PSEUDO NUMERICAL METHODS FOR DIFFUSION MODELS ON MANIFOLDS

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ABSTRACT

Denoising Diffusion Probabilistic Models (DDPMs) can generate high-quality samples such as image and audio samples. However, DDPMs require hundreds to thousands of iterations to produce a sample. Several prior works have successfully accelerated DDPMs through adjusting the variance schedule (e.g., Improved Denoising Diffusion Probabilistic Models) or the denoising equation (e.g., Denoising Diffusion Implicit Models (DDIMs)). However, these acceleration methods cannot maintain the quality of samples and even introduce new noise at high speedup rate, which limit their practicability. To accelerate the inference process while keeping the sample quality, we provide a new perspective that DDPMs should be treated as solving differential equations on manifolds. Under such a perspective, we propose pseudo numerical methods for diffusion models (PNDMs). Specifically, we figure out how to solve differential equations on manifolds and show that DDIMs are simple cases of pseudo numerical methods. We change several classical numerical methods to corresponding pseudo numerical methods and find that pseudo linear multi-step method is the best method in most situations. According to our experiments, by directly using pre-trained models on Cifar10, CelebA and LSUN, PNDMs can generate higher quality synthetic images with only 50 steps compared with 1000-step DDIMs (20x speedup), significantly outperform DDIMs with 250 steps (by around 0.4 in FID) and have good generalization on different variance schedules.[1]

1 INTRODUCTION

Denoising Diffusion Probabilistic Models (DDPMs) (Ho et al., 2020) is a class of generative models which model the data distribution through an iterative denoising process reversing a multi-step noising process. DDPMs have been applied successfully to a variety of applications, including image generation (Ho et al., 2020; Song et al., 2020b; Nichol & Dhariwal, 2021), text generation (Hoogeboom et al., 2021; Austin et al., 2021), 3D point cloud generation (Luo & Hu, 2021), text-to-speech (Kong et al., 2021; Chen et al., 2020) and image super-resolution (Saharia et al., 2021).

Unlike Generative Adversarial Networks (GANs) (Goodfellow et al., 2014), which require careful hyperparameter tuning according to different model structures and datasets, DDPMs can use similar model structures and be trained by a simple denoising objective which makes the models fit the noise in the data. To generate samples, the iterative denoising process starts from white noise and progressively denoises it into the target domain according to the noise predicted by the model at every step. However, a critical drawback of DDPMs is that DDPMs require hundreds to thousands of iterations to produce high-quality samples and need to pass through a network at every step, which makes the generation of a large number of samples extremely slow and infeasible. In contrast, GANs only need one pass through a network.

There have been many recent works focusing on improving the speed of the denoising process. Some works concentrate on searching for better variance schedules, including Nichol & Dhariwal (2021) and Watson et al. (2021). Some works focus on changing the inference equation, including Song et al. (2020a) and Song et al. (2020b). Denoising Diffusion Implicit Models (DDIMs) (Song et al., 2020a) relying on a non-Markovian process accelerate the denoising process by taking multiple steps every iteration. Probability Flows (PFs) (Song et al., 2020b) build a connection between

[1] Our implementation is put in the supplementary materials.

the denoising process and solving ordinary differential equations and use numerical methods of differential equations to accelerate the denoising process of DDPMs. Additional, we introduce more related works in Appendix A.1.

Figure 1: 5, 10, 20, 50 and 100-steps generated results using DDIMs, classical numerical methods and PNDMs.

However, classical numerical methods (Sauer, 2017) have problems when they are applied to DDPMs. Some methods are direct and simple, like forward Euler method, but they can only trade quality for speed. Some methods can accelerate the reverse process without loss of quality, like Runge-Kutta method, but they need to propagate forward more times along a neural network at every step. Furthermore, we also notice that numerical methods can introduce noticeable noise at high speedup rate, which limits their practicability.

To figure out the reason for the performance degradation and what cause these noticeable noise in classical numerical methods, we conduct some analyses and find that classical numerical methods may sample data far away from the main distribution area of the data and models cannot fit the noise in the data correctly in those new areas (see Section 3.2).

To tackle this problem, a natural idea is to iterate our data on the high-density region of the data, which is a certain manifold in $\mathbb{R}^n$. In this work, we provide pseudo numerical methods for diffusion models (PNDMs). We first give a rigorous formula transformation to build a theoretical connection between DDPMs and numerical methods directly and self-consistently. As a byproduct, we can directly use pre-trained models from DDPMs without an additional training process. Considering that classical numerical methods cannot guarantee to sample on certain manifolds, we provide brand-new numerical methods called pseudo numerical methods based on our theoretical analyses and formula transformation. We find that DDIMs are simple cases of pseudo numerical methods, which means that we also provide a new way to understand DDIMs better. Furthermore, we search for the most suitable numerical method for diffusion models and find that pseudo linear multi-step method is the fastest method under similar generated quality.

Besides, we provide a detailed theoretical analysis of our new theory and give visualization results to support our theory intuitively. According to our experiments, our methods have several advantages:

- Our methods only need to change the inference equation in the code and can use pre-trained models directly regardless of the size of the images and the type of the datasets.
- Our methods can make DDIMs 20x faster without loss of quality. On Cifar10, CelebA and LSUN-church datasets, our new denoising process can use only 50 steps to achieve even better FID than 1000-step DDIMs.
- Our methods can reduce the best FID of pre-trained models with even shorter sampling time. With only 250 steps, our new denoising process can reduce the best FID by around 0.4 points Cifar10 and CelebA. We achieve a new SOTA FID score of 2.71 on CelebA.
- Our methods work well with different variance schedules, which means that our methods have good generalization and can be used together with those works introducing better variance schedules to further improve the sampling quality and accelerate the denoising process.

2 BACKGROUND

In this section, we introduce some backgrounds. Firstly, we present the classical understanding of DDPMs. Then we provide another understanding based on Song et al. (2020b), which inspires us to use numerical methods to accelerate the denoising process of DDPMs. After that, we introduce some background on numerical methods that will be used later in this paper.

2.1 DENOISING DIFFUSION PROBABILISTIC MODELS

DDPMs model the data distribution from Gaussian distribution to image distribution through an iterative denoising process. Let x_0 be an image, then the diffusion process is a Markov process and the reverse process has a similar form to the diffusion process, which satisfies:

$$\begin{aligned} x_{t+1} \sim & \mathcal{N}(\sqrt{1-\beta_t}x_t, \beta_t I),\ t = 0, 1, \cdots, N-1. \\ x_{t-1} \sim & \mathcal{N}(\mu_\theta(x_t, t), \beta_\theta(x_t, t)I),\ t = N, N-1, \cdots, 1. \end{aligned} \tag{1}$$

Here, β_t controls the speed of adding noise to the data and we call them the variance schedule. N is the total number of steps of the denoising process. μ_θ and β_θ are two neural networks and θ are their parameters.

Ho et al. (2020) get some statistics estimations of μ_θ and β_θ. According to the properties of the conditional Gaussian distribution, we have:

$$\begin{aligned} q(x_t|x_0) &= \mathcal{N}(\sqrt{\bar{\alpha}_t}x_0, (1-\bar{\alpha}_t)I), \\ q(x_{t-1}|x_t, x_0) &= \mathcal{N}(\bar{\mu}_t(x_t, x_0), \bar{\beta}_t). \end{aligned} \tag{2}$$

Here, $\bar{\alpha}_t = \prod_{i=0}^{t}(1-\beta_t)$, $\bar{\mu}_t = \frac{\sqrt{\bar{\alpha}_{t-1}}\beta_t}{1-\bar{\alpha}_t}x_0 + \frac{\sqrt{\alpha_t}(1-\bar{\alpha}_{t-1})}{1-\bar{\alpha}_t}x_t$ and $\bar{\beta}_t = \frac{1-\bar{\alpha}_{t-1}}{1-\bar{\alpha}_t}\beta_t$.

Objective Function The objective function is defined by:

$$\begin{aligned} L_{t-1} &= \mathbb{E}_q\left[||\bar{\mu}_t(x_t, x_0) - \mu_\theta(x_t, t)||^2\right] \\ &= \mathbb{E}_{x_0,\epsilon}\left[||\frac{1}{\sqrt{\alpha_t}}\left(x_t(x_0, \epsilon) - \frac{\beta_t}{\sqrt{1-\bar{\alpha}_t}}\epsilon\right) - \mu_\theta(x_t(x_0, \epsilon), t)||^2\right] \\ &= \mathbb{E}_{x_0,\epsilon}\left[\frac{\beta_t^2}{\alpha_t(1-\bar{\alpha}_t)}||\epsilon - \epsilon_\theta(\sqrt{\bar{\alpha}_t}x_0 + \sqrt{1-\bar{\alpha}_t}\epsilon, t)||^2\right]. \end{aligned} \tag{3}$$

Here, $x_t(x_0, \epsilon) = \sqrt{\bar{\alpha}_t}x_0 + \sqrt{1-\bar{\alpha}_t}\epsilon$, $\epsilon \sim \mathcal{N}(0, 1)$ and $\mu_\theta = \frac{1}{\sqrt{\alpha_t}}(x_t - \frac{\beta_t}{\sqrt{1-\bar{\alpha}_t}}\epsilon_\theta)$. Because $\epsilon \sim \mathcal{N}(0, 1)$, we can assume that the mean and variance of ϵ_θ are 0 and 1.

2.2 STOCHASTIC DIFFERENTIAL EQUATION

According to Song et al. (2020b); Anderson (1982), the denoising process of DDPMs satisfies a certain stochastic differential equation:

$$dx = \left((\sqrt{1-\beta(t)} - 1)x(t) - \beta(t)\epsilon_\theta(x(t), t)\right)dt + \sqrt{\beta(t)}d\bar{w}. \tag{4}$$

Here, we change the domain of t from $[1, N]$ to $[0, 1]$. When N tends to infinity, $\{\beta_i\}_{i=1}^N$, $\{x_i\}_{i=1}^N$ become continuous functions $\beta(t)$ and $x(t)$ on $[0, 1]$. And this equation has an ordinary differential equation (ODE) version with the same marginal probability density as Equation (4):

$$dx = \left((\sqrt{1-\beta(t)} - 1)x(t) - \frac{1}{2}\beta(t)\epsilon_\theta(x(t), t)\right)dt. \tag{5}$$

This is Probability Flows (PFs), which shows us a new possibility that we can use numerical methods to accelerate the denoising process of DDPMs.

2.3 NUMERICAL METHOD

There are many classical numerical methods that can be used to solve ODEs, including forward Euler method, Runge-Kutta method and linear multi-step method.

Forward Euler Method For a certain differential equation satisfying $\frac{dx}{dt} = f(x, t)$. The trivial numerical method is forward Euler method satisfying $x_{t+\delta} = x_t + \delta f(x_t, t)$. This method and the methods in the original DDPMs and many follow-up works, such as Song et al. (2020a), all use one result of f at every step to control the generation.

Runge-Kutta Method Runge-Kutta method uses more information at every step, so it can achieve higher accuracy [2]. Runge-Kutta method satisfies:

$$\begin{cases} k_1 = f(x_t, t) \quad , \quad k_2 = f(x_t + \frac{\delta}{2}k_1, t + \frac{\delta}{2}) \\ k_3 = f(x_t + \frac{\delta}{2}k_2, t + \frac{\delta}{2}), \quad k_4 = f(x_t + \delta k_3, t + \delta) \\ x_{t+\delta} = x_t + \frac{\delta}{6}(k_1 + 2k_2 + 2k_3 + k_4). \end{cases} \tag{6}$$

Linear Multi-Step Method Linear multi-step method is another numerical method and satisfies:

$$x_{t+\delta} = x_t + \frac{\delta}{24}(55f_t - 59f_{t-\delta} + 37f_{t-2\delta} - 9f_{t-3\delta}). \tag{7}$$

Here, $f_t = f(x_t, t)$.

3 Pseudo Numerical Method for DDPM

In this section, we first give a rigorous formula transformation to build the direct connection between DDPMs and numerical methods. As a byproduct, we can directly use pre-trained models from DDPMs. After establishing this connection, we dive into the structure of numerical methods by dividing their equations into gradient part and transfer part and provide more detailed analyses on the weakness of classical numerical methods. Based on the analyses, we define pseudo numerical methods by introducing nonlinear transfer part and find that DDIMs can be regarded as simple pseudo numerical methods. To make numerical methods faster, we explore the pros and cons of different numerical methods and choose linear multi-step method as it works better with diffusion models than other methods. Finally, we summarize our findings and analyses and safely propose our novel pseudo numerical methods for diffusion models (denoted as PNDMs), which combine our proposed transfer part and the gradient part of linear multi-step method. Furthermore, we analyze the convergence order of pseudo numerical methods to demonstrate the effectiveness of our methods theoretically.

3.1 Formula Transformation

According to Song et al. (2020a), the reverse process of DDPMs satisfies:

$$x_{t-1} = \sqrt{\bar{\alpha}_{t-1}}\left(\frac{x_t - \sqrt{1-\bar{\alpha}_t}\epsilon_\theta(x_t, t)}{\sqrt{\bar{\alpha}_t}}\right) + \sqrt{1 - \bar{\alpha}_{t-1} - \sigma_t^2}\epsilon_\theta(x_t, t) + \sigma_t \epsilon_t. \tag{8}$$

Here, σ_t controls the ratio of random noise. Let σ_t equals zero, and then Equation (8) changes from the discrete form of a stochastic differential equation to that of an ordinary differential equation.

To use numerical methods directly on Equation (8), we change it into a differential form and, according to (Song et al., 2020a) we can replace $t-1$ with a general version $t-\delta$:

$$\begin{aligned} x_{t-\delta} - x_t &= \left(\frac{\sqrt{\bar{\alpha}_{t-\delta}}}{\sqrt{\bar{\alpha}_t}} - 1\right)x_t + \left(\sqrt{1-\bar{\alpha}_{t-\delta}} - \frac{\sqrt{1-\bar{\alpha}_t}\sqrt{\bar{\alpha}_{t-\delta}}}{\sqrt{\bar{\alpha}_t}}\right)\epsilon_\theta(x_t, t) \\ &= (\bar{\alpha}_{t-\delta} - \bar{\alpha}_t)\left(\frac{x_t}{\sqrt{\bar{\alpha}_t}(\sqrt{\bar{\alpha}_{t-\delta}} + \sqrt{\bar{\alpha}_t})} - \frac{\epsilon_\theta(x_t, t)}{\sqrt{\bar{\alpha}_t}(\sqrt{(1-\bar{\alpha}_{t-\delta})\bar{\alpha}_t} + \sqrt{(1-\bar{\alpha}_t)\bar{\alpha}_{t-\delta}})}\right). \end{aligned} \tag{9}$$

Now, we can compute that $\lim_{\delta \to 0} \frac{x_{t-\delta} - x_t}{\delta} = \bar{\alpha}'(t)\left(\frac{x(t)}{2\bar{\alpha}(t)} - \frac{\epsilon_\theta(x(t), t)}{2\bar{\alpha}(t)\sqrt{1-\bar{\alpha}(t)}}\right)$. Here, $\bar{\alpha}(t)$ is the continuous version of $\{\bar{\alpha}_i\}_{i=1}^N$ like the definition of $x(t)$. Therefore, when δ tends to zero, Equation (9) will converge to a certain ODE:

$$\frac{dx}{dt} = -\bar{\alpha}'(t)\left(\frac{x(t)}{2\bar{\alpha}(t)} - \frac{\epsilon_\theta(x(t), t)}{2\bar{\alpha}(t)\sqrt{1-\bar{\alpha}(t)}}\right). \tag{10}$$

[2] To achieve higher accuracy, more information is not enough. The reason why these methods can achieve higher accuracy can be found in Appendix A.2

Equation (10) is the continuous version of DDIMs. No matter which numerical methods we use, we will have the same results when choosing the number of iteration steps big enough. The difference between methods is that they have different convergent speeds and behavior when the number of steps is relatively small. In this paper, we find new numerical methods which have high convergence order and good behavior when the number of steps is relatively small (see Section 4.3).

3.2 Gradient and Transfer Part of Numerical Method

Some works (Ernst Hairer, 1996) have developed many numerical methods to solve different equations on manifolds that have analytic expressions. However, it's challenging to find analytical expressions of the high-density region of the data of DDPMs or even there are no such analytic expressions at all. To avoid this problem, we find a different way to solve differential equations on manifolds. We divide the classical numerical methods into two parts, the gradient part and the transfer part. For example, linear multi-step method can be divided into the gradient part $f' = \frac{\delta}{24}(55f_t - 59f_{t-\delta} + 37f_{t-2\delta} - 9f_{t-3\delta})$ and the transfer part $x_{t+\delta} = x_t + \delta f'$. All classical numerical methods have the same transfer part while their gradient part are different.

However, this fixed transfer part cannot keep the results on certain manifolds, no matter how small δ is. Equation (2) shows that the data x_t is generated along a curve close to an arc. According to Figure 2, most of x_t is concentrated in a band with a width of around 0.1, namely the red area in Figure 2. This means that the neural network ϵ_θ cannot get enough examples away from this area. Therefore, if the denoising process samples an example x'_t away from the main area and uses x'_t to compute $\epsilon_\theta(x'_t, t)$ at the next step, the prediction will be inaccurate. In Section 4.3 we will give more visualization results to support this.

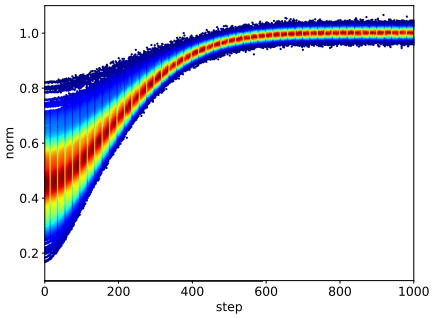

Figure 2: the density distribution of the norm of the data.

There is another problem that limits the effectiveness of classical numerical methods. We find that for most linear variance schedules β_t, Equation (10) tends to infinity when t tends to zero, namely Equation (10) is unbounded (see Appendix A.4), which does not satisfy the condition of classical numerical methods. This is an apparent theoretical weakness that previous works have not explored. And the actual situation is that the last several steps are not essential and the prediction of the noise ϵ_θ in the data should be more and more precise (see Appendix A.5). This means the discrete version of DDPMs does not make a significant error in the last several steps. In contrast, the numerical methods of the continuous version will introduce obvious error when t tends to zero. This also inspires us to change the transfer part to solve our target unbounded ODE Equation (10).

3.3 Pseudo Numerical Method

We define that those numerical methods which use a nonlinear transfer part as pseudo numerical methods. We find that Equation (9) has the property that if ϵ is the precise noise in x_t, then the result of $x_{t-\delta}$ is also precise, no matter how big δ is. When t tends to zero, ϵ_θ is more and more precise, and Equation (9) can keep this accurate to the subsequent results, which means that Equation (9) solves the problem that the linear transfer part cannot give precise results when t is close to zero. Furthermore, according to Song et al. (2020a), Equation (9) is the reverse version of Equation (2), which guarantees that the samples generated by Equation (9) have a high probability of locating in the high-density area of the data generated by Equation (2).

Therefore, we can use:

$$\phi(x_t, \epsilon_t, t, t-\delta) = \frac{\sqrt{\bar{\alpha}_{t-\delta}}}{\sqrt{\bar{\alpha}_t}} x_t - \frac{(\bar{\alpha}_{t-\delta} - \bar{\alpha}_t)}{\sqrt{\bar{\alpha}_t}(\sqrt{(1-\bar{\alpha}_{t-\delta})\bar{\alpha}_t} + \sqrt{(1-\bar{\alpha}_t)\bar{\alpha}_{t-\delta}})} \epsilon_t \tag{11}$$

as the transfer part. A natural idea is to use ϵ_θ as the gradient part then. Because if ϵ_θ is precise, the result of $x_{t-\delta}$ is also precise, which means that ϵ_θ determines the direction of the denoising process to generate the final results. Therefore, such a choice satisfies the definition of gradient part. Now,

we have gradient part ϵ_θ and transfer part ϕ. We find that their combination $\phi(x_t, \epsilon_\theta(x_t, t), t, t-1)$ is just the inference equation used by DDIMs, so DDIMs are simple cases of pseudo numerical methods. Here, we define DDIMs as DDIMs*, emphasizing that it is a pseudo numerical method. Because we split numerical methods into two parts, we can use the same gradient part from different classical numerical methods freely (e.g. linear multi-step method and Runge-Kutta method), although we change the transfer part of our inference equation. Our theoretical analyses and experiments show that the gradient part from different classical methods can work well with our new transfer part (see Section 3.6, 4.2).

By using the same gradient part of linear multi-step method, we have:

$$\begin{cases} e_t = \epsilon_\theta(x_t, t) \\ e'_t = \frac{1}{24}(55e_t - 59e_{t-\delta} + 37e_{t-2\delta} - 9e_{t-3\delta}) \\ x_{t+\delta} = \phi(x_t, e'_t, t, t+\delta). \end{cases} \tag{12}$$

By using the same gradient part of Runge-Kutta method, we have:

$$\begin{cases} e_t^1 = \epsilon_\theta(x_t, t) \\ x_t^1 = \phi(x_t, e_t^1, t, t+\frac{\delta}{2}) \\ e_t^2 = \epsilon_\theta(x_t^1, t+\frac{\delta}{2}) \\ x_t^2 = \phi(x_t, e_t^2, t, t+\frac{\delta}{2}) \\ e_t^3 = \epsilon_\theta(x_t^2, t+\frac{\delta}{2}) \\ x_t^3 = \phi(x_t, e_t^3, t, t+\delta) \\ e_t^4 = \epsilon_\theta(x_t^4, t+\delta) \\ e'_t = \frac{1}{6}(e_t^1 + 2e_t^2 + 2e_t^3 + e_t^4) \\ x_{t-\delta} = \phi(x_t, e'_t, t, t+\delta). \end{cases} \tag{13}$$

Abbreviate Equation (12) and (13) as

$$x_{t+\delta}, e_t = PLMS(x_t, \{e_p\}_{p<t}, t, t+\delta),$$
$$x_{t+\delta}, e_t^1 = PRK(x_t, t, t+\delta).$$

Algorithm 1 DDIMs

1: $x_T \sim \mathcal{N}(0, I)$
2: **for** $t = T-1, \cdots, 1, 0$ **do**
3: $\quad x_t = \phi(x_{t+1}, \epsilon_\theta(x_{t+1}, t+1), t+1, t)$
4: **end for**
5: **return** x_0

Algorithm 2 PNDMs

1: $x_T \sim \mathcal{N}(0, I)$
2: **for** $t = T-1, T-2, T-3$ **do**
3: $\quad x_t, e_t = PRK(x_{t+1}, t+1, t)$
4: **end for**
5: **for** $t = T-4, \cdots, 1, 0$ **do**
6: $\quad x_t, e_t = PLMS(x_{t+1}, \{e_p\}_{p>t}, t+1, t)$
7: **end for**
8: **return** x_0

3.4 Gradient Part

In the above section, we have provided three kinds of pseudo numerical methods. Although advanced numerical methods can accelerate the denoising process, they may have to compute the gradient part ϵ_θ more times at every step, like Runge-Kutta method, no matter we use linear or nonlinear transfer part. Propagating forward four times along a neural network makes the denoising process slower. However, we find that linear multi-step method can reuse the result of ϵ_θ four times and only compute ϵ_θ once at every step. And theoretical analyses tell us that Runge-Kutta method and linear multi-step method have the same convergence order and should have similar generated results.

Therefore, we use the gradient part of linear multi-step method and our new transfer part as our main pseudo numerical methods for diffusion models (PNDMs). In Table 1, we show the relationship between different numerical methods. Here, we can see PNDMs combine the benefits of higher-order classical numerical methods (in the gradient part) and DDIMs (in the transfer part).

ϕ \ order	first	non-first
linear	forward Euler	linear multi-step, Runge-Kutta...
nonlinear	DDIMs	PNDMs

Table 1: The relationship between different numerical methods.

3.5 Algorithm

We can provide our whole algorithm of the denoising process of DDIMs now. According to Song et al. (2020a), the algorithm of the original method satisfies Algorithm 1. And our new algorithm of DNPMs uses pseudo linear multi-step method and pseudo Runge-Kutta method, which satisfies

Algorithm 2. Here, we cannot use linear multi-step at the beginning, because linear multi-step method cannot start automatically, which needs at least three previous steps' information to generate results. So we use Runge-Kutta method to compute the first three steps and then use the linear multi-step method to calculate the remaining part.

We also use the gradient parts of improved Euler method and second-order multi-step method to get another pseudo numerical method. We introduce the details of this method in Appendix A.3. We call it S-PNDMs, because its gradient part uses information from two steps at every step. Similarly, we also call our PNDMs as F-PNDMs, which use data from four steps, when we need to distinguish these two pseudo numerical methods.

3.6 Convergence Order

Change the transfer part of numerical methods may introduce unknown error. To determine the influence of our new transfer part theoretically, we compute the local and global error between the theoretical result of Equation (10) $x(t+\delta)$ and our new methods, we find:

$$x(t+\delta) - x_{\text{S/F-PNDM}}(x+\delta) = O(\delta^3), \tag{14}$$

and $x(t+\delta) - x_{\text{DDIM}}(x+\delta) = O(\delta^2)$. And if the target ODE satisfies Lipschitz condition and local error $e_{\text{local}} = O(\delta^k)$, then there are C and h such that the global error e_{global} satisfies:

$$e_{\text{global}} \leq C\delta^k(1 + e^h + e^{2h} + \cdots) \leq C'\delta^{k-1} \tag{15}$$

And the convergence order is equal to the order of the global error. So we have that DDIMs are first-order convergent and PNDMs are second-order convergent. The proof can be found in Appendix A.6. Therefore, our new transfer part does not influence the convergence order in most cases.

4 Experiment

In this section, we first introduce the experimental settings and then report the results of our experiments. We also put some visualization experiments to demonstrate the effectiveness of our idea.

4.1 Setup

We conduct unconditional image generation experiments on four datasets: Cifar10 (32×32) (Krizhevsky et al., 2009), CelebA (64×64) (Liu et al., 2015), LSUN-church (256×256) and LSUN-bedroom (256×256) (Yu et al., 2016). According to the analysis in Section 3.1, we can use pre-trained models from prior works in our experiments. The pre-trained models for Cifar10, LSUN-church and LSUN-bedroom are taken from Ho et al. (2020) and the pre-trained model for CelebA is taken from Song et al. (2020a). In these models, the number of total steps N is 1000 and the variance schedule is linear schedule. And we also use a pre-trained model for Cifar10, which uses a cosine variance schedule from improved denoising diffusion probabilistic models (iDDPMs (Nichol & Dhariwal, 2021)).

4.2 Sample Efficiency and Quality

To analyze the acceleration effect more objectively, we test Fenchel Inception Distance (FID (Heusel et al., 2018)) on different datasets under different steps and different numerical methods including DDIMs, S-PNDMs, F-PNDMs and classical fourth-order numerical methods (FONs) (e.g. Runge-Kutta method and linear multi-step method). On Cifar10 and CelebA, we first provide the results of previous works DDIMs. Then, we use the same pre-trained models to test numerical methods mentioned in this paper and put the results in Cifar10 / CelebA (linear). We also use models from iDDPMs to test nonlinear variance schedules and put the results in Cifar10 (cosine). Song et al. (2020b) do not provide detailed FID results of probability flows (PFs) under different steps, so we retest the results using its pretrained models by ourselves.

Efficiency Our two baselines are DDIM and PF. DDIM is a simple case of pseudo numerical methods and PF is a case of classical numerical methods. However, PF uses a much bigger model than DDIM and uses some tricks to improve the sample quality. To ensure the experiment's fairness, we

dataset	FID \ step / model	10	20	50	100	250	1000
Cifar10	DDIM	13.4	6.84	4.67	4.16		4.04
	PF		13.8	3.89	3.69	3.71	3.72
Cifar10 (linear)	DDIM*	18.5	10.9	6.99	5.52	4.52	4.00
	FON	13.1	7.41	5.26	4.65	4.12	3.71
	S-PNDM	11.6	7.56	5.18	4.34	3.91	3.80
	F-PNDM	7.03	5.00	3.95	3.72	**3.60**	3.70
Cifar10 (cosine)	DDIM	14.5	8.79	5.86	4.92	4.30	3.69
	S-PNDM	8.64	5.77	4.46	3.94	3.71	3.38
	F-PNDM	7.05	4.61	3.68	3.53	3.49	**3.26**
CelebA	DDIM	17.3	13.7	9.17	6.53		3.51
CelebA (linear)	DDIM*	16.9	13.4	8.95	6.36	4.44	3.41
	FON	16.0	11.6	8.13	6.70	5.14	4.17
	S-PNDM	12.2	9.45	5.69	4.03	3.19	2.99
	F-PNDM	7.71	5.51	3.34	2.81	**2.71**	2.86

Table 2: Cifar10 and CelebA image generation measured in FID. PFs use black box ODE solvers and the number of steps in the generation is unclear, so we use the number of score function evaluations as the step of PFs. DDIM* means a kind of pseudo numerical method and also a retest of DDIM.

use classical fourth-order numerical methods on Equation (10) and the model from DDIM. In Table 2, we find that the performance of FON is limited when the number of steps is small. By contrast, our new methods, including S-PNDM and F-PNDM, can improve the generated results regardless of whether the number of steps used is large or small. According to Cifar10 / CelebA (linear), F-PNDM can achieve lower FID than 1000 steps DDIM using only 50 steps, making diffusion models 20x faster without losing quality.

We draw a histogram of computation cost with FID according to the results of Cifar10 (linear) above in Figure 3. Because F-PNDM uses pseudo Runge-Kutta method to generate the first three steps, it is slower than other methods at the first several steps. Therefore, S-PNDM can achieve the best FID initially, then F-PNDM becomes the best when FID is lower than 8.5 and the acceleration is pronounced then.

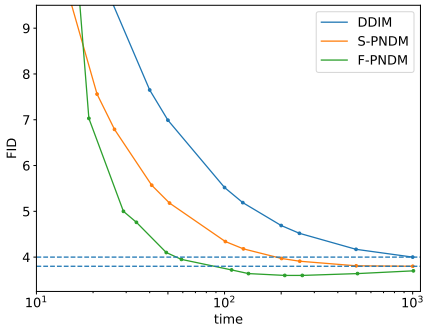

Figure 3: The FID results under different computation costs and different numerical methods on Cifar10.

Quality When the number of steps is relatively big, the results of FON become more and more similar to that of pseudo numerical methods. This is consistent with our theoretical analysis in Section 3.1 that all numerical methods convergent to the same results, namely Equation 10. However, pseudo numerical methods still work better when using a big number of steps. F-PNDM can improve the best FID around 0.4 using pre-trained models and achieves a new SOTA FID score of 2.71 on CelebA, which show that our work can not only accelerate diffusion models but also improve the sample quality topline. We also notice that the FID results of F-PNDM converge after more than 250 steps. The FID results will fluctuate around a value then. This phenomenon is more pronounced when we test our methods on LSUN (see Table 5, 6).

Variance schedule According to Cifar10 (cosine), PNDMs can be used on both linear variance schedule and cosine variance schedule. However, we also notice cosine variance schedule can make FID lower when we use relatively big steps, but the effort is limited when the number of steps is small. F-PNDM uses information from four consecutive steps, so the smoothness of the schedule is more important for F-PNDM than DDIM. According to this experiment, our work can be used with works that pay attention to variance schedules to improve the acceleration effect further. However, a variance schedule that fits pseudo numerical methods better remains to be found in the further work.

We also test our methods on other datasets and provide our FID results in Appendix A.7 and image results in Appendix A.8. We can draw similar conclusions on the acceleration and sampling quality of our methods, regardless of the datasets and the size of the images.

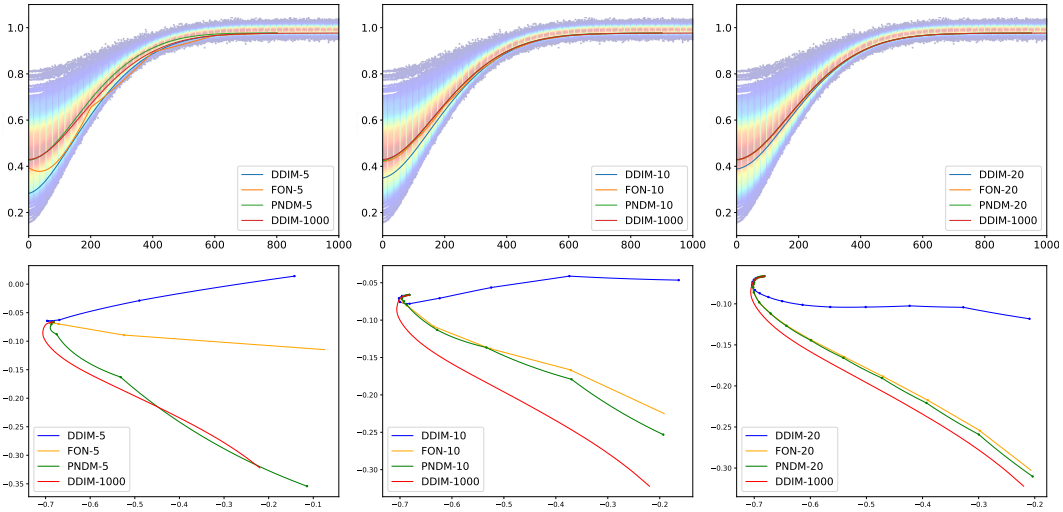

Figure 4: The upper part shows the change of norm with the number of steps using different methods and different steps. The lower part shows the generation curves of two points using different methods and different steps. DDIM-n is n-step DDIM, and the definition of other items is similar.

4.3 Sample on Manifolds

Here, we design visualization experiments to support our analyses. It is hard to visualize high-dimensional data, so we use the change of a global characteristic norm and a local characteristic pixel to show the change of the data under different steps. For pixel, we randomly choose two positions p^1, p^2. Then for a series of images $x_T, x_{T-k}, \cdots, x_0$ derived from the reverse process, we denote y_t^k as the value of x_t at position p^k. Then we draw a polyline $(y_t^1, y_t^2)_{t=T,\dots}$ in $\mathbb{R}^2$. For norm, we first count the distribution of the norm of the training datasets under different steps and use this to make a heat map as the background. After that, we draw the norm of our generated results using different methods and steps above this heat map. Without loss of generality, experiments in this subsection all use the Cifar10 dataset.

Because the analytic result is unavailable, we use the 1000-step first-order result as our target result. In Figure 4, we can see that the FON may run far away from the high-density area of the data, which explains why FON may introduce noticeable noise. However, PNDM can avoid this problem and fit the target result more appropriately. More visualization results supporting our analysis can be found in Appendix A.9.

5 Discussion

In this paper, we provided DNPMs, a new kind of numerical method suitable for solving the corresponding ODEs of DDPMs. DNPMs can generate high-quality images using fewer steps without loss of quality successfully. Based on the idea of this work, further improvement can be explored in our future works: 1) find a better variance schedule for DNPMs: although we tested DNPMs on linear variance schedule and cosine variance schedule in this work, there might be another variance schedule more suitable for our proposed numerical methods. 2) Find higher-order convergent pseudo numerical methods: we analyzed the convergence order of S/F-DNPMs and they are both second-order convergent. However, F-DNPMs achieve better FID than S-DNPMs in most cases. We think this is because the result between our transfer part and target ODE has a higher-order error, which limits the convergence order of F-DNPMs. This error from the change of the transfer part is theoretical but does not influence the quality of images according to the property of Equation (11). However, making the transfer part higher-order convergent and finding the influence of such change is still interesting and need more research. 3) Extend PNDMs to more general applications: when we proved the convergence order of DNPMs, we found that other kinds of transfer parts can keep the convergence order unchanged too, which means that pseudo numerical methods can be used on more general applications, like certain neural ODEs (Chen et al., 2019; Dupont et al., 2019).

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A Appendix

A.1 Related Work

DDPMs have been well developed in the last few years. Some works concentrate on improving the quality and the speed of DDPMs and make DDPMs more practical. Song et al. (2020a) introduce new inference equations to accelerate DDPMs. Nichol & Dhariwal (2021), Watson et al. (2021) and Kong & Ping (2021) choose to find better variance schedules to improve the images quality. Vahdat et al. (2021) combine the advantages of DDPMs and Variational Autoencoders and get better results. Furthermore, Kim et al. (2021) try to solve an existing bottleneck that the inference equations of DDPMs are unbounded in some situations.

Song et al. (2020b) find the similarity between DDPMs and noise conditional score networks (NCSNs (Song & Ermon, 2020b)), which is that they both use a process similar to Langevin dynamics to produce samples. Therefore, some works (Song & Ermon, 2020a; Kim et al., 2021) that can improved the results of NCSNs also can be used in DDPMs. Additional, Song et al. (2020b) combine DDPMs and NCSNs under the framework of neural differential equations (Chen et al., 2019; Dupont et al., 2019). Therefore, numerical methods widely used in neural differential equations can also be applied to accelerate DDPMs. Our work successfully combines the advantages of Song et al. (2020a) and Song et al. (2020b). We use a transfer part from DDIMs and use different gradient part from different numerical methods. Although we and Song et al. (2020b) solve certain differential equations derived from DDPMs, we use different target different equations and different numerical methods, which get better results.

The application of DDPMs is not limited to unconditional image generation. Some works apply DDPMs to various types of data successfully, including text-to-speech (Chen et al., 2020; Lam et al., 2021), 3D Point Cloud (Luo & Hu, 2021), text generation (Austin et al., 2021). Additionally, DDPMs can also be used to generate conditional samples too (Jeong et al., 2021; Choi et al., 2021).

A.2 CONVERGENT ORDER OF METHOD

We use the forward Euler method and linear multi-step method to show what is order of method. Assume that x_t is precise and compute the error at $x_{t+\delta}$. For forward Euler method, we have:

$$\begin{aligned} e_{t,\delta} &= x(t+\delta) - x_{t,\delta} \\ &= \left(x(t) + \delta f(x(t),t) + \frac{\delta^2}{2} f''(c) \right) - (x(t) + \delta f(x_t,t)) \\ &= \frac{\delta^2}{2} f''(c) \leq \frac{\delta^2}{2} M \end{aligned} \tag{16}$$

Here, we assume that f'' is continuous, so f'' is bounded in a close area. $x(t+\delta)$ is the precise result and $x_{t,\delta}$ is the numerical result from t to $t+\delta$.

For linear multi-step method, we have:

$$\begin{aligned} e_{t,\delta} =& x(t+\delta) - x_{t,\delta} \\ =& \left(x(t) + \frac{\delta}{1!} f(x(t),t) + \frac{\delta^2}{2!} f'(x(t),t) + \cdots + \frac{\delta^4}{4!} f^{(3)}(x(t),t) + O\left(\delta^5\right) \right) \\ & - \left(x(t) + b_1 \delta f(x(t),t) + \sum_{s=2}^{4} b_s \delta \left(\sum_{k=0}^{4} \frac{(-(s-1)\delta)^k}{(k)!} f^{(k-1)}(x(t),t) + O\left(\delta^5\right) \right) \right) \\ =& O(\delta^5) \end{aligned} \tag{17}$$

Here, $\{b_s\}$ satisfy $\sum_{s=1}^{4} b_s = 1$ and the following equations for $j \in \{1, \cdots, 3\}$:

$$(-1)^j b_2 + (-2)^j b_3 + (-3)^j b_4 = \frac{1}{j+1}. \tag{18}$$

We call the error at $x_{t,\delta}$ local error, and the error at $x_{t+M\delta}$ (M is big enough but finite) global error. Assume the local error of our method has order k+1 and the target ODE satisfies Lipschitz condition, then:

$$\begin{aligned} x(t+M\delta) - x_{t,M\delta} \leq& |x(t+M\delta) - x_{t+(M-1)\delta,\delta}| + |x_{t+(M-1)\delta,\delta} - x_{t,M\delta}| \\ \leq& e_{t+(M-1)\delta,\delta} + e^{L\delta} |x(t+(M-1)\delta) - x_{t,(M-1)\delta}| \\ \leq& e_{t+(M-1)\delta,\delta} + e^{L\delta} e_{t+(M-2)\delta,\delta} + \cdots \\ \leq& C\delta^{k+1} \left(1 + e^{Lh} + \cdots + e^{(i-1)Lh} \right) \\ =& Ch^{k+1} \frac{e^{iL\delta} - 1}{e^{L\delta} - 1} \leq C\delta^{k+1} \frac{e^{iL\delta} - 1}{L\delta} \\ =& O(\delta^k). \end{aligned} \tag{19}$$

Therefore, the global error will be one order lower than the local error. From Equation (16), we can see the forward Euler method has local error $O(\delta^2)$ and global error $O(\delta)$, so we call it first-order method. And linear multi-step method has local error $O(\delta^5)$ and global error $O(\delta^4)$, and we call it fourth-order method.

In addition, because fourth-order method has kth-order global error, we can compute the convergence speed of a numerical method:

$$\lim_{\delta \to 0} \frac{x_{t+T}^{2\delta} - x(t+T)}{x_{t+T}^{\delta} - x(t+T)} = \frac{(2\delta)^k}{\delta^k} = 2^k. \tag{20}$$

Here, x_{t+T}^{δ} is the result at t+T and move δ every step. This means that fourth-order method can converge to the exact solution faster than first-order method when $\delta \to 0$, which means that we can use bigger iteration interval δ to achieve similar global error and a bigger iteration interval means that we can iterate fewer times to get results with similar quality.

A.3 PSEUDO SECOND-ORDER METHOD

We introduce two second-order numerical methods. First is improved Euler method satisfying:

$$\begin{cases} k_1 = f(x_t, t) \\ k_2 = f(x_t + \delta k_1, t + \delta) \\ x_{t+\delta} = x_t + \frac{\delta}{2}(k_1 + k_2) \end{cases} \tag{21}$$

Second is another linear multi-step method called second-order linear multi-step method satisfying:

$$x_{t+\delta} = x_t + \frac{\delta}{2}(3f_t - f_{t-\delta}) \tag{22}$$

And the corresponding pseudo improved Euler methods satisfying:

$$\begin{cases} e_t^1 = \epsilon_\theta(x_t, t) \\ x_t^1 = \phi(x_t, e_t^1, t, t + \delta) \\ e_t^2 = \epsilon_\theta(x_t^1, t + \delta) \\ e_t' = \frac{1}{2}(e_t^1 + e_t^2) \\ x_{t+\delta} = \phi(x_t, e_t', t, t + \delta) \end{cases} \tag{23}$$

Pseudo second-order linear multi-step method satisfying:

$$\begin{cases} e_t = \epsilon_\theta(x_t, t) \\ e_t' = \frac{1}{2}(3e_t - e_{t-\delta}) \\ x_{t+\delta} = \phi(x_t, e_t', t, t + \delta) \end{cases} \tag{24}$$

Similar to what we do to get F-PNDMs, We combine them to get S-PNDMs. Abbreviate Equation (23) and (24) as

$$x_{t+\delta}, e_t = PIE(x_t, \{e_p\}_{p<t}, t, t + \delta),$$
$$x_{t+\delta}, e_t^1 = PLMS'(x_t, t, t + \delta).$$

Algorithm 3 S-PNDMs

1: $x_T \sim \mathcal{N}(0, I)$
2: **for** $t = T - 1$ **do**
3: $\quad x_t, e_t = PIE(x_{t+1}, t + 1, t)$
4: **end for**
5: **for** $t = T - 2, \cdots, 1, 0$ **do**
6: $\quad x_t, e_t = PLMS'(x_{t+1}, \{e_p\}_{p>t}, t+1, t)$
7: **end for**
8: **return** x_0

A.4 THE EXISTENCE OF A DERIVATIVE

Because $\bar{\alpha}_t$ is usually obtained by multiplying an arithmetic sequence β_t. So we have

$$\bar{\alpha}_t = e^{at^2+bt+c}, \tag{25}$$

and $\bar{\alpha}_0 = 1$, so $c = 0$. Now we have

$$\begin{aligned} &\lim_{\delta\to 0} \frac{x_{t-\delta} - x_t}{\delta} \\ =&\lim_{\delta\to 0} \frac{\bar{\alpha}_{t-\delta} - \bar{\alpha}_t}{\delta} \left(\frac{x_t}{\sqrt{\bar{\alpha}_t}(\sqrt{\bar{\alpha}_{t-\delta}} + \sqrt{\bar{\alpha}_t})} - \frac{\epsilon_\theta(x_t, t)}{\sqrt{\bar{\alpha}_t}(\sqrt{(1 - \bar{\alpha}_{t-\delta})\bar{\alpha}_t} + \sqrt{(1 - \bar{\alpha}_t)\bar{\alpha}_{t-\delta}})} \right) \\ =&\lim_{\delta\to 0} \frac{\bar{\alpha}_{t-\delta} - \bar{\alpha}_t}{\delta} \left(\frac{x_t}{2\bar{\alpha}_t} - \frac{\epsilon_\theta(x_t, t)}{2\sqrt{1 - \bar{\alpha}_t}\bar{\alpha}_t} \right) = (e^{at^2+bt})' \left(\frac{x_t}{2\bar{\alpha}_t} - \frac{\epsilon_\theta(x_t, t)}{2\sqrt{1 - \bar{\alpha}_t}\bar{\alpha}_t} \right) \\ =&(2at + b)\bar{\alpha}_t \left(\frac{x_t}{2\bar{\alpha}_t} - \frac{\epsilon_\theta(x_t, t)}{2\sqrt{1 - \bar{\alpha}_t}\bar{\alpha}_t} \right) = \frac{1}{2}(2at + b)(x_t - \frac{\epsilon_\theta(x_t, t)}{\sqrt{1 - \bar{\alpha}_t}}). \end{aligned} \tag{26}$$

To make should $\lim_{\delta\to 0} \frac{x_{t-\delta}-x_t}{\delta}|_{t=0}$ is well-defined. b must equal to zero, or $(2at + b)\frac{\epsilon_\theta(x_t,t)}{\sqrt{1-\bar{\alpha}_t}}$ will tend to infinity. This is a strong condition that most variance schedules do not satisfy. In practice, DDPMs can choose the variance schedule very freely. This means that treating DDPMs as ODEs directly is not proper and has theoretical weakness.

A.5 CHANGE OF NOISE

In Figure 5, we can see that the denoising process tends to converge, whether in the ϵ_θ domain or the image domain, when the step index tends to zero. Therefore, we can say that the noise becomes more and more precise when step, namely t, tends to zero.

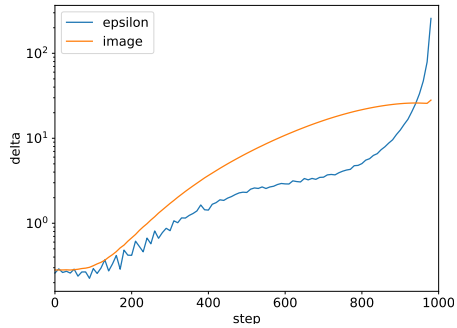

Figure 5: The norm δ of the difference between two adjacent terms under different steps

A.6 ORDER ANALYSIS OF PSEUDO METHOD

For the convenience of theoretical analysis, we generalize the problem into:

$$\begin{aligned} x(1) &= x(0) + \sum_{\delta \to 0} (y(t+\delta) - y(t)) \\ &= x(0) + \sum_{\delta \to 0} \left(f(x(t), t, \delta) + g(t, \delta)\epsilon(x(t), t) \right) \\ &= x(0) + \int_0^1 \left(\frac{\partial f}{\partial \delta}(x(t), t, 0) + \frac{\partial g}{\partial \delta}(t, 0)\epsilon(x(t), t) \right). \end{aligned} \tag{27}$$

Here, we assume that $f(x(t), t, 0) = g(t, 0) = 0$ and $\phi(x(t), \epsilon, t, \delta) = f(x(t), t, \delta) + g(t, \delta)\epsilon(x(t), t)$. And Equation (10) is a special case of this more general version and according to Equation () we have:

$$\begin{aligned} f(x(t), t, \delta) &= \left(\frac{\sqrt{\alpha(t+\delta)}}{\sqrt{\alpha}} - 1 \right) x(t) \\ g(t, \delta) &= \sqrt{1 - \alpha(t+\delta)} - \frac{\sqrt{(1-\alpha(t))\alpha(t+\delta)}}{\sqrt{\alpha(t)}} \end{aligned} \tag{28}$$

Now, we compute the local error of S-PNDMs. We have:

$$\begin{aligned} & x(t+\delta) \\ =& x(t) + \delta \left(\frac{\partial f}{\partial \delta}(x(t), t, 0) + \frac{\partial g}{\partial \delta}(t, 0)\epsilon(x(t), t) \right) + \\ & \frac{\delta^2}{2} \left(\frac{\partial f}{\partial \delta}(x(t), t, 0) + \frac{\partial g}{\partial \delta}(t, 0)\epsilon(x(t), t) \right)' + O(\delta^3) \\ =& x(t) + \delta \left(\frac{\partial f}{\partial \delta}(x(t), t, 0) + \frac{\partial g}{\partial \delta}(t, 0)\epsilon(x(t), t) \right) + O(\delta^3) + \\ & \frac{\delta^2}{2} \left(\frac{\partial^2 f}{\partial \delta \partial t}(x(t), t, 0) + \frac{\partial^2 f}{\partial \delta \partial x}(x(t), t, 0) \left(\frac{\partial f}{\partial \delta}(x(t), t, 0) + \frac{\partial g}{\partial \delta}(t, 0)\epsilon(x(t), t) \right) \right) + \\ & \frac{\delta^2}{2} \left(\frac{\partial^2 g}{\partial \delta \partial t}(t, 0)\epsilon(x(t), t) + \frac{\partial g}{\partial \delta}(t, 0)\epsilon'(x(t), t) \right) \end{aligned} \tag{29}$$

and

$$
\begin{aligned}
& x_{\text{S-PNDM}}(t+\delta) \\
=& x(t) + f(x(t),t,\delta) + g(t,\delta)\frac{1}{2}(\epsilon(x(t),t) + \epsilon(x(t)+\phi(...,t,\delta),t+\delta)) \\
=& x(t) + \delta\frac{\partial f}{\partial \delta}(x(t),t,0) + \frac{\delta^2}{2}\frac{\partial^2 f}{\partial \delta^2}(x(t),t,0) + O(\delta^3) + \\
& \left(\delta\frac{\partial g}{\partial \delta}(t,0) + \frac{\delta^2}{2}\frac{\partial^2 g}{\partial \delta^2}(t,0)\right)\frac{1}{2}(\epsilon(x(t),t) + \epsilon(x(t+\delta)+O(\delta^2),t+\delta)) \\
=& x(t) + \delta\frac{\partial f}{\partial \delta}(x(t),t,0) + \frac{\delta^2}{2}\frac{\partial^2 f}{\partial \delta^2}(x(t),t,0) + O(\delta^3) + \\
& \left(\delta\frac{\partial g}{\partial \delta}(t,0) + \frac{\delta^2}{2}\frac{\partial^2 g}{\partial \delta^2}(t,0)\right)\frac{1}{2}(\epsilon(x(t),t) + \epsilon(x(t+\delta),t+\delta)) \\
=& x(t) + \delta\frac{\partial f}{\partial \delta}(x(t),t,0) + \frac{\delta^2}{2}\frac{\partial^2 f}{\partial \delta^2}(x(t),t,0) + O(\delta^3) + \\
& \left(\delta\frac{\partial g}{\partial \delta}(t,0) + \frac{\delta^2}{2}\frac{\partial^2 g}{\partial \delta^2}(t,0)\right)\frac{1}{2}(\epsilon(x(t),t) + \epsilon(x(t),t) + \delta\epsilon(x(t),t)') \\
=& x(t) + \delta\frac{\partial f}{\partial \delta}(x(t),t,0) + \frac{\delta^2}{2}\frac{\partial^2 f}{\partial \delta^2}(x(t),t,0) + O(\delta^3) + \\
& \delta\frac{\partial g}{\partial \delta}(t,0)\left(\epsilon(x(t),t) + \frac{1}{2}\delta\epsilon(x(t),t)'\right) + \frac{\delta^2}{2}\frac{\partial^2 g}{\partial \delta^2}(t,0)\epsilon(x(t),t) \\
=& x(t) + \delta\left(\frac{\partial f}{\partial \delta}(x(t),t,0) + \frac{\partial g}{\partial \delta}(t,0)\epsilon(x(t),t)\right) + O(\delta^3) + \\
& \frac{\delta^2}{2}\left(\frac{\partial^2 f}{\partial \delta^2}(x(t),t,0) + \frac{\partial g}{\partial \delta}(t,0)\epsilon(x(t),t)' + \frac{\partial^2 g}{\partial \delta^2}(t,0)\epsilon(x(t),t)\right).
\end{aligned} \tag{30}
$$

Now we have:

$$
\begin{aligned}
& x(t+\delta) - x_{\text{S-PNDM}}(x+\delta) \\
=& \frac{\delta^2}{2}\left((\frac{\partial^2 f}{\partial \delta \partial t} - \frac{\partial^2 f}{\partial \delta^2})(x(t),t,0) + \frac{\partial^2 f}{\partial \delta \partial x}(x(t),t,0)\frac{\partial f}{\partial \delta}(x(t),t,0)\right) + \\
& \frac{\delta^2}{2}\left((\frac{\partial^2 g}{\partial \delta \partial t} - \frac{\partial^2 g}{\partial \delta^2})(t,0) + \frac{\partial^2 f}{\partial \delta \partial x}(x(t),t,0)\frac{\partial g}{\partial \delta}(t,0)\right)\epsilon(x(t),t) + O(\delta^3)
\end{aligned} \tag{31}
$$

In our problem, we have:

$$
\begin{aligned}
\frac{\partial g}{\partial \delta}(t,\delta) =& \frac{\partial}{\partial \delta}\left(\sqrt{1-\alpha(t+\delta)} - \frac{\sqrt{(1-\alpha(t))\alpha(t+\delta)}}{\sqrt{\alpha(t)}}\right) \\
=& \frac{-\alpha'(t+\delta)}{2\sqrt{1-\alpha((t+\delta))}} - \frac{\sqrt{1-\alpha(t)}\alpha'(t+\delta)}{2\sqrt{\alpha(t)\alpha(t+\delta)}}
\end{aligned} \tag{32}
$$

$$
\begin{aligned}
\frac{\partial f}{\partial \delta}(x(t),t,\delta) =& \frac{\partial}{\partial \delta}\left(\left(\frac{\sqrt{\alpha(t+\delta)}}{\sqrt{\alpha}} - 1\right)x(t)\right) \\
=& \frac{\alpha'(t+\delta)}{2\sqrt{\alpha(t)\alpha(t+\delta)}}x(t)
\end{aligned} \tag{33}
$$

$$
\frac{\partial^2 f}{\partial \delta^2}(x(t),t,\delta)|_{\delta=0} = \frac{\alpha''(t+\delta)}{2\sqrt{\alpha(t)\alpha(t+\delta)}}x(t) + \frac{-\alpha'(t+\delta)^2}{4\sqrt{\alpha(t)\alpha(t+\delta)^3}}x(t)|_{\delta=0} \tag{34}
$$

$$
\frac{\partial^2 f}{\partial \delta \partial t}(x(t),t,0) = \frac{\alpha''(t)}{2\alpha(t)}x(t) - \frac{\alpha'(t)^2}{2\alpha(t)^2}x(t) \tag{35}
$$

$$
\frac{\partial^2 f}{\partial \delta \partial x}(x(t),t,0) = \frac{\alpha'(t)}{2\alpha(t)} \tag{36}
$$

$$
\begin{aligned}
\frac{\partial^2 g}{\partial \delta^2}(t,\delta)|_{\delta=0} =& \frac{-\alpha''(t+\delta)}{2\sqrt{1-\alpha((t+\delta))}} - \frac{\sqrt{1-\alpha(t)}\alpha''(t+\delta)}{2\sqrt{\alpha(t)\alpha(t+\delta)}} + \\
& \frac{-\alpha'(t+\delta)^2}{4\sqrt{1-\alpha(t+\delta)}^3} + \frac{\sqrt{1-\alpha(t)}\alpha'(t+\delta)^2}{4\sqrt{\alpha(t)\alpha(t+\delta)^3}}|_{\delta=0} \\
=& \frac{-\alpha''(t)}{2\sqrt{1-\alpha((t))}} - \frac{\sqrt{1-\alpha(t)}\alpha''(t)}{2\sqrt{\alpha(t)\alpha(t)}} + \\
& \frac{-\alpha'(t)^2}{4\sqrt{1-\alpha(t)}^3} + \frac{\sqrt{1-\alpha(t)}\alpha'(t)^2}{4\sqrt{\alpha(t)\alpha(t)^3}}
\end{aligned} \tag{37}
$$

$$
\begin{aligned}
\frac{\partial^2 g}{\partial \delta \partial t}(t,\delta)|_{\delta=0} =& \frac{\partial}{\partial t}\left(\frac{-\alpha'(t)}{2\sqrt{1-\alpha((t))}} - \frac{\sqrt{1-\alpha(t)}\alpha'(t)}{2\sqrt{\alpha(t)\alpha(t)}}\right) \\
=& \frac{-\alpha''(t)}{2\sqrt{1-\alpha((t))}} - \frac{\sqrt{1-\alpha(t)}\alpha''(t)}{2\sqrt{\alpha(t)\alpha(t)}} + \\
& \frac{-\alpha'(t)^2}{4\sqrt{1-\alpha(t)}^3} + \frac{\sqrt{1-\alpha(t)}\alpha'(t)^2}{2\alpha(t)^2} + \frac{\alpha'(t)^2}{4\sqrt{\alpha^2(t)(1-\alpha(t))}}
\end{aligned} \tag{38}
$$

Now we have:

$$
\begin{aligned}
& (\frac{\partial^2 f}{\partial \delta \partial t} - \frac{\partial^2 f}{\partial \delta^2})(x(t),t,0) + \frac{\partial^2 f}{\partial \delta \partial x}(x(t),t,0)\frac{\partial f}{\partial \delta}(x(t),t,0) \\
=& \left(\frac{\alpha''(t)}{2\alpha(t)}x(t) - \frac{\alpha'(t)^2}{2\alpha(t)^2}x(t)\right) - \left(\frac{\alpha''(t)}{2\alpha(t)}x(t) + \frac{-\alpha'(t)^2}{4\alpha(t)^2}x(t)\right) + \frac{1}{2\alpha(t)}\frac{\alpha'(t)}{2\alpha(t)}x(t) \\
=& 0
\end{aligned} \tag{39}
$$

and

$$
\begin{aligned}
& (\frac{\partial^2 g}{\partial \delta \partial t} - \frac{\partial^2 g}{\partial \delta^2})(t,0) + \frac{\partial^2 f}{\partial \delta \partial x}(x(t),t,0)\frac{\partial g}{\partial \delta}(t,0) \\
=& \frac{\sqrt{1-\alpha(t)}\alpha'(t)^2}{4\alpha(t)^2} + \frac{\alpha'(t)^2}{4\alpha(t)\sqrt{1-\alpha(t)}} + \frac{\alpha'(t)}{2\alpha(t)}\left(\frac{-\alpha'(t)}{2\sqrt{1-\alpha((t))}} - \frac{\sqrt{1-\alpha(t)}\alpha'(t)}{2\alpha(t)}\right) \\
=& \frac{\alpha'(t)^2}{4\alpha(t)^2\sqrt{1-\alpha(t)}} + \frac{\alpha'(t)}{2\alpha(t)}\left(\frac{-\alpha'(t)}{2\sqrt{1-\alpha(t)}\alpha(t)}\right) \\
=& 0
\end{aligned} \tag{40}
$$

Finally, we get:

$$
x(t+\delta) - x_{\text{S-PNDM}}(x+\delta) = O(\delta^3) \tag{41}
$$

And the computation of the convergence order of F-PNDMs is similar, we ignore it here.

A.7 More FID Results

Here, We provide our more detailed FID results on Cifar10, CelebA, LSUN-church and LSUN-bedroom in Table 3, 4, 5, 6.

steps	5	10	20	25	40	50	100	125	200	250	500	1000
DDIM		13.4		6.84		4.67	4.16					4.04
DDIM*	44.5	18.5	10.9	9.61	7.65	6.99	5.52	5.19	4.69	4.52	4.17	4.00
FON	98.0	13.1	7.41	6.41	5.50	5.26	4.65	4.54	4.23	4.12	3.84	3.71
S-PNDM	22.8	11.6	7.56	6.79	5.57	5.18	4.34	4.18	3.97	3.91	3.81	3.80
F-PNDM	13.9	7.03	5.00	4.76	4.10	3.95	3.72	3.64	3.60	**3.60**	3.64	3.70
DDIM*	28.7	14.5	8.79	7.83	6.41	5.86	4.92	4.75	4.42	4.30	3.98	3.69
S-PNDM	18.3	8.64	5.77	5.45	4.76	4.46	3.94	3.85	3.69	3.71	3.60	3.38
F-PNDM	18.2	7.05	4.61	4.32	3.85	3.68	3.53	3.46	3.47	3.49	3.44	**3.26**

Table 3: Cifar10 image generation measured in FID. The upper part uses linear variance schedule and the bottom half uses cosine variance schedule. The first line shows the FID provided by Song et al. (2020a).

steps	5	10	20	25	40	50	100	125	200	250	500	1000
DDIM		17.3		13.7		9.17	6.53					3.51
DDIM*	24.4	16.9	13.4	12.3	9.99	8.95	6.36	5.74	4.78	4.44	3.75	3.41
FON	60.2	16.0	11.6	10.6	8.89	8.13	6.70	6.28	5.45	5.14	4.49	4.17
S-PNDM	15.2	12.2	9.45	8.42	6.50	5.69	4.03	3.72	3.30	3.19	3.01	2.99
F-PNDM	11.3	7.71	5.51	4.75	3.67	3.34	2.81	2.75	**2.71**	2.71	2.77	2.86

Table 4: CelebA image generation measured in FID. All of them use linear variance schedule.

steps	5	10	20	25	40	50	100	125	200	250
DDIM		19.5	12.5			10.8	10.6			
DDIM*	48.8	18.8	11.7	11.0	10.1	10.0	9.84	9.83	9.85	9.88
S-PNDM	20.5	11.8	9.20	9.13	9.31	9.49	9.82	9.88	10.0	10.0
F-PNDM	14.8	**8.69**	9.13	9.33	9.69	9.89	10.1	9.99	10.1	10.1

Table 5: LSUN-church image generation measured in FID. All of them use linear variance schedule.

A.8 More Image Results

Here, we show more generated images on Cifar10, CelebA, LSUN-church and LSUN-bedroom in Figure 6, 7, 8, 9, 10, 11.

steps	5	10	20	25	40	50	100	125	200	250
DDIM		17.0	8.89			6.75	6.62			
DDIM*	51.3	16.4	8.47	7.41	6.27	6.05	5.97	6.03	6.23	6.32
S-PNDM	18.1	10.2	6.50	6.02	5.74	5.81	6.29	6.44	6.69	6.75
F-PNDM	12.6	6.99	**5.68**	5.74	6.17	6.44	6.91	6.96	7.03	6.92

Table 6: LSUN-bedroom image generation measured in FID. All of them use linear variance schedule.

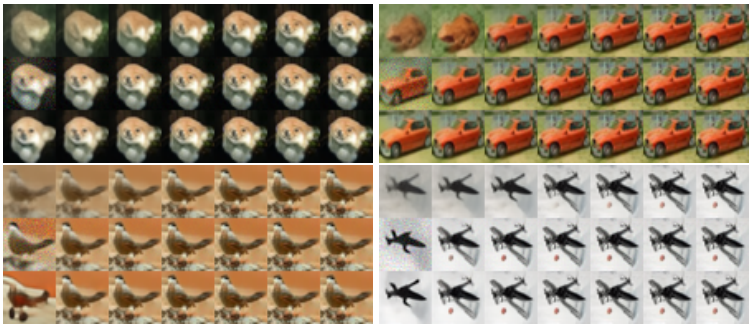

Figure 6: 5, 10, 20, 50, 100, 250, 500-steps generated results using DDIMs, classical numerical methods and PNDMs on Cifar10.

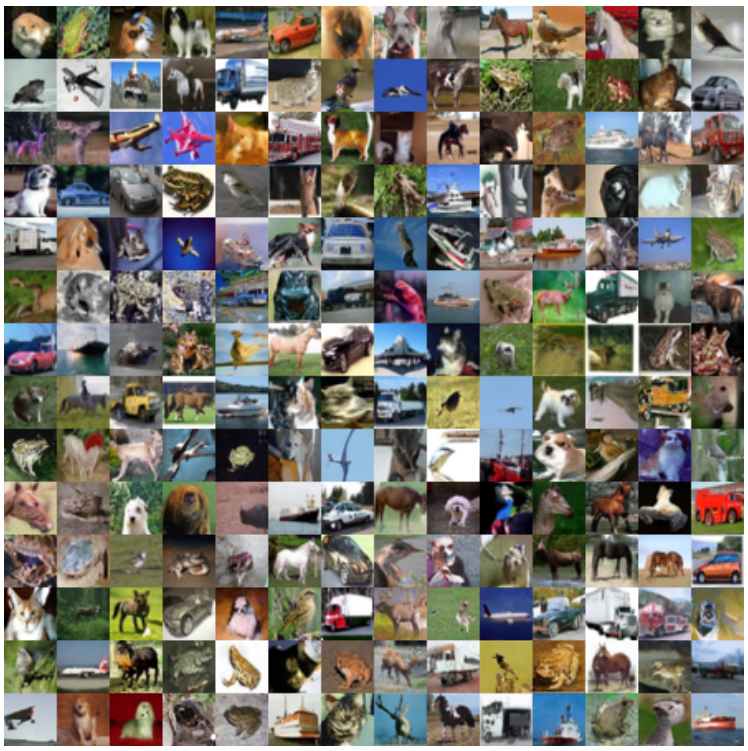

Figure 7: Generated images of PNDMs on Cifar10.

Figure 8: 5, 10, 20, 50, 100, 250, 500-steps generated results using DDIMs, classical numerical methods and PNDMs on CelebA.

Figure 9: Generated images of PNDMs on CelebA.

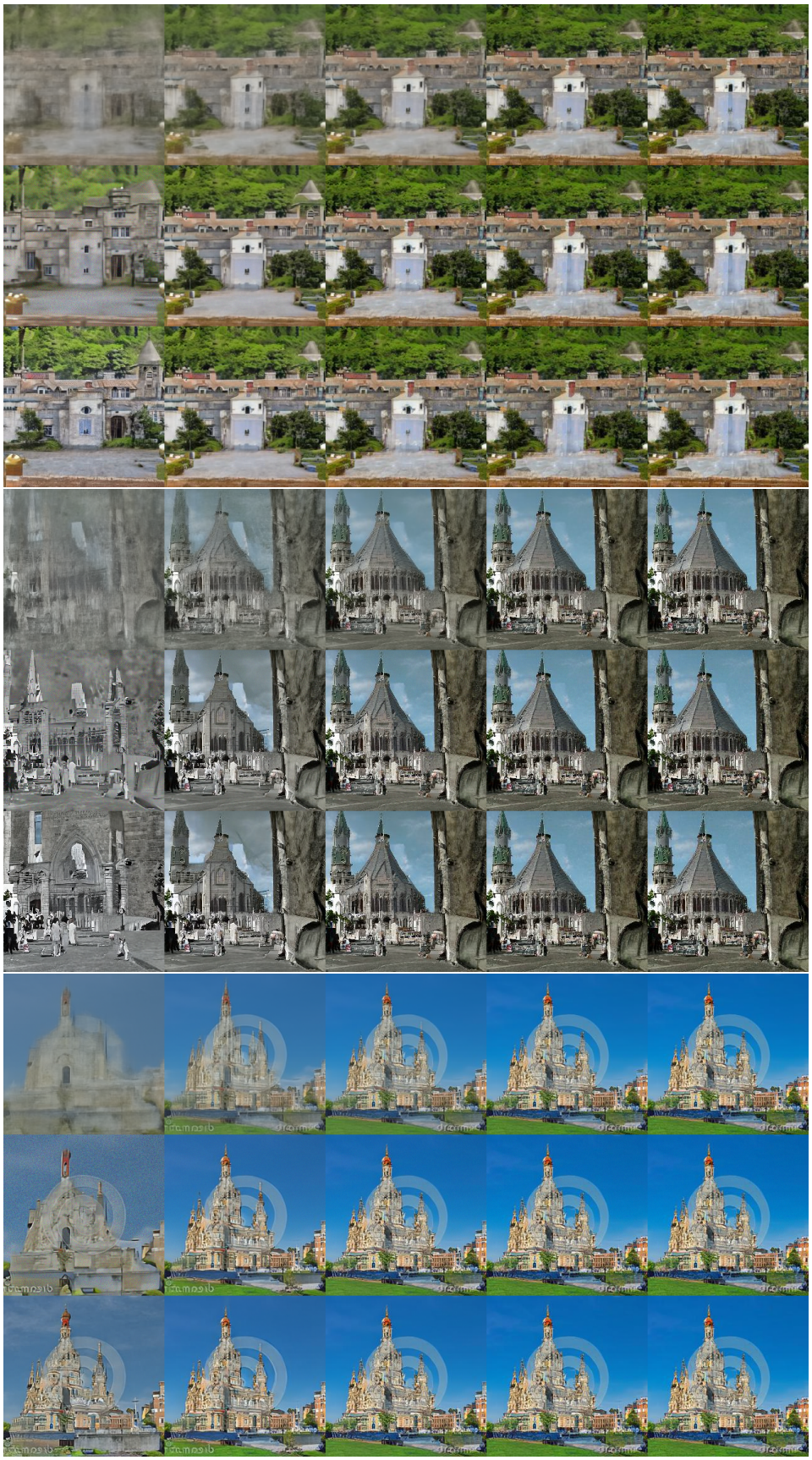

Figure 10: 5, 10, 20, 50, 100-steps generated results using DDIMs, classical numerical methods and PNDMs on LSUN-church.

Figure 11: 5, 10, 20, 50, 100-steps generated results using DDIMs, classical numerical methods and PNDMs on LSUN-bedroom.

A.9 More Visualization Results

Here, we put more visualization results similar to Figure 4 in Figure 12.

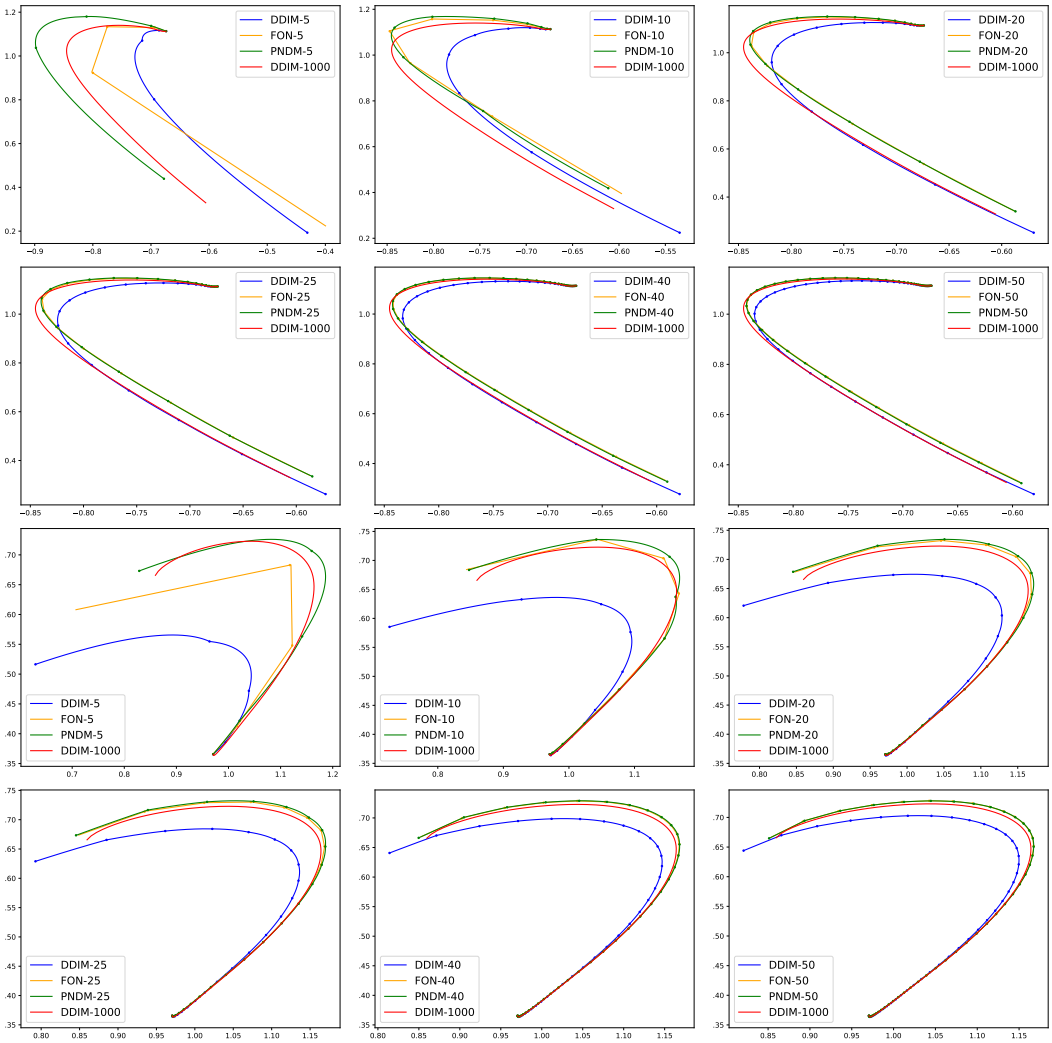

Figure 12: Visualization results under 5, 10, 20, 25, 40 and 50 steps.