Noise Cleaning Digital Camera Images to Improve Color Fidelity Capabilities

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Abstract

In digital cameras, noise in the raw captured image significantly influences the potential color fidelity of the final processed image. This occurs because any amplification of the color values in an image, will also amplify the noise in the image. In order to control the visibility of noise in the final processed image, the camera designer is frequently forced to constrain the tuning of the color correction operation in a way that reduces the final color fidelity. By properly noise cleaning the original image data, the amount of noise in the input image to the color correction step can be greatly reduced. Consequently, the amount of noise in the output is also reduced. If the amount of noise in the color-corrected image is reduced well below the acceptable level, then more aggressive corrections can be achieved without unacceptably high amounts of noise appearing in the final processed image. These aggressive corrections can, in turn, be used to produce higher color fidelity in the finished image.

Introduction

In digital cameras, noise in the raw captured image significantly influences the potential color fidelity of the final processed image. This occurs because any amplification of the color values in an image, will also amplify the noise in the image. In order to control the visibility of noise in the final processed image, the camera designer is frequently forced to constrain the tuning of the color correction operation in a way that reduces the final color fidelity.

As an example of the interactions of noise and color fidelity, consider a color correction achieved with a simple 3 x 3 matrix (Eq. 1).

$$\begin{pmatrix} R_{out} \\ G_{out} \\ B_{out} \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \begin{pmatrix} R_{in} \\ G_{in} \\ B_{in} \end{pmatrix} \tag{1}$$

If we assume that each color channel contains simple, additive Gaussian noise, then the noise in the output can be related to the noise in the input by the familiar relationship given in Eq. 2.

$$\begin{aligned} \sigma_{R,out} &= \sqrt{(a_{11}\sigma_{R,in})^2 + (a_{12}\sigma_{G,in})^2 + (a_{13}\sigma_{B,in})^2} \\ \sigma_{G,out} &= \sqrt{(a_{21}\sigma_{R,in})^2 + (a_{22}\sigma_{G,in})^2 + (a_{23}\sigma_{B,in})^2} \\ \sigma_{B,out} &= \sqrt{(a_{31}\sigma_{R,in})^2 + (a_{32}\sigma_{G,in})^2 + (a_{33}\sigma_{B,in})^2} \end{aligned} \tag{2}$$

Generally, the matrix coefficients will be designed to row sum to unity to preserve the neutral balance of the image. Many digital camera systems will require the diagonal elements to be greater than or equal to one, to achieve optimal color correction. As a consequence of the diagonal coefficients being greater than or equal to one the output will have at least as much noise as the input because of the contributions of the diagonal matrix terms. Non-zero off-diagonal matrix terms will increase the amount of noise in the output even more. These additional noise contributions to the output can be minimized by keeping the magnitudes of the off-diagonal matrix coefficients as small as possible. However, as the off-diagonal matrix coefficients are reduced in magnitude, the color correction matrix is forced towards becoming the identity matrix if the row summing to unity condition is maintained. As a result, the color matrix cannot produce as complete a correction of the color values as might otherwise be desired. Therefore, the consequence of reducing noise in the output signal is likely to be a reduction of color fidelity of the final image. Example images illustrating this compromise are found on the CD-ROM. Image 1 was created using a color correction matrix that reproduced the colors of the original with maximum accuracy. Close examination reveals a significant amount of noise in the image. By reducing the aggressiveness of the color matrix, an image can be created with reduced noise visibility. To this end, image 2 was created using a color matrix that reproduces the colors of the scene with less accuracy, but also less visible noise.

Noise Cleaning Before Interpolation

The fundamental solutions to this problem are to improve the image capture hardware to reduce the amount of noise injected into the image in the first place, adjust the spectral sensitivities of the color capture channels to minimize the required color correction, and to improve the capture conditions of the image, e.g., make sure the scene is properly illuminated. Assuming as much as can be practically done along these lines has occurred, it is up to the image processing chain to address the resulting noise in the image. The main solution available to the image processing chain is to noise clean the image data prior to color correction.

There are many well-known noise cleaning algorithms. However, simply placing a garden-variety noise cleaning operation (just prior to color correction) will probably not lead to an optimum solution. Because most digital cameras have only a single sensor covered with a color filter array, color filter array interpolation must be performed prior to color correction.[2,3] Depending on the nature of the color filter array interpolation algorithm, there is a potential for this operation to introduce noise amplification and it may also introduce patterned noise artifacts into the image. Therefore, the best place to perform noise cleaning is clearly at the very beginning of the image processing chain.

The challenge of noise cleaning at the beginning of the image processing chain is that the color information of the image is encoded into a single plane of image data by the color filter array. Hence, for any given color channel, the data is sparsely populated in a spatial sense. As a result, the chosen noise cleaning algorithm must be aware of the color filter array pattern to avoid mixing pixel information from different channels. Also, due to the sparse sampling of the color channel data, simple linear convolution operations may not perform as well as when applied to fully populated image data. Finally, because a full-color rendering of the image does not exist at this point of the image processing chain, the data must be treated as three separate gray scale images. Color transformation into other spaces, such as a luminance – chrominance space, is not possible. One is forced to work in the capture color space of the camera.

Through a study of known noise cleaning algorithms, it has been found that the sigma noise filter[1] can be adapted to work well with color filter array image data. The resulting version of the sigma noise filter uses a 5×5 kernel arranged to correspond to the color channel being processed at the moment. As an example, if the Bayer color filter array pattern[4] is being used, the resulting 5×5 pixel neighborhoods about each of the three color channels as shown in Fig. 1.

$$\begin{array}{ccccc} R & G & R & G & R \\ G & B & G & B & G \\ R & G & R & G & R \\ G & B & G & B & G \\ R & G & R & G & R \end{array} \qquad \begin{array}{ccccc} G & R & G & R & G \\ B & G & B & G & B \\ G & R & G & R & G \\ B & G & B & G & B \\ G & R & G & R & G \end{array}$$

(a) *(b)*

$$\begin{array}{ccccc} B & G & B & G & B \\ G & R & G & R & G \\ B & G & B & G & B \\ G & R & G & R & G \\ B & G & B & G & B \end{array}$$

(c)

Figure 1. Bayer pattern color filter array neighborhoods centered on red (a), green (b), and blue (c) pixels.

$$\frac{1}{9}\begin{pmatrix} 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 \end{pmatrix} \qquad \frac{1}{13}\begin{pmatrix} 1 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 \end{pmatrix}$$

(a) *(b)*

$$\frac{1}{9}\begin{pmatrix} 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 \end{pmatrix}$$

(c)

Figure 2. Potential blur kernels for Bayer pattern color filter array neighborhoods centered on red (a), green (b), and blue (c) pixels.

Figure 2 shows potential blur kernels that could be used to produce a noise cleaned pixel value for the central pixel in each neighborhood. The word "potential" is used because the sigma noise filter will selectively change one or more of the ones in a given blur kernel into zeros based on the local statistics of the pixel neighborhood. Images on the CD-ROM illustrate the improvements realized by this noise cleaning. The raw data used to create image 4 was first cleaned using a sigma noise filter and then passed to the rest of the image processing chain, using the less aggressive color matrix of image 2. The visible noise in image 4 is significantly reduced the noise in compared to image 2. The same noise cleaned data was used to create image 3, though in this case the more aggressive color matrix of image 1 was used.

Noise Cleaning During Interpolation

Even after noise cleaning the data prior to color filter array interpolation, additional noise cleaning can be performed during interpolation. Adaptive CFA (color filter array) interpolation algorithms[2,3] can make decisions on a pixel neighborhood by neighborhood basis as to the best orientation in which to perform interpolation. Consider the pixel neighborhood in Fig. 3.

$$\begin{array}{ccccc} & & R_1 & & \\ & & G_2 & & \\ R_3 & G_4 & R_5 & G_6 & R_7 \\ & & G_8 & & \\ & & R_9 & & \end{array}$$

Figure 3. Color filter array interpolation neighborhood for computing a green pixel value.

In order to estimate the missing pixel value G_5, pixel values in either the horizontal or vertical directions can be used. Assuming correlation between color planes can be exploited, the two possible estimates are given in Eqs. 3 and 4.

$$\hat{G}_5 = \frac{G_4 + G_6}{2} + \frac{3(2R_5 - R_3 - R_7)}{16} \tag{3}$$

$$\hat{G}_5 = \frac{G_2 + G_8}{2} + \frac{3(2R_5 - R_1 - R_9)}{16} \tag{4}$$

These equations are predicated on the assumption that some significant amount of scene detail can be detected within the pixel neighborhood. If detection of significant spatial information is weak, then the interpolation can switch to a noise cleaning mode, as given in Eq. 5.

$$\hat{G}_5 = \frac{G_2 + G_4 + G_6 + G_8}{4} \tag{5}$$

Similar opportunities exist for noise cleaning during other stages of the color filter array interpolation process. Image 6, found on the CD-ROM, illustrates the improvement had by applying the additional CFA interpolation noise cleaning step to the image processing chain. (Sigma noise filtering is also performed.) The color matrix used in image 6 is the same less aggressive matrix used in images 2 and 4. Differences between images 4 and 6 are most easily seen in the orange-yellow patch of the target. Image 5 also incorporates the CFA interpolation noise cleaning step, while using the more aggressive color matrix used in images 1 and 3. Again, the largest improvements are seen in the orange-yellow patch of the target.

Noise Cleaning After Interpolation

Because of the requirement to treat each color channel as a separate gray scale image, most of the improvements are made in the luminance information of the image. Once a full-color image has been rendered by the image processing chain, transformation into different color spaces can be used to allow for easier separation of noise from genuine scene detail. In particular, transformation into a luminance – chrominance space allows fairly aggressive noise cleaning to occur in the chrominance channels of the image while leaving the luminance data untouched. On the CD-ROM, image 1A is an example of such additional image processing. Image 1A was created from image 1 by transforming image 1 into CIELAB space, aggressively cleaning the a* and b* channels and then transforming the cleaned data back into the original RGB space. The cleaning techniques used on the chrominance channels were textbook implementations of morphological noise filters and the sigma noise filter. The same chrominance noise cleaning was applied to image 5 to produce image 5A. The resulting noise visibility in images 1A and 5A is greatly reduced from images 1 and 5.

Illustrative Images on the CD-ROM

To summarize the images on the CD-ROM, it is desired to produce an image using an aggressive color matrix that does an accurate job of reproducing the colors of the original scene. This results in image 1. Not being pleased with the amount of noise in the image, the aggressiveness of the color matrix is reduced, producing image 2. The noise is now less visible, but the color fidelity is also reduced. The first step to reduce the need to make this tradeoff between noise visibility and color fidelity is to noise clean the original CFA data using a sigma noise filter. This produces image 3 with the more aggressive color matrix and image 4 with the less aggressive color matrix. If the visibility of the noise in the image is still too high, additional noise cleaning is performed during the CFA interpolation operation. This produces image 5 with the more aggressive color matrix and image 6 with the less aggressive color matrix. These images also incorporate sigma noise cleaning of the original CFA data. Up to this point, the noise being addressed was mainly channel independent noise. Since the CFA interpolation process produces full-color image data, chrominance noise may now be targeted by transforming the image to a luminance – chrominance space and aggressively cleaning the chrominance channels. Cleaning the chrominance channels of images 1 and 5 produce images 1A and 5A. Both images 1A and 5A are largely devoid of any visible noise, meaning both images are probably acceptable. Since image 5A was created using a color matrix that produces an image with higher color fidelity, this is the image of choice. A final comparison between image 2 (no noise cleaning, lower color accuracy) and image 5A (noise cleaned, higher color accuracy) shows a significant improvement in the ability to produce acceptable images with higher color fidelity.

Conclusion

As a result of properly noise cleaning the original image data, the amount of noise in the input image to the color correction step is greatly reduced. Consequently, the amount of noise in the output is also reduced. If the amount of noise in the color-corrected image is reduced well below the acceptable level, then more aggressive corrections can be achieved without unacceptably high amounts of noise appearing in the final processed image. These aggressive corrections can, in turn, be used to produce higher color fidelity in the finished image.

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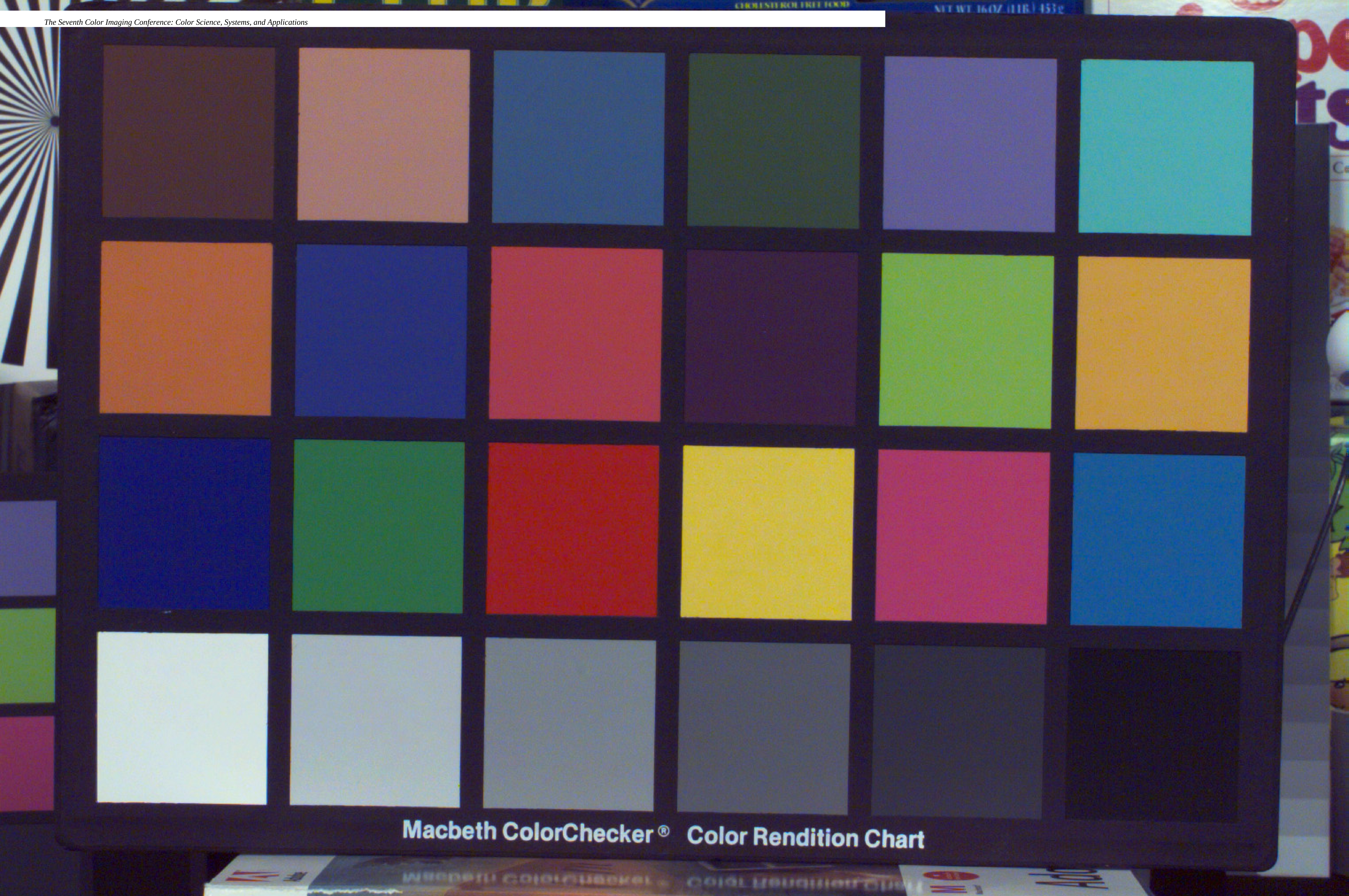
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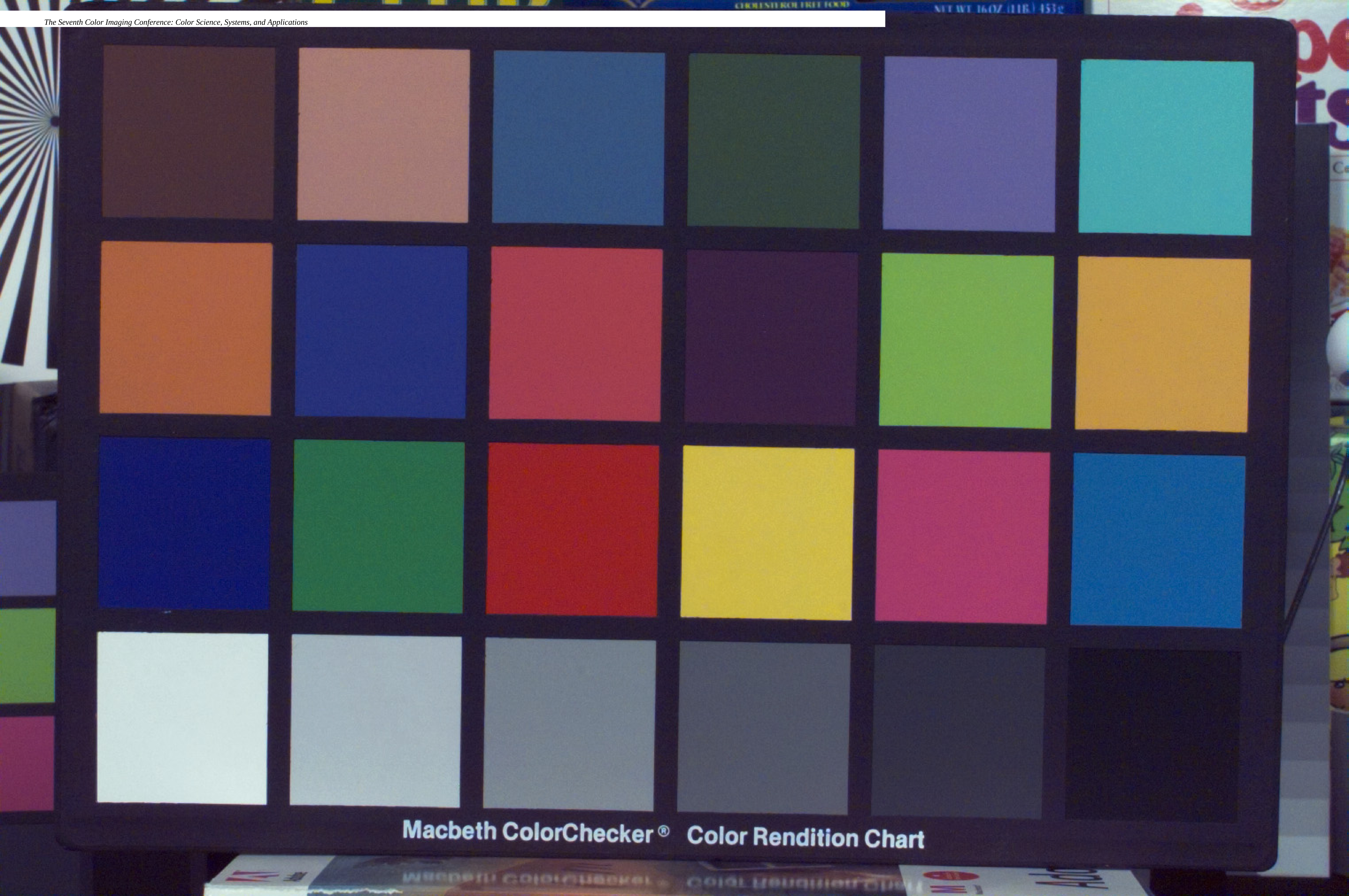

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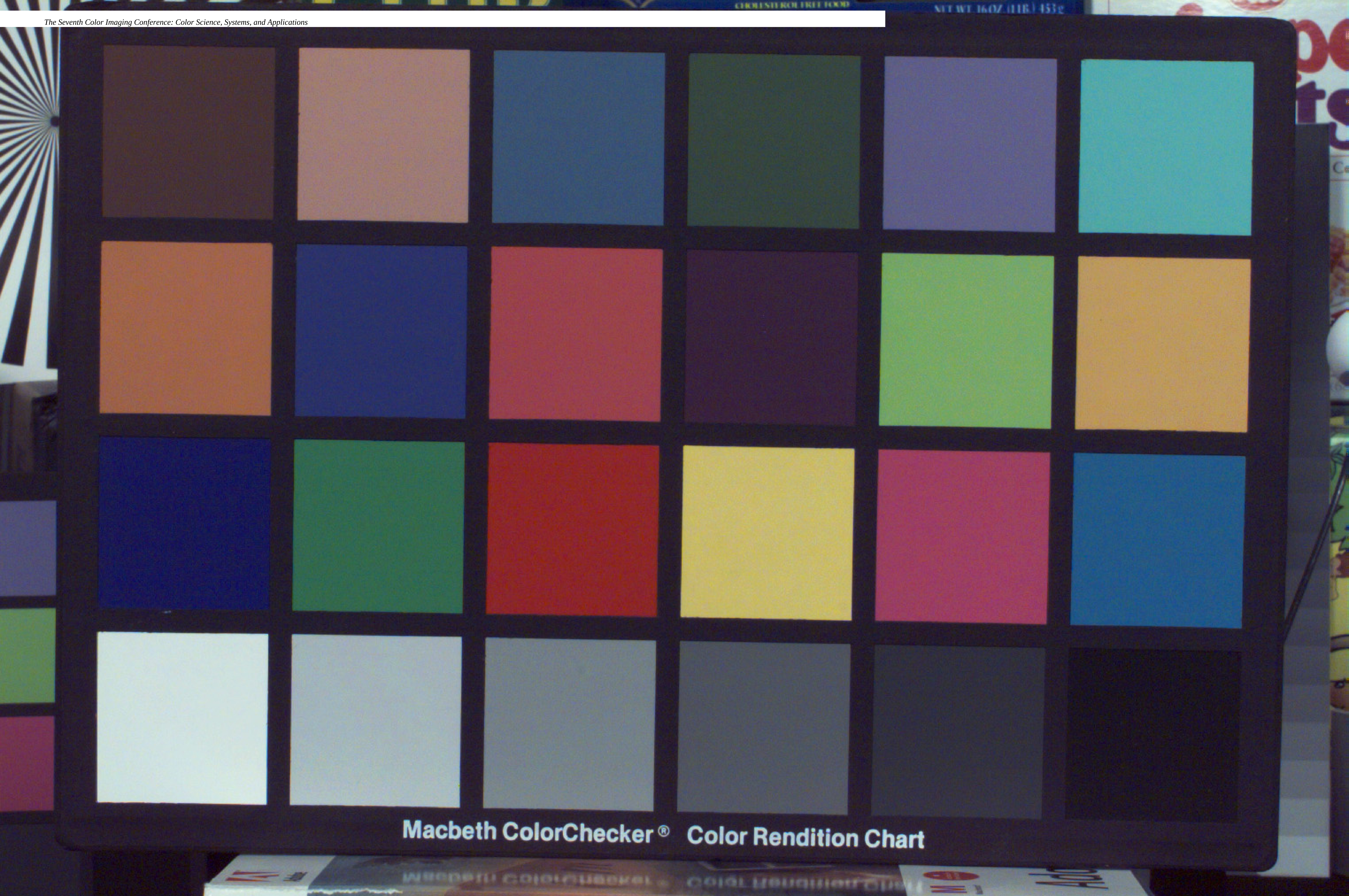
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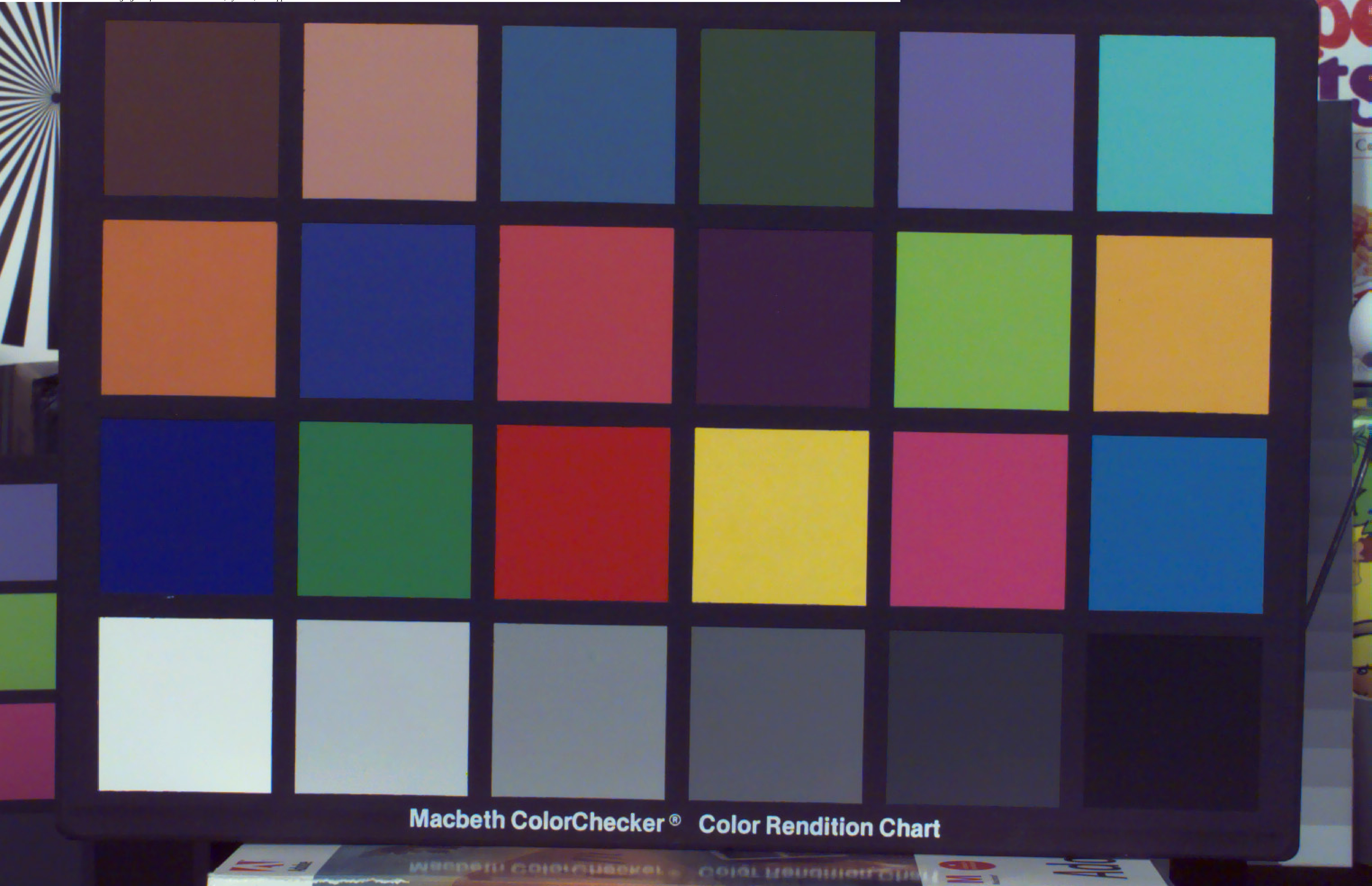
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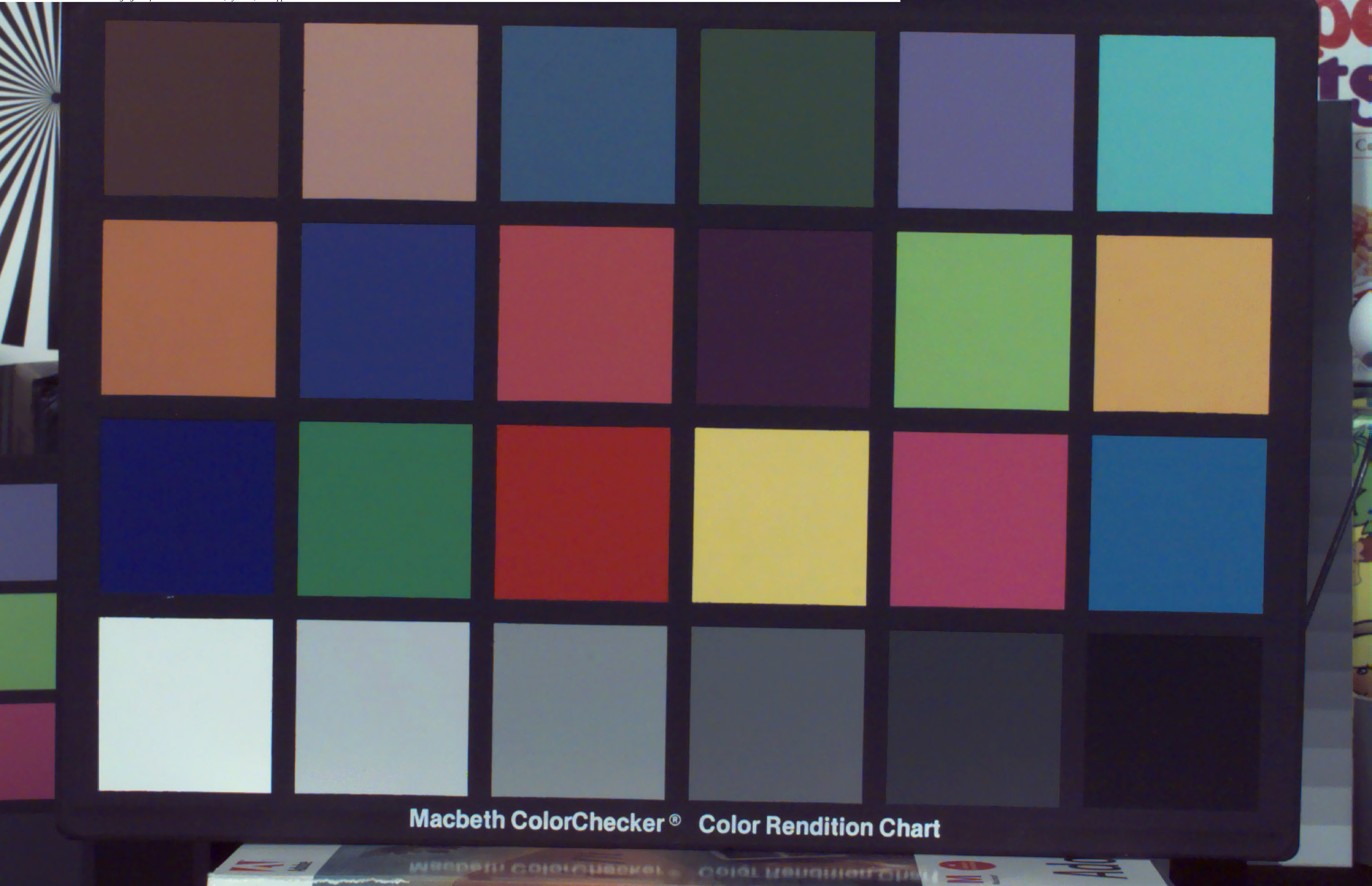
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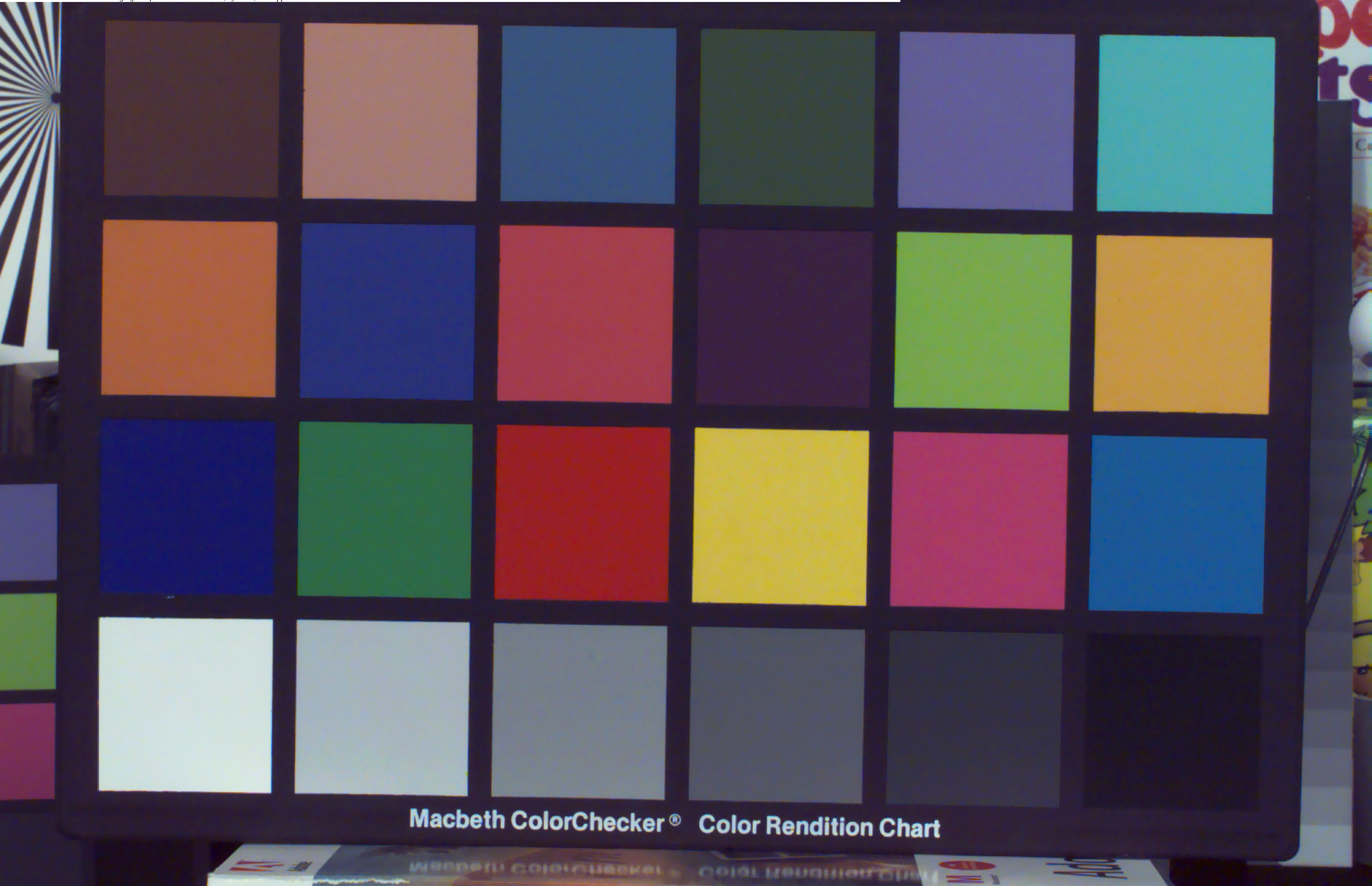
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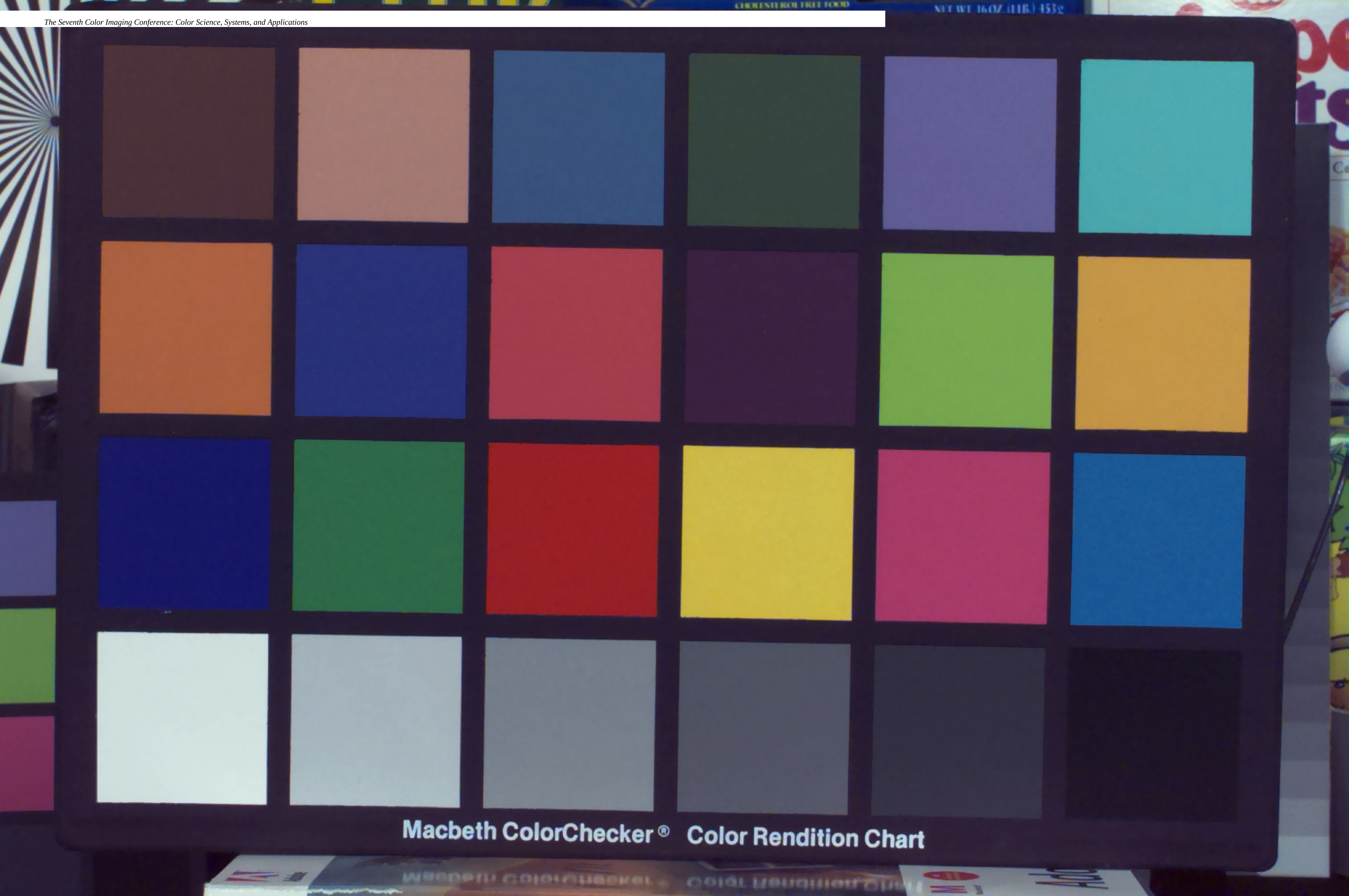
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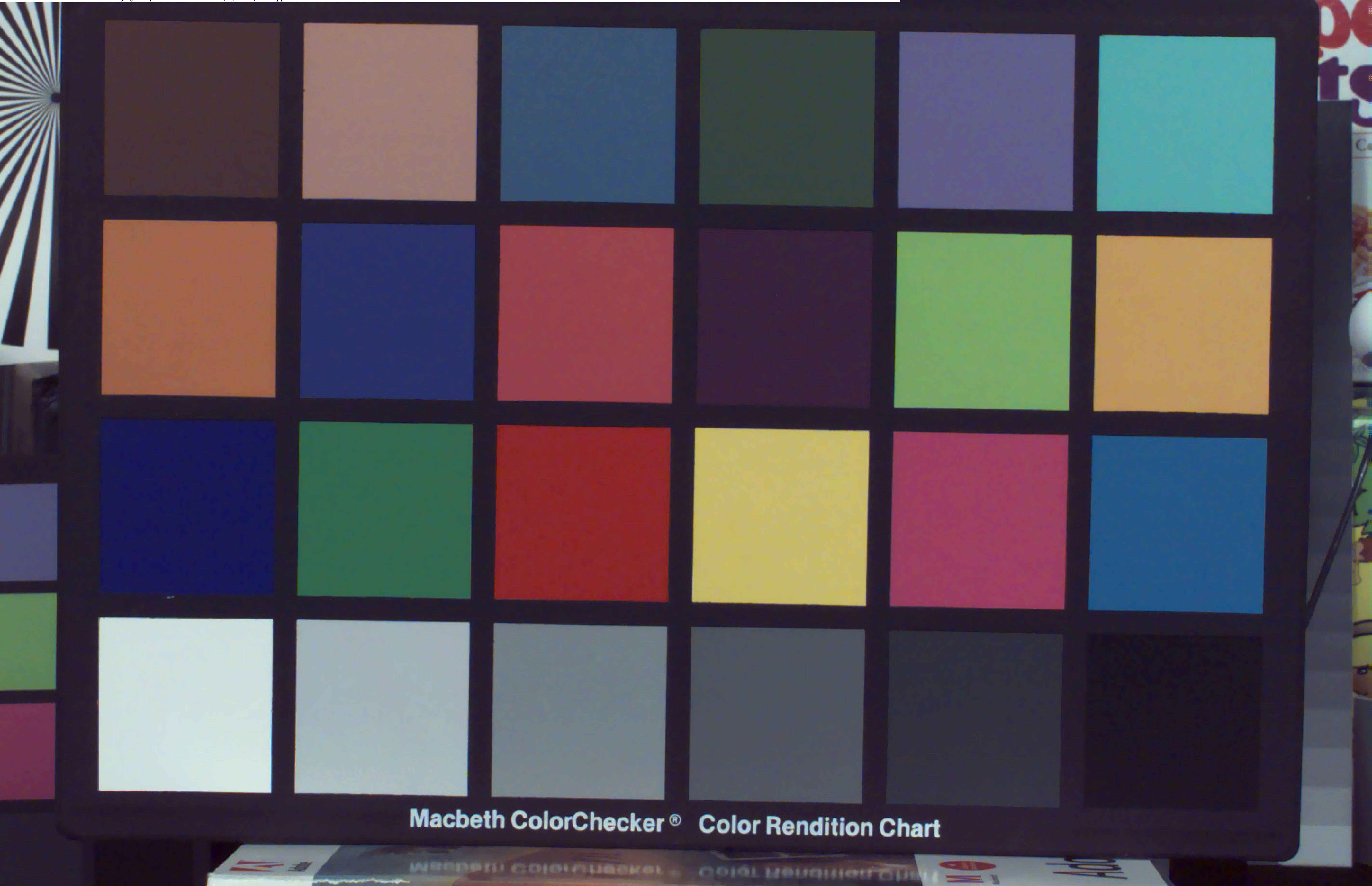
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