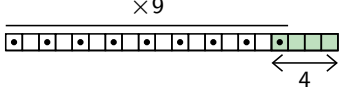
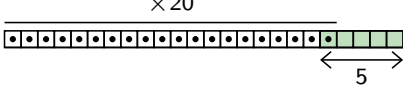
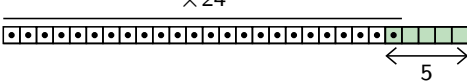
A deep autoencoder combines an encoder composed of convolutional layers, with a decoder composed of the reciprocal transposed convolution layers. *E.g.* for MNIST:

```
AutoEncoder (
  (encoder): Sequential (
    (0): Conv2d(1, 32, kernel_size=(5, 5), stride=(1, 1))
    (1): ReLU (inplace)
    (2): Conv2d(32, 32, kernel_size=(5, 5), stride=(1, 1))
    (3): ReLU (inplace)
    (4): Conv2d(32, 32, kernel_size=(4, 4), stride=(2, 2))
    (5): ReLU (inplace)
    (6): Conv2d(32, 32, kernel_size=(3, 3), stride=(2, 2))
    (7): ReLU (inplace)
    (8): Conv2d(32, 8, kernel_size=(4, 4), stride=(1, 1))
  )
  (decoder): Sequential (
    (0): ConvTranspose2d(8, 32, kernel_size=(4, 4), stride=(1, 1))
    (1): ReLU (inplace)
    (2): ConvTranspose2d(32, 32, kernel_size=(3, 3), stride=(2, 2))
    (3): ReLU (inplace)
    (4): ConvTranspose2d(32, 32, kernel_size=(4, 4), stride=(2, 2))
    (5): ReLU (inplace)
    (6): ConvTranspose2d(32, 32, kernel_size=(5, 5), stride=(1, 1))
    (7): ReLU (inplace)
    (8): ConvTranspose2d(32, 1, kernel_size=(5, 5), stride=(1, 1))
  )
)
```

## Encoder

Tensor sizes / operations	
$1 \times 28 \times 28$	
<code>nn.Conv2d(1, 32, kernel_size=5, stride=1)</code>	
$32 \times 24 \times 24$	
<code>nn.Conv2d(32, 32, kernel_size=5, stride=1)</code>	
$32 \times 20 \times 20$	
<code>nn.Conv2d(32, 32, kernel_size=4, stride=2)</code>	
$32 \times 9 \times 9$	
<code>nn.Conv2d(32, 32, kernel_size=3, stride=2)</code>	
$32 \times 4 \times 4$	
<code>nn.Conv2d(32, 8, kernel_size=4, stride=1)</code>	
$8 \times 1 \times 1$	

## Decoder

Tensor sizes / operations	
$8 \times 1 \times 1$	
<code>nn.ConvTranspose2d(8, 32, kernel_size=4, stride=1)</code>	
$32 \times 4 \times 4$	
<code>nn.ConvTranspose2d(32, 32, kernel_size=3, stride=2)</code>	
$32 \times 9 \times 9$	
<code>nn.ConvTranspose2d(32, 32, kernel_size=4, stride=2)</code>	
$32 \times 20 \times 20$	
<code>nn.ConvTranspose2d(32, 32, kernel_size=5, stride=1)</code>	
$32 \times 24 \times 24$	
<code>nn.ConvTranspose2d(32, 1, kernel_size=5, stride=1)</code>	
$1 \times 28 \times 28$	

Training is achieved with quadratic loss and Adam

```
model = AutoEncoder(nb_channels, embedding_dim)

model.to(device)

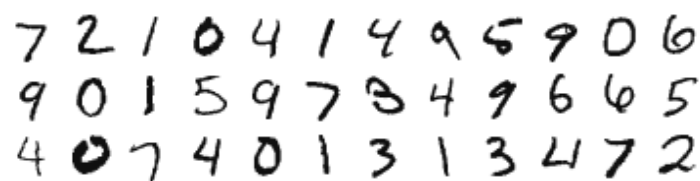
optimizer = optim.Adam(model.parameters(), lr = 1e-3)

for epoch in range(args.nb_epochs):
    for input, _ in iter(train_loader):
        input = input.to(device)

        z = model.encode(input)
        output = model.decode(z)
        loss = 0.5 * (output - input).pow(2).sum() / input.size(0)

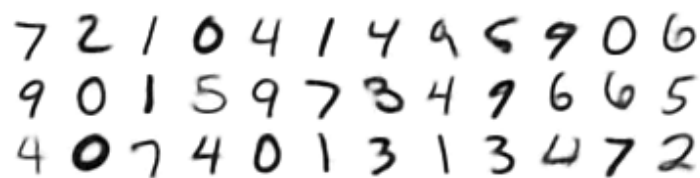
        optimizer.zero_grad()
        loss.backward()
        optimizer.step()
```

$X$  (original samples)



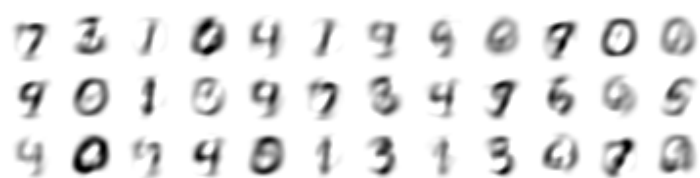
7 2 1 0 4 1 4 9 5 9 0 6  
9 0 1 5 9 7 3 4 9 6 6 5  
4 0 7 4 0 1 3 1 3 4 7 2

$g \circ f(X)$  (CNN,  $d = 8$ )



7 2 1 0 4 1 4 9 5 9 0 6  
9 0 1 5 9 7 3 4 9 6 6 5  
4 0 7 4 0 1 3 1 3 4 7 2

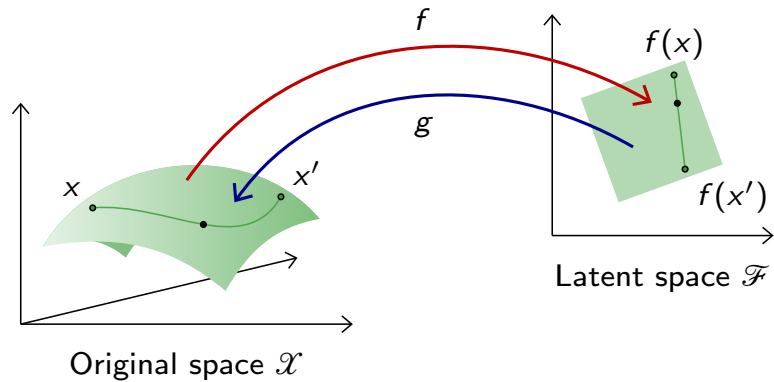
$g \circ f(X)$  (PCA,  $d = 8$ )



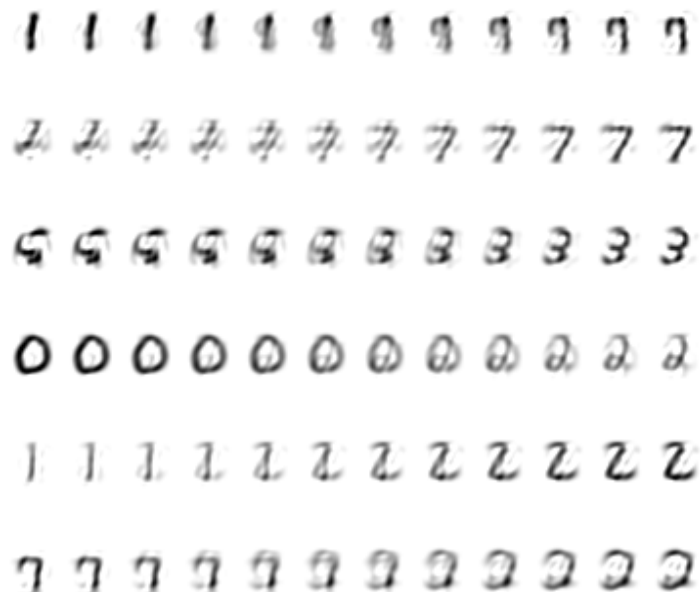
7 2 1 0 4 1 4 9 5 9 0 6  
9 0 1 0 9 7 3 4 9 6 6 5  
4 0 7 4 0 1 3 1 3 0 7 0

To get an intuition of the latent representation, we can pick two samples  $x$  and  $x'$  at random and interpolate samples along the line in the latent space

$$\forall x, x' \in \mathcal{X}^2, \alpha \in [0, 1], \xi(x, x', \alpha) = g((1 - \alpha)f(x) + \alpha f(x')).$$



PCA interpolation ( $d = 32$ )





### Autoencoder interpolation ( $d = 8$ )

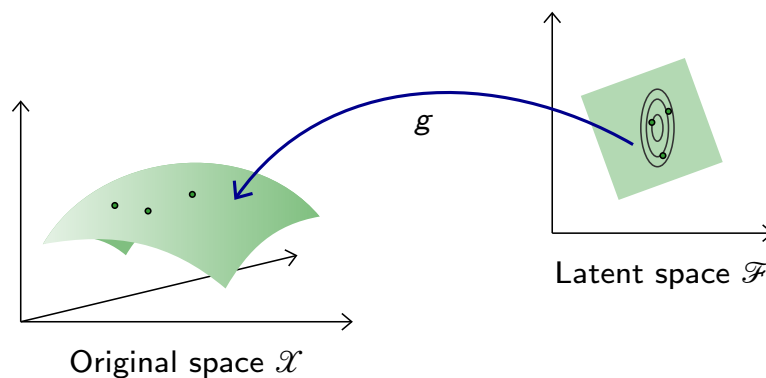


And we can assess the generative capabilities of the decoder  $g$  by introducing a [simple] density model  $q^Z$  over the latent space  $\mathcal{Z}$ , sample there, and map the samples into the image space  $\mathcal{X}$  with  $g$ .

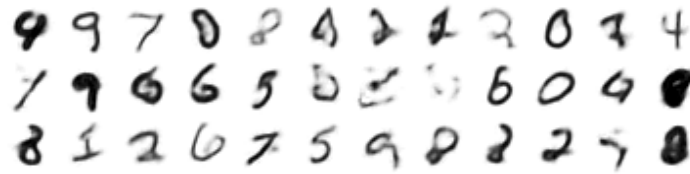
We can for instance use a Gaussian model with diagonal covariance matrix.

$$f(X) \sim \mathcal{N}(\hat{m}, \hat{\Delta})$$

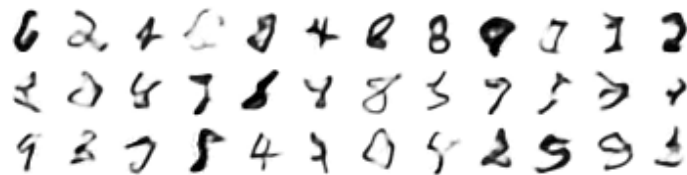
where  $\hat{m}$  is a vector and  $\hat{\Delta}$  a diagonal matrix, both estimated on training data.



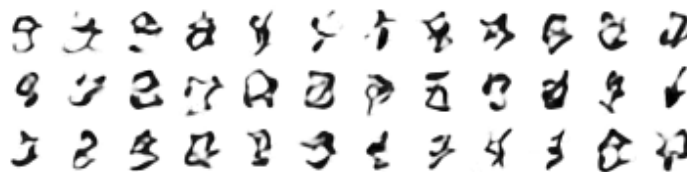
Autoencoder sampling ( $d = 8$ )



Autoencoder sampling ( $d = 16$ )



Autoencoder sampling ( $d = 32$ )



These results are unsatisfying, because the density model used on the latent space  $\mathcal{Z}$  is too simple and inadequate.

Building a “good” model amounts to our original problem of modeling an empirical distribution, although it may now be in a lower dimension space.

## References

- H. Bourlard and Y. Kamp. Auto-association by multilayer perceptrons and singular value decomposition. *Biological Cybernetics*, 59(4):291–294, 1988.
- G. E. Hinton and R. S. Zemel. Autoencoders, minimum description length and helmholtz free energy. In *Neural Information Processing Systems (NIPS)*, pages 3–10, 1994.