Color Flows: A Joint Statistical Model of Color Change

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The Problem: In this research, we address the problem of whether two given images are digital photographs of the same scene under different photic parameter settings, or whether they are different physical scenes altogether. To do this, we develop a statistical linear model of *color change space*, by observing how the colors in static images change under naturally occurring lighting changes. This model describes how colors change *jointly* under typical (statistically common) photic parameter changes. Then, given a pair of images, we ask whether we can describe the difference between the two images, to within some tolerance, using the statistical color change model. If so, we conclude that the images are probably of the same scene.

Motivation: The number of possible images of an object or scene, even when taken from a single viewpoint with a fixed camera, is very large. Light sources, shadows, camera aperture, exposure time, transducer non-linearities, and camera processing (such as auto-gain-control and color balancing) can all affect the final image of a scene [5]. Humans seem to have no trouble at all compensating for these effects when they occur in small or moderate amounts. However, these effects have a significant impact on the digital images obtained with cameras and hence on image processing algorithms, often hampering or eliminating our ability to produce reliable recognition algorithms.

Addressing the variability of images due to these *photic parameters* has been an important problem in machine vision. We distinguish photic parameters from *geometric parameters*, such as camera orientation or blurring, that affect which parts of the scene a particular pixel represents. We also note that photic parameters are more general than "lighting parameters" that would typically only refer to light sources and shadowing. We include in photic parameters anything which affects the final RGB values in an image given that the geometric parameters and the objects in the scene have been fixed.

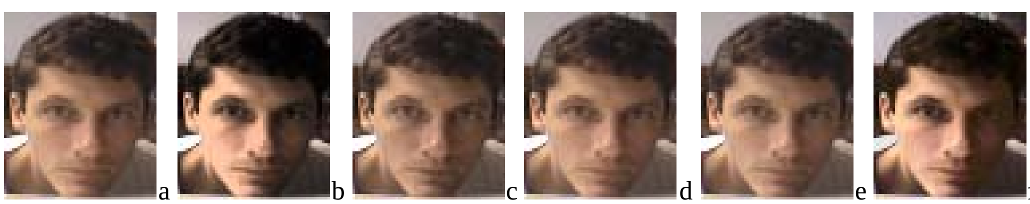

Figure 1: Image **b** is the result of applying a non-linear operator to the colors in image **a**. **c-f** are attempts to match **b** using **a** and four different algorithms. Our algorithm (image **f**) was the only one to capture the non-linearity.

Previous Work: There is a wide range of relevant previous work. A great deal of work has been done on color constancy, including recent contributions to modeling color change such as [6, 3, 7, 4]. Also closely related are discussions of the geometry of the set of images of an object, as discussed in [2, 1]. We differentiate ourselves by focusing on a statistical model. That is, we are interested not in all *possible* ways that colors in a scene can change, but in the *common color changes* which are captured by our model.

Approach: In [8], we introduced a linear statistical model of *joint color changes* in images due to variation in lighting and certain non-geometric camera parameters. By measuring the mappings of colors in one image of a scene to colors in another image of the same scene under different lighting conditions, we obtained a statistical model of common color mappings. We called these mappings *color flows*. They are meant to model not only common global lighting changes (which have an approximately linear effect on scene radiance), but also various non-linear camera

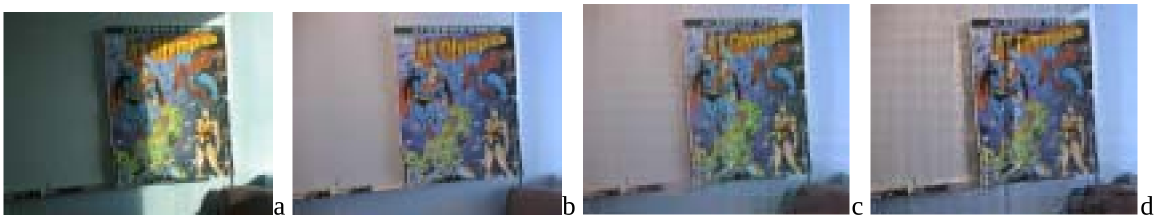

Figure 2: **a.** Image with strong shadow. **b.** The same image under more uniform lighting conditions. **c.** Flow from **a** to **b** using piecewise color flows. **d.** Flow from **a** to **b** using another common algorithm in a piecewise fashion.

effects such as aperture settings, transducer dynamics, and gain correction.

A color flow is a vector field in color space; each vector in the vector field starts at one color and ends at another. Since a vector field can be considered an element of a vector space, an ensemble of color flows can be studied using common statistical methods such as clustering and principal components analysis. We showed that the principal components of the ensemble of color flows (the basis fields that represented the directions of greatest variation in the ensemble) corresponded to common modes of color variation in images due to lighting changes, such as “brightness”, “warmth”, and “contrast”. We then demonstrated how color flows can be used to create a simple model for the variability in images of a new object using only a single example of that object.

Impact: Object recognition is a central problem in machine vision and artificial intelligence. Many innovations will be required to obtain robust object recognition, i.e. object recognition which is successful in different settings. We hope this research will be a significant contribution to improving object recognition in the context of lighting changes and uncalibrated cameras. A large number of potential application areas eagerly await robust object recognition technology, from manufacturing and assembly, to grocery checkout, automated automobile driving, security systems, robotic navigation, and many others.

Future Work: Models of joint color changes can be generalized to generic models of joint feature changes. When the features are colors, we obtain “color flows”. When the features in an image are the coordinates of a particular object, and the camera is moving, we find that the feature change fields are “optical flows”, a familiar object of study in machine vision. We hope to generalize our results to other areas, such as speech, in which models of joint frequency changes can be used to understand natural variability in the spoken word, such as changes in pitch or changes in speed.

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