# Charge-Coupled Devices

Charge-Coupled Devices (CCDs) are an important technology not only for their ubiquity in consumer cameras, but also for their applications in scientific research. They exploit the photoelectric effect to convert incident light intensity to a proportional voltage. Active research is improving aspects of CCDs such as their range of spectral response and readout noise.

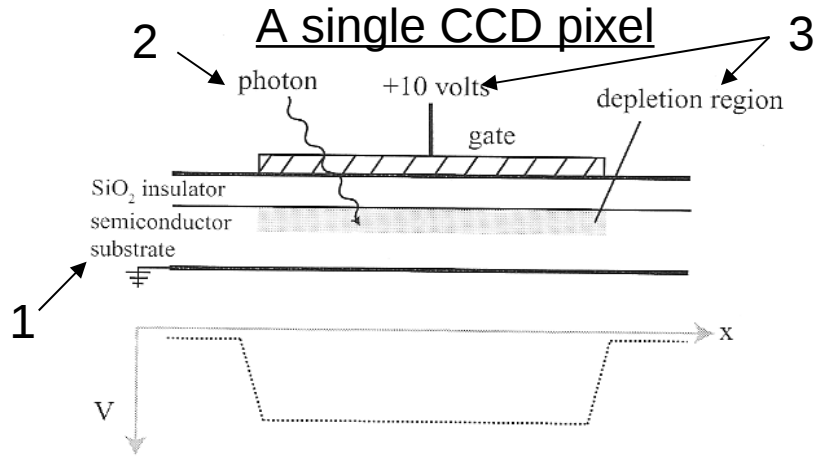Dawn Bezanson
Nathan Sanders
Russell Zarras

Background and history

- Before CCDs, images were captured on **chemical emulsions**.

    - Daguerrotypes and chemical film developed in mid-19th century

    - Color film: three layers of chemical, sensitive to blue, red, green

    - This essentially only preserved qualitative information.

- **Photodiodes** exploited **photoelectric effect** for light intensity measurements.

-CCD imaging does **both**: measures light intensity at thousands of points that together construct an image.

-**Boyle and Smith** devised a new type of electronic memory for Bell Labs in 1970, and published two papers:

    -First: novel theory of collecting and communicating charges

    -Second: experimental demonstration of theory in linear 8-bit shift register

    -Awarded half the **2009 Nobel Prize** in Physics for this invention

- Adding photosensitive elements allowed the device to collect **images** (1971)

-Fairchild Imaging produced the **first commercial** 2d array, 100x100 pixels (1973)
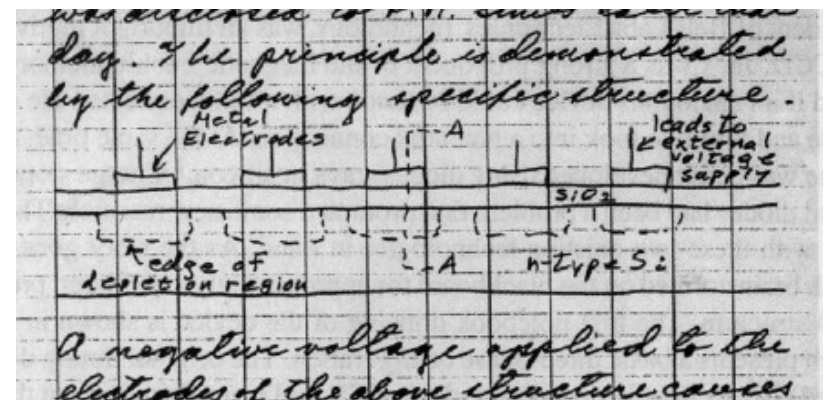
CCD Operation

Charge collection: CCDs are enormous arrays of photosensitive capacitors (pixels).

A single CCD pixel

2

3

photon   +10 volts

gate

depletion region

SiO_2 insulator

semiconductor substrate

1

x

V

Birney, et al. Fig. 8.6

[1]**Semiconductor** material: has a "valence band" of energy levels and then a much higher "conduction band."

[2]An incoming **photon** in a particular frequency can give a valence band electron enough energy to reach the conduction band.

$$hv = E_{band\ gap} = E_{BG,0} - \frac{AT^2}{T+B}$$

[3]A **bias voltage** is applied across the pixel's electrodes which attracts conduction the electron to the depletion region, where it is stored.

Readout: How are the electrons detected? CCDs are *charge coupled* – the **pixels can "communicate."**
The final row in the array is the "readout register."

pixel

output register

electrodes electrons   to output amplifier
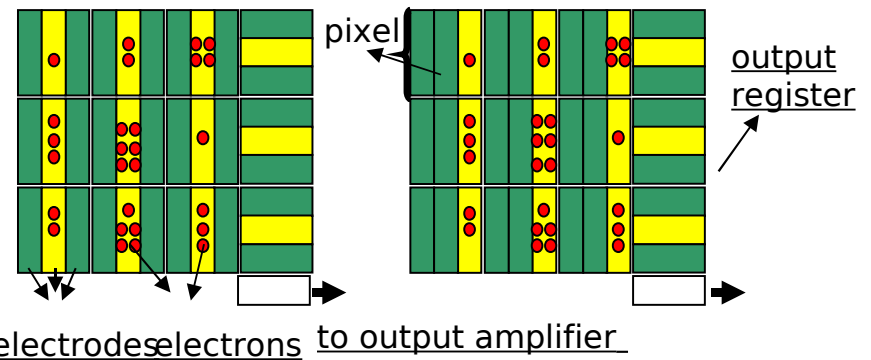
When you are done taking the picture...
Lowering the bias potential in one pixel and raising it in the adjacent pixel transfers the e- to the **readout register** one pixel at a time. At the end of the register, an amplifier converts the charge to a voltage.
An **analog to digital converter** represents the voltage from each pixel as some number of "counts," representing a grayscale image.
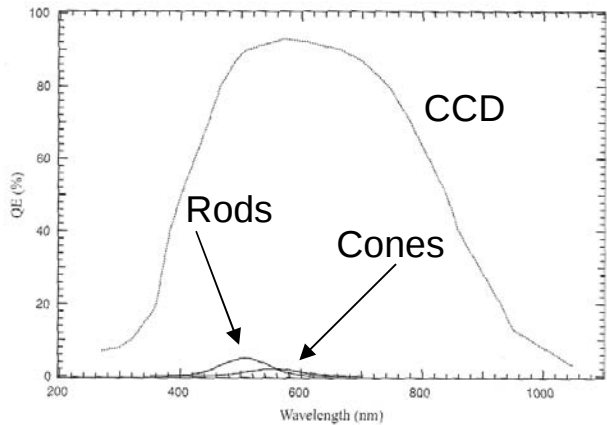
$$Counts = \frac{N_{e^-}}{Gain} \qquad Digitization\ noise = \sqrt{\frac{Gain^2 - 1}{\#\ of\ bits}}$$

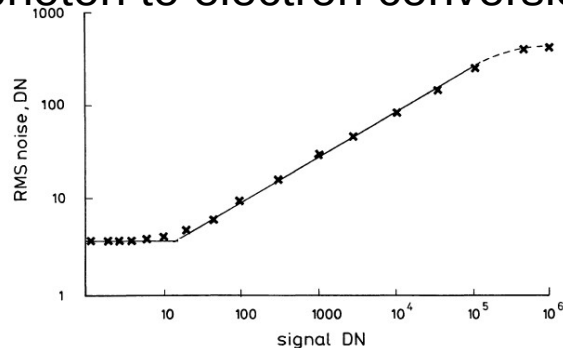# CCD Operation

Important CCD parameters

Quantum efficiency: The fraction of incident photons detected.

      Typically much better than the eye
      Determines the frequency response

Birney, et al. Fig. 8.11

Linearity: Except for readout noise and saturation, CCDs are amazingly consistent in their photon to electron conversion.

Adapted from Mackay Fig. 8

Problems with CCDs

Saturation: Too many photoelectrons in the depletion region can shield e⁻ from the bias voltage. This limits the total number of detectable photons.

      Solution: carefully plan integration times

Dark current: Thermal agitation can cause false detections.

      Diode law: $I = Ae^{\frac{-B}{k_B T}}$
      Solution: cool the CCD to < -60ºC

$$\text{Photon (Poisson) noise} \propto \sqrt{N}$$

Noise:
Solution: CCD noise is well characterized

$$\text{SNR} = \frac{\text{Signal photons}}{\text{Total photons}} = \frac{F_{photo} Q_E t}{\sqrt{\left(F_{photo} + F_{bg}\right) Q_E t + F_{DC} t + N_{read}^2}}$$

Uniformity: Each pixel may have a different sensitivity and individual pixels (or entire rows) may be defective.

      Solution: normalize by "flat field" images of a uniform source and reject bad pixels.

Active Research Using CCDs

EMCCD-Based Gamma Camera

• An **electron-multiplying CCD** (EMCCD) is a CCD in which a gain register is placed between the shift register and the output amplifier. The gain register is split up into a large number of stages. In each stage the electrons are multiplied by impact ionization in a similar way to an avalanche diode. The gain probability at every stage of the register is small ($P < 2\%$) but as the number of elements is large (N > 500), the **overall gain can be very high** ($g = (1 + P)^N$), with single input electrons giving many thousands of output electrons. Reading a signal from a CCD gives a noise background, typically a few electrons. In an EMCCD this noise is superimposed on many thousands of electrons rather than a single electron; the devices thus have **negligible readout noise**.

EMCCD Applications

·CCDs optically coupled to scintillation crystals can be used to construct high resolution gamma cameras. When an EMCCD is paired with a 1000µm thick columnar CsI(Tl) crystal noise can be reduced through **pixel binning**. Binning **increases readout speed and noise** by reducing the number of transfers by summing the signal of multiple lines before it is transferred through the serial readout and gain register. When the CCD images can be read out fast enough, the energy and interaction position of individual **gamma** quanta can be estimated by a real-time image analysis of the scintillation light flashes.[1]

·The combination of the EMCCD and binning **increases the photopeak efficiency and signal to noise** ratio, and it reduces noise induced false-positive counts in CCD-based gamma cameras for imaging.

1. Westra et al., "On-Chip Pixel Binning in Photon-Counting EMCCD-Based Gamma Camera: A Powerful Tool for Noise Reduction."

Fig. 1. EMCCD chip with fiber-optic window (a) and a compact EMCCD based gamma camera (b). A Peltier element cools the CCD chip, thereby reducing the dark current noise.

COLUMNAR SCINTILLATOR

FIBER OPTIC WINDOW

CCD

CCD HEADBOARD

COPPER BLOCK

PELTIER ELEMENT
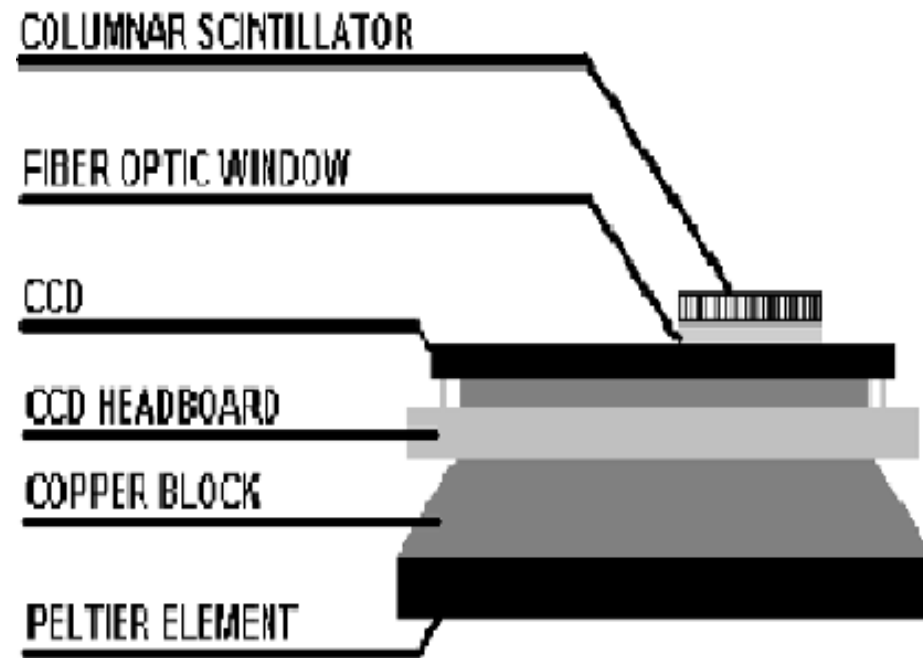
CCD Color Imaging
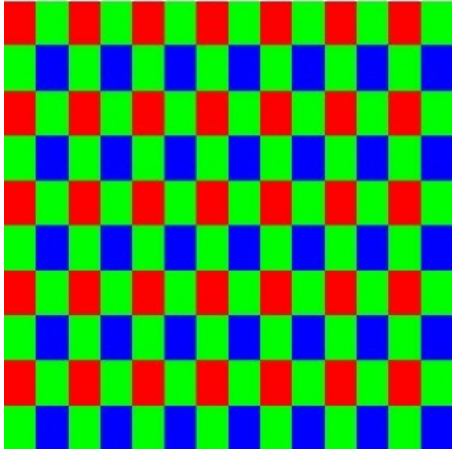
- Each pixel has a **colored filter** over it, so it only responds to that color.
- Typically, filters are arranged as in the figure
    - A row of red and green next to one of blue and green
    - Human eye is **most sensitive to green** light, so having twice as many green pixels is advantageous.
- After image capture, software in the camera determines the **color balance** that is eventually output into a jpeg or tiff file.
- Typically, one pixel in a JPG or TIFF file is comprised of four cells (one red, one blue, and two green) from a CCD array.

Other Applications

- Cooled CCD first used for **long-exposure astronomical imaging** in 1974
- Digital **television cameras** developed in 1975, still by Boyle and Smith
- **Medical endoscopy** began using miniature CCD cameras in 1983
- **3D imaging** in biological microscopy described in 1987 paper
- More recent developments
    - Chemistry: **Echelle spectrometer** uses over 200 linear CCDs positioned so that a unique combination is triggered by the emission spectra from each of 72 elements
    - Astronomy: Pan-STARRS-1 telescope features **1.4 gigapixel camera**

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GRIN LENSES

Jason Jock, Bryan Moore, Kevin Wojcik

Gradient Index (GRIN) lenses are an alternative to using spherical lenses to reshape the wavefront of light. Cylindrical GRIN lenses are often formed with flat ends, making them much easier to use. GRIN lenses can save space, time, money, and materials when used in certain systems.

Qualitative Analysis

- Index of refraction increases or decreases radially from the center
- Multiple curved lenses must be perfectly aligned, but just one GRIN lens can be used for the same effect
- Multiple methods of producing GRIN lenses
  - Insure that the layer thicknesses is smaller than the wavelength of light
  - Can be less than 4 mm in diameter and produce well defined images.

Applications
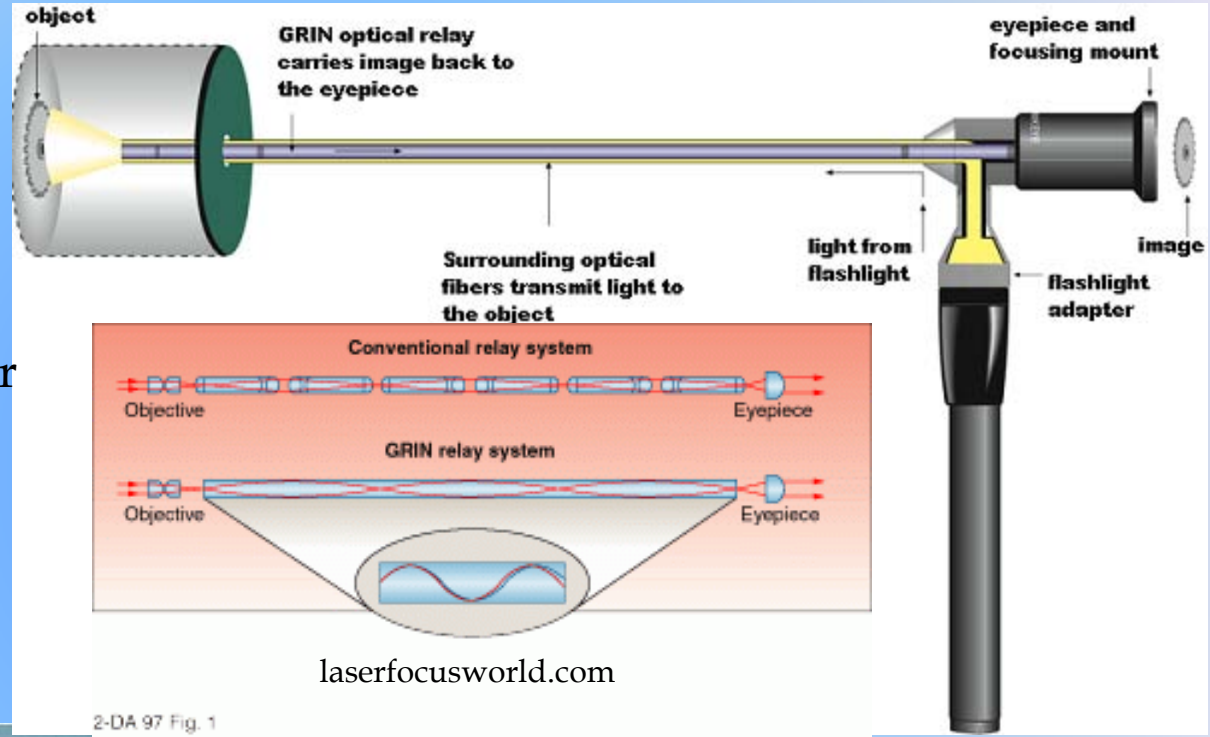
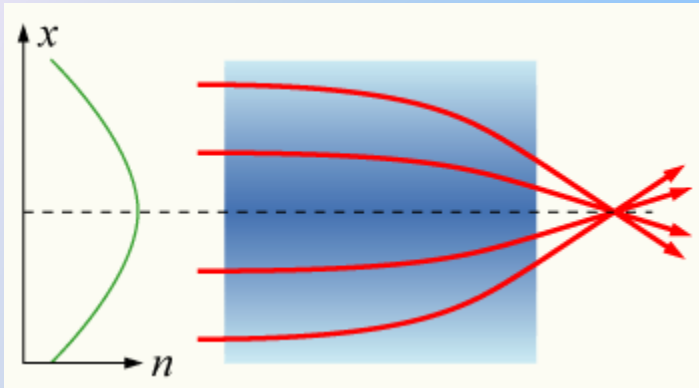Uses include borescopes, laser light coupling, laser focusing or collimating, photocopiers, and eyes, especially those of underwater animals.

apollo.lsc.vsc.edu

laserfocusworld.com

thenakedscientists.com
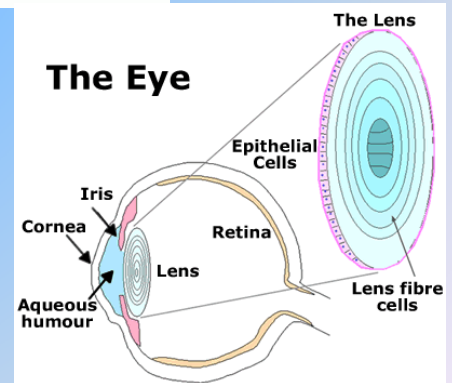
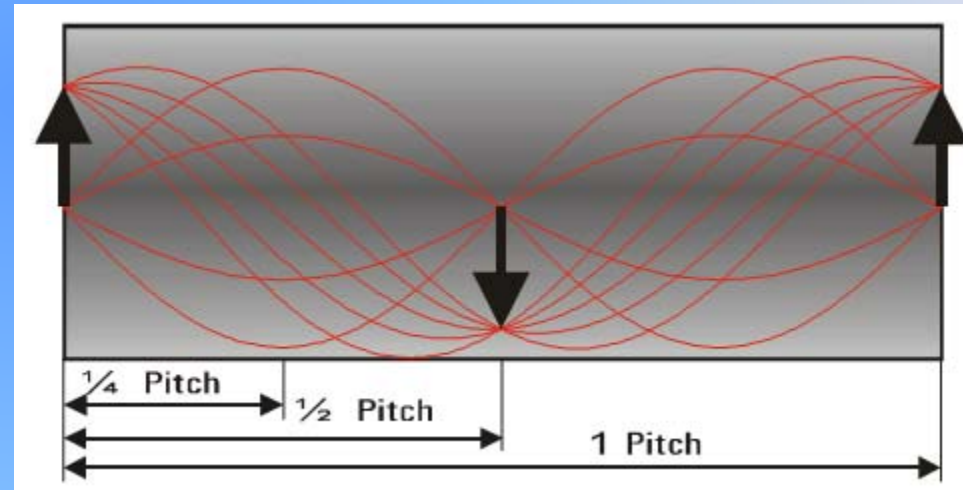# Motion of beam through lens

en.Wikipedia.org

$$n(r) = n_0 \left(1 - \frac{ar^2}{2}\right)$$

$$p = \frac{2\pi}{\sqrt{a}} = \frac{2\pi}{g}$$
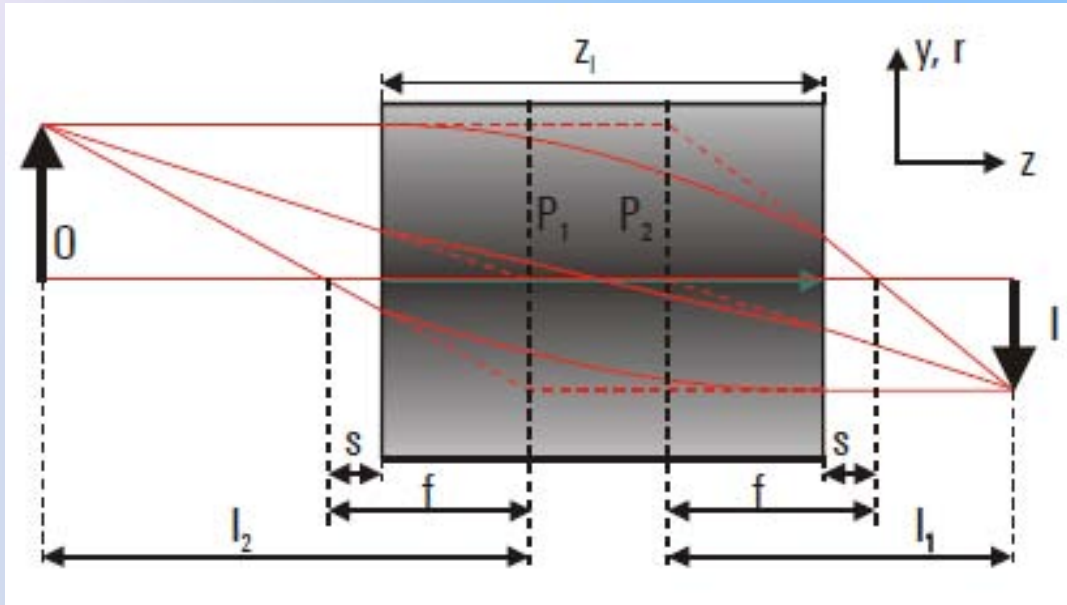
p is the spatial frequency of the wave

g is the gradient constant (defined by wavelength of light and the material)

¼ Pitch

½ Pitch

1 Pitch

Grintech.de

Numerical Aperture $\quad \sin\theta = NA = \sqrt{n_0^2 - n_r^2} = n_0\sqrt{1 - \left(1 - \frac{ad^2}{8}\right)^2}$
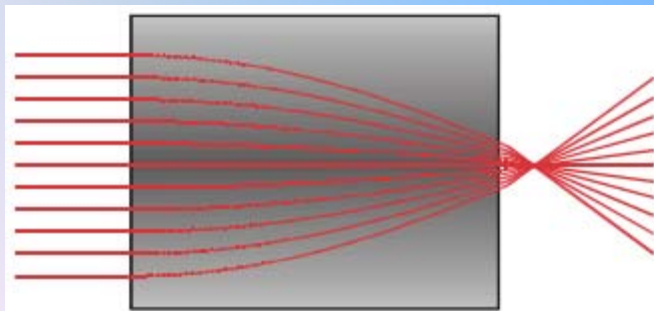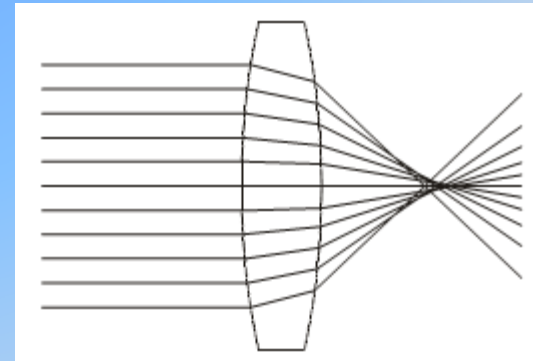
Using GRIN lens instead of multi-lens system

Grintech.de

$$f = \frac{1}{n_0 g \sin(g z_1)}$$

$$s = \frac{1}{n_0 g \tan(g z_1)}$$

n_0 is the index of refraction in the center of the lens

Z_1 is the length of the lens

Grintech.de

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Optical Fibers

Mike Rhoby, Brendon Mikula, Kyle Selleck

Optical fibers are tools used to channel light so information can be transported in a controlled way. Normally made of glass or silicon, these fibers use total internal reflection to send light along the length of the fiber even if the fiber is bent or curved.
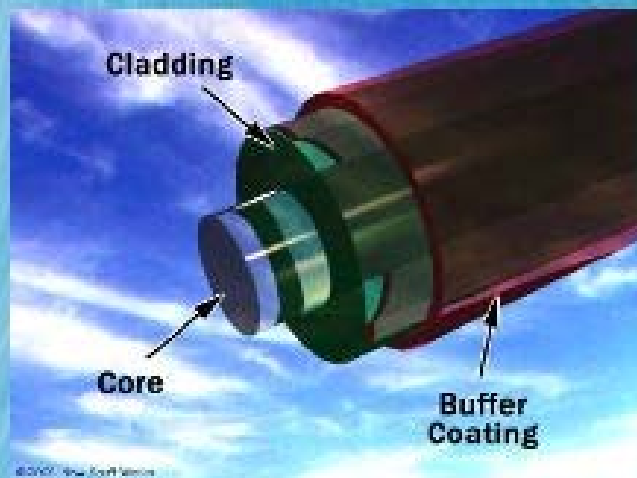
The optical frequencies used can carry 100,000 times more information than electricity or microwaves and optical fibers have lower transmission loss as well as higher security, material abundance and immunity to EM interference. Because of all this, optical fibers are the premier communication device[1].

Qualitative Description

- Optical sensors
- Telecommunication
- Internet
- Local Networking

- Light guides for medical use
- Even used for entertainment

Cladding

Core

Buffer Coating

♦ Optical fibers are usually two layers, the Core surrounded by the Cladding

high-order mode

dispersion

step-index multimode

low-order mode

dispersion

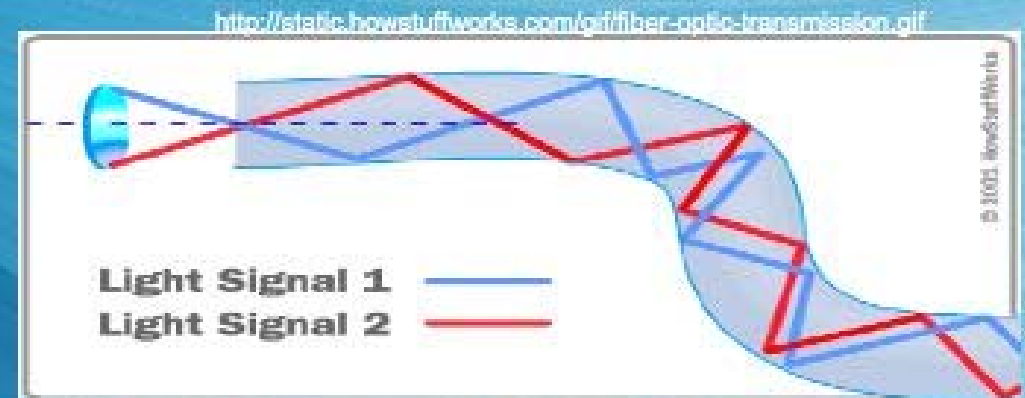graded-index multimode

single-mode

- Single and Multiple mode fibers
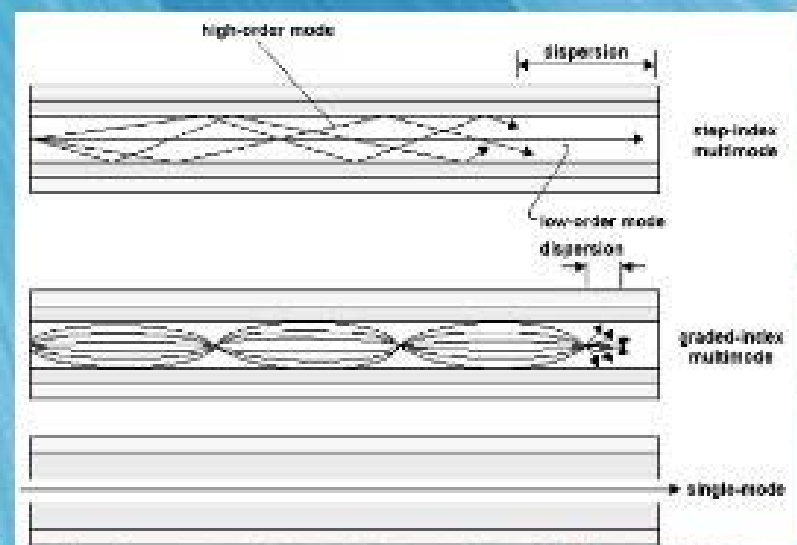
Quantitative Internal Reflection and Numerical Aperture

• Total Internal Reflection carries light along the length of the fibers if the light hits the wall with an angle greater than the critical angle

Light Signal 1 ———
Light Signal 2 ———

The critical angle depends on the index of refraction of the core and the cladding as described by Snell's law. Light entering the fiber then must enter at an angle so the light inside meets this critical angle. The angle the light can enter is the Numerical Aperture of the fiber.

$$\sin(\theta_c) = n_c / n_f$$

So it follows then using Snell's law at the end of the fiber that:

$$\sin(\theta_{max})n_i = (n_f^2 - n_c^2)^{1/2}$$

The term $(n_f^2 - n_c^2)^{1/2}$ is the Numerical Aperture

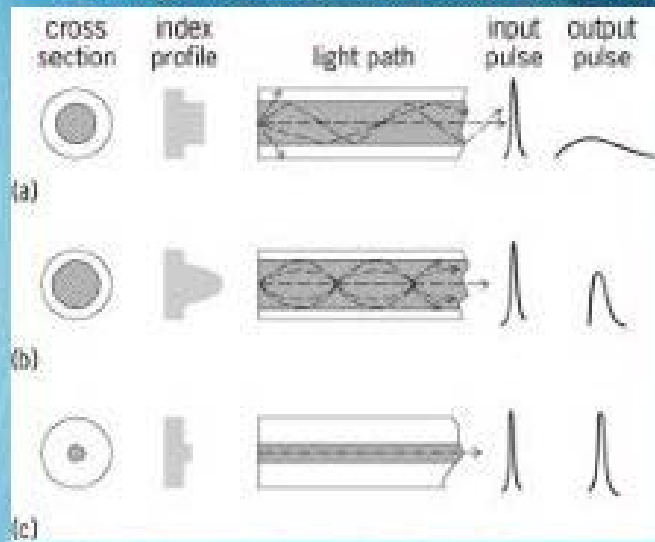θ_{max}

n_i

n_c

θ

n_f

The standard index of refraction for optical fibers is 1.48 for the core and 1.46 for the cladding giving a NA of .242 or a max angle of 14 deg in air.

Quantitative   Modes and dispersion

Multiple mode fibers allow more light and are cheaper to produce but will incur more dispersion over longer distances making them less effective for long range communication. Single mode fibers remove dispersion allowing the signal to remain sharp over long distances but cost more because of its materials and they are harder to splice.
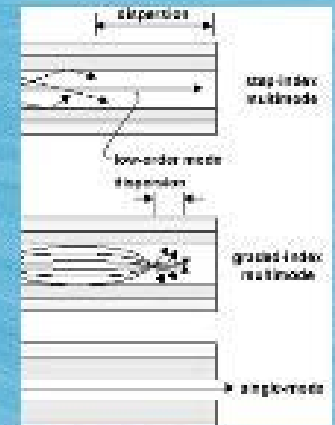
Singe mode fibers usually have a core 8-10 microns wide giving it a much smaller N.A. and making it much harder to splice because of the precision needed when aligning the two fibers.

Multi mode fibers usually have a core of more than 10 microns. The larger center allows for a larger N.A. letting in more information as well as making splicing much easer.

References

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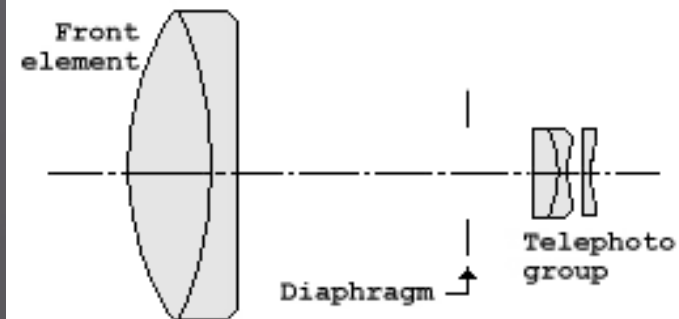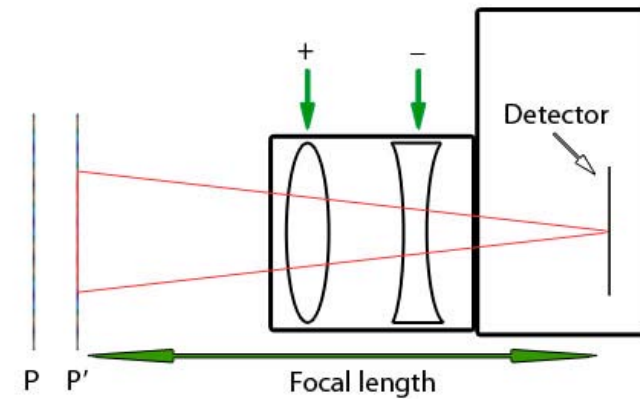
Astronomical Telescopes/Telephoto Lenses

Ryan Majewski   Lindsay Knowlton Sarah Guile

The prefix _tele_ is used to describe an optical instrument that allows us to view objects at a distance at a level of detail we wouldn't be able to with the naked eye. An astronomical telescope is an optical instrument that uses our eye as part of the system which allows us to gaze at distant celestial objects. A telephoto lens also allows us to view objects at a distance, but it's primary use is in photography and was created to achieve the same visual effect as a long focal length lens while decreasing the physical length.

Qualitative Description: Telephoto Lens

▪ Before telephoto lenses were created, a camera would need a long focal length lens in order to focus on objects at great distances. For example, a 300mm lens focused at infinity would need 300mm between it's rear focal plane and it's rear focal point. Because the focal planes in a long focal length lens lie within the lens itself, this means the lens would have to be almost a foot long.

▪ Telephoto lenses were created to achieve the same effect without as much "bulk". There's a rear element within a telephoto lens that has a negative focal length. These achieve the same effect by extending both principle planes past the physical dimensions of the lens. This allows for the same image distance, so the light rays will still converge on the film in the back of the camera. However, it's not limited to the size of the lens anymore.

▪ The third image is a more realistic diagram of a telephoto lens, or more commonly known as a telephoto group. In order to account for various aberrations, lens combinations will be used. This is a common way to correct aberrations in many optical systems.

Qualitative Description: Astronomical Telescope

Focal lengths:

Objective: 0.50 m

Eyepiece: 0.10 m

Angles:

Objective: 4.0 °

Eyepiece: -19.3 °

Magnification: -4.8

© W. Fendt 2000

f_1 f_2

Exit pupil plane

Chief ray

A B C D E

f_o f_e d
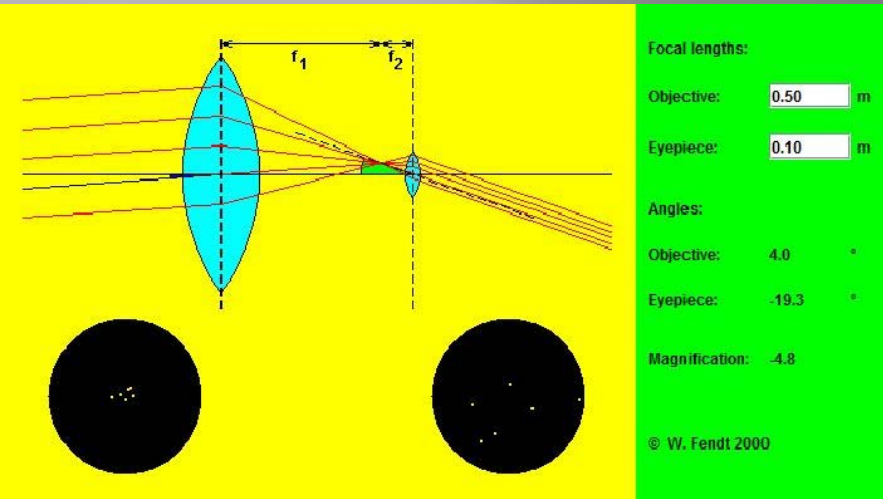
- The astronomical telescope is a simple instrument consisting of two positive lenses. It's considered a refracting telescope, because it takes advantage of the fact that light bends when it enters a material of a different refractive index. Astronomical telescopes will produce an inverted image of the object because the eyepiece is positioned after the objective focal length, exactly it's focal length away from the newly formed inverted image. The rays will leave parallel to one another, and once they enter the eye they refract again and converge for us to see an image. The top diagram used the six brightest stars of Pleiades and what they look like without and with the telescope. When the eye interprets the image, it will see a magnified virtual image. The bottom diagram is a visual representation of how the eye sees a magnified image with an infinite object distance, which is a very common issue when viewing celestial objects.
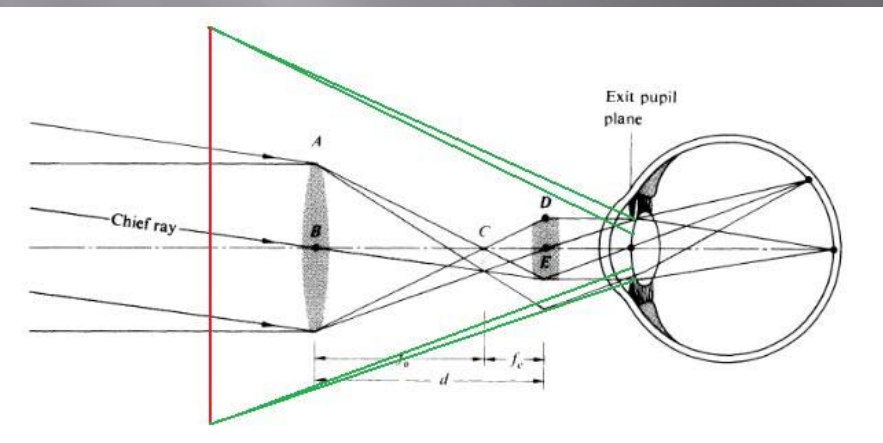
Quantitative Description: Telephoto Lens

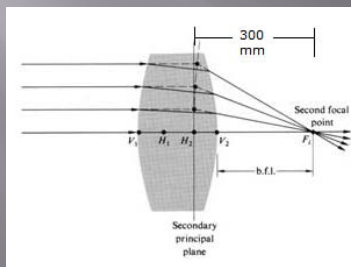Effective focal length: $1/f = 1/f_1 + 1/f_2 - (d/f_1f_2)$
Principal planes: $O1H1 = fd/f_2$, $O2H2 = -fd/f_1$
Front focal length: $f_1(d-f_2)/(d-(f_1+f_2))$
Back focal length: $f_2(d-f_1)/(d-(f_1+f_2))$

Example: When a 300mm converging, thick lens is focused at infinity it will be 300mm from the lens to the rear principal plane.

This means that a camera lens of focal length 300 mm would have to be at least 300 mm away from the sensor in order to be able to focus at infinity.

If a compound thick lens was added consisting of a biconvex lens with an f of +50 mm and a negative lens of -48 mm that have centers that are 10 mm away from each other.

To show that the two lenses have an effective focal length of 300mm:
$1/f = 1/f_1 + 1/f_2 - (d/f_1f_2) = 1/50 + 1/-48 - (10/50*-48)$
$f = 300$ mm

Then, we will locate the principal planes H1 and H2.
$O1H1 = fd/f2 = 300*10/-48 = -62.5$ mm
$O2H2 = -fd/f1 = -300*10/50 = -60$ mm
The negative value indicates they lay in between the object plane and the lenses, which is what we want.

Now we'll calculate the front focal length and the back focal length. These will primarily be used to double check our answers.
f.f.l. $= f_1(d-f_2)/(d-(f_1+f_2)) = 50(10-(-48))/(10-(50-48)) = 362.5$ mm
b.f.l. $= f_2(d-f_1)/(d-(f_1+f_2)) = -48(10-50)/(10-(50-48)) = 240$ mm

We also need to make sure the distances from each of the principal planes to their closest focal points are equal:
f.f.l. – O1H1 = 362.5 – 62.5 = 300 mm
b.f.l. + O2H2 = 240 + 60 = 300 mm

Adding together the distance d between the lenses and the b.f.l., we get the new length of the lens: 10 + 240 = 250 mm, 50 mm less than the original 300 mm.

A figure of this example is to the bottom left
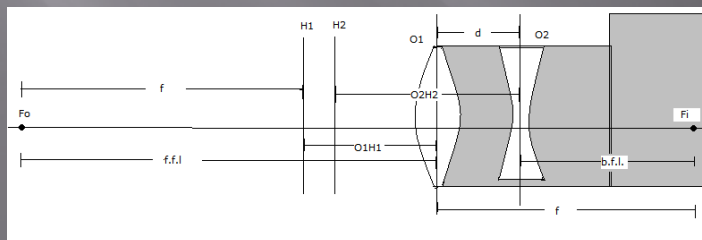
Quantitative Description: Astronomical Telescope

Classic Galilean/Keplerian refracting telescope has 2 lenses: An Objective and an Eyepiece. The eyepiece lens can be either concave(Galilean), or convex(Keplerian). Concave eye pieces produce a upright image, but suffer from a limited field of view because of the diverging rays from the eyepiece. Convex eyepieces have a greater field of view, but produce inverted images. Both lenses have a focal length determined by the lens makers formula:

$$\frac{1}{f} = (n-1)(\frac{1}{R1} + \frac{1}{R2})$$

f= Focal length
n=Index of refraction of material
R1/R2= Radius of curvature of either side of lens

The two lenses are placed a distance (f_{obj} +f_{eye}) apart along each others focal axes. The combination creates a classic telescope with a magnification M, where

$$M = \frac{f(obj)}{f(eye)}$$

The size of the objective lens also has a large role in the efficiency of the telescope. The larger the area of the objective lens, the more light enters the telescope. The "Angular Resolution" of any classical telescope is given by the formula:
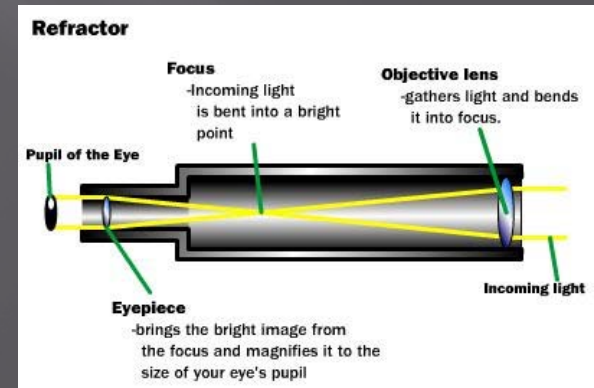
$$\sin(\alpha) = 1.22\frac{\lambda}{D}$$

α=angular resolution(radians)
λ=wavelength of light
D=diameter of objective

In practice, there is a finite limit to the magnification and resolution of a telescope. Having a large magnification does nothing without the resolution that goes with it. Also, the size of the objective also has a physical limit. Large glass lenses tend to sag from gravity, and distort the image greatly.


Refractor

Focus
-Incoming light is bent into a bright point

Objective lens
-gathers light and bends it into focus.

Pupil of the Eye

Incoming light

Eyepiece
-brings the bright image from the focus and magnifies it to the size of your eye's pupil

References

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Did you know: The 400 year Anniversary of the Astronomy Telescope will be in 2010?

BINOCULAR VISION (DEPTH PERCEPTION)

Dung Dao
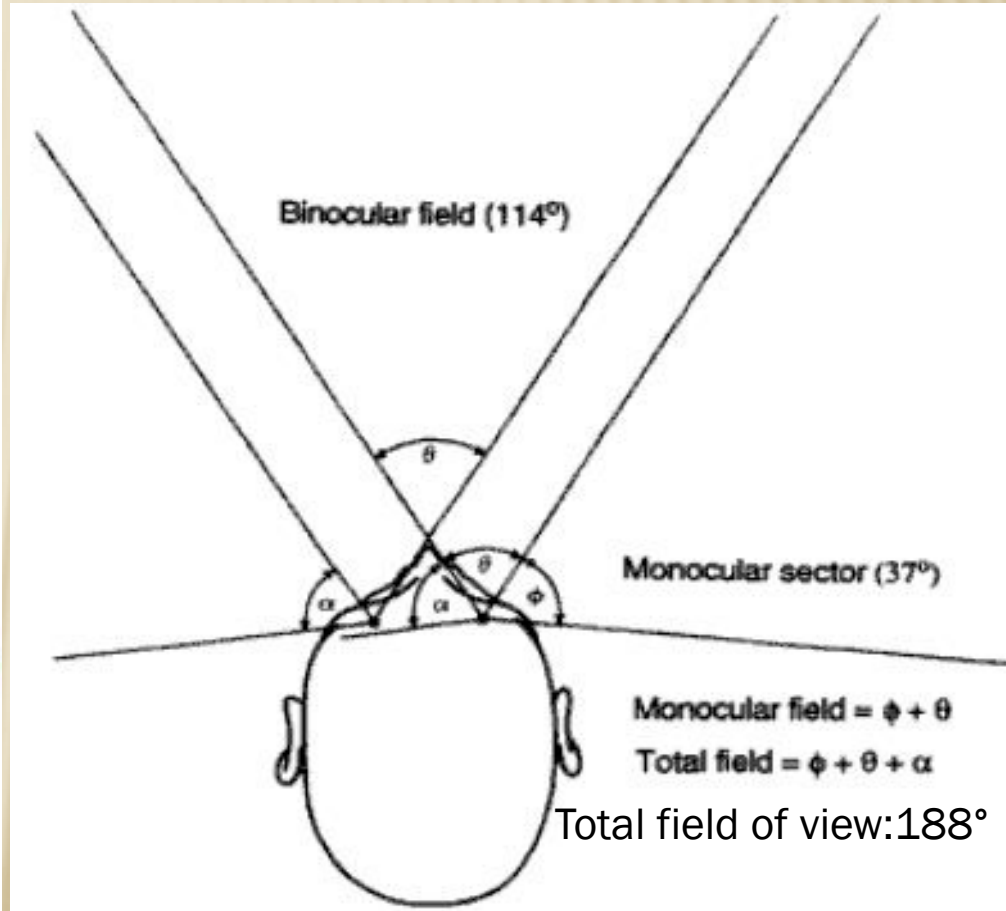Yan Sidronio
Jeff Wyka

(b)

(a)

(c)
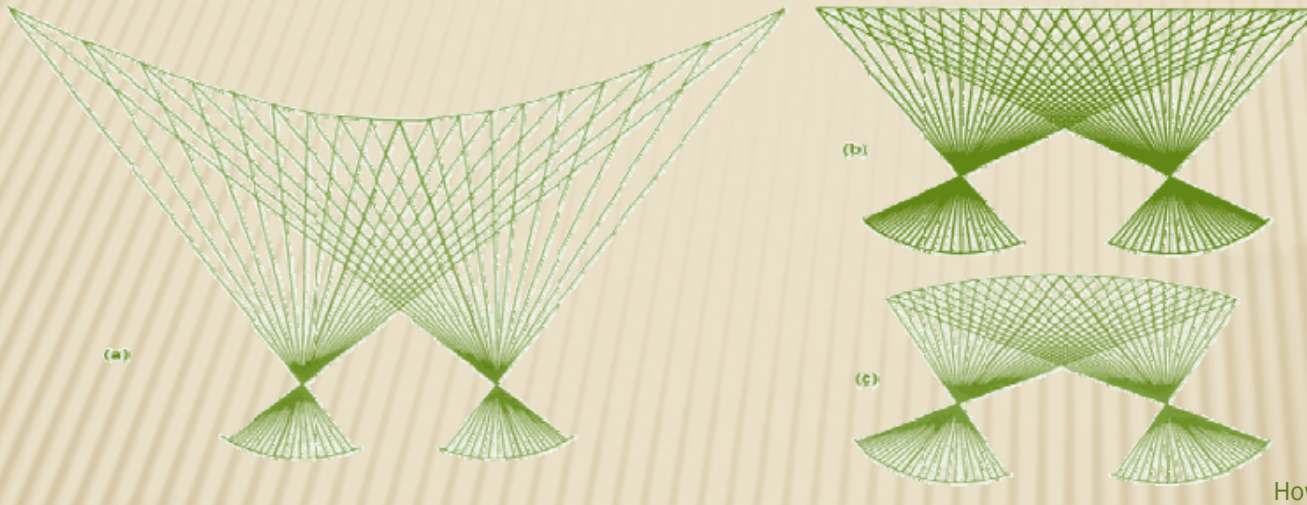
Howard pg. 54

Binocular vision a type is vision in which two eyes are used simultaneously. Coming from the Latin roots *bini* for double, and *oculus* for eye, this type of vision gives many advantages over using only one eye (monoscopic vision), including sensitive depth perception. Stereopsis, which uses convergence angle of the optical axes of the eyes and parallax to determine depth based on the separation of different lines of sight, is how the brain can determine 3D depth.
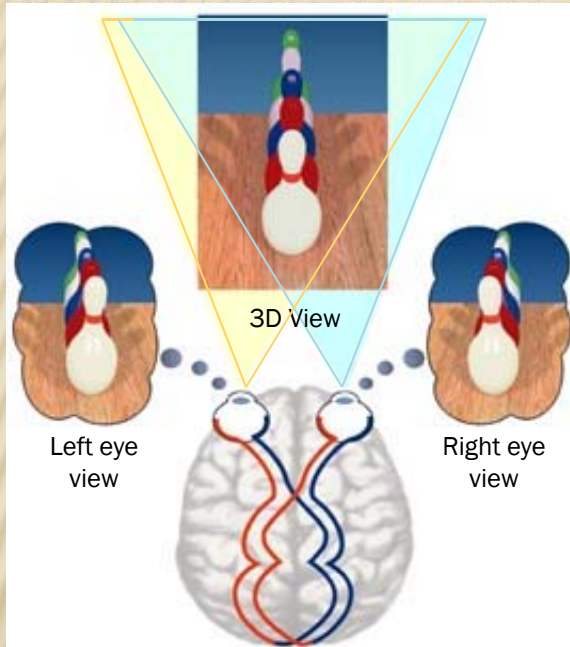
STEREOSCOPIC VS. PANORAMIC

a Panoramic Vision

b Binocular Vision

Binocular field (114°)

Monocular sector (37°)

Monocular field = φ + θ

Total field = φ + θ + α

Total field of view:188°

Varying visual types: *Http://www.physorg.com/newman/gfx/news/hires/varyingvisua.jpg*

Howard, pg. 32

QUALITATIVE ANALYSIS – DEPTH PERCEPTION CUES

3D View

Left eye view

Right eye view

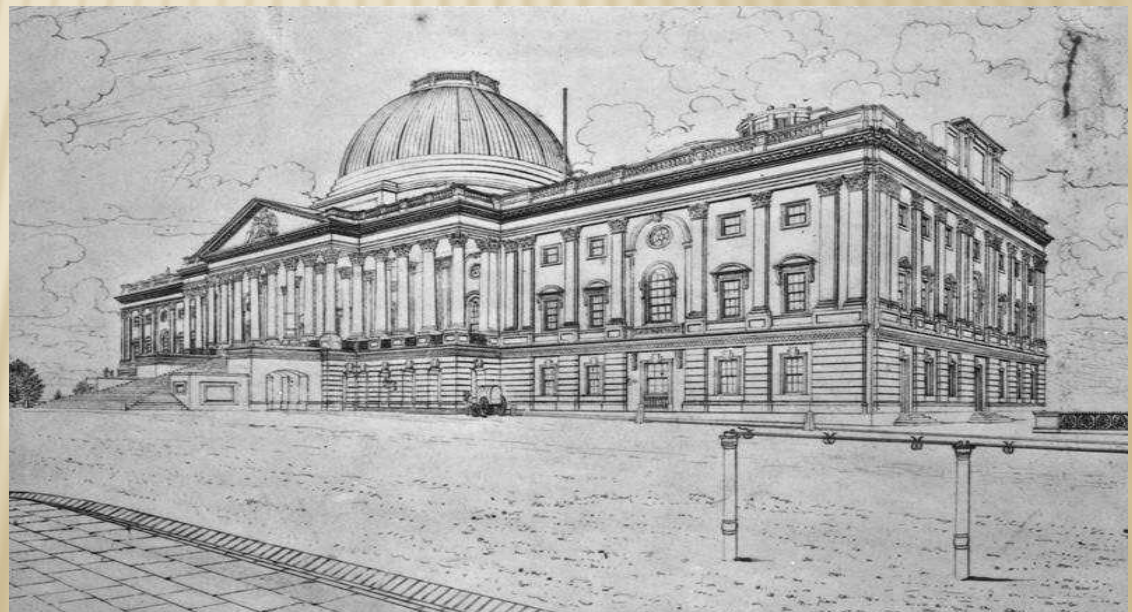http://www.cs.nps.navy.mil/people/faculty/capps/4473/projects/Stereo/bb.jpeg

Binocular cues:

• Convergence and stereopsis: having two slightly different views of the world around you, one for each eye

• Parallax: apparent displacement or difference of orientation of an object viewed along two different lines of sight
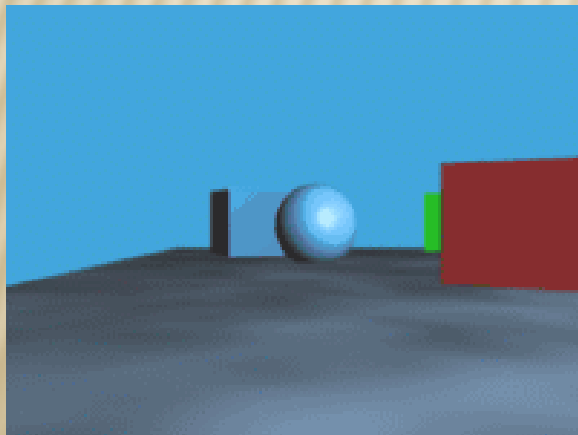
Monocular cues:

•Size: impression of depth due to perspective. Objects far away seem smaller than those near you.

Howard, chapters 1 and 3

http://upload.wikimedia.org/wikipedia/commons/a/ab/Parallax.gif

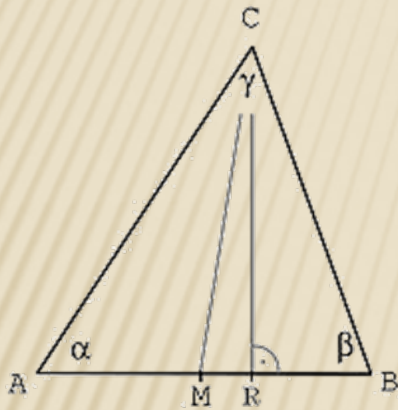http://www.loc.gov/exhibits/us.capitol/oneofour.jpg

QUANTITATIVE ANALYSIS (CONVERGENCE)

Convergence uses triangulation to determine distances accurately. Using the law of sines we can determine the distance to an object.

$$\frac{\sin \alpha}{BC} = \frac{\sin \beta}{AC} = \frac{\sin \gamma}{AB} \quad \Longrightarrow \quad AC = \frac{AB \cdot \sin \beta}{\sin \gamma} \qquad BC = \frac{AB \cdot \sin \alpha}{\sin \gamma}$$

$$\Longrightarrow \quad RC = \frac{AB \cdot \sin \alpha \cdot \sin \beta}{\sin(\alpha + \beta)}$$

Using the above distance, we can find the distance from the midpoint M.

$$MR = AM - RB = \left(\frac{AB}{2}\right) - (BC \cdot \cos \beta) \quad \text{and} \quad MC = \sqrt{MR^2 + RC^2}$$

$$\Longrightarrow \quad MC = \left(\left[\frac{l}{2} - \frac{AB \sin(\alpha)\cos(\beta)}{\sin(\alpha + \beta)}\right]^2 + \left[\frac{AB \sin(\alpha)\sin(\beta)}{\sin(\alpha + \beta)}\right]^2\right)^{\frac{1}{2}}$$

For binocular vision the value MC is the distance to the object that is being fixated upon and all values expressed in the equation are known in most cases.

QUANTITATIVE ANALYSIS (PARALLAX)

Parallax uses the relative position of an object with respect to a very distant background from two viewpoints to determine distances. For binocular vision, parallax is used to find distances relative to a point, or in other words, it doesn't give absolute distances by itself.

For an object with no aim offset and a known fixation point, distances from the fixation point can be determined as seen by the equation:

$$d = \frac{i}{2} * \frac{\sin\left(\frac{\delta}{2}\right)}{\sin\left(\frac{k}{2}\right)\sin\left(\frac{k-\delta}{2}\right)}$$

This is found through the use of triangulation to determine the distance to the fixation point and basic geometry and trigonometry.

This type of depth perception is limited by the area of binocular single vision called Panum's Fusional Area. Outside of this area, qualitative stereopsis takes over in which the perceived depth doesn't change with the distance from the fixation point. Also, when the object becomes far enough, no depth is perceived.

APPLICATIONS

- 3D movies
- ✖ http://www.youtube.com/watch?v=hk1zHaXdcv8
- 3D cameras

- 3D Binocular
- Industrial Robot
- ✖ http://www.youtube.com/watch?v=hfsyvmDUA5k
- ✖ - Many computer based 3D applications such as 3D games, 3D engineer designs, 3D arts…

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Howard, Ian P. *Binocular vision and stereopsis*. New York: Oxford UP, 1995. Print.

Keith Strovan. "Disparity, Convergence and Depth (Visual Depth Perception 10)". The Wolfram Demostrations Project.
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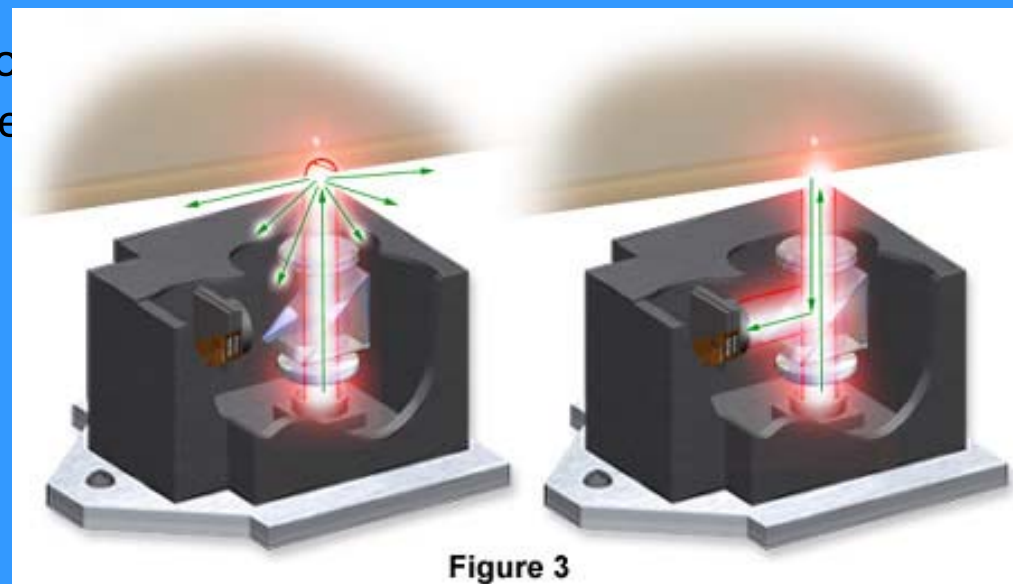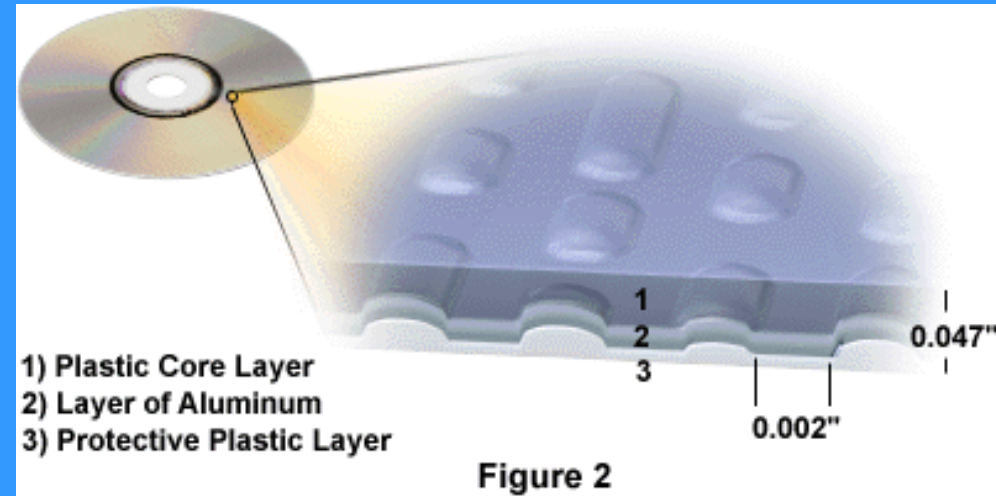
Quick History of a Compact Disc

Recording studios wanted a higher quality storage media that was more durable and could hold larger amounts of information

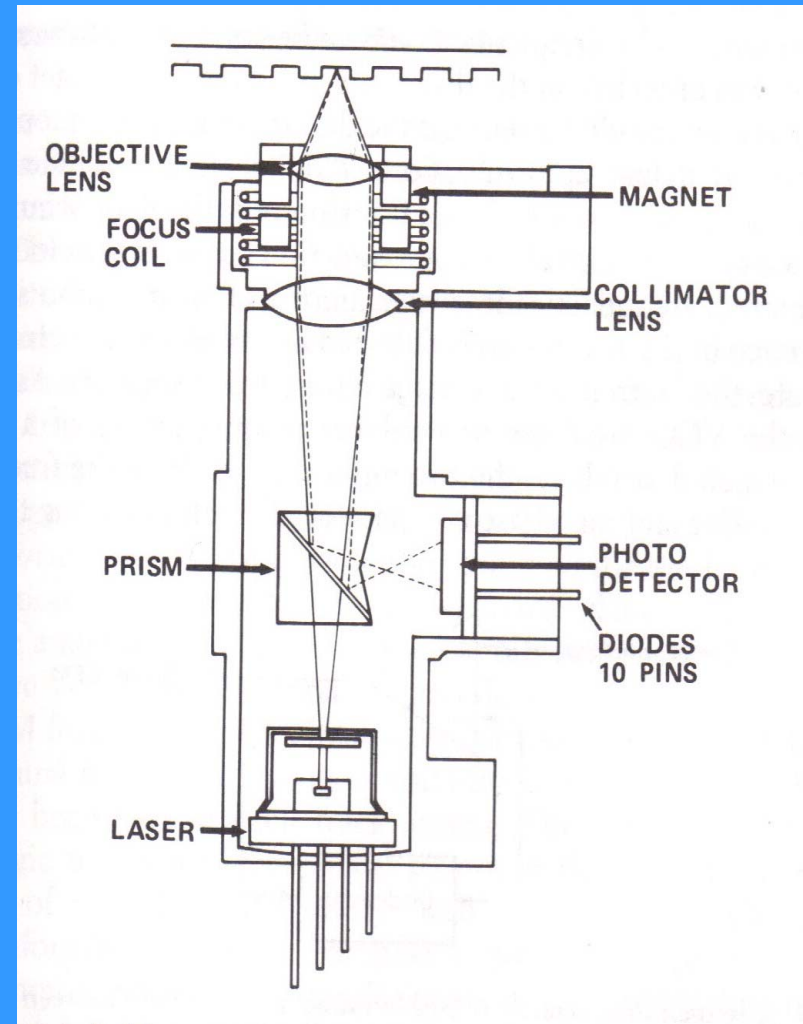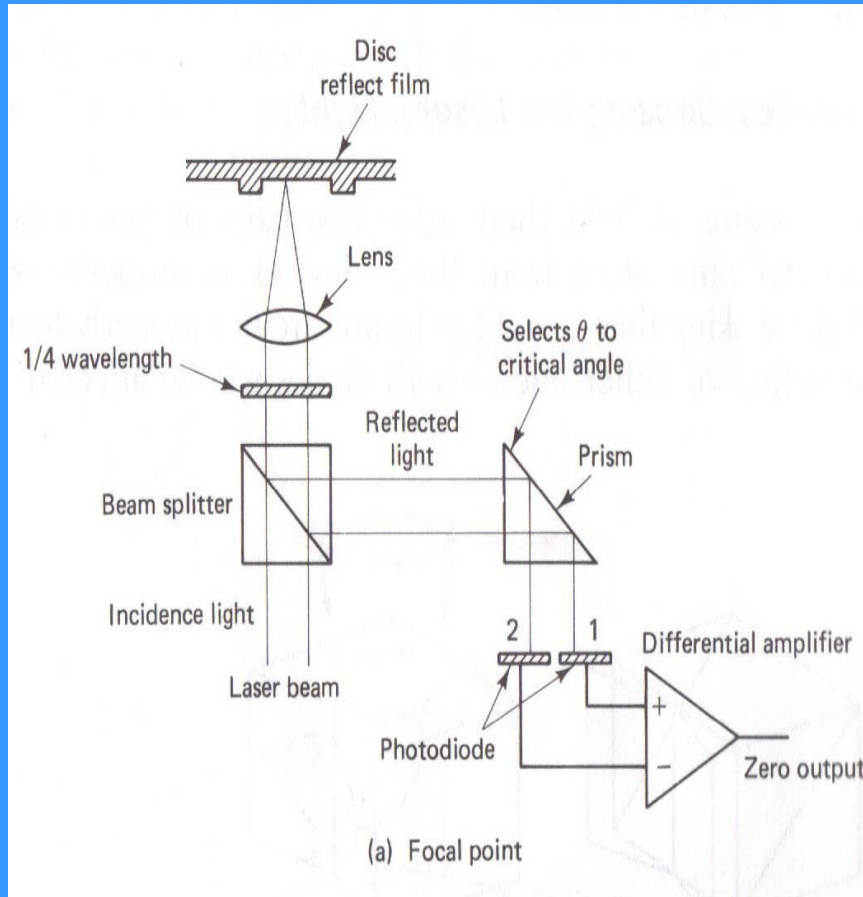Philips and Sony worked together initially trying to create the digital audio disc in 1976

Created the *Red Book* a standard for compact disc in 1980 and set the max time of audio to be 74 minutes, with a limit of 99 tracks

Physical Properties

- 1.2 mm thick, with an almost-pure polycarbonate plastic

- Made up of three to four layers: polycarbonate, colored dyed layer of aluminum, lacquer layer, and artwork screen printed on top

- Each pit is approximately 100 nm deep by 500 nm wide

- A change from pit to land or land to pit indicates a one, while no change indicates a zero

- The distance between tracks is 1.6μm

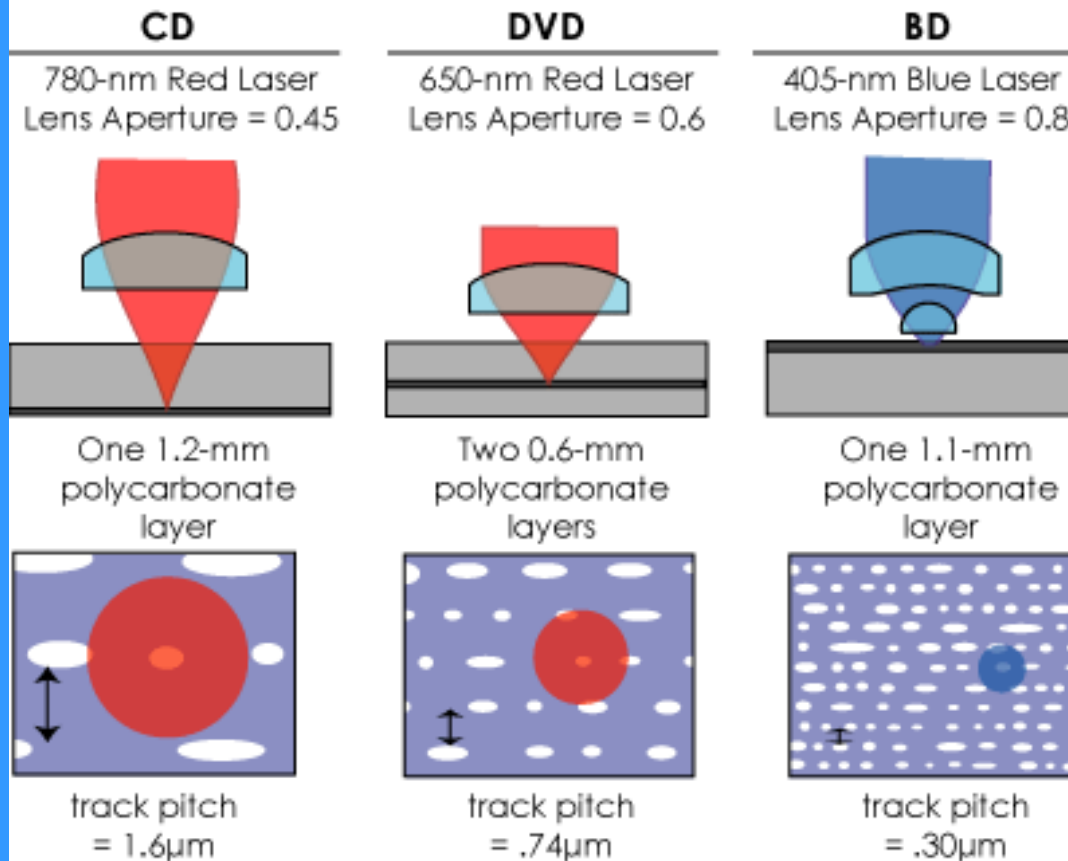- If the spiral was stretched out it would be approximately 3.5 miles long

1) Plastic Core Layer
2) Layer of Aluminum
3) Protective Plastic Layer

0.047"

0.002"

Figure 2

Figure 3

Diagram of the Optics

Disc reflect film

Lens

1/4 wavelength

Beam splitter

Incidence light

Laser beam

Reflected light

Selects θ to critical angle

Prism

2   1

Photodiode

Differential amplifier

+

−

Zero output

(a) Focal point

OBJECTIVE LENS

FOCUS COIL

PRISM

LASER

MAGNET

COLLIMATOR LENS

PHOTO DETECTOR

DIODES 10 PINS

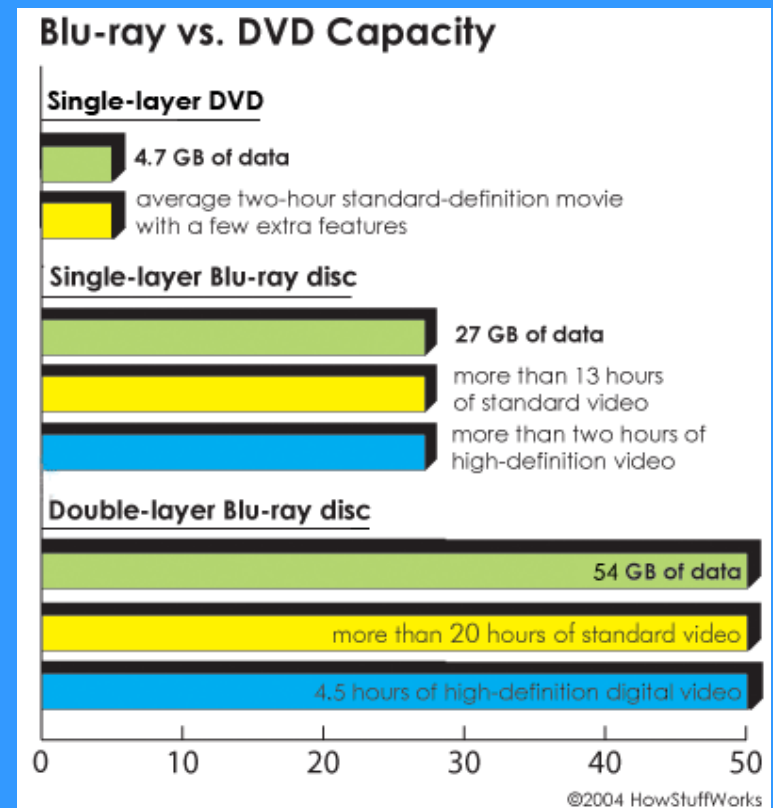# Direct Comparison Between CD, DVD, and Blu-ray

Quick History of Blu-ray

- HDTV sets appeared in the market around 1998, however there was no way to record or play HD content.

- Sony unveiled the first DVR Blue prototypes in October 2000. This was later known as "Blu-ray".

- The physical specifications of Blu-ray were completed in 2004 and the BD-ROM specifications were finalized in 2006.

- The first Blu-ray Disc movies were released in June 2006.

Physical Properties

- Blu-ray discs rely on a blue-violet laser (405nm) rather than the traditional red (650nm).

- This shorter wavelength allows more data to be packed tightly, taking up less space.

- Combined with a change of numerical aperture to 0.85, Blu-ray Discs can hold 25GB/50GB.

Blu-ray vs. DVD Capacity

Single-layer DVD
- 4.7 GB of data
- average two-hour standard-definition movie with a few extra features

Single-layer Blu-ray disc
- 27 GB of data
- more than 13 hours of standard video
- more than two hours of high-definition video

Double-layer Blu-ray disc
- 54 GB of data
- more than 20 hours of standard video
- 4.5 hours of high-definition digital video

0 10 20 30 40 50

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Physical Properties Continued

- The smaller blue laser beam is able to focus more precisely, being able to read information in pits only 0.15μm long.

- Blu-ray only requires a track pitch of 0.32 microns.

- The disc is the same thickness as a DVD (1.2mm).

Questions?

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Missile Warning System

The New Generation of Optical Warfare.

Missile threats on aircraft are a reality on a daily basis for military and civilian aircraft. The Missile Warning System is an aircraft component containing optical sensors to alert pilots of the threat and automatically counter the attack.

Michael Ford
Jon Gilbert
Amir Ouyed

How the System Works (Qualitative)

- A detector is a small piece of semiconductor material which is photosensitive (its electrical properties will change when illuminated by light of a given wavelength.

- Favored materials today are Mercury Cadmium Telluride which is unfortunately very tricky to fabricate but provides superior sensitivity to longer wavelengths over the cheaper more commonly used alternative of Cesium.

- The quantum physical effect is given by the photoelectric effect where photons of impinging light or infrared excite electrons within the detector's material.

- If the photon is energetic enough (if its wavelength is short enough), the electron will be dislodged from its place in the detector and become measurable as a minute electrical current.

- Contains a central computer process to analyze threats/signals and dispense flares.

- Contains an interface for the pilot

Rear Sensors
Top Sensor
Front Sensors
Bottom Sensor

3 Major Types of Missiles

- Radar Guided Missiles (near obsolete)
- Laser Guided Missiles are becoming more common, however are much more expensive to produce.
- IR Guided Missiles (most common today)

  -IR radiation is EM radiation whose wavelength is longer than that of visible light (400-700nm) but shorter than that of microwaves.

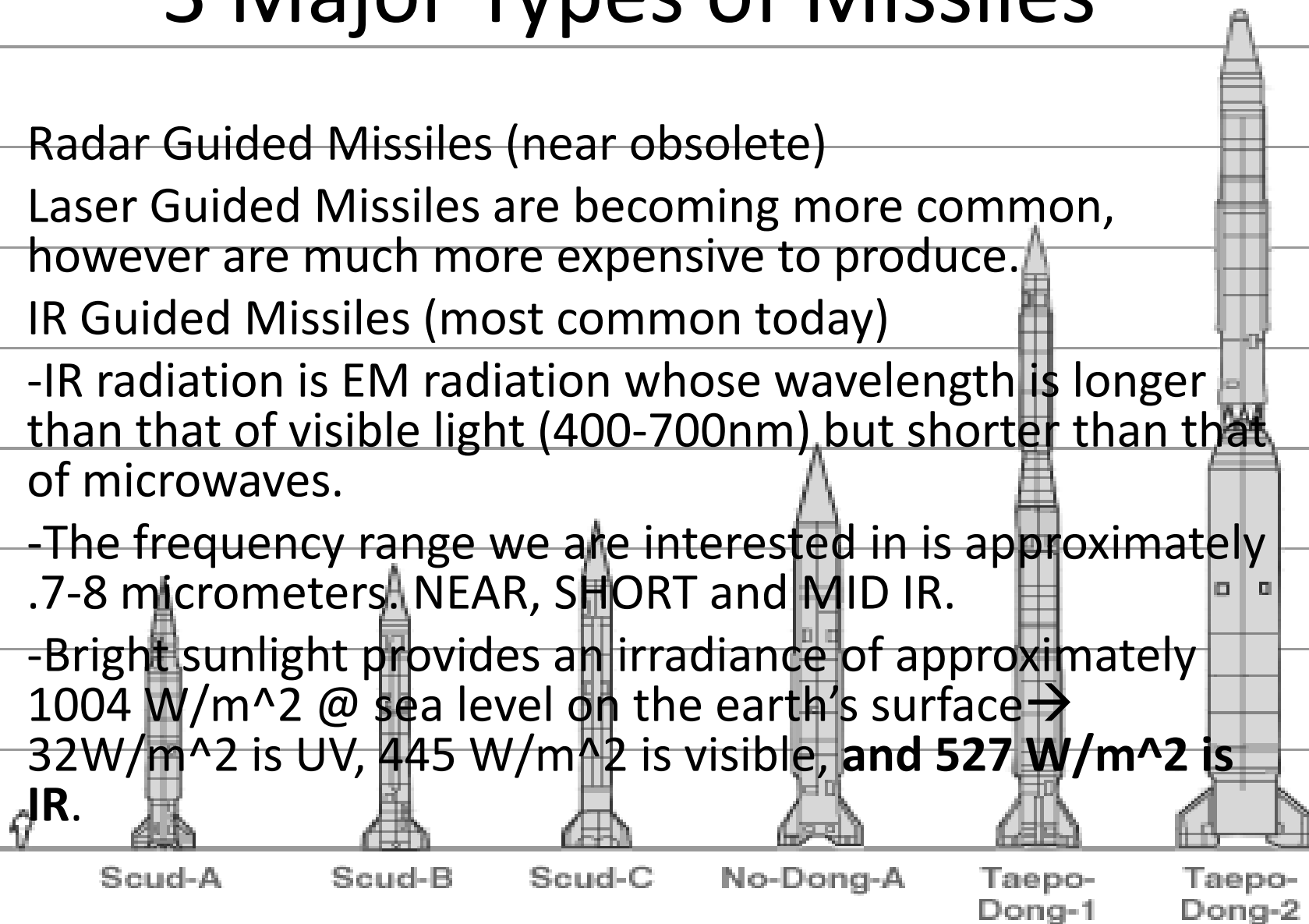 -The frequency range we are interested in is approximately .7-8 micrometers. NEAR, SHORT and MID IR.

  -Bright sunlight provides an irradiance of approximately 1004 W/m^2 @ sea level on the earth's surface→ 32W/m^2 is UV, 445 W/m^2 is visible, **and 527 W/m^2 is IR**.
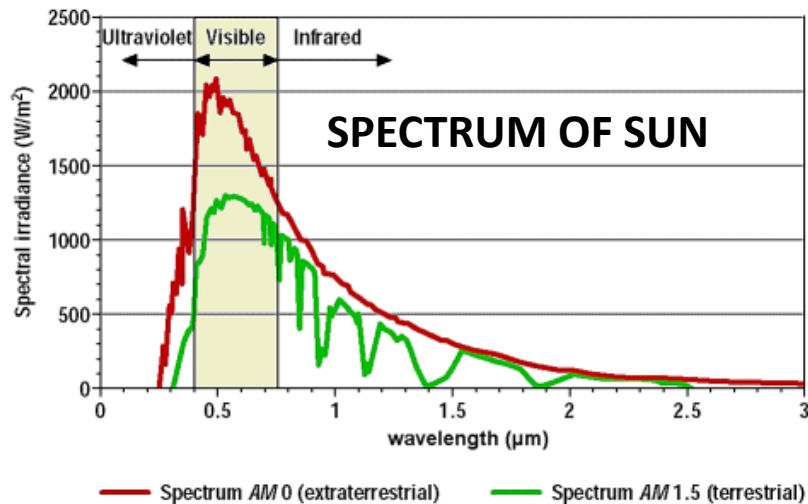
Scud-A   Scud-B   Scud-C   No-Dong-A   Taepo-Dong-1   Taepo-Dong-2

SOURCE: GlobalSecurity

Quantitative Analysis

IR Source

Lens with Anti-Reflective Coating

Photoelectric Metal

Bandpass Filter

Signal

$$W = 2\pi hc\lambda^{-5}(e^{ch/\lambda kT)})-1$$

$$T_L = T - T_H \qquad T_H = \frac{T(N^2 - N_L^2)}{(N_H^2 - N_L^2)}$$

Sun (6000K)

Missile (3000K)
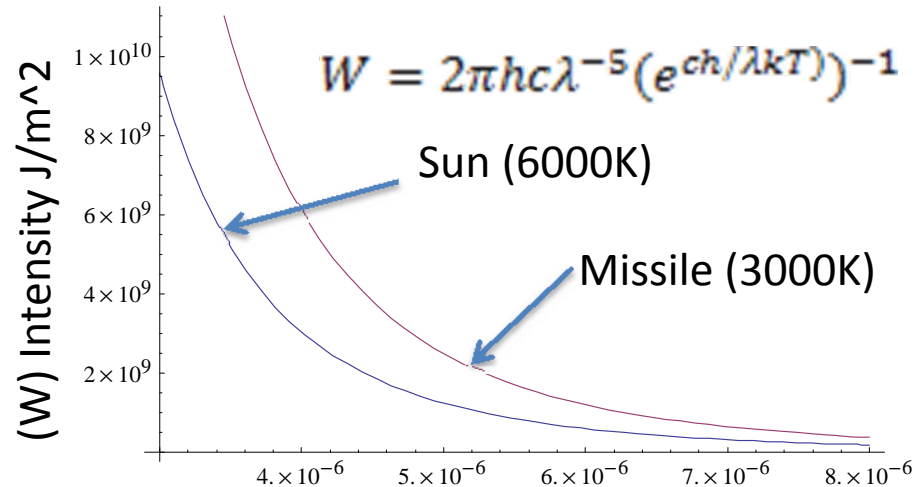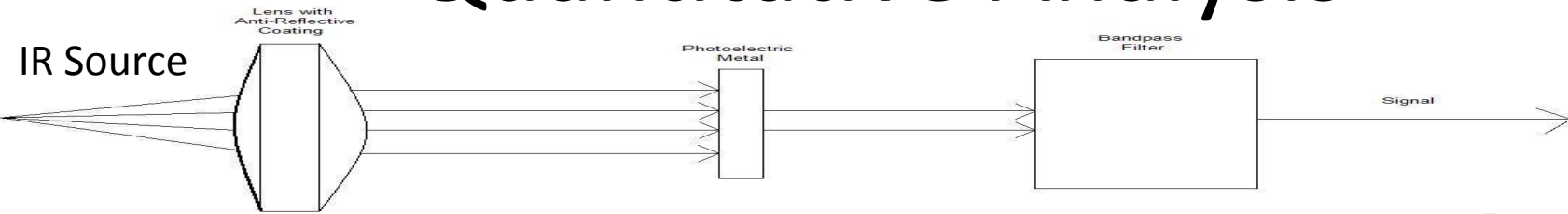
(W) Intensity J/m^2

T_H = Thickness of high index film
N_H = Index of refraction of T_H
T_L = Thickness of low index film
N_L = Index of refraction of T_L

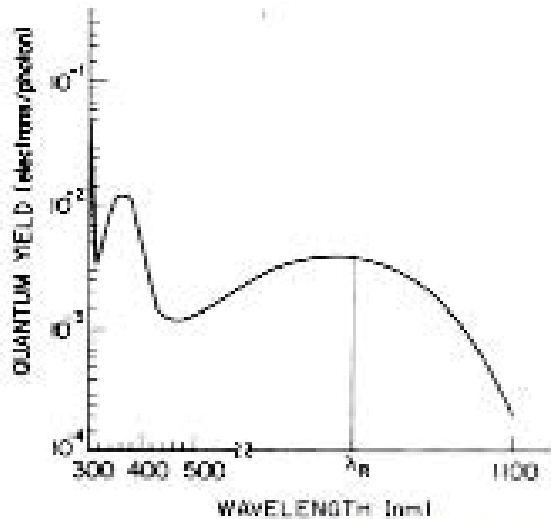**SPECTRUM OF SUN**

Spectral irradiance (W/m²)

Ultraviolet | Visible | Infrared

wavelength (µm)

— Spectrum *AM* 0 (extraterrestrial)   — Spectrum *AM* 1.5 (terrestrial)

T%

N_H = 3.3 (Si)
N_L = 1.45 (ThF$_4$)

Wavelength in µm
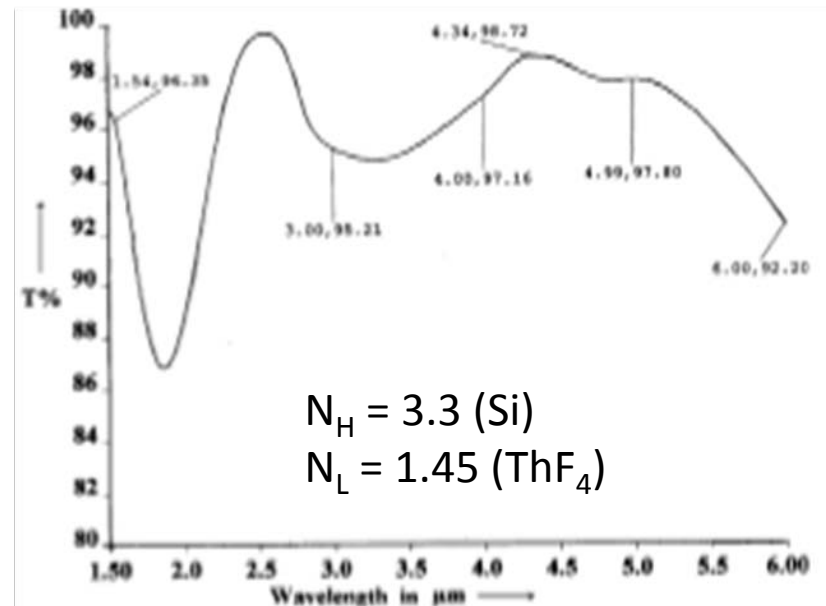
Quantitative Analysis (Cont.)

$$\eta(\nu) = \frac{e_{output}}{h\nu_{incident}} = (1-R)\left(\frac{P_x}{k}\right)\left(\frac{1}{1+\frac{1}{kL}}\right)P_f$$

Figure 3: Quantum efficiency of the Ag-O-Cs photocathode
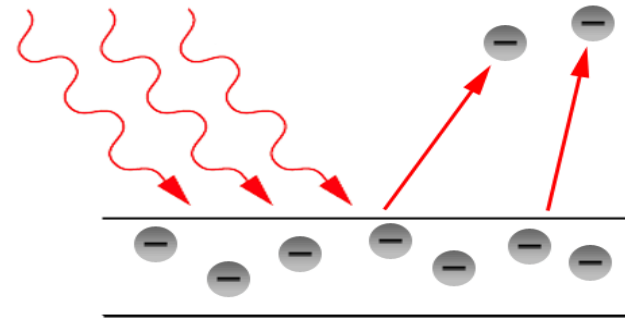
Photoelectric Effect: Φ=hf   λ=c/f

Within freq. range of 700nm-8000nm

λ	Description	Φ
700nm	Start of IR spectrum	1.77
800nm	Highest λ detectable by AgOC	1.55
8000nm	Highest λ of IR Missiles	.155

Some Work-Functions of common materials

Element	eV	Element	eV	Element	eV	Element	eV	Element	eV
Ag:	4.52-4.74	Al:	4.06-4.26	As:	3.75	Au:	5.1-5.47	B:	~4.45
Ba:	2.52-2.7	Be:	4.98	Bi:	4.34	C:	~5	Ca:	2.87
Cd:	4.08	Ce:	2.9	Co:	5	Cr:	4.5	Cs:	2.14

Alternative	µm range
PbS	1-3.6
PbSe	1.5
InSb	2-6

Countering the Attack

- Once a missile is locked on our aircraft and the MWS has alerted the pilot, the system will automatically deploy flares which match the exact signature of our aircraft.

- The flares will provide a decoy target for the missile and diverge the missile away from the aircraft as it simultaneously banks and accelerates away safely.

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