BIL 717
Image Processing
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Modern Image Smoothing

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Review - Smoothing and Edge Detection

- While eliminating noise via smoothing, we also lose some of the (important) image details.
  - Fine details
  - Image edges
  - etc.
- What can we do to preserve such details?
  - Use edge information during denoising!
  - This requires a definition for image edges.

Chicken-and-egg dilemma!

- Edge preserving image smoothing

Today

- Bilateral filtering
- Non-local means denoising
- LARK filter

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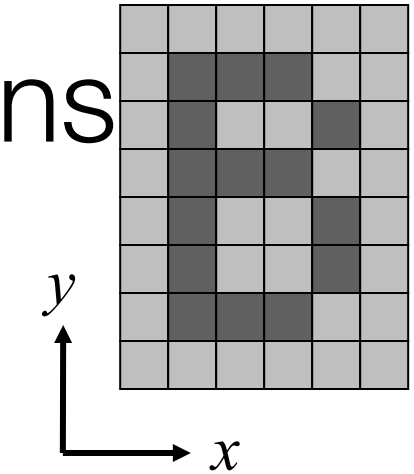
- Non-local means denoising
- LARK filter

Acknowledgement: The slides are adapted from the course “A Gentle Introduction to Bilateral Filtering and its Applications” given by Sylvain Paris, Pierre Kornprobst, Jack Tumblin, and Frédo Durand (http://people.csail.mit.edu/sparis/bf_course/).

Notation and Definitions

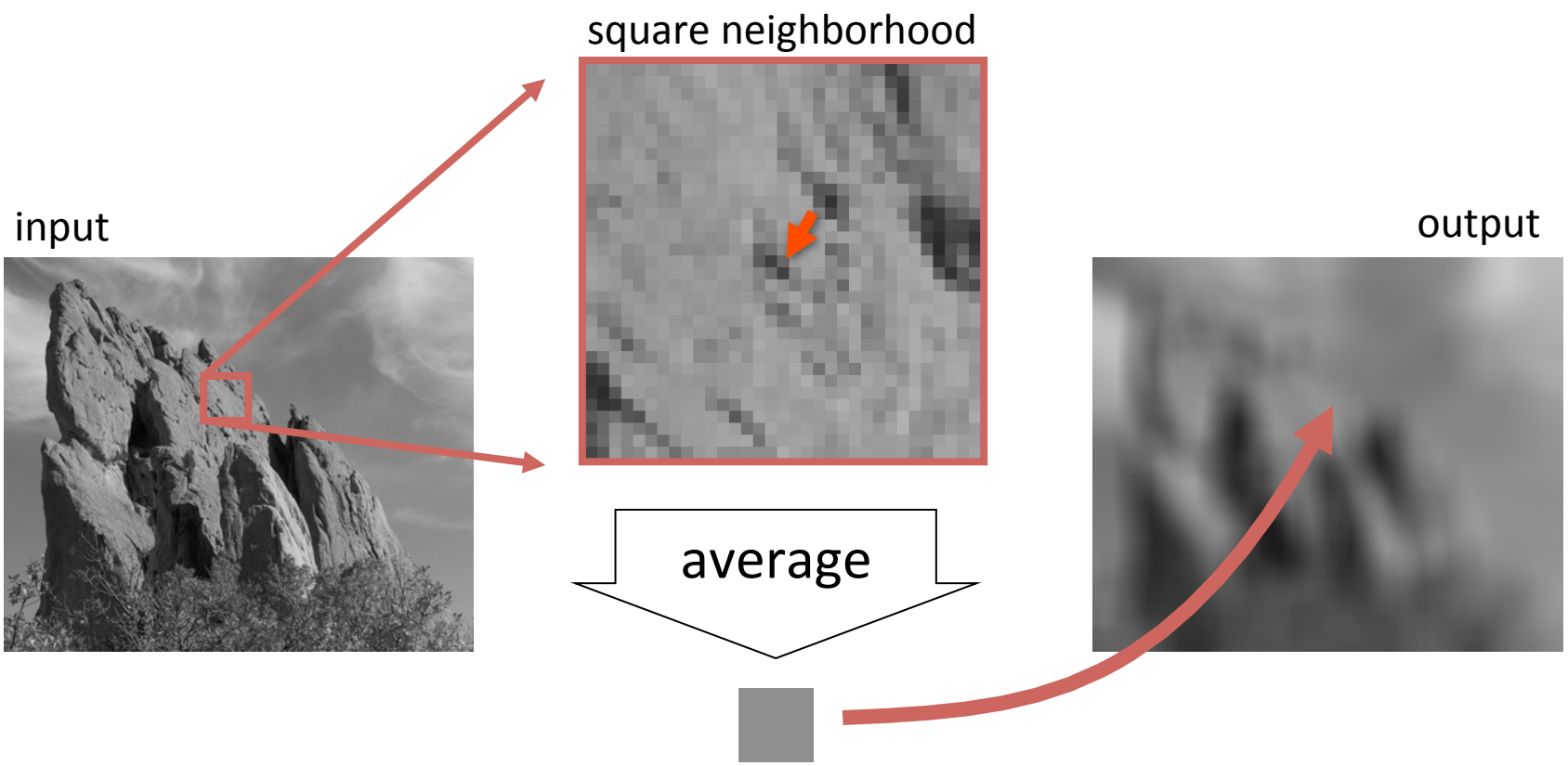


- Image = 2D array of pixels
- Pixel = intensity (scalar) or color (3D vector)
- $I_{\mathbf{p}}$ = value of image I at position: $\mathbf{p} = (p_x, p_y)$
- $F[I]$ = output of filter F applied to image I

Strategy for Smoothing Images

- Images are not smooth because adjacent pixels are different.
- Smoothing = making adjacent pixels look more similar.
- Smoothing strategy
  pixel ~ average of its neighbors

Box Average



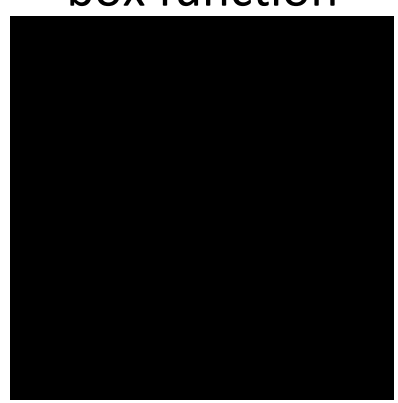
Equation of Box Average

$$BA[I]_{\mathbf{p}} = \sum_{\mathbf{q} \in S} B_{\sigma}(\mathbf{p} - \mathbf{q}) I_{\mathbf{q}}$$

result at pixel $\mathbf{p}$

sum over all pixels $\mathbf{q}$

normalized box function



intensity at pixel $\mathbf{q}$

Square Box Generates Defects

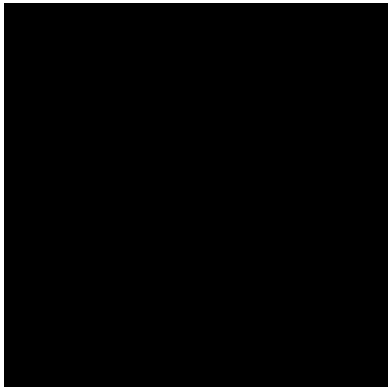
- Axis-aligned streaks
- Blocky results

output

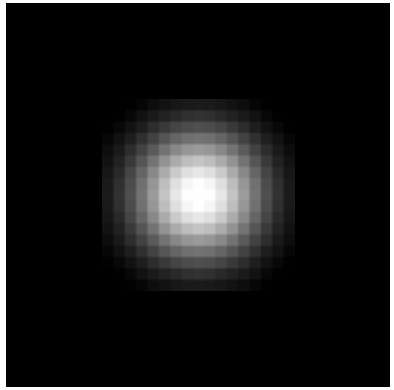
input

Strategy to Solve these Problems

- Use an isotropic (*i.e.* circular) window.
- Use a window with a smooth falloff.

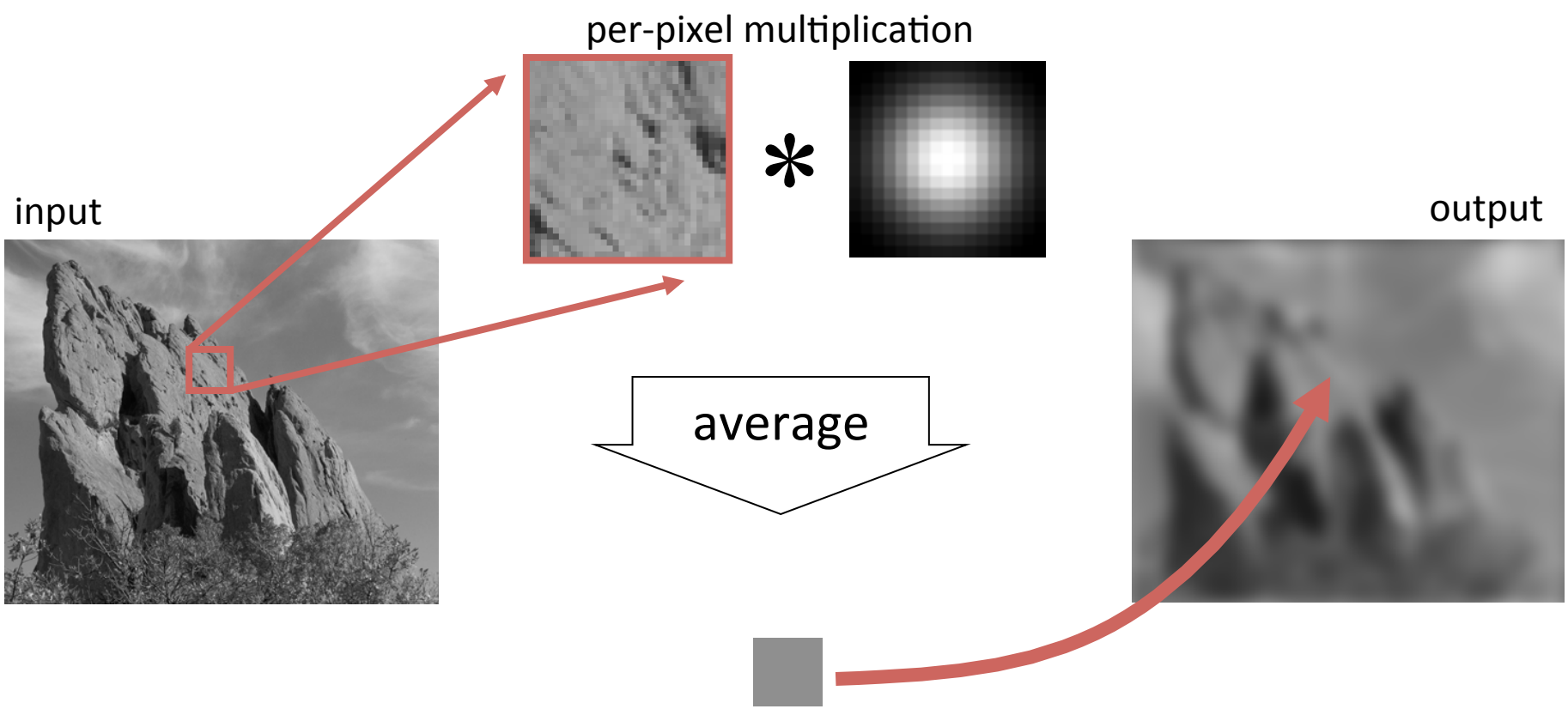


box window



Gaussian window

Gaussian Blur




input


box average

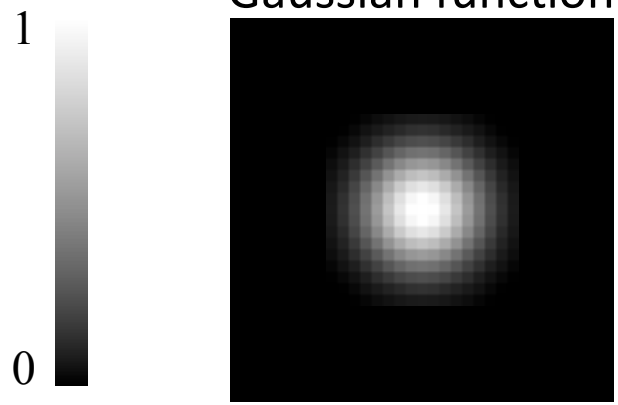

Gaussian blur

Equation of Gaussian Blur

Same idea: **weighted average of pixels**.

$$GB[I]_{\mathbf{p}} = \sum_{\mathbf{q} \in S} G_{\sigma}\left(\| \mathbf{p} - \mathbf{q} \|\right) I_{\mathbf{q}}$$

normalized
Gaussian function

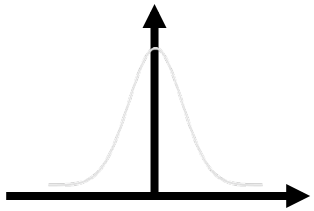


Spatial Parameter

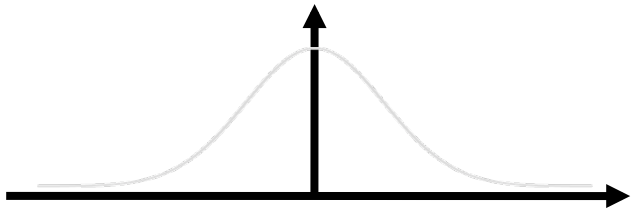
input

$$GB[I]_{\mathbf{p}} = \sum_{\mathbf{q} \in S} G_{\sigma}\left(\| \mathbf{p} - \mathbf{q} \|\right) I_{\mathbf{q}}$$

size of the window



small σ



large σ

limited smoothing

strong smoothing

How to set σ

- Depends on the application.

- Common strategy: proportional to image size
  - e.g. 2% of the image diagonal
  - property: independent of image resolution

Properties of Gaussian Blur

- Weights independent of spatial location
  - linear convolution
  - well-known operation
  - efficient computation (recursive algorithm, FFT…)

Properties of Gaussian Blur

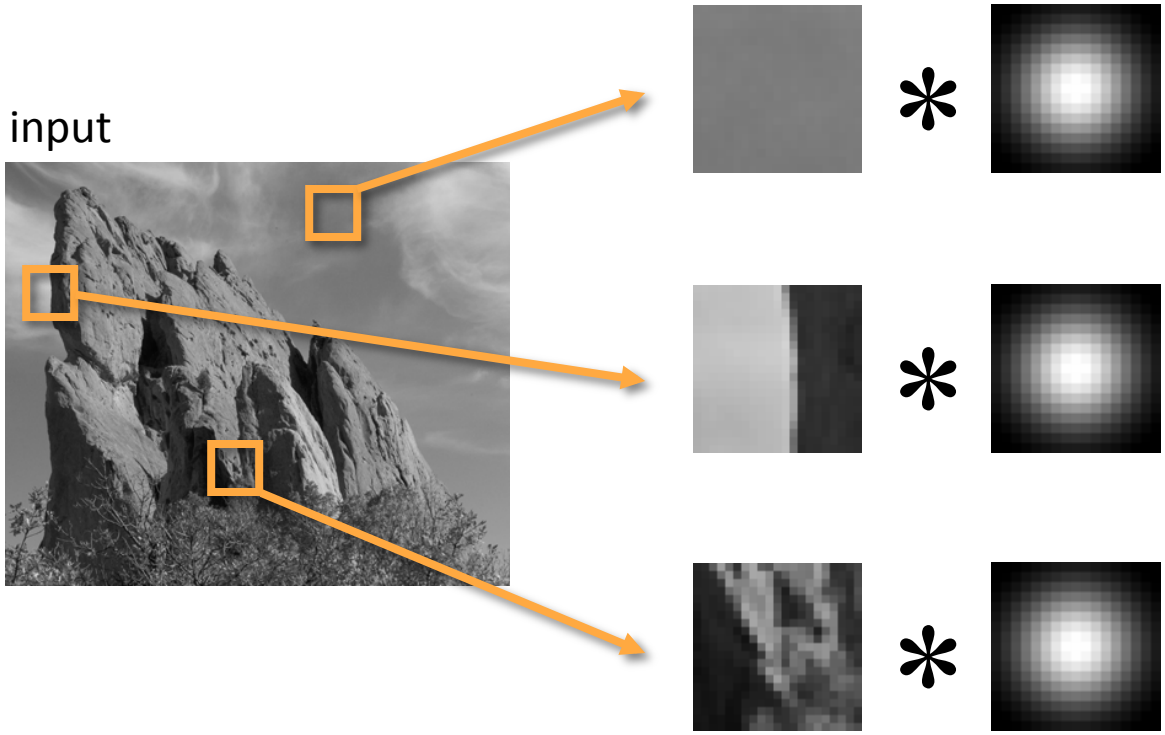
- Does smooth images
- But smoothes too much: **edges are blurred.**
  - Only spatial distance matters
  - No edge term

$$GB[I]_{\mathbf{p}} = \sum_{\mathbf{q} \in S} \underbrace{G_{\sigma}(\| \mathbf{p} - \mathbf{q} \|)}_{\text{space}} I_{\mathbf{q}}$$

input

output

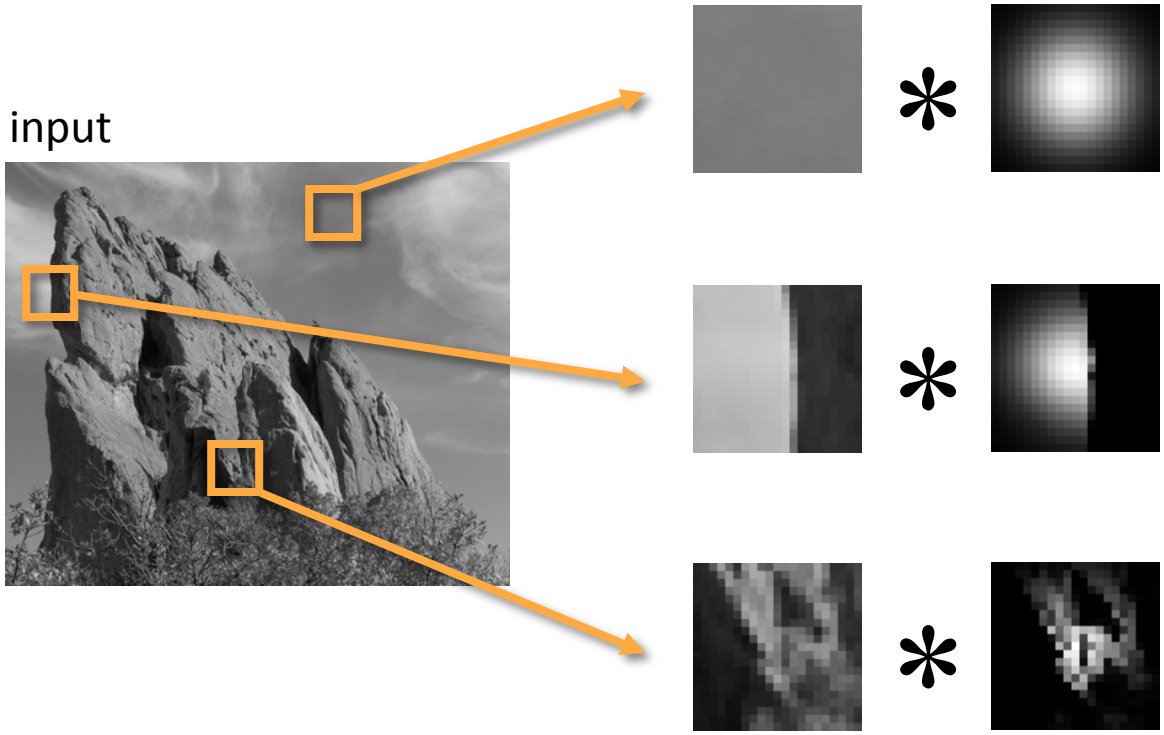
Blur Comes from Averaging across Edges



output

Same Gaussian kernel everywhere.

Bilateral Filter [Aurich 95, Smith 97, Tomasi 98]
No Averaging across Edges



output

The kernel shape depends on the image content.

Bilateral Filter Definition: an Additional Edge Term

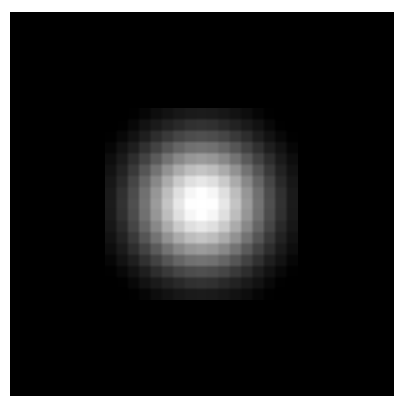
Same idea: **weighted average of pixels**.

new | not new | new

$$BF[I]_{\mathbf{p}} = \frac{1}{W_{\mathbf{p}}} \sum_{\mathbf{q} \in S} G_{\sigma_s}\left(\| \mathbf{p} - \mathbf{q} \|\right) G_{\sigma_r}\left(| I_{\mathbf{p}} - I_{\mathbf{q}} |\right) I_{\mathbf{q}}$$

normalization factor

space weight



range weight

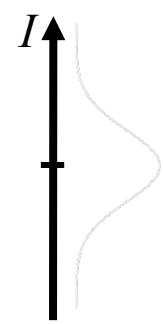
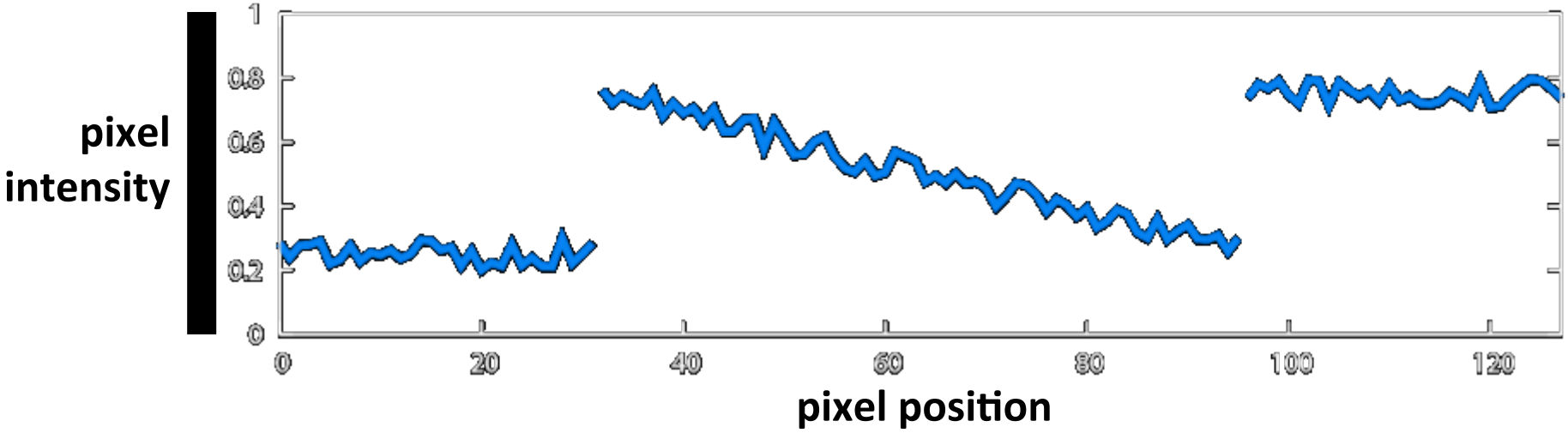


Illustration a 1D Image

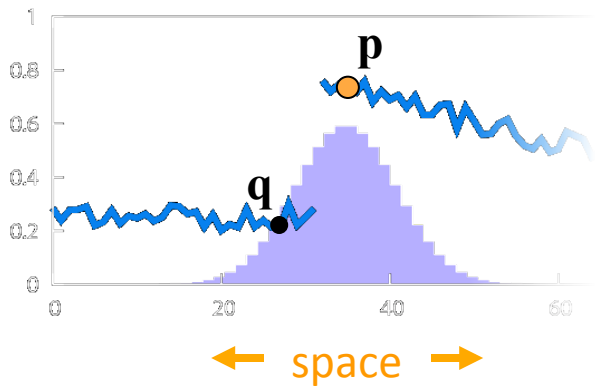
- 1D image = line of pixels

- Better visualized as a plot



Gaussian Blur and Bilateral Filter

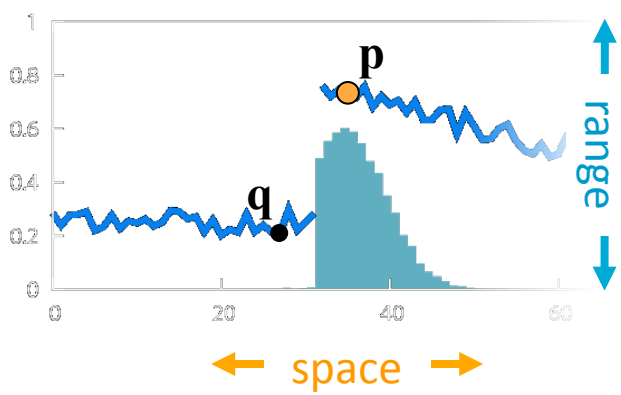
Gaussian blur



$$GB[I]_{\mathbf{p}} = \sum_{\mathbf{q}\in S} \underbrace{G_{\sigma}(\|\mathbf{p}-\mathbf{q}\|)}_{\text{space}} I_{\mathbf{q}}$$

Bilateral filter

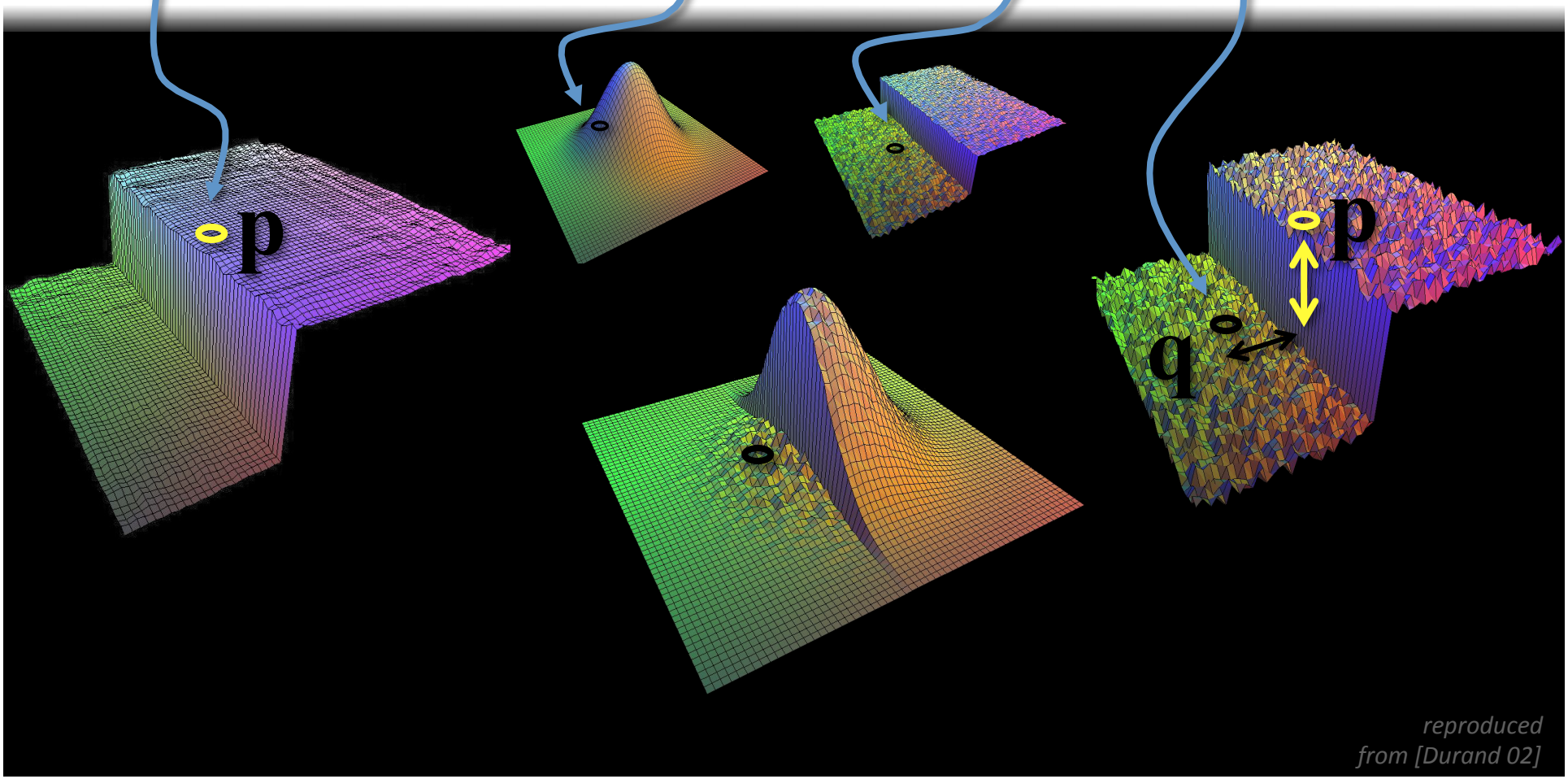
[Aurich 95, Smith 97, Tomasi 98]



$$BF[I]_{\mathbf{p}} = \underbrace{\frac{1}{W_{\mathbf{p}}}}_{\text{normalization}} \sum_{\mathbf{q}\in S} \underbrace{G_{\sigma_s}(\|\mathbf{p}-\mathbf{q}\|)}_{\text{space}} \underbrace{G_{\sigma_r}(|I_{\mathbf{p}}-I_{\mathbf{q}}|)}_{\text{range}} I_{\mathbf{q}}$$

Bilateral Filter on a Height Field

$$BF[I]_{\mathbf{p}} = \frac{1}{W_{\mathbf{p}}} \sum_{\mathbf{q} \in S} G_{\sigma_s}(\|\mathbf{p}-\mathbf{q}\|) \; G_{\sigma_r}(|I_{\mathbf{p}} - I_{\mathbf{q}}|) \; I_{\mathbf{q}}$$



reproduced from [Durand 02]

Space and Range Parameters

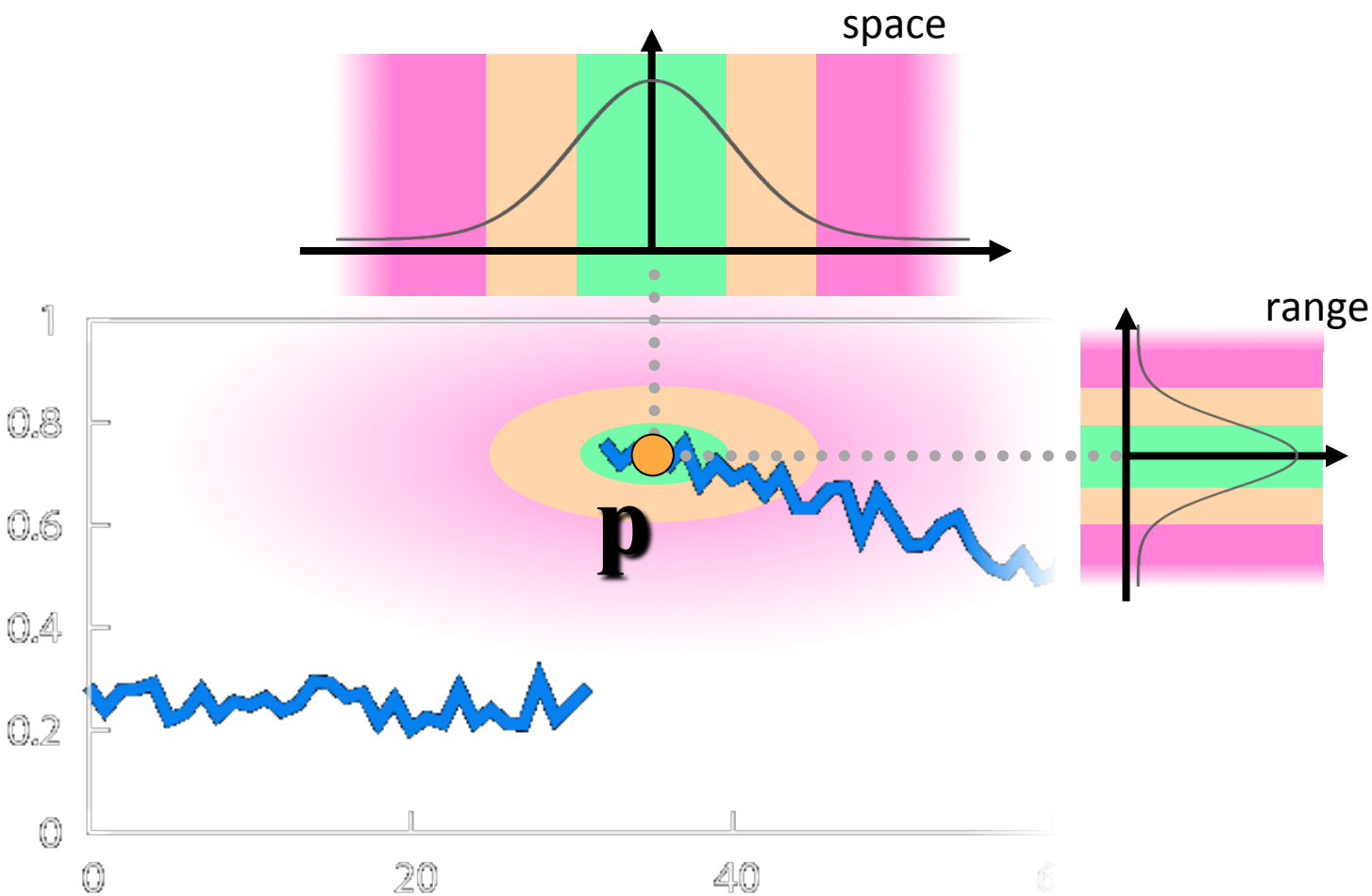
$$BF[I]_{\mathbf{p}} = \frac{1}{W_{\mathbf{p}}} \sum_{\mathbf{q} \in S} G_{\sigma_s}(\| \mathbf{p} - \mathbf{q} \|) G_{\sigma_r}(| I_{\mathbf{p}} - I_{\mathbf{q}} |) I_{\mathbf{q}}$$

- space σ_s : spatial extent of the kernel, size of the considered neighborhood.

- range σ_r : “minimum” amplitude of an edge

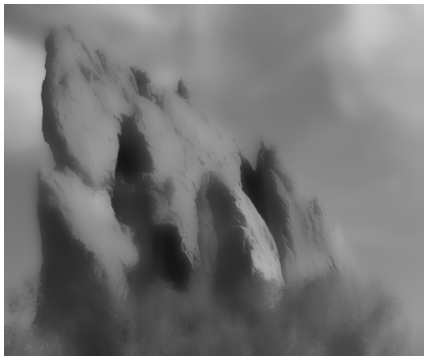
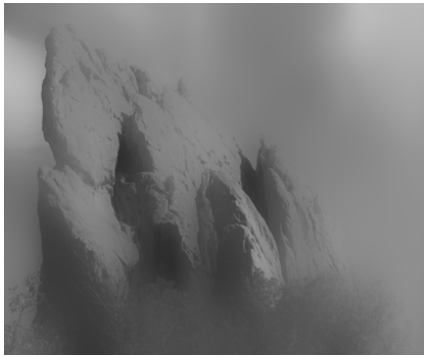
Influence of Pixels

Only pixels close in space and in range are considered.



Exploring the Parameter Space

input

	$\sigma_r = 0.1$	$\sigma_r = 0.25$	$\sigma_r = \infty$ (Gaussian blur)
$\sigma_s = 2$			
$\sigma_s = 6$			
$\sigma_s = 18$			

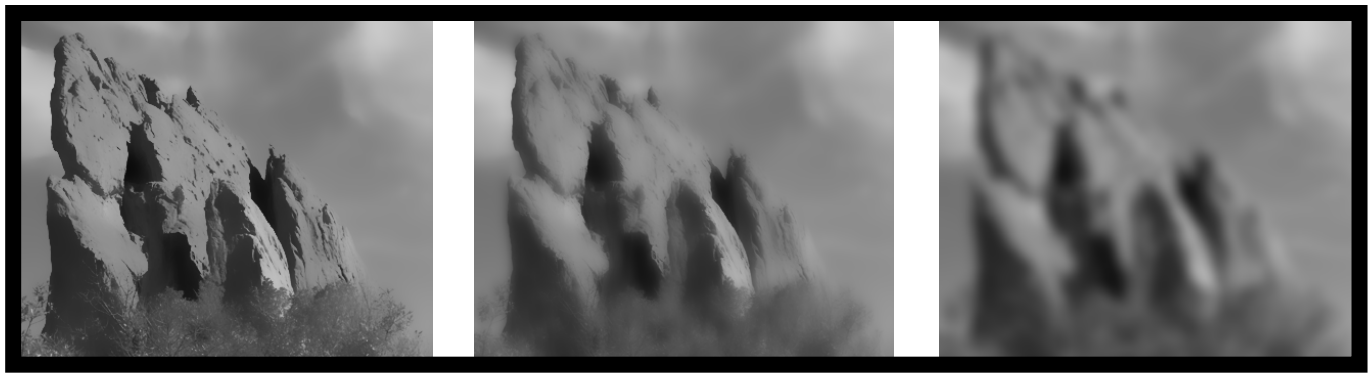
Varying the Range Parameter

input

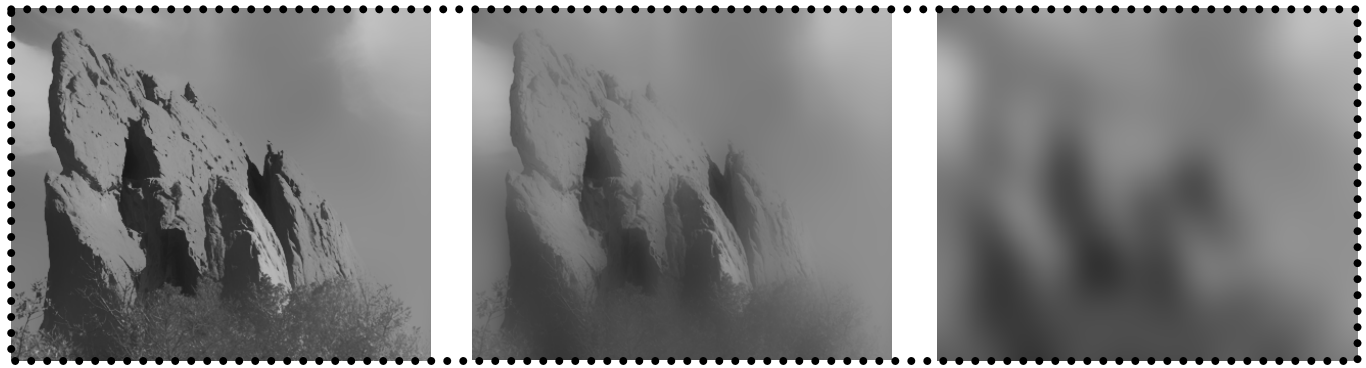
$\sigma_r = 0.1$ | $\sigma_r = 0.25$ | $\sigma_r = \infty$ (Gaussian blur)

$\sigma_s = 2$

$\sigma_s = 6$

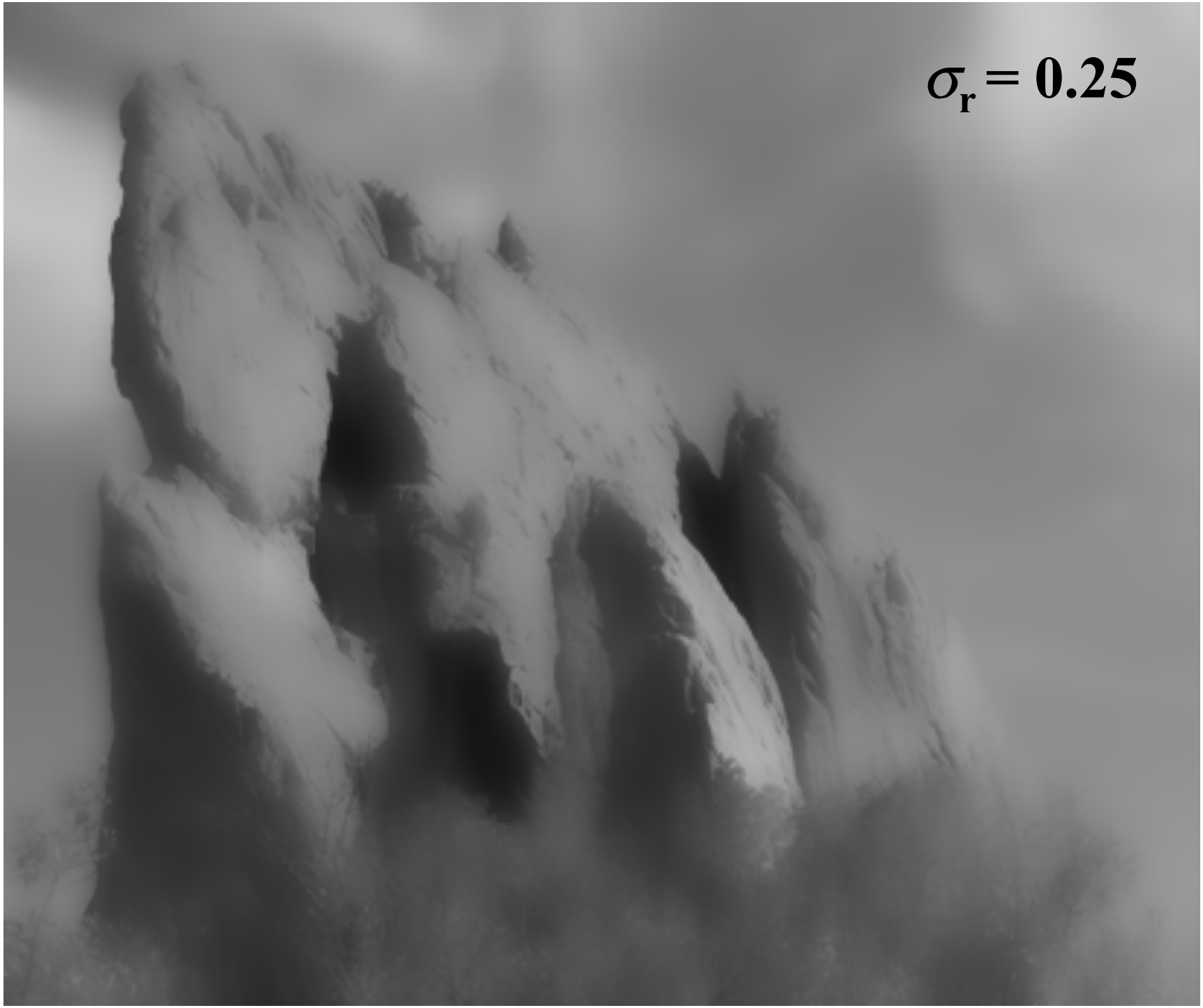


$\sigma_s = 18$




input

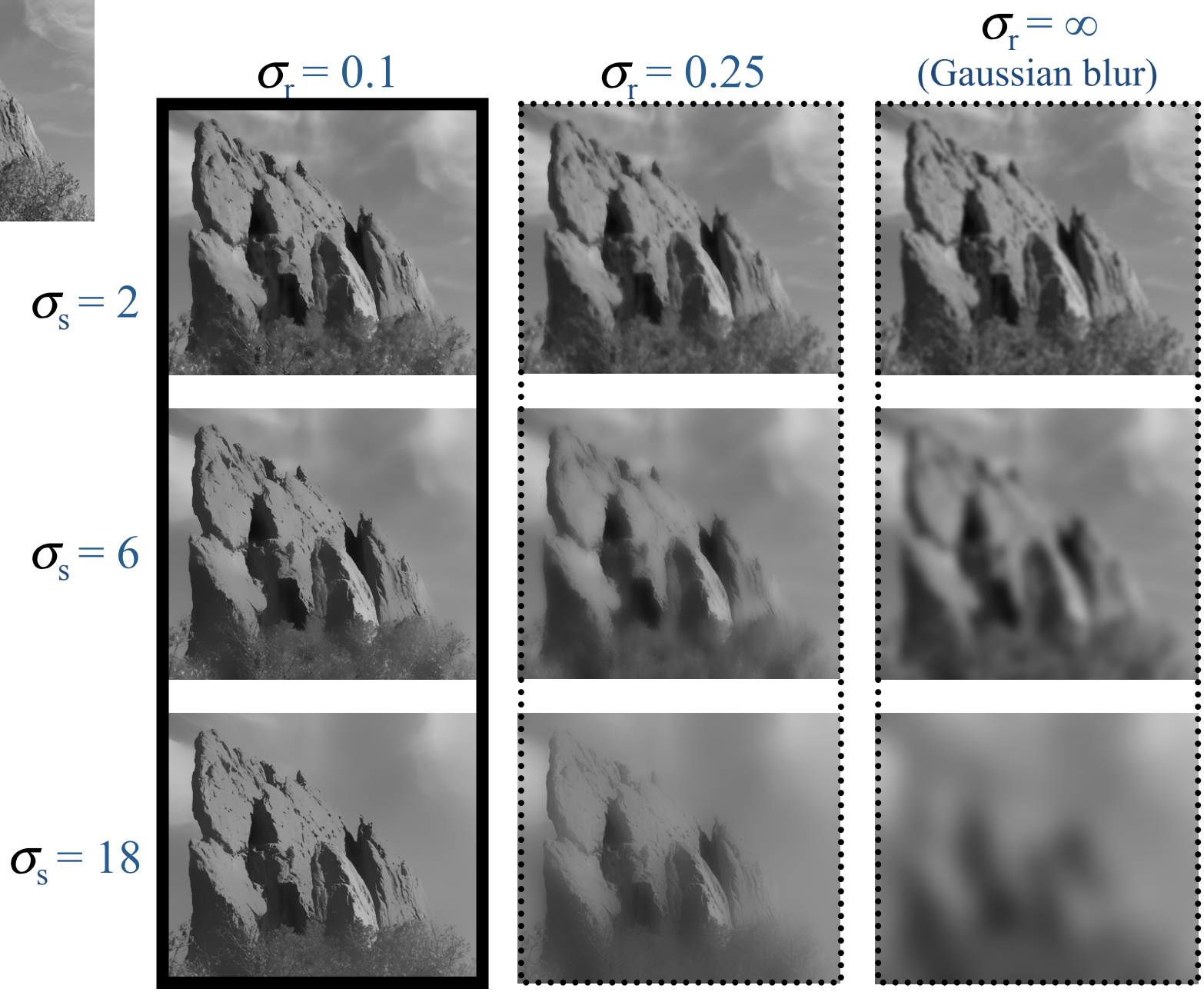

$\sigma_r = 0.1$


$\sigma_r = 0.25$


$\sigma_r = \infty$
(Gaussian blur)

Varying the Space Parameter

input




input


$\sigma_s = 2$


$\sigma_s = 6$


$\sigma_s = 18$

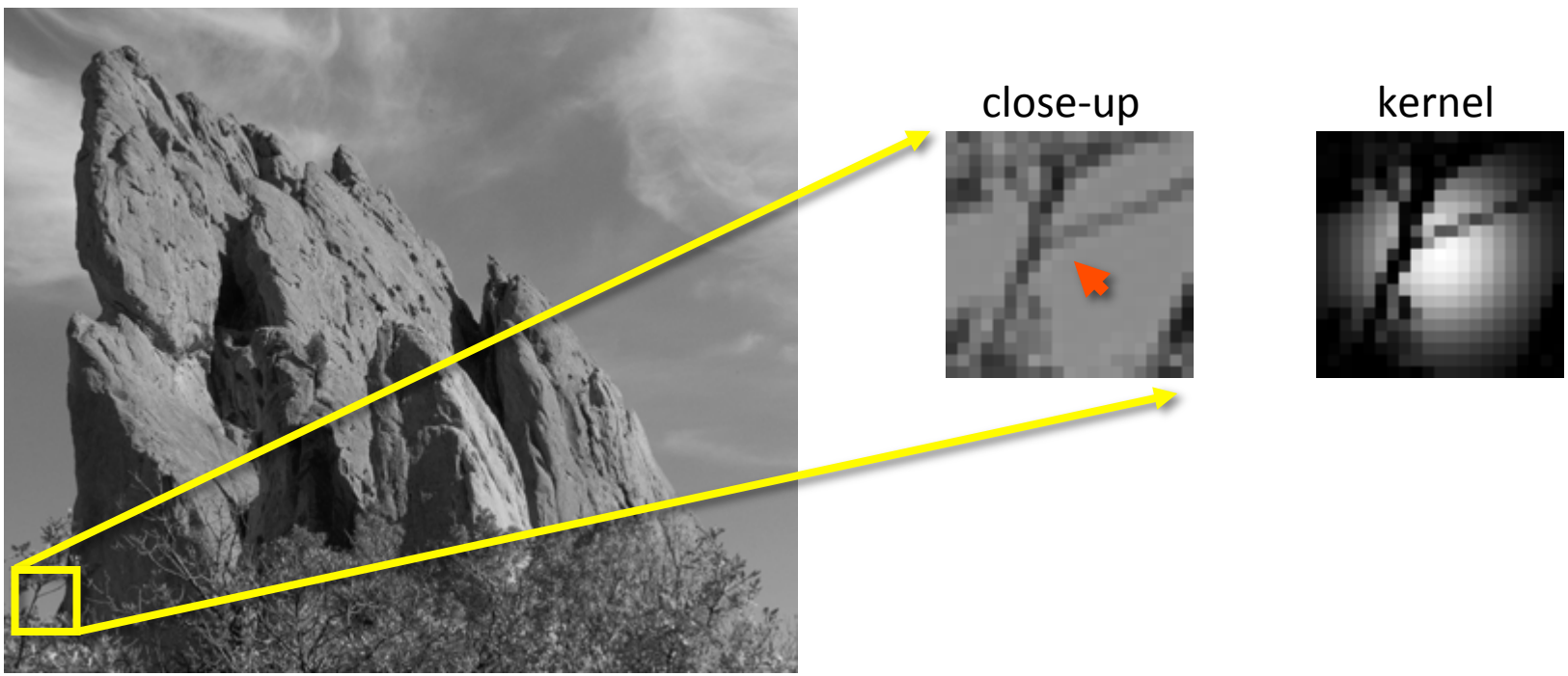
How to Set the Parameters

Depends on the application. For instance:

- space parameter: proportional to image size
  - e.g., 2% of image diagonal
- range parameter: proportional to edge amplitude
  - e.g., mean or median of image gradients
- independent of resolution and exposure

Bilateral Filter Crosses Thin Lines

- Bilateral filter averages across features thinner than ~$2\sigma_s$
- Desirable for smoothing: more pixels = more robust
- Different from diffusion that stops at thin lines



Iterating the Bilateral Filter

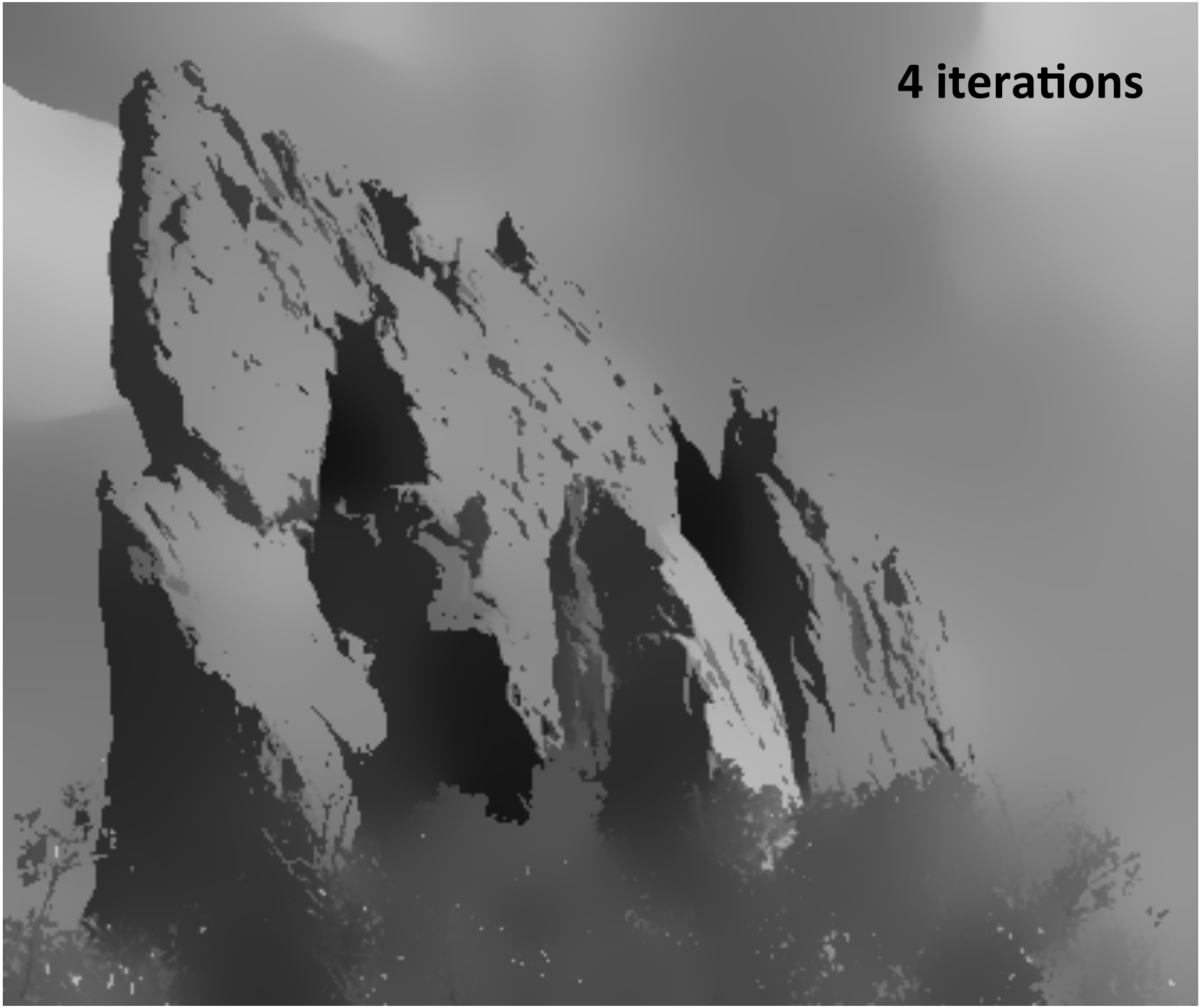
$$I_{(n+1)} = BF[I_{(n)}]$$

- Generate more piecewise-flat images
- Often not needed in computational photo.


input


1 iteration


2 iterations


4 iterations

Bilateral Filtering Color Images

For gray-level images

intensity difference

$$BF[I]_{\mathbf{p}} = \frac{1}{W_{\mathbf{p}}} \sum_{\mathbf{q} \in S} G_{\sigma_s}(\| \mathbf{p} - \mathbf{q} \|) G_{\sigma_r}(| I_{\mathbf{p}} - I_{\mathbf{q}} |) I_{\mathbf{q}}$$

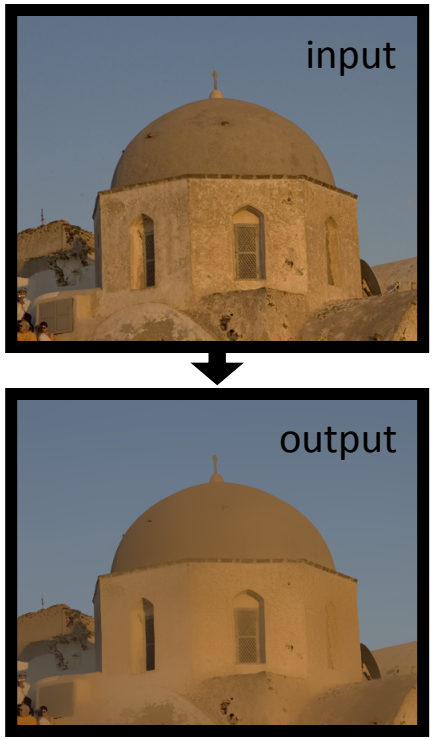
scalar

For color images

color difference

$$BF[I]_{\mathbf{p}} = \frac{1}{W_{\mathbf{p}}} \sum_{\mathbf{q} \in S} G_{\sigma_s}(\| \mathbf{p} - \mathbf{q} \|) G_{\sigma_r}(\| \mathbf{C}_{\mathbf{p}} - \mathbf{C}_{\mathbf{q}} \|) \mathbf{C}_{\mathbf{q}}$$

3D vector
(RGB, Lab)



Hard to Compute

- Nonlinear

$$BF[I]_{\mathbf{p}} = \frac{1}{W_{\mathbf{p}}} \sum_{\mathbf{q} \in S} G_{\sigma_s}(\| \mathbf{p} - \mathbf{q} \|) G_{\sigma_r}(| I_{\mathbf{p}} - I_{\mathbf{q}} |) I_{\mathbf{q}}$$

- Complex, spatially varying kernels
  - Cannot be precomputed, no FFT…

- Brute-force implementation is slow > 10min

<u>Additional Reading:</u> *S. Paris and F. Durand, A Fast Approximation of the Bilateral Filter using a Signal Processing Approach, In Proc. ECCV, 2006*

Basic denoising

Noisy input

Bilateral filter 7x7 window

Basic denoising

Bilateral filter

Median 3x3

Basic denoising

Bilateral filter

Median 5x5

Basic denoising

Bilateral filter

Bilateral filter – lower sigma

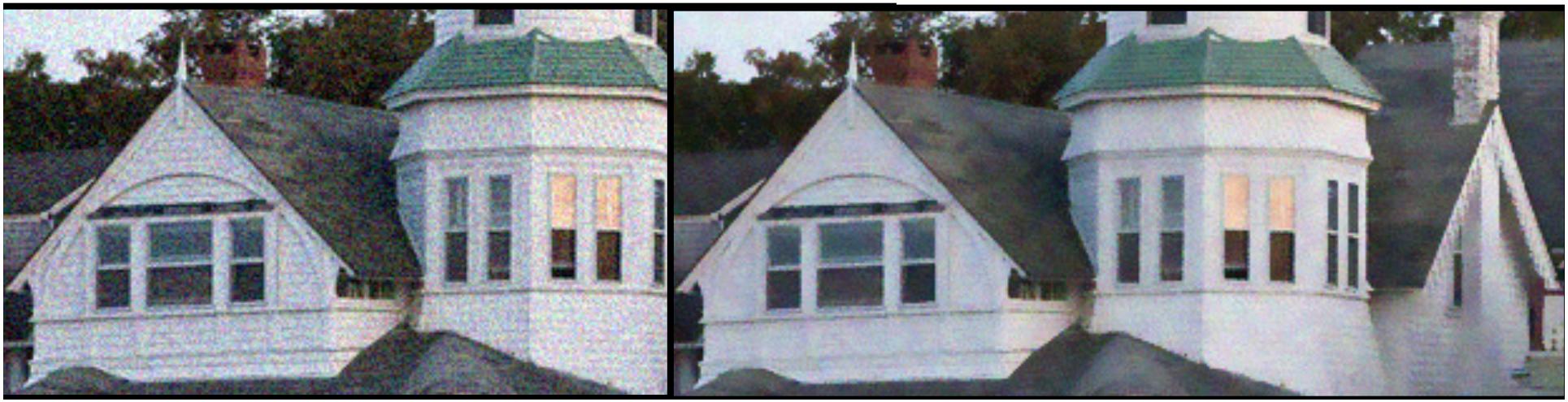
Basic denoising

Bilateral filter

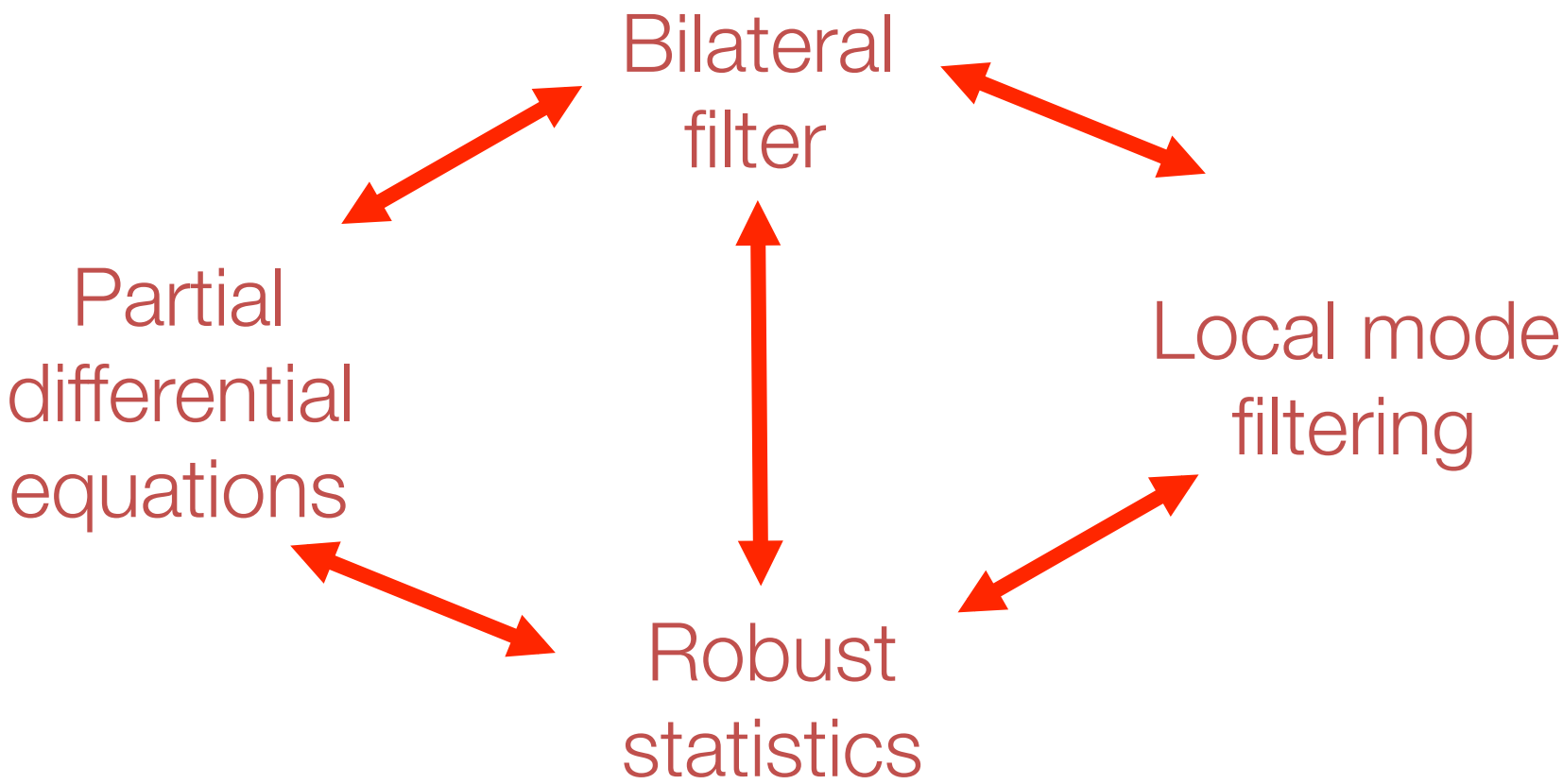
Bilateral filter – higher sigma

Denoising

- Small spatial sigma (e.g. 7x7 window)
- Adapt range sigma to noise level
- Maybe not best denoising method, but best simplicity/quality tradeoff
  - No need for acceleration (small kernel)
  - But the denoising feature in e.g. Photoshop is better



Goal: Understand how does bilateral filter relates with other methods



Today

- Bilateral filtering
- Non-local means denoising
- LARK filter

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New Idea:
NL-Means Filter (Buades 2005)

- Same goals: ‘Smooth within Similar Regions’

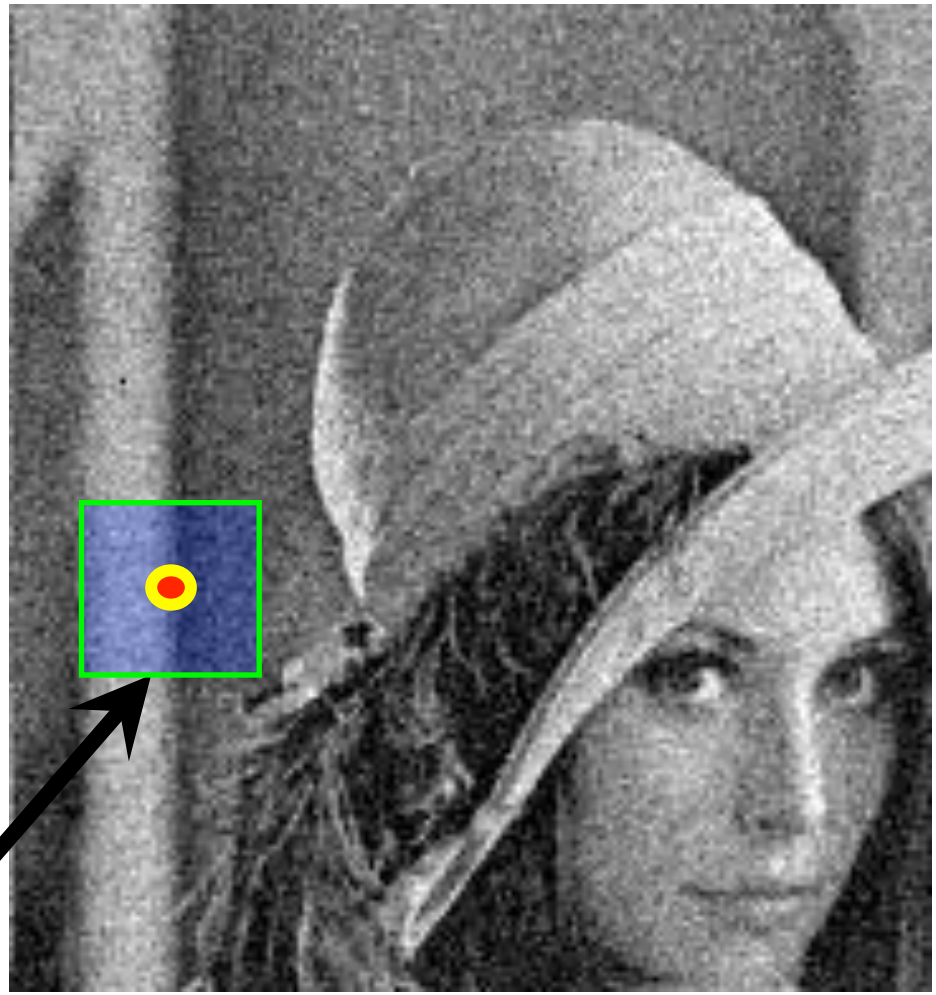
- <u>KEY INSIGHT</u>: Generalize, extend ‘Similarity’
  - Bilateral:
    Averages neighbors with <u>similar intensities</u>;

  - NL-Means:
    Averages neighbors with <u>similar neighborhoods</u>!

NL-Means Method: Buades (2005)

- For each and every pixel **p:**

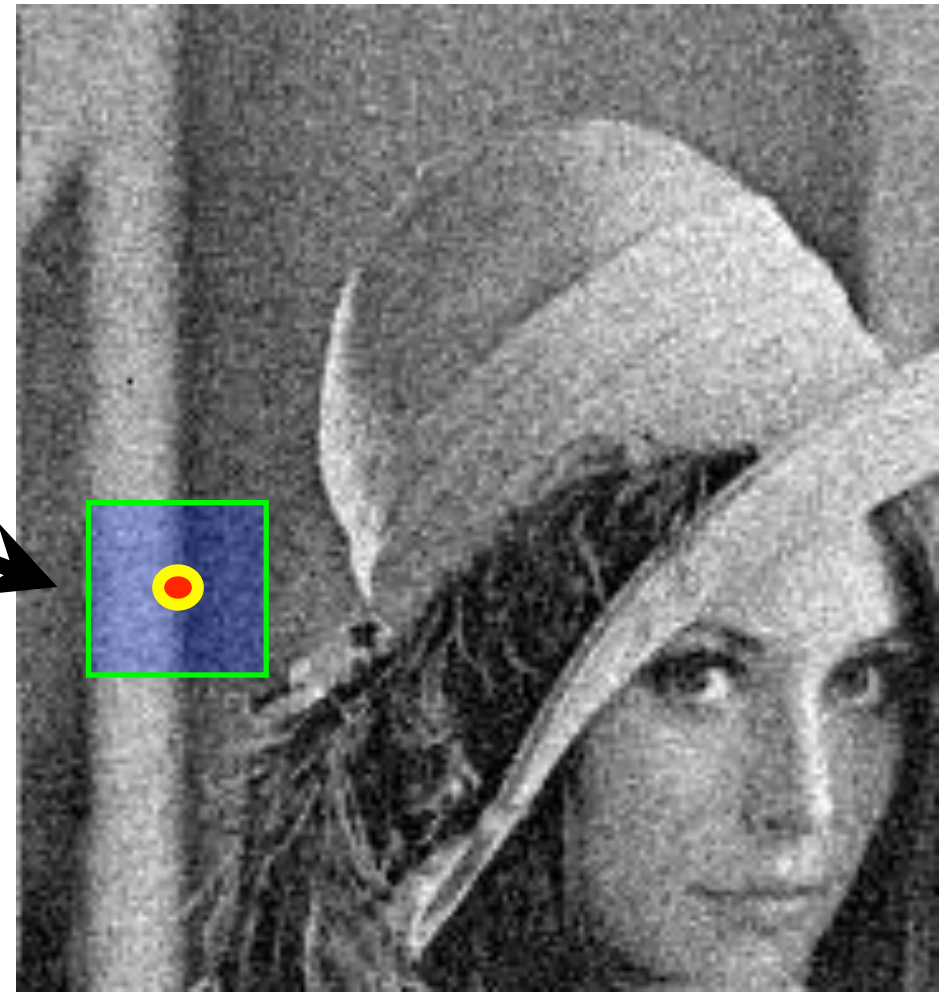
NL-Means Method: Buades (2005)



- For each and every pixel **p:**
  - Define a small, simple fixed size neighborhood;

NL-Means Method: Buades (2005)

$$\mathbf{V_p} = \begin{bmatrix} 0.74 \\ 0.32 \\ 0.41 \\ 0.55 \\ \dots \\ \dots \\ \dots \end{bmatrix}$$



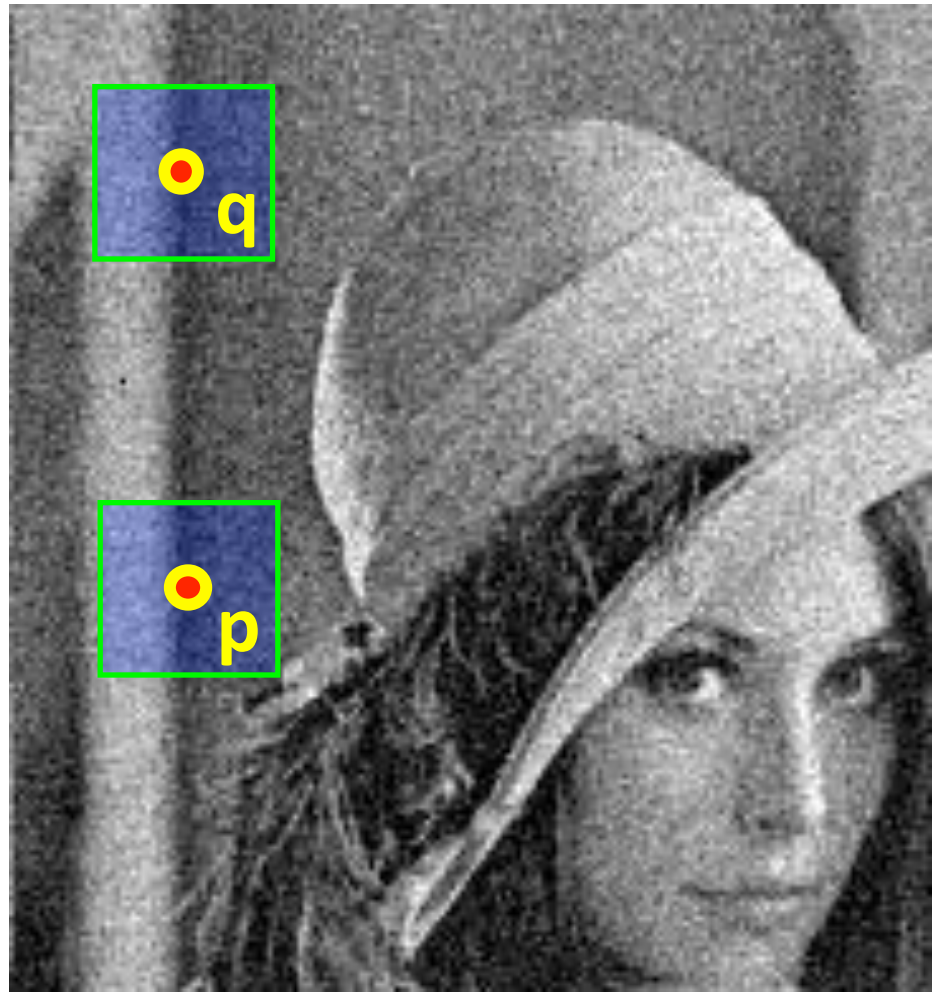
- For each and every pixel **p:**
  - Define a small, simple fixed size neighborhood;
  - Define vector $\mathbf{V_p}$: a list of neighboring pixel values.

NL-Means Method: Buades (2005)

<u>'Similar'</u> pixels **p, q**

→ SMALL vector distance;

$$\| v_p - v_q \|^2$$

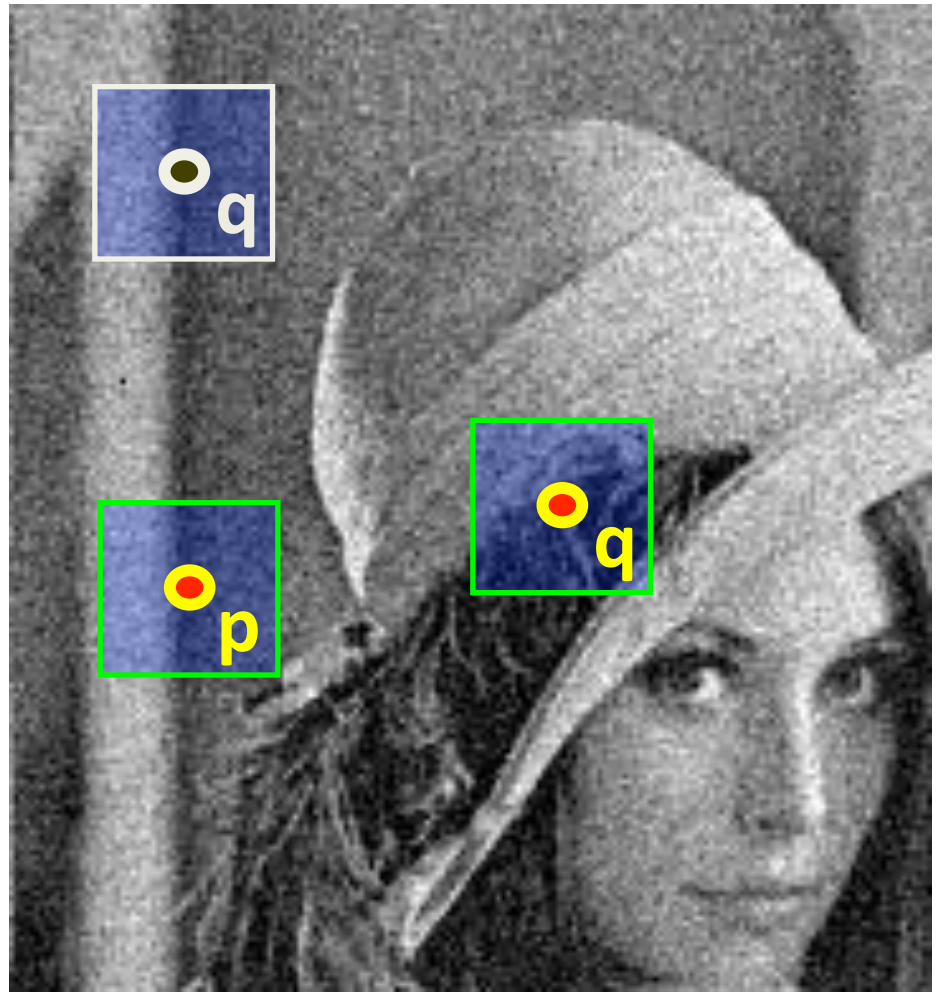


NL-Means Method: Buades (2005)

<u>'Dissimilar'</u> pixels **p, q**

→ LARGE
vector distance;

$$\| v_p - v_q \|^2$$



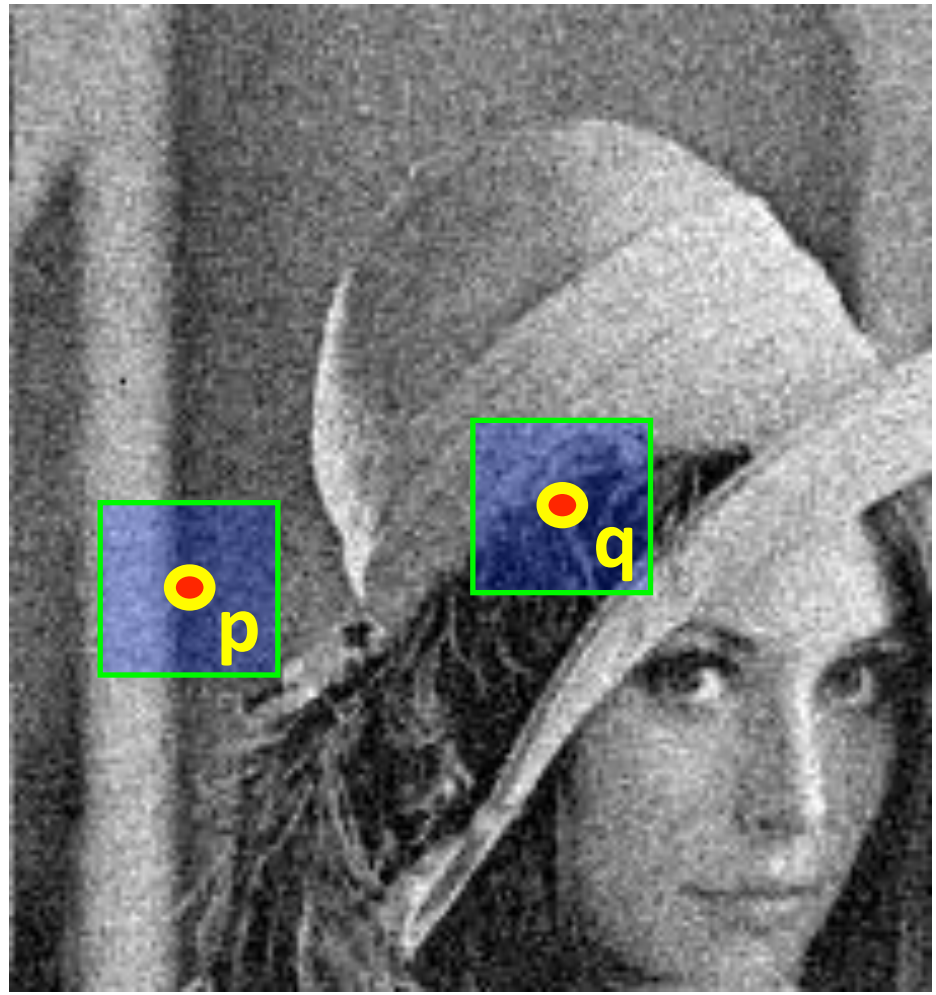
NL-Means Method: Buades (2005)

<u>'Dissimilar'</u> pixels **p, q**

→ LARGE vector distance;

$$\boxed{\| v_p - v_q \|^2}$$

Filter with this!



NL-Means Method: Buades (2005)

p, q neighbors define a vector distance;

$$\boxed{\| v_p - v_q \|^2}$$

Filter with this:

No spatial term!

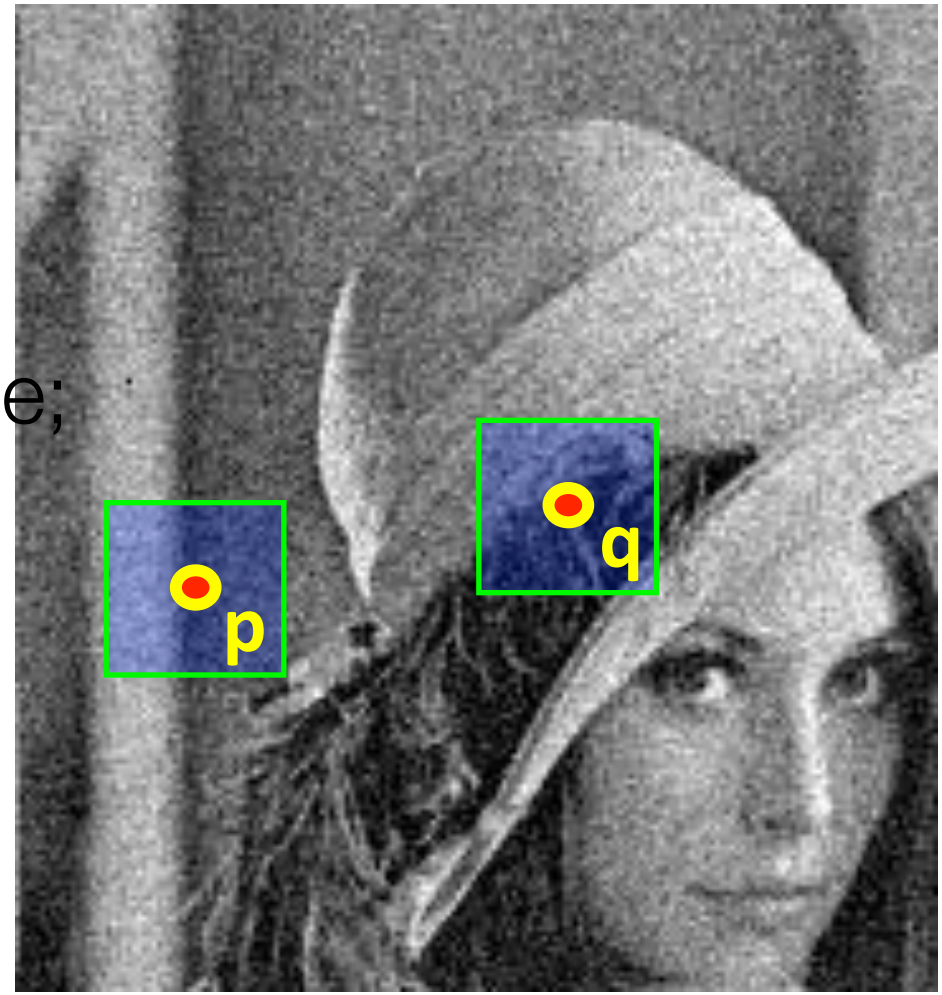
$$NLMF[I]_{\mathbf{p}} = \frac{1}{W_{\mathbf{p}}} \sum_{\mathbf{q} \in S} \cancel{G_{\sigma_s}(\|\mathbf{p}-\mathbf{q}\|)} G_{\sigma_r}\left(\|\vec{V}_{\mathbf{p}} - \vec{V}_{\mathbf{q}}\|^2\right) I_{\mathbf{q}}$$

NL-Means Method: Buades (2005)

pixels **p, q** neighbors
Set a vector distance;

$$\boxed{\| V_p - V_q \|^2}$$

Vector Distance to p sets weight for each pixel q



$$NLMF[I]_{\mathbf{p}} = \frac{1}{W_{\mathbf{p}}} \sum_{\mathbf{q} \in S} G_{\sigma_r}\left(\| \vec{V}_{\mathbf{p}} - \vec{V}_{\mathbf{q}} \|^2\right) I_{\mathbf{q}}$$

NL-Means Method: Buades (2005)

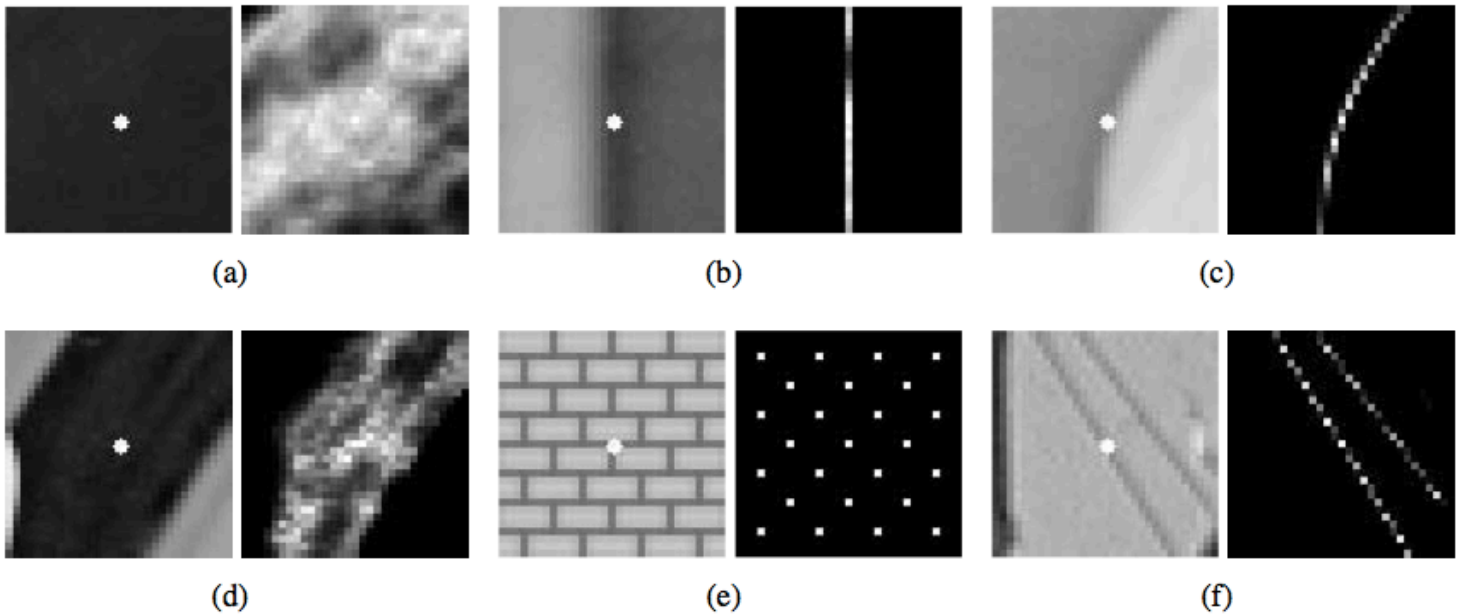


Figure 2. Display of the NL-means weight distribution used to estimate the central pixel of every image. The weights go from 1(white) to zero(black).

NL-Means Method: Buades (2005)

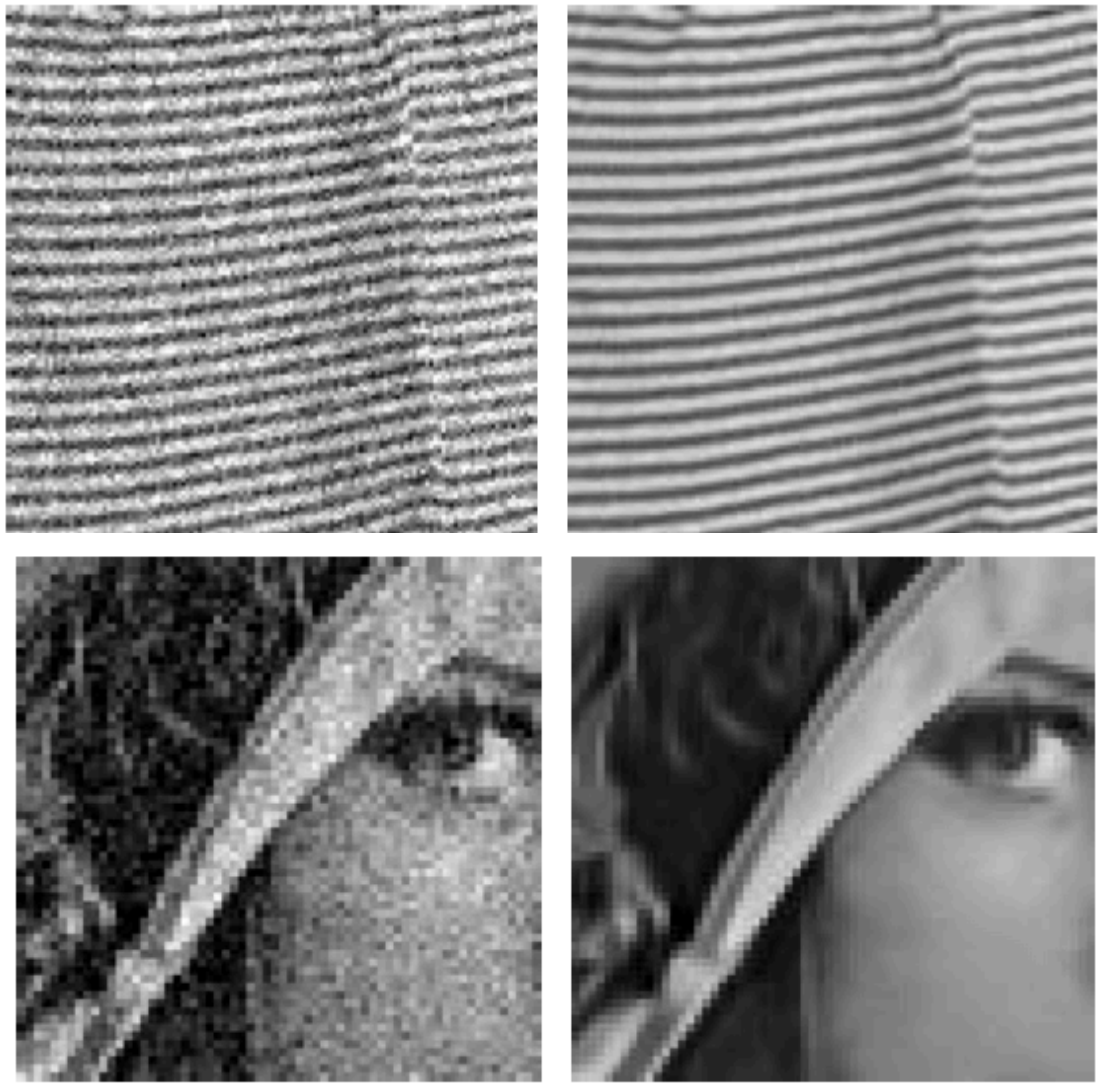


FIG. 9. *NL-means denoising experiment with a natural image. Left: Noisy image with standard deviation* 20. *Right: Restored image.*

NL-Means Method: Buades (2005)

- Noisy source image:

NL-Means Method: Buades (2005)

- Gaussian Filter

Low noise,

Low detail

NL-Means Method: Buades (2005)

- Anisotropic Diffusion

(Note ‘stairsteps’ : ~ piecewise constant)

NL-Means Method: Buades (2005)

- Bilateral Filter

(better, but similar ‘stairsteps’ :

NL-Means Method: Buades (2005)

- NL-Means:

Sharp,
Low noise,
Few artifacts.

NL-Means Method: Buades (2005)

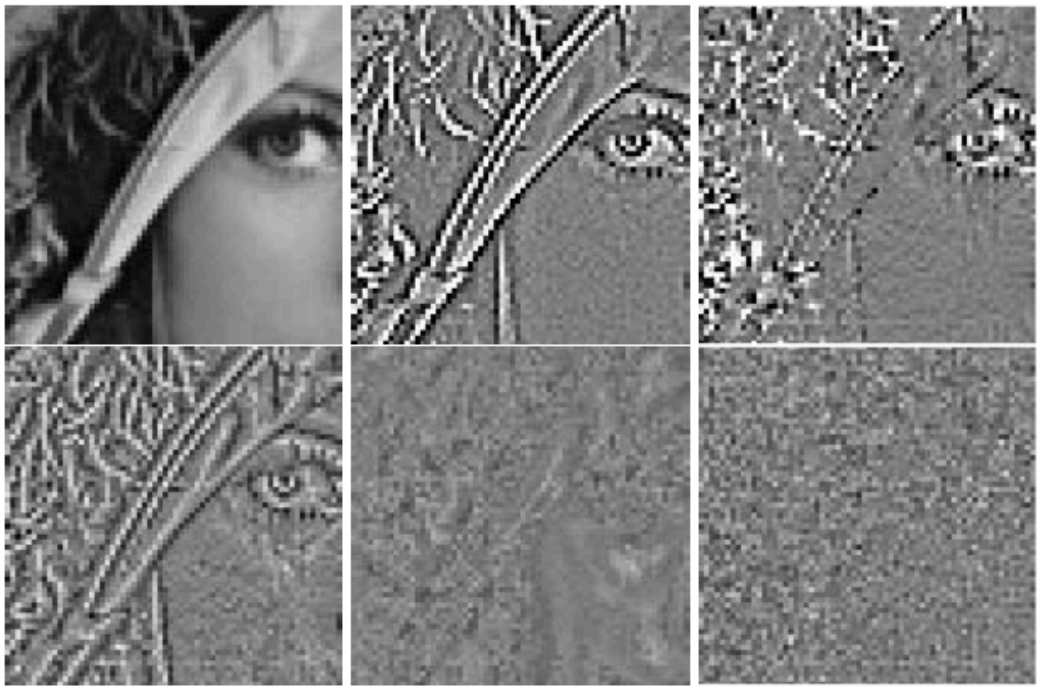


Figure 4. Method noise experience on a natural image. Displaying of the image difference $u - D_h(u)$. From left to right and from top to bottom: original image, Gauss filtering, anisotropic filtering, Total variation minimization, Neighborhood filtering and NL-means algorithm. The visual experiments corroborate the formulas of section 2.

NL-Means Method: Buades (2005)

http://www.ipol.im/pub/algo/bcm_non_local_means_denoising/

NL-Means Method: Buades (2005)

original

http://www.ipol.im/pub/algo/bcm_non_local_means_denoising/

NL-Means Method: Buades (2005)

noisy

http://www.ipol.im/pub/algo/bcm_non_local_means_denoising/

NL-Means Method: Buades (2005)

denoised

http://www.ipol.im/pub/algo/bcm_non_local_means_denoising/

NL-Means Method: Buades (2005)

original

http://www.ipol.im/pub/algo/bcm_non_local_means_denoising/

NL-Means Method: Buades (2005)

noisy

http://www.ipol.im/pub/algo/bcm_non_local_means_denoising/

NL-Means Method: Buades (2005)

denoised

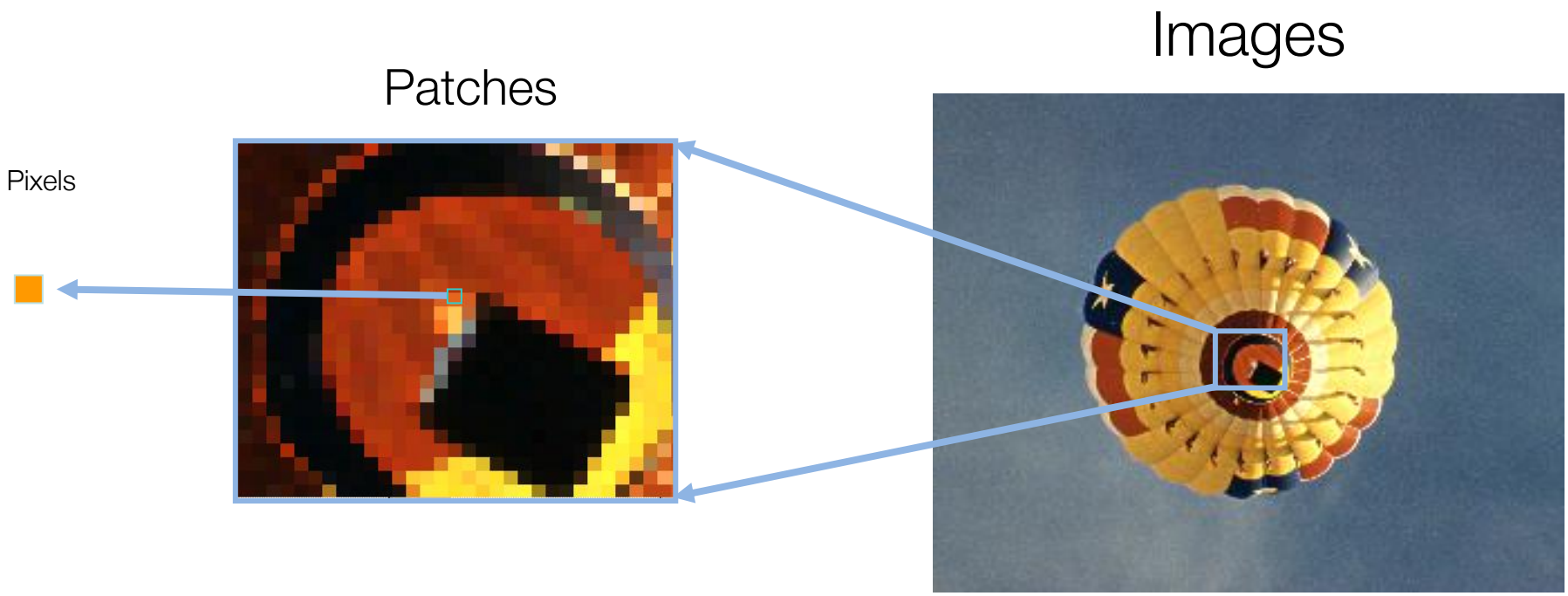
http://www.ipol.im/pub/algo/bcm_non_local_means_denoising/

Today

- Bilateral filtering
- Non-local means denoising
- LARK filter

Acknowledgement: The slides are adapted from the ones prepared by P. Milanfar.

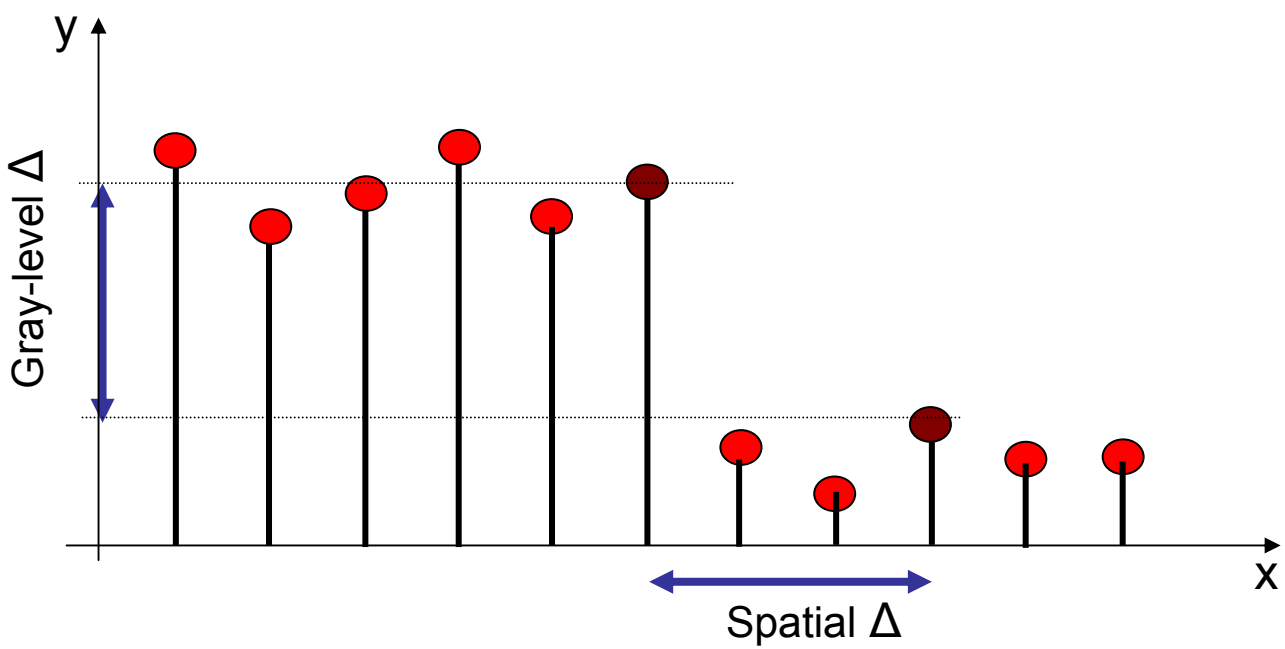
From pixels to patches and to images



Similarities can be defined at different scales..

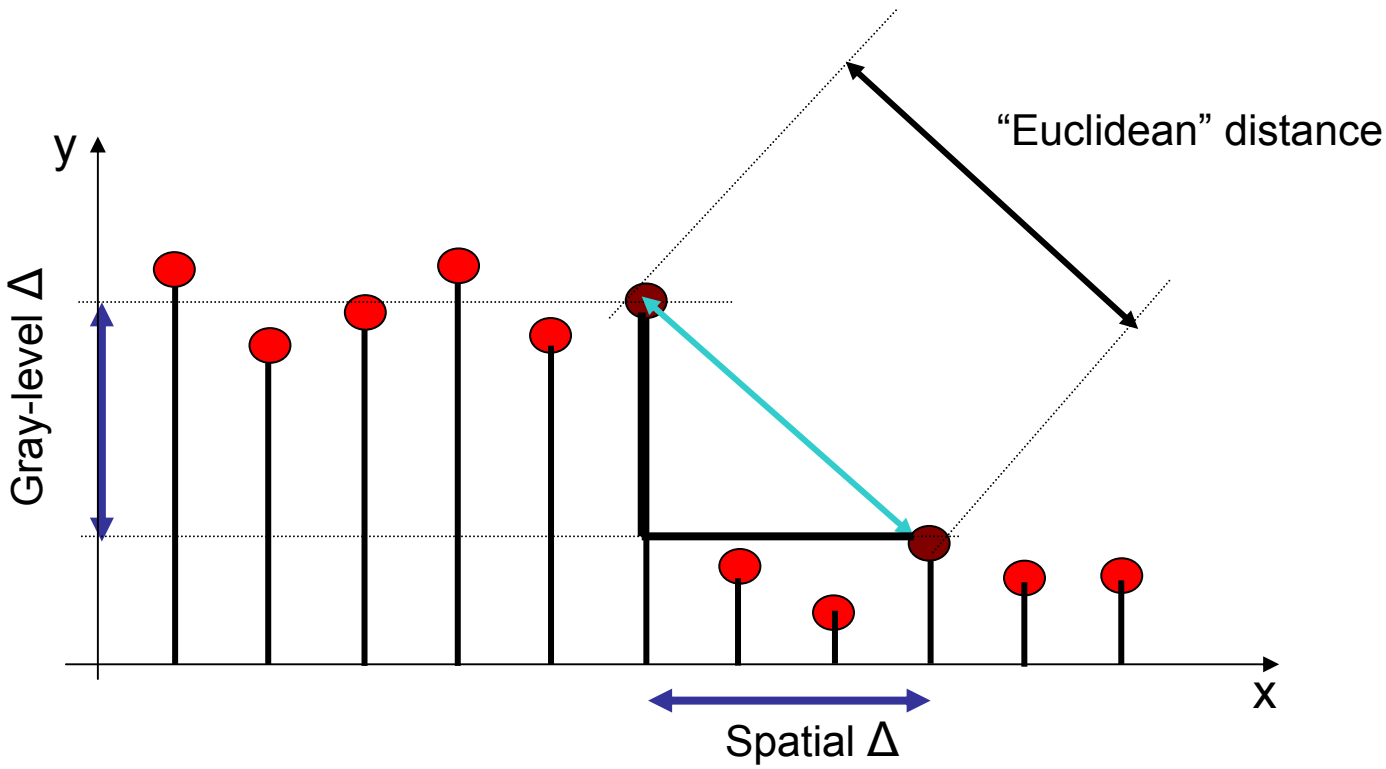
Pixelwise similarity metrics

- To measure the similarity of two pixels, we can consider
  - Spatial distance
  - Gray-level distance



Euclidean metrics

- Natural ways to incorporate the two Δs:
  - Bilateral Kernel [Tomasi, Manduchi, '98] (pixelwise)
  - Non-Local Means Kernel [Buades, et al. '05] (patchwise)

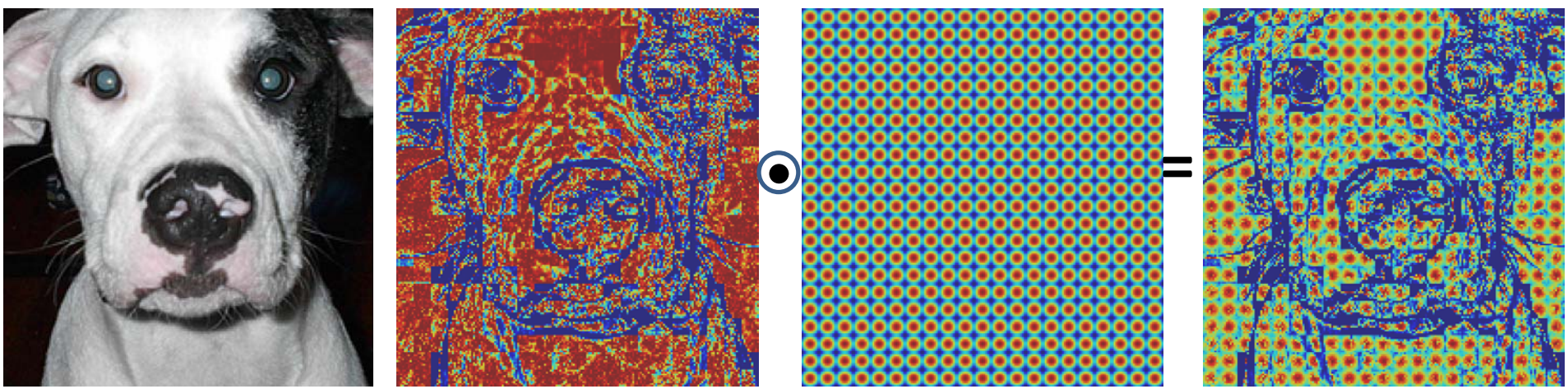


Bilateral Kernel (BL) [Tomasi et al. '98]

Pixels

$$K(\mathbf{x}_l, \mathbf{x}, y_l, y) = \exp\left\{-\frac{\|y_l - y\|^2}{h_r^2} - \frac{\|\mathbf{x}_l - \mathbf{x}\|^2}{h_d^2}\right\}$$

Pixel similarity **Spatial similarity**

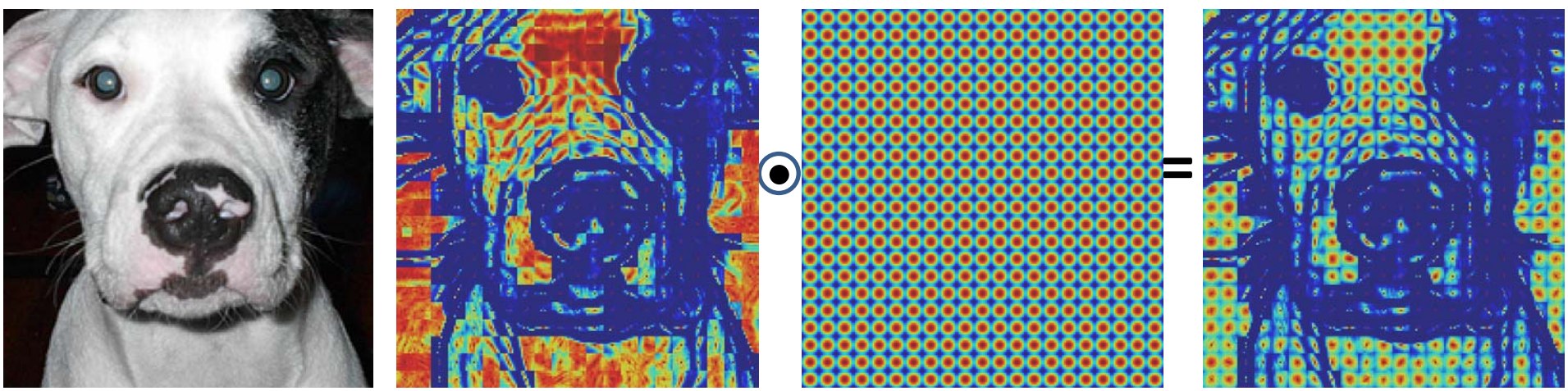


Non-local Means (NLM) [Buades et al. '05]

Patches

$$K(\mathbf{x}_l, \mathbf{x}, \mathbf{y}_l, \mathbf{y}) = \exp\left\{-\frac{\|\mathbf{y}_l - \mathbf{y}\|^2}{h_r^2} - \frac{\|\mathbf{x}_l - \mathbf{x}\|^2}{h_d^2}\right\}$$

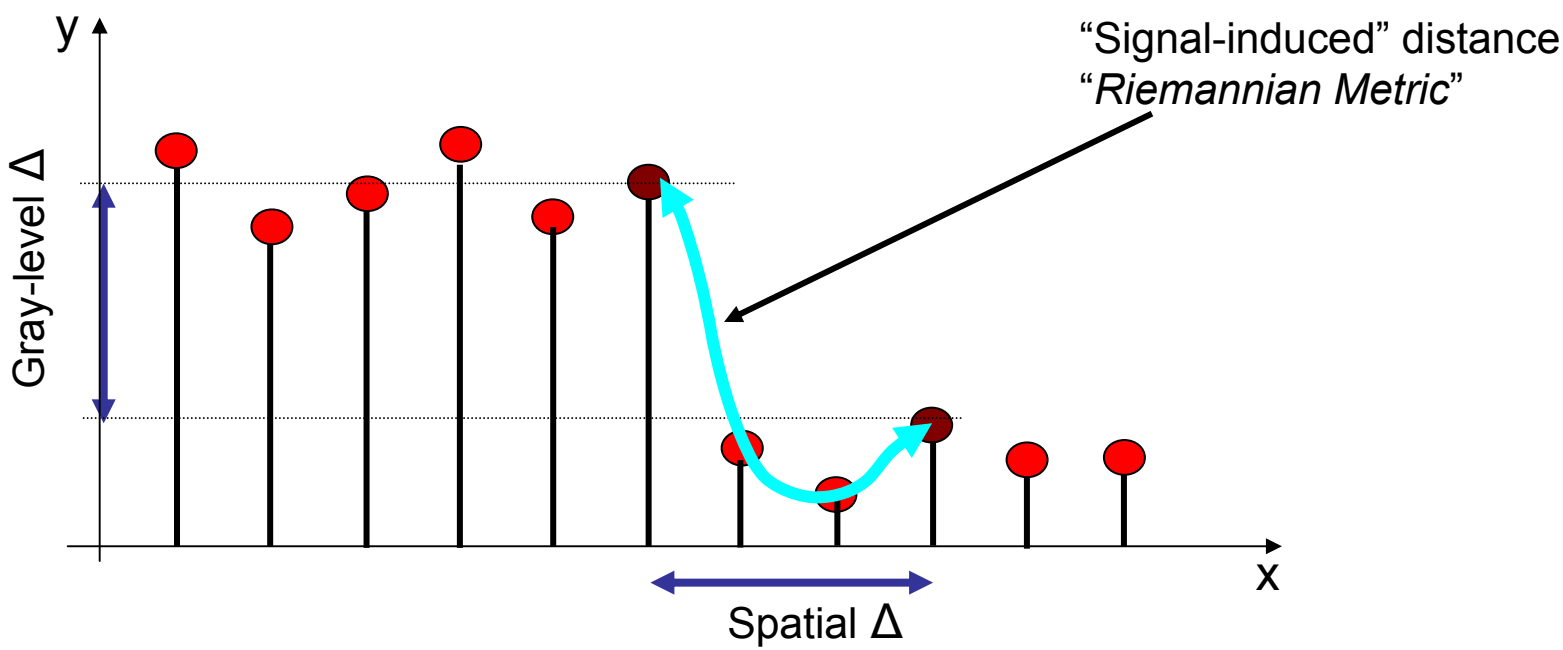
Patch similarity **Spatial similarity**



Smoothing effect

Beyond Euclidean metrics

- Better similarity measures
- More effective ways to combine the two Δs:
  - LARK Kernel [Takeda, et al. '07]
  - Beltrami Kernel [Sochen, et al.'98]



Non-parametric Kernel Regression

- The data fitting problem

Zero-mean, i.i.d noise (No other assump.)

$$y_i = z(\mathbf{x}_i) + \varepsilon_i, \qquad i = 1, 2, \cdots, P$$

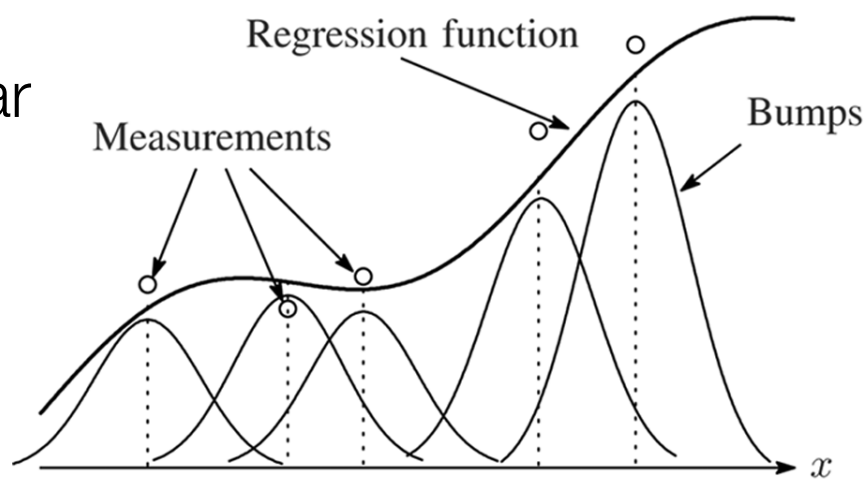
Given samples

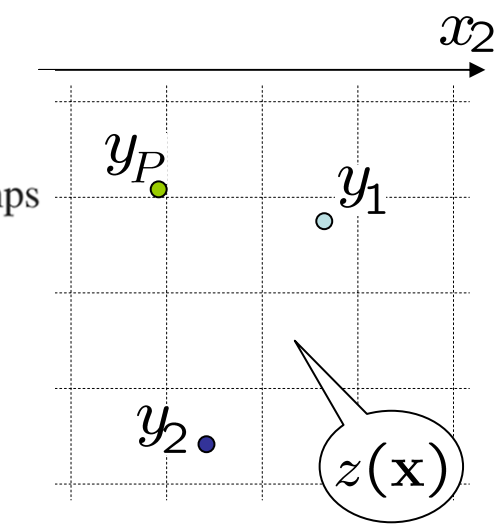
The regression function

The sampling position

The number of samples

- The particular form of z(x) may remain unspecified for now.





Locality in Kernel Regression

- The data model

$$y_i = z(\mathbf{x}_i) + \varepsilon_i, \quad i = 1, 2, \cdots, P$$

- Local representation (N-term Taylor series expansion)

$$\begin{aligned} z(x_i) \approx\, & z(x) + z'(x)(x_i - x) + \frac{1}{2!} z''(x)(x_i - x)^2 \\ & + \cdots + \frac{1}{N!} z^{(N)}(x)(x_i - x)^N \\ =\, & \beta_0 + \beta_1(x_i - x) + \beta_2(x_i - x)^2 \\ & + \cdots + \beta_N(x_i - x)^N. \end{aligned}$$

- Note that with a polynomial basis, we only need to estimate the first unknown β_0

Locality in Kernel Regression

- The data model

$$y_i = z(\mathbf{x}_i) + \varepsilon_i, \quad i = 1, 2, \cdots, P$$

- Local representation (N-term Taylor series expansion)

$$\begin{aligned} z(\mathbf{x}_i) &= \boxed{z(\mathbf{x})} + \boxed{\{\boldsymbol{\nabla} z(\mathbf{x})\}^T}(\mathbf{x}_i - \mathbf{x}) + \boxed{\frac{1}{2!}}(\mathbf{x}_i - \mathbf{x})^T \boxed{\{\boldsymbol{\mathcal{H}} z(\mathbf{x})\}}(\mathbf{x}_i - \mathbf{x}) + \cdots \\ &= \boxed{\beta_0} + \boxed{\boldsymbol{\beta}_1^T}(\mathbf{x}_i - \mathbf{x}) + \boxed{\boldsymbol{\beta}_2^T} \text{vech}\left\{(\mathbf{x}_i - \mathbf{x})(\mathbf{x}_i - \mathbf{x})^T\right\} + \cdots, \end{aligned}$$

Unknowns

- Note that with a polynomial basis, we only need to estimate the first unknown β_0

Finding the unknowns via optimization

- We have a local representation with respect to each sample:

$$
\begin{aligned}
y_1 &= \beta_0 + \boldsymbol{\beta}_1^T (\mathbf{x}_1 - \mathbf{x}) + \boldsymbol{\beta}_2^T \,\mathsf{vech}\left\{(\mathbf{x}_1 - \mathbf{x})(\mathbf{x}_1 - \mathbf{x})^T\right\} + \cdots + \varepsilon_1, \\
y_2 &= \beta_0 + \boldsymbol{\beta}_1^T (\mathbf{x}_2 - \mathbf{x}) + \boldsymbol{\beta}_2^T \,\mathsf{vech}\left\{(\mathbf{x}_2 - \mathbf{x})(\mathbf{x}_2 - \mathbf{x})^T\right\} + \cdots + \varepsilon_2, \\
&\vdots \qquad\qquad\qquad\qquad\qquad \vdots \\
y_P &= \beta_0 + \boldsymbol{\beta}_1^T (\mathbf{x}_P - \mathbf{x}) + \boldsymbol{\beta}_2^T \,\mathsf{vech}\left\{(\mathbf{x}_P - \mathbf{x})(\mathbf{x}_P - \mathbf{x})^T\right\} + \cdots + \varepsilon_P,
\end{aligned}
$$

- Estimate the parameters $\{\beta_n\}_{n=0}^{N}$ from the data while giving the nearby samples higher weight than samples farther away.

$$
\min_{\{\beta_n\}} \sum_{i=1}^{P} \left[y_i - \beta_0 - \beta_1(x_i - x) - \beta_2(x_i - x)^2 - \cdots - \beta_N(x_i - x)^N\right]^2 \frac{1}{h} K\left(\frac{x_i - x}{h}\right)
$$

Finding the unknowns via optimization

- We have a local representation with respect to each sample:

$$
\begin{aligned}
y_1 &= \beta_0 + \boldsymbol{\beta}_1^T (\mathbf{x}_1 - \mathbf{x}) + \boldsymbol{\beta}_2^T \,\mathrm{vech}\left\{(\mathbf{x}_1 - \mathbf{x})(\mathbf{x}_1 - \mathbf{x})^T\right\} + \cdots + \varepsilon_1, \\
y_2 &= \beta_0 + \boldsymbol{\beta}_1^T (\mathbf{x}_2 - \mathbf{x}) + \boldsymbol{\beta}_2^T \,\mathrm{vech}\left\{(\mathbf{x}_2 - \mathbf{x})(\mathbf{x}_2 - \mathbf{x})^T\right\} + \cdots + \varepsilon_2, \\
&\vdots \qquad\qquad\qquad\qquad \vdots \\
y_P &= \beta_0 + \boldsymbol{\beta}_1^T (\mathbf{x}_P - \mathbf{x}) + \boldsymbol{\beta}_2^T \,\mathrm{vech}\left\{(\mathbf{x}_P - \mathbf{x})(\mathbf{x}_P - \mathbf{x})^T\right\} + \cdots + \varepsilon_P,
\end{aligned}
$$

- Optimization

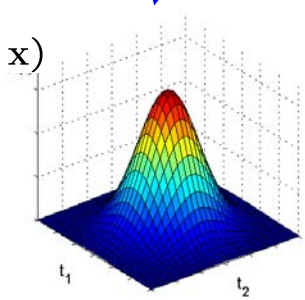
The regression order

$$
\min_{\{\boldsymbol{\beta}_n\}_{n=0}^{N}} \sum_{i=1}^{P} \Big[y_i - \overbrace{\beta_0 - \boldsymbol{\beta}_1^T(\mathbf{x}_i - \mathbf{x}) - \boldsymbol{\beta}_2^T \mathrm{vech}\left\{(\mathbf{x}_i - \mathbf{x})(\mathbf{x}_i - \mathbf{x})^T\right\} - \cdots}^{\text{N+1 terms}} \Big]^2 \mathrm{K}(\mathbf{x}_i - \mathbf{x})
$$

This term give the estimated pixel value z(x).

The choice of the kernel function is open, e.g. Gaussian.

$\mathrm{K}(\mathbf{x}_i - \mathbf{x})$



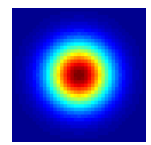
$$
\boxed{\hat{z}(\mathbf{x}) = \sum_{i=1}^{P} W_i(\mathbf{x}, K, h, N)\, y_i}
$$

Defining Data-Adaptive Kernels

- *Classic* Kernel: Locally Linear Filter:

$$\hat{z}(\mathbf{x}) = \hat{\beta}_0 = \sum_i W(\mathbf{x}_i, \mathbf{x}, N)\, y_i$$

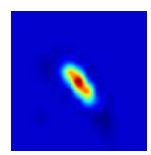
Uses distance $x-x_i$



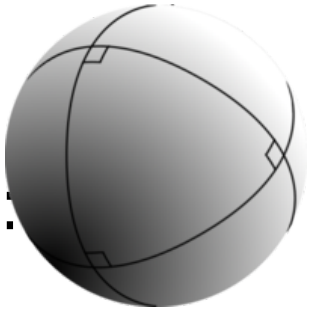
- *Data-Adaptive* Kernel:
  Locally Non-Linear Filter:

$$\hat{z}(\mathbf{x}) = \hat{\beta}_0 = \sum_i W(\mathbf{x}_i, \mathbf{x}, y_i, y, N)\, y_i$$

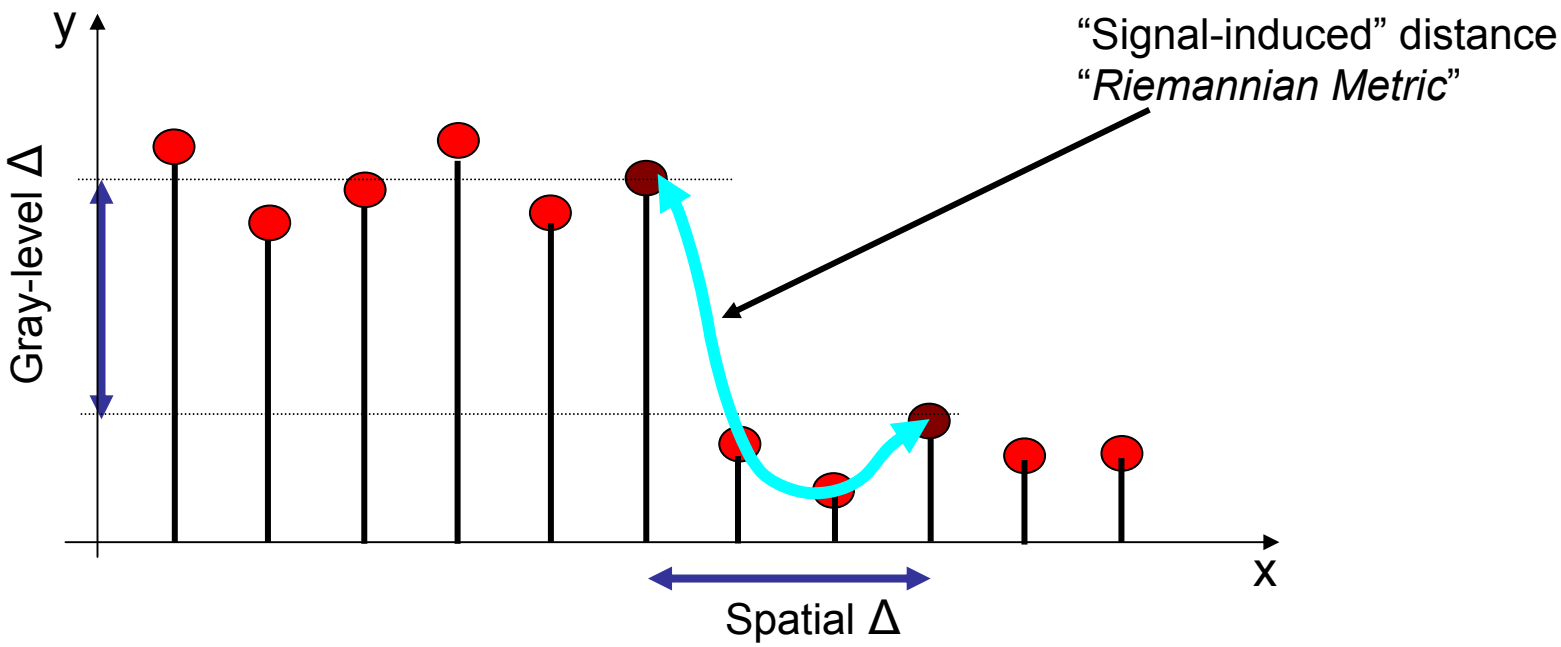
Uses $x-x_i$ and $y-y_i$



Recall - Beyond Euclidean metrics

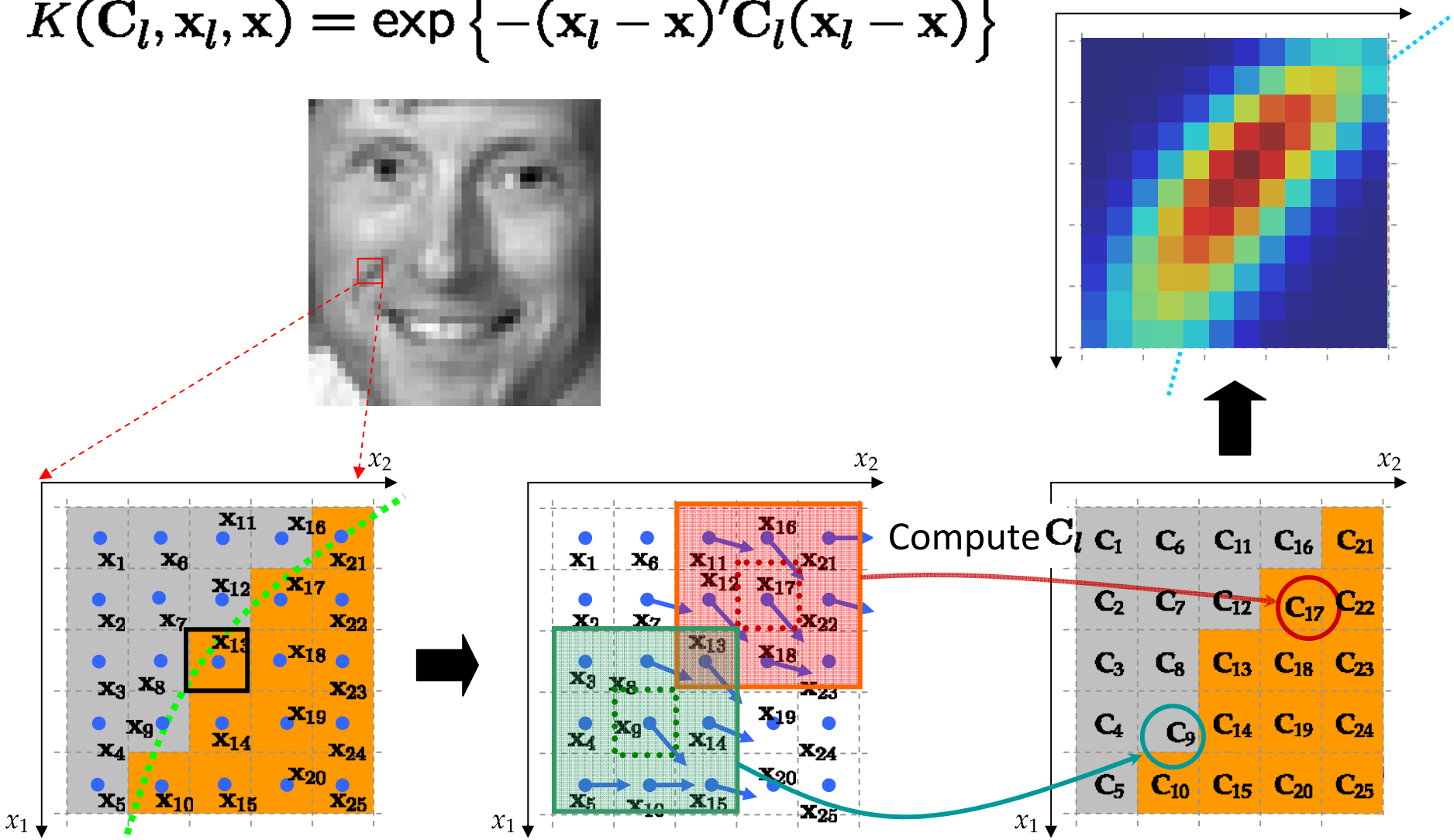


- Better similarity measures
- More effective ways to combine the two Δs:
  - LARK Kernel [Takeda, et al. '07]
  - Beltrami Kernel [Sochen, et al.'98]

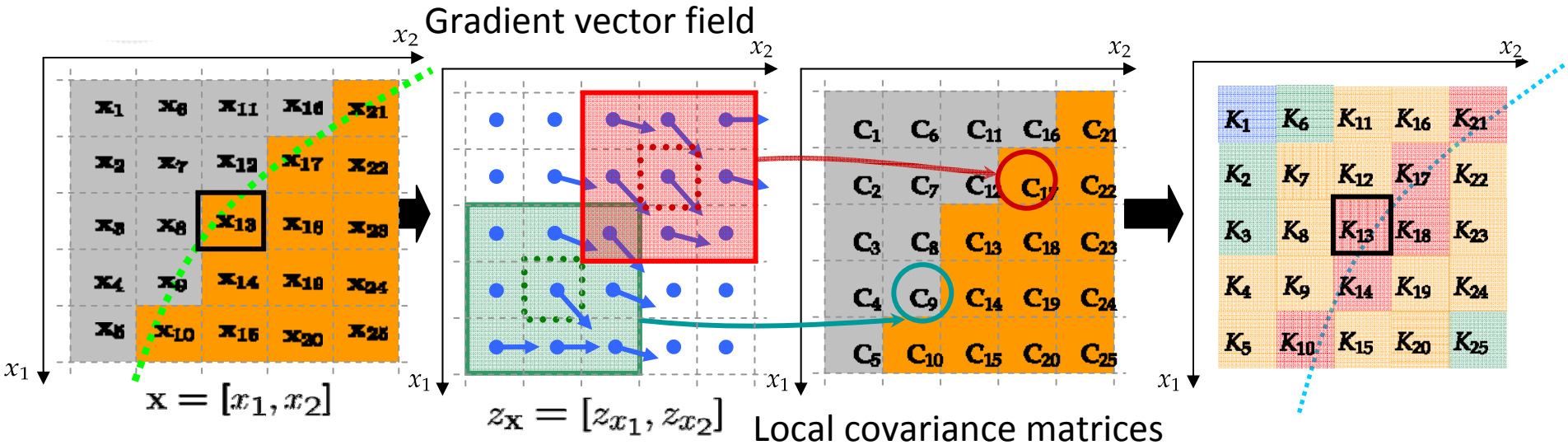


LARK Kernels

$$K(\mathbf{C}_l, \mathbf{x}_l, \mathbf{x}) = \exp\left\{-(\mathbf{x}_l - \mathbf{x})'\mathbf{C}_l(\mathbf{x}_l - \mathbf{x})\right\}$$



LARK Kernels



Locally Adaptive Regression Kernel: LARK

$$K(\mathbf{C}_l, \mathbf{x}_l, \mathbf{x}) = \exp\left\{-(\mathbf{x}_l - \mathbf{x})'\underline{\mathbf{C}_l}(\mathbf{x}_l - \mathbf{x})\right\}$$

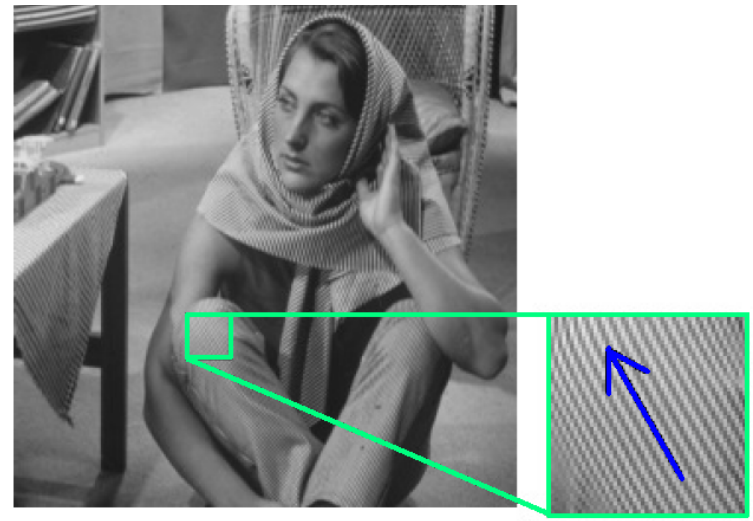
"Structure tensor"

$$\mathbf{C}_l = \sum_{k \in \Omega_l} \begin{bmatrix} z_{x_1}^2(\mathbf{x}_k) & z_{x_1}(\mathbf{x}_k) z_{x_2}(\mathbf{x}_k) \\ z_{x_1}(\mathbf{x}_k) z_{x_2}(\mathbf{x}_k) & z_{x_2}^2(\mathbf{x}_k) \end{bmatrix}$$

Gradient Covariance Matrix and Local Geometry

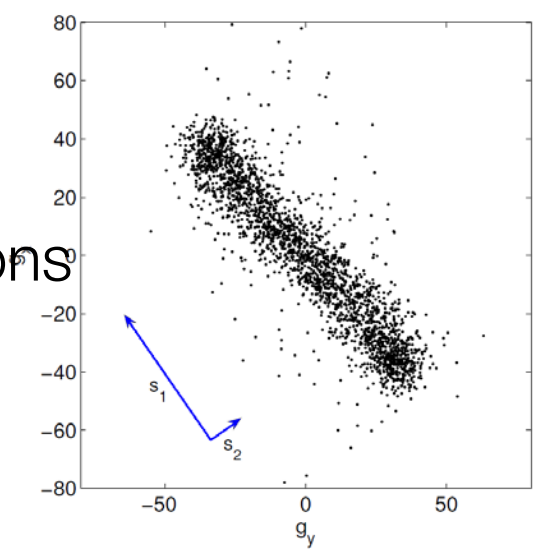
Gradient matrix over a local patch:

$$\mathbf{C}_l = \sum_{k \in \Omega_l} \begin{bmatrix} z_{x_1}^2(\mathbf{x}_k) & z_{x_1}(\mathbf{x}_k) z_{x_2}(\mathbf{x}_k) \\ z_{x_1}(\mathbf{x}_k) z_{x_2}(\mathbf{x}_k) & z_{x_2}^2(\mathbf{x}_k) \end{bmatrix}$$



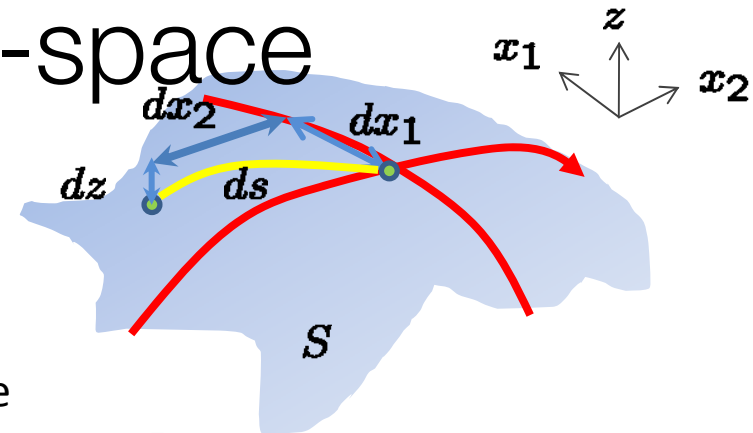
$$\mathbf{C}_l = \mathbf{G}^{\mathbf{T}} \mathbf{G}$$

$$\mathbf{G} = \mathbf{U}\mathbf{S}\mathbf{V}^T = \mathbf{U} \begin{bmatrix} s_1 & 0 \\ 0 & s_2 \end{bmatrix} \begin{bmatrix} \mathbf{v}_1 & \mathbf{v}_2 \end{bmatrix}^T$$



Capturing locally dominant orientations

Image as a Surface Embedded in the Euclidean 3-space



$$S(x_1, x_2) = \{x_1, x_2, z(x_1, x_2)\} \in \mathbb{R}^3$$

Arclength on the surface

$$\begin{aligned} ds^2 &= dx_1^2 + dx_2^2 + dz^2 \\ &= dx_1^2 + dx_2^2 + (z_{x_1} dx_1 + z_{x_2} dx_2)^2 \\ &= (1 + z_{x_1}^2) dx_1^2 + 2 z_{x_1} z_{x_2} dx_1 dx_2 + (1 + z_{x_2}^2) dx_2^2 \end{aligned}$$

Chain rule

$$= (dx_1 \quad dx_2) \begin{pmatrix} 1 + z_{x_1}^2 & z_{x_1} z_{x_2} \\ z_{x_1} z_{x_2} & 1 + z_{x_2}^2 \end{pmatrix} \begin{pmatrix} dx_1 \\ dx_2 \end{pmatrix}$$

$$\Rightarrow (\mathbf{x}_l - \mathbf{x})^T (\mathbf{C}_l + \mathbf{I})(\mathbf{x}_l - \mathbf{x})$$

Riemannian metric

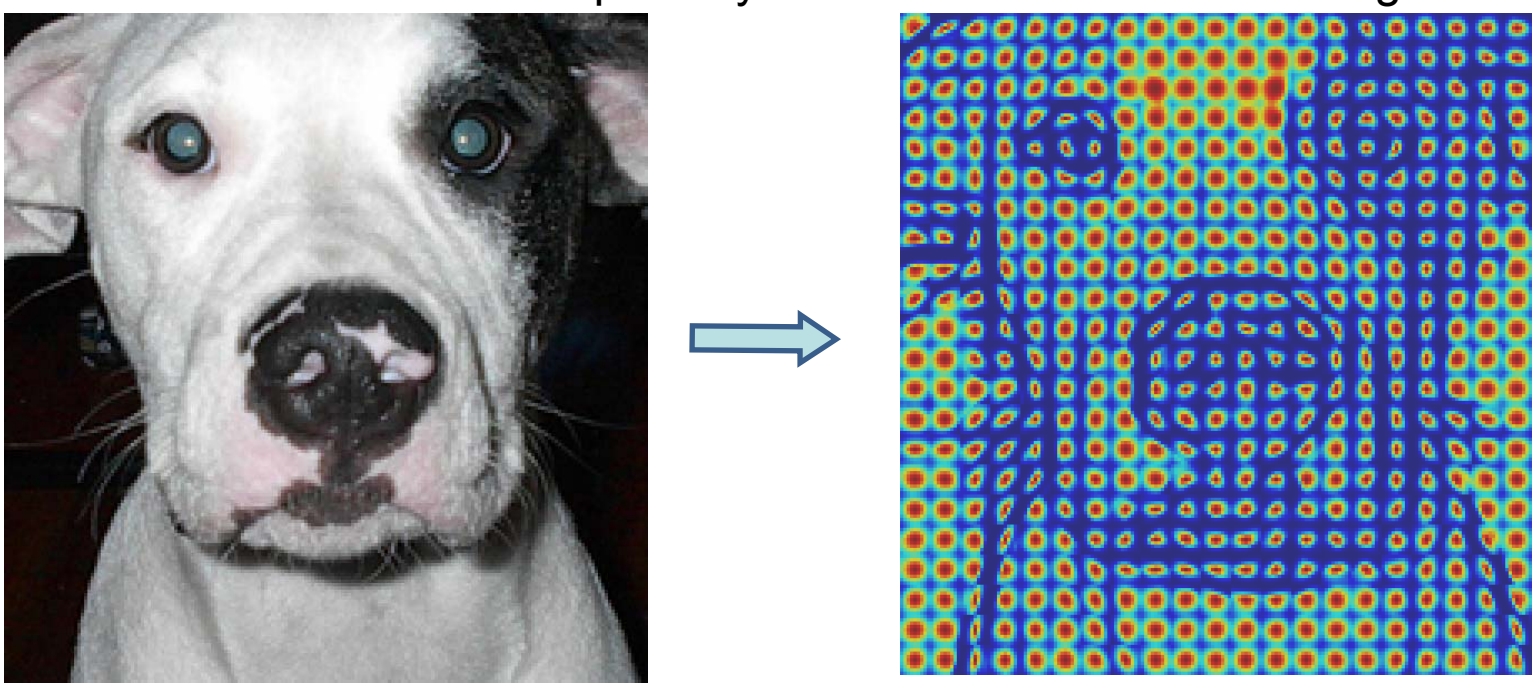
Regularization term

$$K(\mathbf{C}_l, \mathbf{x}_l, \mathbf{x}) = \exp\left\{-(\mathbf{x}_l - \mathbf{x})' \mathbf{C}_l (\mathbf{x}_l - \mathbf{x})\right\}$$

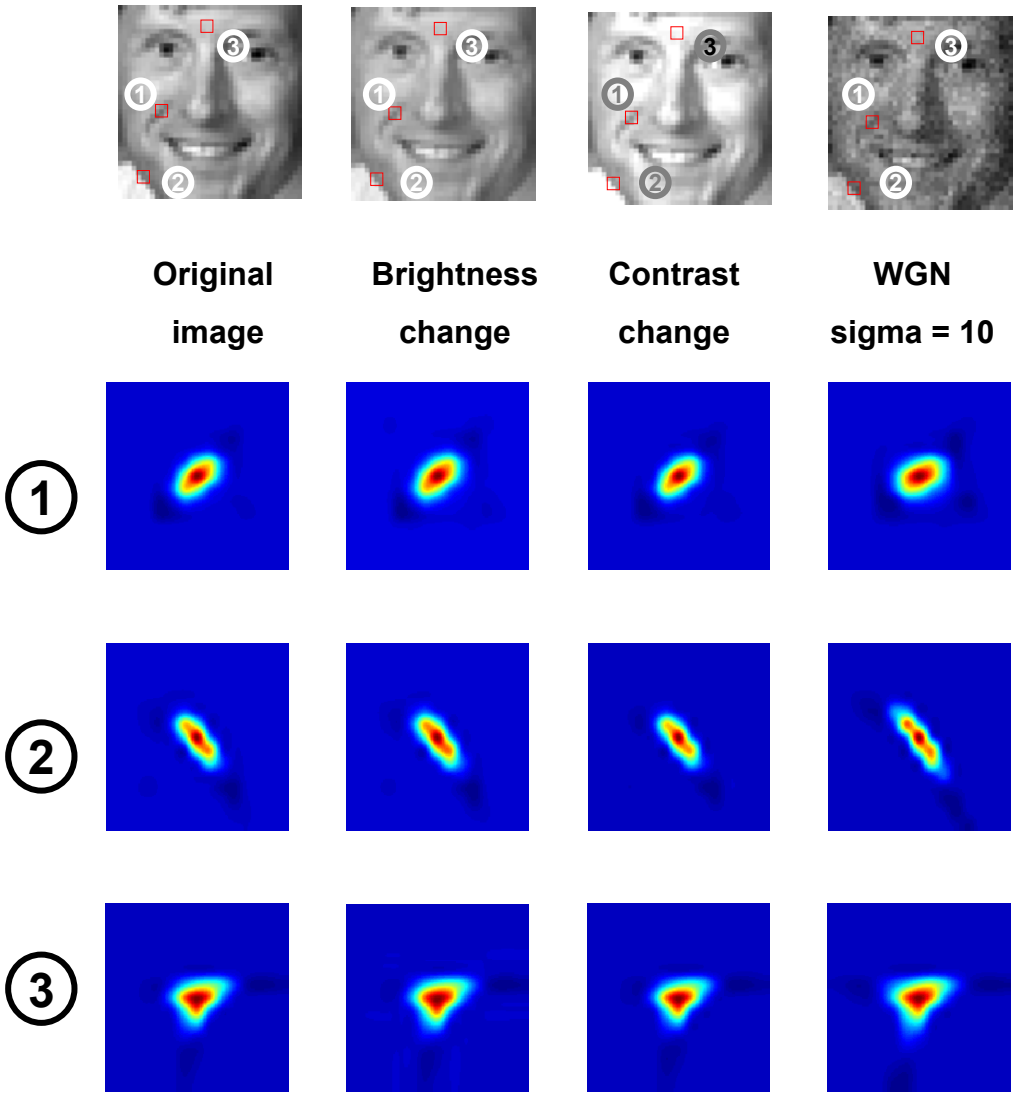
(Dense) LARK Kernels as Visual Descriptors [Seo and Milanfar '10]

$$K(\mathbf{C}_l, \mathbf{x}_l, \mathbf{x}) = \exp\left\{-\underbrace{(\mathbf{x}_l - \mathbf{x})'\mathbf{C}_l(\mathbf{x}_l - \mathbf{x})}\right\}$$

Measure the similarity of pixels using the metric implied by the local structure of the image

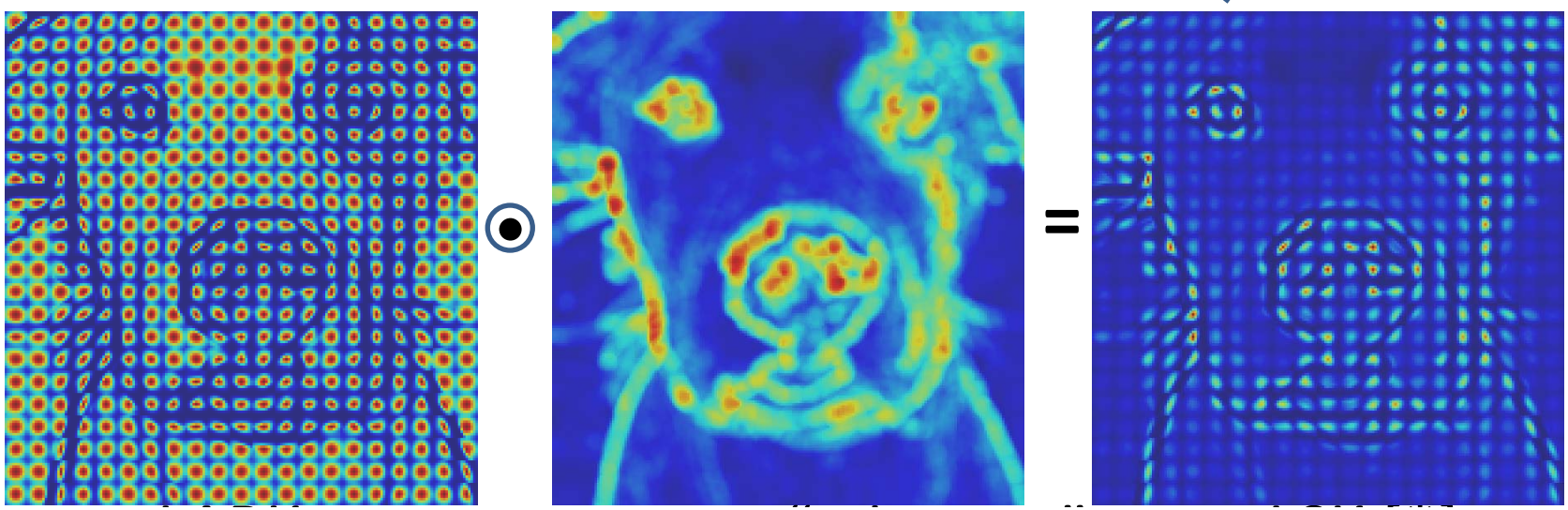


Robustness of LARK Descriptors



A Variant Better-suited for Restoration [Takeda et al. ’07]

$$K(\mathbf{C}_l, \mathbf{x}_l, \mathbf{x}) = \sqrt{\det \mathbf{C}_l} \exp\left\{-(\mathbf{x}_l - \mathbf{x})' \mathbf{C}_l (\mathbf{x}_l - \mathbf{x})\right\}$$



LARK Edge strength LSK

Film Grain Reduction (Real Noise)

Noisy image

Film Grain Reduction (Real Noise)

LARK

Film Grain Reduction (Real Noise)

LARK

KSVD

BM3D

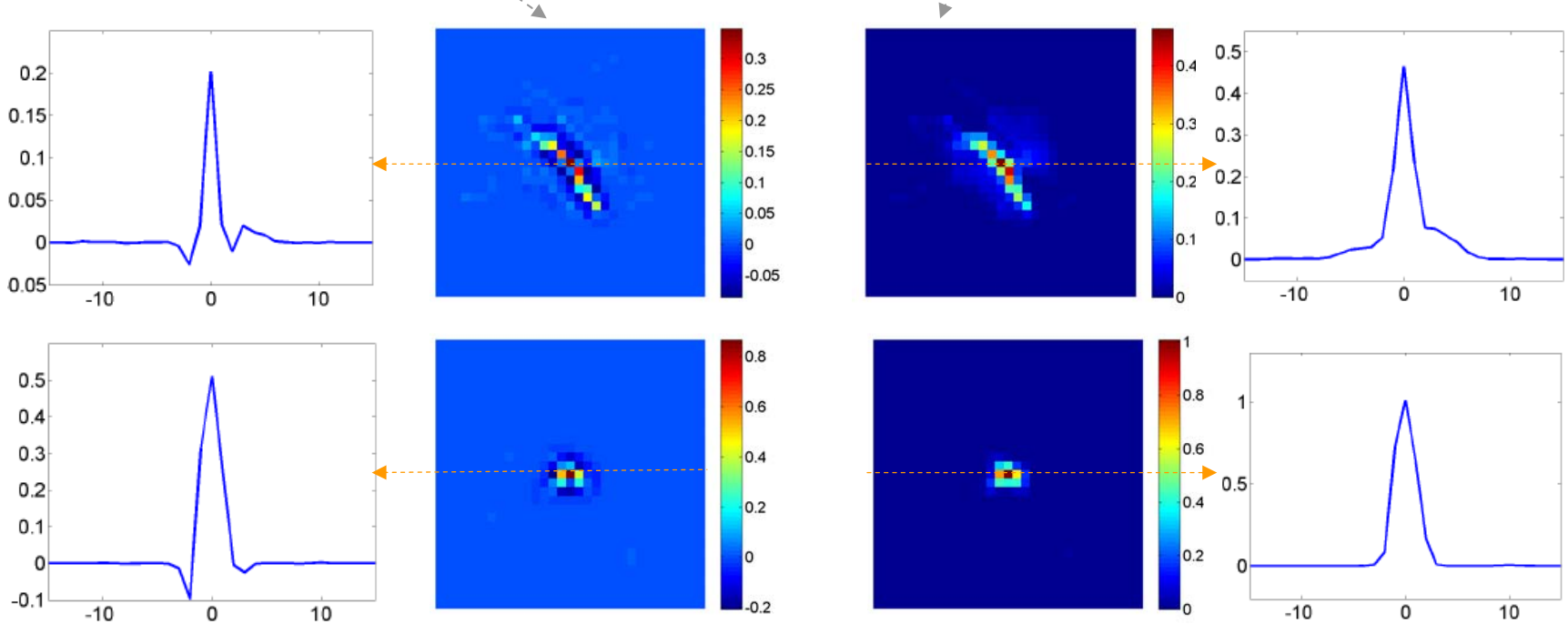
Adaptive Sharpening/Denoising

- Sharpening the LARK Kernel

"Sharpness" parameter

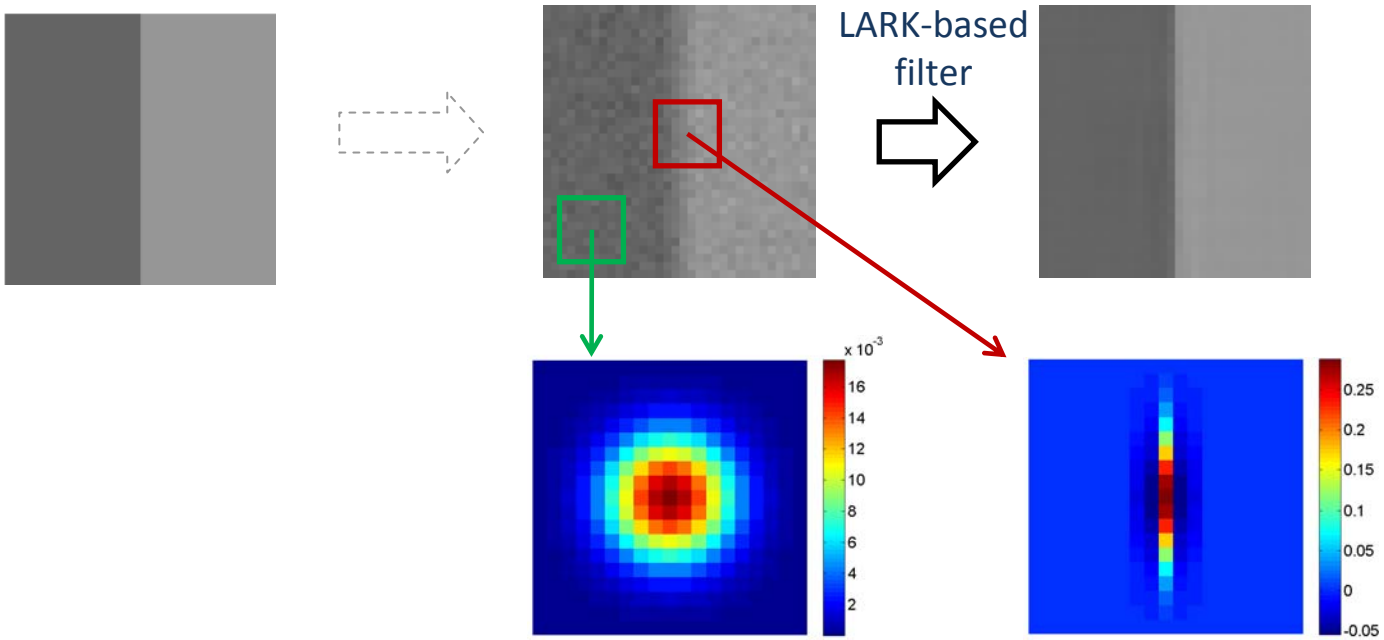
Laplacian operator

$$S = K - \kappa L \otimes K$$



LARK-based Simultaneous Sharpening/Deblurring/Denoising

- Net effect:
  - aggressive denoising in “flat” areas
  - Selective denoising and sharpening in “edgy”



Locally adaptive denoise/deblur filters

Examples

original image

original image

LARK

state-of-the-are methods

Examples

Examples

LARK