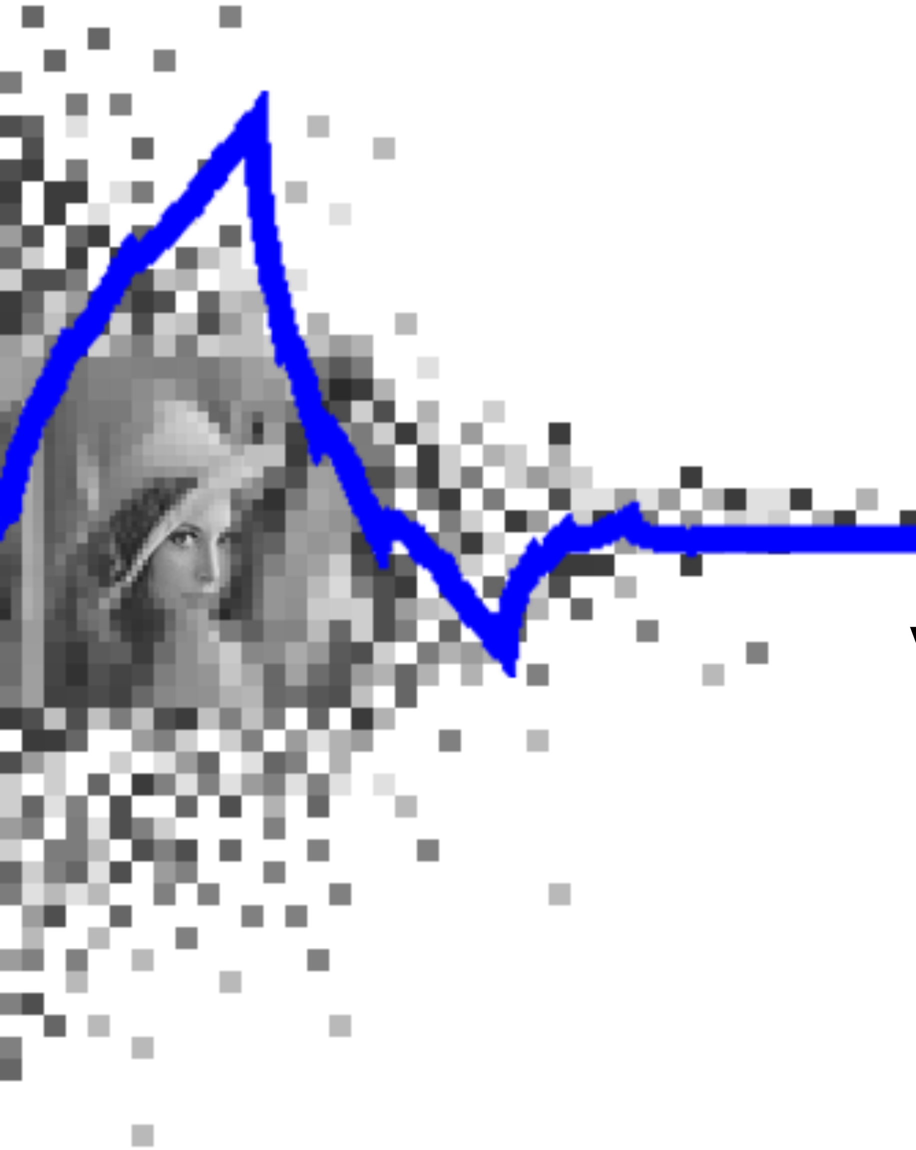

Image Processing with Manifold Models

Gabriel Peyré

NatImages Project
http://www.ceremade.dauphine.fr/~peyre/natimages/

CEREMADE
Université Paris Dauphine

Toward Adaptive Image Priors

Variational image prior: $J(f)$ depends on ∇f.

Sparsity in ortho-basis $\{\psi_m\}_m$: $J(f) = \sum_m |\langle f,\, \psi_m \rangle|$.

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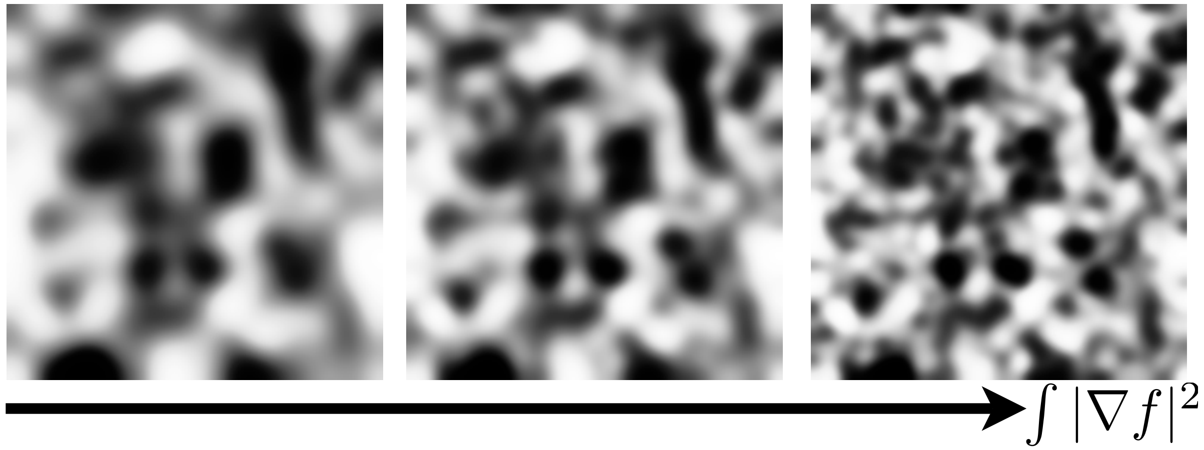
Uniformly smooth C^α image.

$$J(f) = \int |\nabla f|^2, \quad \mathcal{B} = \text{Fourier}.$$



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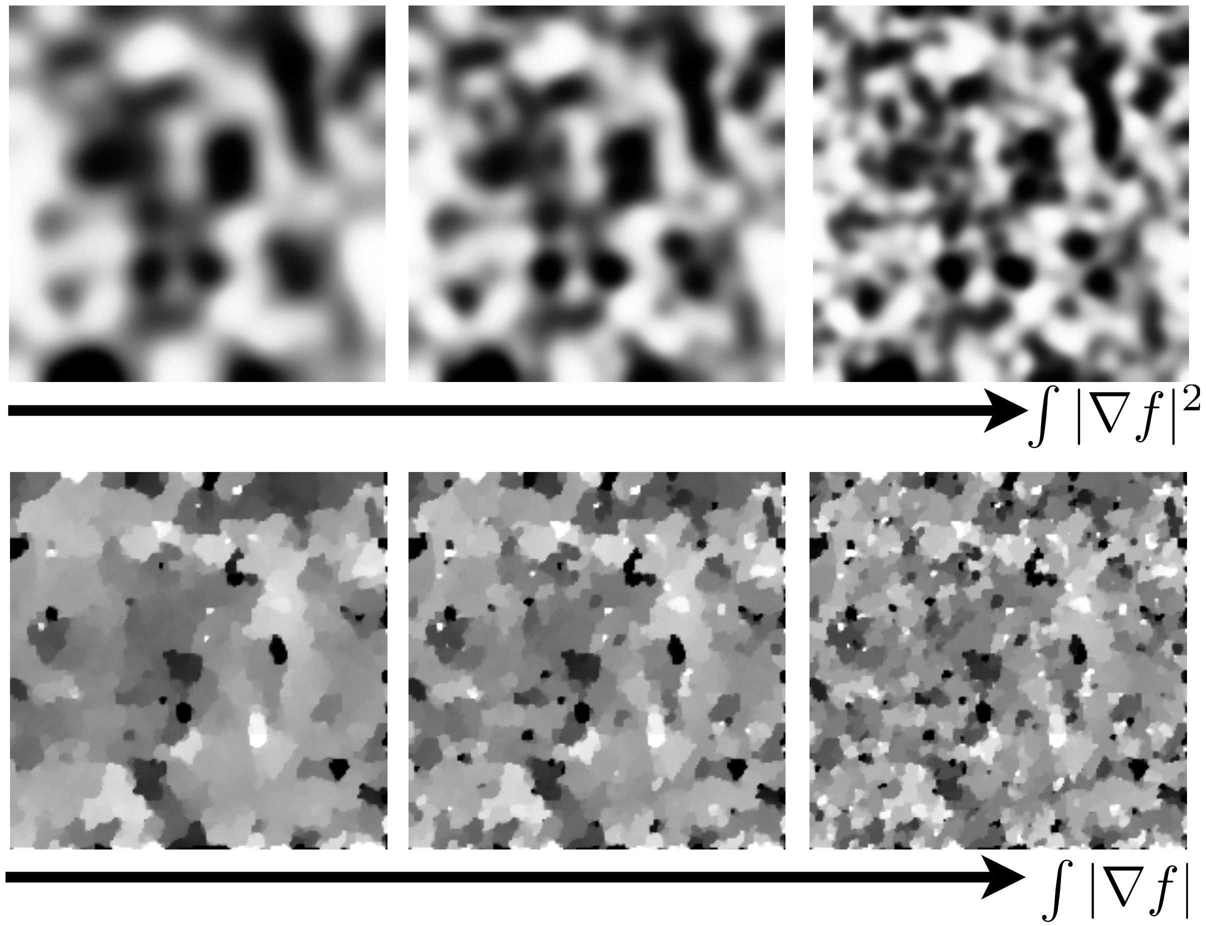
Discontinuous image with bounded variation.

$$J(f) = \int |\nabla f|, \quad \mathcal{B} = \text{wavelets}.$$



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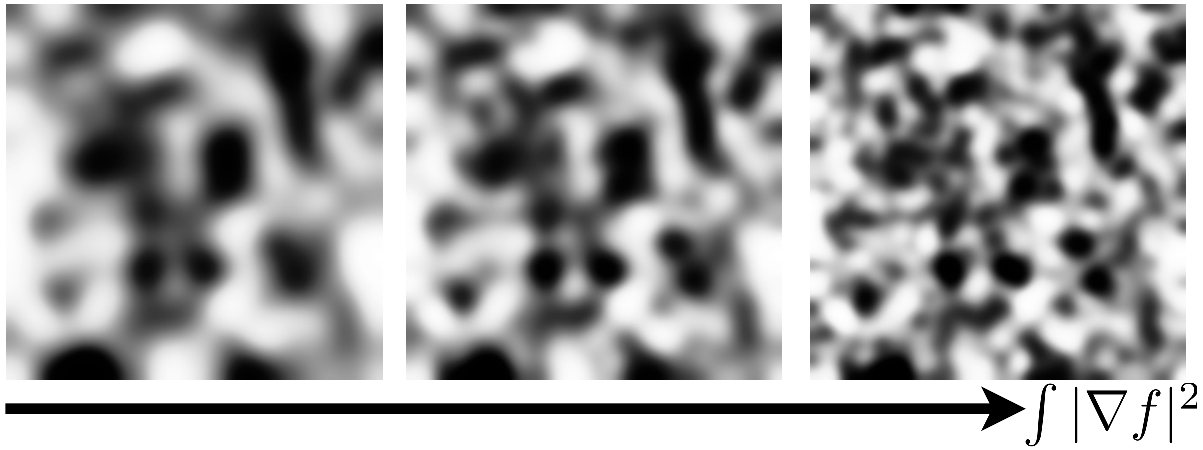

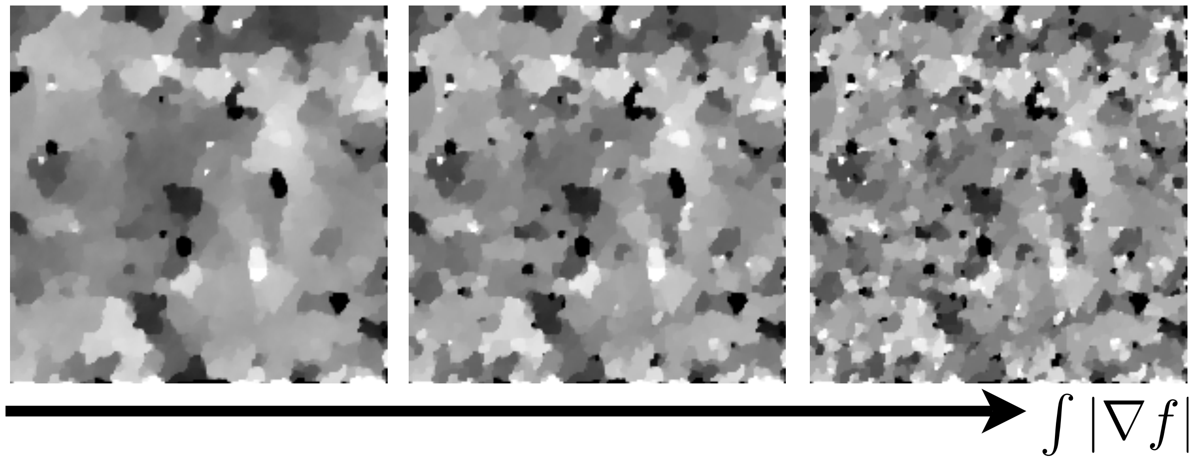

Adaptive prior: $J(f) = J_w(f)$, w =geometry.

– denoising: w estimated from noisy image.

– inverse pbm: adapt w to the image to recover

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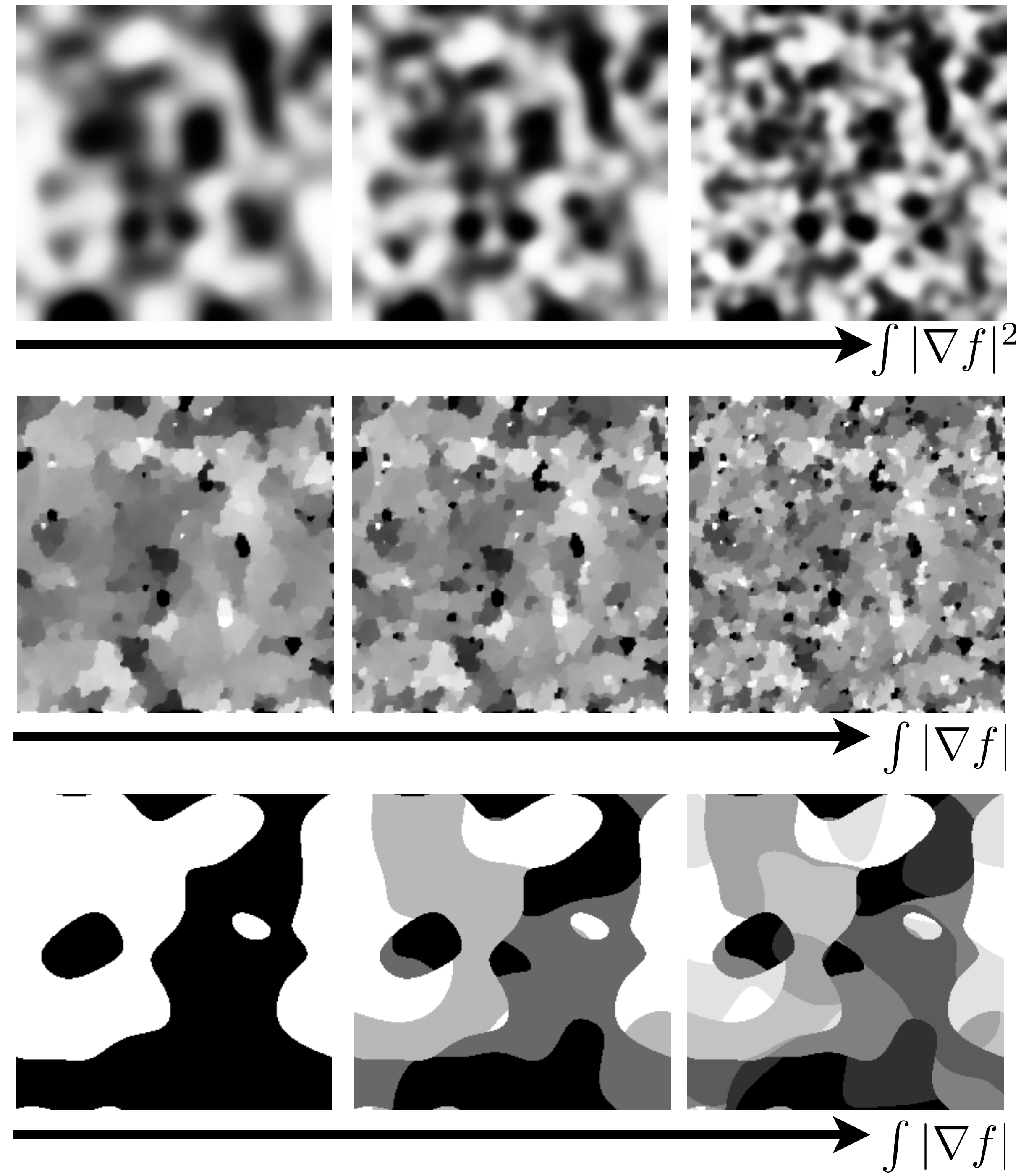
Cartoon image with C^α edges.

$\longrightarrow$ Adaptivity to the edge **direction** w.



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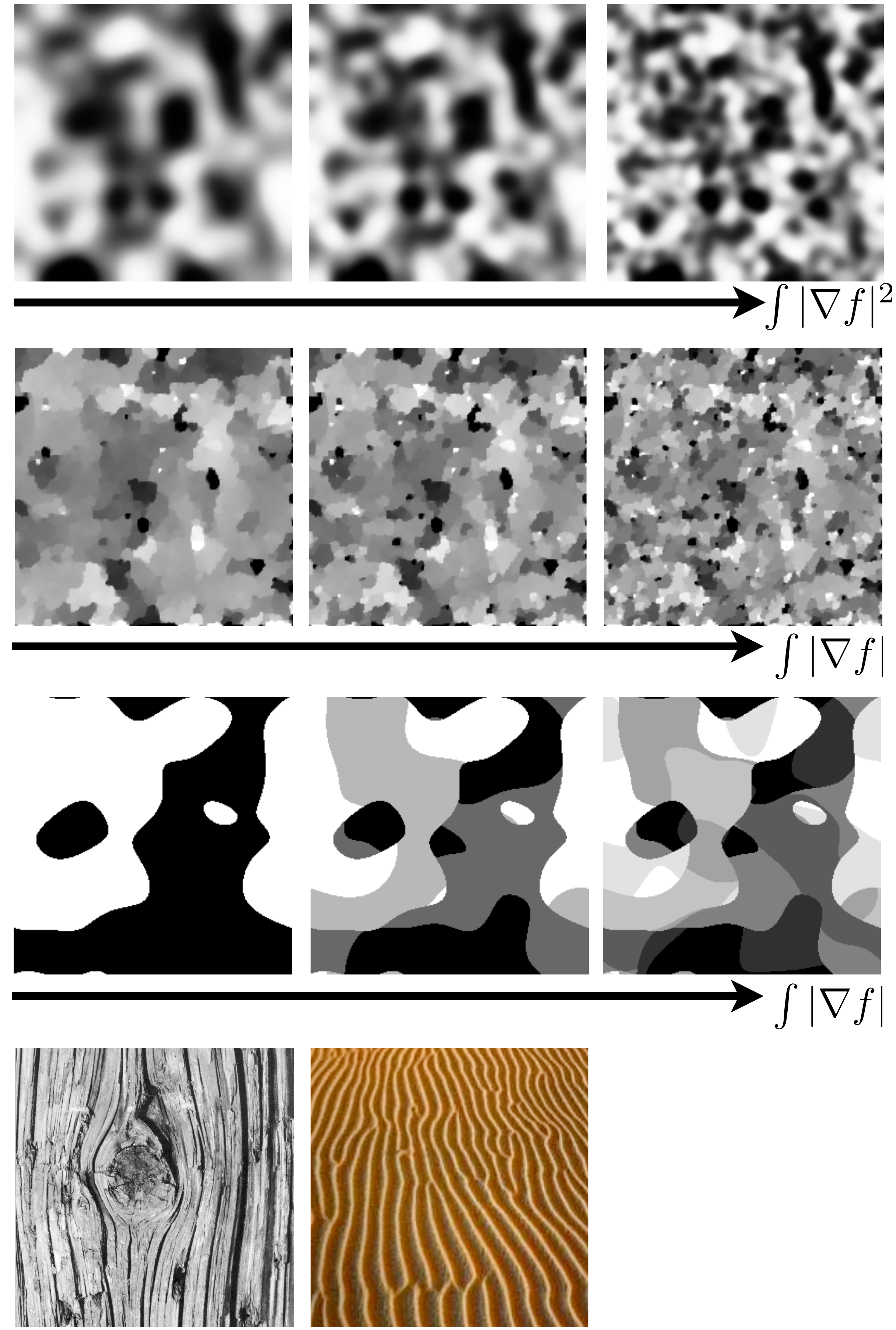
Locally parallel, turbulent textures.

$\longrightarrow$ Adaptivity to the texture **orientation** w.



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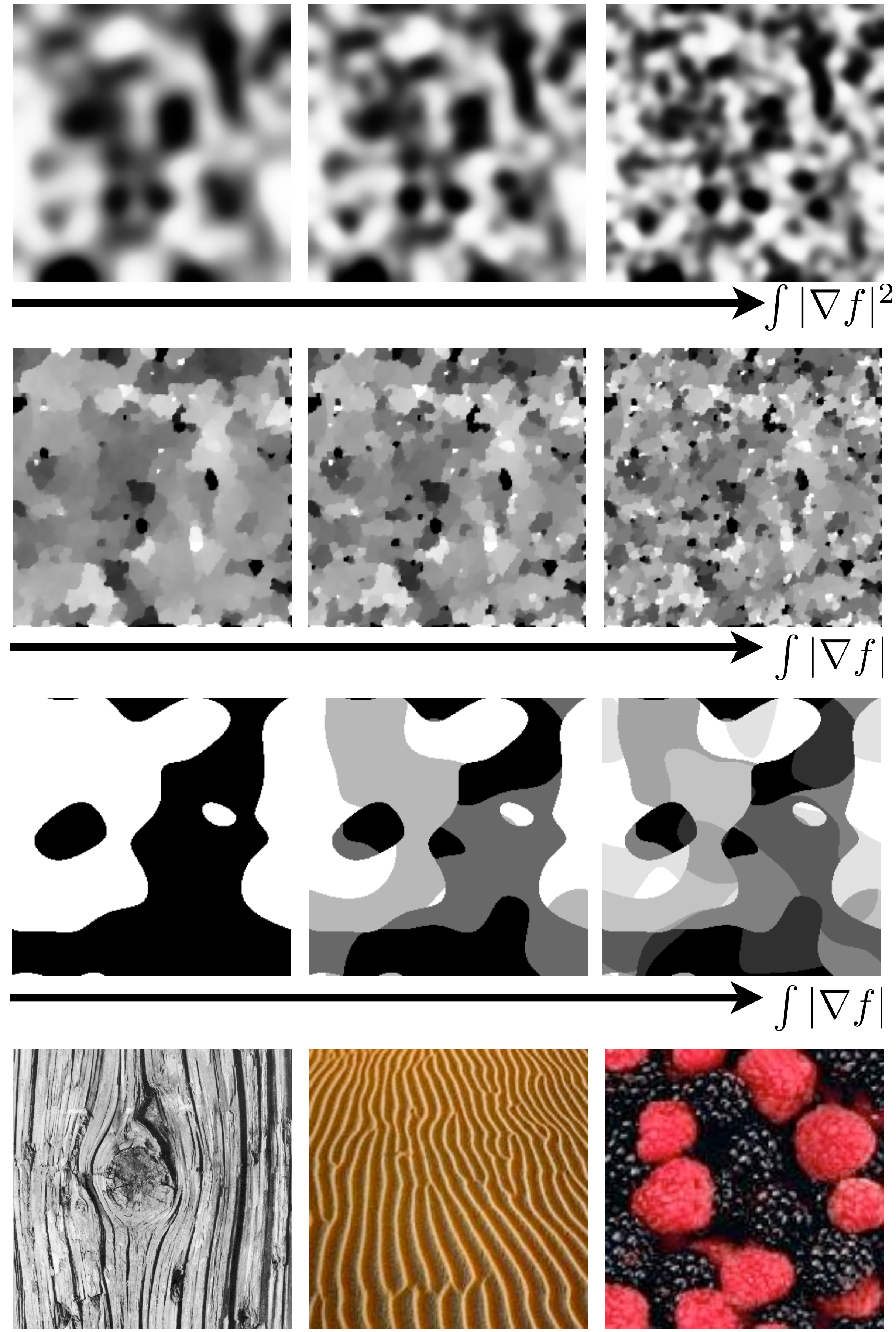
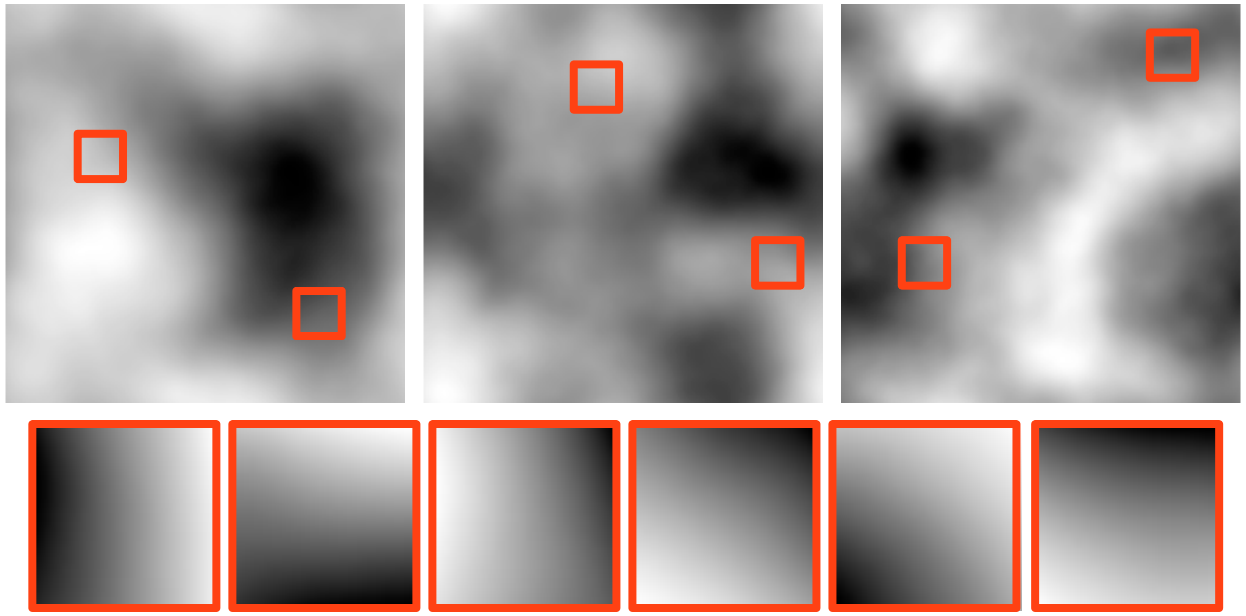
Complex natural images: open question …



The Local Geometry of Images



Model: C^2 uniformly regular image.
Patches: linear gradient of intensity.

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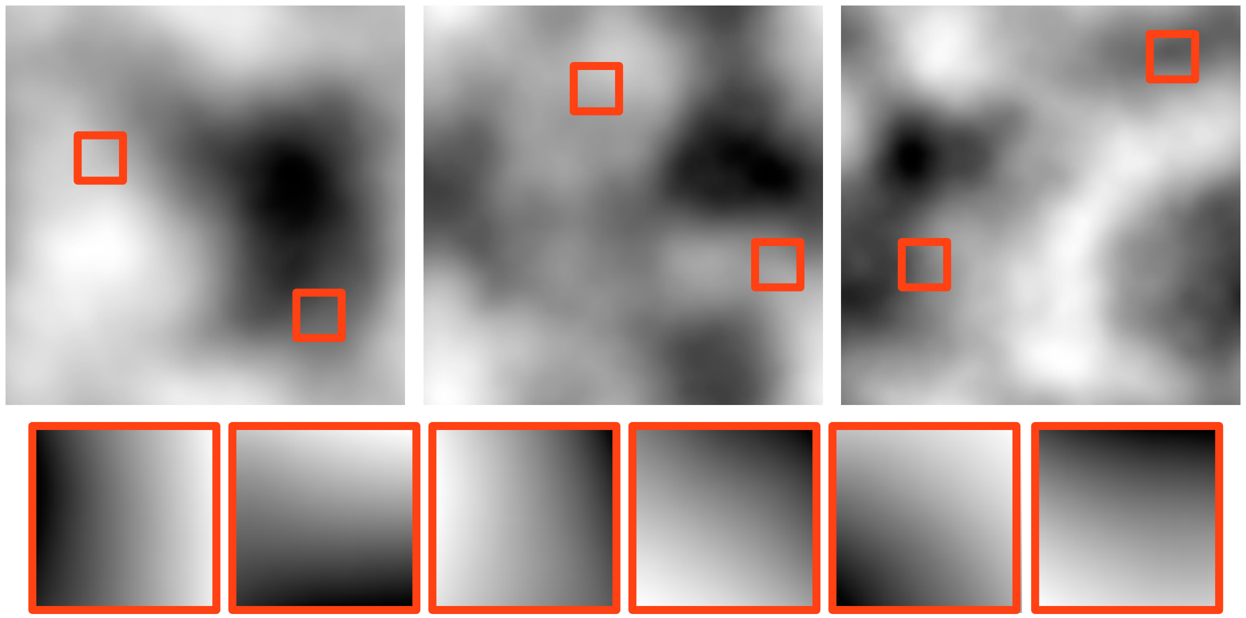

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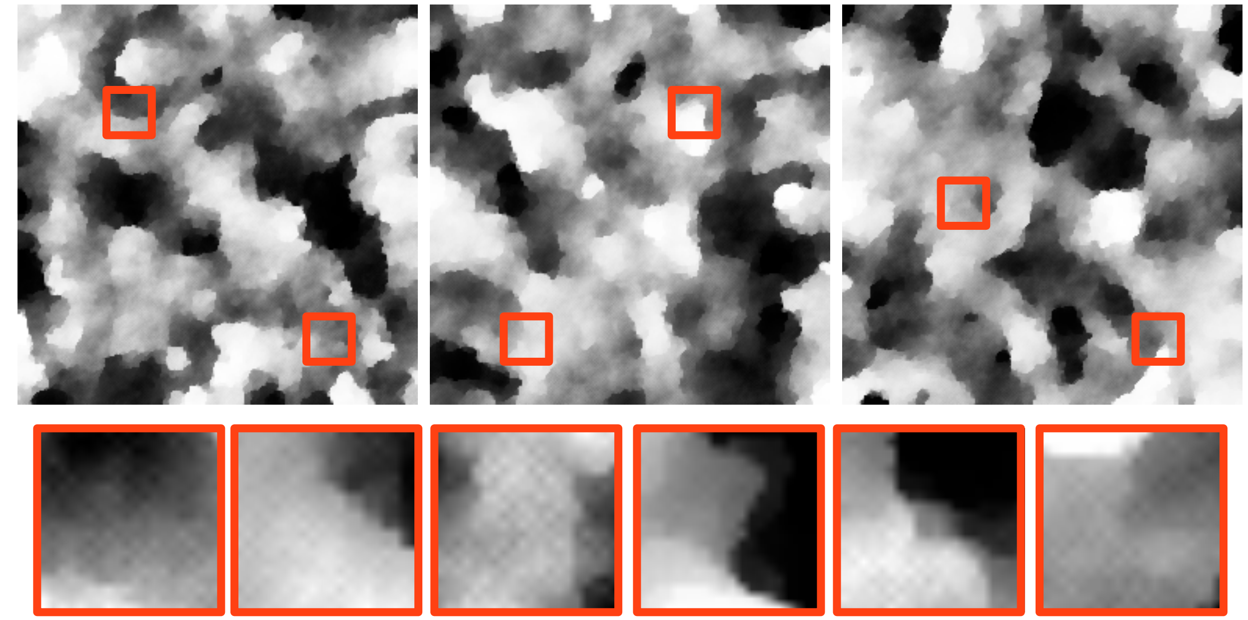

Model: bounded variation image.
Patches: finite length level sets.

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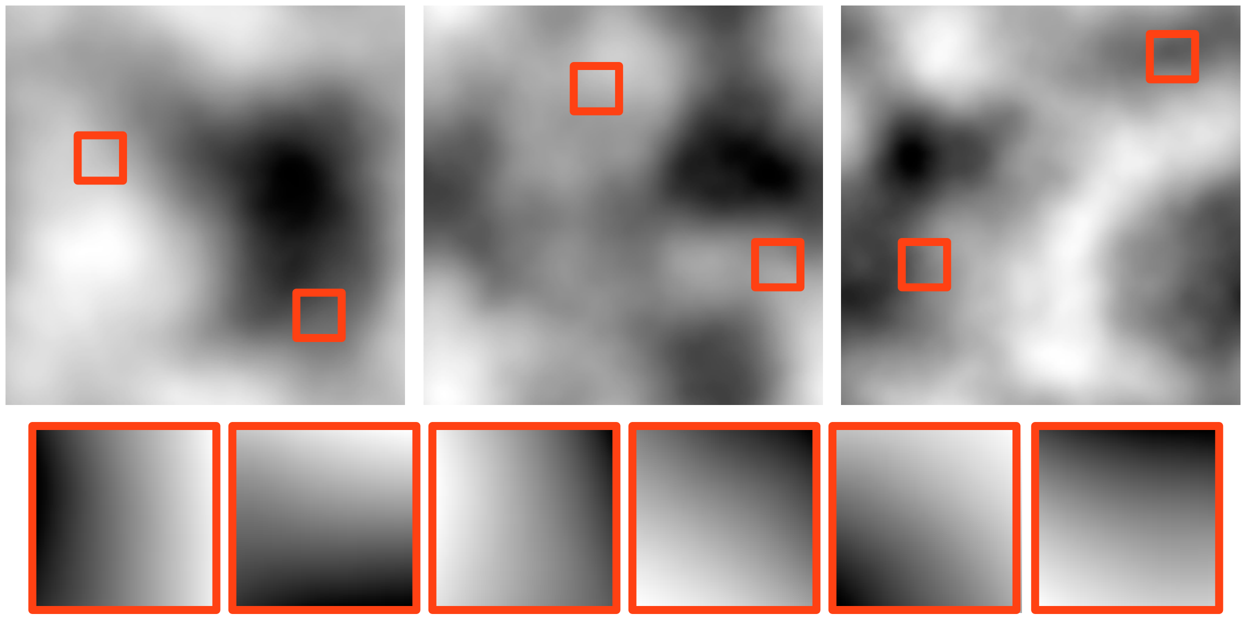

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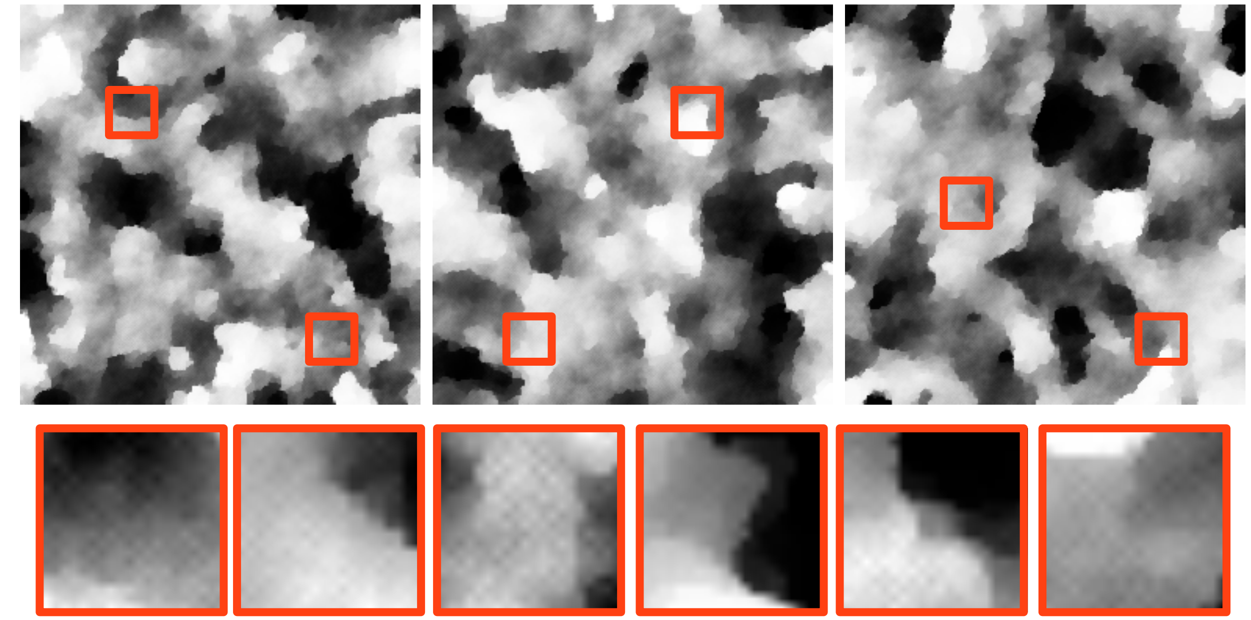

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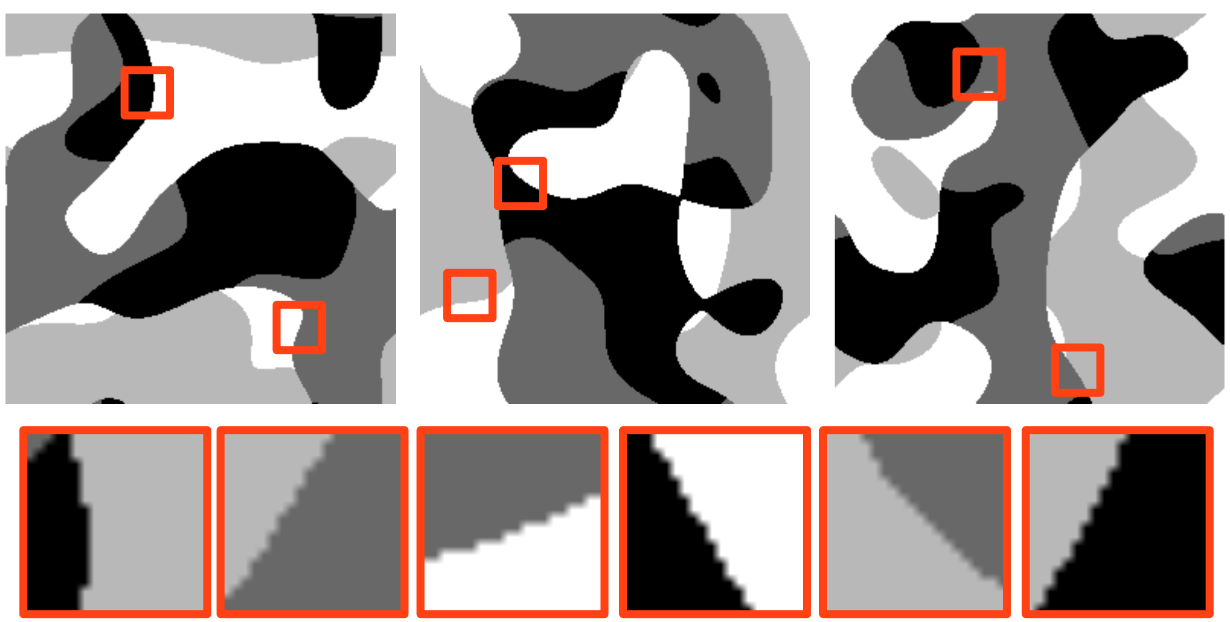
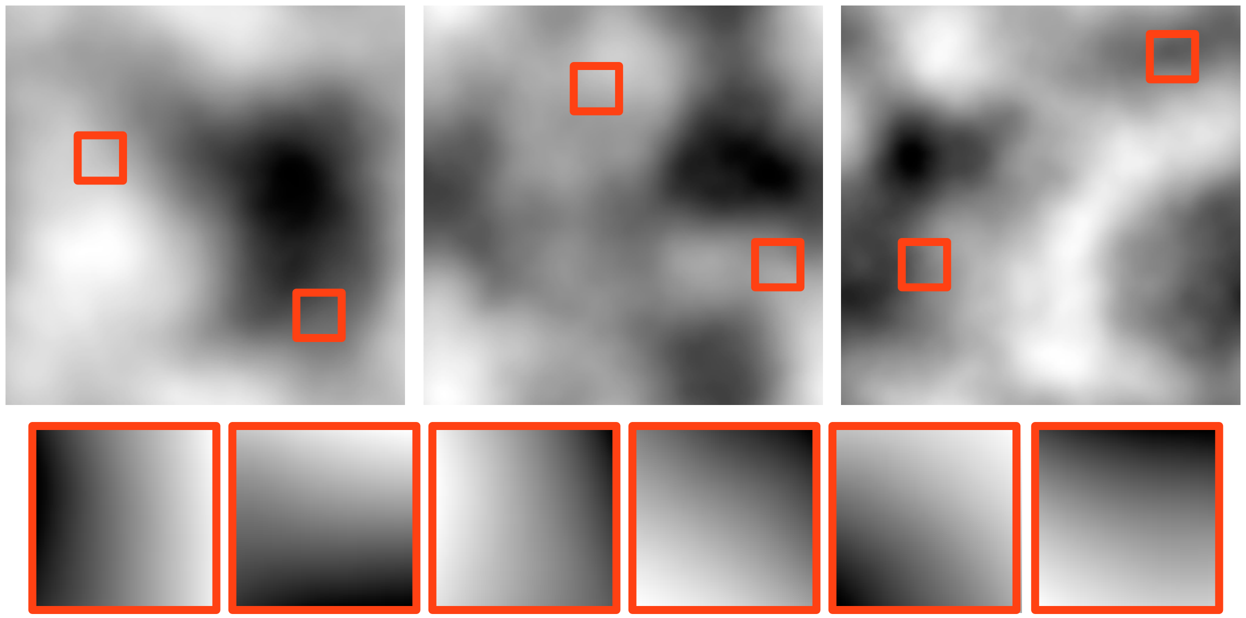


Model: cartoon image.
Patches: binary straight edge.

The Local Geometry of Images



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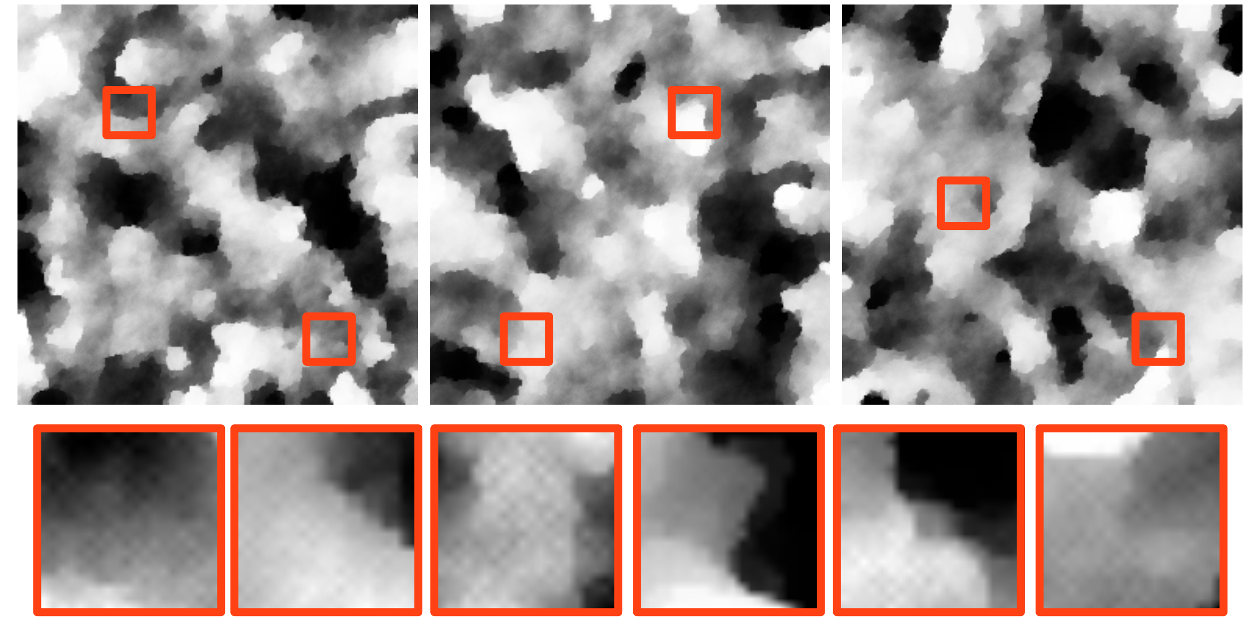

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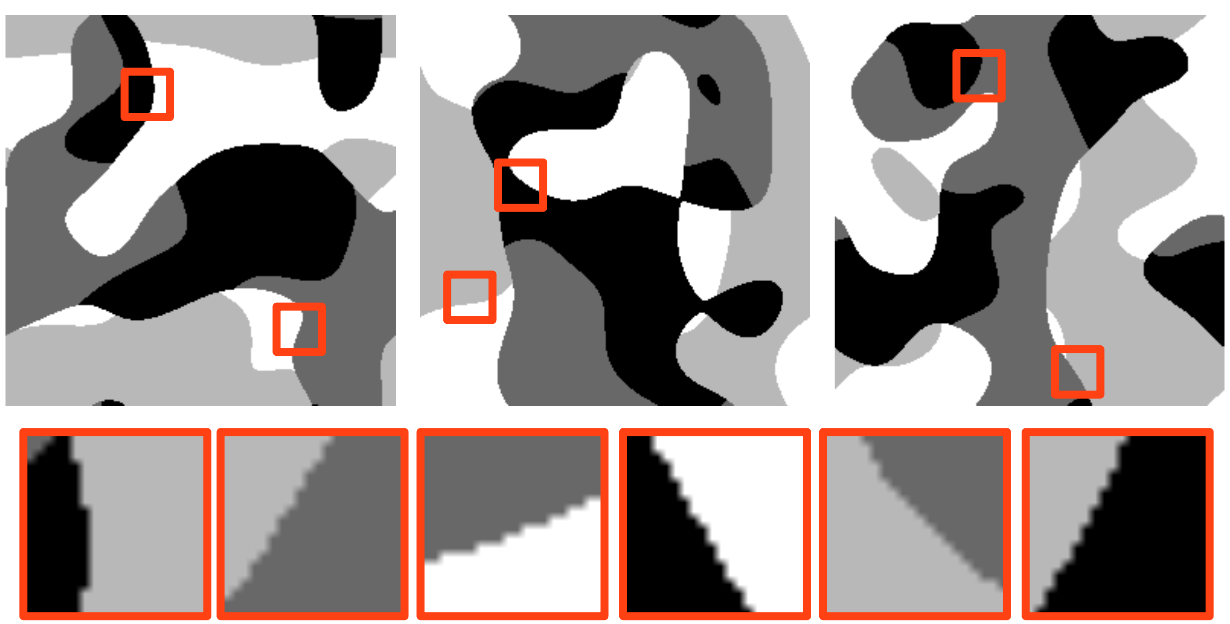

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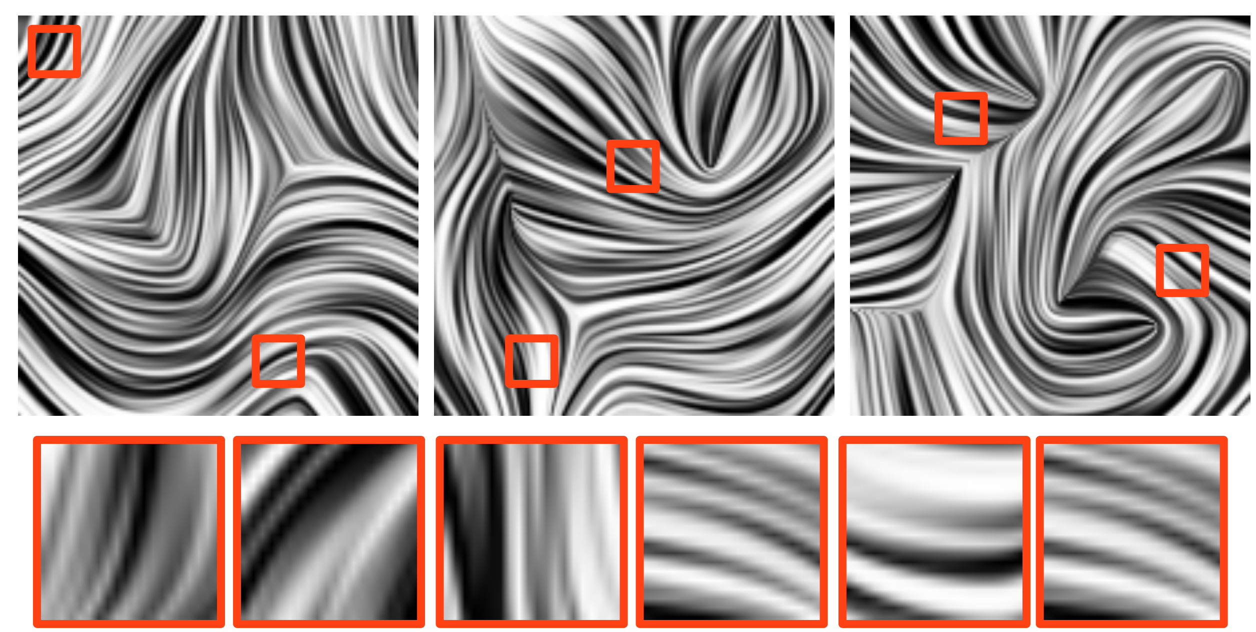
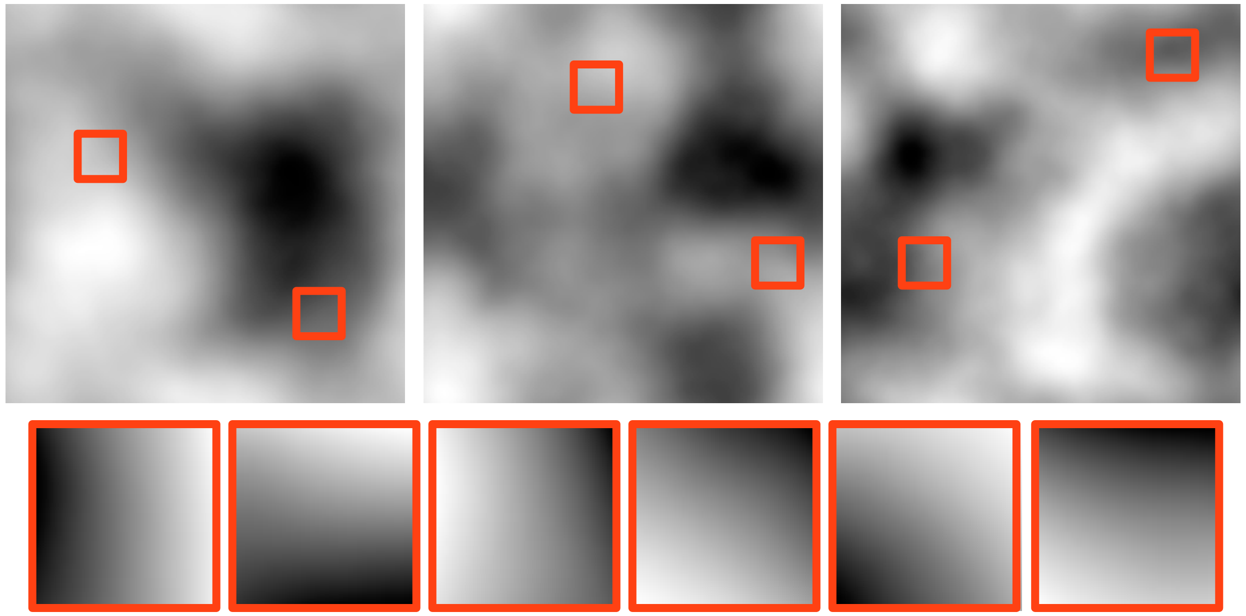


Model: locally parallel texture.
Patches: directional oscillations.

The Local Geometry of Images



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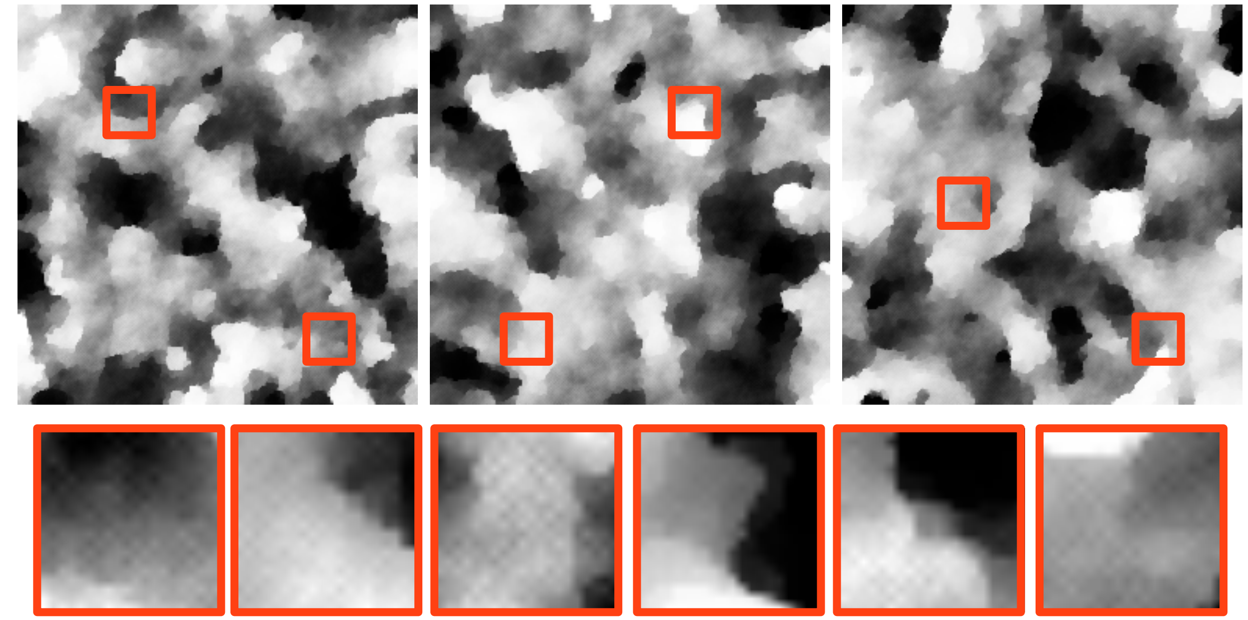

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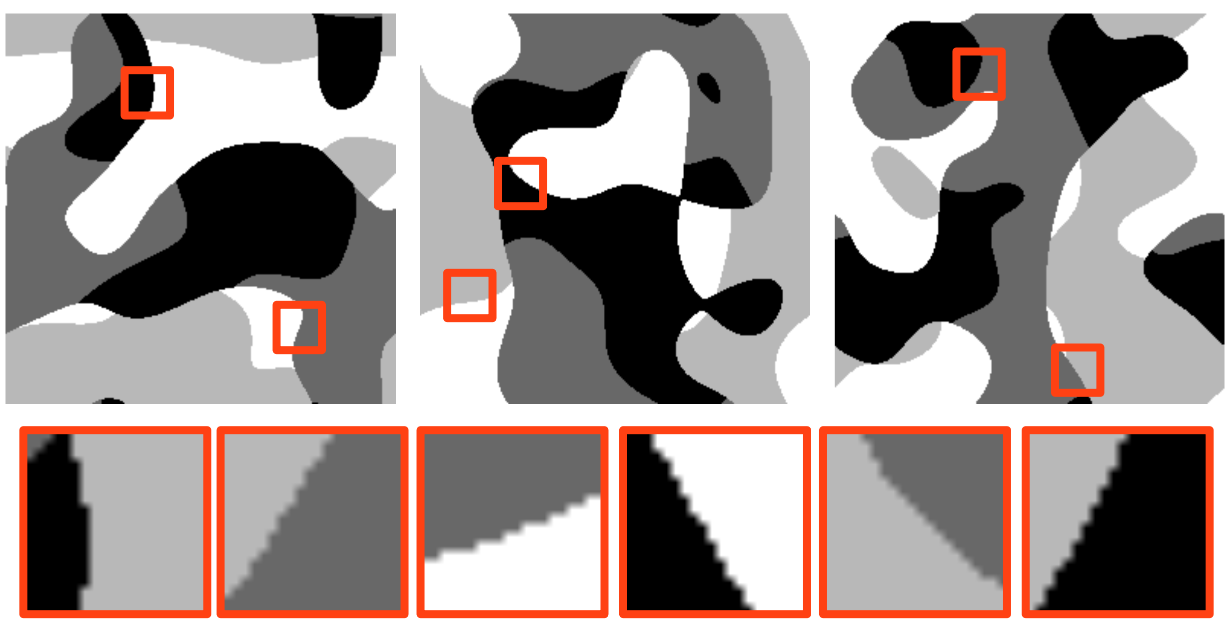

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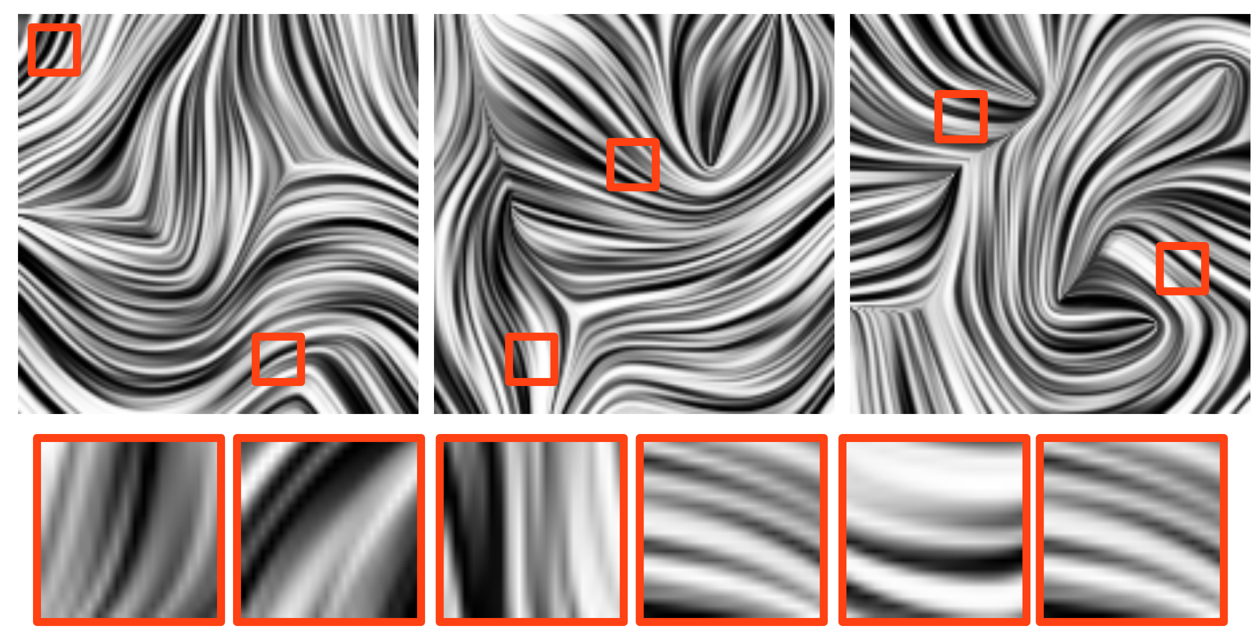


Model: locally parallel texture.
Patches: directional oscillations.

$\longrightarrow$ represent patches with a small number of parameters.

Overview

- Manifolds: Image Libraries vs. Patches
- Examples of Patch Manifolds
- Manifold Energies for Inverse Problems
- Non-adaptive Manifold Models
- Adaptive Manifold Models ⟵ Joint work with Sebastien Bougleux & Laurent Cohen

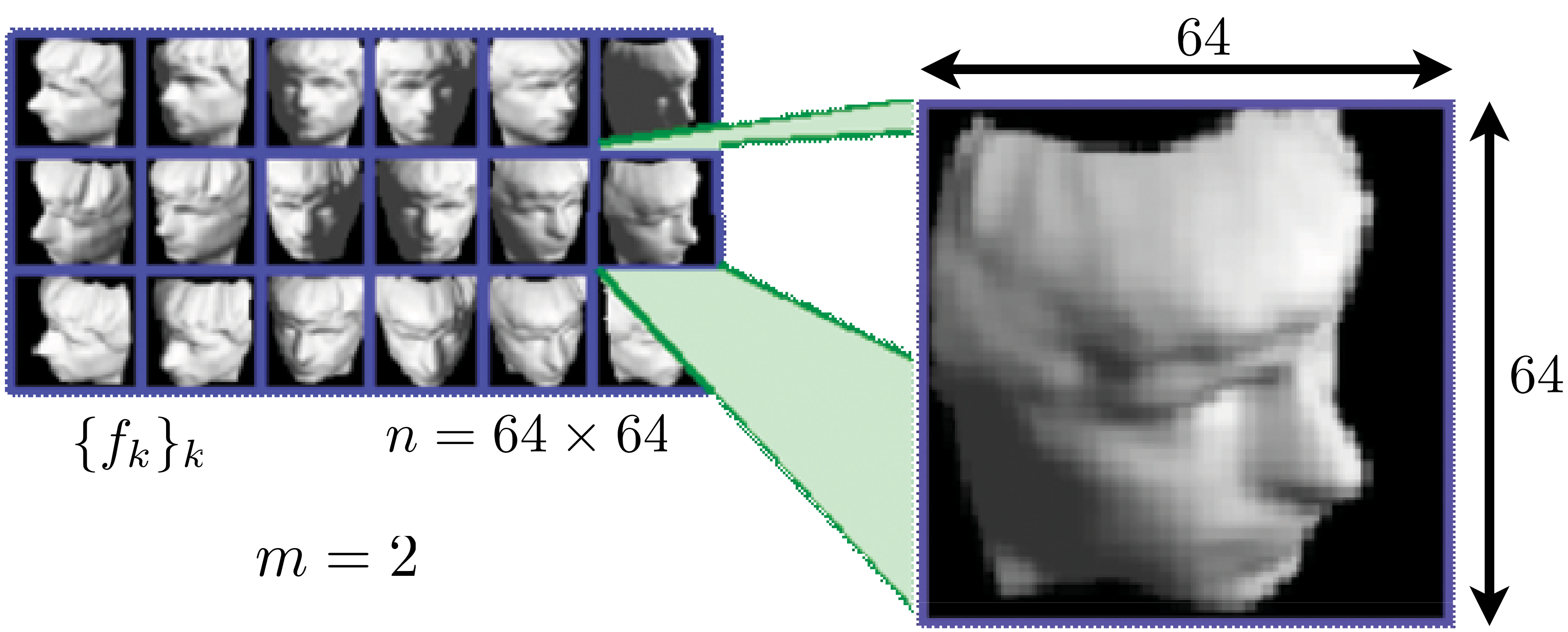
Manifold of Images Ensembles

Library of images of n pixels: $\{f_k\}_k \subset \mathbb{R}^n$.

Parameterized by a small number $m \ll n$ of parameters

Example: V/H rotation $\theta_v, \theta_h \quad \Longrightarrow \quad f_k(x) = f_0(R_{\theta_h,\theta_v} x)$.

Hypothesis: $\{f_k\} \subset \mathcal{M} \subset \mathbb{R}^n$ smooth manifold of dimension m.



$$\varphi \begin{cases} S^1 \times S^1 & \longrightarrow & \mathcal{M} \\ (\theta_h, \theta_v) & \longmapsto & f_0(R_{\theta_h,\theta_v} x) \end{cases}$$

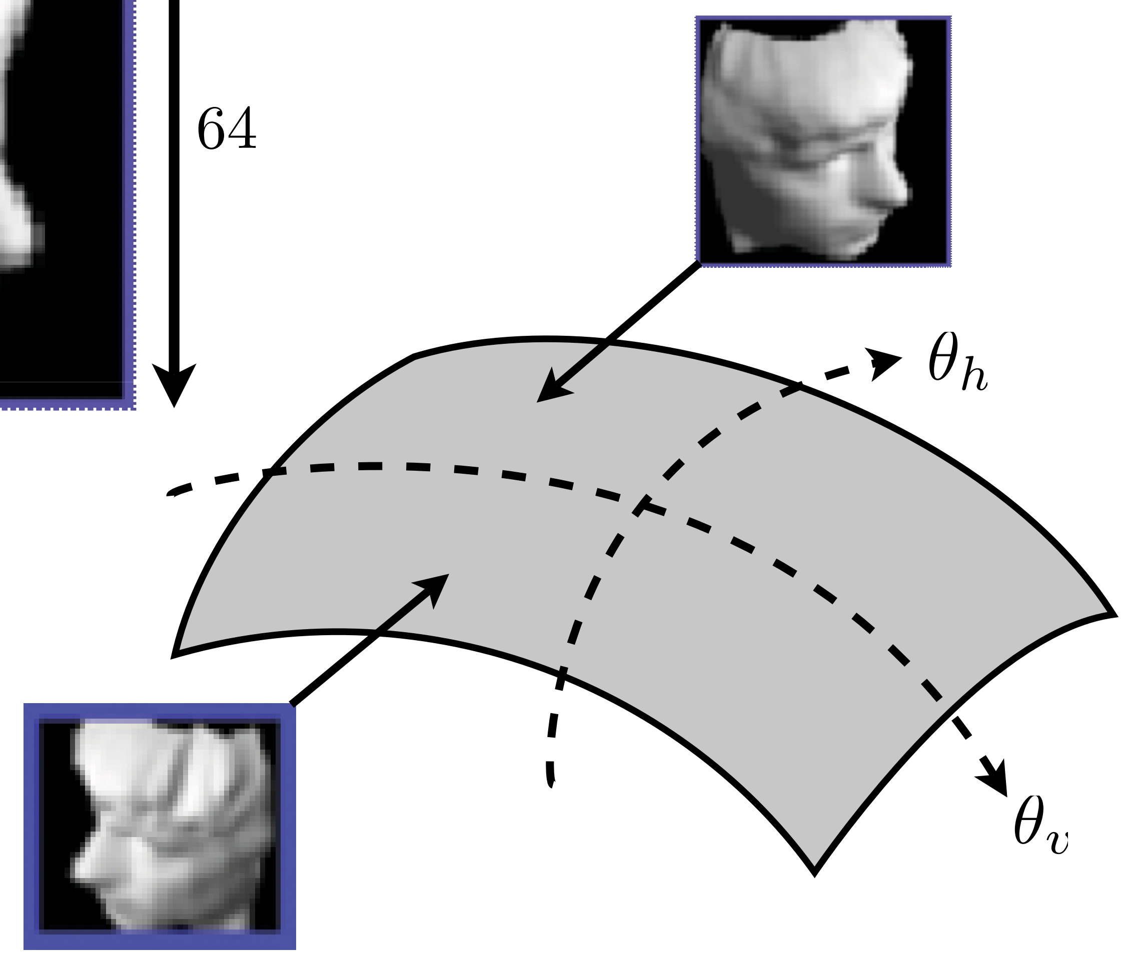


Image Models and Patch Manifolds

Patch extracted from f at location $x \in [0,1]^2$:

$$\forall\, |t| \leqslant \tau/2, \quad p_x(f)(t) = f(x+t)$$

f

$\{p_x(f)\}_x$

Image Models and Patch Manifolds

Patch extracted from f at location $x \in [0,1]^2$:

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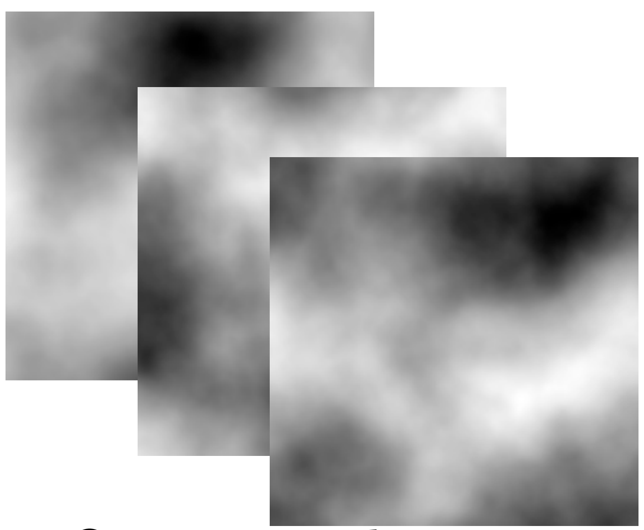
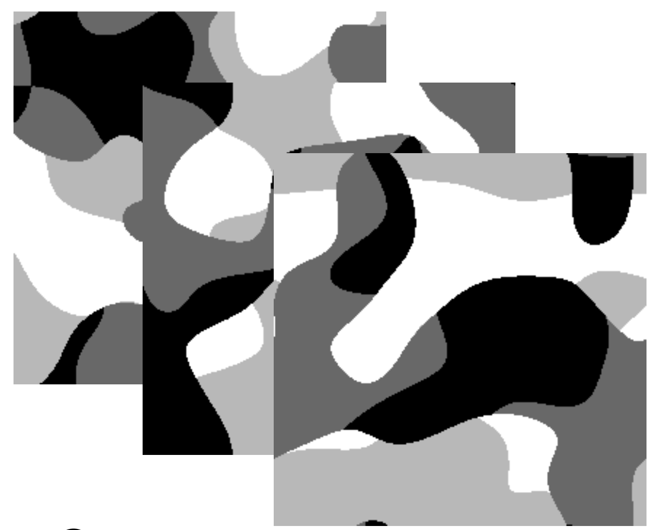
Image model: exploit an image ensemble $\Theta \subset \mathrm{L}^2([0,1]^d)$,



Θ =smooth images



Θ =cartoon images

Θ =oscilating textures

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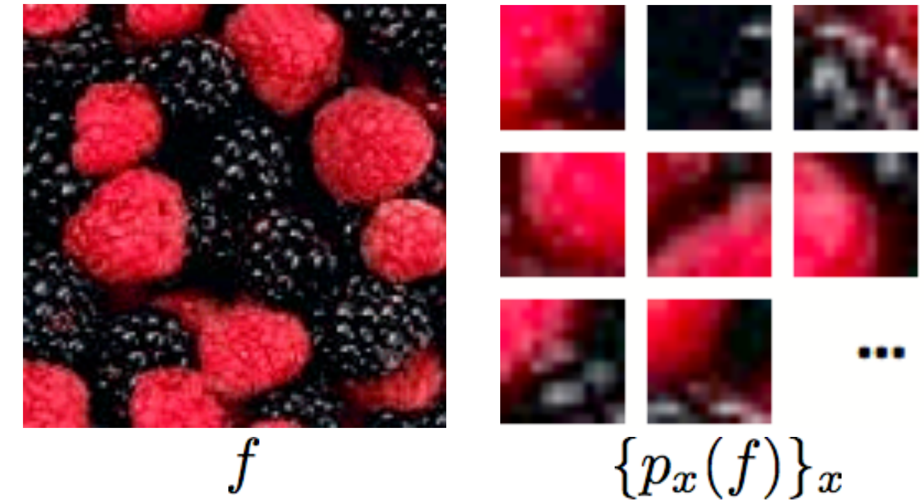

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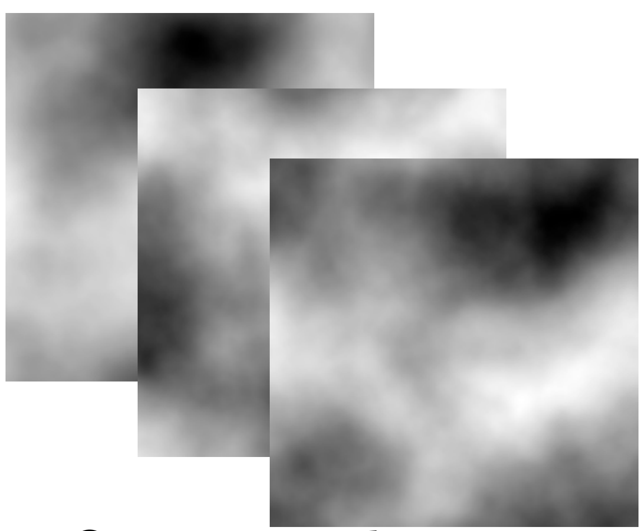

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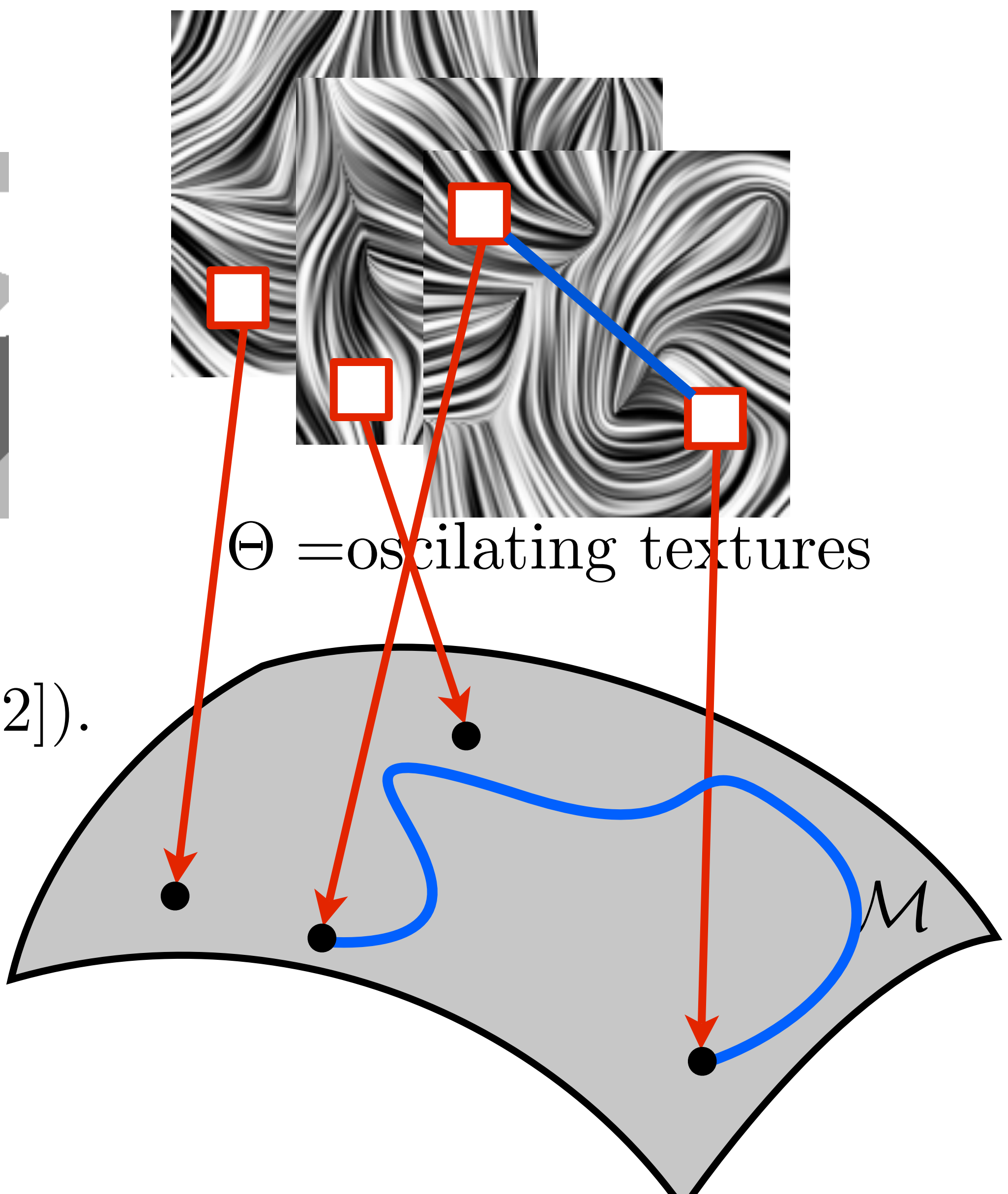


Θ =oscilating textures

$$\mathcal{M} = \{p_x(g) \setminus x \in [0,1]^d \quad \text{and} \quad g \in \Theta\} \subset \mathrm{L}^2([-\tau/2, \tau/2]).$$

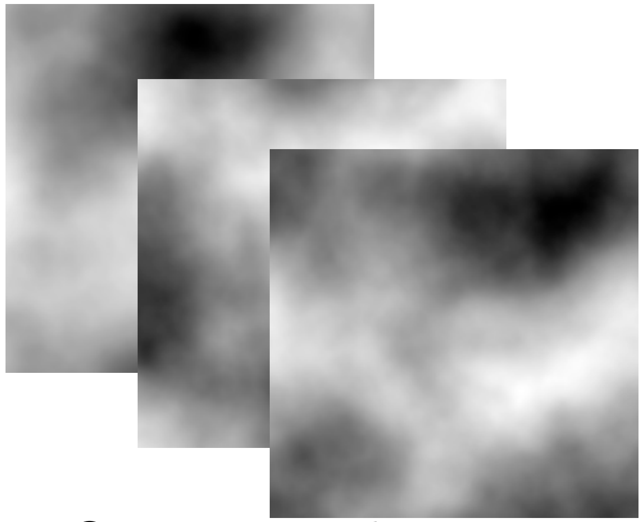
What is the topology / geometry of $\mathcal{M}$?

Use it for synthesis of geometrical images.

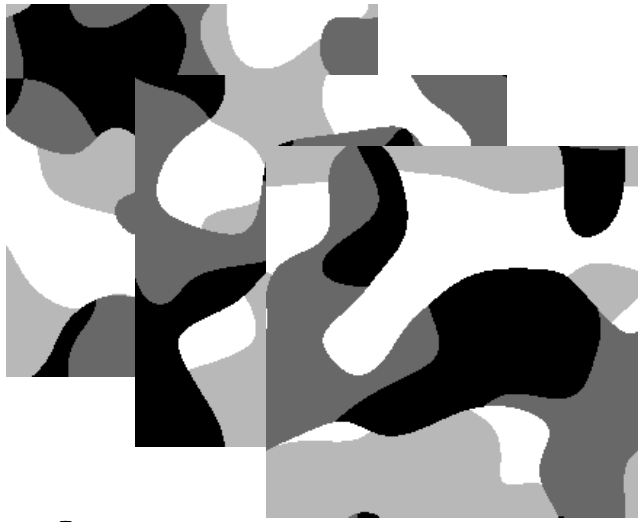
Non-adaptive setting: $\mathcal{M}$ is fixed.

Image Models and Patch Manifolds

Non-adaptive processing: exploit a signal ensemble $\Theta \subset \mathrm{L}^2([0,1]^d)$,



$\Theta =$smooth images



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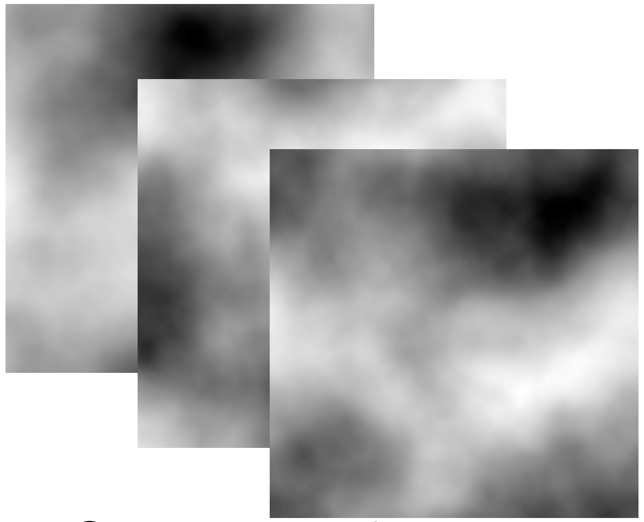

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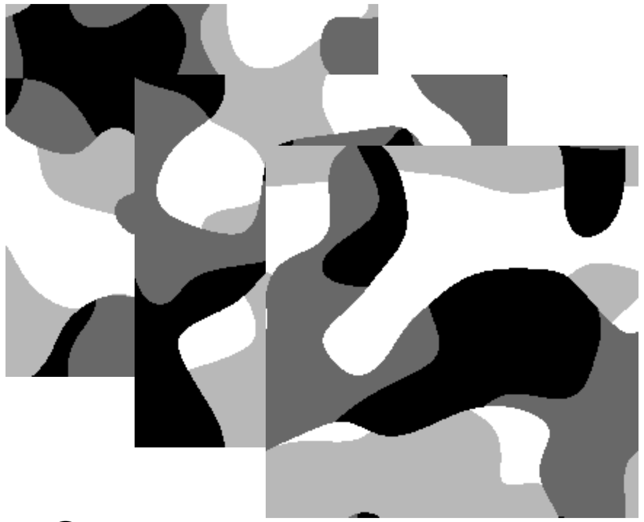

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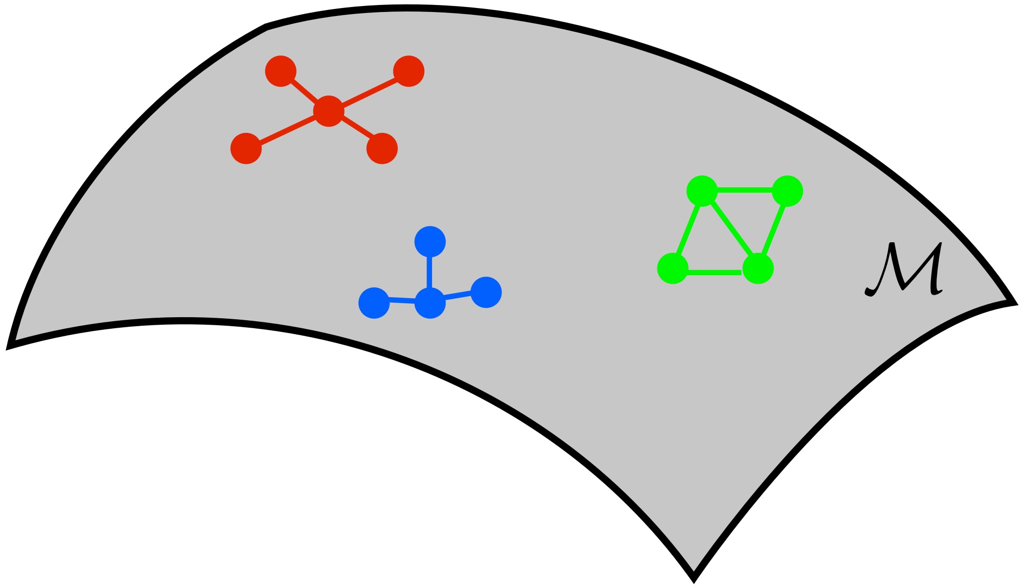
Adaptive processing: $\mathcal{M} = \mathcal{M}_f$ is estimated from some $f \in \mathrm{L}^2([0,1]^d)$

Estimating $\mathcal{M}_f \quad \Longleftrightarrow \quad$ estimating connexions between the points $\{p_x(f)\}_x$.



$\longrightarrow$ use $\mathcal{M}$ or $\mathcal{M}_f$ to regularize image processing problems.

Overview

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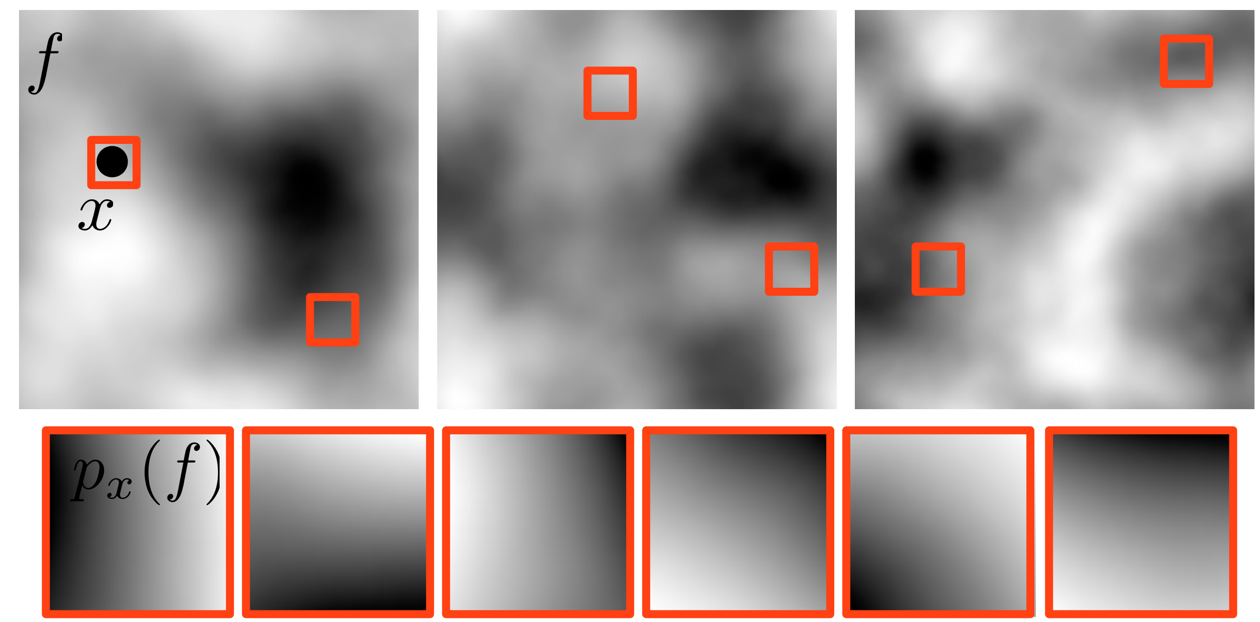
Manifold of Smooth Images

$$\Theta = \{ f \in \mathrm{C}^2 \setminus \|f\|_\infty \leqslant C_1, \|\nabla f\|_\infty \leqslant C_2 \}$$

Patch $\approx$ linear gradient of intensity.

$$p_x(f)(t) \approx a(x) + \langle b(x),\, t \rangle$$

where $\quad a(x) = f(x) \quad$ and $\quad b(x) = \nabla_x f$



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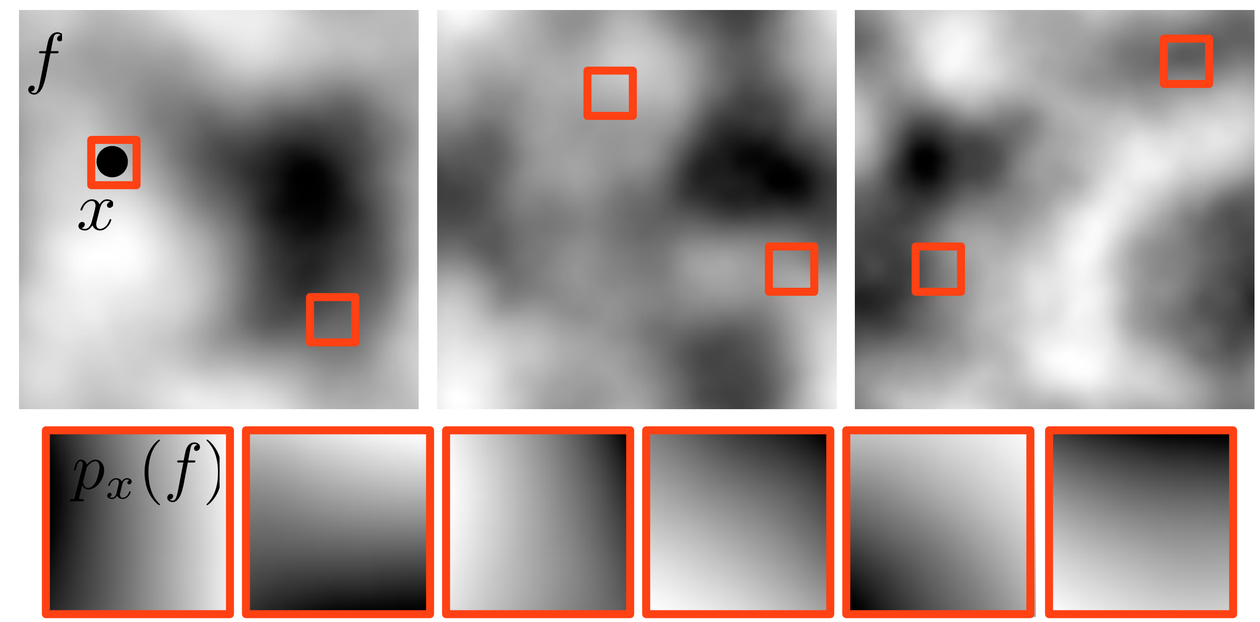

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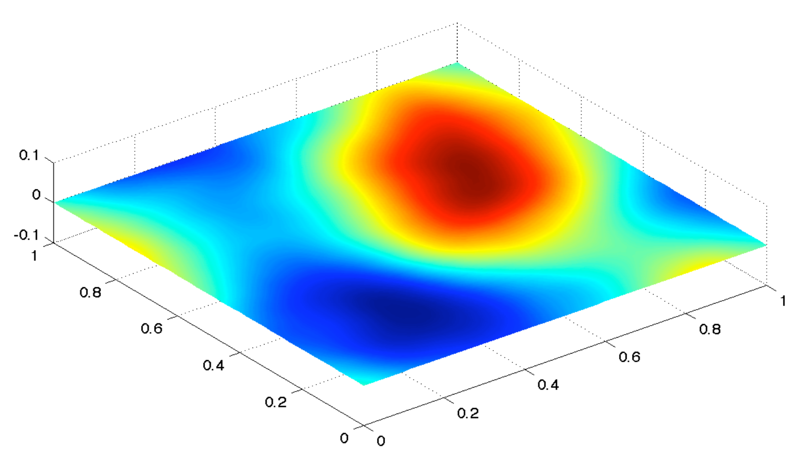
$$p_x(f)(t) \approx a(x) + \langle b(x),\, t \rangle$$

where $\quad a(x) = f(x) \quad$ and $\quad b(x) = \nabla_x f$

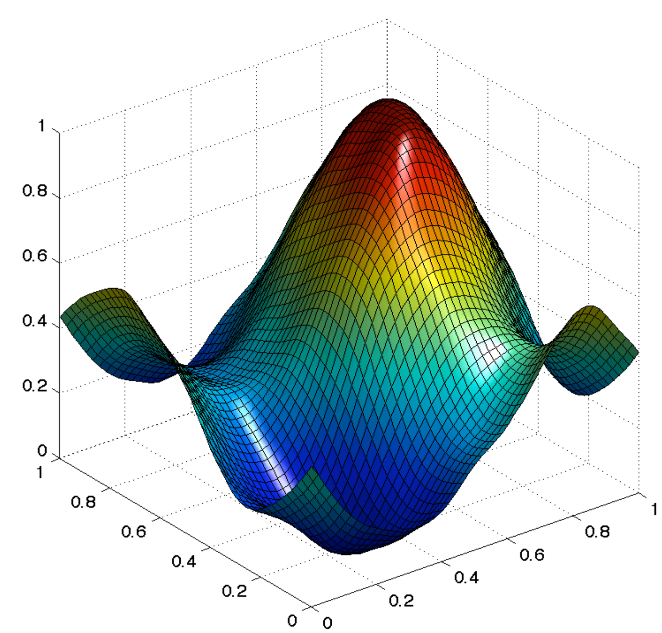
Manifold of affine patches: $\quad \mathcal{M} = \{ t \mapsto a + \langle b,\, t \rangle \setminus |a| \leqslant C_1, |b| \leqslant C_2 \}$

$\mathcal{M} \simeq [-C_1, C_1] \times [-C_2, C_2] \times [-C_2, C_2]$ "3D cube"

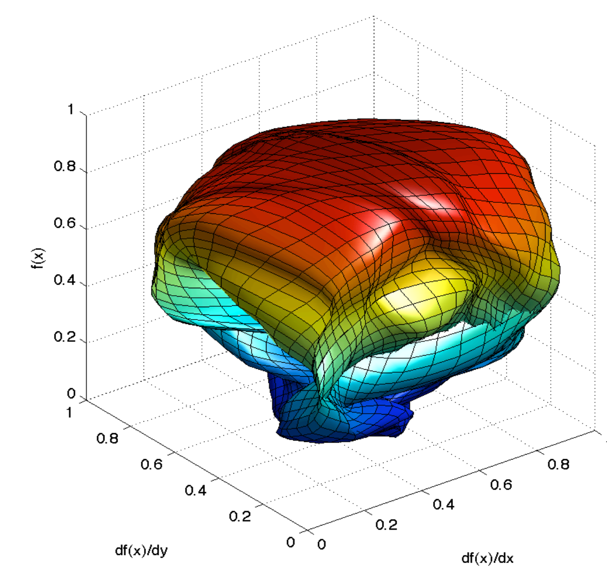
$\mathcal{M}$ is a flat (Euclidean) manifold.



$x \mapsto f(x)$



$x \mapsto (x, f(x))$



$x \mapsto p_x(f)$

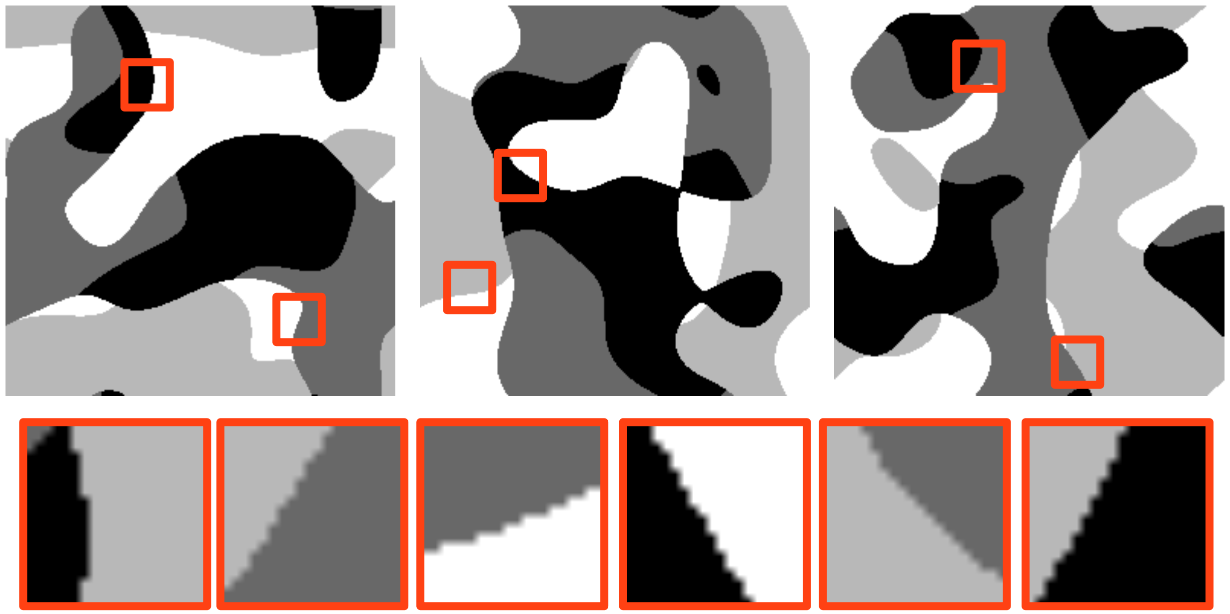
Manifold of Cartoon Images

$$\Theta_{\text{cartoon}} = \{ f \setminus f \text{ is } \mathrm{C}^\alpha \text{ outside } \mathrm{C}^\alpha \text{ curves} \}\,.$$

$$\Theta = \{ f = 1_\Omega \setminus \partial\Omega \text{ a } \mathrm{C}^\alpha \text{ curve } \}\,.$$

$$p_x(f)(t) = P_{\theta(x),\delta(x)}(t)$$

$$\text{where} \quad \begin{cases} P_{\theta,\delta}(t) = P_{0,0}(R_\theta(t-\delta)) \\ P_{0,0}(x) = 1_{x_1 \geqslant 0}(x) \end{cases}$$



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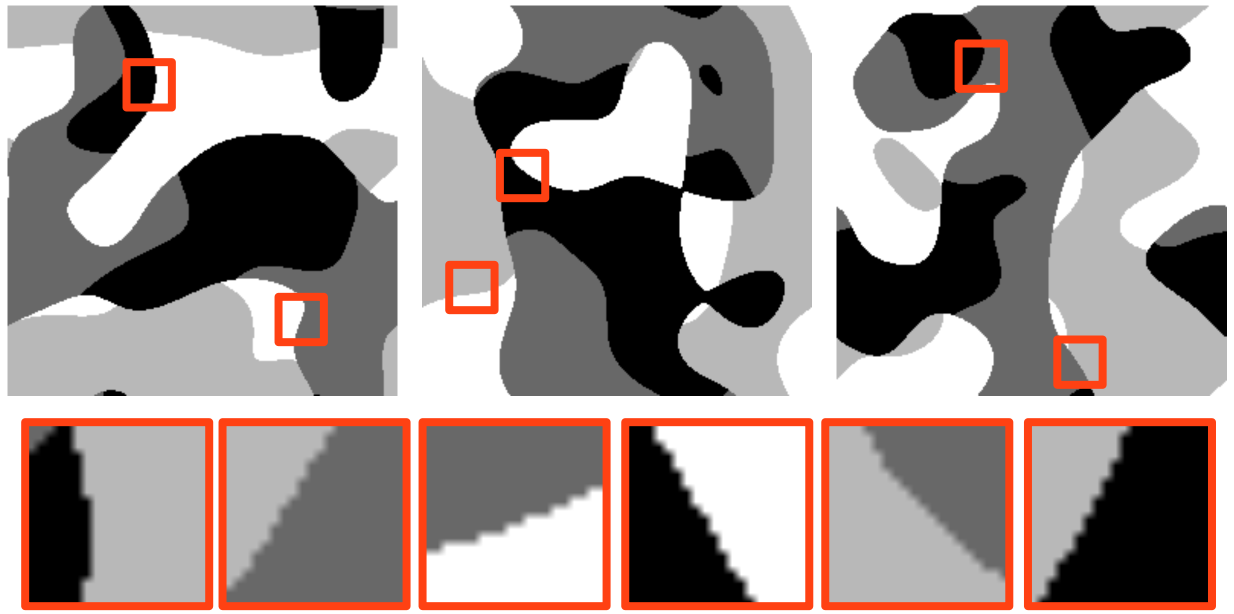

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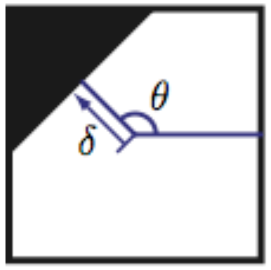
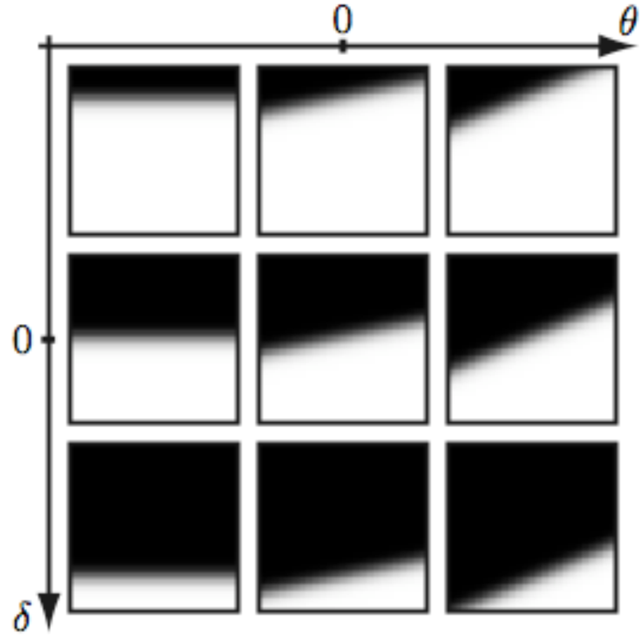
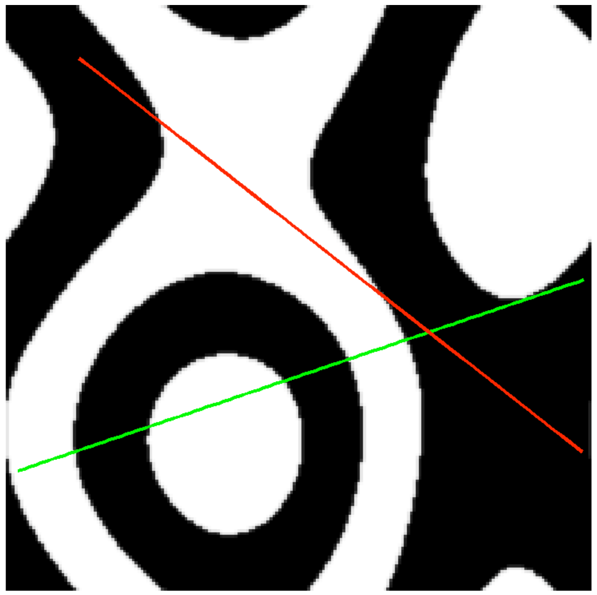
Manifold of binary edges:

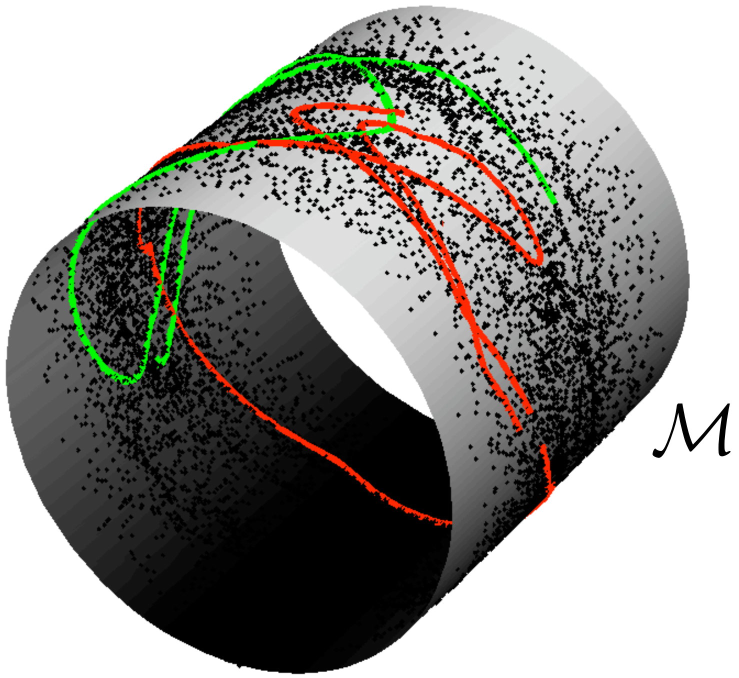




$$\mathcal{M} = \{P_{\theta,\delta} \setminus \theta \in [0, 2\pi), \delta \in \mathbb{R}\}$$

$$\mathcal{M} \simeq S^1 \times \mathbb{R} \qquad \text{(cylinder)}$$



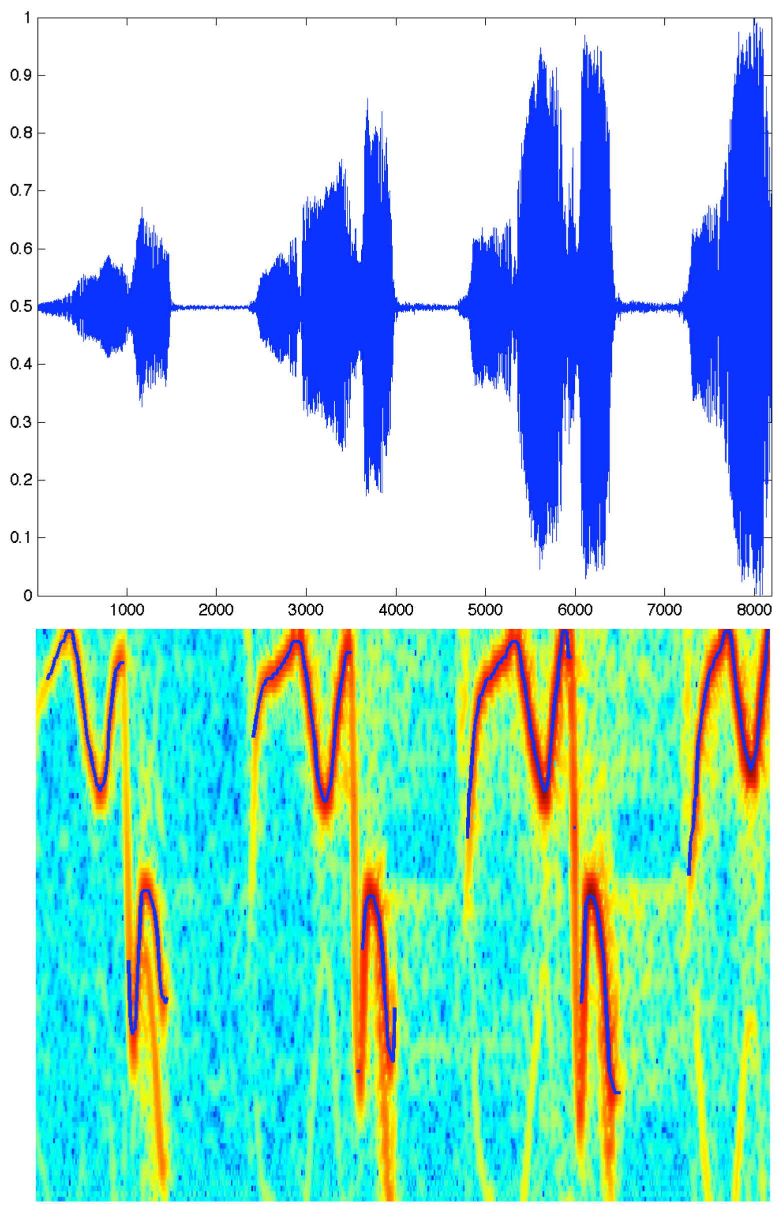


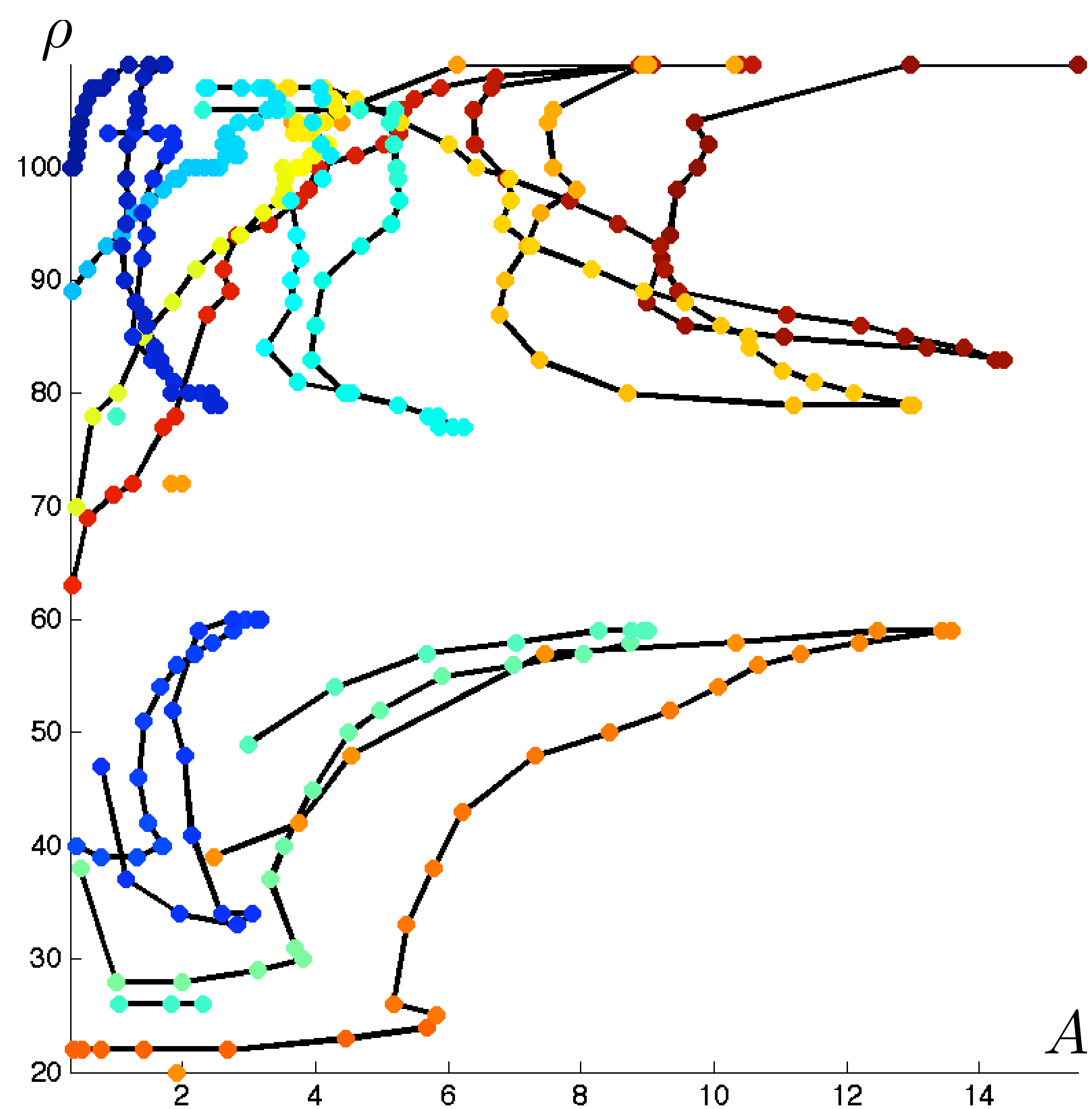
Manifold of Locally Stationary Sounds

$$\Theta \overset{\text{def.}}{=} \{x \mapsto f(x) = A(x)\cos(\Psi(x)) \setminus \|A'\|_\infty \leqslant A_{\max} \quad \text{and} \quad \|\Psi''\|_\infty \leqslant \Psi_{\max}.\}$$

$$\mathcal{M} = \left\{ P_{(A,\rho,\delta)} \setminus A \geqslant 0 \quad \text{and} \quad \rho \geqslant 0 \quad \text{and} \quad \delta \in \mathrm{S}^1 \right\}$$

where $\quad P_{(A,\rho,\delta)}(x) \overset{\text{def.}}{=} A\cos(\rho x + \delta).$





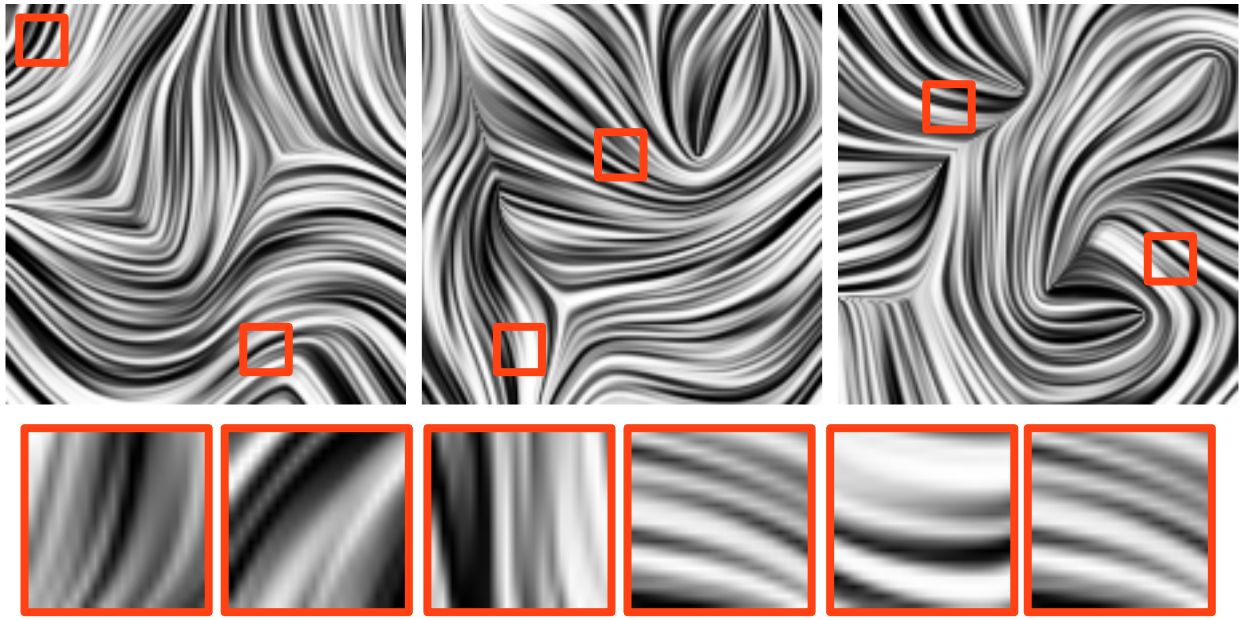
Manifold of Locally Parallel Textures

$$f(x) = A(x)\cos(\Phi(x))$$

Phase Φ slowly varying.

Orientation: $\nabla_x \Phi$

Amplitude: $A(x)$



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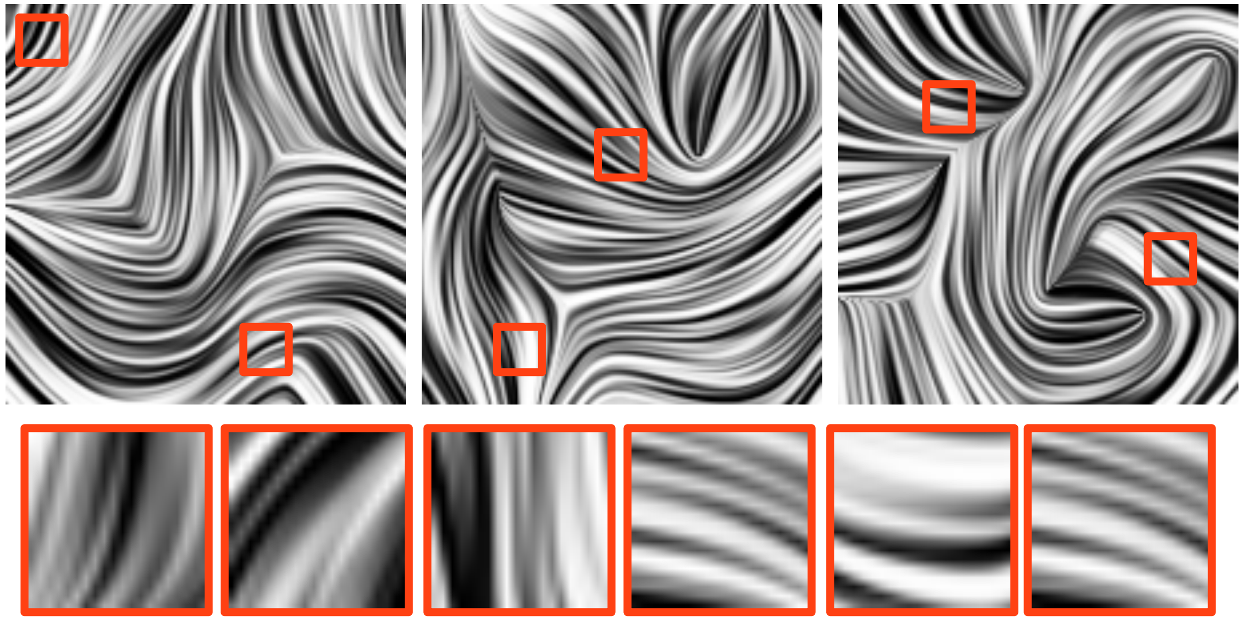


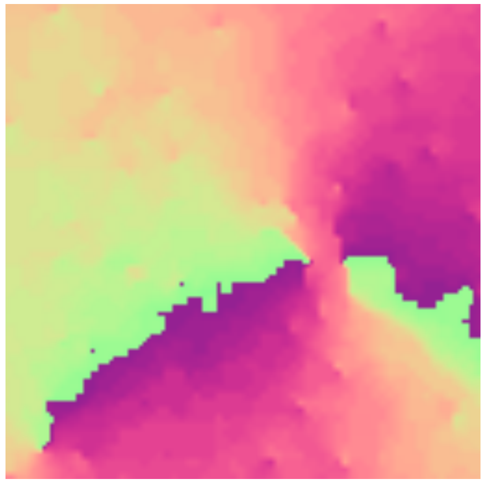
$$p_x(f) \approx A(x) P_{\rho(x),\theta(x),\delta(x)} \quad \text{where} \quad P_{\rho,\theta,\delta}(t) = \cos(\rho\langle t,\, \theta\rangle + \delta)$$

$$\mathcal{M} = \{A P_{\rho,\theta,\delta} \setminus A \leqslant C_1,\ \rho \leqslant C_2\}$$

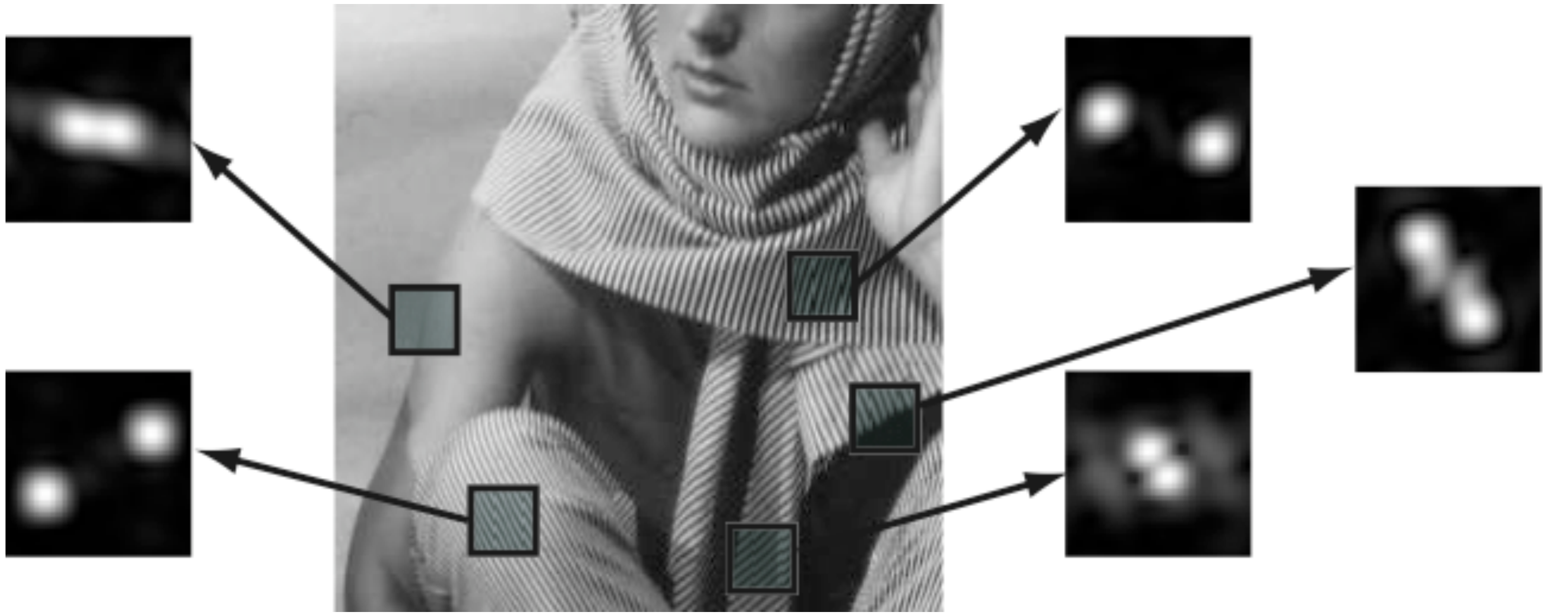
$$\mathcal{M} \simeq [0, C_1] \times [0, C_2] \times \tilde{S}^1 \times S^1 \qquad \theta \in \tilde{S}^1 \quad \text{(orientation but no direction)}$$

$(A(x), \rho(x), \theta(x), \delta(x))$ can be estimated with a local Fourier transform.

$f(x)$



$\theta(x)$



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Inverse Problems

Recovering f from q noisy measurements $y = \Phi f$+noise.

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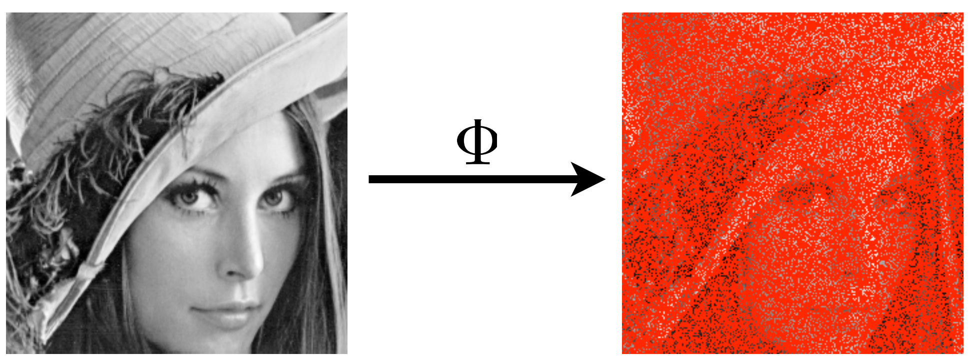

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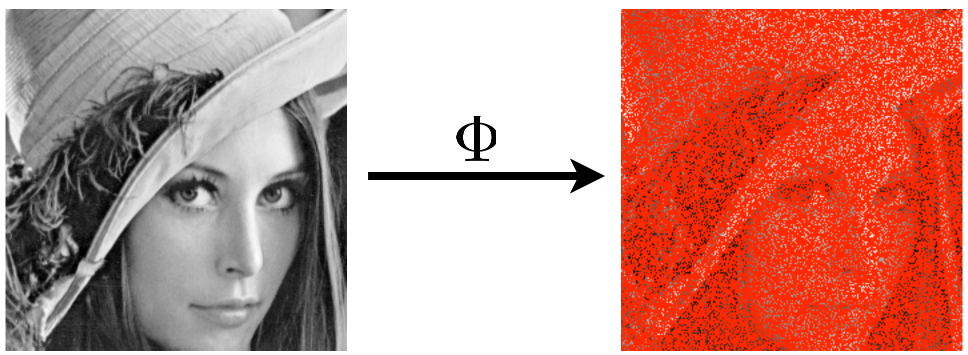

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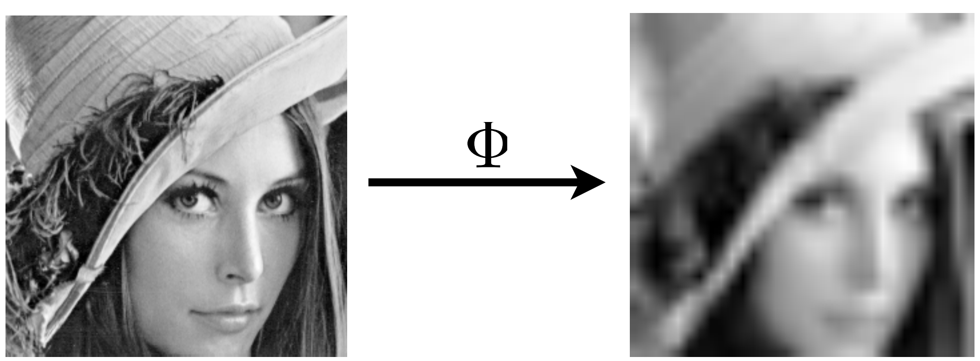

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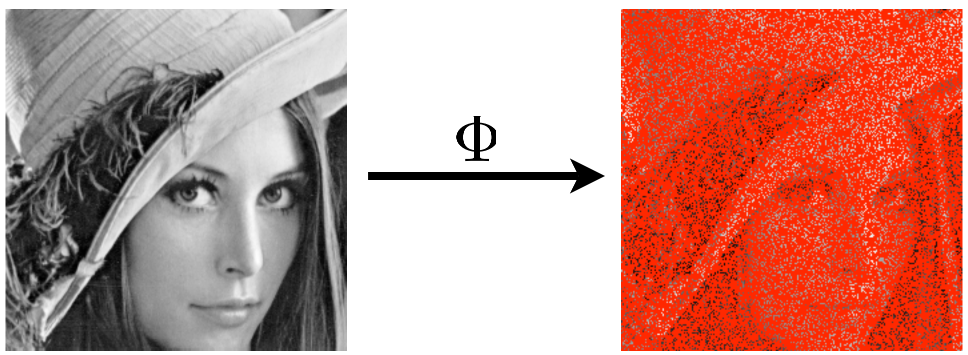

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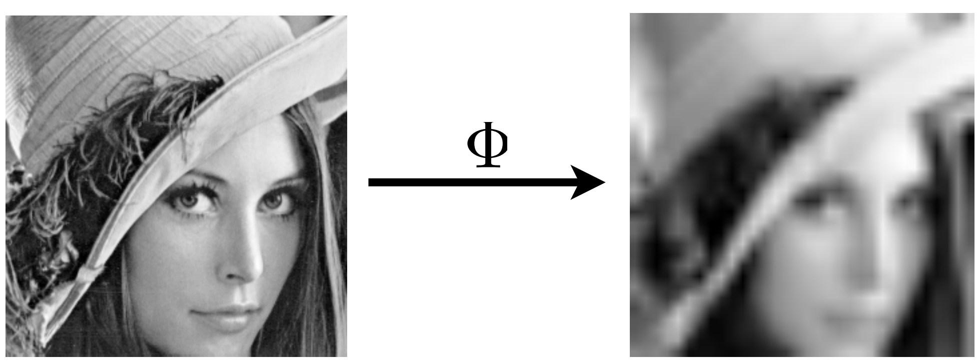

Compressed sampling: $(\Phi f)_i = \langle f, \varphi_i \rangle$, φ_i random vector.

$$\Phi f \in \mathbb{R}^q \text{ is a "compressed" version of } f.$$

CS theory [Candès, Tao, Donoho, 2004]:

f can be well recovered if f is sparse in an ortho-basis.

Inverse Problems Regularization

Prior model: energy $J(f)$ low for images of the model $f \in \Theta$.

Penalized inversion: $$f^\star = \underset{g}{\operatorname{argmin}} \frac{1}{2}\|\Phi g - y\|^2 + \lambda J(g)$$

λ should be adapted to the measurement noise $\|\Phi f - y\|$ and the prior $J(f)$

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Total variation regularization: $$J(f) = \int \|\nabla_x f\| \mathrm{d}x$$

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Manifold regularization:

Non-adaptive regularization: $\mathcal{M}$ fixed from a image model $f \in \Theta$.

$J_{\mathcal{M}}(g)$ measures how much patches $\mathcal{C}_f = (p_x(f))_x$ are close to $\mathcal{M}$.

Adaptive regularization: $\mathcal{M} = \mathcal{M}_f = (p_x(f))_x$ estimated from some f.

$J_w(g)$ measures the smoothness of g with respect to the geometry of $\mathcal{M}_f$.

w is a graph that represent the geometry of $\mathcal{M}_f$.

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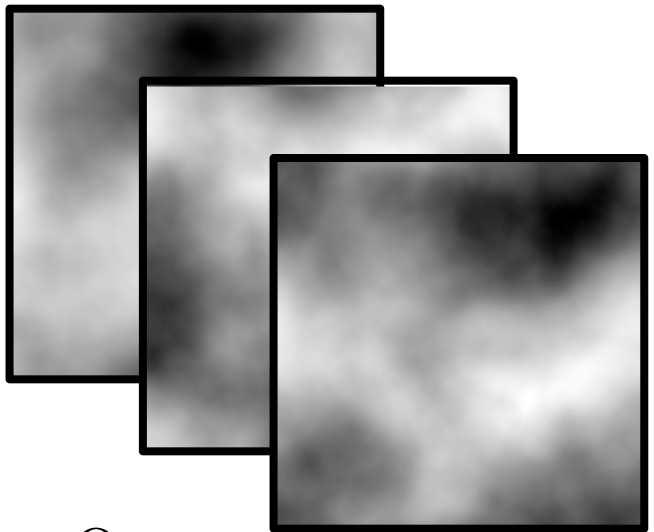
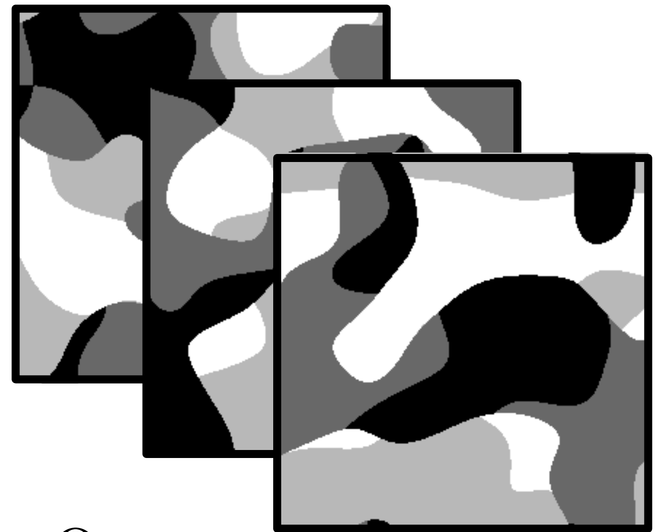
Non-adaptive Manifold Energies

Setting #1: manifold $\mathcal{M}$ defined by an a priori model $f \in \Theta$.

$$\mathcal{M} = \left\{ p_x(g) \setminus x \in [0,1]^d \quad \text{and} \quad g \in \Theta \right\} \subset \mathrm{L}^2([-\tau/2, \tau/2]).$$



Θ =smooth images



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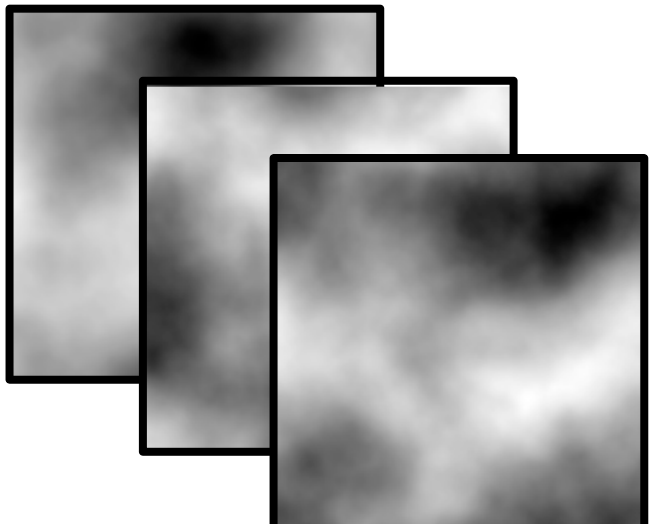

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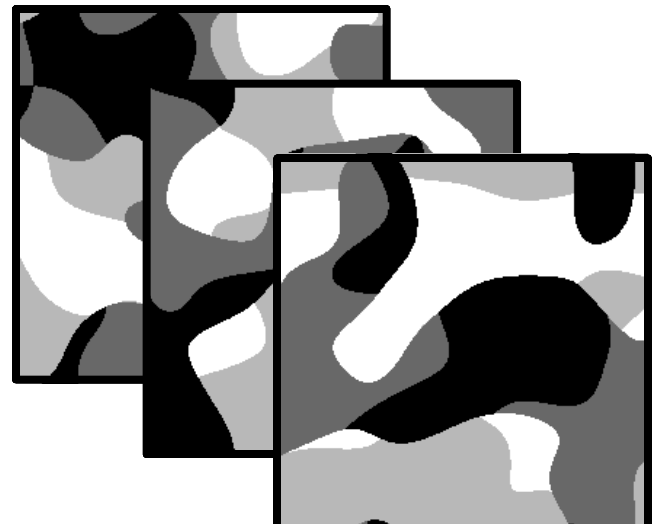

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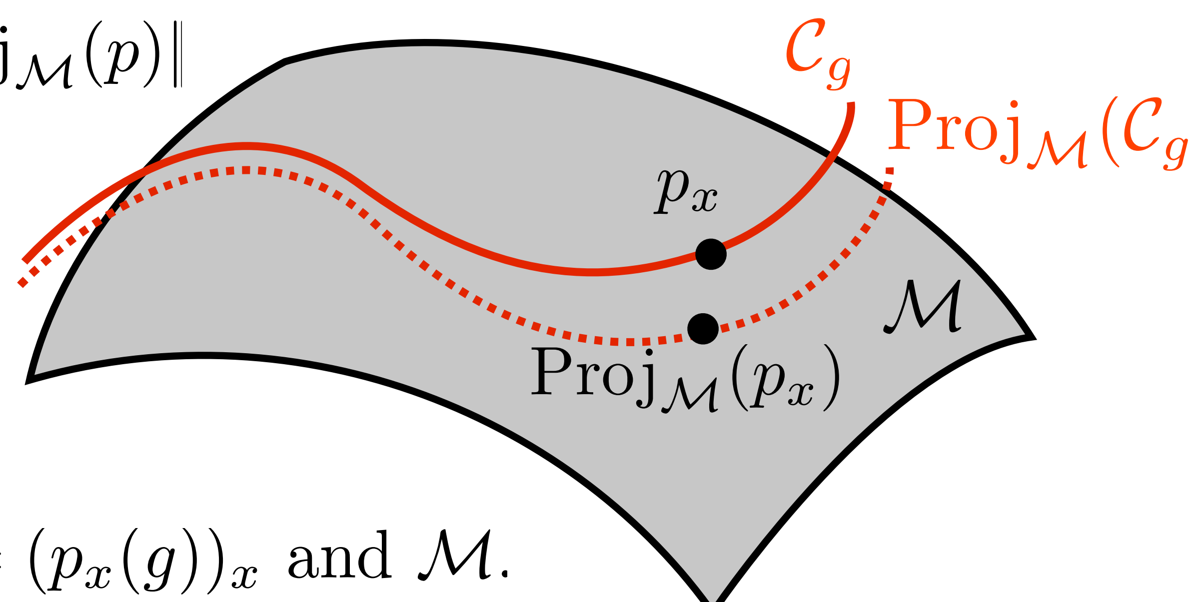
Non-adaptive manifold energy: $\quad J_{\mathcal{M}}(g) = \int \mathrm{dist}_{\mathcal{M}}(p_x(g))\mathrm{d}x$

where $\quad \mathrm{dist}_{\mathcal{M}}(p) = \min_{q \in \mathcal{M}} \|p - q\| = \|p - \mathrm{Proj}_{\mathcal{M}}(p)\|$



$\longrightarrow$ $J_{\mathcal{M}}(g)$ is small if $\ \forall\, x,\ p_x(g)$ is close to $\mathcal{M}$.

$\longrightarrow$ Average distance between the "surface" $\mathcal{C}_g = (p_x(g))_x$ and $\mathcal{M}$.

Non-adaptive Manifold Energy Minimization

Manifold energy: $J_{\mathcal{M}}(g) = \sum_x \mathrm{dist}_{\mathcal{M}}(p_x(g))$

Regularized inversion: $$f^\star = \underset{g}{\mathrm{argmin}}\ \|y - \Phi g\|^2 + \lambda J_{\mathcal{M}}(g)$$

$$\{f^\star, (p_x^\star)\} = \underset{g,(p_x)_x}{\mathrm{argmin}}\ \|y - \Phi g\|^2 + \lambda \sum_x \|p_x(g) - p_x\|^2$$

Include patches $(p_x)_x$

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Step #1: the image $f^\star$ is fixed, $\quad p_x^\star \leftarrow \mathrm{Proj}_{\mathcal{M}}(p_x(f^\star))$.

Step #2: $(p_x^\star)_x$ fixed, $f^\star$ computed by linear best fit

$$(\Phi^*\Phi + \lambda \mathrm{Id})\, f^\star = \Phi^* y + \lambda \bar{p}^\star$$

where $\quad \bar{p}^\star(x) = \frac{1}{\tau^2} \sum_{|x-y| \leqslant \tau/2} p_y^\star(x - y)$

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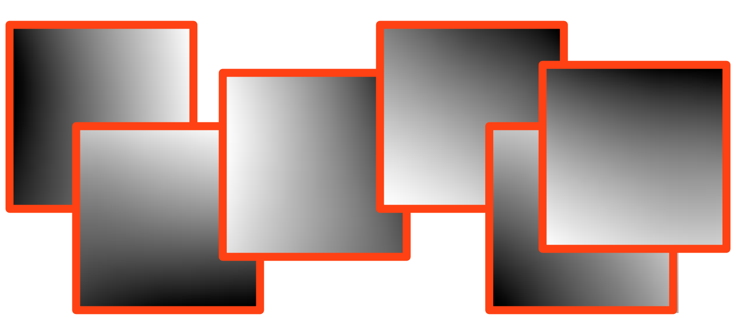
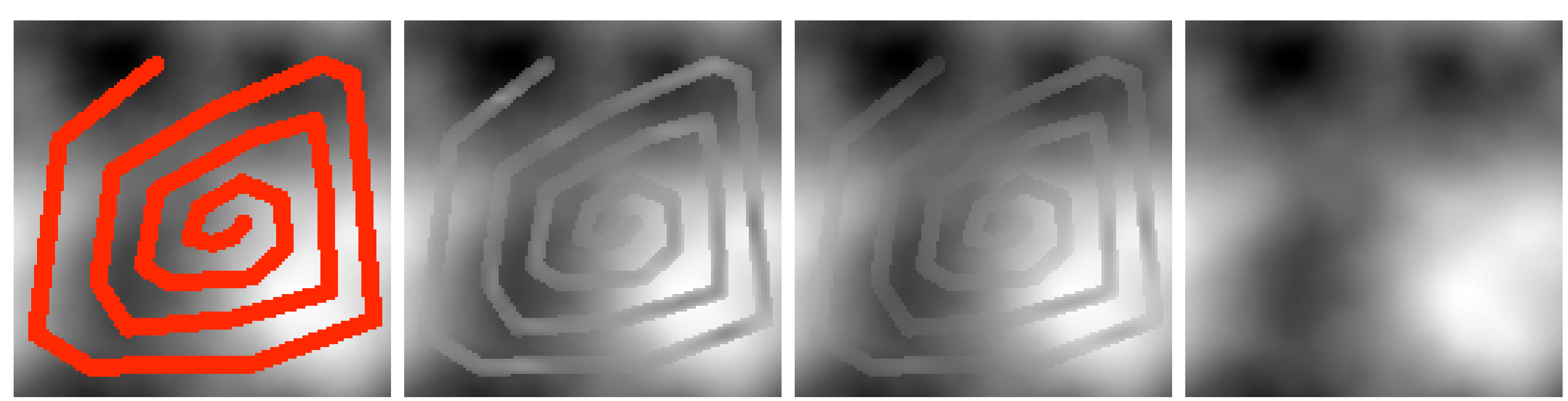
Manifold $\mathcal{M}$ of smooth patches.

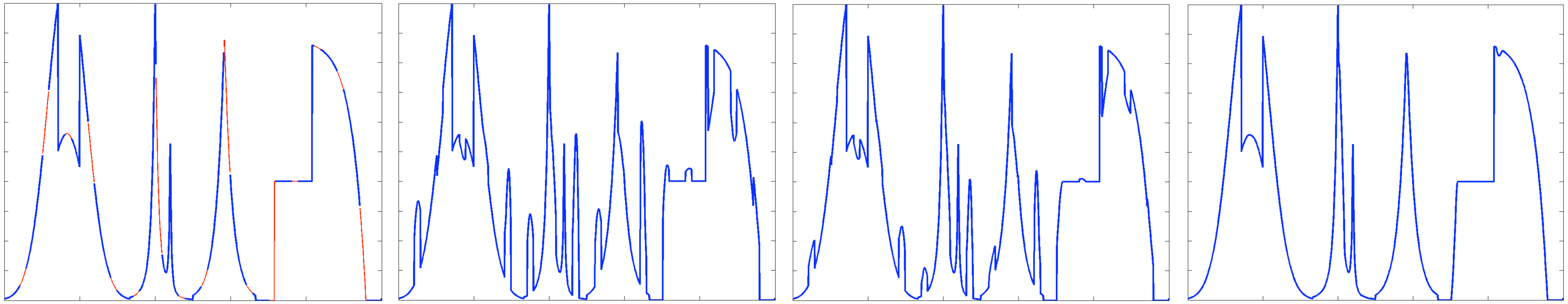
$\mathcal{M} =$ 



Measurements y Iter. #1   Iter. #3   Iter. #50

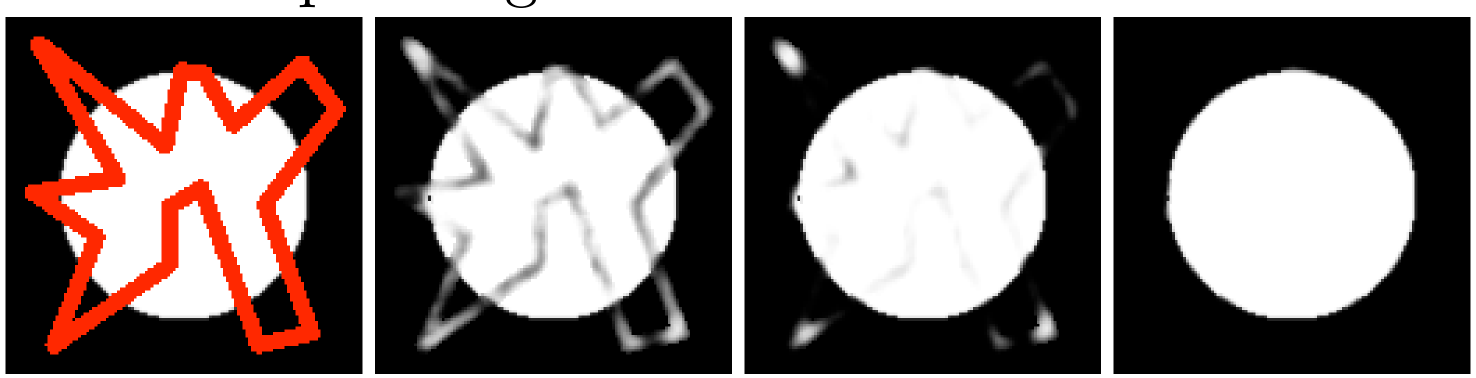
Cartoon Manifold Model

Inpainting of a 1D curve with manifold of piecewise linear patches:



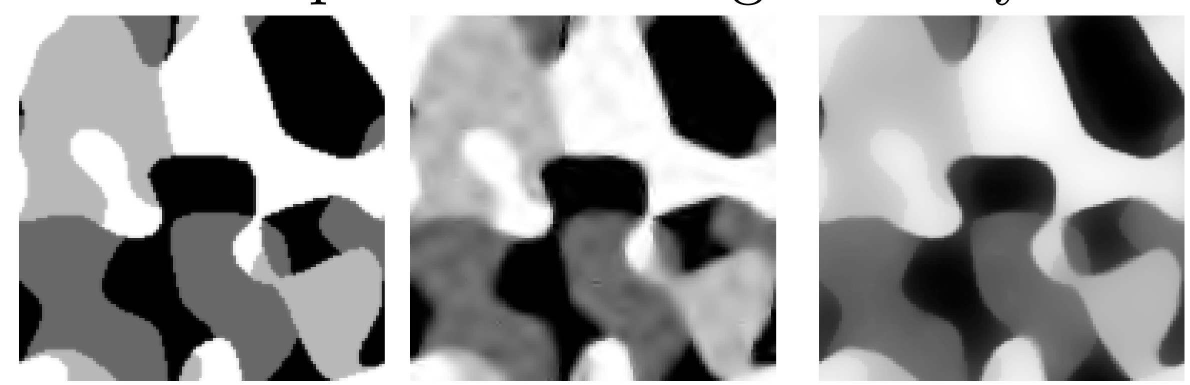
Measurements y | Iter. #1 | Iter. #3 | Iter. #50

Inpainting with cartoon manifold:



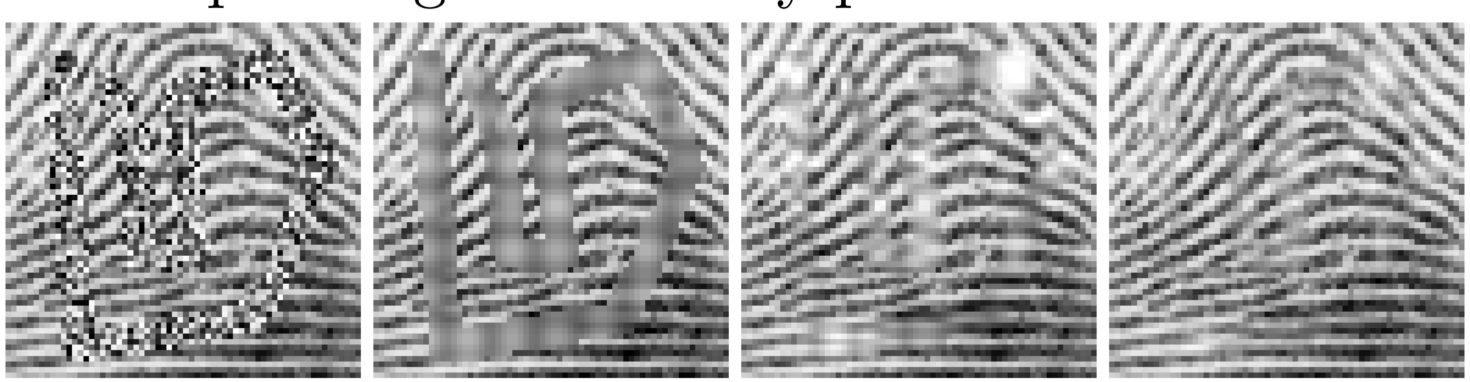
Measurements y | Iter. #1 | Iter. #3 | Iter. #50

Compressed Sensing recovery:



Original f | Wavelets, PSNR=25.7dB | Manifold, PSNR=31.3dB

Inpainting with locally parallel manifold:



Iter. #1 | Iter. #2 | Iter. #3 | Iter. #50

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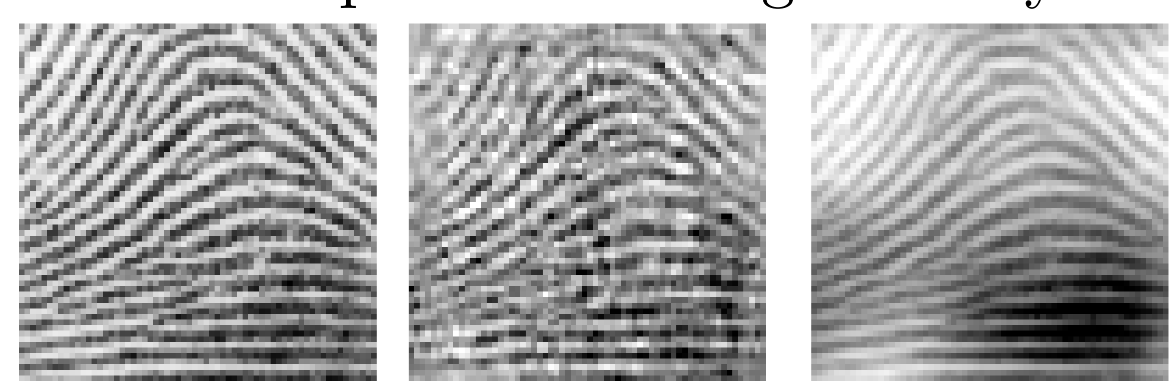

Original f | Local DCT, PSNR=21.9dB | Manifold, PSNR=22.1dB

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Weights for Image Patches

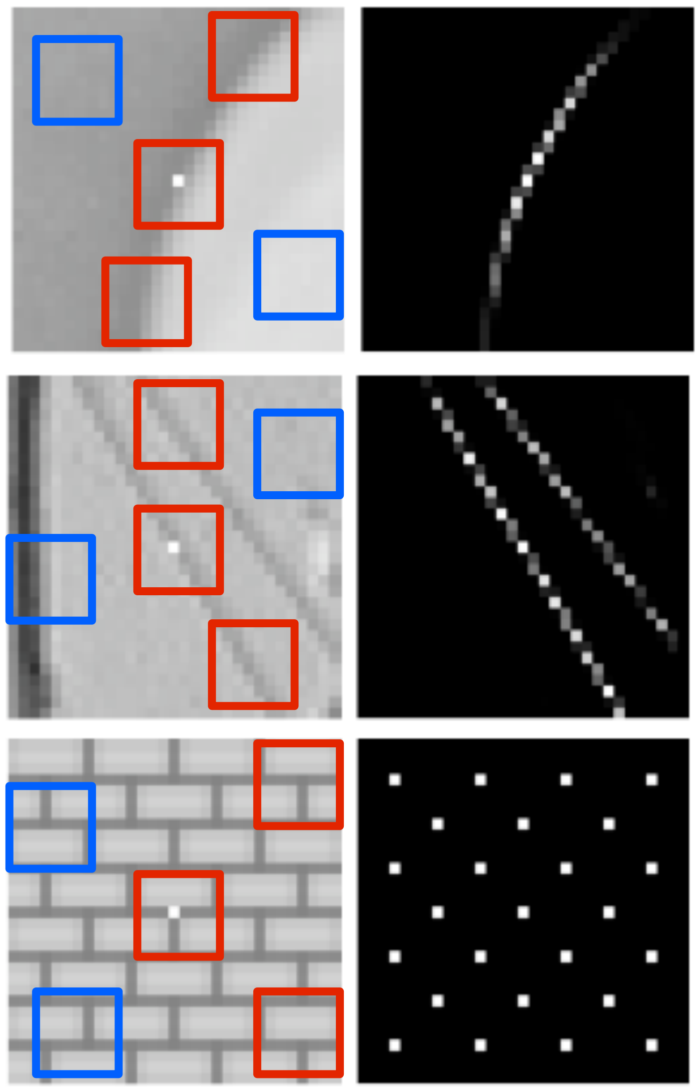
Weights for a patch manifolds estimated from an image f:

$$w_f(x,y) = w(p_x(f), p_y(f)) = \exp\left(-\frac{\|p_x(f) - p_y(f)\|^2}{2\varepsilon^2} \right)$$

Non-local means [Buades, Coll, Morel, 2005]

Image filtering W_f associated to $w_f(x,y)$

$$W_f g(x) = \frac{1}{Z_x} \sum_y w_f(x,y) g(x) \quad \text{where} \quad Z_x = \sum_y w_f(x,y)$$



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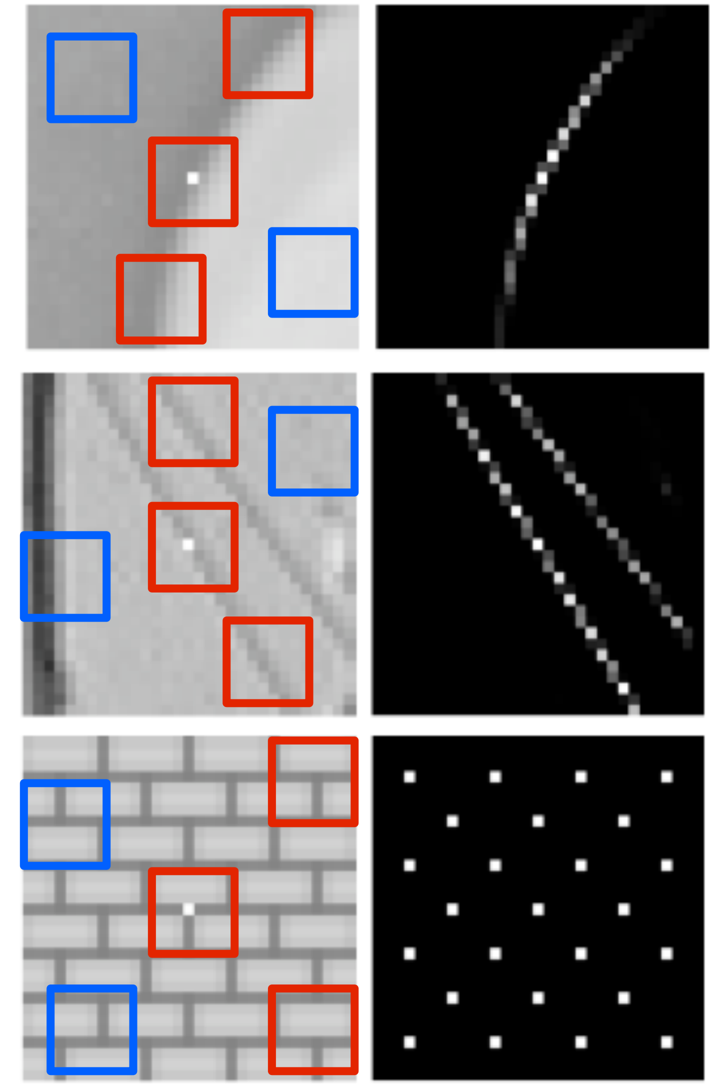

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Non-local means: apply W_f to f itself!

$$\tilde{f} = W_f f$$

$\longrightarrow$ adaptive filtering

Noisy f

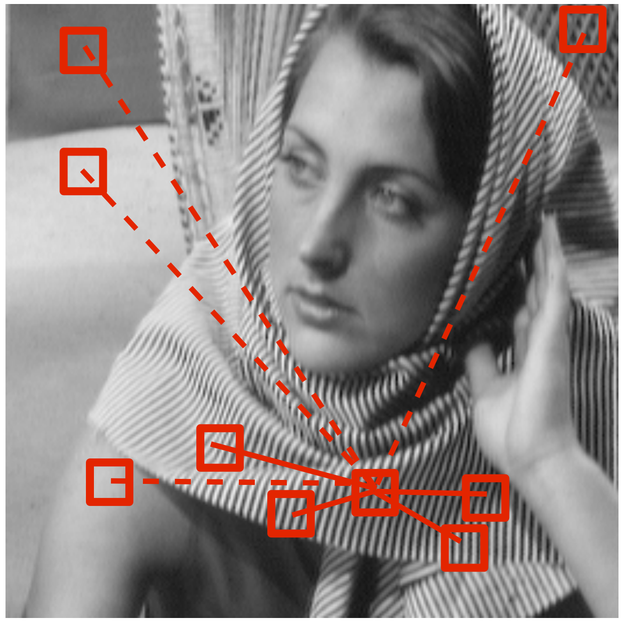
Gaussian blurring

NL-means $\tilde{f}$

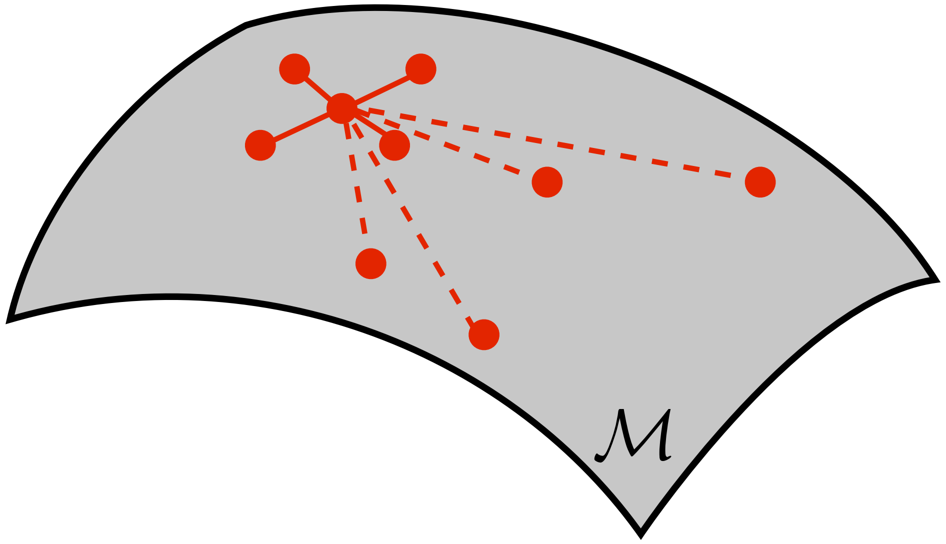
Adaptive Manifold Energies

Setting #2: $\mathcal{M} = \mathcal{M}_f = (p_x(f))_x$ is computed from some image f.

Weighted graph $w_f(p_x, p_y) = \exp\left(-\frac{\|p_x - p_y\|^2}{2\varepsilon^2}\right)$



Weight $w_f(x, y)$ on image.



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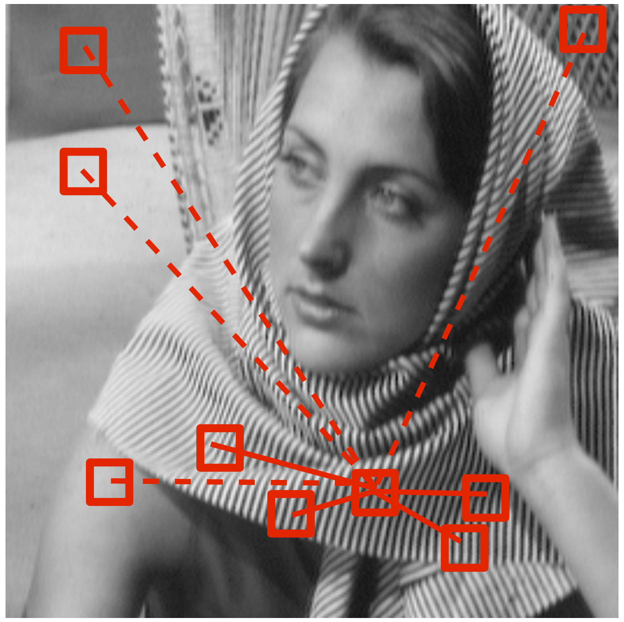

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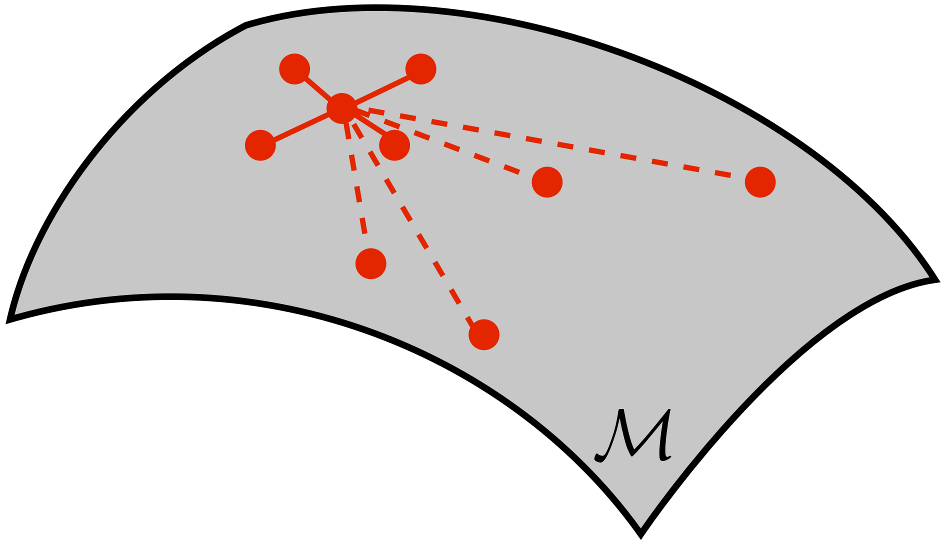

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Manifold Sobolev energy: $J_w^{\text{sob}}(g) = \sum_{x,y} w_f(x, y)|g(x) - g(y)|^2$.

Manifold TV energy: $J_w^{\text{tv}}(g) = \sum_{x,y} w_f(x, y)|g(x) - g(y)|$.

$\forall\, (x, y), \quad g(x) \approx g(y)$ for points $(p_x(f), p_y(f))$ close on the manifold $\mathcal{M}_f$.

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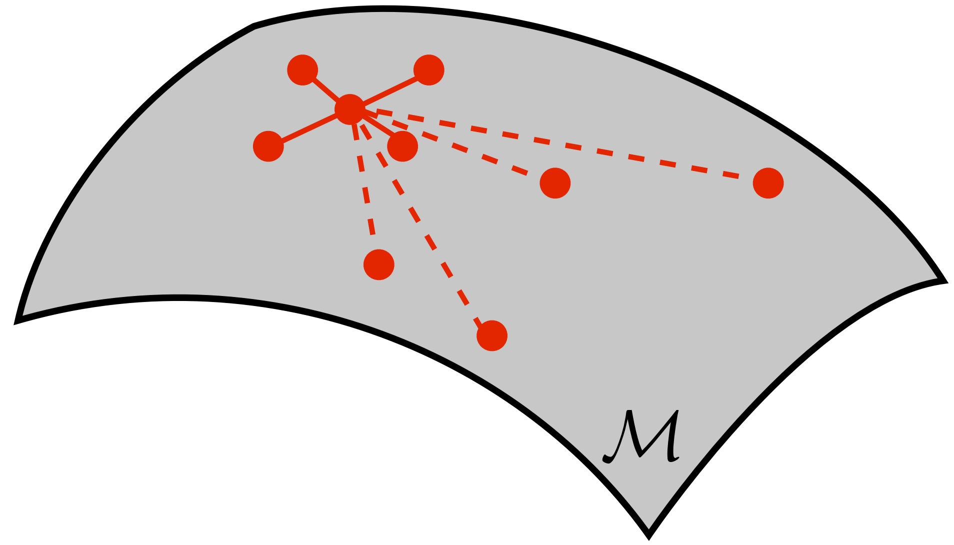

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Optimize w to the geometry of the solution.

$\longrightarrow$ denoising: easy, adapt w to the noisy observation f+noise.

[Coifman, Lafon et al. 2005] [Gilboa et al. 2007] $\cdots$

$\longrightarrow$ inverse problems: difficult, needs to find both w and $f^\star$.

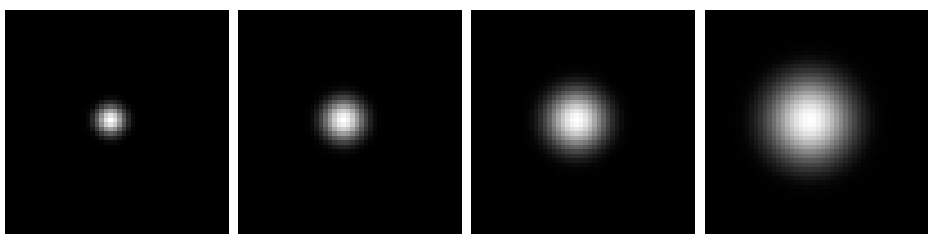
Differential Operators and Energies

Manifold Sobolev energy: $J_w^{\text{sob}}(g) = \sum_{x,y} w_f(x,y)|g(x) - g(y)|^2 = \langle g,\, \Delta^w g \rangle$.

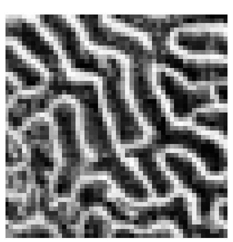
Laplacian: $\Delta^w g(x) = \left(\sum_y w_f(x,y)\right) g(x) - \left(\sum_y w_f(x,y) g(y)\right)$

Gradient descent: non-local heat equation $\dfrac{\partial^2 g_t}{\partial t^2} = -\Delta^{w_f} g_t$ and $g_0 = g$

Denoise by heat diffusion $t \mapsto f_t$ with weights w_f and $f_0 = f$.

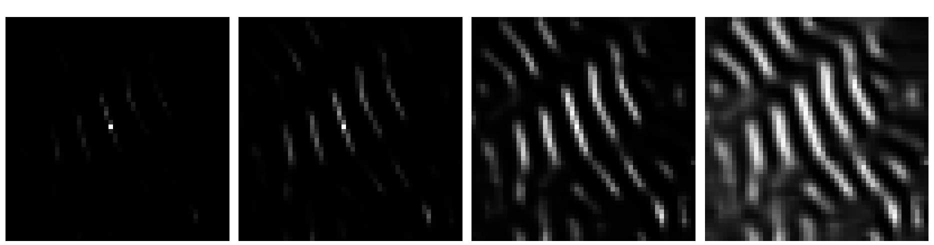


Local manifold $p_x = x$

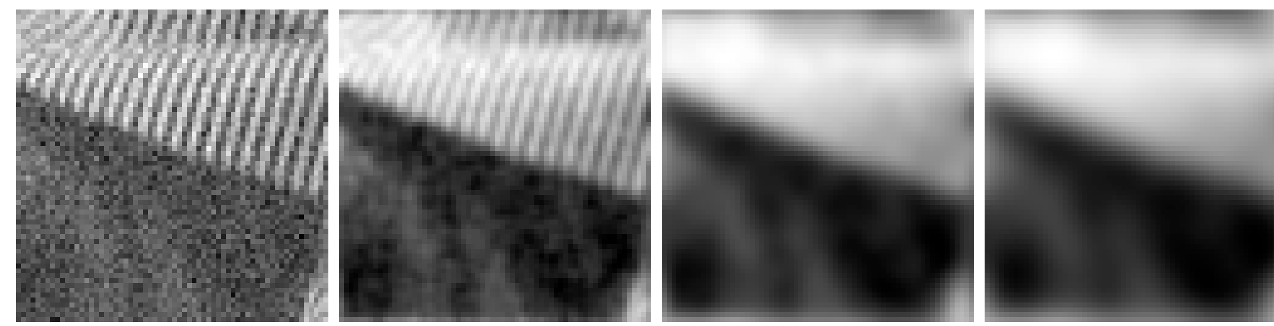


f

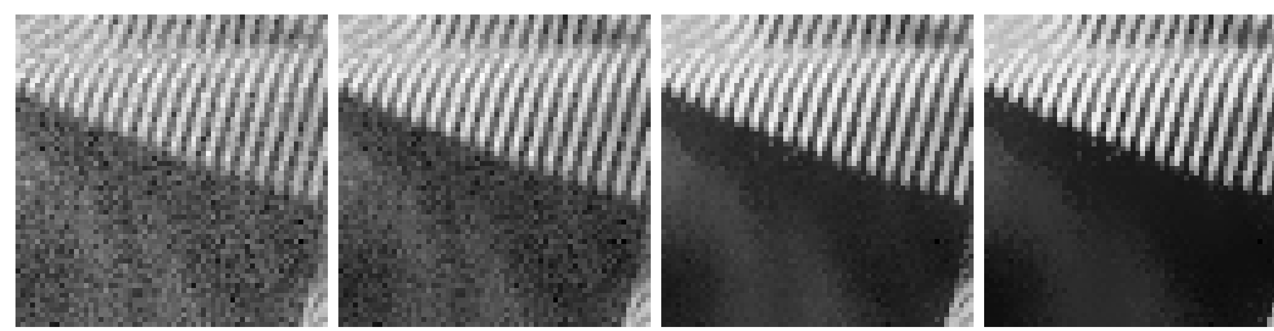
Semi-local manifold $p_x = (x, f(x))$



Non-local manifold $p_x = p_x(f)$



Local manifold $p_x = x$



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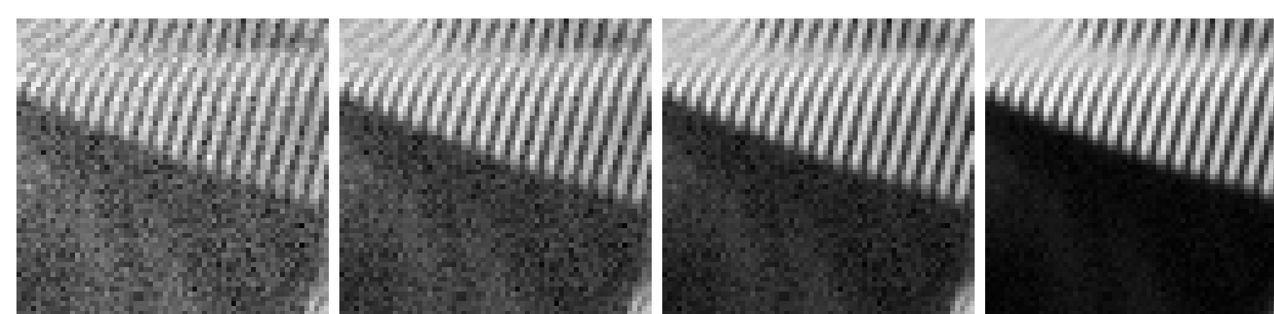


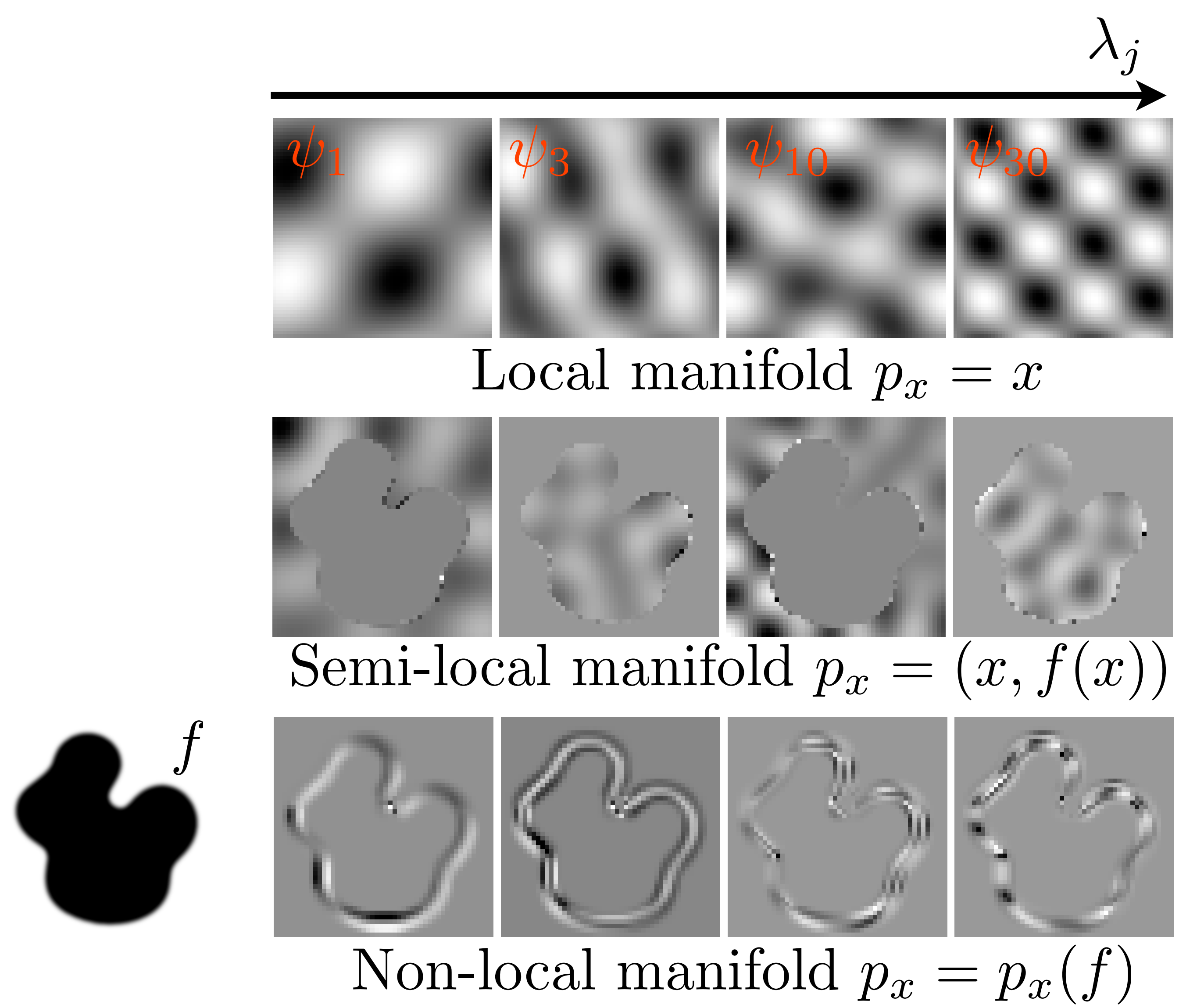
Non-local manifold $p_x = p_x(f)$

Manifold Spectral Basis

Eigenvectors of the Laplacian Δ^w: $\mathcal{B}(w) = \{\psi_j^w\}_j$ ortho-basis of $\mathbb{R}^n$.

$$\Delta^w \psi_j^w = \lambda_j \psi_k^w \qquad \lambda_j \simeq \text{frequency.}$$

$$J_w^{\text{sob}}(g) = \langle g,\, \Delta^w g \rangle = \sum_j \lambda_j |\langle f,\, \psi_j^w \rangle|^2 \qquad J_w^{\text{spars}}(g) = \sum_j |\langle f,\, \psi_j^w \rangle|$$



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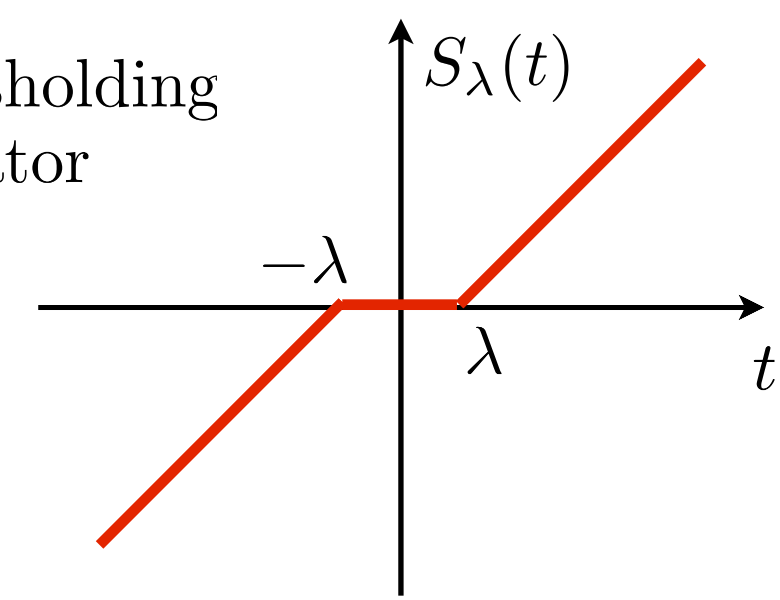
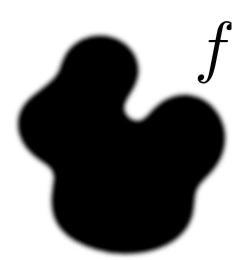
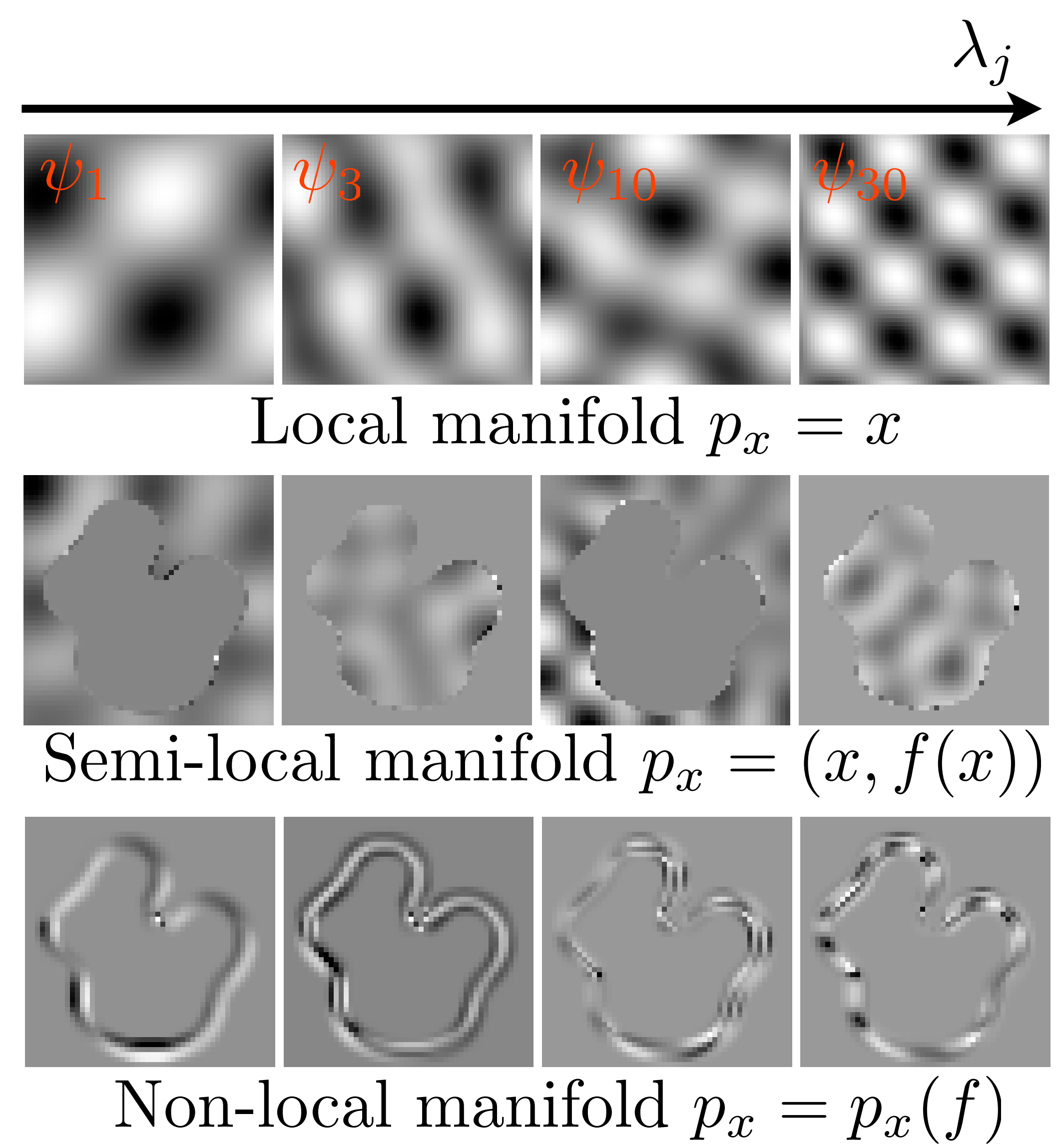
$$\underset{g}{\operatorname{argmin}}\ \|f-g\|^2 + \lambda J_w^{\text{sob}}(g) = \sum_j \frac{\langle f,\, \psi_j^w\rangle}{1+\lambda\lambda_j}\psi_j^w$$

$$\underset{g}{\operatorname{argmin}}\ \frac{1}{2}\|f-g\|^2 + \lambda J_w^{\text{spars}}(g) = \sum_j S_\lambda(\langle f,\, \psi_j^w\rangle)\psi_j^w$$

Soft thresholding operator







See [Peyré, SIAM MMS 2008]

Adaptive Manifold Regularization

Find both solution $f^\star$ and adapted weights $w^\star$:

$$(f^\star, w^\star) = \underset{(g,w)}{\operatorname{argmin}} \frac{1}{2}\|y - \Phi g\|^2 + \lambda J_w(g)$$

Iterative minimization algorithm for $J_w = J_w^{\text{sob}}$:

Step 1: $w^\star$ fixed, gradient descent with step τ

$$f^\star \leftarrow f^\star + \tau \Phi^*(\Phi f^\star - y) - \tau\lambda\Delta^{w^\star} f^\star$$

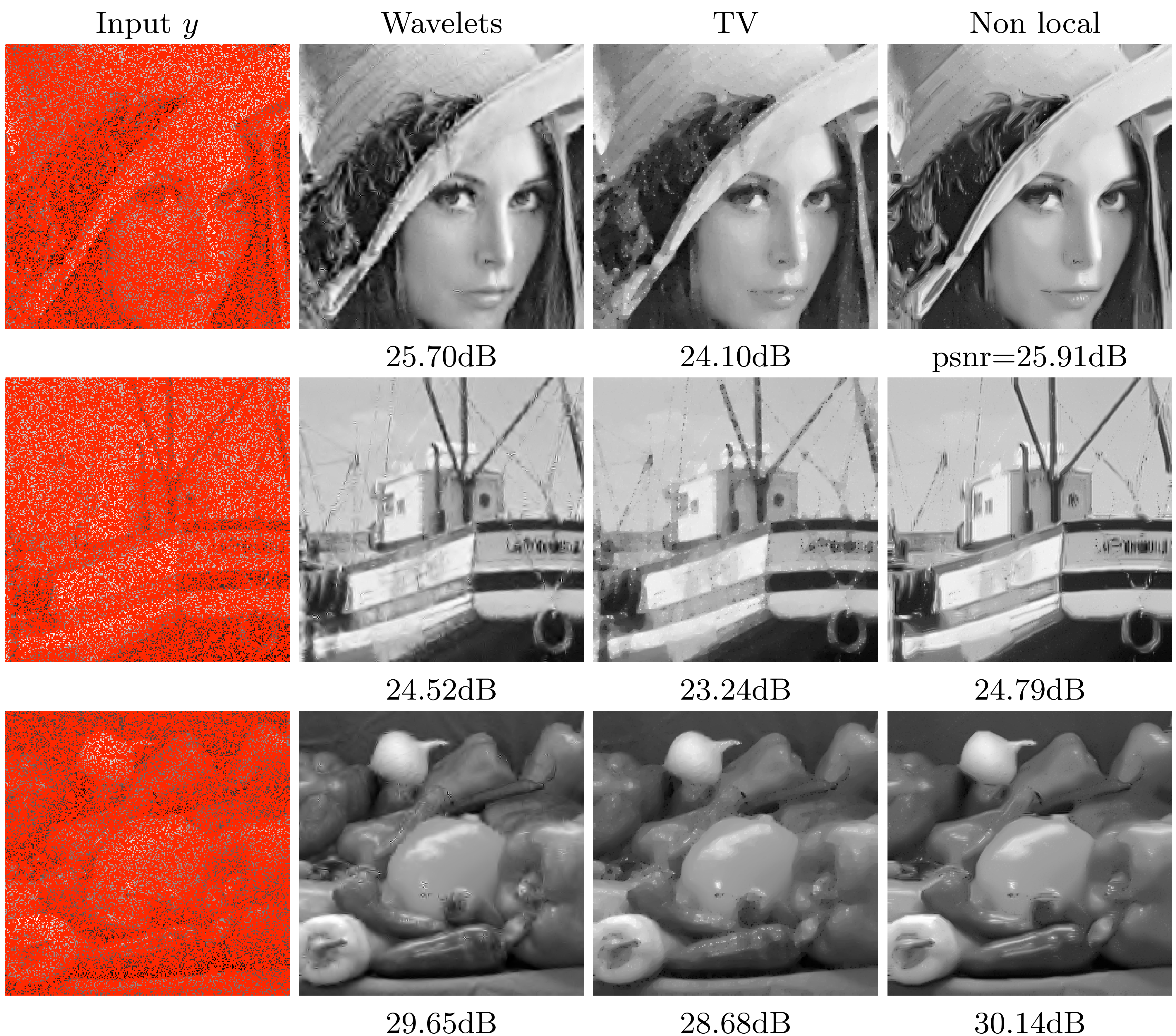
Step 2: $f^\star$ fixed, estimate the graph $w^\star$

$$w^\star(x,y) \leftarrow \exp\left(-\frac{\|p_x(f^\star) - p_y(f^\star)\|^2}{2\varepsilon^2}\right)$$

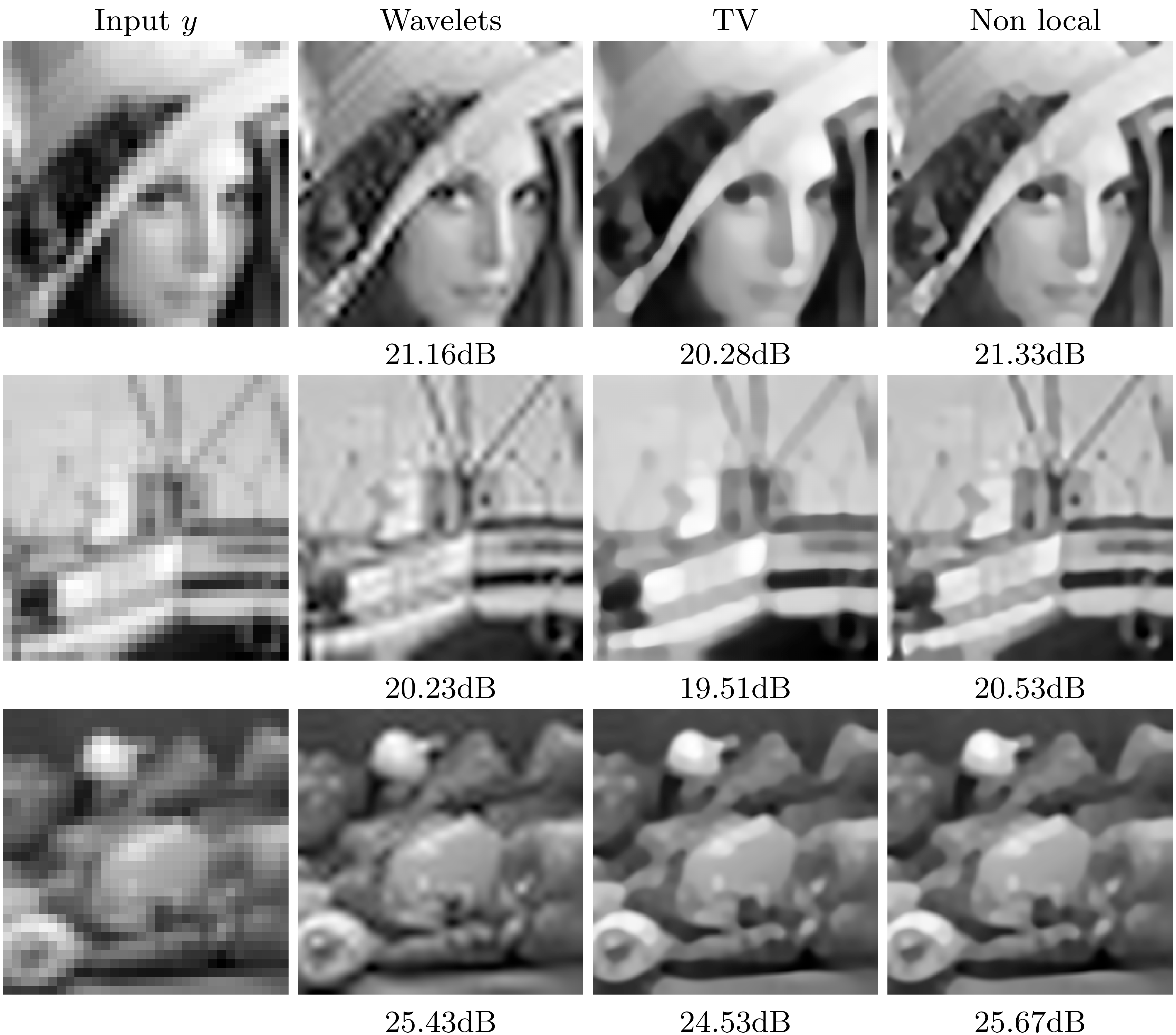
For non-smooth $J_w = J_w^{\text{tv}}$ replace gradient descent by proximal iterations.

See [Peyré, Bougleux, Cohen, ECCV'08]

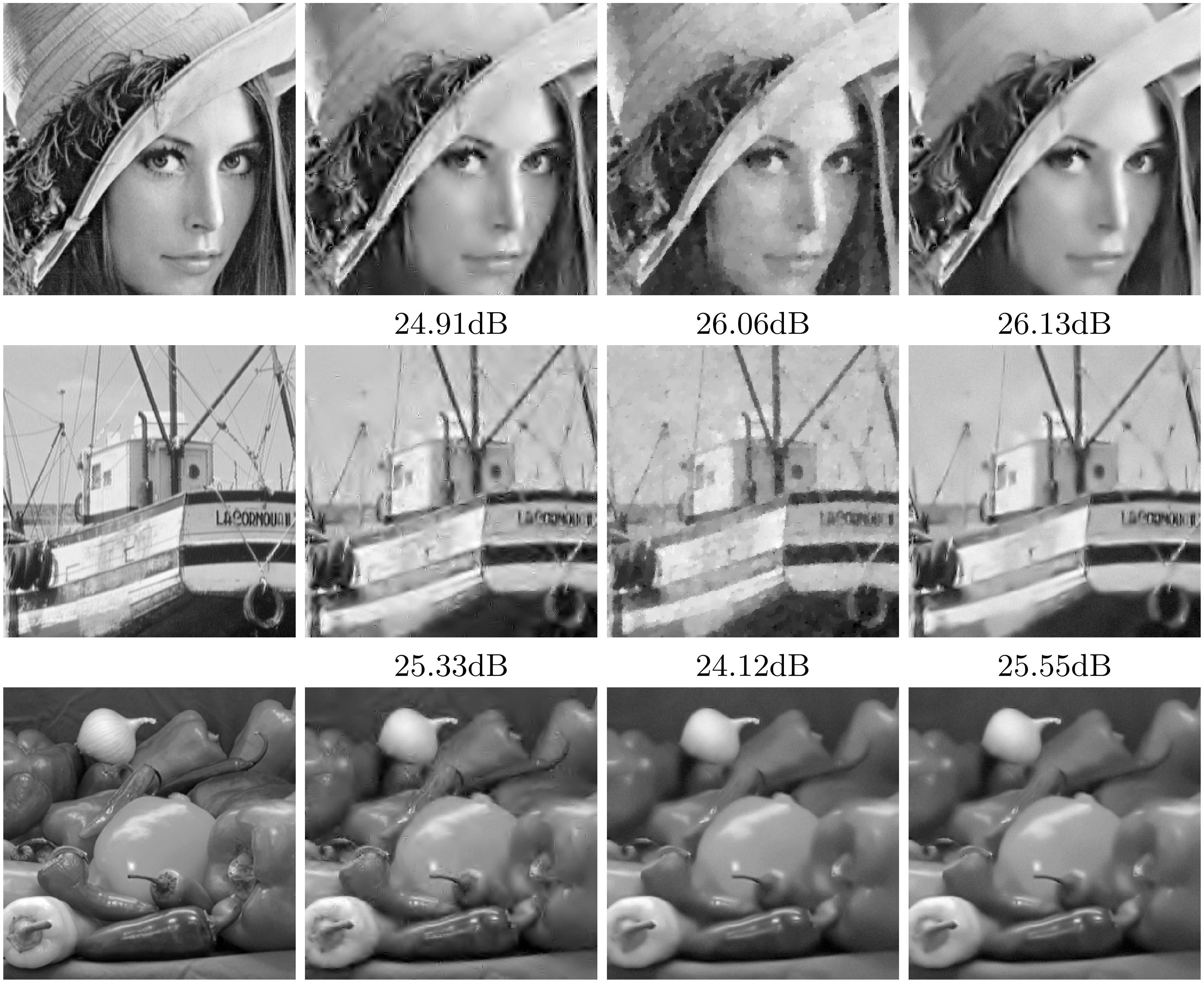
Inpainting Results



Super-resolution Results



Compressed Sensing Results

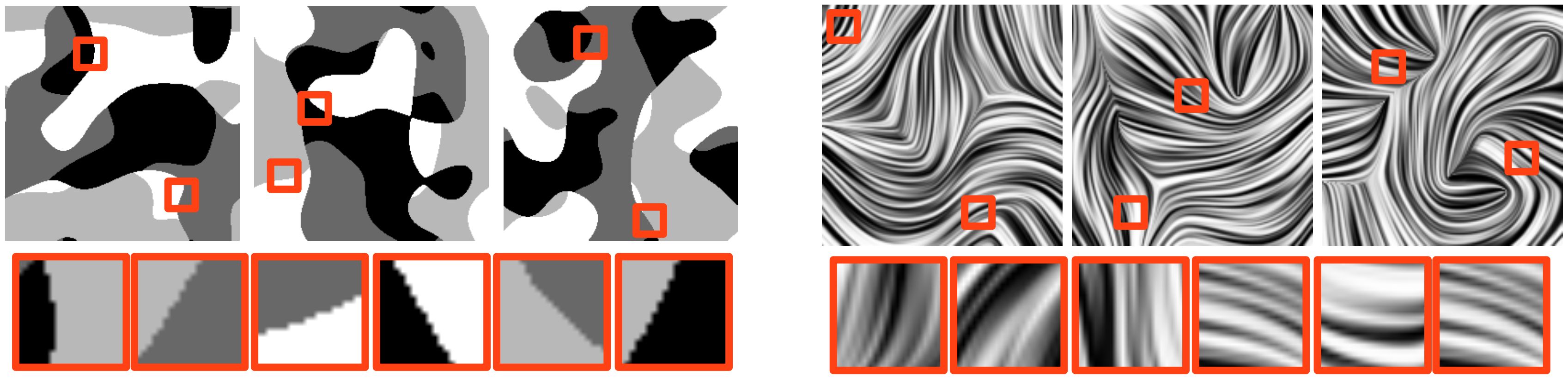


Original f	Wavelets	TV	Non local
	24.91dB	26.06dB	26.13dB
	25.33dB	24.12dB	25.55dB
	32.21dB	30.47dB	32.20dB

Conclusion

The local geometry of images can sometimes be captured by a manifold $\mathcal{M}$.

$\longrightarrow$ low dimensional parameterization of the features.



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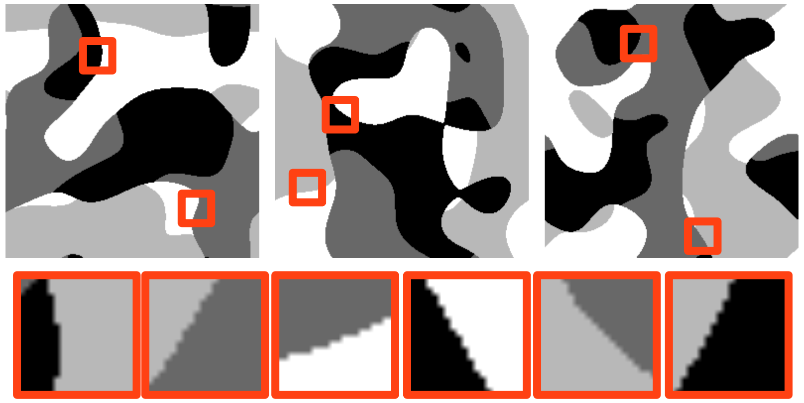
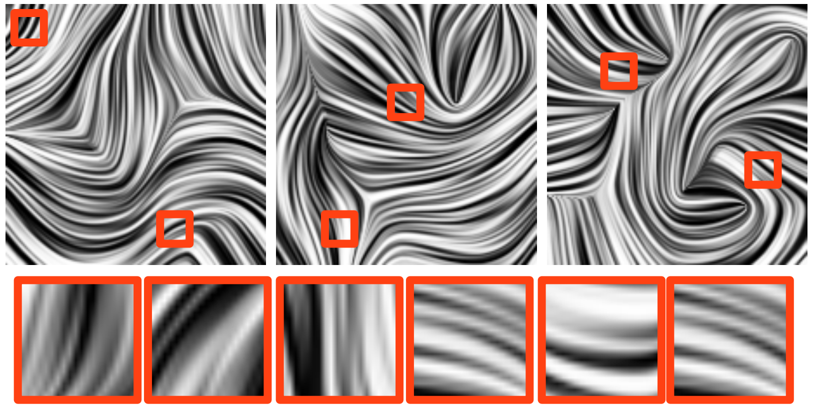
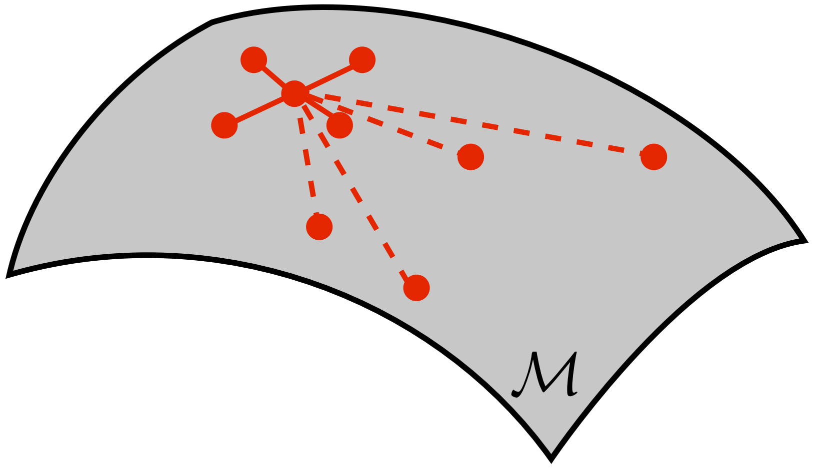




For complex images, the manifold can be learned from the data.

$\longrightarrow$ computing non-local connexions between pixels.



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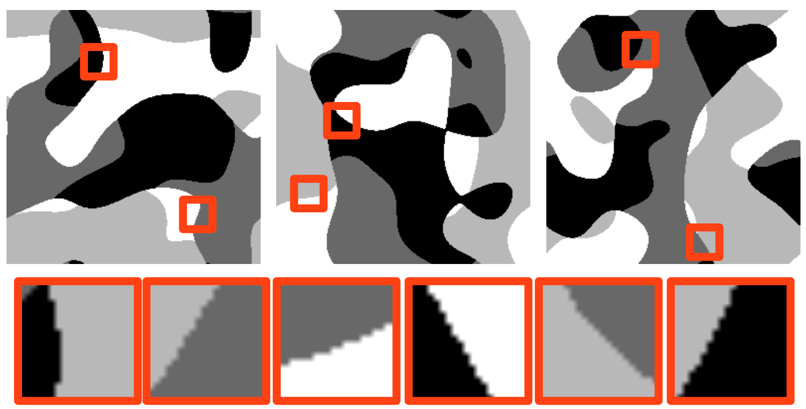

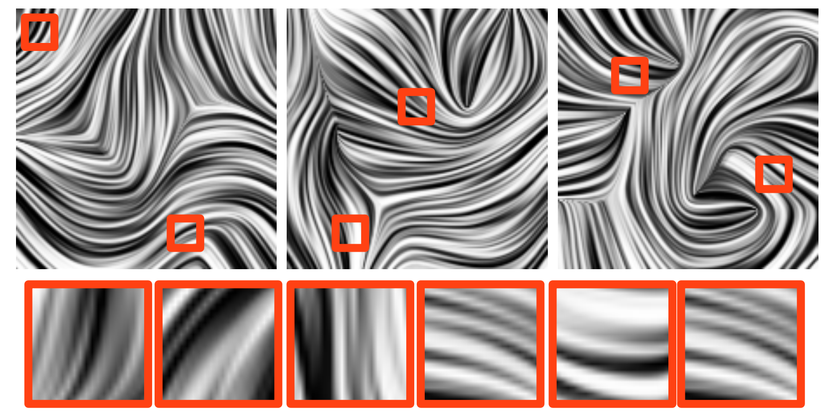

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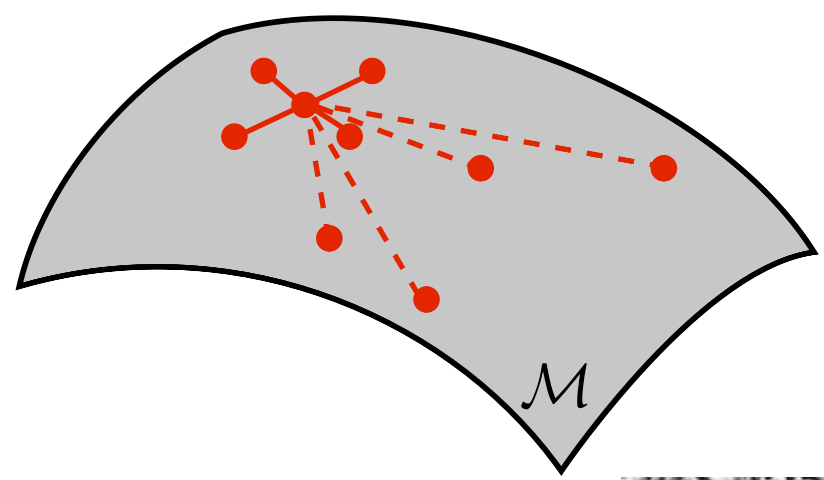

Inverse problem resolution: energy design and minimization.

$\longrightarrow$ fixed manifold $\mathcal{M}$: iterative projection.

$\longrightarrow$ adaptive manifold $\mathcal{M}_w$: optimizing the connexions w.