Computational Aesthetics in Graphics, Visualization and Imaging (2005)
L. Neumann, M. Sbert, B. Gooch, W. Purgathofer (Editors)

Color Search and Replace

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Abstract

We present an interactive image enhancement technique to adjust the global color composition of an image by finding and replacing color gradients. We show how color gradient transformations can perform the basic operations of color editing. To recolor an image, the user designates a mapping of source color gradients to corresponding target color gradients. Each color gradient can be represented by a spherical parameterization, consisting of its midpoint color, contrast radius, as well as hue and luminance angles, in order to give the user separate and independent control over color shift, contrast adjustment, and color variation. Color gradients provide not only a flexible way of selecting color features but also a powerful way of manipulating image colors, as each mapping between a source and a target color gradient defines an affine color transformation. To determine the region of influence of each color mapping, perceptual similarity between colors is evaluated by applying Shepard's law of generalization to color differences. Through a feature-based warping approach, our color warping algorithm applies a continuous, nonlinear, volumetric deformation to the color space in order to approximate the requested color mappings. By making interactive color correction easier to control, our technique may prove useful in a variety of color image enhancement tasks in digital photography, video processing, and information visualization.

Categories and Subject Descriptors (according to ACM CCS): I.3.6 [Computer Graphics]: Methodology and Techniques — Interaction Techniques; I.4.3 [Image Processing and Computer Vision]: Enhancement

It's not blood, it's red. — *Jean-Luc Godard*

1. Introduction

Search and replace is a fundamental data processing operation. It involves finding the instances of one element and substituting another element in its place. Search and replace is a basic mechanism for propagating change while preserving consistency. The user decides what needs to be changed and what change needs to be made. Automated search and replace can be indispensable to certain interactive editing tasks. It is best known for helping to make a word processor and a database more efficient than a typewriter and a filing cabinet. However, from as far back as Sutherland's 1963 SketchPad [Sut63], drawing systems have enabled the same visual transformation to be applied to all instances of a graphical object. In 1988, Kurlander and Bier [KB88] further developed graphical search and replace for vector graphics into a generic approach for composing and editing illustrations. Image search and replace has only recently begun to be investigated [Gla03]. Exhibiting structure without syntax, images pose a hard problem. Indeed, the design of an intelligent system for image transformation, which would be at least as powerful as regular expressions for text processing, could constitute a grand challenge for the convergence of vision, graphics and interaction. To make progress toward that goal, we investigate color search and replace. We present a simple interactive image enhancement technique (Figure 1) for adjusting the global color balance of an image by finding and replacing color gradients. To guide the algorithm in transforming image colors, the user designates a set of source color gradients to be replaced by a corresponding set of target color gradients. Our color correction technique enables the user to improve the color composition of an image by choosing a harmonious combination of colors and adjusting their contrasts to highlight the key elements of the picture. It can assist in calibrating the effects of scene illumi-

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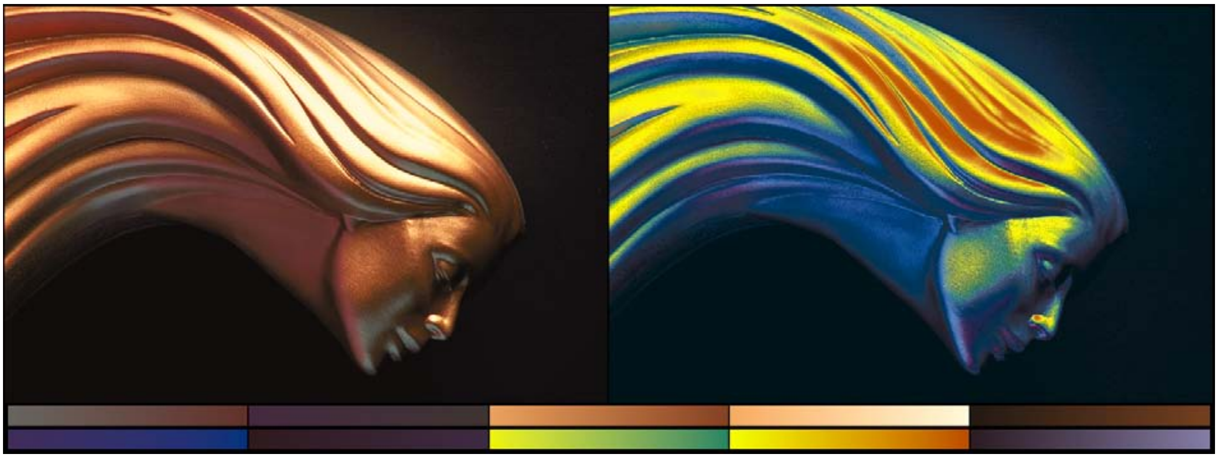

Figure 1: *Image recoloring. The source color gradients (top row) are mapped to the target color gradient (bottom row).*

nation, selectively emphasizing scene details, and applying a color scheme to impart a particular mood or theme.

2. Motivation

Our aim is to make interactive color correction easier for the artist to control. Here, we outline the rationale for our work.

In so far as an image is designed to communicate experience, serving to make the intended impression upon its viewer, one can either attempt to accurately reproduce the actual physical stimulus or to expressively elicit the desired psychological response. In the case of color, exact reproduction is often not possible and the visual artist is charged with finding creative ways to compensate. A picture viewed in isolation can never quite match the way the colors in the scene appear in their natural context. From sunlight and starlight, the real world portrays a dynamic range well beyond the scope of any other representational medium. To capture the splendor of a sunset takes more than a shade of orange. In art, color is seeing and feeling intimately combined. The artist purposefully arranges the simultaneous harmonies and contrasts of a color palette to make the picture come alive for its viewer, evoking not merely a semblance of the scene but also a sensation of being there. Even in skilled hands, the result bears the mark of the tools and materials at hand. While a photograph relies on its subject for its colors, each stroke of color on a canvas is there by an express dispensation from the artist. In the making of a color composition, mixing pigments affords a freedom of expression that recording light does not yield so readily. As colorists, the painter and the animator retain a conspicuous advantage over the photographer and the cinematographer. Many photographers still regard a black and white print to be inherently more evocative than its color counterpart. Others have responded by hand coloring photographs and even entire films in search of their personal vision, projecting their imagination upon the image. These attitudes are a reaction not so much to the physical limitations of the film medium but rather to the technological limitations of the optical instruments used to manipulate it. To orchestrate color composition, photographers and cinematographers still lack adequate means both to ask for what they want and to get what they asked for. Resisting the temptation to take what they are given and declare it to be the manifest truth, they proceed to apply all manner of make-up, lighting, camera angles, lenses, filters and film stocks. Even so, it is hard to get the colors to look just right, especially in cinema where the composition keeps changing twenty-four times a second. Electronic imaging can give to the photographer and the cinematographer the fine control over color composition that the painter and the animator have enjoyed for so long.

Color makes visual communication compelling. Often, where contrast conveys the message, color evokes the emotion. In graphic design [BM91], the principal functions of color are to render information visible, legible, memorable and appealing. Color is used to attract and hold attention, catching the viewer's eye and directing it to where it needs to go. Each color brings across its own palette of associations and memories, likes and dislikes. These nonverbal semantics are what makes color composition so difficult to automate. Furthermore, visual artists often apply color in subtle ways [Wol01] to exploit the subtleties of visual perception. Color mediates important perceptual relations, such as illumination and reflection, opacity and transparency, figure and ground, unity and variety. Adjacent colors can appear to interact through simultaneous contrast, becoming more intense or more subdued, popping out or blending together. Alternating colors can appear to vibrate through regular repetition, shimmering of their accord. As warm and bright colors advance while cool and dull colors recede, they add depth to the picture. As some colors accord while others clash, they impart an ambience to the scene. Artists have developed their own sophisticated vocabulary [Kri92] to describe the various aspects of color in a composition: tone, chroma, hue, contrast, counterpoint, repetition, proportion, scale, balance, tension, rhythm, articulation, temperament, signification and symbolism. Effective color composition [Kri92] demands the exercise of aesthetic judgement, a task more befitting the aptitudes of an artist than a machine. Traditionally, color image processing has been engineered for fidelity rather than expression, concentrating on automation rather than interaction. We undertake a complementary approach to image recoloring by giving the user better control over the process of interactive color correction.

3. Related work

Interactive approaches to global color correction differ in the level of user control that they support. Color transfer [WSM99,RAG*01,MS03,CSN03,GH03,PNS03,GD05] demands the least interaction. To impose a specific color distribution on an image, these techniques extend grayscale histogram specification to color histogram specification. They transform the colors of the source image to resemble a target color scheme, usually exemplified by a reference image which the user supplies. To selectively apply color transformations, the user can always manually select source image regions and designate different target color schemes for them [RAG*01]. Color transfer may be accomplished by either the 3D transformation of color space [PNS03], the 1D transformation of color axes [WSM99, RAG*01, GD05], or the discrete mapping of color palettes [MS03, CSN03, GH03]. In practice, color transfer remains a hit-and-miss operation. The common flaw of all the color transfer methods is that they do not give the user sufficient control to ensure consistently reliable results. Unlike color search and replace, color transfer relies on its algorithm rather than its user to decide which source color should be mapped to which target color. For instance, a user has no direct way to tell a color transfer algorithm to turn a red traffic light green, not without running the risk that the street lights will turn green instead. The algorithm can give no assurance of producing a meaningful color mapping since it lacks understanding of how color lends meaning to an image. With color transfer, it is difficult to exchange colors, to adjust contrast, or to specify a target color scheme without access to a ready made example of it. Color search and replace resolves these issues by placing the user in charge of defining the color mapping.

To replicate the effect of our technique, most other color correction approaches demand more laborious user interaction. Methods exist for color adjustment of designated hue ranges [IT97], color emphasis of designated colors [GD05] as well as volumetric editing of color gamuts visualized in color space [FH02]. Image processing systems, such as Photoshop, offer powerful tools for selecting image regions, including selection by color. They also provide facilities for making color changes, including adjusting the dynamic range for each color channel, drawing color mapping curves for each color channel, performing color shifts along predetermined color axes, and selecting color variations from a gallery of precomputed possibilities. Using these color editing tools, the user can perform color search and replace but usually on only one color at a time. The results may depend on the order in which the color changes are applied. The outcome can become difficult to control, especially when the same color is affected by multiple color transformations. Our color search and replace technique avoids these problems by performing multiple color substitutions simultaneously.

As some texture editing tools [HJO*01, BD02, BCD03] can be used to find and replace textures, they could also be harnessed for color editing tasks, but only where the image exhibits the self-similar characteristics of a texture. They hinder the making of coherent color changes across luminance, color and texture boundaries, which may or may not be desirable depending on what the user is trying to achieve. This dilemma is inherent in interactive image recoloring over an image segmentation [RB02]. It also affects powerful methods that combine region selection and color editing into a single operation [LLW04], where the user paints colors over the image with a few rough brush strokes and the algorithm propagates the indicated color changes with respect to the image boundaries. For instance, to recolor a striped shirt, the user needs to annotate the color change for each stripe separately. Better interactive methods for grouping image regions can make annotating color changes somewhat easier [RB02, BCD03]. We focus on making global color changes easier to control, while leaving image region selection to tools dedicated to the task.

To the best of our knowledge, the closest precedent for our color search and replace technique is the Hardeberg et al. color substitution method [HFK*02]. The authors present their work in the context of color management tools, surveying the color transformations used in color gamut characterization. Their system supports color calibration of digital video through the transfer of color properties from one video source to another. Similar to our technique, it enables the user to simultaneously find and replace multiple image colors, performing the desired color substitutions using volumetric color warping. However, as discussed in the next section, there is a crucial difference that distinguishes our color search and replace technique from their method.

4. Interaction

Compared with previous interactive color correction methods, what renders our color search and replace technique uniquely effective is that it operates on color gradients rather than just individual colors. A linear color gradient is a smoothly varying sequence of colors defined by a line segment in color space. While an individual color can only denote a color position, a color gradient also designates a contrast magnitude and orientation. In the degenerate case, when

Adjustment	Parameter	Transformation
color	(L,a,b)	translation
luminance	L	translation
color contrast	ρ	uniform scaling
luminance contrast	ρ_L	nonuniform scaling
color inversion	$-\rho$	reflection
hue variation	θ	rotation
luminance variation	ϕ	rotation

Table 1: *Summary of color gradient transformations.*

the endpoints of its color span are equal, a color gradient collapses to represent a particular color. In general, a color gradient represents a particular range of colors. It can describe color changes from light to dark, neutral to saturated, cooler to warmer. As color gradients express color differences, they offer a natural basis for color editing. This approach is in keeping with human color vision, which is specifically tuned to perceive color differences.

Color gradients provide a flexible way both to select and to adjust colors. As areas of flat color are largely absent from natural scenes, color gradients prove more convenient for selecting object features, encompassing variations in surface orientation, reflectance and illumination. While mapping one color to another [HFK*02] is limited to producing a color shift by a translation in color space, mapping one color gradient to another can express a more general affine color transformation. A color gradient mapping offers the degrees of freedom (Table 1) required for effective color editing, providing separate and independent control over color shift, contrast adjustment, and color variations.

4.1. Color gradient specification

A color gradient is formed by linear interpolation between a pair of colors. Its appearance is thus dependent on the choice of color space. Color gradients demand that convex linear combinations of color values should produce a proportionally linear perceptual response. Our implementation relies on the *Lab* color space [Kue03]. Unlike the default *RGB* and *CMY* color spaces for displaying and printing images, the *Lab* color space is approximately perceptually uniform. In *Lab*, Euclidean distance between color values approximates the perceptual difference between them, thereby providing a visually plausible color difference metric. This property justifies our use of geometric transformations in color space. As equal increments in color values give rise to perceptually equal color changes, the smoothness of the color gradients is assured, enabling the user to make precise color adjustments. For color specification, the *Lab* color space has the advantage of distinguishing the achromatic luminance L component from the chromatic red-green a and yellow-blue b components. Experiments in color selection [MSK04] report that *Lab* seems preferable to *RGB* for rendering aesthetically pleasing color gradients. For instance, in a *Lab* color gradient between saturated hues, the midpoint color appears more subdued than the endpoint colors, exhibiting their average luminance as well as a lower saturation. However, combing equal measures of complementary hues need not produce a neutral gray in *Lab* since, unlike the additive *RGB* and subtractive *CMY* color spaces, *Lab* color interpolation does not obey Grassman's laws of color mixing. In general, the *Lab* color space appears better at modeling small color differences than large ones. A disadvantage of color interpolation in *Lab* is that typical display and printer color gamuts, including *sRGB*, do not form convex polytopes. It is possible for some intermediate colors of a highly saturated color gradient to be out of gamut when its endpoints remain in gamut. Whenever we encounter out of gamut colors, we simply clip their color values to fit the dynamic range of the *RGB* color cube. As clipping risks detail loss, better gamut mapping for color search and replace is a subject for future research.

A color gradient is a line segment in color space. Normally, it is parameterized by the rectangular color coordinates of its endpoints, (L_1,a_1,b_1) and (L_2,a_2,b_2). In this parameterization, though defining a color gradient is straightforward, adjusting its color properties becomes needlessly difficult. Both endpoints need to be displaced in tandem to perform a contrast preserving color shift or a color preserving contrast adjustment. For directing color changes, a spherical parameterization proves more convenient. We therefore define a color gradient's location $\vec{G}=(L,a,b)$ in color space to be its midpoint color, the average of its endpoint colors:

$$L=\tfrac{1}{2}(L_1+L_2), \quad a=\tfrac{1}{2}(a_1+a_2), \quad b=\tfrac{1}{2}(b_1+b_2).$$

A color gradient's displacement $\Delta\vec{G}=(\Delta L,\Delta a,\Delta b)$ in color space determines its Euclidean color distance $\Delta E=\|\Delta\vec{G}\|$, along with its color difference direction $\Delta\hat{G}=\Delta\vec{G}/\|\Delta\vec{G}\|$:

$$\Delta L=L_1-L_2, \quad \Delta a=a_1-a_2, \quad \Delta b=b_1-b_2,$$
$$\Delta E=\sqrt{\Delta L^2+\Delta a^2+\Delta b^2}.$$

We model a color gradient as the diameter of a color sphere, its color neighborhood in color space. Its color contrast radius ρ is a measure of the color difference, while the luminance contrast ρ_L is a measure of the luminance difference. Centered at the midpoint color, the azimuthal and polar angles of its spherical color coordinates (ρ,θ,ϕ) are the hue angle $-\pi\leq\theta\leq\pi$ and the luminance angle $0\leq\phi\leq\pi$:

$$\rho=\frac{\Delta E}{2}, \quad \rho_L=\frac{\Delta L}{2}, \quad \theta=\arctan\frac{\Delta b}{\Delta a}, \quad \phi=\arccos\frac{\Delta L}{\Delta E}.$$

This transformation can be reversed by observing:

$$\Delta L=2\rho\cos\phi, \quad \Delta a=2\rho\cos\theta\sin\phi, \quad \Delta b=2\rho\sin\theta\sin\phi.$$

These parameters directly relate affine color transformations with the basic color editing operations on a color gradient (Table 1), including color shift, contrast adjustment, and

Figure 2: *User interface for color search and replace.*

color variation. Furthermore, these operations can be constrained to act on just luminance and leave hue unaltered. The user can easily change one color gradient property without affecting another, as each parameter controls a different color editing operation. A color shift need not entail an overall contrast change while a contrast adjustment need not entail an overall color change. Moreover, the hue and luminance variations can produce subtle color effects that cause neither an overall color shift nor an overall contrast change.

4.2. Color editing interface

Our user interface (Figure 2) enables the user to edit the global color composition of an image by performing basic color editing operations (Table 1) on color gradients. For color selection, to change one color for another takes two clicks of the mouse, the first selects the old color and the second chooses the new color. For color correction, to map one color gradient to another takes as little as three clicks of the mouse, the first and the second choose the endpoints of the source color gradient while the third applies a color editing operation to it and thereby specifies the target color gradient. Since direct manipulation relies on continuous feedback, the results are updated as each color change is made. Our user interface displays the original image as well as the resulting image, enabling the user to sample colors from them. For applying a preconceived color scheme, as in color transfer, it could also be helpful to display an additional reference image. To assist in color selection, our implementation uses a standard color spectrum as a reference. Below the images, the color gradient mappings are shown ("Edit Gradients"). The top row lists the source color gradients while the bottom row lists the target color gradients. Each column corresponds to a color gradient mapping. The user can add, delete, and select the color gradient mappings. For the selected color gradient mapping, its source and target color gradients are displayed ("Find Gradient" and "Replace Gradient").

The user can edit a color gradient through either its rectangular parameterization by selecting one of its endpoint colors or its spherical parameterization by selecting the color gradient swatch displayed between them. The contrast properties of the currently selected color gradient can be adjusted using the contrast pickers ("Adjust Contrast"). From top to bottom, they control color contrast, luminance contrast, luminance angle and hue angle. Along with an indicator of the current parameter setting, each contrast picker previews how changing the parameter affects the endpoint colors of the selected color gradient. Where a parameter change would send one of the endpoint colors out of gamut, the contrast picker displays a dotted boundary to warn the user, since a contrast adjustment that causes the color gradient to be clipped may also cause a color shift by displacing its midpoint color. The color properties of the currently selected color gradient can be adjusted using the color pickers ("Adjust Color"). From top to bottom, their color bars display the range of available colors along the currently selected color gradient followed by the luminance, saturation, hue, red-cyan, green-magenta, and blue-yellow color axes. To aid in color space navigation, each color bar is centered on the currently chosen color. The color pickers can be applied to the midpoint color or to the endpoint colors. While the rest of the interface relies on *Lab* color interpolation, our color pickers use *HSV, RGB,* and *CMY* color axes because they are likely to be more familiar to our users. However, according to user studies [DK99], visual feedback has much greater impact on accuracy of color selection than the choice of color space. More advanced color pickers [MSK04] can incorporate color relationships, groupings, contexts, and juxtapositions. Alternatively, synchronized views of orthogonal color planes can allow the user to draw a color gradient in color space [RHO97].

The user can fine tune the results in several ways. Globally, the user can balance the preservation λ of the original image colors with the influence ω that all the color gradient mappings exert over their surrounding colors (by default $\lambda = \frac{1}{5}$ and $\omega = 5$). For each color gradient mapping, the user can adjust the additional scope σ_i of its influence over its surrounding colors as well as the additional contrast emphasis τ_i of its surrounding colors (by default $\sigma_i = 1$ and $\tau_i = 1$). Our interface lets the user adjust these values, λ ("Preservation"), ω ("Influence"), σ_i ("Scope"), and τ_i ("Emphasis").

5. Algorithm

We calculate a continuous, nonlinear, volumetric warping of color space, which is guided by the mapping of source color gradients $\vec{G}_i$ to target color gradients $\vec{G}'_i$. We approximate rather than interpolate the user's wishes to avoid color discontinuities in cases where one color gradient mapping contradicts another. First, the search step uses perceptual color similarity to ascertain each source color gradient's region of influence S_i. Second, the replace step derives the linear transformation T_i that maps each source color gradient to its target color gradient. Finally, the combine step generates the resulting image $\vec{P}'$ from a composite of the original image $\vec{P}_0$ and its color gradient transformations $\vec{P}_i$, where the effect of each transformation is masked by its region of influence.

5.1. Search step: Color similarity evaluation

To close the gap between color perception and colorimetric measurement, many color difference formulas have been proposed [Kue03]. A standard measure of color difference between a pair of colors is their Euclidean distance ΔE in the *Lab* color space. For some applications, it could be worthwhile to more carefully consider how chroma $\bar{C}$ affects the perception of color differences. Such an approach could better account for the relative importance of luminance ΔL, chroma ΔC, and hue ΔH differences:

$$C_1 = \sqrt{a_1^2 + b_1^2}, \quad C_2 = \sqrt{a_2^2 + b_2^2}, \quad \bar{C} = \sqrt{C_1 C_2},$$
$$\Delta C = C_1 - C_2, \quad \Delta H = \sqrt{\Delta E^2 - \Delta L^2 - \Delta C^2}.$$

A weighted color difference formula D can accommodate different luminance κ_L, chroma κ_C, and hue κ_H weights:

$$D = \sqrt{\left(\frac{\Delta L}{\kappa_L}\right)^2 + \left(\frac{\Delta C}{\kappa_C}\right)^2 + \left(\frac{\Delta H}{\kappa_H}\right)^2}.$$

For the examples shown in this paper, we only required the default setting $\kappa_L = \kappa_C = \kappa_H = 1$ so that $D = \Delta E$. However, for improved perceptual fidelity, the weights could be chosen $\kappa_L \le \kappa_H \le \kappa_C$ to reflect psychophysical evidence that, in general, luminance exerts greater effect than hue which in turn exerts greater effect than chroma. To accurately model small color differences, the *CIE94* formula [Kue03] uses $\kappa_L = 1$, $\kappa_C = 1 + 0.045\bar{C}$, and $\kappa_H = 1 + 0.015\bar{C}$. To accurately model larger color differences, the *GLAB* formula [GL99] uses $\kappa_L = 0.76$, $\kappa_C = 1 + 0.016\bar{C}$, and $\kappa_H = 1$. Color gamut mapping experiments [KIO99] suggest that $\kappa_L = 1$, $\kappa_C = 2$, and $\kappa_H = \sqrt{2}$ yields results that are better than ΔE and about on par with *CIE94*. Weighted color differences can also serve to make color selection more flexible. The weights could be set to reflect the user's priorities in searching for colors. For instance, by setting $\kappa_L = \infty$, the user could select a range of hues irrespective of their luminance, a useful strategy for dealing with a color cast. Moreover, different weights could be used for different color gradient mappings.

In general, color difference formulas are most effective at measuring the perceptual similarity between closely related colors. Unrelated colors are perceived to be categorically dissimilar. For example, a yellow can be judged more or less similar to an orange but it no more resembles a red than a purple. Hence, perceptual similarity should vary linearly with small color differences, while vanishing entirely as color differences become excessive. This observation is expressed by Shepard's law of generalization [She87], which is based on evidence in many perceptual domains that the likelihood of confusing one stimulus with another decreases exponentially as the perceptual distance between them increases. Previously, this approach has been used to improve feature detection in color image analysis [RT01]. Using scaling factor δ, we evaluate perceptual similarity $0 \le S \le 1$:

$$S = \exp\left(\frac{-D}{\delta}\right).$$

Without reference to Shepard's law, Hardeberg et al. [HFK*02] used a more abrupt scaling of color differences, by setting $D = \Delta E^2 + \ln \Delta E$ in the above equation, to determine the influence of a color change on surrounding colors.

In color search, perceptual similarity facilitates the selection of image regions by color. To determine the region of

Figure 3: *Contrast enhancement. The source color gradients (top row) are mapped to the target color gradient (bottom row).*

influence of each color gradient mapping, we use its perceptual similarity map S_i. Its extent can be adjusted by the user through the combined scaling factor $\delta_i = \omega\sigma_i$. At each pixel, we evaluate the similarity S_i between the pixel color $\vec{P}_0$ and the closest color $\vec{Q}_i$ present in the source color gradient $\vec{G}_i$:

$$\vec{Q}_i = \vec{G}_i + r_i \Delta\hat{G}_i \text{ for } r_i = \text{median}\{-\rho_i, (\vec{P}_0 - \vec{G}_i)\cdot\Delta\hat{G}_i, \rho_i\}.$$

5.2. Replace step: Color gradient mapping

A color gradient mapping can be interpreted geometrically in color space as an affine transformation [Gol03] that maps one line segment to another. Affine color transformations have been previously used in automatic color cast removal [KKK*01]. For each color gradient mapping, a translation maps the source midpoint color $\vec{G}_i$ to the target midpoint color $\vec{G}'_i$ while a linear transformation $T_i = \Phi_i\Psi_i$ combines the scaling Ψ_i and the rotation Φ_i required to align the source color gradient with the target color gradient. At each pixel $\vec{P}_0$, we calculate the effect $\vec{P}_i$ of the color gradient mapping:

$$\vec{P}_i = T_i(\vec{P}_0 - \vec{G}_i) + \vec{G}'_i.$$

To adjust contrast, a general scaling [Gol03] transformation Ψ_i applies a parallel scaling factor ν_i along a designated direction $(\Psi_i^L, \Psi_i^a, \Psi_i^b)$ as well as a perpendicular scaling factor τ_i in the perpendicular plane. The color gradient contrast ratio $\nu_i = \rho'_i/\rho_i$ specifies the contrast adjustment of the source color gradient $(\Psi_i^L, \Psi_i^a, \Psi_i^b) = \Delta\hat{G}_i$, while the user parameter τ_i controls contrast in the perpendicular color plane:

$$\Psi_i = \begin{pmatrix} \tau_i + (\nu_i - \tau_i)\Psi_i^L\Psi_i^L & (\nu_i - \tau_i)\Psi_i^L\Psi_i^a & (\nu_i - \tau_i)\Psi_i^L\Psi_i^b \\ (\nu_i - \tau_i)\Psi_i^a\Psi_i^L & \tau_i + (\nu_i - \tau_i)\Psi_i^a\Psi_i^a & (\nu_i - \tau_i)\Psi_i^a\Psi_i^b \\ (\nu_i - \tau_i)\Psi_i^b\Psi_i^L & (\nu_i - \tau_i)\Psi_i^b\Psi_i^a & \tau_i + (\nu_i - \tau_i)\Psi_i^b\Psi_i^b \end{pmatrix}.$$

To adjust color, using Rodrigues formula, a general rotation [Gol03] transformation Φ_i directs a rotation around a designated unit axis $(\Phi_i^L, \Phi_i^a, \Phi_i^b)$ through a counterclockwise angle φ_i. To align the directions of the source and target color gradients, their normal direction is selected as the axis of rotation $(\Phi_i^L, \Phi_i^a, \Phi_i^b) = (\Delta\hat{G}_i \times \Delta\hat{G}'_i)/\|\Delta\hat{G}_i \times \Delta\hat{G}'_i\|$, so that $\alpha_i = \cos\varphi_i = (\Delta\hat{G}_i \cdot \Delta\hat{G}'_i)$ and $\beta_i = \sin\varphi_i = \|\Delta\hat{G}_i \times \Delta\hat{G}'_i\|$:

$$\Phi_i = \begin{pmatrix} (1-\alpha_i)\Phi_i^L\Phi_i^L + \alpha_i & (1-\alpha_i)\Phi_i^L\Phi_i^a - \beta_i\Phi_i^b & (1-\alpha_i)\Phi_i^L\Phi_i^b + \beta_i\Phi_i^a \\ (1-\alpha_i)\Phi_i^L\Phi_i^a + \beta_i\Phi_i^b & (1-\alpha_i)\Phi_i^a\Phi_i^a + \alpha_i & (1-\alpha_i)\Phi_i^a\Phi_i^b - \beta_i\Phi_i^L \\ (1-\alpha_i)\Phi_i^L\Phi_i^b - \beta_i\Phi_i^a & (1-\alpha_i)\Phi_i^a\Phi_i^b + \beta_i\Phi_i^L & (1-\alpha_i)\Phi_i^b\Phi_i^b + \alpha_i \end{pmatrix}.$$

In the degenerate case, either the source, the target, or both color gradients specify a single color rather than a range of colors, exhibiting a color difference that is too small to be noticeable (we set the perceptual threshold to $\varepsilon = 1.5$ *Lab* units). This situation may arise when the user wishes to edit uniformly colored image regions. Such a color mapping designates a color shift, performed by a translation, as well as a contrast adjustment, performed by a uniform scaling:

$$T_i = \tau_i \frac{\max\{\rho'_i, \varepsilon\}}{\max\{\rho_i, \varepsilon\}} \text{ when } \min\{\rho'_i, \rho_i\} \leq \varepsilon.$$

5.3. Combine step: Color gamut warping

As each color gradient mapping affects a different color space region, we apply interpolation to smoothly combine these transformations to produce a volumetric warping of the entire color space. We adapt a feature-based warping approach [BN92] originally developed for image morphing. In color gamut mapping [SES95], color warping has been previously applied to ensure a smooth transition between gamut mapping strategies for different subsets of the color space. In another application, the perceptual uniformity of a color space was improved by a free-form deformation [TR98], which was optimized to make distances between designated color samples match their psychophysically estimated color differences. In our color warping approach, we map each pixel color $\vec{P}_0$ to a new color $\vec{P}'$ by compositing the colors $\vec{P}_i$ produced by the color gradient transformations:

$$\vec{P}' = w_0\vec{P}_0 + \sum w_i\vec{P}_i.$$

Figure 4: *Color transfer. The color scheme of the reference image (bottom left) is applied to the input image (left) to produce the output image (right). The reference and input images were taken from different camera angles at different times of day.*

In determining the new color of a pixel, the influence of a color gradient mapping should be proportional to the similarity of its source color gradient to the original image color. Hence, for each color gradient mapping, its perceptual similarity map S_i governs its relative contribution w_i to the outcome of the color warping. However, to the degree w_0 that the original image color differs from all of the source color gradients, it should remain unaffected by any of the color gradient mappings. Our method enables the user to control the tradeoff λ between color change and color preservation:

$$\text{if } \lambda \geq \sum S_i \quad \text{then} \quad w_i = \frac{S_i}{\lambda} \text{ and } w_0 = 1 - \sum w_i,$$
$$\text{if } \lambda \leq \sum S_i \quad \text{then} \quad w_i = \frac{S_i}{\sum S_i} \text{ and } w_0 = 0.$$

6. Results and Applications

We demonstrate our technique on several examples. In Figure 1, we amplify subtle variations of shading to dramatically recolor an image. Figure 2 shows how we can edit the color composition of an image, painting the background blue and the parrot red. Notice the isolated blue patches among the parrot's feathers. Our global color editing technique can not distinguish foreground from background when they share the same color. Of course, within an image processing environment, the user could select the image region that should receive the color changes. In Figure 3, interactive contrast enhancement is performed by raising the luminance contrast of the chosen color gradients while leaving their hues unaffected. Figure 4 shows interactive color transfer, where the source colors are selected from the input image and the matching target colors are chosen from a reference image. This operation could be useful in harmonizing the colors of film footage taken under different lighting conditions. There are other possible applications of our technique. In information visualization, color adjustment is often used in post-processing to draw color distinctions that direct the viewer's attention to the relevant structure of the data. Also, our technique could assist in the mapping between the disparate color gamuts of different capture and display devices.

7. Conclusion and Future Work

Visual search and replace is an emerging approach to image editing. We have presented a novel color search and replace technique designed to make interactive color correction easier to control. The central contribution of our work is to establish color gradient transformation as a primitive operation for image recoloring in interactive image enhancement. Through a spherical parameterization, a color gradient transformation has the flexibility to perform all the basic tasks of color correction, including color shift, contrast adjustment, and color variation. For color editing, our user interface offers separate control over color and contrast changes. To perform multiple color gradient mappings simultaneously, our color warping algorithm relies on a perceptual measure of color similarity to determine which colors should be affected by which color gradient mappings. In future work, we look forward to addressing how our technique may be integrated with other interactive methods for image selection [RB02,LLW04] and texturing [HJO*01,BD02,BCD03].

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