

# Cameras

Digital Visual Effects, Spring 2007

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*with slides by Fredo Durand, Brian Curless, Steve Seitz and Alexei Efros*

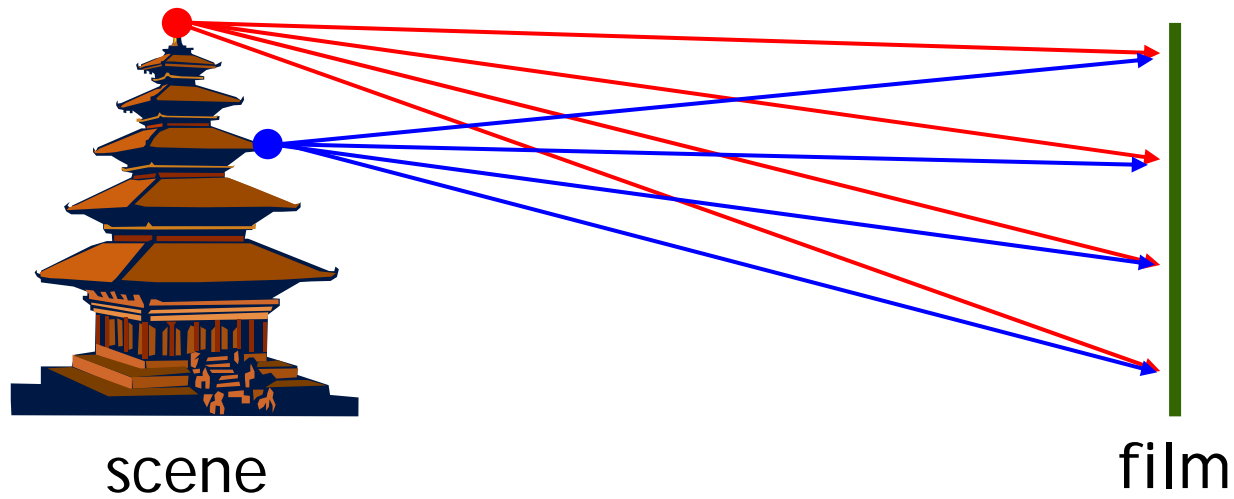
# Outline

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- Pinhole camera
- Film camera
- Digital camera
- Video camera

# Camera trial #1

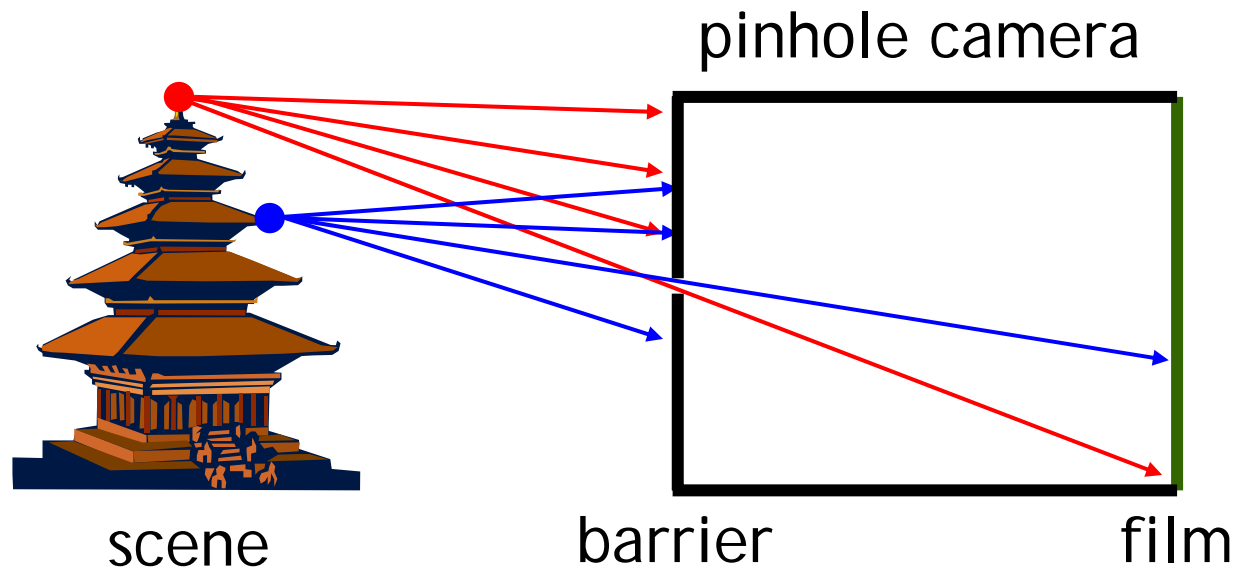
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Put a piece of film in front of an object.

# Pinhole camera

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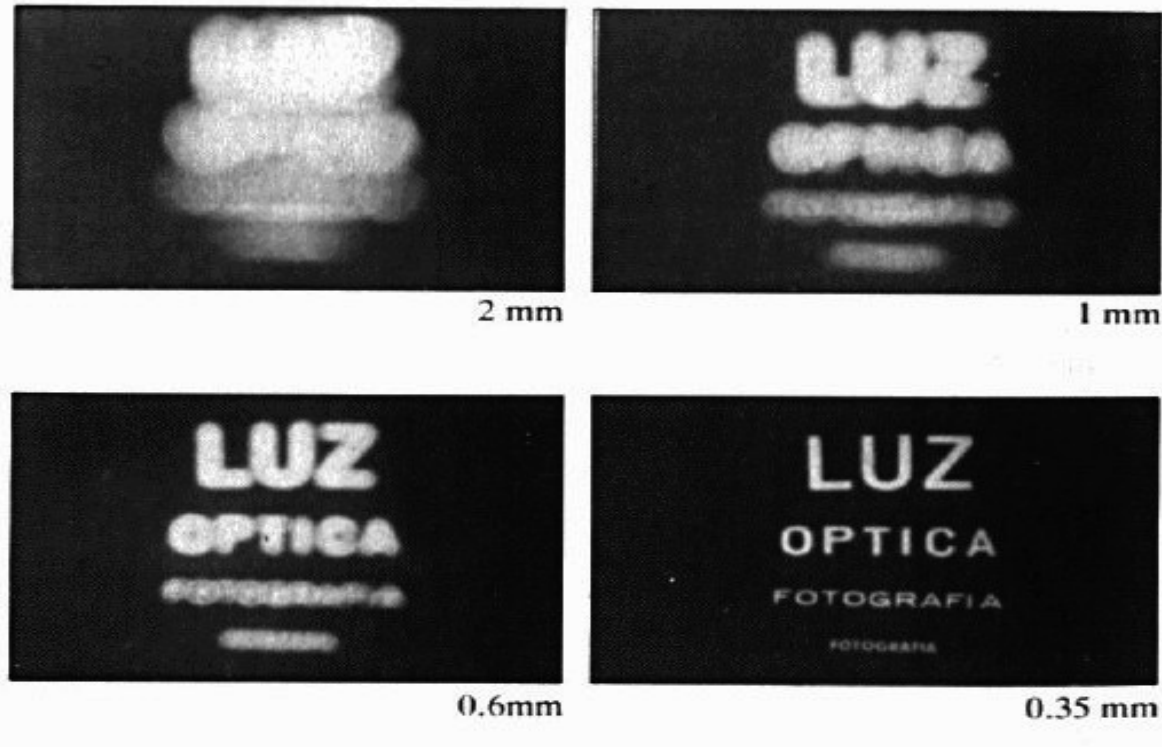


Add a barrier to block off most of the rays.

- It reduces blurring
- The pinhole is known as the aperture
- The image is inverted

# Shrinking the aperture

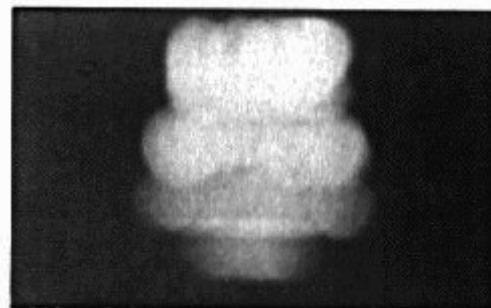
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Why not making the aperture as small as possible?

- Less light gets through
- Diffraction effect

# Shrinking the aperture



2 mm



1 mm



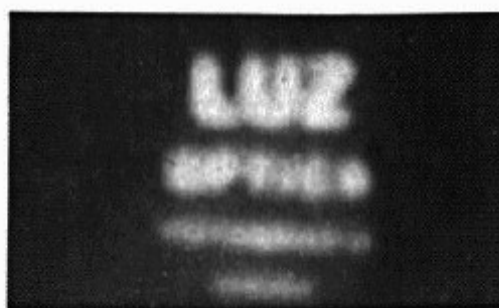
0.6 mm



0.35 mm



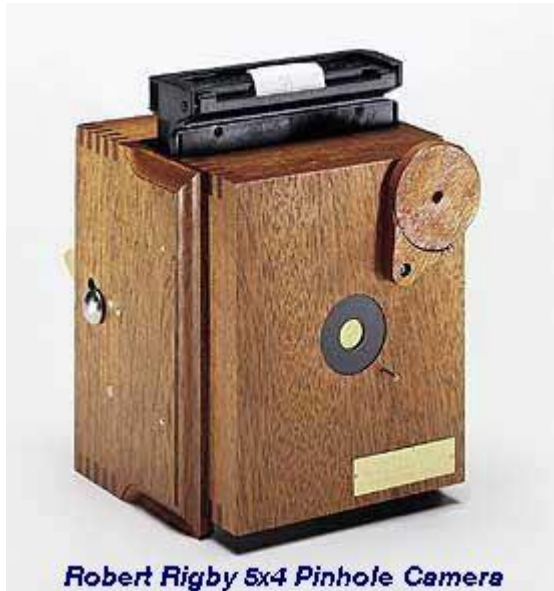
0.15 mm



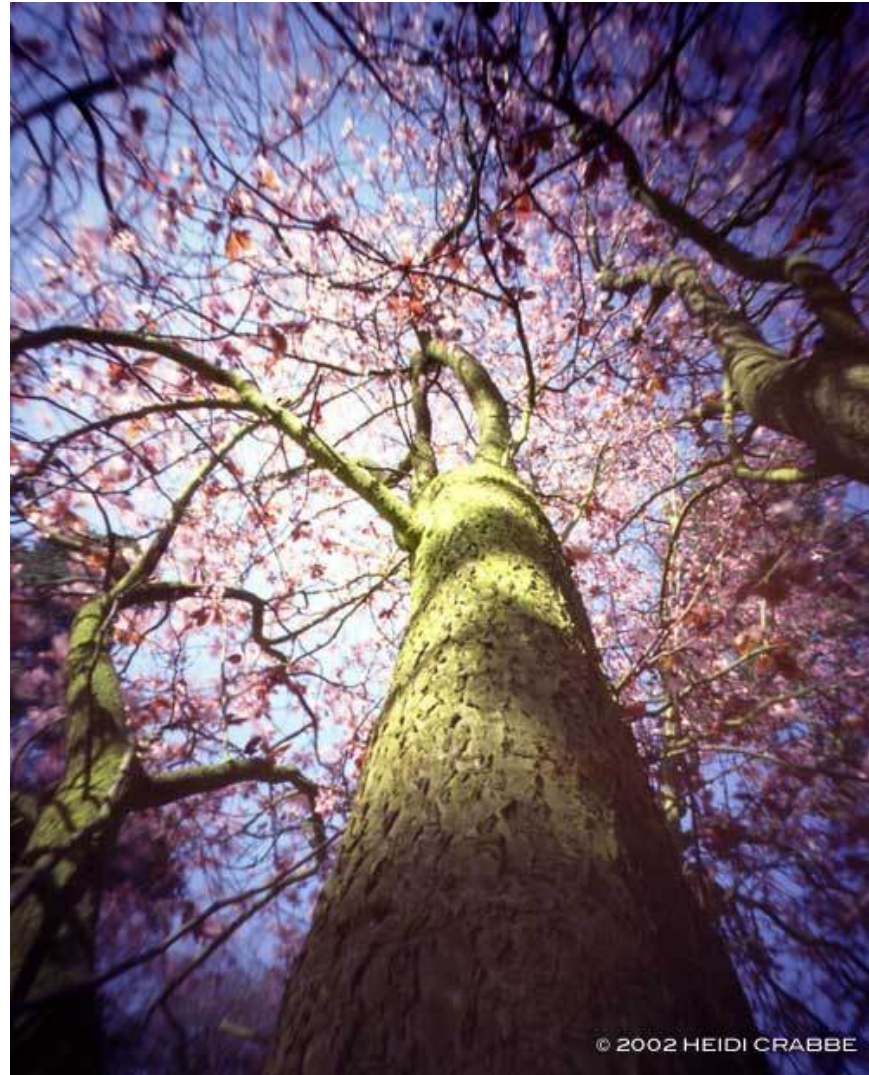
0.07 mm

# High-end commercial pinhole cameras

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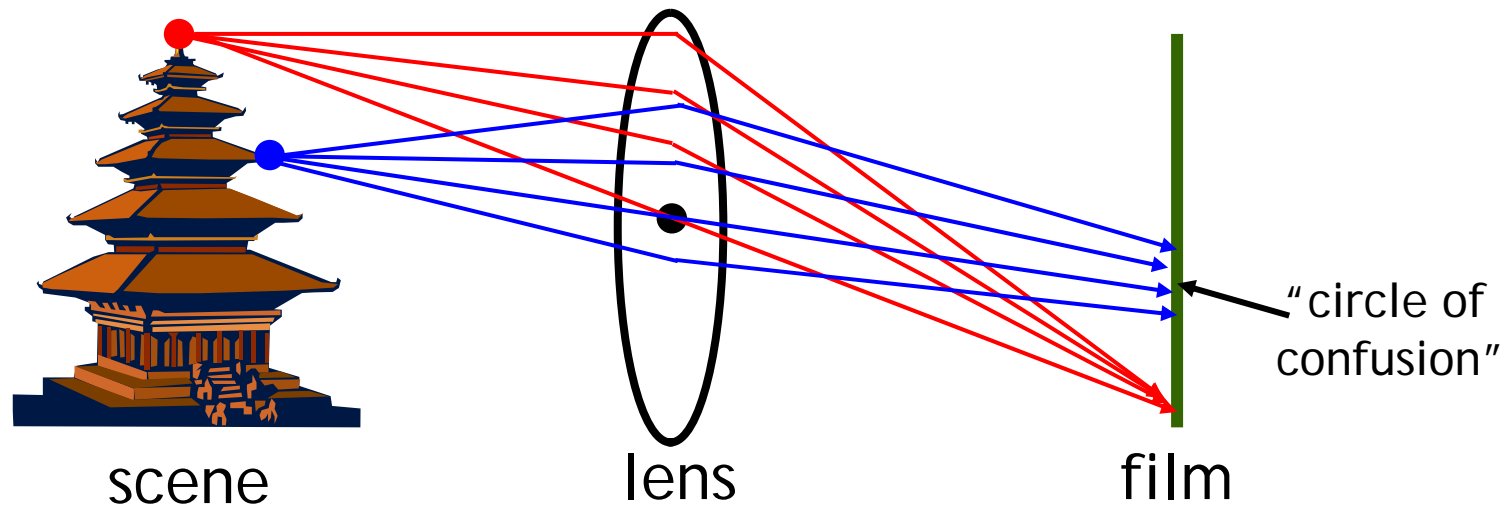


\$200~\$700



# Adding a lens

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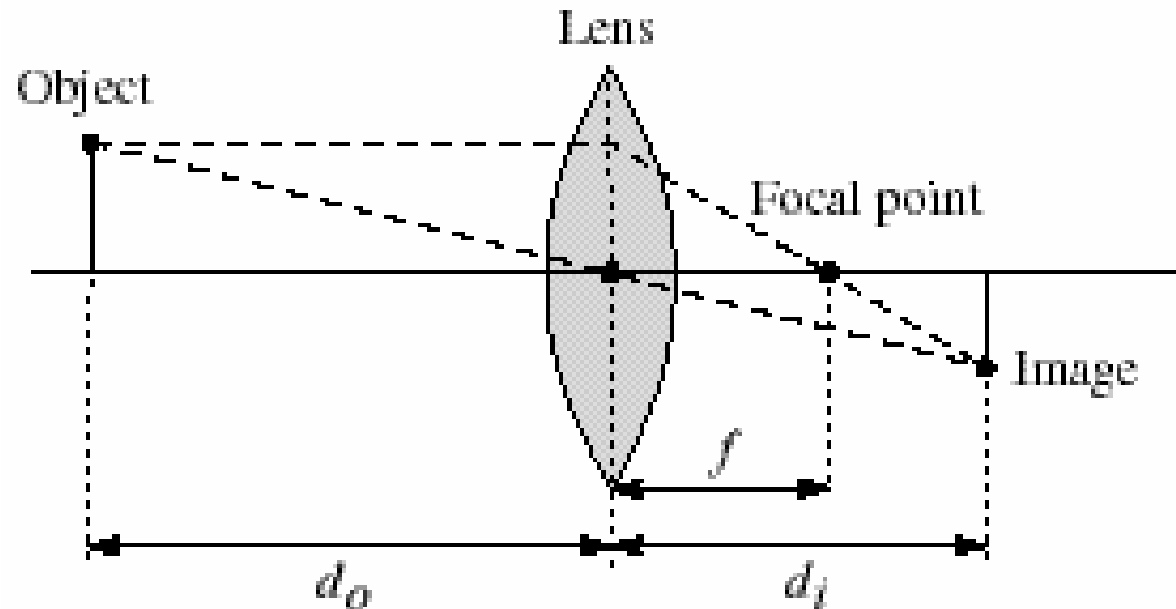


A lens focuses light onto the film

- There is a specific distance at which objects are "in focus"
- other points project to a "circle of confusion" in the image



# Lenses



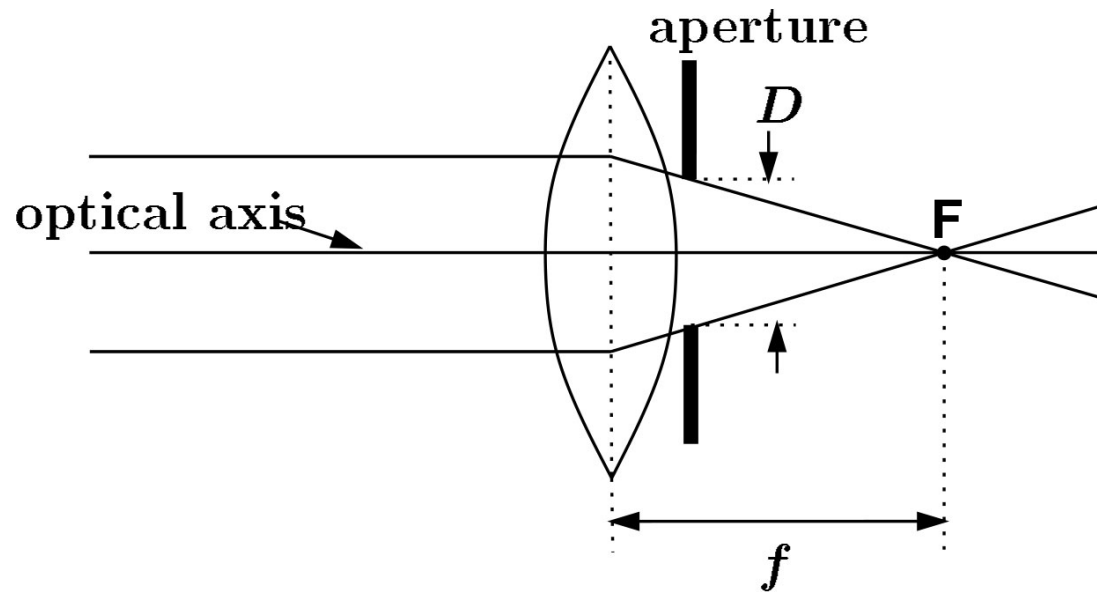
Thin lens equation:  $\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$

- Any object point satisfying this equation is in focus
- Thin lens applet:

[http://www.phy.ntnu.edu.tw/java/Lens/lens\\_e.html](http://www.phy.ntnu.edu.tw/java/Lens/lens_e.html)

# Exposure = aperture + shutter speed

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- Aperture of diameter  $D$  restricts the range of rays (aperture may be on either side of the lens)
- Shutter speed is the amount of time that light is allowed to pass through the aperture

# Exposure

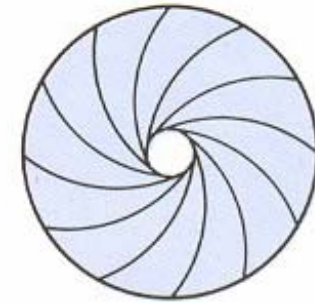
- Two main parameters:
  - Aperture (in f stop)



Full aperture



Medium aperture

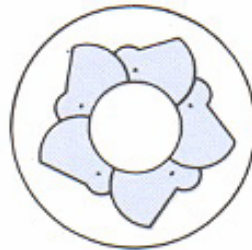


Stopped down

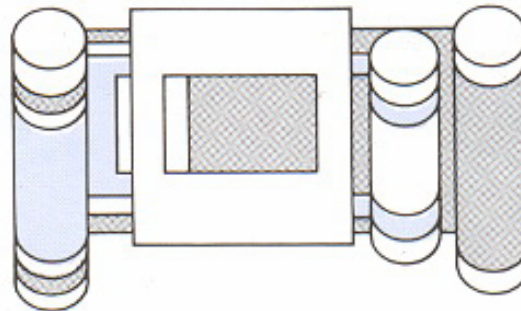
- Shutter speed (in fraction of a second)



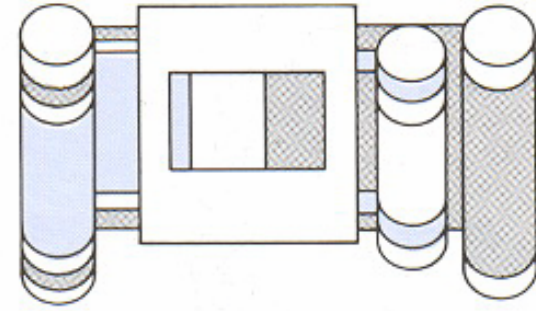
Blade (closing)



Blade (open)



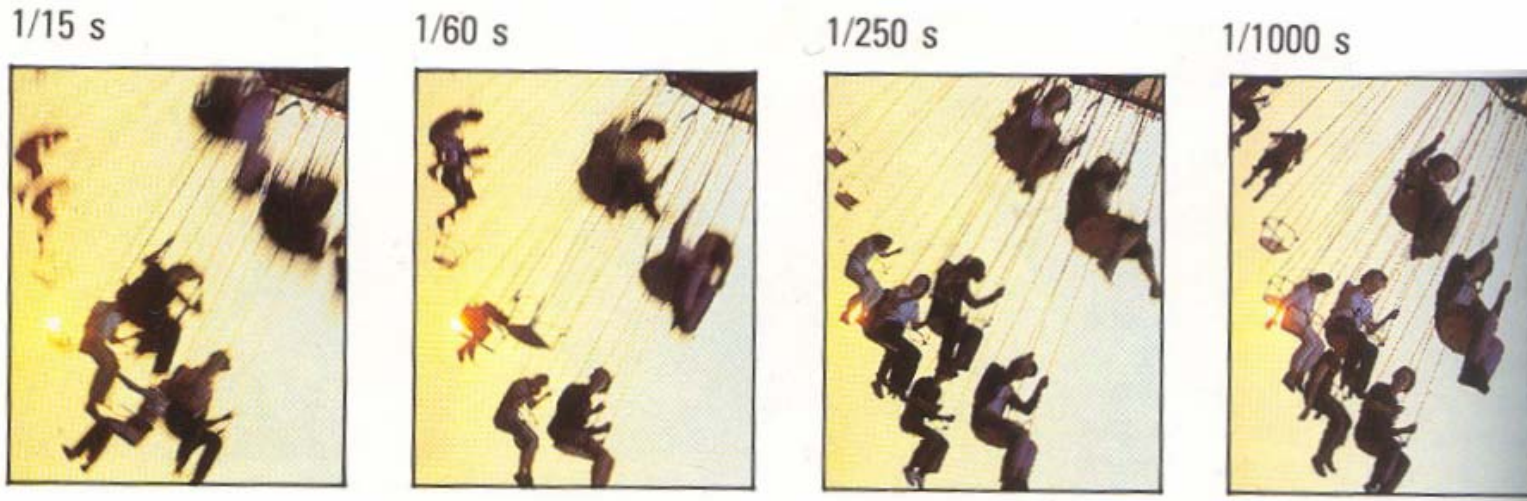
Focal plane (closed)



Focal plane (open)

# Effects of shutter speeds

- Slower shutter speed => more light, but more motion blur



- Faster shutter speed freezes motion



# Aperture

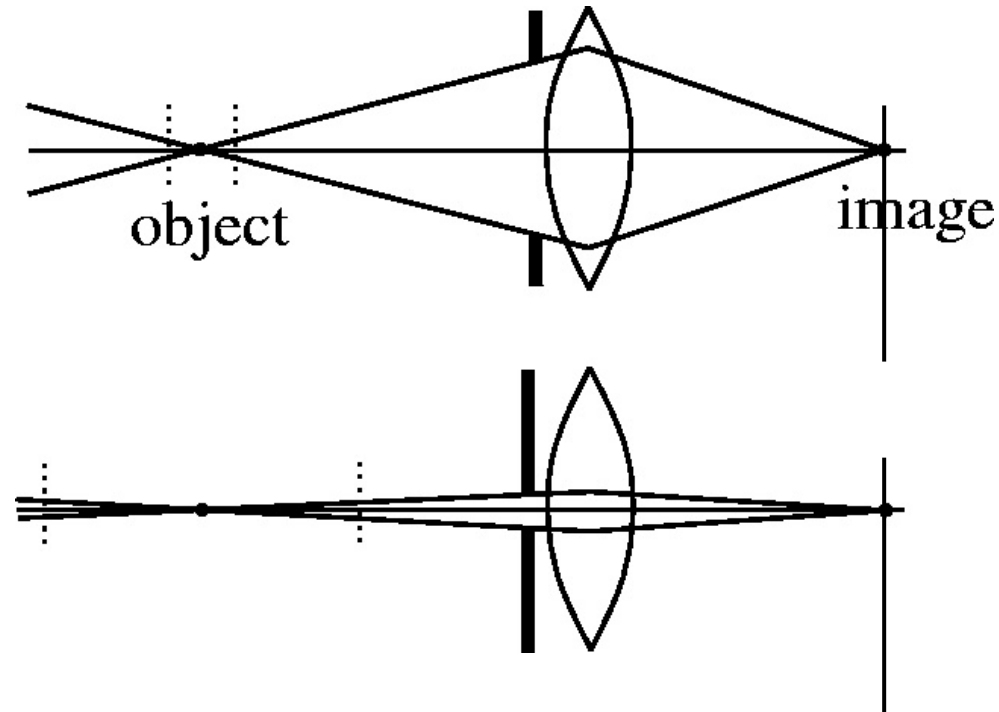
- Aperture is the diameter of the lens opening, usually specified by f-stop,  $f/D$ , a fraction of the focal length.
  - $f/2.0$  on a 50mm means that the aperture is 25mm
  - $f/2.0$  on a 100mm means that the aperture is 50mm
- When a change in f-stop occurs, the light is either doubled or cut in half.
- Lower f-stop, more light (larger lens opening)
- Higher f-stop, less light (smaller lens opening)





# Depth of field

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Changing the aperture size affects depth of field. A smaller aperture increases the range in which the object is approximately in focus

See <http://www.photonhead.com/simcam/>

# Exposure & metering

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- The camera metering system measures how bright the scene is
- In Aperture priority mode, the photographer sets the aperture, the camera sets the shutter speed
- In Shutter-speed priority mode, photographers sets the shutter speed and the camera deduces the aperture
- In Program mode, the camera decides both exposure and shutter speed (middle value more or less)
- In Manual mode, the user decides everything (but can get feedback)

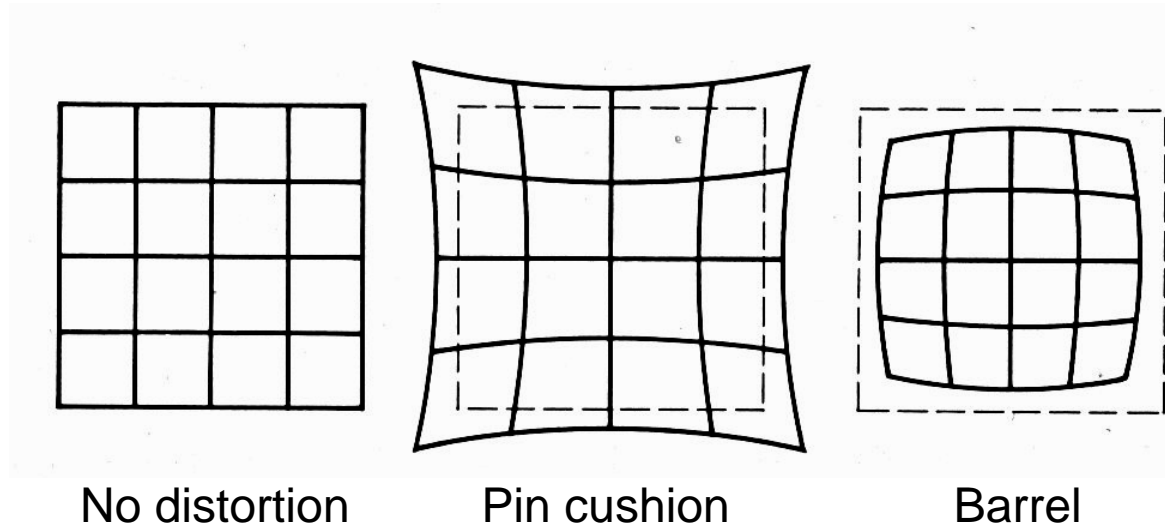
# Pros and cons of various modes

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- Aperture priority
  - Direct depth of field control
  - Cons: can require impossible shutter speed (e.g. with f/1.4 for a bright scene)
- Shutter speed priority
  - Direct motion blur control
  - Cons: can require impossible aperture (e.g. when requesting a 1/1000 speed for a dark scene)
    - Note that aperture is somewhat more restricted
- Program
  - Almost no control, but no need for neurons
- Manual
  - Full control, but takes more time and thinking



# Distortion



- Radial distortion of the image
  - Caused by imperfect lenses
  - Deviations are most noticeable for rays that pass through the edge of the lens

# Correcting radial distortion

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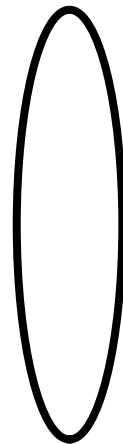
from [Helmut Dersch](#)

# Film camera

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scene



lens &  
motor

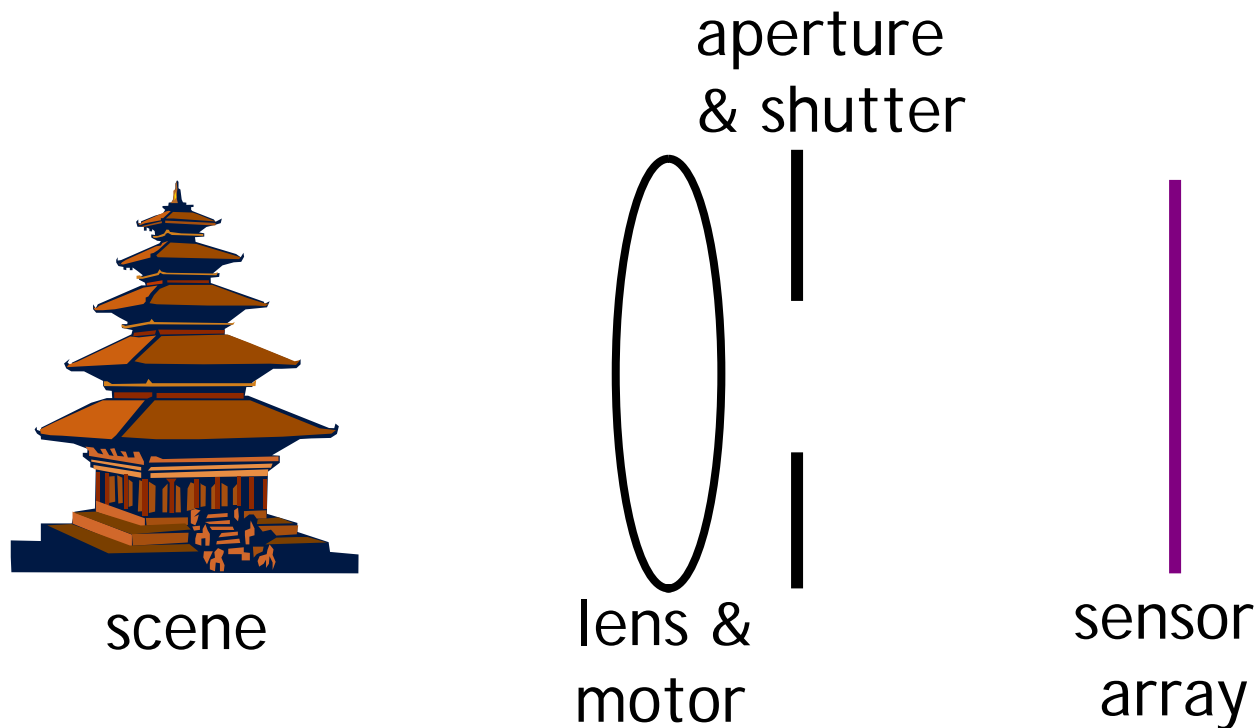
aperture  
& shutter



film

# Digital camera

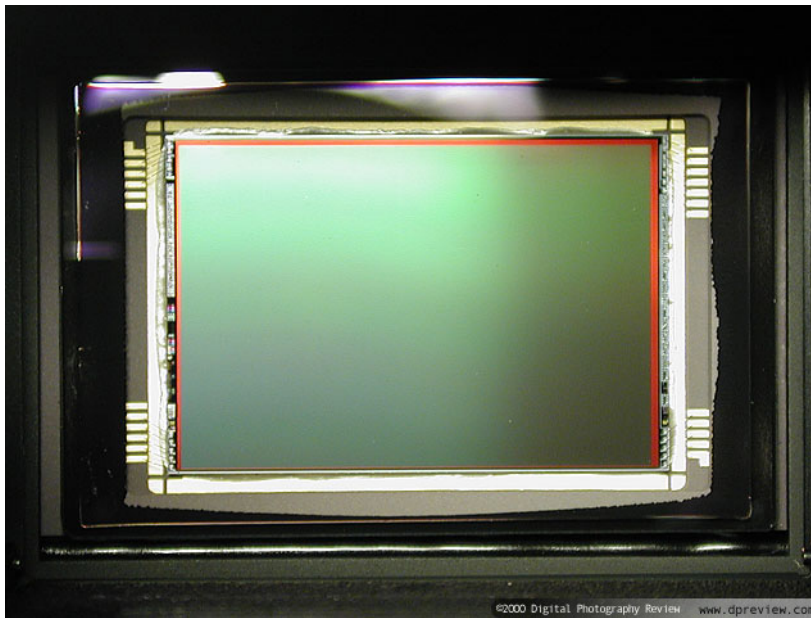
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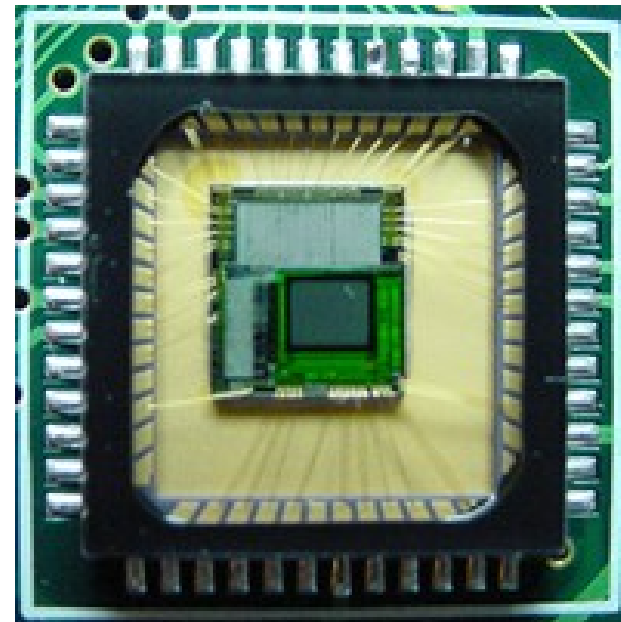
- A digital camera replaces film with a sensor array
- Each cell in the array is a light-sensitive diode that converts photons to electrons

# CCD v.s. CMOS

- CCD is less susceptible to noise (special process, higher fill factor)
- CMOS is more flexible, less expensive (standard process), less power consumption



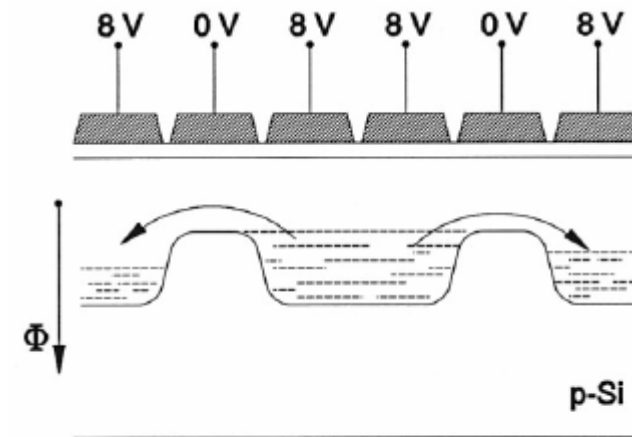
CCD



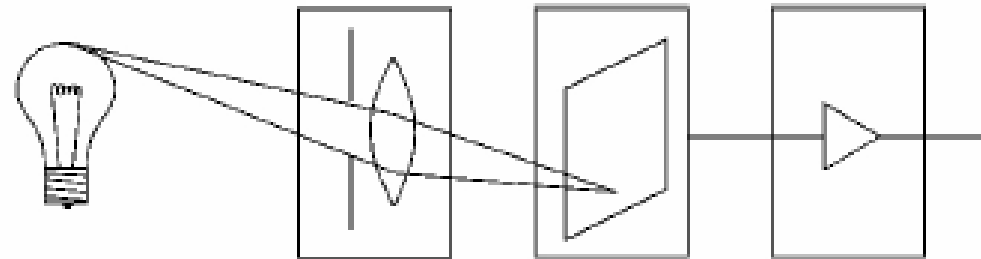
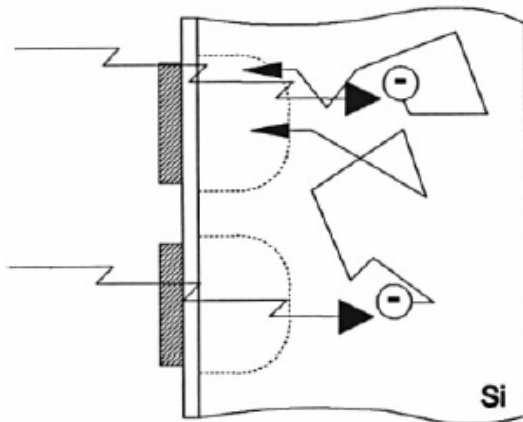
CMOS

# Sensor noise

- Blooming
- Diffusion
- Dark current
- Photon shot noise
- Amplifier readout noise



Blooming



Real world

Optics

Recorder

Digitizer

# SLR (Single-Lens Reflex)

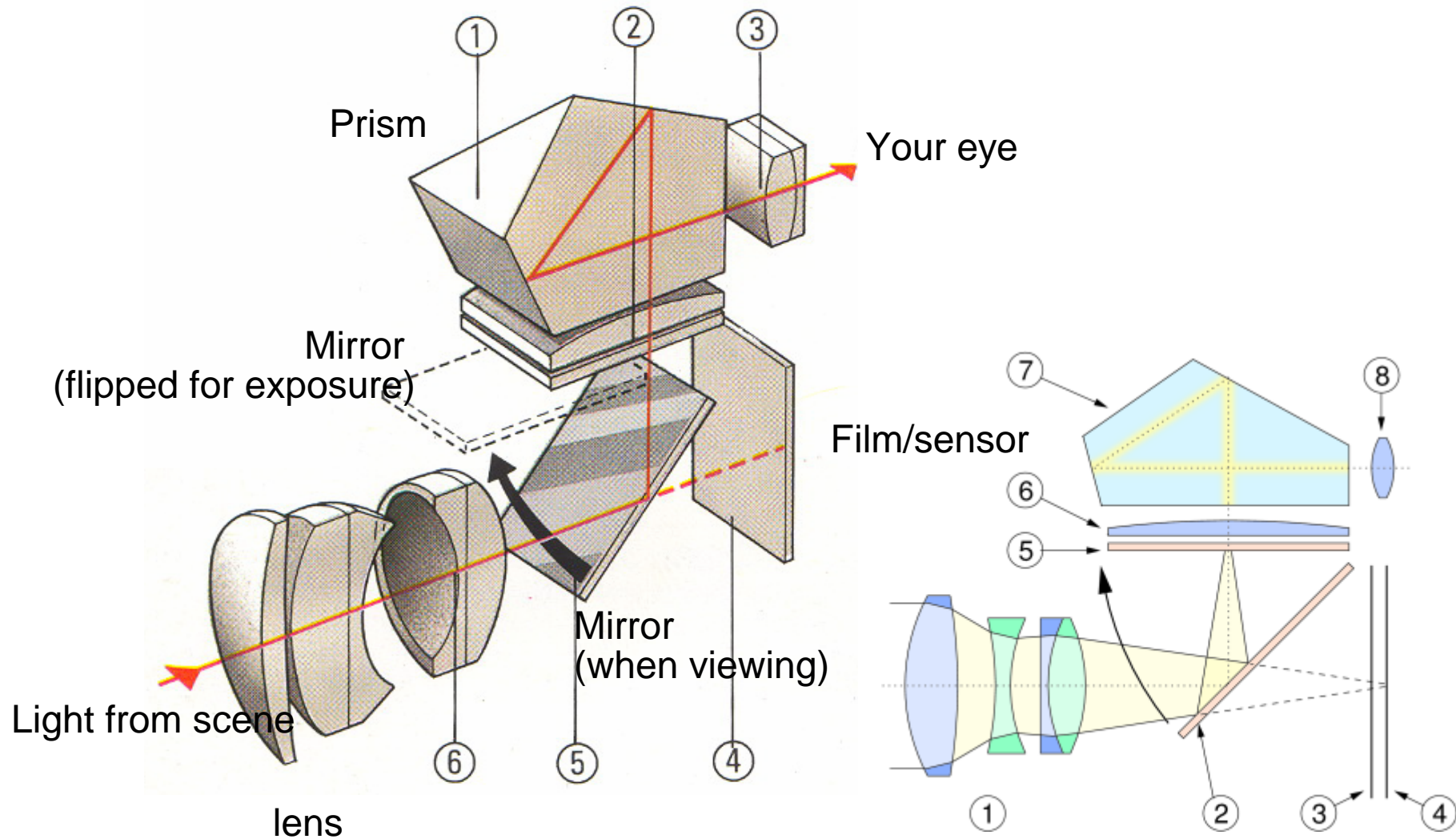
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- Reflex (R in SLR) means that we see through the same lens used to take the image.
- Not the case for compact cameras





# SLR view finder





# Color

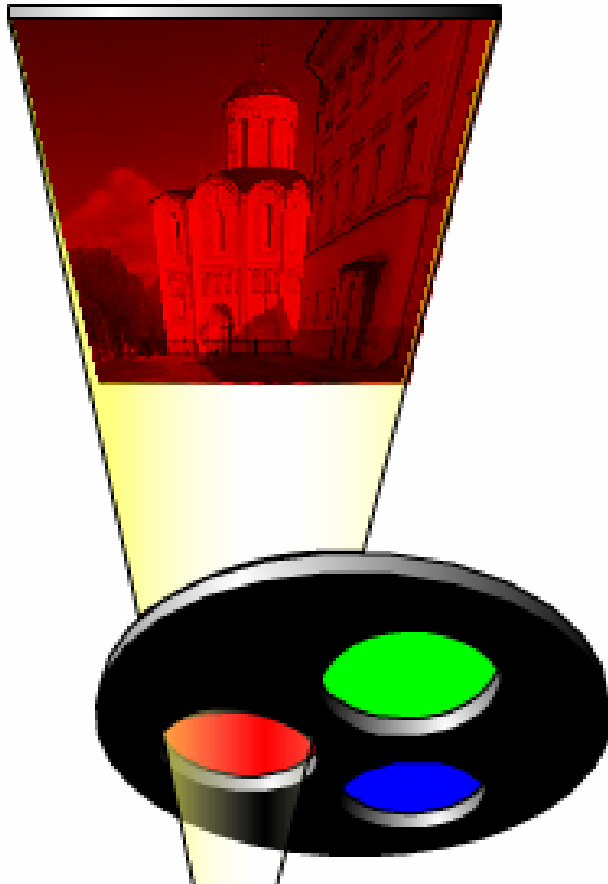
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So far, we've only talked about monochrome sensors. Color imaging has been implemented in a number of ways:

- Field sequential
- Multi-chip
- Color filter array
- X3 sensor

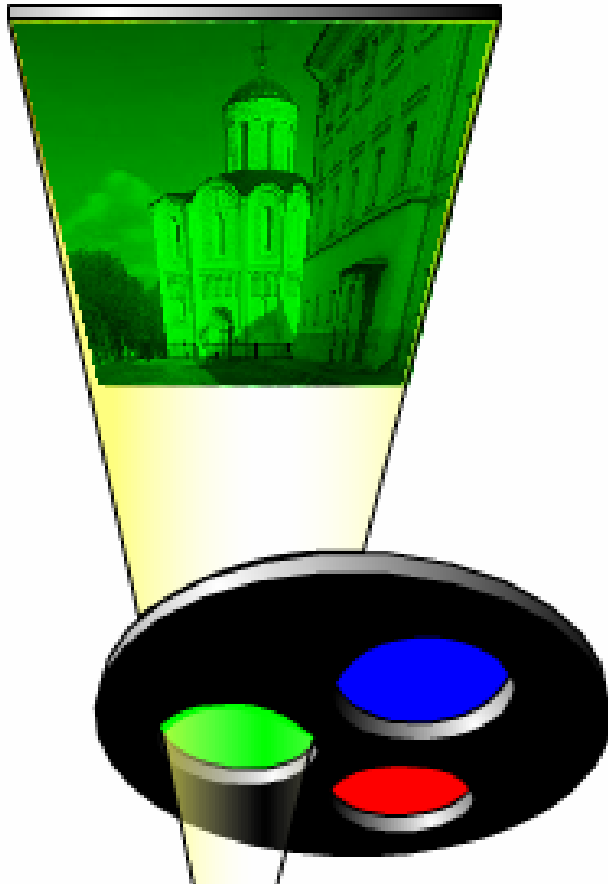
# Field sequential

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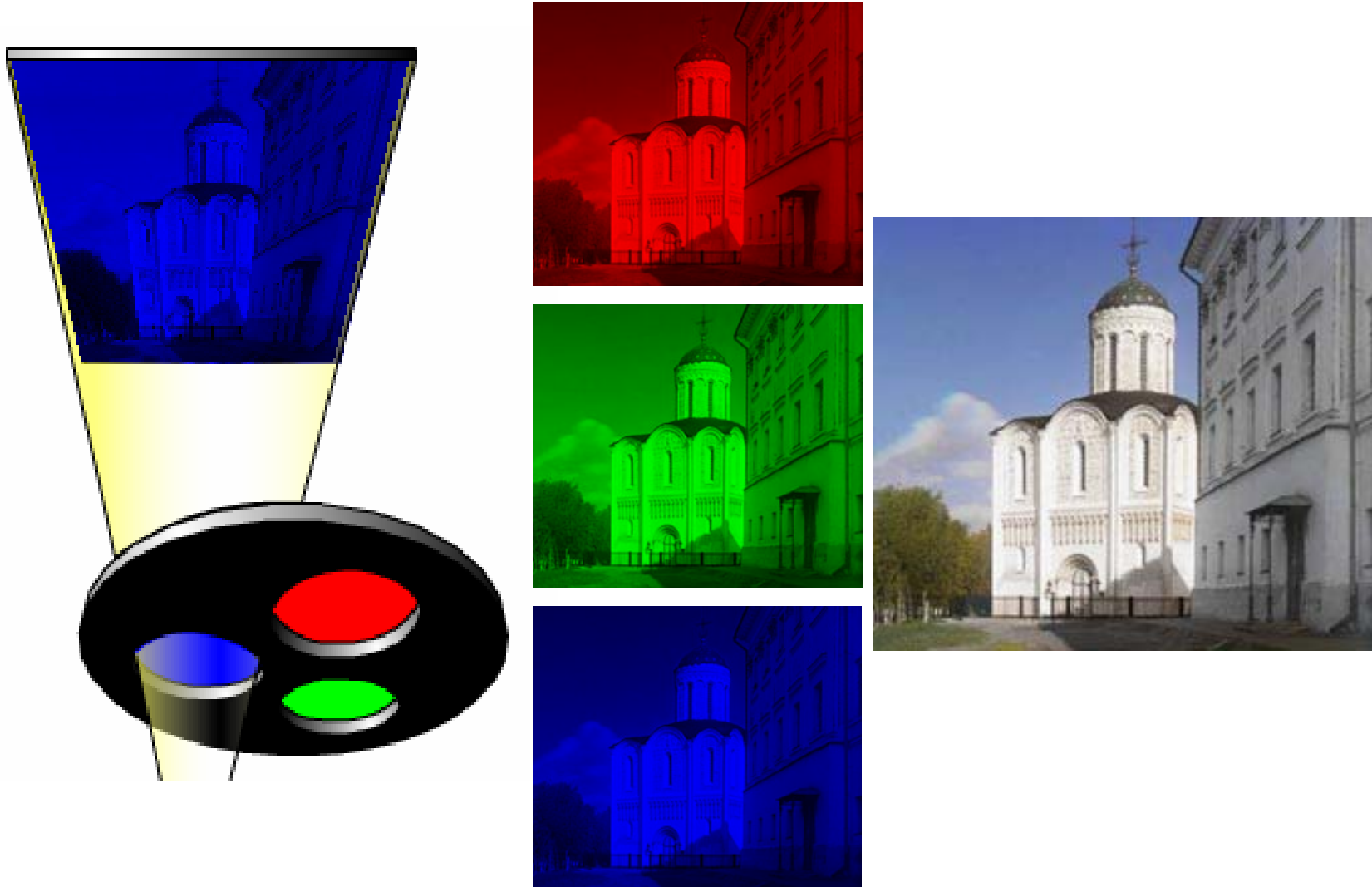
# Field sequential

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# Field sequential

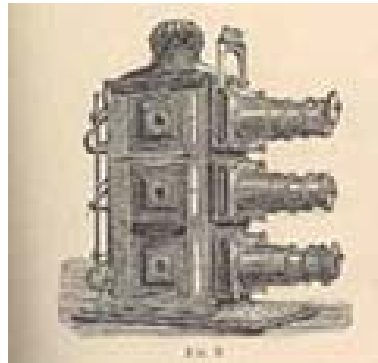
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# Prokudin-Gorskii (early 1900's)

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DigiVFX



Lantern  
projector



<http://www.loc.gov/exhibits/empire/>



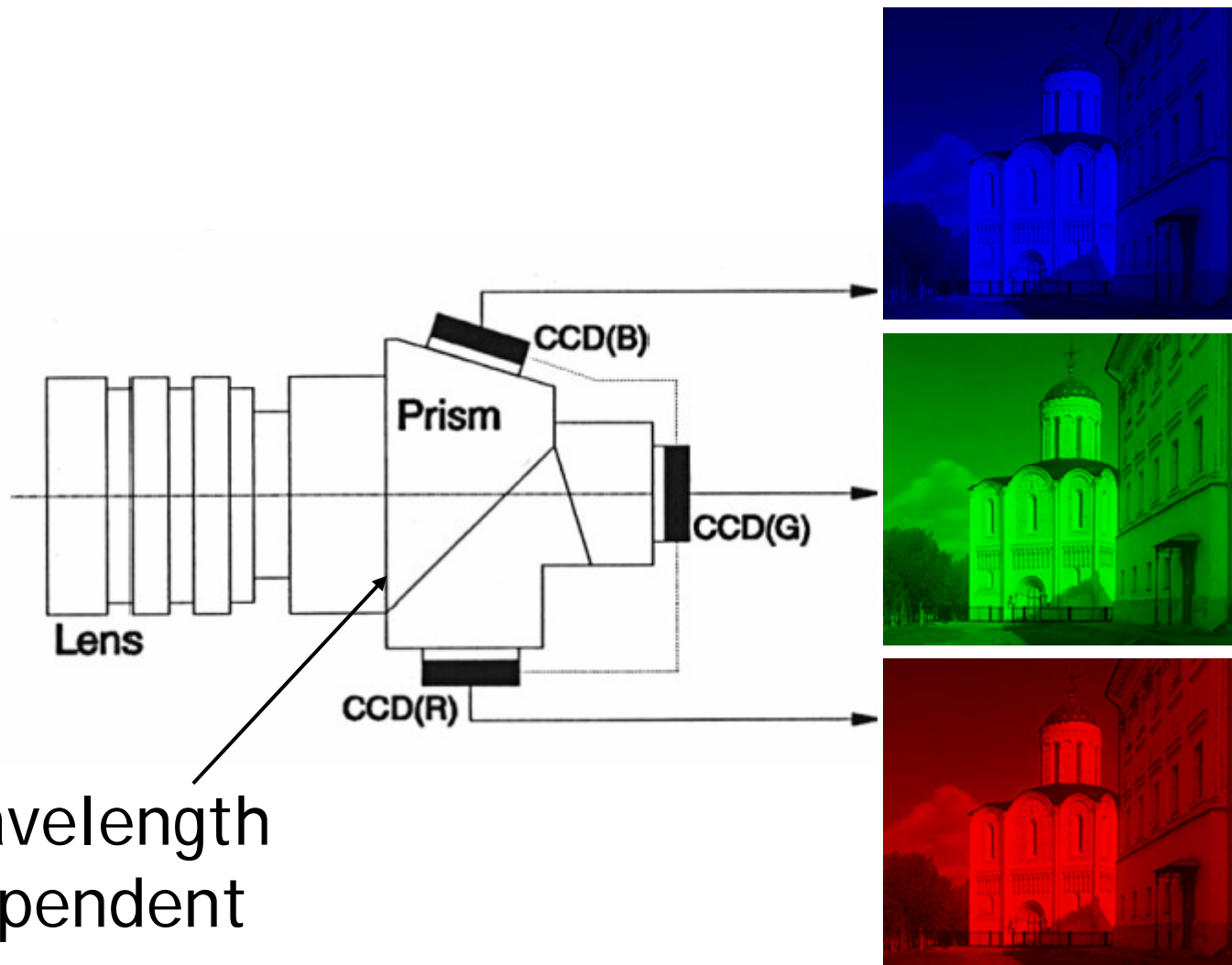
# Prokudin-Gorskii (early 1990's)

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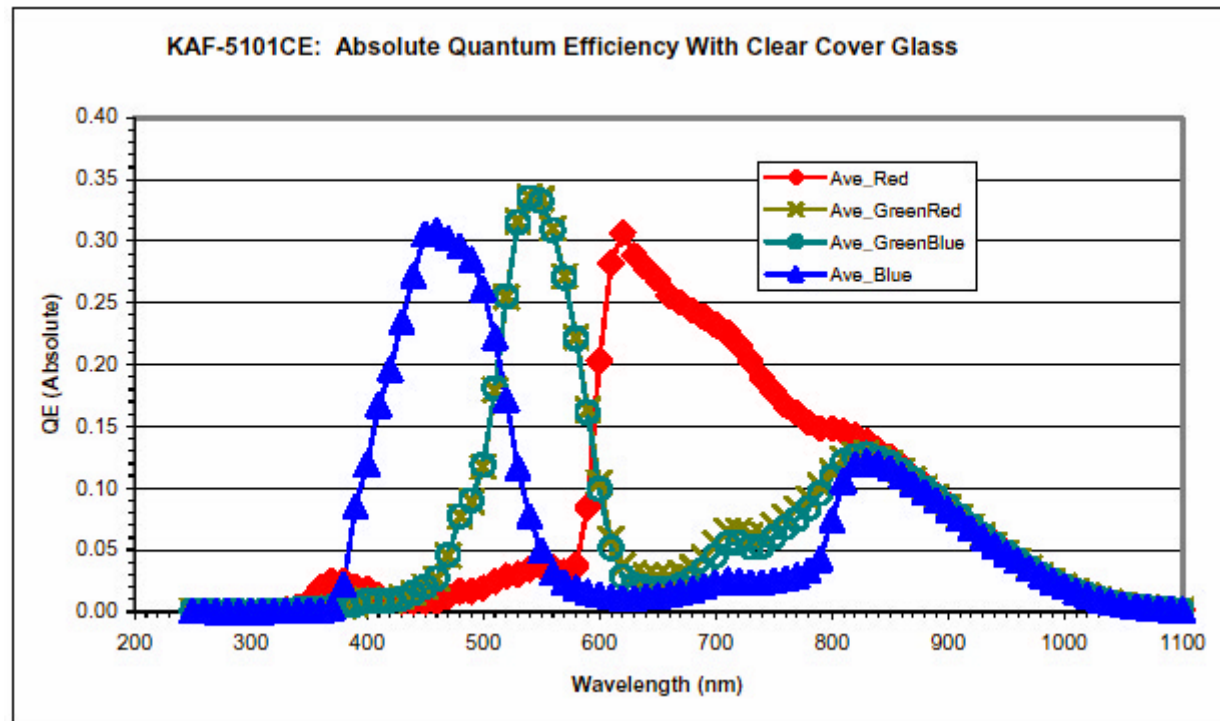
DigiVFX



# Multi-chip



# Embedded color filters



Color filters can be manufactured directly onto the photodetectors.



# Color filter array

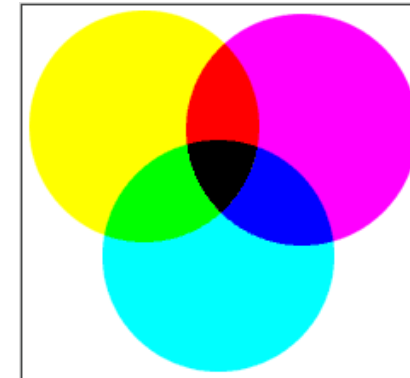
Kodak DCS620x

R	G	B
R	G	B
R	G	B
R	G	B

R	G	B	G
R	G	B	G
R	G	B	G
R	G	B	G

Ye	G	Cy	G
Ye	G	Cy	G
Ye	G	Cy	G
Ye	G	Cy	G

**Stripes**

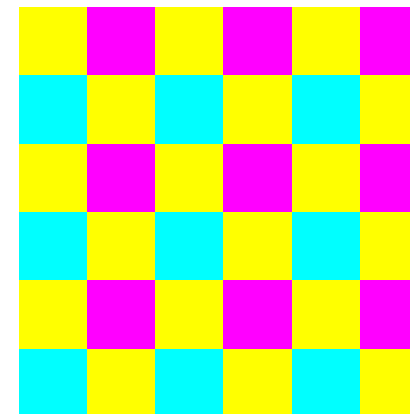


Cy	W	Ye	G
Ye	G	Cy	W
Cy	W	Ye	G
Ye	G	Cy	W

G	Mg	G	Mg
Cy	Ye	Cy	Ye
Mg	G	Mg	G
Cy	Ye	Cy	Ye

R	G	R	G
G	B	G	B
R	G	R	G
G	B	G	B

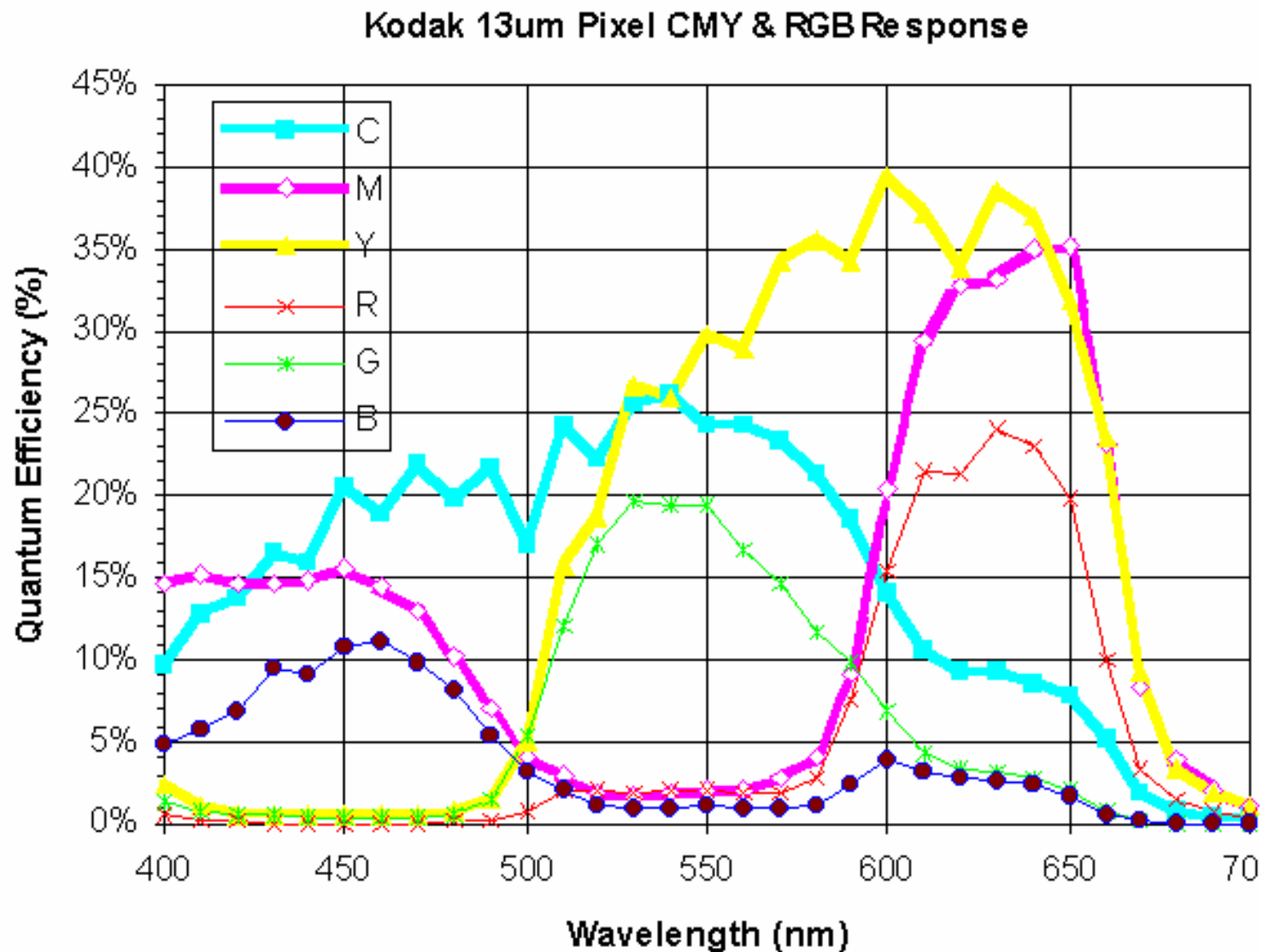
**Mosaics**



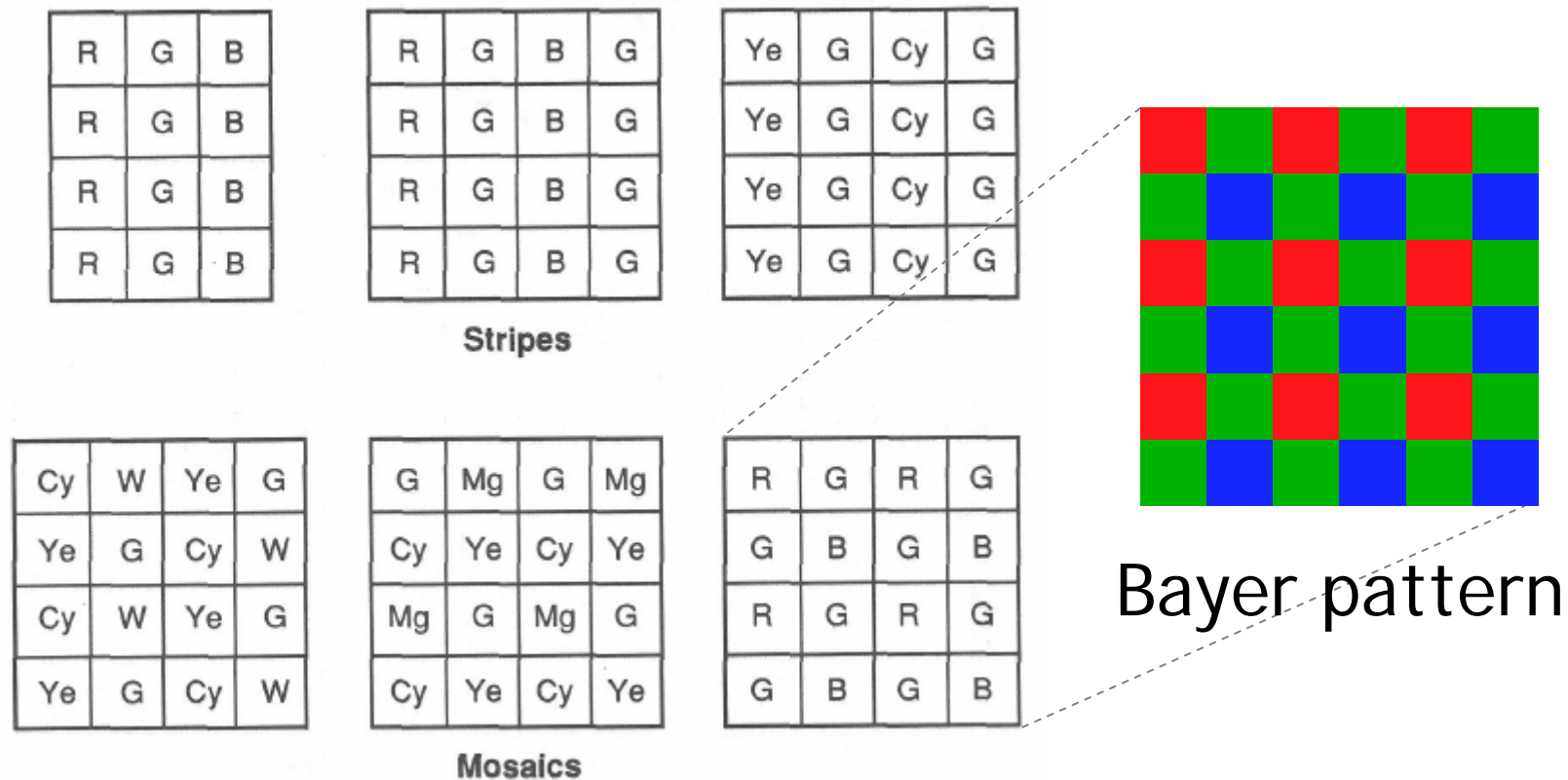
**CMY**

Color filter arrays (CFAs)/color filter mosaics

# Why CMY CFA might be better



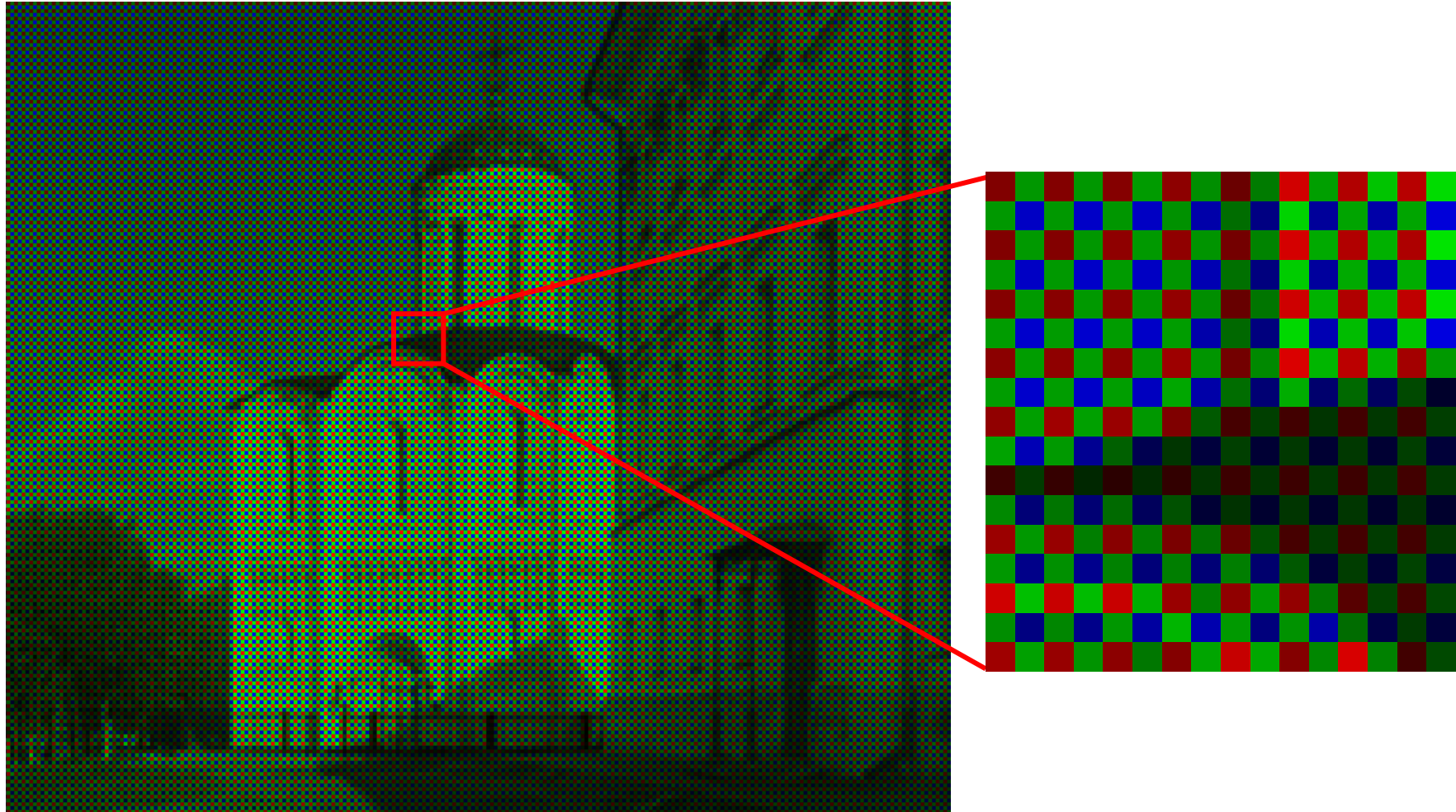
# Color filter array



Color filter arrays (CFAs)/color filter mosaics

# Bayer's pattern

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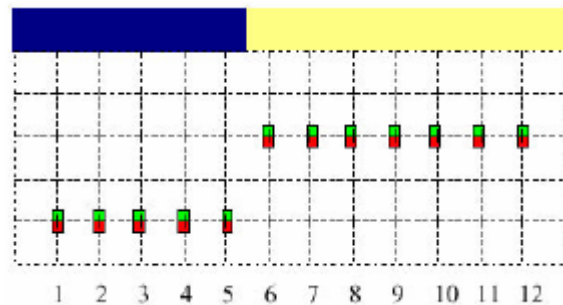
# Demosaicking CFA's

R <sub>11</sub>	G <sub>12</sub>	R <sub>13</sub>	G <sub>14</sub>	R <sub>15</sub>	G <sub>16</sub>	R <sub>17</sub>
G <sub>21</sub>	B <sub>22</sub>	G <sub>23</sub>	B <sub>24</sub>	G <sub>25</sub>	B <sub>26</sub>	G <sub>27</sub>
R <sub>31</sub>	G <sub>32</sub>	R <sub>33</sub>	G <sub>34</sub>	R <sub>35</sub>	G <sub>36</sub>	R <sub>37</sub>
G <sub>41</sub>	B <sub>42</sub>	G <sub>43</sub>	B <sub>44</sub>	G <sub>45</sub>	B <sub>46</sub>	G <sub>47</sub>
R <sub>51</sub>	G <sub>52</sub>	R <sub>53</sub>	G <sub>54</sub>	R <sub>55</sub>	G <sub>56</sub>	R <sub>57</sub>

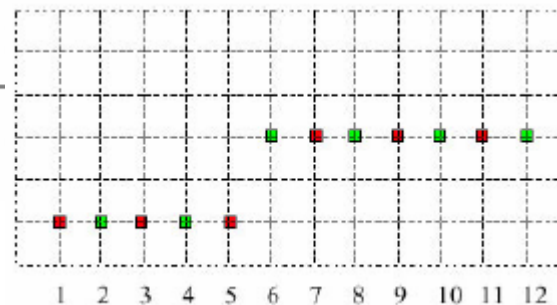
bilinear interpolation

$$G_{44} = (G_{34} + G_{43} + G_{45} + G_{54}) / 4$$

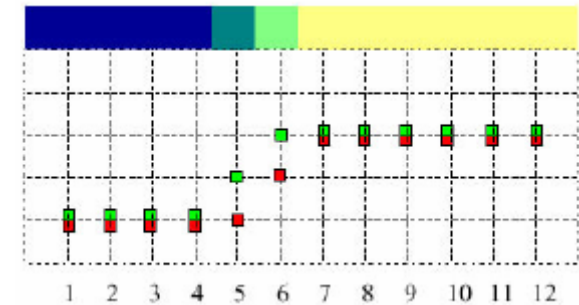
$$R_{44} = (R_{33} + R_{35} + R_{53} + R_{55}) / 4$$



original



input



linear interpolation

# Demosaicking CFA's

R <sub>11</sub>	G <sub>12</sub>	R <sub>13</sub>	G <sub>14</sub>	R <sub>15</sub>	G <sub>16</sub>	R <sub>17</sub>
G <sub>21</sub>	B <sub>22</sub>	G <sub>23</sub>	B <sub>24</sub>	G <sub>25</sub>	B <sub>26</sub>	G <sub>27</sub>
R <sub>31</sub>	G <sub>32</sub>	R <sub>33</sub>	G <sub>34</sub>	R <sub>35</sub>	G <sub>36</sub>	R <sub>37</sub>
G <sub>41</sub>	B <sub>42</sub>	G <sub>43</sub>	B <sub>44</sub>	G <sub>45</sub>	B <sub>46</sub>	G <sub>47</sub>
R <sub>51</sub>	G <sub>52</sub>	R <sub>53</sub>	G <sub>54</sub>	R <sub>55</sub>	G <sub>56</sub>	R <sub>57</sub>
G <sub>61</sub>	B <sub>62</sub>	G <sub>63</sub>	B <sub>64</sub>	G <sub>65</sub>	B <sub>66</sub>	G <sub>67</sub>
R <sub>71</sub>	G <sub>72</sub>	R <sub>73</sub>	G <sub>74</sub>	R <sub>75</sub>	G <sub>76</sub>	R <sub>77</sub>

Constant hue-based interpolation (Cok)

Hue:  $(R/G, B/G)$

Interpolate G first

$$R_{44} = G_{44} \frac{\frac{R_{33}}{G_{33}} + \frac{R_{35}}{G_{35}} + \frac{R_{53}}{G_{53}} + \frac{R_{55}}{G_{55}}}{4}$$

$$B_{33} = G_{33} \frac{\frac{B_{22}}{G_{22}} + \frac{B_{24}}{G_{24}} + \frac{B_{42}}{G_{42}} + \frac{B_{44}}{G_{44}}}{4}$$

# Demosaicking CFA's

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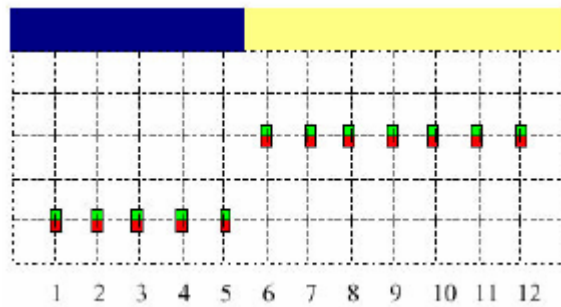
R <sub>11</sub>	G <sub>12</sub>	R <sub>13</sub>	G <sub>14</sub>	R <sub>15</sub>	G <sub>16</sub>	R <sub>17</sub>
G <sub>21</sub>	B <sub>22</sub>	G <sub>23</sub>	B <sub>24</sub>	G <sub>25</sub>	B <sub>26</sub>	G <sub>27</sub>
R <sub>31</sub>	G <sub>32</sub>	R <sub>33</sub>	G <sub>34</sub>	R <sub>35</sub>	G <sub>36</sub>	R <sub>37</sub>
G <sub>41</sub>	B <sub>42</sub>	G <sub>43</sub>	B <sub>44</sub>	G <sub>45</sub>	B <sub>46</sub>	G <sub>47</sub>
R <sub>51</sub>	G <sub>52</sub>	R <sub>53</sub>	G <sub>54</sub>	R <sub>55</sub>	G <sub>56</sub>	R <sub>57</sub>
G <sub>61</sub>	B <sub>62</sub>	G <sub>63</sub>	B <sub>64</sub>	G <sub>65</sub>	B <sub>66</sub>	G <sub>67</sub>
R <sub>71</sub>	G <sub>72</sub>	R <sub>73</sub>	G <sub>74</sub>	R <sub>75</sub>	G <sub>76</sub>	R <sub>77</sub>

Median-based interpolation  
(Freeman)

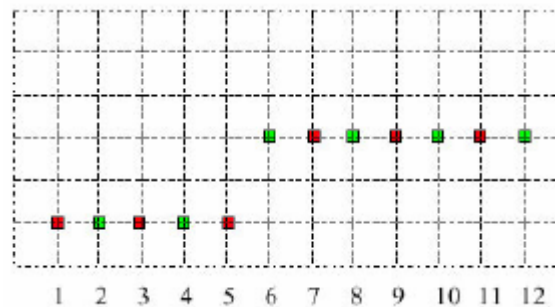
1. Linear interpolation
2. Median filter on color differences

# Demosaicking CFA's

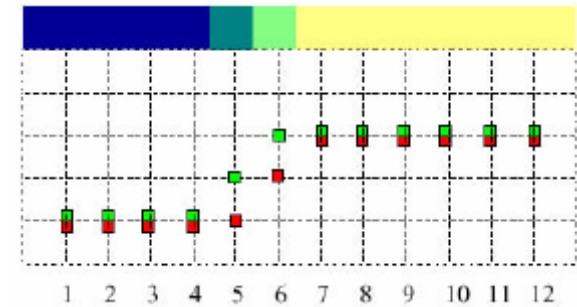
## Median-based interpolation (Freeman)



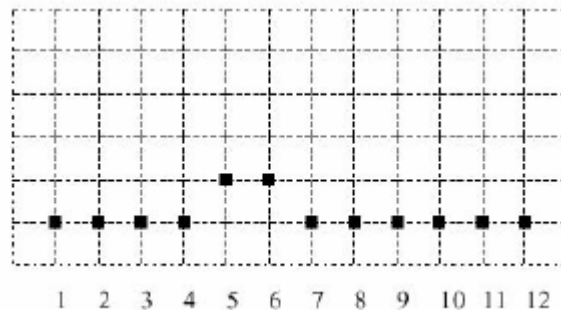
original



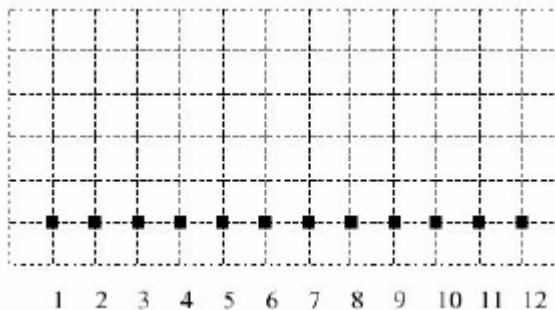
input



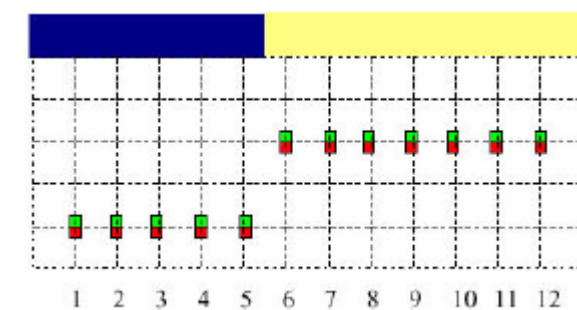
linear interpolation



color difference  
(e.g. G-R)



median filter  
(kernel size 5)



Reconstruction  
( $G=R+\text{filtered difference}$ )



# Demosaicking CFA's

R <sub>11</sub>	G <sub>12</sub>	R <sub>13</sub>	G <sub>14</sub>	R <sub>15</sub>	G <sub>16</sub>	R <sub>17</sub>
G <sub>21</sub>	B <sub>22</sub>	G <sub>23</sub>	B <sub>24</sub>	G <sub>25</sub>	B <sub>26</sub>	G <sub>27</sub>
R <sub>31</sub>	G <sub>32</sub>	R <sub>33</sub>	G <sub>34</sub>	R <sub>35</sub>	G <sub>36</sub>	R <sub>37</sub>
G <sub>41</sub>	B <sub>42</sub>	G <sub>43</sub>	B <sub>44</sub>	G <sub>45</sub>	B <sub>46</sub>	G <sub>47</sub>
R <sub>51</sub>	G <sub>52</sub>	R <sub>53</sub>	G <sub>54</sub>	R <sub>55</sub>	G <sub>56</sub>	R <sub>57</sub>
G <sub>61</sub>	B <sub>62</sub>	G <sub>63</sub>	B <sub>64</sub>	G <sub>65</sub>	B <sub>66</sub>	G <sub>67</sub>
R <sub>71</sub>	G <sub>72</sub>	R <sub>73</sub>	G <sub>74</sub>	R <sub>75</sub>	G <sub>76</sub>	R <sub>77</sub>

Gradient-based interpolation  
(LaRoche-Prescott)

1. Interpolation on G

$$\alpha = \text{abs}[(B_{42} + B_{46})/2 - B_{44}]$$

$$\beta = \text{abs}[(B_{24} + B_{64})/2 - B_{44}]$$

$$G_{44} = \begin{cases} \frac{G_{43} + G_{45}}{2} & \text{if } \alpha < \beta \\ \frac{G_{34} + G_{54}}{2} & \text{if } \alpha > \beta \\ \frac{G_{43} + G_{45} + G_{34} + G_{54}}{4} & \text{if } \alpha = \beta \end{cases}$$

# Demosaicking CFA's

$R_{11}$	$G_{12}$	$R_{13}$	$G_{14}$	$R_{15}$	$G_{16}$	$R_{17}$
$G_{21}$	$B_{22}$	$G_{23}$	$B_{24}$	$G_{25}$	$B_{26}$	$G_{27}$
$R_{31}$	$G_{32}$	$R_{33}$	$G_{34}$	$R_{35}$	$G_{36}$	$R_{37}$
$G_{41}$	$B_{42}$	$G_{43}$	$B_{44}$	$G_{45}$	$B_{46}$	$G_{47}$
$R_{51}$	$G_{52}$	$R_{53}$	$G_{54}$	$R_{55}$	$G_{56}$	$R_{57}$
$G_{61}$	$B_{62}$	$G_{63}$	$B_{64}$	$G_{65}$	$B_{66}$	$G_{67}$
$R_{71}$	$G_{72}$	$R_{73}$	$G_{74}$	$R_{75}$	$G_{76}$	$R_{77}$

Gradient-based interpolation  
(LaRoche-Prescott)

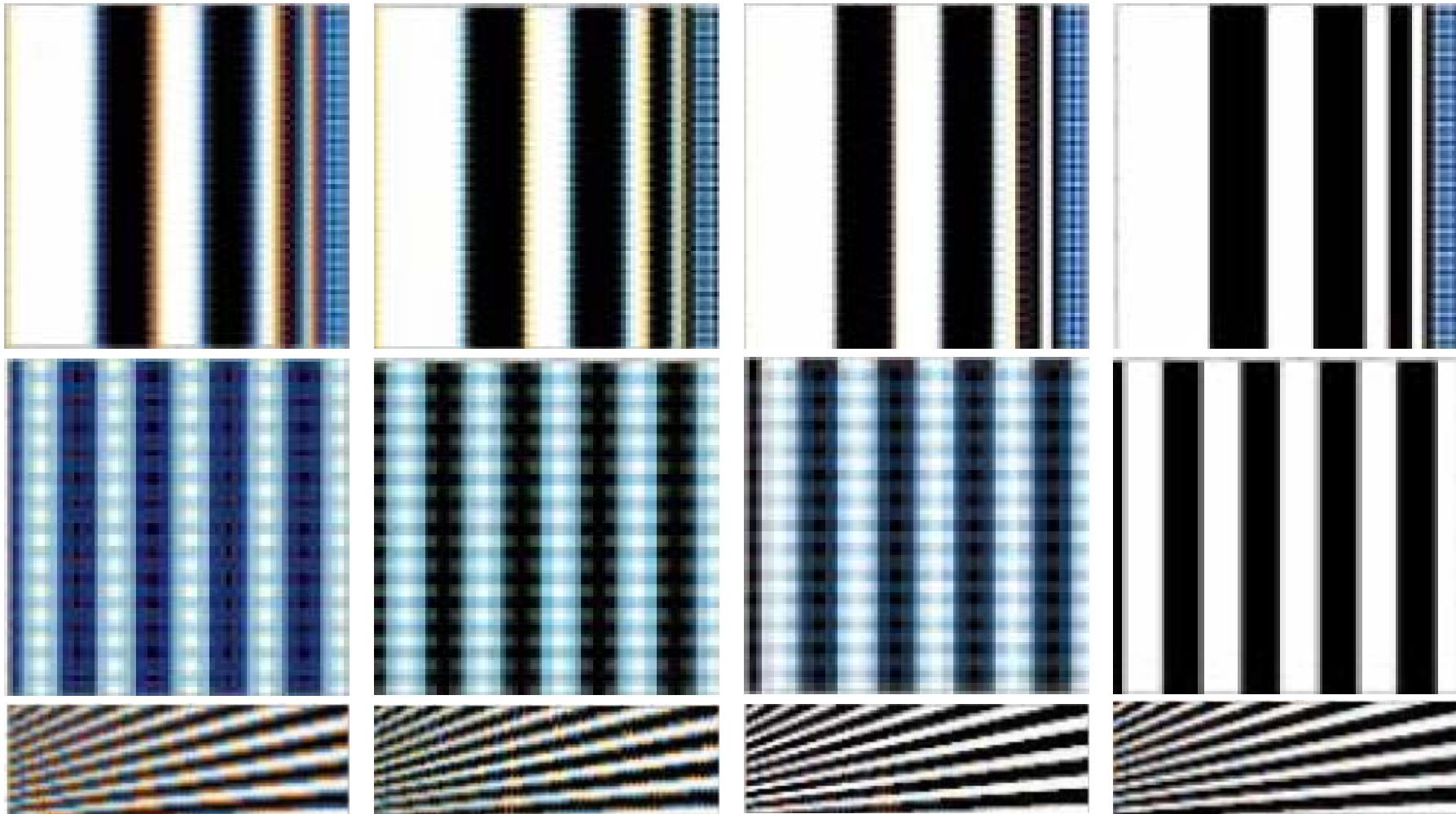
2. Interpolation of color differences

$$R_{34} = \frac{(R_{33} - G_{33}) + (R_{35} - G_{35})}{2} + G_{34},$$

$$R_{43} = \frac{(R_{33} - G_{33}) + (R_{53} - G_{53})}{2} + G_{43},$$

$$R_{44} = \frac{(R_{33} - G_{33}) + (R_{35} - G_{35}) + (R_{53} - G_{53}) + (R_{55} - G_{55})}{4} + G_{44}.$$

# Demosaicking CFA's



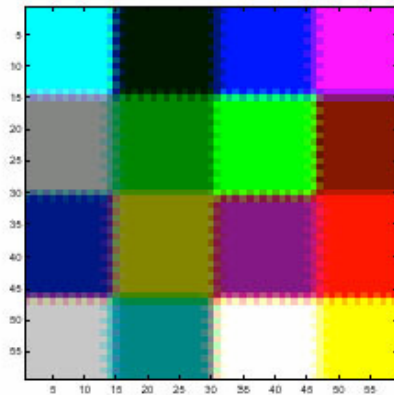
bilinear

Cok

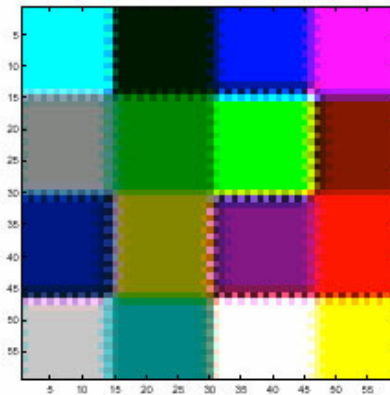
Freeman

LaRoche

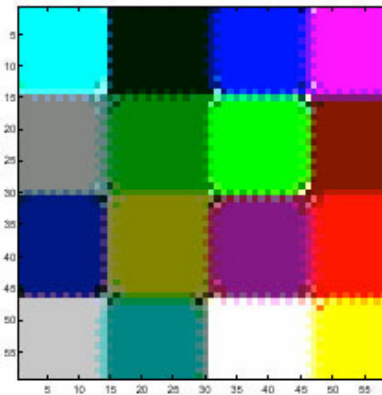
# Demosaicking CFA's



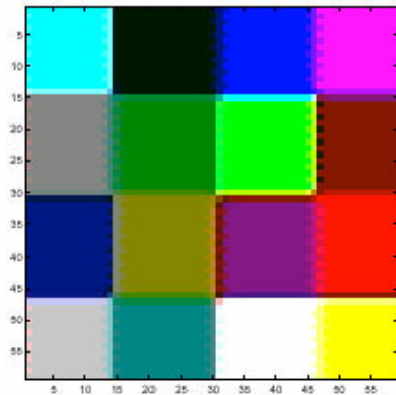
*Bilinear*



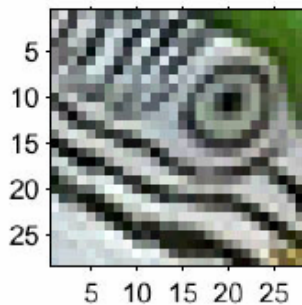
*Cok*



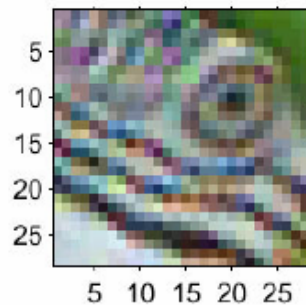
*Freeman*



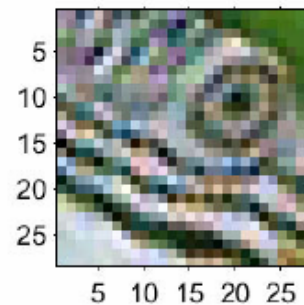
*LaRoche*



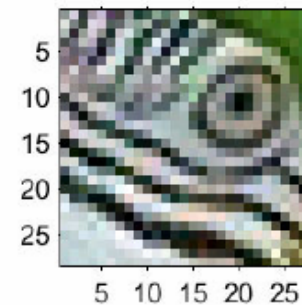
*Input*



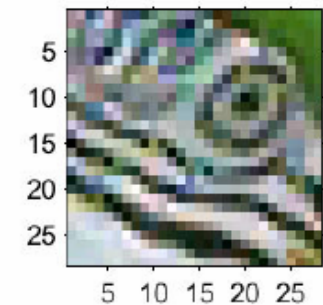
*Bilinear*



*Cok*



*Freeman*

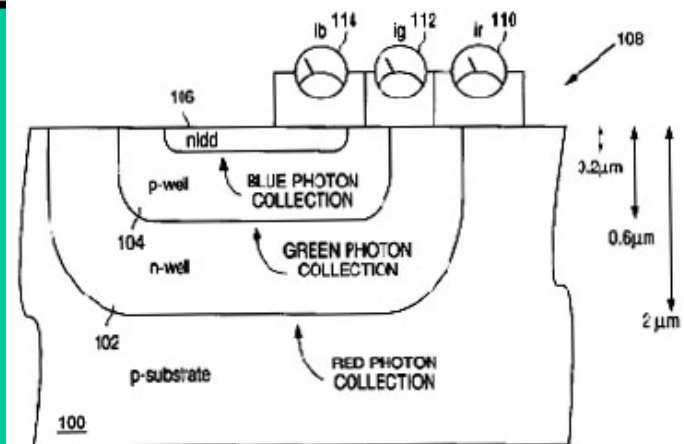
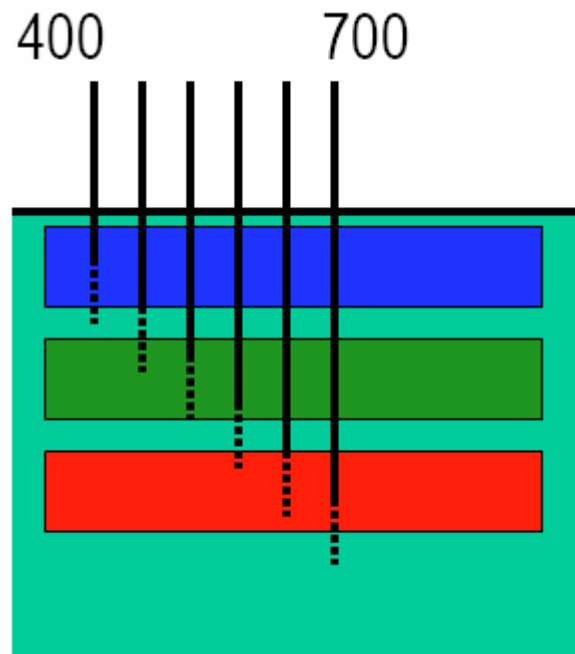
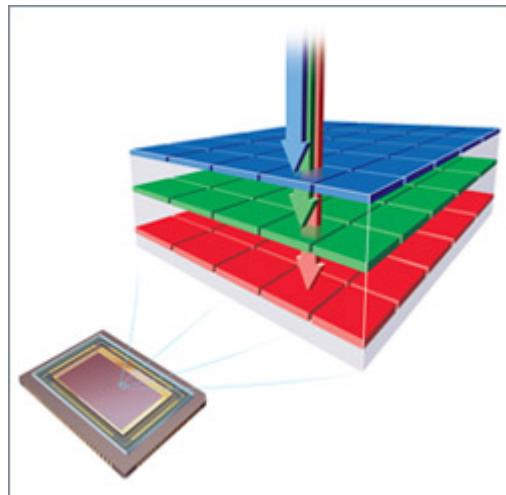


*LaRoche*

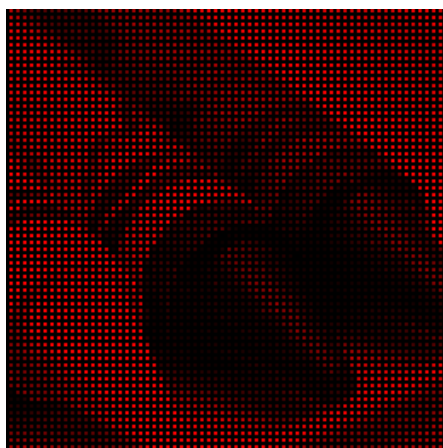
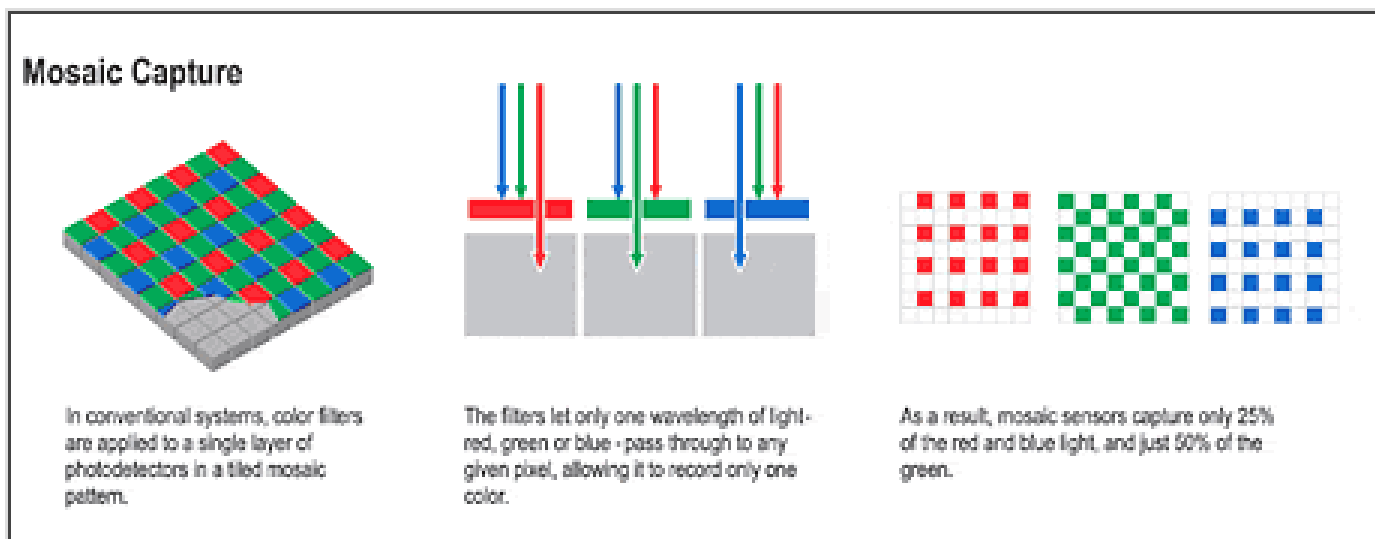
Generally, Freeman's is the best, especially for natural images.

# Foveon X3 sensor

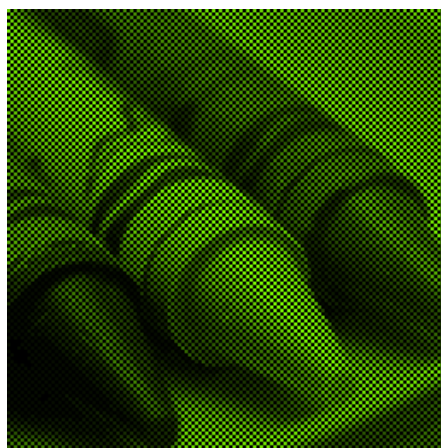
- light penetrates to different depths for different wavelengths
- multilayer CMOS sensor gets 3 different spectral sensitivities



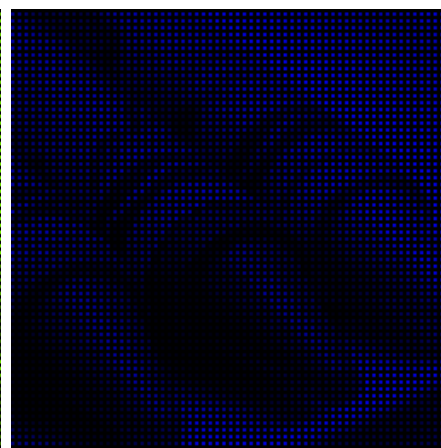
# Color filter array



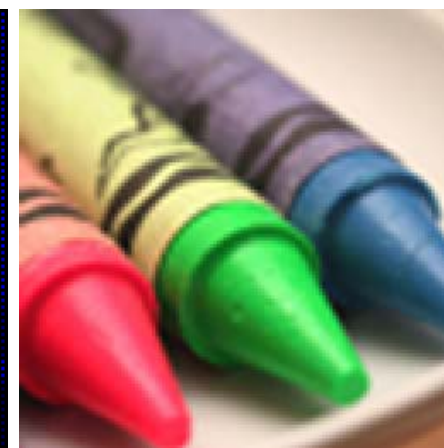
red



green

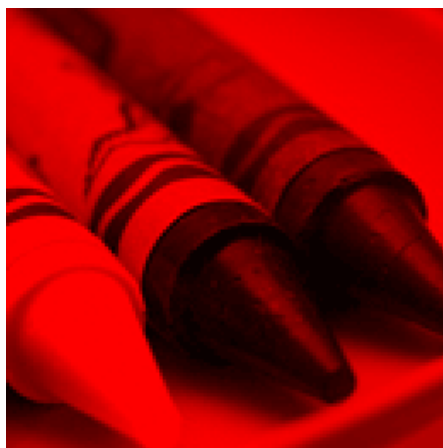
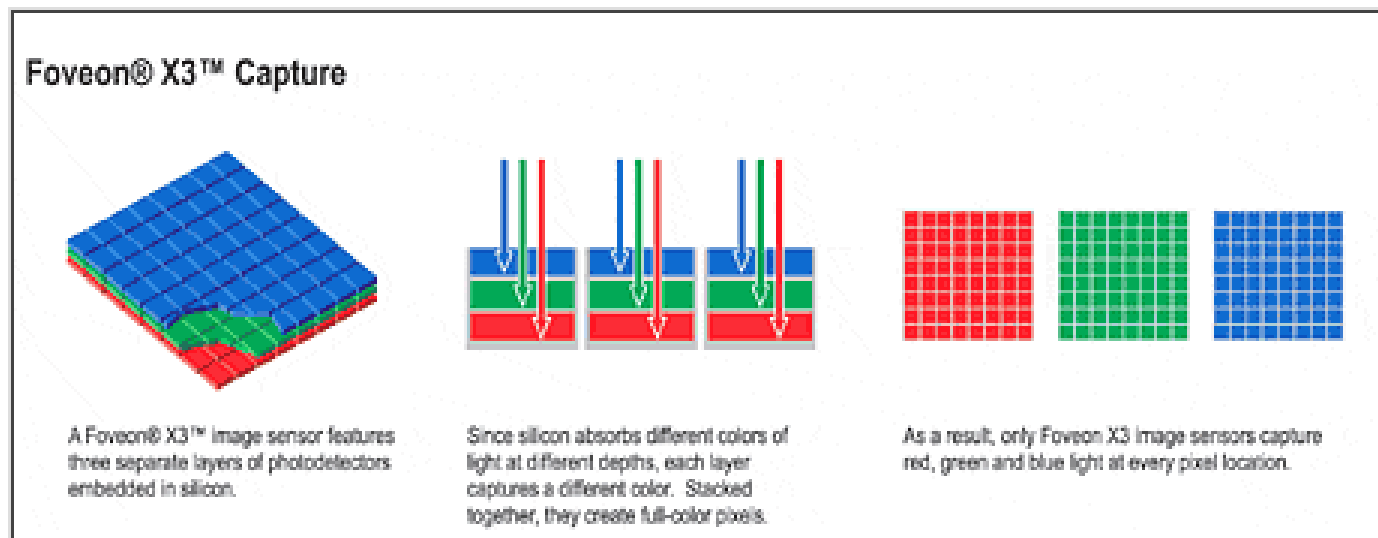


blue



output

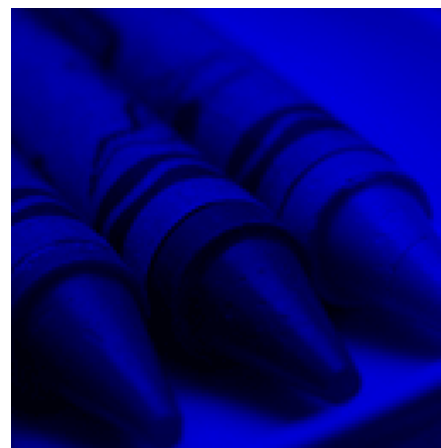
# X3 technology



red



green



blue

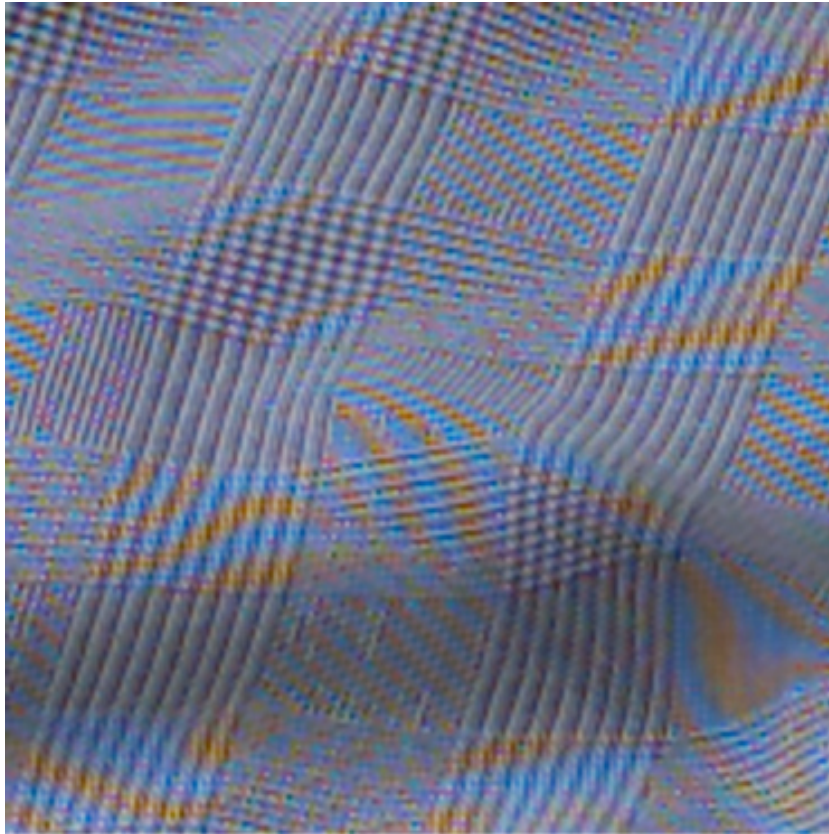


output

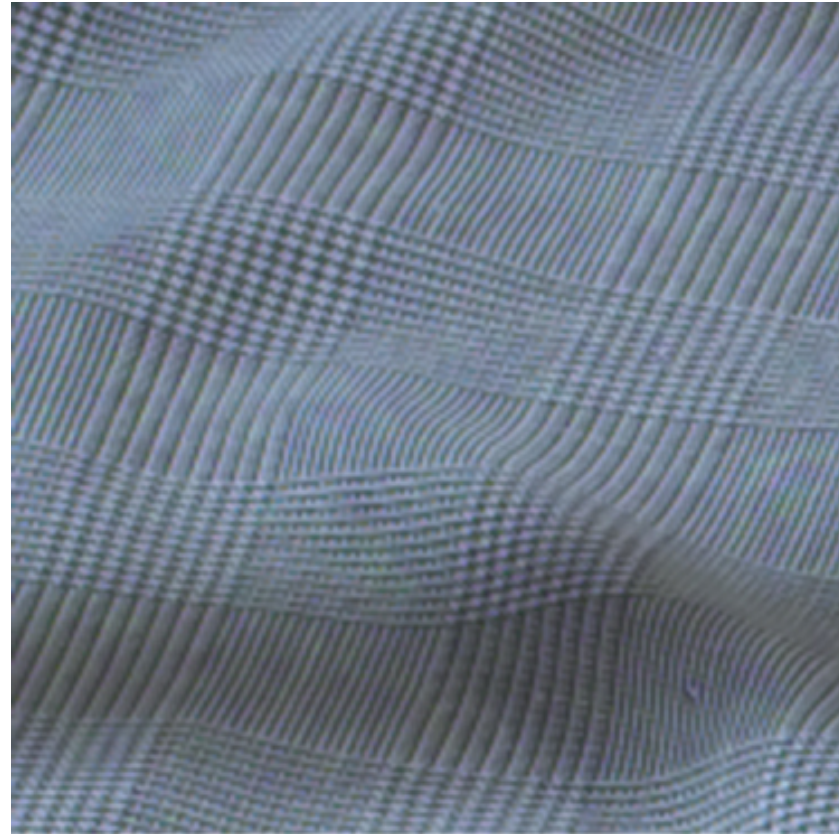


# Foveon X3 sensor

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Bayer CFA



X3 sensor

# Cameras with X3

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**Sigma SD10, SD9**



**Polaroid X530**

# Sigma SD9 vs Canon D30



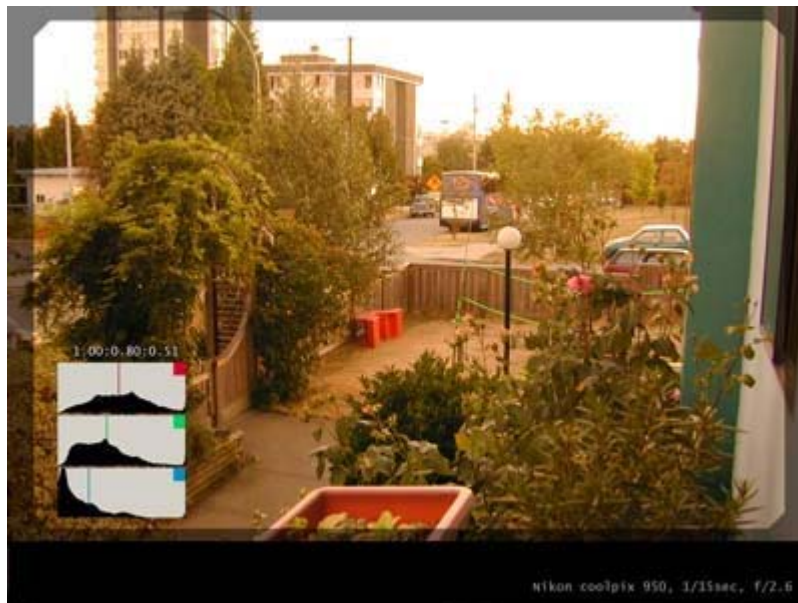
# Color processing

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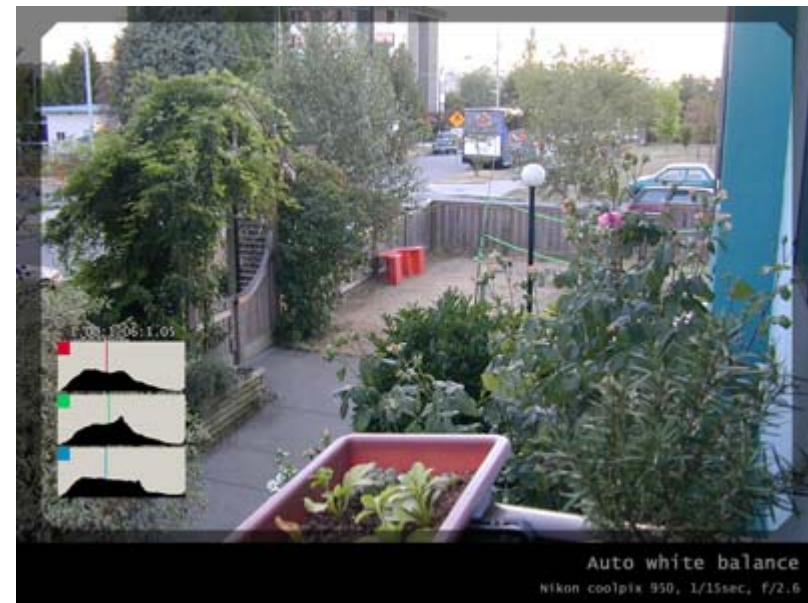
- After color values are recorded, more color processing usually happens:
  - White balance
  - Non-linearity to approximate film response or match TV monitor gamma



# White Balance



warmer +3



automatic white balance

# Manual white balance



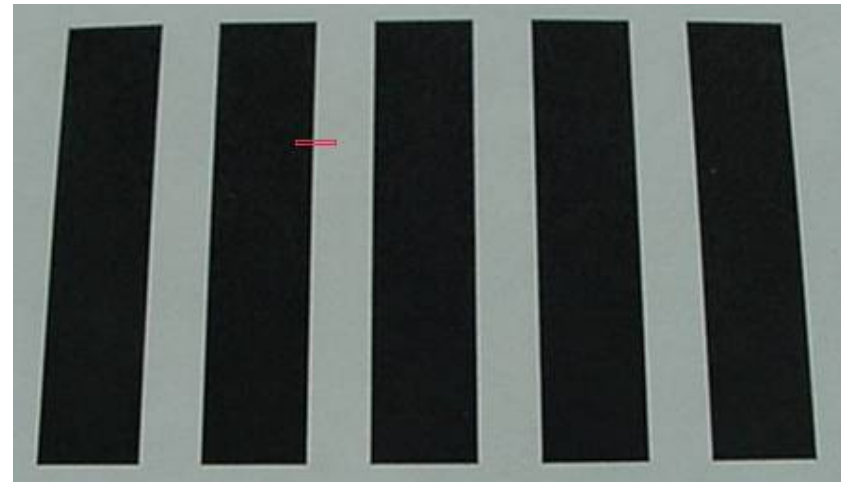
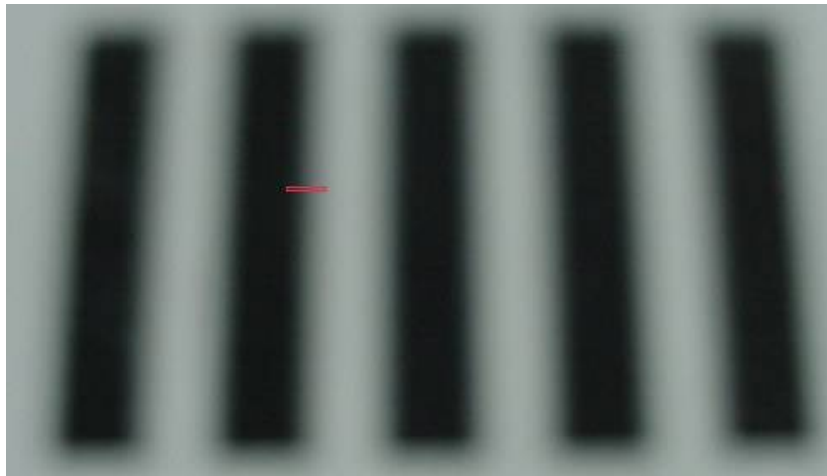
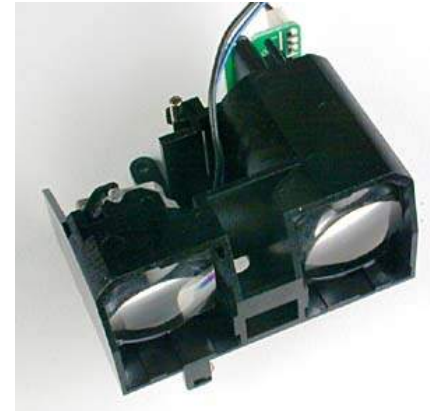
white balance with  
the white book



white balance with  
the red book

# Autofocus

- Active
  - Sonar
  - Infrared
- Passive





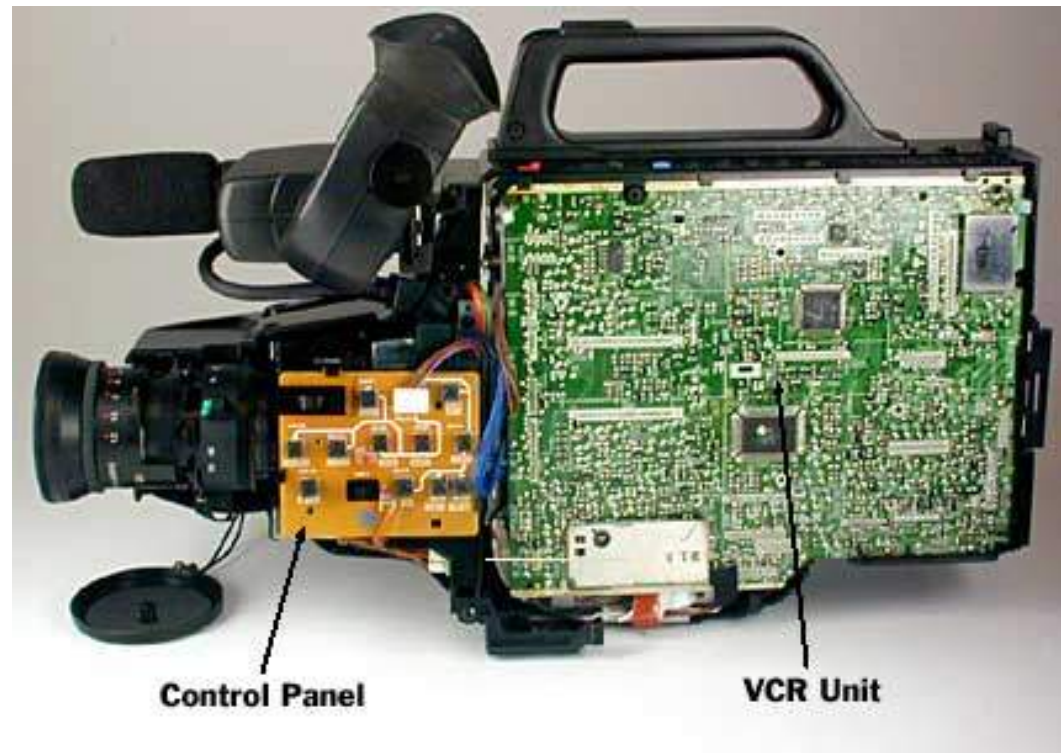
# Digital camera review website

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- [Demonstration of digital cameras](#)
- <http://www.dpreview.com/>
- [A cool video of digital camera illustration](#)

# Camcorder

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# Interlacing

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without interlacing



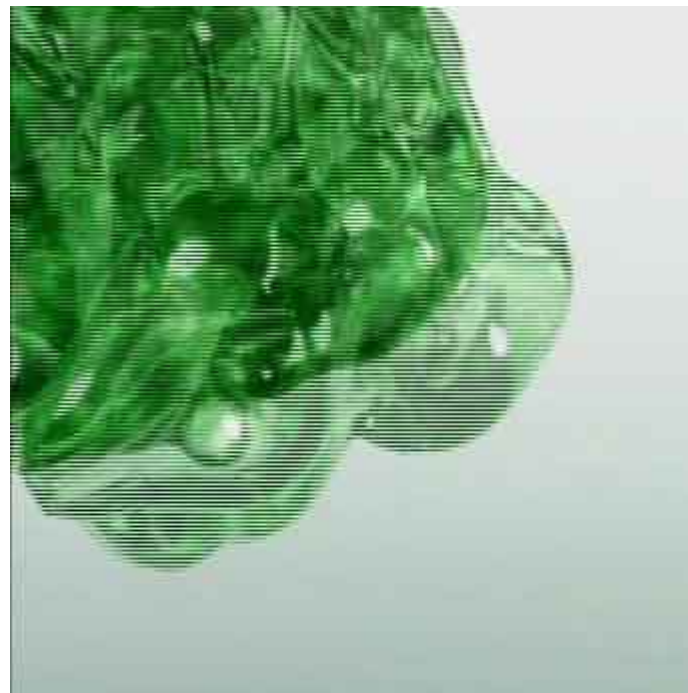
with interlacing

# Deinterlacing

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blend



weave

# Deinterlacing

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Discard  
(even field only or  
odd field only)



Progressive scan

# References

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- <http://www.howstuffworks.com/digital-camera.htm>
- <http://electronics.howstuffworks.com/autofocus.htm>
- Ramanath, Snyder, Bilbro, and Sander. [Demosaicking Methods for Bayer Color Arrays](#), Journal of Electronic Imaging, 11(3), pp306-315.
- Rajeev Ramanath, Wesley E. Snyder, Youngjun Yoo, Mark S. Drew, [Color Image Processing Pipeline in Digital Still Cameras](#), IEEE Signal Processing Magazine Special Issue on Color Image Processing, vol. 22, no. 1, pp. 34-43, 2005.
- <http://www.worldatwar.org/photos/whitebalance/index.mhtml>
- <http://www.100fps.com/>