Bilateral Filtering

What is Bilateral filtering?

- It is a technique to smooth images while preserving edges.

(a) Input image (b) Output of the bilateral filter

[1] V. Aurich and J. Weule, "Non-linear gaussian filters performing edge preserving diffusion," in Proceedings of the DAGM Symposium, pp. 538–545, 1995.
[2] C. Tomasi and R. Manduchi, "Bilateral filtering for gray and color images," in Proceedings of the IEEE international Conference on Computer Vision, pp. 839–846, 1998.

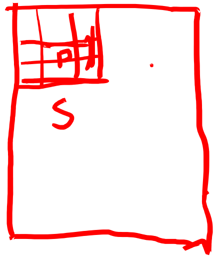
Qualities of Bilateral filter

- Formulation is simple.
- Depends on less no. of parameters.
- Can be used non-iterative manners.
- Availability of numerical schemes makes the computation easier.

Image Smoothing with Gaussian Convolution

- Blurring is perhaps the simplest way to smooth an image.
- It can be done by convoluting the image with simple Gaussian kernel.

$$GC[I]_{\mathbf{p}} = \sum_{\mathbf{q} \in \mathcal{S}} G_{\sigma}(\|\mathbf{p} - \mathbf{q}\|) \, I_{\mathbf{q}},$$

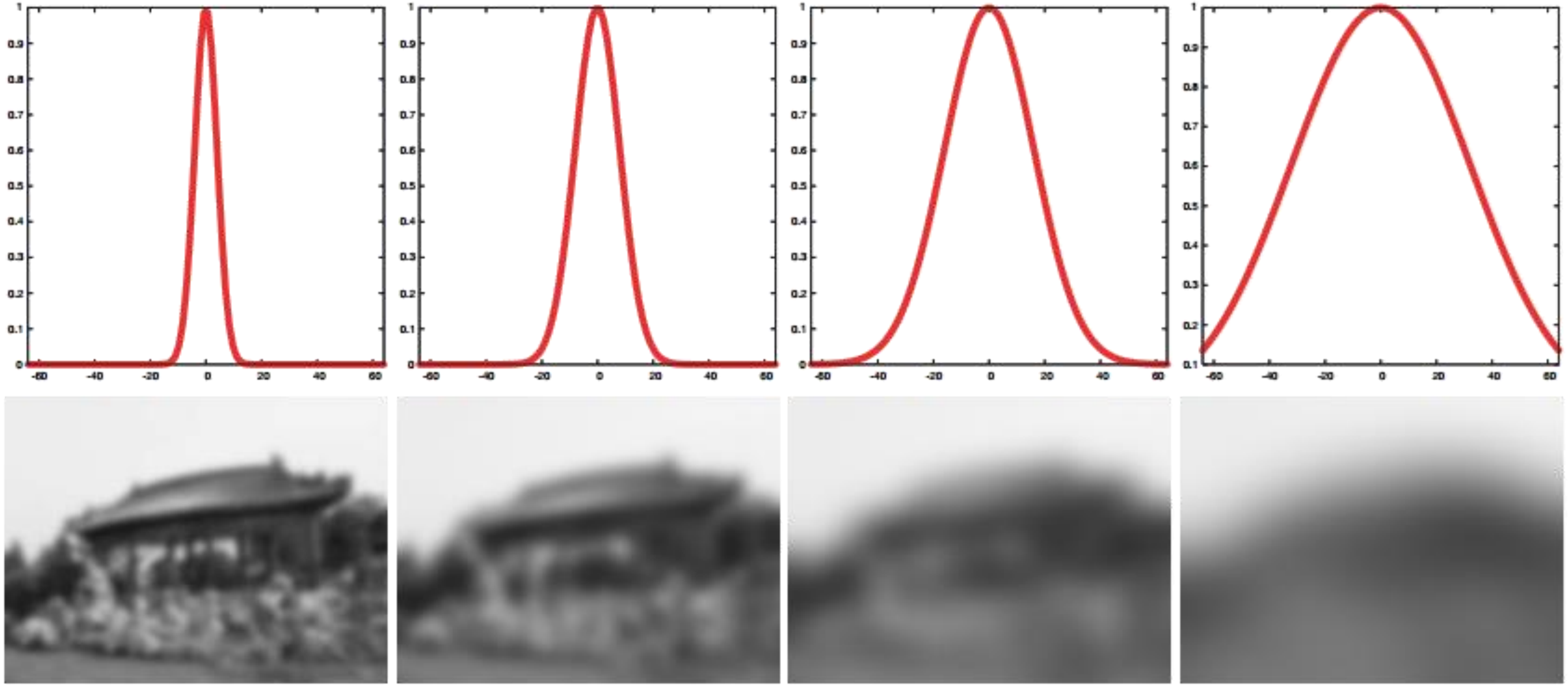


- where

$$G_{\sigma}(x) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{x^2}{2\sigma^2}\right)$$

1.5

An illustration



$\sigma = 4$ $\sigma = 8$ $\sigma = 16$ $\sigma = 32$

Problem with Gaussian smoothing

- It is independent of image content.
- Weight depends only on the spatial distance between the pixels.
- As a result it tends to smooth the edges, which is not desired.

Edge-preserving Filtering with the Bilateral Filter

- The key idea of the bilateral filter is that for a pixel to influence another pixel, it should not only occupy a nearby location but also have a similar value.

- Where

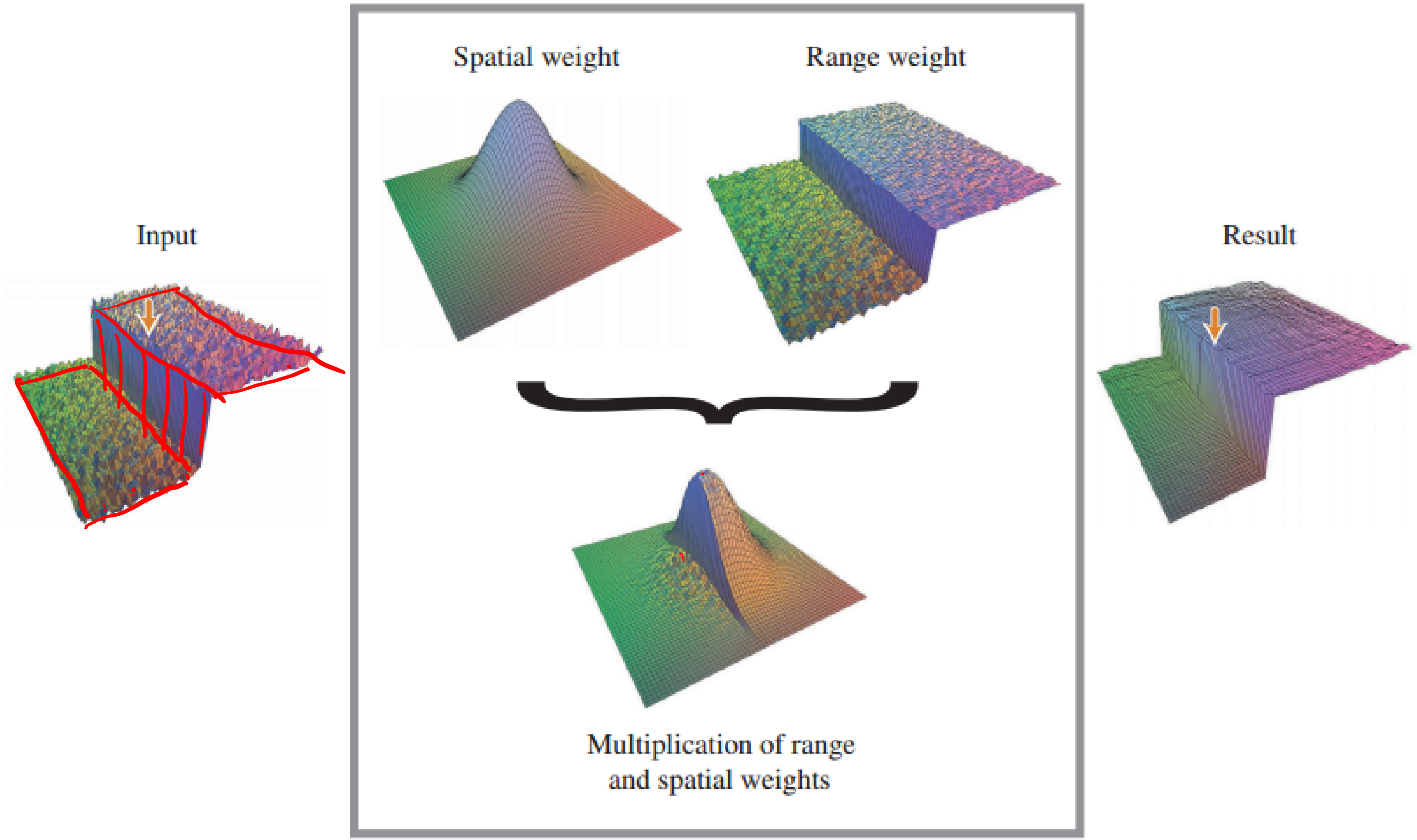
$$BF[I]_{\mathbf{p}} = \frac{1}{W_{\mathbf{p}}} \sum_{\mathbf{q} \in \mathcal{S}} G_{\sigma_s}(\|\mathbf{p} - \mathbf{q}\|)\, \underbrace{G_{\sigma_r}(|I_{\mathbf{p}} - I_{\mathbf{q}}|)}_{0.01}\, I_{\mathbf{q}},$$

$I_p \approx I_q$

$$W_{\mathbf{p}} = \sum_{\mathbf{q} \in \mathcal{S}} G_{\sigma_s}(\|\mathbf{p} - \mathbf{q}\|)\, G_{\sigma_r}(|I_{\mathbf{p}} - I_{\mathbf{q}}|).$$

$|I_p - I_q|$

Bilateral filter weights at the central pixel



Parameters

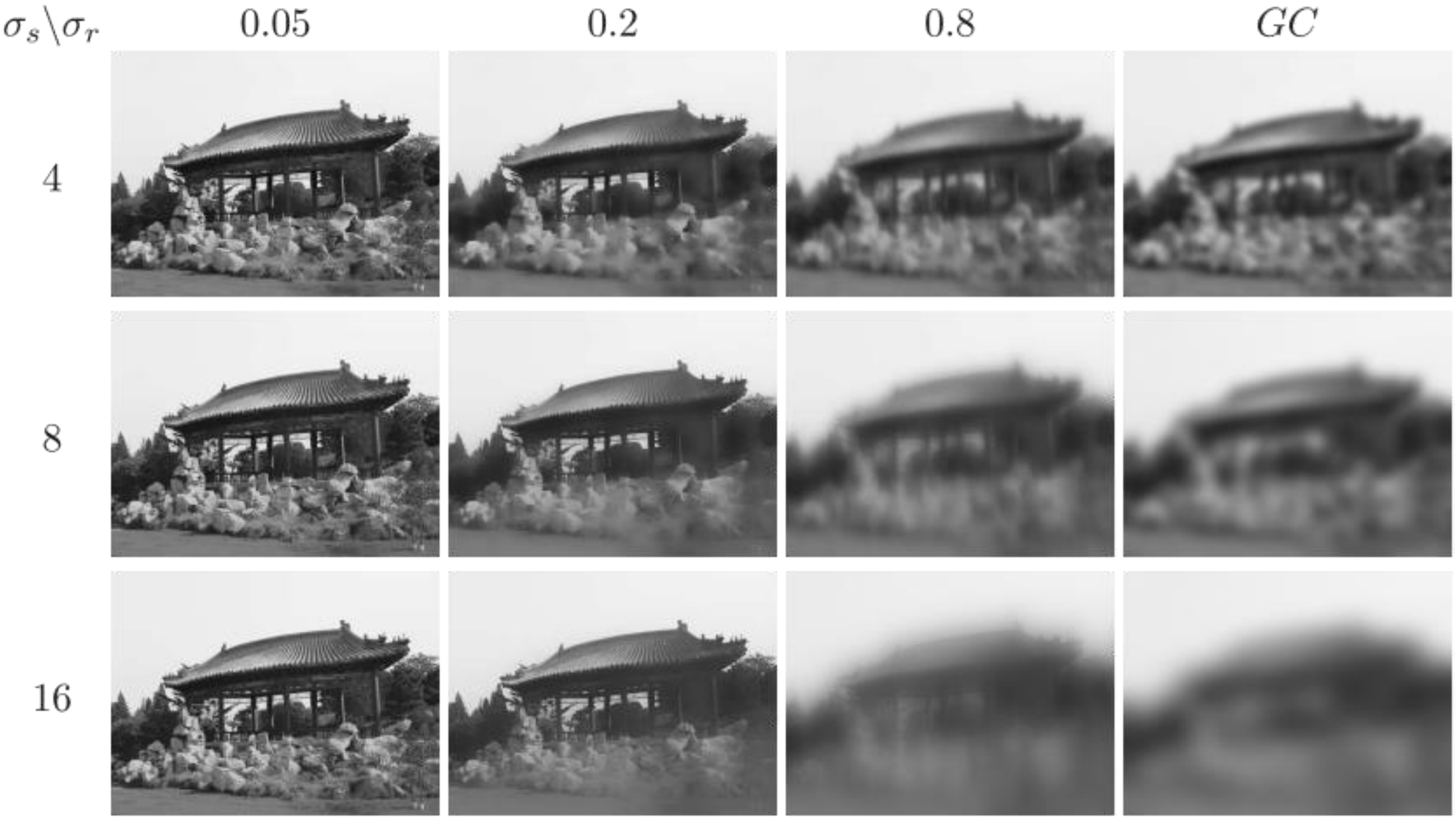
- It is controlled by two parameters: a) Range parameter, b) Spatial parameter.

a)

As the range parameter σ_r increases, the bilateral filter gradually approximates Gaussian convolution more closely because the range Gaussian G_{σ_r} widens and flattens, i.e., is nearly constant over the intensity interval of the image.

b)

Increasing the spatial parameter σ_s smooths larger features.

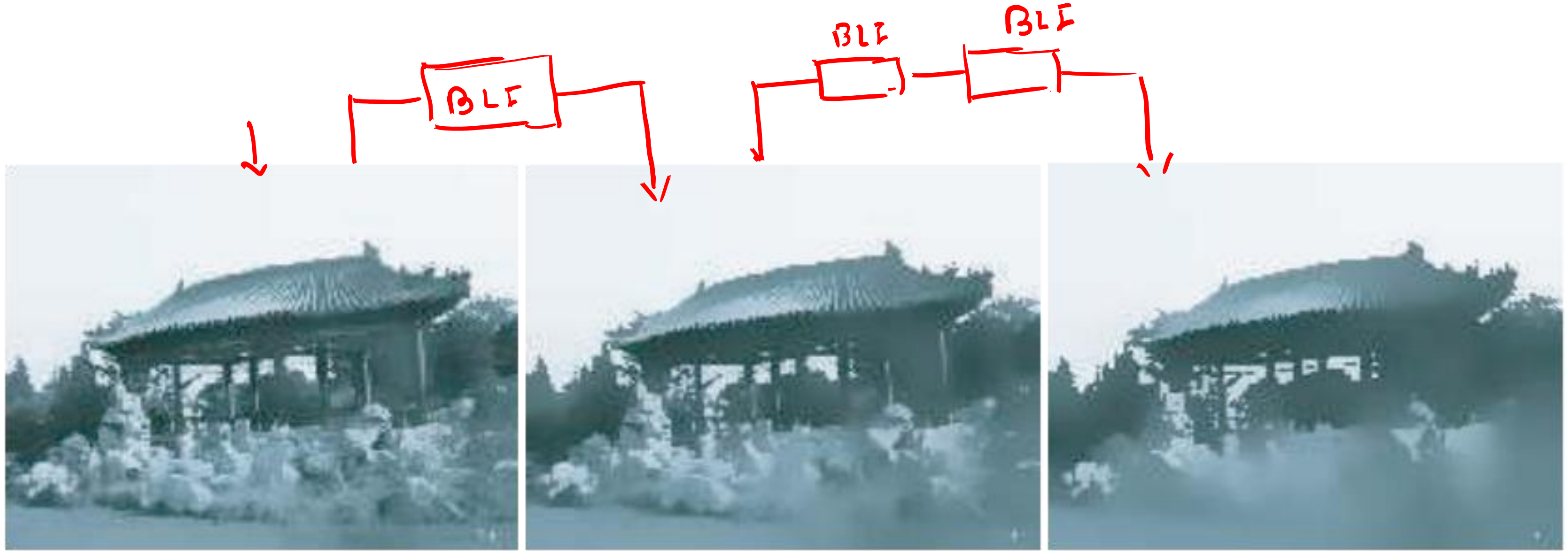

$\sigma_s \backslash \sigma_r$
0.05
0.2
0.8
GC
4
8
16

How to set 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

Iterations

- The bilateral filter can be iterated.
- This leads to results that are almost piecewise constant.



1 Iteration | 2 Iterations | 4 Iterations

Iterations (contd.)

Separation

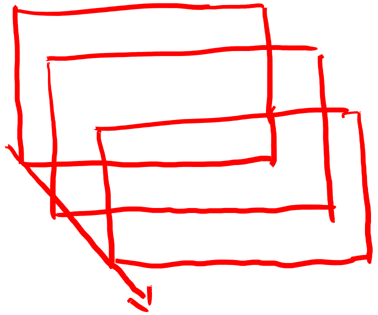
- The bilateral filter can split an image into two parts: the filtered image and its residual image.

(a) Input (b) Bilateral filter (c) Residual

Applications

- De-noising
- Contrast management
- Depth reconstruction
- Data fusion
- 3D fairing etc.

Image De-noising



E. P. Bennett and L. McMillan, “Video enhancement using per-pixel virtual exposures,” *ACM Transactions on Graphics*, vol. 24, no. 3, pp. 845–852, Proceedings of the ACM SIGGRAPH conference, July, 2005.

Orientation Smoothing

(a) Zoom on input image (b) Orientations before bilateral filtering (c) Orientations after bilateral filtering

S. Paris, H. Brice˜no, and F. Sillion, “Capture of hair geometry from multiple images,” *ACM Transactions on Graphics*, vol. 23, no. 3, pp. 712–719, Proceedings of the ACM SIGGRAPH conference, 2004.

Contrast Enhancement

$\bar{f} = BLF(f)$

$f \rightarrow \bar{f}$

$f - \bar{f} = \Delta f$

$k = 1$

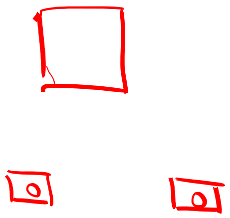
$\hat{f} = f + k\Delta f \rightarrow$ Unsharp masking

$k > 1 \rightarrow$ High Boost filtering

(a) Sample input images (b) Output with enhanced details

R. Fattal, M. Agrawala, and S. Rusinkiewicz, “Multiscale shape and detail enhancement from multi-light image collections,” *ACM Transactions on Graphics*, vol. 26, no. 3, p. 51, Proceedings of the ACM SIGGRAPH conference, 2007.

Depth Reconstruction



(a) Sample input image (b) Coarse resolution computation (c) Refinement using bilateral aggregation

Yáng et al. use the bilateral filter to achieve stereo reconstruction from photographs (a). First, they build a coarse depth map (b) and then use a scheme inspired from the bilateral filter to aggregate local information and compute a refined, more accurate depth map (c). Figure reproduced from Yang et al.

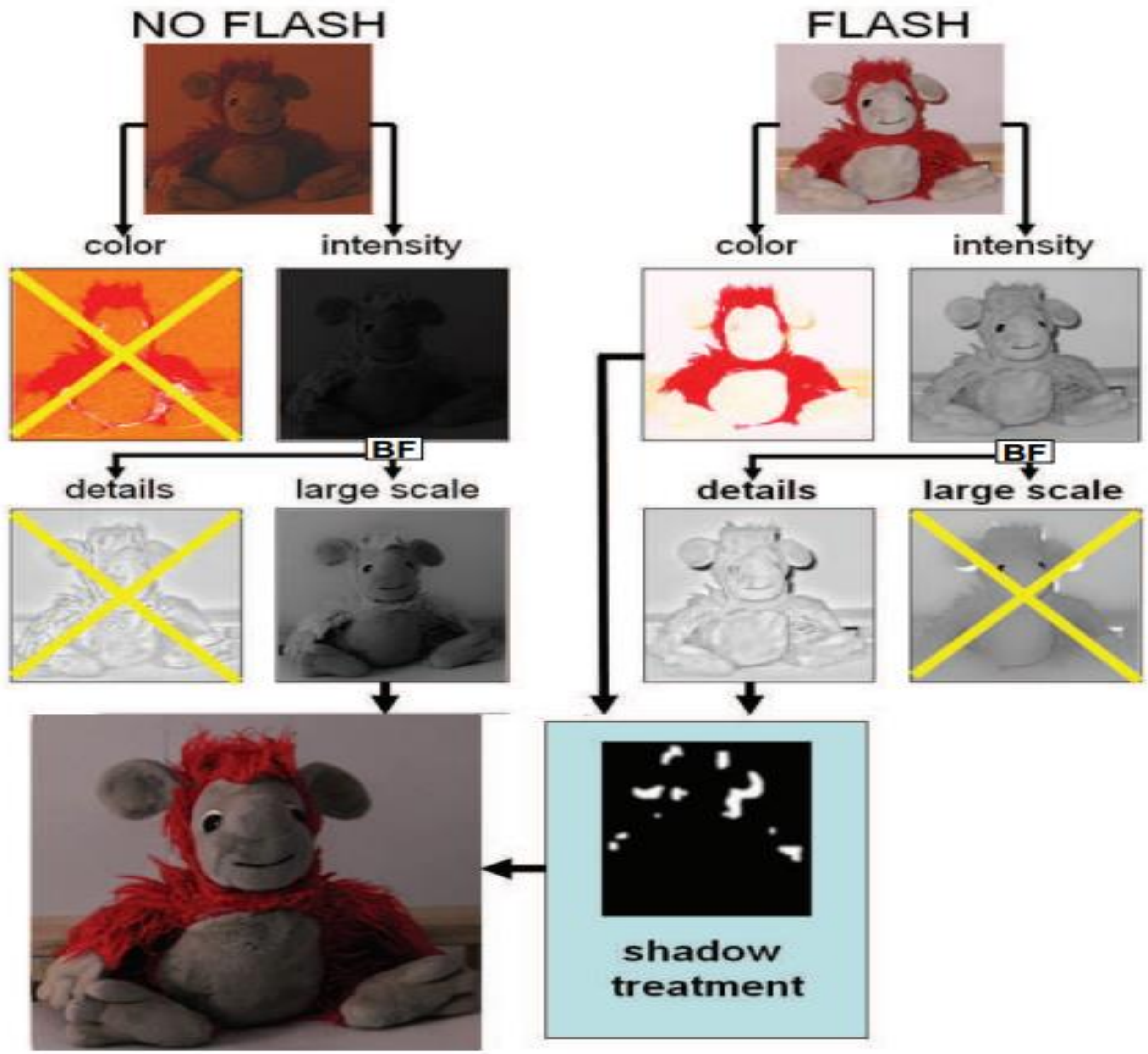
Q. Y´ ang, R. Yang, J. Davis, and D. Nist´er, “Spatial-depth super resolution for range images,” inProceedings of the conference on IEEE Computer Vision and PatternRecognition, pp. 1–8, 2007.

Data Fusion

(a) Photograph with flash (b) Photograph without flash (c) Combination

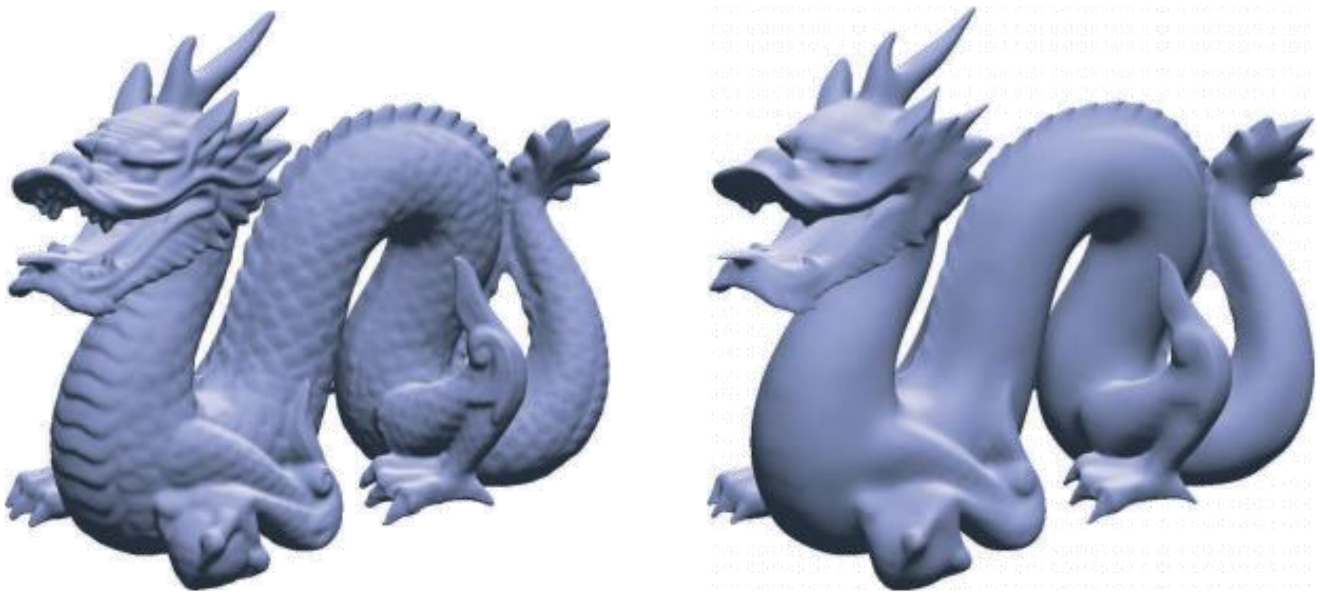
RGB

$Y \; C_b C_r$ X



E. Eisemann and F. Durand, “Flash photography enhancement via intrinsic relighting,” *ACM Transactions on Graphics*, vol. 23, no. 3, pp. 673–678, Proceedings of the ACM SIGGRAPH conference, July, 2004.

3D fairing



(a) Input mesh (b) Smoothed mesh

T. R. Jones, F. Durand, and M. Desbrun, “Non-iterative, feature-preserving mesh smoothing,” *ACM Transactions on Graphics*, vol. 22, no. 3, Proceedings of the ACM SIGGRAPH conference, July, 2003.

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- Sylvain Paris, Pierre Kornprobst, Jack Tumblin and Fr´edo Durand, “Bilateral Filtering: Theory and Applications”, Foundations and Trends in Computer Graphics and Vision, Vol. 4, No. 1 (2008) 1–73.
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