

# Deep Generative Models

## Lecture 6

Roman Isachenko

Ozon Masters

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# Gaussian autoregressive model

Consider autoregressive model

$$p(\mathbf{x}|\boldsymbol{\theta}) = \prod_{i=1}^m p(x_i|\mathbf{x}_{1:i-1}, \boldsymbol{\theta}),$$

with conditionals

$$p(x_i|\mathbf{x}_{1:i-1}, \boldsymbol{\theta}) = \mathcal{N}(\hat{\mu}_i(\mathbf{x}_{1:i-1}), \hat{\sigma}_i^2(\mathbf{x}_{1:i-1})).$$

Forward and inverse

$$x_i = \hat{\sigma}_i(\mathbf{x}_{1:i-1}) \cdot z_i + \hat{\mu}_i(\mathbf{x}_{1:i-1}), \quad z_i \sim \mathcal{N}(0, 1).$$

$$z_i = (x_i - \hat{\mu}_i(\mathbf{x}_{1:i-1})) \cdot \frac{1}{\hat{\sigma}_i(\mathbf{x}_{1:i-1})}.$$

# Gaussian autoregressive model

## Forward and inverse

$$\mathbf{x} = g(\mathbf{z}, \boldsymbol{\theta}); \quad x_i = \hat{\sigma}_i(\mathbf{x}_{1:i-1}) \cdot z_i + \hat{\mu}_i(\mathbf{x}_{1:i-1}), \quad z_i \sim \mathcal{N}(0, 1).$$

$$\mathbf{z} = f(\mathbf{x}, \boldsymbol{\theta}); \quad z_i = (x_i - \hat{\mu}_i(\mathbf{x}_{1:i-1})) \cdot \frac{1}{\hat{\sigma}_i(\mathbf{x}_{1:i-1})}.$$

## Jacobian

$$\log \left| \det \left( \frac{\partial f(\mathbf{x}, \boldsymbol{\theta})}{\partial \mathbf{x}} \right) \right| = -\log \left| \det \left( \frac{\partial g(\mathbf{z}, \boldsymbol{\theta})}{\partial \mathbf{z}} \right) \right| = -\sum_{i=1}^m \log \hat{\sigma}_i(\mathbf{x}_{1:i-1}).$$

We get an autoregressive model with tractable (triangular) Jacobian, which is easily invertible. It is a flow!

# Inverse autoregressive flow (IAF)

## Gaussian autoregressive model ( $\mathbf{z} \rightarrow \mathbf{x}$ )

$$x_i = \hat{\sigma}_i(\mathbf{x}_{1:i-1}) \cdot z_i + \hat{\mu}_i(\mathbf{x}_{1:i-1}).$$

$$z_i = (x_i - \hat{\mu}_i(\mathbf{x}_{1:i-1})) \cdot \frac{1}{\hat{\sigma}_i(\mathbf{x}_{1:i-1})}.$$

This process is sequential.

Let use the following reparametrization:  $\sigma = \frac{1}{\hat{\sigma}}$ ;  $\mu = -\frac{\hat{\mu}}{\hat{\sigma}}$ .

## Inverse transform ( $\mathbf{x} \rightarrow \mathbf{z}$ )

$$z_i = \sigma_i(\mathbf{x}_{1:i-1}) \cdot x_i + \mu_i(\mathbf{x}_{1:i-1}).$$

$$x_i = (z_i - \mu_i(\mathbf{x}_{1:i-1})) \cdot \frac{1}{\sigma_i(\mathbf{x}_{1:i-1})}.$$

This process is **not** sequential.

# Inverse autoregressive flow (IAF)

## Gaussian autoregressive model

$$x_i = \hat{\sigma}_i(\mathbf{x}_{1:i-1}) \cdot z_i + \hat{\mu}_i(\mathbf{x}_{1:i-1}).$$

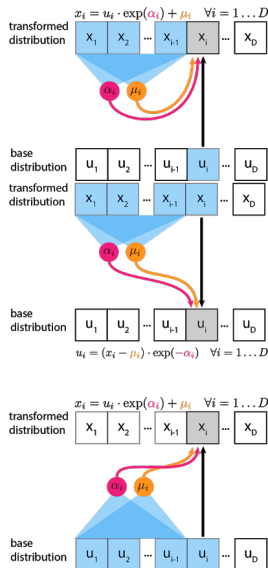
## Inverse transform

$$z_i = (x_i - \hat{\mu}_i(\mathbf{x}_{1:i-1})) \cdot \frac{1}{\hat{\sigma}_i(\mathbf{x}_{1:i-1})};$$

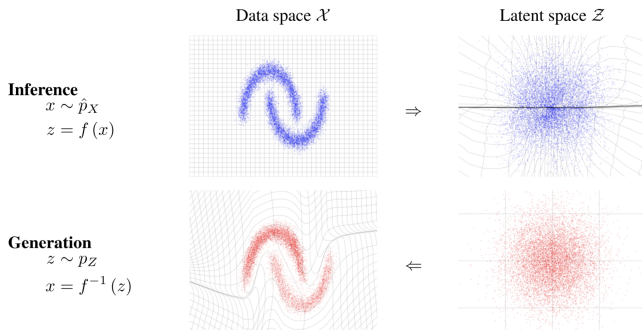
$$z_i = \sigma_i(\mathbf{x}_{1:i-1}) \cdot x_i + \mu_i(\mathbf{x}_{1:i-1}).$$

## Inverse autoregressive flow

$$x_i = \sigma_i(\mathbf{z}_{1:i-1}) \cdot z_i + \mu_i(\mathbf{z}_{1:i-1}).$$



# Flows



- ▶ Inference mode in autoregressive flows is used for density estimation task.
- ▶ Generation mode in autoregressive flows (IAF) is used for stochastic variational inference to get more flexible posterior distribution.

# Inverse autoregressive flow (IAF)

## Inverse transform ( $\mathbf{x} \rightarrow \mathbf{z}$ )

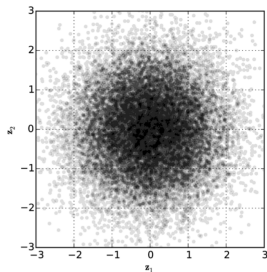
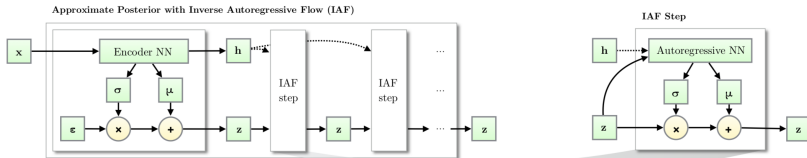
$$z_i = \sigma_i(\mathbf{x}_{1:i-1}) \cdot x_i + \mu_i(\mathbf{x}_{1:i-1}).$$
$$x_i = (z_i - \mu_i(\mathbf{x}_{1:i-1})) \cdot \frac{1}{\sigma_i(\mathbf{x}_{1:i-1})}.$$

Inverse autoregressive flow use such inverted autoregressive model as a flow in VAE:

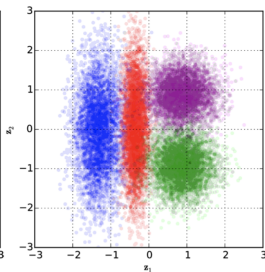
$$\mathbf{z}_0 = \sigma(\mathbf{x}) \cdot \epsilon + \mu(\mathbf{x}), \quad \epsilon \sim \mathcal{N}(0, 1); \quad \sim q(\mathbf{z}_0 | \mathbf{x}, \phi).$$

$$\mathbf{z}_k = \sigma_k(\mathbf{z}_{k-1}) \cdot \mathbf{z}_{k-1} + \mu_k(\mathbf{z}_{k-1}), \quad k \geq 1; \quad \sim q_k(\mathbf{z}_k | \mathbf{x}, \phi, \{\phi_j\}_{j=1}^k).$$

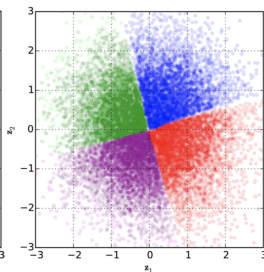
# Inverse autoregressive flow (IAF)



(a) Prior distribution



(b) Posteriors in standard VAE



(c) Posteriors in VAE with IAF

Kingma D. P. et al. *Improving Variational Inference with Inverse Autoregressive Flow*, 2016

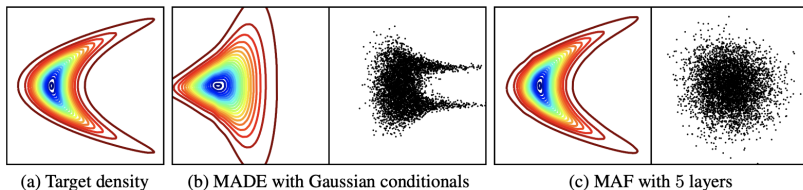


# Masked autoregressive flow (MAF)

## Gaussian autoregressive model

$$p(\mathbf{x}|\boldsymbol{\theta}) = \prod_{i=1}^m p(x_i|\mathbf{x}_{1:i-1}, \boldsymbol{\theta}) = \prod_{i=1}^m \mathcal{N}(x_i|\mu_i(\mathbf{x}_{1:i-1}), \sigma_i^2(\mathbf{x}_{1:i-1})) .$$

We could use MADE (masked autoencoder) as conditional model.  
The sampling order could be crucial.



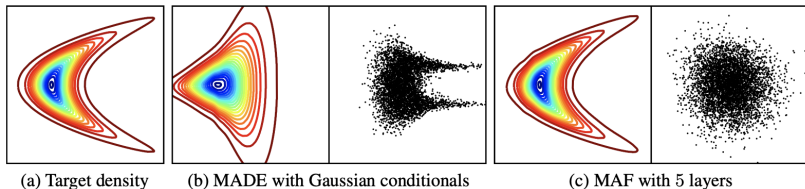
Samples from the base distribution could be an indicator of how good the flow was fitted.

*Papamakarios G., Pavlakou T., Murray I. Masked Autoregressive Flow for Density Estimation, 2017*

# Masked autoregressive flow (MAF)

## Gaussian autoregressive model

$$p(\mathbf{x}|\boldsymbol{\theta}) = \prod_{i=1}^m p(x_i|\mathbf{x}_{1:i-1}, \boldsymbol{\theta}) = \prod_{i=1}^m \mathcal{N}(x_i|\mu_i(\mathbf{x}_{1:i-1}), \sigma_i^2(\mathbf{x}_{1:i-1})) .$$



MAF is just a stacked MADE model.

# MAF vs IAF

## Sampling and inverse transform in MAF

$$x_i = \hat{\sigma}_i(\mathbf{x}_{1:i-1}) \cdot z_i + \hat{\mu}_i(\mathbf{x}_{1:i-1}).$$

$$z_i = (x_i - \hat{\mu}_i(\mathbf{x}_{1:i-1})) \cdot \frac{1}{\hat{\sigma}_i(\mathbf{x}_{1:i-1})}.$$

- ▶ Sampling is slow (sequential).
- ▶ Density estimation is fast.

## Sampling and inverse transform in IAF

$$x_i = \sigma_i(\mathbf{z}_{1:i-1}) \cdot z_i + \mu_i(\mathbf{z}_{1:i-1}).$$

$$z_i = (x_i - \mu_i(\mathbf{z}_{1:i-1})) \cdot \frac{1}{\sigma_i(\mathbf{z}_{1:i-1})}.$$

- ▶ Sampling is fast.
- ▶ Density estimation is slow (sequential).

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*Papamakarios G., Pavlakou T., Murray I. Masked Autoregressive Flow for Density Estimation, 2017*

# MAF vs IAF

## Theorem

Training a MAF with maximum likelihood corresponds to fitting an implicit IAF with stochastic variational inference where the posterior is taken to be the base density  $\pi(\mathbf{z})$ :

$$\max_{\theta} p(\mathbf{X}|\theta) \quad \Leftrightarrow \quad \min_{\theta} KL(p(\mathbf{z}|\theta) || \pi(\mathbf{z})) .$$

- ▶  $\pi(\mathbf{z})$  is a base distribution;  $\pi(\mathbf{x})$  is a data distribution.
- ▶  $\mathbf{z} = f(\mathbf{x}, \theta)$  – MAF model;  $\mathbf{x} = g(\mathbf{z}, \theta)$  – IAF model.

$$\log p(\mathbf{z}|\theta) = \log \pi(g(\mathbf{z}, \theta)) + \log \left| \det \left( \frac{\partial g(\mathbf{z}, \theta)}{\partial \mathbf{z}} \right) \right|$$

$$\log p(\mathbf{x}|\theta) = \log \pi(f(\mathbf{x}, \theta)) + \log \left| \det \left( \frac{\partial f(\mathbf{x}, \theta)}{\partial \mathbf{x}} \right) \right|$$

# MAF vs IAF

## Theorem

Training a MAF with maximum likelihood corresponds to fitting an implicit IAF with stochastic variational inference where the posterior is taken to be the base density  $\pi(\mathbf{z})$ :

$$\max_{\theta} p(\mathbf{X}|\theta) \quad \Leftrightarrow \quad \min_{\theta} KL(p(\mathbf{z}|\theta)||\pi(\mathbf{z})).$$

## Proof

$$\begin{aligned} KL(p(\mathbf{z}|\theta)||\pi(\mathbf{z})) &= \mathbb{E}_{p(\mathbf{z}|\theta)} [\log p(\mathbf{z}|\theta) - \log \pi(\mathbf{z})] = \\ &= \mathbb{E}_{p(\mathbf{z}|\theta)} \left[ \log \pi(g(\mathbf{z}, \theta)) + \log \left| \det \left( \frac{\partial g(\mathbf{z}, \theta)}{\partial \mathbf{z}} \right) \right| - \log \pi(\mathbf{z}) \right] = \\ &= \mathbb{E}_{\pi(\mathbf{x})} \left[ \log \pi(\mathbf{x}) - \log \left| \det \left( \frac{\partial f(\mathbf{x}, \theta)}{\partial \mathbf{x}} \right) \right| - \log \pi(f(\mathbf{x}, \theta)) \right]. \end{aligned}$$

# MAF vs IAF

## Proof (continued)

$$\begin{aligned} KL(p(\mathbf{z}|\boldsymbol{\theta})||\pi(\mathbf{z})) &= \\ &= \mathbb{E}_{\pi(\mathbf{x})} \left[ \log \pi(\mathbf{x}) - \log \left| \det \left( \frac{\partial f(\mathbf{x}, \boldsymbol{\theta})}{\partial \mathbf{x}} \right) \right| - \log \pi(f(\mathbf{x}, \boldsymbol{\theta})) \right] = \\ &= \mathbb{E}_{\pi(\mathbf{x})} [\log \pi(\mathbf{x}) - \log p(\mathbf{x}|\boldsymbol{\theta})] = KL(\pi(\mathbf{x})||p(\mathbf{x}|\boldsymbol{\theta})). \end{aligned}$$

$$\begin{aligned} \arg \min_{\boldsymbol{\theta}} KL(\pi(\mathbf{x})||p(\mathbf{x}|\boldsymbol{\theta})) &= \arg \min_{\boldsymbol{\theta}} \mathbb{E}_{\pi(\mathbf{x})} [\log \pi(\mathbf{x}) - \log p(\mathbf{x}|\boldsymbol{\theta})] \\ &= \arg \max_{\boldsymbol{\theta}} \mathbb{E}_{\pi(\mathbf{x})} \log p(\mathbf{x}|\boldsymbol{\theta}) \end{aligned}$$

Unbiased estimator is MLE:

$$\mathbb{E}_{\pi(\mathbf{x})} \log p(\mathbf{x}|\boldsymbol{\theta}) = \sum_{i=1}^n \log p(\mathbf{x}_i|\boldsymbol{\theta}).$$

# MAF vs IAF vs RealNVP

## MAF

$$\mathbf{x} = \hat{\sigma}(\mathbf{x}) \odot \mathbf{z} + \hat{\mu}(\mathbf{x}).$$

- ▶ Calculating the density  $p(\mathbf{x}|\theta)$  - 1 pass.
- ▶ Sampling -  $m$  passes.

## IAF

$$\mathbf{x} = \sigma(\mathbf{z}) \odot \mathbf{z} + \mu(\mathbf{z}).$$

- ▶ Calculating the density  $p(\mathbf{x}|\theta)$  -  $m$  passes.
- ▶ Sampling - 1 pass.

## RealNVP

$$\mathbf{x}_{1:d} = \mathbf{z}_{1:d};$$

$$\mathbf{x}_{d:m} = \mathbf{z}_{d:m} \odot \exp(c_1(\mathbf{z}_{1:d}, \theta)) + c_2(\mathbf{x}_{1:d}, \theta).$$

# MAF vs IAF vs RealNVP

## RealNVP

$$\mathbf{x}_{1:d} = \mathbf{z}_{1:d};$$

$$\mathbf{x}_{d:m} = \mathbf{z}_{d:m} \odot \exp(c_1(\mathbf{z}_{1:d}, \boldsymbol{\theta})) + c_2(\mathbf{x}_{1:d}, \boldsymbol{\theta}).$$

- ▶ Calculating the density  $p(\mathbf{x}|\boldsymbol{\theta})$  - 1 pass.
- ▶ Sampling - 1 pass.

RealNVP is a special case of MAF and IAF:

## MAF

$$\begin{cases} \hat{\mu}_i = \hat{\sigma}_i = 0, i = 1, \dots, d; \\ \hat{\mu}_i, \hat{\sigma}_i - \text{functions of } \mathbf{x}_{1:d}, i = d + 1, \dots, m. \end{cases}$$

## IAF

$$\begin{cases} \mu_i = \sigma_i = 0, i = 1, \dots, d; \\ \mu_i, \sigma_i - \text{functions of } \mathbf{z}_{1:d}, i = d + 1, \dots, m. \end{cases}$$



# MAF/IAF pros and cons

## MAF

- ▶ Sampling is slow.
- ▶ Likelihood evaluation is fast.

## IAF

- ▶ Sampling is fast.
- ▶ Likelihood evaluation is slow.

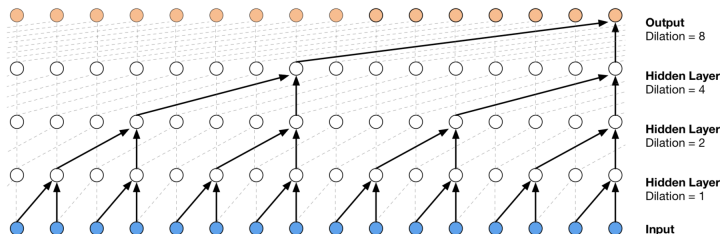
How to take the best of both worlds?

# WaveNet (2016)

Autoregressive model for raw audio waveforms generation

$$p(\mathbf{x}|\theta) = \prod_{t=1}^T p(x_t|\mathbf{x}_{1:t-1}, \theta).$$

The model uses causal dilated convolutions.



<https://arxiv.org/pdf/1609.03499.pdf>

# Parallel WaveNet, 2017

## Previous WaveNet model

- ▶ raw audio is high-dimensional (e.g. 16000 samples per second for 16kHz audio);
- ▶ WaveNet encodes 8-bit signal with 256-way categorical distribution.

## Goal

- ▶ improved fidelity (24kHz instead of 16kHz) → increase dilated convolution filter size from 2 to 3;
- ▶ 16-bit signals → mixture of logistics instead of categorical distribution.

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<https://arxiv.org/pdf/1711.10433.pdf>

# Parallel WaveNet, 2017

## Probability density distillation

1. Train usual WaveNet (MAF) via MLE (teacher network).
2. Train IAF WaveNet model (student network), which attempts to match the probability of its own samples under the distribution learned by the teacher.

## Student objective

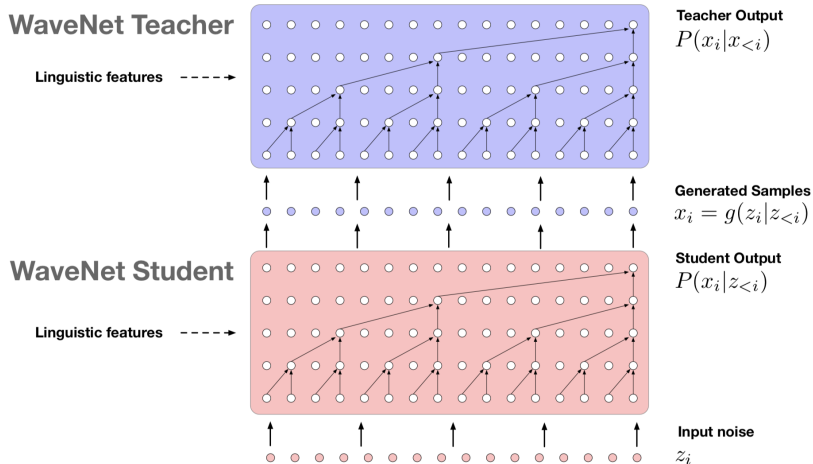
$$KL(p_s||p_t) = H(p_s, p_t) - H(p_s).$$

More than 1000x speed-up relative to original WaveNet!

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<https://arxiv.org/pdf/1711.10433.pdf>

# Parallel WaveNet, 2017



<https://arxiv.org/pdf/1711.10433.pdf>

# Summary

- ▶ Flows is a continuous model. To use it for discrete distribution, the data should be dequantized.
- ▶ Original VAE model has lot of limitations. One of them is a restricted class of variational posteriors.
- ▶ Using flows in a latent space of VAE could give more flexible posterior distribution.
- ▶ Gaussian autoregressive model is a special type of flow (RealNVP model is a special type of this autoregressive model)
- ▶ MAF is an example of such model which is suitable for density estimation tasks.
- ▶ IAF used the inverse autoregressive transformation for variational inference task.

# VAE limitations

- ▶ Poor variational posterior distribution (encoder)

$$q(\mathbf{z}|\mathbf{x}, \phi) = \mathcal{N}(\mathbf{z}|\boldsymbol{\mu}_{\phi}(\mathbf{x}), \boldsymbol{\sigma}_{\phi}^2(\mathbf{x})).$$

- ▶ Poor prior distribution

$$p(\mathbf{z}) = \mathcal{N}(0, \mathbf{I}).$$

- ▶ Poor probabilistic model (decoder)

$$p(\mathbf{x}|\mathbf{z}, \theta) = \mathcal{N}(\mathbf{x}|\boldsymbol{\mu}_{\theta}(\mathbf{z}), \boldsymbol{\sigma}_{\theta}^2(\mathbf{z})).$$

- ▶ Loose lower bound

$$p(\mathbf{x}|\theta) - \mathcal{L}(q, \theta) = (?).$$

$$\mathcal{L}(q, \theta) = \int q(\mathbf{Z}|\mathbf{X}) \log \frac{p(\mathbf{X}, \mathbf{Z}|\theta)}{q(\mathbf{Z}|\mathbf{X})} d\mathbf{Z}.$$

## ELBO interpretations

- ▶ Evidence minus posterior KL

$$\mathcal{L}(q, \theta) = \log p(\mathbf{X}|\theta) - KL(q(\mathbf{Z}|\mathbf{X})||p(\mathbf{Z}|\mathbf{X}, \theta)).$$

- ▶ Average negative energy plus entropy

$$\mathcal{L}(q, \theta) = \mathbb{E}_{q(\mathbf{Z}|\mathbf{X})} p(\mathbf{X}, \mathbf{Z}|\theta) + \mathbb{H}[q(\mathbf{Z}|\mathbf{X})].$$

- ▶ Average term-by-term reconstruction minus KL to prior

$$\mathcal{L}(q, \theta) = \frac{1}{n} \sum_{i=1}^n \left[ \mathbb{E}_{q(\mathbf{z}_i|\mathbf{x}_i)} \log p(\mathbf{x}_i|\mathbf{z}_i, \theta) - KL(q(\mathbf{z}_i|\mathbf{x}_i)||p(\mathbf{z}_i)) \right].$$



$$\mathcal{L}(q, \theta) = \frac{1}{n} \sum_{i=1}^n \left[ \mathbb{E}_{q(\mathbf{z}_i|\mathbf{x}_i)} \log p(\mathbf{x}_i|\mathbf{z}_i, \theta) - KL(q(\mathbf{z}_i|\mathbf{x}_i)||p(\mathbf{z}_i)) \right].$$

## Theorem

$$\frac{1}{n} \sum_{i=1}^n KL(q(\mathbf{z}_i|\mathbf{x}_i)||p(\mathbf{z}_i)) = KL(q(\mathbf{z})||p(\mathbf{z})) + \mathbb{I}_{q(i,\mathbf{z})}[i, \mathbf{z}],$$

where  $i$  is treated as random variable:

$$q(i, \mathbf{z}) = q(i)q(\mathbf{z}|i); \quad p(i, \mathbf{z}) = p(i)p(\mathbf{z}); \quad q(i) = p(i) = \frac{1}{n}; \quad q(\mathbf{z}|i) = q(\mathbf{z}|\mathbf{x}_i).$$

$$q(\mathbf{z}) = \sum_{i=1}^n q(i, \mathbf{z}) = \frac{1}{n} \sum_{i=1}^n q(\mathbf{z}|\mathbf{x}_i); \quad \mathbb{I}_{q(i,\mathbf{z})}[i, \mathbf{z}] = \mathbb{E}_{q(i,\mathbf{z})} \log \frac{q(i, \mathbf{z})}{q(i)q(\mathbf{z})}.$$

## Theorem

$$\frac{1}{n} \sum_{i=1}^n KL(q(\mathbf{z}_i | \mathbf{x}_i) || p(\mathbf{z}_i)) = KL(q(\mathbf{z}) || p(\mathbf{z})) + \mathbb{I}_{q(i, \mathbf{z})}[i, \mathbf{z}].$$

## Proof

$$\begin{aligned} \frac{1}{n} \sum_{i=1}^n KL(q(\mathbf{z}_i | \mathbf{x}_i) || p(\mathbf{z}_i)) &= \sum_{i=1}^n \int q(i) q(\mathbf{z} | i) \log \frac{q(\mathbf{z} | i)}{p(\mathbf{z})} d\mathbf{z} = \\ &= \sum_{i=1}^n \int q(i, \mathbf{z}) \log \frac{q(i, \mathbf{z})}{p(\mathbf{z}) p(i)} d\mathbf{z} = \int \sum_{i=1}^n q(i, \mathbf{z}) \log \frac{q(\mathbf{z}) q(i | \mathbf{z})}{p(\mathbf{z}) p(i)} d\mathbf{z} = \\ &= \int q(\mathbf{z}) \log \frac{q(\mathbf{z})}{p(\mathbf{z})} d\mathbf{z} + \int \sum_{i=1}^n q(i | \mathbf{z}) q(\mathbf{z}) \log \frac{q(i | \mathbf{z})}{p(i)} d\mathbf{z} = \\ &= KL(q(\mathbf{z}) || p(\mathbf{z})) - \mathbb{E}_{q(\mathbf{z})} \mathbb{H}[q(i | \mathbf{z})] + \log n. \end{aligned}$$

## Theorem

$$\frac{1}{n} \sum_{i=1}^n KL(q(\mathbf{z}_i | \mathbf{x}_i) || p(\mathbf{z}_i)) = KL(q(\mathbf{z}) || p(\mathbf{z})) + \mathbb{I}_{q(i, \mathbf{z})}[i, \mathbf{z}].$$

## Proof (continued)

$$\frac{1}{n} \sum_{i=1}^n KL(q(\mathbf{z}_i | \mathbf{x}_i) || p(\mathbf{z}_i)) = KL(q(\mathbf{z}) || p(\mathbf{z})) - \mathbb{E}_{q(\mathbf{z})} \mathbb{H}[q(i | \mathbf{z})] + \log n$$

$$\begin{aligned} \mathbb{I}_{q(i, \mathbf{z})}[i, \mathbf{z}] &= \mathbb{E}_{q(i, \mathbf{z})} \log \frac{q(i, \mathbf{z})}{q(i)q(\mathbf{z})} = \mathbb{E}_{q(\mathbf{z})} \mathbb{E}_{q(i | \mathbf{z})} \log \frac{q(i | \mathbf{z})q(\mathbf{z})}{q(i)q(\mathbf{z})} = \\ &= \mathbb{E}_{q(\mathbf{z})} \mathbb{E}_{q(i | \mathbf{z})} \log \frac{q(i | \mathbf{z})}{q(i)} = -\mathbb{E}_{q(\mathbf{z})} \mathbb{H}[q(i | \mathbf{z})] + \log n. \end{aligned}$$

# ELBO surgery, 2016

## Theorem

$$\frac{1}{n} \sum_{i=1}^n KL(q(\mathbf{z}_i | \mathbf{x}_i) || p(\mathbf{z}_i)) = KL(q(\mathbf{z}) || p(\mathbf{z})) + \mathbb{I}_{q(i, \mathbf{z})}[i, \mathbf{z}].$$

## ELBO revisiting

$$\begin{aligned} \mathcal{L}(q, \theta) &= \frac{1}{n} \sum_{i=1}^n [\mathbb{E}_{q(\mathbf{z}_i | \mathbf{x}_i)} \log p(\mathbf{x}_i | \mathbf{z}_i, \theta) - KL(q(\mathbf{z}_i | \mathbf{x}_i) || p(\mathbf{z}_i))] = \\ &= \frac{1}{n} \sum_{i=1}^n \mathbb{E}_{q(\mathbf{z}_i | \mathbf{x}_i)} \log p(\mathbf{x}_i | \mathbf{z}_i, \theta) - \mathbb{I}_{q(i, \mathbf{z})}[i, \mathbf{z}] - KL(q(\mathbf{z}) || p(\mathbf{z})) = \\ &= \underbrace{\frac{1}{n} \sum_{i=1}^n \mathbb{E}_{q(\mathbf{z}_i | \mathbf{x}_i)} \log p(\mathbf{x}_i | \mathbf{z}_i, \theta)}_{\text{Reconstruction loss}} - \underbrace{(\log n - \mathbb{E}_{q(\mathbf{z})} \mathbb{H}[q(i | \mathbf{z})])}_{0 \leq \text{Mutual info} \leq \log n} - \underbrace{KL(q(\mathbf{z}) || p(\mathbf{z}))}_{\text{Marginal KL}} \end{aligned}$$

# ELBO surgery, 2016

## ELBO revisiting

$$\mathcal{L}(q, \theta) = \underbrace{\frac{1}{n} \sum_{i=1}^n \mathbb{E}_{q(\mathbf{z}_i | \mathbf{x}_i)} \log p(\mathbf{x}_i | \mathbf{z}_i, \theta)}_{\text{Reconstruction loss}} - \underbrace{(\log n - \mathbb{E}_{q(\mathbf{z})} \mathbb{H}[q(i | \mathbf{z})])}_{0 \leq \text{Mutual info} \leq \log n} - \underbrace{KL(q(\mathbf{z}) || p(\mathbf{z}))}_{\text{Marginal KL}}$$

$$KL(q(\mathbf{z}) || p(\mathbf{z})) = 0 \quad \Leftrightarrow \quad p(\mathbf{z}) = q(\mathbf{z}) = \frac{1}{n} \sum_{i=1}^n q(\mathbf{z} | \mathbf{x}_i).$$

	ELBO	Avg. KL	Mutual info. ②	Marg. KL ③
2D latents	-129.63	7.41	7.20	0.21
10D latents	-88.95	19.17	10.82	8.35
20D latents	-87.45	20.2	10.67	9.53

$$\log n \approx 11.0021$$

## ELBO revisiting

$$\mathcal{L}(q, \theta) = \underbrace{\frac{1}{n} \sum_{i=1}^n \mathbb{E}_{q(\mathbf{z}_i | \mathbf{x}_i)} \log p(\mathbf{x}_i | \mathbf{z}_i, \theta)}_{\text{Reconstruction loss}} - \underbrace{(\log n - \mathbb{E}_{q(\mathbf{z})} \mathbb{H}[q(i | \mathbf{z})])}_{0 \leq \text{Mutual info} \leq \log N} - \underbrace{KL(q(\mathbf{z}) || p(\mathbf{z}))}_{\text{Marginal KL}}$$

How to choose the optimal  $p(\mathbf{z})$ ?

- ▶ SG:  $p(\mathbf{z}) = \mathcal{N}(0, I) \Rightarrow$  over-regularization;
- ▶ MoG:  $p(\mathbf{z} | \lambda) = \frac{1}{K} \sum_{k=1}^K \mathcal{N}(\mu_k, \sigma_k^2) \Rightarrow (*), (**);$
- ▶  $p(\mathbf{z}) = q(\mathbf{z}) = \frac{1}{n} \sum_{i=1}^n q(\mathbf{z} | \mathbf{x}_i) \Rightarrow$  overfitting and highly expensive.

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(\*) <https://arxiv.org/abs/1611.02648>

(\*\*) <https://pdfs.semanticscholar.org/f6fe/5e8e25994c188ba6a124462e2cc55f2c5a67.pdf>

# References

- ▶ **IAF:** Improving Variational Inference with Inverse Autoregressive Flow  
<https://arxiv.org/abs/1606.04934>  
**Summary:** Introduce inverse autoregressive flow (IAF). Models each autoregressive conditional as gaussian with autoregressive means and covariances. Inverse transformation allows to parallelize sampling.
- ▶ **MAF:** Masked Autoregressive Flow for Density Estimation  
<https://arxiv.org/pdf/1705.07057.pdf>  
**Summary:** Similar to IAF. Give comprehensive overview with link to IAF and RealNVP. MAF is suitable for density estimation, IAF as a recognition network.
- ▶ **Parallel WaveNet:** Fast High-Fidelity Speech Synthesis  
<https://arxiv.org/pdf/1711.10433.pdf>  
**Summary:** WaveNet is MAF (sequential generation). To exploit IAF fast sampling, knowledge distillation used. Teacher network is large WaveNet, student - is a IAF small WaveNet (generate samples from noise is parallel). The loss is KL divergence between student and teacher distributions. The additional perceptual, contrastive and power losses used to create more natural sounds.
- ▶ **ELBO surgery:** yet another way to carve up the variational evidence lower bound  
<http://approximateinference.org/accepted/HoffmanJohnson2016.pdf>  
**Summary:** Propose the decomposition of standard ELBO into 3 terms. The prior distribution should be close to average posterior. Show empirically that weak prior has a significant impact on ELBO value.