Gradient Domain High Dynamic Range Compression

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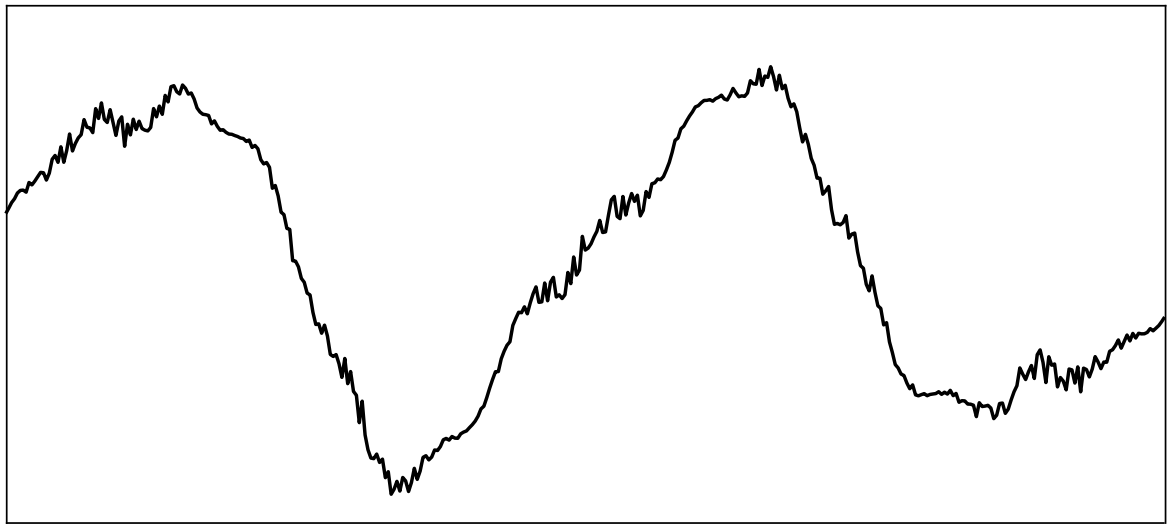
In A Nutshell...

Dynamic Range

- Quantity defined as the ratio between highest and lowest value a signal can attain:



Dynamic Range of Light

dim interior

daylit interior, x1500

outdoor shade, x16

outdoor sunlit, x4

the Sun

x80,000

1 : 7,500,000,000

High Dynamic Range Scenes

1/1000

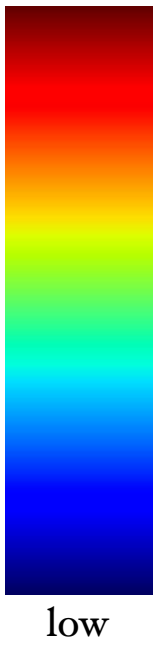
1/500

1/250

1/60

1/30 1/15 1/8 1/4

High Dynamic Range Images



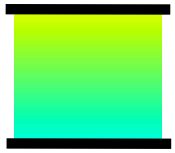
High Dynamic Range Images

high

low

High Dynamic Range Images

high



low

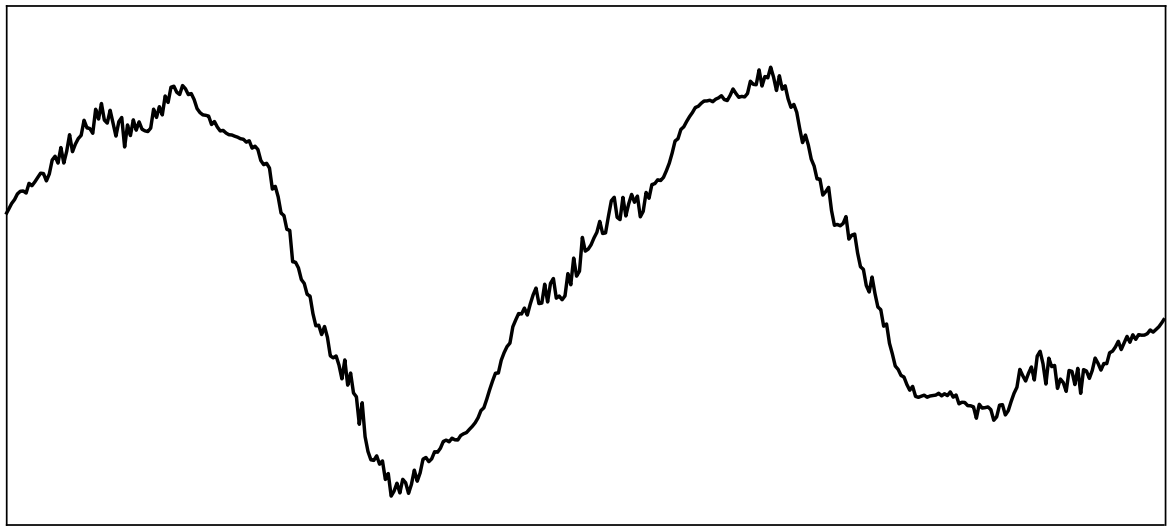
High Dynamic Range Images

high

low

High Dynamic Range Images

- Large ratio between brightest and darkest intensities in the image.
- Small magnitude, local variations in intensity are present across the entire range:



Where do they come from?

- Physically-based illumination simulations.

- Digital photography:
  - Camera RAW images (12 bits per pixel).
  - HDR digital cameras.
  - Combining several differently exposed LDR images into a single HDR image (Debevec & Malik 1997).
  - HDR panoramic video mosaics (Schechner & Nayar 2001).

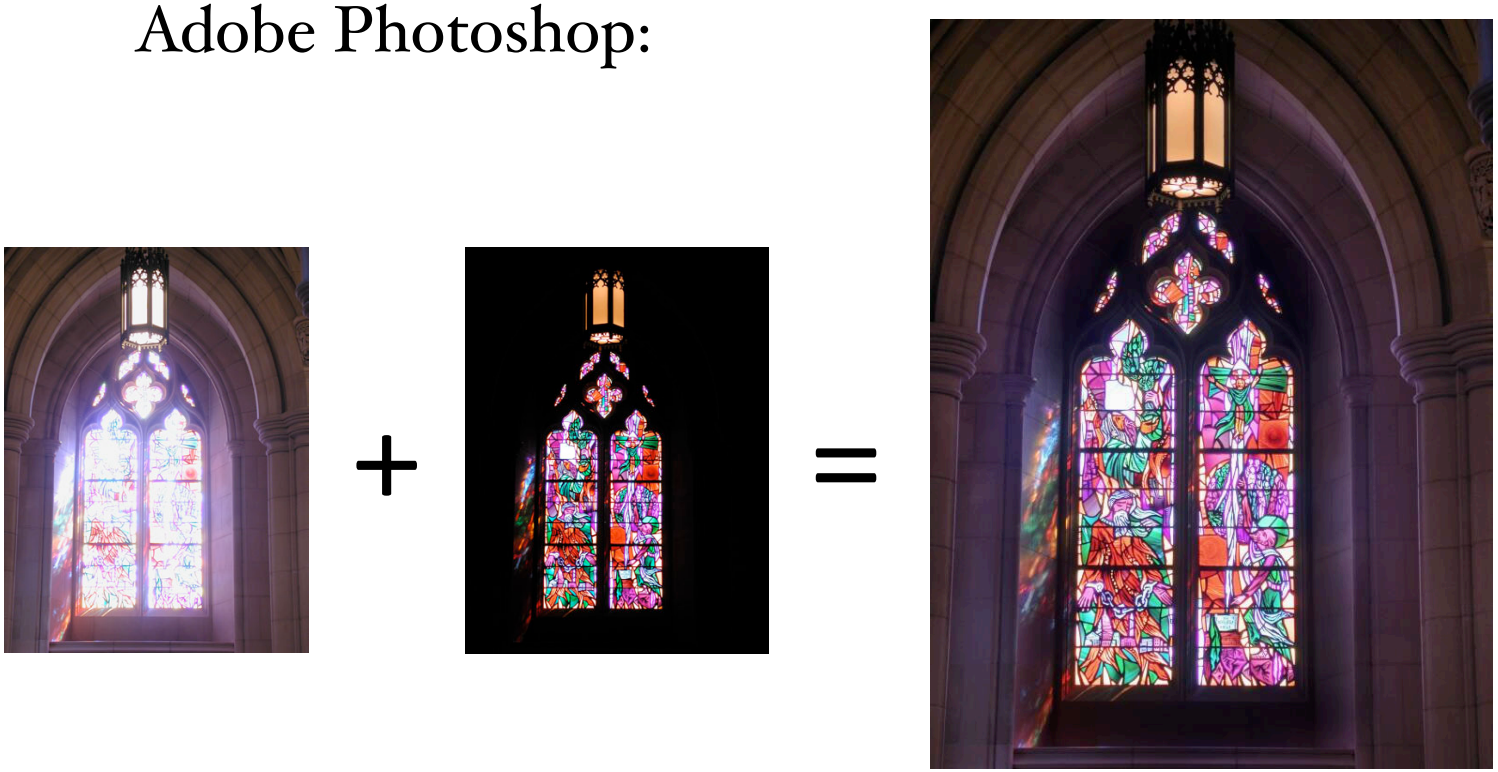
Our Goal

- Compression of dynamic range to enable rendering HDR images on LDR devices.

- Desirable features:
  - Avoid large over/under exposed regions.
  - Preserve visibility of fine details (local contrasts).
  - Avoid introducing artifacts to the image.

Previous Solutions

- Manually combining several exposures into a single image using an interactive tool, such as Adobe Photoshop:



Previous Solutions

- Spatially invariant tone mapping operators
  - Image-independent curves:
    - Linear scaling, Gamma correction, logarithmic mappings...
  - Image-dependent curves:
    - Histogram equalization
    - Visibility matching tone reproduction (Ward et al. 97)

Linear Scaling

Gamma Correction

Exposure + Gamma

Histogram Equalization

Previous Solutions

- Spatially invariant tone mapping operators
  - Image-independent curves:
    - Linear scaling, Gamma correction, logarithmic mappings...
  - Image-dependent curves:
    - Histogram equalization
    - Visibility matching tone reproduction (Ward et al. 97)

- Problem: monotonic mapping leads to loss of local contrast!

Previous Solutions

- Spatially variant tone mapping operators
  - Homomorphic filtering (Stockham 72, Horn 74)
  - Retinex-based operators (Jobson et al. 97)
  - Adaptive histogram equalization (Pizer et al. 87)
  - Multi-scale operators (Pattanaik et al. 98)

- Problem: “halo” artifacts

Example: multi-scale operator

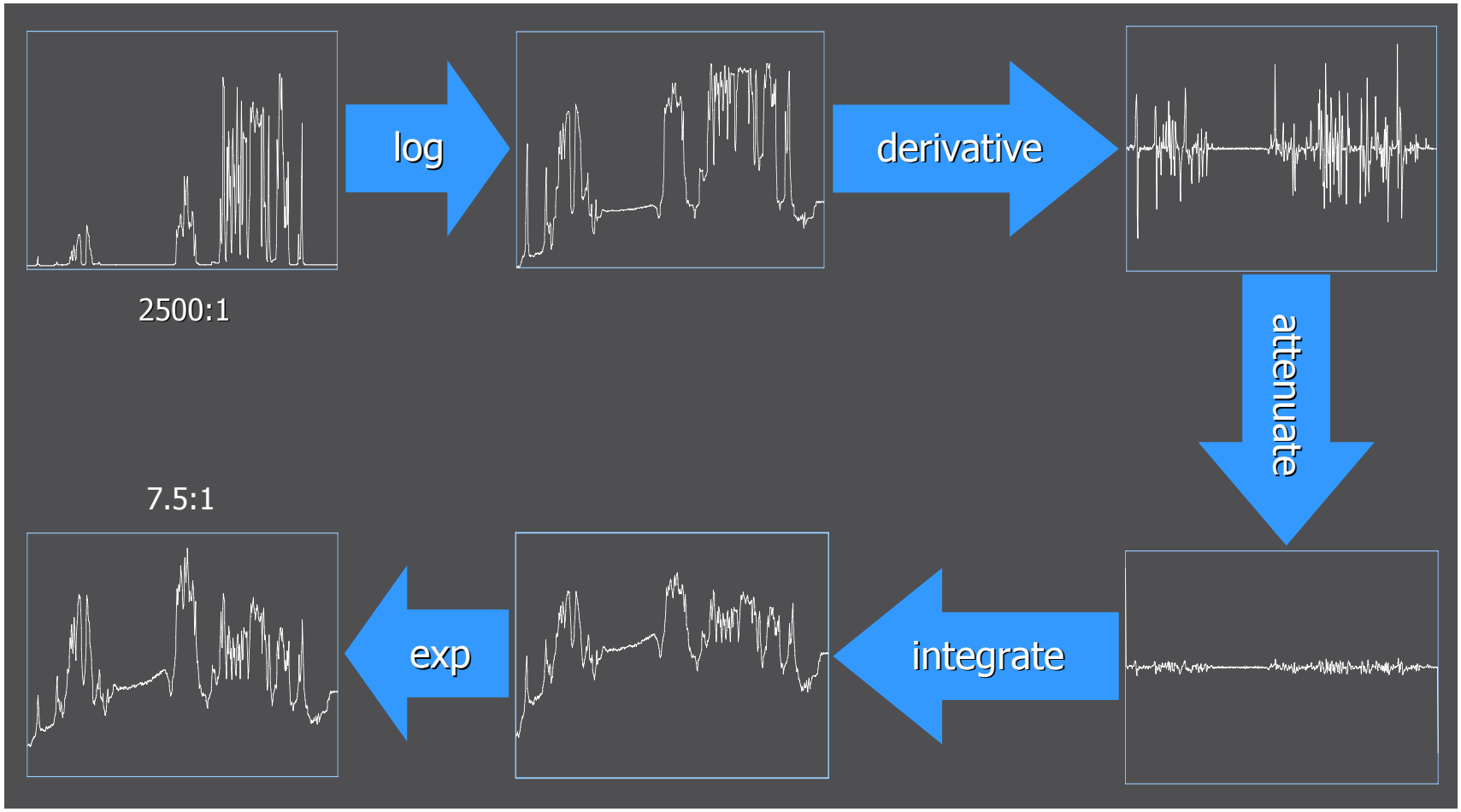
Local Adaptation

Our Approach – Overview

- Observations:
  - High dynamic range results from strong luminance changes
  - Absolute change magnitude is not important

- Method:
  - Examine gradients to identify luminance changes
  - Attenuate high luminance gradients
  - Reconstruct a low-dynamic range image

The Method in 1D



The Method in 2D

- Given: a log-luminance image $H(x,y)$
- Compute an ***attenuation map*** $\Phi(\|\nabla H\|)$
- Compute an attenuated gradient field G:

$$G(x,y) = \nabla H(x,y) \cdot \Phi(\|\nabla H\|)$$

- Problem: G is not integrable!

Aside: Conservative Fields

- In vector calculus an ***irrotational*** or ***conservative*** vector field is a vector field whose curl is zero:

$$\operatorname{curl} \mathbf{v} = \nabla \times \mathbf{v} = 0$$

- Any gradient field is conservative.
- Any conservative field $\mathbf{v}$ may be expressed as a gradient of a scalar potential:

$$\mathbf{v} = \nabla \phi$$

Solution

- Look for image I with gradient closest to G in the least squares sense.
- Two possible, but equivalent, formulations:
  - Continuous formulation via the Euler - Lagrange equation
  - Discrete formulation

Continuous Formulation

- Look for a 2D function I whose gradient is the closest to G in the least squares sense.
- Image I minimizes the integral:

$$\iint F(\nabla I, G)\, dx\, dy$$

- where:

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

Euler - Lagrange Equation

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

- Substitute F:

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

$$\frac{\partial F}{\partial I} = 0$$

$$\frac{\partial F}{\partial I_x} = 2\left(\frac{\partial I}{\partial x} - G_x\right)$$

$$\frac{d}{dx}\frac{\partial F}{\partial I_x} = 2\left(\frac{\partial^2 I}{\partial x^2} - \frac{\partial G_x}{\partial x}\right)$$

Euler - Lagrange Equation

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

$$2\left(\frac{\partial^2 I}{\partial x^2} - \frac{\partial G_x}{\partial x}\right) + 2\left(\frac{\partial^2 I}{\partial y^2} - \frac{\partial G_y}{\partial y}\right) = 0$$

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

The Poisson equation: $\nabla^2 I = \operatorname{div} G$

Discrete Formulation

- Look for an image I^* whose gradient (at each pixel) is the closest to G in the least squares sense:

$$J(I) = \sum_{x,y} \|\nabla I(x,y) - G(x,y)\|^2$$

$$I^* = \arg\min_I J(I)$$

- Use finite differences for approximating the derivatives of I:

$$\nabla I(x,y) = \begin{bmatrix} I(x+1,y) - I(x,y) \\ I(x,y+1) - I(x,y) \end{bmatrix}$$

Discrete Formulation

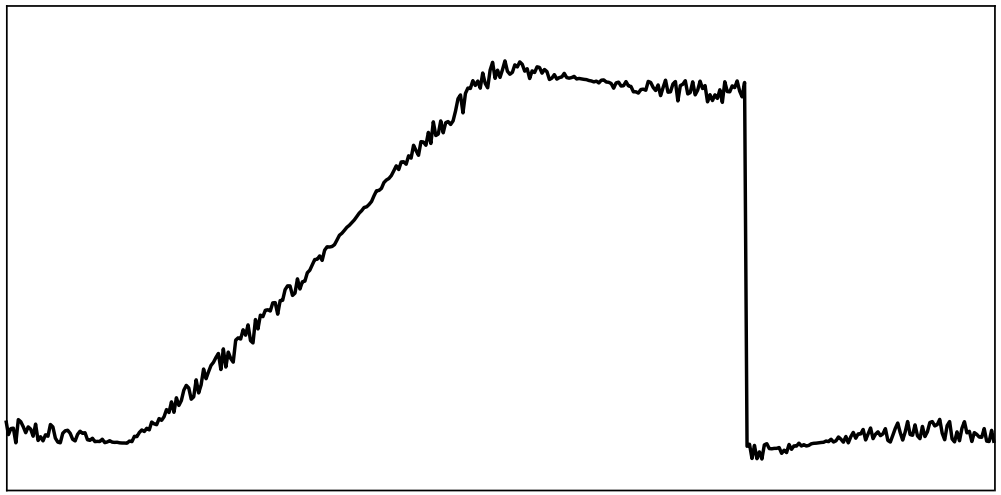
- J is a quadratic functional, with a unique minimum, attained at: $\nabla J = 0$

$$\nabla J = \begin{bmatrix} \vdots \\ \frac{d}{dI(x,y)} \sum_{x,y} (I_x(x,y) - G_x(x,y))^2 + (I_y(x,y) - G_y(x,y))^2 \\ \vdots \end{bmatrix} = 0$$

The Poisson equation: $\nabla^2 I = \operatorname{div} G$

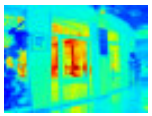
Gradient Attenuation

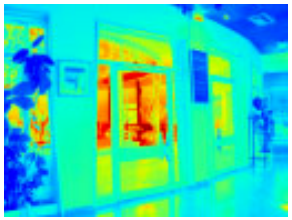
- Strong luminance changes may occur at different rates:

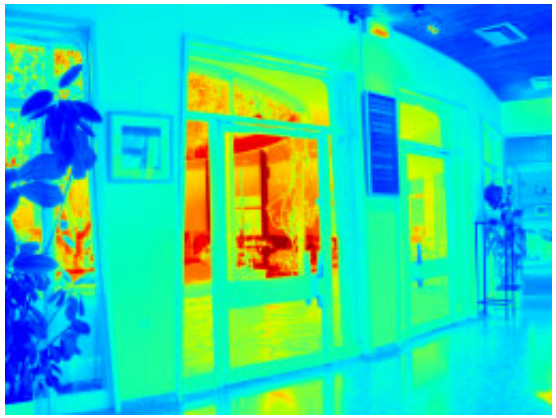


- Must examine gradients at multiple scales!

Multiscale Gradient Attenuation

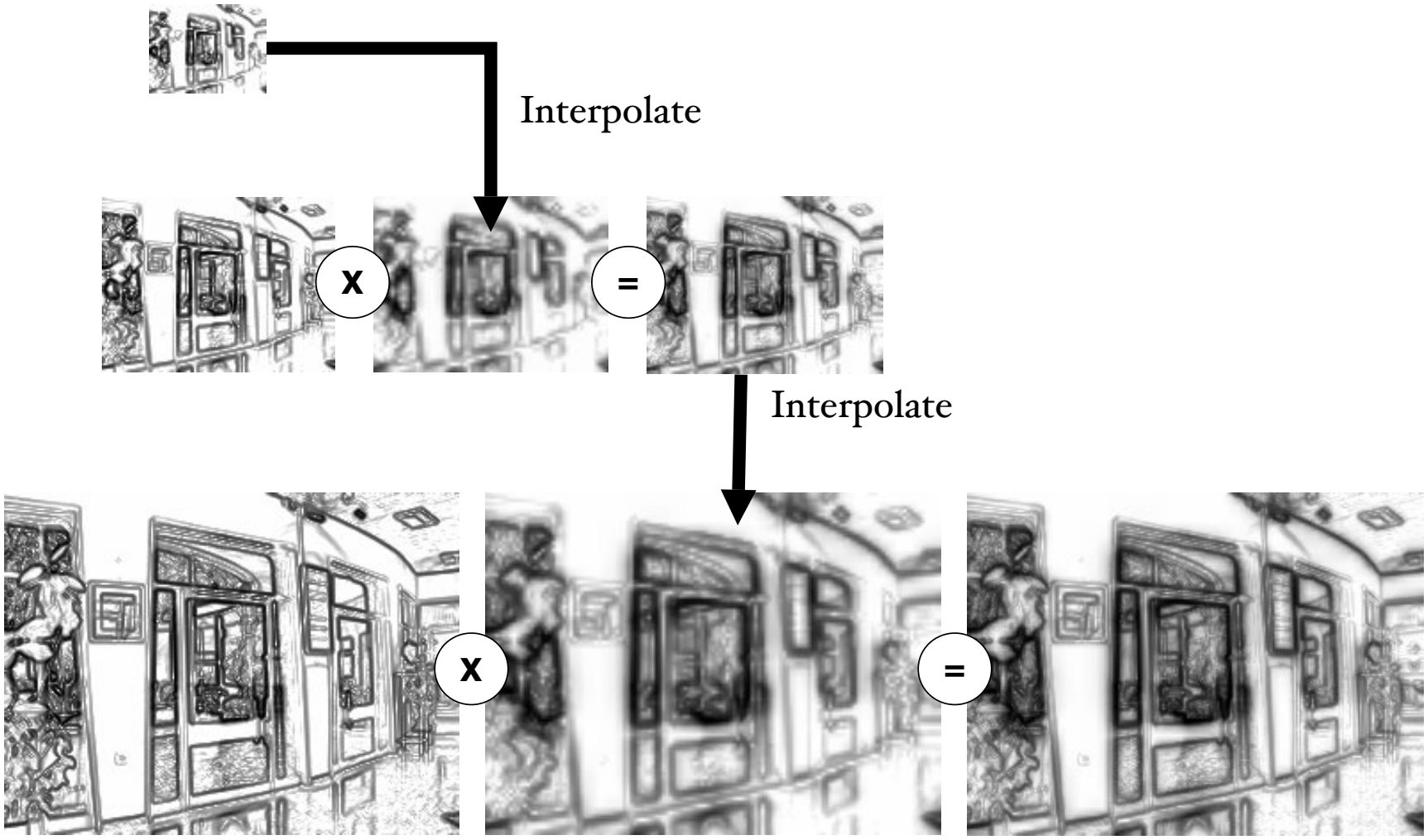




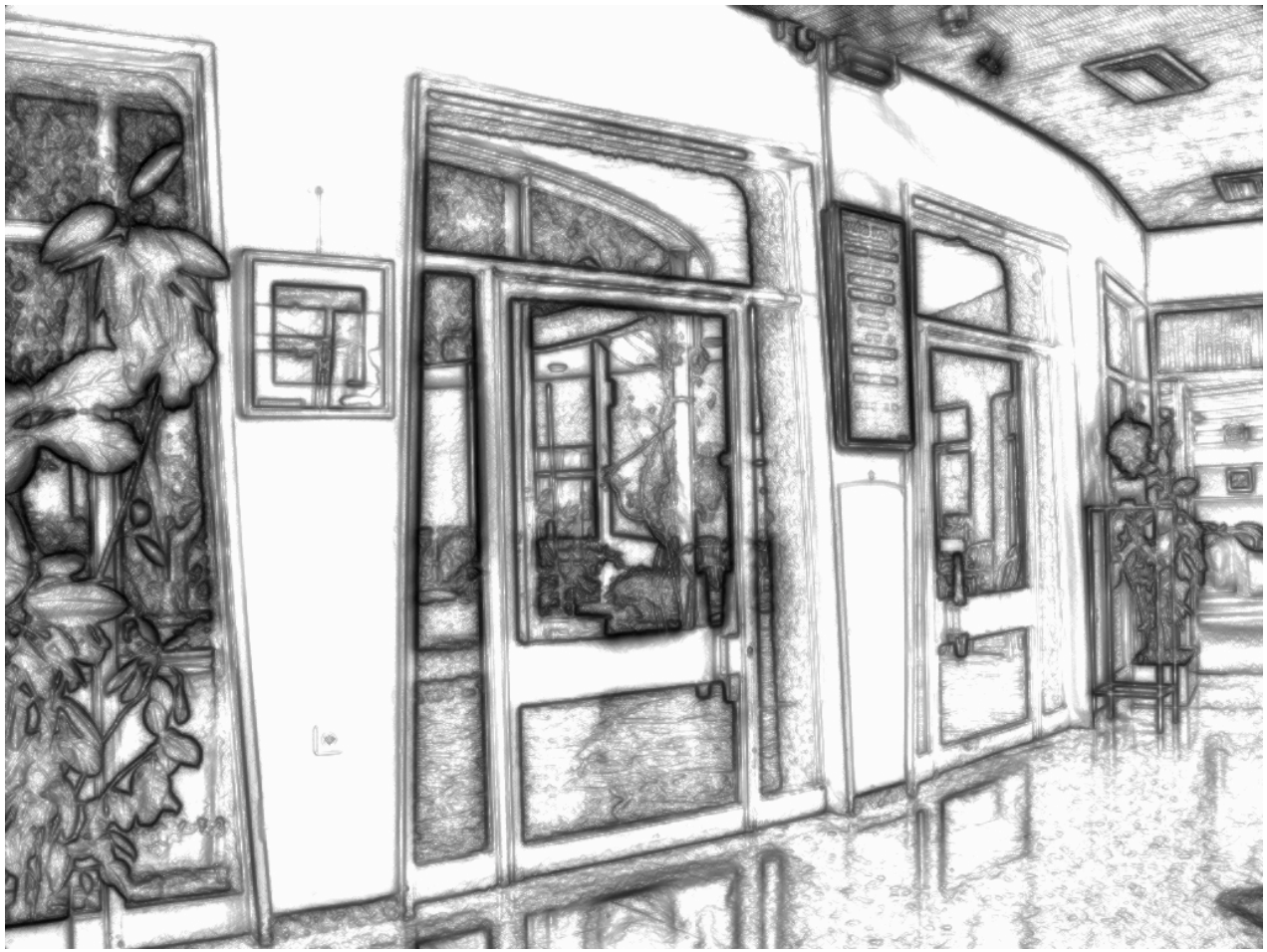


log(Luminance) Gradient magnitude Attenuation map

Multiscale Gradient Attenuation

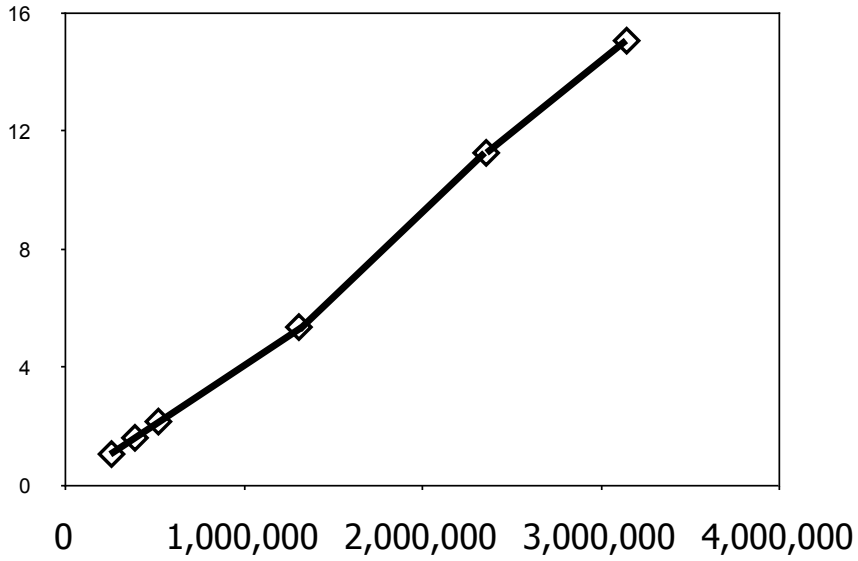


Final Gradient Attenuation Map



Performance

- Measured on 1.8 GHz Pentium 4:
  - 512 x 384: 1.1 sec
  - 1024 x 768: 4.5 sec



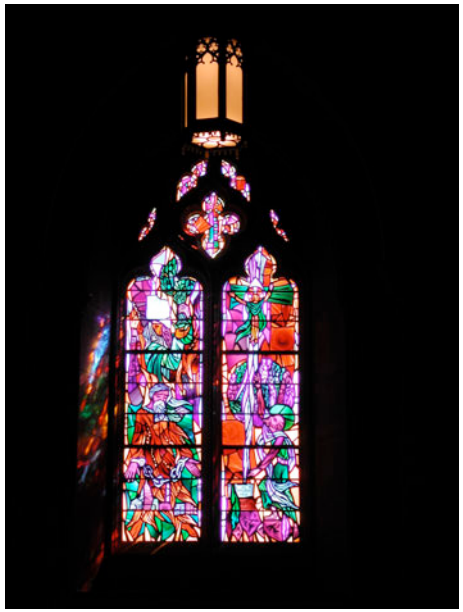
- Can be accelerated using processor-optimized libraries.

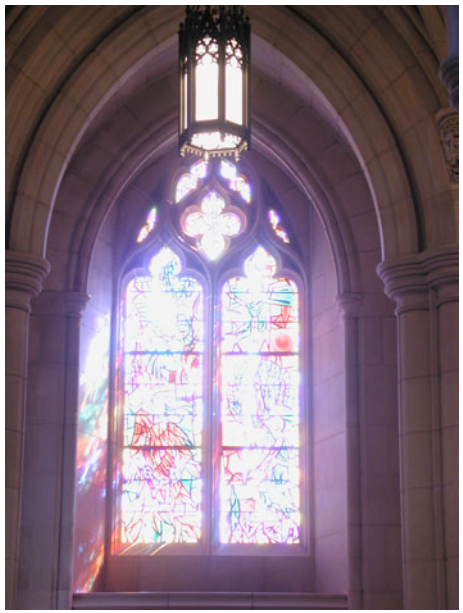
Results (Ward et al. 1997)

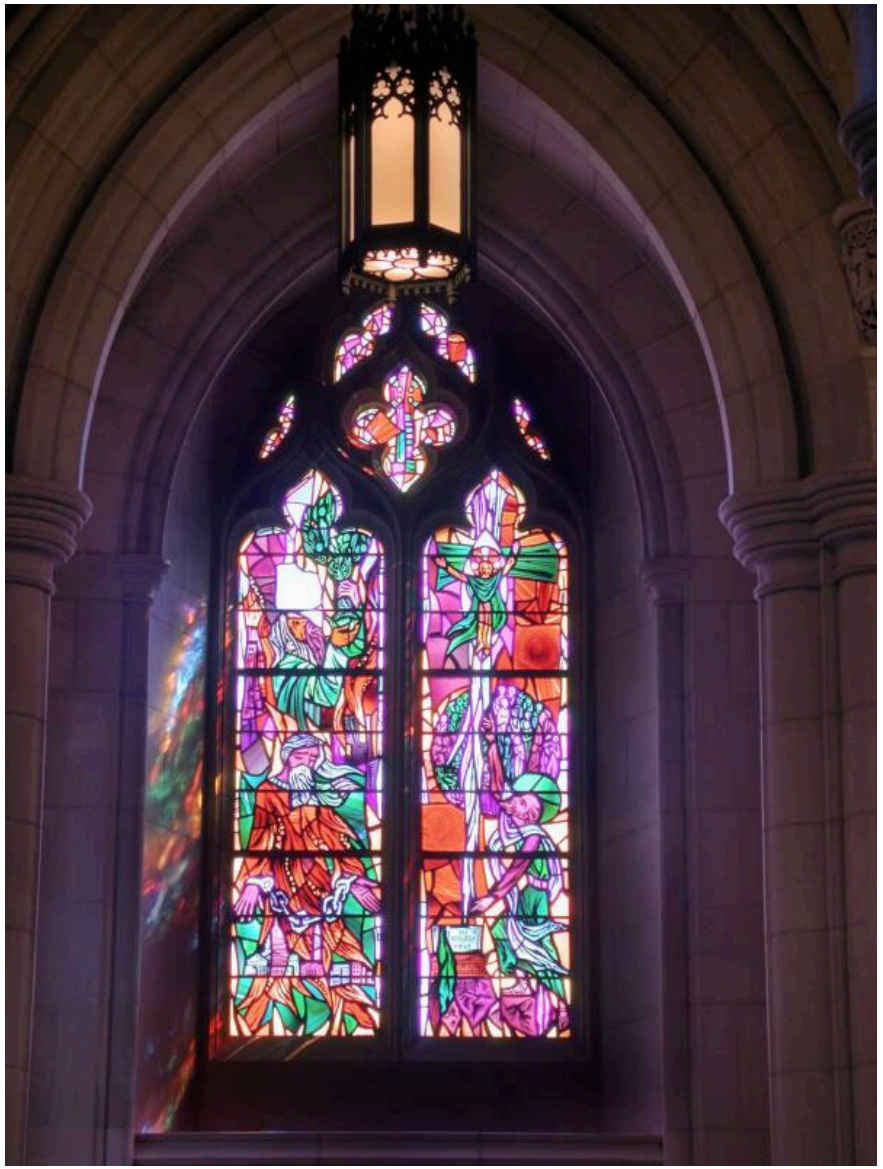
Results (LCIS)

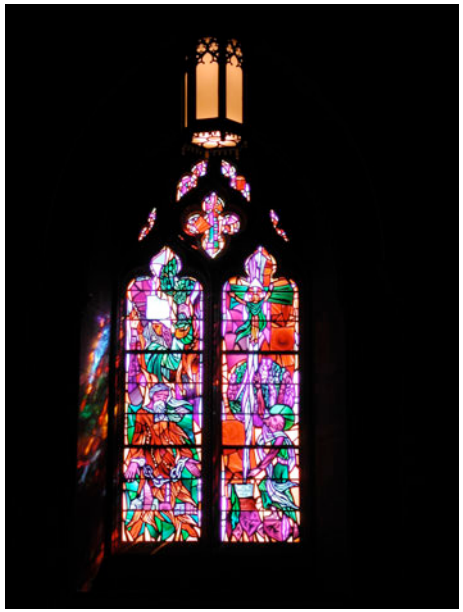
Results (our method)

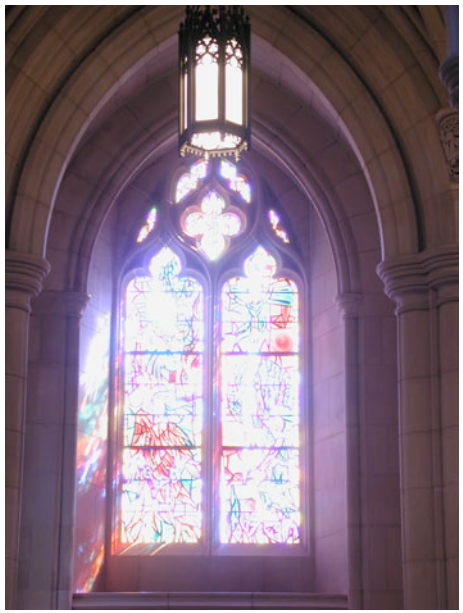
Local Adaptation

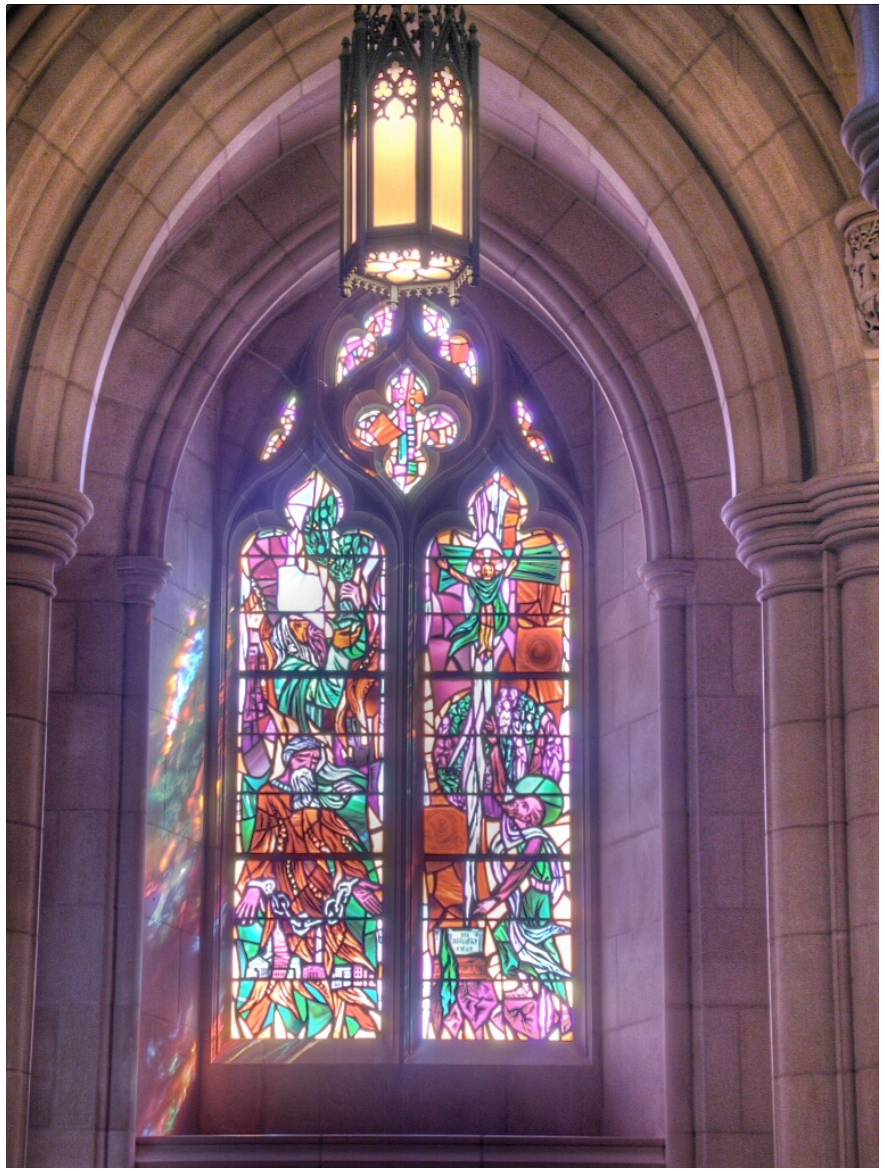












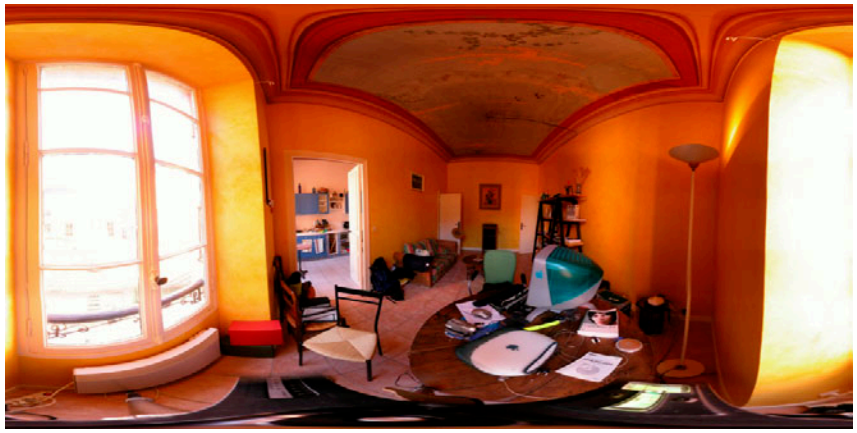


Image Enhancement

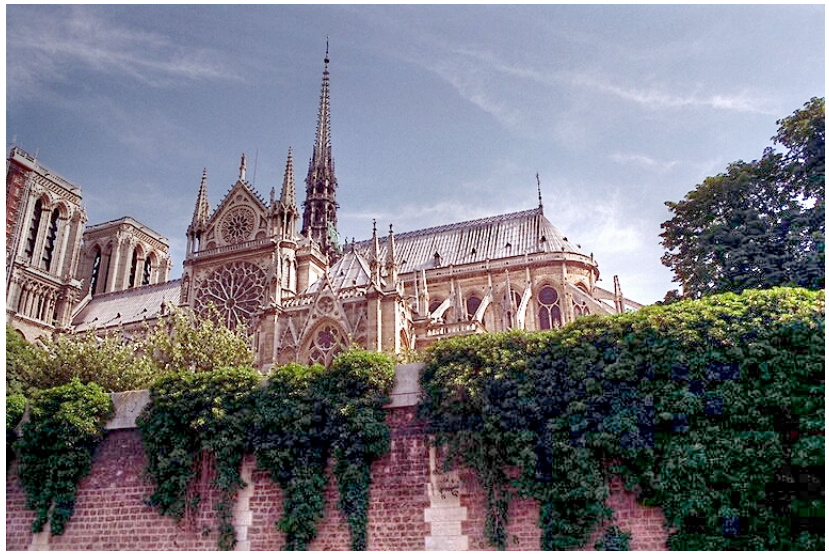


Image Enhancement

Summary

- New method for detail-preserving compression of dynamic range.
- Also useful for enhancing ordinary images.

- Future work:
  - Better handling of color
  - Incorporate psychophysical properties of the HVS
  - Explore other applications of gradient field manipulations.

Acknowledgments

- Thanks to: Paul Debevec, Max Lyons, Shree Nayar, Jack Tumblin, Greg Ward (and many others) for sharing their code and images.

- Work funded by the Israel Science Foundation founded by the Israel Academy of Sciences and Humanities.