# PRINCIPLED METHODS FOR COLOR DITHERING BASED ON MODELS OF THE HUMAN VISUAL SYSTEM

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## 1. Introduction

The problem of representing gray-level images on a binary display device is variously known as "dithering" or "halftoning." Previous approaches to the problem[1, 2, 3, 4, 5] have started with an algorithm, usually one which is easily computed, and then judged the results by visual comparison with the competing algorithms. An alternative approach begins by trying to characterize computationally what makes one image visually "better" than another. It is then possible in principle to find the halftone which is optimal in terms of visual quality, and the problem becomes one of searching for the optimum. This approach has been applied to monochrome images[6, 7, 8] with encouraging results. Here we apply this approach to color.

There are several ways in which monochrome dithering algorithms may be generalized to color images. The advent of video frame buffer devices with color lookup tables has spawned a class of algorithms which begin by computing a custom color palette for each image. In this paper, we will assume that the palette is fixed, which is the case for many printers and liquid crystal displays. When the palette is one which is "separable" in the red, green and blue components (i.e. a given level of one phosphor may be displayed regardless of the states of the other phosphors), then a simple approach is to apply your favorite achromatic dithering algorithm to the red, green and blue component images. We shall refer to this as the "independent component" method, since the resulting dither image for the red component does not depend on the values in the green or blue component images. (This method may not be suitable for printers, since the inks in general will not combine additively.)

A weakness of the independent component method (as well as most other standard methods) is that it does not exploit the fact that the human visual system has relatively poor acuity for chromatic signals[9] which do not vary in luminance. Humans can see quite fine detail when it is represented by luminance, but the same cannot be said for chromatic information. This fact of human perception made it feasible for the NTSC video broadcast standard to encode the chromatic information at a lower bandwidth than the luminance information. What we seek is a method that allows us to gain an increase in luminance resolution at the expense of introducing additional chromatic error, which will be less visible.

Our development follows previous work[6, 7, 8] applying search algorithms to the problem of halftoning monochromatic images. There has been at least one previous effort to apply these algorithms to color images[10] , but this work did not attempt to exploit the differential spatial sensitivity of the human visual system.

## 2. Algorithm

We assume the input target image is represented by an array of triples which represent the desired colors for each of the locations. We also maintain a representation of the current output halftone image; in general the results will depend on the details of how this image is initialized. Good results have been obtained by initializing with both a blank field and with a noise image. We define the *local quantization error* to be the difference between the desired image and the quantized image at each point. For color images, this is a three dimensional vector.

The contrast sensitivity function[11] describes the visibility of a near-threshold signal on a uniform background, and can be used to predict the visibility of the halftone quantization error in a region of uniform gray level. While this simple model for the visibility of errors may not be completely accurate for regions where the target image is *not* uniform, it is nevertheless a good starting point. The contrast sensitivity function (CSF) describes the visibility of signals as a function of spatial frequency; for each spatial frequency and orientation, the sensitivity is defined to be the reciprocal of the contrast of the weakest signal that can be seen. Analogous measurements have been made for purely chromatic signals[9] and show decreased sensitivity at high frequencies, but relatively constant sensitivity at low the log of the total squared error for each of the components. The important feature of the graph is that it confirms our intuition that we can use the weights in the procedure to achieve a tradeoff between the component errors in the output images.

## 4. Summary

We have formulated the color dithering problem as an optimization problem with respect to a simple model of the visibility of errors to the human visual system. The method is capable of producing output images which are superior to competing methods (or indistinguishable in the case where both are indistinguishable from the target image). We feel that our results will be valuable in terms of establishing an upper bound on the performance of any and all halftoning schemes which have yet to be invented; the knowledge that a theoretically optimal solution exists may tell other researchers when the law of diminishing returns dictates that further efforts to improve the quality of halftone images will be fruitless.

The availability of an algorithm to find the optimal halftone is also important in evaluating the potential quality of various hardware designs for display devices. In order to fairly compare two given display designs (possibly differing in dot pitch, or pixel chromaticities), we should not assume that a good halftone rendition for one display will be a good rendition for the second display.

Finally, we note that the quality of the final halftones produced by our algorithm depends critically on the quality of our visual model. This is an area where there is still work to be done. The simple model presented here is based on the detection threshold of small signals; we believe that a different type of model is needed for the case where the quantization errors are well above threshold, in which case a better goal might be to make the quantization errors maximally segregable from the image to be rendered.

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