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Acknowledgments:

Jason Hu, Bowen Song, Xiaojian Xu, Liyue Shen

[arXiv 2406.02462 \(NeurIPS 2024\)](#)

[arXiv 2406.10211 \(NeurIPS 2024\)](#)

[arXiv 2410.11730 \(IEEE T-CI, July 2025\)](#)

Introduction

- Inverse problems

- Generative models

- Score matching / diffusion models

Patch-based models

- Non-overlapping patch model

- Patch Diffusion Inverse Solver (PaDIS)

- CT reconstruction results

- 3D CT reconstruction

Distribution shifts

Summary

Book

Bibliography

- Applications: compressed sensing MRI, sparse-view CT, PET, inpainting, ...
All have *linear* forward models for data:

$$\mathbf{y} = \mathbf{A}\mathbf{x} + \varepsilon$$

$\mathbf{y}$: sensor data (e.g., sinogram)

$\mathbf{A}$: wide system matrix (known)

$\mathbf{x}$: latent image (or image series in dynamic problems)

ε : noise with known distribution provides likelihood $p(\mathbf{y}|\mathbf{x})$

- Maximum-likelihood estimation (physics-based fitting) is usually non-unique:

$$\hat{\mathbf{x}} = \arg \max_{\mathbf{x}} \log p(\mathbf{y}|\mathbf{x}) = \underbrace{\arg \min_{\mathbf{x}} \|\mathbf{A}\mathbf{x} - \mathbf{y}\|_2^2}_{\text{(for gaussian noise)}}$$

- Minimum-norm least-squares solution is unique but usually impractical or useless:

$$\hat{\mathbf{x}} = \mathbf{A}^+ \mathbf{y} = \mathbf{y} \text{ for inpainting problem}$$

- ▶ hand-crafted **regularizers**:

$$\hat{\mathbf{x}} = \arg \min_{\mathbf{x}} -\log p(\mathbf{y}|\mathbf{x}) + R(\mathbf{x}) = \arg \min_{\mathbf{x}} \frac{1}{2\sigma_{\epsilon}^2} \|\mathbf{A}\mathbf{x} - \mathbf{y}\|_2^2 + R(\mathbf{x})$$

- ▶ black-box data-driven supervised methods:

$$\mathbf{A}^+ \mathbf{y} \rightarrow \boxed{\text{NN}} \rightarrow \hat{\mathbf{x}}$$

- ▶ unrolled deep learning methods (PNP, RED, MoDL, ...)
- ▶ Bayesian methods (e.g., MAP) based on a **prior** $p(\mathbf{x})$,
lately (?) relabeled as **generative models** (or “genAI”)
- ▶

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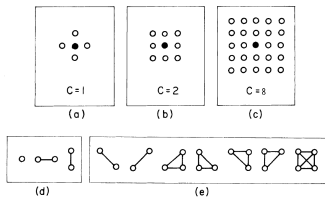
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- ▶ Bayesian methods (e.g., MAP) based on a **prior** $p(\mathbf{x})$, lately (?) relabeled as **generative models** (or “genAI”)
- ▶ Appeal:
 - PNP-like training independent of $\mathbf{A}$ or $p(\mathbf{y}|\mathbf{x})$
 - Strong priors for complex systems with aggressive under-sampling
 - Posterior sampling from $p(\mathbf{x}|\mathbf{y})$ for uncertainty quantification

Markov random field models

(e.g.) Geman & Geman 1984 [1]



Mostly for inference?

GEMAN AND GEMAN: STOCHASTIC RELAXATION, GIBBS DISTRIBUTIONS, AND BAYESIAN RESTORATION

737

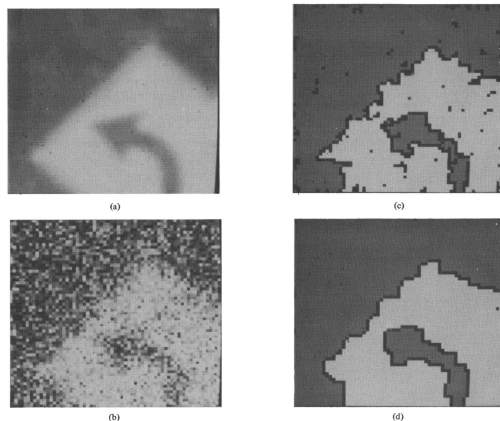


Fig. 7. (a) Blurred image (roadside scene). (b) Degraded image: Additive noise. (c) Restoration including line process; 100 iterations. (d) Restoration including line process; 1000 iterations.

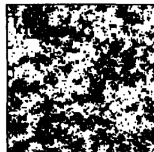
MRF as generators?

[2] T-PAMI 1994

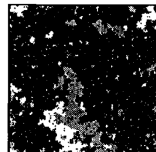
An Empirical Study of the Simulation of Various Models Used for Images

A. J. Gray, J. W. Kay, and D. M. Titterington

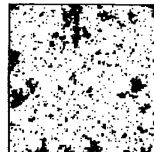
Abstract— Markov random fields are typically used as priors in Bayesian image restoration methods to represent spatial information in the image. Commonly used Markov random fields are **not** in fact capable of **representing the moderate-to-large scale clustering** present in naturally occurring images and can also be time consuming to simulate,



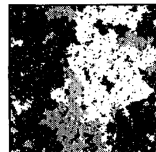
(b)



(f)



(c)



(g)

Gray, Kay, Titterton [2] T-PAMI 1994

... the local properties of spatial Markov models are undoubtedly plausible descriptors of the local associations typical of many images, which is the way in which the models are often used. Nevertheless, it would be reassuring if models used as priors did in fact provide a realistic representation of our prior assumptions and if their (empirical) properties were more widely known.

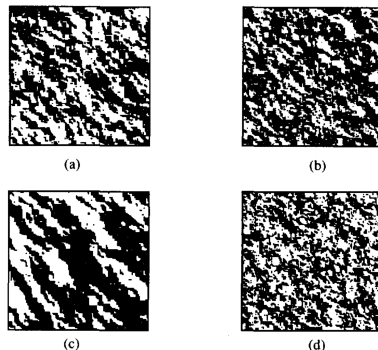


Fig. 4. Realizations of two-dimensional, one-parameter, autologistic Markov Mesh models: (a) binary, second-order model with $\beta = \log 5$; (b) three-color second-order model with $\beta = \log 5$; (c) binary second-order model with $\beta = \log 10$; (d) binary second-order model with $\beta = \log 3$.

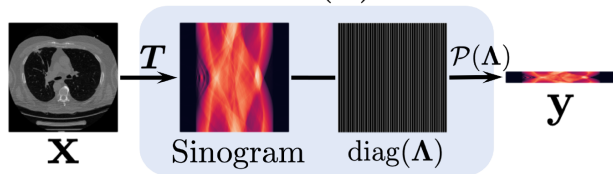
Zhao, Ye, Bresler: Jan. 2023 IEEE SpMag survey paper [3]

- ▶ Generative adversarial network (GAN) models
- ▶ Variation auto-encoder (VAE) models [4]
- ▶ Normalizing flows [5, 6]
- ▶ Score-based diffusion models
 - Zaccharie Ramzi et al., NeurIPS Workshop 2020 [7]
 - Yang Song & Liyue Shen et al., NeurIPS Workshop 2021, ICLR 2022 [8, 9]
 - Ajil Jalal et al. ... Jon Tamir, NeurIPS 2021 [10]
 - Hyungjin Chung & Jong Chul Ye, MIA, Aug. 2022 [11]
 - Luo et al., MRM, 2023 [12]
 - ...
- ▶ Kazerouni et al. [13] have github catalog, including >20 (!) survey papers
- ▶ ... (hopelessly incomplete lists)

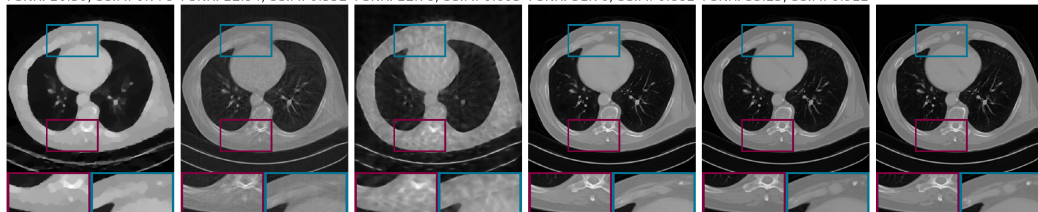
From Song & Shen et al., ICLR 2022 [9].

Trained with **47K 2D CT images**. Recon 23 projection views (≈ 17 -fold dose reduction)

$$\mathbf{A} = \mathcal{P}(\Lambda)\mathbf{T}$$



PSNR: 20.30, SSIM: 0.778 PSNR: 22.94, SSIM: 0.552 PSNR: 22.78, SSIM: 0.603 PSNR: 31.76, SSIM: 0.882 PSNR: 35.23, SSIM: 0.912



(a) FISTA-TV

(b) cGAN

(c) Neumann

(d) SIN-4c-PRN

(e) Ours

(f) Ground truth

1. Learning whole-image prior models requires **many** high-quality training images
Some applications like dynamic MRI have few *if any* realistic training samples
 - Curse of dimensionality
 - Images live near manifolds (unsuitable for traditional density estimators)
 - Implicit bias of model is crucial
- 2.

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2. Existing models **scale poorly** to 3D or 3D+time
 - GPU memory
 - training data requirements
- 3.

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3. Training images should arise from **relevant distribution** $p(\mathbf{x})$
Imaging-system aspects like X-ray source spectrum may cause **domain shift**
- 4.

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Imaging-system aspects like X-ray source spectrum may cause **domain shift**
4. What does “uncertainty” mean if prior is misspecified?

- ▶ Bayesian inference methods use the posterior:

$$p(\mathbf{x}|\mathbf{y}) = \underbrace{p(\mathbf{y}|\mathbf{x})}_{\text{physics}} \underbrace{p(\mathbf{x})}_{\text{prior}} / p(\mathbf{y})$$

- ▶ Here the prior $p(\mathbf{x})$ is for quantifying (prior) probability, not necessarily for generation.
- ▶ A model for the posterior $p(\mathbf{x}|\mathbf{y})$ opens many doors:
 - ▶ Maximizing $p(\mathbf{x}|\mathbf{y})$ is maximum a posteriori (MAP) estimation
 - ▶ The conditional mean $E[\mathbf{x}|\mathbf{y}] = \int \mathbf{x} p(\mathbf{x}|\mathbf{y}) d\mathbf{x}$ is the MMSE estimator
 - ▶ Sampling from the posterior $p(\mathbf{x}|\mathbf{y})$ facilitates uncertainty quantification in inference
- ▶ All these methods require the prior $p(\mathbf{x})$, *i.e.*, a prior model $p(\mathbf{x}; \boldsymbol{\theta})$.
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- ▶ All these methods require the prior $p(\mathbf{x})$, *i.e.*, a prior model $p(\mathbf{x}; \boldsymbol{\theta})$.
- ▶ Or do they?

Sampling from a *prior* $p(\mathbf{x}; \boldsymbol{\theta})$ just needs its **score function** $\nabla_{\mathbf{x}} \log p(\mathbf{x}; \boldsymbol{\theta})$, using Langevin dynamics, aka stochastic gradient ascent of log-prior:

$$\mathbf{x}_t = \mathbf{x}_{t-1} + \alpha_t \underbrace{\nabla \log p(\mathbf{x}_{t-1}; \boldsymbol{\theta})}_{\text{score function}} + \beta_t \mathcal{N}(\mathbf{0}, \mathbf{I}), \quad t = 1, \dots, T.$$

- Draws samples from $p(\mathbf{x}; \boldsymbol{\theta})$ for suitable choices of $\{\alpha_t\}$, $\{\beta_t\}$, and (large) T [14].
- If $\alpha_t = 0$ and $\beta_t = \beta$, then akin to (isotropic) diffusion or Brownian motion

- ▶ Typical distribution models: $p(\mathbf{x}; \boldsymbol{\theta}) = \frac{1}{Z(\boldsymbol{\theta})} e^{-U(\mathbf{x}; \boldsymbol{\theta})}$.
Goal: learn $\boldsymbol{\theta}$ from training data $\mathbf{x}_1, \dots, \mathbf{x}_T$
- ▶ For IID samples $\{\mathbf{x}_t\}$, one could try to learn $\boldsymbol{\theta}$ by ML estimation:

$$\begin{aligned}\hat{\boldsymbol{\theta}} &= \arg \max_{\boldsymbol{\theta}} p(\mathbf{x}_1, \dots, \mathbf{x}_T; \boldsymbol{\theta}) = \arg \max_{\boldsymbol{\theta}} \sum_{t=1}^T \log(p(\mathbf{x}_t; \boldsymbol{\theta})) \\ &= \arg \max_{\boldsymbol{\theta}} \left(-T Z(\boldsymbol{\theta}) + \sum_{t=1}^T -U(\mathbf{x}_t; \boldsymbol{\theta}) \right).\end{aligned}$$

Typically intractable due to the partition function $Z(\boldsymbol{\theta})$.



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- ▶ In contrast, the score function is easier to handle:

$$\mathbf{s}(\mathbf{x}; \boldsymbol{\theta}) \triangleq \nabla_{\mathbf{x}} \log p(\mathbf{x}; \boldsymbol{\theta}) = \nabla_{\mathbf{x}} (-\log Z(\boldsymbol{\theta}) - U(\mathbf{x}; \boldsymbol{\theta})) = -\nabla_{\mathbf{x}} U(\mathbf{x}; \boldsymbol{\theta}).$$

- ▶ Given training data $\mathbf{x}_1, \dots, \mathbf{x}_T$, learn score function $\mathbf{s}(\mathbf{x}; \boldsymbol{\theta}) \stackrel{?}{=} \nabla_{\mathbf{x}} \log p(\mathbf{x}; \boldsymbol{\theta})$
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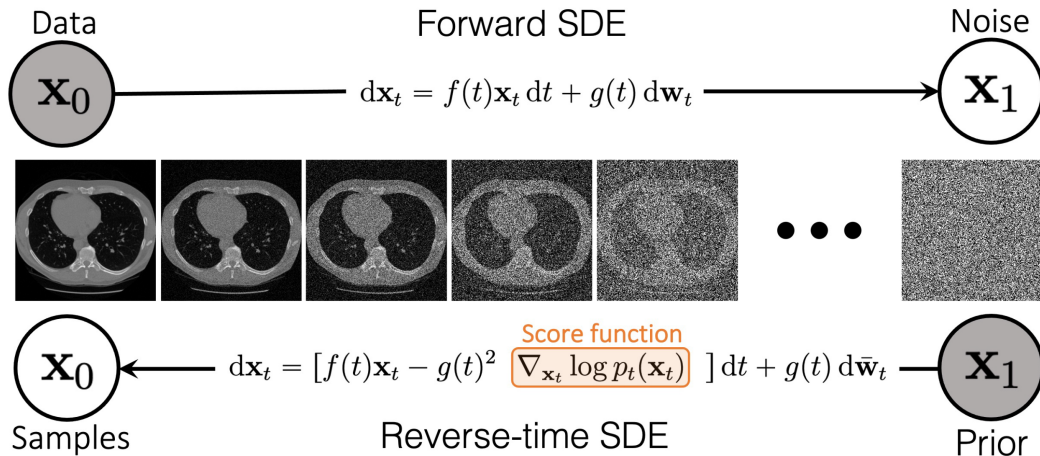
- ▶ Given training data $\mathbf{x}_1, \dots, \mathbf{x}_T$, learn score function $\mathbf{s}(\mathbf{x}; \boldsymbol{\theta}) \stackrel{?}{=} \nabla_{\mathbf{x}} \log p(\mathbf{x}; \boldsymbol{\theta})$
- ▶ Explicit score matching (ESM) (Hyvärinen, 2005 [15])
- ▶ Implicit score matching (ISM)
- ▶ Denoising score matching (DSM) (Vincent, 2011 [16])
- ▶ Noise-conditional score matching (NCSM) (Song, 2019 [17, eqn. (5)]):

$$\ell(\boldsymbol{\theta}; \sigma) \triangleq \frac{1}{2} \mathbb{E}_{\mathbf{q}_0(\mathbf{x})} \left[\mathbb{E}_{g_\sigma(\mathbf{z})} \left[\left\| \mathbf{s}(\mathbf{x} + \mathbf{z}; \boldsymbol{\theta}, \sigma) + \frac{\mathbf{z}}{\sigma^2} \right\|_2^2 \right] \right], \quad \mathcal{L}(\boldsymbol{\theta}; \{\sigma_l\}) = \frac{1}{L} \sum_{l=1}^L \sigma_l^2 \ell(\boldsymbol{\theta}; \sigma_l),$$

where $\mathbf{s}(\mathbf{x}; \boldsymbol{\theta}, \sigma)$ denotes a *noise-conditional score network* (NCSN).

- ▶ $\mathbf{d}(\mathbf{x}; \boldsymbol{\theta}) \triangleq \mathbf{x} + \sigma^2 \mathbf{s}(\mathbf{x}; \boldsymbol{\theta}, \sigma)$: equivalent image denoiser by Tweedie's formula [18]
- ▶ Recommended choice [19]: $\mathbf{s}(\mathbf{x}; \boldsymbol{\theta}, \sigma) \triangleq \tilde{\mathbf{s}}(\mathbf{x}; \boldsymbol{\theta})/\sigma$, where $\tilde{\mathbf{s}}$ is unitless

Shen & Song et al., NeurIPS 2021 [8]



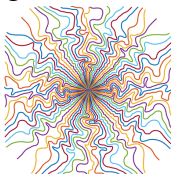
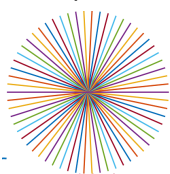
- ▶ No adversarial training needed
- ▶ High quality sample generation (if enough training data)
- ▶

- ▶ No adversarial training needed
- ▶ High quality sample generation (if enough training data)
- ▶ Expensive sample generation (vs GAN models)
 - Distillation methods [20]
 - Consistency models [21]
 - Geometric decomposition [22]
 - Multi-scale [23, 24] and pyramidal [25] and coarse-to-fine [26] models
 - Faster ODE solvers [27]
 - Warm starts [28]
 - Latent diffusion models: use VAE and diffuse in latent space [29–31].
Used in Stable Diffusion by start-up Stability AI
 - 3D image reconstruction using 2D models [32, 33]
- ▶ Learning 3D (or 3D+T) whole-image generative models is challenging (training data, GPU memory, ...)

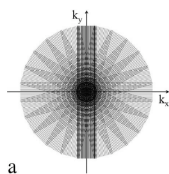
Challenge 1: Data availability

Jan. 2023 survey paper on generative models [3] does not mention “patch” once!?

MRI k-space sampling:

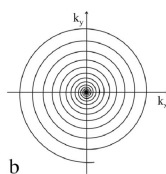


[34]

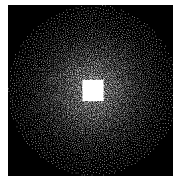


a

[35]



b



[36]

Patch-based models have long history in inverse problems, *e.g.*,

- patch GAN [37–39]
- patch dictionary models [40, 41]
- non-local means, BM3D
- Wasserstein patch prior [42, 43] . . .

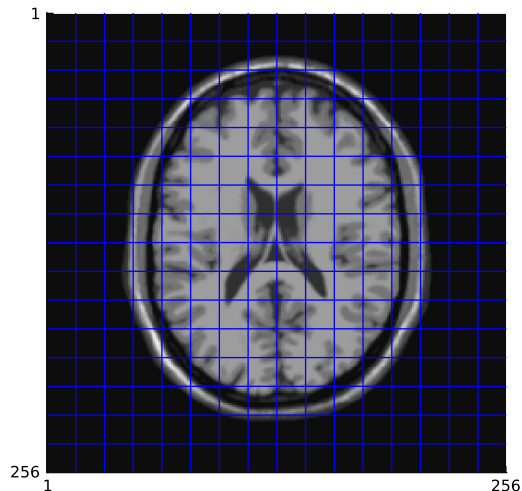
- ▶ Can patch-based generative models be effective priors for inverse problems in applications with very limited training data?
e.g., dynamic MRI
- ▶ Can patch-based generative models provide better robustness to distribution shifts, perhaps at the cost of reduced in-distribution performance?
- ▶ Can we use the “latest” generative models, *e.g.*, score-based models, for patches?

Warm up:

simple, but less effective, approach:

- Fixed patch size
- Fixed patch grid
- No position information

(Fessler, Hu, Xu, BASP 2023 [46])



- ▶ Start with MRF formulation, aka *fields of experts* model [51–53] for image $\mathbf{x}$:

$$p(\mathbf{x}; \boldsymbol{\theta}) = \frac{1}{Z(\boldsymbol{\theta})} e^{-\sum_c V_c(\mathbf{x}; \boldsymbol{\theta})} = \frac{1}{Z(\boldsymbol{\theta})} \prod_c e^{-V_c(\mathbf{x}; \boldsymbol{\theta})}.$$

- $\boldsymbol{\theta}$: parameter vector that describes the prior
 - V_c : *clique potential* for the c th image *patch*
 - $Z(\boldsymbol{\theta})$: (intractable) partition function
- ▶ Assume (temporarily) statistical spatial stationarity (image shift invariance):

$$V_c(\mathbf{x}; \boldsymbol{\theta}) = V(\mathbf{G}_c \mathbf{x}; \boldsymbol{\theta})$$

- $\mathbf{G}_c$: wide binary matrix that grabs pixels of the c th patch from image $\mathbf{x}$
- $V(\mathbf{v}; \boldsymbol{\theta})$: common patch clique function

- ▶ Resulting log-prior:

$$\log p(\mathbf{x}; \boldsymbol{\theta}) = -\log Z(\boldsymbol{\theta}) - \sum_c V(\mathbf{G}_c \mathbf{x}; \boldsymbol{\theta})$$

- ▶ Corresponding overall *image score function* arises from *patch score function*:

$$\mathbf{s}(\mathbf{x}; \boldsymbol{\theta}) \triangleq \nabla_{\mathbf{x}} \log p(\mathbf{x}; \boldsymbol{\theta}) = \sum_c \mathbf{G}'_c \mathbf{s}_V(\mathbf{G}_c \mathbf{x}; \boldsymbol{\theta}), \quad \mathbf{s}_V(\mathbf{v}; \boldsymbol{\theta}) \triangleq -\nabla_{\mathbf{v}} V(\mathbf{v}; \boldsymbol{\theta}).$$

- ▶ All we must learn is the patch score function $\mathbf{s}_V(\mathbf{v}; \boldsymbol{\theta}) : \mathbb{R}^n \mapsto \mathbb{R}^n$, e.g., a UNet.
- ▶ For non-overlapping patches:

$$\underbrace{\left\| \mathbf{s}(\mathbf{x} + \mathbf{z}; \boldsymbol{\theta}) + \mathbf{z}/\sigma^2 \right\|_2^2}_{\text{image "denoise"}} = \left\| \sum_c \mathbf{G}'_c \mathbf{s}_V(\mathbf{G}_c(\mathbf{x} + \mathbf{z}); \boldsymbol{\theta}) + \mathbf{z}/\sigma^2 \right\|_2^2 \\ = \sum_c \underbrace{\left\| \mathbf{s}_V(\mathbf{x}_c + \mathbf{z}_c); \boldsymbol{\theta}) + \mathbf{z}_c/\sigma^2 \right\|_2^2}_{\text{patch "denoise"}}, \quad \mathbf{z}_c \triangleq \mathbf{G}_c \mathbf{z}$$

- ▶ For training image patches $\{\mathbf{v}_1, \dots, \mathbf{v}_T\}$, apply *denoising score matching* (DSM) of Vincent, 2011 [16], typically for a range of noise variances σ^2 [14]:

$$\hat{\boldsymbol{\theta}} = \arg \min_{\boldsymbol{\theta}} \frac{1}{T} \sum_{t=1}^T \mathbb{E}_{\sigma \sim p(\sigma)} \left[\sigma^2 \mathbb{E}_{\mathbf{z} \sim \mathcal{N}(0, \sigma^2 \mathbf{I}_n)} \left[\frac{1}{2} \left\| \mathbf{s}_V(\mathbf{v}_t + \mathbf{z}; \boldsymbol{\theta}, \sigma) + \frac{\mathbf{z}}{\sigma^2} \right\|_2^2 \right] \right].$$

- ▶ Final patch score model is $\mathbf{s}_V(\mathbf{v}; \hat{\boldsymbol{\theta}}, \sigma_{\min})$.



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- ▶ Network input is just image patches, never the entire image
 $\implies$ scales to large 2D images, 3D, 4D, etc.
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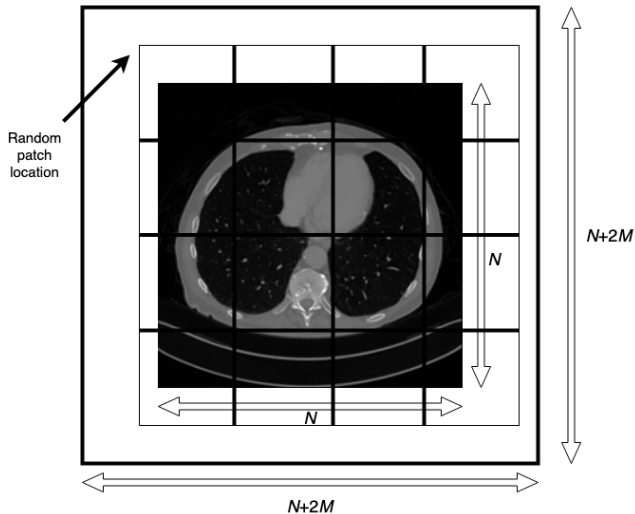
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- ▶ Network input is just image patches, never the entire image
 $\implies$ scales to large 2D images, 3D, 4D, etc.
- ▶ Drawbacks:
 - Visible patch boundaries
 - Fixed patch size slows learning
 - Suboptimal stationarity assumption (*cf.* vertebrae)

- ▶ zero-pad image x
- ▶ use multiple grid locations

Inspirations:

- Wavelet “cycle spinning”
[47, 54–57]
- Wang, NeurIPS 2023 [58]



- ▶ $N_1 \times N_2$: original image size
- ▶ $P_1 \times P_2$: patch size
- ▶ $K_i \triangleq 1 + \lfloor N_i/P_i \rfloor$, $i = 1, 2$: # non-overlapping patches for original image
- ▶ $(N_1 + 2M_1) \times (N_2 + 2M_2)$: padded image size; $M_i \triangleq K_i P_i - N_i$
- ▶ Product probability model:

$$p(\mathbf{x}) \triangleq \frac{1}{Z} \underbrace{\prod_{m=1}^{M_1 M_2}}_{\text{grid shifts}} \left(\underbrace{p_{m,B}(\mathbf{x}_{m,B})}_{\text{border region}} \underbrace{\prod_{k=1}^{K_1 K_2} p_{m,k}(\mathbf{x}_{m,k})}_{\text{patches}} \right) = \frac{1}{Z} \prod_{m=1}^{M_1 M_2} \prod_{k=1}^{K_1 K_2} \underbrace{e^{-V(\mathbf{x}_{m,k}; \mathbf{m}, \mathbf{k})}}_{\text{position encoding}}$$

- $\mathbf{x}_{m,B}$: border pixels for m th shift (all zero)
- $\mathbf{x}_{m,k}$: k th patch for m th shift



- ▶ $N_1 \times N_2$: original image size
- ▶ $P_1 \times P_2$: patch size
- ▶ $K_i \triangleq 1 + \lfloor N_i/P_i \rfloor$, $i = 1, 2$: # non-overlapping patches for original image
- ▶ $(N_1 + 2M_1) \times (N_2 + 2M_2)$: padded image size; $M_i \triangleq K_i P_i - N_i$
- ▶ Product probability model:

$$p(\mathbf{x}) \triangleq \frac{1}{Z} \underbrace{\prod_{m=1}^{M_1 M_2}}_{\text{grid shifts}} \left(\underbrace{p_{m,B}(\mathbf{x}_{m,B})}_{\text{border region}} \underbrace{\prod_{k=1}^{K_1 K_2} p_{m,k}(\mathbf{x}_{m,k})}_{\text{patches}} \right) = \frac{1}{Z} \prod_{m=1}^{M_1 M_2} \prod_{k=1}^{K_1 K_2} \underbrace{e^{-V(\mathbf{x}_{m,k}; \mathbf{m}, k)}}_{\text{position encoding}}$$

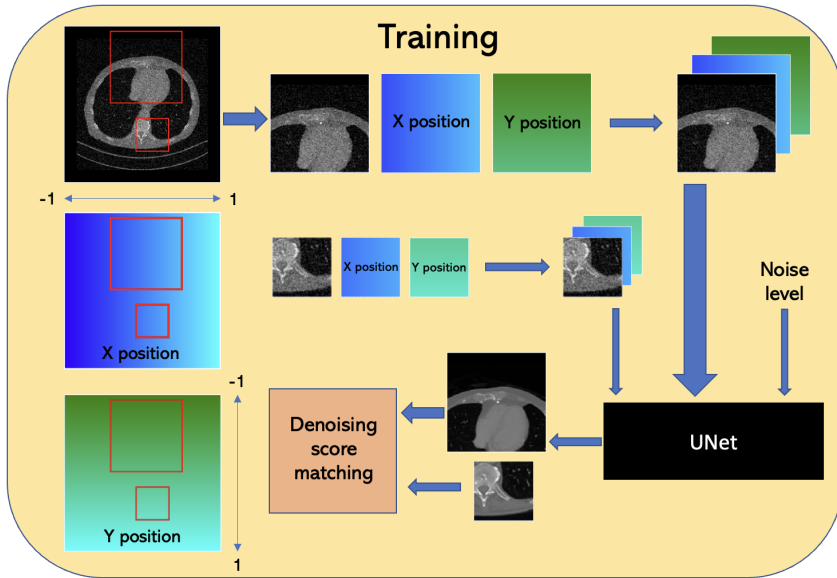
- $\mathbf{x}_{m,B}$: border pixels for m th shift (all zero)
- $\mathbf{x}_{m,k}$: k th patch for m th shift
- ▶ Learn position-dependent patch score function $\mathbf{s}(\mathbf{v}; \boldsymbol{\theta}, m, k) = -\nabla_{\mathbf{v}} V(\mathbf{v}; m, k)$

Patch Diffusion Inverse Solver (PaDIS): Training

J. Fessler
EfficientCI

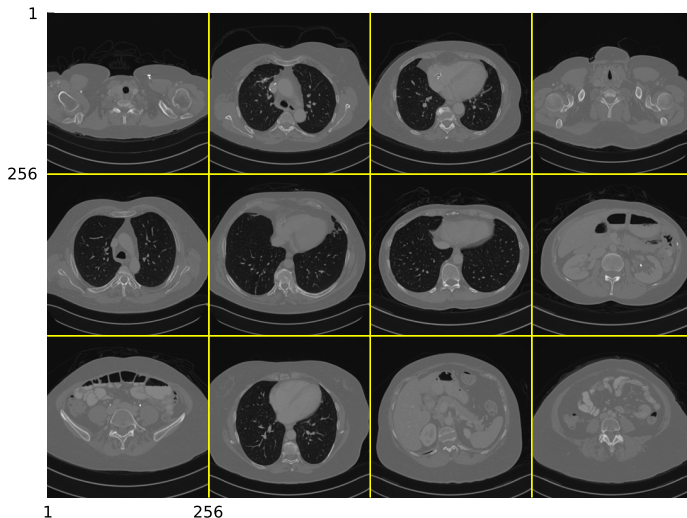


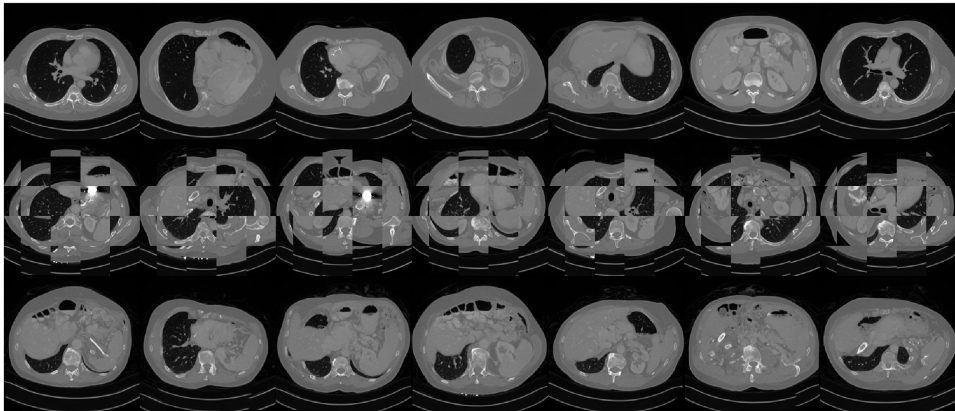
NeurIPS 2024 [60]
arXiv 2406.02462



AAPM 2016 CT chal-
lenge data [61];
10 3D volumes,
rescaled to 256^3

Example slices:

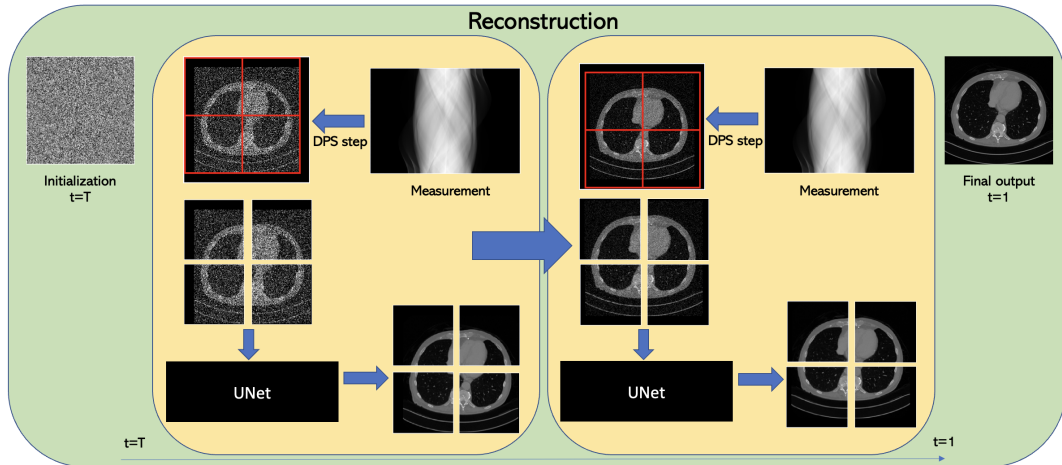




- Top: generation with a network trained on whole images (2D...)
- Middle: patch-only version of [58] (non-overlapping patches).
- Bottom: generation with proposed PaDIS prior.

2 A40 GPUs using PyTorch and ADAM

- ▶ whole image model: 24 – 36 hours
- ▶ patch-based model: $\approx$ 12 hours



Diffusion posterior sampling (DPS) (Chung et al., ICLR 2023 [62]) with Langevin dynamics, modified to use patch score with random grid shifts.

Input: $\mathbf{y}$, $\mathbf{A}$, T , $\sigma_1 < \sigma_2 < \dots < \sigma_T$, $\epsilon > 0$, $\{\zeta_t > 0\}$, P_1, P_2, M_1, M_2 ,
trained noise-conditional, position-encoded patch denoiser $\mathbf{d}(\cdot; \theta_*, m, k, \sigma)$

Initialize random image $\mathbf{x} \sim \mathcal{N}(\mathbf{0}, \sigma_T^2 \mathbf{I})$

for $t = T : 1$ **do**

Randomly select grid integer $m \in \{1, \dots, M_1 M_2\}$

for $k = 1 : (K_1 K_2)$ **do** (parallelizable)

Extract patch $\mathbf{x}_{m,k}$

Denoise patch: $\mathbf{d}_{m,k} \triangleq \mathbf{d}(\mathbf{x}_{m,k}; \theta_*, m, k, \sigma_t)$

end for

Combine denoised patches to get denoised image $\mathbf{d}$

Compute image score function: $\mathbf{s} = (\mathbf{d} - \mathbf{x}) / \sigma_t^2$

Data term: $\mathbf{x} := \mathbf{x} - \zeta_t \nabla_{\mathbf{x}} \|\mathbf{A} \mathbf{d}(\mathbf{x}) - \mathbf{y}\|_2^2$

Sample $\mathbf{z} \sim \mathcal{N}(\mathbf{0}, \sigma_t^2 \mathbf{I})$

Step size $\alpha_t \triangleq \epsilon \sigma_t^2$

Langevin update: $\mathbf{x} := \mathbf{x} + \frac{\alpha_t}{2} \mathbf{s} + \sqrt{\alpha_t} \mathbf{z}$

end for

Default setup:

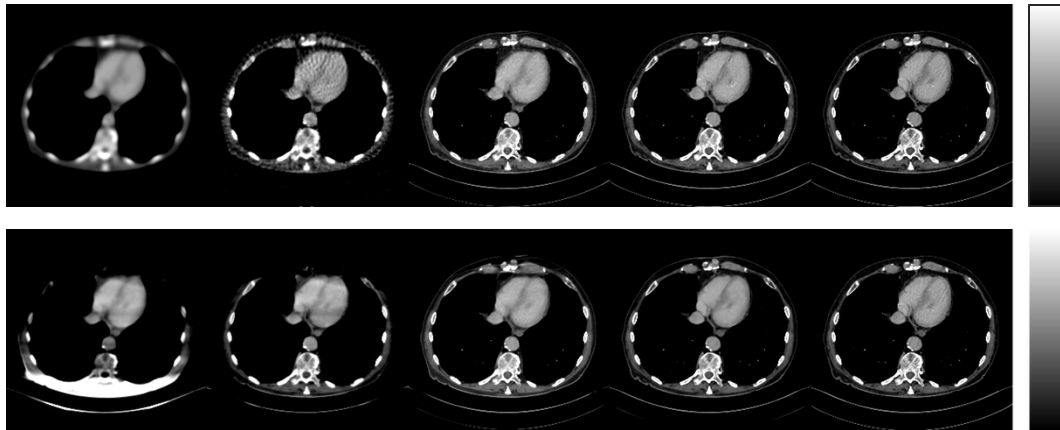
- 9 of 10 volumes for training $\implies$ 2304 slices
- 25 slices of 10th volume for testing
- 512 element parallel-beam CT detector
- $\mathbf{A}$ from Operator Discretization Library (ODL)
- 56×56 patch size
- U-Net of Karras 2022 [59]
- Step size $\zeta_t = \zeta / \|\mathbf{A}d(\mathbf{x}_t) - \mathbf{y}\|_2$
- 1000 neural function evaluations (NFEs) [59]

Method	CT, 20 Views		CT, 8 Views		Deblurring		Superresolution	
	PSNR $\uparrow$	SSIM $\uparrow$	PSNR $\uparrow$	SSIM $\uparrow$	PSNR $\uparrow$	SSIM $\uparrow$	PSNR $\uparrow$	SSIM $\uparrow$
Baseline	24.93	0.595	21.39	0.415	24.54	0.688	25.86	0.739
ADMM-TV	26.82	0.724	23.09	0.555	28.22	0.792	25.66	0.745
PnP-ADMM [63]	26.86	0.607	22.39	0.489	28.82	0.818	26.61	0.785
PnP-RED [64]	27.99	0.622	23.08	0.441	29.91	0.867	26.36	0.766
Whole image diffusion	32.84	0.835	25.74	0.706	30.19	0.853	29.17	0.827
Langevin dynamics [17]	33.03	0.846	27.03	0.689	30.60	0.867	26.83	0.744
Predictor-corrector [11]	32.35	0.820	23.65	0.546	28.42	0.724	26.97	0.685
VE-DDNM [65]	31.98	0.861	27.71	0.759	-	-	26.01	0.727
Patch Averaging [50]	33.35	0.850	28.43	0.765	29.41	0.847	27.67	0.802
Patch Stitching	32.87	0.837	26.71	0.710	29.69	0.849	27.50	0.780
PaDIS (Ours)	33.57	0.854	29.48	0.767	30.80	0.870	29.47	0.846

(Averages across all test images.)

Method	CT, 60 Views		CT, Fan Beam		Heavy Deblurring	
	PSNR↑	SSIM↑	PSNR↑	SSIM↑	PSNR↑	SSIM↑
Baseline	25.89	0.746	20.07	0.521	21.14	0.569
ADMM-TV	30.93	0.833	25.78	0.719	26.03	0.724
Whole image diffusion	35.83	0.894	26.89	0.835	28.35	0.808
PaDIS (Ours)	39.28	0.941	29.91	0.932	28.91	0.818

baseline FBP ADMM-TV whole image
diffusion PaDIS ground truth



Top: 60 view CT

Bottom: fan-beam CT

≈ 400 HU window width

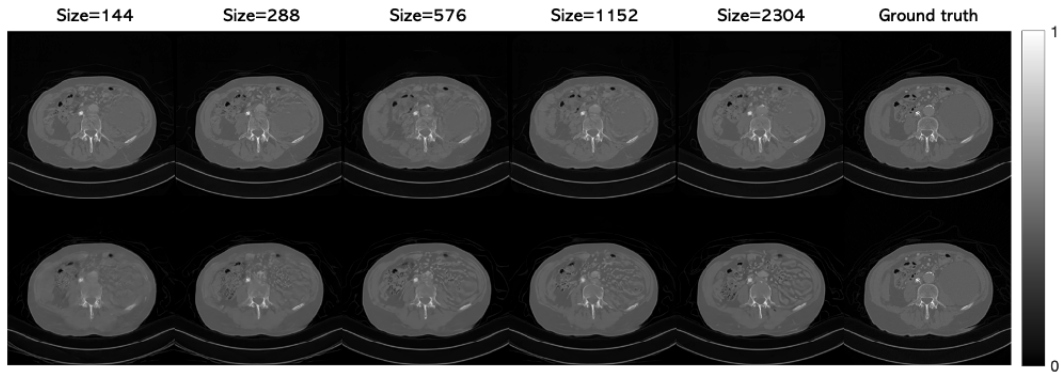
Patchsize

P	PSNR $\uparrow$	SSIM $\uparrow$
8	32.57	0.844
16	32.57	0.829
32	32.72	0.853
56	33.57	0.854
96	33.36	0.854
256	32.84	0.835

Positional encoding

	PSNR $\uparrow$	SSIM $\uparrow$
no position enc.	23.25	0.459
no position+init	24.51	0.518
with position enc.	33.57	0.854

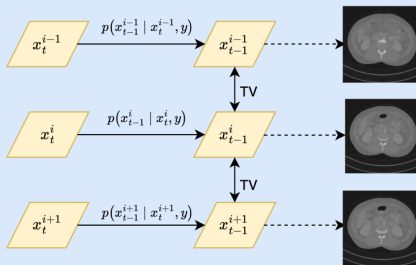
Dataset size	Patches 56×56		Whole image 256×256	
	PSNR $\uparrow$	SSIM $\uparrow$	PSNR $\uparrow$	SSIM $\uparrow$
144	32.28	0.841	29.12	0.804
288	32.43	0.837	31.09	0.829
576	33.03	0.846	31.81	0.835
1152	33.01	0.849	31.36	0.834
2304	33.57	0.854	32.84	0.835



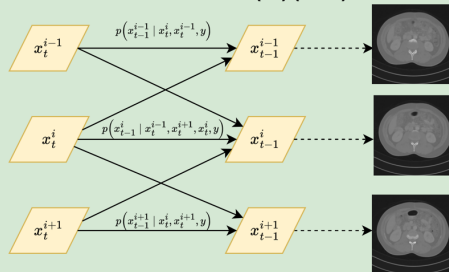
Challenge 2: Data dimensions & scaling to 3D (and 4D)

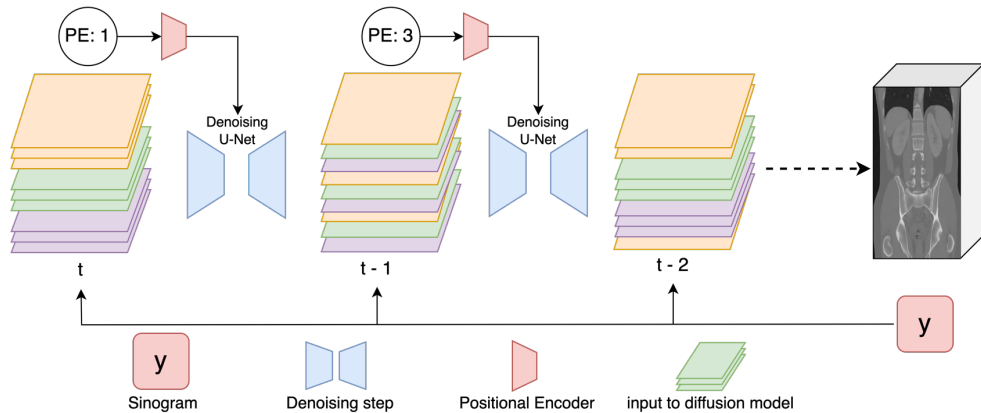
arXiv 2406.10211 (NeurIPS 2024) [66]

DDS/DiffusionMBIR



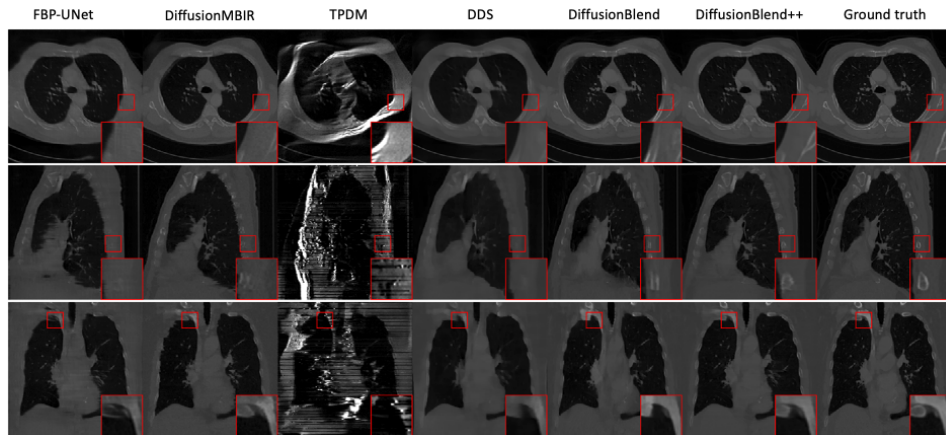
DiffusionBlend(++)(Ours)





Method	Distribution Model
DiffusionMBIR (2D) [32]	$\frac{1}{Z} \prod_{i=1}^H p(\mathbf{x}[:, :, i])$
TPDM ($\perp$ 2D) [33]	$\frac{1}{Z} \left(\prod_{i=1}^N q_{\theta}(\mathbf{x}[:, :, i])^{\alpha} \right) \left(\prod_{j=1}^N q_{\phi}(\mathbf{x}[j, :, :])^{\beta} \right)$
DiffusionBlend	$\frac{1}{Z} \prod_{i=1}^H p(\mathbf{x}[:, :, i] \mathbf{x}[:, :, i-j : i-1], \mathbf{x}[:, :, i+1 : i+j])$
DiffusionBlend++	$\frac{1}{Z} \prod_{i=1}^r p(\mathbf{x}[:, :, \mathcal{S}_i])$

90° angular range



Improved quality both qualitatively and quantitatively with strong prior.

Method	AAPM Dataset						LIDC Dataset					
	Axial		Sagittal		Coronal		Axial		Sagittal		Coronal	
	PSNR↑	SSIM↑	PSNR↑	SSIM↑	PSNR↑	SSIM↑	PSNR↑	SSIM↑	PSNR↑	SSIM↑	PSNR↑	SSIM↑
FBP	16.36	0.643	16.36	0.524	15.62	0.531	18.79	0.672	19.84	0.675	20.01	0.676
FBP-UNet	27.38	0.910	27.81	0.918	28.44	0.930	29.42	0.885	29.50	0.884	29.54	0.887
DiffusionMBIR	25.98	0.872	27.14	0.877	27.74	0.903	<u>30.52</u>	0.906	30.57	0.906	30.68	0.907
TPDM	-	-	-	-	-	-	14.44	0.141	14.06	0.141	14.54	0.313
DDS 2D	28.05	0.916	27.99	0.916	28.82	0.922	27.92	0.843	27.89	0.835	27.96	0.842
DDS	28.20	0.918	28.17	0.926	29.03	0.934	28.12	0.865	28.06	0.869	28.13	0.879
DiffusionBlend (Ours)	<u>35.38</u>	<u>0.971</u>	<u>35.85</u>	<u>0.972</u>	37.62	<u>0.972</u>	30.43	<u>0.917</u>	<u>31.24</u>	<u>0.920</u>	<u>31.02</u>	<u>0.924</u>
DiffusionBlend++ (Ours)	35.86	0.975	36.03	0.976	<u>37.45</u>	0.976	34.33	0.957	34.48	0.957	34.64	0.956

[66, Table 4]

Challenge 3: Distribution shifts

Test-time latent $\mathbf{x}$ far from training distribution:

$$\mathbf{y} = \mathbf{A}\mathbf{x} + \epsilon, \quad \mathbf{x} \sim \tilde{p}(\cdot) \neq p(\cdot)$$

► Non-Bayes approach

Abandon training via self-supervision, e.g., deep image prior (DIP) [67]:

$$\hat{\mathbf{x}} = f_{\hat{\theta}}(\mathbf{z}), \quad \hat{\theta} = \arg \min_{\theta} \|\mathbf{y} - \mathbf{A}f_{\theta}(\mathbf{z})\|_2^2, \quad \mathbf{z} \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$$

Neural network $f_{\theta}(\cdot)$ acts as implicit regularizer.

DIP is prone to overfitting of noisy measurements [67];

remedies such as early stopping, regularization, network initialization [68–70].

- ▶ Self-supervised (whole-image) diffusion models [71, 72]
“Deep diffusion image prior” (DDIP) or “steerable conditional diffusion:”

$$L(\theta) = \|\mathbf{y} - \mathbf{A} \text{CG}(\hat{\mathbf{x}}_{0|t}(\mathbf{x}_t; \theta))\|_2^2$$
$$\text{CG}(\hat{\mathbf{x}}_{0|t}) \triangleq \arg \min_{\mathbf{x}} \frac{\gamma}{2} \|\mathbf{y} - \mathbf{A}\mathbf{x}\|_2^2 + \frac{1}{2} \|\mathbf{x} - \hat{\mathbf{x}}_{0|t}\|_2^2$$

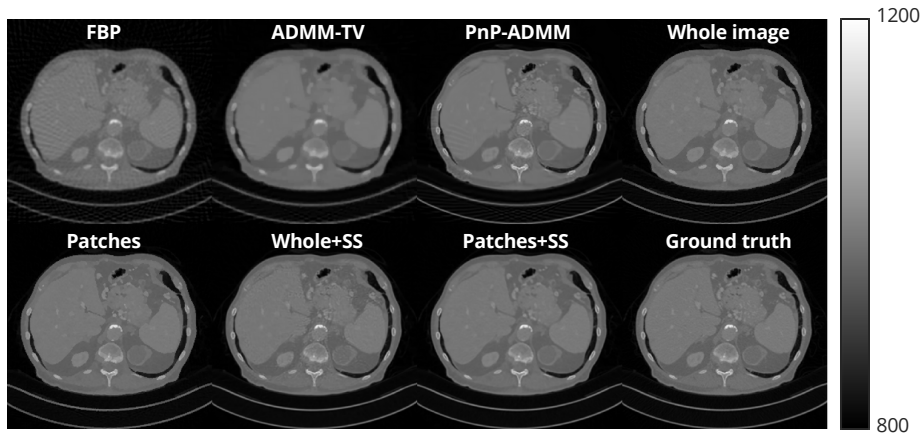
Conjugate gradient (CG) descent is used to enforce data fidelity.
Still requires early stopping to avoid over-fitting.

- Patch-based test-time adaptation [73, 74] arXiv 2410.11730 (IEEE T-CI, in-press)
Test-time loss for diffusion model adaptation:

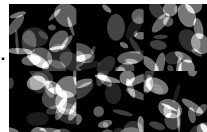
$$L(\theta) = \left\| \mathbf{y} - \mathbf{A} \sum_c \mathbf{G}'_c D_\theta(\mathbf{G}_c \mathbf{x}_t, c | \mathbf{y}) \right\|_2^2$$

Patch-based denoiser for diffusion model

$$D_\theta(\mathbf{x}) = \sum_c \mathbf{G}'_c D_\theta(\mathbf{G}_c \mathbf{x}, c),$$

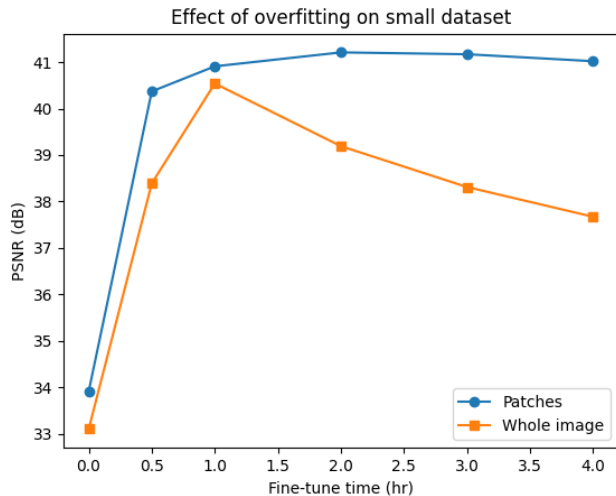


No in-distribution training data. Pre-trained with random ellipses.
Results of 60-view CT reconstruction using self supervised (SS) loss.

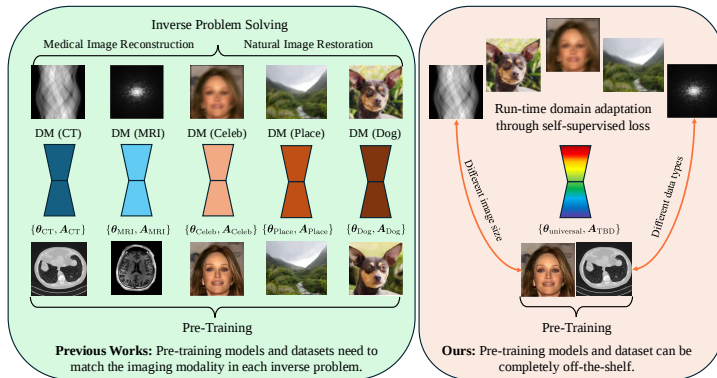


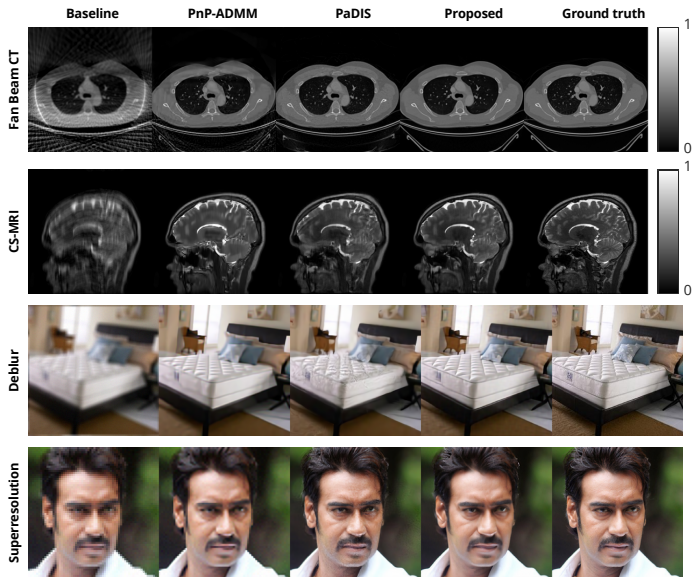
Method	CT, 20 Views		CT, 60 Views		Deblurring		Superresolution	
	PSNR $\uparrow$	SSIM $\uparrow$	PSNR $\uparrow$	SSIM $\uparrow$	PSNR $\uparrow$	SSIM $\uparrow$	PSNR $\uparrow$	SSIM $\uparrow$
Baseline	24.93	0.613	30.15	0.784	23.93	0.666	25.42	0.724
ADMM-TV	26.81	0.750	31.14	0.862	27.58	0.773	25.22	0.729
PnP-ADMM [63]	30.20	0.838	36.75	0.932	28.98	0.815	27.29	0.796
PnP-RED [64]	27.12	0.682	32.68	0.876	28.37	0.793	27.73	0.809
Whole image	28.11	0.800	33.10	0.911	25.85	0.742	25.65	0.742
Patches [60]	27.44	0.719	33.97	0.934	26.77	0.782	26.12	0.759
Whole+SS [72]	33.19	0.861	40.47	0.957	29.50	0.831	27.07	0.701
Patches+SS (Ours)	33.77	0.874	41.45	0.969	30.34	0.860	28.10	0.827

“SS” = self-supervision, aka test-time adaptation



- Extension to cases where # of channels at test time differs from training data, e.g., MR reconstruction (real/imag) from patch-based diffusion model pre-trained on color (RGB) natural images and grayscale CT images [75]





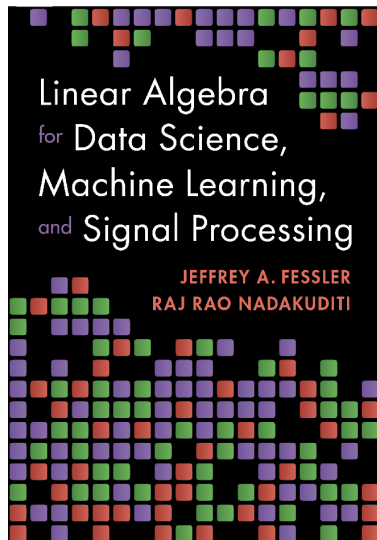
Comparison of quantitative results on four different medical imaging inverse problems.

Method	PBCT, 60 Views		FBCT, 40 Views		512 × 512 CT		CS-MRI, 7×	
	PSNR↑	SSIM↑	PSNR↑	SSIM↑	PSNR↑	SSIM↑	PSNR↑	SSIM↑
Baseline	30.15	0.784	17.86	0.381	28.33	0.700	33.94	0.894
ADMM-TV	31.14	0.862	24.20	0.628	29.36	0.788	36.74	0.924
PnP-ADMM [63]	36.75	0.932	28.86	0.747	37.48	0.910	35.77	0.907
PaDIS+FC [60]	39.16	0.942	27.91	0.796	33.11	0.831	35.17	0.904
SCD [72]	41.16	0.962	21.28	0.463	–	–	–	–
Ours (SPAR)	42.72	0.972	36.11	0.918	38.81	0.929	39.15	0.949
Ideal*	42.82	0.973	36.34	0.923	38.94	0.930	39.42	0.953

*not available in practice with a single diffusion model

- ▶ Challenges
 - ▶ Dearth of data
 - ▶ Dimensionality
 - ▶ Distribution shifts
- ▶ Promise
 - ▶ Generative models are promising for under-determined inverse problems
 - ▶ Learning patch score models is feasible with denoising score matching
 - ▶ For limited training data, patch-models can outperform whole-image models
- ▶ Future steps
 - ▶ Integrate invariances: amplitude scale / rotation / flip / DC offset ...
 - ▶ Explore trade-offs between generalizability and in-distribution performance
 - ▶ Extend to 3D, 3D+Time, 3D+Multicontrast

Tutorial Julia code: <https://github.com/JeffFessler/ScoreMatching.jl>



- Online demos:
<https://github.com/JeffFessler/book-la-demo>
- Topics include: low-rank matrix approximation, robust PCA, photometric stereo, video foreground/background separation, spectral clustering, matrix completion, ...
- Cambridge Univ. Press, 2024

Talk and code available online at
<http://web.eecs.umich.edu/~fessler>



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