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Low Noise Color Error Diffusion using the 8-Color Planes

Hidemasa Nakai, Koji Nakano *

Abstract—**Digital color halftoning is a process to convert a continuous-tone color image into an image with a limited number of colors. This process is required to generate an image reproducing the colors, the tone, and the details of the original continuous-tone color image. An elementary color halftoning method is to apply halftoning techniques independently to each of the color planes. For example, a full color image is separated into three continuous-tone images with C (Cyan), M (Magenta), and Y (Yellow) process colors, and each of them is independently converted to a binary image. Since this method ignores the relation among color planes, three process colors are overlapped randomly and it produces noisy and poor printing results. The main contribution of this paper is to present a new color error diffusion method. The key idea of our new method is to uniformly distribute pixels of 8 combination colors CMY, CM, CY, MY, C, M, Y, and W obtained by combining three process colors C, M, and Y. Also, the brightness of the resulting images are equalized using the error diffusion. The experimental results show that our new color halftoning technique generates better quality printing results compared to the independent color error diffusion method.**

Keywords: Image processing, Color halftoning, Error diffusion, 8-color planes

1 Introduction

Digital color halftoning is an important process to convert a continuous-tone color image into an image with a limited number of colors such as low-cost displays and printers [1, 2, 3]. This process is necessary when printing a digital color image by a printer with C (Cyan), M (Magenta), and Y (Yellow) process color inks. It is required to generate images reproducing the color, the tone, and the details of the original full color continuous-tone color image. Sometimes, Black ink (K) is used to get better printing results for black colors. In this paper, for simplicity, we assume that three colors CMY is used to print images. However, it is not difficult to extend our color halftoning technique to use four colors CMYK.

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Suppose that three color continuous-tone images G_C (Cyan), G_M (Magenta), and G_Y (Yellow) of size $N \times N$ are given. For simplicity, we assume that all images in this paper is square. Let $g_p(i, j)$ ($p \in \{C, M, Y\}$) denote the color density of pixel at position (i, j) ($0 \le i, j \le N-1$) of G_p taking a real number in the range $[0, 1]$. The task of a color halftoning is to generate three binary images B_C (Cyan), B_M (Magenta), and B_Y (Yellow) of size $N \times N$. Let $b_p(i, j)$ ($p \in \{C, M, Y\}$) denote the pixel value at position (i, j) ($0 \le i, j \le N-1$) of G_p taking a binary value either 0 (white) or 1 (color p).

A lot of gray-scale halftoning methods, which generate a binary image from a gray-scale image, have been presented [1]. One of the most popular gray-scale halftoning algorithms is error diffusion [3, 4, 5, 6] that propagates quantize errors to unprocessed neighboring pixels according to some fixed ratios. However, since the error diffusion may generate worm artifacts especially in the image areas of flat intensity, various algorithm are proposed [5, 6, 7]. Most of color inkjet printers are using the error diffusion technique to generate binary images B_C, B_M, and B_Y for printing. They use the elementary color halftoning that generates B_C, B_M, and B_Y independently from three continuous-tone images G_C, G_M, and G_Y. Since this independent color halftoning method ignores the relation among color planes, it produces noisy and poor printing results [8, 9, 10, 11].

The main contribution of this paper is to present a new color error diffusion method which takes care of pixel distribution of each of the 8-color planes. In our new method, the input three gray-scale images G_C, G_M, and G_Y are converted to 8 gray-scale images $G_{\mathcal{CMY}}$, $G_{\mathcal{CM}}$, $G_{\mathcal{CY}}$, $G_{\mathcal{MY}}$, $G_{\mathcal{C}}$, $G_{\mathcal{M}}$, $G_{\mathcal{Y}}$, and $G_{\mathcal{W}}$ which correspond to CMY (Black), CM (Blue), CY (Green), MY (Red), C (Cyan), M (Magenta) Y (Yellow), and W (White) colors. Based on these combination colors, the brightness image G_b is generated using the brightness data of Japan Color 2001 Coated (JCC). The key idea of our new method is to select one of the 8 colors that minimizes the the total error of the 8-color planes, the 3-color planes, and the brightness image using the error diffusion technique. Thus, our color halftoning method distribute the pixels of 8 combined colors as equal as possible, and also the tone of 3 process colors of the original image are reproduces. Also, since the error of brightness, for which human eyes

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are sensitive, is minimized, the noise of the resulting image is quite small. Since we use the brightness data of the JCC, the resulting binary images are optimized for offset printing for coated papers. Although the resulting image optimized for the JCC, our method can be applied for other printing devices if the brightness data is available. The experimental results show that our new color halftoning technique generates better quality printing results compared to the independent color error diffusion method.

2 Error Diffusion

The main purpose of this section is to review the error diffusion method [4] that generates a binary image from a gray-scale image.

The error diffusion method is designed to preserve the average density level between input and output images by propagating the quantization errors to unprocessed neighboring pixels according to some fixed ratios. The algorithm is one of the most popular gray-scale halftoning algorithms. Suppose that a gray-scale image G is given. The error diffusion method generates a binary image B reproduces the original tone of G. Let $g(i,j)$ denote the density of pixel at position (i,j) $(0 \leq i,j \leq N-1)$ of G taking a real number in the range $[0,1]$. Also, let $b(i,j)$ denote the density of pixel position (i,j) $(0 \leq i,j \leq N-1)$ of B taking a binary value either 0 (white) or 1 (black).

The error diffusion method determines the values of all $b(i,j)$ in the raster scan order. Suppose that we are now in position to determine the value of $b(i,j)$. We define that the error $e(i,j)$ as follows:

$$e(i,j) = g(i,j) - b(i,j).$$

The value of $b(i,j)$ is selected such that the absolute value of error $|e(i,j)|$ is minimized. In other words, the value of $b(i,j)$ can be determined by simply compared with the threshold value $\frac{1}{2}$ as follows:

$$b(i,j) = \begin{cases} 1 & \text{if } g(i,j) > \frac{1}{2}, \\ 0 & \text{if } g(i,j) \leq \frac{1}{2}. \end{cases}$$

The error $e(i,j)$ is diffused unprocessed pixels using filter in Figure 1 as follows:

$$g(i+k, j+l) \quad \leftarrow \quad g(i+k, j+l) + \omega_{k,l} \cdot e(i,j). \quad (1)$$

Since the sum of the coefficient of $e(i,j)$ is 1, the total density of pixels is preserved.

Figure 2 illustrates the block diagram of the error diffusion.

3 Our New Color Halftonig Method

The main purpose of this section is to show the overview of our color halftoning method. Recall that

	●	7/16
3/16	5/16	1/16

Figure 1: Floyd and Steinberg error filter

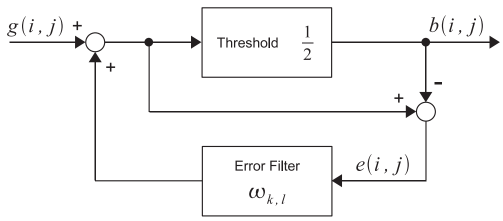

Figure 2: The block diagram of the error diffusion

G_C (Cyan), G_M (Magenta), and G_Y (Yellow) are the input continuous-tone images of size $N \times N$ with each pixel $g_C(i,j)$, $g_M(i,j)$, and $g_Y(i,j)$ at position (i,j) taking real numbers in range $[0,1]$. Our goal is to compute binary images B_C, B_M, and B_Y of size $N \times N$ with each pixel $b_C(i,j)$, $b_M(i,j)$, and $b_Y(i,j)$ taking a binary value either 0 or 1.

For later reference, let P_3 be the set of 3 process colors $\{C, M, Y\}$. Also let $P_8 = \{\mathcal{CMY}, \mathcal{CM}, \mathcal{CY}, \mathcal{MY}, \mathcal{C}, \mathcal{M}, \mathcal{Y}, \mathcal{W}\}$ be a set of combination of the three process colors, which is essentially the power set of three process colors $\{C, M, Y\}$. The color $\mathcal{W}$ corresponds to no color, i.e. White.

Our color halftoning method has three steps as follows:

Step 1 From the input gray-scale images G_C, G_M, G_Y, the eight gray-scale images $G_{\mathcal{CMY}}$, $G_{\mathcal{CM}}$, $G_{\mathcal{CY}}$, $G_{\mathcal{MY}}$, $G_{\mathcal{C}}$, $G_{\mathcal{M}}$, $G_{\mathcal{Y}}$, and, $G_{\mathcal{W}}$ of size $N \times N$ are generated.

Step 2 Using the error diffusion based color halftoning, eight binary images $B_{\mathcal{CMY}}$, $B_{\mathcal{CM}}$, $B_{\mathcal{CY}}$, $B_{\mathcal{MY}}$, $B_{\mathcal{C}}$, $B_{\mathcal{M}}$, $B_{\mathcal{Y}}$, $B_{\mathcal{W}}$ are computed.

Step 3 Three binary images B_C, B_M, and B_Y are computed from the eight binary images.

Note that, in Step 1, the subscripts of G corresponds to an element (i.e. combined color) of P_8. For example, the pixel values of $G_{\mathcal{CM}}$ represent the combination of C and M colors. Let $g_p(i,j)$ denote the pixel density of G_p for each combination color $p \in P_8$. We will omit argument (i,j) of $g_p(i,j)$ if it is clear. Intuitively, each $g_p(i,j)$ denote *the probability that combination color* $p \in P_8$ is used for pixel at position (i,j) of the output binary images. The eight gray-scale images are computed such that the densities of process colors C, M, and Y are preserved. In

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other words, for each pixel at position (i, j)

$$\begin{aligned} g_C &= g_{\mathcal{CMY}} + g_{\mathcal{CM}} + g_{\mathcal{CY}} + g_{\mathcal{C}} \\ g_M &= g_{\mathcal{CMY}} + g_{\mathcal{CM}} + g_{\mathcal{MY}} + g_{\mathcal{M}} \\ g_Y &= g_{\mathcal{CMY}} + g_{\mathcal{CY}} + g_{\mathcal{MY}} + g_{\mathcal{Y}} \end{aligned} \tag{2}$$

must be satisfied. Also, since each g_p corresponds to the probability of combination color $p \in P_8$ the sum of them is 1, that is,

$$\begin{aligned} g_{\mathcal{CMY}} + g_{\mathcal{CM}} + g_{\mathcal{CY}} + g_{\mathcal{M}} & \\ + g_{\mathcal{C}} + g_{\mathcal{M}} + g_{\mathcal{Y}} + g_{\mathcal{W}} &= 1 \end{aligned} \tag{3}$$

must be satisfied.

In Step 2, the error diffusion technique is used to determine binary image B_p for each combination color $p \in P_8$. Let $b_p(i, j)$ denote the value of B_p at position (i, j). Similarly, we omit the argument (i, j) if it is clear. The values are determined such that exactly one of $b_p(i, j)$ is 1 and $b_p(i, j)$ is 0 for the other colors. In other words,

$$\begin{aligned} b_{\mathcal{CMY}} + b_{\mathcal{CM}} + b_{\mathcal{CY}} + b_{\mathcal{M}} & \\ + b_{\mathcal{C}} + b_{\mathcal{M}} + b_{\mathcal{Y}} + b_{\mathcal{W}} &= 1 \end{aligned} \tag{4}$$

is satisfied. After that, in Step 3, pixels $b_C(i, j)$, $b_M(i, j)$, and $b_Y(i, j)$ in the three output binary images B_C, B_M, and B_Y are computed by the following formula:

$$\begin{aligned} b_C &= b_{\mathcal{CMY}} + b_{\mathcal{CM}} + b_{\mathcal{CY}} + b_{\mathcal{C}}, \\ b_M &= b_{\mathcal{CMY}} + b_{\mathcal{CM}} + b_{\mathcal{MY}} + b_{\mathcal{M}}, \\ b_Y &= b_{\mathcal{CMY}} + b_{\mathcal{CY}} + b_{\mathcal{MY}} + b_{\mathcal{Y}}. \end{aligned} \tag{5}$$

For example, if $b_{\mathcal{CM}} = 1$, then $b_C = b_M = 1$ and $b_Y = 0$.

In the following sections, we will show the details of Steps 1 and 2.

4 8-Color Space Separation

This section shows the details of Step 1. The goal of Step 1 is to determine eight gray-scale images $G_{\mathcal{CMY}}$, $G_{\mathcal{CM}}$, $G_{\mathcal{CY}}$, $G_{\mathcal{MY}}$, $G_{\mathcal{C}}$, $G_{\mathcal{M}}$, $G_{\mathcal{Y}}$, and $G_{\mathcal{W}}$ from the input three gray-scale images G_C, G_M, and G_Y.

Intuitively, we can consider that $g_C(i, j)$, $g_M(i, j)$, and $g_Y(i, j)$ correspond to the probability that $b_C(i, j) = 1$, $b_M(i, j) = 1$, and $b_Y(i, j) = 1$, respectively. We also consider that $g_{\mathcal{CMY}}$ corresponds the probability that $b_C(i, j) = b_M(i, j) = b_Y(i, j) = 1$. Similarly, $g_{\mathcal{CM}}$ corresponds to the probability that $b_C(i, j) = b_M(i, j) = 1$ and $b_Y(i, j) = 0$. Also, $g_{\mathcal{C}}$ is the probability that $b_C(i, j) = 1$ and $b_M(i, j) = b_Y(i, j) = 0$, and $g_{\mathcal{W}}$ is the probability that $b_C(i, j) = b_M(i, j) = b_Y(i, j) = 0$. Based on this consideration, we compute the values of eight color gray-scale images by the following formulas:

$$\begin{aligned} g_{\mathcal{CMY}} &= g_C \cdot g_M \cdot g_Y, \\ g_{\mathcal{CM}} &= g_C \cdot g_M - g_{\mathcal{CMY}}, \\ g_{\mathcal{CY}} &= g_C \cdot g_Y - g_{\mathcal{CMY}}, \\ g_{\mathcal{MY}} &= g_M \cdot g_Y - g_{\mathcal{CMY}}, \\ g_{\mathcal{C}} &= g_C - (g_{\mathcal{CMY}} + g_{\mathcal{CM}} + g_{\mathcal{CY}}), \\ g_{\mathcal{M}} &= g_M - (g_{\mathcal{CMY}} + g_{\mathcal{CM}} + g_{\mathcal{MY}}), \\ g_{\mathcal{Y}} &= g_Y - (g_{\mathcal{CMY}} + g_{\mathcal{CY}} + g_{\mathcal{MY}}), \\ g_{\mathcal{W}} &= 1 - (g_{\mathcal{CMY}} + g_{\mathcal{CM}} + g_{\mathcal{CY}} + \\ & \qquad g_{\mathcal{MY}} + g_{\mathcal{C}} + g_{\mathcal{M}} + g_{\mathcal{Y}}). \end{aligned} \tag{6}$$

Clearly, the values computed by these formulas satisfy the formulas (2) and (3). Thus, the eight gray-scale images $G_{\mathcal{CMY}}$, $G_{\mathcal{CM}}$, $G_{\mathcal{CY}}$, $G_{\mathcal{MY}}$, $G_{\mathcal{C}}$, $G_{\mathcal{M}}$, $G_{\mathcal{Y}}$, and $G_{\mathcal{W}}$ preserve the color of the input three gray-scale images G_C, G_M, and G_Y.

5 Error Diffusion for 8-Color Planes

This section is devoted to show the details of Step 2 of our halftoning algorithm. In Step 2, eight gray-scale images G_p $(p \in P_8)$ are given and we compute eight binary images B_p to satisfy formula (4). We use the sum of three errors that we define in this section.

In our algorithm, the pixel values of the three binary images are determined in the raster scan order in parallel. Assume that we are now in position to determine the binary value of $b_q(i, j)$ $(q \in P_8)$. Suppose that a combination color $p \in P_8$ is selected for the pixel at position (i, j). In other words,

$$\begin{aligned} b_q(i, j) &= 1 \quad \text{if } q = p, \\ &= 0 \quad \text{if } q \neq p. \end{aligned}$$

We will define the three types errors $e_8(i, j)$, $e_3(i, j)$, and $e_b(i, j)$.

The error of combination color $q \in P_8$ at position (i, j) can be computed by the following formula:

$$e_q(i, j) = g_q(i, j) - b_q(i, j). \tag{7}$$

We compute the total error $e_8(i, j)$ of the 8-color planes by the average of the absolute values:

$$e_8(i, j) = \frac{\sum_{q \in P_8} |e_q(i, j)|}{8}.$$

We also define the error for process color $q \in P_3$. Using formula (5) we can determine the value of $b_C(i, j)$, $b_M(i, j)$, and $b_Y(i, j)$. Similarly, we can define the error for color q using the formula (7). The total error $e_3(i, j)$ of the 3-color planes in the same way as follows:

$$e_3(i, j) = \frac{\sum_{q \in P_3} |e_q(i, j)|}{3}.$$

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Table 1: Brightness by the JCC

color q	brightness d_q
$\mathcal{CMY}$ ■	0.686
$\mathcal{CM}$ ■	0.682
$\mathcal{CY}$ ■	0.357
$\mathcal{MY}$ ■	0.384
$\mathcal{C}$ ■	0.310
$\mathcal{M}$ ■	0.384
$\mathcal{Y}$ ■	0.039
$\mathcal{W}$ □	0

From the values of eight color images G_q ($q \in P_8$), we generate the brightness image G_b based on the brightness defined in Japan Color 2001 Coated (JCC) which is a color profile for offset printing using standard coated papers in Japan. Let d_q be the brightness of the JCC shown in Table 1. Let $g_b(i,j)$ denote the density of brightness image G_b at position (i,j). The value of $g_b(i,j)$ can be computed by the following formula:

$$g_b(i,j) = \sum_{q \in P_8} d_q \cdot g_q(i,j).$$

For selected color p ($\in P_8$), we can compute the error $e_b(i,j)$ as follows:

$$e_b(i,j) = g_b(i,j) - \sum_{q \in P_8} d_q \cdot b_q(i,j).$$

We compute the total error $e(i,j)$ of the three errors:

$$e(i,j) = e_8(i,j) + e_3(i,j) + |e_b(i,j)|.$$

We select color p in $\in P$ that minimizes the error $e(i,j)$. In other words, we select p such that

$$p = \arg\min_{p \in P_8} e(i,j).$$

Figure 3 illustrates the block diagram of the error computation in our new color halftoning algorithm.

If color p is selected, we diffuse the error of the 8-color planes to unprocessed pixels. The error $e_q(i,j)$ ($q \in P_8$) is distributed to the neighboring pixels in G_q using formula (1).

6 Experimental Results

This section shows the experimental results. We compare our new color error diffusion method with the elementary independent color error diffusion.

Figure 4 shows the resulting binary image for a solid patch with color $g_C = 0.4$ and $g_M = 0.3$. In Figure 4 (a), the independent color error diffusion generates a noisy and poor printing result. On the other hand, our color halftoning algorithm (Figure 4 (b)) generates better quality image. It has few noises and the variation of the brightness in the resulting image is small.

Let us analyze the resulting images in Figure 4 by partitioning them into combination color planes. Figures 5 and 6 show the resulting image of combined color planes $B_{\mathcal{CM}}$, $B_{\mathcal{C}}$, $B_{\mathcal{M}}$, and $B_{\mathcal{W}}$ for the images in Figure 4. Note that white and black pixels of $B_{\mathcal{W}}$ in the figure correspond to the pixels such that $b_{\mathcal{W}}(i,j) = 1$ and $b_{\mathcal{W}}(i,j) = 0$, respectively. Each color plane of the independent color error diffusion is somewhat noisy due to the randomness of the overlapping of the colors. Therefore, the image in Figure 4 (a) is noisy and poor. Clearly, each of combination images of our color halftoning method in Figure 4 (b) has uniform pixel distribution, which results a few noise and high quality image.

Figure 7 shows the input color ramp image and the resulting images obtained by the independent color error diffusion and our new color halftoning algorithm. The resulting image of the independent color diffusion has too many dots with combined colors CMY (black) and W (white), that results noisy feeling. We can see that the resulting image of our new halftoning algorithm reproduces the tone of the original ramp image and has fewer artifacts and CMY and W dots.

7 Conclusions

In this paper, we have presented a low noise color error diffusion method using the 8-color planes. Our color error diffusion method can generate the low noise color halftone images to select one of the 8 colors that minimizes the error of the sum of 8-color planes, 3-color planes, and the brightness image by the JCC. As a result, our color error diffusion method achieves better quality printing results compared to the elementary independent color error diffusion and get the images optimized for offset printing.

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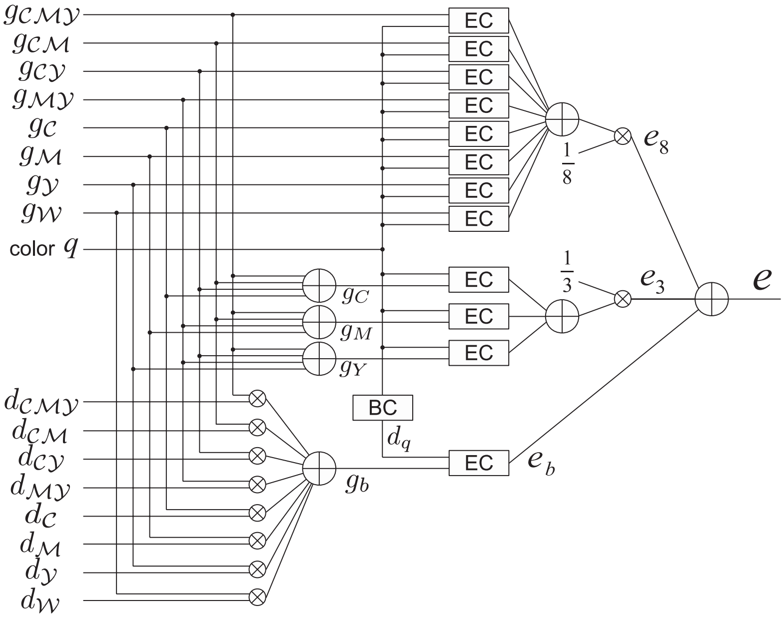

EC: Error Computation, BC: Brightness Conversion

Figure 3: The block diagram of the operation for computing error e

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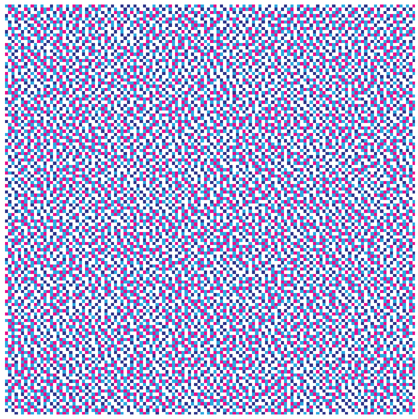
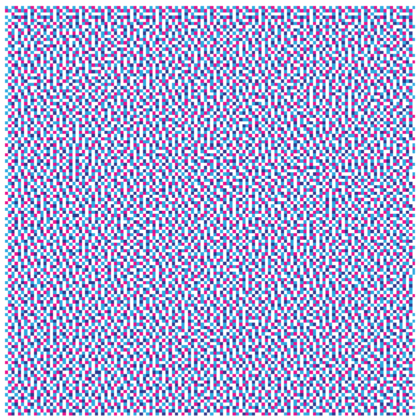


(a) The independent color error diffusion



(b) Our new color halftoning

Figure 4: The resulting image for a solid color patch, $g_C = 0.4$, $g_M = 0.3$

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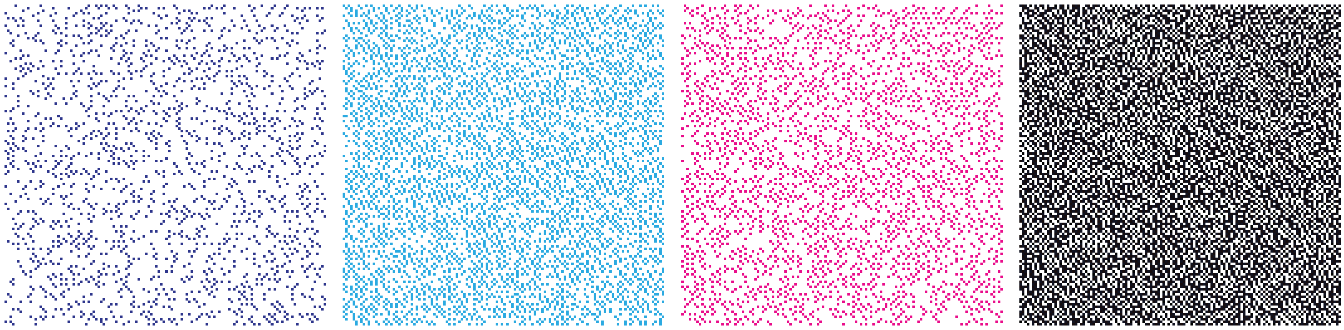
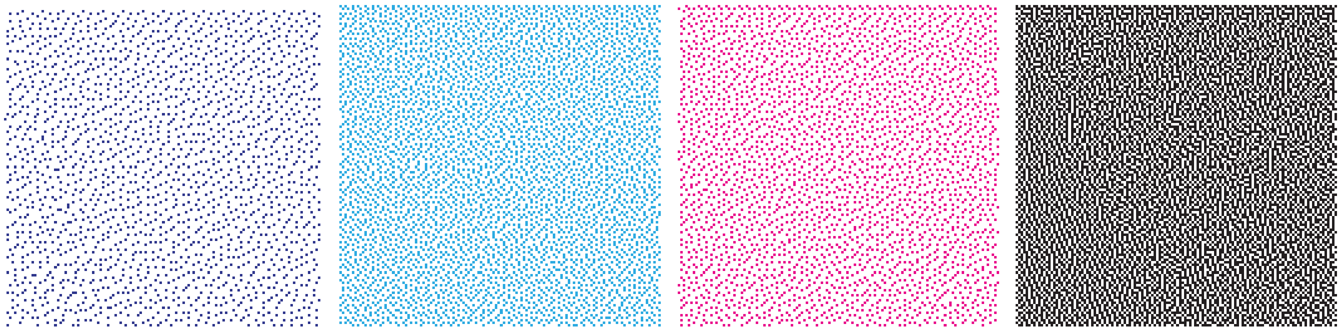


(a) plane $B_{\mathcal{CM}}$ (b) plane $B_{\mathcal{C}}$ (c) plane $B_{\mathcal{M}}$ (d) plane $B_{\mathcal{W}}$

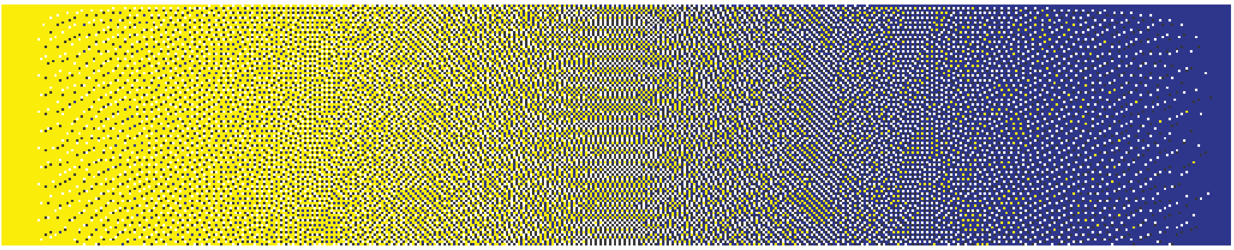
Figure 5: Each of the color planes for a solid color patch by the independent color error diffusion



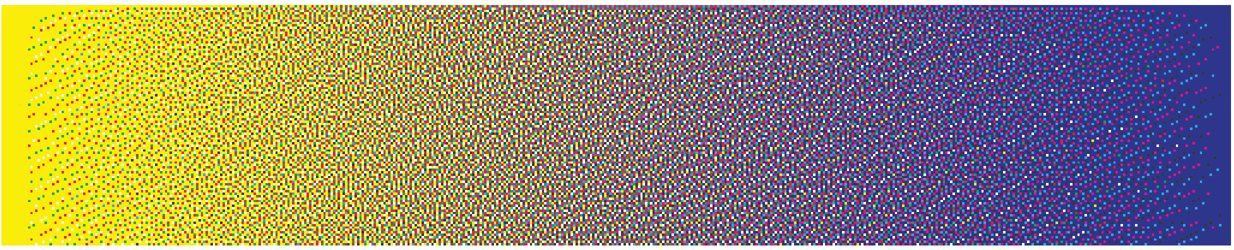
(a) plane $B_{\mathcal{CM}}$ (b) plane $B_{\mathcal{C}}$ (c) plane $B_{\mathcal{M}}$ (d) plane $B_{\mathcal{W}}$

Figure 6: Each of the color planes for a solid color patch by our new color halftoning

(a) The original color ramp image



(b) The resulting image by the independent color error diffusion



(c) The resulting image by our new color halftoning

Figure 7: The resulting color halftone images for a color ramp

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