

# Diffusion Models

How AI Learns to Create Images from Noise

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Course Presentation

# Roadmap

Motivation

Forward Process

Reverse Process

Training & Score Matching

Applications

Conclusion

- **10 min talk**

Speaker 1 (Anindya Biswas) 3 min

Speaker 2 (Tasnim Tamal) 3 min

Speaker 3 (Din Mohammad) 3 min

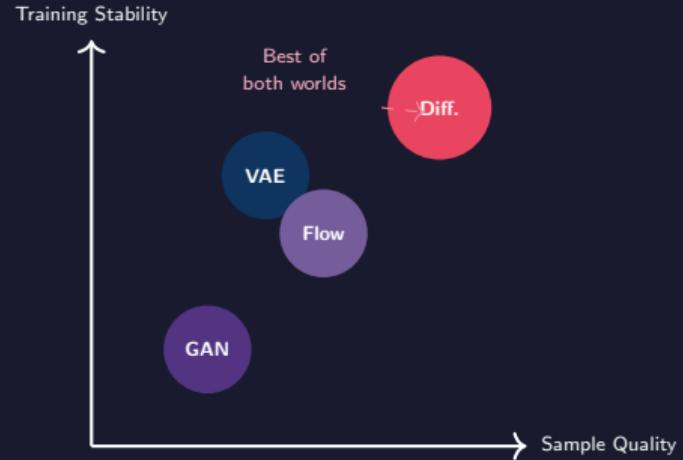
Buffer / Transition 1 min

# Why Diffusion Models?

## In One Line

A diffusion model learns to **turn random noise into meaningful data** (like realistic images).

- **GANs**: high quality, but training is often unstable
- **VAEs**: stable and fast, but outputs can look blurry
- **Flows**: mathematically clean, but architecture is restricted
- **Diffusion**: stable training + very strong output quality



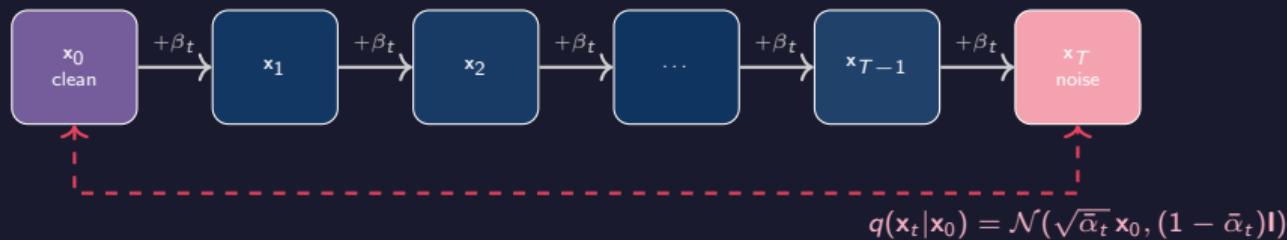
Used in tools like DALL·E 3, Stable Diffusion, and Sora

# The Forward (Noising) Process

## Key Idea

Gradually corrupt data  $\mathbf{x}_0$  into pure Gaussian noise  $\mathbf{x}_T$  through a fixed Markov chain.

$$q(\mathbf{x}_t | \mathbf{x}_{t-1}) = \mathcal{N}\left(\mathbf{x}_t; \sqrt{1 - \beta_t} \mathbf{x}_{t-1}, \beta_t \mathbf{I}\right)$$



Plainly: start from a real sample and add a little noise repeatedly until almost all information is gone.

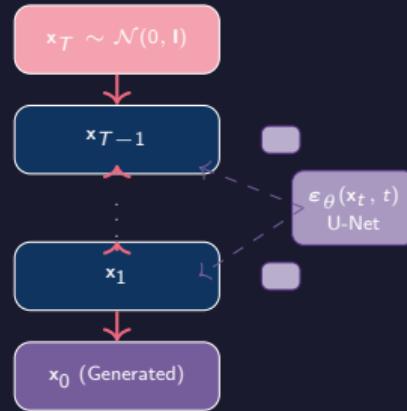
# The Reverse (Denoising) Process

**Goal:** Learn  $p_\theta(x_{t-1}|x_t)$  to reverse the noise.

A **neural network**  $\epsilon_\theta$  predicts the noise present at each step:

$$x_{t-1} \approx x_t - \text{predicted noise}$$

- Backbone: usually a **U-Net**
- Input includes both noisy sample and timestep  $t$
- Repeat many times to gradually recover clean data



# Training Objective

## Training Idea (Simple Version)

$$\mathcal{L}_{\text{simple}} = \mathbb{E}_{t, \mathbf{x}_0, \boldsymbol{\varepsilon}} \left[ \| \boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}_{\theta}(\sqrt{\bar{\alpha}_t} \mathbf{x}_0 + \sqrt{1 - \bar{\alpha}_t} \boldsymbol{\varepsilon}, t) \|^2 \right]$$

## Algorithm — Training

1. Sample  $\mathbf{x}_0 \sim q(\mathbf{x}_0)$



2. Sample timestep  $t \sim \mathcal{U}\{1, T\}$



3. Sample  $\boldsymbol{\varepsilon} \sim \mathcal{N}(0, \mathbf{I})$



4. Compute noisy sample  $\mathbf{x}_t$



5. Minimise  $\|\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}_{\theta}(\mathbf{x}_t, t)\|^2$

## What this loss means

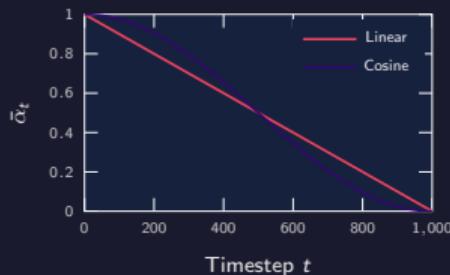
- We add known noise to a clean sample
- The model guesses that exact noise
- If guess is close, the model is learning correctly
- After training, we can remove noise step by step

**Key insight:** learning to denoise is enough for generation.

# Noise Schedule & Sampling Speed

## Noise Schedules

- *Linear*: increase noise at a constant rate
- *Cosine*: keeps more structure early on
- *Learned*: schedule is optimized by data

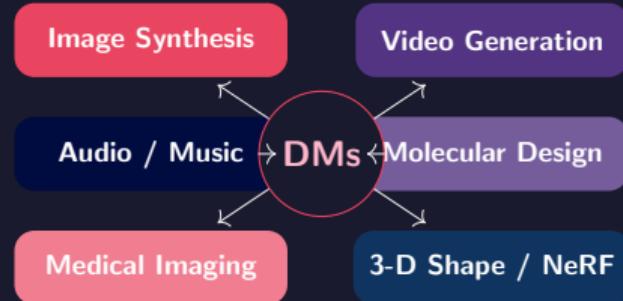


## Accelerated Sampling

- DDPM:  $T = 1000$  steps (slow)
- **DDIM** (Song et al., 2020): deterministic,  $\sim 50$  steps, same quality
- **DPM-Solver**:  $\sim 20$  steps
- **Consistency Models**: 1–2 steps!

Speed-quality trade-off is an active research frontier.

# Applications & Variants



## Conditional Generation

- **Classifier guidance:** steer outputs to a target label
- **Classifier-free:** steer generation without a separate classifier
- **Text conditioning:** prompt-based image generation

Notable: Stable Diffusion (latent space), DALL-E 3 (GPT captions), Sora (video)

# Takeaways & Open Challenges

## • Key Takeaways

- Diffusion = iterative **denoising**
- Training objective is **simple MSE**
- Grounded in **score matching** theory
- Sets **state-of-the-art** across modalities

## • Open Challenges

- Slow sampling (active research)
- High compute cost
- Evaluation metrics (FID, CLIP-S)
- Alignment & safety of generated content

### Core Formula to Remember

$$\mathcal{L} = \mathbb{E}_{t, \mathbf{x}_0, \varepsilon} \left[ \left\| \varepsilon - \varepsilon_\theta(\sqrt{\bar{\alpha}_t} \mathbf{x}_0 + \sqrt{1 - \bar{\alpha}_t} \varepsilon, t) \right\|^2 \right]$$

# Thank You!

Thanks for listening

Ho et al. (2020) — *Denoising Diffusion Probabilistic Models*

Song & Ermon (2019) — *Score-Based Generative Modelling*

Song et al. (2020) — *DDIM*

Nichol & Dhariwal (2021) — *Improved DDPM*