Real-time Edge-aware Image Processing with the Bilateral Grid

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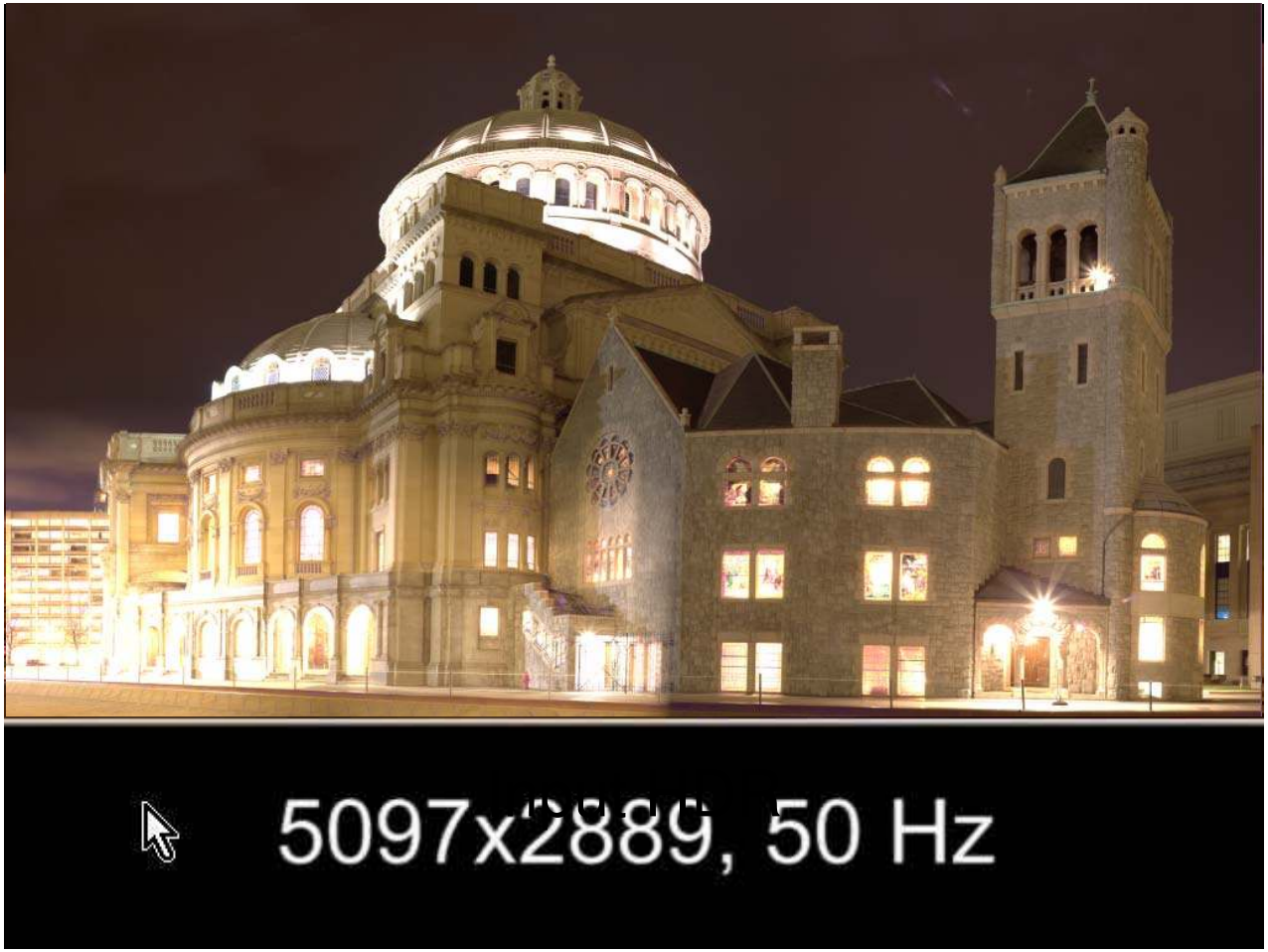
Interactive Local Tone Mapping

- Tone map image using Durand and Dorsey [2002]
- **Edge-aware** brush locally adjusts parameters



Tone mapped output

Motivation – Tone Mapping

- Reduce contrast
- Spatially-varying remapping
- Edge-aware map eliminates halos

  [Tumblin 99] [Durand 02]

Input HDR

Edge-aware operator

Tone mapping with the bilateral filter [Durand 02]

Edge-aware Image Processing

- Output that is **smooth, except at strong edges** of input

- Important in computational photography
- Challenge: Performance
  - Brute force: **minutes** per MPixel
  - Fastest techniques: ~1 second / MPixel
- Our contribution: the Bilateral Grid
  - New data structure
  - Many edge-aware operations
  - Fast

Previous Work

- Optimization
  [Levin 04, Lischinski 06, Szeliski 06]
  - Inhomogeneous energy

- Anisotropic diffusion
  [Perona 90]
  - Iterative PDEs

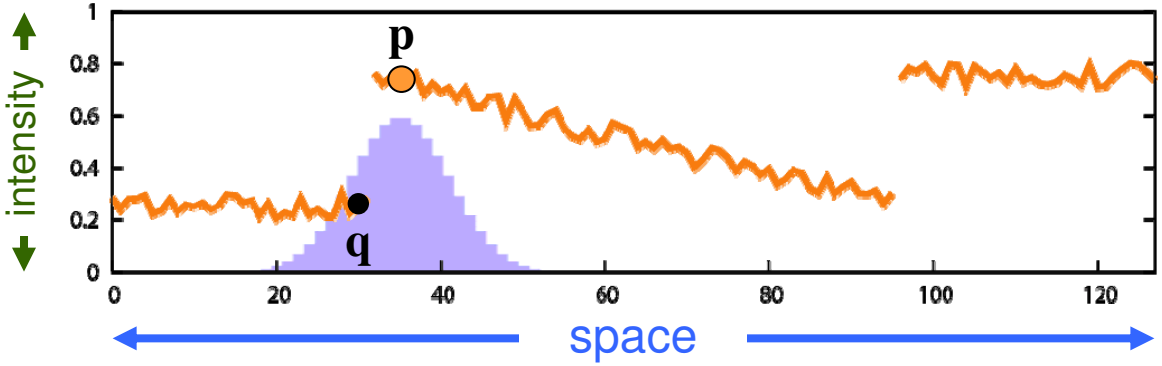
- Bilateral filter [Aurich 95, Smith 97, Tomasi 98]
  - Handles large kernels common in computational photography
  - Fast, but not enough for real time
    [Pham 05, Weiss 06, Paris 06, Fattal 07]
  - We build upon Paris and Durand [2006]

Gaussian Blur

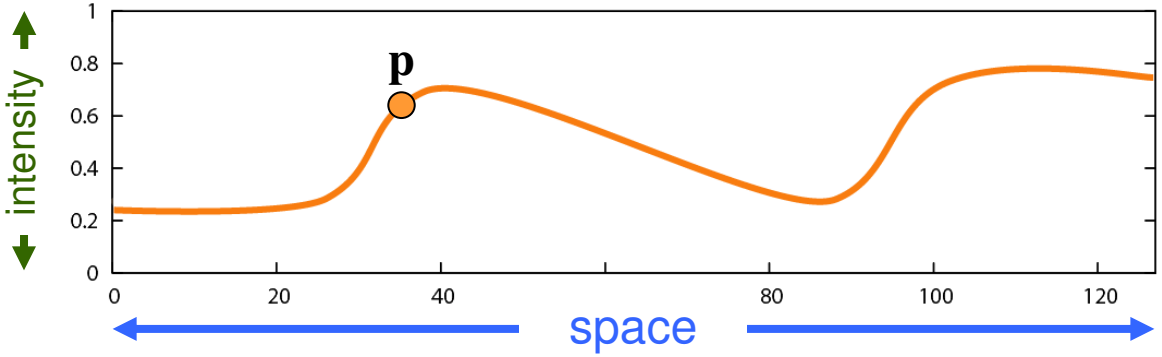
$$gb(I)_{\mathbf{p}} = \sum_{\mathbf{q}} G_{\sigma}(\|\mathbf{p}-\mathbf{q}\|) I_{\mathbf{q}}$$

space

- weighted average of neighbors
- depends only on spatial distance
- no **edge term**



Input



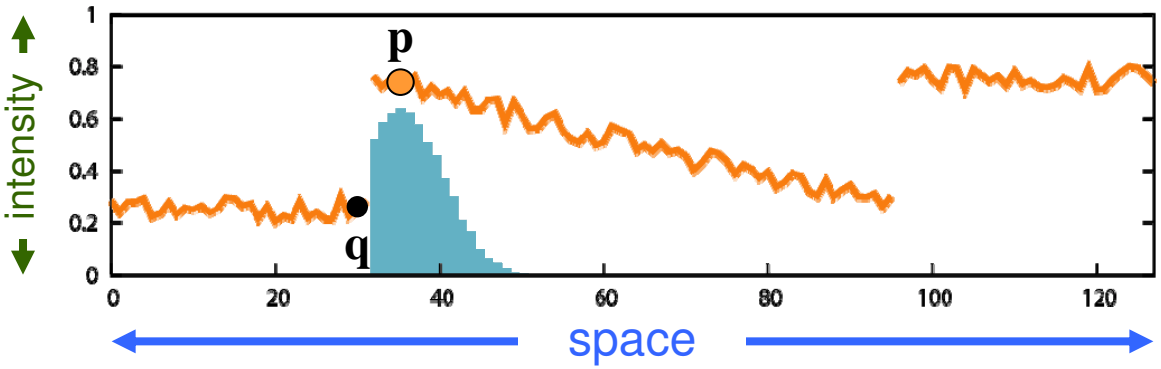
Output

Bilateral Filter [Aurich 95, Smith 97, Tomasi 98]

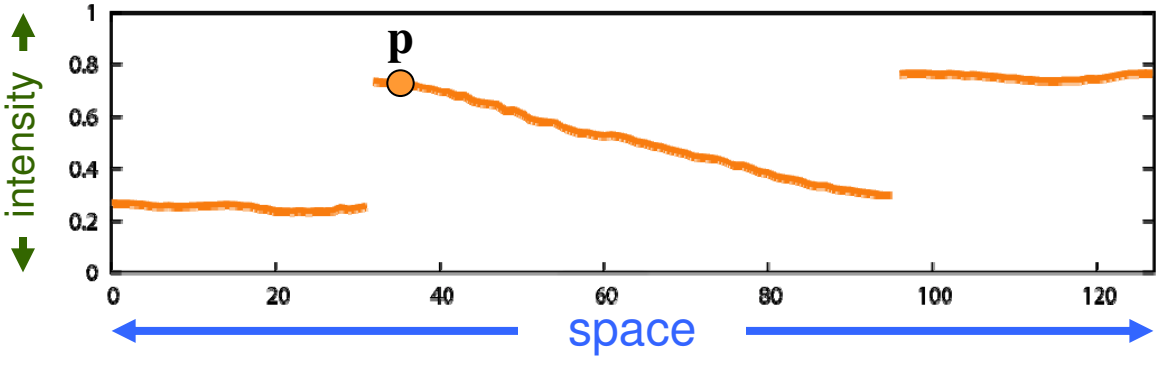
$$bf(I)_{\mathbf{p}} = \frac{1}{W_{\mathbf{p}}} \sum_{\mathbf{q}} G_{\sigma_s}(\|\mathbf{p}-\mathbf{q}\|) G_{\sigma_r}(|I_{\mathbf{p}}-I_{\mathbf{q}}|) I_{\mathbf{q}}$$

space intensity

- weighted average of neighbors
- depends on **spatial** and **intensity** difference



Input



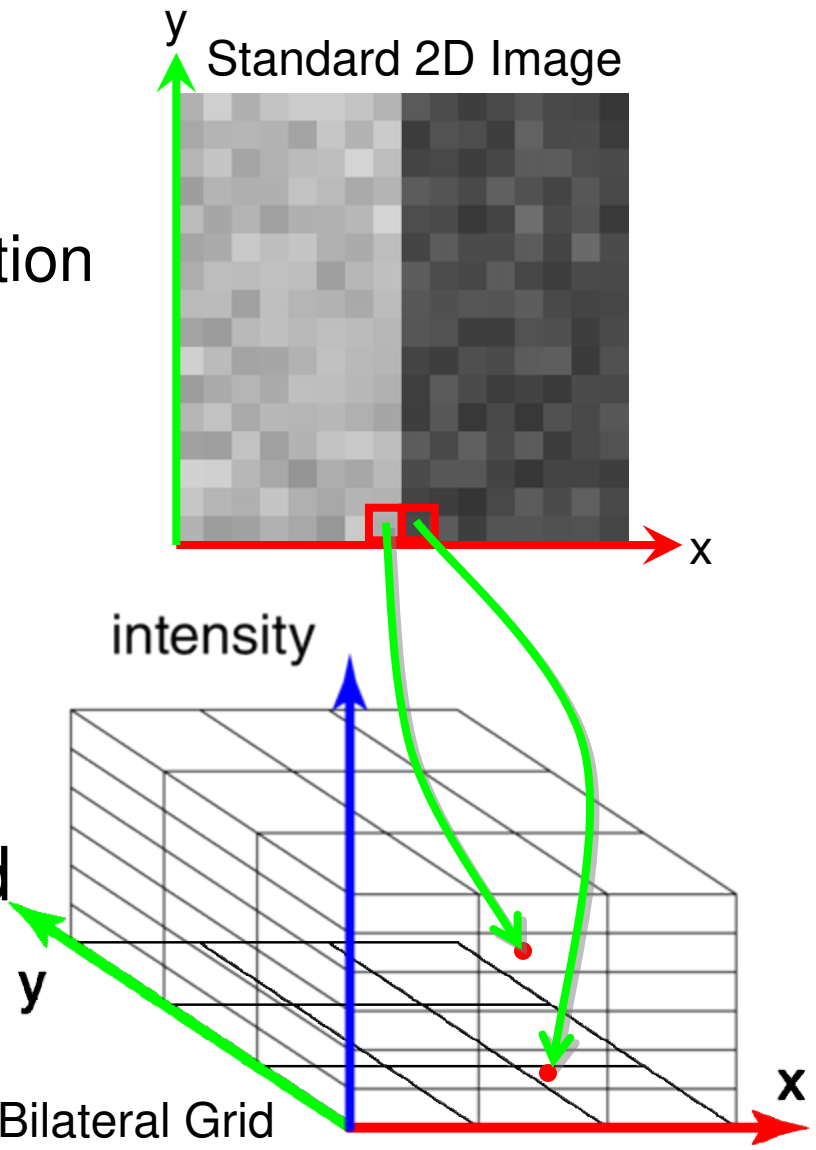
Output

Our Contribution: the Bilateral Grid

- 3D representation for 2D image data
- Edge-aware computation is simple in the grid
  - Smooth functions on grid are **piecewise-smooth** in image space
- Fast (milliseconds vs. seconds)
  - Coarse resolution
  - Parallel algorithms (GPU)

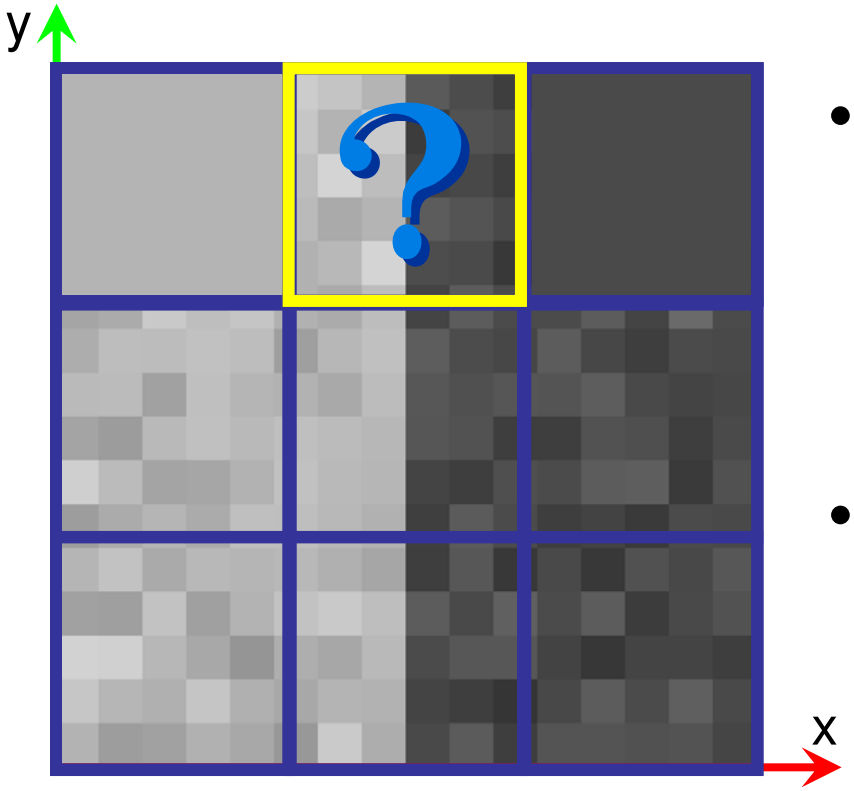
Bilateral Grid – Definition

- Bilateral grid = 3D array
  - ***x*** and ***y*** correspond to pixel position
  - ***z*** corresponds to pixel intensity
  - Euclidean distance accounts for edges
    - space distance (x,y) and intensity distance (z)
- Grid can be coarsely sampled
  - E.g., 70 x 70 x 10 for an 8 megapixel image



2D vs. Bilateral Grid Downsampling

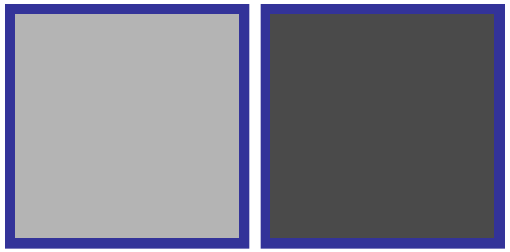
- Bilateral grid enables aggressive downsampling
- Extra dimension preserves edges



Downsampling in 2D

- Nearest neighbor

  arbitrarily bright or dark



- Bicubic

  intermediate value not in original

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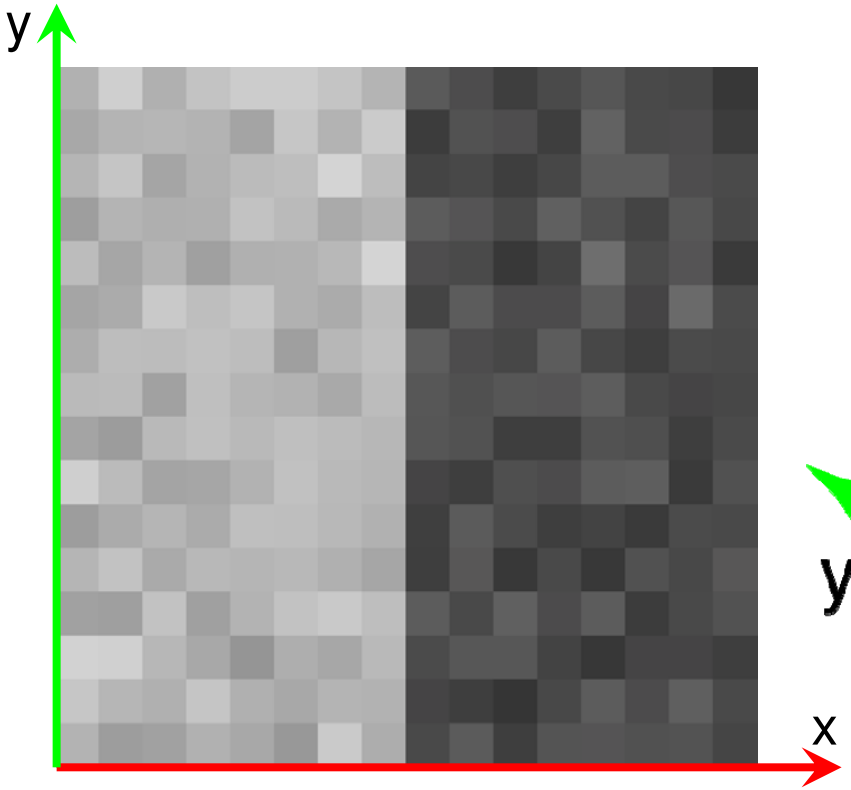
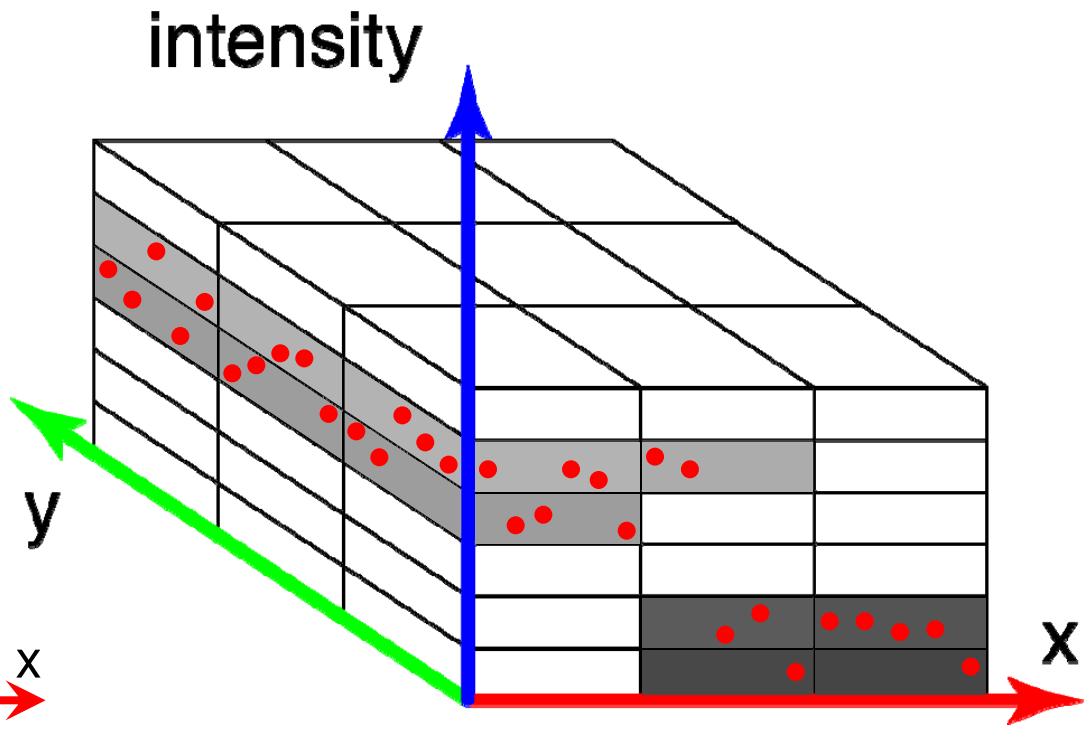


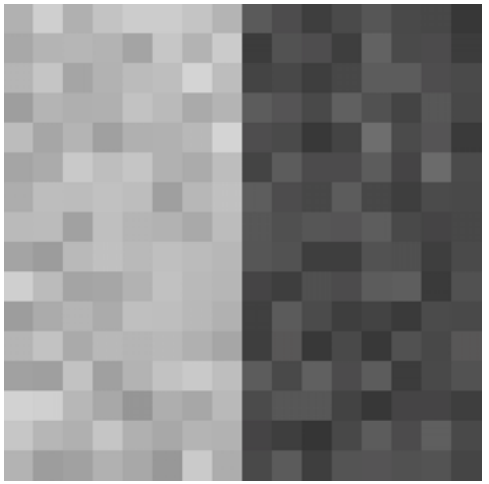
Downsampling in 2D



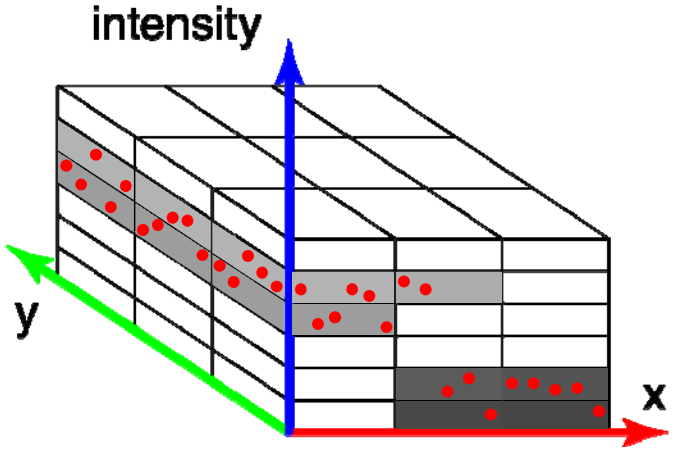
Bilateral Grid

Discussion

- Grid operations could be defined in image space

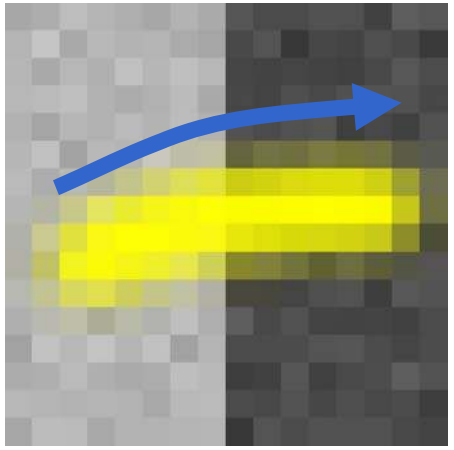


- Advantages of the Bilateral Grid
  - Edge-awareness built-in
  - Speed: aggressive downsampling



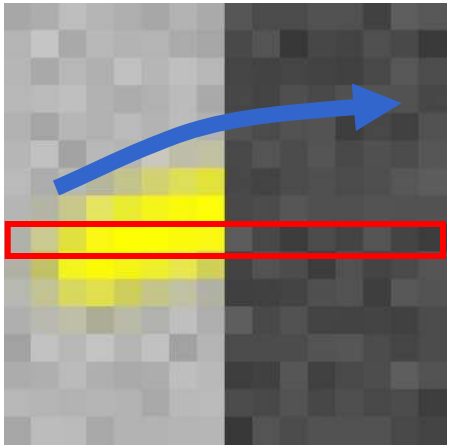
A Simple Illustration

- Classical paint brush
  - Ignores edges



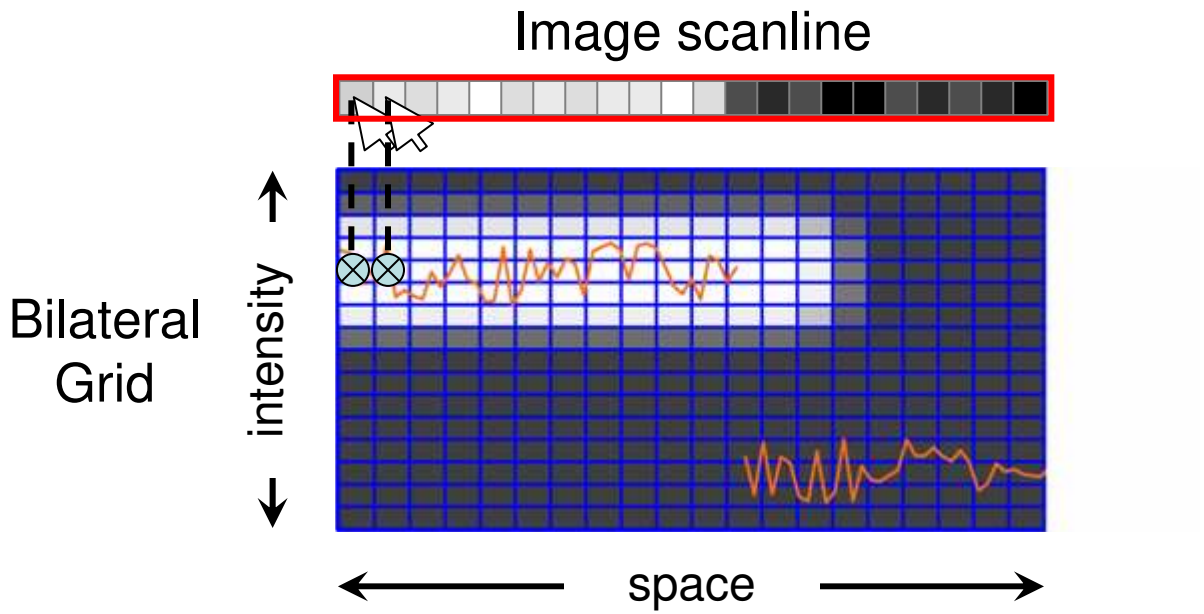
Stroke with classical brush

- Our edge-aware brush
  - Respects edges

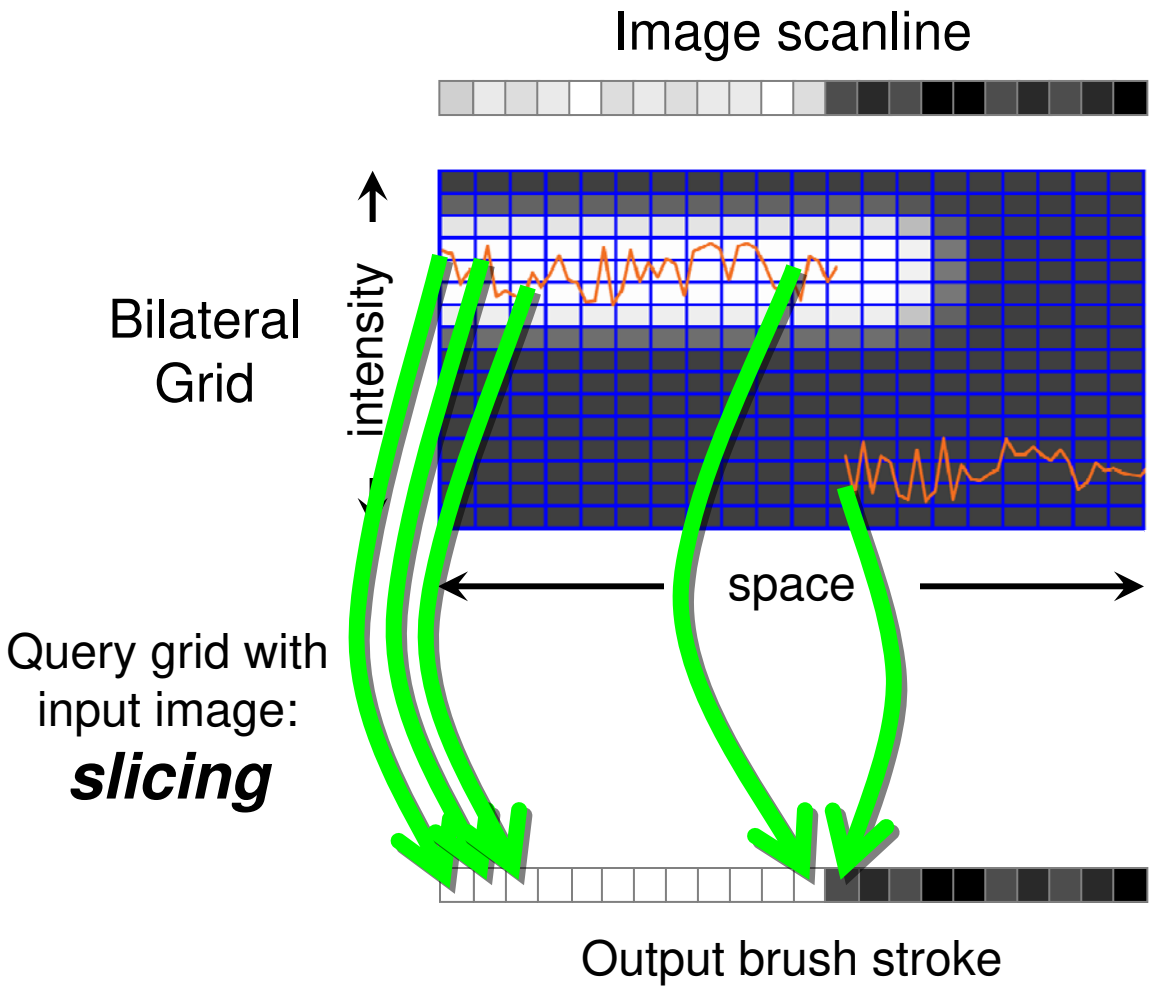


Stroke with bilateral brush

Bilateral Grid Painting

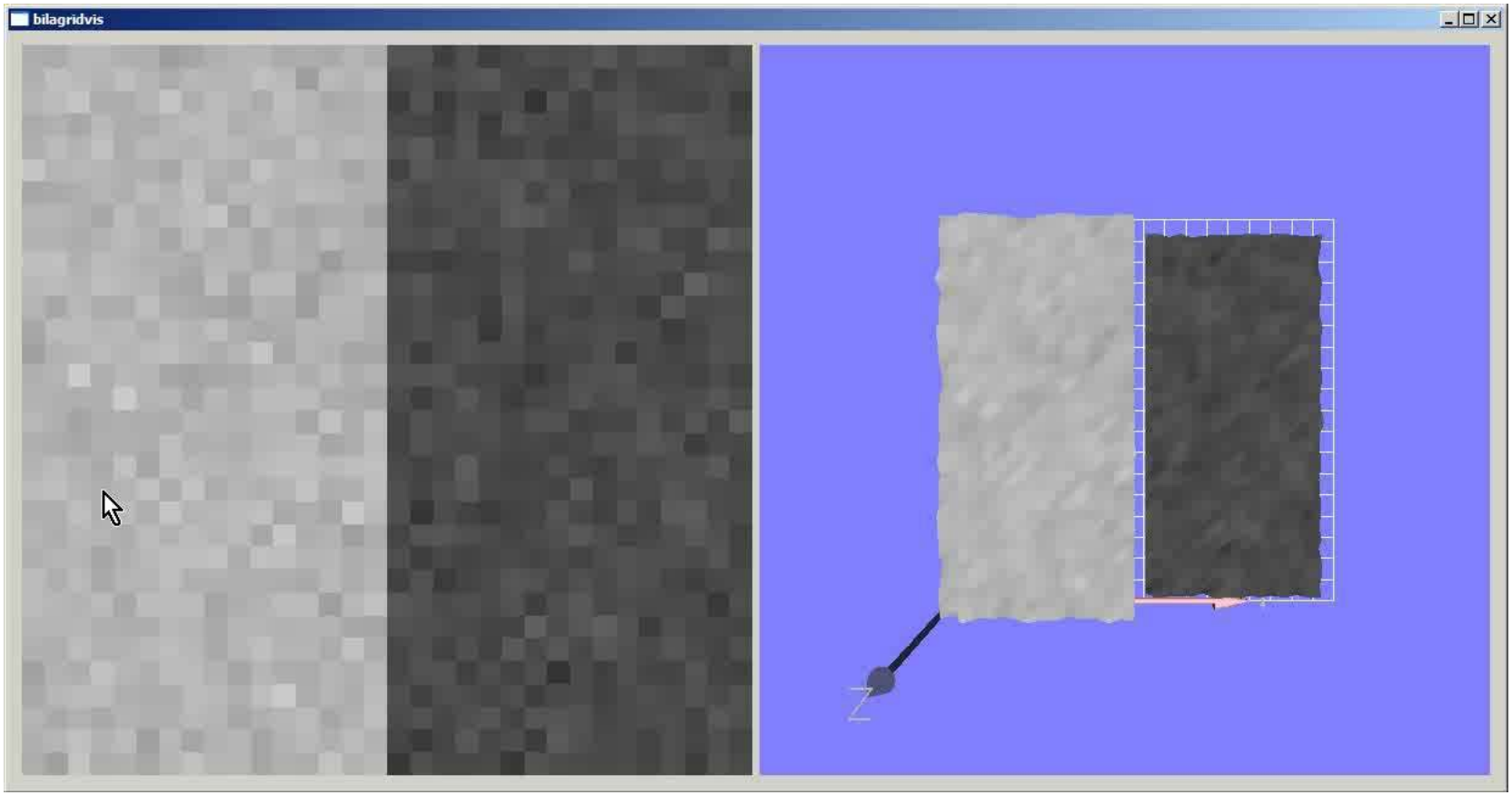


Bilateral Grid Painting



Bilateral Grid Painting

- When mouse is held down, paint only at intensity level of initial mouse click



Input image

Bilateral Grid

Bilateral Grid Painting

- Edge-aware brush used to change hue

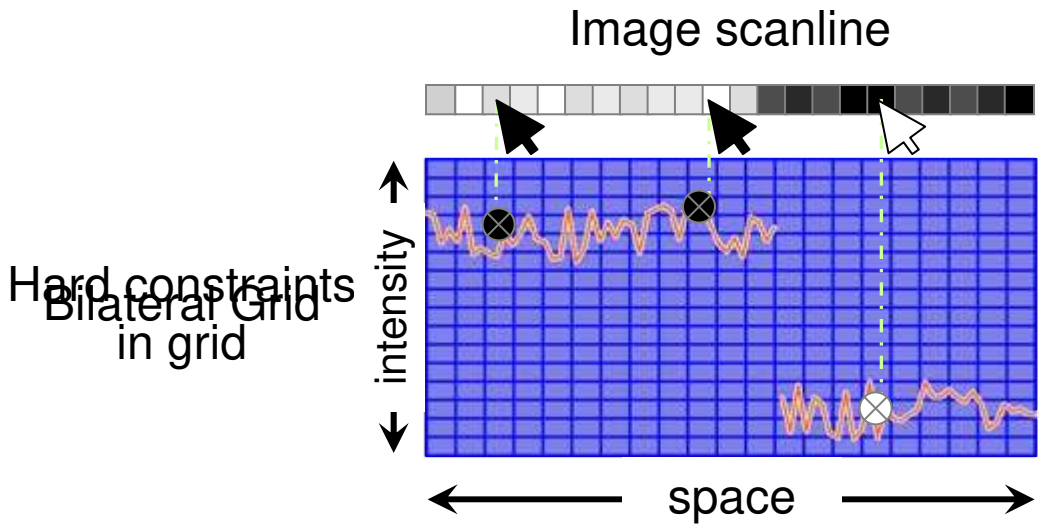
Scribble-based Selection

- User scribbles to specify selection [Lischinski 06]
- Piecewise-smooth interpolation to get full selection
  - Respects intensity discontinuities

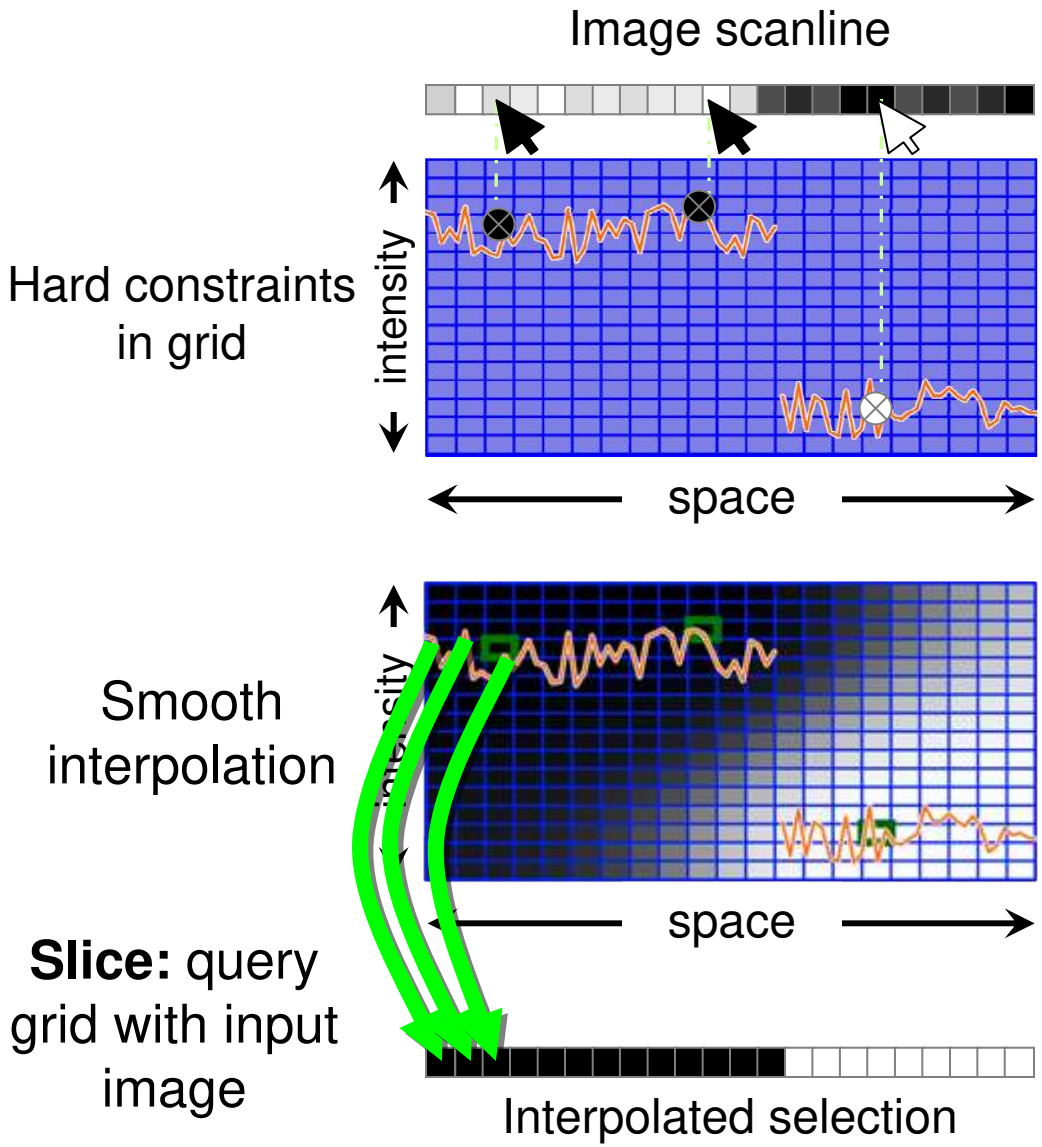
Input with scribbles

Our interpolated selection

Scribble-based Selection



Scribble-based Selection



Bilateral Filter [Tomasi 98]

- Smooth image except across strong edges
- Ubiquitous in computational photography

[Oh 01, Durand 02, Eisemann 04, Petschnigg 04, Bennett 05, Bae 06, Fattal 07, Kopf 07, …]

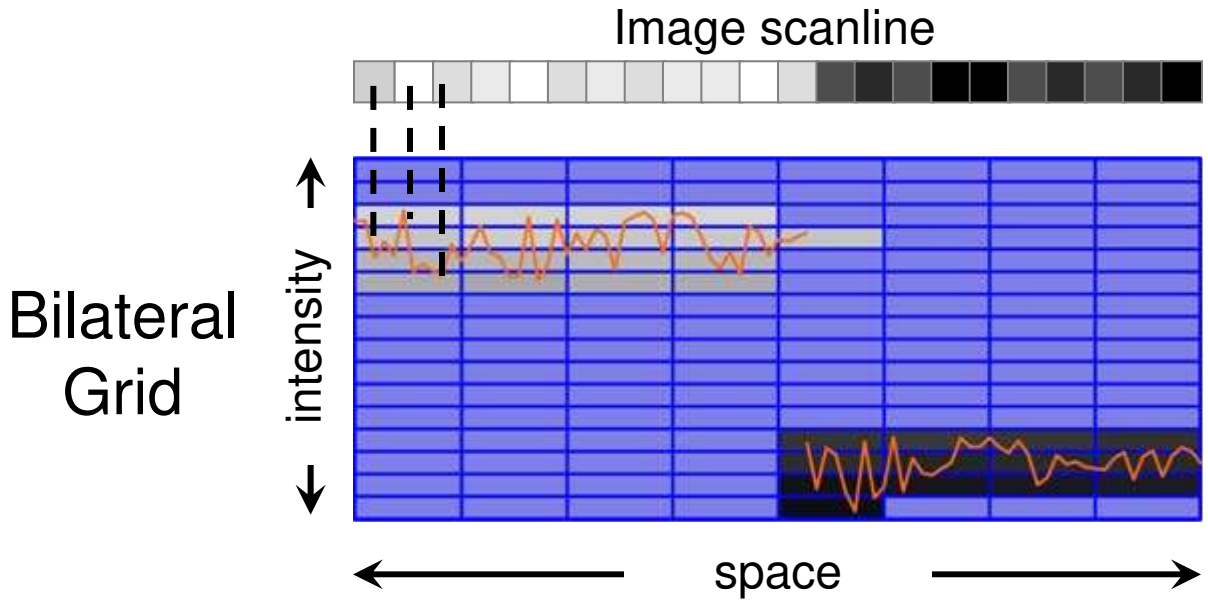
Input

Filtered Output

Brute force computation: 10 minutes

With the bilateral grid: 9 ms

Bilateral Filter on the Bilateral Grid



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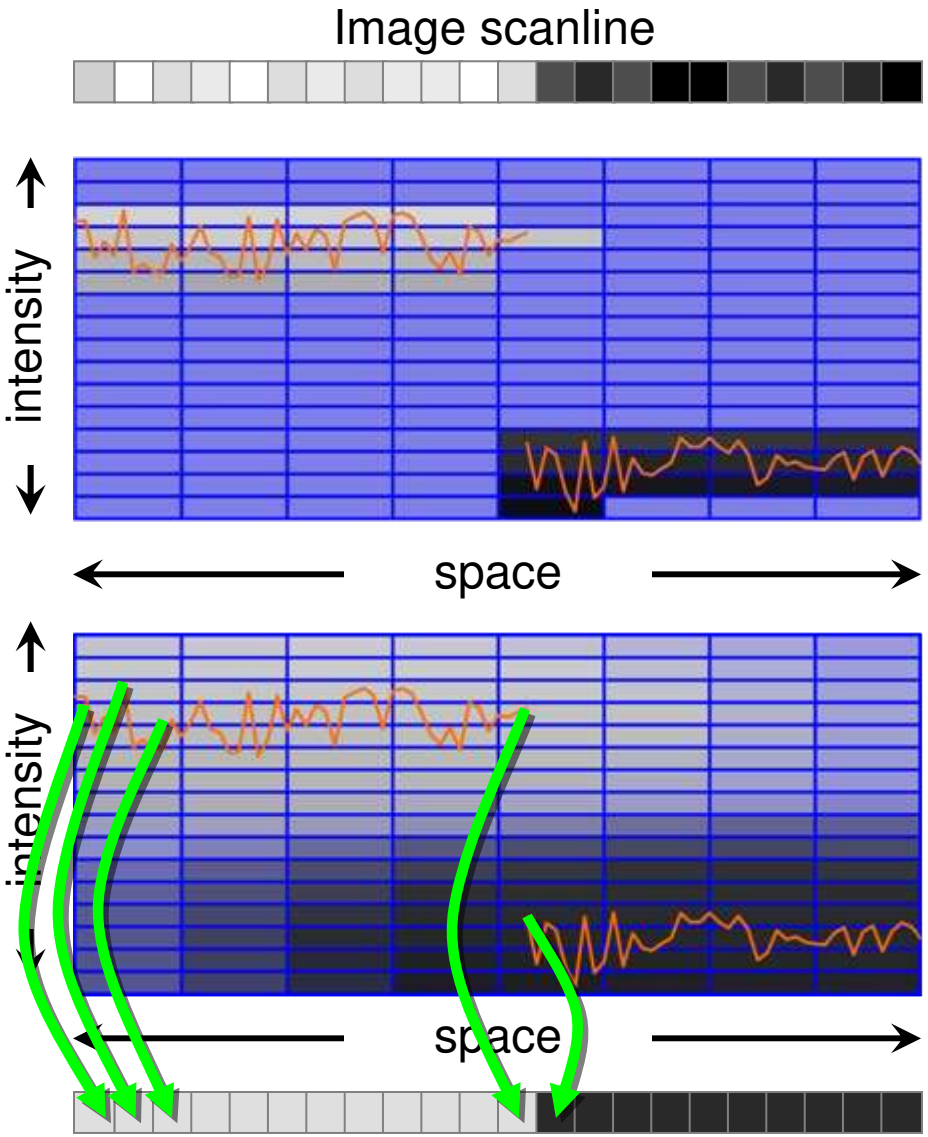
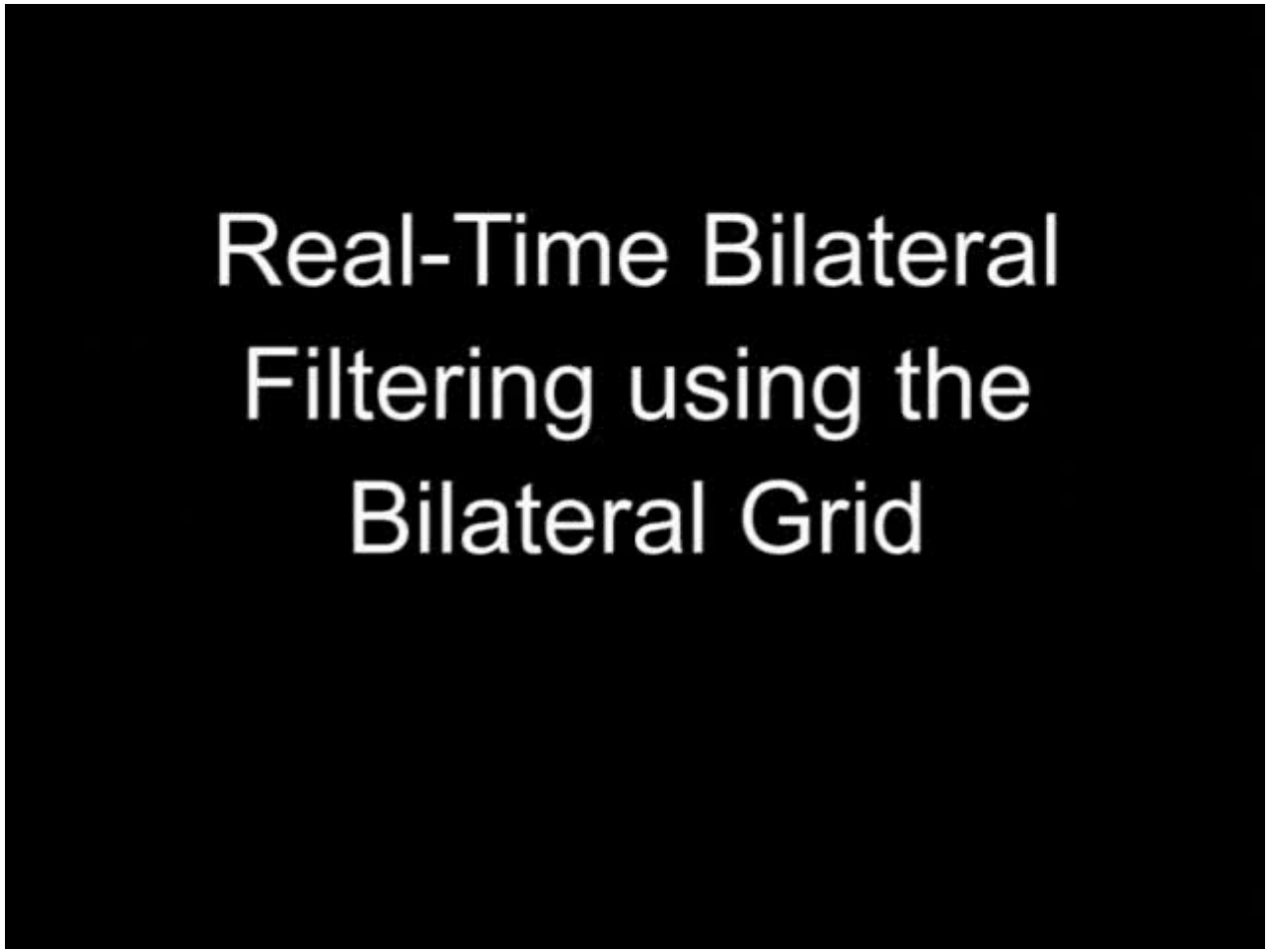


Slice: query grid with input image

Performance: Bilateral Filter

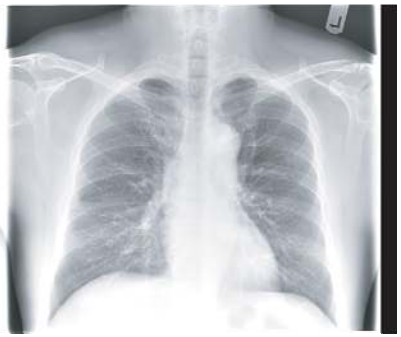
Image size: 2 MPixels

- CPU
  - Brute force: **10 minutes**
  - State of the art ’06: **1 second** [Weiss 06, Paris 06]
- Our Bilateral Grid with GPU
  - 2004 card (NV40): **28 ms** (36 Hz)
  - 2006 card (G80): **9 ms** (111 Hz)
- For bilateral filter, algorithm similar to Paris & Durand [06]
  - We parallelize on GPU
  - Another **2 orders of magnitude** speedup


Real-Time Bilateral
Filtering using the
Bilateral Grid

Many Operations and Applications

- Local histogram equalization
- Interactive tone mapping



- Video abstraction
  [Winnemoller 06, DeCarlo 02]

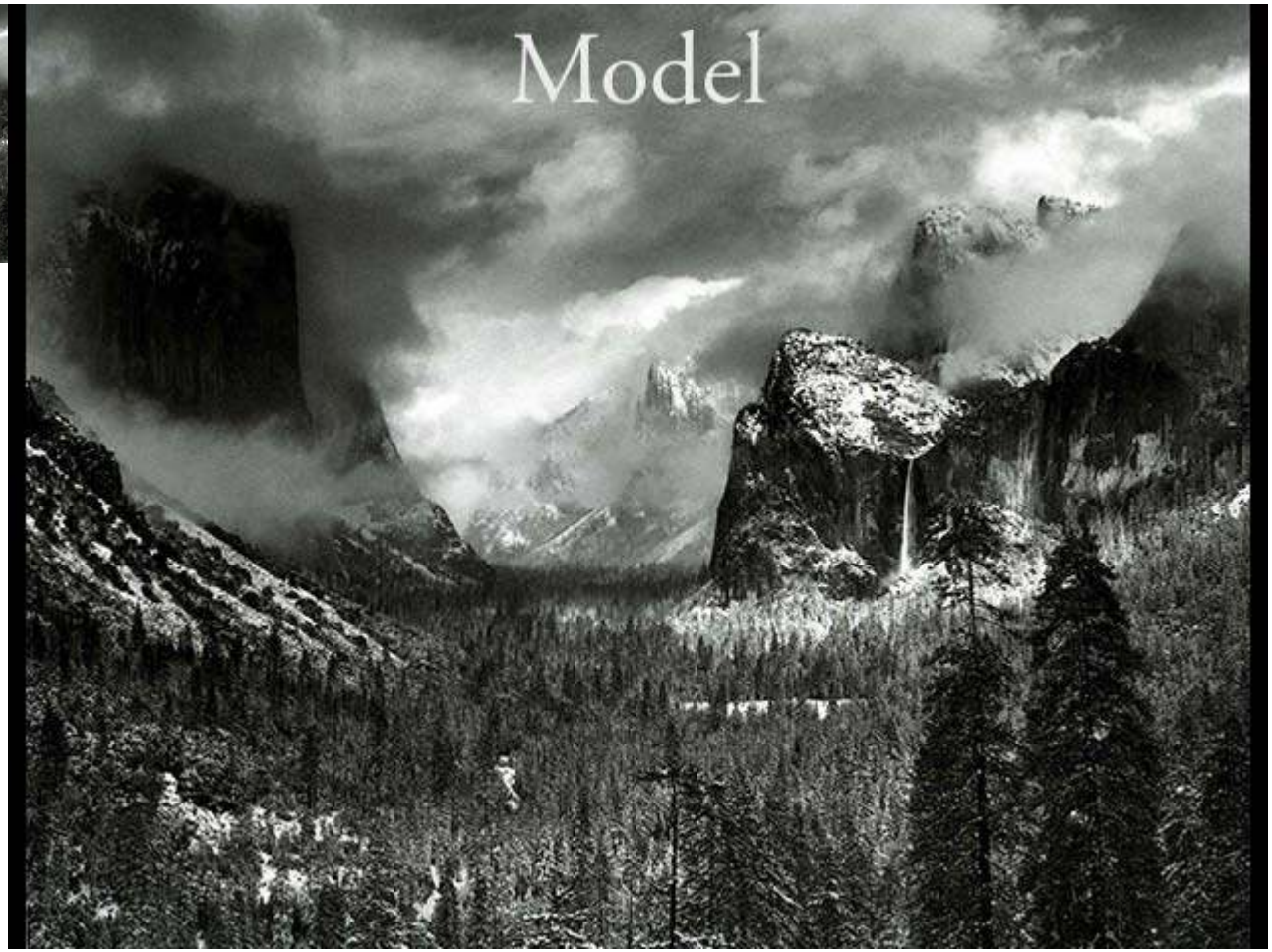
- Photographic style transfer [Bae 06]

Multiscale HD Video Abstraction

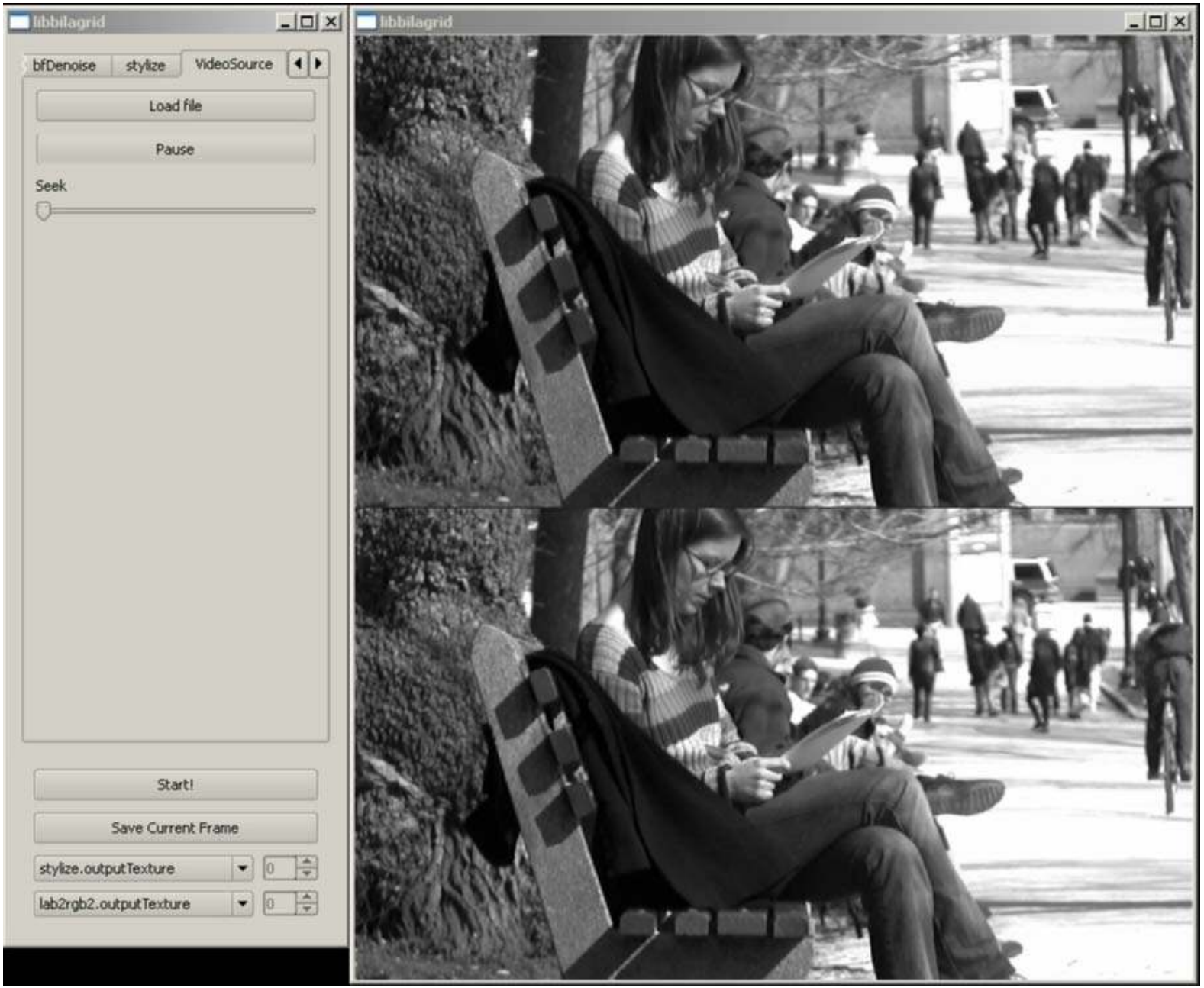
Transfer of Photographic Style

- Temporally coherent transfer
- **2 orders of magnitude** speedup: real-time in HD

Model



Live demo


libbilagrid
bfDenoise
stylize
VideoSource
Load file
Pause
Seek
Start!
Save Current Frame
stylize.outputTexture
lab2rgb2.outputTexture
libbilagrid

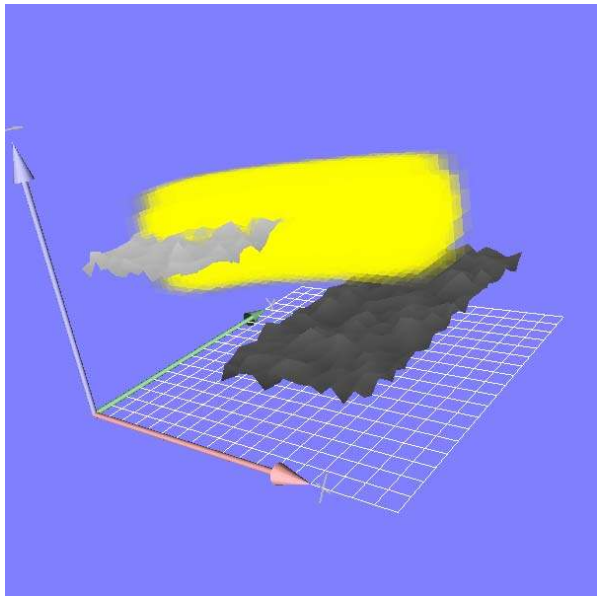
Discussion

- Respects luminance edges
- Color bilateral grid would be 5D
  - Does not fit on current hardware
  - Luminance edges are often sufficient

Bilateral brush crosses thin lines

- Crosses thin lines
  - Diffusion vs. bilateral filter
  - Useful in many cases

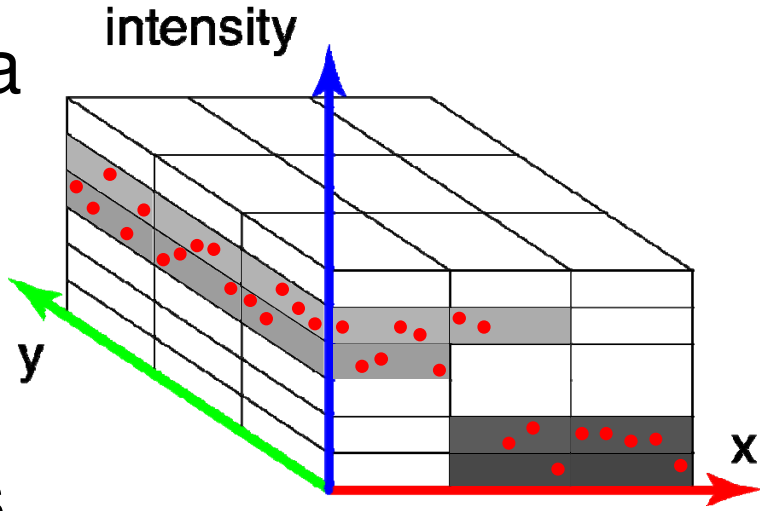
- Grid resolution depends on the operator
  - E.g., for edge-aware brush:
    space sampling rate ~ brush radius
    intensity sampling rate ~ edge-awareness



Edge-aware brush

Summary: the Bilateral Grid

- 3D representation for 2D data



- Intelligent downsampling
- Many edge-aware operations
  - Painting, scribble interpolation, bilateral filter, local histogram equalization

- Real-time for HD video

Acknowledgements

- Jonathan Ragan-Kelley
- Aleksey Golovinskiy
- MIT Graphics Group
- Anonymous reviewers
- IMAX and Warner Brothers
- NVIDIA
- NSF, Sloan, MSR, Shell

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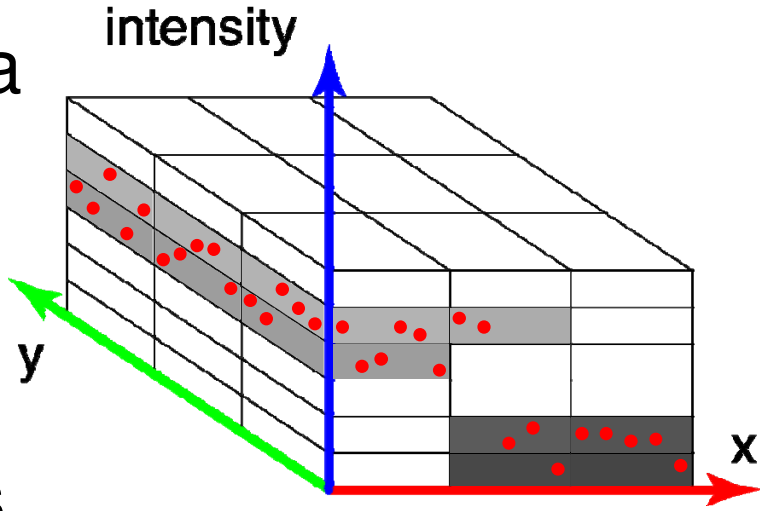

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