

Sotirios A. Tsaftaris, Kristin H. Lister, Inge Fiedler,  
Francesca Casadio, and Aggelos K. Katsaggelos

## Colorizing a Masterpiece

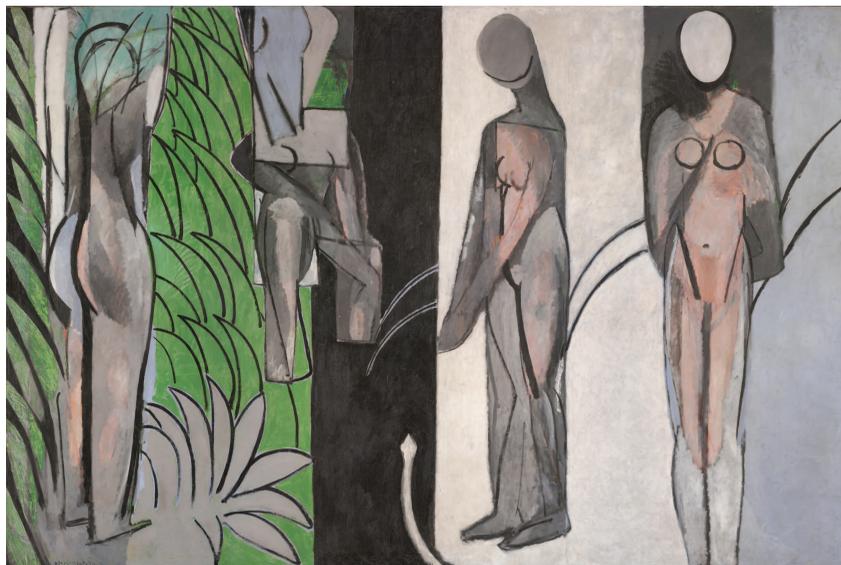
The purpose of this article is to discuss the process of colorizing a historical artifact—a black and white archival photo of *Bathers by a River*, 1909–1917, by Henri Matisse (Art Institute of Chicago 1953.158), taken in November 1913, when the artist was still working on the painting and showing it in a significantly different state compared to the one seen today. Historical accounts describe a painting that was originally a more naturalistic, pastoral image; but over the course of several years, and under the influence of Cubism and the circumstances of World War I, Matisse radically revised his monumental canvas (measuring 260 × 392 cm). Matisse later considered *Bathers by a River* to be one of the five most pivotal works of his career [1]. Historical photographs unearthed by archival research depict the painting at various stages. The painting, along with these historical photographs, our colorized image, and other works documenting the experimental nature of the artist's output during a period that has been studied very little until now, have been the centerpiece of a recent exhibit, *Matisse: Radical Invention 1913–1917*, that was at the Art Institute of Chicago and the Museum of Modern Art in New York City in March–October 2010 [1].

Colorizing this archival photograph helped conservators and art historians visualize Matisse's artistic intention as expressed in his working process. It would also allow art historians to connect the painting with other Matisse works that share a similar palette.

Painting colorization differs from the usual applications of colorization; it requires high accuracy and fidelity and is adapted and dependent on the style of the artist. In this article, first a description of the painting and its transformation is given to provide insight to how the painter radically transformed his art work. This is followed by a description of the customized colorization algorithm and the process with which we extracted color information from the painting as it appears today. Subsequently, we discuss issues of illumination in the original photographs that had to be corrected first to have a historically accurate colorization. Finally, we present our colorized photograph, discuss its historical value, and draw conclusions from this experience.

### BATHERS BY A RIVER: THE EVOLUTION OF A MASTERPIECE

Matisse worked on *Bathers by a River* (Figure 1) over the course of at least eight years [1]. During its long evolution, the painting became an important vehicle for his “methods of modern construction,” and its many stages reveal the deep connections with many works made during the 1913–1917 period. The idea for the painting was first inspired by Sergei Shchuckin, a wealthy Russian collector who commissioned Matisse to paint two decorative panels for his home. While the project ultimately focused on canvases of dance and music (which inspired other monumental Matisse works), Matisse nonetheless began the bathers' composition in March 1909. As he worked on it through the fall of 1910, he modified his initially idyllic scene of four figures resting



**[FIG1]** *Bathers by a River* by Henri Matisse, as it appears now. In text it is referred to as image M; its luminance component (not shown) is referred to as  $M^l$ . (*Bathers by a River*, Issy-les-Moulineaux, March–May 1909, fall 1909–spring 1910, May–November 1913, early spring–November 1916, January–October (?) 1917. Oil on canvas. The Art Institute of Chicago, Charles H. and Mary F. S. Worcester Collection, 1953.158. ©2010 Succession H. Matisse/ Artists Rights Society (ARS), New York.)



**[FIG2]** *Bathers by a River* by Henri Matisse, as it appeared on November 1913, photographed by Eugène Druet in the artist's Issy studio. In text it is referred to as image D.

in a landscape, rendering them in bright colors and stiffer poses. In May 1913, the artist returned to the canvas, and by November of that year he had transformed the Arcadian image into a cubist-inspired scene described in a monochromatic palette. Three years later, he reinvented the scene again, segmenting the composition into large bands of color that reinforce the contours and geometric forms of the figures. He would work on the canvas again the following year, refining his last painting campaign and making subtle changes that reflected a new interest in a softer kind of light. We welcome our readers to visit the Web site in [2] for a detailed online tutorial and interactive demo on this painting and its radical transformation.

Sometime around the beginning of November 1913, Matisse arranged for photographer and dealer Eugène Druet to record the fourth state of *Bathers by a River* (see Figure 2). Matisse retained most aspects from the previous stages, such as the high horizon that is the source of the waterfall in the center; he also kept the general position of the four bathers and the snake (shown at the low-middle part of the painting), although shifting their positions slightly. The artist also took a more angular, abstracted, cubist approach to form and reduced the figures' individuality to give them a gen-

eralized hieratic quality. By adding foreground grasses and background foliage, he introduced a sense of atmosphere and place. But Matisse drastically transformed the picture's mood with an austere palette of primarily grays—a fact unknown to scholars until the research discussed here took place.

This photograph taken by Eugène Druet, shown in Figure 2, became the focus of this interdisciplinary research effort. Colorizing the photograph assisted art historians in visualizing the earlier appearance and unraveling the evolution of this monumental masterpiece.

#### **FROM CANVAS AND DEALER'S PHOTOGRAPHS TO DIGITAL IMAGES**

Digital representations of works of art have become immensely useful in the conservation and art historical fields, facilitating the collaboration among different groups that may not be collocated in the same place and aiding in the preservation or restoration of the work itself [3], [4].

The digital image of the modern state of the painting (termed here as **M** for modern) is the result of stitched digital color photographs of very high resolution. A digital camera with a ring flash was used to capture each subsection in color, and the stitching algorithm of Adobe Photoshop was used to stitch the sections together.

The Druet photograph (termed here as **D** for Druet) was digitally scanned from the dealer's catalog using a desktop scanner at 1,200 dpi resolution and 16-b depth. The painting was photographed by Druet propped on crates inside the artist's studio, using an analog camera of unknown make and model circa 1913, under unknown illumination conditions. To facilitate comparison and further research, the images were cropped and coregistered such that both had the same size ( $4,020 \times 2,715$  pixels) and pixel-to-pixel correspondence [1], [5]. We urge our readers to visit the Web site in [2] to explore the painting in high resolution.

#### **A COLORIZATION ALGORITHM TAILORED TO MATISSE'S STYLE**

Colorization is a computer-assisted process of adding color to a monochrome image or movie [6]. The research in this field was driven by a consumer-oriented goal: colorization of black and white movies [6]. The first colorized movies were cartoons, and the technique to accomplish this task was first introduced in the early 20th century. Colorization of gray-scale images as we know it today has been a research problem in the image processing community since the 1970s. The process, disclosed in a patent by Markle and Hunt, was first used in 1970 to colorize monochrome footage from the Apollo mission on the moon [6].

The process of colorization was highly (and still is somewhat) dependent on human input. At the beginning, a human supervisor played an active role in manually segmenting the image into regions, specifying the colors to be used in each of them and, for the colorization of movies, was responsible for keeping track of the segments and making necessary adjustments where motion tracking techniques failed to perform adequately. As colorization techniques evolved, the process became semi- or fully automatic; both segmentation and choice of the appropriate segment color are automated processes today, with minimal human input. Nevertheless, these procedures vary in segmentation, color annotation

method, and the actual colorization technique used.

For the problem at hand we considered and implemented a number of colorization approaches [7]–[11]. The requirements for painting colorization are different since high accuracy and fidelity are necessary and the image formation model differs significantly from natural or cartoon images. For the particular application, the methodology in [9] was found more suitable because it allowed for more adaptation. This optimization-based colorization algorithm aims at colorizing an image using a few predefined color hints [9]. Assuming a YUV color space our goal was to estimate the U and V components using only the gray scale or luminance or intensity component Y, which in our case is the Druet image, and color hints, which will be described in a following section. Since the procedure is the same for both U and V components, only the procedure for U is presented.

We adapted the linear optimization colorization method in [9] for painting colorization and to perform better with thick edges (the result of thick brush strokes). Briefly described, the method in [9] relies on the fact that the color information at specific locations (termed color hints) is defined a priori by the user or via another method. The basic premise of the algorithm is that pixels with similar luminance values will have similar chrominance values. To accomplish this goal, a linear optimization problem is cast with respect to the pixels with unknown color. More specifically, for colorizing the U chrominance component the following cost function is minimized with respect to the uncolorized pixels  $U(\mathbf{s})$ :

$$J(U) = \sum_{\mathbf{r}} \left( U(\mathbf{r}) - \sum_{\mathbf{s} \in N(\mathbf{r})} w_{rs} U(\mathbf{s}) \right) \quad (1)$$

where vectors  $\mathbf{r}$ ,  $\mathbf{s}$  denote pixel location;  $U(\mathbf{r})$ ,  $U(\mathbf{s})$  are the color values at the  $\mathbf{r}$ ,  $\mathbf{s}$  pixel locations;  $N(\mathbf{r})$  the neighborhood of  $\mathbf{r}$ ; and  $w_{rs}$  a weight function determining the degree of similarity of  $U(\mathbf{r})$  and  $U(\mathbf{s})$  [9]. It is defined based on the luminance values so as to enforce similarity in color based on similarity in intensity. We

experimented with various definitions of it, and the one we used for the colorization shown in this article is given by

$$w_{rs} \propto \exp \left( - \frac{(Y(\mathbf{r}) - Y(\mathbf{s}))^2}{2\sigma_r^2} \right), \quad (2)$$

where  $\sigma_r$  is the variance of intensities in the neighborhood  $N(\mathbf{r})$ . We experimented with various shapes and sizes of the neighborhood  $N(\mathbf{r})$ . According to [9], minimization of (1) results in the solution of the linear set of equations

$$\mathbf{A} \cdot \mathbf{u} = \mathbf{b}, \quad (3)$$

where  $\mathbf{u}$  is the vector of the unknown chrominance components,  $\mathbf{b}$  the vector of the known values of the chrominance at predefined locations (color hints) and zeros otherwise, and  $\mathbf{A}$  is large square sparse matrix in which every row represents the relationship of each pixel with its neighbors as defined by the weight function  $w_{rs}$ . The solution of (3) provides the U component for the image, and the process is repeated for the V component.

In contrast to the colorization of photos of natural scenery, portraits, and cartoons, for accurate colorization of paintings the algorithm must be tailored to the specific style of the artist. For example, abstract and cubist works have a completely different, less naturalistic style compared to renaissance or impressionist works. To customize our colorization algorithm we used image  $\mathbf{M}$ , shown in Figure 1, as ground truth and aimed to colorize its gray-scale version (luminance component, denoted as  $M^Y$ ) using only a fixed set of color hints. In the following we denote as  $M'$  the result of colorizing  $M^Y$ .

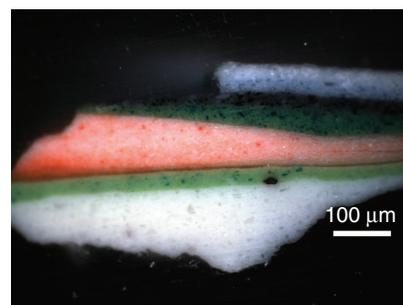
We modified the neighborhood weights of the matrix  $\mathbf{A}$  for pixels on (or around) edges, as discussed next, to reduce color bleeding over the edges, which can occur when the edges are not sharp due to digitization [11]. This was also necessary due to the particular style of Matisse in delineating his composition by thick black brush strokes (see, for example, foliage on the left part of Figure 1).

To accomplish our goal we found the edges in  $M^Y$  using a Canny edge detector

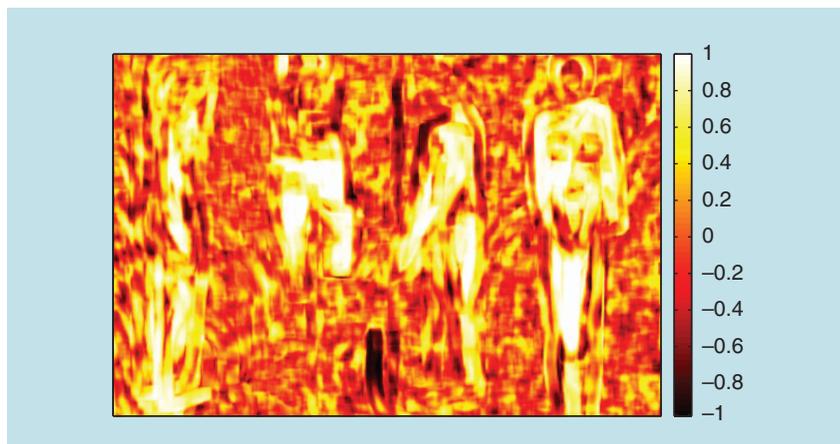
and dilated them with a disk operator to obtain an edge mask. For pixels not falling on an edge but having edge pixels in their neighborhood, we exclude those edge pixels from the construction of  $\mathbf{A}$  in (3). If the pixel falls on an edge, then we only include pixels falling on the edge mask as part of its neighborhood in constructing  $\mathbf{A}$ . The various variables in the problem formulation were optimized by minimizing the mean squared error between  $M'$  and  $\mathbf{M}$ . Our analysis identified that the optimal neighborhood  $N(\mathbf{r})$  is a  $3 \times 3$  square and that a  $5 \times 5$  disk operator provides optimal performance around edges.

### UNCOVERING SIMILARITIES BETWEEN THE STAGES OF THE PAINTING

Using x-ray radiographs coregistered with the images of Druet and modern state, the conservation team at AIC identified compositional changes hidden under visible layers of paint [1], [5]. (These images can also be seen in [2].) This finding motivated the conservators to perform microscopic analysis of extracted cross sections and identify the color of previous layers below the current surface. During this process a microscale sample is removed at specific locations, ideally containing all paint and ground layers down to the support. These cross sections (see, for example, Figure 3), enabled conservators and



**[FIG3]** An example of a microscopic cross section at 200x original magnification taken from the white head of the standing figure at farthest right. The dark gray layer that is present between the darker green and light blue relates to the November 1913 campaign documented in Druet's photograph. The thick white layer at the bottom is the ground, or preparation layer, applied on top of the canvas support.



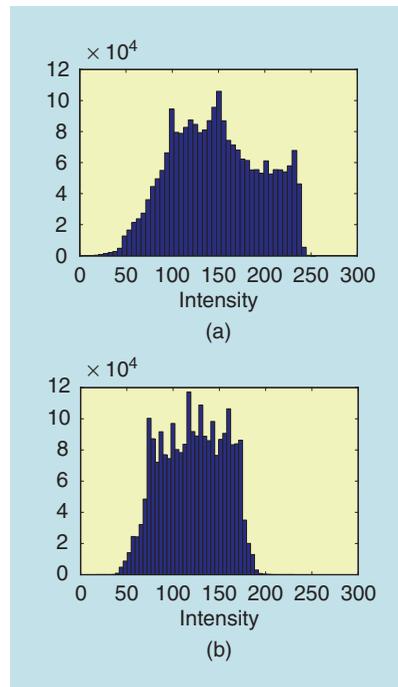
**[FIG4]** Correlation map between the two images (Figure 1 and Figure 2). Values range from  $-1$  to  $1$  for negative maximum correlation to maximum positive correlation, respectively. Using this map, regions of high similarity between the two images can be easily extracted.

historians to view the succession of underlying layers of colors belonging to previous states of the painting. The samples thus provided us with color information for the areas where the cross sections were taken.

Another source of color information (which we collectively term as color “hints”) are areas that Matisse retained from the November 1913 state (Figure 2) and remain visible on the surface of his final composition. In particular this includes the legs and torsos of the bathers (seen in Figures 1 and 2) [1]. Although it is possible to visually identify regions between the Druet and present day photos that are similar, we opted for an automated and objective method. Since the two images were coregistered, we could employ statistical correlation to identify areas of similarity. First, both images **D** and  $M^y$  (the luminance component of **M**) were smoothed with a Gaussian filter to reduce the effects of noise (possibly introduced during acquisition). A  $15 \times 15$  sliding window and raster scanning were used to define vectors  $y_D, y_M$  of size  $225 \times 1$ , in the smoothed **D** and  $M^y$  images, respectively. We proceeded to find the Pearson product-moment correlation coefficient among  $y_D$ , and  $y_M$ , for each  $15 \times 15$  window. Figure 4 shows the correlation map between the two images when all the sliding windows were processed. For our purpose we

identified as similar those regions that had a correlation larger than 0.8. To eliminate boundary issues at each region, erosion with a  $1 \times 1$  morphological operator was used to reduce the perimeter of each region by one pixel.

This process provided us with a binary mask, which identified regions of



**[FIG5]** Histogram intensities of regions of high similarity for both images (Figure 1 and Figure 2) for (a) Druet and (b) modern state. Comparison indicates a saturation of whites in the Druet photograph, possibly attributed to illumination differences, film saturation properties, and digitization distortions.

high similarity between Druet and (the gray-scale version of) the modern state of the painting. When our mask was compared with similar masks derived from visual observation, the overlap was significant. Furthermore, additional regions of similarity were identified that were not apparent to the human eye, facilitating further the analysis of how the painting evolved.

For these regions of high similarity, we can assume that color information is now available. Correlation estimation involved the normalization of the vectors by subtracting their mean and dividing by their standard deviation, which helped account for variations in illumination when estimating similarity. However, when the color is to be transferred to the Druet photograph for colorization, these differences in illumination must be accounted for to achieve high levels of accuracy.

#### ADJUSTING FOR ILLUMINATION AND FILM SATURATION

It is evident from our previous discussion that the two digital images of the Druet and modern state were acquired with different methods and under different conditions. When the colors of the regions of high similarity were transferred to the Druet photograph, the colors appeared overly pale and overexposed, indicating that illumination and saturation effects were present.

To investigate the existence of these phenomena, we pooled together the luminance values for the regions of high similarity from each of the images (**D** and **M**) and estimated their histograms. As Figure 5 illustrates, the two images have distinctly different histograms at these regions. Druet appears to have saturated whites and shows a stretched histogram [Figure 5(a)]. It is possible that this saturation was due to the film/plate used in the acquisition of the photograph by Druet. This process allowed us to demonstrate that there is a global variation in intensity but did not provide us with any insight into a potential spatial dependency of this variation.

For this reason we generated a new synthetic image,  $R = 1 - (D^*/M^*)$ ,

where  $D^*$  and  $M^*$  are the result of convolving the luminance components of the  $\mathbf{D}$  and  $\mathbf{M}$  images, respectively, with a Gaussian kernel to reduce the effects of noise. Figure 6 shows a color-coded version of this synthetic image illustrating essentially the per-pixel percent change in intensity between the two images. One can observe that excluding registration (or other) errors, there is an appreciable variation in intensities.

To estimate the location of the illumination source, we assumed an illumination field  $F$  modeled as a smoothly varying polynomial field, composed of Legendre polynomials up to third degree, following a similar approach as in [12]. Assuming a unit illumination field for the modern state, due to the characteristics of its digital acquisition (ring flash producing uniform illumination), we estimated the field  $F$  based on the relationship  $\mathbf{D} \propto F \cdot \mathbf{M}$  (here “ $\cdot$ ” denotes point wise multiplication) but fitting only for values in regions of high similarity, recovered from our previous analysis. Although the result is not shown, it indicated that there is a light source directly above the canvas in the Druet photograph. Despite our lack of historical records attesting to the exact conditions under which the photograph was taken, our findings indicate that either ambient afternoon sunlight was present in the room or possibly a magnesium-based flash was used (typical of the era). Conversely, we might argue that this finding provides additional historical information as to the time or conditions under which the photograph was taken.

Illumination and saturation differences among the two images had to be accounted for and corrected prior to color transfer and colorization. The obvious solution would be to use either a histogram matching algorithm to scale the intensities of Druet [13] or the estimated illumination field (from above) to match an illumination point directly in front of the photograph. However, both approaches required the alteration of the pixel intensities in the photograph—an important historic artifact—which was deemed undesirable.



**[FIG6]** Ratio image  $R$ . Values  $-0.1$  to  $0.1$  are color coded as green, corresponding to less than 10% change in illumination. Blue/magenta hues denote that the Druet is darker than the modern state ( $>0.1$ ), while yellow hues ( $<-0.1$ ) denote that Druet was brighter than modern state. Values larger than 1.3 are not color coded (white). Red hues correspond to large ratios.

We opted instead to adjust the color values prior to the transfer such that we can depict the painting as it would have been captured with a hypothetical “color” camera circa 1913.

To adjust the color values in each region of similarity, prior to color transfer, we used a  $15 \times 15$  distinct window to estimate local intensity variations. For each  $15 \times 15$  distinct block in a region of similarity, we collected the luminance values of  $\mathbf{D}$  and  $\mathbf{M}$ , converted the two  $15 \times 15$  blocks to two 225 column vectors ( $\mathbf{y}_D$ ,  $\mathbf{y}_M$ ) with raster scanning, and finally regressed  $\mathbf{y}_D = \alpha \mathbf{y}_M + \beta$ . (If the region had fewer than  $15 \times 15$  pixels, then all the intensities in the region were used in the construction of  $\mathbf{y}_D$  and  $\mathbf{y}_M$ .) Based on the regression estimates, for each pixel in this region we scaled the chrominance values of the present state ( $U_M, V_M$ ) as follows  $U_D = \alpha U_M + \beta$ ,  $V_D = \alpha V_M + \beta$ , and we subsequently transferred them to the Druet photograph.

### REVEALING A NUANCED PALETTE OF GRAYS

We combined all the modules described above and composed an image illustrating the color hints shown in Figure 7, which reflects the color hints unearthed from similarity analysis, micro cross section, and historical analysis. All of the computational and estimation operations

were performed in MATLAB, and all results were visualized using Adobe Photoshop with the same color profile. Initially, we performed all operations on lower resolution images to fine-tune color hints and other parameters. Due to the high resolution and size of the images ( $4,020 \times 2,715$  pixels) the complexity of the optimization problem at hand was significant. The  $\mathbf{A}$  matrix was approximately an  $11M \times 11M$  sparse matrix, occupying more than 2 GB in memory. To obtain a final high-resolution colorized image, we used a computer from Northwestern’s computational cluster with 64 GB of memory and a quad core Intel CPU.

The final colorized Druet photograph is shown in Figure 8. The colorized result is smooth, has limited color bleeding, and is consistent with conservation and art history research. The colorized result reaffirmed historical accounts of how the painting appeared in that time frame. We finally had visual confirmation that Matisse tamped down earlier layers of pinks, greens, and blues into a somber palette of modulated grays, punctuated with some pinks and turquoise. This agrees with how the artist and visitors who saw the painting at that time described it [1]. That insight helps support research that has for the first time uncovered how Matisse began the work as a highly chromatic, more



**[FIG7]** Color hints used to colorize Figure 2 based on the proposed techniques and input from conservators and art historians.



**[FIG8]** *Bathers by the River*, as appeared in November 1913, colorized by the proposed technique.

naturalistic scene but changed it to boldly explore new artistic directions, at the same time reflecting the graver national mood brought on by World War I [1]. Furthermore, the colorized version helped curators and art historians visualize the process by which Matisse composed and transformed this complex work to reach its final form and to identify other works by the artist reflecting a sensibility similar to the painting at its various stages. We encourage our read-

ers to visit the Web site in [2] for an online tutorial and interactive demo on this painting and its reconstruction.

#### MOVING AHEAD

Painting colorization is a particularly interesting colorization application since it poses significant requirements on the accuracy and precision of the colorization and color transfer process. Although colorization may have lost ground in the broadcast arena [6], in

the arts it offers a unique exploration and visualization tool for art historians and conservators that can sometimes lead to revelatory consequences. This work involved a large interdisciplinary team of engineers, conservators, scientists, and art historians to bring it to fruition. It took almost three years to reach our goal and we were faced with computational, organizational, and visualization challenges. Images colorized at Northwestern would look different when viewed at the Art Institute of Chicago, only because our computer monitors adhered to different display standards and characteristics. Therefore, we had to agree on display profiles and use the same application to view our results. Data transfer and copyrights were important since certain findings and artifacts were not publicly available and copyrights were not cleared. Dedicated servers were deployed to facilitate the transfer of large data sets (in the hundreds of megabytes) in a private manner. Due to copyright restrictions, all publications were embargoed until the unveiling of the exhibit in Chicago in spring 2010. (In [3], the authors warn engineers about issues of copyright and ownership and the not so timely, according to academic standards, public dissemination of findings.)

This has been a wonderful learning experience for all parties involved. Other museums and collections have expressed interest in adopting our methodologies in colorizing works of Willem de Kooning and Pablo Picasso. Through this process we discovered that other tools, such as the automated method to find regions of similarity, image registration, and techniques to correct for illumination, are very helpful to art conservation and research. When packaged in an easy-to-use and intuitive interface these techniques truly facilitate day-to-day conservation and scholarly work.

The partnership between Northwestern University and the Art Institute of Chicago is the first nondegree-granting multiyear collaboration in conservation science to involve an art museum in

the United States and a university and aims in building such tools. Works of art are dynamic entities and express a deep communication between the artist and viewer that does not need to be translated into words. It is direct and inspiring. The more we understand the visual message, the more we come to appreciate the artist's particular depth of expression. That is why art historians and conservators, with the aid of scientists, are always looking for new ways of getting under the skin and clarifying a work of art.

With this article we hope to invigorate research in the digital conservation of artworks and inspire a new generation of engineering students in tackling such problems that can bridge the world of science with the arts.

#### ACKNOWLEDGMENTS

This work was supported in part by a grant from the Andrew W. Mellon Foundation. The authors would like to thank Prof. Robert Erdmann of the University of Arizona in Tucson for making available his registered images of Druet and modern state. They would also like to thank Stephanie D'Alessandro, curator at the Art Institute of Chicago (AIC) and John Elderfield, cocurator of the exhibition, *Matisse: Radical Invention 1913–1917*, for providing the motivation for this work. They would also like to thank

Frank Zuccari, Grainger executive director of conservation at AIC, conservators (in particular Kelly Keegan and Lucia Bay), art historians, and imaging specialists at AIC that participated in this effort. Finally they would like to acknowledge the assistance of Jana Zujovic, Kai Hayashi, Benjamin Prosnitz, and Anna Targowska (students at Northwestern University at the time).

#### AUTHORS

**Sotirios A. Tsaftaris** (s-tsaftaris@northwestern.edu) is a research assistant professor with the Department of Electrical Engineering and Computer Science and the Department of Radiology, Feinberg School of Medicine at Northwestern University.

**Kristin H. Lister** (klister@artic.edu) is a paintings conservator at the Art Institute of Chicago where she specializes in modern and contemporary paintings.

**Inge Fiedler** (ifiedler@artic.edu) is the conservation microscopist at the Art Institute of Chicago.

**Francesca Casadio** (fcasadio@artic.edu) is the Andrew W. Mellon senior conservation scientist at the Art Institute of Chicago.

**Aggelos K. Katsaggelos** (aggk@eecs.northwestern.edu) is currently a professor with the Department of Electrical Engineering and Computer Science at Northwestern University.

#### REFERENCES

- [1] S. D'Alessandro and J. Elderfield, *Matisse: Radical Invention, 1913–1917*. Chicago, IL: Art Institute of Chicago, 2010.
- [2] Art Institute of Chicago. (25 Aug 2010). *Matisse: Radical Invention 1913–1917*. Exhibition Web site [Online]. Available: <http://www.artic.edu/aic/exhibitions/matisse/splash.html>
- [3] M. Barni, A. Pelagotti, and A. Piva, "Image processing for the analysis and conservation of paintings: Opportunities and challenges," *IEEE Signal Processing Mag.*, vol. 22, no. 5, pp. 141–144, 2005.
- [4] R. S. Berns, S. Byrns, F. Casadio, I. Fiedler, C. Gallagher, F. H. Imai, A. Newman, and L. A. Taplin, "Rejuvenating the color palette of Georges Seurat's a Sunday on La Grande Jatte—1884: A simulation," *Color Res. Appl.*, vol. 31, no. 4, pp. 278–293, 2006.
- [5] J. Glausiusz, "Matisse's methods revealed," *Nature*, vol. 464, no. 7288, pp. 493–494, Mar. 2010.
- [6] G. Burns. (2008). *Colorization. Encyclopedia of Television*. [Online]. Museum of Broadcast Communications, Chicago, IL. Available: <http://www.museum.tv/archives/etv/index.html>
- [7] T. Welsh, M. Ashikhmin, and K. Mueller, "Transferring color to greyscale images," *ACM Trans. Graph.*, vol. 21, no. 3, pp. 277–280, 2002.
- [8] D. Sýkora, J. Buriánek, and J. Žára, "Unsupervised colorization of black-and-white cartoons," in *NPAR '04: Proc. 3rd Int. Symp. Non-Photorealistic Animation and Rendering*, 2004, pp. 121–127.
- [9] A. Levin, D. Lischinski, and Y. Weiss, "Colorization using optimization," *ACM Trans. Graph.*, vol. 23, no. 3, pp. 689–694, 2004.
- [10] L. Yatziv and G. Sapiro, "Fast image and video colorization using chrominance blending," *IEEE Trans. Image Processing*, vol. 15, no. 5, pp. 1120–1129, 2006.
- [11] Q. Luan, F. Wen, D. Cohen-Or, L. Liang, Y. Xu, and H. Shum, "Natural image colorization," in *Proc. Eurographics Symp. Rendering Techniques*, Grenoble, France, 2007.
- [12] M. Styner, C. Brechbuhler, G. Szckely, and G. Gerig, "Parametric estimate of intensity inhomogeneities applied to MRI," *IEEE Trans. Med. Imag.*, vol. 19, no. 3, pp. 153–165, 2000.
- [13] I. J. Cox, S. Roy, and S. L. Hingorani, "Dynamic histogram warping of image pairs for constant image brightness," in *Proc. IEEE Int. Conf. Image Processing*, 1995, vol. 2, pp. 366–369.



Antonio Plaza, Javier Plaza,  
Abel Paz, and Sergio Sánchez

## Parallel Hyperspectral Image and Signal Processing

**R**emotely sensed hyperspectral imaging instruments are capable of collecting hundreds of images corresponding to different wave-

length channels for the same area on the surface of the Earth. For instance, NASA is continuously gathering high-dimensional image data with instruments such as the Jet Propulsion Laboratory's Airborne Visible-Infrared Imaging Spectrometer (AVIRIS). This advanced sensor for Earth observation

records the visible and near-infrared spectrum of the reflected light using more than 200 spectral bands, thus producing a stack of images in which each pixel (vector) is represented by a spectral signal that uniquely characterizes the underlying objects. The resulting data volume typically comprises several

Digital Object Identifier 10.1109/MSP.2011.940409  
Date of publication: 19 April 2011