Gradient domain operations

Digital Visual Effects, Spring 2009

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2009/6/4

with slides by Fredo Durand, Ramesh Raskar, Amit Agrawal

Gradient domain operators

sources/destinations cloning seamless cloning

Gradient Domain Manipulations

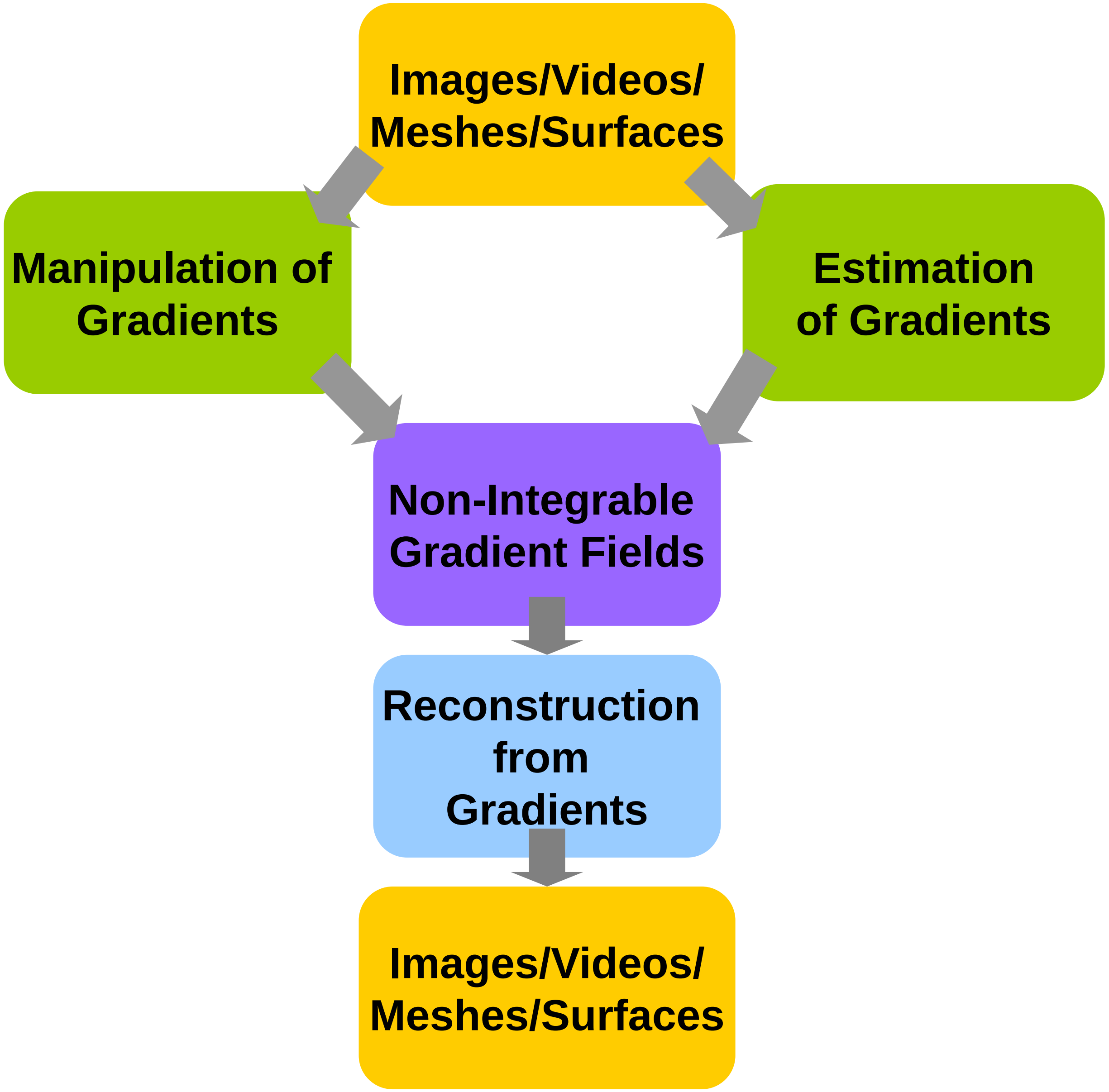
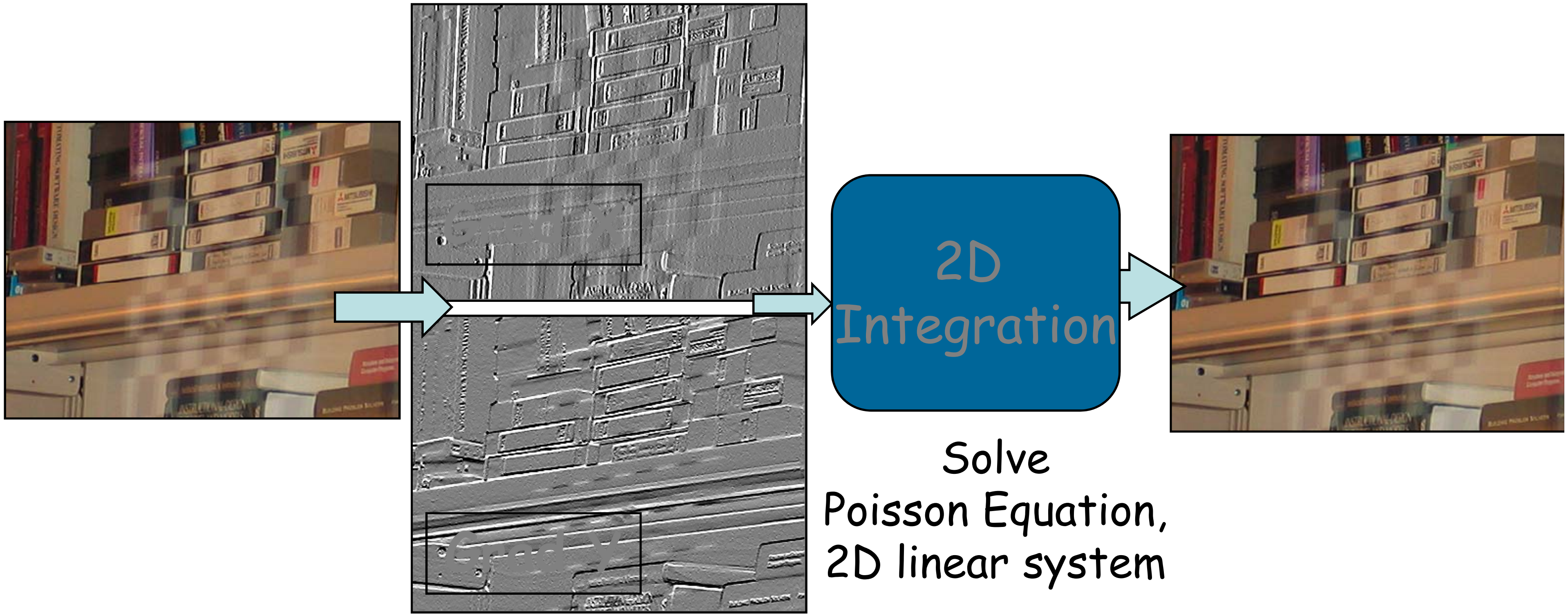


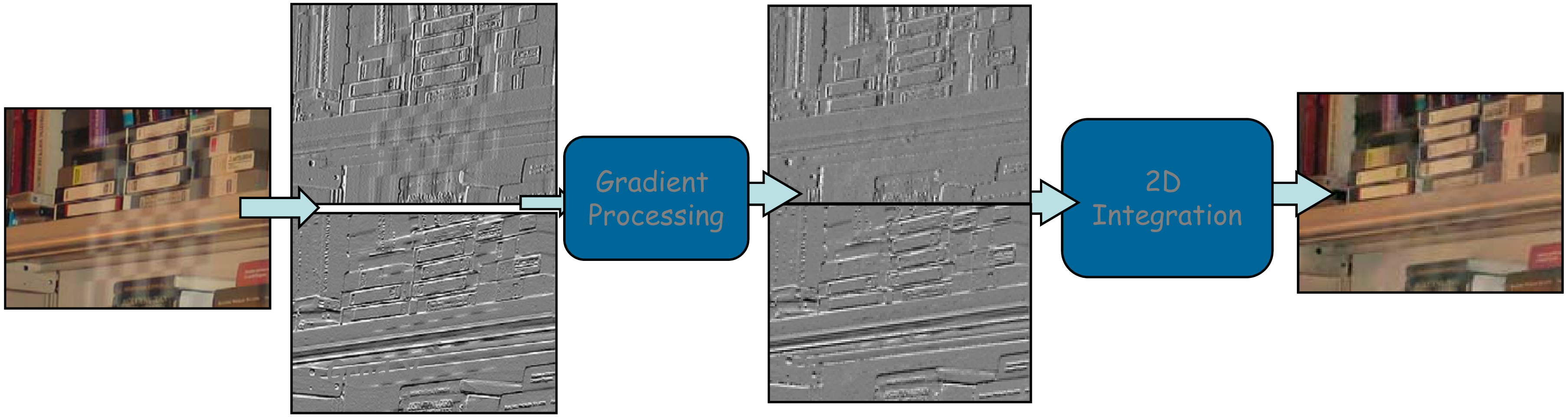
Image Intensity Gradients in 2D

DigiVFX



Intensity Gradient Manipulation

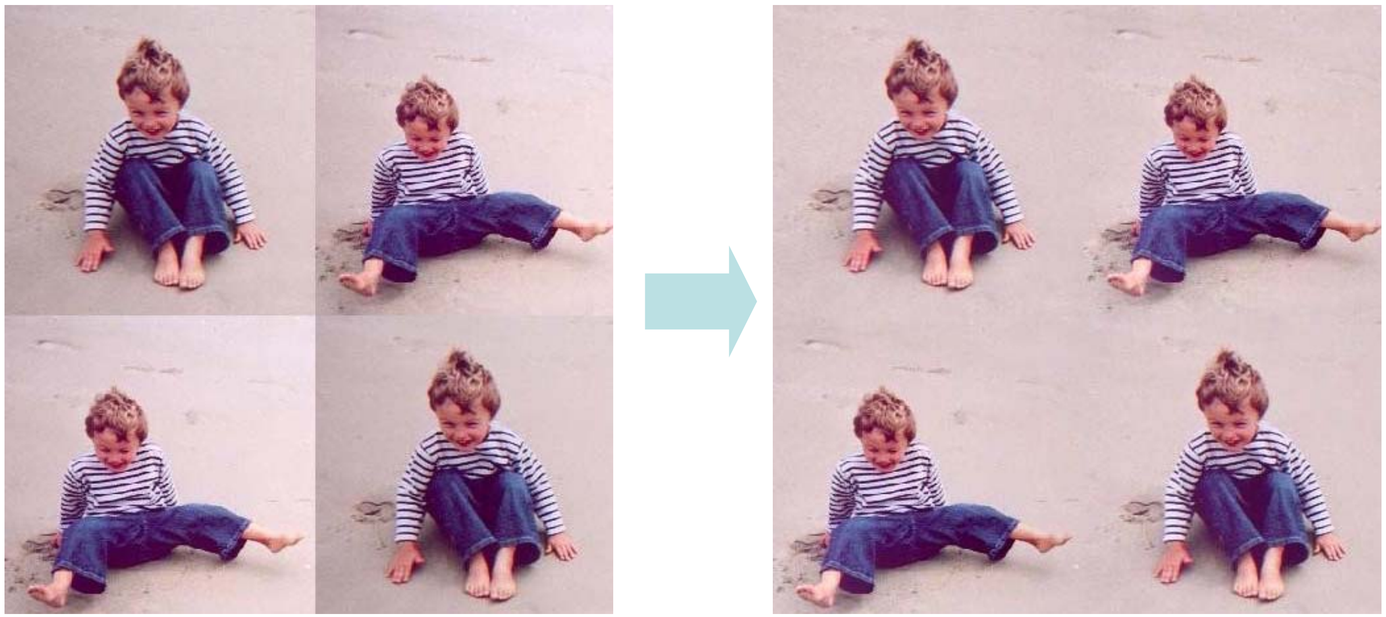
A Common Pipeline



1. Gradient manipulation
2. Reconstruction from gradients

Example Applications

Removing Glass Reflections



Seamless Image Stitching

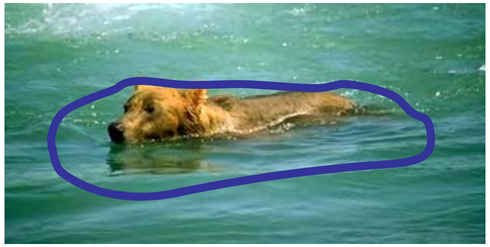
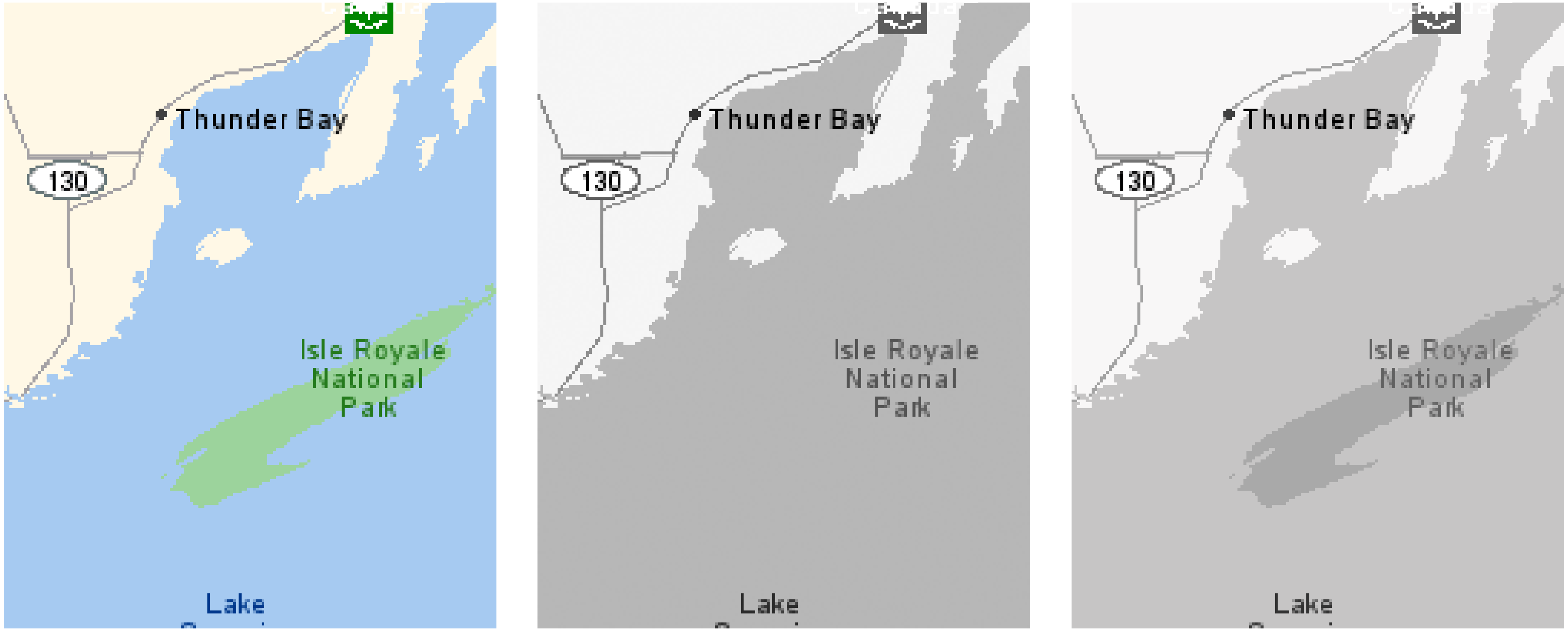


Image Editing


Changing Local Illumination



Original PhotoshopGrey Color2Gray

Color to Gray Conversion

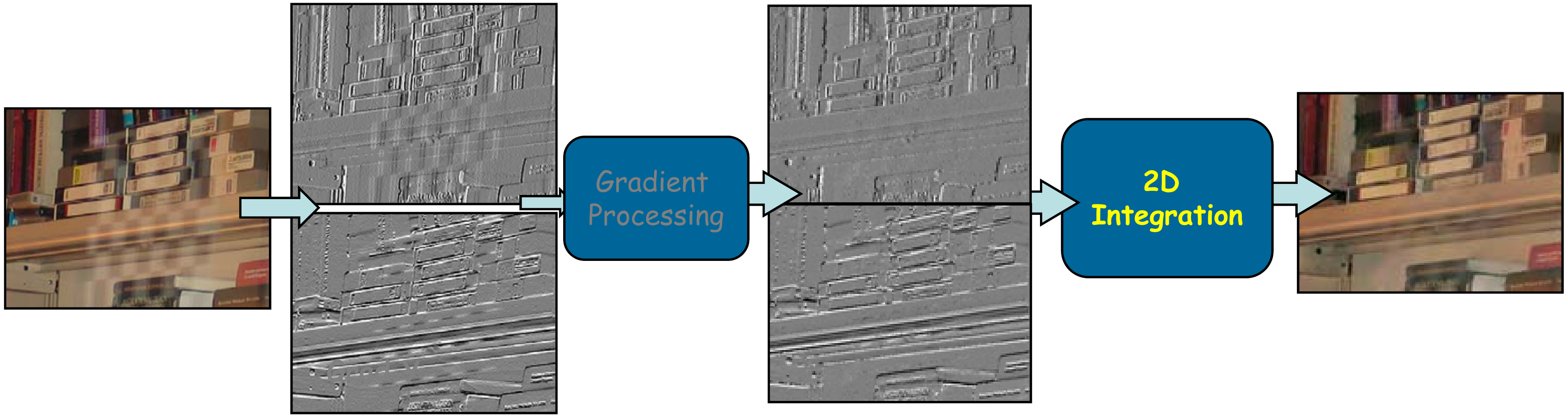
High Dynamic Range Compression

Edge Suppression under Significant Illumination Variations

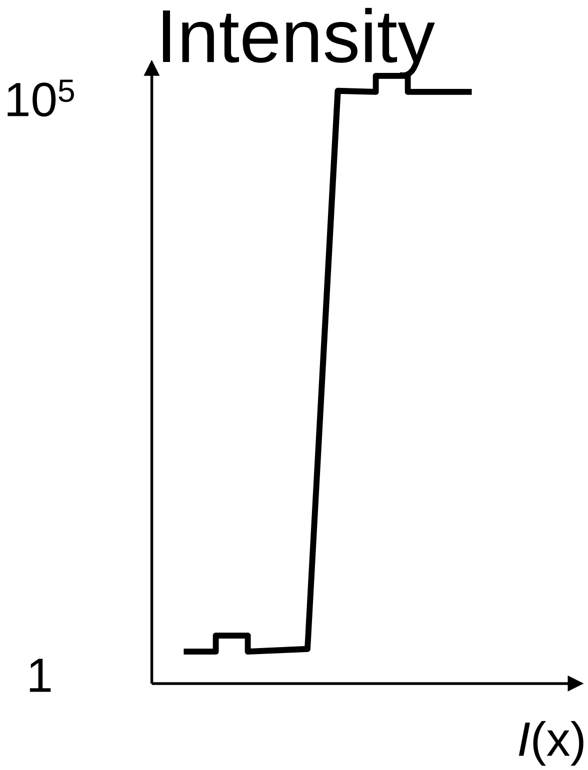
Fusion of day and night images

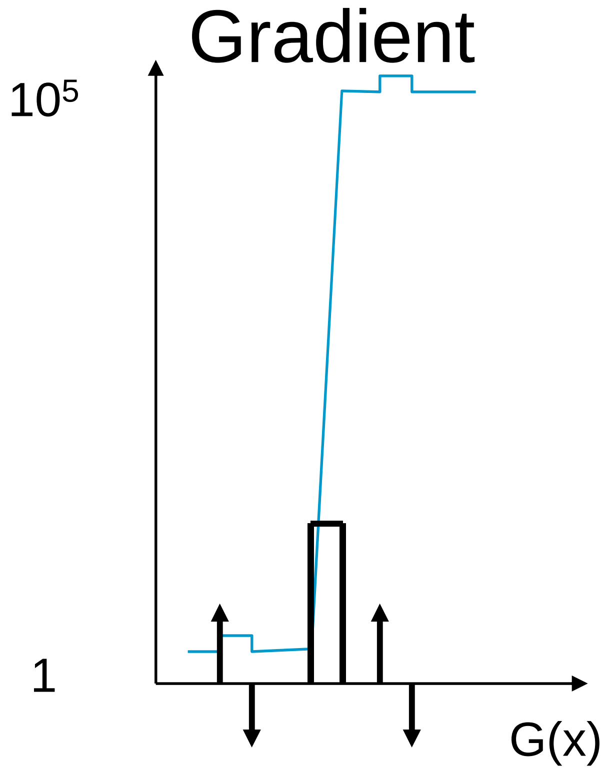
Intensity Gradient Manipulation

A Common Pipeline



Intensity Gradient in 1D



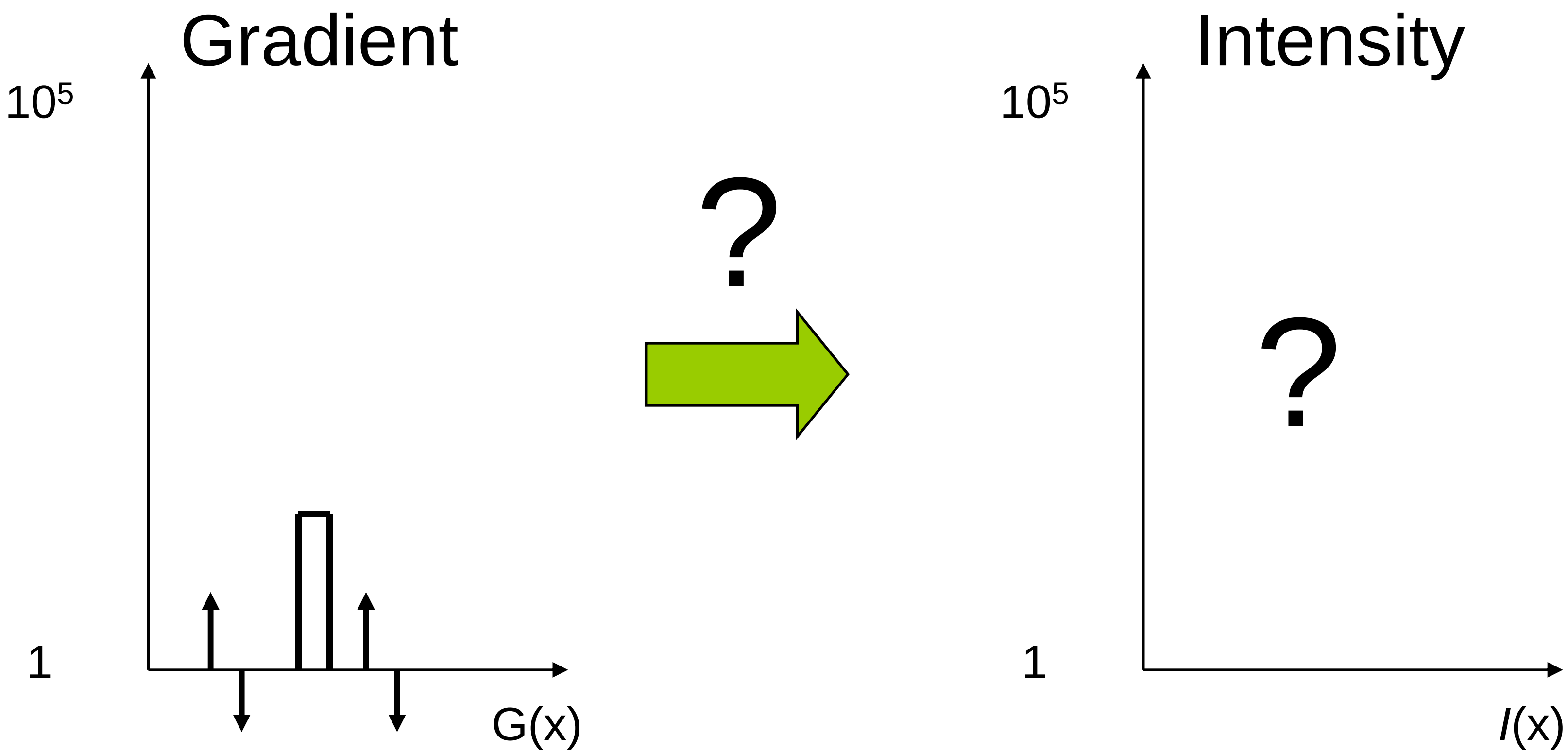


Gradient at x,

$$G(x) = I(x+1) - I(x)$$

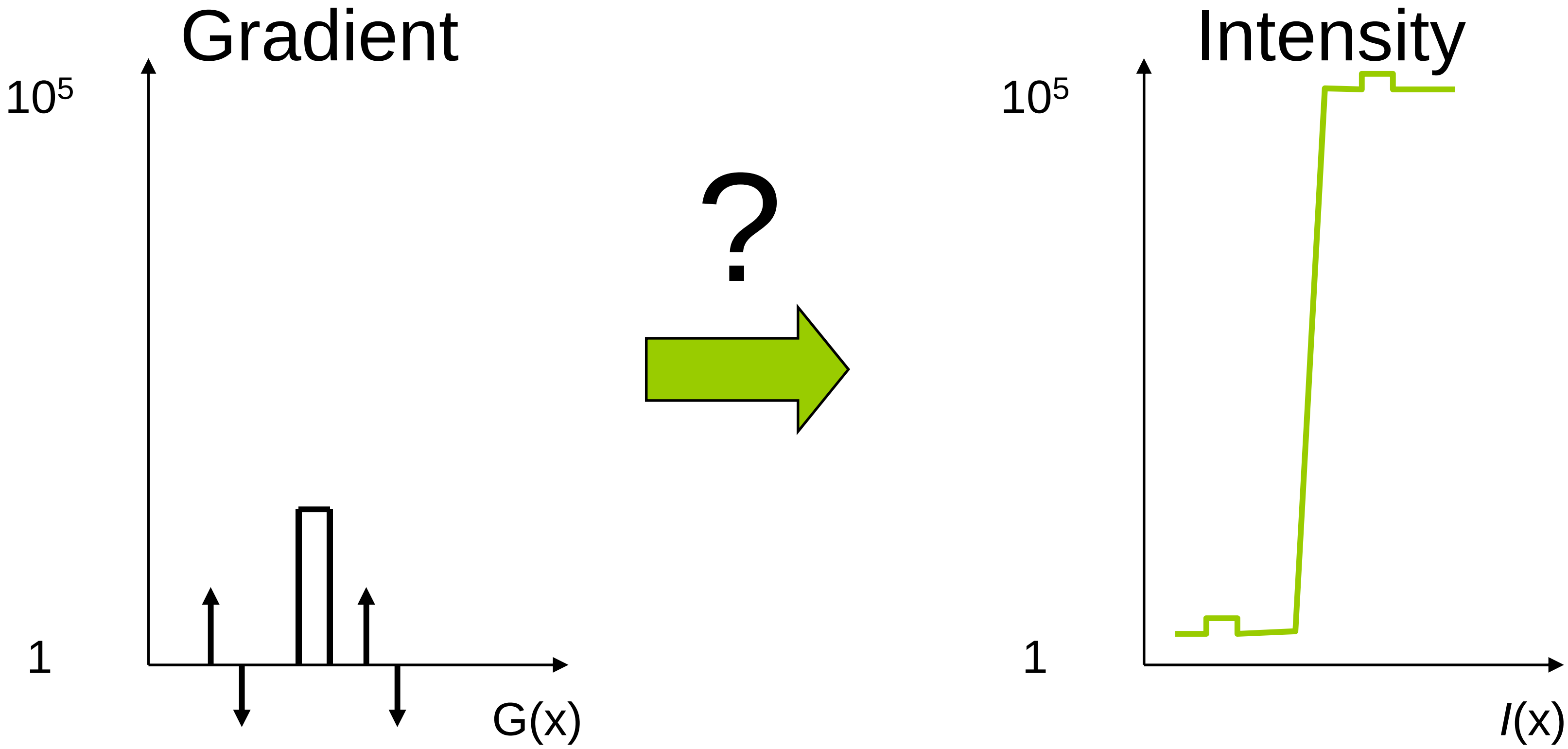
Forward Difference

Reconstruction from Gradients



For *n* intensity values, about *n* gradients

Reconstruction from Gradients

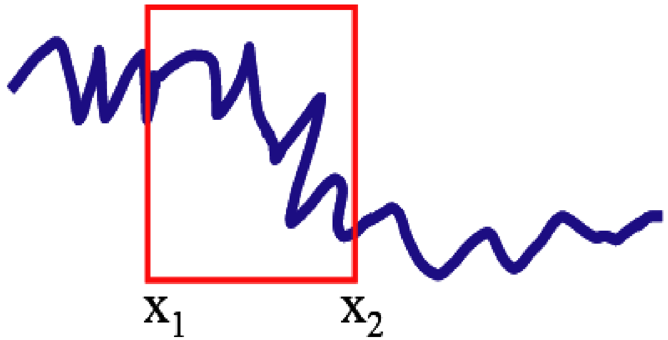


1D Integration

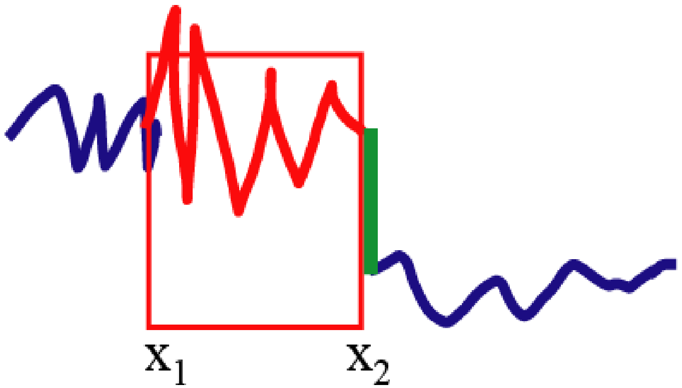
$$I(x) = I(x-1) + G(x)$$

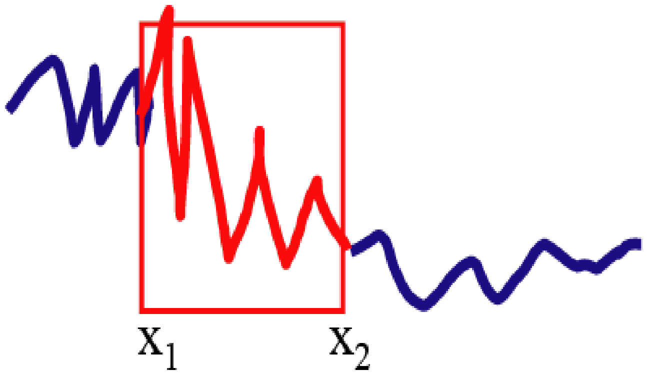
Cumulative sum

1D case with constraints

Seamlessly paste  onto 

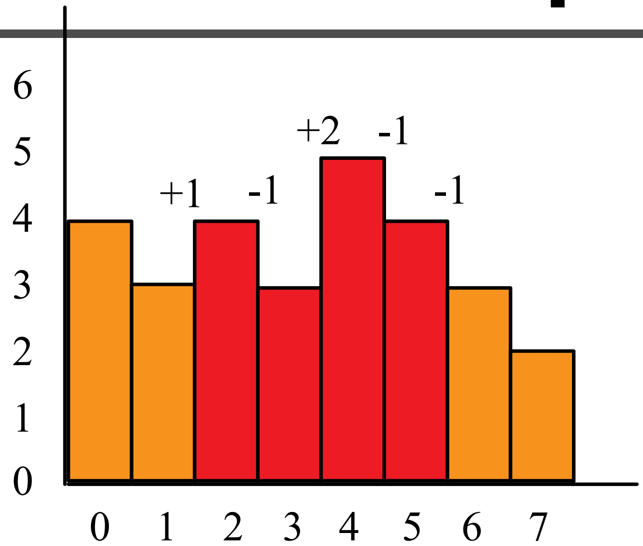
Just add a linear function so that the boundary condition is respected



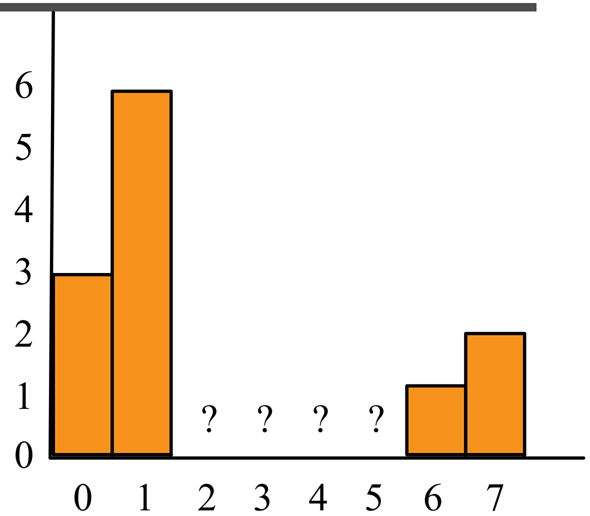


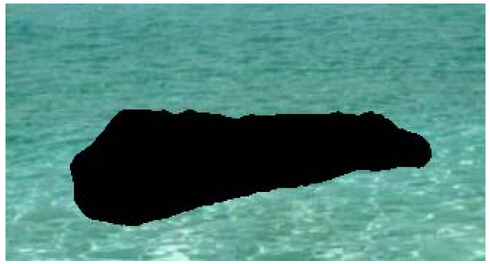
Discrete 1D example: minimization

- Copy



to

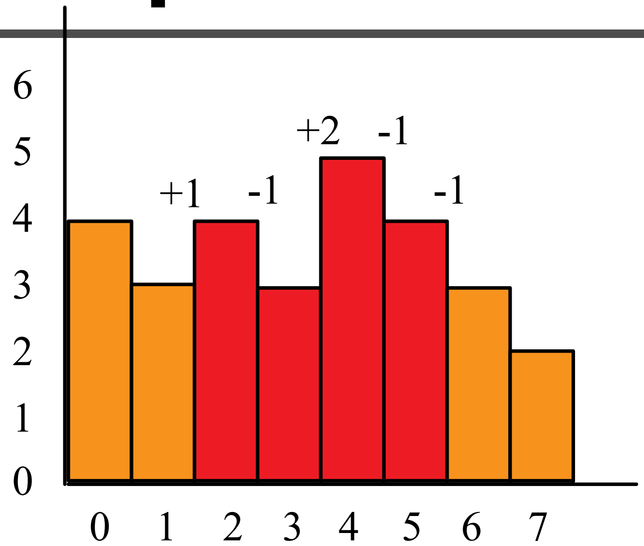


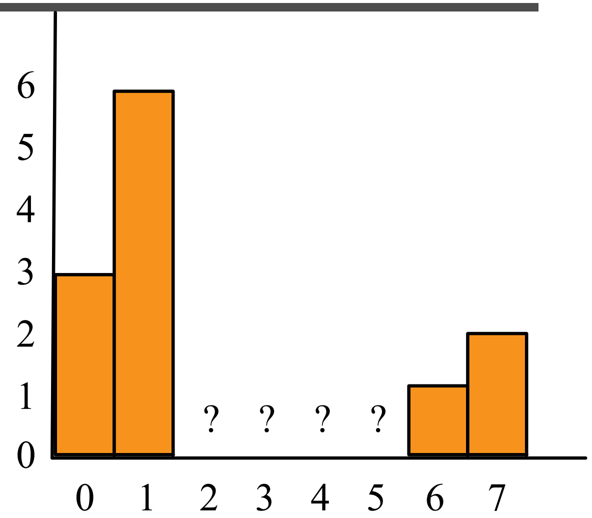


- Min $((f_2-f_1)-1)^2$
- Min $((f_3-f_2)-(-1))^2$
- Min $((f_4-f_3)-2)^2$
- Min $((f_5-f_4)-(-1))^2$
- Min $((f_6-f_5)-(-1))^2$

With
$f_1=6$
$f_6=1$

1D example: minimization

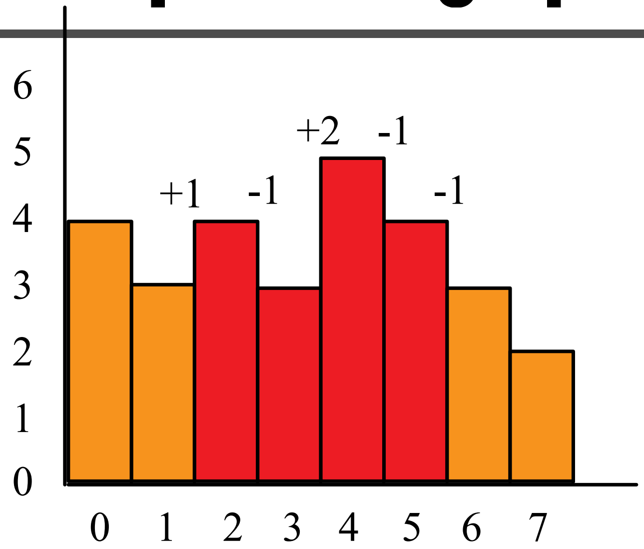
- Copy 

to 

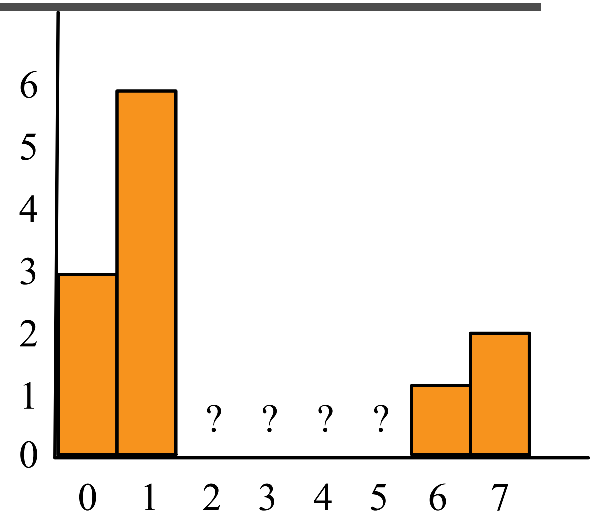
- Min $((f_2-6)-1)^2$ ==> $f_2^2+49-14f_2$
- Min $((f_3-f_2)-(-1))^2$ ==> $f_3^2+f_2^2+1-2f_3f_2+2f_3-2f_2$
- Min $((f_4-f_3)-2)^2$ ==> $f_4^2+f_3^2+4-2f_3f_4-4f_4+4f_3$
- Min $((f_5-f_4)-(-1))^2$ ==> $f_5^2+f_4^2+1-2f_5f_4+2f_5-2f_4$
- Min $((1-f_5)-(-1))^2$ ==> $f_5^2+4-4f_5$

1D example: big quadratic

- Copy



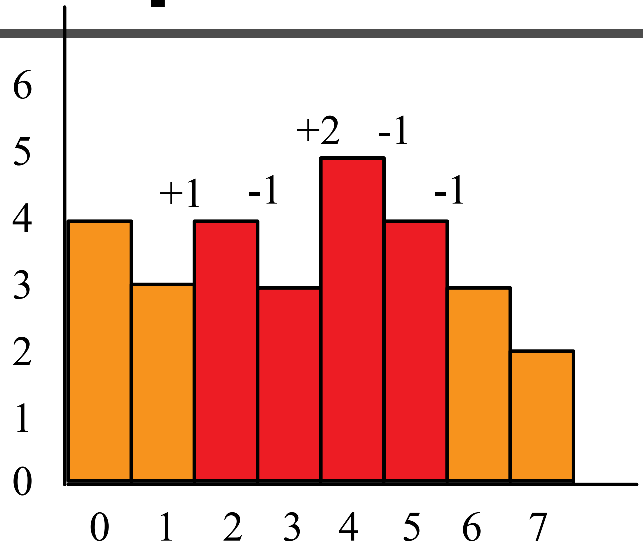
to



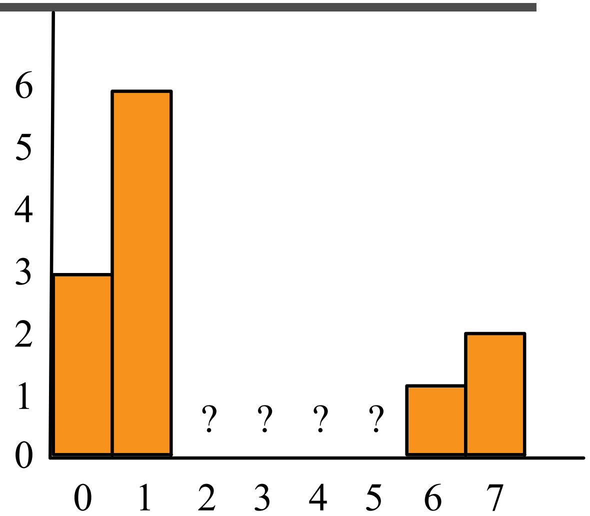
- Min $(f_2^2+49-14f_2$
  $+ f_3^2+f_2^2+1-2f_3f_2 +2f_3-2f_2$
  $+ f_4^2+f_3^2+4-2f_3f_4 -4f_4+4f_3$
  $+ f_5^2+f_4^2+1-2f_5f_4 +2f_5-2f_4$
  $+ f_5^2+4-4f_5)$
  Denote it Q

1D example: derivatives

- Copy



to



Min $(f_2^2+49-14f_2$
$+ f_3^2+f_2^2+1-2f_3f_2 +2f_3-2f_2$
$+ f_4^2+f_3^2+4-2f_3f_4 -4f_4+4f_3$
$+ f_5^2+f_4^2+1-2f_5f_4 +2f_5-2f_4$
$+ f_5^2+4-4f_5)$

Denote it Q

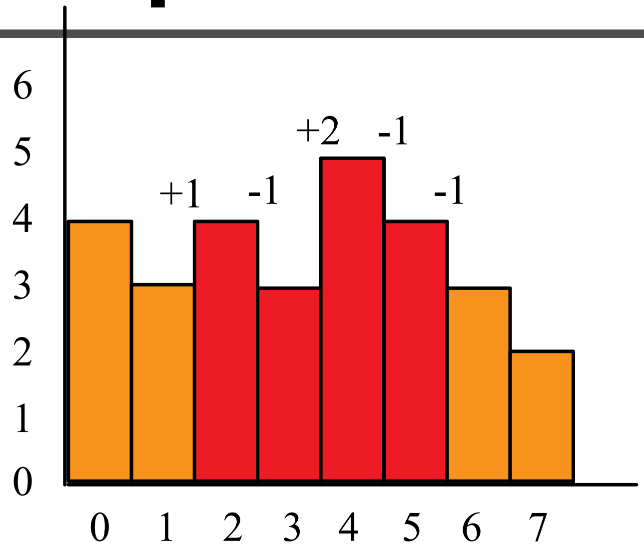
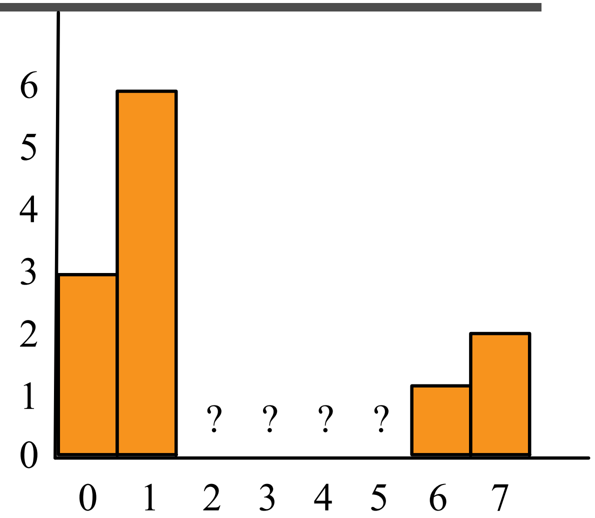
$$\frac{dQ}{df_2} = 2f_2 + 2f_2 - 2f_3 - 16$$

$$\frac{dQ}{df_3} = 2f_3 - 2f_2 + 2 + 2f_3 - 2f_4 + 4$$

$$\frac{dQ}{df_4} = 2f_4 - 2f_3 - 4 + 2f_4 - 2f_5 - 2$$

$$\frac{dQ}{df_5} = 2f_5 - 2f_4 + 2 + 2f_5 - 4$$

1D example: set derivatives to zero

- Copy  to 

$$\frac{dQ}{df_2} = 2f_2 + 2f_2 - 2f_3 - 16$$

$$\frac{dQ}{df_3} = 2f_3 - 2f_2 + 2 + 2f_3 - 2f_4 + 4$$

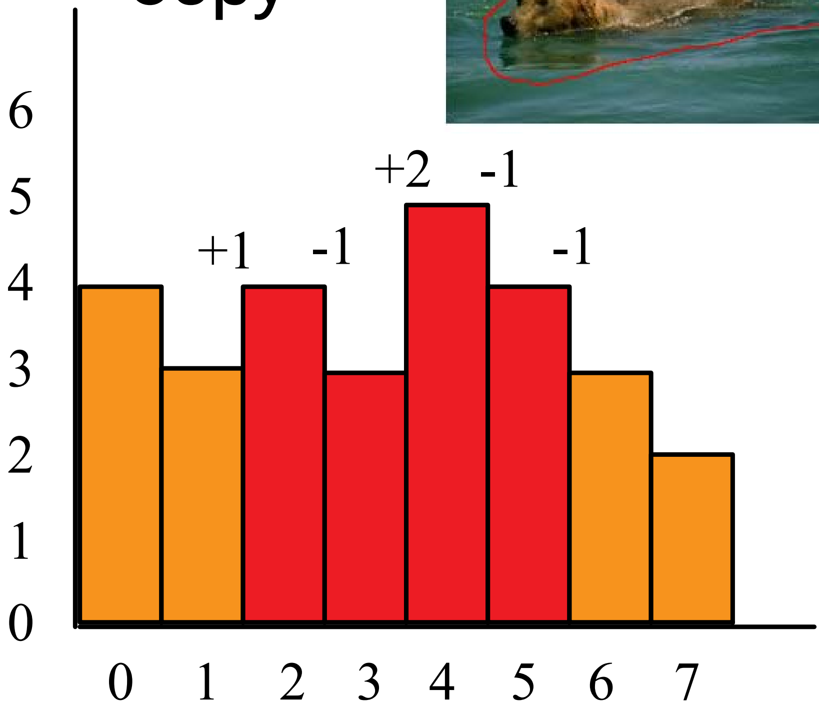
$$\frac{dQ}{df_4} = 2f_4 - 2f_3 - 4 + 2f_4 - 2f_5 - 2$$

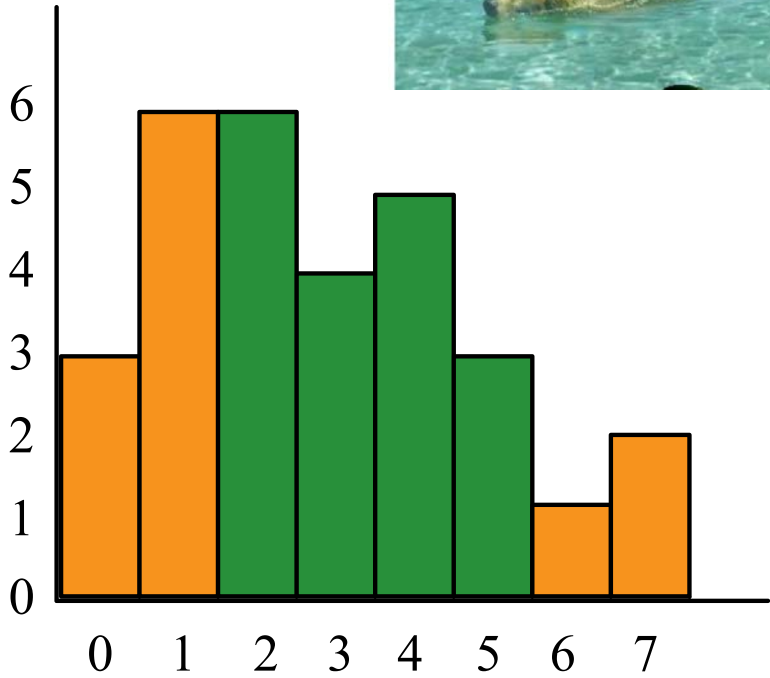
$$\frac{dQ}{df_5} = 2f_5 - 2f_4 + 2 + 2f_5 - 4$$

$$\Longrightarrow \begin{pmatrix} 4 & -2 & 0 & 0 \\ -2 & 4 & -2 & 0 \\ 0 & -2 & 4 & -2 \\ 0 & 0 & -2 & 4 \end{pmatrix} \begin{pmatrix} f_2 \\ f_3 \\ f_4 \\ f_5 \end{pmatrix} = \begin{pmatrix} 16 \\ -6 \\ 6 \\ 2 \end{pmatrix}$$

1D example

- Copy  to 

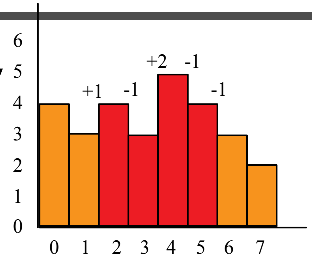
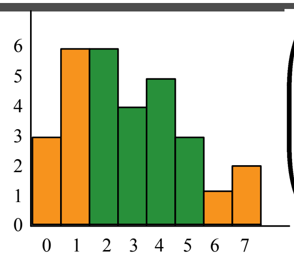




$$\begin{pmatrix} 4 & -2 & 0 & 0 \\ -2 & 4 & -2 & 0 \\ 0 & -2 & 4 & -2 \\ 0 & 0 & -2 & 4 \end{pmatrix} \begin{pmatrix} f_2 \\ f_3 \\ f_4 \\ f_5 \end{pmatrix} = \begin{pmatrix} 16 \\ -6 \\ 6 \\ 2 \end{pmatrix}$$

$$\begin{pmatrix} f_2 \\ f_3 \\ f_4 \\ f_5 \end{pmatrix} = \begin{pmatrix} 6 \\ 4 \\ 5 \\ 3 \end{pmatrix}$$

1D example: remarks

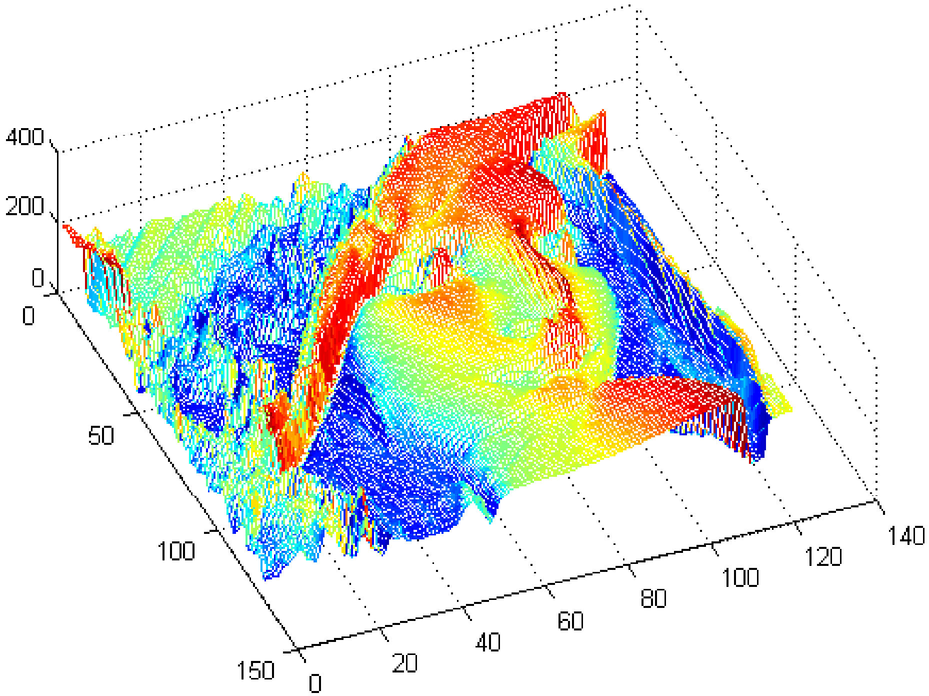
- Copy  to 

$$\begin{pmatrix} 4 & -2 & 0 & 0 \\ -2 & 4 & -2 & 0 \\ 0 & -2 & 4 & -2 \\ 0 & 0 & -2 & 4 \end{pmatrix} \begin{pmatrix} f_2 \\ f_3 \\ f_4 \\ f_5 \end{pmatrix} = \begin{pmatrix} 16 \\ -6 \\ 6 \\ 2 \end{pmatrix}$$

- Matrix is sparse
- Matrix is symmetric
- Everything is a multiple of 2
  - because square and derivative of square
- Matrix is a convolution (kernel -2 4 -2)
- Matrix is independent of gradient field. Only RHS is
- Matrix is a second derivative

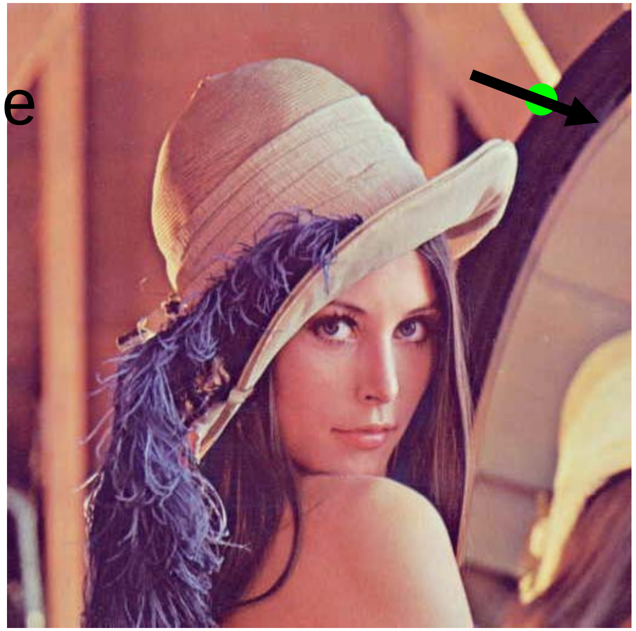
2D example: images

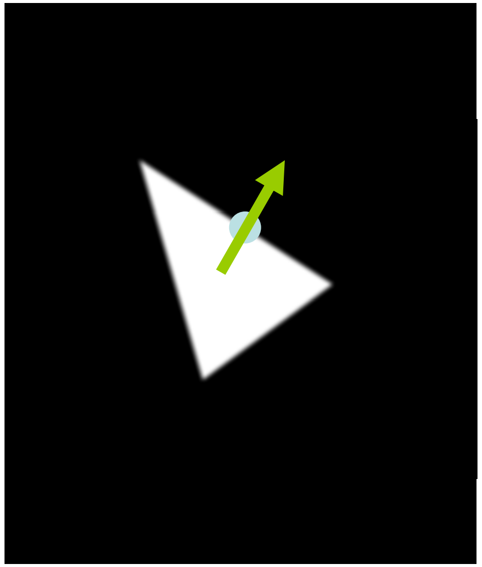
- Images as scalar fields
  - R^2 -> R



Gradients

- Vector field (gradient field)
  - Derivative of a scalar field
- Direction
  - Maximum rate of change of scalar field
- Magnitude
  - Rate of change





Gradient Field

- Components of gradient
  - Partial derivatives of scalar field

$$I(x, y) \qquad \nabla I = \{\frac{\partial I}{\partial x}, \frac{\partial I}{\partial y}\}$$

$$I(x, y, t) \qquad \nabla I = \{\frac{\partial I}{\partial x}, \frac{\partial I}{\partial y}, \frac{\partial I}{\partial t}\}$$

Example

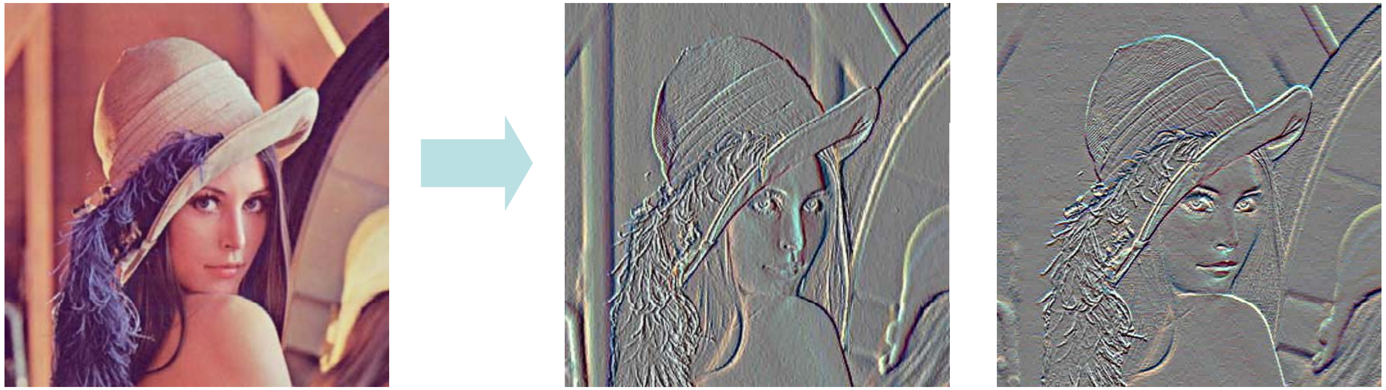


Image I(x,y) | I_x | I_y

Gradient at x,y as Forward Differences

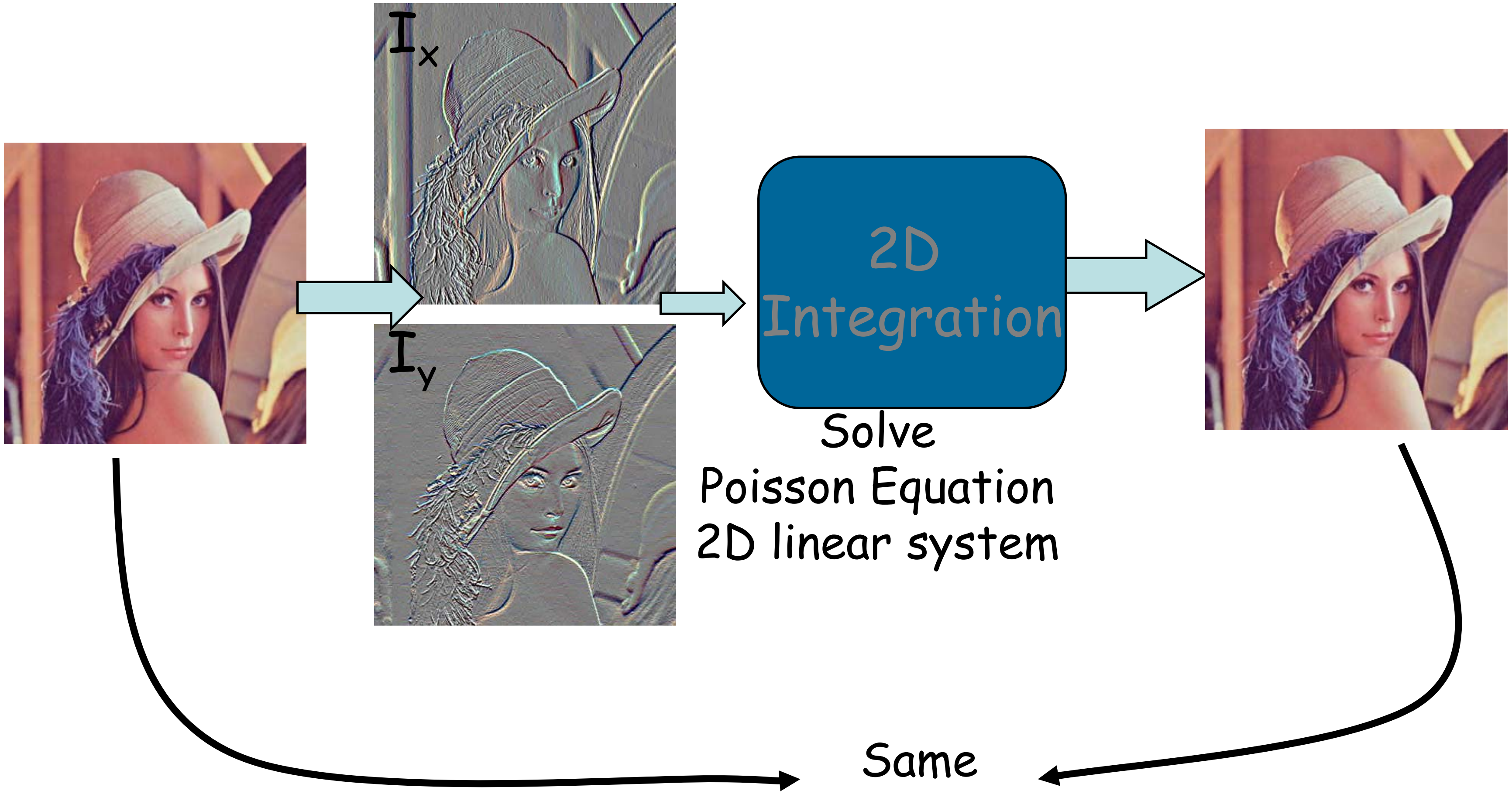
$$G_x(x,y) = I(x+1\ ,\ y) - I(x,y)$$

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

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

Reconstruction from Gradients

Sanity Check:
Recovering Original Image

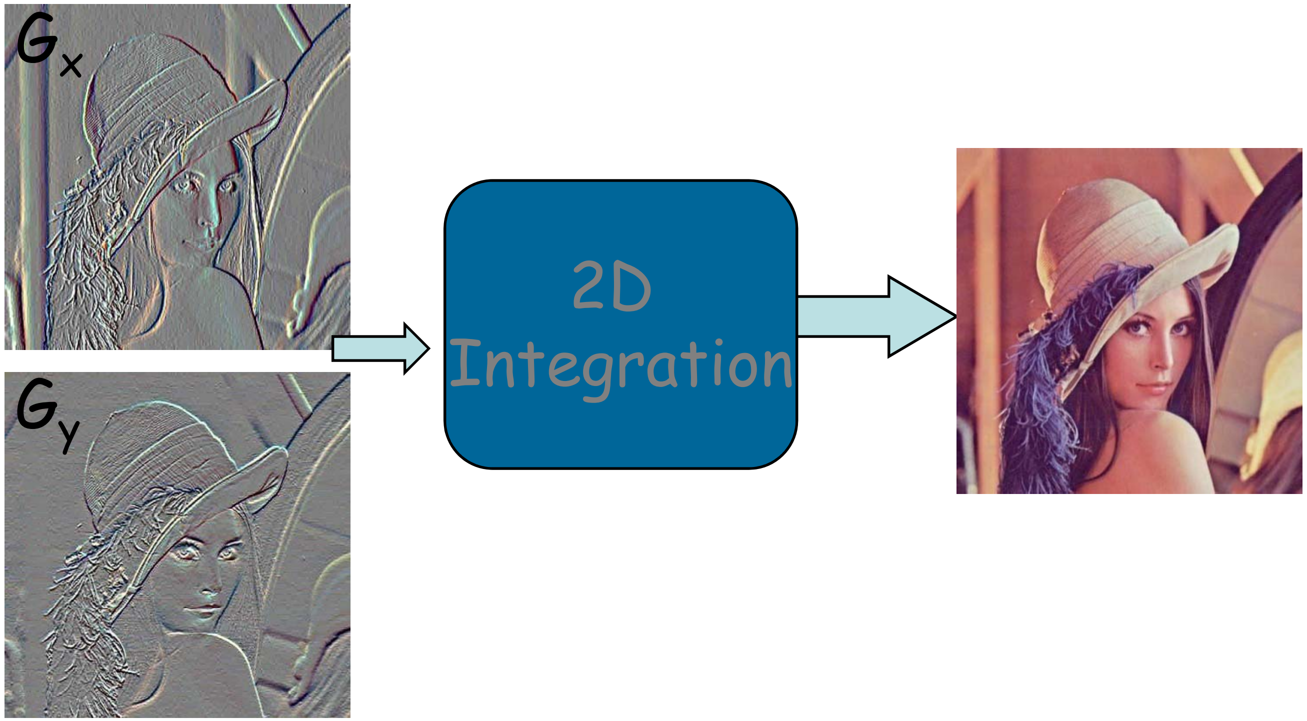


Reconstruction from Gradients

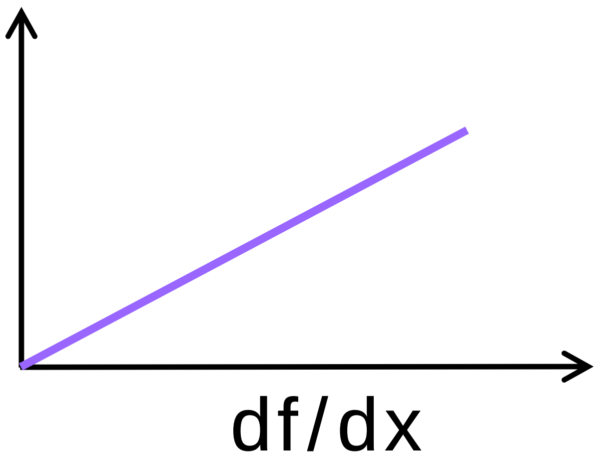
Given $G(x,y) = (G_x , G_y)$

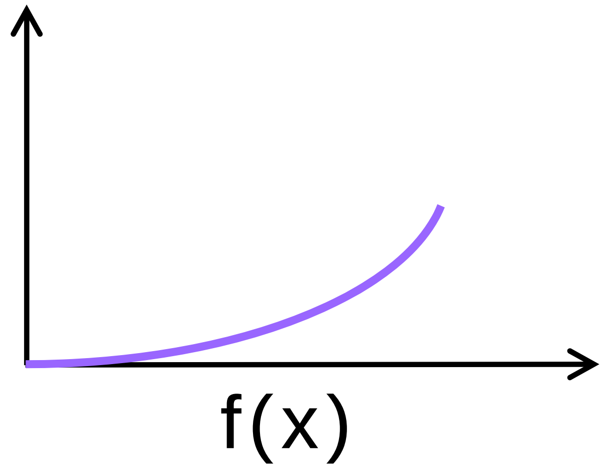
How to compute $I(x,y)$ for the image ?

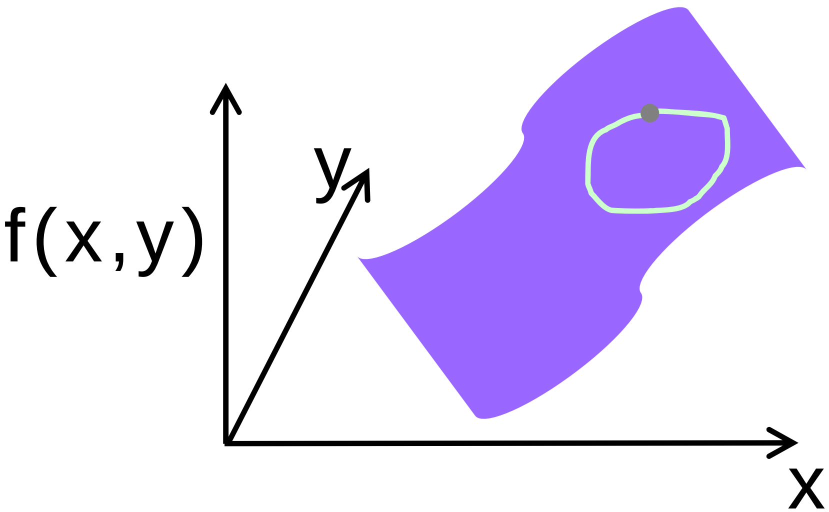
For n^2 image pixels, $2n^2$ gradients !



2D Integration is non-trivial







Reconstruction depends on chosen path

Reconstruction from Gradient Field G

- Look for image ***I*** with gradient closest to ***G*** in the least squares sense.
- ***I*** minimizes the integral: $\iint F(\nabla I, G)\,dxdy$

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

$$\Rightarrow \quad \frac{\partial^2 I}{\partial x^2} + \frac{\partial^2 I}{\partial y^2} = \frac{\partial G_x}{\partial x} + \frac{\partial G_y}{\partial y}$$

Solve $$\frac{\partial^2 I}{\partial x^2} + \frac{\partial^2 I}{\partial y^2} = \frac{\partial G_x}{\partial x} + \frac{\partial G_y}{\partial y}$$

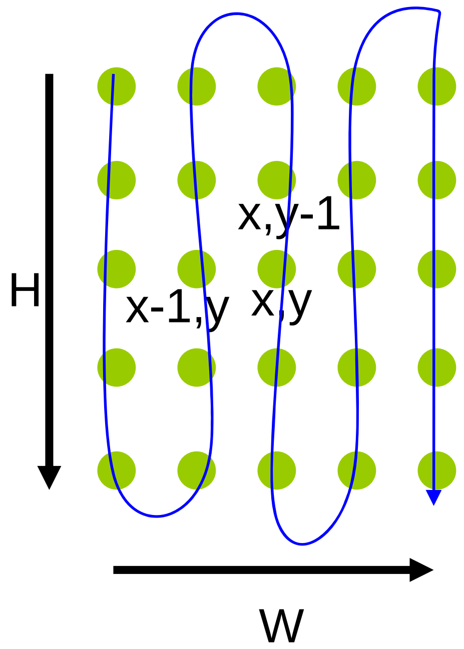
$$G_x(x, y) - G_x(x-1, y) + G_y(x, y) - G_y(x, y-1)$$

$$I(x+1, y) + I(x-1, y) + I(x, y+1) + I(x, y-1) - 4I(x, y)$$

$$\begin{bmatrix} \\ ..\,1\,\ldots\quad 1\;\text{-}4\;1\,\ldots\quad 1\,.. \\ \\ \end{bmatrix} \begin{bmatrix} \\ \mathbf{I} \\ \\ \end{bmatrix} = \begin{bmatrix} \\ \quad \\ \\ \end{bmatrix}$$

Linear System

$$-4I(x,y)+I(x,y+1)+I(x,y-1)+I(x+1,y)+I(x-1,y)=u(x,y)$$



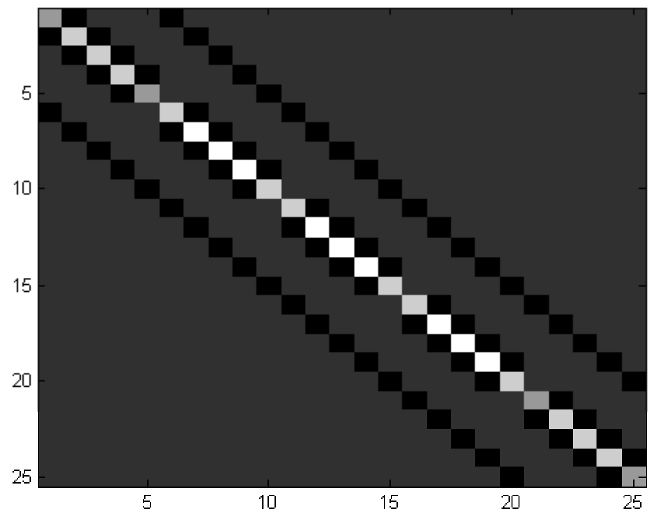
$$\underbrace{\begin{bmatrix} . & 1 & . & . & . & 1 & -4 & 1 & . & . & . & 1 & . \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} . \\ . \\ I(x-1,y) \\ . \\ . \\ . \\ I(x,y-1) \\ I(x,y) \\ I(x,y+1) \\ . \\ . \\ . \\ I(x+1,y) \\ . \\ . \end{bmatrix}}_{x} = \underbrace{\begin{bmatrix} . \\ . \\ . \\ . \\ . \\ . \\ \\ u(x,y) \\ . \\ . \\ . \\ . \\ . \\ . \\ . \end{bmatrix}}_{b}$$

(H marks the span from the first 1 to −4 in the row of A, and the span from $I(x-1,y)$ to $I(x,y)$ in x.)

Sparse Linear system

$$
\begin{bmatrix}
 & & 1 & -4 & 1 & & & & 1 & & & & \\
 & & & 1 & -4 & 1 & & & & 1 & & & \\
1 & & & & 1 & -4 & 1 & & & & 1 & & \\
 & 1 & & & & 1 & -4 & 1 & & & & 1 & \\
 & & 1 & & & & 1 & -4 & 1 & & & & 1 \\
 & & & 1 & & & & 1 & -4 & 1 & & & \\
 & & & & 1 & & & & 1 & -4 & 1 & &
\end{bmatrix}
$$

A matrix



Solving Linear System

- Image size N*N

- Size of A ~ N^2 by N^2

- Impractical to form and store A

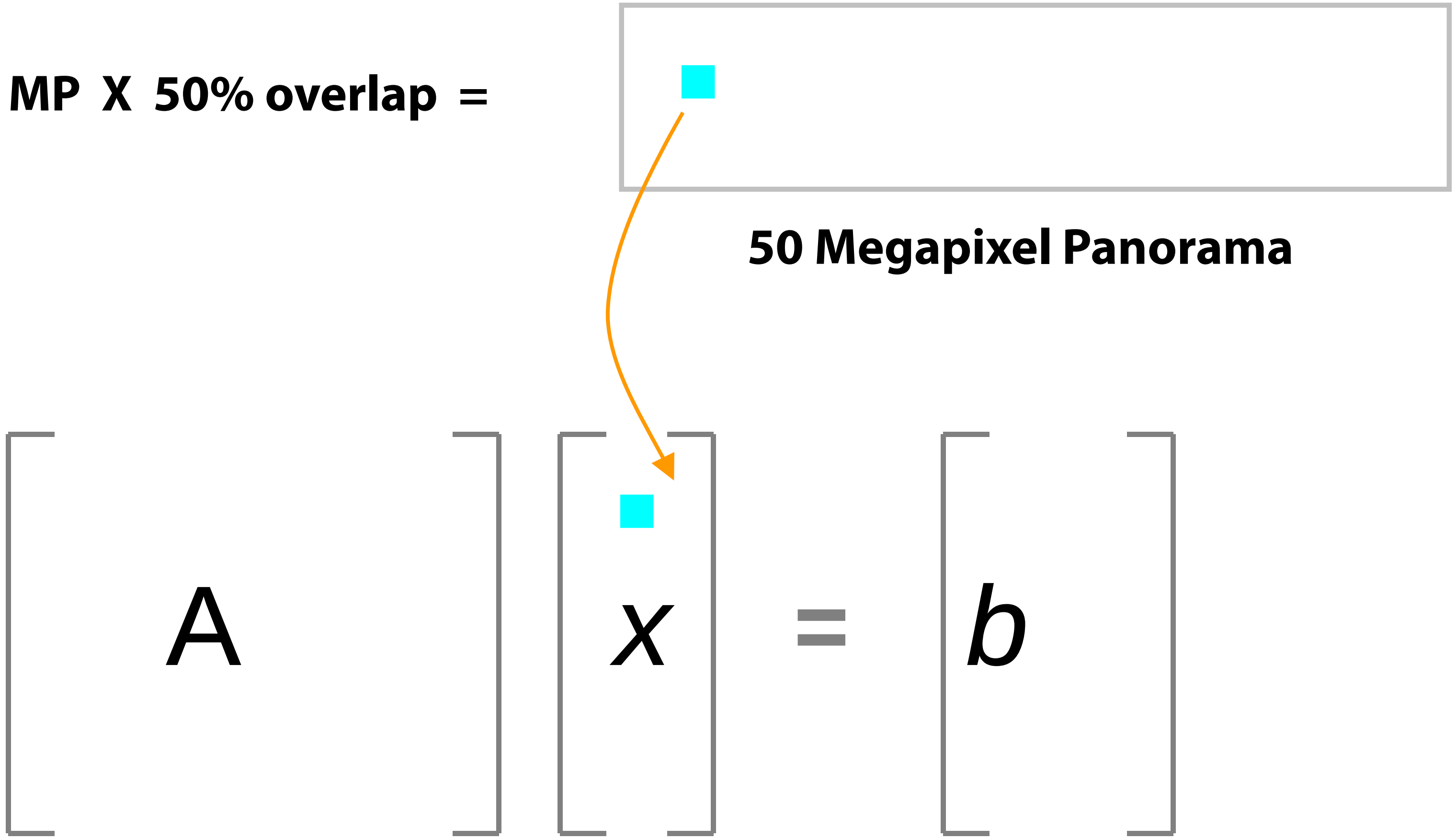
- Direct Solvers
- Basis Functions
- Multigrid
- Conjugate Gradients

Approximate Solution for Large Scale Problems

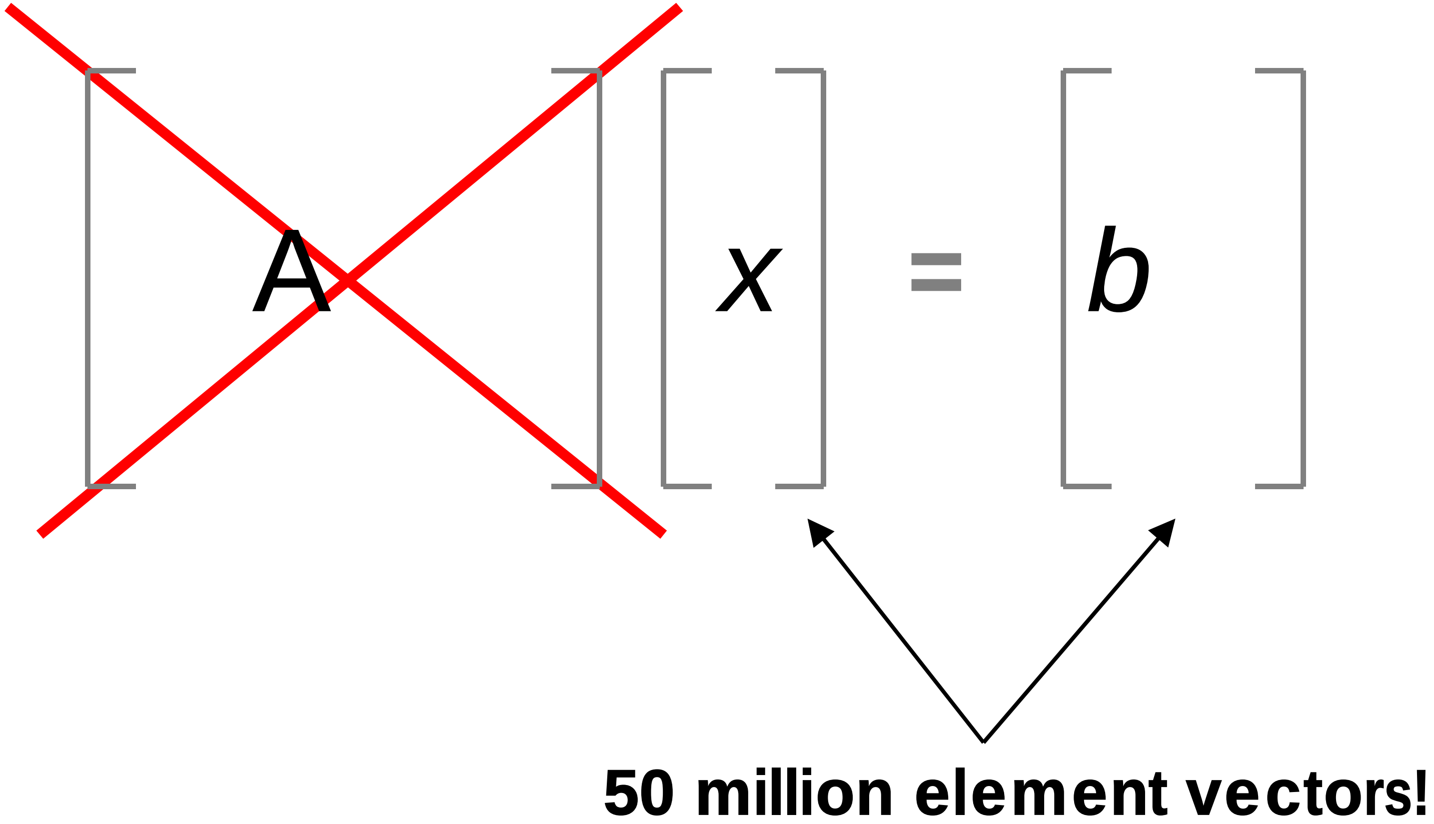
- Resolution is increasing in digital cameras
- Stitching, Alignment requires solving large linear system

Scalability problem

10 X 10 MP X 50% overlap =



Scalability problem



Approximate Solution

- Reduce size of linear system
- Handle high resolution images
- Part of Photoshop CS3

Aseem Agarwala. "Efficient gradient-domain compositing using quadtrees," ACM Transactions on Graphics (Proceedings of SIGGRAPH 2007)

The key insight

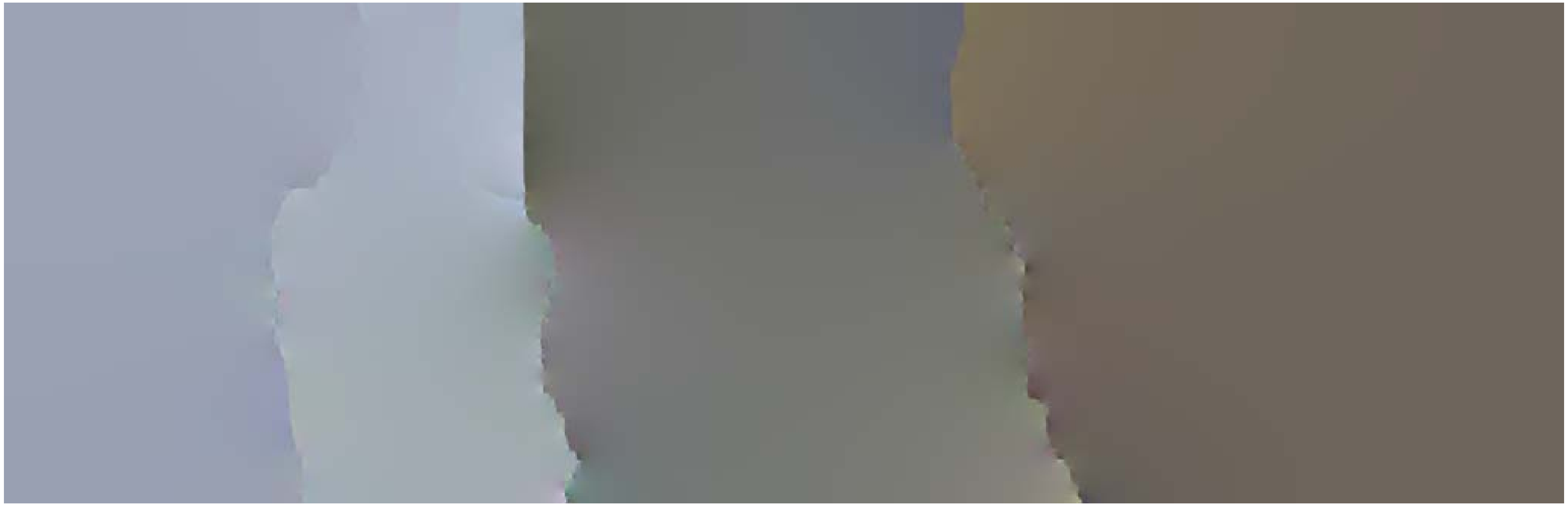
Desired solution x

−

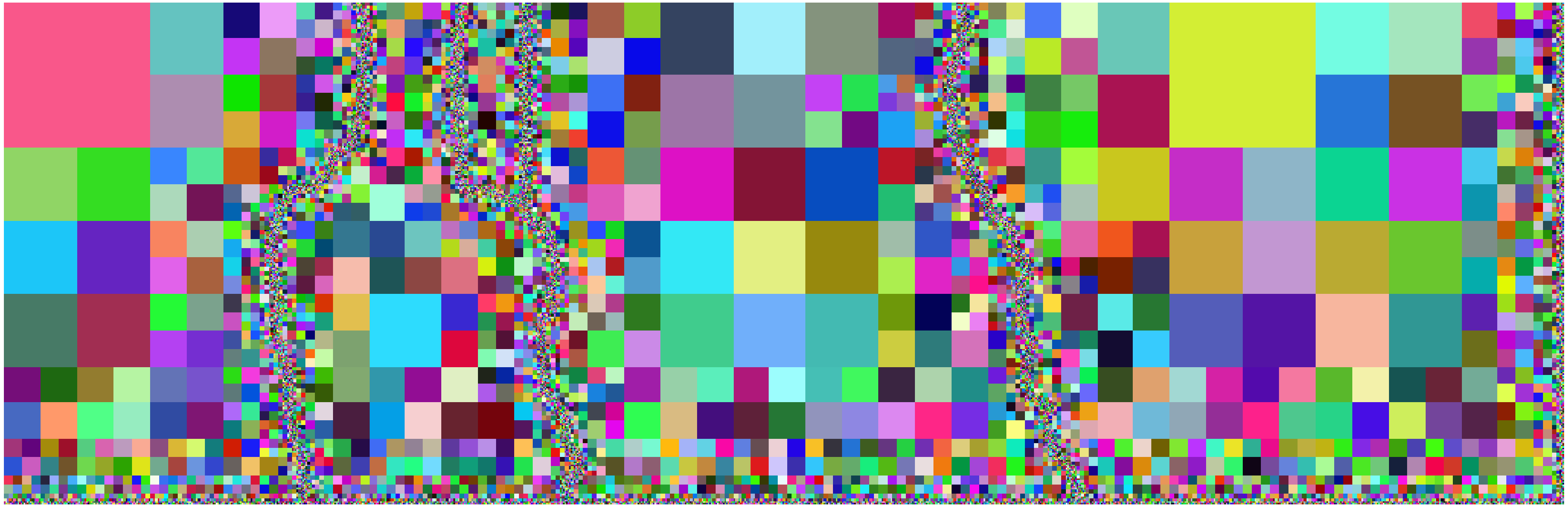
Initial Solution x_0

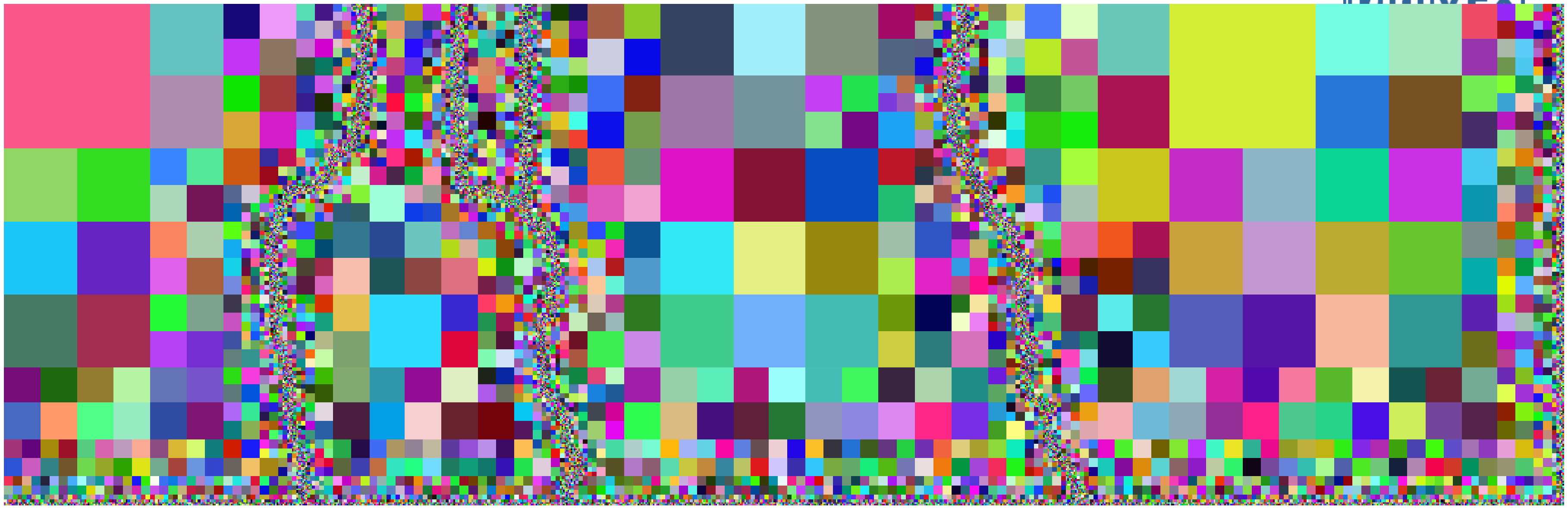
=

Difference x_δ



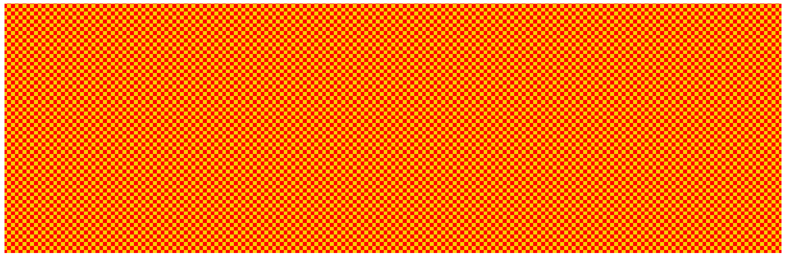
Quadtree decomposition





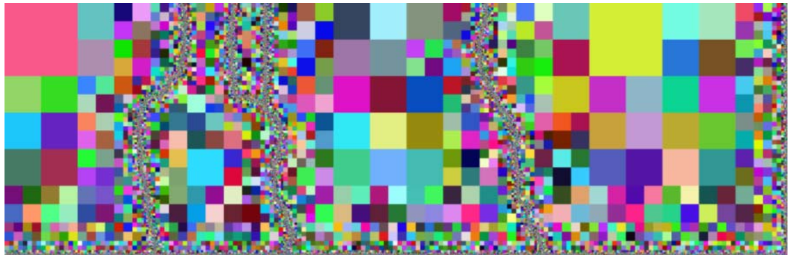
- Maximally subdivide quadtree along seams
- Variables placed at node corners
- Restricted quadtree
- Bi-linear interpolation reconstructs full solution
- Square nodes

Reduced space



x

n variables

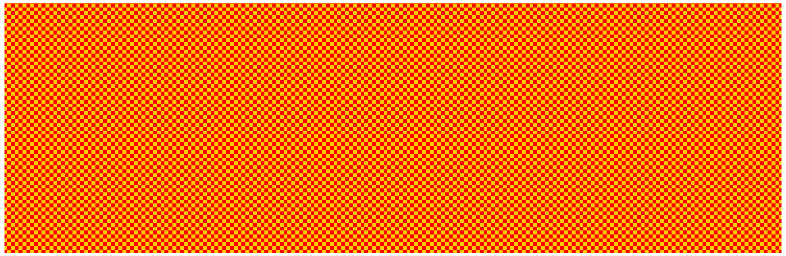


y

m variables

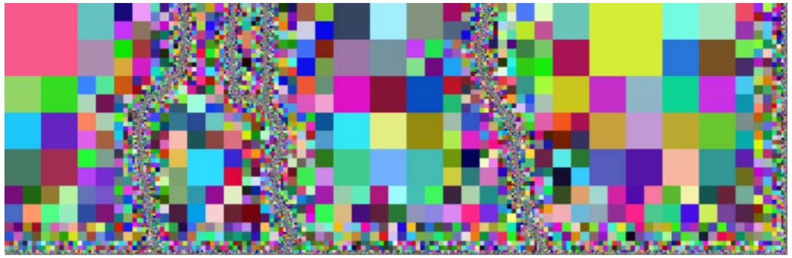
$$m << n$$

Reduced space



x

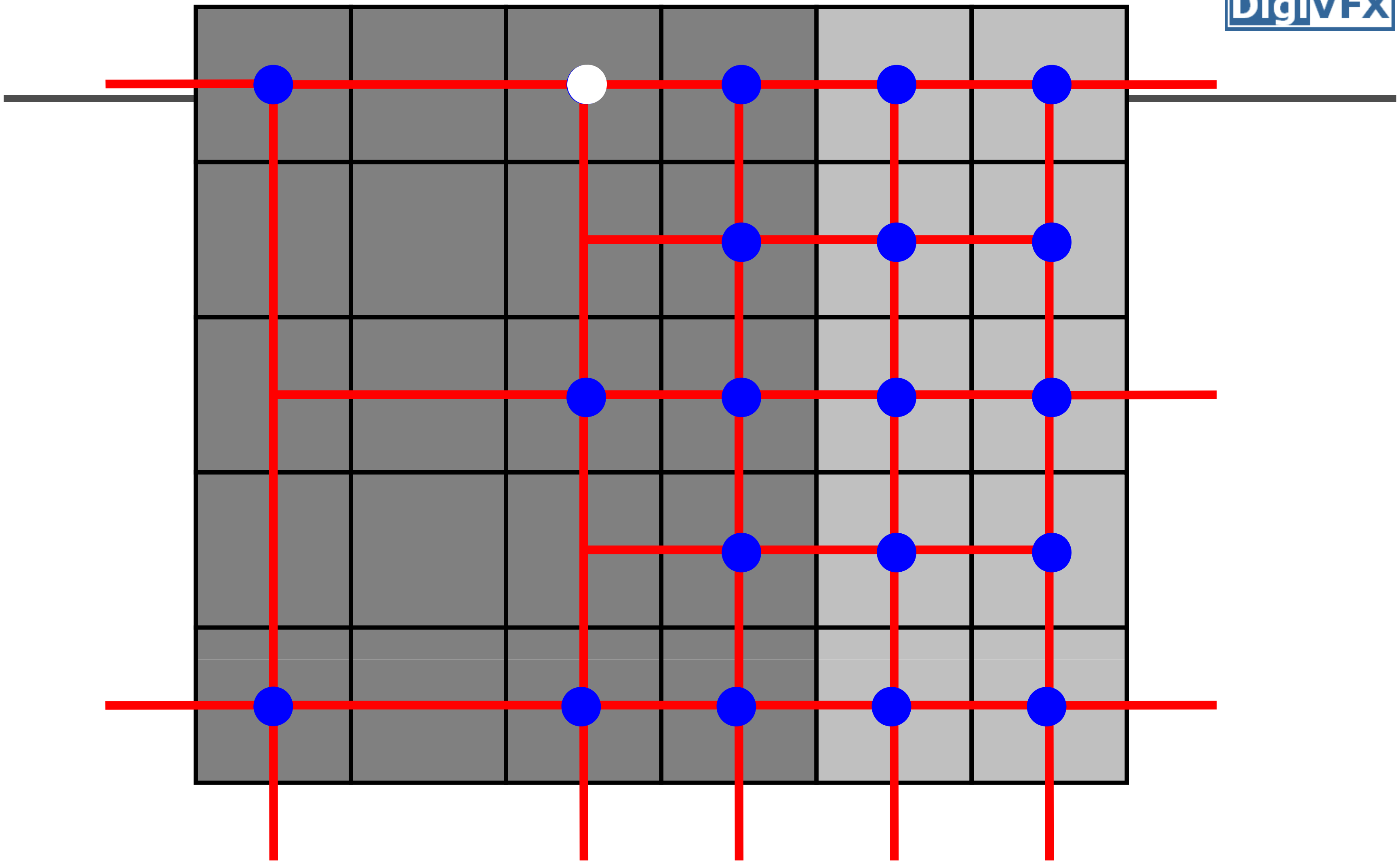
n variables



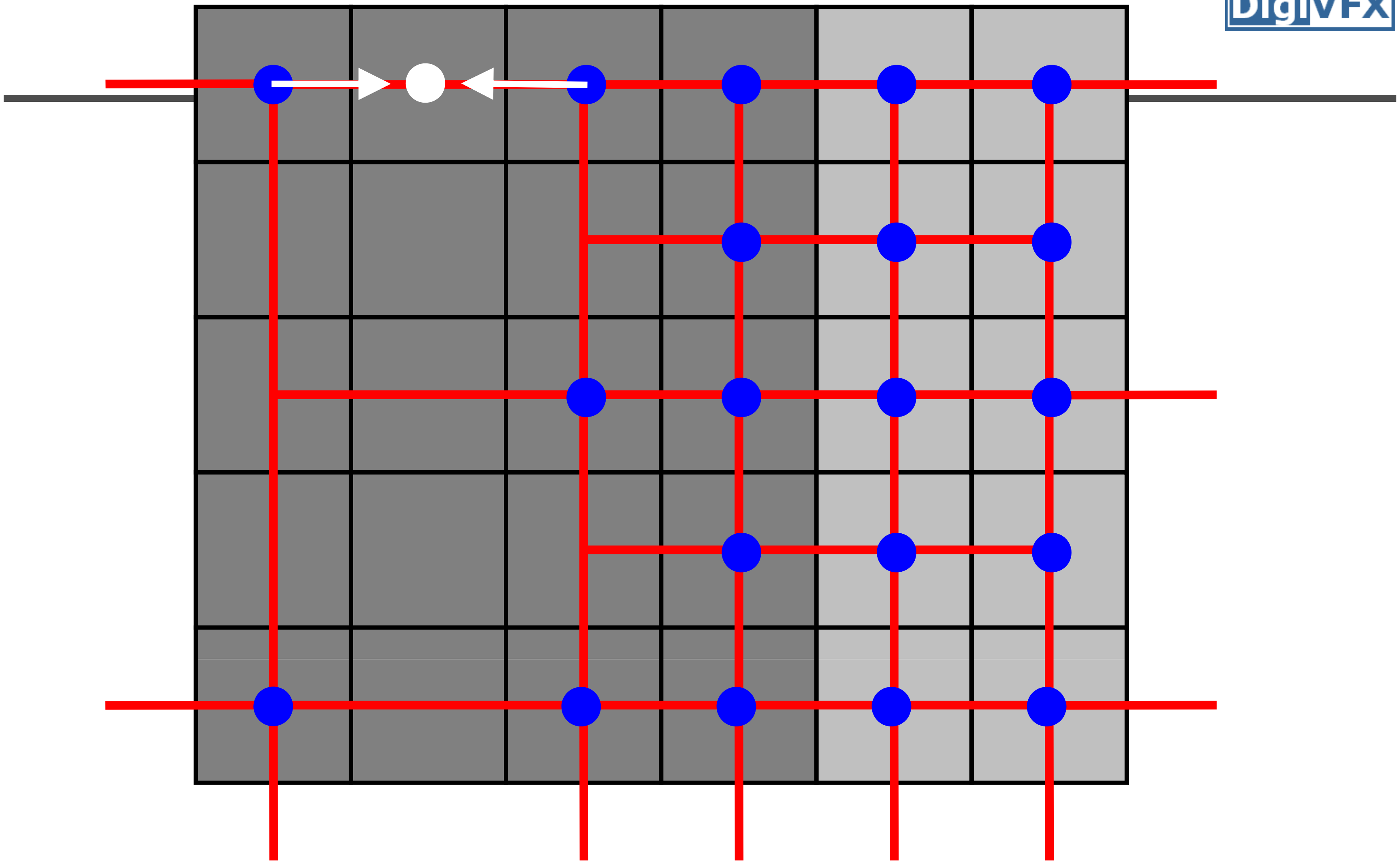
y

m variables

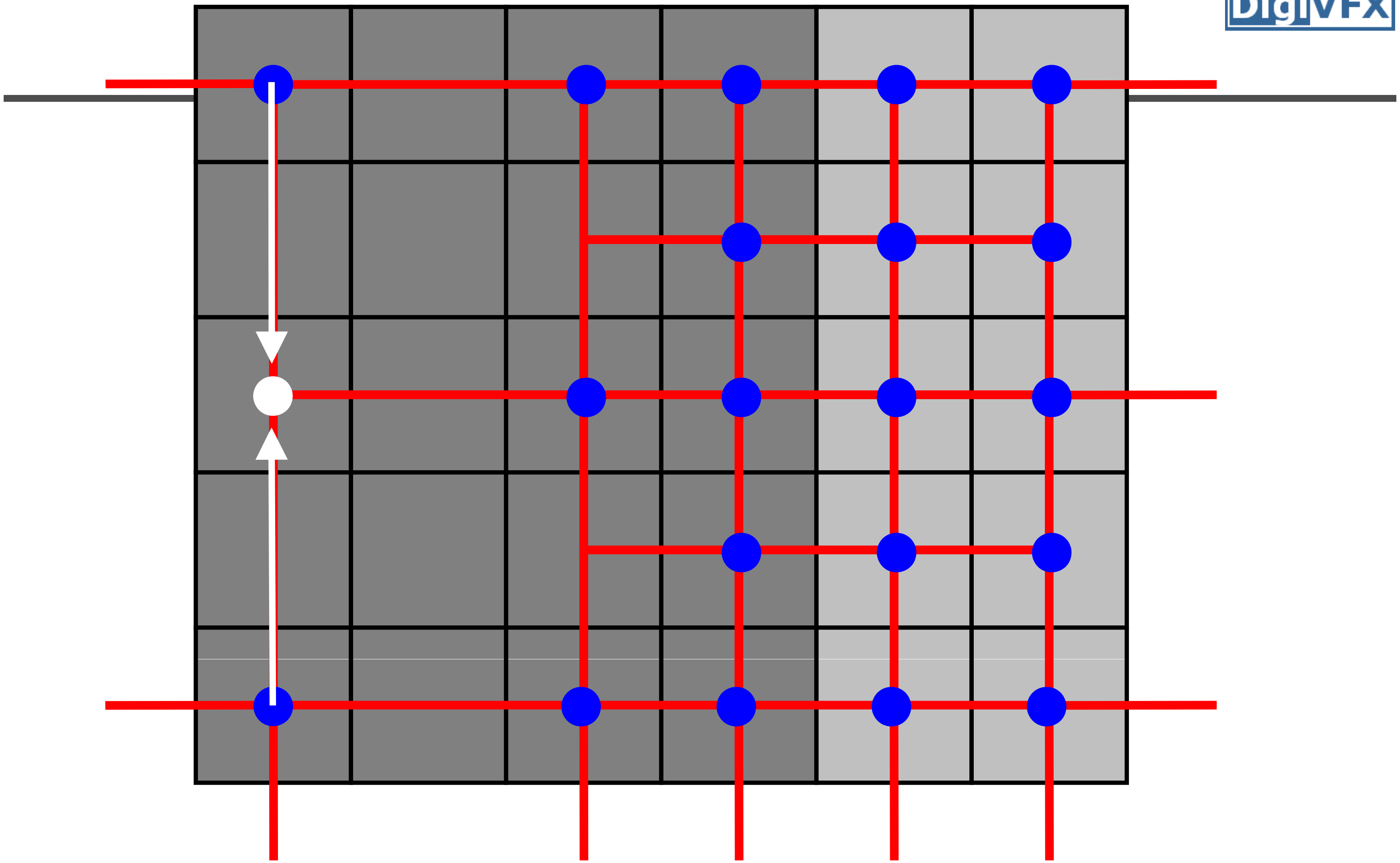
$$x = Sy$$



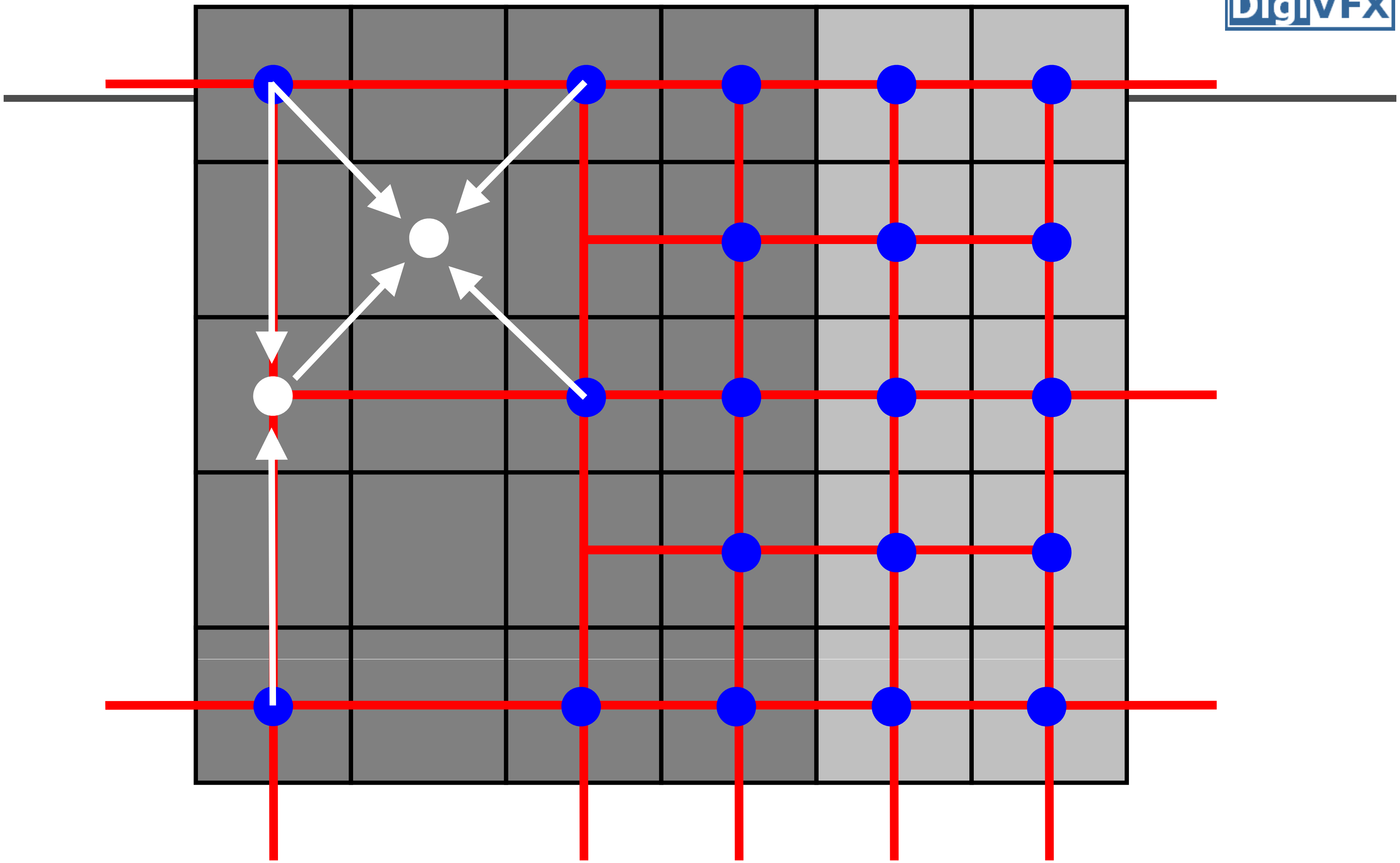
$$x = Sy$$



$$x = Sy$$

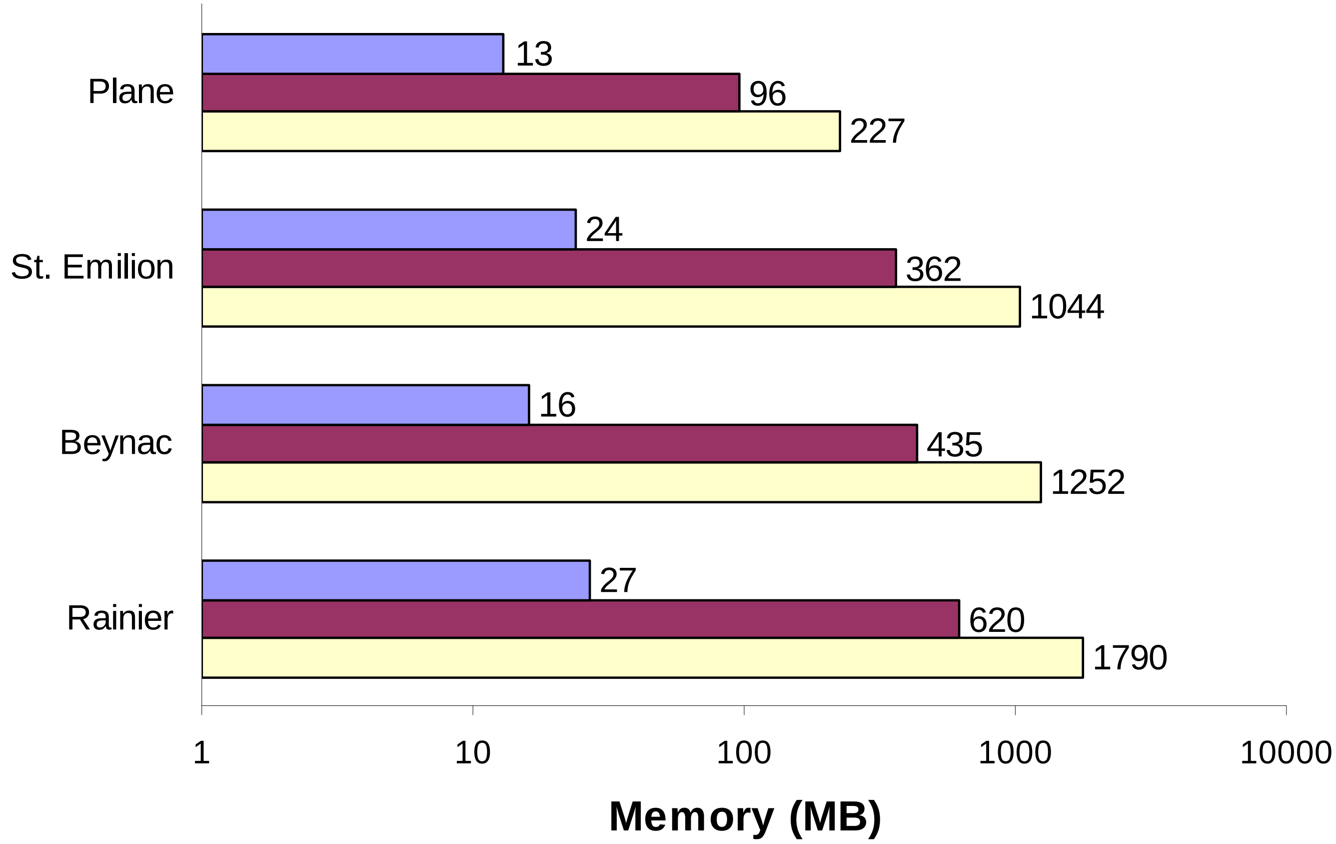


$$x = Sy$$



$$x = Sy$$

Performance



Quadtree [Agarwala 07]

Hierarchical basis preconditioning [Szeliski 90]

Locally-adapted hierarchical basis preconditioning [Szeliski 06]

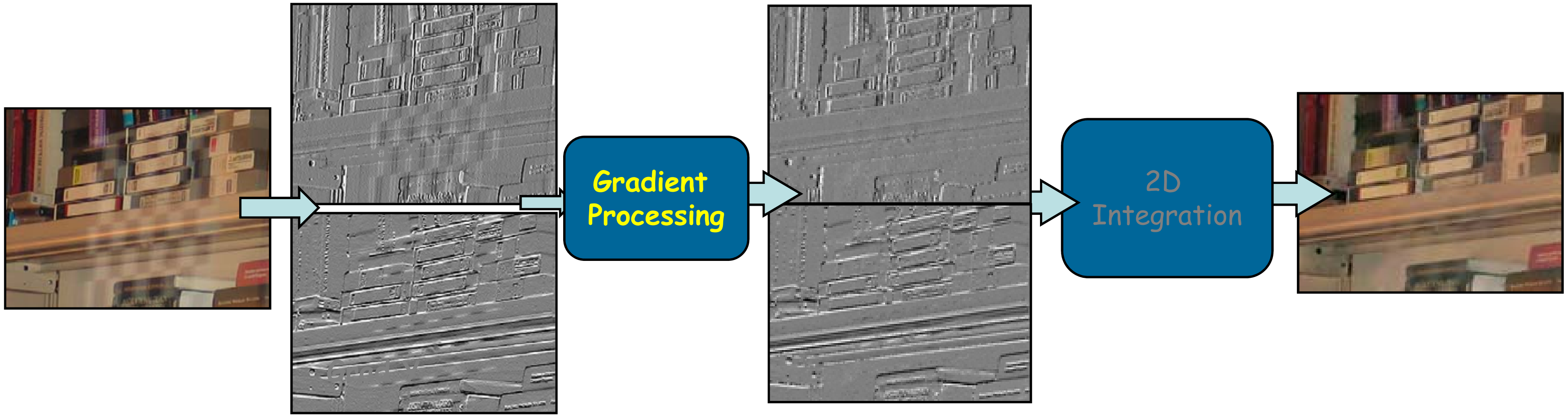
Cut-and-paste

Cut-and-paste

Intensity Gradient Manipulation

DigiVFX

A Common Pipeline



Gradient Domain Manipulations: Overview

(A) Per pixel

(B) Corresponding gradients in two images

(C) Corresponding gradients in multiple images

(D) Combining gradients along seams

Gradient Domain Manipulations: Overview

(A) Per pixel

- Non-linear operations (HDR compression, local illumination change)
- Set to zero (shadow removal, intrinsic images, texture de-emphasis)
- Poisson Matting

(B) Corresponding gradients in two images

- Vector operations (gradient projection)
  - Combining flash/no-flash images, Reflection removal
- Projection Tensors
  - Reflection removal, Shadow removal
- Max operator
  - Day/Night fusion, Visible/IR fusion, Extending DoF
- Binary, choose from first or second, copying
  - Image editing, seamless cloning

Gradient Domain Manipulations

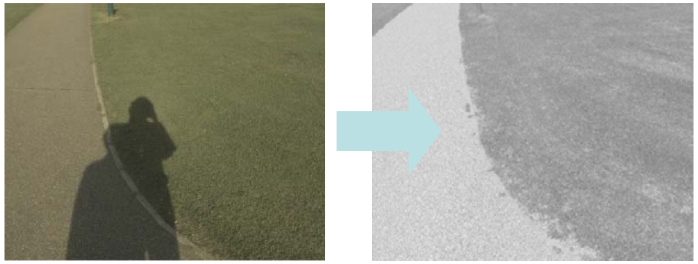
(C) Corresponding gradients in multiple images
- Median operator
  - Specularity reduction
  - Intrinsic images
- Max operation
  - Extended DOF

(D) Combining gradients along seams
- Weighted averaging
- Optimal seam using graph cut
  - Image stitching, Mosaics, Panoramas, Image fusion
  - A usual pipeline: Graph cut to find seams + gradient domain fusion

A. Per Pixel Manipulations

- Non-linear operations
  - HDR compression, local illumination change

- Set to zero
  - Shadow removal, intrinsic images, texture de-emphasis



- Poisson Matting

High Dynamic Range Imaging

Images from Raanan Fattal

Gradient Domain Compression

HDR Image L

Log L

Gradients L_x, L_y

Multiply

2D Integration

Gradient Attenuation Function G

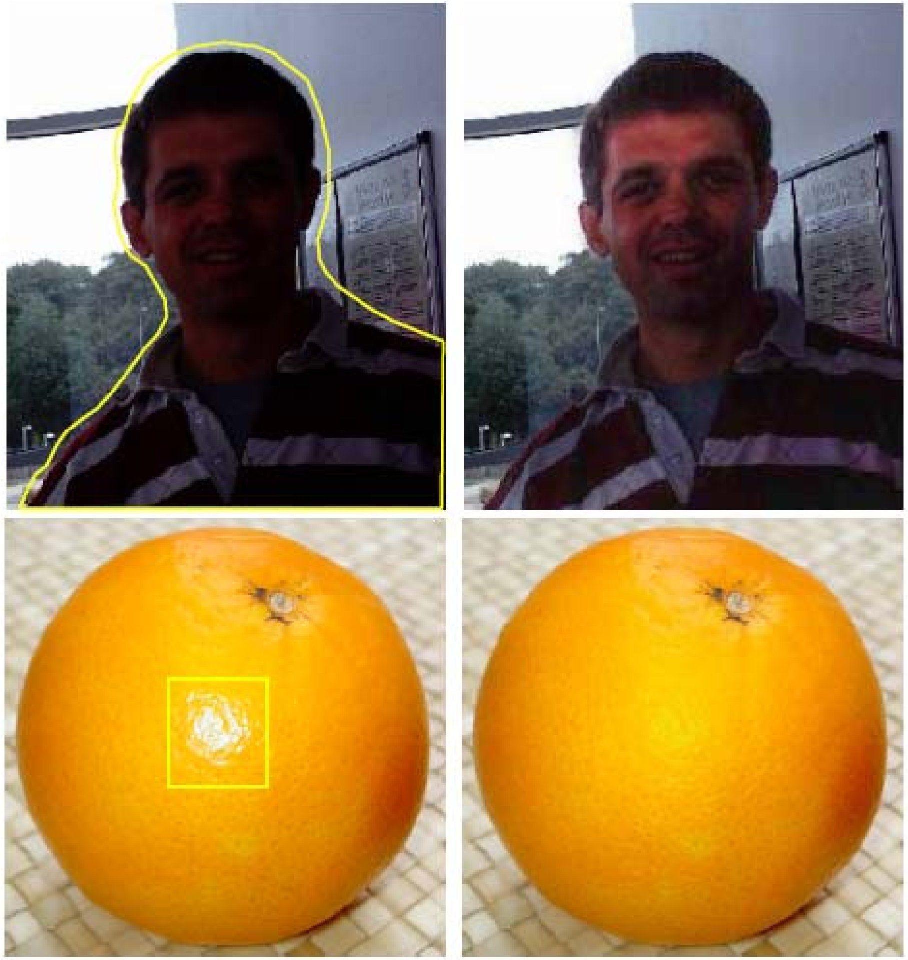
Local Illumination Change

Original Image: f

$$\mathbf{v} = \alpha^{\beta} |\nabla f^*|^{-\beta} \nabla f^*,$$

Original gradient field: ∇f^*

Modified gradient field: v



Perez et al. Poisson Image editing, SIGGRAPH 2003

Illumination Invariant Image

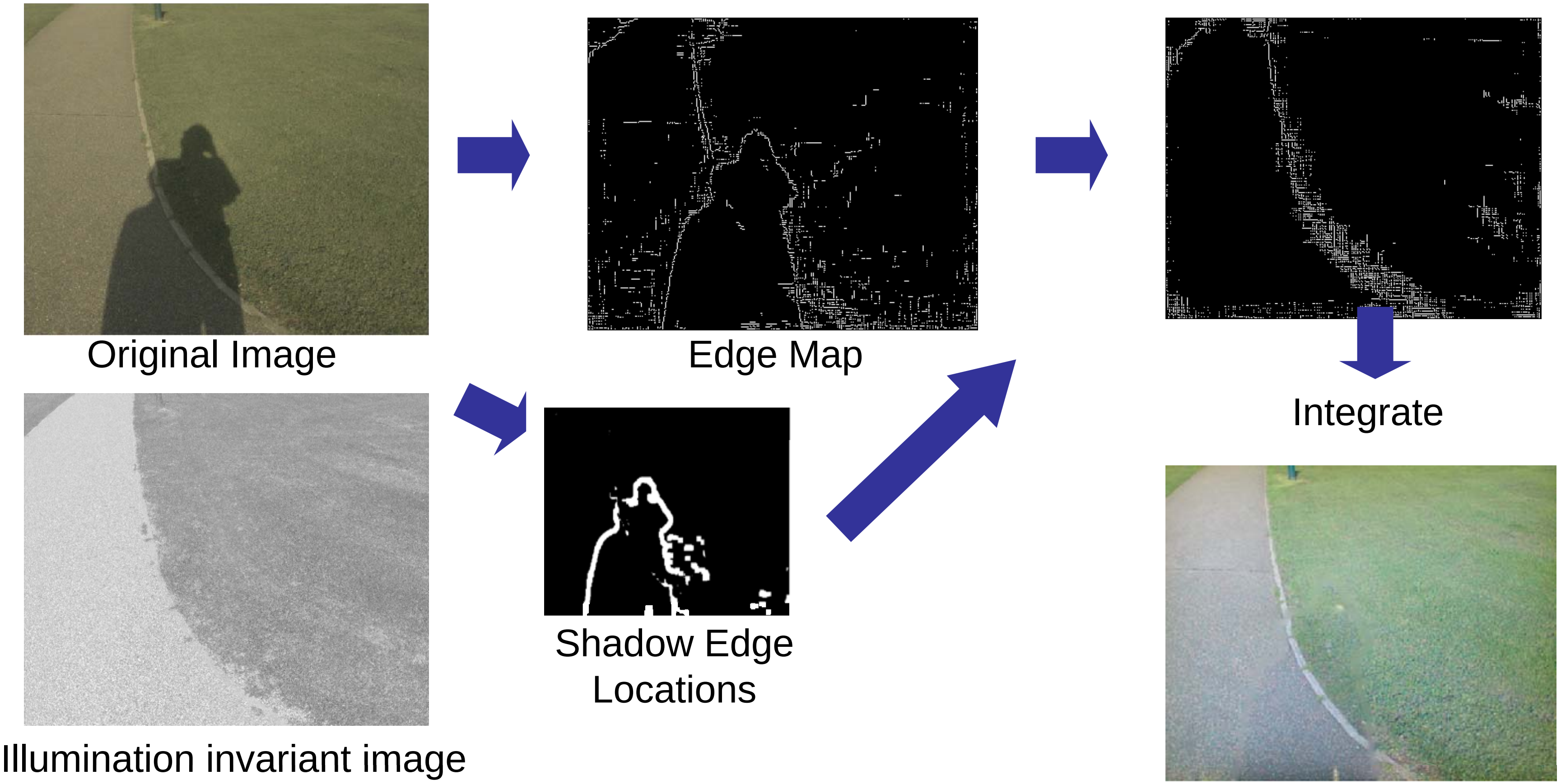
Original Image

Illumination invariant image

- Assumptions
  - Sensor response = delta functions R, G, B in wavelength spectrum
  - Illumination restricted to Outdoor Illumination

G. D. Finlayson, S.D. Hordley & M.S. Drew, Removing Shadows From Images, ECCV 2002

Shadow Removal Using Illumination Invariant Image



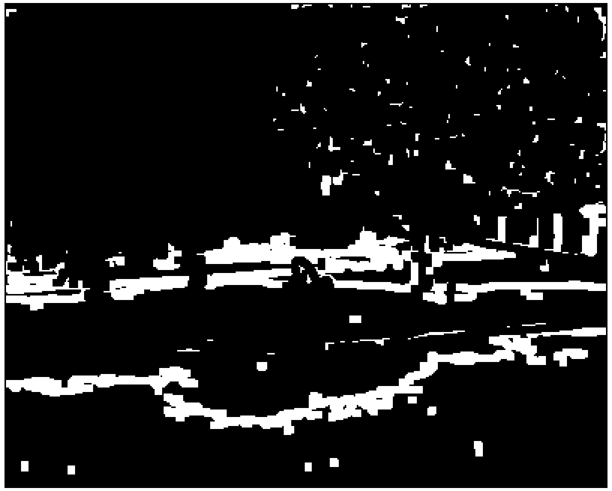
G. D. Finlayson, S.D. Hordley & M.S. Drew, Removing Shadows From Images, ECCV 2002

Illumination invariant image

Original Image

Invariant Image

Detected Shadow Edges



Shadow Removed

G. D. Finlayson, S.D. Hordley & M.S. Drew, Removing Shadows From Images, ECCV 2002

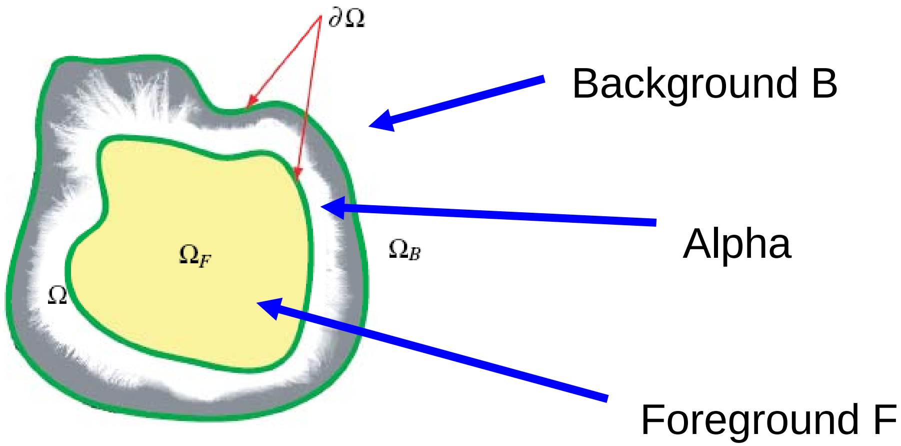
Intrinsic Image

- Photo = Illumination Image * Intrinsic Image
- Retinex [Land & McCann 1971, Horn 1974]
  - Illumination is smoothly varying
  - Reflectance, piece-wise constant, has strong edges
  - Keep strong image gradients, integrate to obtain reflectance

low-frequency attenuate more

high-frequency attenuate less

Poisson Matting



Trimap: User specified

Jian Sun, Jiaya Jia, Chi-Keung Tang, Heung-Yeung Shum, Poisson Matting, SIGGRAPH 2004

Poisson Matting

$$I = \alpha F + (1-\alpha)B$$

$$\nabla I = (F-B)\nabla\alpha + \alpha\nabla F + (1-\alpha)\nabla B$$

Approximate: Assume F and B are smooth

$$\nabla I = (F-B)\nabla\alpha$$

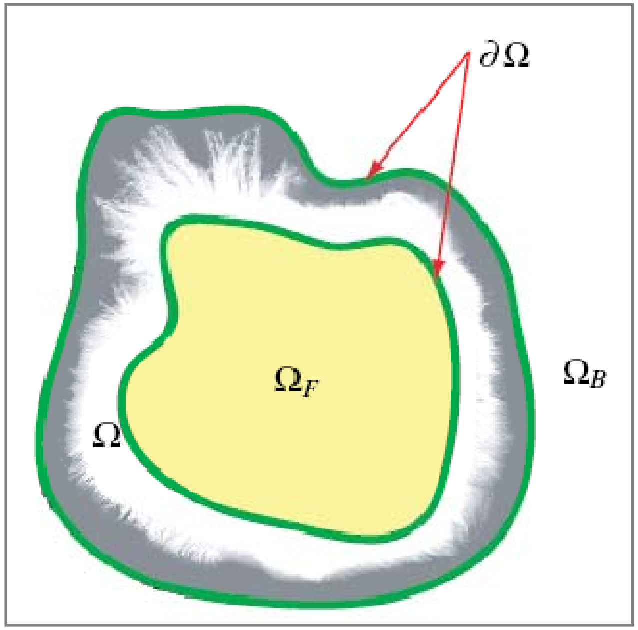
$$\nabla\alpha \approx \frac{1}{F-B}\nabla I \quad \Rightarrow \quad \Delta\alpha = div\left(\frac{\nabla I}{F-B}\right)$$

F and B in tri-map using nearest pixels

Poisson Equation

Poisson Matting

- Steps
  - Approximate F and B in trimap Ω.
  - Solve for α $$\Delta\alpha = div\left(\frac{\nabla I}{F-B}\right)$$
  - Refine F and B using α
  - Iterate



Gradient Domain Manipulations: Overview

(A) Per pixel

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(C) Corresponding gradients in multiple images

(D) Combining gradients along seams

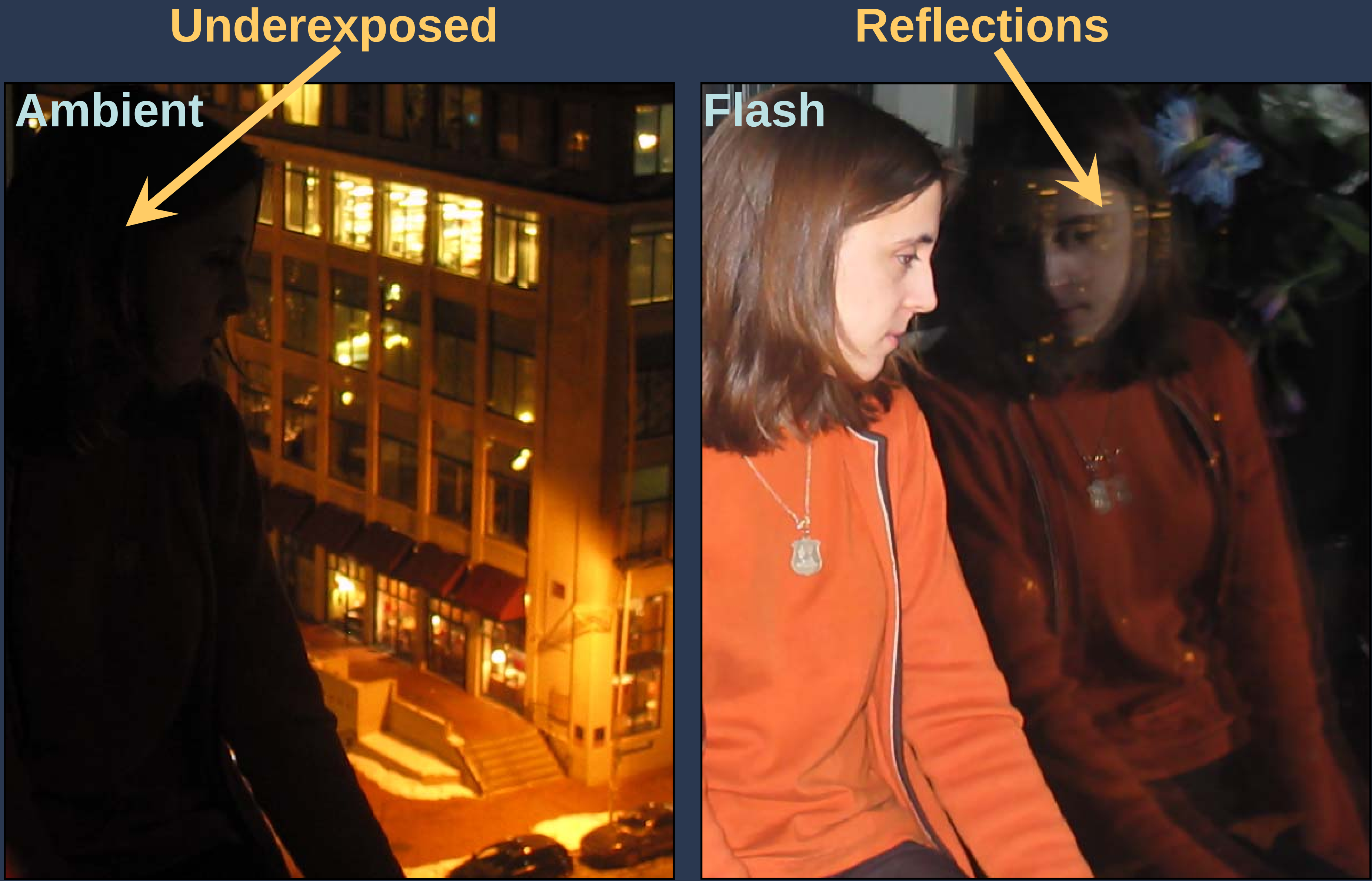
Photography Artifacts: Flash Hotspot

Ambient

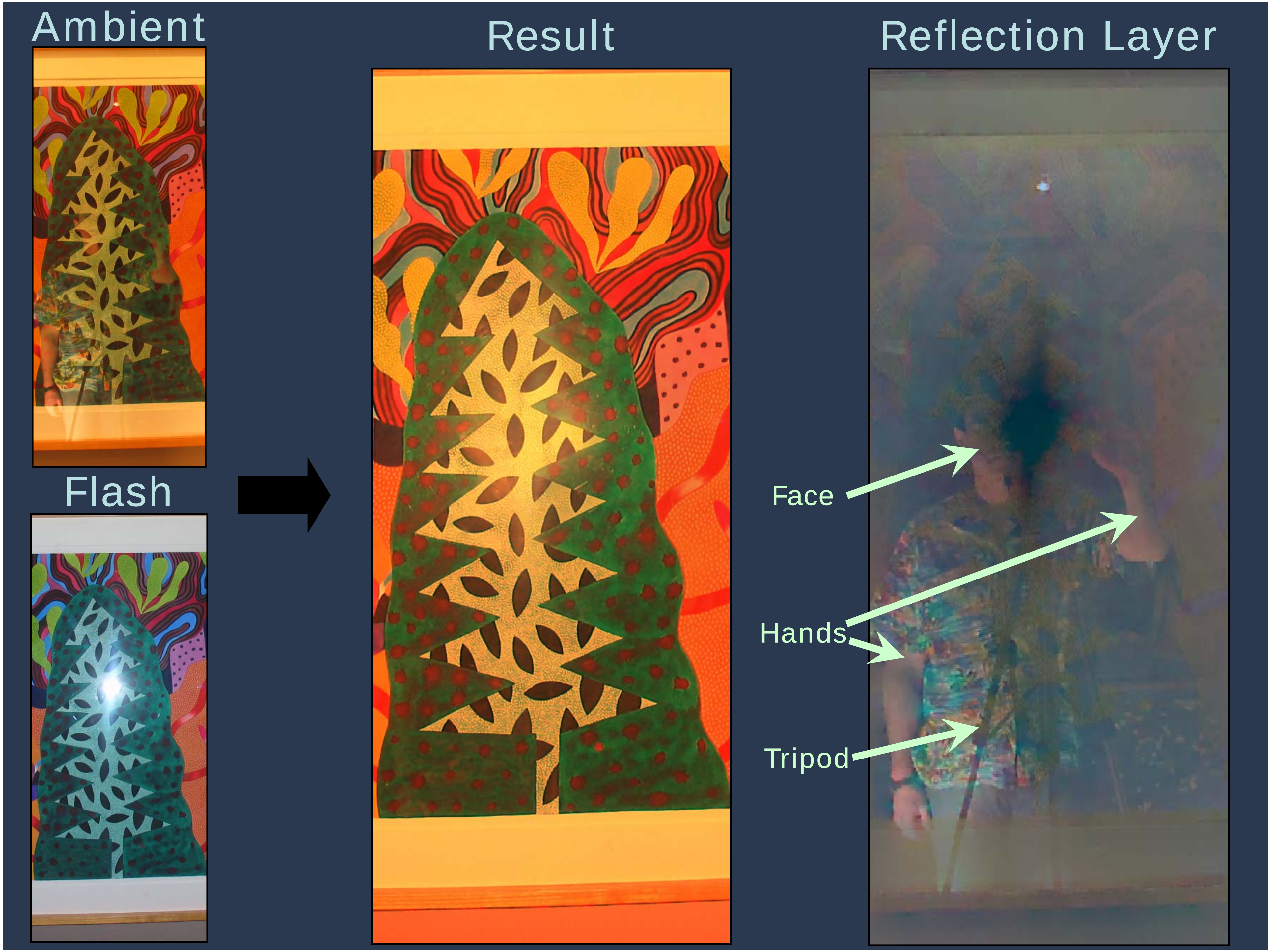
Flash

Flash Hotspot

Reflections due to Flash

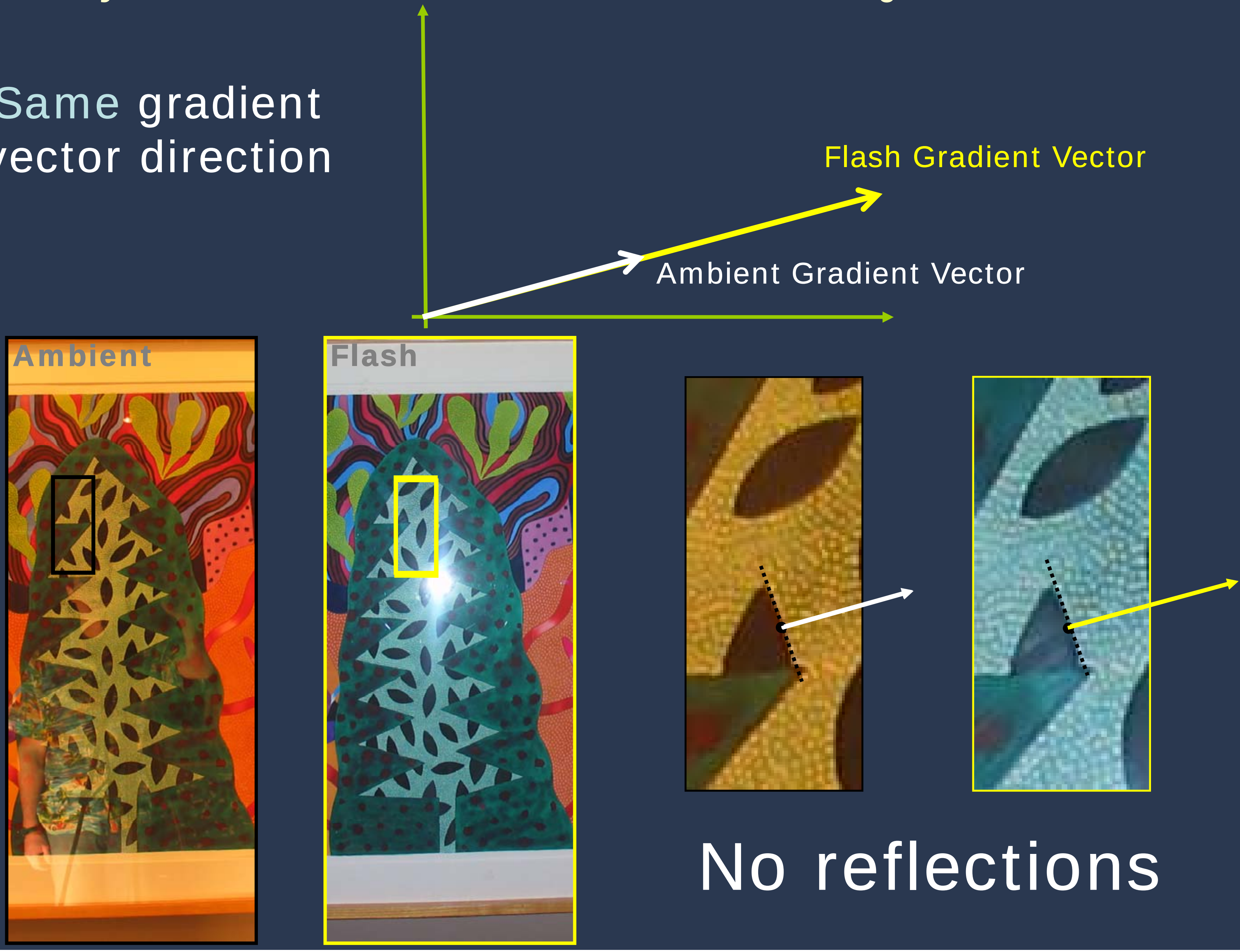


Self-Reflections and Flash Hotspot


Ambient
Flash
Result
Reflection Layer
Face
Hands
Tripod

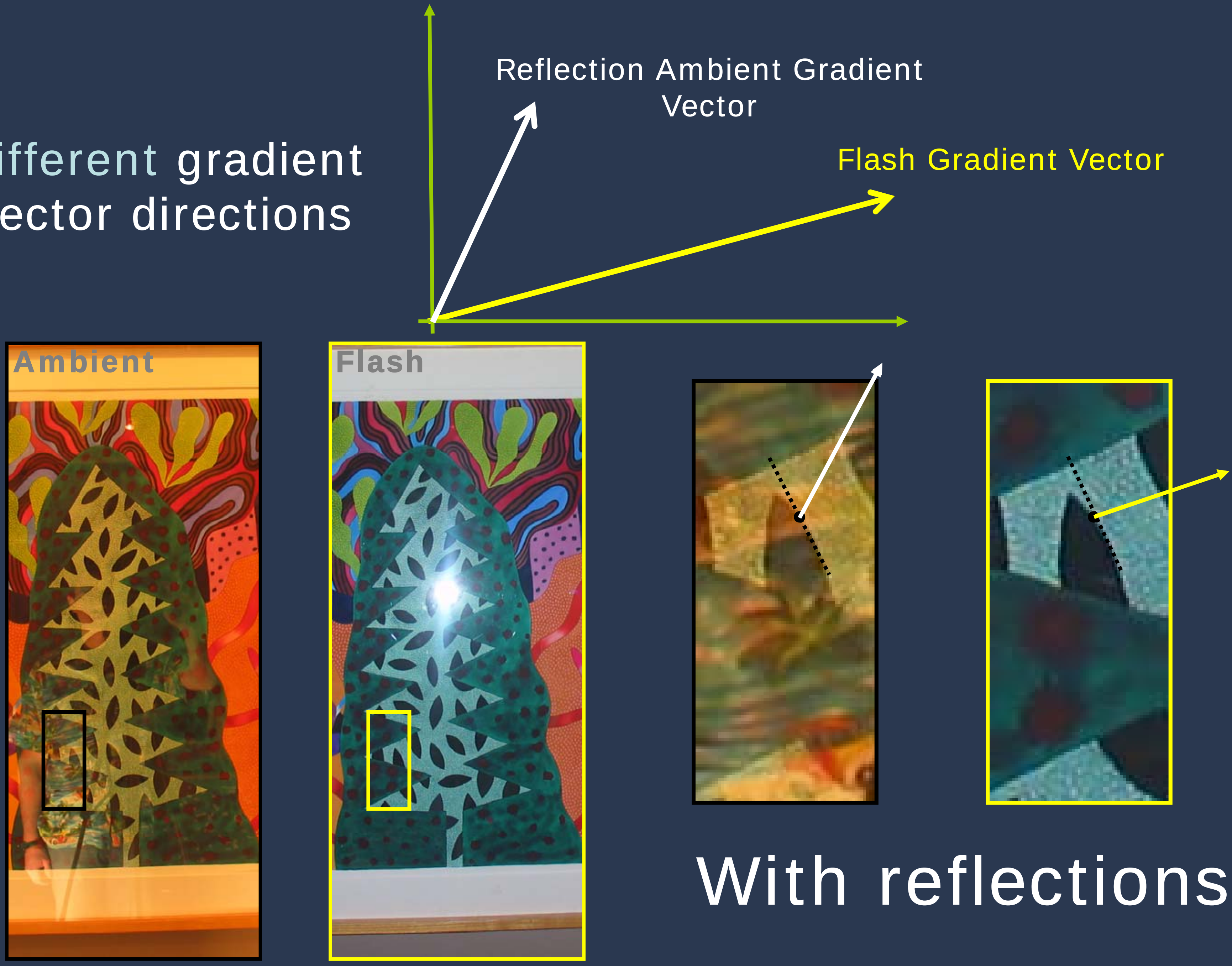
Intensity Gradient Vectors in Flash and Ambient Images

Same gradient vector direction



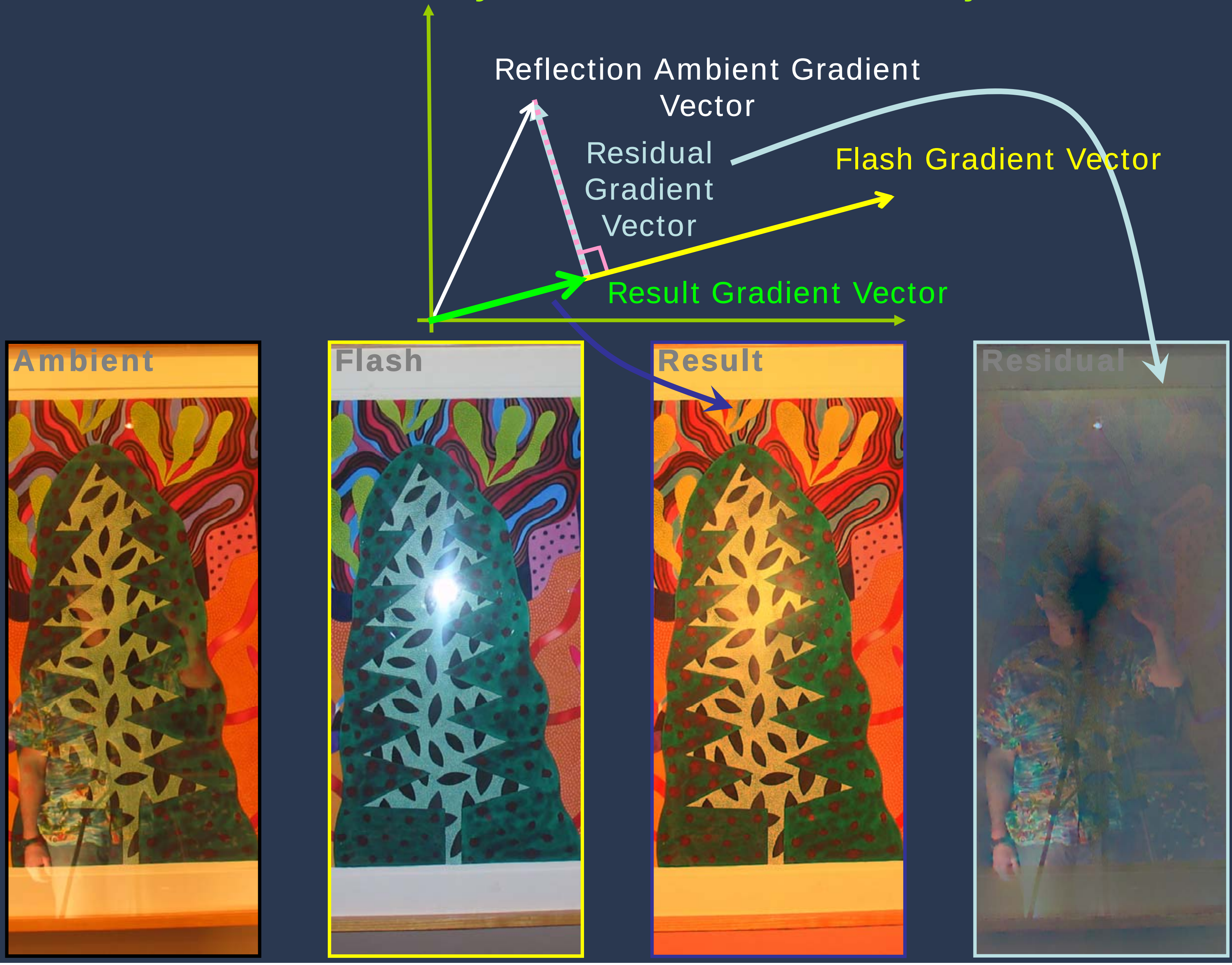
No reflections

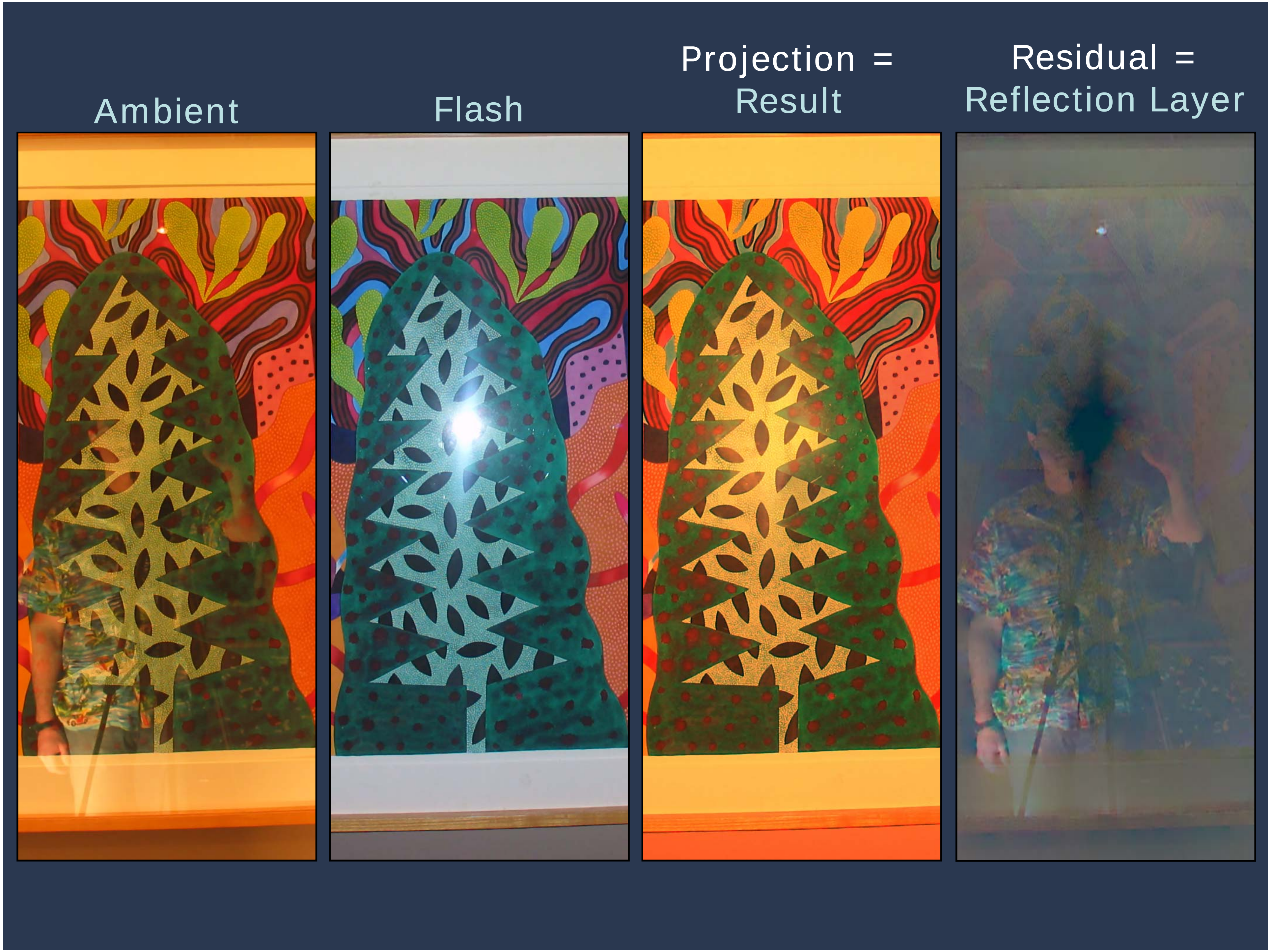
Different gradient vector directions



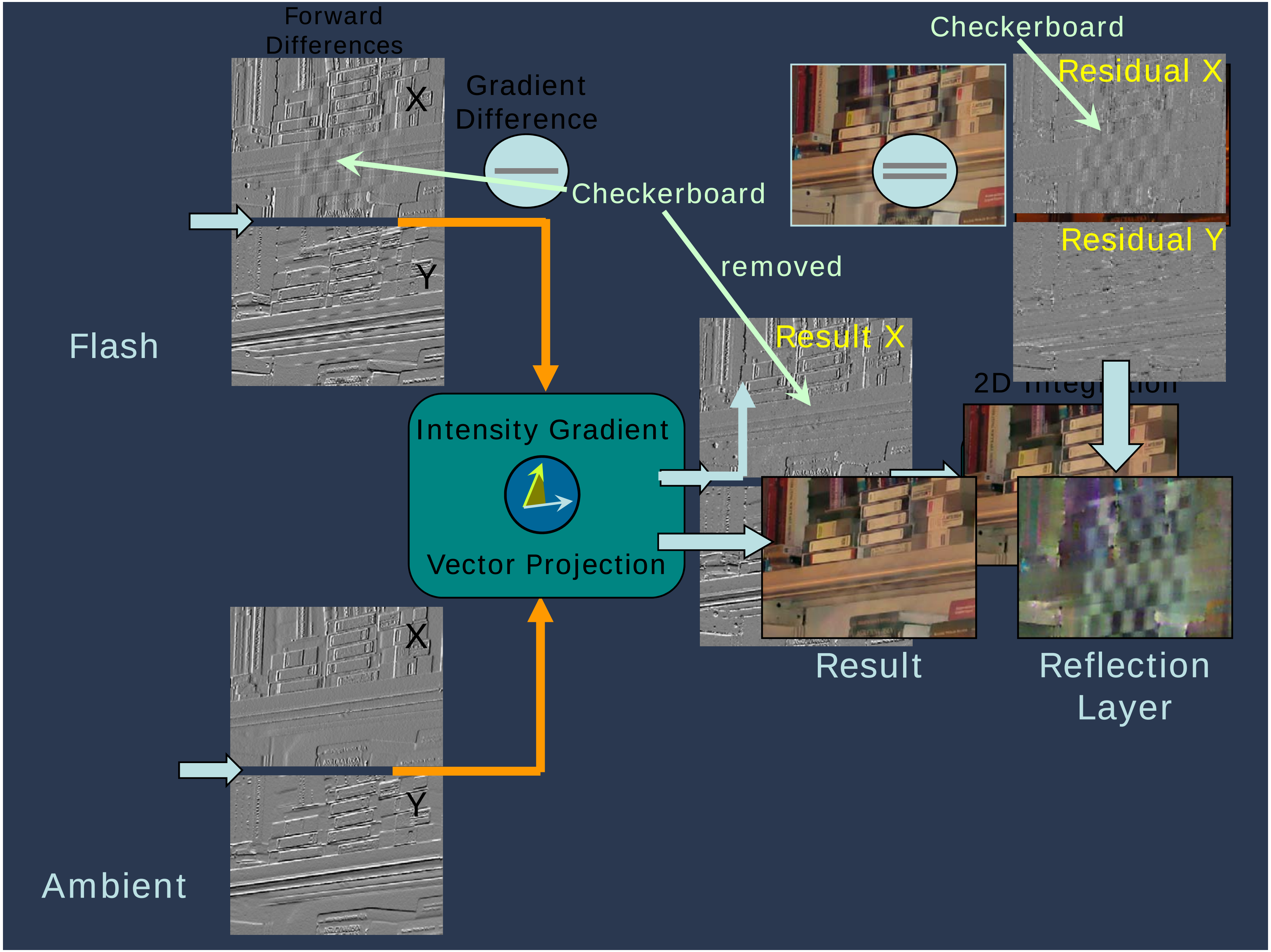
With reflections

Intensity Gradient Vector Projection




Ambient
Flash
Projection = Result
Residual = Reflection Layer


Flash
Ambient
Checkerboard
outside glass window
Reflections on
glass window



Forward Differences
X
Y
Gradient Difference
Checkerboard
removed
Flash
Intensity Gradient
Vector Projection
Ambient
X
Y
Checkerboard
Residual X
Residual Y
Result X
2D Integration
Result
Reflection Layer

Image Fusion for Context Enhancement and Video Surrealism

Ramesh Raskar

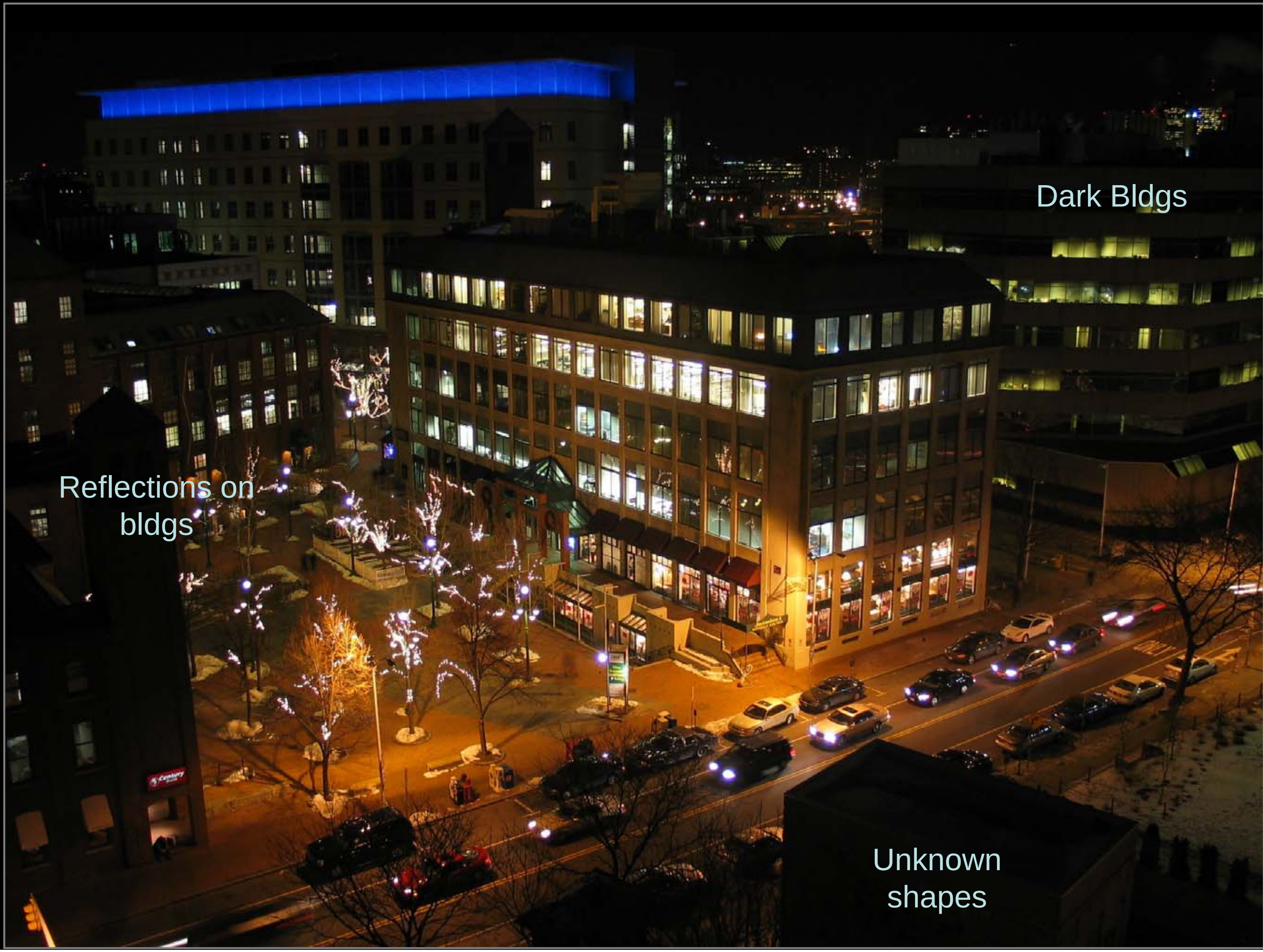
Mitsubishi Electric Research Labs, (MERL)

Adrian Ilie

UNC Chapel Hill

Jingyi Yu

MIT


Dark Bldgs
Reflections on bldgs
Unknown shapes

Night Image

Background is captured from day-time scene using the same fixed camera

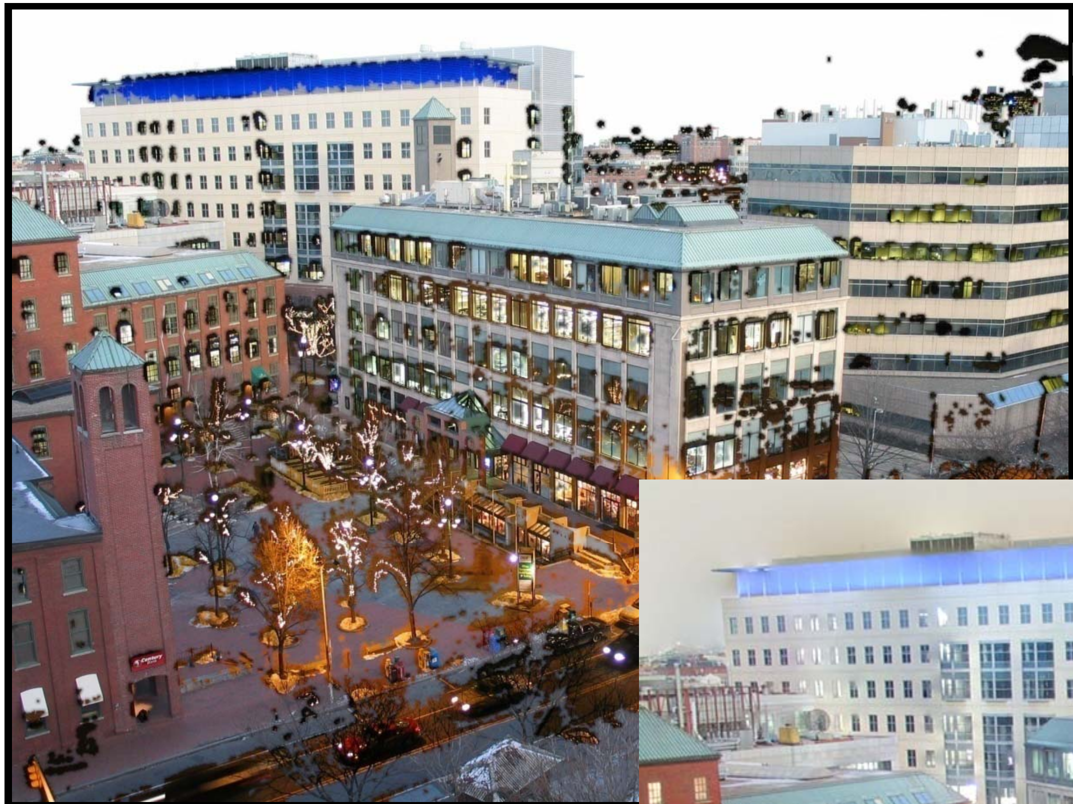
Context Enhanced Image

Day Image

Mask is automatically computed from scene contrast

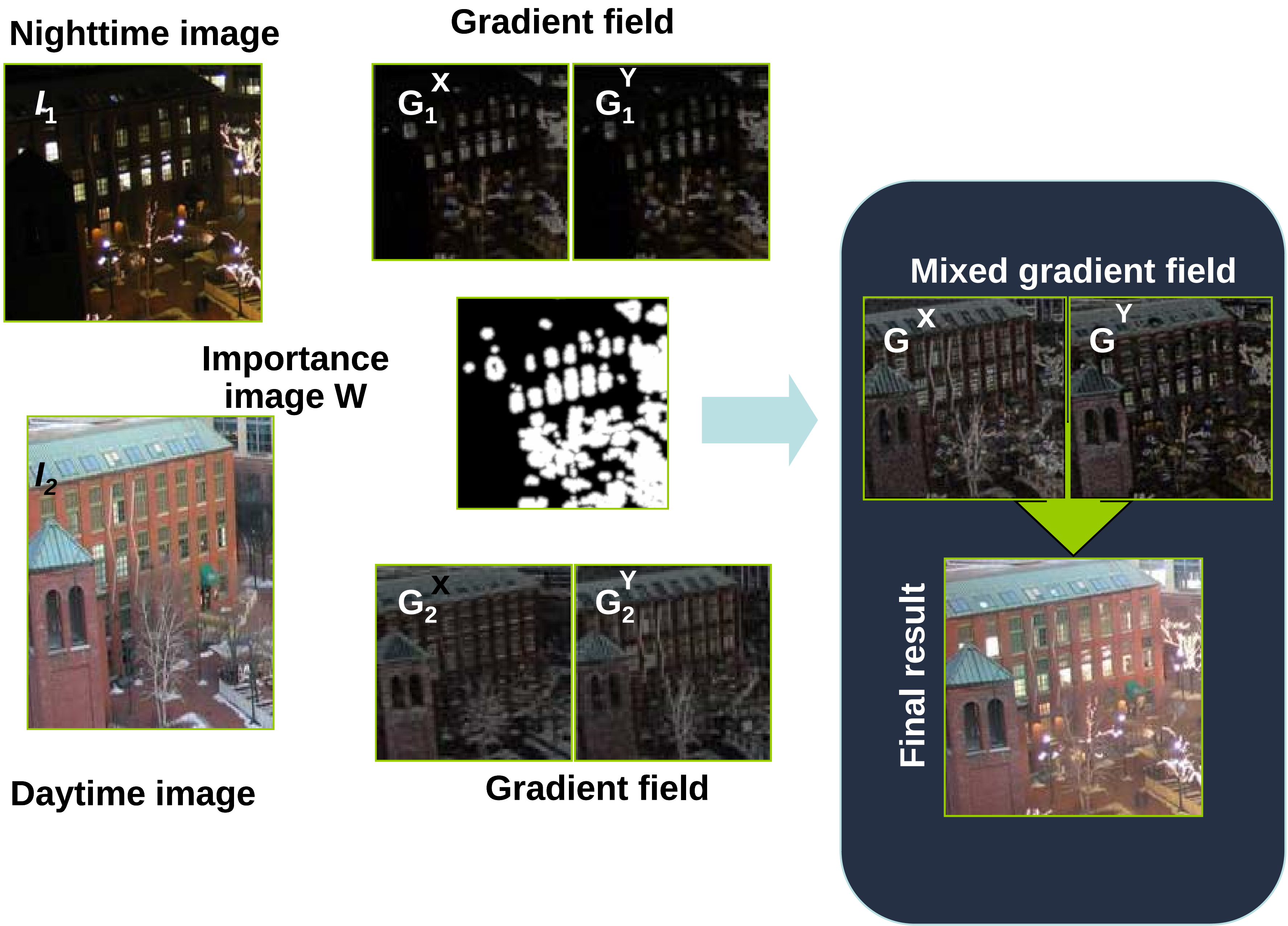
But, Simple Pixel Blending Creates Ugly Artifacts


Century



Pixel Blending

<u>solution</u>:
Integration of
blended Gradients



Nighttime image
I_1
Gradient field
G_1^X
G_1^Y
Importance image W
I_2
G_2^X
G_2^Y
Gradient field
Daytime image
Mixed gradient field
G^X
G^Y
Final result

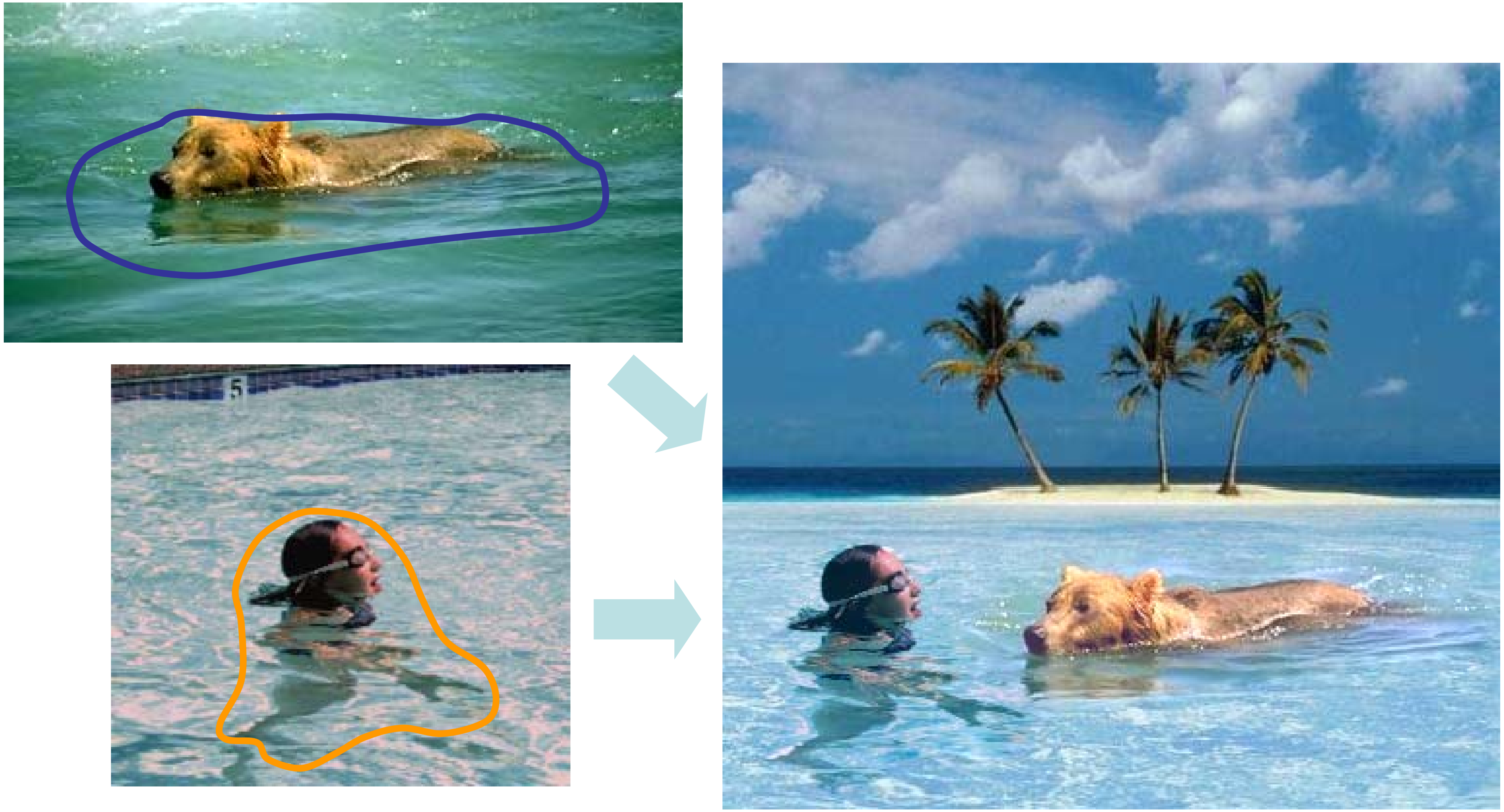
Poisson Image Editing

- Precise selection: tedious and unsatisfactory
- Alpha-Matting: powerful but involved
- Seamless cloning: loose selection but no seams?

Conceal

Copy Background gradients (user strokes)

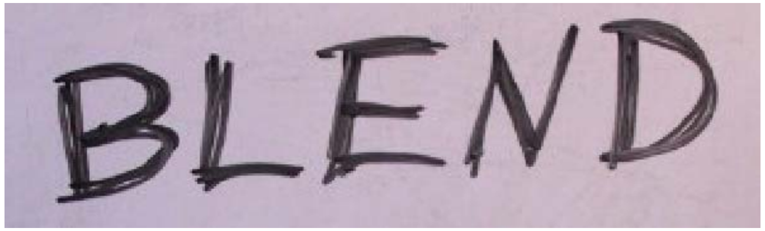
Compose

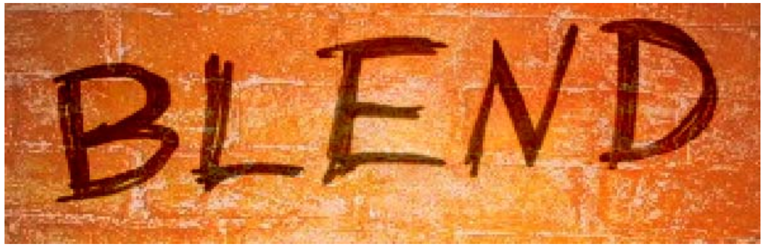


Source Images

Target Image

Transparent Cloning





$$\mathbf{v} = \frac{\nabla f^* + \nabla g}{2}$$

Largest variation from source and destination at each point

Gradient Domain Manipulations: Overview

(A) Per pixel

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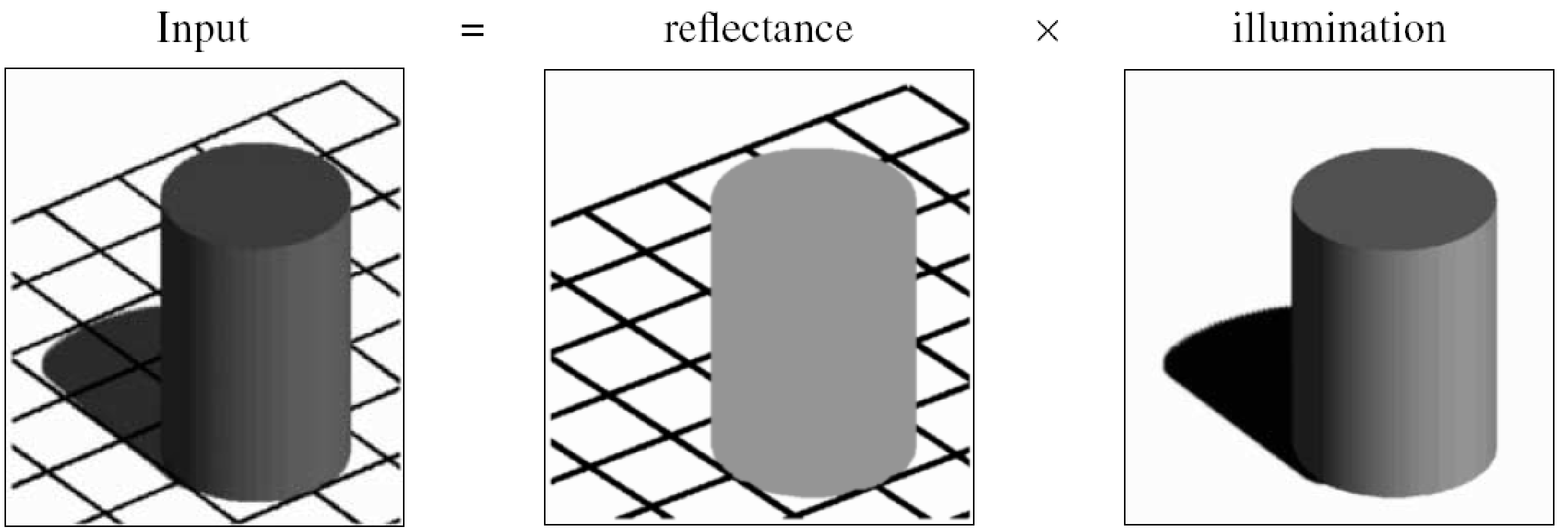
(D) Combining gradients along seams

Intrinsic images

- I = L * R
- L = illumination image
- R = reflectance image



Intrinsic images

- Use multiple images under different illumination
- Assumption
  - Illumination image gradients = Laplacian PDF
  - Under Laplacian PDF, Median = ML estimator

- At each pixel, take Median of gradients across images
- Integrate to remove shadows

Yair Weiss, "Deriving intrinsic images from image sequences", ICCV 2001

frame 1

frame 11

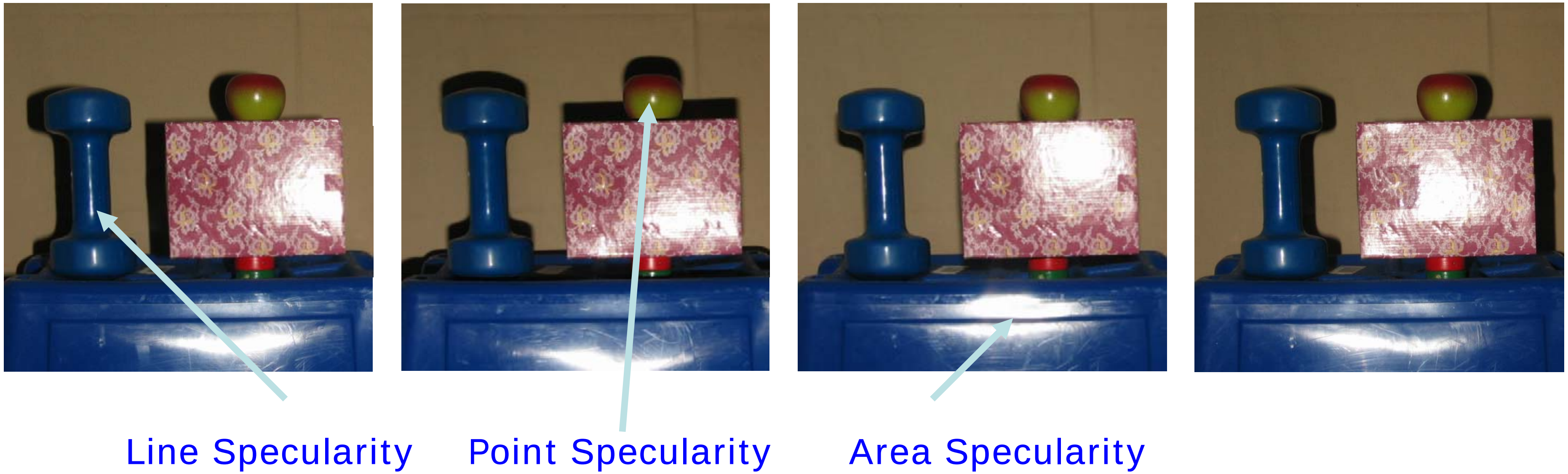
ML reflectance

Shadow free

Intrinsic Image

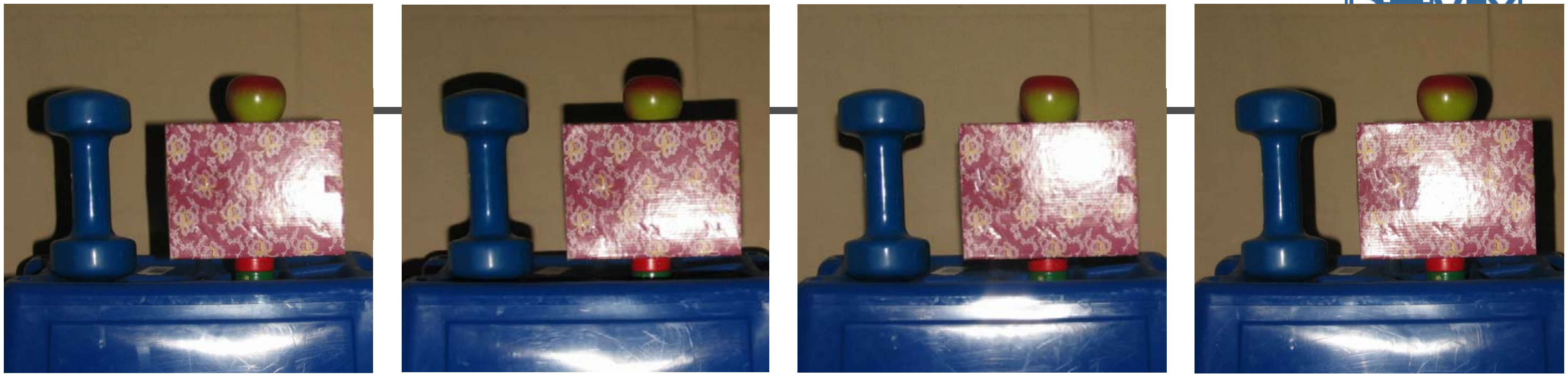
Result = Illumination Image * (Label in Intrinsic Image)

Specularity Reduction in Active Illumination



Multiple images with same viewpoint, varying illumination

How do we remove highlights?



Specularity Reduced Image

Gradient Domain Manipulations: Overview

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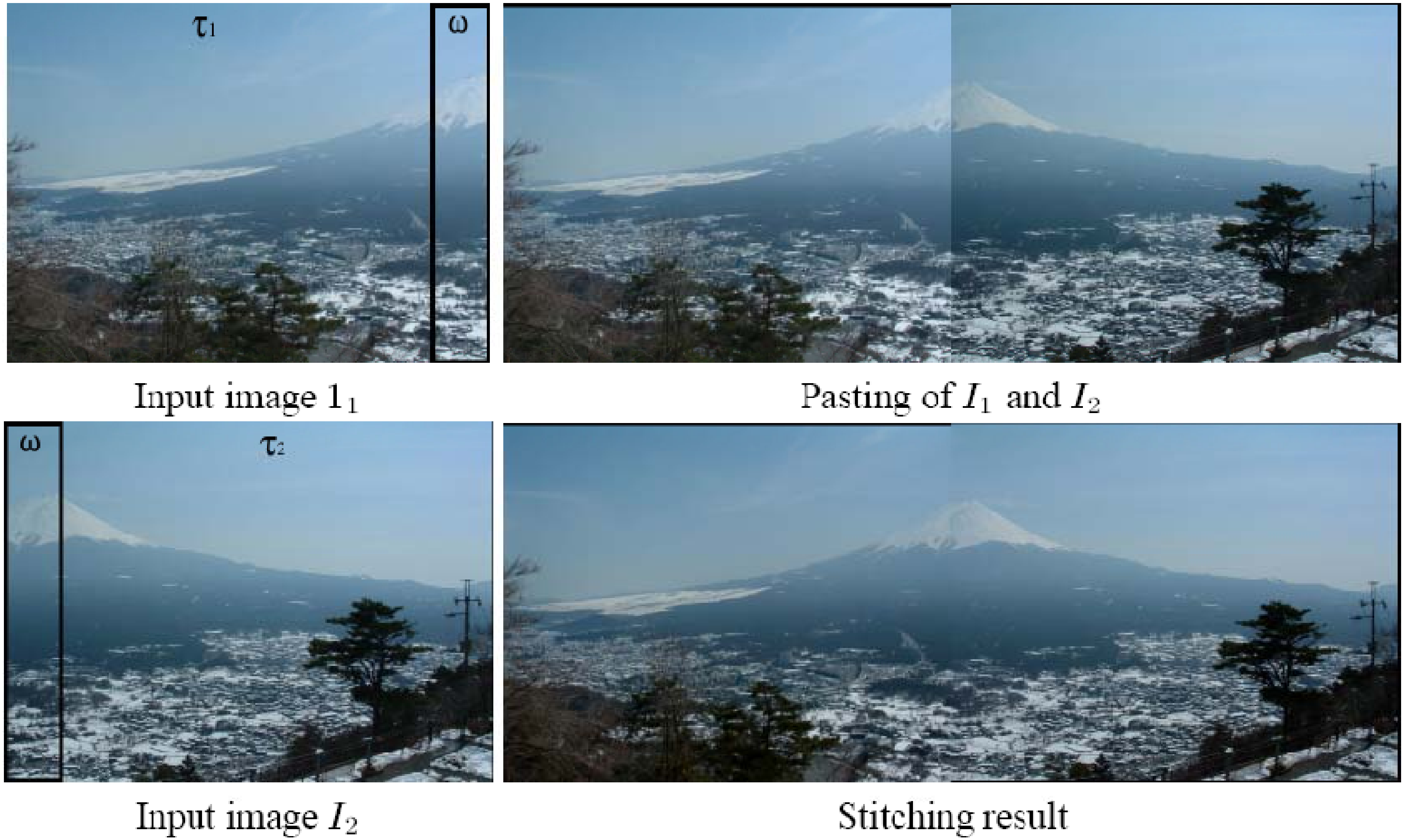
Seamless Image Stitching



Anat Levin, Assaf Zomet, Shmuel Peleg and Yair Weiss, "Seamless Image Stitching in the Gradient Domain", ECCV 2004