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Overview of non-imaging optics

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A Brief Overview of Non-Imaging Optics

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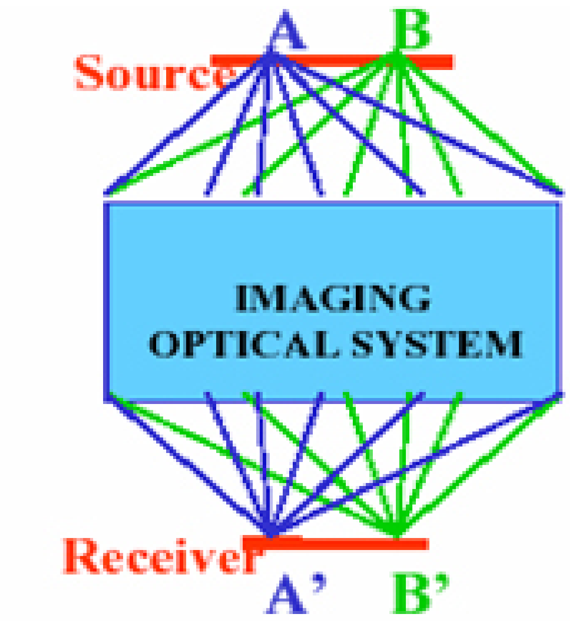
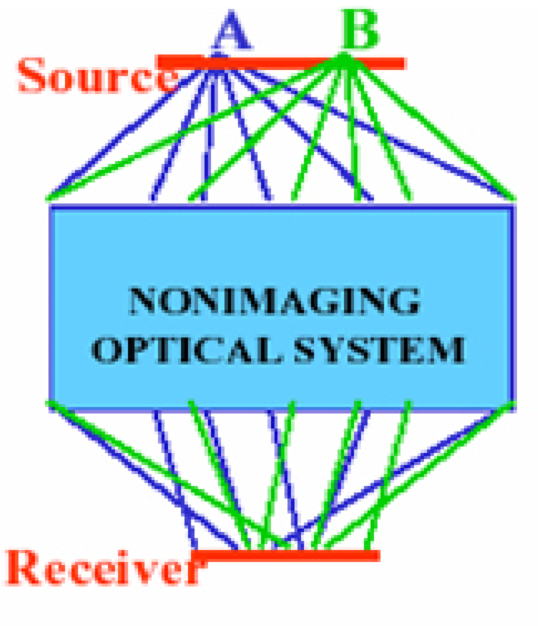
What is Non-Imaging Optics?

- Is the branch of optics which deals with transfer of light between a source and an object.
- Techniques do not form an optimized (non-aberrated) image of source.
- Optimized for radiative transfer from source to target





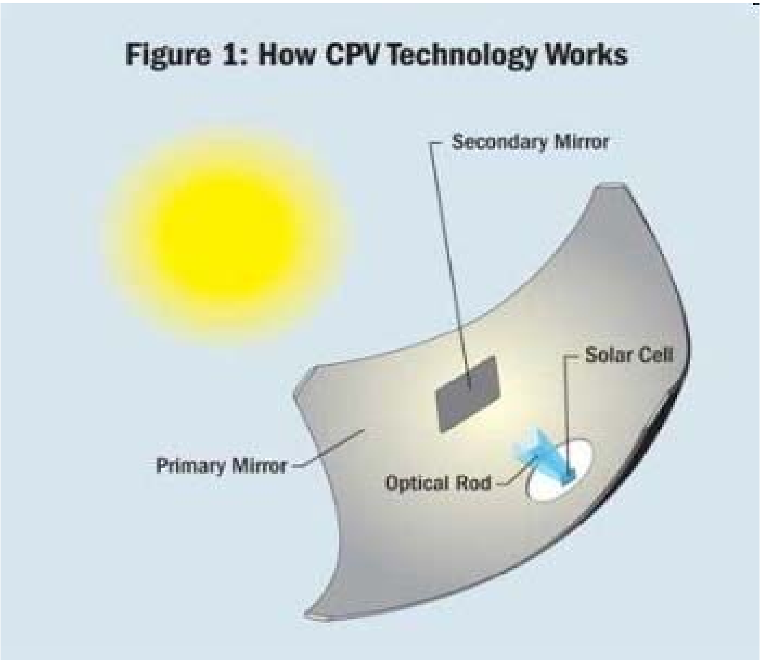


Figure 1: How CPV Technology Works

Some examples

- Optical light guides, non-imaging reflectors, nonimaging lenses, etc.
- Practical examples: auto headlamps, LCD backlights, illuminated instrument panel displays, fiber optics illumination devices, projection display systems, concentration of sunlight for solar power, illumination by solar pipes, etc.

Two major components of a non-imaging optics system

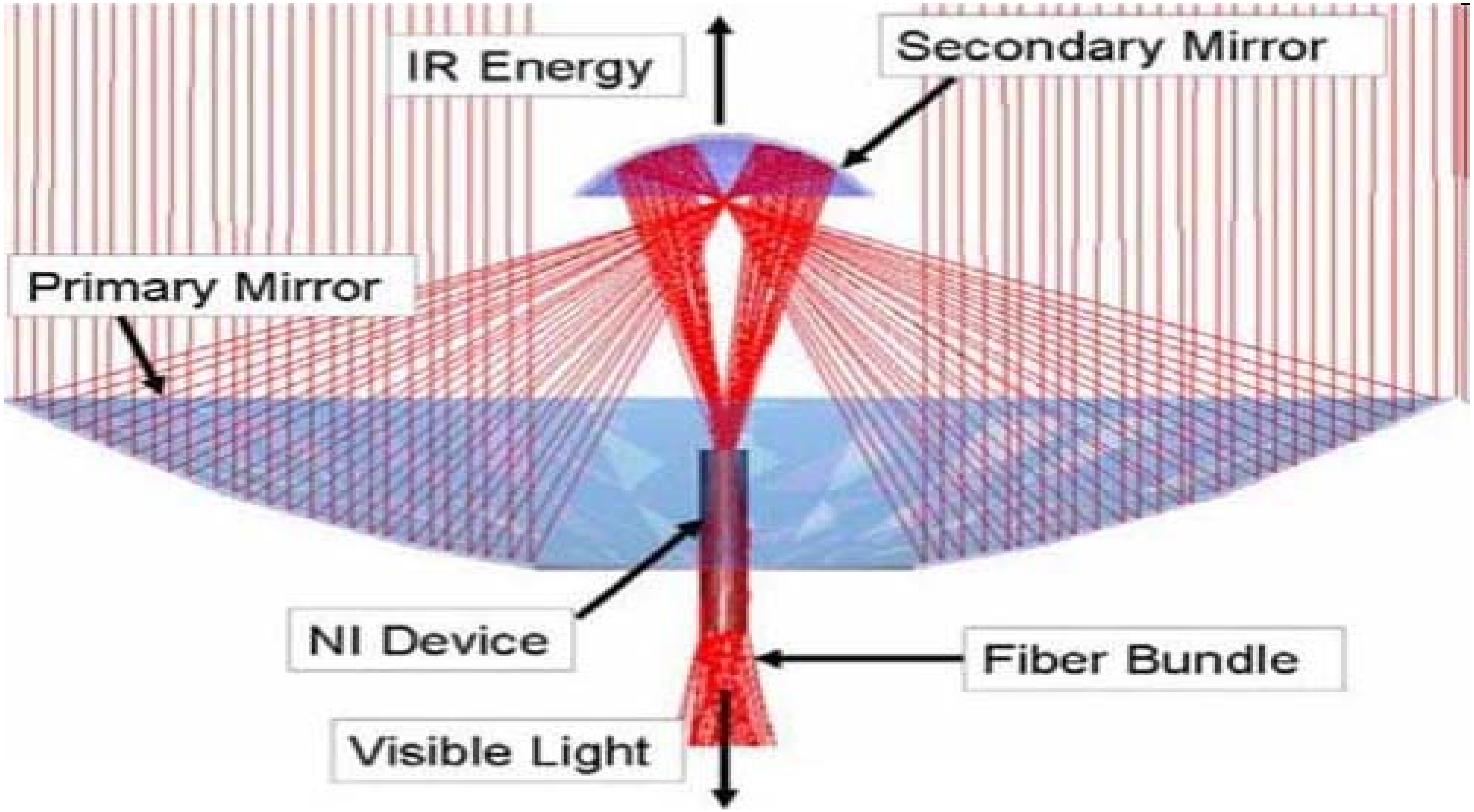
- 1. ***Concentration*** – maximize the amount of energy that “falls” on a target –ie., as in solar power
- 2. ***Illumination*** – control the distribution of light, i.e.,it is evenly spread of some areas and completely blocked in other areas - i.e., automobile lamps

- Variables: Total radiant flux, angular distribution of optical radiation, spatial distribution of optical radiation
- Collection efficiency

An Optimized non-imaging optics example

- **THE flux at the surface of the Sun, 6.3 kW cm^{-2}, falls off with the square of distance to a value of 137 mW cm^{-2} above the Earth's atmosphere, or typically 80–100 mW cm^{-2} at the ground. In principle, the second law of thermodynamics permits an optical device to concentrate the solar flux to obtain temperatures at the Earth's surface not exceeding the Sun's surface temperature. In practice, conventional means for flux concentration fall short of this maximum because imaging optical designs are inefficient at delivering maximum concentration. Non-imaging light-gathering devices can improve on focusing designs by a factor of four or more, and approach the thermodynamic limit. We have used a non-imaging design to concentrate terrestrial sunlight by a factor of 56,000, producing an irradiance that could exceed that of the solar surface. This opens up a variety of new applications for making use of solar energy.**

- Abstract from: *Nature* **339**, 198 - 200 (18 May 1989);


IR Energy
Secondary Mirror
Primary Mirror
NI Device
Fiber Bundle
Visible Light

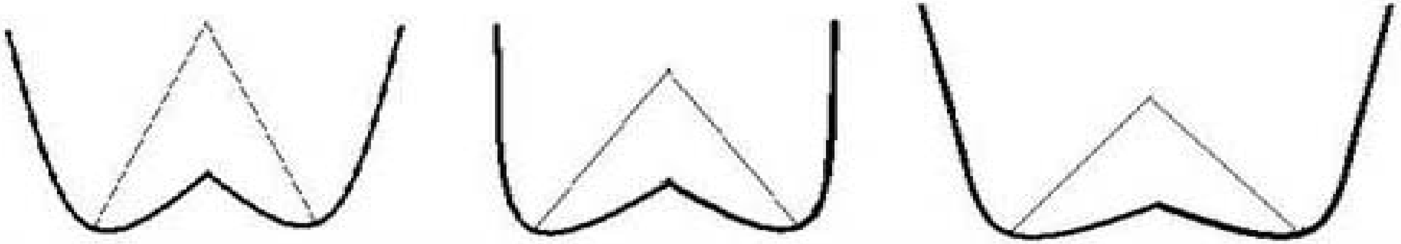


FIG 9-12 INWARD FACING COMPOUND PARABOLAS CAN BE DESIGNED TO HAVE OVERLAPING FOCAL POINTS!

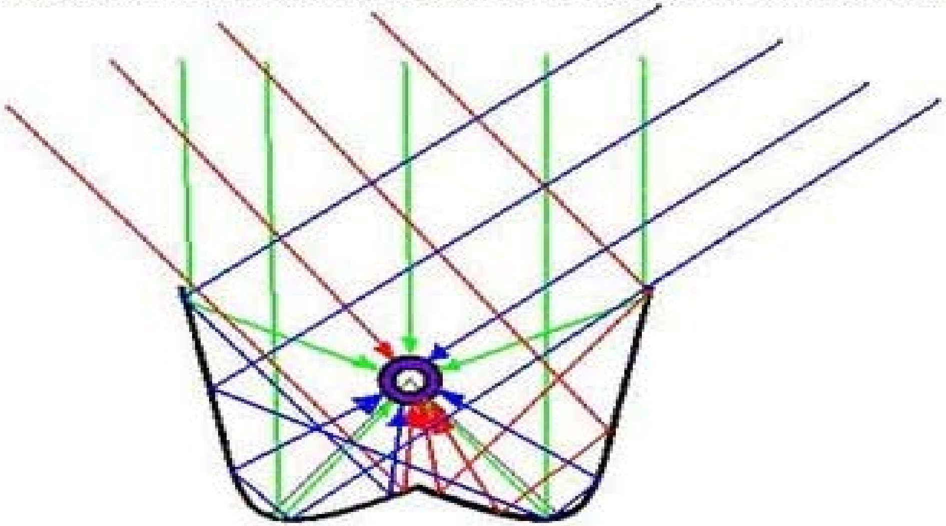
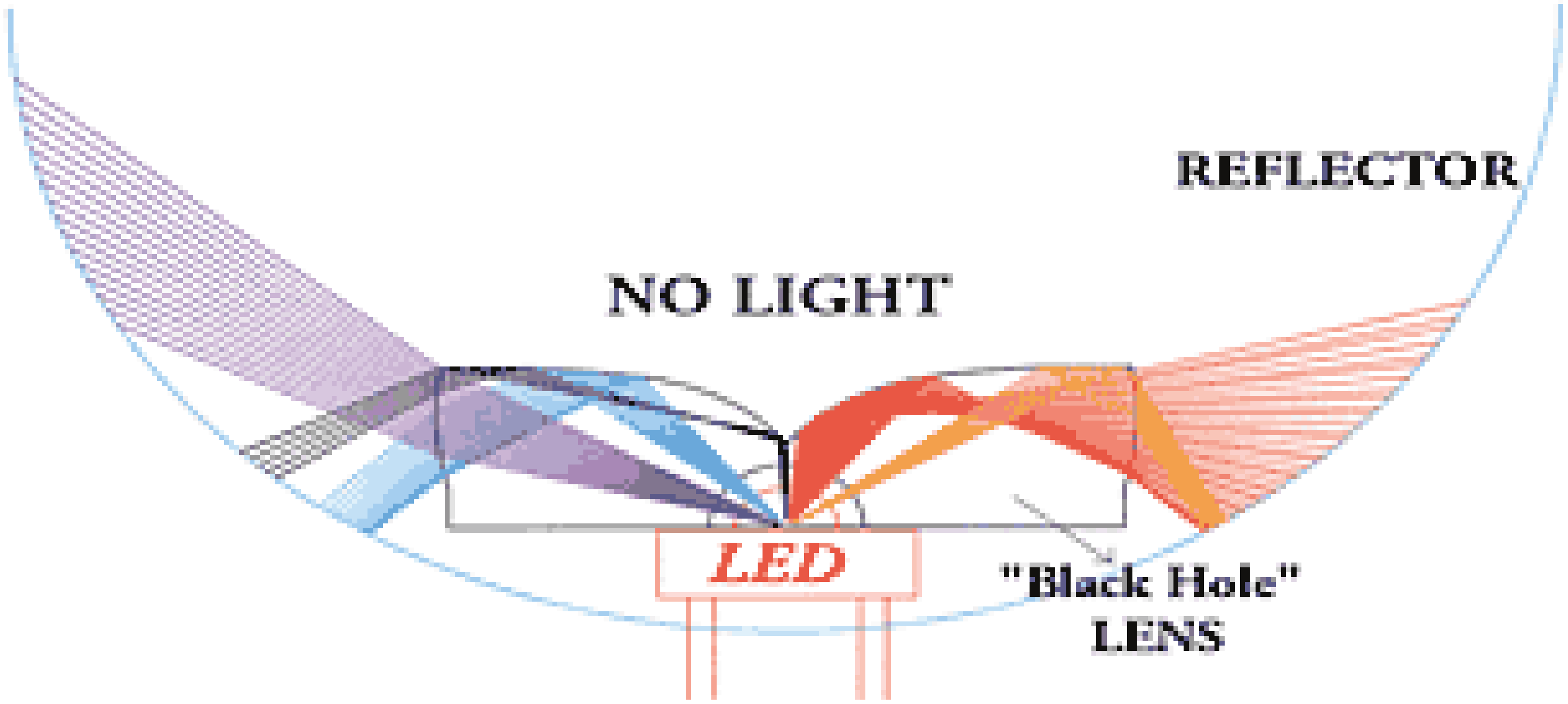


FIG 9-13 PROPERLY DESIGNED COMPOUND PARABOLAS CAN FOCUS SUNLIGHT FROM MANY AND VARIOUS ANGLES TO A COMMON FOCAL POINT. THUS A COMPOUND PARABOLA SOLAR COLLECTOR DOES NOT NEED TO TRACK THE SUN IN ORDER TO CONCENTRATE THE SUN'S ENERGY, TO MUCH HIGHER ENERGY DENSITY LEVELS.

Example of nonimaging optics designed to “channel” light from LED sideways

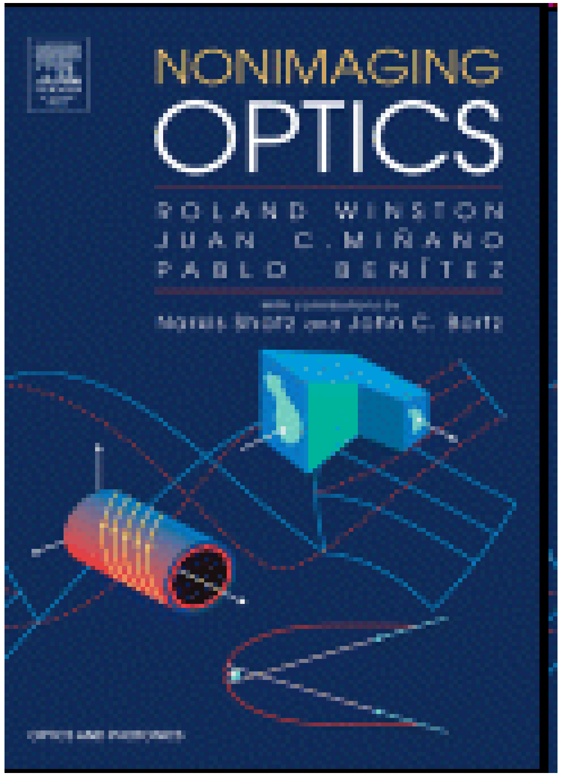


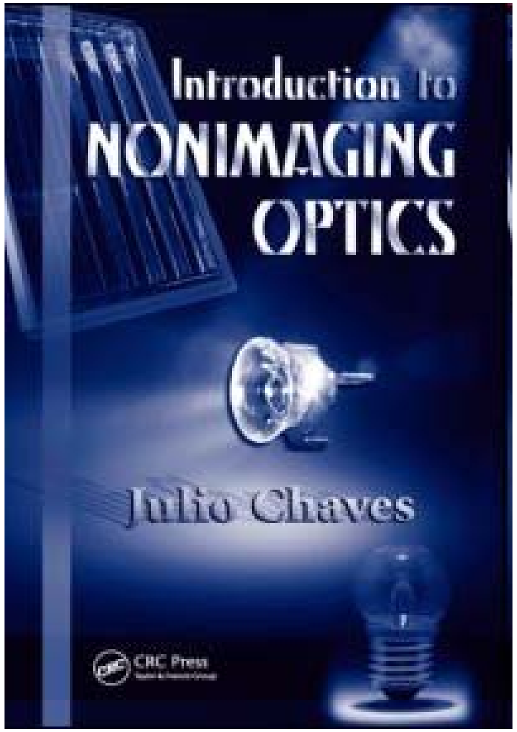
Brief History

- The field of non-imaging optics got its start in the United States in the 1930s in luminary design at lighting companies such as General Electric. The field did not really begin to take hold, however, until the 1970s when Roland Winston, (then at the Physics Department of the University of Chicago, and now at the University of California at Merced) and Walter Welford of the Physics Department of University of London (London, UK), began formulating the principles, theory, and mathematics of non-imaging optics.

Standard References

Also see: W.T.Welford, Optics of Nonimaging Concentrators: Light and Solar Energy, Academic Press, 1978





Light Collection: fundamental question

- Given a set of light rays with a specified angular divergence and distributed over an entrance aperture, how can we direct these rays efficiently onto the smallest possible exit aperture?
- Note: in traditional optical system design, we use Abbe sine law; in non-imaging optics something different

Some physics

- Review radiometry and photometry

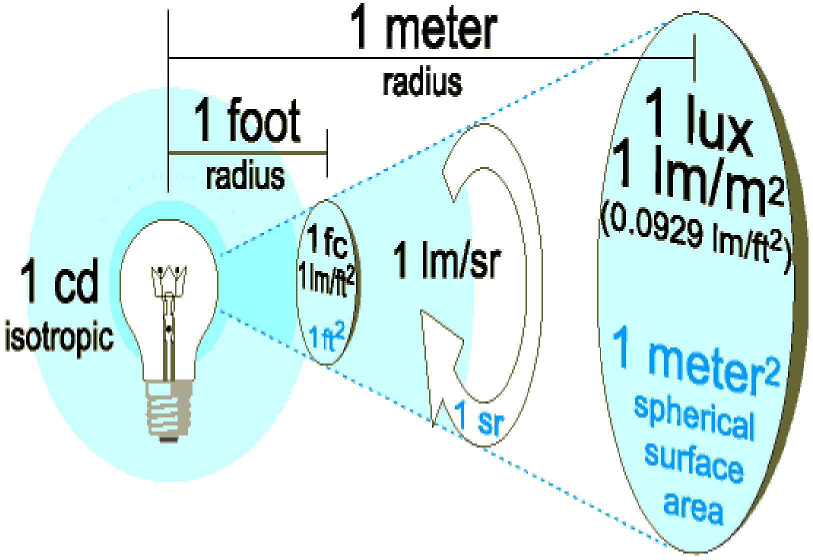


Fig. 7.4 Irradiance.

QUANTITY	**RADIOMETRIC**	**PHOTOMETRIC**
power	watt (W)	lumen (lm)
power per unit area	W/m^2	lm/m^2 = lux (lx)
power per unit solid angle	W/sr	lm/sr = candela (cd)
power per area per solid angle	W/m^2-sr	lm/m^2-sr = cd/m^2 = nit

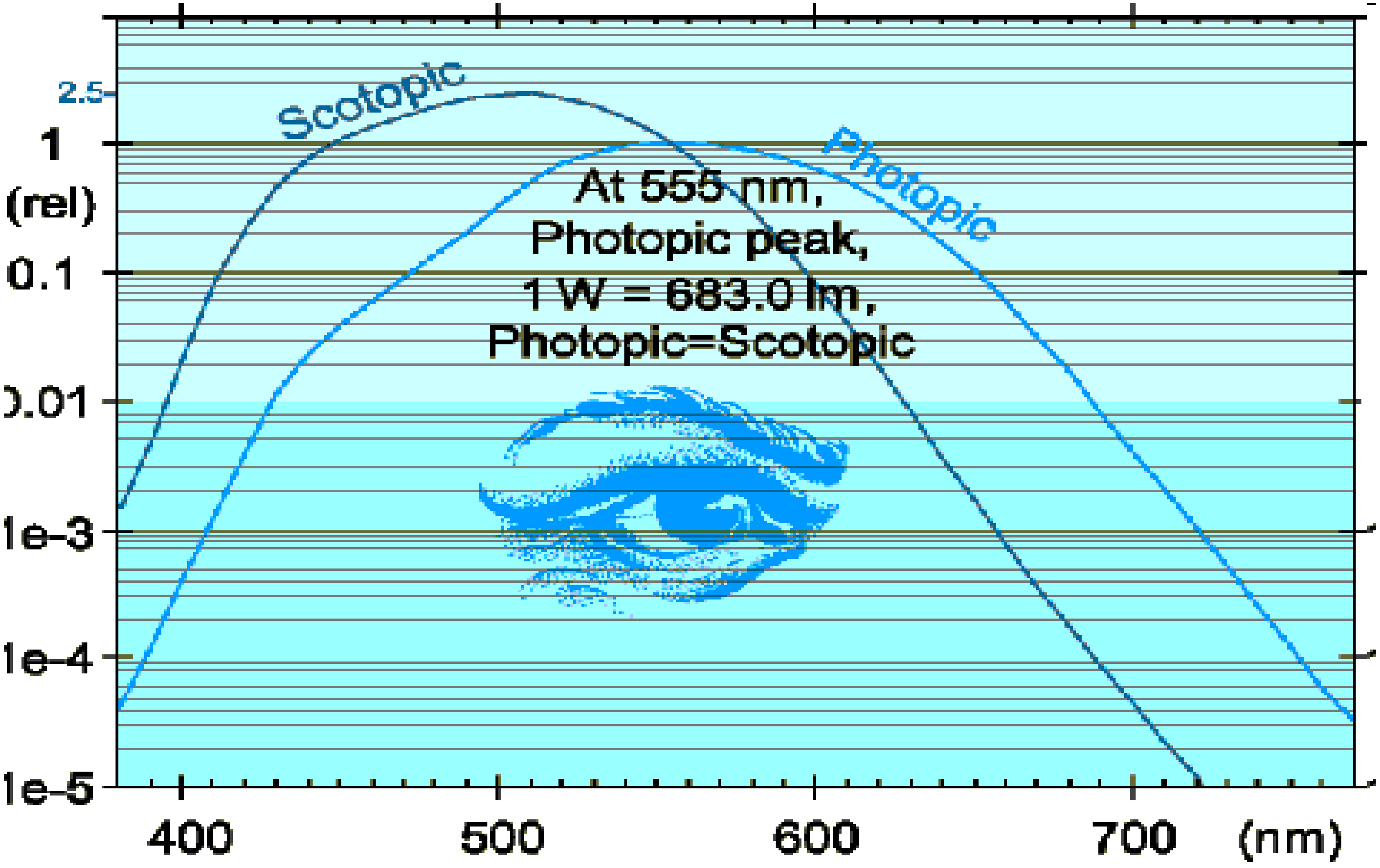


Fig. 2.3 CIE Photopic and Scotopic sensitivity curves.

The etendue

- Also known as acceptance, throughput, light-grasp, collecting power and A-Omega product
- Characterizes how spread out light is in area and angle.
- Is the area of the entrance pupil times the solid angle the source subtends as seen from the pupil.
- Is an invariant in any optical system (assuming no obstructions and ignore losses such as absorption and scattering). A perfect optical system produces an image with the same etendue as the source. This is related to the Lagrange invariant and the optical invariant.

The etendue and theoretical maximum concentration

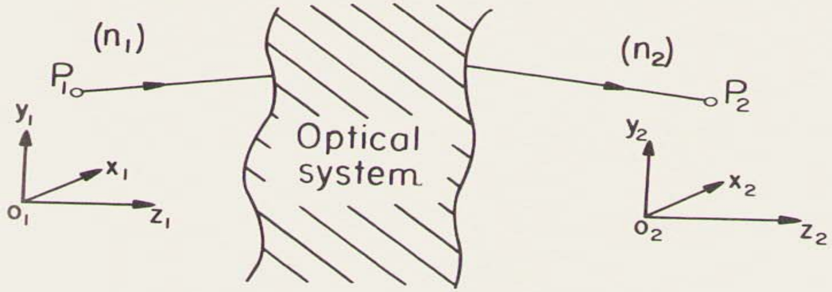


Fig.8.1. The étendue of an optical system

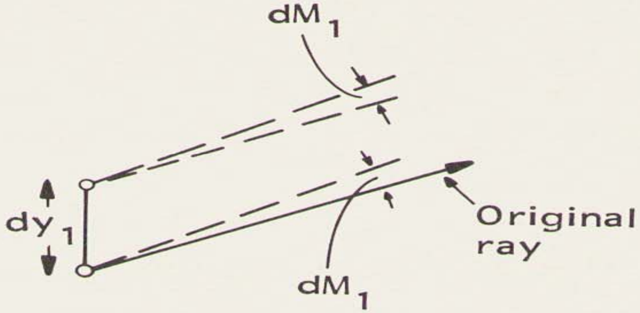


Fig.8.2. The étendue in the y_1 section

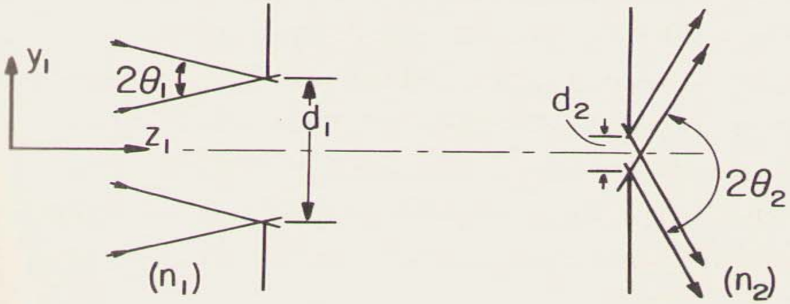


Fig.8.3. The theoretical maximum concentration ratio for a two-dimensional optical system

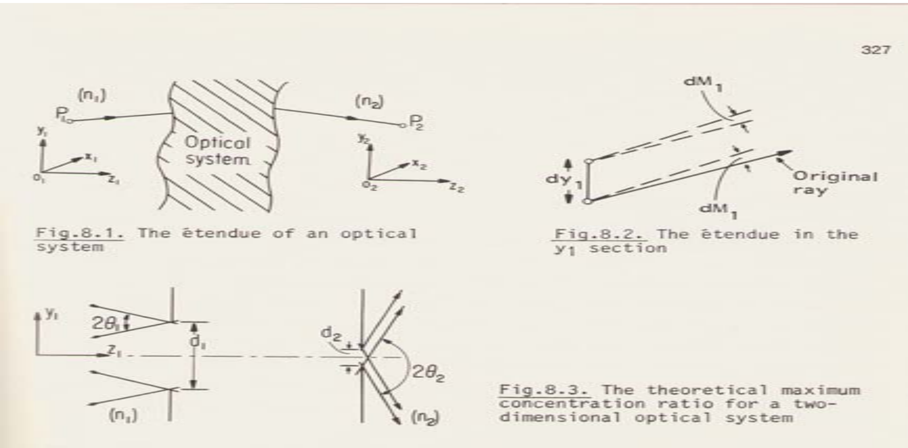


Fig.8.1. The ètendue of an optical system

Fig.8.2. The ètendue in the y_1 section

Fig.8.3. The theoretical maximum concentration ratio for a two-dimensional optical system

- Input ray coordinates: $P_1(x_1,y_1,z_1)$
- Output ray coordinates: $P_2(x_2,y_2,z_2)$
- Direction cosines: (L_1,M_1,N_1) and (L_2,M_2,N_2)
- Consider a small displacement to P_1 by dx_1 and dy_1; dL_1, dM_1; corresponding increments will occur in the output ray and direction

- The etendue is given by:$n^2dxdydLdM$
- And the invariant is:
- $n_2^2dx_2dy_2dL_2dM_2=n_1^2dx_1dy_1dL_1dM_1$

- The etendue can be defined as:

$$etendue = n^2 \iint \cos(\theta) dA d\Omega$$

- Where n is the refractive index and theta is the angle between the normal to the differential area dA and the centroid of the differential solid angle

- In phase space coordinates, the entendue is described by:

$$etendue = \iint dxdyndLndM = \iint dxdydpdq$$

- Where dL and dM are differential changes in the driection cosines (L,M,N) dxdy is the differential area and dpdq is the differential projected solid angle within the material of the index n.
- The term phase space is used to describe the area and solid angle over which the etendue integral is evaluated.

A note on luminance

- The luminance divided by the index of refraction squared is the ratio of the differential flux to the differential etendue

$$L/n^2 = d\Phi / \det endue$$

$$= d\Phi /(n^2 \cos(\theta) d\Omega$$

Using the etendue to calculate the theoretical maximum concentration of light collectors

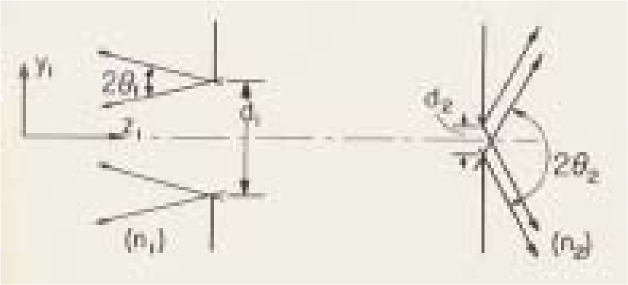
- For an ideal system, we can define the concentration in terms of the etendue. Since the etendue at the input and output aperture are the same, we can define the concentration (characterized by the ratio of the output area to the input area):

$$concentration_{2D} = n_{out} \sin\theta_{out} / n_{in} \sin\theta_{in}$$

$$concentration_{3D} = n_{out}^2 \sin^2\theta_{out} / n_{in}^2 \sin^2\theta_{in}$$

Concentration ratio

- Consider a two dimensional light collector. For any ray bundle that traverses the system
- $n_1 dy_1 dM_1 = n_2 dy_2 dM_2$
- Integrate over y and M,
- $2n_1 d_1 \sin\theta_1 = 2n_2 d_2 \sin\theta_2$
- C = d1/d2
- d2 is the dimension of the exit aperture large enough to permit any ray that reaches it to pass and θ2 is the largest angle of all emergent rays.
- Since the maximum of sin function is 1, we get the theoretical maximum value.

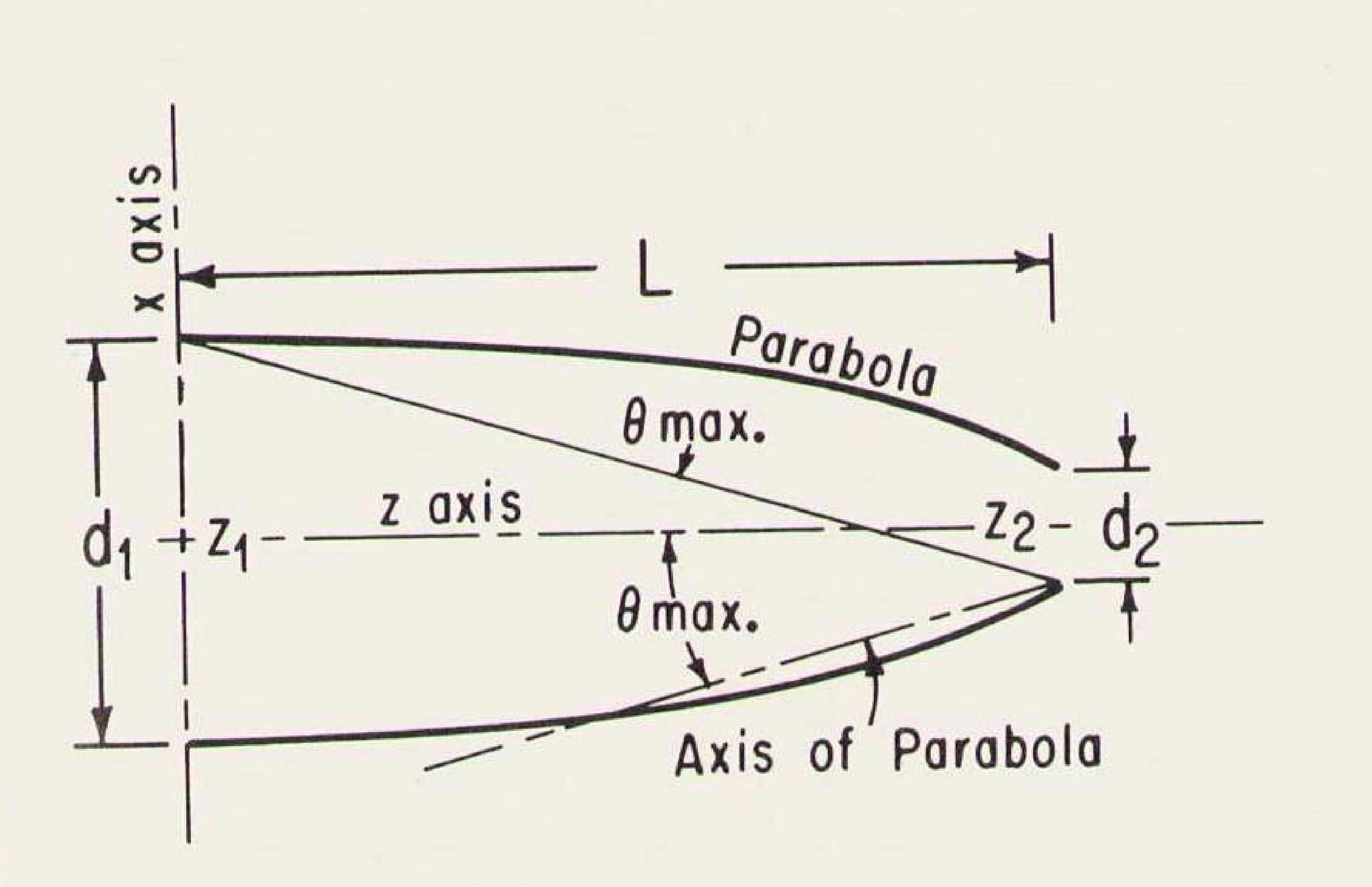


$$C_{\max} = n_2 / n_1 \sin\theta_{\max}$$

Ideal Light Collectors

- Any system that attains the theoretical maximum concentration ratio
- Imaging systems fall significantly short of ideal collector performance.
- Note: the concept arose in the context of optimization of Cerenkov radiation

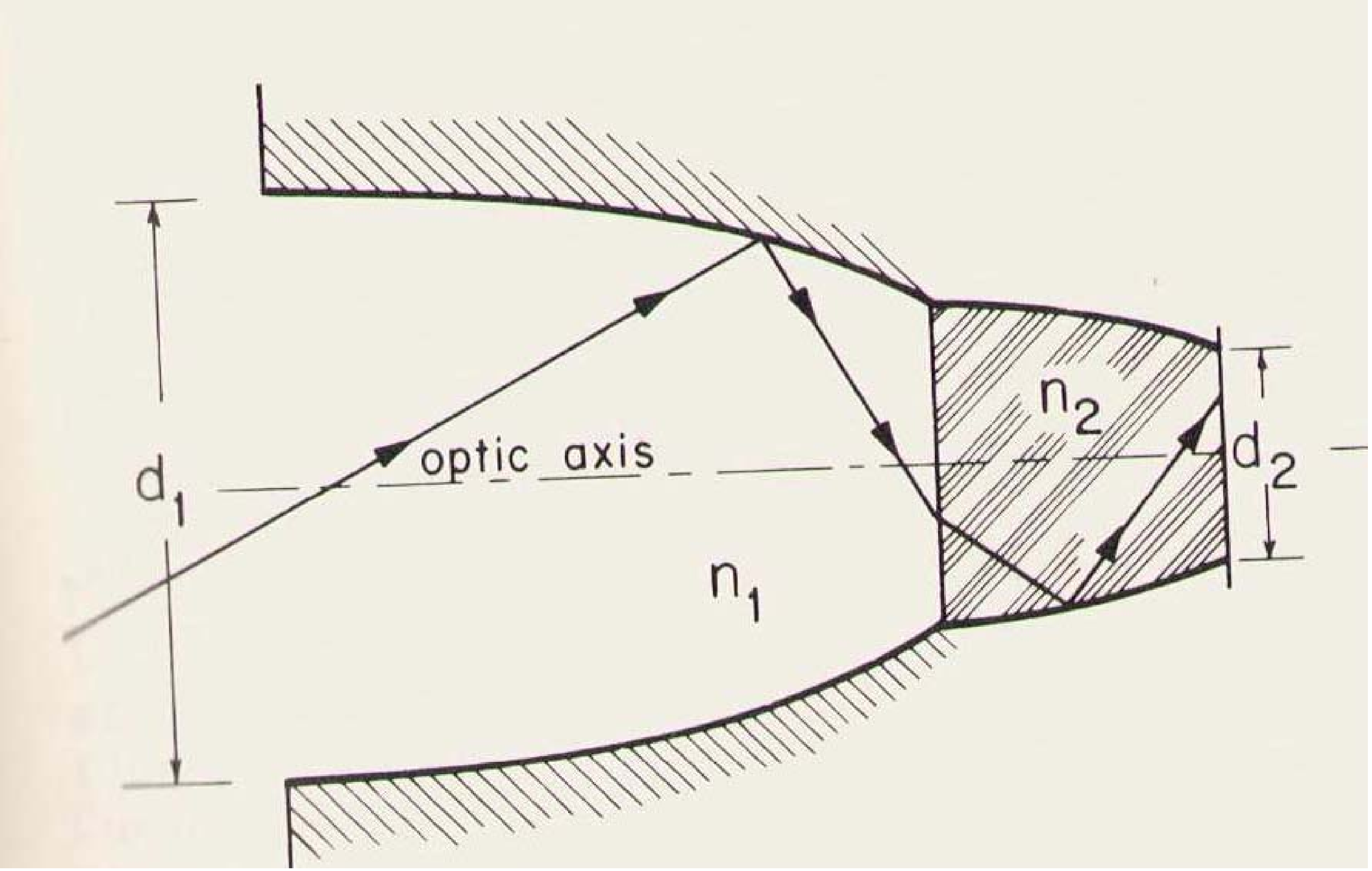
Ideal light collector: constant index of refraction



- All light rays incident on the entrance aperture d_1 at and angle $\theta<\theta_{max}$ are channeled through the exit aperture d_2 after undergoing one of more reflections. The rays emerge with a diffuse angular spread approaching 90 degrees to the optic axis. The flux concentration is related to the angular acceptance by:
- $C = 1/\sin^2\theta_{max}$
- The overall collector length L is given by:
- $L = (1/2)(d_1+d_2)\cot\theta_{max}$

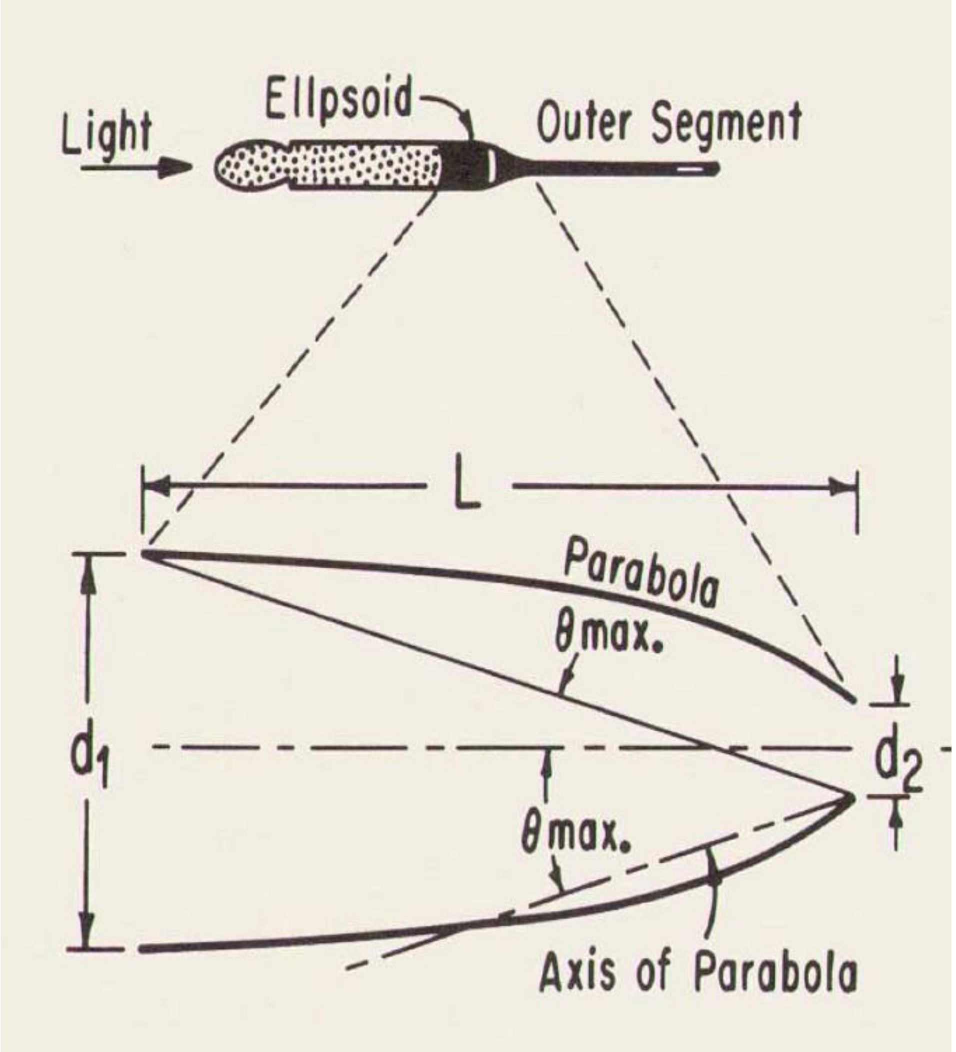
- All stray light incident at angles greater than theta max will be excluded.

Ideal light collector; distinct indices of refraction; $n_2 > n_1$



- Two collectors in tandem. The first is immersed in a medium of index n_1 is designed for a value of θ_{max} appropriate to the angular acceptance at the entrance aperture d_1. The second immersed in a medium of index n_2 is designed for a value of $\theta_{max} = \sin^{-1}(n_1/n_2)$, the critical angle. The overall flux concentration is:
- $C= (n_2/n_1)^2(1/\sin^2\theta_{max})$

An example of light collector from biology – cone photoreceptor cells from the human retina



- Striking similarity between ideal light collector and structure of cones. Consider the highly tapered cone photoreceptor ellipsoid portion.
- Theta max is calculated to be 13 degrees; This value is compatible with the numerical aperture of the receptor and is consistent with the maximum angle of incidence allowed by limit of the human exit pupil. d1 and d2 correspond to the diameters of the inner and outer segments; length of the ellipsoid corresponds to the collector length.

Lambertians and clipped lambertians

- If luminance of radiation source does not vary with angle or position, it is called a Lambertian source.
- If we can assume a constant L/n^2 for a given problem, then we can use the etendue to understand spatial and angular distributions of the radiation.
- A clipped Lambertian is one where the source of flux is lambertian only over a finite range of angles. Is similar to apodization. Example: source at infinity and flux at a planar aperture.
- The output of a fiber optic cable is often assumed to have a spatially apodized lambertian distribution.

- The etendue of a clipped Lambertian is :

For a infinite strip of width 2R, with a clipped lambertian defined betwee +/- θ_{max} relative to the normal, = $n(2R)(2 \sin \theta_{max})$ (assumes the distribution in the third dimension is infinite)

For a lambertian disk with the half cone angle θ_{max} the etendue is: $n^2 \pi R^2 \sin^2 \theta_{max}$

Some components

- Question: how do you collect flux when large angles are involved?
- Use:
- Lenses, including Fresnel Lenses
- Conic reflectors
- Used also in imaging optics, but are not a requirement for nonimaging.

Spherical lenses

- Use aplanatic points of a spherical lens to convert wide angles to smaller angles.
- Obey Abbe sine condition
- How can a spherical surface be aplanatic?
- 1. image formed at surface as in a field lens
- 2.Object and image located at center of curvature
- 3. Object and image located on radii that are rn/n’ and rn’/n away from center of curvature
- Case # 3 are hyperhemispheric lenses and are often used in high power microscope objectives, LED packages, IR detectors, etc.

- Aspheric lenses are also used – condensers in projection systems, auto headlamps, overhead projectors, etc. – act as conic collimators

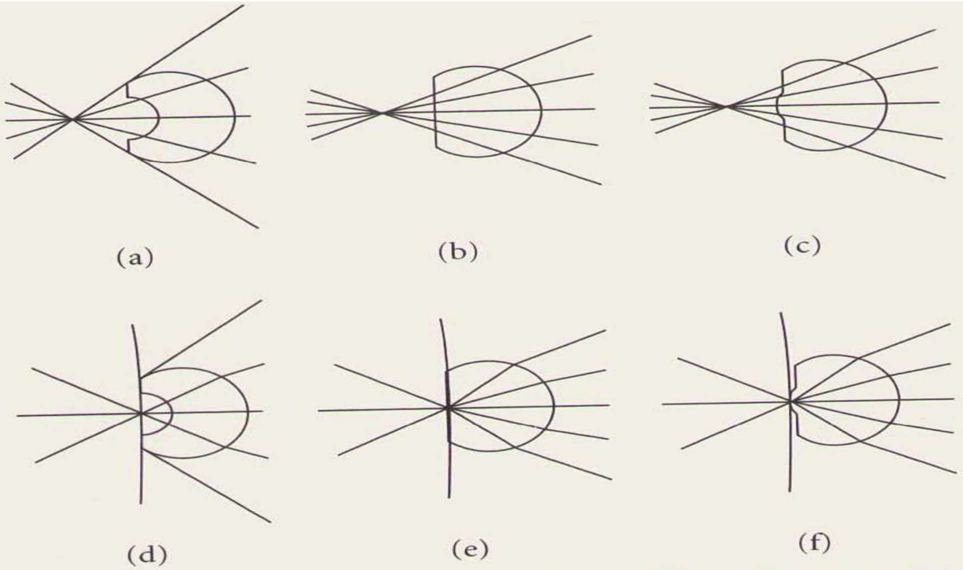


FIGURE 4 Several aplanats used to concentrate a virtual source. (*a–c*) The rays superimposed on top of the aplanats. (*d–f*) the ray trace. (*d*) A meniscus lens with hyperhemisphic outer surface and a spherical surface centered about the high concentration point. (*e*) A hyperhemisphere. (*f*) A hyperhemisphere with curved output surface.

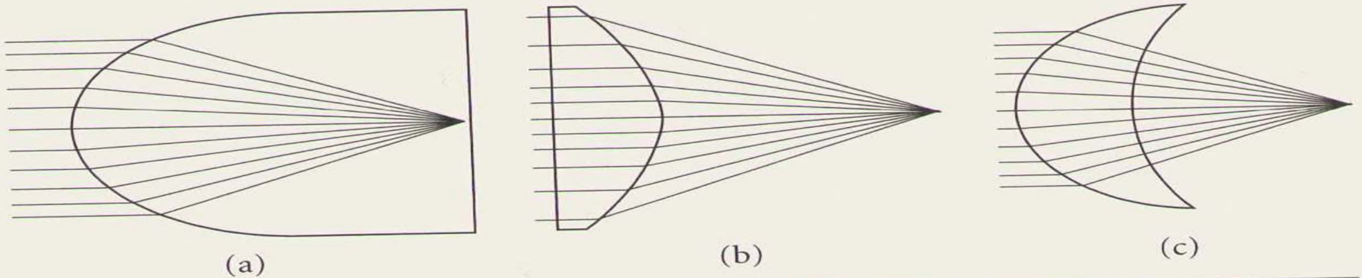


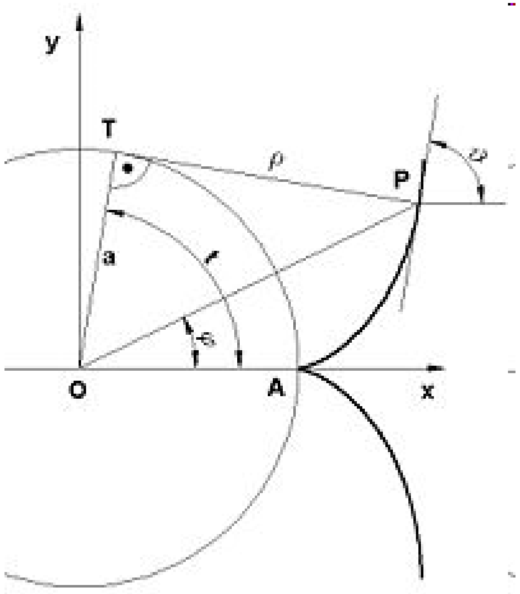
FIGURE 5 Conic collimators. (*a*) $e = 1/n$ and $f = Rn/(n-1)$. (*b*) $e = n$ and $f = R/(n-1)$. (*c*) $e = 1/n$ with other surface being spherical. e = eccentricity, n = index of refraction, $k = -e^2$.

Conical reflectors

- Reflectors are made from conic sections
- Provide spherical aberration free transfer
- However, there can be coma defects.
- Standard conic reflectors map center of sphere to a single point. Sometime it is necessary to map the edge of sphere to single point. These are called macrofocal reflectors or extinction reflectors

Conic reflectors

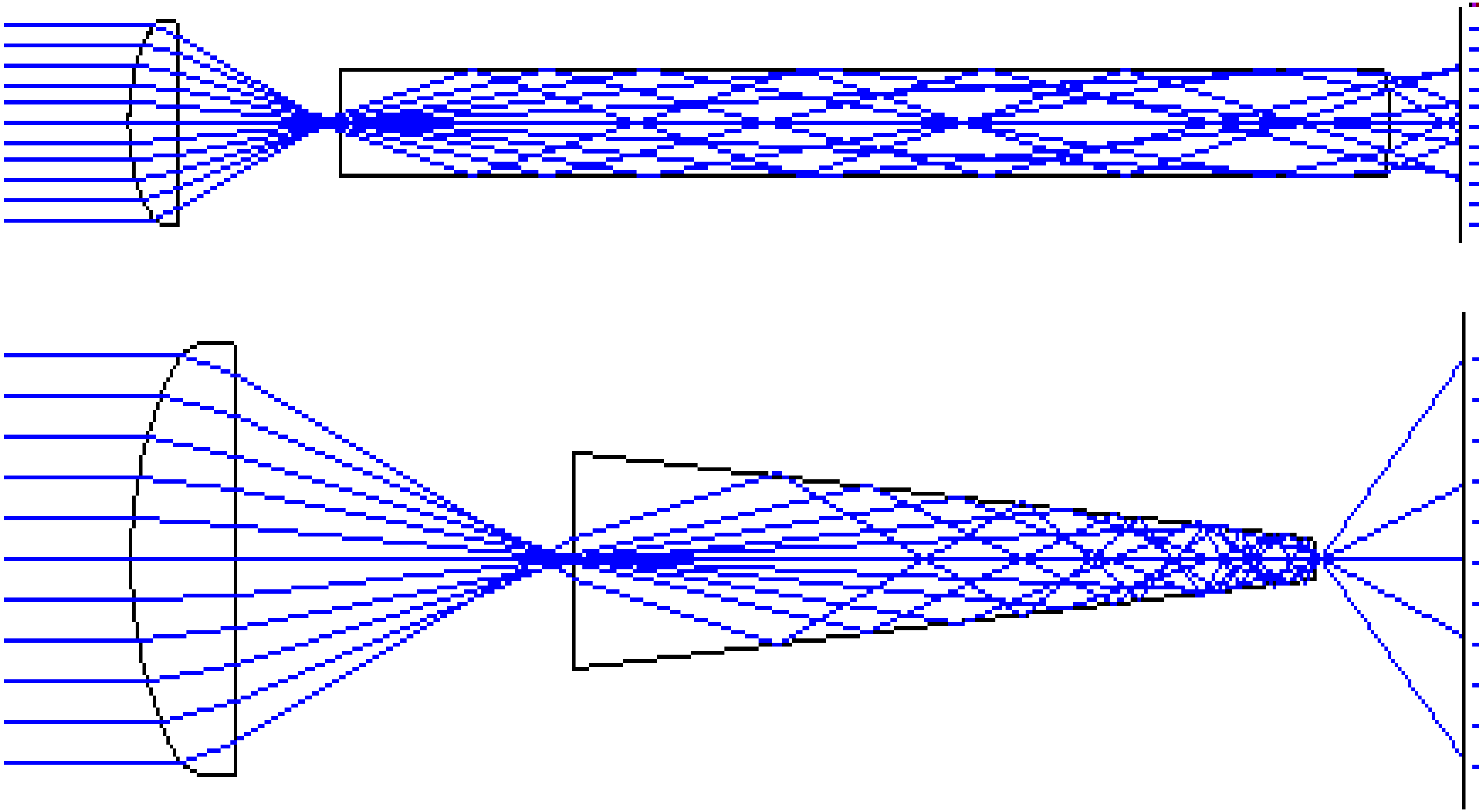
- Involute: used in many nonimaging systems. Sends tangential rays from the source back onto themselves.
- Equation:
- $x = r(\sin\theta - \theta\cos\theta)$
- $y = -r(\cos\theta + \theta\sin\theta)$



Concentration: basic elements

- 1. light pipes – efficient method; usually total internal reflection at lightpipe surface is used to provide lossless reflection.
- Prefer tapered lightpipes – size changes from input to output over the length – change in area produces change in angles. -

Light Pipes



- Light pipes allow sunlight to be transmitted into a building to illuminate interior spaces. A light pipe consists of a collector, a tube, and an emitter that is usually fitted with a diffuser to improve light quality . Standard light pipes are coated internally with reflective material, which allows the pipes to transmit sunlight using internal reflection. This allows installation in buildings with large roof-ceiling separations that are less amenable to skylights. Integration of light pipes, especially in conjunction with artificial lights and dimmers controlled by sensors, can significantly reduce the amount of energy used for lighting. However, current light pipe designs do have some disadvantages. They are less effective in cloudy weather as clouds obstruct incident sunlight from the rooftop collector. Additionally, light pipes can still allow some heat transfer as well as condensation, which can increase the heating or cooling load for the space.
- The longer the pipe is, and the more bends that it has, the more times the light is internally reflected before reaching its intended target. Each time the light is reflected within the light pipe, the transmitted intensity decreases. One way to counter this effect is by increasing the width of the light pipe, so the light travels further down the pipe between reflections. But even with a very reflective surface, unless the sun is aligned with the axis of the light pipe to reduce the number of reflections, intensity and efficiency will be diminished. Newer, more complex light pipe designs include a “sun-tracking” feature to address this issue, allowing the collector to effectively follow the direction of incident sunlight and thus increase efficiency. The drawback is that the added complexity to increase efficiency results in more expensive designs.

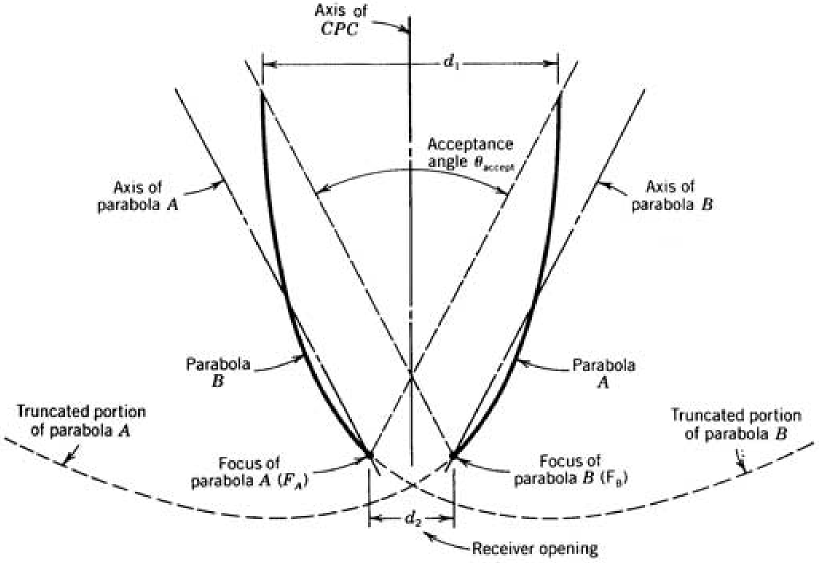
A solar light pipe

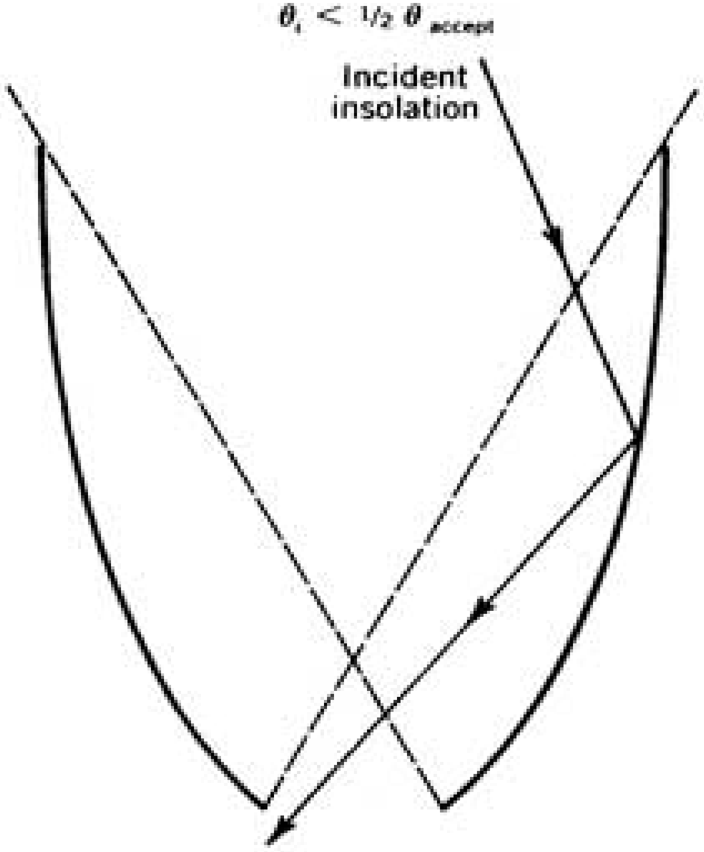
Photo: Raimund Koch, New York

Compound parabolic concentrator

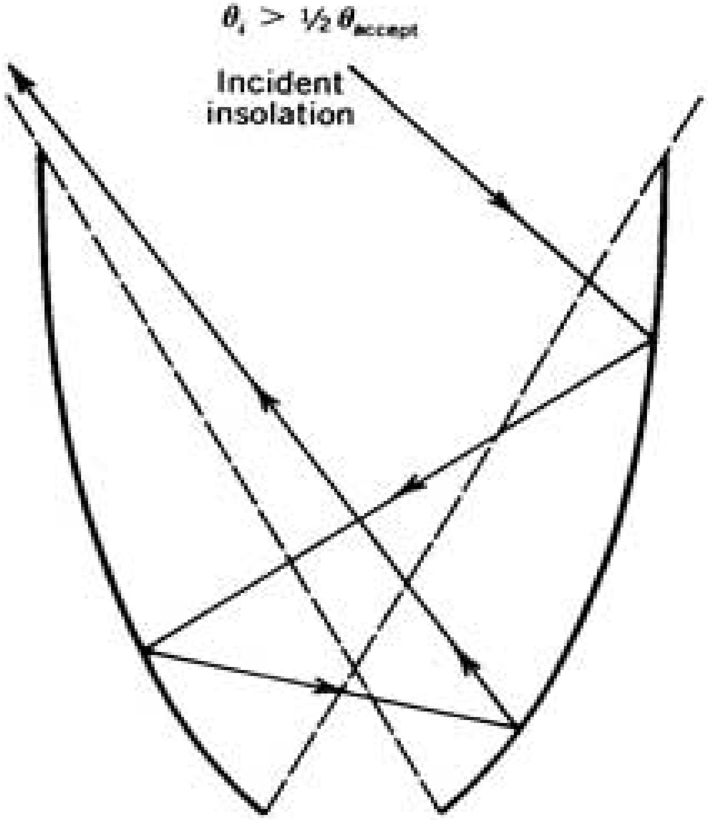
- Get light from a clipped lambertian source and concentrate.The two parabolic curves are not on the same optic axis. The name, compound parabolic concentrator, derives from the fact that the CPC is comprised of two parabolic mirror segments with different focal points as indicated. The focal point for parabola *A (FA)* lies on parabola *B,* whereas the focal point of parabola *B (FB)* lies on parabola *A*. The two parabolic surfaces are

  symmetrical with respect to reflection through the axis of the CPC.




$\theta_i < 1/2\, \theta_{accept}$
Incident insolation

(a)


$\theta_i > 1/2\, \theta_{accept}$
Incident insolation

(b)

- Length of CPC is minimized for the case where the input port can see the exit port.
- Major application: LCDs, illumination and solar collection

CEC

- Source of radiation is close (finite) distance from input port of concentrator, use CEC; except reflector surface is elliptical; if source of radiation is virtual, then reflector curvature is hyperbolic.
- There are other types of concentrators: multiple surface concentrators – usually have a condensing lens before the concentrator or have the optical surface of the primary and optical surface of concentrator designed together.
- Can also Mirrors, etc.

- The End??