Palette-based Photo Recoloring

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Figure 1: *Palette-based photo recoloring. From left: original (computed palette below); user changes green palette entry to red (underlined), and the system recolors photo to match; user changes multiple colors to make two other styles.* Photo courtesy of the MIT-Adobe FiveK Dataset [2011].

Abstract

Image editing applications offer a wide array of tools for color manipulation. Some of these tools are easy to understand but offer a limited range of expressiveness. Other more powerful tools are time consuming for experts and inscrutable to novices. Researchers have described a variety of more sophisticated methods but these are typically not interactive, which is crucial for creative exploration. This paper introduces a simple, intuitive and interactive tool that allows non-experts to recolor an image by editing a color palette. This system is comprised of several components: a GUI that is easy to learn and understand, an efficient algorithm for creating a color palette from an image, and a novel color transfer algorithm that recolors the image based on a user-modified palette. We evaluate our approach via a user study, showing that it is faster and easier to use than two alternatives, and allows untrained users to achieve results comparable to those of experts using professional software.

CR Categories: I.3.4 [Computer Graphics]: Graphics Utilities

Keywords: photo recoloring, color transformation, palette

1 Introduction

Research and commercial software offer a myriad of tools for manipulating the colors in photographs. Unfortunately these tools remain largely inscrutable to non-experts. Many features like the "levels tool" in software like Photoshop and iPhoto require the user to interpret histograms and to have a good mental model of how color spaces like RGB work, so non-experts have weak intuition about their behavior. There is a natural tradeoff between ease of use and range of expressiveness, so for example a simple hue slider, while easier to understand and manipulate than the levels tool, offers substantially less control over the resulting image. This paper introduces a tool that is easy for novices to learn while offering a broad expressive range.

Methods like that of Reinhard et al. [2001] and Yoo et al. [2013] allow a user to specify complex image modifications by simply providing an example; however an example of the kind of change the user would like to make is often unavailable. The method of Liu et al. [2014] allows users to modify the global statistics of an image by simply typing a text query like "vintage" or "new york." However, for many desired color modifications it is hard to predict what text query would yield the desired effect. Another challenge in color manipulation is to selectively apply modifications – either locally within the image (e.g., this hat) or locally in color space (e.g., this range of blue colors) instead of globally. Selection is particularly challenging for non-experts, and a binary selection mask often leads to visual artifacts at the selection boundaries.

Our approach specifies both the colors to be manipulated and the modifications to these colors via a *color palette* – a small set of colors that digest the full range of colors in the image. Given an image, we generate a suitable palette. The user can then modify the image by modifying the colors in the palette (Figure 1). The image is changed globally such that the chosen colors are interpolated exactly with a smooth falloff in color space expressed through radial basis functions. These operations are performed in LAB color space to provide perceptual uniformity in the falloff. The naive application of this paradigm would in general lead to several kinds of artifacts. First, some pixels could go out of gamut. Simply clamping to the gamut can cause a color gradient to be lost. Therefore we formulate the radial falloff in color space so as to squeeze colors towards the gamut boundary. Second, many natural palette modifications would give rise to unpleasant visual artifacts wherein the relative brightness of different pixels is inverted. Thus, our color transfer function is tightly coupled with a subtle GUI affordance that together ensure monotonicity in the resulting changes in luminance.

This kind of color editing interface offers the best creative freedom when the user has interactive feedback while they explore various options. Therefore we show that our algorithm can easily be accelerated by a table-based approach that allows it to run at interactive frame rates, even when implemented in javascript running in a web browser. It is even fast enough to recolor video in the browser as it is being streamed over the network.

We perform a study showing that with our tool untrained users can produce similar results to those of expert Photoshop users. Finally, we show that our palette-based color transfer framework also supports other interfaces including a stroke-based interface, localized editing via a selection mask, fully-automatic palette improvement, and editing a collection of images simultaneously.

2 Related work

Color Transfer (Example based Recoloring) Researchers have proposed many recoloring methods requiring an example image as input Reinhard et al. [2001] exploit the Lab color space and apply a statistical transformation to map colors from another image. When the reference is dissimilar, users need to manually point out the region correspondence by swatches. Tai et al. [2005] modify a Gaussian mixture model by adding spatial smoothness and do parametric matching between source and reference images. Chang et al. [2005] classify pixels into basic color categories (experimentally derived), then match input pixels to reference pixels within the same category. HaCohen et al. [2011] utilize dense correspondences between images to enhance a collection. Their results are compelling but the dependence on compatibility between images is high. Yoo et al. [2013] find local region correspondences between two images by exploiting their dominant colors in order to apply a statistical transfer. It is important to note that all these methods require a reference image as input, which needs to be provided by the user or produced by another algorithm.

Automatic Color Enhancement Bychkovsky et al. [2011] build a large retouching dataset collected from professional photographers to learn an automatic model for tone adjustment in the luminance channel. Cohen-Or et al. [2006] propose to automatically enhance image colors according to harmonization rules. However, the user can only control the hue template type and rotation, which is not flexible enough for our needs. Hou and Zhang [2007] provide several concepts for users to change the mood of an image. The concepts are extracted by clustering hue histograms for different topics. They only provide 8 concepts, which limits their transformation and editing styles. More flexibly, Wang et al. [2013] and Csurka et al. [2010] use a semantic word to describe a desired editing style or emotions. The semantic word is automatically quantified by a color palette, however, people cannot set the target palette directly. Shapira et al. [2009] enable users to explore editing alternatives interactively using a Gaussian mixture models (GMM). In Section 4 we compare against a GMM based algorithm.

Edit Propagation (Stroke Based Recoloring) Stroke-based methods [Levin et al. 2004; Qu et al. 2006; An and Pellacini 2008; Li et al. 2008; Li and Chen 2009; Li et al. 2010] propose to recolor images by drawing scribbles in a desired color on different regions, automatically propagating these edits to similar pixels. Levin et al. [2004] allow UV changes (in YUV). Qu et al. [2006] are specific for manga recoloring. An and Pellacini [2008] propose to approximate the all-pairs affinity matrix for propagation, and Xu et al. [2009] further accelerate it by using adaptive clustering based on k-d trees. Chen et al. [2014] propose sparsity-based edit propagation by computing only on a set of sparse, representative samples instead of the whole image or video. This accelerates and saves memory, especially for high-resolution inputs; we compare against this approach in Section 4. Section 5.5 describes our unified framework that uses both stroke-based and palette-based interactions.

Palette based Recoloring A recent work [Lin et al. 2013] proposes a method for coloring vector art by palettes based on a probabilistic model. They learn and predict the distribution of properties such as saturation, lightness and contrast for individual regions and adjacent regions, and use the predicted distributions and color compatibility model by [O'Donovan et al. 2011] to score pattern colorings. Wang et al. [2010] adapt the edit propagation method in An and Pellacini [2008] to obtain a soft image segmentation and recolor an image. While our method works for a pair of initial and final values for each palette entry, they only have the final palette colors. Thus the bulk of their method addresses how to associate pixels in the image with the final palette colors (which can be ill-posed, and also leads to a complex and slow method).

Figure 2: *Our GUI shows a representative color palette. The user adjusts a selected palette color via an HSL controller, and the image updates interactively.* Photo courtesy of the MIT-Adobe FiveK Dataset [2011].

3 Approach

This section introduces a new, simple approach for palette-based photo recoloring. Section 3.1 describes our user interface, as motivated by a set of explicit goals that support non-expert as well as expert users. Second, Section 3.2 introduces a clustering approach based on k-means suitable for creating an initial palette from a photo. Section 3.3 describes the goals that motivate our color transfer algorithm, which is introduced in the subsequent two sections. Section 3.4 describes our approach for preserving monotonicity in luminance, while Section 3.5 introduces our color transfer algorithm. Finally, Section 3.6 shows a table-based acceleration that allows the algorithm to run at interactive rates.

3.1 User interface

These criteria are important for a color manipulation user interface:

Simple. The GUI should be simple enough to learn and use, even for non-expert users. For example it should not require a deep understanding of color theory or various color spaces.

Expressive. The GUI should offer sufficient degrees of freedom that it is possible to achieve what the user wants.

Intuitive. Assuming there exist *some* settings that achieve what the user wants (previous goal), the user should be able to find them quickly and easily.

Responsive. The GUI should produce results at interactive frame rates so as to facilitate creative freedom in exploration and experimentation.

While there are many existing tools that allow users to recolor images, to our knowledge none of them simultaneously achieve these goals (especially when coupled with the algorithmic goals described in Section 3.3). Sliders like those in Photoshop that adjust *hue, saturation,* and *lightness* (or similarly in iPhoto *exposure, contrast, saturation, temperature* and *tint*) while they are simple, responsive, and (to a lesser extent) intuitive, they are not sufficiently expressive to achieve many of the effects shown in this paper. On the other hand, histogram adjustment methods like the *levels tool* in Photoshop provide huge expressive range at responsive rates, but are neither simple nor intuitive. Methods that match the statistics of a reference image (e.g. [Yoo et al. 2013; Liu et al. 2014]) address all four goals above, but succeeds for expressiveness only when the user already has an example of what they want.

We describe a palette-based GUI, shown in Figure 2. When a photo is loaded into the application, a palette is automatically generated (Section 3.2). The user needs only to click on a palette color (C)

and change it (to C') via a HSL color picker. As the user interactively adjusts C' in the color picker, the overall color statistics of the photo are smoothly adjusted such that pixels colored C in the original photo become C'. Our interface meets all four criteria above. Section 4 shows that novice users are able to learn the interface in a few minutes and then quickly produce edited images that are qualitatively (and numerically) similar to those produced by experts in Photoshop. This paper is not the first to describe this kind of palette-based recoloring. However, some existing palette based approaches are not sufficiently responsive while others are less expressive than ours, as discussed in Section 4.1.

3.2 Automatic Palette Selection

This section describes our automatic approach for creating a palette based on an image, using a variant of the k-means algorithm. Our goal is to select a set of k colors $\{C_i\}$ that distill the main color groups in the image, to be used as "controls" during editing. The choice of k matters, and often depends on the image as well as the user's desired modifications. If k is too small, then some colors to be changed might not be well-represented among $\{C_i\}$. On the other hand if k is too large, the user may have to change a large subset of $\{C_i\}$ to get a desired change. There are automatic methods for choosing k (e.g., [Pelleg and Moore 2000]), but in our application this choice depends heavily on the user's intentions. Thus we leave the choice of k up to the user. We find that $k \in [3, 7]$ works well for typical operations, and use $k = 5$ by default.

The literature describes a number of methods for creating a palette from an image. Based on a large dataset of user-rated "color themes," O'Donovan et al. [2011] build a measure of the compatibility of a set of colors as well as a method for extracting a theme from an image. Because the dataset they use is targeted at graphic design applications, we find the method tends not to produce high-quality palettes for natural photographs. Lin et al. [2013] describe a method for creating color themes that works well for natural photos, built on a study of how people do so. The study assumes a palette of exactly five colors and thus their model intrinsically uses $k = 5$, as does that of O'Donovan et al. [2011]. However, as discussed above, we find that for many editing goals a different k works better. While the $k = 5$ assumption is not a fundamental limitation of these previous approaches, they rely on large datasets that do assume $k = 5$ so to change k would require new datasets. Moreover, their methods are slow to compute the palette. Therefore we propose a simpler approach that produces comparably good palettes (at least for our application), but works for any choice of k. Shapira et al. [2009] describe a method for clustering image pixels based on a Gaussian mixture model (GMM). The straightforward application of GMM is too slow for interactive use with moderately large images. While acceleration options are available for GMM, we describe a variant of k-means that is already faster than GMM (by a factor of about three for megapixel images, but still too slow in typical cases) and then further improve its performance. In Section 4 we compare our method to the GMM-based approach.

In a naive application of k-means to the colors in an image, each iteration of the algorithm touches each pixel in the image, which is costly for large images. Researchers have identified various opportunities to accelerate k-means, for example by organizing the data in K-D trees [Kanungo et al. 2002]. Exploiting the property that our data are colors restricted to $R, G, B \in [0, 1]$, we assign them to bins in a $b \times b \times b$ histogram (we use $b = 16$ in RGB). For each bin we compute the mean color in Lab space, and these b^3 colors c_i (or less because some bins may be empty) are the data we use for k-means – typically at least a couple orders of magnitude smaller than the number of pixels in the image, and now independent of image size. Because each data point c_i now


Figure 3: *Automatic palette methods: (D) O'Donovan et al. [2011] build on a color theme dataset targeted at graphic design, which is not ideal for natural photos. (L) Lin et al. [2013] acquire and build on a dataset for natural imagery. Both of these methods take more than one minute, and also assume a palette of size $k = 5$ (so are omitted from the third column). (G) Gaussian mixture models (GMMs) used by Shapira et al. [2009] are also slow to compute (10 sec). (K) K-means is faster (2 sec) but is non-deterministic and often yields too many dark colors. (O) Our method takes 60ms.* Photos courtesy of the MIT-Adobe FiveK Dataset [2011].

represents the n_i pixels associated with that bin, we use a *weighted* mean (weighted by n_i) when finding each of the k means in each iteration. The weighted k-means approach has been used in other applications, for example the automatic stippling method of Secord [2002].

For generating color palettes for our GUI, k-means suffers from two related problems: the basic formulation uses randomly selected data points to initialize the means, and the convergence of the algorithm can be sensitive to this initialization (as discussed by Pelleg and Moore [2000]). To present the most helpful GUI to the user, we prefer that the algorithm be deterministic, and that palette colors be far from one another. Thus, instead of randomizing, we initialize the means as follows. We initialize the first "mean" as the color c_i representing the bin with the largest weight n_i. Next we attenuate all other weights n_j by a factor $(1 - \exp(-d_{ij}^2/\sigma_a^2))$ where d_{ij} is the distance in Lab space from c_i to c_j and σ_a expresses a falloff (we use $\sigma_a = 80$ which is 80% of the distance from black to white, and have found the algorithm to be relatively insensitive to this parameter). Next we choose bin with the highest remaining weight n_i, repeating until k initial "means" have been chosen. This approach is deterministic and initializes the k-means with large clusters that are far from each other.

Finally, we have observed that choosing a palette based on pixel color clustering often leads to a very dark (near black) palette entry, because typically a significant number of image pixels are dark. However, editing the dark palette entry is rarely fruitful for the user, because dark colors are hard to distinguish (regardless of hue and saturation). Essentially it offers the user a set of controls with little or no effect. Therefore we discourage very dark palette entries as follows. Rather than computing k-means, we actually compute $(k + 1)$-means, where one of them is initialized and perpetually locked to black. The darkest colors in the image will be assigned to this mean, and will therefore not pull the other nearby means towards black. After computing the $(k + 1)$-means, we discard the black entry to leave k remaining palette colors. For a comparison of our approach with the previously described methods, see Figure 3.

Original	Result 1	Result 2	Result 3
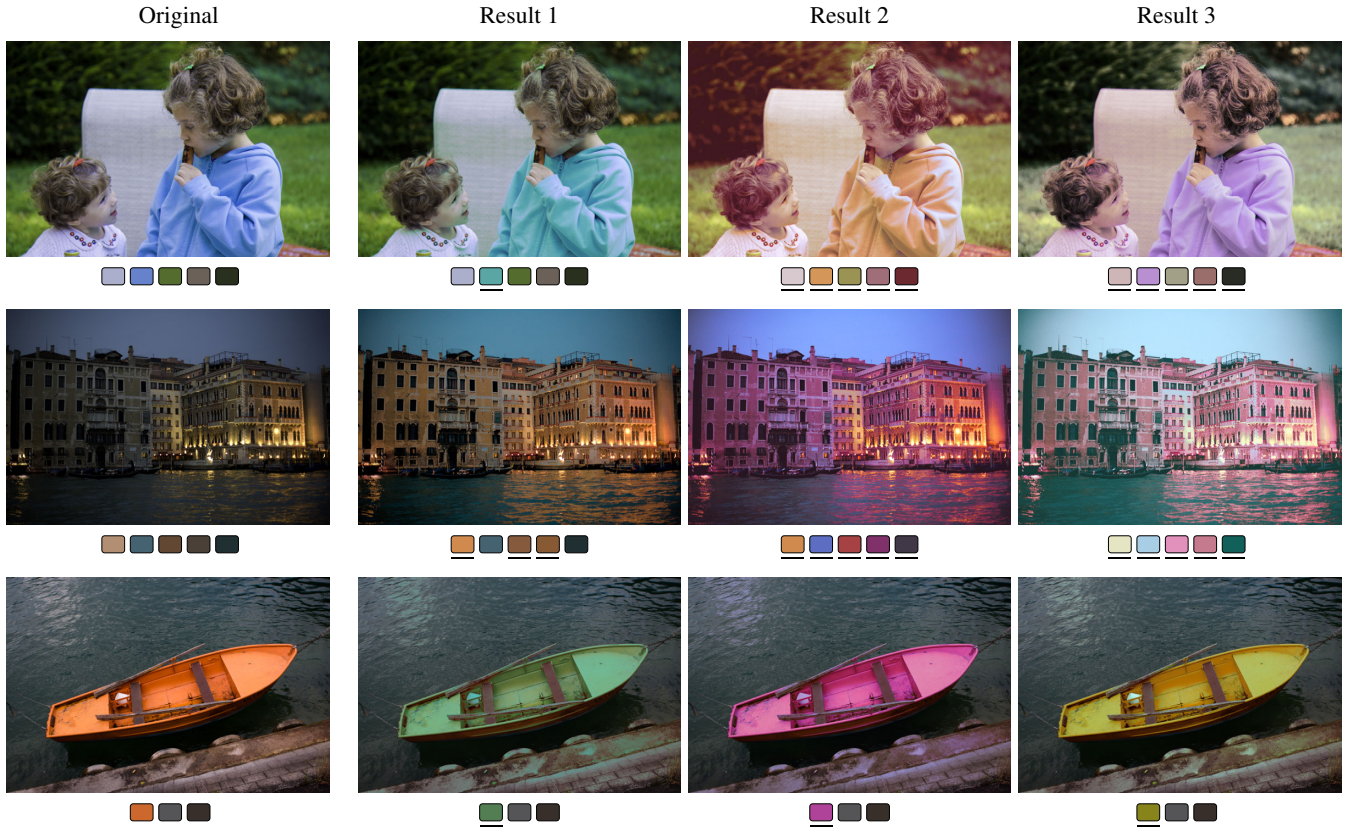
Figure 4: *More recoloring examples. Originals on left, followed by various edits with our system including both local changes (e.g. make the girl's shirt turquoise) and global changes (e.g. change the image tone to orange).* Photos courtesy of the MIT-Adobe FiveK Dataset [2011].

We find that this algorithm produces useful palettes, and all of the results shown in this paper and accompanying materials (including the study described in Section 4) use this approach, except for Figures 8 and 12 which require other methods. However, our GUI also allows the user to select some or all of the palette entries explicitly by a color picker or by clicking on the image. Any remaining unspecified palette entries are then automatically chosen via the algorithm described above.

3.3 Color Transfer Goals

Now we have a set of palette colors $\{C_i\}$, and our GUI allows the user to modify the palette colors to $\{C_i'\}$ as a way of adjusting the colors in the image. That is, the association $(\{C_i\}, \{C_i'\})$ defines a transfer function f that maps colors in the original image to colors in the edited image. We assume that f acts on colors independently of pixel location or context in the image. Some color mapping approaches relax this assumption, for example the high-quality high dynamic range compression approach of Fattal et al. [2002] which operates in the gradient domain. Nevertheless, for our application the assumption is reasonable and permits the acceleration method described in Section 3.6.

Here we identify some key properties we would like in f that address the GUI criteria described at the beginning of Section 3.1, particularly the "expressive" and "intuitive" qualities:

Interpolation. Any pixel in the original image with the same color as one of the original palette colors C_i should be transformed exactly as the user changed the palette color: $f(C_i) = C_i'$.

In Gamut. The output should remain in gamut $\mathcal{G} : f(p \in \mathcal{G}) \in \mathcal{G}$.

Pixel Continuity. The transfer function should be continuous with respect to pixel color p: $\lim_{q \to p} f(q) = f(p)$.

Palette Continuity. The function should be continuous with respect to changes in the palette: $\lim_{\bar{C} \to C'} f_{\bar{C}}(p) = f_{C'}(p)$.

One-to-One. The function should be one-to-one. Together with the continuity requirement this prevents the function from folding over itself, which could lead to counter-intuitive behaviors. Formally: $f(p) = f(q) \implies p = q$.

Monotonicity in L. The transformation in the luminance L should be monotonic. In our early prototype applications we found that transformation functions that allowed relative brightness of different pixels to flip often led to undesirable imagery. Thus we require: $L(p) < L(q) \implies L(f(p)) <= L(f(q))$.

Dynamic Range A gradient in the input maps to a gradient in the output (not a single value). For example an algorithm that shifts all colors in some direction uniformly and then clamps to the gamut is bad by this criterion.

The literature describes a variety of transformation models that might be used for this application, for example Gaussian mixture models (GMM) [McLachlan and Peel 2004], histogram methods [Liu et al. 2014], or non-parametric approaches [HaCohen et al. 2013]. However, to our knowledge no existing approaches can be easily adapted to meet the requirements listed above. For example, GMM-based editing can easily send colors out of gamut. Of course it is easy to clamp to the gamut boundary but this would violate the one-to-one and dynamic range qualities.

(a) Lab slices   (b) edit one color   (c) RBF blending
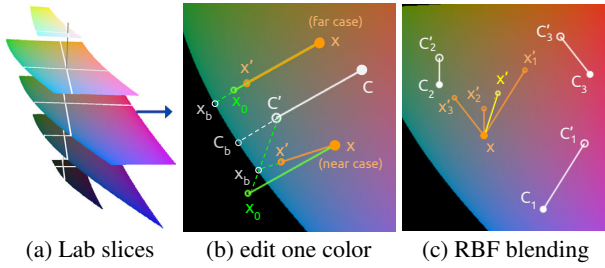
Figure 5: *Transfer in AB space: (a) constant-L slices of Lab space; (b) when a single palette color C is changed to C' the resulting editing effect at different locations x; (c) how the effects of changing multiple palette colors C_i are blended at location x using RBFs.*

input   naive transfer   our transfer

Figure 6: *A naive transfer function that copies the color offset from the palette to every color in the image, even if clamped to remain in gamut, reduces dynamic range in the image (middle). Our transfer function (right) is able to make better use of the dynamic range. Photo courtesy of the MIT-Adobe FiveK Dataset [2011].*

To make matters worse, the requirements themselves are inconsistent. For example, it is not possible to simultaneously satisfy the interpolation and monotonicity requirements. If the user changes the relative brightness of two palette colors, interpolating those colors in the resulting image would violate the monotonicity requirement. However, we would like to satisfy these requirements insofar as is possible, and the following section directly addresses the monotonicity concern.

3.4 Monotonic Luminance Transfer

Our application preserves monotonicity in luminance via two mechanisms, one in the GUI and one in the transfer function.

First, the GUI constrains the relative *ordering* of luminance L'_i of the edited palette colors C'_i. That is, suppose that $L_{i<j} < L_j$ in the input palette. Then the GUI constrains $L'_{i<j} < L'_j$ in the edited palette, as follows. Whenever the user modifies C'_i, the GUI also sets $L'_{j>i} = \max(\bar{L}'_j, L'_{j-1})$, where $\bar{L}'_j$ is the most recently user-edited value for palette entry j (or the initial value, if never edited). To change the luminance of a palette entry we simply modify the L channel in Lab space. This operation is evaluated in increasing order for all palette entries $j > i$; and the symmetric operation (involving $\min$ and L'_{j+1}) is applied in decreasing order for entries where $j < i$. This policy has the nice property that if the user brightens L'_i in such a way that $L'_{j>i}$ is also brightened, but then the user reverts L'_i back to the original value, then L'_j also reverts (avoiding hysteresis).

The second aspect of our treatment of luminance is that we design a transfer function that has two orthogonal components – f_L (which modifies pixel luminance based on the palette luminance) and f_{ab} (which modifies the corresponding ab values, and is discussed in the next section). The luminance transfer function simply takes a weighted combination of the two nearest palette entries (or one nearest entry and either black or white if the pixel is darker or brighter than all the palette entries).

With regard to luminance, these two strategies together ensure that both the interpolation and monotonicity requirements are satisfied as well as some others – in-gamut and the two continuity requirements. However, this approach can violate the one-to-one and dynamic range requirements, because a range of shades of gray can be collapsed into a single luminance value when one or more palette colors are pushed to the same luminance. However, we have found through experimentation that these concerns are less critical than interpolation and monotonicity. While it might be possible to satisfy all four requirements by disallowing changes in luminance in the GUI, we find this is an important feature for expressive control.

3.5 Color Transfer (ab)

In the last section we devised a simple luminance transfer function f_L that adjusts the luminances of pixels based on those of the palette. In this section we introduce a more complex transfer function f_{ab} that plays an analogous role in the ab channels. The design of this function is not guided by the monotonicity concern, but it does target the other requirements.

First we devise the function f_1 for the simple case where the original palette contains a single color C, and the user modifies it to be color C' (Figure 5b). For any color x we would like to know $x' = f_1(x)$. In general we want to translate colors in the same direction, and a naive strategy might simply add exactly the same offset vector $(C' - C)$ to every x. However, it would be easy to go out of gamut, and simply clamping to the nearest in-gamut value would violate the one-to-one and dynamic range goals, as illustrated in Figure 6. Instead we devise a scheme that translates colors that are far away from the boundary of the gamut, but squeezes values nearer to the boundary towards the boundary and towards the C' as follows. First we find C_b, the point where the ray from C towards C' intersects the gamut boundary. Next, we determine if $x_o = x + C' - C$ is in gamut. If so (the "far" case) we find x_b the location where the parallel ray from x intersects the gamut boundary. If not (the "near" case) we take x_b to be the point where the ray from C' towards x_o intersects the boundary. These intersections are found by binary search. Finally, we take $f_1(x) = x'$, the point on the ray from x to x_b such that:

$$\frac{||x' - x||}{||C' - C||} = min(1, \frac{||x_b - x||}{||C_b - C||})$$

In the far case this policy squeezes $f_1(x)$ toward the boundary in proportion to $C' - C$ with a maximum ratio of 1, meaning very far from the boundary we just translate colors parallel to the palette change. Very close to the boundary, the offset vectors swivel towards C', which we found by experimentation helps to achieve a desired palette change in those areas. Also note that this transfer function enjoys several of the desired properties descried above. Assuming C and C' are in gamut, so is $f_1(x)$. It interpolates: $f_1(C) = C'$. If the gamut were convex, then it would one-to-one and continuous with respect to x and C'. Of course the gamut is only *close* to convex, so these properties are almost satisfied. While it is possible to devise cases where they are violated, we find in practice that it does not happen when performing reasonable color palette edits.

Now that we have $f_1(x)$ we will generalize it to handle the case of larger palettes containing $k > 1$ entries. Our strategy is to define k transfer functions $f_i(x)$, each equivalent to the $f_1(x)$ map

described above as if it were the only palette entry, and then blend them, weighted by proximity:

$$f(x) = \sum_i^k w_i(x)f_i(x) \quad \text{and} \quad \sum_i^k w_i(x) = 1$$

For the weights we use radial basis functions (RBFs):

$$w_i(x) = \sum_j^k \lambda_{ij}\phi(||x - C_j||)$$

We tried various kernel functions and found that the Gaussian kernel works well in our application:

$$\phi(r) = exp(-r^2/2\sigma_r^2)$$

where the scalar parameter σ_r is chosen to be the mean distance between all pairs of colors in the original palette. The k^2 unknown coefficients λ_{ij} are found by solving a system of k^2 equations: k of which require $w_i(C_i) = 1$ and $k^2 - k$ of which require $w_{j\neq i}(C_i) = 0$.

This approach leads to smooth interpolation of the individual transfer functions f_i at C_i. Unfortunately solving the system of equations set up by the RBFs can lead to negative weights, with two potential hazards. First, it will add some component of the *opposite* behavior of some palette changes. Second, and more dangerously, it can throw the result out of gamut. We therefore use a simple fix – we clamp any negative weights to zero and renormalize the non-zero weights. We find in practice this solution works well. The final weighted combination is illustrated in Figure 5c for a palette size of $k = 3$.

3.6 Acceleration

The RBF interpolation scheme described in Section 3.5 is relatively fast, but its naive application to the image would require making this computation for every unique color in the image (often in the *millions*). This section describes an acceleration scheme that allows it to be usable in an interactive application. First, note that the weights $w_i(x)$ are found based only on the color x and the initial palette colors C_i. Therefore, in principle the RBF computations need only be performed when the initial palette is established (not during color palette editing). We further accelerate the computation by caching these weights w_i only at a $g \times g \times g$ grid of locations

g=4, t = 3ms, d = 5.3   g=12, t = 39ms, d = 1.0   g=64, t = 5615ms, d = 0
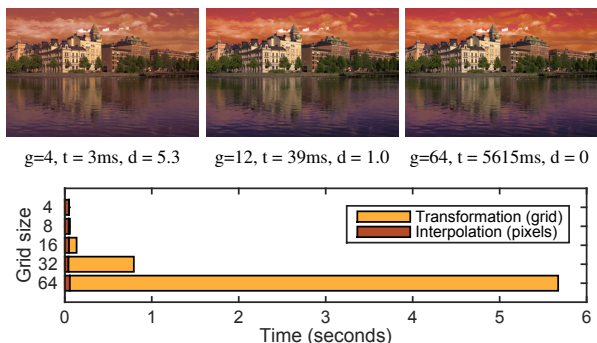
Figure 7: *Acceleration. Top: results of varying grid size g. Time t is to update the grid values (averaged). d is CIEDE distance from the g = 64 version. Small grid sizes give visual differences, whereas g = 12 is indistinguishable from g = 64 (but roughly 140 times faster). Bottom: Update time vs. grid size. The time to update the pixels of the image remains near constant (brown, about 50ms for a 1 MP image). Photo courtesy of the MIT-Adobe FiveK Dataset [2011].*
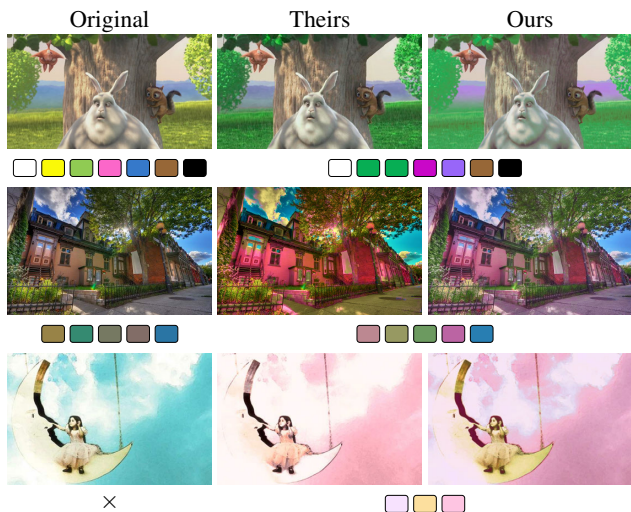
Figure 8: *Comparison to the methods of (top to bottom) Chen et al. [2014], Shapira et al. [2009], and Wang et al. [2010]. Left to right: original photo, their result, our result. We used the same initial and final palettes as in their paper, except for Wang et al., who do not use an initial palette.*

uniformly sampled in the RGB cube. Next, during color editing when the C_i' are known, we can compute the output color $f(x)$ at these g^3 locations using the precomputed weights. Finally, to recolor each pixel in the image use trilinear interpolation on eight nearest grid values. This strategy not only gives our implementation interactive performance (in javascript running in a web browser), but also ameliorates any small discontinuities in $f(x)$ due to the non-convex gamut.
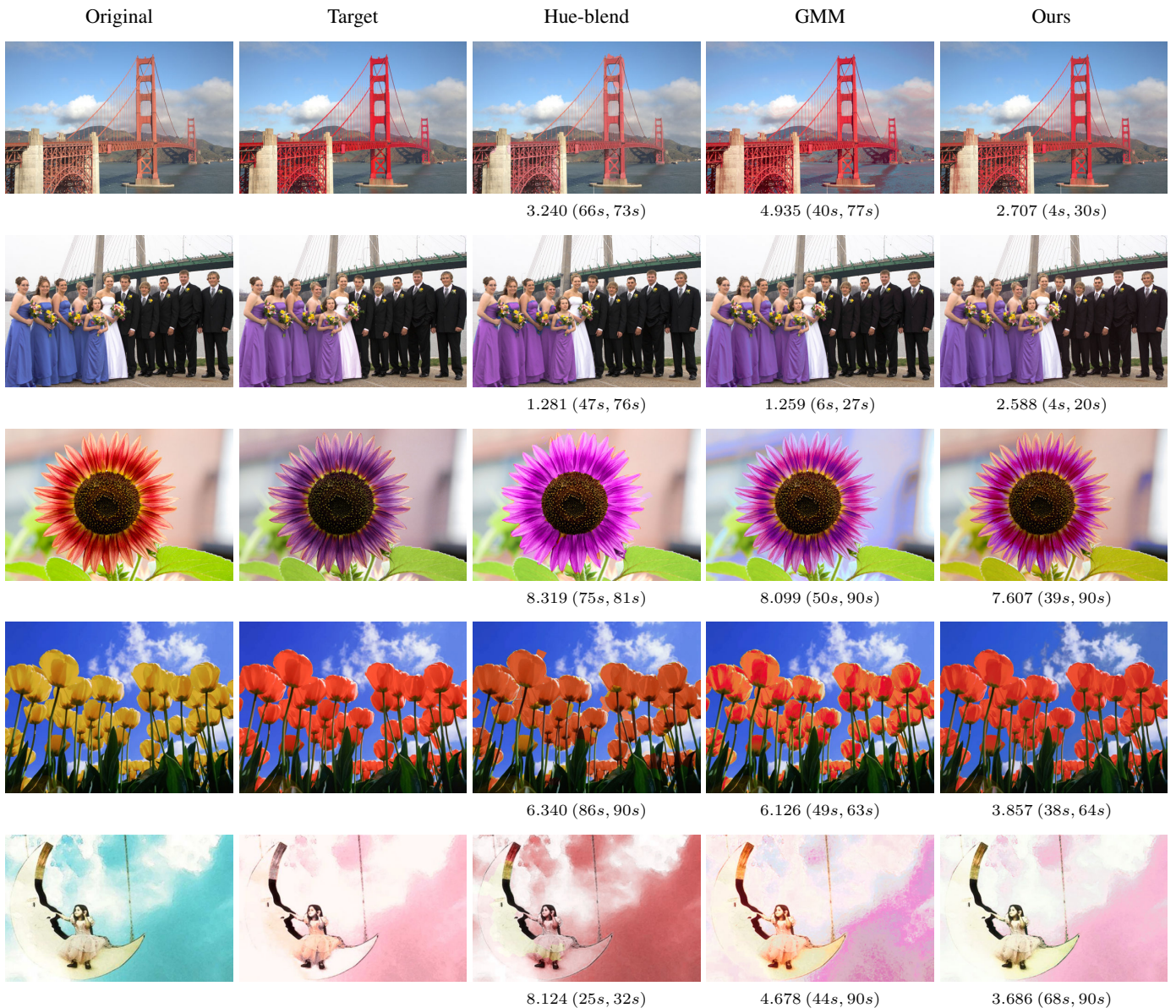
Figure 7 demonstrates the performance advantage. We see that using larger grid sizes g has a diminishing return in image quality such that $g = 12$ is almost indistinguishable from $g = 64$, while running about 140 times faster. Without acceleration, our runtime is Tp where T is the time to transform one color and p is the number of pixels. With acceleration, runtime is $Tg^3 + Ip$ where I is the time to perform trilinear interpolation of grid samples, and $I \ll T$. Throughout this paper and in our demo we use $g = 12$, because it performs well across a range of computers and images, so $g^3 \ll p$. Moreover, while in principle for very large images p could grow to overwhelm the runtime, in practice p is limited by how many pixels we could reasonably "preview" on the screen. Finally we note that splitting the calculation to a pre-processing step followed by sampling and interpolation steps lends itself well to shader programming. While we did not test this idea, implementing the interpolation as an OpenGL shader would be trivial, and should achieve substantially faster performance, even for huge images or dense grids.

4 Evaluation

In this section we evaluate our method in two ways. Section 4.1 directly compares our approach to some existing methods in the literature. Section 4.2 presents a user study in which we ask novice users to use our method, using two alternate methods as a baseline.

4.1 Other Recoloring Methods

Figure 8 shows a comparison to three other palette based recoloring methods, and in each case we believe our method responds more faithfully to the specified palette. The method of Chen et al. [2014]

Original	Target	Hue-blend	GMM	Ours
		3.240 (66s, 73s)	4.935 (40s, 77s)	2.707 (4s, 30s)
		1.281 (47s, 76s)	1.259 (6s, 27s)	2.588 (4s, 20s)
		8.319 (75s, 81s)	8.099 (50s, 90s)	7.607 (39s, 90s)
		6.340 (86s, 90s)	6.126 (49s, 63s)	3.857 (38s, 64s)
		8.124 (25s, 32s)	4.678 (44s, 90s)	3.686 (68s, 90s)

Figure 9: *Examples from our user study. Left to right: original, target, results of hue-blend approach, GMM approach and our method. Under each result is the distance to target (RMS of CIEDE2000), and for each method this figure shows the best result out of all subjects according to this distance. Times in parentheses: number of seconds in which there was some user interaction, total number of seconds until task completion. Photos courtesy of the MIT-Adobe FiveK Dataset [2011] (top three), Chen et al. [2012] (fourth), Wang et al. [2010] (bottom).*

(top) offers a fast and space efficient recoloring algorithm that also works for video. Our method is faster, e.g., at least $10\times$ for Big Buck Bunny. The method of Shapira et al. [2009] (middle) focuses an interface for exploration, in the spirit of the *design galleries* of Marks et al. [1997]. Wang et al. [2010] (bottom) address the harder problem of how to map the colors when no initial palette is present, and thus their method is more complex and slower than ours.

4.2 User Study

Evaluating a task that has a component of personal taste is always challenging. Here we describe a user study showing that our method is easily learned by non-experts, sufficiently fast, expressive enough to produce a variety of imagery. In order to judge expressiveness, the task we give our users is a matching task: they are given a target image (created from the original by manipulating its

colors) and the user is asked to manipulate the original to match the target, using our method and two others. Thus we can judge whether our method can achieve a spectrum of desired results, and can use the other methods as baseline comparisons.

With the goal of capturing a broad spectrum of color editing operations, we collected 32 original-target pairs as follows. Half (16) were selected from eight papers in the literature that perform color manipulation [An and Pellacini 2008; Chen et al. 2014; Hou and Zhang 2007; Liu et al. 2014; Pitie et al. 2005; Shapira et al. 2009; wing Tai et al. 2005; Wang et al. 2010]. The other half were created by two expert Photoshop users (having the entire Photoshop tool-set at their disposal) according to a written task description like "Change the color of the bridge to be a richer red color." or "Brighten everything to make it look more like daytime."

	Ours	GMM	Hue Blend	Photoshop
Min	3	7	17	~ 60
Max	90^*	90^*	90^*	~ 720
Median	71	69	90	~ 210

* our user study task was capped at 90 seconds per image.

Table 1: *Task completion times. The table shows time (seconds) to recolor an image, for each of the methods in our user study. Last column is approximate time for expert Photoshop user to recolor the same images. Note that the user study task was capped at 90 seconds, and we observe that most of the hue blend mode users did not complete the task within that time frame. Using our full method and GMM takes roughly the same amount of time, while hue blend is slower and using Photoshop was the slowest.*

For the study we used Amazon's Mechanical Turk framework. In each task (called a "HIT"), the subject was asked to edit four images (selected randomly without repetition per worker) from among the 32 original-target pairs. They were instructed to attempt to edit the original to match the target as best as they could within 90 seconds. Subjects who satisfied earlier were able to click a button to advance to the next image. Before beginning the task they were given a brief set of instructions that took a few minutes to complete.

Each worker was assigned randomly to one of three different conditions: our method, GMM, and hue-blend (described below). Most workers did just one task for us, but any workers that did more than one were always assigned the same condition. Our method was the approach described in Section 3, but with a fixed five-color palette automatically selected that could not be changed. GMM used the same GUI and instructions as our method, but the underlying color manipulation algorithm used a Gaussian mixture model both to select the palette and to manipulate it. Hue-blend was similar to a hue blend layer in Photoshop. In this interface the user "paints" hue into the image, which replaces the hue in the image but leaves saturation and luminance unchanged. Subjects were given a choice of three brush sizes which were either circular or a "smart brush" that reshapes according to gradients in the image. (Specifically, we segment the image into superpixels [Mori 2005] and paint any superpixel intersected by the circular brush.)

Via this study we collected 1820 images, of which 592, 608 and 620 were produced respectively by our method, GMM and hue-blend. The number of results for each target in each condition ranged from 15 to 25. Next we compare the three methods it terms of expressibility (were the workers able to reach the target?) and ease of use (were they able to do so within the 90 seconds?).

Figure 9 shows a few examples: the original image, the target image (either from related papers or created using Photoshop) and the best results for each method, measured by CIEDE2000 distance from the target [Luo et al. 2001]. In the figure (and in the study) our method produced the single best performing result by this measure more often than the other methods. Figure 10 aggregates all distance-from-target results. The median distance for our method is smaller than that of GMM ($p < 0.001$) and that of hue-blend ($p < 0.0001$). Statistical significance was found via a randomized permutation test with Bonferroni correction. Because the hue-blend mode did not allow subjects to adjust luminance (which is required for some of the targets) we also calculated the same distances but first using histogram equalization on the luminance channel of the result. Of course this changed all individual distances but the relative performances of the different methods (and the p-values) were comparable.

Table 1 shows completion times over all subjects, for each of the three methods. It also shows the time it took an expert Photoshop
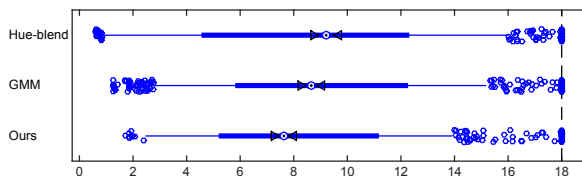
Figure 10: *Distance comparison across methods. For all user study results, we calculate the CIEDE2000 distance between result image and target. The plot shows results for the 3 methods: hue-blend, GMM and ours (lower is better). Thick line indicates range between 25th and 75th percentiles. Dotted circle on the thick line indicates the median, which is lower (with statistical significance) for our method than for GMM and hue-blend.*

user to produce the corresponding 16 target images. From the table it is clear that our GUI is the fastest (using either our algorithm or GMM) while using a brush to paint hues is slower. The Photoshop experts took the longest to edit images, although we note that the other three interfaces explicitly capped the amount of time available whereas the Photoshop experts had no time pressure.

Moreover, inspection of the pool of results leads us to believe that these distance measures were overly kind to the other methods. Qualitatively we observe that: (1) GMM results often contain highlights and halos that did not seem to hugely adverse effect their distance scores. (2) Hue-blend results often exhibit visual artifacts, as users had difficulty painting accurately. When these artifacts are small (yet noticeable) they do not adversely effect the distance commensurate with their visual impact. (3) Some of our results that have high distances actually look very similar to the target. The L-monotonicity constraint described in Section 3.4 allows the user to make subtle changes in luminance overall that induce high distance values even though they are not visually objectionable. While researchers have investigated other distance measures that better capture human perception (e.g., [Wang et al. 2004]) this remains an open research problem.

Finally we note that inasmuch as the results of our method did not exactly match those produced by the Photoshop experts (with the entire suite of color manipulation tools in that software and unlimited time to work on the images), it is not obvious that one or the other is "better."

5 Results

Figures 1 and 4 show examples of using our method with palettes of size 3, 4 and 5. They demonstrate both local and global changes (and a combination of the two).

Our method supports masks, constraining the edits to specific image regions, as can be seen in Figure 11. Using a mask is necessary only if similarly colored objects should be edited in a different manner. Except for Figure 11, all results in this paper do *not* use masks.

Figure 11: *Using a mask. Left-to-right: original, mask, result.*
Photo courtesy of the MIT-Adobe FiveK Dataset [2011].

The remainder of this section describes various other applications made possible by our palette based approach.

5.1 Video Recoloring

Our method is fast enough to be applied to a video, in real time. The interaction uses the same interface as for photos, shown in Figure 2. An example may be seen in the accompanying video. For this application, we need to choose a source palette for each frame. Our implementation selects a palette from one of the frames and uses it throughout the sequence. This approach encourages temporal coherence, but might not be suitable for long sequences. The selection method could be extended to a sliding window scheme, thus making is usable for longer, more heterogeneous sequences.

5.2 Duotone

Duotone reproduction is a traditional printing technique that typically involves two colors of ink applied via halftone patterns over white paper. This style gives an overall sense of coloration and has a nostalgic quality (but costs less than full-color printing involving three or four inks). Digital imaging software like Photoshop provides a duotone function to produce this effect, while allowing the user to choose the ink color(s). Our method can easily produce a similar effect as follows. We start with a grayscale image (or desaturate a color image). We select a 3-color palette and force one of the colors to be white (paper), letting the automatic algorithm of Section 3.2 choose the other two palette colors. Finally the user can adjust the two darker (ink) palette colors to achieve various imagery in the style of a duotone. Figure 12 shows an example.


Figure 12: *Duotone. Starting from a grayscale image, we use a three color palette (white and two other colors) to create this effect. Photo courtesy of the MIT-Adobe FiveK Dataset [2011].*

5.3 Automatic Color Manipulation

Our methods was constructed with controllability in mind, allowing the user to select the resulting colors manually. While we believe that to be the most common use case, some users might prefer a fully automatic method. There are many on-line repositories of "good" color palettes, such as the Adobe Color CC database used by O'Donovan et al. [2011]. We can automatically pick a top rated palette and apply it to an image.

For this application we need to enhance our method with an automatic way to match source and target palette colors. Using the annotation in Section 3.2, there we know that $C_1, C_2...C_k$ correspond to $C'_1, C'_2, ..., C'_k$ (e.g. C_1 corresponds to C'_1). This matching is given to us via our GUI (the user selects a palette color, then changes it) but is not available for the fully automatic method. Thus we augment our method with a palette matching step
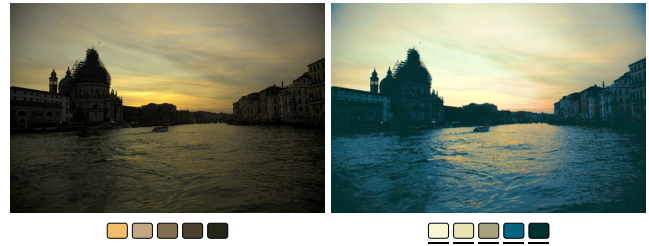

Figure 13: *Fully automatic pipeline. As an example, we use the top rated palette from Adobe Color CC and apply it to an image. The input and output palettes are matched in increasing luminance order. Left: original, right: result of applying the "sandy stone beach ocean diver" palette. Photo courtesy of the MIT-Adobe FiveK Dataset [2011].*

that decides on the correct permutation of colors. As discussed in Section 3.4, we found that sorting colors according the luminance value is a good matching strategy. Figure 13 shows automatic image recoloring result using the top Adobe Color CC palettes.

5.4 Editing an Image Collection

HaCohen et al. [2013] describe a method of consistently editing a whole collection of photos that share content. Inspired by their approach, we show that our system can trivially operate on a collection of images simultaneously. We calculate a single color palette for the entire collection, thus editing operations will change all images in a consistent manner. Figure 14 shows an example of an edited photo collection. Notice that all photos (combined) were edited with less than 20 seconds of user input, and this number is constant regardless of the number of images we are editing. Moreover, because of the acceleration scheme described in Section 3.6, the resulting output can be rendered at interactive frame rates even for collections containing many millions of pixels.
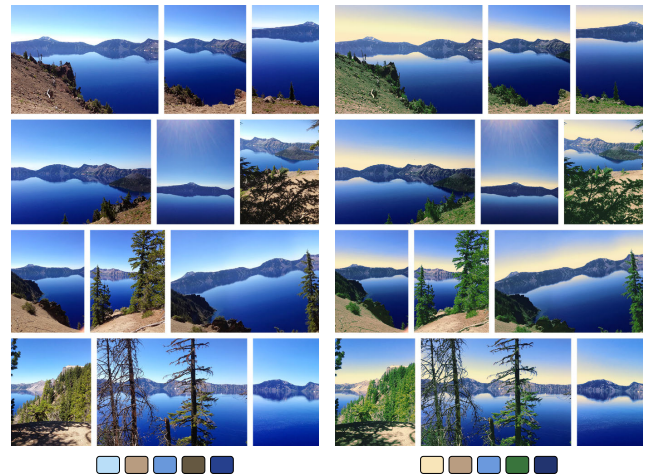
Figure 14: *Image collection editing. Our system can be applied to multiple images at once. The user manipulates the joint palette of all input images, thus achieving a consistent result across the collection. Left: original collection. Right: result. In this example the user changed the sky to have a sunrise effect, made the greens more saturated and changed the water to a deeper shade. The entire editing session took less than 20 seconds. Photos ©Jingwan Lu.*

5.5 Stroke-Based Interface

Finally, our palette based editing method can easily be augmented with a stroke-based interface that relies on the same algorithms described in Section 3. Using a mouse (or tablet or multitouch device) the user draws a stroke over the image as a way of indicating a "selection" in color space. This operation essentially specifies a palette and a selected palette color as follows. We take the mean color of the pixels under the stroke to be the selected palette color to be edited. The remainder of the palette is filled using the approach described in Section 3.2. Next as the user changes the color of the selected palette entry, the corresponding colors in the image are modified using the color transfer approach in Section 3.

As observed in Section 3.1, the size of the palette governs the locality in color space of various edits. We set the palette size:

$$k = \max(3, 7 - \lfloor \frac{7\sigma_s}{\sigma_I} \rfloor)$$

where σ_s and σ_I are the standard deviations of the pixel colors under the stroke and of the whole image. This gives a palette size between 3 and 7, depending on whether the colors under the stroke have high or low variance relative to those of the image. This approach offers the user a simple control of the locality, as illustrated in Figure 15-top. A small brush stroke in the blue of the sky (left) yields a palette size of 7 and thus the color edits are localized to blue colors; in contrast a large stroke that crosses the blue sky and gray clouds gives a palette of size 3 and thus affects a broader swath of colors in the result (right). Comparing this interface to that of Chen et al. [2012] which requires brushes indicating both colors to be modified (red stroke in the lower-left) and colors to be left untouched (black stroke) we find that we are able to produce similar effects with only the modifying strokes (lower-right).

Note that our current implementation uses strokes to select color ranges, regardless of location in the image. A more sophisticated approach might select for *both* color and location (in 5D rather than 3D). However, adding these dimensions to the lookup table described in Section 3.6 would have a performance impact.

6 Conclusion

We introduce a new method for image color editing. Our method includes a carefully considered GUI along with a new color transfer mechanism. We show results for recoloring, image collection editing and video editing, and validate via a user study.

The realm of possibilities for color transfer is far from explored. In future works we would like to tackle some of the challenges we encountered while creating the current system. First, in the current work we do not take pixel location into consideration, which leads to a fast algorithm that allows interactive exploration. However, it would be interesting to incorporate spatial information into the algorithm. Second, one of our main goals is to create an intuitive user interface, that behaves "as the user expects." We believe that this goal could be enhanced by considering a computational model of color names, for example that of Mojsilovic [2005]. Most people think in terms of color names (e.g. change black to red) and we believe incorporating such notion of colors into the system (forcing the transformation to respect color boundaries) would enhance its intuitiveness. Lastly, while we show a completely automatic pipeline using user-rated palettes, we believe full automation can be extended beyond the realm of human curation, to an algorithm that combines automatic palette selection with recoloring.
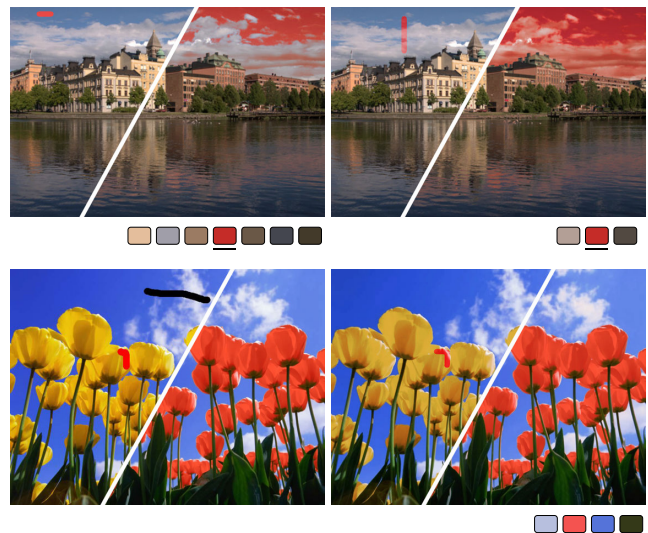
Figure 15: *Stroke-based editing. Top: Different brush marks select local (left) or global (right) color ranges for editing. Input images with red brush marks are left of diagonals while output is to the right with automatic palettes below. Photo courtesy of the MIT-Adobe FiveK Dataset [2011]. Bottom: Comparing to the approach of Chen et al. [2012] (left), our method achieves similar effects with fewer marks (right).*

7 Acknowledgments

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