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](image1)

![Naïve mapping](image2)

![Edge-aware operator](image3)

![Tone mapping with the bilateral filter](image4)
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**

\[
g_b(I)_p = \sum_{q} G_\sigma(\|p - q\|) I_q
\]

- weighted average of neighbors
- depends only on spatial distance
- no edge term
Bilateral Filter [Aurich 95, Smith 97, Tomasi 98]

\[
bf(I)_p = \frac{1}{W_p} \sum_{q} G_{\sigma_s}(\|p - q\|) G_{\sigma_r}(\|I_p - I_q\|) I_q
\]

- weighted average of neighbors
- depends on **spatial** and **intensity** difference
Our Contribution: the Bilateral Grid

• 3D representation for 2D image data

• Edge-aware computation is simple in the grid
  • Smooth functions on grid are \textit{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

- Nearest neighbor arbitrarily bright or dark
- Bicubic intermediate value not in original
2D vs. Bilateral Grid Downsampling

- Bilateral grid enables aggressive downsampling
- Extra dimension preserves edges
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

- Our edge-aware brush
  - Respects edges

Stroke with classical brush

Stroke with bilateral brush
Bilateral Grid Painting

Image scanline

Bilateral Grid

intensity

space

up

down
Bilateral Grid Painting

Image scanline

Bilateral Grid

Query grid with input image: **slicing**

Output brush stroke
Bilateral Grid Painting

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

Hard constraints in grid

Bilateral Grid

Image scanline

Intensity

Space
Scribble-based Selection

Image scanline

Hard constraints in grid

Smooth interpolation

Slice: query grid with input image

Interpolated 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, …]

Brute force computation: 10 minutes
With the bilateral grid: 9 ms
Bilateral Filter on the Bilateral Grid
Bilateral Filter on the Bilateral Grid

**Bilateral Grid**
- Gaussian blur grid values
- **Slice:** query grid with input image

**Image scanline**

**Filtered scanline**
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

1280 x 720
Multiscale Abstraction: 30 Hz
Transfer of Photographic Style

- Temporally coherent transfer
- 2 orders of magnitude speedup: real-time in HD
Live demo
Discussion

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

- 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
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
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