Lecture 4:

Imaging by Visible Light II

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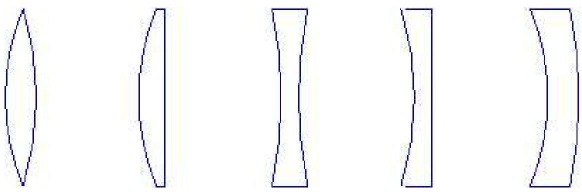
Lens Optics

Lenses

- Lenses bend light beams by refraction.



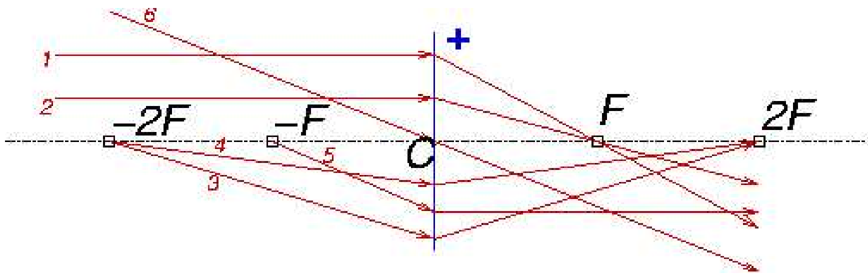
Different types of lenses: biconvex, plan-convex, biconcave, plan-concave, convex-concave.

- A convex lense bundles parallel beams such that they leave as convergent beams.
- A concave lense creates divergent beams.

Lens Optics (2)

Ideal Convex Lens

- Beams entering the ideal convex lens parallel to its *optical axis* leave it convergent to the *focal point* F at distance f (*focal length*) from the lens on the optical axis (1, 2).
- Beams through the center C of the lens are not bent. (6).
- Beams diverging from the point $-2F$ at double focal length before the lens converge after refraction to $+2F$ at double focal length behind the lens (3, 4).
- Beams diverging from the point $-F$ at focal length before the lens leave the lens parallel to the optical axis (5).



Lens Optics (3)

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Image Formation by Convex Lenses

- Light beams from object points converge to image points, or appear to diverge from them after passing the lens.
- *Real image:* image behind the lens that is indeed reached by the light beams. Real images can be captured by sensors.
- *Virtual image:* image before the lens that is not reached by the light beams.

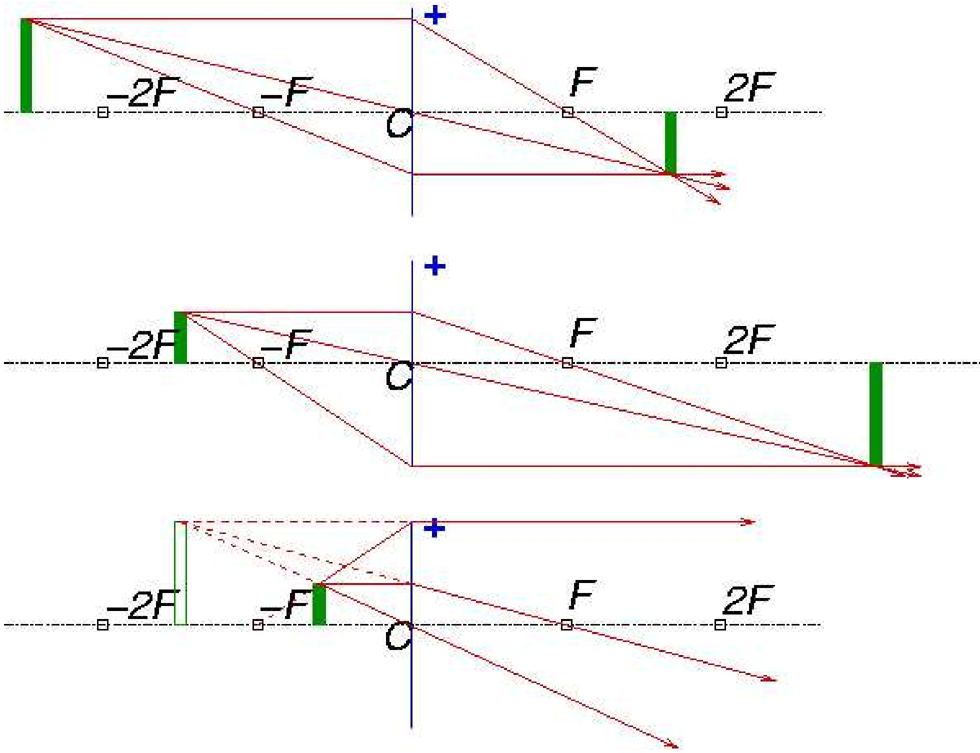
Assume an ideal convex lens with focal length f is given.

An object point at distance s from the lens and h from the axis (measured upward) is transferred to an image point at distance s' from the lens and h' from the axis (measured downward), with

$$\frac{1}{f} = \frac{1}{s} + \frac{1}{s'} , \qquad \frac{h}{s} = \frac{h'}{s'} .$$

Positive s' indicates an upside-down real image.
Negative s' indicates an upright virtual image.

Lens Optics (4)



Top: Real image when $s > 2f$, **middle:** real image when $f < s < 2f$, **bottom:** virtual image for $s < f$.

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Lens Optics (5)

Aberrations

Real lenses do not behave exactly like ideal ones.
The different discrepancies are called *aberrations*.

- *Spherical Aberration*
  A bispherical convex lens works ideally only for beams close to the axis.
  For beams more distant from the axis, the effective focal length varies.
  This aberration can be reduced by using more expensive *aspherical lenses*.

- *Chromatic Aberration*
  Dispersion leads to different focal lengths for different wavelengths.
  Remedy: *acromats* (combination of lenses of different sorts of glass with different dispersion)

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Multiple-Lens Systems

- In general, multiple-lens systems can compensate aberrations and thus approximate much better ideal lens behaviour than single lenses.
- Objective lenses for cameras therefore mostly consist of 3 to 15 lenses.
- With so many glass surfaces, however, a special treatment of the surfaces (coating) is needed to avoid dramatic losses of light by reflection.
- Multiple-lens systems can be designed to allow adjustment of focal length by relative movement of some components (*zoom lens*).

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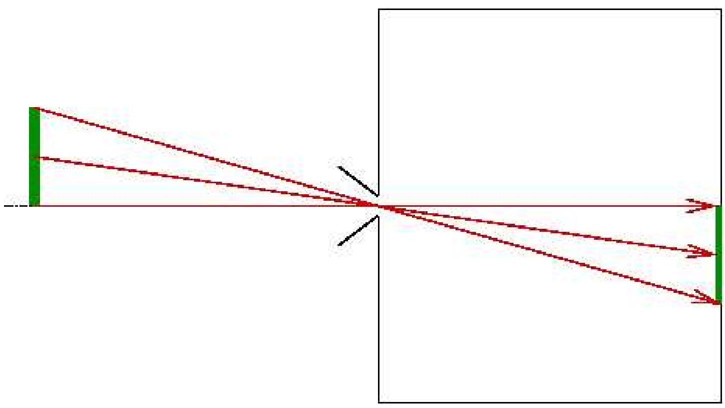
Camera Models

Pinhole Camera (Camera Obscura)



Pinhole camera, schematic.

- simplest camera model
- maps objects at any distance by projection through a small hole (diameter: *aperture*).
- image is captured on a screen/sensor at the rear side of the camera. (sensors: next lecture)

Camera Models (2)

Tradeoff Sharpness Versus Brightness

- Ideal sharpness for zero aperture.

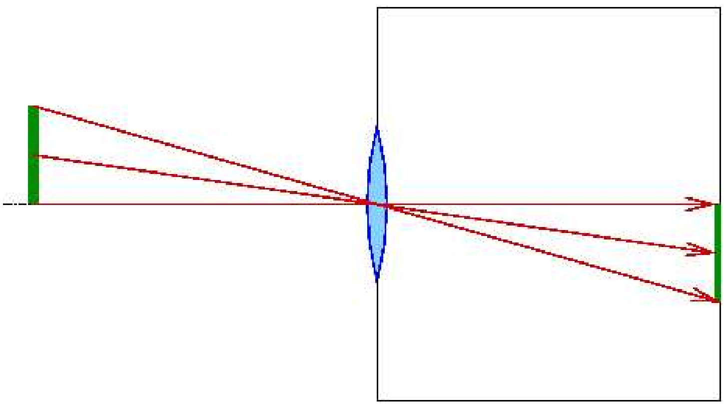
- For positive aperture, (far) object points are imaged into discs of (approx.) the radius of aperture, leading to a blurring almost independent of the object distance.

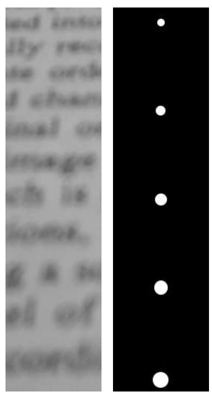
- The disc into which an object point is images is called *disc of confusion.*

Camera Models (3)

Camera with Lens

- Allows sharp images with positive aperture. The real image generated by the (objective) lens is captured on a screen/sensor at the rear side of the camera.
- Requires focussing. Defocussed object points appear as disk-shaped spots.
- Image quality depends on precise focussing and on the optical quality of the lens. Small aperture helps to suppress aberrations.





Left: Camera with lens, schematic. **Right:** Distance-dependent defocussing by camera optics, with approximate discs of confusion for different locations.

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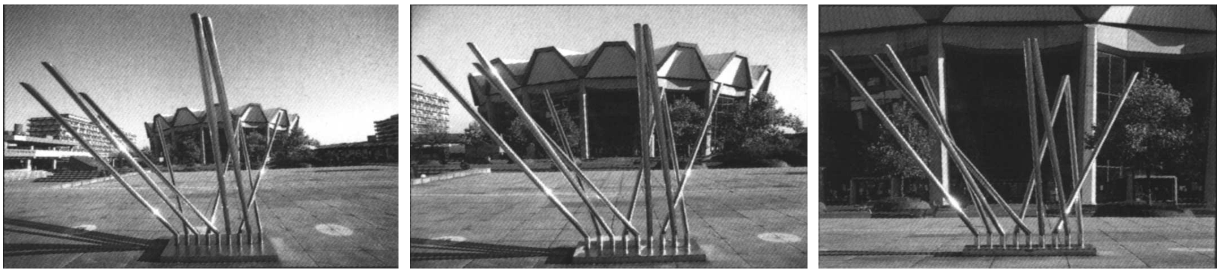
Basic Classification by Focal Length

- For images that have natural proportions, the focal length approximately equals the image diagonal. For example, for $24 \times 36\,\mathrm{mm}$ film (diagonal measures $43\,\mathrm{mm}$), the *normal focal length* is $50\,\mathrm{mm}$.
- Shorter focal length: *wide-angle lens*
  Longer focal length: *tele lens*



Same motiv photographed with different focal lengths. **Left to right:** $20\,\mathrm{mm}$, $50\,\mathrm{mm}$, $200\,\mathrm{mm}$. *(Freier 1992)*

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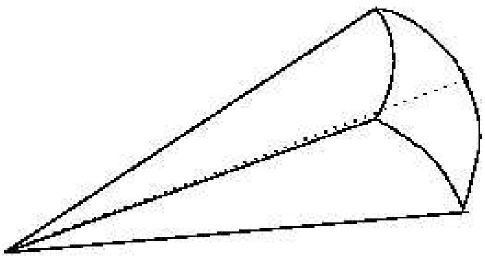
Measuring Light

Radiometry

The measurement of radiation energy emitted by light sources, received by sensors or received and reflected by surfaces is the domain of *radiometry*. Energy can either be measured totally, or per surface area, or per solid angle.

- Energy is measured in Ws (Watt-second), $1\,\mathrm{Ws} = 1\,\mathrm{J} = 1\,\mathrm{Nm}$.
- Area is measured in square metres m^2.
- Solid angle is measured in *steradians* sr. One steradian is the solid angle cutting out $1\,\mathrm{m}^2$ of area from a sphere of $1\,\mathrm{m}$ radius (similar as $1\,\mathrm{rad}$ is the angle which cuts out $1\,\mathrm{m}$ of circumference from a circle with radius $1\,\mathrm{m}$).



Frequently Used Quantities

Quantity	Symbol	Unit	Definition
Radiant energy	Q	Ws	Total energy emitted/received
Radiant flux	Φ	W	Total power (energy per time) emitted/received
Radiant exitance	M	$\mathrm{W/m^2}$	Power emitted per surface area
Irradiance	E	$\mathrm{W/m^2}$	Power received per surface area
Radiant intensity	I	$\mathrm{W/sr}$	Power leaving a surface point per solid angle
Radiance	L	$\mathrm{W/(m^2\,sr)}$	Power leaving a surface per area per solid angle

(Table adapted from Haußecker 1999)

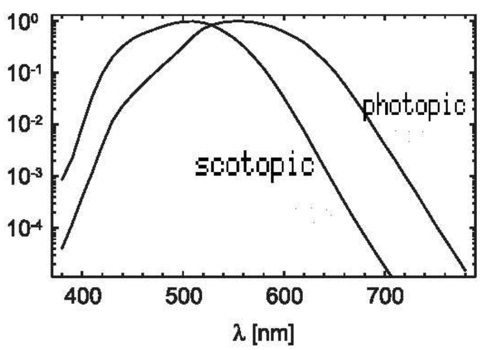
Sensitivity of Human Eye

The radiometric power needed to create a brightness perception in the human eye varies with wavelength, and also differs between *photopic vision* (vision under high illumination, using the cones of the retina) and *scotopic vision* (vision under poor illumination, using the rods of the retina).

For each radiometric quantity X_r, a corresponding spectrally weighted quantity X_ν measuring visual impression can be derived using the spectral response $V(\lambda)$ and a normalisation factor N via

$$X_\nu = N \int_{\lambda_1}^{\lambda_2} X_\mathrm{r} V(\lambda)\,\mathrm{d}\lambda \,.$$

$\lambda_1 = 380\,\mathrm{nm}$ $\lambda_2 = 780\,\mathrm{nm}$	for visible light;
$N = 683\,\mathrm{lm/W}$	for photopic vision
$N = 1754\,\mathrm{lm/W}$	for scotopic vision
$V(\lambda)$	luminous efficiency (see diagram)



Luminous efficiency $V(\lambda)$ for human visual system *(Haußecker 1999)*

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Photometry

The resulting quantities X_ν are called *photometric quantities*:

Quantity	Symbol	Unit	Definition
Luminous energy	Q_ν	$\mathrm{lm\,s}$	Total spectrally weighted energy emitted/received
Luminous flux	Φ_ν	lm (lumen)	Total luminous power (energy per time) emitted/received
Luminous exitance	M_ν	$\mathrm{lm/m^2}$	Luminous power emitted per surface area
Illuminance	E_ν	$\mathrm{lm/m^2}$ $= \mathrm{lx}$ (lux)	Luminous power received per surface area
Luminous intensity	I_ν	$\mathrm{lm/sr}$ $= \mathrm{cd}$ (candela)	Luminous power leaving a surface point per solid angle
Luminance	L_ν	$\mathrm{W/(m^2\,sr)}$ $= \mathrm{cd/m^2}$	Luminous power leaving a surface per area per solid angle

(Table adapted from Haußecker 1999)

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Fechner's Law

The subjective impression of brightness given a luminous power received follows the logarithm of the luminous power, i.e. it is a multiple of

$$\ln \frac{\Phi_\nu}{\Phi_{\nu\,\mathrm{min}}}, \qquad \Phi_{\nu\,\mathrm{min}} \le \Phi_\nu \le \Phi_{\nu\,\mathrm{max}}$$

where $\Phi_{\nu\,\mathrm{min}}$ and $\Phi_{\nu\,\mathrm{max}}$ represent the threshold of visibility and some saturation threshold.

Since laws of illumination tie the radiance emitted by a surface multiplicatively to the received irradiance, perceived brightness differences according to Fechner's law are illumination independent.

Gustav Theodor Fechner (1801–1887) *(Insel-Verlag, 1996)*

Logarithms of ratios are often measured in *decibels (dB)*. For given energies E_1, E_2 (or analogously for other energy-derived quantities) one has the correspondence

$$\text{ratio} \quad \frac{E_1}{E_2} \qquad \longleftrightarrow \qquad \text{logarithmic measure} \quad 10\,\mathrm{lg}\,\frac{E_1}{E_2}\,\mathrm{dB}\,.$$

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Image Sensorics

Photochemical Processes

Photochemical processes dominated the longest time in the history of photography, and still play an important role.

- Typical processes are based on photographic emulsions containing grains of *silver halides*. These emulsions are the active component of photographic films. By exposure to light, silver halide is transformed to metallic silver at the surface of grains.
- In the most common process, the transformation is continued by development to metalise entire grains followed by washing out the remaining silver halide. This results in a *negative image* with inverse contrast: regions exposed to strongest light are darkest, because of the silver.

Top: Negative.
Bottom: Positive.

- *Positive images* with normal contrast are obtained from negatives by copying to another photographic emulsion (on paper).
- Modified processes allow the direct generation of positives (*films for slides*).

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- The most probable inventor of photography is N. Niépce who was able to take photographs around 1827.
- The earliest analog photography technique which was in broader use (starting 1839) were *daguerreotypes* which led directly to positive images on metal surfaces.
- From the viewpoint of digital imaging, photochemical processes conserve image information in an intermediate (analog) storage because another image acquisition step with other sensors (e.g. scanning) is needed to obtain a digital image.

Left to right: (a) Nicéphore Niépce (1765–1833). – (b) Louis Daguerre (1787–1851). – (c) View of Saint-Loup-de-Varennes. Probably the oldest existing photograph (Niépce 1827). – (d) Daguerreotype of Edgar Allan Poe, 1848.

(Image sources: Spektrum der Wissenschaft 2/1997 (a, c), Wikipedia (b, d).)

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Image Sensorics (3)

Electrophotography

An alternative analog process of storing image information is *electrophotography*, also known as *xerography* (invented in 1938 by C. Carlson).

- A foil of a special material is charged electrostatically (via corotrons, i.e. wires under high voltage).
- Exposure to light discharges the foil locally.
- Remaining charge attracts a pigmented powder (*toner*).
- Toner is transferred to film or paper and fixed there by melting.

Chester Carlson (1906–1968) *(image: Wikipedia)*

This process is used in photocopiers and laser printers.

Again, from the digital imaging viewpoint, it is just an intermediate storage procedure that must precede another imaging step.

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Image Sensorics (4)

Semiconductor Photosensors: Photon Detection

- A photon absorbed in a semiconductor pushes one or more electrons from their places in the semiconductor crystal, leading to *electron-hole pairs*.
- To make the electron-hole pairs usable for image sensing, the charges need to be separated. This is done by electric fields in which a *photocurrent* results.
- The photocurrent depends linearly on the light intensity over approx. 10 orders of magnitude. However, linearity may be lost in later steps.

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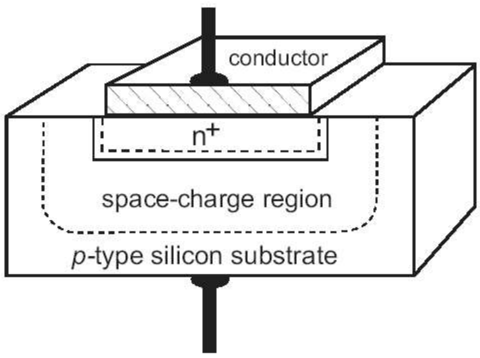
Image Sensorics (5)

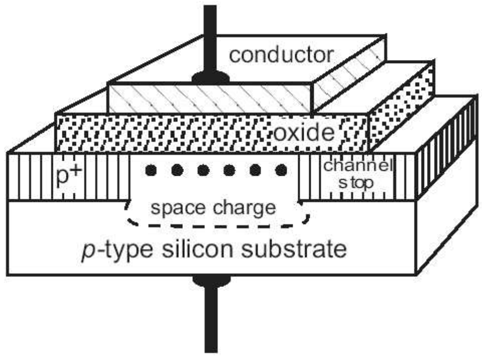
Semiconductor Photosensors: Charge Accumulation

There are two ways how separated charges are stored for measurement.

- In *photodiodes*, charges move in the electrical field of a pre-charged capacity, reducing its voltage. This decay in stored voltage is measured after exposition.
- In *metal-oxide semiconductors (MOS)*, charges again move in an electrical field but this time they are stored in a "trap" formed by isolating metal oxide. Charges can be accumulated and manipulated there.



Photodiode, schematic view.
(both: Seitz, 1999)

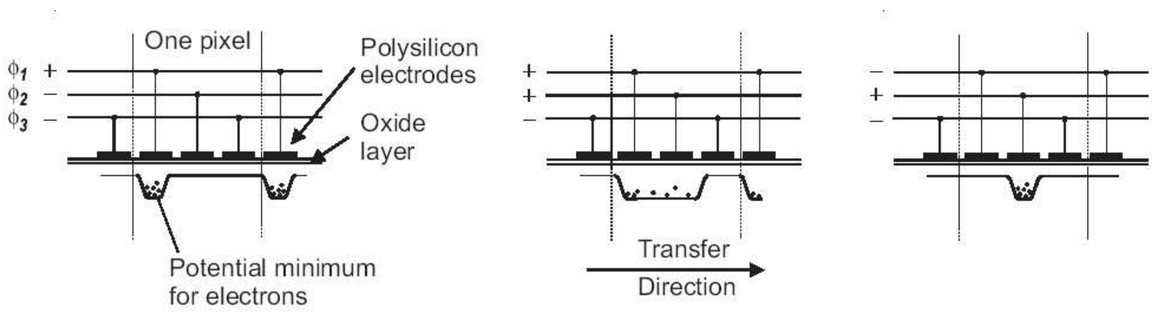


MOS element, schematic view.

Image Sensorics (6)

Semiconductor Photosensors: CCD Sensors

- *Charge-coupled devices (CCD)* use MOS elements for the pixels
- Instead of addressing pixels individually by electrodes, accumulated charges are moved along lines by clock-switched electrical fields and read out sequentially at the end.
- Various modifications of this basic read-out architecture for different needs exist.



Charge transport in CCD by step-wise switching of electrical fields. *(Seitz 1999)*

- Special configurations (*buried channel CCD, B-CCD*) are used to raise the *charge transfer efficiency (CTE)* up to $99.99995\,\%$.

Image Sensorics (7)

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Semiconductor Photosensors: Active Pixel Sensors

- *Active pixel sensors* integrate semiconductor-based photosensors (photodiodes or MOS elements) with further MOS/CMOS field-effect transistors in each pixel. Currently most important type: *CMOS sensors* (e.g. in more expensive digital cameras)
- Amplification in each pixel instead of moving unamplified charges along rows reduces artifacts caused by interactions between pixels.
- Readout typically by an array logic: One input line per row, one output line per column; readout of a row is triggered via the input line.
- Nonlinear responses can be electronically realised on pixel level.

Image Sensorics (8)

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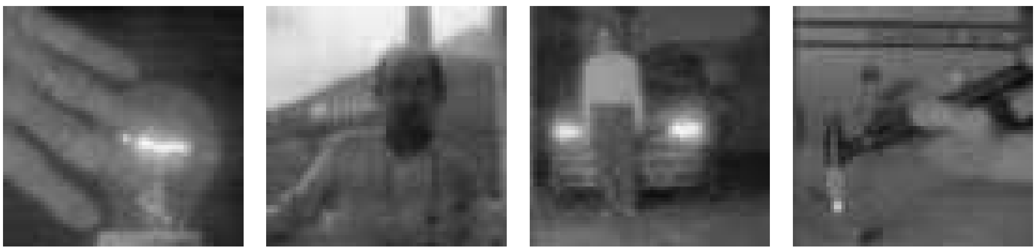
High Dynamic Range Sensors

- Important case of nonlinear response in active pixel sensors: logarithmic response.
- Used for *high dynamic range (HDR) sensors,* e.g. *high dynamic range CMOS (HDRC)*
- With logarithmic response, brightness differences are illumination independent.



High dynamic range images acquired using a 64×64 pixel logarithmic sensor. *(Seitz 1999)*

Photographic Parameters

- *Image (sensor) diagonal.* For a fixed number of pixels, larger sensors suffer less from noise.
- *Focal length.* For $24 \times 36\,\mathrm{mm}$ image format ($35\,\mathrm{mm}$ film), $50\,\mathrm{mm}$ are normal focus. Shorter focal length: wide-angle lens, longer focal length: tele lens. Caution: Focal length for CCD cameras is sometimes given by absolute values, sometimes by equivalents for 24×36 format!
- *Exposure time.* Standard scale: $\frac{1}{1000}, \frac{1}{500}, \frac{1}{250}, \frac{1}{125}, \frac{1}{60}, \frac{1}{30}, \frac{1}{15}, \frac{1}{8}, \frac{1}{4}, \frac{1}{2}, 1$ s.
- *Aperture.* Measured by the quotient $f/d =$focal length/aperture diameter. Standard scale: 1 (very large), 1.4, 2, 2.8, 4, 5.6, 8, 11, 16, 22, 32, 45 (very small).
- *Sensitivity.* Mostly given in ISO (also ASA) scale. Typical general-purpose films range around ISO 100, moderate high-speed films ISO 400, extreme high-speed ISO 3200.
  CCD cameras also allow setting ISO-equivalent sensitivity. Note that ISO 400 or higher typically leads to noticeably increased noise.

Sources of Image Degradation in Visible Light Photography

- *Motion blurs:* Caused by movement of objects during exposure (or movement of camera).
- *Aberrations:* Imperfection of camera optics (spherical aberration, chromatic aberration).
- *Diaphragm diffraction:* Imperfection of camera optics. Diffraction occurs at the edges of the diaphragm used to adjust aperture. As a result, points are blurred depending on the shape of the diaphragm.
- *Defocussing:* Misadjustment of camera optics. Results in disk-shaped blur.
- *Grain:* Physical limitation of photographic film.
- *Mosaic:* A problem specific to digital colour photography. See next lecture.
- *Quantum noise:* Physical perturbation in CCD sensors.

Summary

- Lenses bend light beams by refraction.
- An ideal convex lens can be used to create an upside-down real image.
- Real lenses suffer from aberrations such as spherical and chromatic aberrations. Some aberrations can be reduced by lens systems.
- The pinhole camera is the simplest camera model (no lenses).
- A camera with lens(es) requires focussing.
- Fechner's law states a logarithmic brightness impression.
- Photochemical films and electrophotography create analog images.
- Semiconductor photosensors create a photocurrent that can be separated and collected in CCD sensors. They give digital images.
- Active pixel sensors such as the CMOS sensors allow a nonlinear amplification. With a logarithmic response one obtains high dynamic range sensors.

References

- B. Jähne, H. Haußecker, P. Geißler, editors, *Handbook of Computer Vision and Its Applications. Volume 1: Sensors and Imaging.* Academic Press, San Diego 1999.
(Chapter 4 bei Geißler deals with imaging optics, Chapter 7 by Seitz describes sensors)
- W. Greulich, editor, *Lexikon der Physik in sechs Bänden* (in German). Spektrum, Heidelberg 1998.
(additional information on physics)

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