Image Inpainting: An Overview

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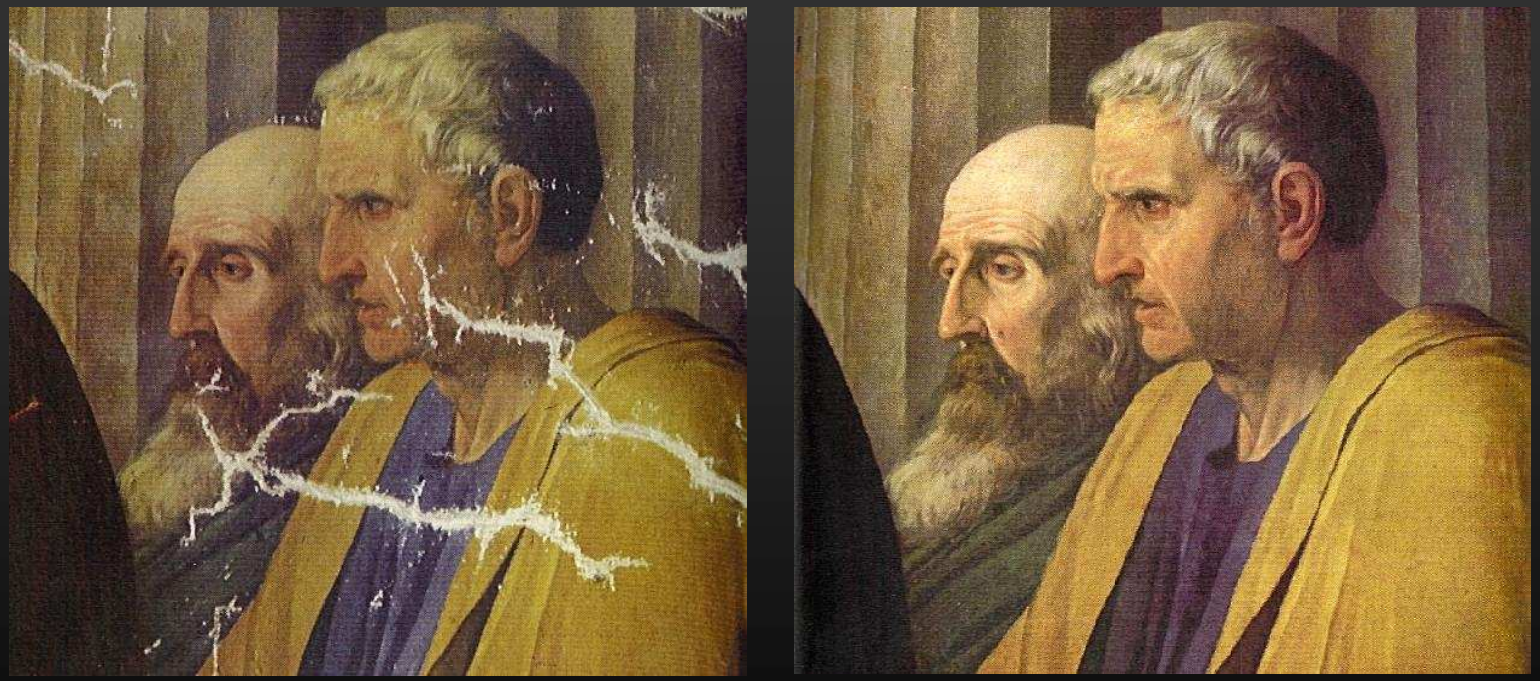
Overview

- **Goal and background**
  - Art, biology, math, and engineering come together
- **Related work**
- **Inpainting**
- **Filling-in**
- **Inpainting and image decomposition**
- **3D surface filling-in**

What is inpainting?

- Modifying an image in a non-detectable form



"Cornelia, Mother of the Gracchi" by J. Suvee (Louvre). Emile-Male “The Restorer’s Handbook of easel painting”.

Another example

From Geary Gallery

Real world example: Photo restoration

- Restorations courtesy of Photo Imaging Studio, Image Enigma, Alleycat Designs

Real world example: Object removal

- From D. King, “The Commissar vanishes”.

Real world example: Object removal

- From D. King, “The Commissar vanishes”.

Real world example: Object removal

Lenin and friend Trotsky

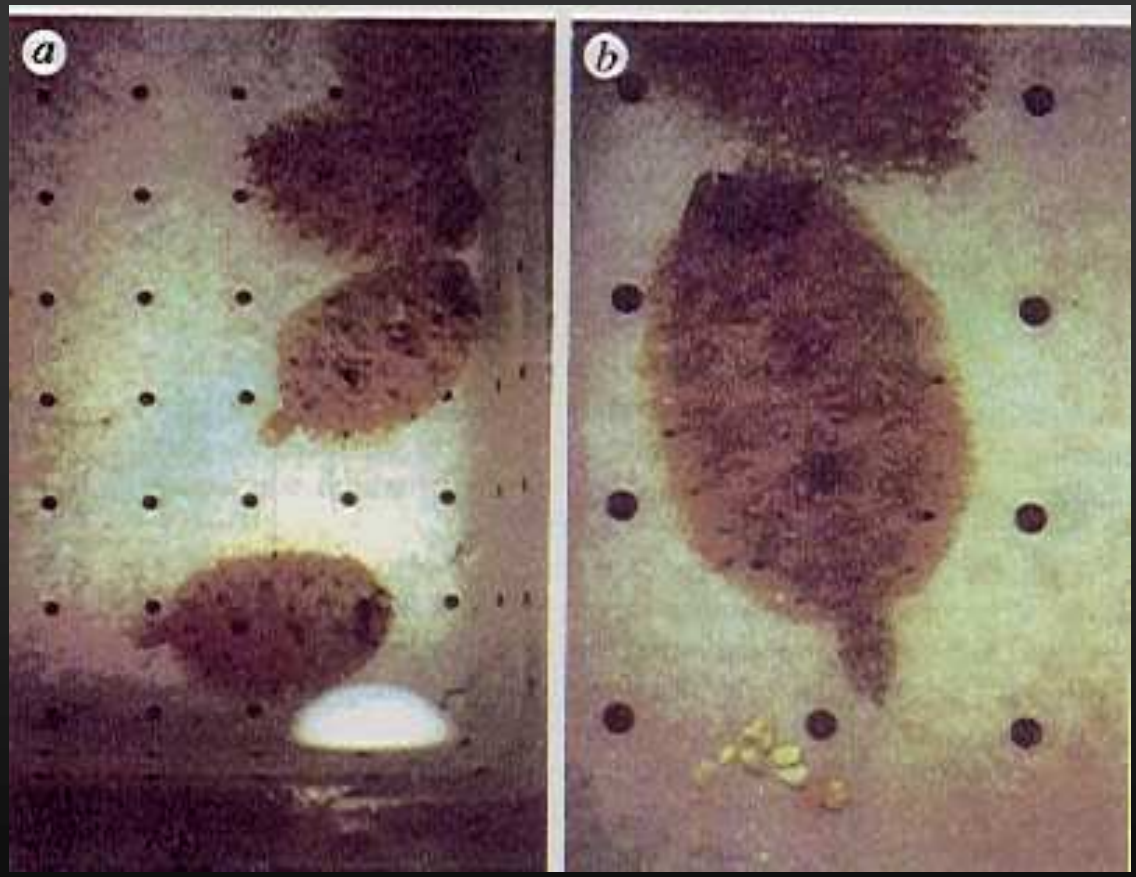
Where is Trotsky?

- From www.newseum.org

Biological inpainting

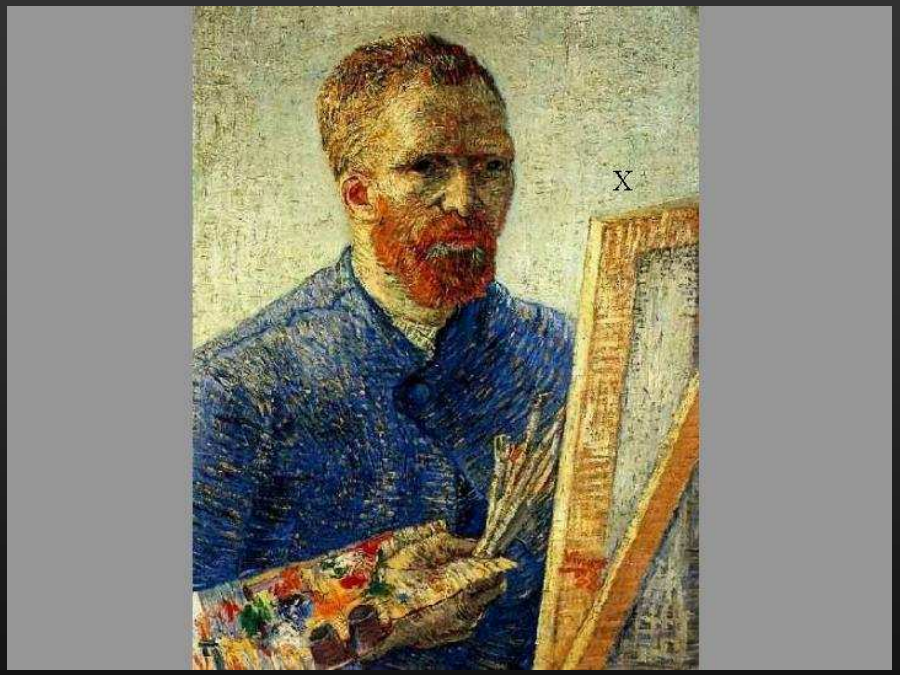
Biological inpainting

Biological inpainting



From Ramachandran et el.

Human Blind Spot



http://info.med.yale.edu/neurobio/mccormick/fill_in_seminar/figure16.html

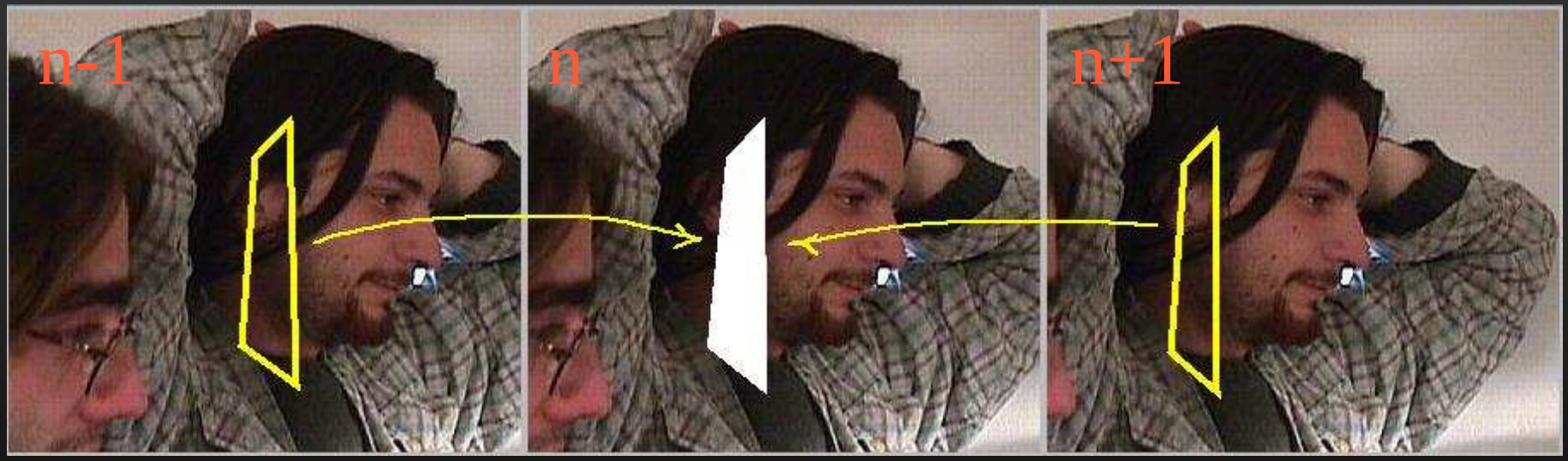
Real world example: Object removal and missing information

- From ProSpec-UK.

The goal

Related work: Films

- e.g. Kokaram et al., Geman et al.



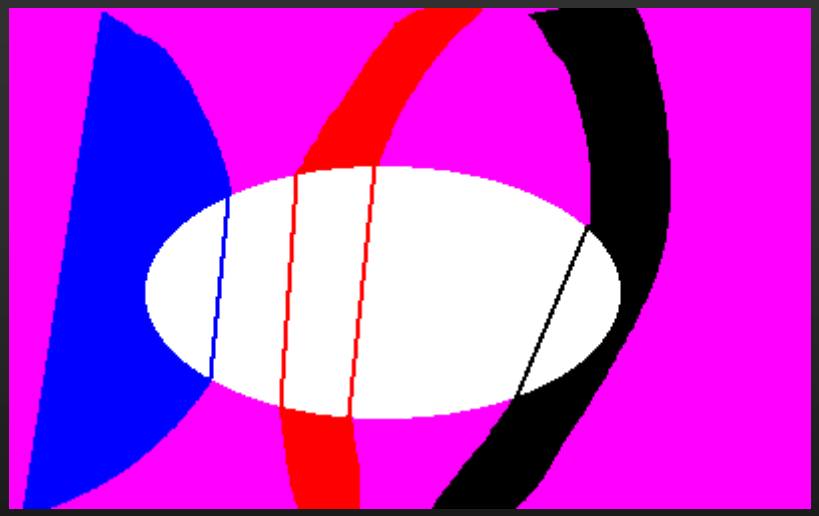
- Doesn’t work for stills or static objects

Related work: Texture synthesis

- Hirani, Efros, Heeger, DeBonet, Simoncelli, Zhu, etc.
- Not practical for rich regions
- Not (originally) designed for structured regions
- “Copy” information instead of “see and interpolate”

Related work: Disocclusion

- Masnou-Morel, Nitzberg-Mumford, etc.



- Limitations: Topology, angles

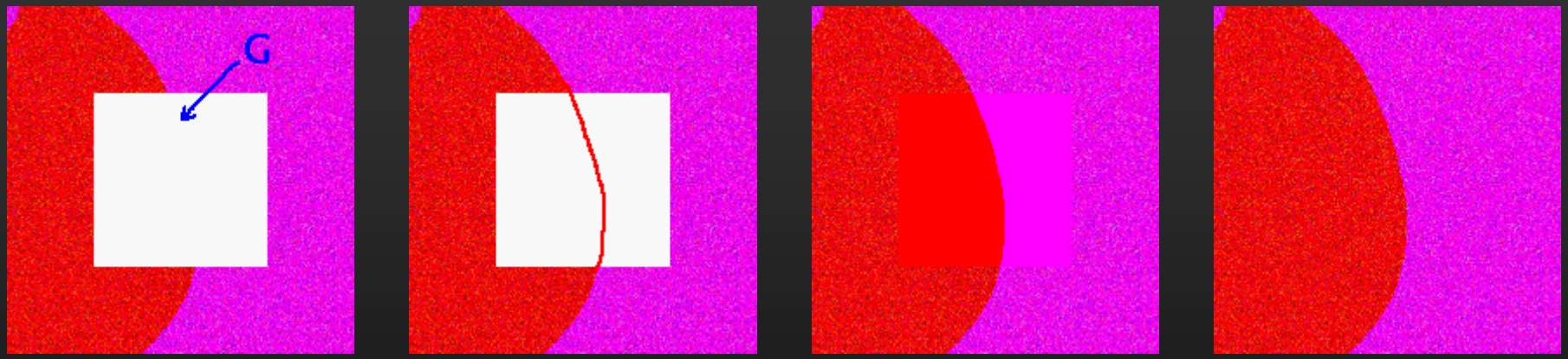
See also Jacobs, Basri, Zucker, etc, and Chan-Shen ‘00, Zhu-Mumford

Our Contribution

- User only selects region to inpaint
- Rich background and topology not an issue
- Less than 1 minute on a PC

How conservators inpaint

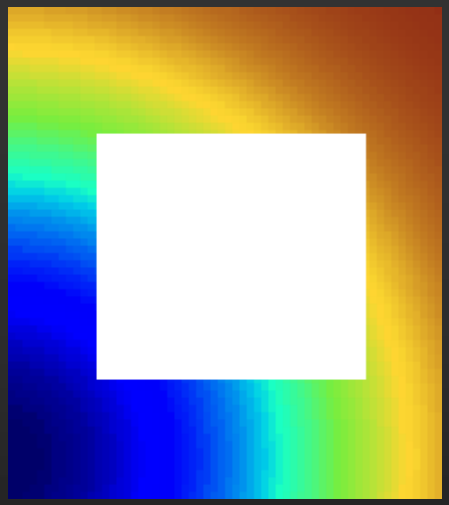
- Minneapolis Institute of Art

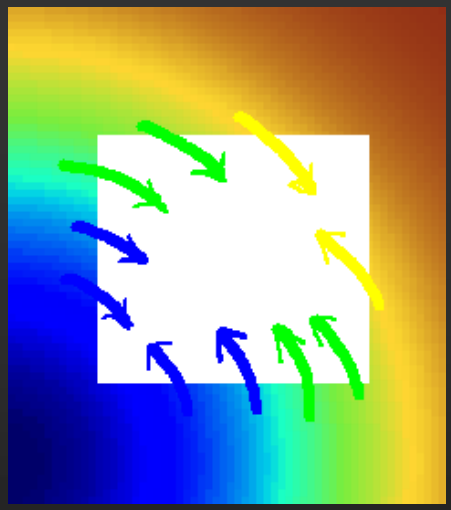


Approach 1

Bertalmio, Sapiro, Caselles, Ballester,
SIGGRAPH 2000

Automatic digital inpainting

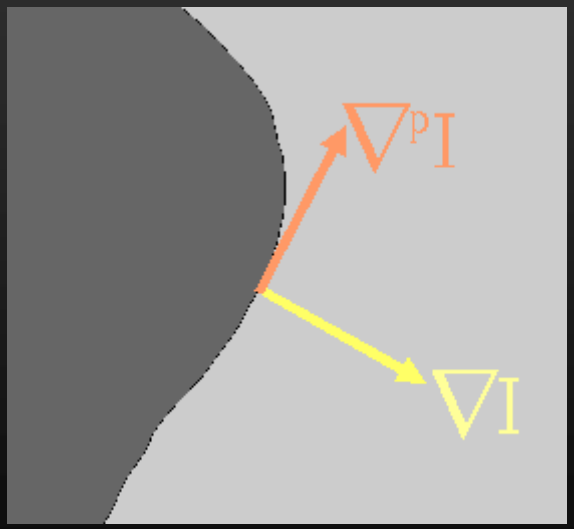


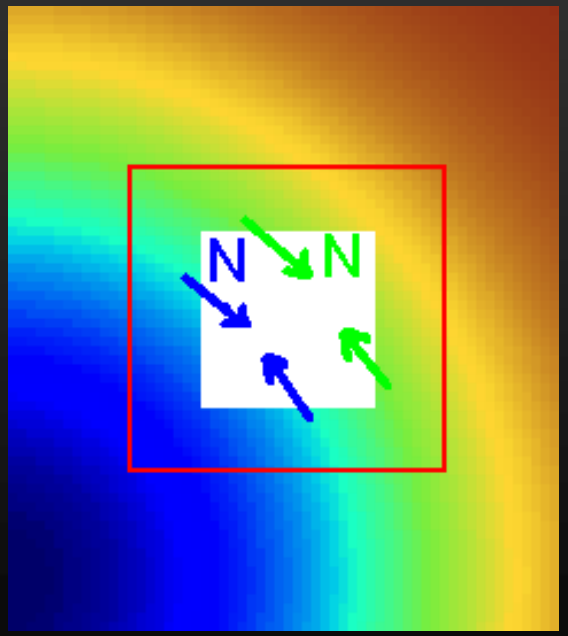


- Propagate information $\nabla L \bullet \vec{N} = 0$
- Evolutionary form $\frac{\partial I}{\partial t} = \nabla L \bullet \vec{N}$

Digital inpainting (cont'd)

- L = smoothness estimator (Laplacian)
- N = isophote direction (time variant)

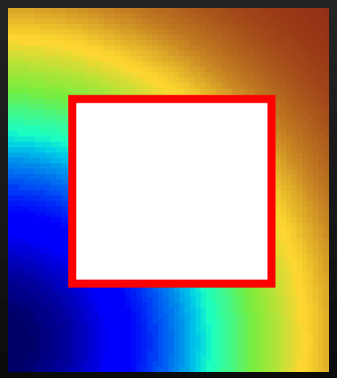




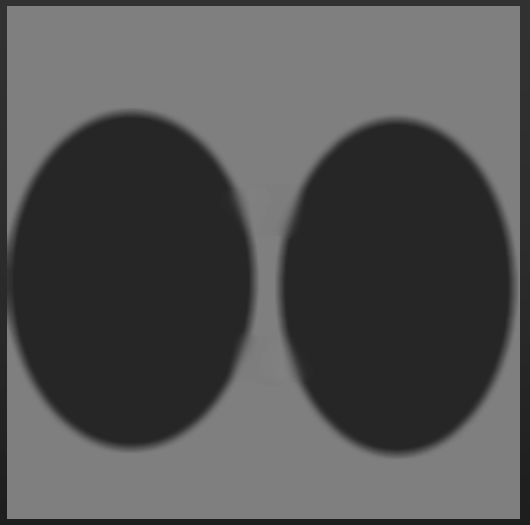
The equation

$$\frac{\partial I}{\partial t} = \nabla(\Delta I) \bullet \nabla^{\perp} I$$

- **Plus numerical schemes (Osher-Marquina)**
- **Boundary conditions**
  - Gray values (in a band)
  - Directions (in a band)

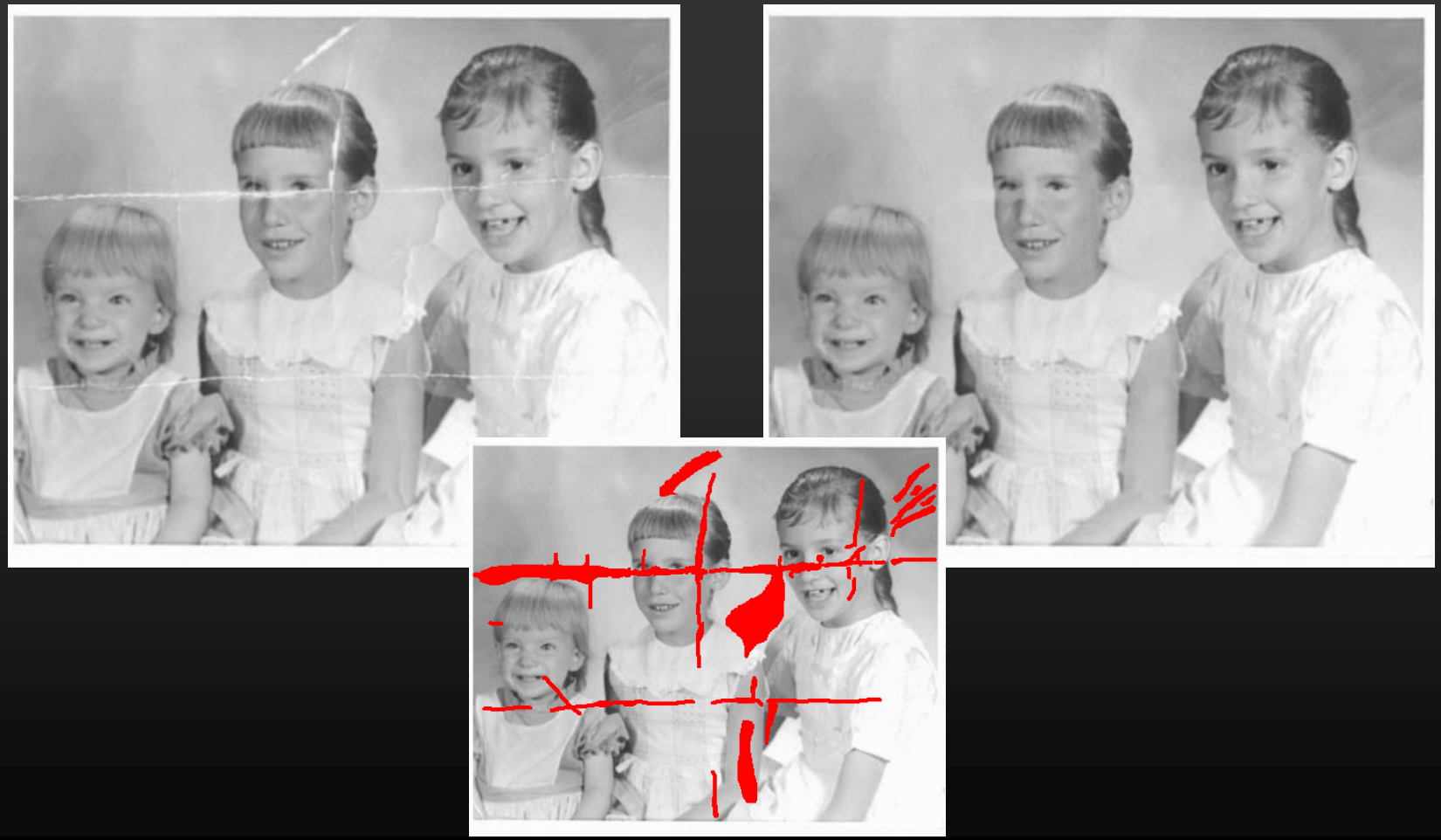


Example



Example: Text removal

Example: Photo restoration

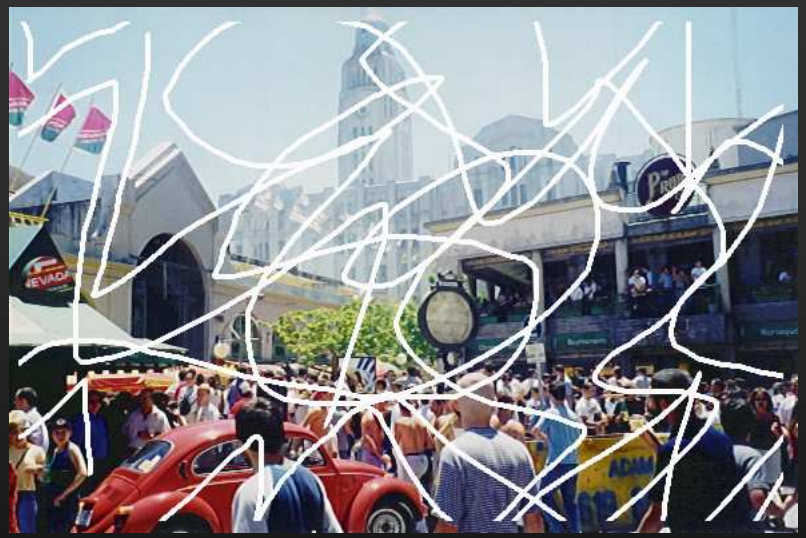


Example: Special effects

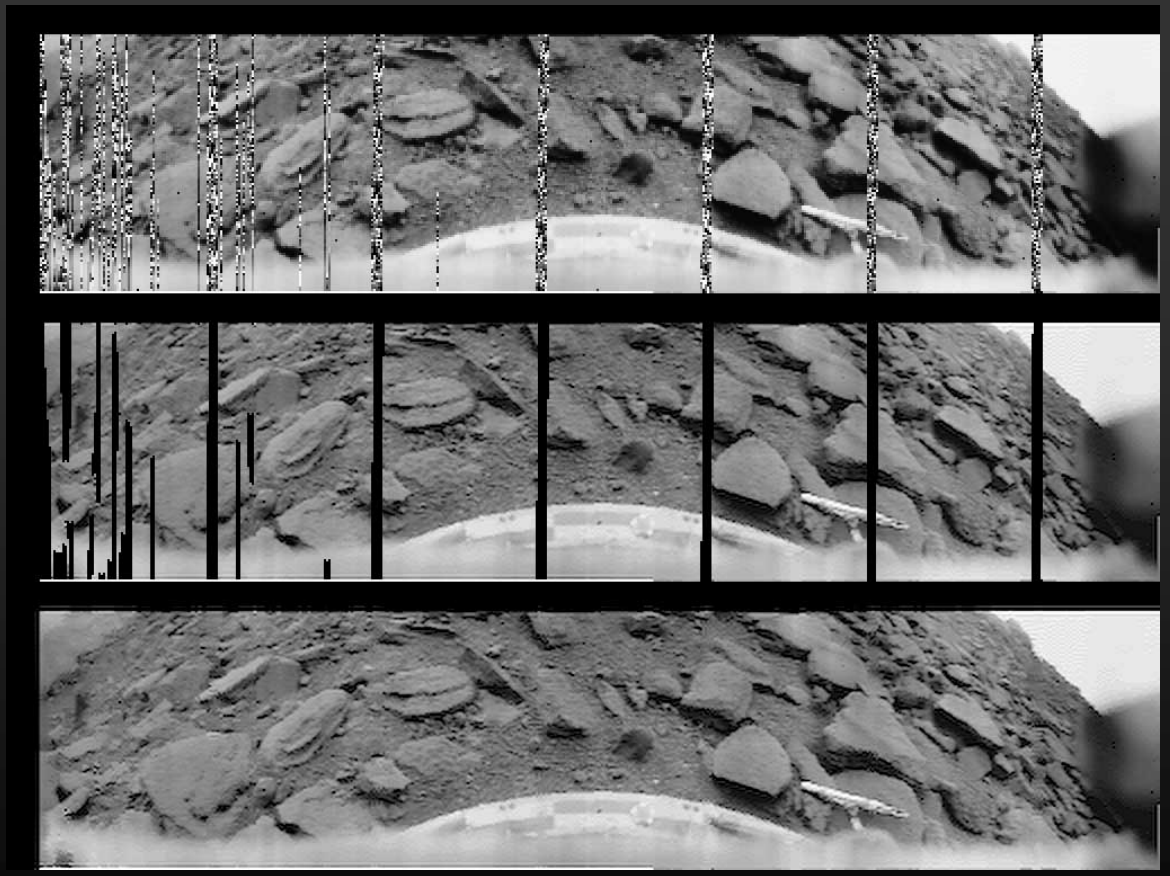
Example: Special effects

Example: Special effects

Example: Scratch removal

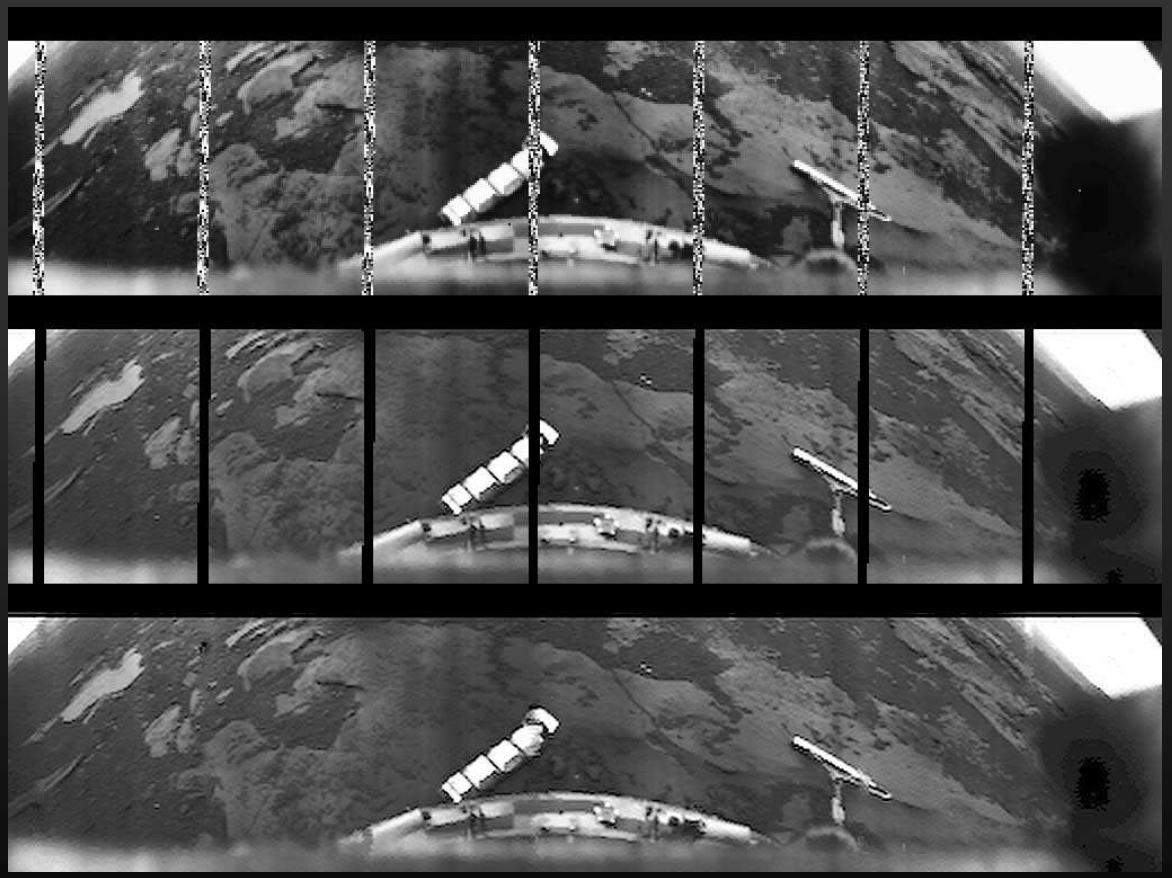


Russian Venus Mission
Venera 9



From Don Mitchell

Russian Venus Mission
Venera 10

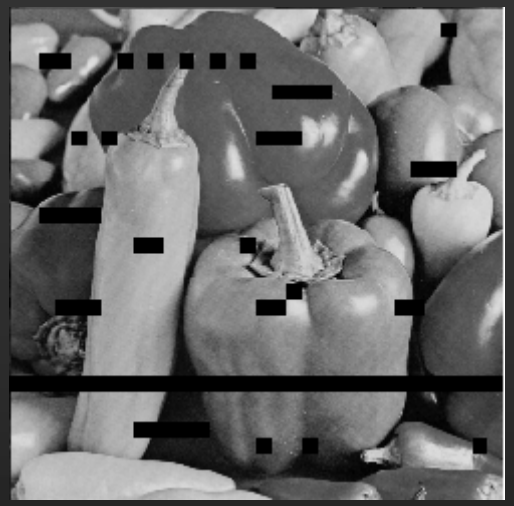


From Don Mitchell

Automatic image inpainting/interpolation for compression and wireless transmission

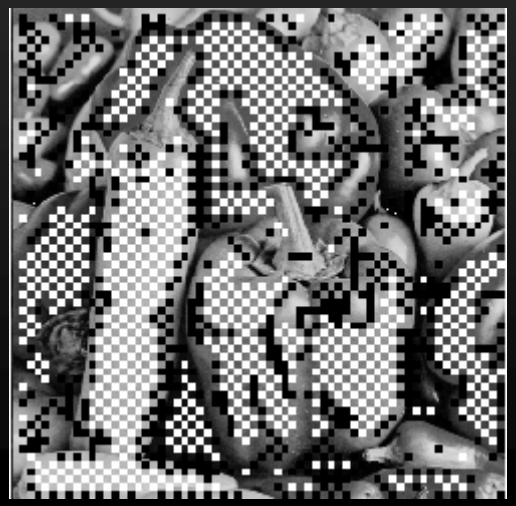
(Rane-Sapiro-Bertalmio) JPEG and/or JPEG-2000 compatible

Transmitted



Automatic reconstruction

Transmitted



Automatic reconstruction

Automatic image inpainting/interpolation for compression and wireless transmission

(Rane-Sapiro-Bertalmio) JPEG and/or JPEG-2000 compatible

Transmitted

Automatic image inpainting/interpolation for compression and wireless transmission

(Rane-Sapiro-Bertalmio) JPEG and/or JPEG-2000 compatible

Automatic reconstruction

Approach 1:
Concluding remarks

- **Technique imitates professionals**
- **Key concepts**
  - Information propagation
  - Both gray values and directions are needed
  - Use a band surrounding the region
- **Sharp results**
- **Low complexity**
- **Texture is not (yet) reproduced**

Concluding remarks (cont.)

- Connected to fluid dynamics (see Bertalmio-Bertozzi-Sapiro CVPR 2001)

$$\frac{\partial(\Delta I)}{\partial t} = \nabla(\Delta I) \cdot \nabla I^{\perp}$$

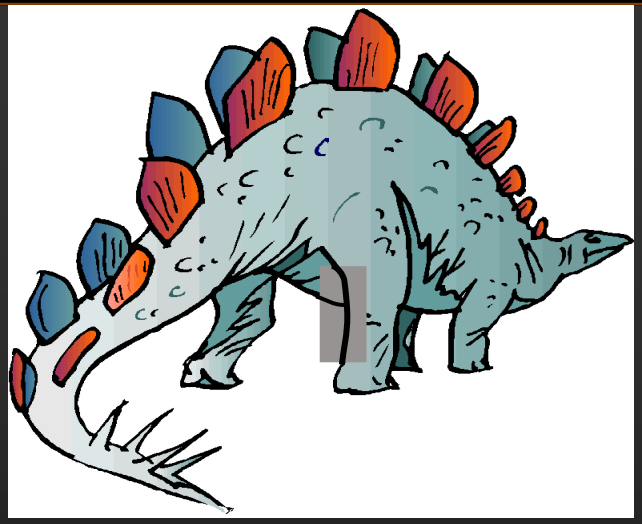
- Opens then door to high order PDE's
- Extended to a variational formulation: Approach 2...

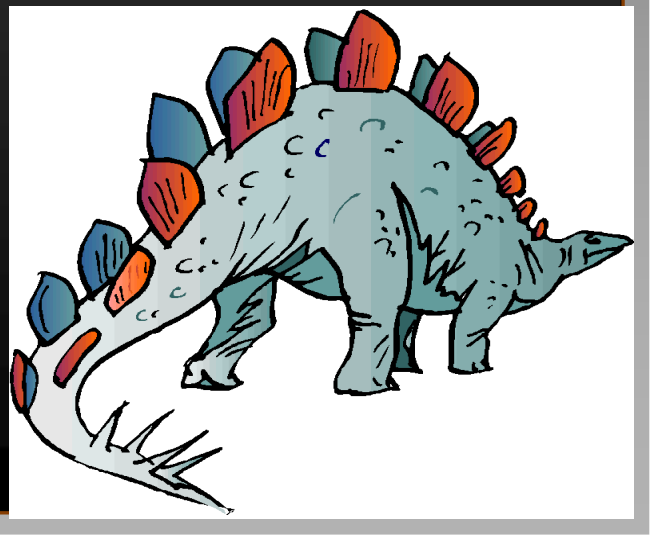
Approach 2

C. Ballester, M. Bertalmio, V. Caselles, G. Sapiro, and J. Verdera,
IMA Report 2000, IEEE Trans. IP 2001

How conservators fill-in

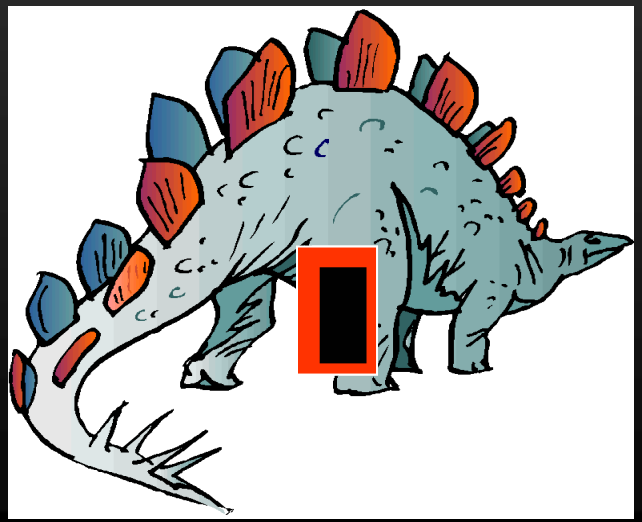
(Minneapolis Institute of Art)



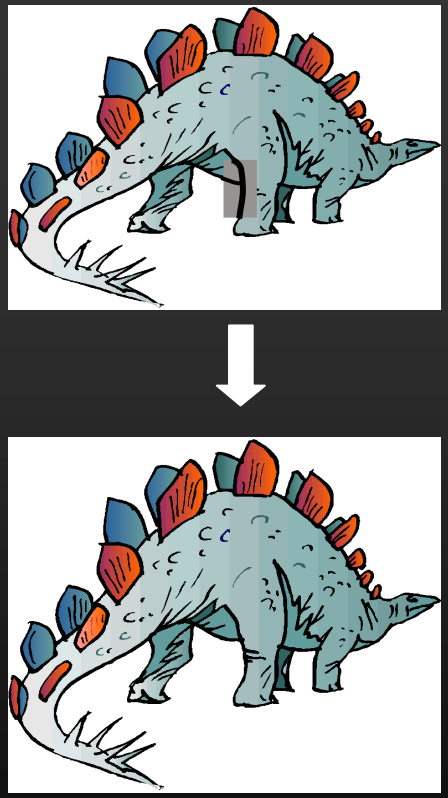


Our approach

- Jointly continue/interpolate level-lines (geometry) and gray values (photometry) in a smooth fashion



Interpolate the gray values given the edges



$$\theta = \text{normalized gradient} \Rightarrow \theta \bullet \nabla I = \|\nabla I\|$$

$$\min(I) \int_{\Omega Y Band} |\,\|\nabla I\| - \theta \bullet \nabla I\,| \, d\Omega$$

$$\frac{\partial I}{\partial t} = div\left(\frac{\nabla I}{\|\nabla I\|}\right) - div(\theta)$$

Theorem: The minimizer exists in BV space

Example



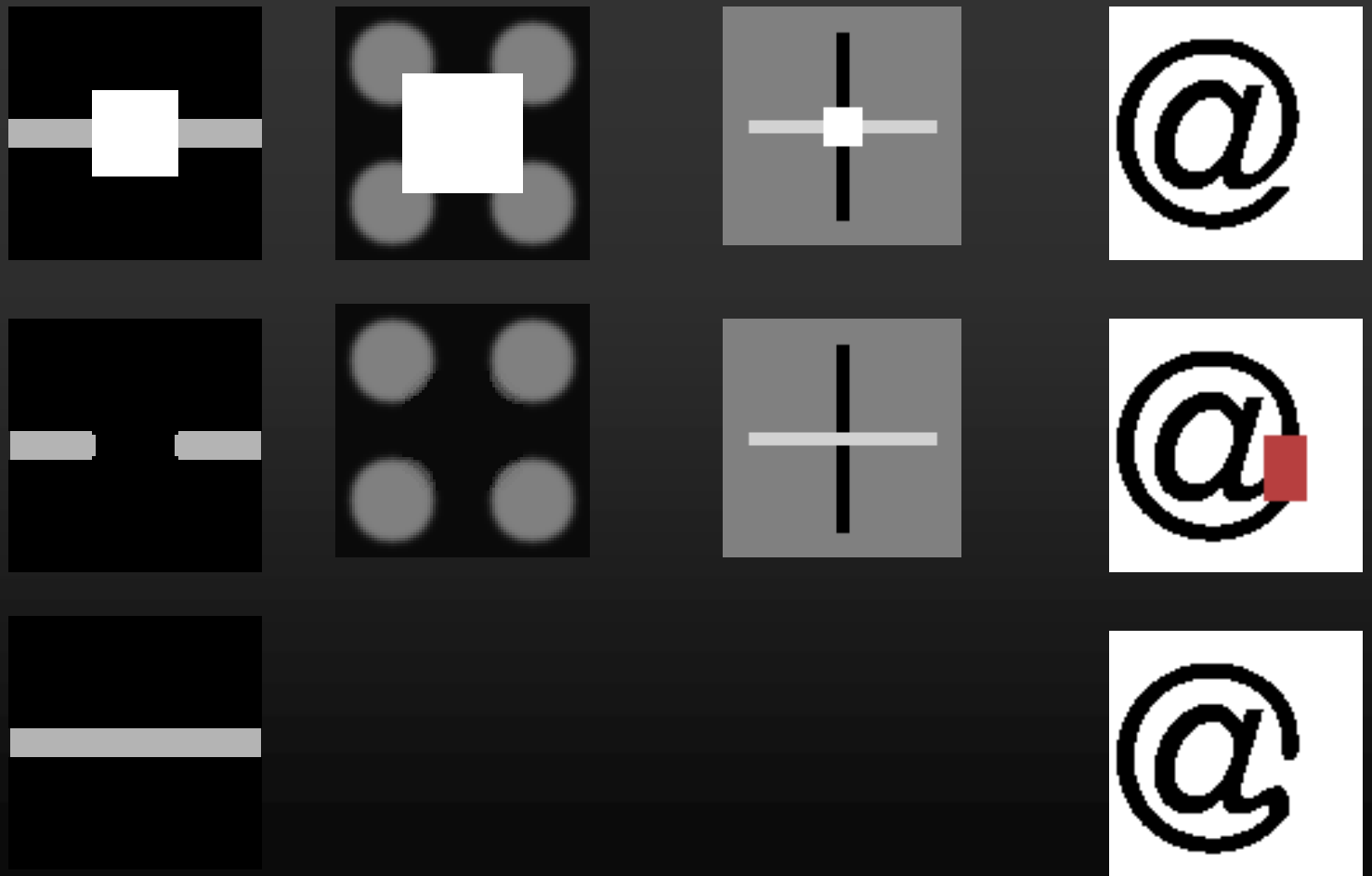
The full functional

$$\min_{(I,\theta)} \int_{\Omega \times Band} div(\theta)^p (a + b\|\nabla G * I\|) + c(\|\nabla I\| - \theta \bullet \nabla I)$$

- Solved via E-L: Coupled 2nd order PDE's
- Implicit discretization used
- Connected to Euler's elastica (Mumford)

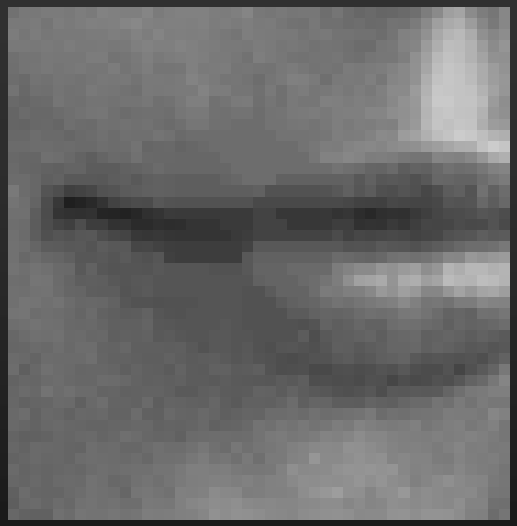
- **Theorem:** For p>1 the minimizer exists

Examples

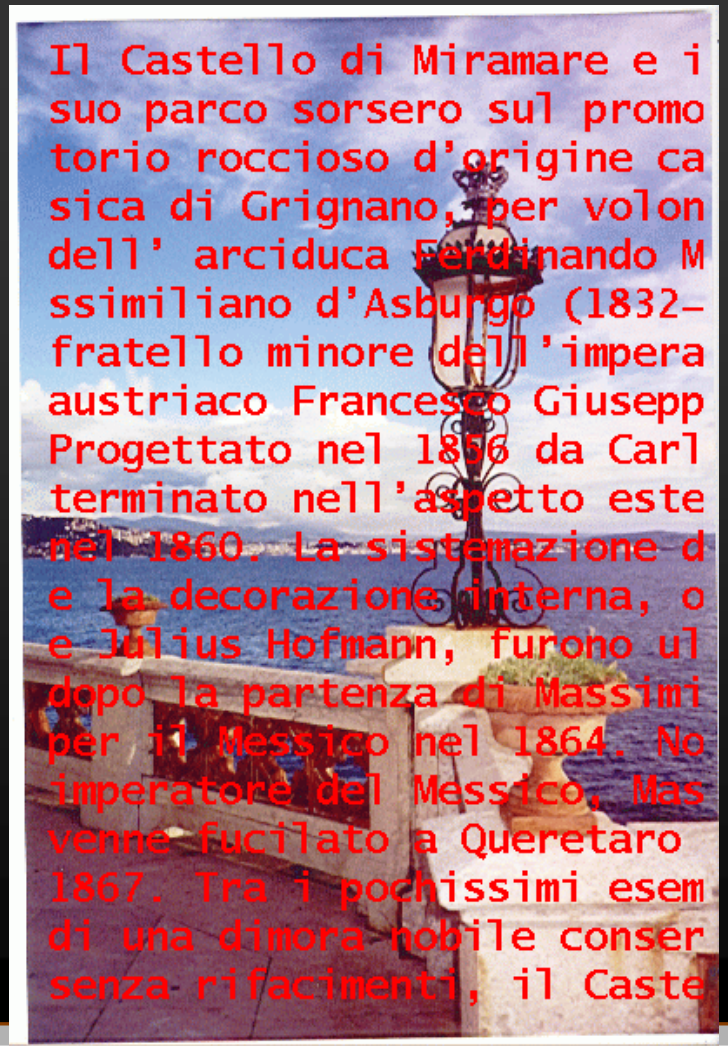


Examples

Examples



Examples


Il Castello di Miramare e i
suo parco sorsero sul promo
torio roccioso d'origine ca
sica di Grignano, per volon
dell' arciduca Ferdinando M
ssimiliano d'Asburgo (1832-
fratello minore dell'impera
austriaco Francesco Giusepp
Progettato nel 1856 da Carl
terminato nell'aspetto este
nel 1860. La sistemazione d
e la decorazione interna, o
e Julius Hofmann, furono ul
dopo la partenza di Massimi
per il Messico nel 1864. No
imperatore del Messico. Mas
venne fucilato a Queretaro
1867. Tra i pochissimi esem
di una dimora nobile conser
senza rifacimenti, il Caste

Approach 2:
Concluding remarks

- **Technique imitates professionals**
- **Key concepts**
  - Information propagation
  - Both gray values and directions are needed
  - Use a band surrounding the region
- **Sharp results**
- **Low complexity**
- **Texture is not (yet) reproduced**

Inpainting and Image Decomposition

Bertalmio, Vese, Sapiro, Osher, July 2002

IEEE Trans. IP, 2003

Basic Idea

Image decomposition

Definition (Meyer) $G =$ Banach space of generalized functions $v(x,y)$:

$$v(x,y) = \partial_x g_1(x,y) + \partial_y g_2(x,y),\ \ g_1, g_2 \in L^\infty(R^2),$$

$$g := (g_1, g_2), |g(x,y)| = \sqrt{g_1(x,y)^2 + g_2(x,y)^2},$$

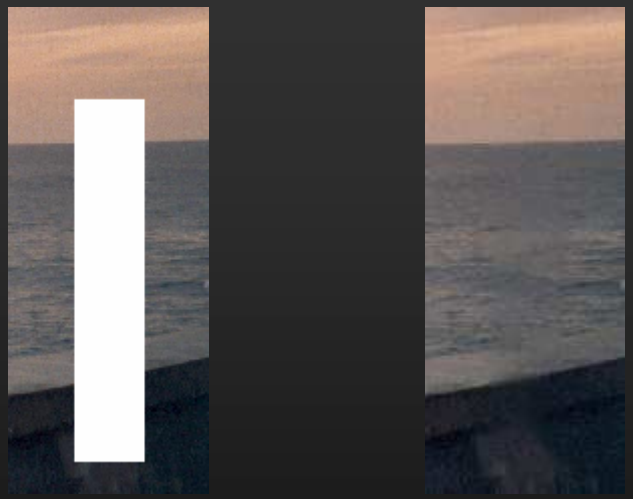
and use the infimum over all possible decompositions.

Definition (Vese-Osher) The image I is decomposed in *structure* (u) and *texture* (v) solving via gradient descent the variational problem

$$\inf_{u,g_1,g_2} \Big\{ G_p(u,g_1,g_2) \quad = \quad \int |\nabla u| + \lambda \int |I - u - \partial_x g_1 - \partial_y g_2|^2 dxdy$$

$$+ \quad \mu \Big[\int \Big(\sqrt{g_1^2 + g_2^2} \Big)^p dxdy \Big]^{\frac{1}{p}} \Big\}$$

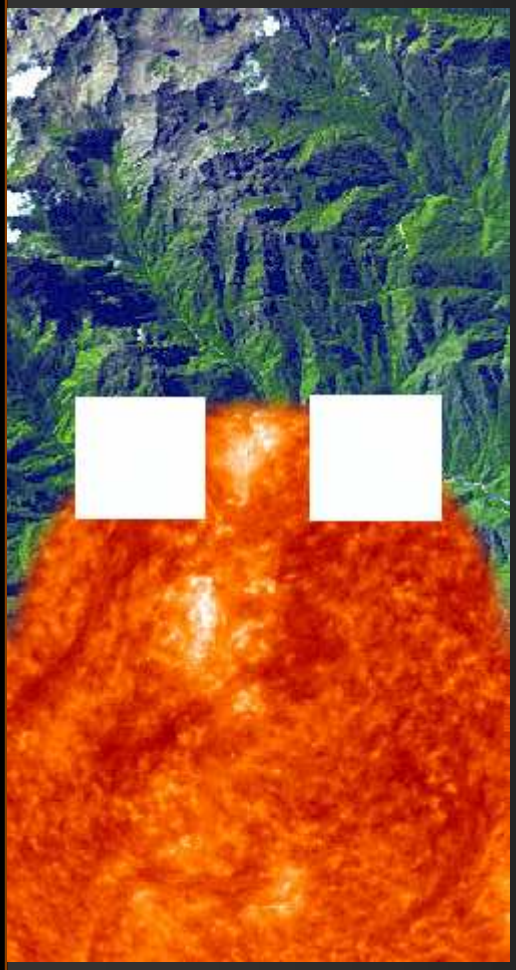
Example

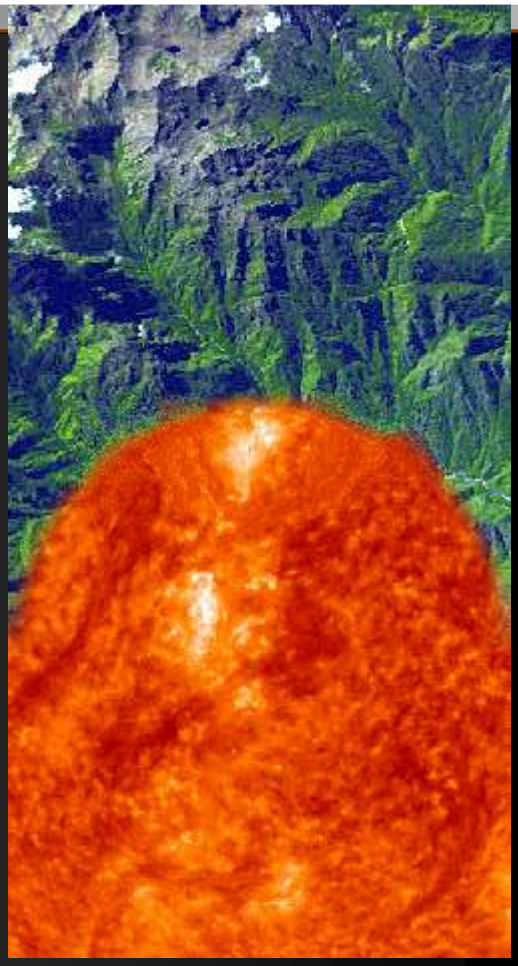


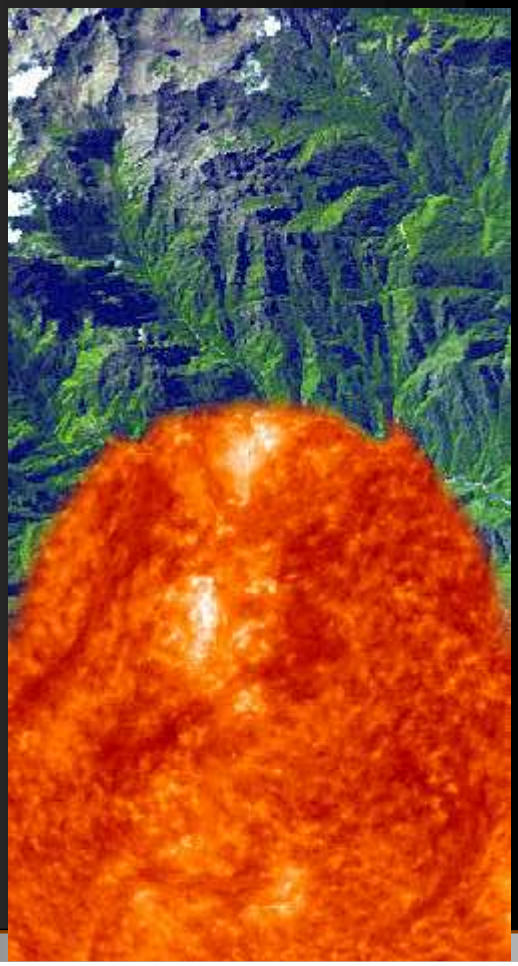
Example

Texture only

Ours



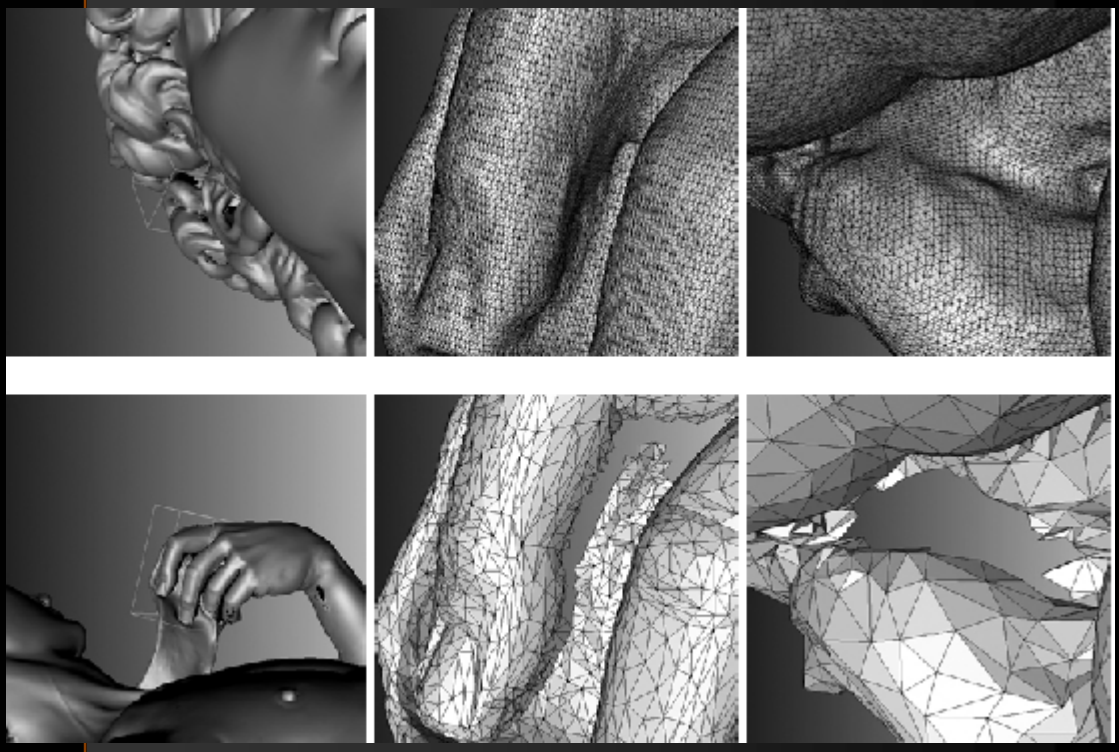


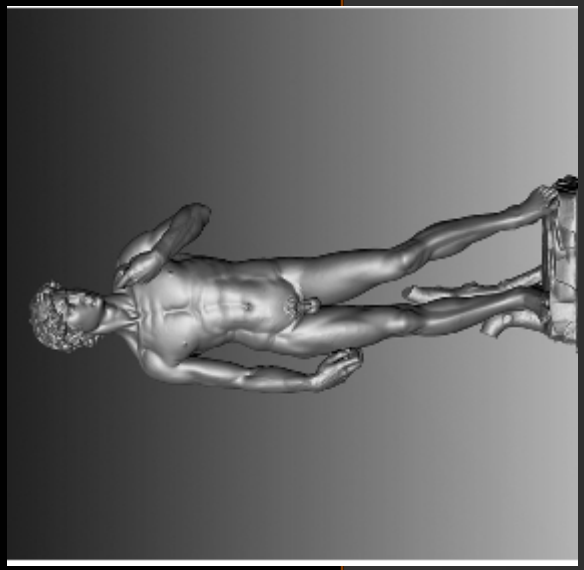


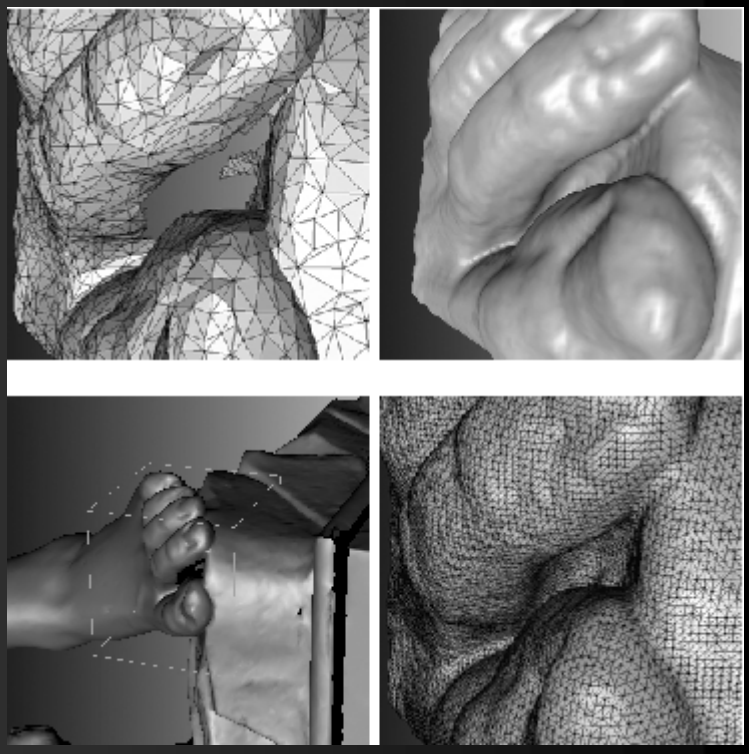
Filling surface holes

Verdera, Bertalmio, Caselles, Sapiro,
IEEE ICIP 2003

Data and inspiration from Levoy and the Michelangelo Project







Inpainting from Sensor Arrays

Yatziv, Sapiro, Levoy

Example

Inpainting the Colors

Guillermo Sapiro

Colorization

Inspired by work of Levin et al.

Basic Idea

- **Inpaint with**
  - Edges from monochromatic image (Chung-Sapiro, Caselles et al, Kimmel)
  - Boundary conditions from given color strokes

$$\min_{Cb} \int_{\Omega} \rho(\| \nabla Y - \nabla Cb \|) d\Omega$$

$$\Delta Cb = \Delta Y$$

See also Kenney et. al., Perez et al.

Basic idea (cont.)

$$\min_{Cb} \int_{\Omega} \rho \left(\frac{\nabla Y}{\| \nabla Y \|} \cdot \nabla Cb - \| \nabla Cb \| \right) d\Omega$$

$$\operatorname{div} \left(\frac{\nabla Cb}{\| \nabla Cb \|} \right) = \operatorname{div} \left(\frac{\nabla Y}{\| \nabla Y \|} \right)$$

Example

Example

Movies

- **Use 2D+time gradients**
  - Color constancy
  - All channels “sharing” spatial gradients
  - All channels having same motion vectors

Conclusion

- Inpainting 2D and 3D via PDEs (flows)
- Inpainting in a decomposition space
- Inpainting light-fields
- Inpainting the colors
- Connections with biology and art

- See also recent works such as Tensor Voting (CVPR'03), Edge directed Efros (CVPR'03), Global inpainting (ICCV'03).

Acknowledgments

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- T. Robbins, E. Buschor, S. Betelú, S. Osher, E. Simoncelli, A. Bertozzi, T. Chan, C. Kenney, P. L. Lions, J. M. Morel, J. Shen.
- Supported by ONR-Math, ONR Young Investigator Award, Presidential Early Career Awards for Scientists and Engineers, NSF CAREER Award, NSF-LIS, Europen project on viscosity solutions, and IIE-Uruguay.

The end

Thank you