

## Digital Photographs, Image Sensors and Matrices

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## Digital Camera Image Sensors

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The physical appearance of an image sensor is an electronics package which can be imagined to replace the film in a standard film camera.



**Figure 1.** An IBM Image sensor

## Electron Counts

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Images focused through the camera lens cause photons to hit image sensor photosites and knock loose electrons, which are then captured and stored. The electron count at a photosite is directly proportional to the light intensity. When the image is read off the sensor, the stored electrons are converted to a series of analog charges which are then converted to integer counts by an analog to digital converter (ADC).

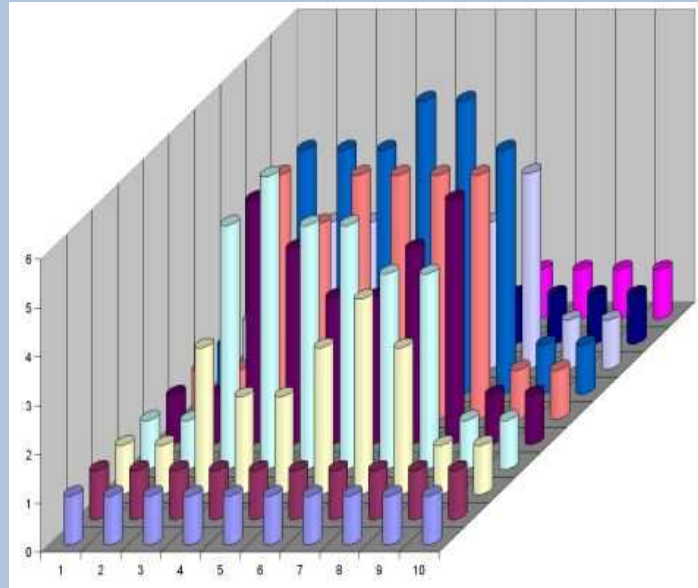
|   |   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 3 | 2 | 2 | 3 | 4 | 3 | 1 | 1 |
| 1 | 1 | 5 | 6 | 5 | 5 | 4 | 4 | 1 | 1 |
| 1 | 1 | 5 | 4 | 3 | 3 | 4 | 5 | 1 | 1 |
| 1 | 1 | 5 | 4 | 5 | 5 | 5 | 5 | 1 | 1 |
| 1 | 1 | 5 | 5 | 5 | 6 | 6 | 5 | 1 | 1 |
| 1 | 1 | 3 | 3 | 2 | 2 | 3 | 4 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

**Figure 2.** Integer counts of light intensity on an image sensor. One unit of intensity corresponds to a certain large electron count at the photosite.

## The Checkerboard Analogy

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After the image is stored, the light intensity data is like a checkerboard with so many checkers stacked on each square.



**Figure 3.** Checkerboard Analogy of Image Sensor Data

## Monochrome Intensities to Color Photo

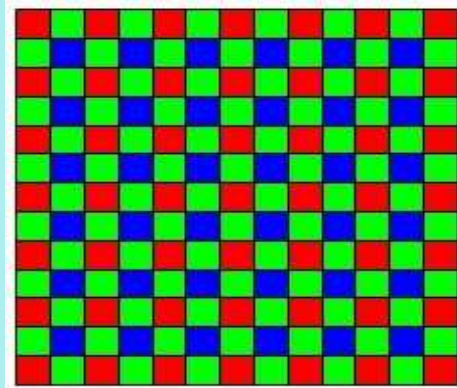
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The monochrome intensity data is post-processed to create the corresponding color image that is stored on disk and viewed on the camera's LCD screen. Details next.

## The Bayer Mosaic

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Bryce Bayer at Kodak invented a **mosaic**, which is a pattern of red, green and blue filters arranged on a grid resembling a checkerboard. Half the squares are green, because the human eye is not equally sensitive to all three colors. The image sensor is an array of photodiodes with the Bayer color filter array atop, and a matching array of light-focusing micro-lenses atop each filter [3 layers like a BLT sandwich].



**Figure 4.** Bryce Bayer's Mosaic Color Filter Array.

A digital camera stores raw image sensor data as a matrix  $\mathbf{A}$  of numbers. The numbers correspond to the light intensity at a red, green or blue filter site. The photosensor sits below the filter and estimates intensity as the number of electrons knocked off by incident photons.

## Image Sensor Data to Matrix Data

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The matrix  $A$  of photosensor intensities representing the Bayer mosaic must be translated to a matrix  $B$  of RGB data and then stored in TIFF or JPG format for print processing.

In an image sensor for 24-bit color, a photo pixel is RGB interpolated data from 4 or more adjacent Bayer mosaic filter sites. The process of using other filter squares in the neighborhood of a sensor site to make an educated guess of the RGB data is called interpolation or de-mosaicing.

A matrix  $B$  which stores the interpolated RGB data has one entry for each mosaic filter square. The square's new intensity data is a coded integer  $a$ . One scheme is

$$a = r + (256)g + (65536)b.$$

Symbols  $r$ ,  $g$ ,  $b$  are integers between 0 and 255 which specify the interpolated intensity of colors red, green and blue, respectively. Computer experts recognize this encoding as bit shifting.

## Visualization of Matrix Addition and Scalar Multiplication

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- **Matrix addition** can be visualized through matrices representing color separations [idea due to **James Clerk Maxwell**; browse *Wikipedia*]. When three monochrome transparencies of colors red, green and blue (RGB) are projected simultaneously by a projector, the colors add to make a full color screen projection. The three transparencies can be associated with matrices  $\mathbf{R}$ ,  $\mathbf{G}$ ,  $\mathbf{B}$  which contain pixel data for the monochrome images. Then the projected image is associated with the matrix sum  $\mathbf{R} + \mathbf{G} + \mathbf{B}$ .
- **Scalar multiplication** of matrices has a similar visualization. The pixel information in a red, green or blue monochrome image is coded for intensity. The associated matrix  $\mathbf{A}$  of pixel data when multiplied by a scalar  $k$  gives a new matrix  $k\mathbf{A}$  of pixel data with the intensity of each pixel adjusted by factor  $k$ . The photographic effect is to adjust the range of intensities.

In the *checkerboard visualization* of an image sensor, factor  $k$  increases or decreases the tri-color checker stack height at each square.

## Different Technologies

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- The Foveon X3 sensor has three layers of photodiodes embedded at different silicon strata levels, emulating the three emulsion layers of color film [*fovea* is an area on the retina]. The sensor requires no interpolation. An X3 sensor with 4.7MP for each of red, green, blue colors was used in the Sigma SD14 digital camera, boasting 14MP and a host of advantages over Bayer arrays.
- Kodak sensor technology from 2007 uses the Bayer pattern but adds panchromatic squares to boost luminance data. This sensor realizes one to two F-stops of low light performance.

## Reference

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A short course on sensors and digital cameras can be found at

<http://www.shortcourses.com/sensors/index.html>



## Charge Coupled Devices

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Digital cameras replace film with a charge-coupled device, or CCD. The CCD is a semiconductor with a *checkerboard* of capacitors that each store an electrical charge. Each photosite of the CCD can be imagined to produce one pixel of a digital image. When the camera shutter is opened, photons of light hit the CCD and knock loose electrons, which are then stored in the capacitors. The number of electrons displaced is proportional to the intensity of light, thus forming an image. The image is *read* from the CCD device by a method called *coupling*, judged too technical for discussion here.

The CCD device was invented in 1969 by Bell Labs employees Willard S. Boyle and George E. Smith, who were awarded the **2009 Nobel Prize in Physics** for their effort. Nikon switched to Sony CMOS devices about 2012.

## Direct Image Sensor

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The direct image sensor is a CMOS [complementary metal-oxide semiconductor] device designed to replicate the separate red-green-blue light recording of a charge-coupled device in the film model of three emulsion layers.

The Direct sensor is an array of photosites, each of which consists of three vertically stacked photodiodes, that are organized in a two-dimensional grid.

Each photodiode stack responds to a different wavelength of light, which means each stack has a different spectral sensitivity curve. The idea is based upon different wavelengths of light penetrating silicon to different depths. The signals from three vertically-stacked photodiodes are post-processed to provide red, green, and blue data at a single pixel.

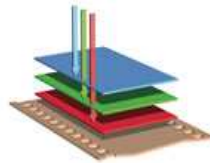
Bayer sensors record intensity at a single depth, while the Direct sensor records *original light intensity* at each of three depths, one for each primary filter color.

Experts argue that a Direct sensor must have about 1.5 times as many green or panchromatic photosites as a Bayer sensor to convey the same amount of edge detail. Disagreement continues, because quality depends on more than edge detail.



**The Foveon X3<sup>®</sup> direct image sensor.**

*The only image sensor that directly captures full color in three layers, just like film.*



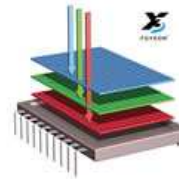
*First came film.*

COLOR FILM contains three layers of emulsion which directly record red, green, and blue light.



*Then came digital.*

TYPICAL DIGITAL SENSORS have just one layer of pixels and capture only part of the color.



*Now there's Foveon X3.*

FOVEON X3 direct image sensors have three layers of pixels which directly capture all of the color.

**Figure 5.** Foveon X3 direct image sensor.

## **Foveon Sensor in the Sigma SD14 Digital Camera 2007**

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The Foveon X3 Model F19X3-A50 is a low-cost 4.7MP CMOS sensor that boasts 14MP resolution without interpolation. The manufacturer's claims:

- **Foveon X3 Technology**
  - Three pixel sensors are layered in silicon to achieve full-measured color.
  - Images have improved sharpness and immunity to sampling artifacts (moiré).
- **Ultra Low Power**
  - Ultra low power requirements.
  - Power consumption is less than 200mW during readout, less than 40mW in standby mode, and less than 1mW in power down mode.
- **Low Noise**
  - Extremely low-noise readout and high dynamic range.
  - Suppression of fixed pattern noise artifacts associated with CMOS image sensors.