UiO : Department of Informatics
University of Oslo

**INF5442 – Image Sensor Circuits and Systems**

# Lecture 1 – Systems overview and basic optics

25-August-2014

# Agenda

- Recap from previous week
- Lecture1 – Systems overview and basic optics

  - References (Nakamura):
    - Ch. 1 (background material, only)
    - Ch. 2 (until 2.1.2 only)
    - Appendix-1

Automotive camera
(DR=120dB (20bit pixels))

Security camera
(low light, <0.1lux)

High-speed camera
>500 frames/sec

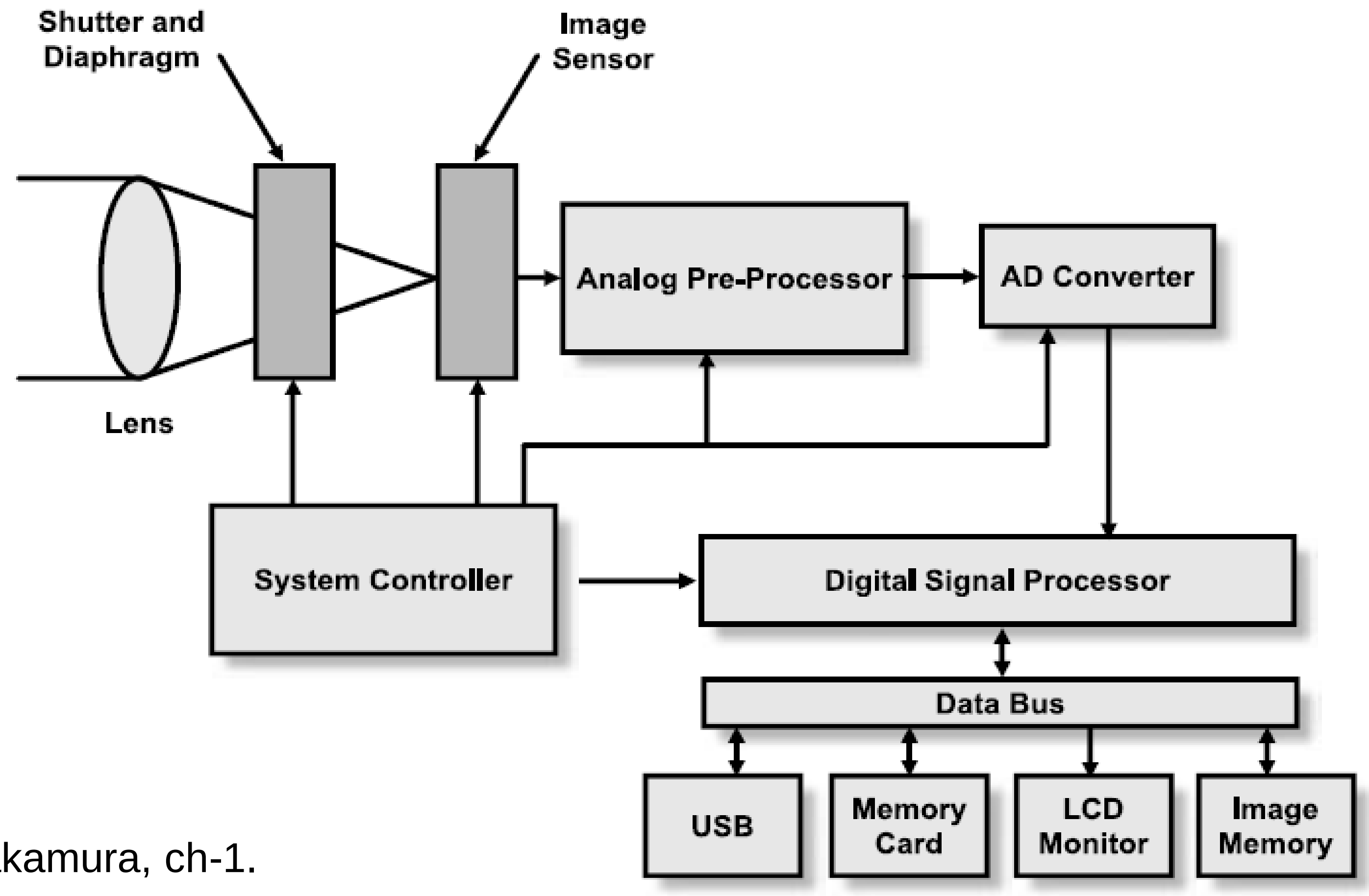
## Camera system is application dependent

Phone camera
(low cost)

Pill camera
(low power)

Digital still camera
>20Mpixels

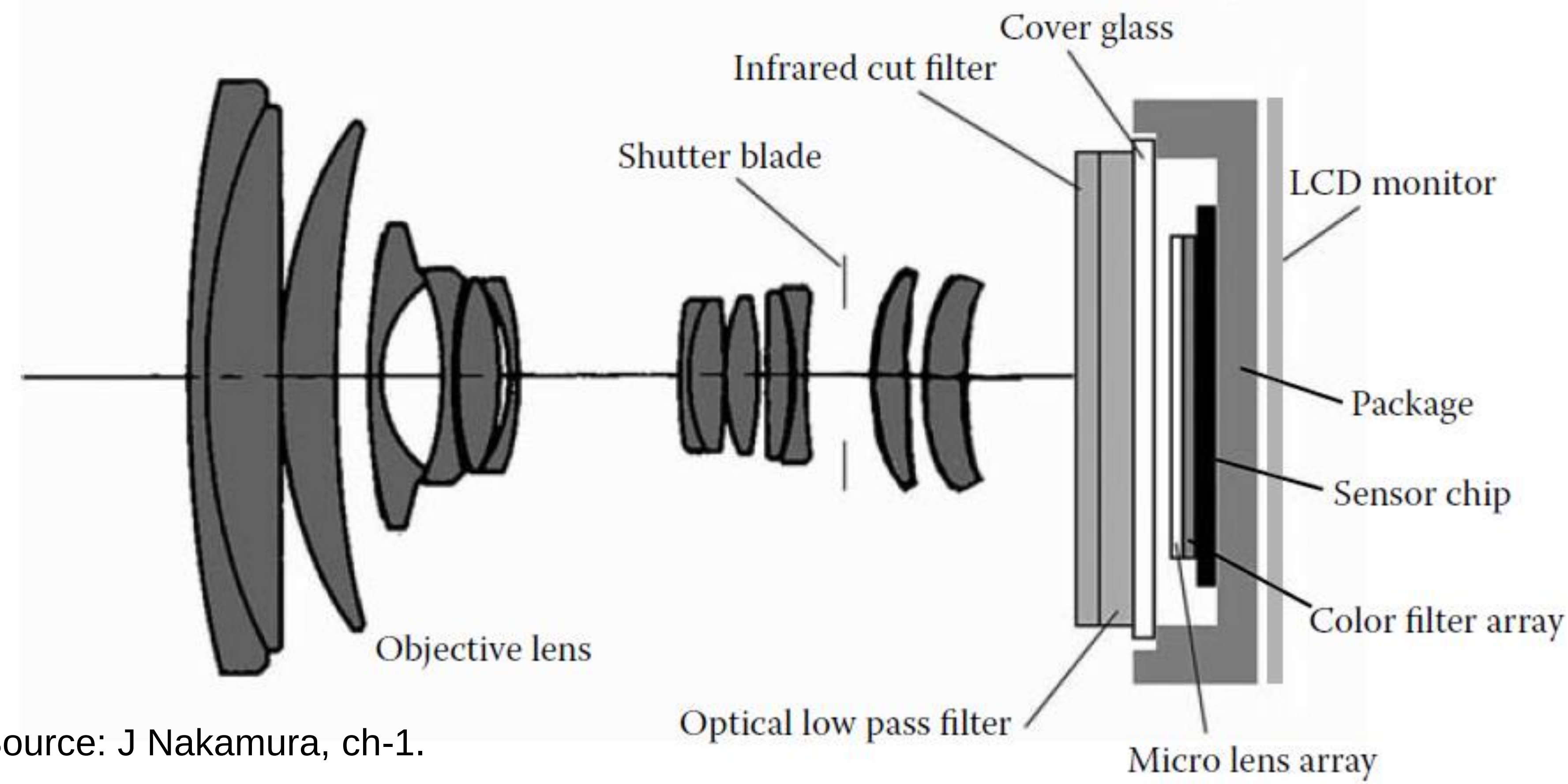
# Digital Camera System




Source: J Nakamura, ch-1.

**FIGURE 1.27** Typical block diagram of a digital still camera.

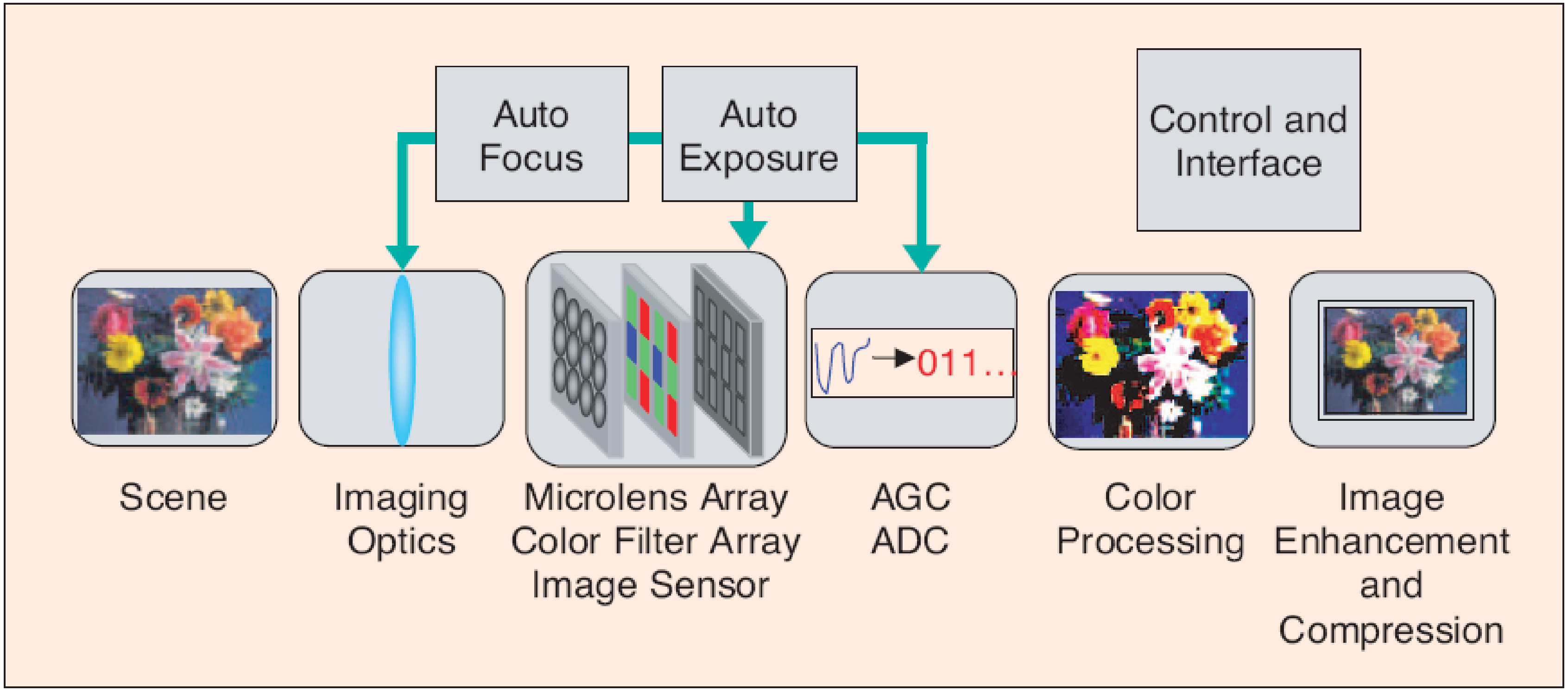
# Digital Camera System




Source: J Nakamura, ch-1.

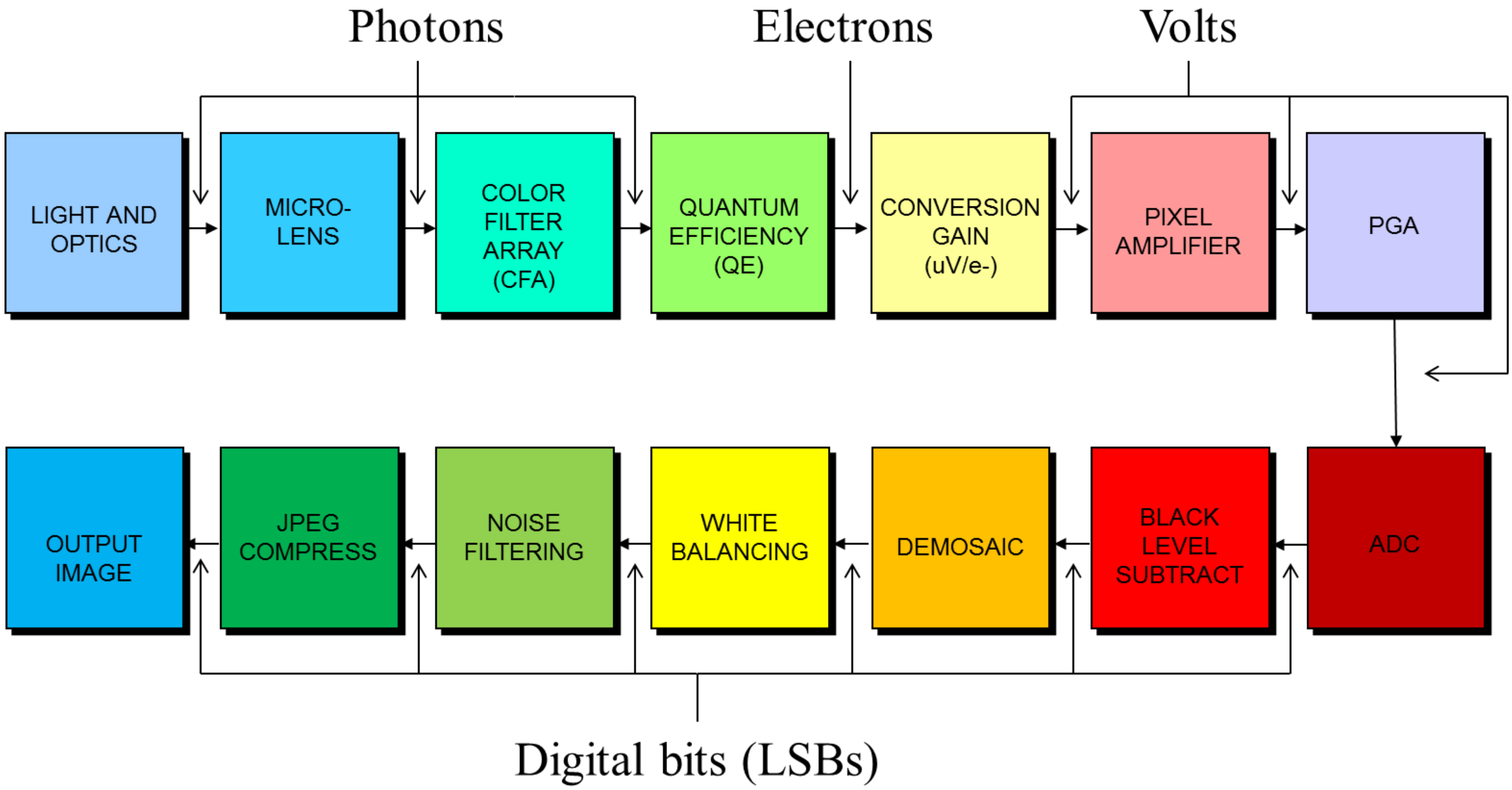
**FIGURE 1.20** Typical arrangement of a point-and-shoot digital still camera.

# CMOS camera signal chain




Source: A.E.Gamal, et al. “CMOS Image Sensors”, IEEE Circuits and Device Magazine, May. 2005

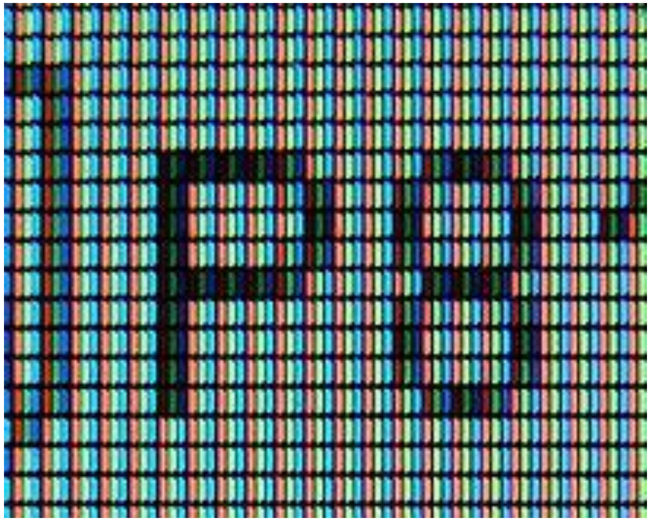
# Digital camera signal chain example

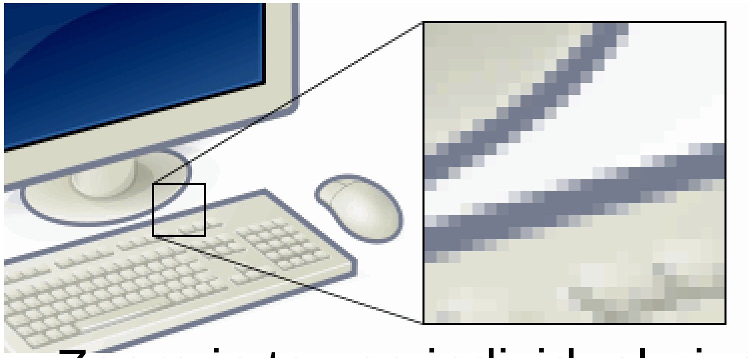


# Digital picture file

- Defn: 2D array of pixels (picture elements) each containing numbers (R+G+B or Y+U+V) to describe the pixel color and its brightness (intensity)

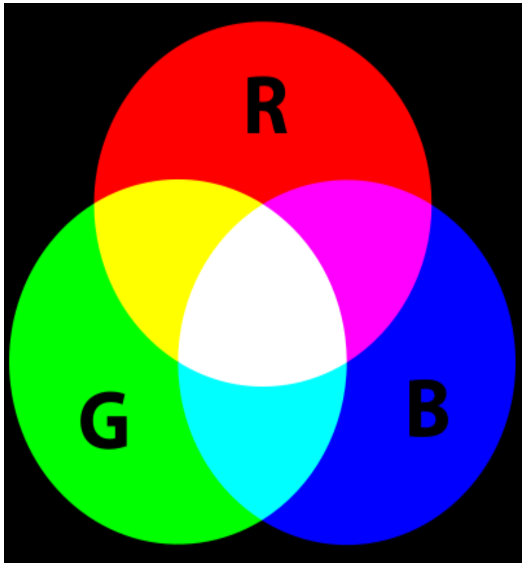
Zoom-in on LCD monitor w/RGB pixels



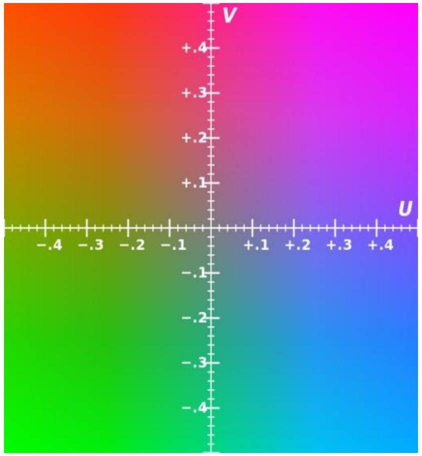


Zoom-in to see individual pixel elements

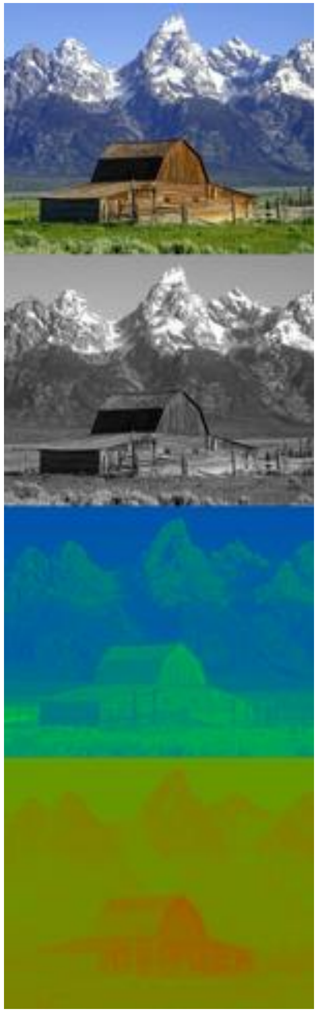
# RGV and YUV color space




Mixing primary colors (RGB)




U-V color plane (Y=0.5)



YUV image along with its

Y,

U, and

V components.

# From RGB to YUV, and vice-versa

$$Y' = 0.299R + 0.587G + 0.114B$$

$$U = 0.492(B - Y')$$

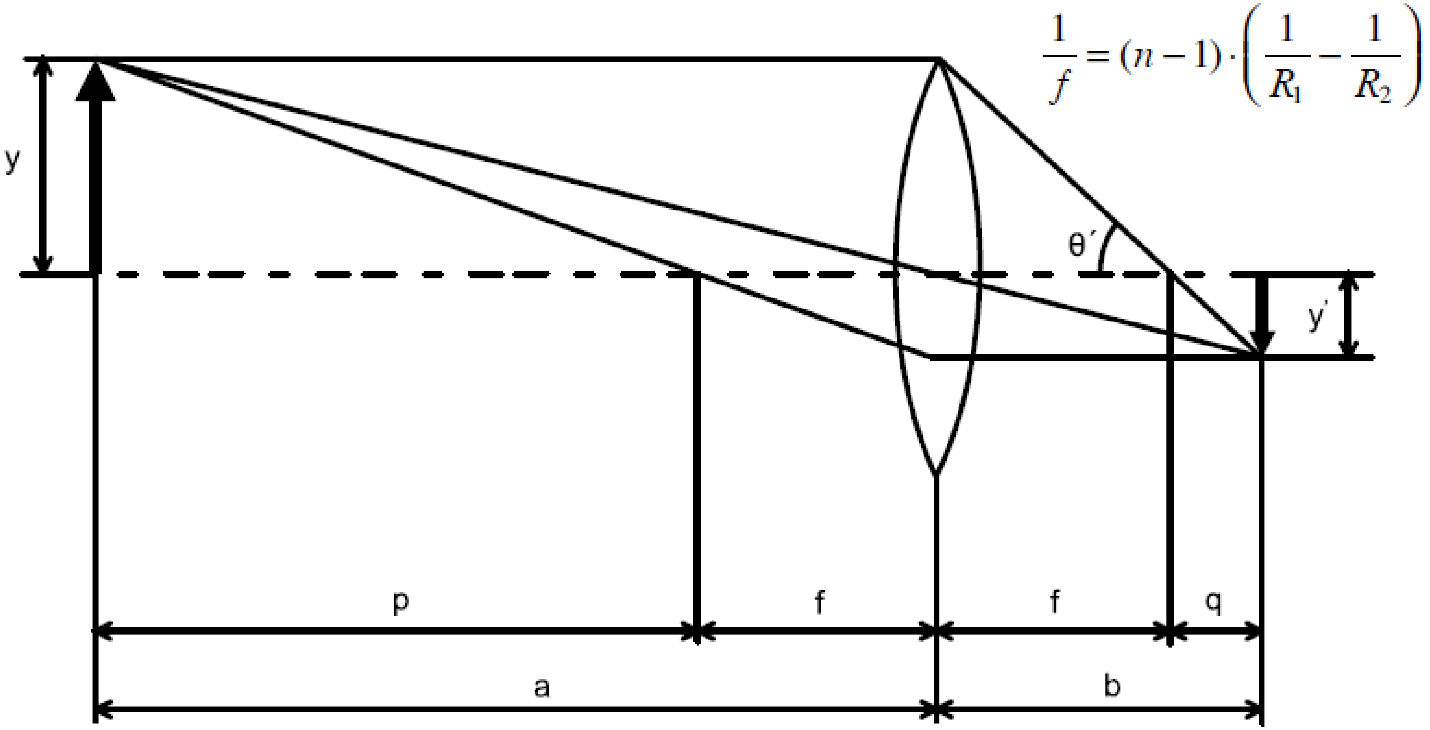
$$V = 0.877(R - Y')$$

$$\Rightarrow \begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.2988 & 0.5869 & 0.1143 \\ -0.1689 & -0.3311 & 0.5000 \\ 0.5000 & -0.4189 & -0.0811 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$\Rightarrow \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1.402 \\ 1 & -0.3441 & -0.7141 \\ 1 & 1.772 & 0.00015 \end{bmatrix} \begin{bmatrix} Y \\ U \\ V \end{bmatrix}$$

# OPTICS

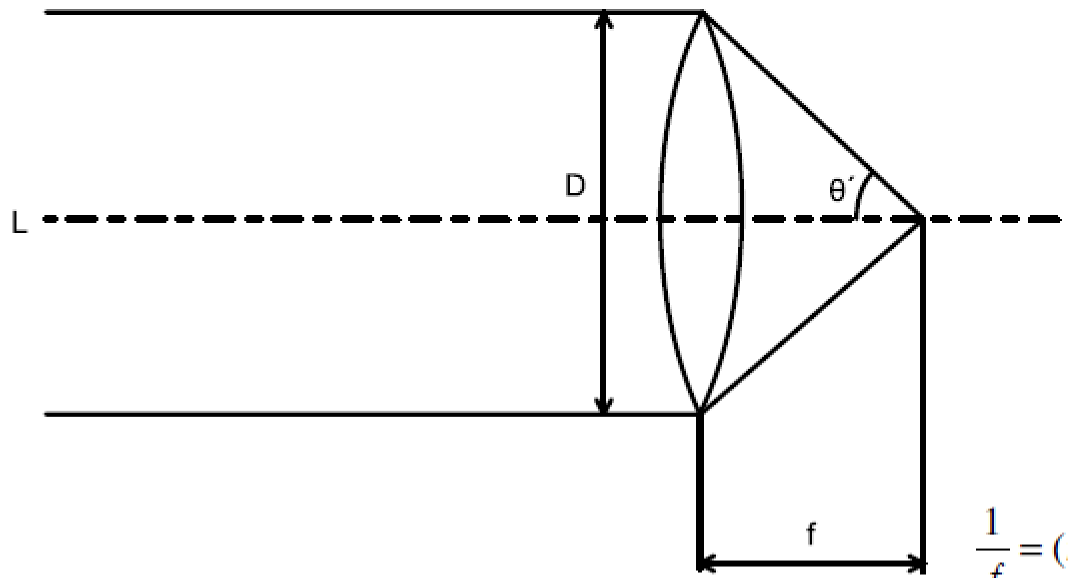
# Basic optics




Focal length, 1/f = 1/a + 1/b (~1/b)
Imaging magnification, m = y'/y = b/a (~0)
Field of view, 2Θ' = tan$^{-1}$(y'/f)

Source: J Nakamura, ch-2.

# Lens F-number




$$\frac{1}{f} = (n-1)\cdot\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

Lens F-number: $F = 1/(2\sin\Theta') \approx f/D$

Source: J Nakamura, ch-2.

# Luminance vs Illuminance

Assuming Lambertian (difffuse) scene surface:

$$E_i = \frac{\pi}{4} E_o T \left( \frac{1}{(1+m)F} \right)^2$$

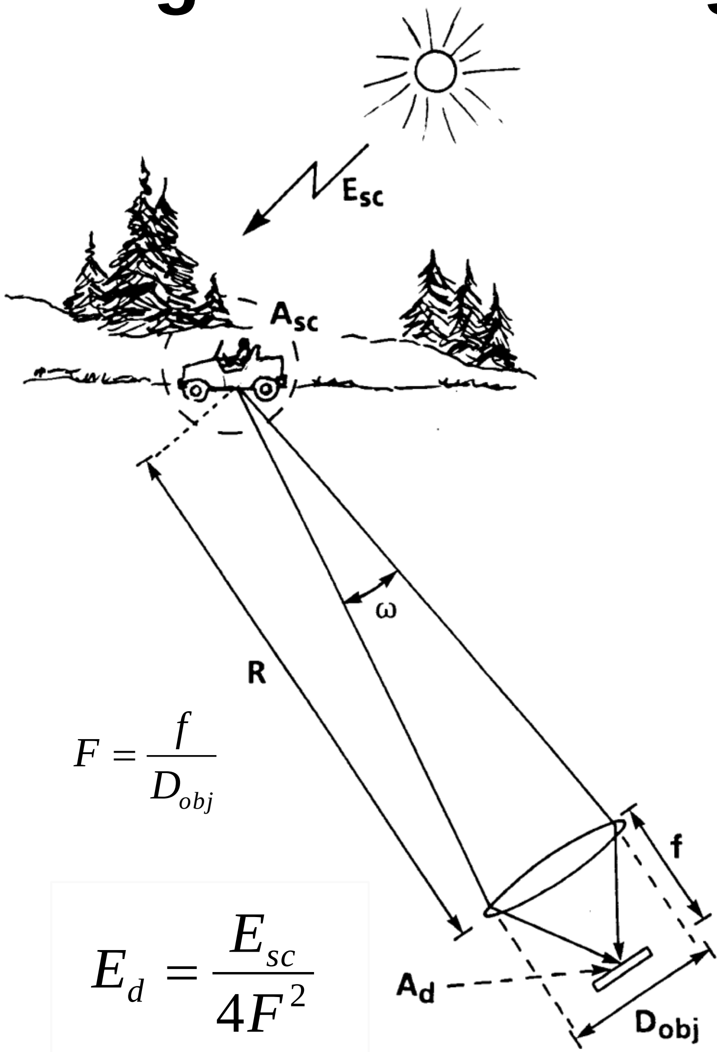
(lumen/m$^2$) or (W/m$^2$)

≈ ¶ $E_o$T / (4F$^2$)

= $E_{sc}$T/(4F$^2$)

Source: J Nakamura, ch-2.

# Light flux on image sensor chip




$$F = \frac{f}{D_{obj}}$$

$$E_d = \frac{E_{sc}}{4F^2}$$

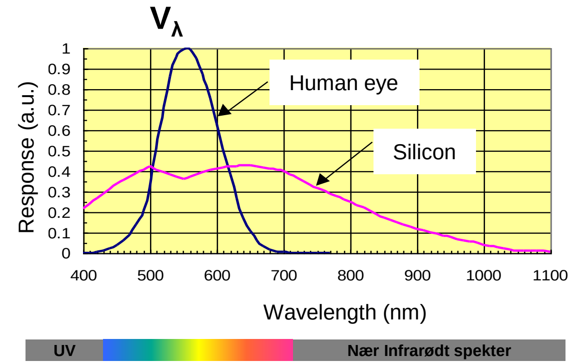
$E_{sc}$=scene illumination (lux or W/m$^2$)
$\rho_{sc}$=scene reflectivity (no unit)
$T_{int}$=camera exposure time (s)
F=lense F-nummer (=f/$D_{obj}$)
h=Plancks constant (6.6x10$^{-34}$ J s)
c=speed of light (3x10$^8$ m/s)
$D_{obj}$= lens aperture (m)
f = lens focal length (m)
$A_d$=detector area (m$^2$)
$E_d$=detector illumination (lux or W/m$^2$)
λ=light spectral wavelength (m)
$S_d$=detector photon count (no unit)

$$S_d = \frac{T_{\text{int}} A_d}{hc4F^2} E_{sc} \rho_{sc}$$

# Measuring light in Lux

- Lux is a measure of light intensity on a surface
- Light detector measures Watt/m$^2$ which is converted to lumen/m$^2$ (lux) using a calibrating factor

| Illuminans | Example |
|---|---|
| $10^{-4}$ lux | Moonless, overcast night sky |
| 0.002 lux | Moonless clear night sky |
| 0.27–1.0 lux | Full moon on a clear night |
| 50 lux | Family living room lights |
| 80 lux | Office building hallway |
| 100 lux | Very dark overcast day |
| 320–500 lux | Office lighting |
| 400 lux | Sunrise or sunset on a clear day. |
| 1,000 lux | Overcast day |
| 10,000–25,000 lux | Full daylight (not direct sun) |
| 32,000–130,000 lux | Direct sunlight |




Silicon detector $^{w}/V_\lambda$-filter


Lux meter

# Radiometry vs Photometry

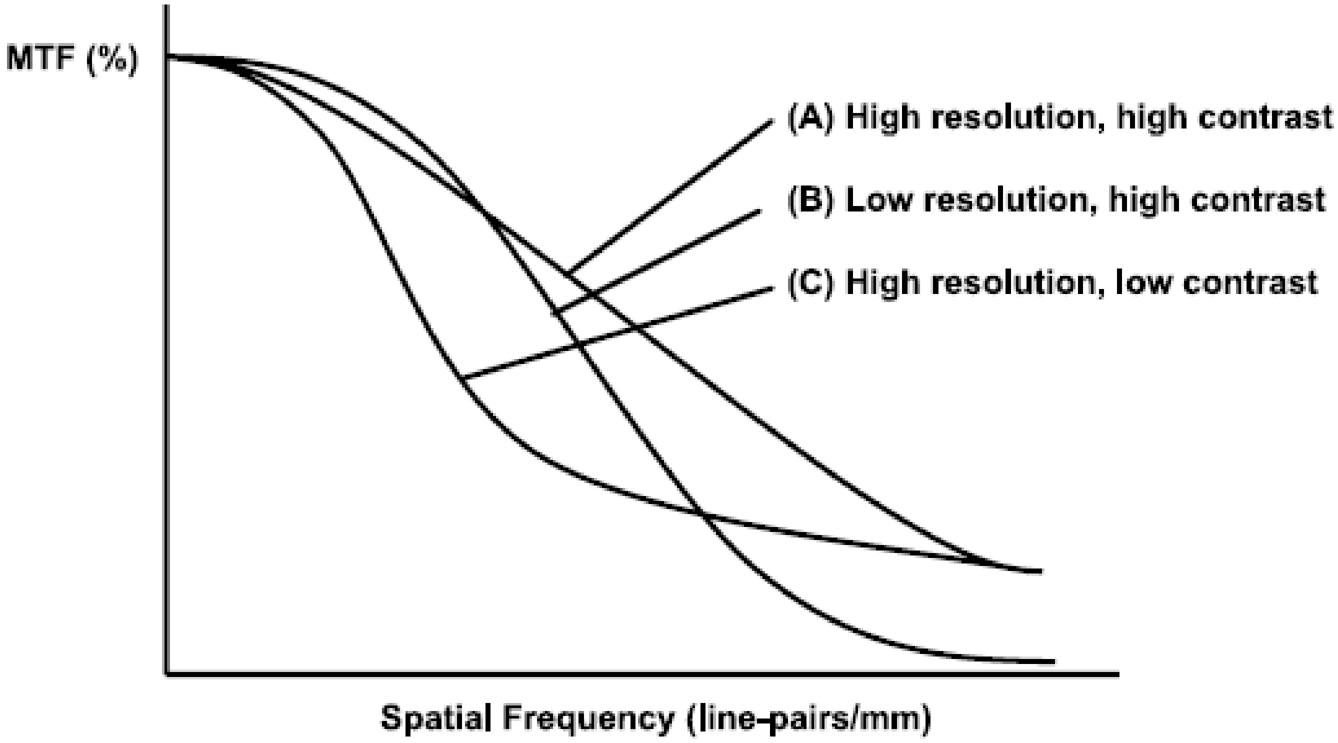
- Radiometry measures light energy in Watts
- Photometry measures light energy in Lumen. Photometric sensors use a $V_\lambda$ filter to only measure light visible to human eye

$$X_v = K_m \cdot \int_{\lambda_1}^{\lambda_2} X_{e,\lambda}(\lambda) \cdot V_\lambda \cdot d\lambda$$

$X_v$= photometric illuminance (lux or lumen/m$^2$)
$X_{e,\lambda}$ = spectral irradiance (watt/m/m$^2$)
$V_\lambda$= spectral response of human eye,
$K_m$= constant (683lumens/watt)
$\lambda_1$= 0.38um, $\lambda_2$= 0.78um

 Source: Nakamura et al

# Modulation Trasfer Function




Source: J Nakamura, ch-2.

(a) High resolution, high contrast

(b) Low resolution, high contrast

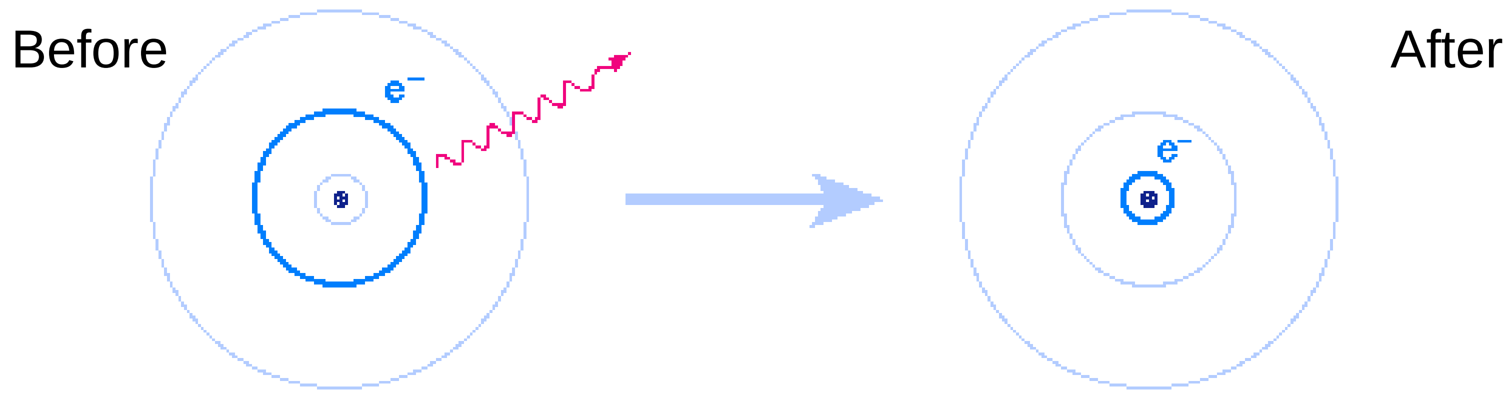
(c) High resolution, low contrast

# Example of light sources

- The Sun
- Incandescent
- Halogen lamp
- Fluorescing tubes
- Light emitting diode (LED)



# Photons created by atoms changing energy state

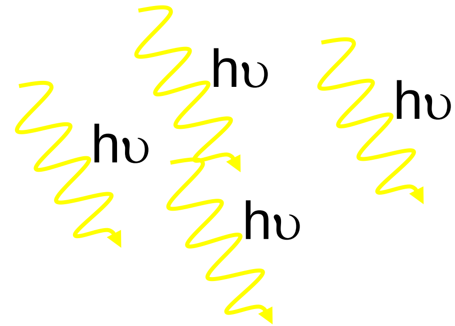



Atom in excited state, $E_1$
(electron spinning in high energy state)

Atom in basic condition, $E_2$
(electron spinning in lower energy state)

(PS: the opposite effect takes place in CMOS image sensors when they detect incoming light. This is called the photoelectric effect.)

# Light particles (photons)

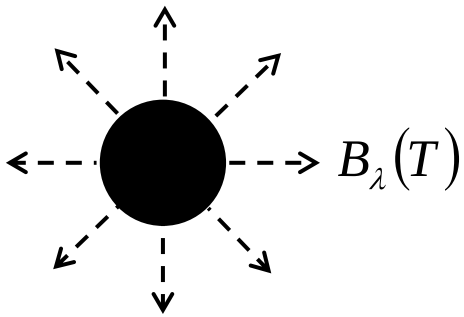



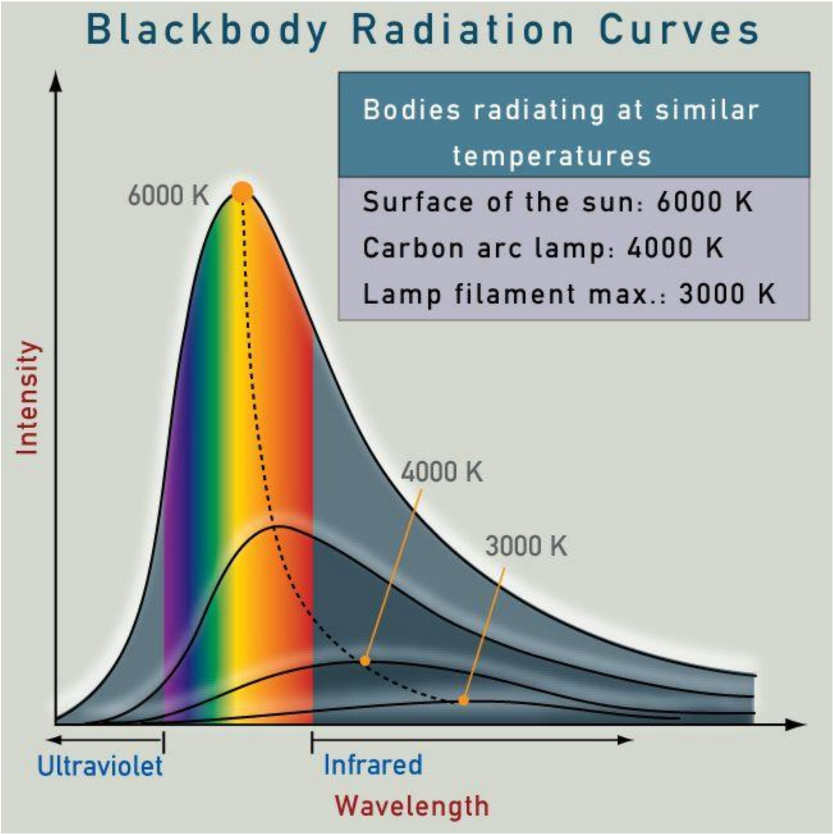

$$\boxed{E_{foton} = h\upsilon = h\frac{c}{\lambda}}$$

$E_{photon}$ = energy of photon particle's (J)
h = Planck's constant ($6{,}6 \times 10^{-34}$Js)
υ = spectral frequency (Hz)
c = speed of light ($3 \times 10^{8}$m/s)
λ = spectral wavelength (m)

Example: 1µW of green light => 2.7Terra-photons-per-second

# Light spectrum from a blackbody is determined by its body temperature




Planck's radiation law:

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5} \cdot \frac{1}{e^{\frac{hc}{\lambda kT}} - 1}$$

$B_\lambda(T)$=spectral energy (J/(s sr m$^3$))
h=Planck's constant (6,6 x $10^{-34}$ Js)
λ=wavelength (m)
c=speed of light (3x$10^8$ m/s)
k=Boltzmann's constant (1,38x$10^{-23}$ J/K)

More details: J Nakamura, Appendix-1.

# Electromagnetic spectrum