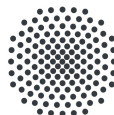


Data-driven Turbulence Prediction with Latent Diffusion Models

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Universität Stuttgart

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Customized Citation Format

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Limitations of Traditional Models I

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Limitations of Traditional Models II

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Diffusion Models: Idea

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- ▶ **Forward process (Diffusion process):** add noise
 - ▶ Add i.i.d. Gaussian noise to data samples over many steps
 - ▶ Progressively degrade the data into pure noise (prior distribution, often i.i.d. Gaussian)
 - ▶ Explicitly prescribed, no modeling needed
- ▶ **Backward/Reverse process (Denoising process):** remove noise
 - ▶ Added noise approximated by a neural network
 - ▶ Recover the original data by gradually removing the noise using neural network, starting from pure noise

Diffusion Models: Overall Architecture

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► Forward Process:

- Given a data sample x_0 , each forward step adds a small amount of Gaussian noise:

$$x_t = \sqrt{1 - \beta_t}x_{t-1} + \sqrt{\beta_t}\epsilon, \quad \epsilon \sim \mathcal{N}(0, I), \quad t \in [1, T]$$

- β_t : noise schedule, ϵ : sampled Gaussian noise

► Model Training:

- Get x_t from x_0 .
- Train a model ϵ_θ to predict the added noise at a specified time step t .
- Approximate backwards process using

$$x_{t-1} = \frac{1}{\sqrt{\alpha_t}} \left(x_t - \frac{1 - \alpha_t}{\sqrt{1 - \bar{\alpha}_t}} \epsilon_\theta(x_t, t) \right) + \sqrt{\beta_t} \epsilon$$

where $\alpha_t = 1 - \beta_t$, $\bar{\alpha}_t = \prod_{i=1}^t \alpha_i$

Diffusion Models: Conditional Diffusion Models

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Summary

- ▶ *Diffusion model*: learn the probabilistic distribution $p(\mathbf{x})$
- ▶ *Conditional diffusion model*: learn the conditional probability of $p(\mathbf{x}|\mathbf{y})$
- ▶ What \mathbf{y} (conditions) can be:
 - ▶ Class labels, text prompt, attributes, or any conditioning signal ...
- ▶ When you ask ChatGPT questions
 - ▶ You input text \mathbf{y} .
 - ▶ ChatGPT give you answers by sampling $p(\mathbf{x}|\mathbf{y})$, either text or images.

Conditional Diffusion Models for Flow Field Prediction

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- ▶ In fluid dynamics, y (conditions) can be:
 - ▶ Labels: Reynolds number ...
 - ▶ Constraints: physical laws
 - ▶ Incomplete information: sparse measurements
 - ▶ Integral information without details: lift, drag
- ▶ Matches the distribution of the training data, unlike deterministic models.

Conditional Diffusion Models for Data Assimilation

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Generative Prediction of Urban-scale Extreme Events: Project Idea I

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Generative Prediction of Urban-scale Extreme Events: Project Idea II

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Generative Prediction of Urban-scale Extreme Events: Results

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Generative Modeling of Kolmogorov Flow: Kolmogorov Method

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Generative Modeling of Kolmogorov Flow: Data Assimilation Method

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Generative Modeling of Kolmogorov Flow: State Results

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Generative Modeling for Windfarm Prediction: Reduced Order Modeling

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Generative Modeling for Windfarm Prediction: Neural Network Framework

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Thank you!

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Thank you for your attention!

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