

ICCV 2007 Short Course Proposal

Title

Gradient Domain Manipulation Techniques in Vision and Graphics

Proposer's name, address, email

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Course description

The last decade has seen a tremendous interest in gradient domain manipulation techniques for applications in vision and graphics including retinex, high dynamic range (HDR) tone mapping, image fusion (mosaics), image editing, image matting, video synthesis, texture de-emphasis and 3D mesh editing. These techniques manipulate gradients of single image/multiple images/video/surfaces and reconstruct images/video/surfaces from the manipulated gradient fields. Reconstruction from gradient fields, itself, has a long history in computer vision, going back to the work in Photometric Stereo, Shape from Shading and brightness constancy.

In this course, we address the theoretical aspects of curl, divergence and integrability of vector fields, relevant to vision and graphics problems. We discuss scenarios where it is beneficial to operate on gradients than image intensities for image understanding, manipulation and synthesis. We review gradient domain techniques; address issues involved in 2D and 3D reconstructions from gradients, discuss implementations/numerical methods and give in-depth technical insight into the modern applications that exploit gradient domain manipulations.

The participants will learn about topics for extracting scene properties for computer vision as well as image manipulation methods for generating compelling pictures for computer graphics, with several examples. We hope to provide enough fundamentals to satisfy the technical specialist as well as tools/software's to aid graphics and vision researchers, including graduate students.

Course outline

Section 1: Introduction (45 mins) (Agrawal)

- Introduction to Gradients in Images/Surfaces
 - Gradients as Vector fields, Curl, Divergence, Integrability
- Non-integrable Vector Fields in Vision and Graphics
 - Example Application: High Dynamic Range Tone Mapping, Shape from Shading
 - Importance of Integrability
 - Reconstruction from Non-integrable Fields
 - Space of All Possible Reconstructions
 - What Solution does Poisson Equation give?
 - Boundary Conditions: Dirichlet vs. Neumann
- Traditional Applications: Reconstruction from Measured Gradients
 - Photometric Stereo
 - Shape from Shading
 - Phase unwrapping
- Modern Applications: Manipulation & Reconstruction of Image Gradients
 - Single Image Manipulation: Example, Cartooning via texture de-emphasis
 - Multi image Manipulation: Example, Image Fusion for context enhancement
 - Video Manipulation: Example, Video Editing
- Q & A: 10 mins

Section 2: Gradient-domain Manipulation of Images (45 mins) (Raskar)

- Decomposing Images and Scene Parameters
 - Retinex, Illumination/Reflectance
 - Time-Varying Illumination Estimation
 - Poisson Image Matting
 - Gradient Projection to Remove Flash Photography Artifacts
 - Projection Tensors for Edge Suppression
 - Removing Shadows from Images
- Image Editing
 - Cut and Paste
 - Photoshop Healing Brush
 - Covariant Image Editing
 - Drag and Drop Pasting
 - Image Inpainting
- Image Fusion and Enhancement
 - Detail-preserving Fusion of Multi-Spectral, Satellite Imagery
 - Multi-modal fusion (Visible/IR, Day/Night)
 - Mosaics and Panoramas
 - Digital Photomontage
 - Seamless Image Stitching
 - Image Enhancement by Unsharp Masking
- Q & A: 10 mins

Break (20 mins)

Section 3: Techniques to Reconstruct from Gradients (45 mins) (Agrawal)

- Numerical Solutions
 - Multi-grid 2D and 3D
 - Programmable graphics hardware
 - Reconstruction using Projection on Basis Functions
 - Fourier Domain Methods
 - Frankot-Chellappa Algorithm
 - Shaplets
 - Wavelets
 - Hierarchical Basis Preconditioning
- Robust Reconstruction Techniques
 - Poisson equation is based on least squares
 - RANSAC, M-estimators and Anisotropic Techniques
 - Graph based Approaches
 - Covariant Derivatives
- Q & A: 10 mins

Section 4: Advanced Gradient-based Operations (45 mins) (Raskar)

- Video Synthesis
 - Spatio-Temporal Editing
 - Videoshop
 - High dynamic range video
 - Video operations in Gradient Domain
- Texture
 - TextureShop
 - Panoramic video textures
 - Geometry completion and detail generation by texture synthesis
 - Texture De-emphasis/Cartooning in Gradient Domain
 - Image and Video Retexturing
- Meshes and Surface Descriptors
 - Laplacian Surface Editing
 - Laplacian Mesh Optimization
 - Mesh Editing with Poisson-Based Gradient Field Manipulation
 - Multigrid Algorithm for Mesh Deformation
 - Poisson Surface Reconstruction
 - Shape Representations using Poisson Equation
- Others
 - Gradient Camera
 - Bixels
 - Color to Gray conversion
 - Image Compression
 - Specularity Removal
- Q & A: 10 mins

Names of other lecturers and short bio-sketches

None

Relevant publications of the proposer(s) with respect to the topic

- **A. Agrawal**, "Scene Analysis under Variable Illumination using Gradient Domain Methods", **PhD Thesis**, Dept. of Electrical and Computer Engineering, University of Maryland, College Park, 2006
- **A. Agrawal**, **R. Raskar**, S.K. Nayar & Y. Li, "Removing Photography Artifacts using Gradient Projection and Flash-Exposure Sampling", ACM Transactions on Graphics (Proceedings of SIGGRAPH) 2005
- **A. Agrawal**, **R. Raskar** and R. Chellappa, "Edge Suppression by Gradient Field Transformation Using Cross-Projection Tensors", IEEE Conference on Computer Vision and Pattern Recognition (CVPR) 2006
- **A. Agrawal**, **R. Raskar** and R. Chellappa, "What is the Range of Surface Reconstructions from a Gradient Field?", European Conference on Computer Vision (ECCV), 2006
- **A. Agrawal**, R. Chellappa & **R. Raskar**, "An Algebraic Approach to Surface Reconstruction from Gradient Fields", IEEE International Conference on Computer Vision (ICCV), 2005
- J. Tumblin, **A. Agrawal** & **R. Raskar**, "Why I Want A Gradient Camera", IEEE Conference on Computer Vision and Pattern Recognition (CVPR) 2005
- **R. Raskar**, Kar-Han Tan, R. Feris, J. Yu, M. Turk. Non-photorealistic camera: depth edge detection and stylized rendering using multi-flash imaging, ACM Transactions on Graphics. 23(3), pp. 679-688, 2004.
- H. Wang, N. Xu, **R. Raskar** and N. Ahuja, "Videoshop: A new framework for spatio-temporal video editing in gradient domain", Graphical Models Volume 69, Issue 1, Pages 1-88 (January 2007)
- **R. Raskar**, A Ilie, J. Yu, "Image Fusion for Enhancing Context in Images and Video" ACM Nonphotorealistic Animation and Rendering (NPAR) 2004
- R. Feris, M. Turk, **R. Raskar** and K. Tan, "Specular Reflection Reduction with Multi-Flash Photography", International Journal of the Brazilian Computer Society, 2005.
- H. Wang, **R Raskar**, N Ahuja , "Seamless Video Editing", ICPR 2004
- H. Wang, **R. Raskar** and N. Ahuja, "High Dynamic Range Video Using Split Aperture Camera", IEEE 6th Workshop on Omnidirectional Vision, Camera Networks and Non-classical Cameras (OMNIVIS, in conjunction with ICCV'05), Beijing, China, Oct. 2005
- R. S. Feris, **R. Raskar**, L. Chen, K. Tan and M. Turk. Discontinuity Preserving Stereo with Small Baseline Multi-Flash Illumination. IEEE International Conference on Computer Vision (ICCV'05)

Length of course & estimated attendance

Half day 3.5 - 4 hours.

Intended audience: Computer vision/graphics researchers, graduate students

Whether PDF slides will be available for inclusion in the CDROM

Yes

Whether there will be a web page about the short course including slides.

- Course webpage will be hosted at <http://www.merl.com/people/agrawal/ICCV2007Course/> and at <http://www.cfar.umd.edu/~aagrawal/ICCV2007Course/>
- Webpage will include bibliography of the relevant papers in vision and graphics along with Matlab and C code contributed by the proposers.
- Some of the Matlab and C source code is already available at <http://www.merl.com/people/agrawal/software.html>

Specifically, course notes will include

- Slides
- Relevant papers
- Reference list, links to websites
- Pseudo-code for gradient domain operations, Poisson solver, gradient projection

In the document below, we have included

- Reference list of papers. We will continue to update this reference list.
- Pseudo-code for solving Poisson Equation
- Slides for Section 2

Bio:

Amit Agrawal received the B.Tech degree in Electrical Engineering from Indian Institute of Technology (IIT), Kanpur, in 2000 and M.S. and PhD degrees in EECS from University of Maryland, College Park, in 2003 and 2006 respectively. Prior to his graduate studies, he worked as a DSP engineer at Hughes Software Systems, India, for one year. He is currently a visiting research scientist at MERL. His research interests are in computer vision, image processing and computational photography. Recent projects include surface reconstruction from gradient fields, gradient domain algorithms for scene analysis, gradient camera for high dynamic range imaging and coded exposure photography. His papers have appeared in several vision and graphics conferences including SIGGRAPH, CVPR, ICCV and ECCV. He is a member of IEEE and ACM.

Ramesh Raskar is a Senior Research Scientist at MERL. His research interests include projector-based graphics, computational photography and non-photorealistic rendering. He has published several articles on imaging and photography including multi-flash photography for depth edge detection, image fusion, gradient-domain imaging and projector-camera systems. His

papers have appeared in SIGGRAPH, EuroGraphics, IEEE Visualization, CVPR, ICCV, ECCV and many other graphics and vision conferences. He was a course organizer at Siggraph 2002 through 2006. He was the panel organizer at the Symposium on Computational Photography and Video in Cambridge, MA in May 2005 and taught a graduate level class on Computational Photography at Northeastern University, Fall 2005. He is a member of the ACM and IEEE.

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Published Research on Gradient Domain Manipulation Techniques

Decomposing Images and Scene Parameters

- Y. Weiss. Deriving intrinsic images from image sequences. In *Proceedings of ICCV*, volume 2, pages 68–75, 2001.
- Y. Matsushita, S. Lin, S.B. Kang, and H.Y. Shum. Estimating intrinsic images from image sequences with biased illumination. In *Proc. European Conf. Computer Vision*, pages 274–286, 2004.
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- A. Agrawal, R. Raskar, S.K. Nayar, and Y. Li. Removing photography artifacts using gradient projection and flash-exposure sampling. *ACM Trans. Graph.*, 24(3):828–835, 2005.
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Image Editing

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Image Fusion and Enhancement

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- Aseem Agarwala, Ke Colin Zheng, Chris Pal, Maneesh Agrawala, Michael Cohen, Brian Curless, David H. Salesin, and Richard Szeliski. Panoramic video textures. *ACM Transactions on Graphics*, 24(3):821–827, August 2005.
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High Dynamic Range Imaging

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Reconstruction from Gradients/Interpolation

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Photometric Stereo, Shape from Shading & Phase Unwrapping

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Meshes and Shape Descriptors

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Texture

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Others

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- Jack Tumblin and Prason Choudhury. Bixels: Picture samples with sharp embedded boundaries. In *Rendering Techniques 2004: 15th Eurographics Workshop on Rendering*, pages 255–264, June 2004.
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We will continue to update this bibliography.

Matlab Code for Poisson Image Reconstruction from Image Gradients

% Read Input Gray Image

```
imgstr = 'test.png'; disp(sprintf('Reading Image %s',imgstr));
img = imread(imgstr); [H,W,C] = size(img); img = double(img);
```

% Find gradinets

```
gx = zeros(H,W); gy = zeros(H,W); j = 1:H-1; k = 1:W-1;
gx(j,k) = (img(j,k+1) - img(j,k)); gy(j,k) = (img(j+1,k) - img(j,k));
```

% Reconstruct image from gradients for verification

```
img_rec = poisson_solver_function(gx,gy,img);
```

```
figure;imagesc(img);colormap gray;colorbar;title('Image')
figure;imagesc(img_rec);colormap gray;colorbar;title('Reconstructed');
figure;imagesc(abs(img_rec-img));colormap gray;colorbar;title('Abs error');
```

```
function [img_direct] = poisson_solver_function(gx,gy,boundary_image);
```

```
% function [img_direct] = poisson_solver_function(gx,gy,boundary_image)
```

```
% Inputs; Gx and Gy -> Gradients
```

```
% Boundary Image -> Boundary image intensities
```

```
% Gx Gy and boundary image should be of same size
```

```
[H,W] = size(boundary_image);
gxx = zeros(H,W); gyy = zeros(H,W);
f = zeros(H,W); j = 1:H-1; k = 1:W-1;
```

% Laplacian

```
gyy(j+1,k) = gy(j+1,k) - gy(j,k); gxx(j,k+1) = gx(j,k+1) - gx(j,k);
f = gxx + gyy; clear j k gxx gyy gyyd gxxd
```

```
% boundary image contains image intensities at boundaries
```

```
boundary_image(2:end-1,2:end-1) = 0;
disp('Solving Poisson Equation Using DST'); tic
j = 2:H-1; k = 2:W-1; f_bp = zeros(H,W);
f_bp(j,k) = -4*boundary_image(j,k) + boundary_image(j,k+1) +
    boundary_image(j,k-1) + boundary_image(j-1,k) + boundary_image(j+1,k);
clear j k
```

```
f1 = f - reshape(f_bp,H,W); % subtract boundary points contribution
clear f_bp f
```

```
% DST Sine Transform algo starts here
```

```
f2 = f1(2:end-1,2:end-1); clear f1
%compute sine transform
tt = dst(f2); f2sin = dst(tt)'; clear f2
```

```
%compute Eigen Values
```

```
[x,y] = meshgrid(1:W-2,1:H-2); denom = (2*cos(pi*x/(W-1))-2) + (2*cos(pi*y/(H-1)) - 2) ;
```

```
%divide
```

```
f3 = f2sin./denom; clear f2sin x y
```

```
%compute Inverse Sine Transform
```

```
tt = idst(f3); clear f3; img_tt = idst(tt)'; clear tt
```

```
time_used = toc; disp(sprintf('Time for Poisson Reconstruction = %f secs',time_used));
```

```
% put solution in inner points; outer points obtained from boundary image
```

```
img_direct = boundary_image;
img_direct(2:end-1,2:end-1) = 0;
img_direct(2:end-1,2:end-1) = img_tt;
```

```

function b=dst(a,n)
%DST Discrete sine transform (Used in Poisson reconstruction)
% Y = DST(X) returns the discrete sine transform of X.
% The vector Y is the same size as X and contains the
% discrete sine transform coefficients.
% Y = DST(X,N) pads or truncates the vector X to length N
% before transforming.
% If X is a matrix, the DST operation is applied to each
% column. This transform can be inverted using IDST.

error(nargchk(1,2,nargin));

if min(size(a))==1
    if size(a,2)>1
        do_trans = 1;
    else
        do_trans = 0;
    end
    a = a(:);
else
    do_trans = 0;
end
if nargin==1, n = size(a,1); end
m = size(a,2);

% Pad or truncate a if necessary
if size(a,1)<n,
    aa = zeros(n,m); aa(1:size(a,1),:) = a;
else
    aa = a(1:n,:);
end

y=zeros(2*(n+1),m); y(2:n+1,:)=aa; y(n+3:2*(n+1),:)=flipud(aa);
yy=fft(y); b=yy(2:n+1,:)/(-2*sqrt(-1));

if isreal(a), b = real(b); end
if do_trans, b = b.'; end

```

```

function b=idst(a,n)
%IDST Inverse discrete sine transform (Used in Poisson reconstruction)
%
% X = IDST(Y) inverts the DST transform, returning the
% original vector if Y was obtained using Y = DST(X).
% X = IDST(Y,N) pads or truncates the vector Y to length N
% before transforming.
% If Y is a matrix, the IDST operation is applied to
% each column.

if nargin==1
    if min(size(a))==1
        n=length(a);
    else
        n=size(a,1);
    end
end

nn=n+1; b=2/nn*dst(a,n);

```

Section 1

Modern Applications: Manipulation & Reconstruction of Image Gradients



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Mitsubishi Electric Research Labs
Cambridge, MA

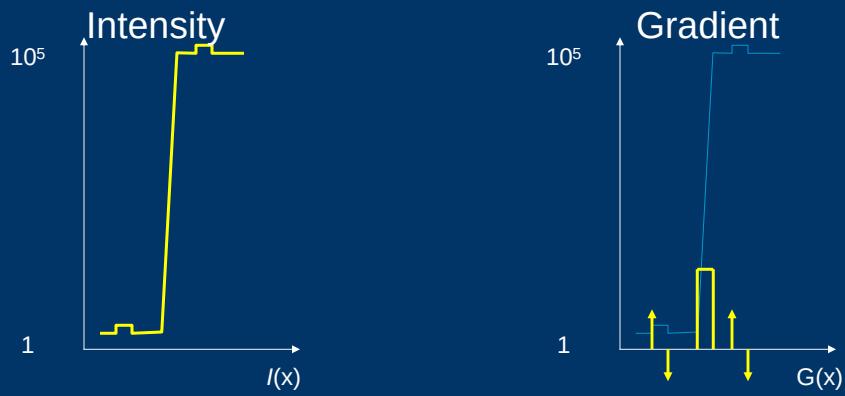
Course: Gradient Domain Techniques

ICCV 2007

Image Tools

- Gradient domain operations,
 - Applications in tone mapping, fusion and matting
- Graph cuts,
 - Applications in segmentation and mosaicing
- Bilateral and Trilateral filters,
 - Applications in image enhancement

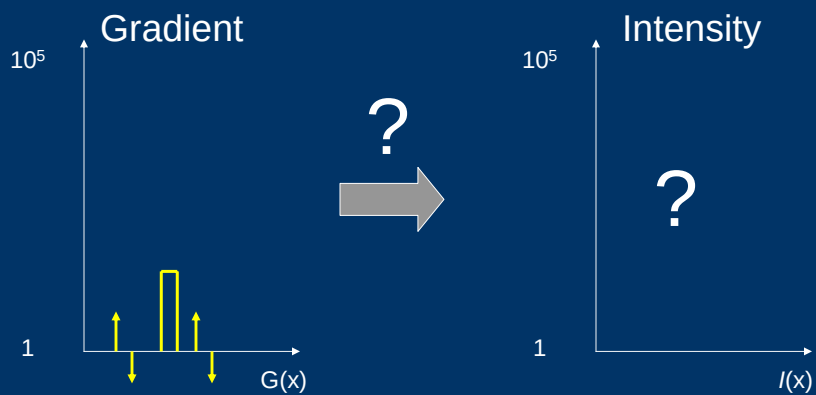
Intensity Gradient in 1D



Gradient at x ,

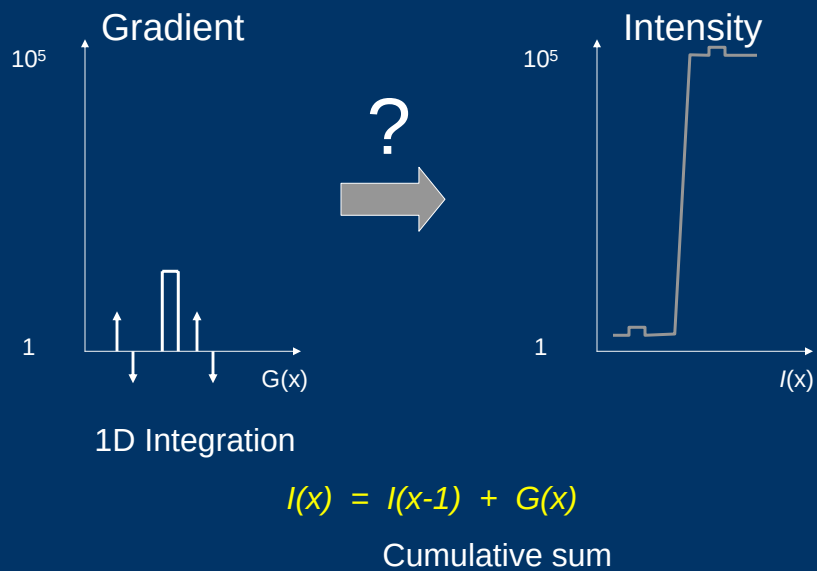
$$G(x) = \frac{I(x+1) - I(x)}{1}$$
 Forward Difference

Reconstruction from Gradients



For n intensity values, about n gradients

Reconstruction from Gradients



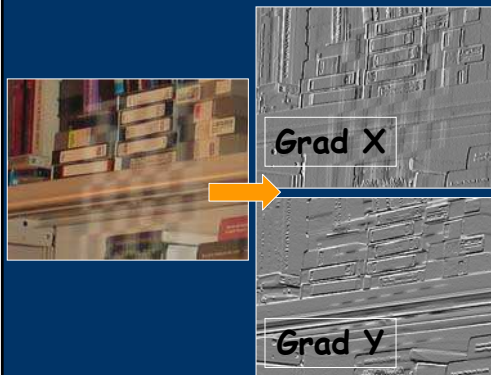
Intensity Gradient in 2D

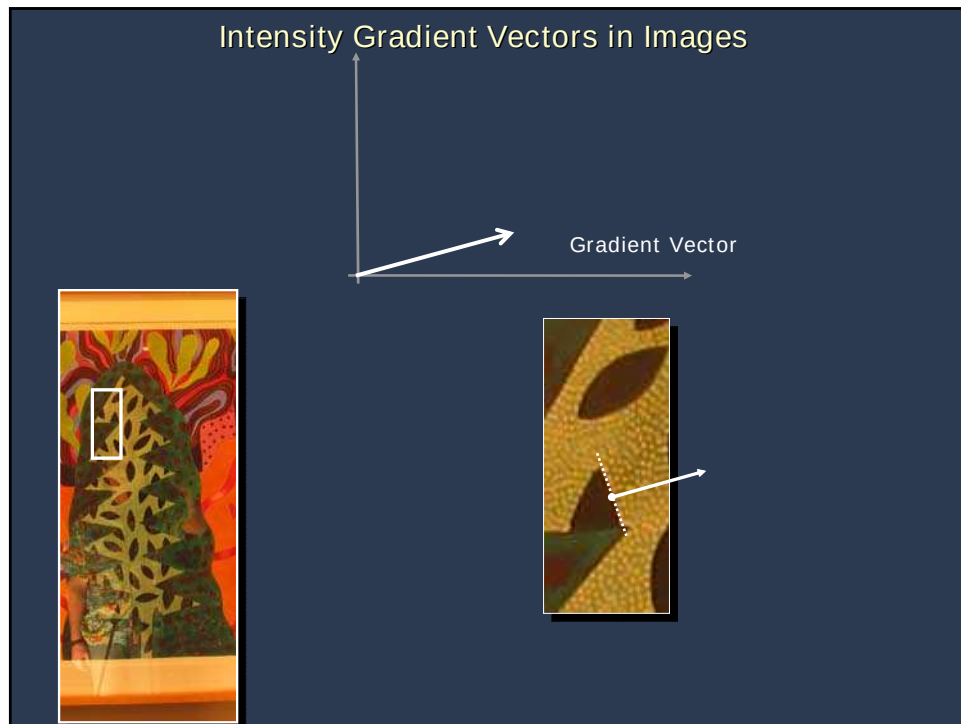
Gradient at x, y as Forward Differences

$$G_x(x, y) = I(x+1, y) - I(x, y)$$

$$G_y(x, y) = I(x, y+1) - I(x, y)$$

$$G(x, y) = (G_x, G_y)$$





Course: Gradient Domain Techniques
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Reconstruction from Gradients

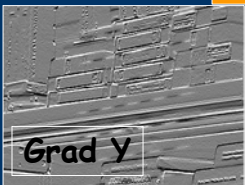
Given $G(x,y) = (G_x, G_y)$

How to compute $I(x,y)$ for the image ?

For n^2 image pixels, $2n^2$ gradients !



Grad X



Grad Y



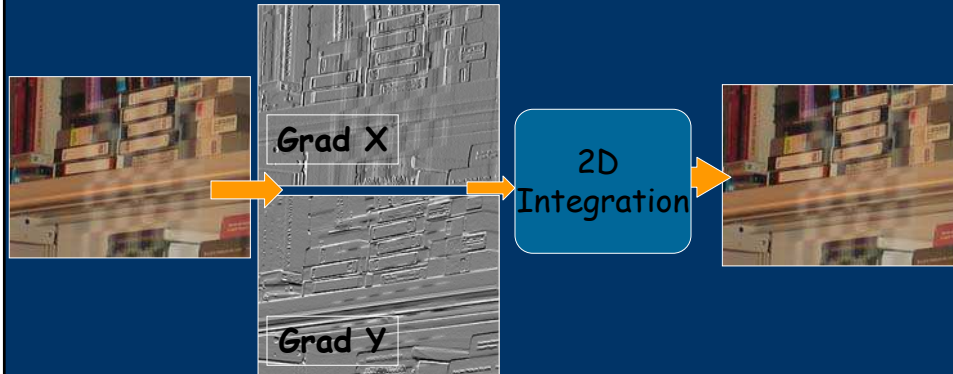
2D
Integration





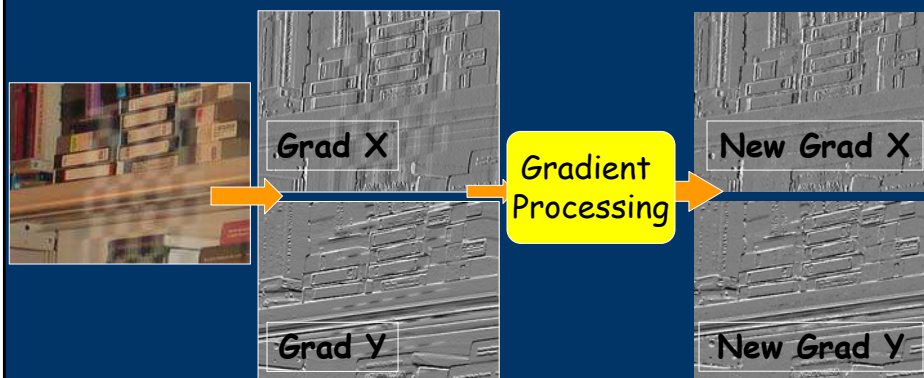
Intensity Gradient in 2D

Recovering Original Image



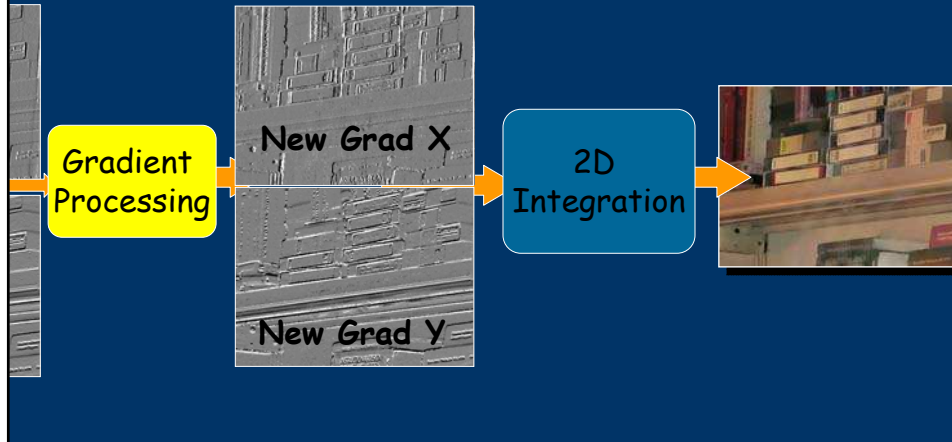
Intensity Gradient Manipulation

Recovering Manipulated Image



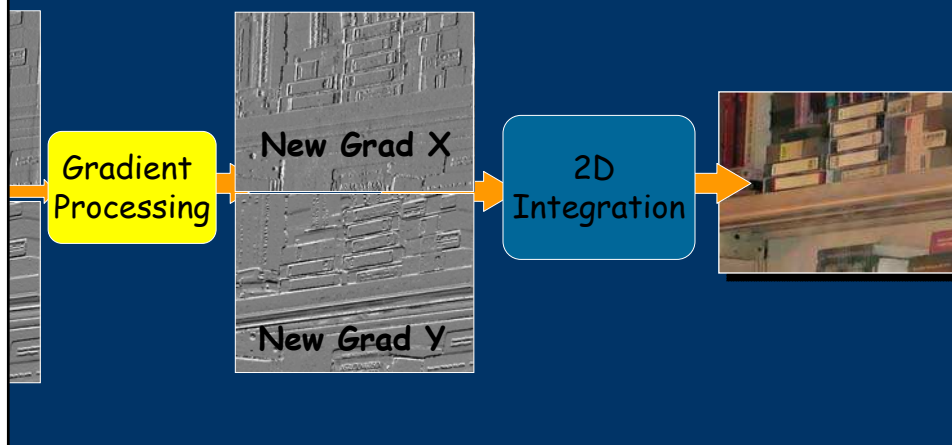
Intensity Gradient Manipulation

Recovering Manipulated Image



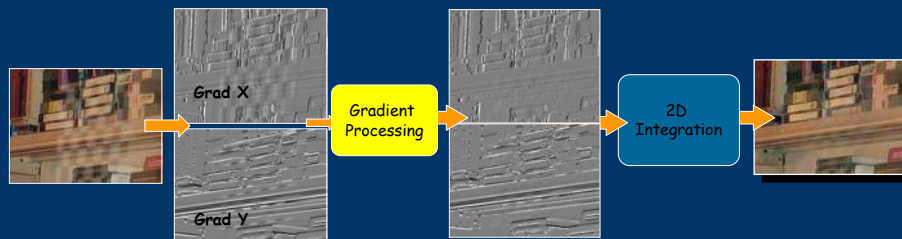
Intensity Gradient Manipulation

Recovering Manipulated Image



Intensity Gradient Manipulation

A Common Pipeline



Reconstruction from Gradients

- Look for image I with gradient closest to G in the least squares sense.

- I minimizes the integral: $\iint F(\nabla I, G) dx dy$

$$F(\nabla I, G) = \|\nabla I - G\|^2 = \left(\frac{\partial I}{\partial x} - G_x \right)^2 + \left(\frac{\partial I}{\partial y} - G_y \right)^2$$

Euler-Lagrange Equation

- I must satisfy:
$$\frac{\partial F}{\partial I} - \frac{d}{dx} \frac{\partial F}{\partial I_x} - \frac{d}{dy} \frac{\partial F}{\partial I_y} = 0$$

- Substituting F we get:

$$2 \left(\frac{\partial^2 I}{\partial x^2} - \frac{\partial G_x}{\partial x} \right) + 2 \left(\frac{\partial^2 I}{\partial y^2} - \frac{\partial G_y}{\partial y} \right)$$

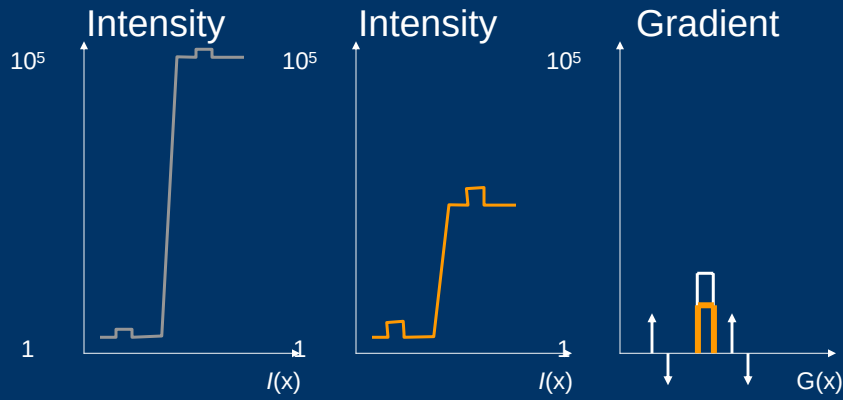
$$\nabla^2 I = \text{div } G$$

Application: Compressing Dynamic Range

How could you put all this information into one Image ?



Attenuate High Gradients



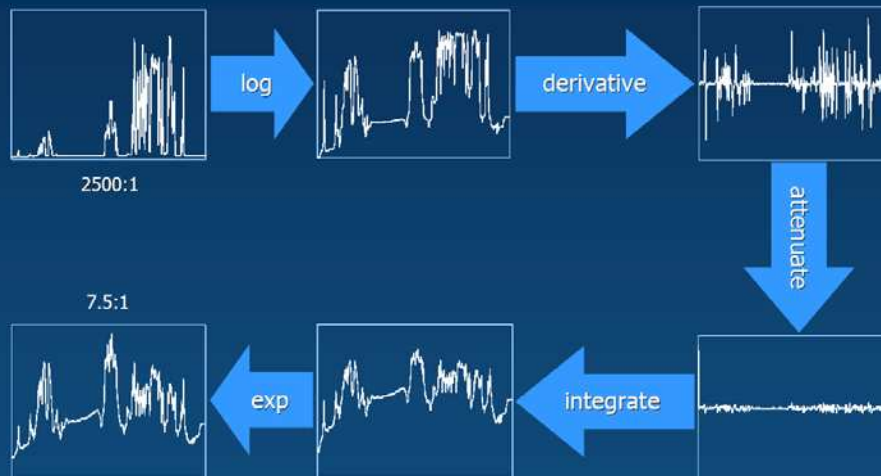
Maintain local detail at the cost of global range

Fattal et al Siggraph 2002

Basic Assumptions

- The eye responds more to local intensity differences (ratios) than global illumination
- A HDR image must have some large magnitude gradients
- Fine details consist only of smaller magnitude gradients

Gradient Compression in 1D



Gradient Domain Method



Basic Method

- Take the log of the luminances
- Calculate the gradient at each point
- Scale the magnitudes of the gradients with a progressive scaling function (Large magnitudes are scaled down more than small magnitudes)
- Re-integrate the gradients and invert the log to get the final image

Summary: Intensity Gradient Manipulation

