

# Deep Generative Models: Diffusion Models

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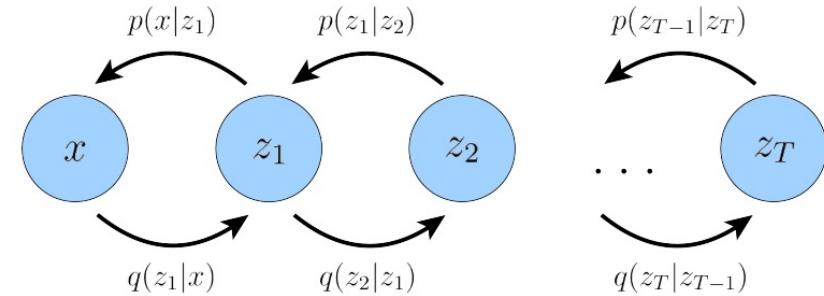
# Outline

- Markov Hierarchical Variational Auto Encoders (MHVAEs)
  - Autoregressive Encoder and Autoregressive Decoder of an MHVAE
  - Derivation of the ELBO of an MHVAE
- Diffusion Models as MHVAEs with a Linear Gaussian Autoregressive Latent Space
  - Forward Diffusion Process
  - Reverse Diffusion Process
  - ELBO for Diffusion Models as a particular case of the ELBO for MHVAEs
- **Implementation Details: UNet architecture, Training and Sampling Strategies**
- Application of Diffusion Models
  - Stable Diffusion: Text-Conditioned Diffusion Model
  - ControlNet: Multimodal Control for Consistent Synthesis

# Implementation (DDPM)

- The Denoising Diffusion Probabilistic Model (DDPM) fixes the noise variances  $\alpha_t$  of the forward process and **learns only the backward (denoising) process** [Ho et al., 2020].

$$q_{\phi}(x_t | x_{t-1}) = \mathcal{N}(x_t; \sqrt{\alpha_t}x_{t-1}, (1 - \alpha_t)I)$$



- For the backward process, we use reparameterization of ELBO

$$\begin{aligned}
 \log p(x) &\geq \underbrace{\mathbb{E}_{q_{\phi}(x_1|x_0)}[\log p_{\theta}(x_0|x_1)]}_{\text{reconstruction term}} - \underbrace{D_{\text{KL}}(q_{\phi}(x_T|x_0) || p_{\theta}(x_T))}_{\text{prior matching term}} - \underbrace{\sum_{t=2}^T \mathbb{E}_{q_{\phi}(x_t|x_0)}[D_{\text{KL}}(q_{\phi}(x_{t-1}|x_t, x_0) || p_{\theta}(x_{t-1}|x_t))]}_{\text{score matching term}} \\
 &= - \underbrace{\sum_{t=1}^T \mathbb{E}_{q_{\phi}(x_t|x_0)}[D_{\text{KL}}(q_{\phi}(x_{t-1}|x_t, x_0) || p_{\theta}(x_{t-1}|x_t))]}_{\text{reconstruction term} + \text{score matching term}} = - \sum_{t=1}^T \mathbb{E}_{q_{\phi}(x_t|x_0)} \left[ \frac{1}{2\sigma_q^2(t)} \frac{(1-\alpha_t)^2}{(1-\bar{\alpha}_t)\alpha_t} [\|\epsilon_0 - \hat{\epsilon}_{\theta}(x_t, t)\|_2^2] \right]
 \end{aligned}$$

$$\sigma_q^2(t) = \frac{(1 - \alpha_t)(1 - \bar{\alpha}_{t-1})}{1 - \bar{\alpha}_t}$$

- For each  $x$ , we need to compute  $T$  terms in the sum, which is **expensive** for typical values of  $T$  ( $T=1000$ ).

# SGD over time-steps

- DDPM minimizes the ELBO **efficiently** by performing SGD over the set of timesteps  $[T] = \{1, 2, \dots, T\}$ .
- Using linearity of expectation and letting  $t \sim \text{Unif}([T])$

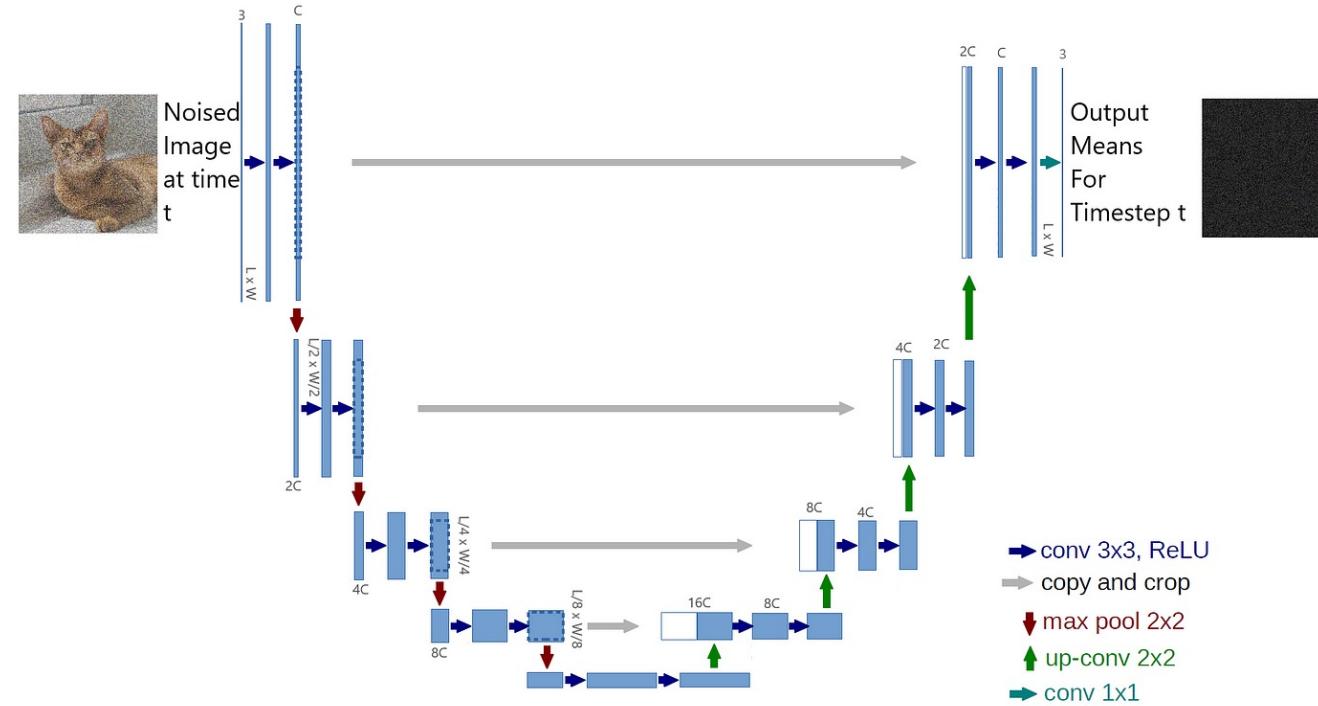
$$\begin{aligned}\log p(x) &\geq -D_{\text{KL}}(q_{\phi}(x_T | x_0) || p_{\theta}(x_T)) - \sum_{t=1}^T \mathbb{E}_{q_{\phi}(x_t | x_0)} \left[ \frac{1}{2\sigma_q^2(t)} \frac{(1-\alpha_t)^2}{(1-\bar{\alpha}_t)\alpha_t} \|\epsilon_0 - \hat{\epsilon}_{\theta}(x_t, t)\|_2^2 \right] \\ &= -D_{\text{KL}}(q_{\phi}(x_T | x_0) || p_{\theta}(x_T)) - \mathbb{E}_{q_{\phi}(x_t | x_0)} \left[ \sum_{t=1}^T \frac{1}{2\sigma_q^2(t)} \frac{(1-\alpha_t)^2}{(1-\bar{\alpha}_t)\alpha_t} \|\epsilon_0 - \hat{\epsilon}_{\theta}(x_t, t)\|_2^2 \right] \\ &= -D_{\text{KL}}(q_{\phi}(x_T | x_0) || p_{\theta}(x_T)) - \mathbb{E}_{q_{\phi}(x_t | x_0), t} \left[ \frac{T}{2\sigma_q^2(t)} \frac{(1-\alpha_t)^2}{(1-\bar{\alpha}_t)\alpha_t} \|\epsilon_0 - \hat{\epsilon}_{\theta}(x_t, t)\|_2^2 \right]\end{aligned}$$

- Thus, the sampling procedure computes only 1 term instead of  $T$  terms.
- The term  $-D_{\text{KL}}(q_{\phi}(x_T | x_0) || p_{\theta}(x_T))$  is **constant** during training, since  $q_{\phi}(x_T | x_0)$  is not learnable.
- Thus, the simplified (unweighted) learning objective used in DDPM is

$$\mathbb{E}_{q_{\phi}(x_t | x_0), t} [\|\epsilon_0 - \hat{\epsilon}_{\theta}(x_t, t)\|_2^2]$$

# Architecture of DDPM

- DDPM uses a **U-Net** with residual connection and self-attention layers to represent the noise  $\overline{\epsilon_\theta}(x_t, t)$ .
- Since the parameter  $\overline{\epsilon_\theta}(x_t, t)$  depends both on  $x_t$  and on time  $t$ , a time embedding needs to be provided as input to each unit of the U-Net.

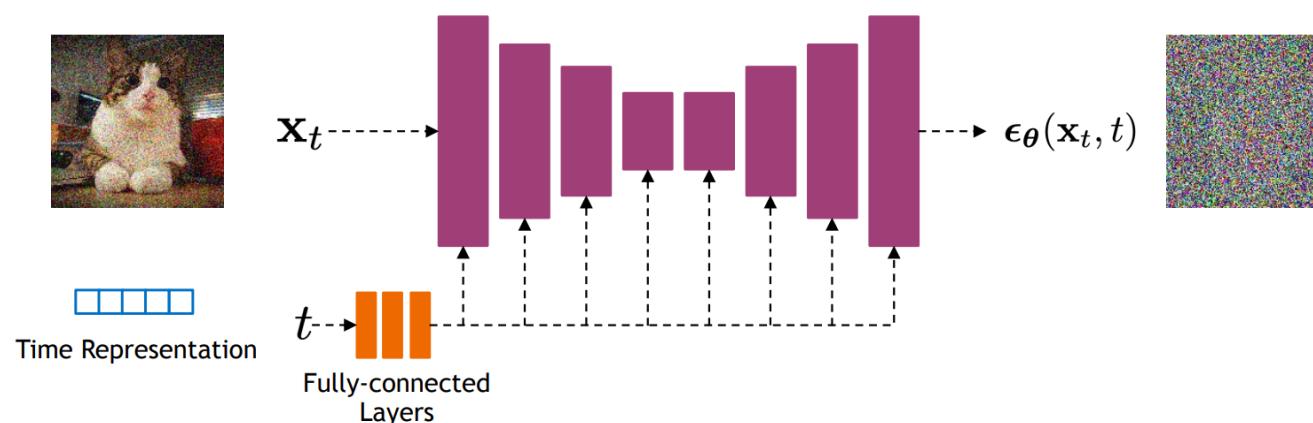


# Time Encoding

- The time representation is implemented using **sinusoidal positional embeddings**.
- Given a time step  $t \in [T]$  and an embedding dimension  $d$ , the sinusoidal positional embedding  $\text{SPE}(t)$  is given for  $i = 0, 1, \dots, \frac{d}{2} - 1$  as

$$\text{SPE}(t)_{2i} = \sin\left(\frac{t}{10^{\frac{6i}{d}}}\right), \text{SPE}(t)_{2i+1} = \cos\left(\frac{t}{10^{\frac{6i}{d}}}\right)$$

- This produces a fixed-length vector  $\text{SPE}(t)$  that encodes the time smoothly, since small changes in  $t$  cause predictable oscillations in the time embedding.
- The time embedding is given as input to all units of the U-Net.



# Training and Sampling in DDPM

- DDPM implements the training procedure by performing SGD on the set of training images over timesteps.
- The sampling procedure executes iteratively the denoising process from a Gaussian initialization  $x_T$ .

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## Algorithm 1 Training

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```
1: repeat  
2:  $\mathbf{x}_0 \sim q(\mathbf{x}_0)$   
3:  $t \sim \text{Uniform}(\{1, \dots, T\})$   
4:  $\epsilon \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$   
5: Take gradient descent step on  
    $\nabla_{\theta} \|\epsilon - \epsilon_{\theta}(\sqrt{\bar{\alpha}_t} \mathbf{x}_0 + \sqrt{1 - \bar{\alpha}_t} \epsilon, t)\|^2$   
6: until converged
```

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## Algorithm 2 Sampling

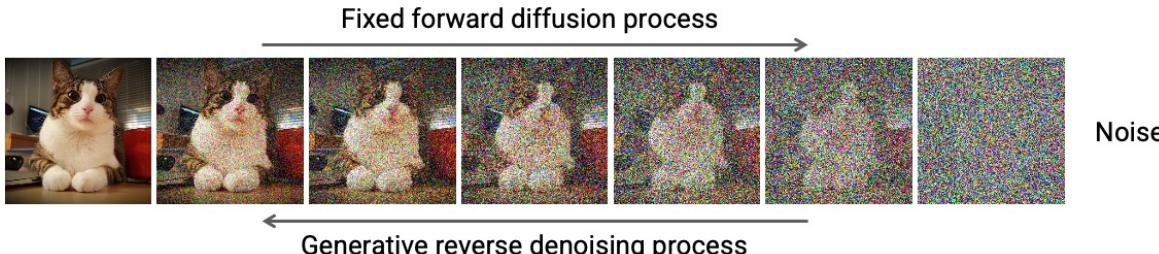
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```
1:  $\mathbf{x}_T \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$   
2: for  $t = T, \dots, 1$  do  
3:  $\mathbf{z} \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$  if  $t > 1$ , else  $\mathbf{z} = \mathbf{0}$   
4:  $\mathbf{x}_{t-1} = \frac{1}{\sqrt{\alpha_t}} \left( \mathbf{x}_t - \frac{1 - \alpha_t}{\sqrt{1 - \bar{\alpha}_t}} \epsilon_{\theta}(\mathbf{x}_t, t) \right) + \sigma_t \mathbf{z}$   
5: end for  
6: return  $\mathbf{x}_0$ 
```

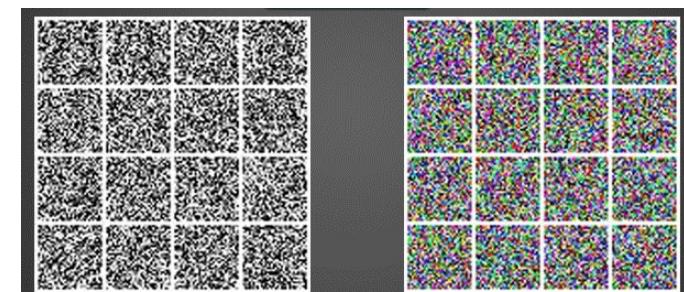
$$\mu_{\theta}(\mathbf{x}_t, t) \quad \sigma_t = \sqrt{\beta_t}$$

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Data



Noise



# DDPM Noise Scheduler

- **Noise Scheduler for Forward Process:** in DDPM, the scheduler refers to how the noise variance ( $\beta_t = 1 - \alpha_t$ ) changes across the diffusion timesteps  $t = 1, \dots, T$ .
  - **Linear Schedule:**  $\beta_t$  increases linearly from initial value ( $10^{-4}$ ) to a maximum value (0.02)

$$\beta_t = \beta_{\text{start}} + t \frac{\beta_{\text{end}} - \beta_{\text{start}}}{T - 1}, t = 0, \dots, T - 1$$

- **Cosine Schedule:** Uses a cosine function to define  $\beta_t$ , which better preserves signal early in the process and decays more gently near the end. It helps maintain more information in the intermediate steps, improve sample quality, require fewer steps for comparable results.

$$f(t) = \cos\left(\frac{t/T+s}{1+s} \cdot \frac{\pi}{2}\right), t = 0, \dots, T - 1, \quad \bar{\alpha}_t = \frac{f(t)}{f(0)}, \quad \beta_t = 1 - \frac{\bar{\alpha}_t}{\bar{\alpha}_{t-1}}, \quad s = 0.008.$$

- **Training Data:** For each training image  $x_0$  and timestep  $t$ , a noisy image  $x_t$  is generated as:  $x_t = \sqrt{\bar{\alpha}_t}x_0 + \sqrt{1 - \bar{\alpha}_t} \epsilon, \quad \epsilon \sim \mathcal{N}(\epsilon; 0, I)$ .

# Training Curves & Test Metrics

- The **Inception Score** (IS) and **Fréchet Inception Distance** (FID) are two common metrics for evaluating the quality of generated images.
- IS measures how realistic and diverse the generated samples are by comparing the distribution of generated samples  $p_g$  with the output of an Inceptionv3 network
$$\text{IS} = \exp \left( \mathbb{E}_{x \sim p_g} [D_{KL}(p(y|x) \parallel p(y))] \right), p(y|x) = \text{InceptionNet}(x)$$
- The FID measures how close the distribution of the generated images with parameters  $(\mu_g, \Sigma_g)$  to the real data distribution with parameters  $(\mu_r, \Sigma_r)$ 
$$\text{FID} = \|\mu_r - \mu_g\|^2 + \text{Tr} \left( \Sigma_r + \Sigma_g - 2(\Sigma_r \Sigma_g)^{\frac{1}{2}} \right)$$

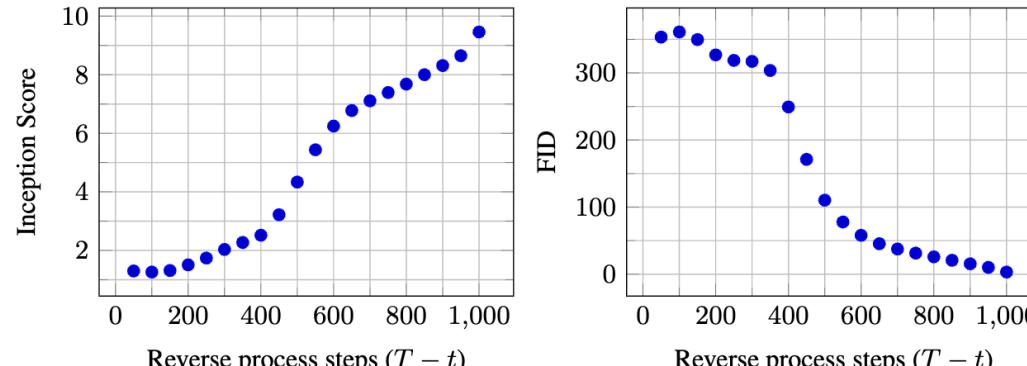


Figure 10: Unconditional CIFAR10 progressive sampling quality over time

# Generated Samples of DDPM

