How Color Cameras Work

The idea of a CCD is simple. We can imagine it as a memory chip without a "top". Photons encountering the memory cells create electrons in these cells (photoelectric effect) thereby the number of photons is proportional to the number of electrons. The photon's wavelength, however, is not "transferred' to the electrons. Hence CCD chips are color blind.

In the following we describe how color cameras work despite of the CCD chips' color blindness.

Please note:

- It is the responsibility of an on-site engineer to correctly integrate FireWire cameras in the context of real applications.

Content

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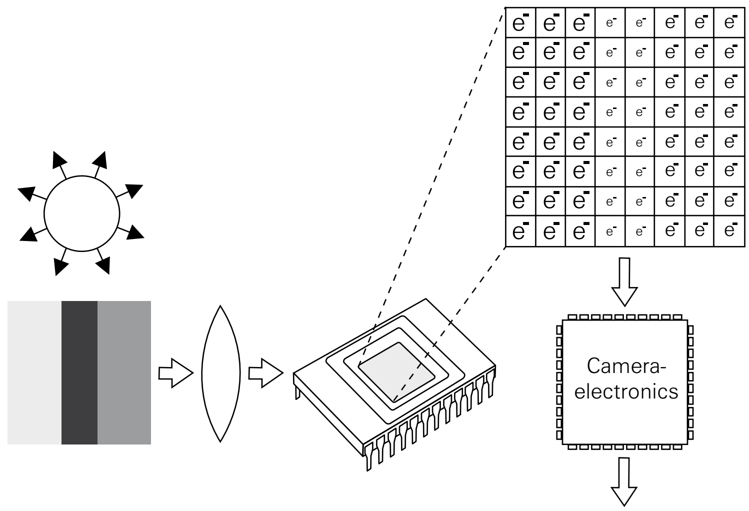
Principles

Starting Point Monochrome Camera

The idea of a CCD is simple. We can imagine it as a memory chip without a "top". Thus, the memory cells can be reached by rays of light. Due to the so called "photo effect", these rays of light create negative charges in these cells (on the top right of the image).

After the exposure time, these charges are read out to be pre-processed by the camera electronics. A digital image is available at the output of this camera electronics.

Should the camera require an analog video output the digital original image has to be converted accordingly. However, this question is not relevant in the context of the subject discussed here, which is "How color cameras work". We only need to consider the digital original image.



220	220	220	50	50	130	130	130
220	220	220	50	50	130	130	130
220	220	220	50	50	130	130	130
220	220	220	50	50	130	130	130
220	220	220	50	50	130	130	130
220	220	220	50	50	130	130	130
220	220	220	50	50	130	130	130
220	220	220	50	50	130	130	130

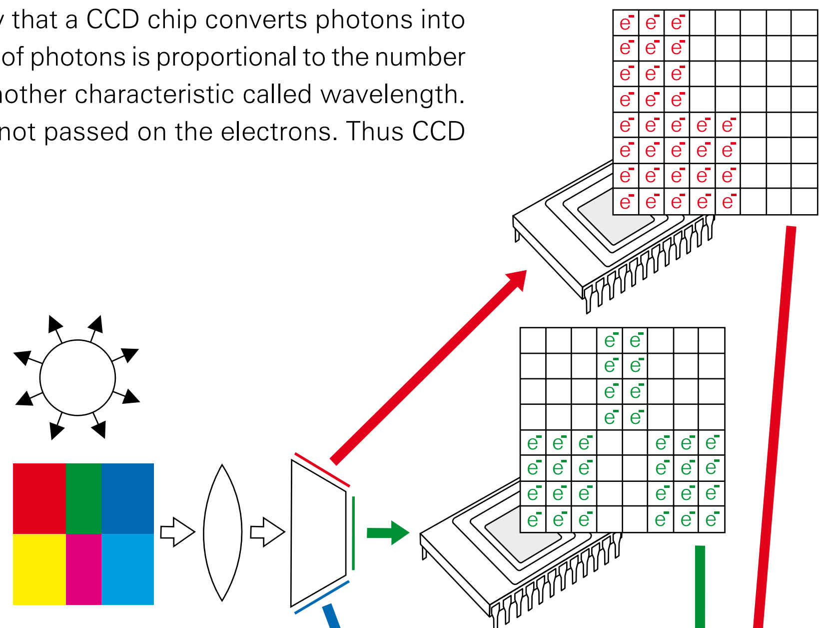
Digital original image

Principles

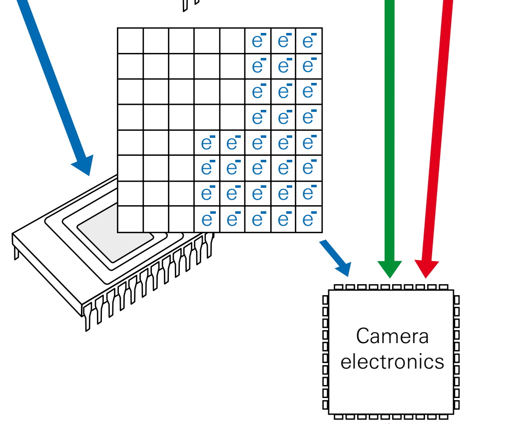
3CCD Color Camera

To put it bluntly, you could say that a CCD chip converts photons into electrons in which the number of photons is proportional to the number of electrons. Photons have another characteristic called wavelength. This information, however, is not passed on the electrons. Thus CCD chips are color-blind.

Should the camera electronics be required to output a red value AND a green value AND a blue value for every pixel, a CCD for each of these primary colors would have to be applied. Each of the CCDs only obtains "filtered photons": one CCD "sees red", a second one "sees green" while the third one "sees blue". These three "photon channels" are created by a prism.



This evident solution also leads to excellent results in practice. The decisive disadvantage, however, is the high price. Color camera concepts based on only one CCD have been developed from early on. The following section describes the most common one.



255	255	255	0	0	0	0	0
255	255	255	0	0	0	0	0
255	255	255	0	0	0	0	0
255	255	255	0	0	0	0	0
255	255	255	255	255	0	0	0
255	255	255	255	255	0	0	0
255	255	255	255	255	0	0	0
255	255	255	255	255	0	0	0

Digitale original-image:
red channel

0	0	0	255	255	0	0	0
0	0	0	255	255	0	0	0
0	0	0	255	255	0	0	0
0	0	0	255	255	0	0	0
255	255	255	0	0	255	255	255
255	255	255	0	0	255	255	255
255	255	255	0	0	255	255	255
255	255	255	0	0	255	255	255

Digitale original-image:
green channel

0	0	0	0	0	255	255	255
0	0	0	0	0	255	255	255
0	0	0	0	0	255	255	255
0	0	0	0	0	255	255	255
0	0	0	255	255	255	255	255
0	0	0	255	255	255	255	255
0	0	0	255	255	255	255	255
0	0	0	255	255	255	255	255

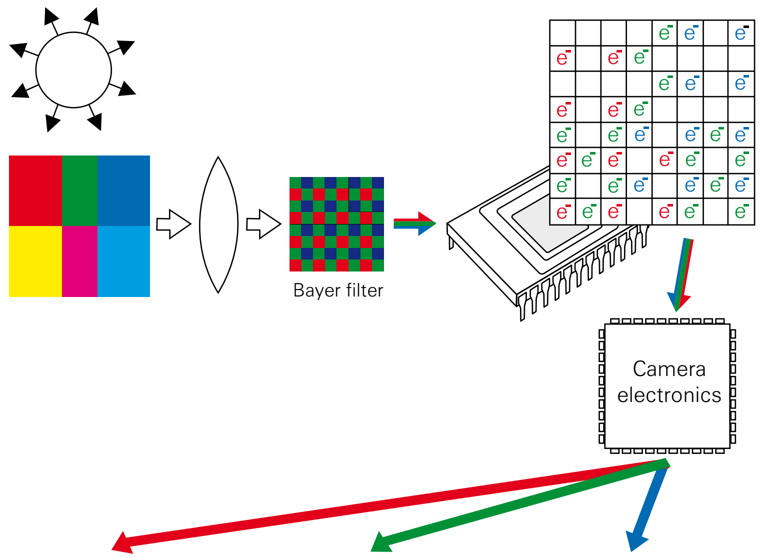
Digitale original-image:
blue channel

Principles

The Single CCD Color Camera

Should, only one CCD chip be used due to cost reasons, the color filters must be spread, similar to a mosaic, across all pixels of the CCD. This concept is also known as Mosaic filter or Bayer filter, a concept originally invented by Mr. Bayer.

Thus one pixel EITHER yields a red value OR a green value OR a blue value. The output, however, should provide pixels with a red value AND a green value AND a blue value. So, how do we obtain the missing values?



255	255	255	0	0	0	0	0
255	255	255	0	0	0	0	0
255	255	255	0	0	0	0	0
255	255	255	0	0	0	0	0
255	255	255	255	255	0	0	0
255	255	255	255	255	0	0	0
255	255	255	255	255	0	0	0
255	255	255	255	255	0	0	0

Digital original image: red channel

0	0	0	255	255	0	0	0
0	0	0	255	255	0	0	0
0	0	0	255	255	0	0	0
0	0	0	255	255	0	0	0
255	255	255	0	0	255	255	255
255	255	255	0	0	255	255	255
255	255	255	0	0	255	255	255
255	255	255	0	0	255	255	255

Digital original image: green channel

0	0	0	0	0	255	255	255
0	0	0	0	0	255	255	255
0	0	0	0	0	255	255	255
0	0	0	0	0	255	255	255
0	0	0	255	255	255	255	255
0	0	0	255	255	255	255	255
0	0	0	255	255	255	255	255
0	0	0	255	255	255	255	255

Digital original image: blue channel

The solution is called "Spatial Color Interpolation" carried out by the camera electronics. Let us take the red pixel in the bottom left corner as an example (figure on the right). We are looking for the missing green and blue values. The interpolation algorithm estimates these two missing values by analyzing the pixels neighboring the one in red. In our example it finds green pixels containing much charge and blue pixels which are completely uncharged. Thus our red pixel actually is yellow. In section Color interpolation you will find detailled information concerning this subject.

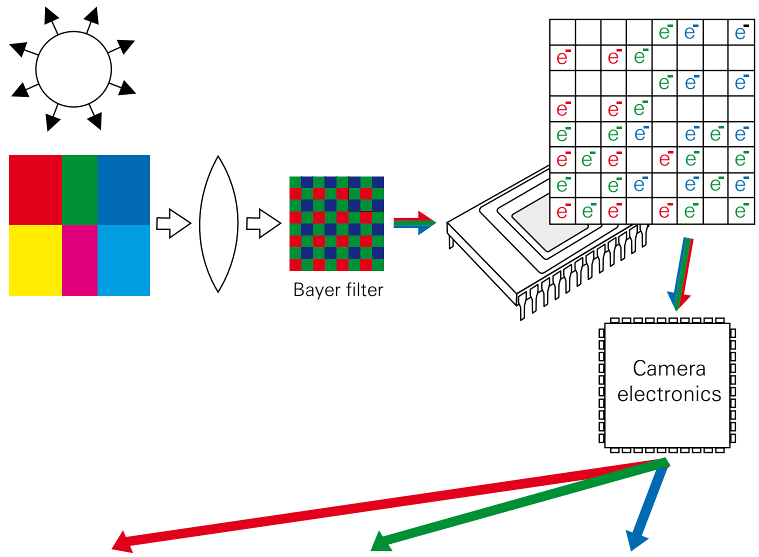
When comparing the 3 digital original-images of the 3CCD camera to the single CCD camera they seem identical. But this is actually only true for our simplified examples. In practice even the most excellent color space interpolation methods cause a low-pass effect. Thus single CCD cameras yield images which are more blurred than those of 3CCD or of monochrome cameras. This is especially evident in cases of subtle, fiber-shaped image structures.

Visualization

We already saw the function of a single CCD color camera for visualization purpose in section Principles. A mosaic filter (also known as Bayer filter) forces a pixel EITHER to see red OR green OR blue.

But, as we expect the camera to output a red value AND a green value AND a blue value for each pixel, the camera electronics interpolate the missing color values. In section Color interpolation you will find more details.

The decisive advantage of this approach is the low price. Additionally, the quality of todays single CCD cameras is astonishingly high. Therefore, the vast majority of color cameras are based on this technique.



255	255	255	0	0	0	0	0
255	255	255	0	0	0	0	0
255	255	255	0	0	0	0	0
255	255	255	0	0	0	0	0
255	255	255	255	255	0	0	0
255	255	255	255	255	0	0	0
255	255	255	255	255	0	0	0
255	255	255	255	255	0	0	0

Digital original image: red channel

0	0	0	255	255	0	0	0
0	0	0	255	255	0	0	0
0	0	0	255	255	0	0	0
0	0	0	255	255	0	0	0
255	255	255	0	0	255	255	255
255	255	255	0	0	255	255	255
255	255	255	0	0	255	255	255
255	255	255	0	0	255	255	255

Digital original image: green channel

0	0	0	0	0	255	255	255
0	0	0	0	0	255	255	255
0	0	0	0	0	255	255	255
0	0	0	0	0	255	255	255
0	0	0	255	255	255	255	255
0	0	0	255	255	255	255	255
0	0	0	255	255	255	255	255
0	0	0	255	255	255	255	255

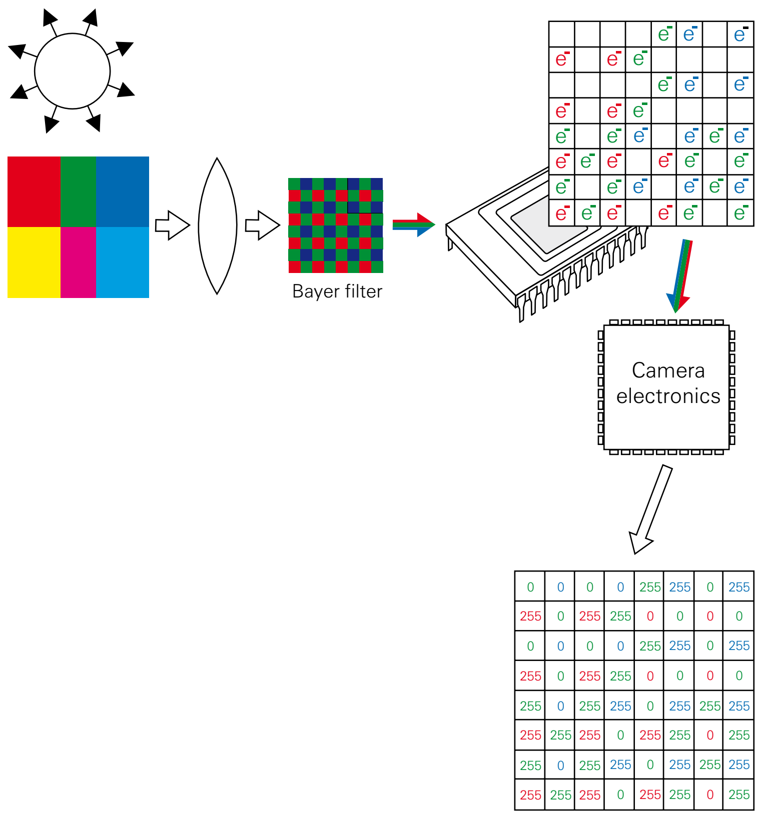
Digital original image: blue channel

Measurement

The color interpolation has decisive disadvantages for measurement orientated imaging applications:

- We have a red value and a green value and a blue value for every pixel, but only one of these values is actually provided by the CCD. The other two values are interpolated and thus are more or less ESTIMATED.
- These estimated values do not only interfere with the measurement procedure itself but, to top it all, they are a needless load for the bus and for the processor of the evaluating computer.

For measurement purposes it is favorable to switch off the color interpolation and to transform the charges collected by the CCD directly into the digital original-image.



0	0	0	0	255	255	0	255
255	0	255	255	0	0	0	0
0	0	0	0	255	255	0	255
255	0	255	255	0	0	0	0
255	0	255	255	0	255	255	255
255	255	255	0	255	255	0	255
255	0	255	255	0	255	255	255
255	255	255	0	255	255	0	255

Digital original image

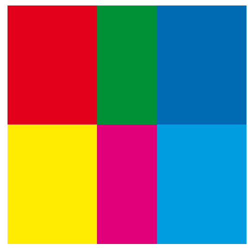
Important: Today, the majority of software for the evaluation of color images assumes every pixel consists of a red value and a green value and a blue value. Handling a digital original-image is, however, new for many of us. Therefore, the basic idea of the evaluation of a digital original image is described in more detail in section Color Interpretation.

Color Interpolation (for Visualization)

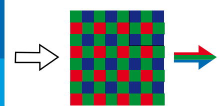
Introduction

In section Principles the idea of color interpolation is described by means of an example. In order to keep this example clear, the three resulting images (the three color channels of the digital original image) have been represented in an idealized way.

Below we describe two simple interpolation procedures in detail. As a starting point we use the digital original-image already described in section Single CCD cameras for visualization and measurement (subsection "Measurement"). To make life easier this digital original-image, its source image as well as the Bayer filter can be seen on the right



Source image



Bayer filter

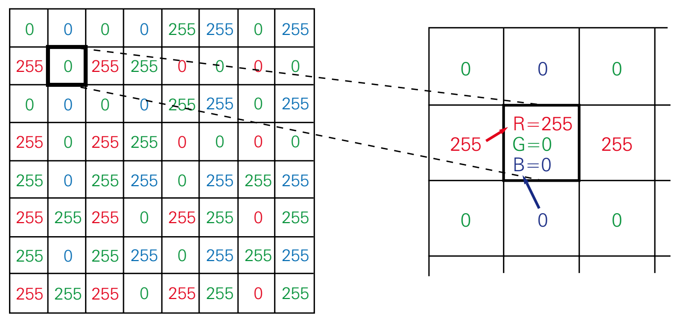
0	0	0	0	255	255	0	255
255	0	255	255	0	0	0	0
0	0	0	0	255	255	0	255
255	0	255	255	0	0	0	0
255	0	255	255	0	255	255	255
255	255	255	0	255	255	0	255
255	0	255	255	0	255	255	255
255	255	255	0	255	255	0	255

Digital original image

Color Interpolation (for Visualization)

Copy of Neighbor Pixels (Nearest Neighbor Replication)

The most simple method of "filling up" the missing color values is the absorption of neighboring values. Let us take the first green pixel (of the Bayer filter) in the second line as an example. This pixel is bordered in bold black in the figure on the right.



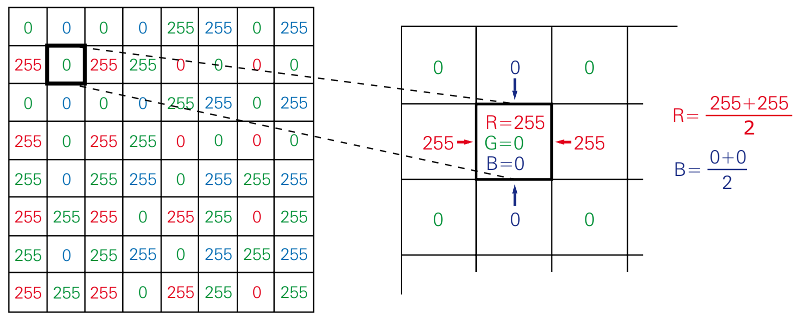
Digital original image

As the source image actually is red at this point (see Introduction) the scanning with the Bayer filter's green pixel results in an 0. We simply take the missing red and blue values (as shown on the right) from the neighboring red and blue pixels. In this way we obtain a RGB value of (255,0,0).

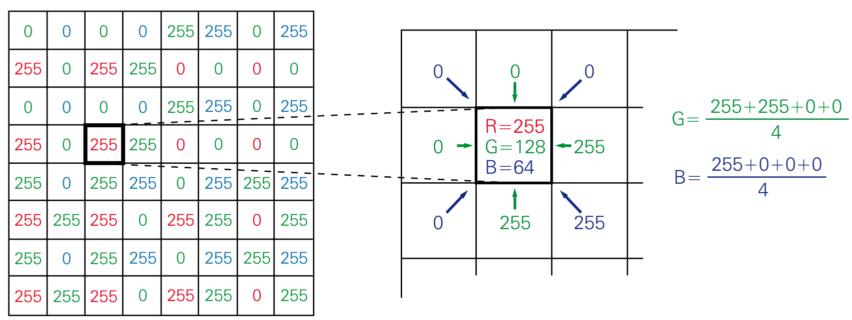
For the example on the right the interpolation actually yields the correct RGB value. In practice, however, this primitive interpolation method leads to bad results which are seldom acceptable for static images. But, as this method is not very time-consuming, it can be suitable for video streams in which a high quality standard is not demanded (e.g. a preview).

Color Interpolation (for Visualization)

Mean Value of Neighbor Pixels (Bilinear Interpolation)



Digital original image



Digital original image

A first improvement of the simple "interpolation by copy" is the use of the mean of several neighboring pixels (bilinear interpolation). As shown in the figure this method also results in the correct RGB value of (255,0,0).

The example below, however, shows the decisive disadvantage of the mean value method. It is associated with a low-pass behaviour and therefore it smooths sharp edges. The RGB value should be (255,0,0) at this point but actually it is (255,128,64) and thus a brownish orange.

The quality of the interpolation methods used in modern cameras is considerably higher than that of the above mentioned basic approaches. The survey A Study of Spatial Color Interpolation Algorithms for Single-Detector Digital Cameras offers an excellent overview and a comparison of these methods.

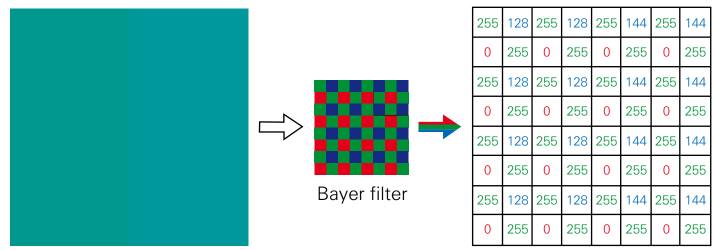
It is seldom possible to influence the interpolation procedure of a "normal" color camera. With the DBK 21F04, the DBK 21AF04, the DBK 21BF04, the DBK 31AF03, the DBK 31BF03, the DBK 41AF02 and the DBK 41BF02 The Imaging Source Company offers color cameras without interpolation. They are especially suitable for color interpretation.

Color Interpretation (for Measurement)

Introduction

In section Single CCD cameras for visualization and measurement we learned that interpolated images are not well suited for measurement purposes. The reason for this is described below using the example on the right.

The source image consists of two homogeneous regions which color value only differ slightly. The pixels of the left half yield a RGB value of (0,255,128) while those of the right half are (0,255,144).



Source image

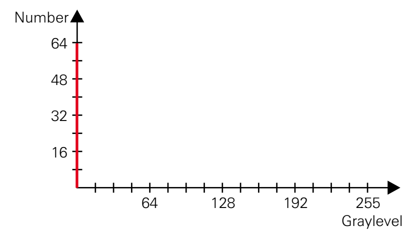
Digital original image

Color Interpretation (for Measurement)

Interpretation Based on an Interpolated Image

0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

Interpolated red channel

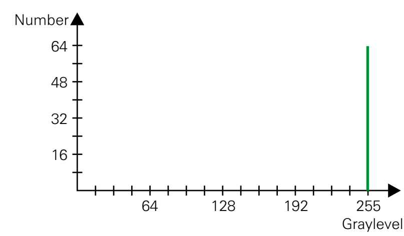


255	128	255	128	255	144	255	144
0	255	0	255	0	255	0	255
255	128	255	128	255	144	255	144
0	255	0	255	0	255	0	255
255	128	255	128	255	144	255	144
0	255	0	255	0	255	0	255
255	128	255	128	255	144	255	144
0	255	0	255	0	255	0	255

Digital original image

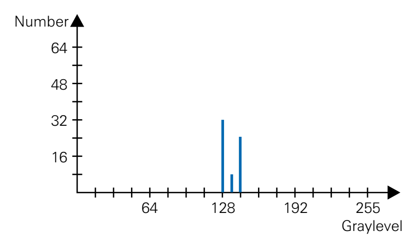
255	255	255	255	255	255	255	255
255	255	255	255	255	255	255	255
255	255	255	255	255	255	255	255
255	255	255	255	255	255	255	255
255	255	255	255	255	255	255	255
255	255	255	255	255	255	255	255
255	255	255	255	255	255	255	255
255	255	255	255	255	255	255	255

Interpolated green channel



128	128	128	128	136	144	144	144
128	128	128	128	136	144	144	144
128	128	128	128	136	144	144	144
128	128	128	128	136	144	144	144
128	128	128	128	136	144	144	144
128	128	128	128	136	144	144	144
128	128	128	128	136	144	144	144
128	128	128	128	136	144	144	144

Interpolated blue channel



The figure shows the result of the color interpolation of our source image. To make life easy, color interpolation by mean value (bilinear interpolation) as described in section Color interpolation has been applied. As a result of this interpolation we obtain one image for every channel: the red one, the green one and the blue one.

A typical method for the separation of image regions is based upon histogram analysis. As shown in the diagrams on the right, the red channel only contains 64 values "0". The green channel, however, offers 64 values "255". Thus, these two channels are useless for the separation of the two regions.

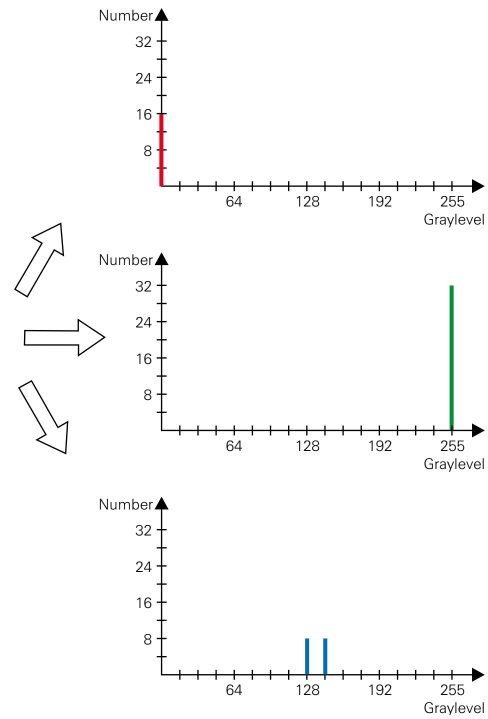
Only the blue channel shows a "valley" in its histogram between 32 values "128" and 24 values "144". There are also 8 values "136" which are the result of the color interpolation's low-pass effect. This effect leads to a "smearing" of the edge between the two regions which was originally sharp.

Color Interpretation (for Measurement)

Interpretation Based on the Digital Original-Image

255	128	255	128	255	144	255	144
0	255	0	255	0	255	0	255
255	128	255	128	255	144	255	144
0	255	0	255	0	255	0	255
255	128	255	128	255	144	255	144
0	255	0	255	0	255	0	255
255	128	255	128	255	144	255	144
0	255	0	255	0	255	0	255

Digital original image



Simply applying histogam analysis directly to the digital original-image has two advantages:

- We do not burden ourselves with information, 2/3 of which is redundant.
- As no interpolation is applied no disturbances are encountered as e.g. smeared edges.

The three histograms again indicate that the red channel and the green channel are useless for our evaluation. The histogram of the blue channel, once again exactly reflects the relationship of the source image.

One objection may be, that the interpolation by mean values is no longer applied today (bilinear interpolation) as much more efficient methods are used. Nevertheless, this efficiency is related to a maximization of a good quality visualization and therefore the human visual system is used as a reference. From a measurement point of view, however, these "very efficient" interpolation methods lead to various kinds of interferences which may obstruct an image interpretation.