Colorization Using Optimization

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Colorization

Colorization: a computer-assisted process of adding color to a monochrome image or movie. (Invented by Wilson Markle, 1970)

Motivation

- Colorizing black and white movies?
- Maybe not...
- But what about black and white TV shows?

Motivation

- Colorizing black and white movies / TV shows
- Recoloring color images for special effects

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Color 101

- Typically represented by points in a three dimensional *color space*:
  - (**R**ed, **G**reen, **B**lue)
  - (**C**yan, **M**agenta, **Y**ellow)

- Some color spaces separate between the grayscale and the chromatic components of a color:

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.14713 & -0.28886 & 0.436 \\ 0.615 & -0.51498 & -0.10001 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Typical Colorization Process

Images from: “Yet Another Colorization Tutorial”

http://www.worth1000.com/tutorial.asp?sid=161018

Typical Colorization Process

- Delineate region boundary

Images from: "Yet Another Colorization Tutorial"

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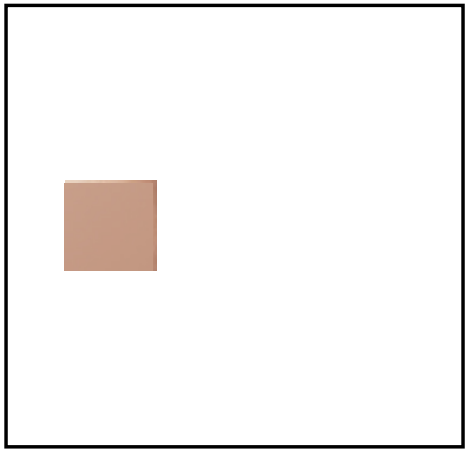
Typical Colorization Process

- Delineate region boundary
- Choose region color from palette



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Typical Colorization Process

- Delineate region boundary
- Choose region color from palette

Images from: "Yet Another Colorization Tutorial"

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Video Colorization Process

- Delineate region boundary
- Choose region color from palette

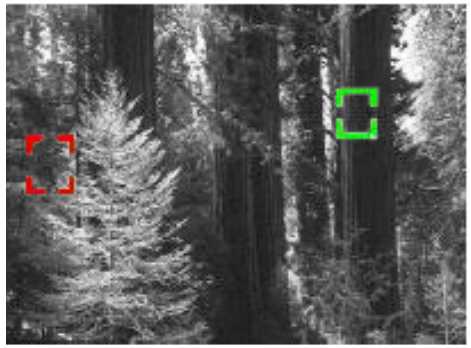
- Track regions across video frames

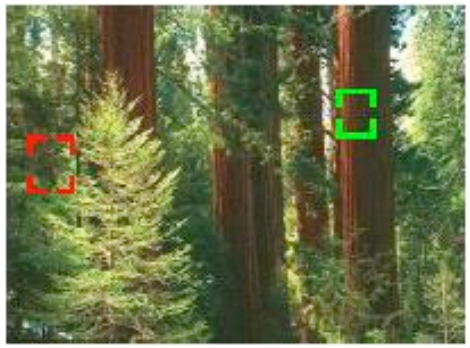
Process Limitations

- Time consuming and labor intensive
- Difficult to delineate detailed or fuzzy boundaries
- Failures in tracking

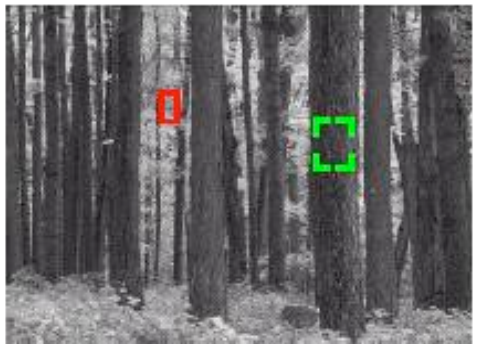
Colorization by Analogy

A : A’





B : B’



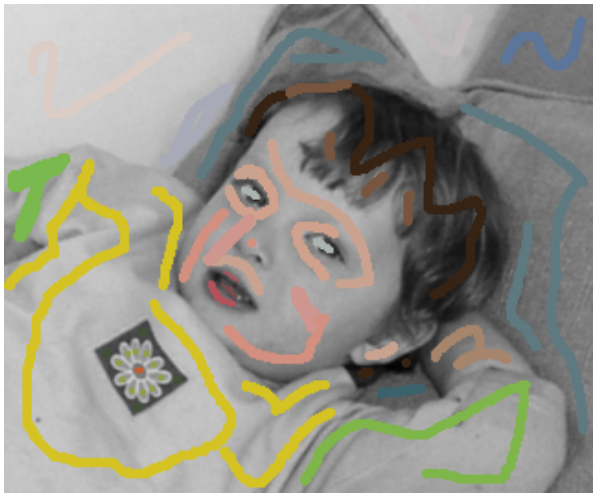
Hertzmann et al. 2001, Welsh et al. 2002

Colorization by Analogy - Discussion

- Indirect artistic control
- No spatial continuity constraint

Our Approach

Our Approach



Artist scribbles desired colors inside regions

Our Approach

Colors are propagated to all pixels

“Nearby pixels with similar intensities should have the same color”

Propagation using Optimization

$$Y \Rightarrow U, V$$

Intensity channel **Color channels**

Assumption: Neighboring pixels with similar intensities should have similar colors

Propagation using Optimization

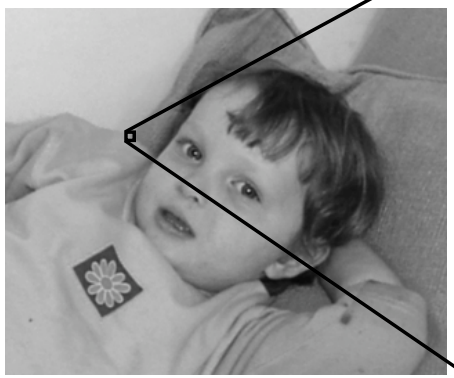
$$Y \Rightarrow U, V$$

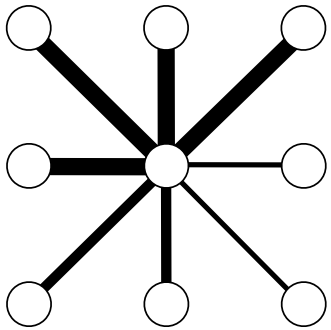
Intensity channel **Color channels**

Minimize the sum of affinity-weighed squared distances between the colors of adjacent pixels:

$$J(U) = \sum_{r,s} w_{rs} \left(U(r) - U(s)\right)^2$$

Affinity Functions



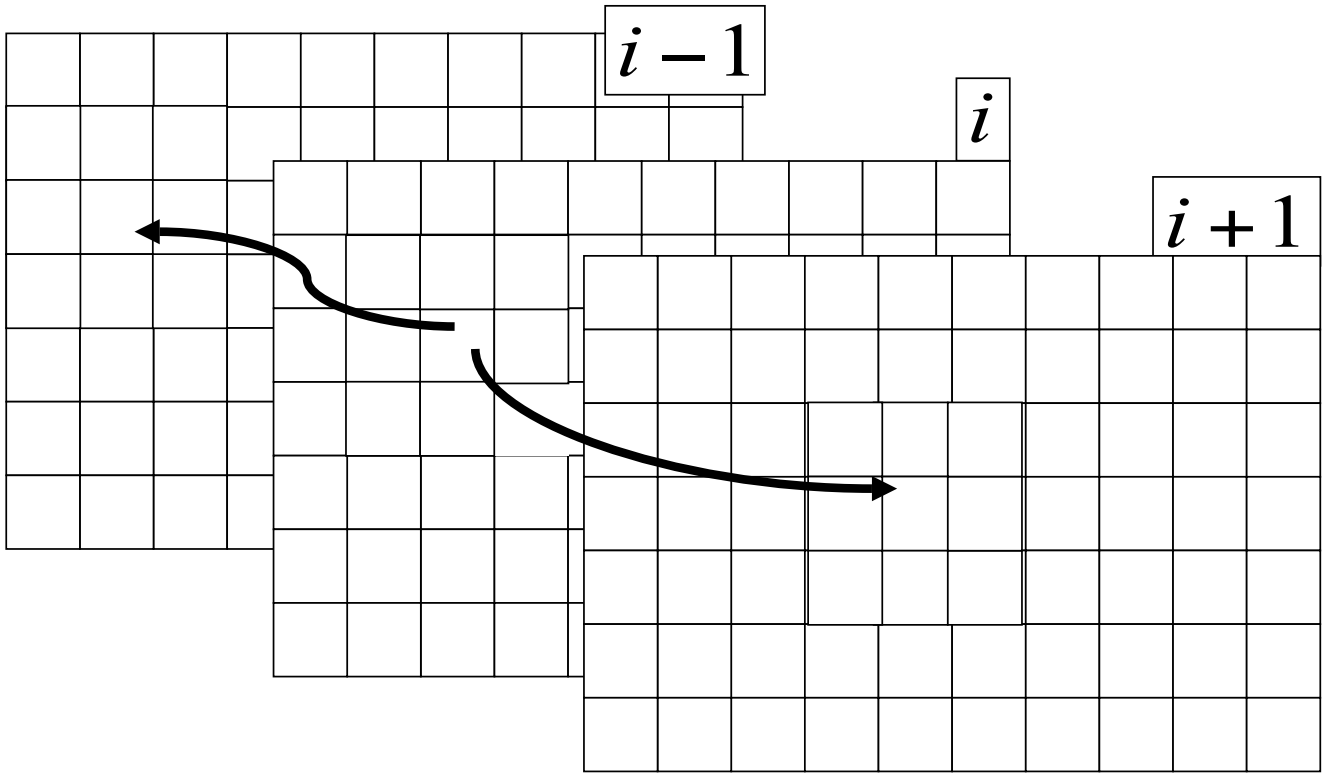


$$w_{rs} \propto e^{-(Y(r)-Y(s))^2/2\sigma_r^2}$$

σ_r proportional to local variance

Space-time Affinity

$$w_{rs} \propto e^{-(Y(r)-Y(s))^2/2\sigma_r^2}$$



Optimization

Minimize the cost function:

$$J(U) = \sum_{r,s} w_{rs} \left(U(r) - U(s)\right)^2$$

Subject to labeling constraints $\left\{U(r_k) = \tilde{U}_k\right\}$

Since the cost function is quadratic, its minimum may be found by solving sparse system of linear equations.

Optimization

$$U^* = \arg\min_U J(U)$$

$$V^* = \arg\min_V J(V)$$

Minimize by solving the equations:

$$\nabla J(U) = \mathbf{0}$$

$$\nabla J(V) = \mathbf{0}$$

Derivation

$$
\begin{aligned}
J(U) &= \sum_{r,s} w_{rs} \left(U_r - U_s\right)^2 \\
&= \sum_{r,s} w_{rs} \left(U_r^2 - 2U_r U_s + U_s^2\right) \\
&= \sum_{r,s} w_{rs} U_r^2 - 2\sum_{r,s} w_{rs} U_r U_s + \sum_{r,s} w_{rs} U_s^2 \\
&= \sum_{r} D_{rr} U_r^2 - 2\sum_{r,s} w_{rs} U_r U_s + \sum_{s} D_{ss} U_s^2 \\
&= 2U^{\mathrm{T}} \left(D - W\right) U
\end{aligned}
$$

Derivation

$$J(U) = 2U^{\mathrm{T}}(D - W)U$$

$$\nabla J(U) = 4(D - W)U = \mathbf{0}$$

Unconstrained system:

$$(D - W)U = \mathbf{0}$$

Note: has a trivial solution (any constant vector U).

Derivation

Add constraints:

$$J(U) = U^{\mathrm{T}}(D - W)U + \lambda \sum_k \left(U_k - \tilde{U}_k\right)^2$$

$$J(U) = U^{\mathrm{T}}(D - W)U + \lambda \left(U - \tilde{U}\right)^{\mathrm{T}} C \left(U - \tilde{U}\right)$$

$$\nabla J(U) = 2(D - W)U + 2\lambda C\left(U - \tilde{U}\right) = \mathbf{0}$$

Constrained system:

$$(D - W + \lambda C)U = \lambda C\tilde{U}$$

Color Interpolation

Colorizing Stills

Colorizing Stills

Original

Colorized

Colorizing Stills

Colorizing Stills

Challenging Case

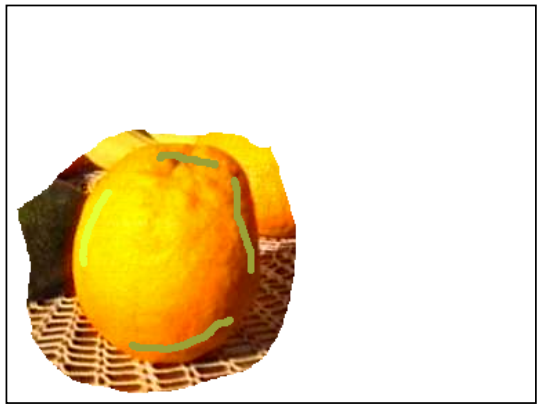
Segmentation?

NCuts Segmentation
(Shi & Malik 97)

Segmentation aided
colorization

Our result

Recoloring



Affinity between pixels – based on intensity AND color similarities.

Recoloring

Recoloring

Colorizing Video

13 out of 92 frames

Colorizing Video

16 out of 101 frames

Matting

Red channel<->matte

Matting

Future Work

- Import image segmentation advantages: affinity functions, optimization techniques.
- Alternative color spaces, propagating hue and saturation differently

Summary

★ **Interface: User scribbles color on a small number of pixels**

★ **Colors propagate in space-time volume respecting intensity boundaries**

★ **Convincing colorization with a small amount of user effort**

Code & examples available:

www.cs.huji.ac.i/~yweiss/Colorization/