

# Variational Autoencoder Mathematics

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# Introduction

The **Variational Autoencoder** (aka **VAE**) is a generative model. This means that it is a model which produces new unseen data. Unlike the normal Autoencoder, VAE focuses on understanding the distribution of a smaller representation of the data. This lower-dimensional representation of the data is known as “latent vector  $\mathbf{z}$ ”.

The dimension of the latent vector  $\mathbf{z}$  is a hyperparameter which we choose along with the architecture of the Network. Keep in mind that we don’t want  $\mathbf{z}$  to be too large. It should be a relatively small vector, so that an information bottleneck is created. One other reason for  $\mathbf{z}$  being small, is that we want to be able to sample easily new vectors, without having to take into consideration many features.

With that said, the question arises: How can we pick the values of  $\mathbf{z}$  which will make sense, that is, which will generate a new data point from the distribution of our original data?

Here is the beauty of the **Variational Autoencoder**: We will learn the distribution of  $\mathbf{z}$ . That is, for every component of  $\mathbf{z}$ , we will learn a mean and a standard deviation.

Suppose  $\mathbf{z}$  has  $k$  components:

$$\mathbf{z} = \begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_k \end{bmatrix}$$

Then, the mean and standard deviation vectors are defined as:

$$\mu = \begin{bmatrix} \mu_1 \\ \mu_2 \\ \vdots \\ \mu_k \end{bmatrix}, \quad \sigma = \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \vdots \\ \sigma_k \end{bmatrix}$$

Our goal is to learn the  $\mu$  and  $\sigma$  vectors in order to be able to sample  $\mathbf{z}$  as follows

$$\mathbf{z} = \mu + \epsilon \odot \sigma$$

where  $\epsilon \sim N(0, 1)$  is a gaussian with mean 0 and standard deviation 1.

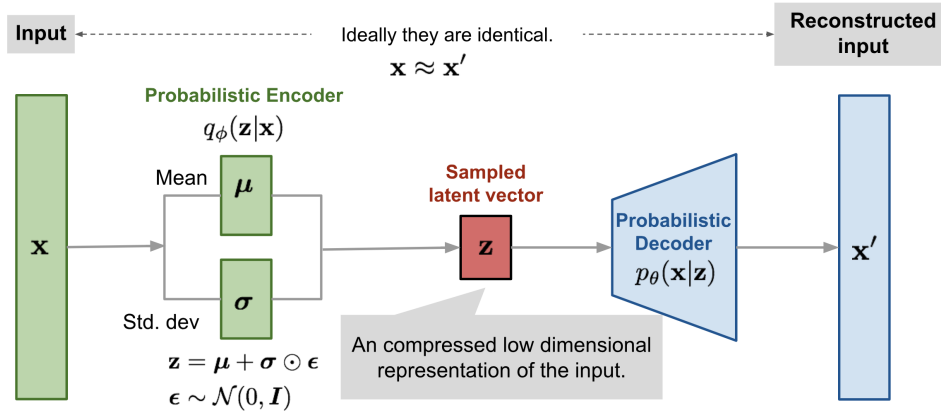


Figure 1: This picture demonstrates the architecture of a Variational Autoencoder. The input  $\mathbf{x}$  gets fed in a Probabilistic Encoder  $q_\phi(z|x)$ , which in turns connects with the  $\mu$  and  $\sigma$  layers. Note that usually there is a encoder Network before the mean and std layers, but here in the figure it is ommitted. Then, they sample  $\mathbf{z}$  which in turn is fed to the Probabilistic Decoder  $p_\theta(x|z)$ . The result is then fed to an output layer which represents the reconstructed input data. The original picture can be found [here](#).

## Brief Explanation of architecture

The architecture of a **VAE** is briefly portrayed in Figure 1. Let's take a closer look in each part:

1. The encoder part consists of a Probabilistic Encoder  $q_\phi(z|x)$ . Given some parameters  $\phi$  (which are parameters of the model),  $q_\phi(z|x)$  models the probability of obtaining the latent vector  $\mathbf{z}$  given input data  $\mathbf{x}$ . Afterwards, it connects to the  $\mu$  and  $\sigma$  layers, as there might a whole encoder network before those.
2. The latent vector  $\mathbf{z}$ .
3. The decoder part which consists of a Probabilistic Decoder  $p_\theta(x|z)$ . As with the probabilistic encoder, given some parameters  $\theta$  which are parameters of the model, we want to learn the probability of obtaining a data point  $\mathbf{x}$  given a latent vector  $\mathbf{z}$ .
4. The reconstructed input  $\hat{x}$ .

## Loss function

The loss function of the VAE is:

$$L(\theta, \phi, x) = -\mathbb{E}_{z \sim q_\phi(z|x)} [\log p_\theta(x|z)] + D_{KL}[q_\phi(z|x) \parallel p_\theta(z)]$$

It may seem daunting at first, but if we break it down into pieces then it gets much simpler.

## KL-Divergence and multivariate Normal Distribution

Let's start by explaining what the second term of the loss function is. The **Kullback Leibler Divergence**, also known as **Relative Entropy**, is a measure of similarity between two probability distributions. It is denoted by  $D_{KL}(\cdot \parallel \cdot)$ , its unit of measure it called **nat** and it can computed by the formula (for continuous probability distributions  $P, Q$ ):

$$D_{KL}[P \parallel Q] = \int P(x) \log \left( \frac{P(x)}{Q(x)} \right) dx \quad (1)$$

Of course, this implies that  $D_{KL}(P \parallel Q) \neq D_{KL}(Q \parallel P)$ .

Now, let's suppose that both  $P, Q$  are multivariate normal distributions with means  $\mu_1, \mu_2$  and **covariance** matrices  $\Sigma_1, \Sigma_2$ :

$$P(x) = N(x; \mu_1, \Sigma_1) = \frac{1}{\sqrt{(2\pi)^k |\Sigma_1|}} e^{-\frac{1}{2}(x-\mu_1)^T \Sigma_1^{-1} (x-\mu_1)}$$
$$Q(x) = N(x; \mu_2, \Sigma_2) = \frac{1}{\sqrt{(2\pi)^k |\Sigma_2|}} e^{-\frac{1}{2}(x-\mu_2)^T \Sigma_2^{-1} (x-\mu_2)}$$

where  $k$  is the magnitude (length) of vector  $x$ .

Hence

$$\begin{aligned} \log(P(x)) &= \log \left( \frac{1}{\sqrt{(2\pi)^k |\Sigma_1|}} e^{-\frac{1}{2}(x-\mu_1)^T \Sigma_1^{-1} (x-\mu_1)} \right) \\ &= \log \left( \frac{1}{\sqrt{(2\pi)^k |\Sigma_1|}} \right) + \log \left( e^{-\frac{1}{2}(x-\mu_1)^T \Sigma_1^{-1} (x-\mu_1)} \right) \\ &= -\frac{k}{2} \log(2\pi) - \frac{1}{2} \log(|\Sigma_1|) - \frac{1}{2} (x - \mu_1)^T \Sigma_1^{-1} (x - \mu_1) \end{aligned}$$

Following the exact same steps, we also get that

$$\log(Q(x)) = -\frac{k}{2} \log(2\pi) - \frac{1}{2} \log(|\Sigma_2|) - \frac{1}{2} (x - \mu_2)^T \Sigma_2^{-1} (x - \mu_2)$$

With the help of the above equalities, expanding (1) yields:

$$\begin{aligned} D_{KL}[P \parallel Q] &= \int P(x) [\log(P(x)) - \log(Q(x))] dx \\ &= \int P(x) \left[ \frac{1}{2} \log\left(\frac{|\Sigma_2|}{|\Sigma_1|}\right) - \frac{1}{2} (x - \mu_1)^T \Sigma_1^{-1} (x - \mu_1) \right. \\ &\quad \left. + \frac{1}{2} (x - \mu_2)^T \Sigma_2^{-1} (x - \mu_2) \right] dx \end{aligned}$$

We can rewrite the above term as an Expectation over  $P$ :

$$\begin{aligned} D_{KL}[P \parallel Q] &= \mathbb{E}_P \left[ \frac{1}{2} \log\left(\frac{|\Sigma_2|}{|\Sigma_1|}\right) - \frac{1}{2} (x - \mu_1)^T \Sigma_1^{-1} (x - \mu_1) \right. \\ &\quad \left. + \frac{1}{2} (x - \mu_2)^T \Sigma_2^{-1} (x - \mu_2) \right] \end{aligned}$$

Since the logarithmic term is independent of  $x$ , we can move it outside the expectation. This leaves us with

$$\begin{aligned} D_{KL}[P \parallel Q] &= \frac{1}{2} \log\left(\frac{|\Sigma_2|}{|\Sigma_1|}\right) \\ &\quad - \frac{1}{2} \mathbb{E}_P [(x - \mu_1)^T \Sigma_1^{-1} (x - \mu_1)] \\ &\quad + \frac{1}{2} \mathbb{E}_P [(x - \mu_2)^T \Sigma_2^{-1} (x - \mu_2)] \end{aligned} \tag{2}$$

Let's now try to simplify the 2nd and 3rd terms of the above expression.

First, we have to recall the [trace](#) function and some of its properties. The trace of a square matrix  $A$ , denoted as  $tr(A)$ , is the sum of the elements along the main diagonal of  $A$ . The [properties](#) of the trace function which we will need are:

1. [Trace of scalar](#): Considering the scalar as a  $1 \times 1$  matrix, gives:  $x = tr(x)$
2. [Trace of Expectation](#): From 1:  $\mathbb{E}[x] = \mathbb{E}[tr(x)] \Rightarrow tr(\mathbb{E}[x]) = \mathbb{E}[tr(x)]$
3. [Cyclic Property](#):  $tr(ABC) = tr(CAB)$

Having these properties in mind, we are now ready to simplify the expectation terms computed before during the simplification of the KL Divergence.

- Term 2. Note that the matrix multiplications inside the expectation reduce to a scalar value.

$$\begin{aligned}\mathbb{E}_P \left[ (x - \mu_1)^T \Sigma_1^{-1} (x - \mu_1) \right] &\stackrel{(1)}{=} \mathbb{E}_P \left[ \text{tr} \left( (x - \mu_1)^T \Sigma_1^{-1} (x - \mu_1) \right) \right] \\ &\stackrel{(3)}{=} \mathbb{E}_P \left[ \text{tr} \left( (x - \mu_1)(x - \mu_1)^T \Sigma_1^{-1} \right) \right] \\ &\stackrel{(2)}{=} \text{tr} \left( \mathbb{E}_P \left[ (x - \mu_1)(x - \mu_1)^T \Sigma_1^{-1} \right] \right)\end{aligned}$$

$\Sigma_1^{-1}$  is independent from the expectation over  $P$ , so it can be moved outside, thus giving:

$$\mathbb{E}_P \left[ (x - \mu_1)^T \Sigma_1^{-1} (x - \mu_1) \right] = \text{tr} \left( \mathbb{E}_P \left[ (x - \mu_1)(x - \mu_1)^T \right] \Sigma_1^{-1} \right)$$

But the term  $\mathbb{E}_P \left[ (x - \mu_1)(x - \mu_1)^T \right]$  is equal to the [Covariance Matrix](#)  $\Sigma_1$ , thus yielding

$$\mathbb{E}_P \left[ (x - \mu_1)^T \Sigma_1^{-1} (x - \mu_1) \right] = \text{tr} \left( \Sigma_1 \Sigma_1^{-1} \right) = \text{tr}(I_k) = k \quad (3)$$

- Term 3. Again, the term inside the expectation reduces to a scalar.

$$\mathbb{E}_P \left[ (x - \mu_2)^T \Sigma_2^{-1} (x - \mu_2) \right]$$

Add and subtract  $\mu_1$  :

$$\begin{aligned}&= \mathbb{E}_P \left[ [(x - \mu_1) + (\mu_1 - \mu_2)]^T \Sigma_2^{-1} [(x - \mu_1) + (\mu_1 - \mu_2)] \right] \\ &= \mathbb{E}_P \left[ [(x - \mu_1)^T + (\mu_1 - \mu_2)^T] \Sigma_2^{-1} [(x - \mu_1) + (\mu_1 - \mu_2)] \right]\end{aligned}$$

$$(A^T + B^T)C(A + B) = A^T C A + A^T C B + B^T C A + B^T B :$$

$$\begin{aligned}&= \mathbb{E}_P \left[ (x - \mu_1)^T \Sigma_2^{-1} (x - \mu_1) + (x - \mu_1)^T \Sigma_2^{-1} (\mu_1 - \mu_2) + \right. \\ &\quad \left. (\mu_1 - \mu_2)^T \Sigma_2^{-1} (x - \mu_1) + (\mu_1 - \mu_2)^T \Sigma_2^{-1} (\mu_1 - \mu_2) \right]\end{aligned}$$

Taking the expectation over each term individually:

$$\begin{aligned}\mathbb{E}_P \left[ (x - \mu_2)^T \Sigma_2^{-1} (x - \mu_2) \right] &= \mathbb{E}_P \left[ (x - \mu_1)^T \Sigma_2^{-1} (x - \mu_1) \right] + \\ &\quad \mathbb{E}_P \left[ (x - \mu_1)^T \Sigma_2^{-1} (\mu_1 - \mu_2) \right] + \\ &\quad \mathbb{E}_P \left[ (\mu_1 - \mu_2)^T \Sigma_2^{-1} (x - \mu_1) \right] + \\ &\quad \mathbb{E}_P \left[ (\mu_1 - \mu_2)^T \Sigma_2^{-1} (\mu_1 - \mu_2) \right]\end{aligned}$$

- The first sub-term has the same derivation as the first term from before:

$$\mathbb{E}_P \left[ (x - \mu_1)^T \Sigma_2^{-1} (x - \mu_1) \right] = \text{tr}(\Sigma_1 \Sigma_2^{-1})$$

- The second and third sub-terms are equal to 0 due to the expectation over  $(x - \mu_1)^T$ . Specifically, the factor  $\Sigma_2^{-1}(\mu_1 - \mu_2)$  can be moved out of the expectation as it is a constant:

$$\begin{aligned}\mathbb{E}_P \left[ (x - \mu_1)^T \Sigma_2^{-1} (\mu_1 - \mu_2) \right] &= \mathbb{E}_P \left[ (x - \mu_1)^T \right] \Sigma_2^{-1} (\mu_1 - \mu_2) \\ &= 0_k \Sigma_2^{-1} (\mu_1 - \mu_2) = 0 \\ \mathbb{E}_P \left[ (\mu_1 - \mu_2)^T \Sigma_2^{-1} (x - \mu_1) \right] &= (\mu_1 - \mu_2)^T \Sigma_2^{-1} \mathbb{E}_P \left[ (x - \mu_1)^T \right] \\ &= \Sigma_2^{-1} (\mu_1 - \mu_2) 0_k = 0\end{aligned}$$

- The fourth sub-term is the expectation of a constant, so it is equal to the constant itself:

$$\mathbb{E}_P \left[ (\mu_1 - \mu_2)^T \Sigma_2^{-1} (\mu_1 - \mu_2) \right] = (\mu_1 - \mu_2)^T \Sigma_2^{-1} (\mu_1 - \mu_2)$$

These simplifications leave us with:

$$\begin{aligned}\mathbb{E}_P \left[ (x - \mu_2)^T \Sigma_2^{-1} (x - \mu_2) \right] &= \text{tr}(\Sigma_1 \Sigma_2^{-1}) + \\ &\quad (\mu_1 - \mu_2)^T \Sigma_2^{-1} (\mu_1 - \mu_2)\end{aligned}\tag{4}$$

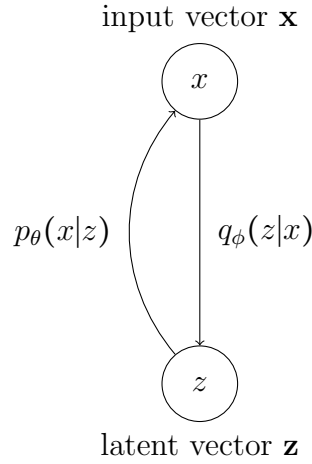
Finally, formula (2) for the KL-Divergence can be ultimately simplified using equations (3), (4) to:

$$D_{KL} [P \| Q] = \frac{1}{2} \left[ \log \left( \frac{|\Sigma_2|}{|\Sigma_1|} \right) - k + \text{tr}(\Sigma_1 \Sigma_2^{-1}) + (\mu_1 - \mu_2)^T \Sigma_2^{-1} (\mu_1 - \mu_2) \right] \tag{5}$$

■

## Goal of VAE

As mentioned in the introduction, the goal of the **VAE** is to learn the distribution  $q_\phi(\mathbf{z}|\mathbf{x})$  of the latent vector  $\mathbf{z}$ . After the distribution of the latent vector has been learnt, we can sample  $\mathbf{z}$  and feed it to the Generator Network defined by the distribution  $p_\theta(\mathbf{x}|\mathbf{z})$  (aka decoder) in order to obtain a new data point  $\tilde{x}$ . Of course during training, we want  $\tilde{x} \approx x$ . The training process can be thought of graphically as follows



## Derivation of Loss Function

We would like the two distributions to be approximately same, that is

$$q_\phi(z|x) \approx p_\theta(z|x)$$

How can we force the two distributions to come close? We could view this as a minimization problem of the KL-Divergence between  $Q$  and  $P$ .

$$D_{KL}[q_\phi(z|x) || p_\theta(z|x)] = \int q_\phi(z|x) \log \left( \frac{q_\phi(z|x)}{p_\theta(z|x)} \right) dz$$



Rewriting this term as an Expectation yields:

$$\begin{aligned}
& D_{KL} [q_\phi(z|x) \| p_\theta(z|x)] \\
&= \mathbb{E}_{z \sim q_\phi(z|x)} \left[ \log \left( \frac{q_\phi(z|x)}{p_\theta(z|x)} \right) \right] \\
&= \mathbb{E}_{z \sim q_\phi(z|x)} [\log q_\phi(z|x) - \log p_\theta(z|x)] \\
&= \mathbb{E}_{z \sim q_\phi(z|x)} \left[ \log q_\phi(z|x) - \log \left( \frac{p_\theta(x|z) p_\theta(z)}{p_\theta(x)} \right) \right] \\
&= \mathbb{E}_{z \sim q_\phi(z|x)} [\log q_\phi(z|x) - \log p_\theta(x|z) - \log p_\theta(z) + \log p_\theta(x)]
\end{aligned}$$

Since  $\log p_\theta(x)$  is independent from the Expectation of  $z$ , it can be moved outside, thus giving

$$\begin{aligned}
& D_{KL} [q_\phi(z|x) \| p_\theta(z|x)] - \log p_\theta(x) \\
&= -\mathbb{E}_{z \sim q_\phi(z|x)} [\log p_\theta(x|z)] + \mathbb{E}_{z \sim q_\phi(z|x)} [\log q_\phi(z|x) - \log p_\theta(z)] \\
&= -\mathbb{E}_{z \sim q_\phi(z|x)} [\log p_\theta(x|z)] + \mathbb{E}_{z \sim q_\phi(z|x)} \left[ \log \left( \frac{q_\phi(z|x)}{p_\theta(z)} \right) \right] \\
&= -\mathbb{E}_{z \sim q_\phi(z|x)} [\log p_\theta(x|z)] + D_{KL} [q_\phi(z|x) \| p_\theta(z)]
\end{aligned}$$

which is the loss function  $L$ , defined in terms of  $\phi$ ,  $\theta$ ,  $x$ :

$$L(\theta, \phi, x) = -\mathbb{E}_{z \sim q_\phi(z|x)} [\log p_\theta(x|z)] + D_{KL} [q_\phi(z|x) \| p_\theta(z)]$$

which is also known as [Evidence Lower BOund](#) (ELBO). Of course, our target is to find the  $\theta$ ,  $\phi$  that minimize the loss  $L(\theta, \phi, x)$  for all data points  $x$  in the training set,  $X$  that is:

$$\theta^*, \phi^* = \underset{\phi, \theta}{\operatorname{argmin}} L(\theta, \phi, x) \text{ over all } x \in X$$

Where in our case  $\theta^*$  are the weights of the Recognition Network (aka encoder) and  $\phi^*$  are the weights of the Generator Network (aka decoder).

## Simplifying the Loss Function

How could we simplify the Loss function  $L(\theta, \phi, x)$  such that it can be computed using known information? The problem is the KL-Divergence term, as we don't have a closed form for it. The first solution that comes to mind is to model both distributions of the KL-Divergence term as Gaussians, with  $p_\theta(z)$  having mean 0 and standard deviation 1, thus pushing  $q_\phi(z|x)$  to come close to it. Specifically:

1.  $q_\phi(z|x) \sim N(\mu_\phi(x), \Sigma_\phi(x))$
2.  $p_\theta(z) \sim N(0_k, I_k)$

This in turn allows us to use eq. (5), substituting the values

1.  $\mu_1 = \mu_\phi(x), \Sigma_1 = \Sigma_\phi(x)$
2.  $\mu_2 = 0_k, \Sigma_2 = I_k$

Thus yielding:

$$\begin{aligned}
 D_{KL}[q_\phi(z|x) \parallel p_\theta(z)] &= \frac{1}{2} \left[ \log \left( \frac{|I_k|}{|\Sigma_\phi(x)|} \right) - k + \text{tr}(\Sigma_\phi(x) I_k) + (\mu_\phi(x) - 0_k)^T I_k (\mu_\phi(x) - 0_k) \right] \\
 &= \frac{1}{2} \left[ -\log |\Sigma_\phi(x)| - k + \text{tr}(\Sigma_\phi(x)) + \mu_\phi(x)^T \mu_\phi(x) \right]
 \end{aligned}$$

Note that  $\Sigma_\phi(x)$  is a diagonal matrix with  $k$  elements. Hence we can write

$$\begin{aligned}
 D_{KL}[q_\phi(z|x) \parallel p_\theta(z)] &= \frac{1}{2} \left[ -\log \left( \prod_k \Sigma_{\phi_k}(x) \right) - k + \sum_{i=1}^k \Sigma_{\phi_i}(x) + \sum_{i=1}^k \mu_{\phi_i}^2 \right] \\
 &= \frac{1}{2} \left[ -\sum_{i=1}^k \log \Sigma_{\phi_i}(x) - \sum_{i=1}^k 1 + \sum_{i=1}^k \Sigma_{\phi_i}(x) + \sum_{i=1}^k \mu_{\phi_i}^2 \right] \\
 &= \frac{1}{2} \sum_{i=1}^k \left[ -\log \Sigma_{\phi_i}(x) - 1 + \Sigma_{\phi_i}(x) + \mu_{\phi_i}^2 \right]
 \end{aligned}$$

which is the fully simplified version of the KL-Divergence term. The final loss function will is

$$L(\theta, \phi, x) = -\mathbb{E}_{z \sim q_\phi(z|x)} [\log p_\theta(x|z)] + \frac{1}{2} \sum_{i=1}^k [-\log \Sigma_{\phi_i}(x) - 1 + \Sigma_{\phi_i}(x) + \mu_{\phi_i}^2] \quad (6)$$

## Backpropagation

In order to perform backpropagation in the VAE model, we need to compute the partial derivatives

$$\frac{\partial L}{\partial \theta}, \quad \frac{\partial L}{\partial \phi}$$

1. Partial derivative w.r.t.  $\theta$ :

$$\begin{aligned} \frac{\partial L}{\partial \theta} &= \frac{\partial}{\partial \theta} [-\mathbb{E}_{z \sim q_\phi(z|x)} [\log p_\theta(x|z)] + D_{KL}[q_\phi(z|x) \parallel p_\theta(z)]] \\ &= -\frac{\partial}{\partial \theta} \mathbb{E}_{z \sim q_\phi(z|x)} [\log p_\theta(x|z)] \end{aligned}$$

Using a [Monte Carlo Estimator](#) for the Expectation, we get

$$\frac{\partial L}{\partial \theta} = -\frac{1}{L} \sum_{l=1}^L \frac{\partial}{\partial \theta} \log p_\theta(x|z^{(l)})$$

where  $z^{(l)} \sim q_\phi(z|x)$

2. Partial derivative w.r.t.  $\phi$ :

Here, a problem arises. If we try to take the partial derivative of the first term w.r.t.  $\phi$ , then the gradient is being blocked by the distribution  $q_\phi$  for which the expectation is taken. This problem can be solved by using the [Reparameterization Trick](#), that is, performing a linear substitution  $z = g_\phi(\epsilon, x)$  with  $\epsilon \sim N(0, 1)$  in order to “push” the stochasticity out of the latent vector  $z$ , into the newly introduced  $\epsilon$  node.

The linear transformation  $g$  can be as simple as

$$g_\phi(\epsilon, x) = \mu_\phi(x) + \epsilon \odot \Sigma_\phi^{\frac{1}{2}}(x) = z \sim N(\mu_\phi(x), \Sigma_\phi(x))$$

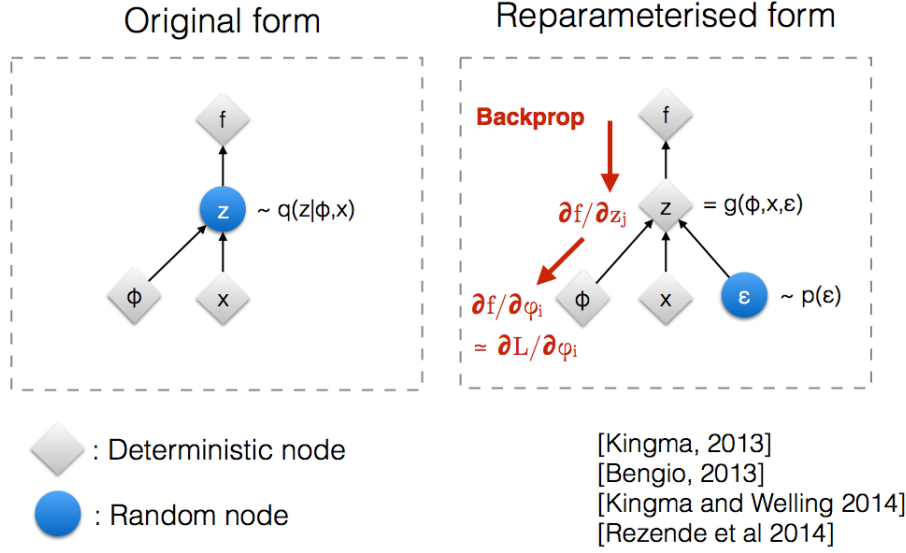


Figure 2: Visual Representation of the effect of the Reparameterization Trick. The linear substitution introduces the stochastic node  $\epsilon$ , thus removing the stochasticity from  $z$  and allowing the gradients to flow backwards. This fig. can be found in the Introduction to Variational Autoencoders paper, [here](#).

Figure 2 is a visual representation of the reparameterization trick. Now, again using a Monte Carlo Estimator for the Expectation of the first term, we can compute the gradient of the loss function  $L$  w.r.t.  $\phi$  as follows

$$\begin{aligned}
 \frac{\partial L}{\partial \phi} &= -\mathbb{E}_{z \sim p(\epsilon)} \left[ \frac{\partial}{\partial \phi} \log p_{\theta}(x|z^{(l)}) \right] + \frac{\partial}{\partial \phi} \frac{1}{2} \sum_{i=1}^k \left[ -\log \Sigma_{\phi_i}(x) - 1 + \Sigma_{\phi_i}(x) + \mu_{\phi_i}^2 \right] \\
 &= -\frac{1}{S} \sum_{s=1}^S \frac{\partial}{\partial \phi} \log p_{\theta}(x|z^{(l)}) + \frac{1}{2} \sum_{i=1}^k \left[ -\frac{\partial}{\partial \phi} \log \Sigma_{\phi_i}(x) + \frac{\partial}{\partial \phi} \Sigma_{\phi_i}(x) + \frac{\partial}{\partial \phi} \mu_{\phi_i}^2 \right]
 \end{aligned}$$

where  $z^{(l)} = m_{\phi}(x) + \epsilon \odot \sigma_{\phi}(x)$  and  $\epsilon^{(l)} \sim N(0, 1)$ .

## Resources

- Papers:
  - [Auto-Encoding Variational Bayes](#)
  - [An Introduction to Variational Autoencoders](#)
  - [Early Visual Concept Learning with Unsupervised Deep Learning](#)
- Online Lectures:
  - [Ahlad Kumar](#)
  - [Ali Ghodsi](#)