光學系統設計
(Optical System Designs – 11A)

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課程總目錄

幾何光學集要: 完美成像與高斯光學、像差理論估算與案例分析	第一週
物理光學集要: 繞射、點分散函數、MTF、偏振、高斯光束、部份同調與散射	第二週
鏡組最佳化分析及簡例說明	第三週
公差容忍度分析與光學測試及簡例說明	第四週
非球面鏡頭理論、設計與案例說明	第五週
投影鏡頭理論、設計與案例說明	第六週
變焦鏡頭理論、系統設計與案例說明	第七週
相機鏡頭設計與案例說明	第八週
鏡頭設計、資料庫與專利深論	第九週
非傳統鏡頭系統之設計與案例說明	第十週

課程總目錄（續）

照明基礎理論與光通量(throughtput)估算	第十一週
色彩學（colorimetry）與應用	第十二週
照明光源與典型照明工法（schemes）	第十三週
照明光學設計法I:反射片（reflectors）	第十四週
照明光學設計法II: Condenser and lenslet arrays	第十五週
照明光學設計法III:光管（lightpipe）	第十六週
照明光學設計法IV: Fresnel lenses	第十七週
照明應用實例與解析	第十八週

Course motivation

- This part of course is to provide basic theory and training of illumination design and analysis

Smurfit before and after using Reflex lamps

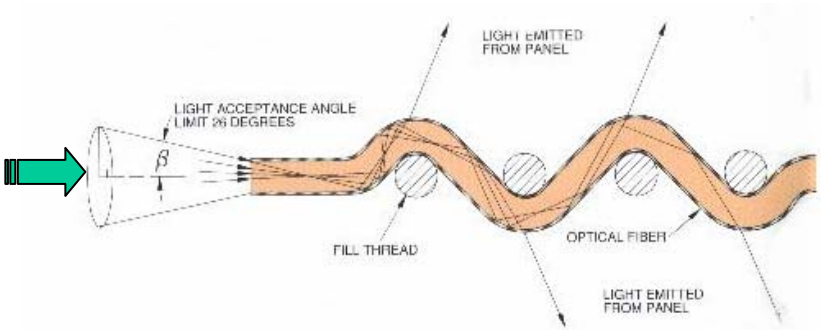
Why illumination?

- We need illumination for
  - Better seeing
    - For eye viewing
    - For medical investigation (microscope)
  - Fancy show (light show)
  - Clear Indication
  - Illuminator for non-self-luminous display (LCD/DMD)
- Maybe, much more important is for energy saving
  - Better illumination design saves energy
  - Better illumination analysis helps design

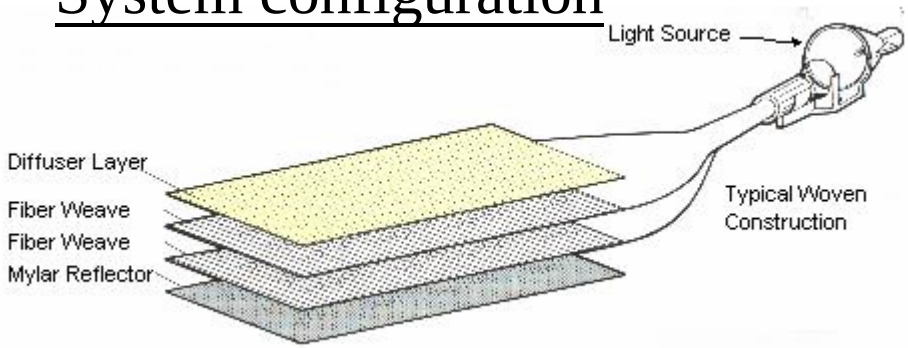
- In the following, I only show two examples which may be not so familiar to you
  - It is hoping that by these two examples, you may appreciate the other important applications of illumination which is also of commercial values
    - Illumination is NOT just limited to display

Lumitex (Poly-Optical) fiber optical illumination

Basic principle



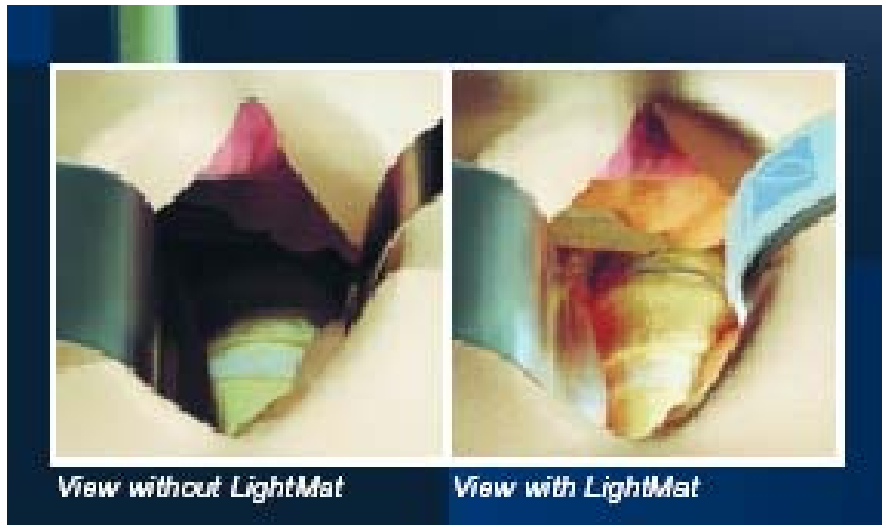
System configuration



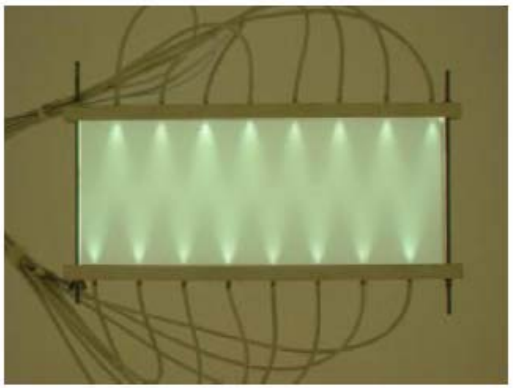
Applications

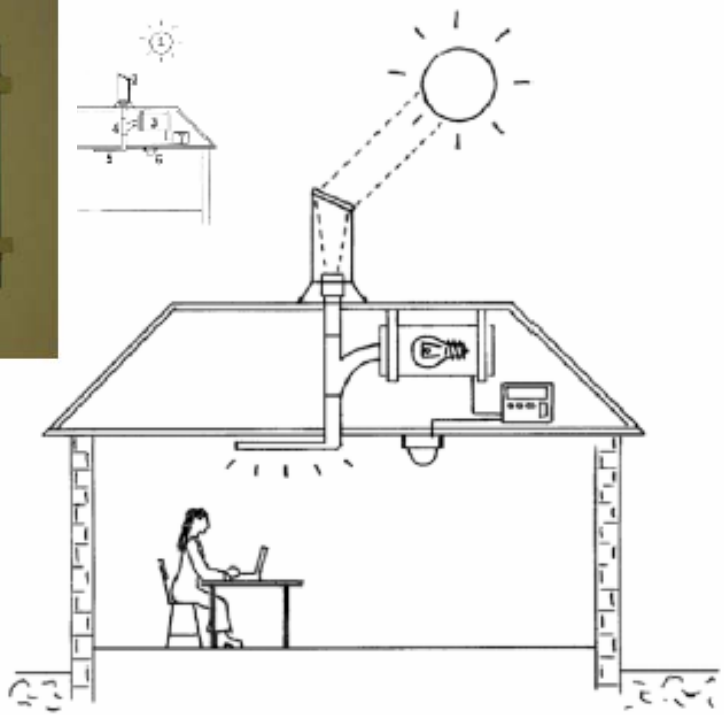
BiliBlanket Phototherapy System

LightMat Surgical Light



Sunlight collector and room internal illumination





SUNLIGHT, FIBRES AND LIQUID OPTICS: THE UFO PROJECT

M. Wilson et al.

UFO: universal fiber optics
http://www.unl.ac.uk/LEARN/port/2000/ufo-pub/index.html

第十一一講大綱

- Before starting – something important should be addressed
  - Specifications
- The difference between imaging and nonimaging optics
- From searchlight to edge ray principle
- Throughput estimate
- From single ray to ray bundle
  - Lagrange invariant and etendue
- Radiometry and photometry
- More on illumination design
- Homework

Before starting,

Something important that should be addressed

1. Optical design is highly application-driven
   - to clarify the targets/goals of design is most important
2. Optical design is an engineering issue
   - Specification is most critical to success
     - It is important to have a list of performance request
3. Optical design is generally not a stand-alone object
   - Interface issues have to be included
4. Optical design has to be practical
   - Tolerance has to be considered

What are "Requests":
Specification and Performance

- Commonly, there are two different kinds of requests before design
  - Specification
  - Performance
  - These two items may be mixed
    - In general,
      - Specifications specify system
        - » Physical dimensions, weight, and so on
      - Performances specify optical quality

However, you can't find engineer's specification in public.
So, what we can see is …???

Example: Sam Sung's LCD TV

液晶電視

LTM1525

全球最薄的液晶電視

厚度僅2公分、重量僅2.8公斤的超輕薄機身，及極簡時尚的造型，是您兼顧畫質與生活品味的最佳選擇！

顯示	螢幕尺寸	15"
	外觀比例	4 : 3
	亮度（cd/m2）	450
	對比	400 : 1
	可視角（H/V）	150° / 120°
	解析度	1280 x 768

畫面	可視角（H/V）	150° / 120°
	解析度	1280 x 768
	數位電視格式相容(480i/480p/720p/1080i)	O
	循序掃瞄	O
	色調控制	O
	數位梳形濾波器	O(3D)
音效	輸出功率（RMS）	3W x 2
	杜比音效	虛擬杜比
	環繞音效	O
	各聲道立體音效（MTS）	O
	音效模式	標準/音樂/電影/演講/自訂
特色	內建選台器	O
	OSG（螢幕圖示操作）	O
	子母畫面（PIP）	1T
	畫面靜止功能	O
	睡眠計時器/開/關計時器	O/O
	自動電源關閉	O
端子	S端子	O
	AV端子	O
	SD色差輸入(480i)	O
	HD色差輸入(480p/720p/1080i)	O
	PC輸入	D-sub 15 pin
	PC音訊	O
	耳機（輸出）	O
電源	開機消耗功率	50W
	待機消耗功率	<1.5W
尺寸	主機(寬x高x深），不含底座	346 x 350 x 26公釐
	主機(寬x高x深），含底座	346 x 365 x 159公釐
重量	主機，不含底座	2.9公斤

自訂/標準/自然/柔和/電影

3W x 2

虛擬杜比

You only can find some simple items here

Another Example:

Lumitex's backlight module

- Fiber optics

High Brightness – You get the brightness of electroluminescence (EL) – 30 Ft-L and more in many applications – without the degradation in brightness commonly associated with EL.

Longer Life – Durable fiber optic panel never needs replacement. Remote light source offers 10,000 to 100,000 hours of useful life, and replacement is simple and easy.

Lower Power – Requires less power than EL, CCFL, or LED Array – as low as 10-20 mA at 2 VDC – and no inverter. Lumitex fiber optic backlighting is so effective in uniformly spreading out the light from a single LED that it can cover up to approx. 4 inches (100 mm) in width and 10 inches (250 mm) in length. A single LED is typically driven at 20-30 mA (and can be driven at as low as 10 mA) and 2 to 4 VDC.

Compact Size – Panels are thin, as low as .013 inches (0.33 mm), and remote light sources are smaller than many EL or CCFL inverters.

Heat/EMI Free – Fiber optic panel generates no heat or EMI.

Durable – Optical fibers are not affected by extremes in humidity (0% to 100%) or temperature (-40° to +85°C). Shock, vibration and hazardous environments do not pose a problem.

Thin, Low Profile – Typical construction is 0.068 inches thick (1.7 mm). Thinner constructions are available.

Range of Colors – Standard LED colors include green, white, blue, red, amber and yellow-green.

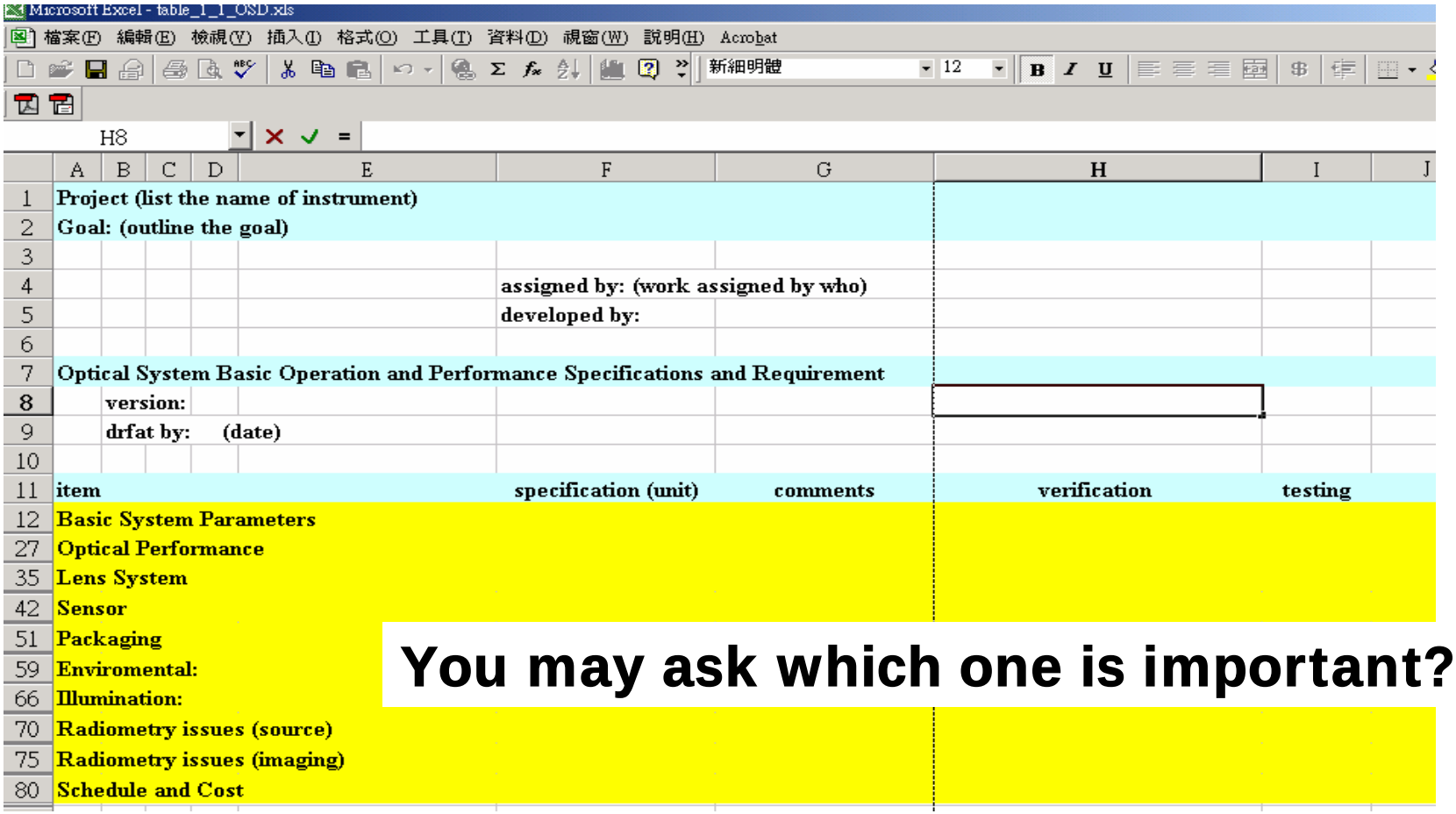
You only can find some simple items here

Design specification

- Back to engineer's side, …
  - Specifications have to be different at different levels
    - In lab,
      - Engineers has their specifications
      - The specification should be complete
        - » tightest
    - In market (to buyer)
      - The specification should be clear and simple
      - Specification is, in general, with only a few items

Example of performance list

- There is no definitive format for the list.

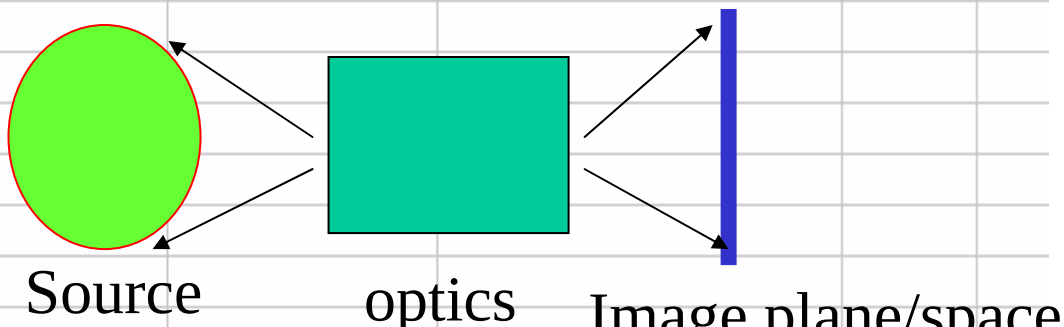


You may ask which one is important?

Specification list: items on system

11	item	specification (unit)	comments	verification	testing
12	**Basic System Parameters**				
13	object distance				
14	image distance				
15	object to image total track				
16	focal length				
17	f/number (or numerical aperture)				
18	entrance pupil diameter				
19	wavelength band				
20	wavelength weight for 3 to 5 λ				
21	full field of view				
22	magnification (if finite conjugate)				
23	zoom ratio (if zoom system)				
24	image surface size and shape				
25	detector type				
26					

1. Review from source to image
2. Specify in module
3. Identify the interfaces



Cont'd -1

items on performance and lens system

11	item	specification (unit)	comments	verification	testing
12	**Basic System Parameters**				
27	**Optical Performance**				
28	transmission				
29	relative illumination (vignetting)				
30	encirled energy				
31	MTF as a function of line pars/mm				
32	distoration				
33	field curvature				
34					
35	**Lens System**				
36	number of elements				
37	materials (glass versus plastic)				
38	aspheric surfaces				
39	diffractive surfaces				
40	coatings				
41					

1. Energy (throughput)
2. Quality

1. Materials
2. Source available
3. Technology available

Cont'd -2

items on sensor and packaging

	item	specification (unit)	comments	verification	testing
11					
12	**Basic System Parameters**				
27	**Optical Performance**				
35	**Lens System**				
42	**Sensor**				
43	sensor type				
44	full diagonal				
45	number of pixels (horizontal)				
46	number of pixels (vertical)				
47	pixel pitch (horizontal)				
48	pixel pitch (vertical)				
49	Nyquest frequency at sensor, line pairs/mm				
50					
51	**Packaging**				
52	object to image total track				
53	entrance and exit pupil location and szie				
54	back focal distance				
55	maximum diameter				
56	maximum length				
57	weight				
58					

1. Response
2. Acceptance angle

1. Alignment
2. (how to test with first-order optics)

Cont'd -3

items on environmental and illumination

	item	specification (unit)	comments	verification	testing
11					
12	**Basic System Parameters**				
27	**Optical Performance**				
35	**Lens System**				
42	**Sensor**				
51	**Packaging**				
59	**Enviromental:**				
60	thermal soak range to perform over				
61	therma; soak range to survive over				
62	vibration				
63	shock				
64	Other (condensation, humidity, sealing, etc.)				
65					
66	**Illumination:**				
67	source type				
68	power (in watts)				
69					

1. Tolerance analysis
2. Temperature variation

Discuss later

Cont'd -4

items on radiometry and schedule/cost

	item	specification (unit)	comments	verification	testing
11					
12	**Basic System Parameters**				
27	**Optical Performance**				
35	**Lens System**				
42	**Sensor**				
51	**Packaging**				
59	**Enviromental:**				
66	**Illumination:**				
70	**Radiometry issues (source)**				
71	relative illumination				
72	illumination method				
73	veiling glare and ghost images				
74					
75	**Radiometry issues (imaging)**				
76	transmission				
77	relative illumination				
78	stray light attentuation				
79					
80	**Schedule and Cost**				
81	number of systems required				
82	initial delivery data				
83	target cost goal				
84					

Discuss later

Discuss later

Consider this always

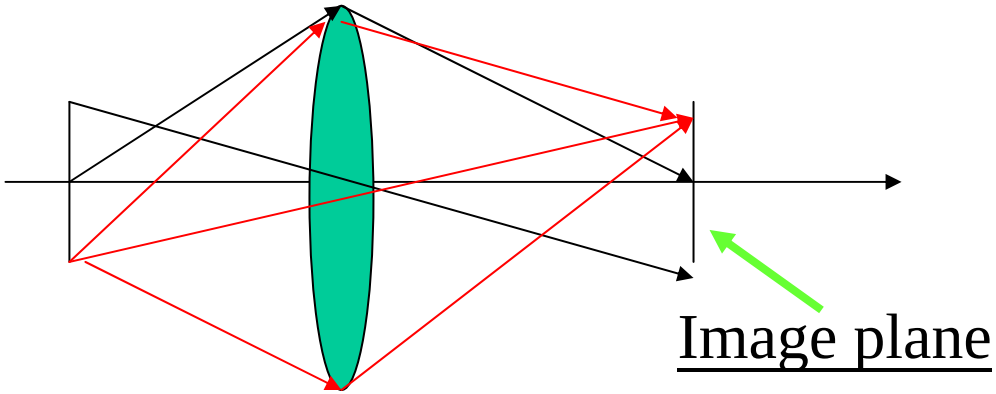
- Illumination is better to categorized as “non-imaging optics”
  - Although many imaging optics can be utilized for illumination

The differences between imaging and non-imaging optics

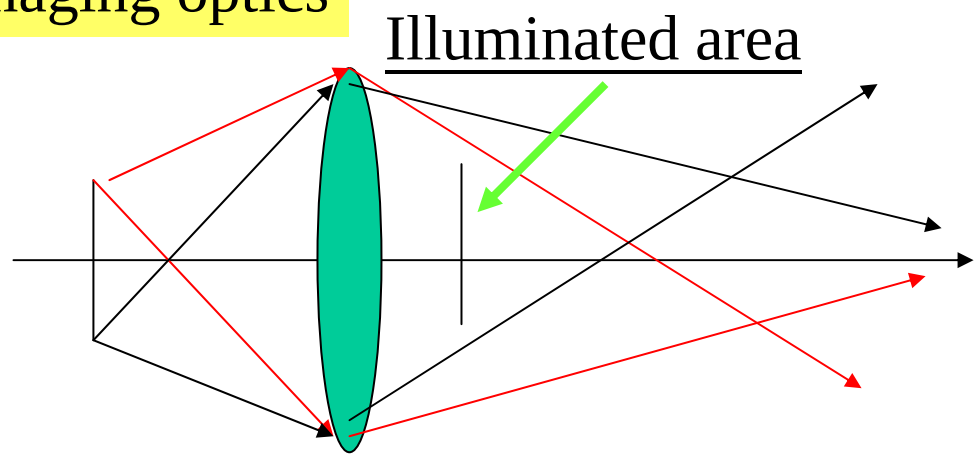
	Imaging optics	Non-imaging optics
Basic concerns	Imaging quality (how to achieve perfect imaging is first priority)	➢Irradiance (light distribution in illuminated area): (1) uniform, (2) reshaping, (3) focusing ➢Throughput manipulation (optical energy relay)
Optics that utilized	Mostly refractive element Handling specular rays (essentially follow pure Snell's law)	Reflective element is most useful Lightpipes that handle ray bundle are crucial Handling non-specular rays (scattering) bring more advantages Fresnel loss should be included in consideration
Input	Planar object for imaging first, though field depth is also concerned	A variety of sources with finite size and irregular emitting distribution
Output	Magnification fitted to sensor Relative illumination is crucial for imaging quality	Fitted to the illuminated area Light distribution per the request of specification

Schematic diagram of ray tracing

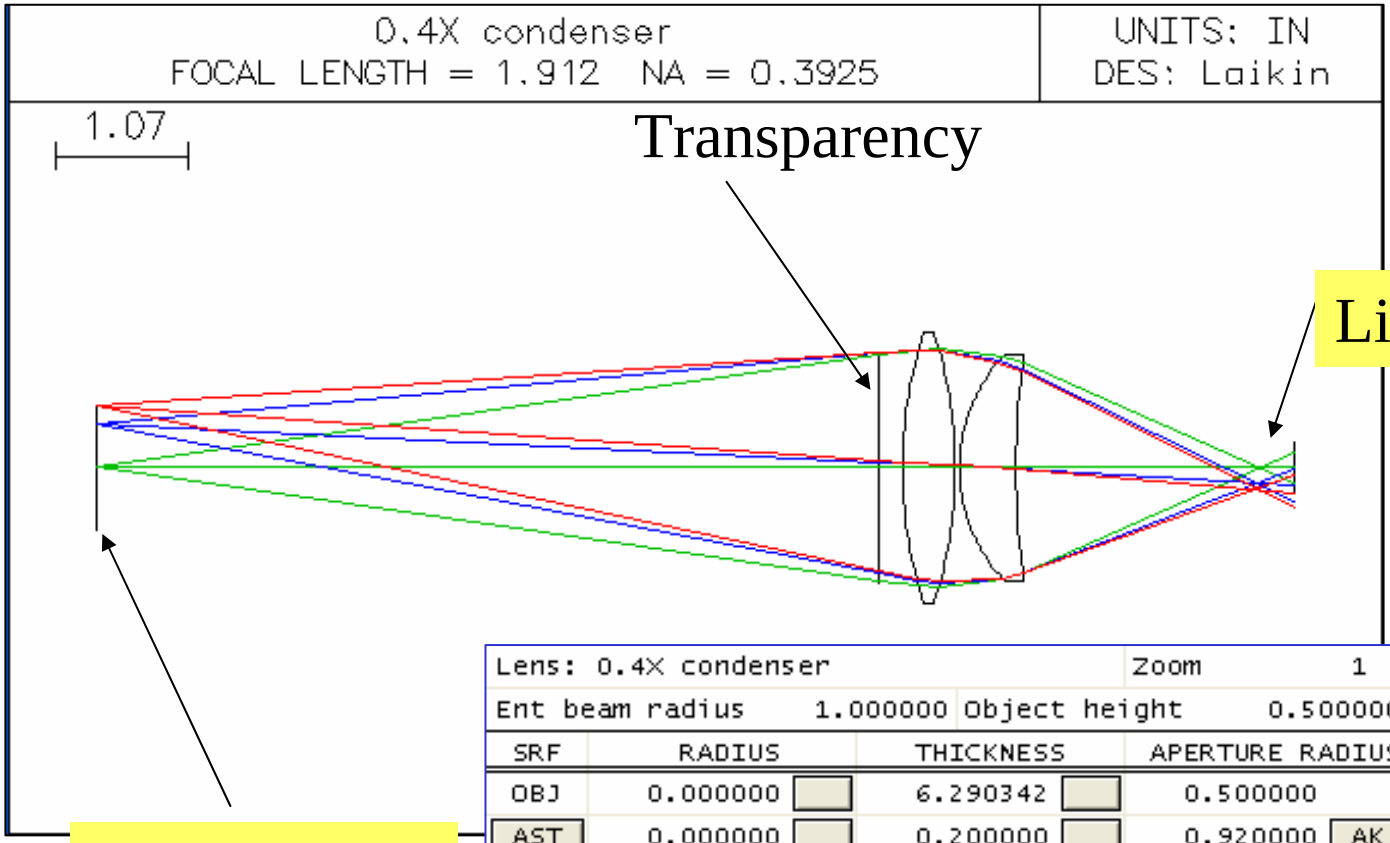
Imaging optics



Nonimaging optics



Example with condenser lens



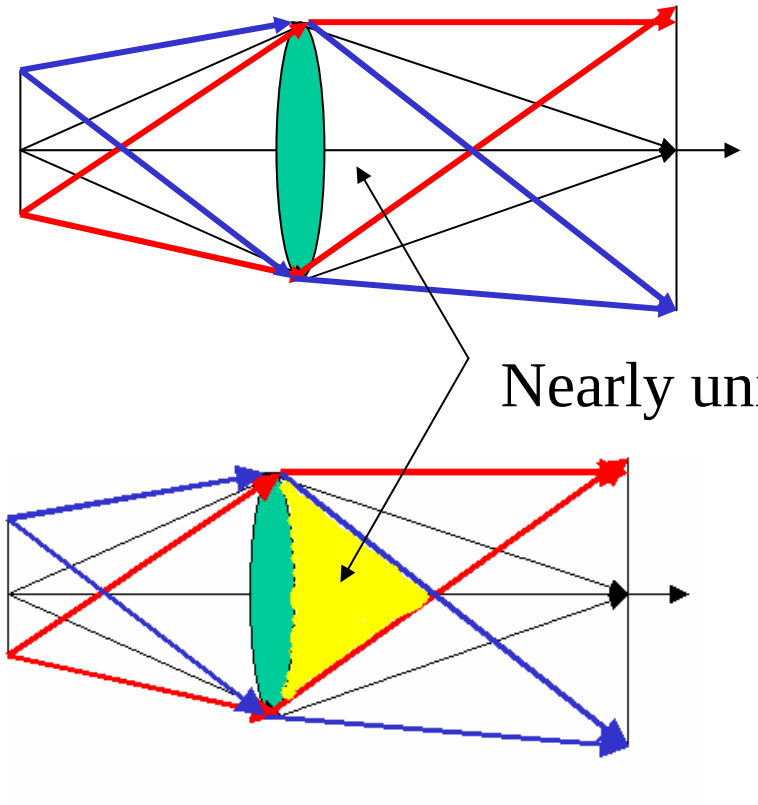
Lens: 0.4X condenser | Zoom 1 of 1 | Efl 1.912024
Ent beam radius 1.000000 | Object height 0.500000 | Primary wavln 0.587560

SRF	RADIUS		THICKNESS		APERTURE RADIUS		GLASS		SPECIAL
OBJ	0.000000		6.290342		0.500000		AIR		NF
AST	0.000000		0.200000		0.920000	AK	AIR		F
2	3.635000		0.421000		1.090000	K	QUARTZ	C	
3	-3.635000		0.035000		1.090000	K	AIR		
4	1.319000		0.454000		0.910000	K	QUARTZ	C	
5	6.269000		2.245653		0.840000	K	AIR		
IMS	0.000000		0.000000		0.200000	S			F

(note that actually, this condenser is not good.)

On searchlight

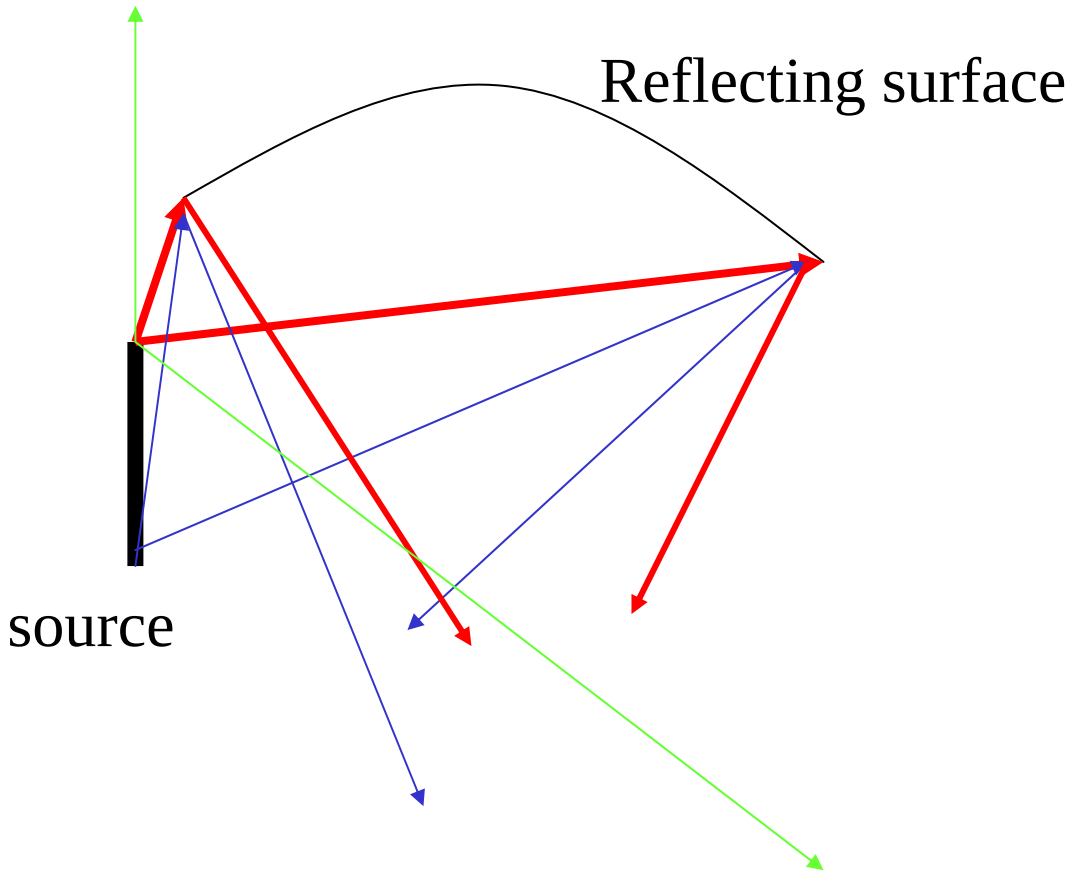
Where the film should be located?



This has been called as an example of “searchlight”

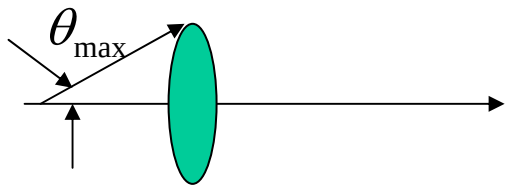
So, the film should be located as close to the condenser lens as possible as one could

Extension to edge ray principle



Throughput estimate

Throughput collected by the condenser:



Assuming a Lambertian source: $I(\theta)=I_0 \cos\theta$

$$\int_0^{\Omega} I_0 \cos\theta d\Omega = \int_0^{\theta_{max}} BA\cos\theta(2\pi\sin\theta)d\theta$$

$$= \pi BA\sin^2\theta_{max}$$

Efficiency: $\dfrac{\pi BA\sin^2\theta_{max}}{\pi BA\sin^2 90^o} = \sin^2\theta_{max}$

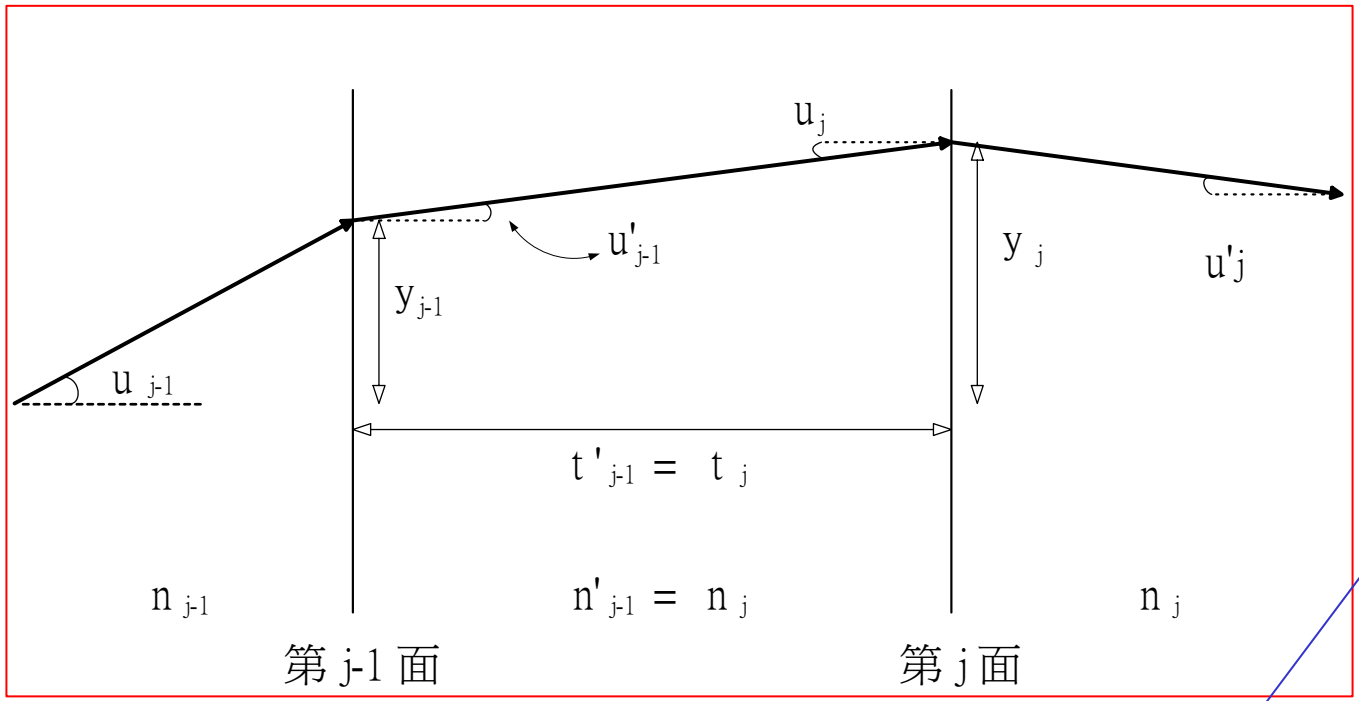
Half-angle (θ_{max})	Sin(θ_{max})	NA=n* Sin(θ_{max})	Efficiency
10	**0.1736**	**~0.1736 (n~1)**	**3%**
20	**0.3642**	**~0.3642 (n~1)**	**11.69%**
40	**0.6427**	**~0.64 (n~1)**	**41.31%**
60	**0.866**	**~0.866 (n~1)**	**74.99%**

Nearly 97% loss

We need another tool to improve the throughput!

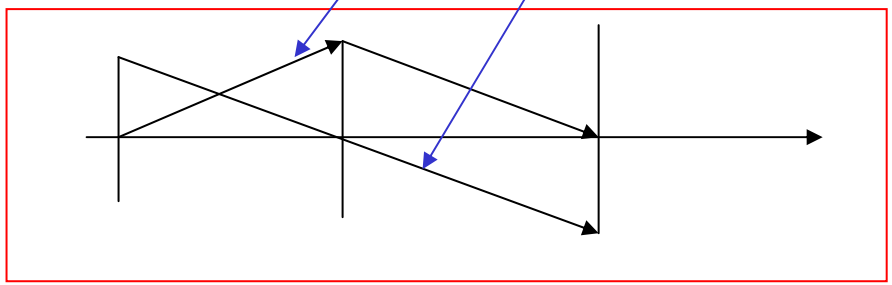
Lagrange Invariant

from single ray to ray bundle



Axial ray
(marginal ray)
→ a-ray

chief ray
(principal ray)
→ b-ray



$$L_{ab} = ny_b u_a - ny_a u_b = \text{常數}$$

Object plane: $L_{ab}=ny_b u_a$

Check closely for the other planes.

軸光線在物面上，根據定義是線高度爲零，這表示在物面上 Lagrange 不變量爲

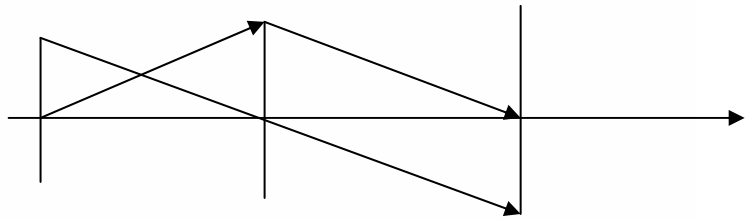
$$L_{ab} = n_1 y_{b0} u_{a1} = h n_1 u_{a1}$$

其中的高 h 用來定義主光線(b 光線)的高度。根據定義，在像平面上的軸光線高度也是零，所以那裡的 Lagrange 不變量爲：

$$L_{ab} = n_k y_{bk} u_{ak} = h' n_k u_{ak}$$

此兩種表示法的 Lagrange 不變量相等，所以：

$$h n_1 u_{a1} = h' n_k u_{ak}$$



或是

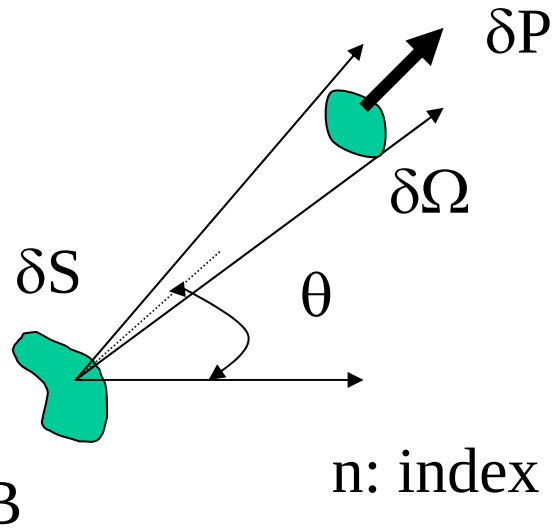
$$m = \frac{h'}{h} = \frac{n_1 u_{a1}}{n_k u_{ak}}$$

所以橫向放大率等於物空間內軸光線的光學斜率($n_1 u_{a1}$)對像空間內的光學斜率($n_k u_{ak}$)比值。因此一個影像的位置與橫向放大率由軸光線決定。再者，放大率既然只與光線的斜率有關，所以要得到影像的尺寸並不需要知道影像的精確位置。Lagrange 定律是幾何光學的不變量原理中最有用的一個。除了使用於尋找影像的放大率之外，也可用作尋找瞳(pupils)的放大率、決定一個光學系統的匯入能量(throughput)或一個給定孔鏡大小繞射極限系統的資訊容量。

More on Flux and energy

- The collected power δP

$$\delta P \propto \delta S$$
$$\delta P \propto \cos\theta$$
$$\delta P \propto \delta\Omega$$
$$\delta P \propto B$$



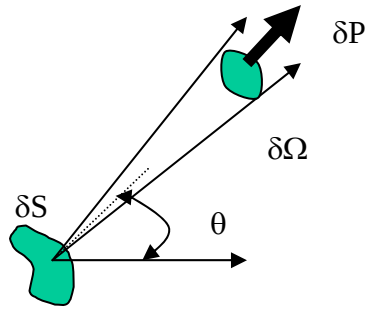
B: radiance if δP is measured in watts
B: luminance, if δP is measured in visual unit

$$\Rightarrow \quad \delta P = B \times n^2 \delta S \delta\Omega \cos\theta$$

(the n^2 is introduced such that a connection to numerical aperture can be established

Etendue

- Etendue and radiance



$$\delta(etendue) \equiv n^2 \delta S \delta\Omega \cos(\theta)$$

$$\delta P = B \times n^2 \delta S \delta\Omega \cos(\theta) \quad \Rightarrow \quad \boxed{P = B \times (etendue)}$$

Examples of etendue:

- Into a cone with semi-angle θ_{max}

$$etendue = n^2 \Delta S \int \cos(\theta) d\Omega = \Delta S (n \sin\theta_{max})^2 = \Delta S (NA)^2$$

- A small angle

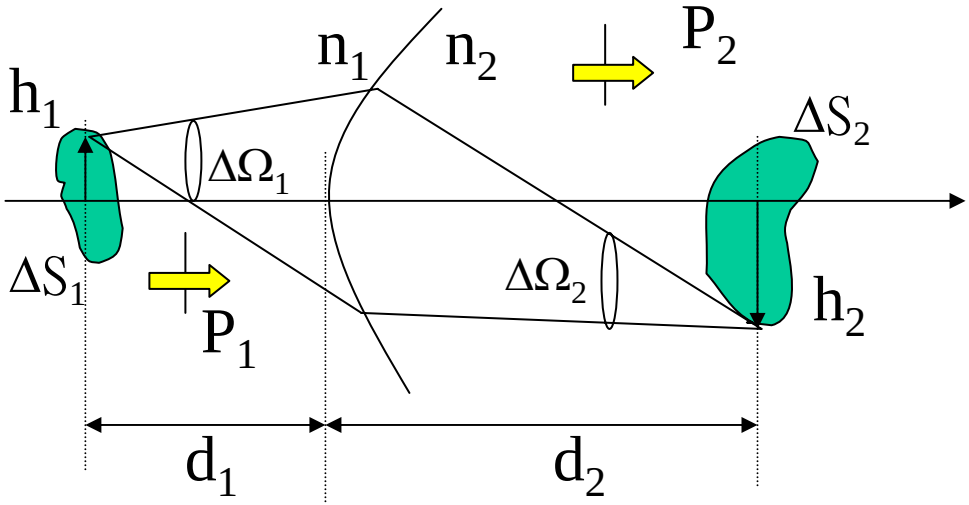
$$etendue \approx n^2 \Delta S \Delta\Omega$$

Etendue - meaning

- Etendue is a geometrical factor
  - examples
    - ~ product of (source size) and (numerical aperture)^2
    - ~ product of (source size) and (solid angle)

- Illuminated Power = (source's brightness)X(etendue)
  - So, as long as we can determine etendue and get the source's brightness data at hand, then we can calculate the power over the illuminated surface

The importance of “etendue”



From paraxial optics, we can deduce

$$\frac{h_2}{h_1} = \frac{d_2}{d_1}\frac{n_1}{n_2}$$

$$\frac{\Delta S_2}{\Delta S_1} = \frac{d_2^2}{d_1^2}\frac{n_1^2}{n_1^2}$$

$$\frac{\Delta \Omega_2}{\Delta \Omega_1} = \frac{d_1^2}{d_2^2}$$

$$(etendue)_2 = n_2^2 \Delta S_2 \Delta \Omega_2 = n_1^2 \Delta S_1 \Delta \Omega_1 = (etendue)_1$$

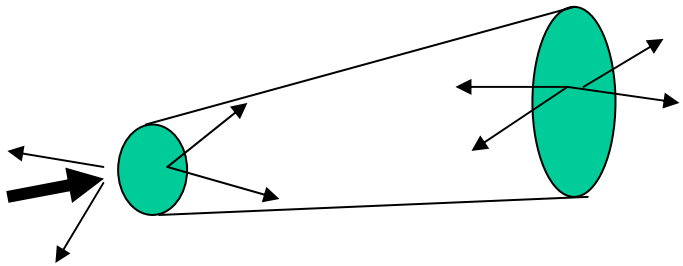
Key Result: **etendue is an invariant**

(radiance of image of source) ≤ (radiance of original source)

Application example

- Light-pipe

$$(etendue)_2 = (etendue)_1$$



$$n_2^2 \Delta S_2 \sin^2\theta_2 = n_1^2 \Delta S_1 \sin^2\theta_1$$

$$n_2 R_2 \sin\theta_2 = n_1 R_1 \sin\theta_1$$

R: radius
D: diameter

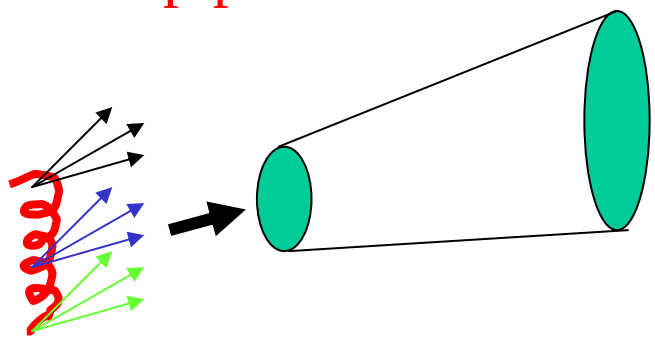
$$\frac{R_{out}}{R_{in}} = \frac{\sin\theta_{in}}{\sin\theta_{out}} = \frac{D_{out}}{D_{in}}$$

Case illustration :

Given R_{in}, θ_{in}, θ_{out}, then possible illuminated area's R_{out} is automatically fixed. In other words, using a larger output dimension of lightpipe is useless.

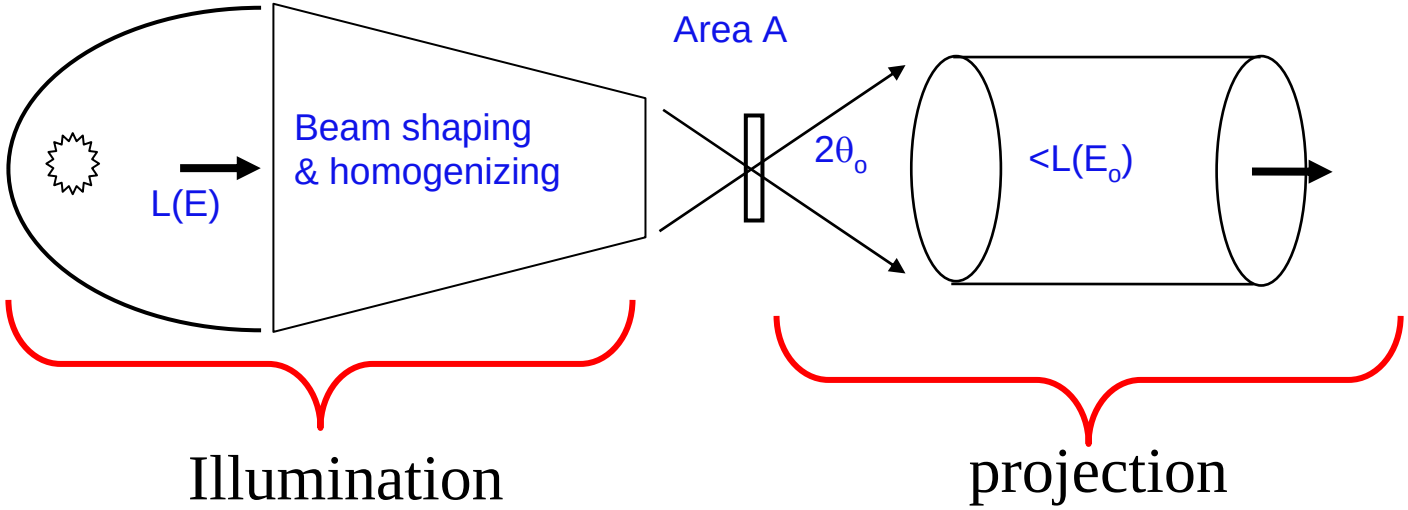
Cont'd

- What we happen if we just want to have a larger illuminated area?
  - Modify your deign of lightpipe
  - Using etendue repeatedly to spatially homogenize the brightness at the output of the pipe.



- Be aware of that irradiance (power) is equal to the product of "brightness" and "etendue."

Example: how etendue helps design



Usually, the micro-display chip (LCD plate) has been selected.
We have two questions:
How the illumination source be selected?
How to couple the displayed image to be projected with maximum efficiency?

What etendue helps us in considering the source?

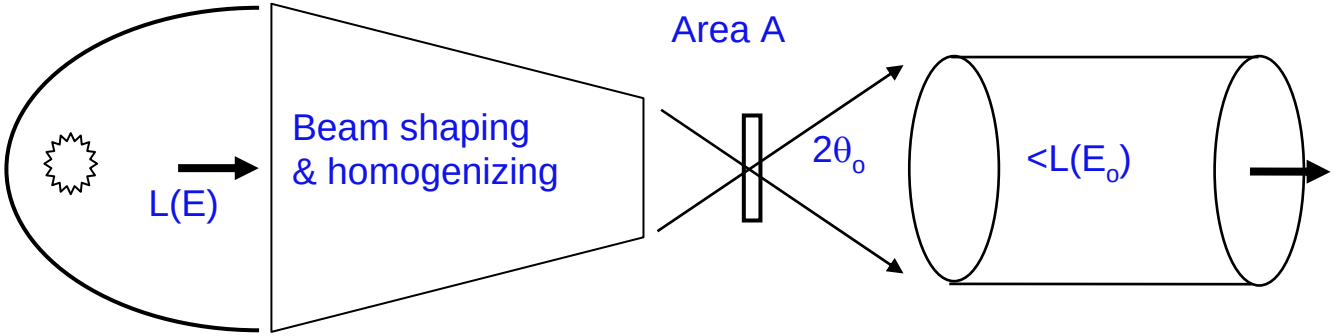
$$etendue = n^2 \Delta S \int \cos(\theta) d\Omega = \Delta S (n \sin\theta_{\max})^2 = \Delta S (NA)^2$$

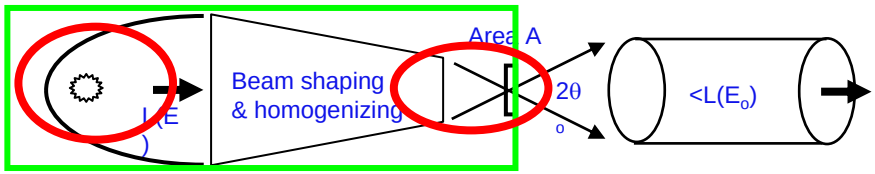
$$etendue \approx n^2 \Delta S \Delta\Omega$$

Consider object plane:
If ΔS is large, then we need to have a large source
If ΔΩ is large, then we need to have light source with bigger emitting cone

Now, we need to have a criterion to judge the etendue inside the system!!!
Determined by the LCD plate, here.

Etendue estimate and application





How to match these two parts such that throughput loss can be minimized?

See next page

Equivalently, an etendue

$$E_o = \pi A \sin^2 \theta_o$$

$$= \frac{\pi A}{4(F\#)^2} = \pi A * (NA)^2$$

Analysis

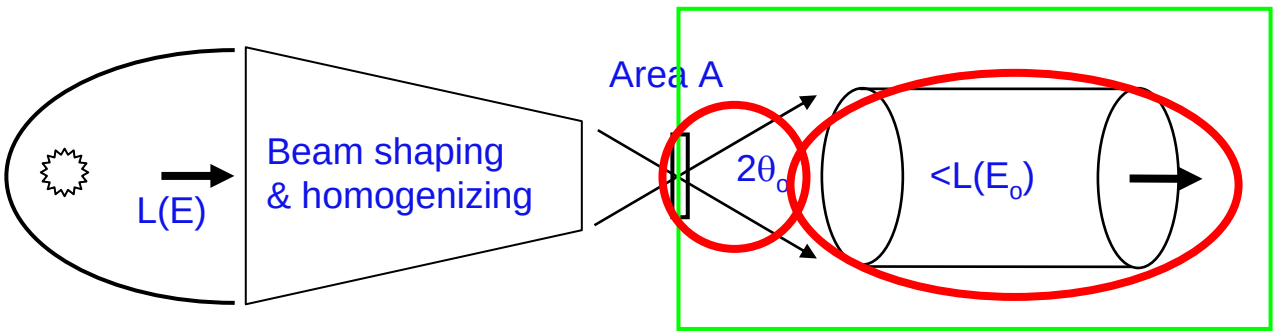
- Specification of A SXGA (1280x1024) micro-display
  - Pixel size=9 um
  - F#=2.4
    - Or, be specified by the corresponding number aperture
- Etendue result:
  - A=106 mm^2
  - E_o=14.5 mm^2Sr ← **A small quantity**

Be aware of limitation of etendue estimate!!

- What kind of source should be applied?
  - Small etendue
    - But, the opening of reflector is so large, i.e., wide incident NA

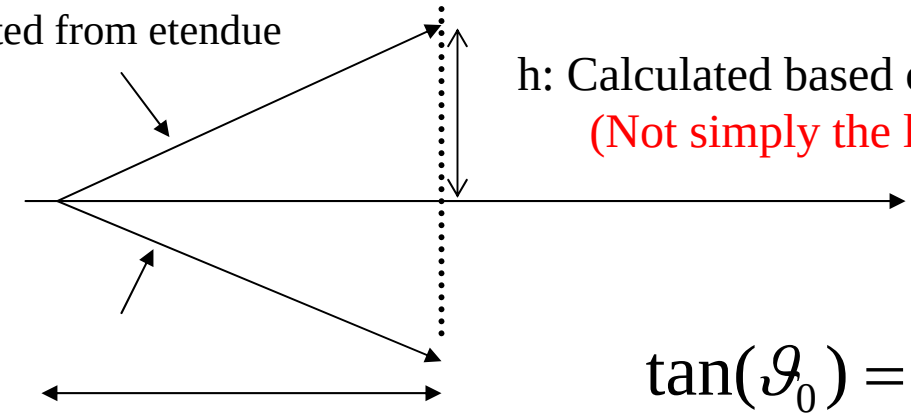
→In other words, Short arc (point source) is preferred

Etendue estimate and pupil combination



How to match these two parts such that throughput loss can be minimized?

Angle is estimated from etendue

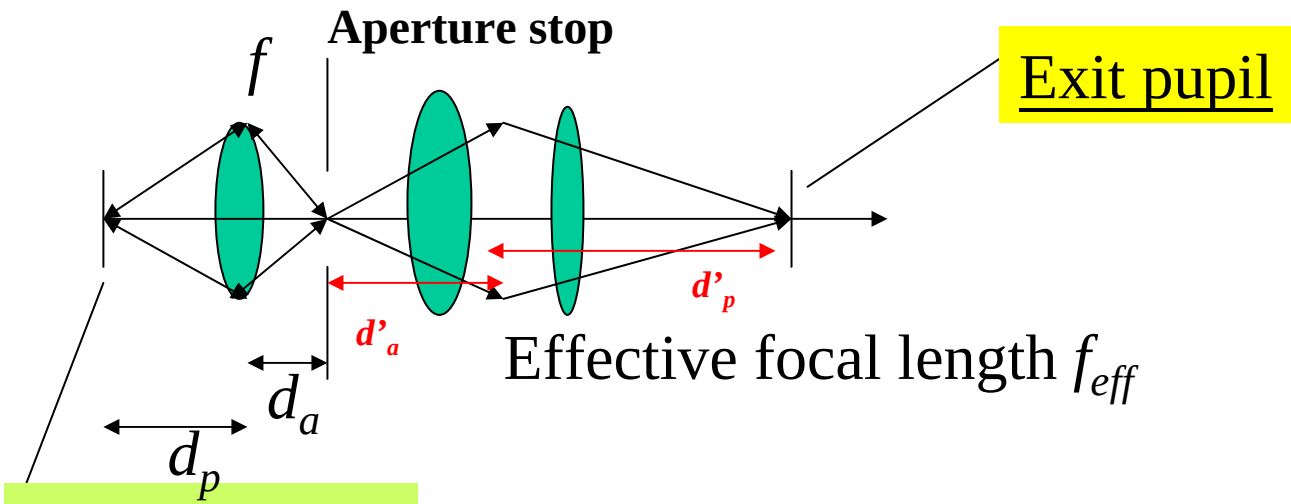


h: Calculated based on pupil consideration
(Not simply the lens' clear aperture)

$$\tan(\vartheta_0) = \frac{h}{d}$$

d: Known from specification

On entrance pupil



Effective focal length f_{eff}

Location:

$$\begin{cases} \frac{1}{f} = \frac{1}{d_a} + \frac{1}{d_p} \\ \frac{1}{f_{eff}} = \frac{1}{d'_a} + \frac{1}{d'_p} \end{cases}$$

Size:

$$\begin{cases} M = \frac{d_p}{d_a} \left(M' = \frac{d'_p}{d'_a}\right) \\ \text{Pupil size} = M * \text{Stop size} \end{cases}$$

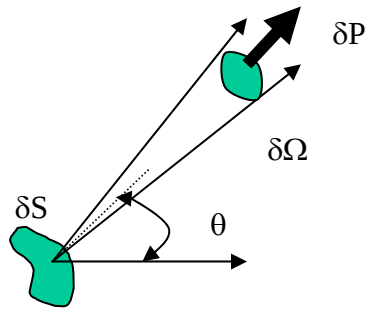
More on etendue

- It remains a nontrivial challenge to extend the concept of etendue invariant to the regime of physical optics

$$\delta(etendue) \equiv n^2 \cdot \delta S \cdot \delta\Omega \cdot \cos(\theta)$$

$$B(\nu)\delta\nu = \frac{P(\nu)\delta\nu}{etendue}$$

$\delta\nu$ is the range of frequencies occupied by the photons



Radiometry and Photometry

- *Radiometry* is the basis for all light measurements.
  - It is defined by the Institute of Electrical and Electronics Engineers (IEEE) as the measurement of quantities associated with radiant energy.
  - Not limited to any particular spectrum
  - Generally for instruments
- *Photometry* is a subset of radiometry.
  - In radiometry, the detector has a flat spectral response.
  - In photometry, on the other hand, the spectral response useful to the visual system is considered.
    - To accomplish that, the detector should be closely matched to the spectral response curve of the eye.
  - Generally for visible light and human uses

Units and correspondences

	item	meaning	unit
1	Flux	The total power emitted by the source (the power in radiometry)	lumen
2	Intensity	•The flux per unit solid angle •A solid angle flux density •Flux angular distribution (assume the flux from a point source)	Candela=lumex/steradian
3	Illuminance	•The flux per unit area incident onto the surface being illuminated •The area flux density	•Foot-Candela=Lumen/ft^2 •Lux=lumex/m^2
4	Brightness	Flux per solid angle per unit area The area and solid angle flux density	Nit=candela/m^2

Be careful about the limitation of these quantities!!

Classification

Items we used (in source side):

1. Brightness/ Radiance/luminance
2. Flux (emitted)
   > 3. intensity

Item we used (on image side):

1. Irradiance/Illuminance
2. Flux (flow into)
   > 3. intensity

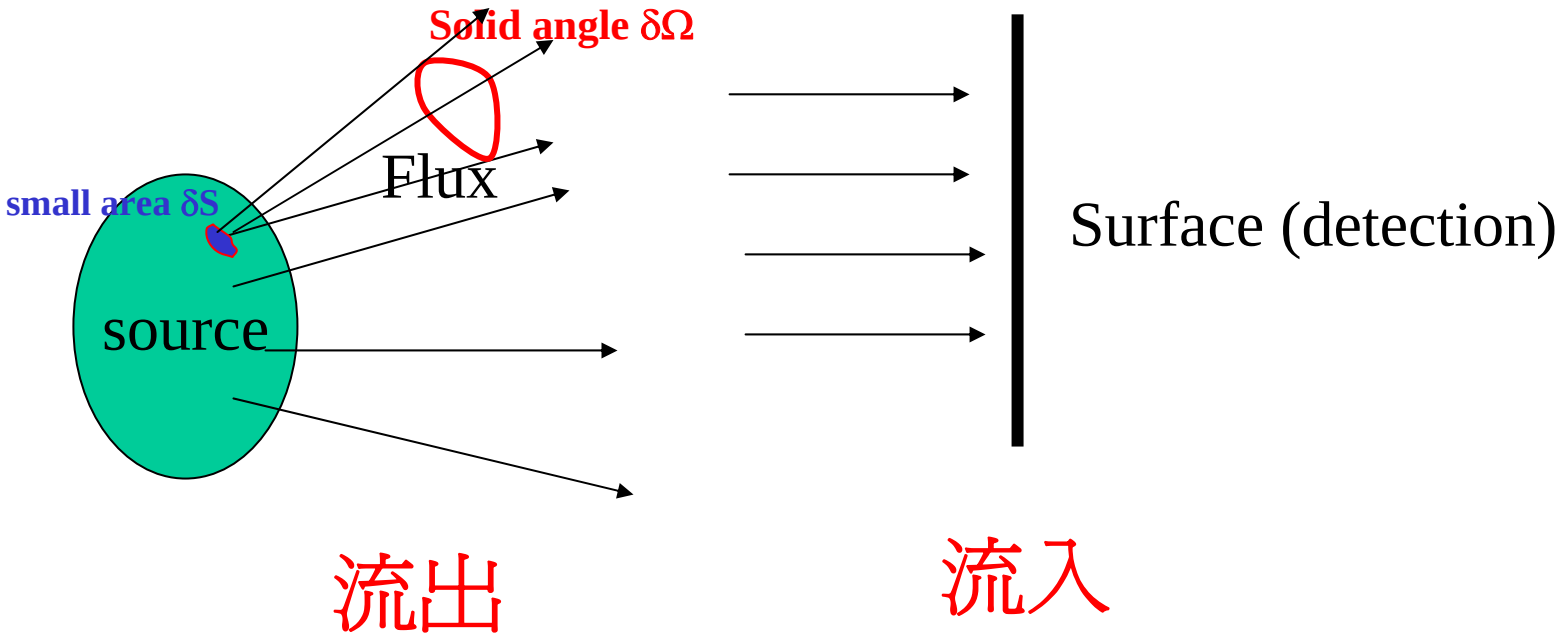
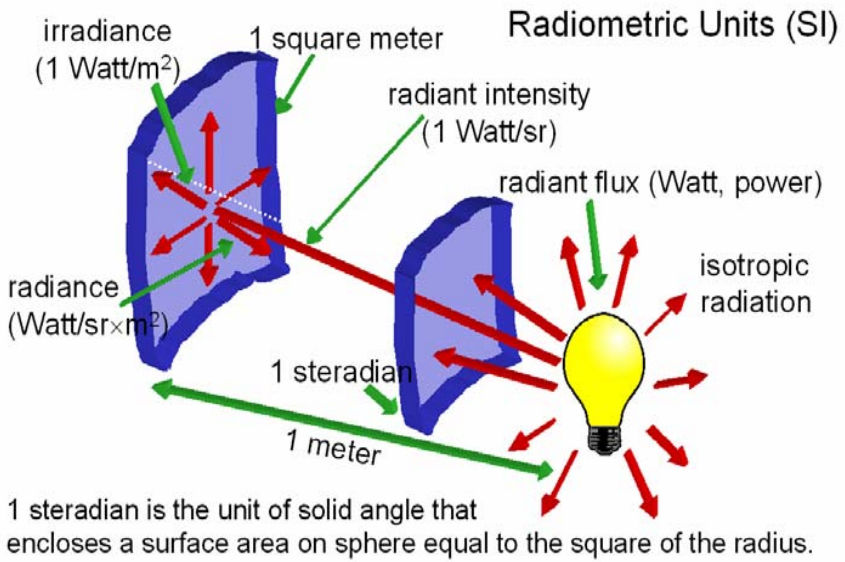
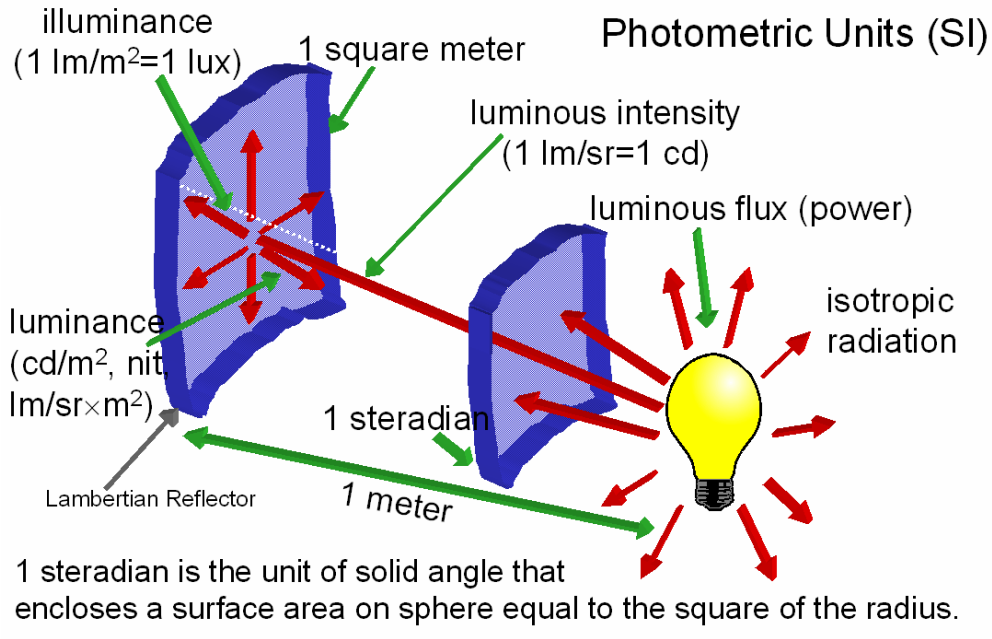


Illustration with figures





(from Crawford)

Examples-- Used in Radiometry

1	Total flux from a 100W incandescent light bulb	82 W
2	Typical He-Ne laser	5 mW
3	Radiant flux from a 40 W fluorescent lamp	23.2 W
4	Solar irradiance (in earth orbit)	1357 W/m^2
5	Terrestrial solar irradiance	600-900 W/m^2
6	Radiance of sun at its surface	$2.3X10^7$ $w/(m^2\ sr)$

Examples -Used in Photometry

1	Total luminous flux from a 100 W light bulb	1740 lm
2	Luminous flux from a 5-mW He-Ne laser	0.818 lm
3	Luminance of a blackbody at 6500° K	$3X10^9$ cd/m^2

Examples of Illuminance

	lux
Sunlight alone (maximum)	102,000
Television stage	25,000
Skylight alone (maximum)	16,000
Dull day	1,000
Merchandise display (indoors)	1,000
Recommended for reading	500
Public areas in buildings	300
Moonlight	0.4
Starlight	0.002

The sensitivity of some home video cameras allows them to take pictures in light as low as one lux.

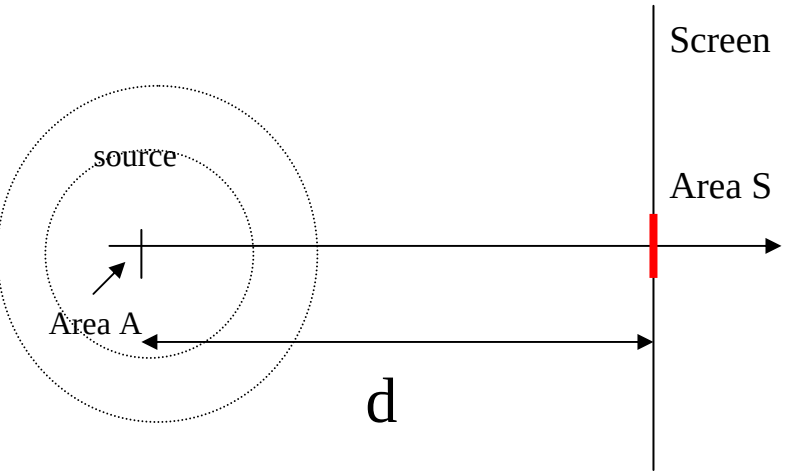
An older unit is the footcandle
1 footcandle = 10.8 lux

From Williamson & Cummins

Basic theory

- The light flux emitted by a small plane source
- Axial illumination from a finite circular source
- Oblique illumination from a circular source
- Application examples

Light flux: small plane source



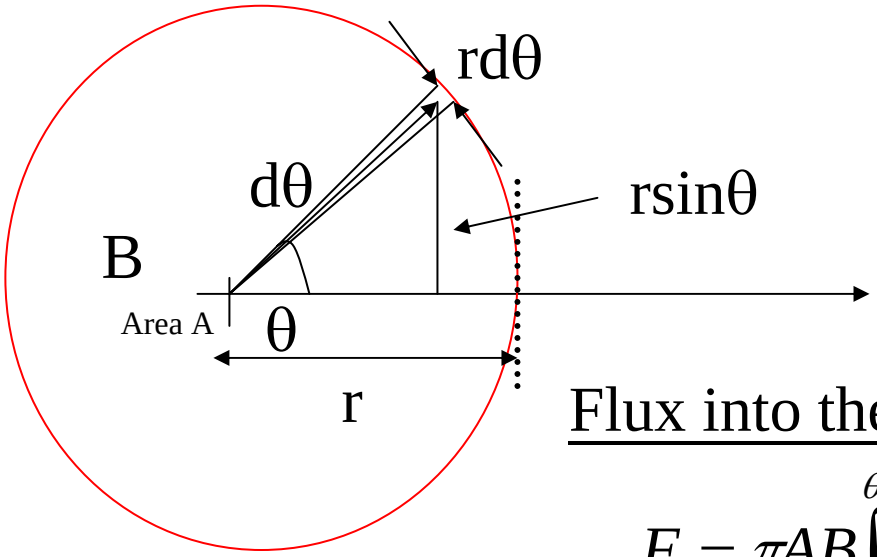
(assuming a source of dipole radiation, in nature)

$$E = \frac{AB}{d^2}$$ (illuminance on the screen)

$$F = \frac{ABS}{d^2}$$ (flux to small area S)

Flux per unit area at S $\hat{F} = \frac{AB}{d^2}$

Cont'd



Flux into the conical shall

$$dF = (\text{intensity}) \times (\text{solid angle})$$

$$= \left(\frac{AB\cos\theta}{r^2}\right)(2\pi r \cdot \sin\theta \cdot r d\theta)$$

$$= \pi AB 2\sin\theta\cos\theta d\theta$$

Flux into the solid cone of half angle θ

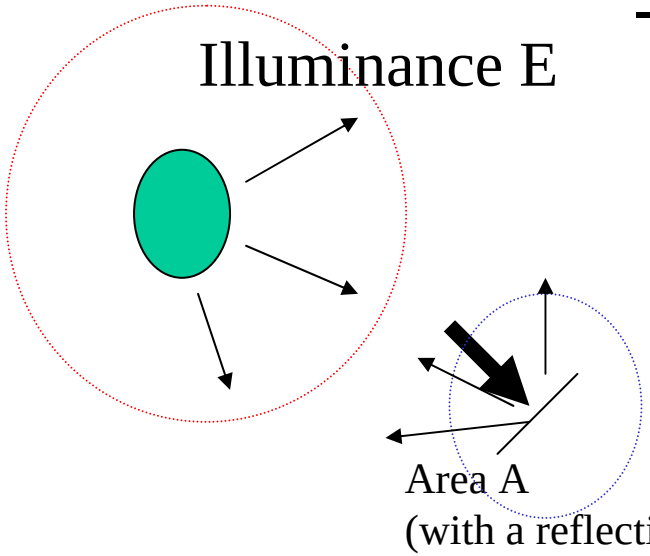
$$F = \pi AB\int_0^{\theta} 2\sin\theta\cos\theta d\theta = \pi AB\sin^2\theta$$

example: semi-hemisphere $F = \pi AB$

If luminance B varies with the direction of observation B(θ)

$$F = \pi A\int_0^{\theta} 2B(\theta)\sin\theta\cos\theta d\theta = \pi A\int_0^{\theta} B(\theta)\sin 2\theta d\theta$$

Application



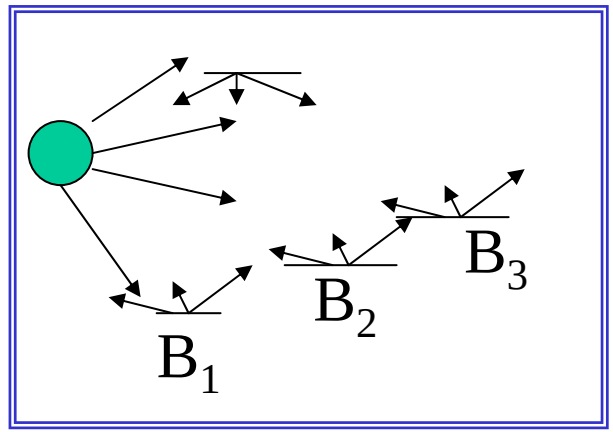
Falling flux on A F=AE

How the plate A be a secondary light source?
What is the equivalent brightness B for A?

(consider a hemisphere)

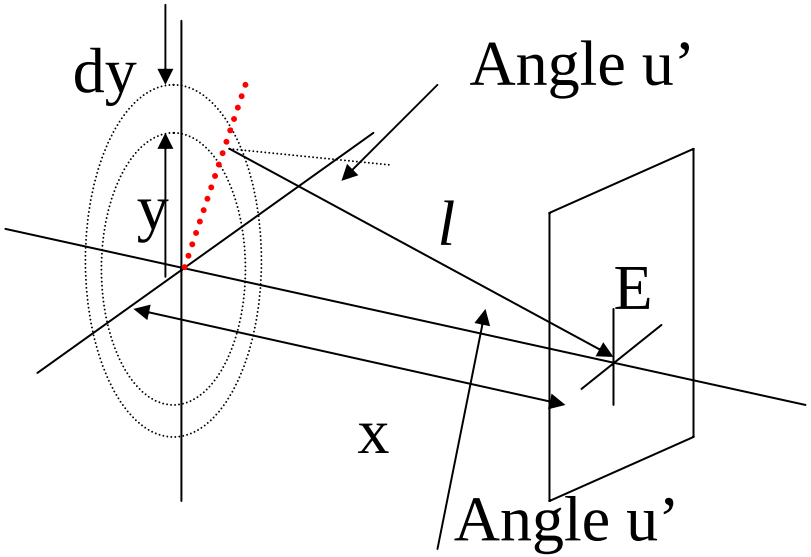
Energy conservation $kAE=\pi AB$

$\Rightarrow$ $B=kE/\pi$



You can apply this estimate to deduce brightness of successive illumination.

Axial illumination



Illuminance at E

$$dE = (2\pi y dy \cdot B \cdot \cos^2 U') / l^2$$

$$y = x \tan U'$$

$$dy = x \sec^2 U' dU'$$

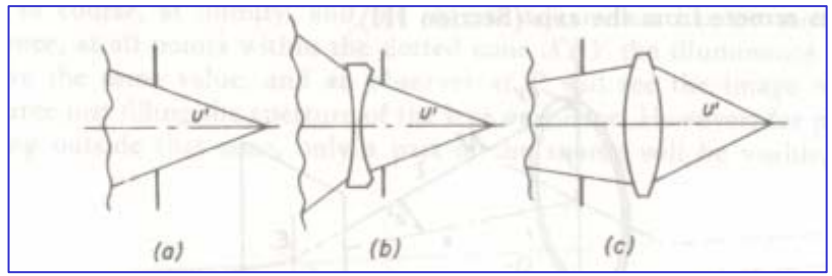
$$l = x \sec U'$$

$$E = 2\pi B \int_0^{U_{max}} \frac{x \tan U' \cdot x \sec^2 U' dU' \cdot \cos^2 U'}{x^2 \sec^2 U'}$$

$$= \pi B \int_0^{U\,max} 2 \sin U' \cos U' dU'$$

$$= \pi B \sin^2 U_{max}$$

Determination Umax when lens is used



Applications

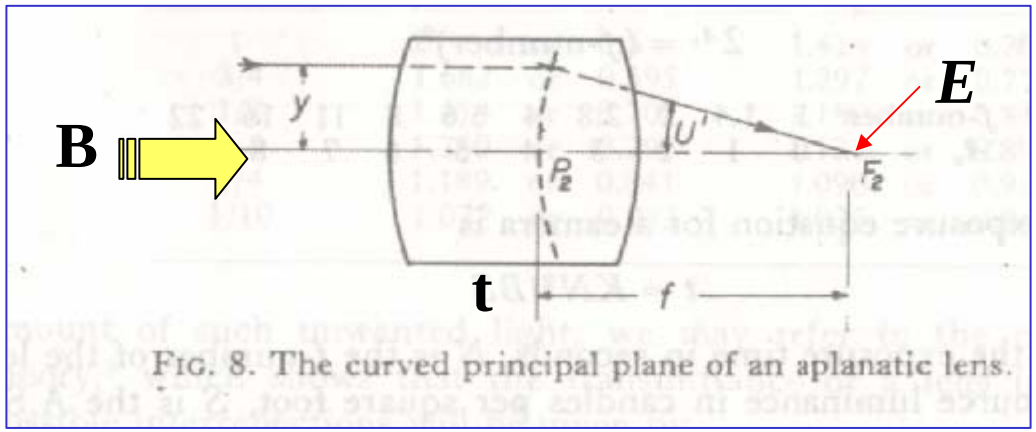


FIG. 8. The curved principal plane of an aplanatic lens.

Under aplanatic lens
(Abbe sine condition)

From Kingslake

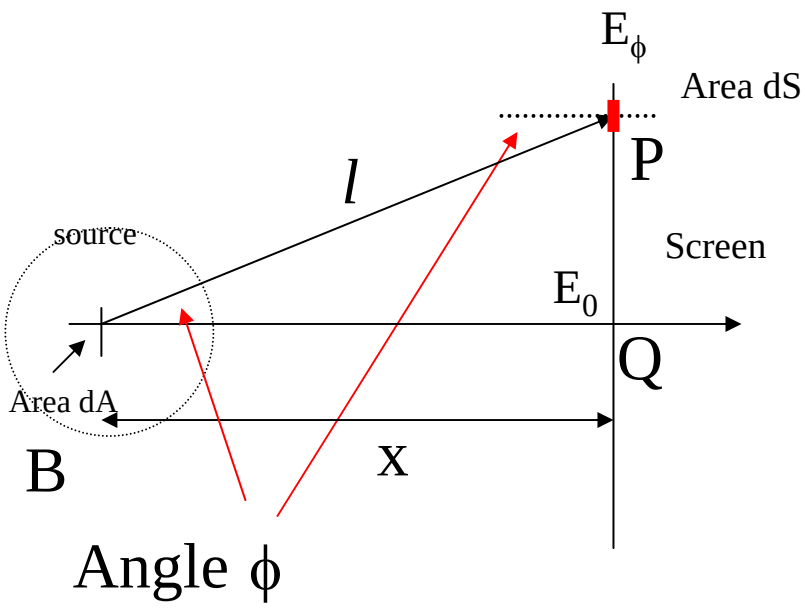
$$E = \pi B \sin^2 U_{\max} = \pi B (\frac{y}{f})^2$$

$$= \frac{\pi B}{4(f-number)^2} = \frac{\pi B}{4(f\#)^2}$$

Look back to p.38 of this lecture note

Oblique illumination

A very small circular source



Luminance B

Normal intensity BdA

Illuminance at Q: E_0=BdA/x^2

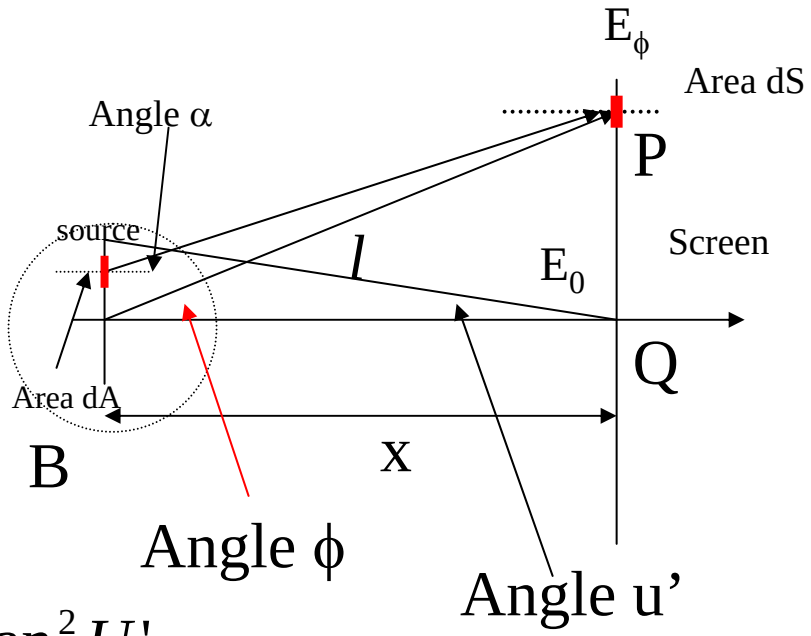
At P:

$$E_\phi = \frac{BdA\cos^2\phi}{l^2} = \frac{BdA\cos^2\phi}{(x\sec\phi)^2}$$

$$= \frac{BdA\cos^4\phi}{x^2} = E_0\cos^4\phi$$

This has been called as the $\cos^4$ law

Cont'd



A finite circular source

$$dE_\alpha = \frac{B\cos^4\alpha}{x^2}dA$$

$$E_\phi = \frac{\pi B}{2}\{1-\frac{1+\tan^2\phi-\tan^2 U'}{\sqrt{\tan^4\phi+2\tan^2\phi(1-\tan^2 U')+\sec^4 U'}}\}$$

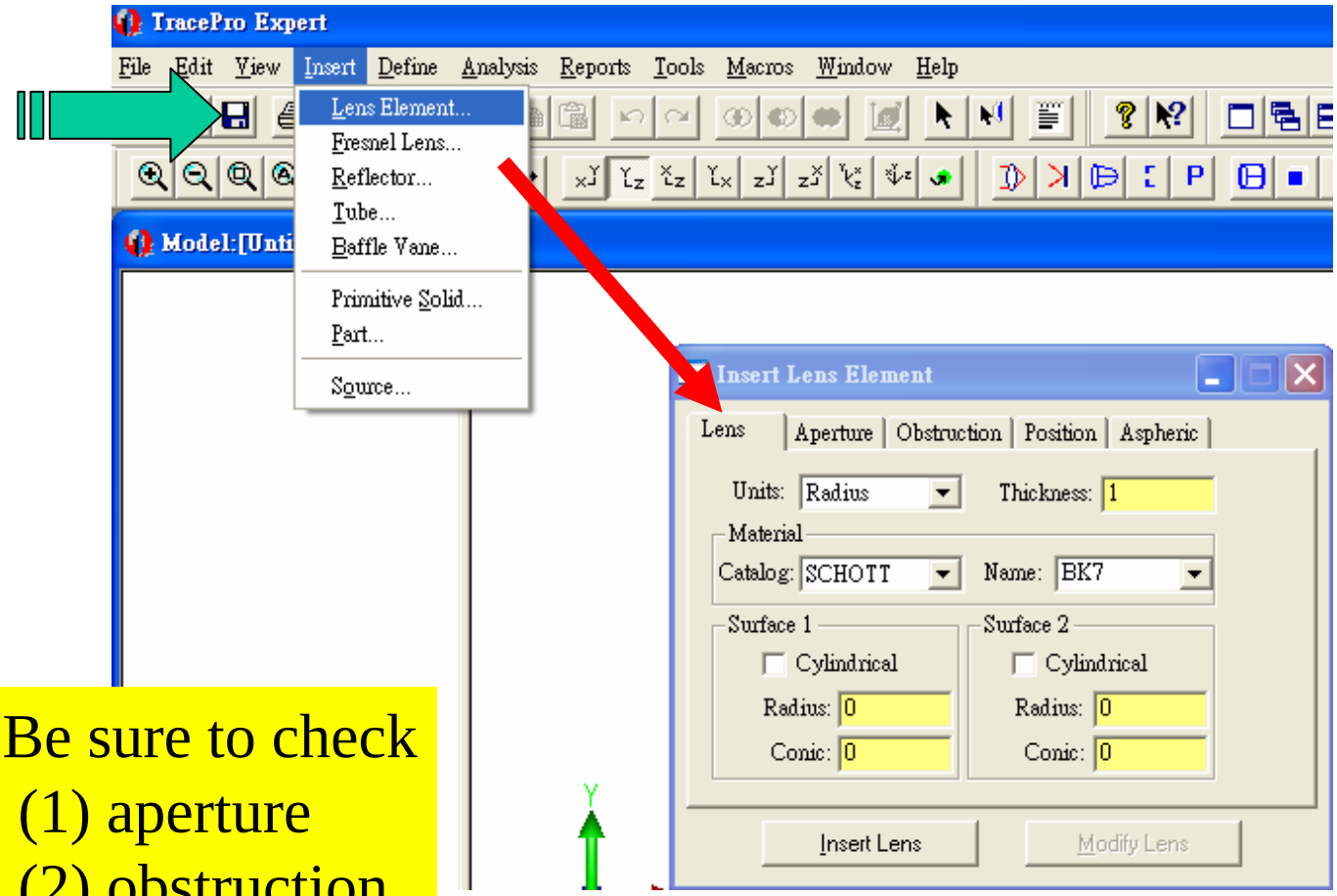
$$= \pi B\cdot\sin^2 U'\cdot\cos^4\phi\cdot[F']$$

[F'] is "increase factor"

[F']	U'=3.58 deg. (f/8)	7.18 (f/4)	14.48 (f/2)
ϕ=0 deg.	1.000	1.000	1.000
20	1.000	1.007	1.027
30	1.002	1.013	1.052
40	1.004	1.018	1.076

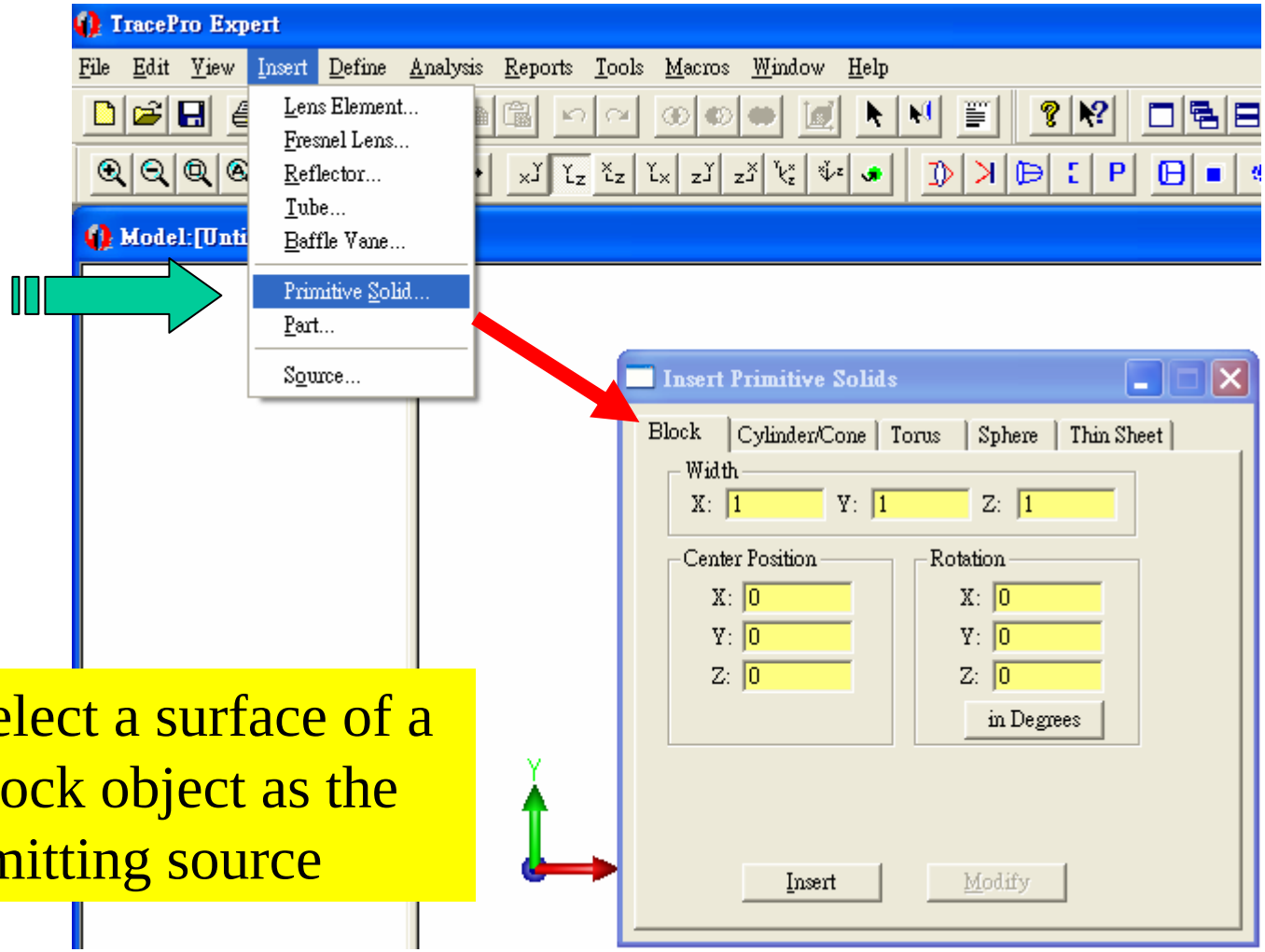
- The basic theory shown above is basically for dipole-radiation light source
  - The key feature is the dropping of intensity in inverse proportion to the square of distance
    - You may need to modify the factor of distance for different kind of light source
- Extension to different light source $B(\theta)$ can be done straightforwardly

Inserting a lens element



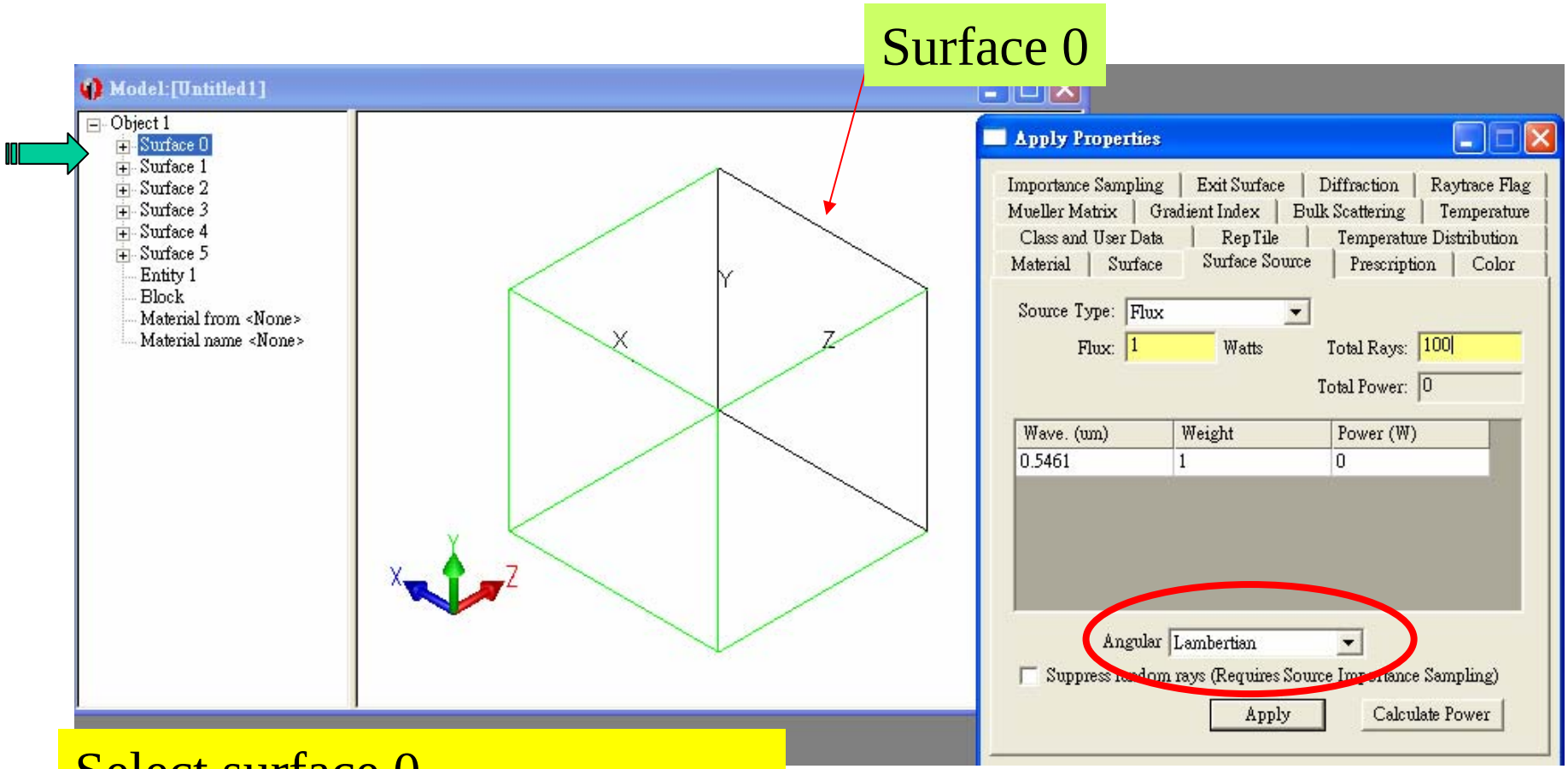
Be sure to check
(1) aperture
(2) obstruction

Creating a Lambertian source (1)



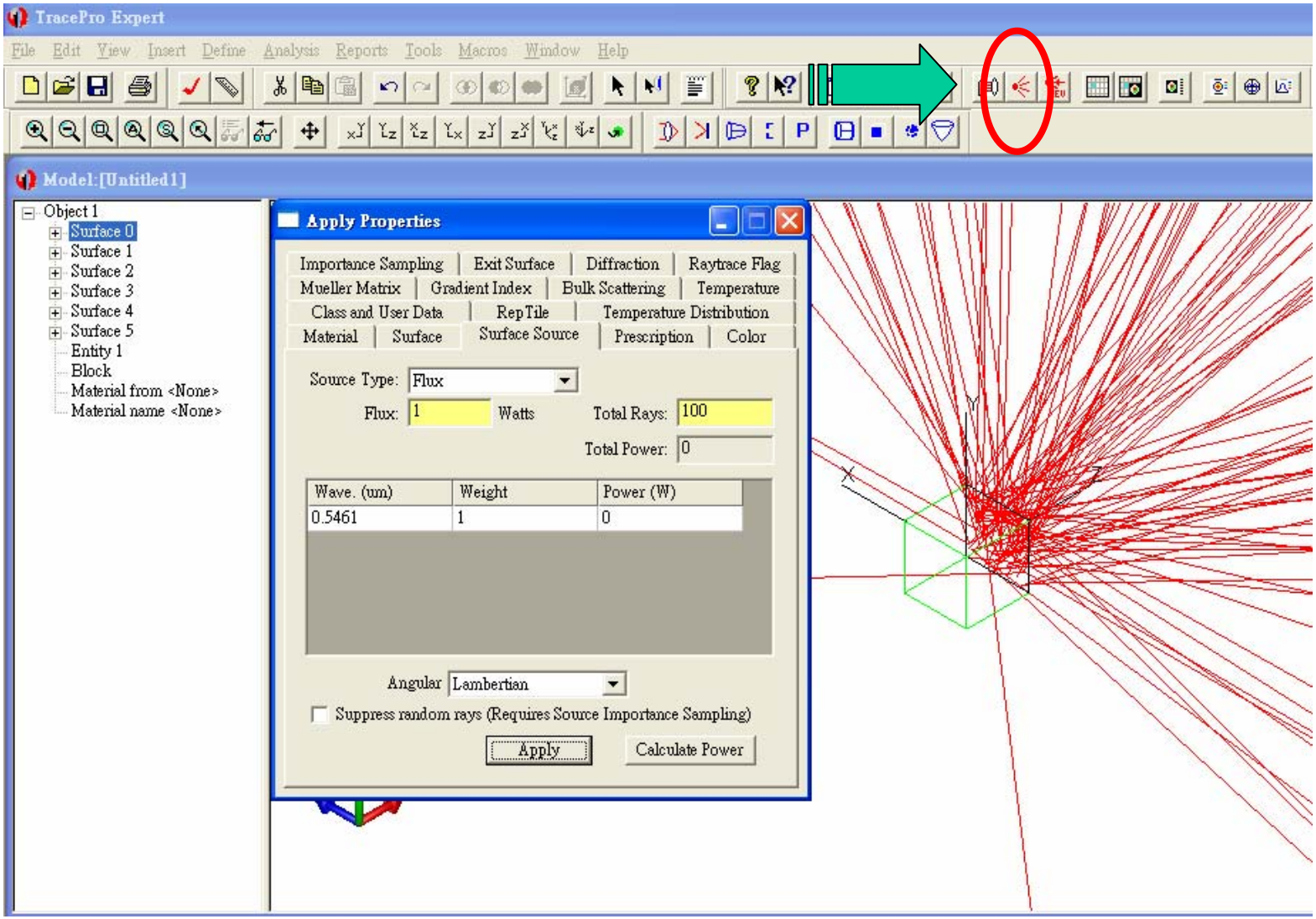
Select a surface of a block object as the emitting source

Creating a Lambertian source (2)

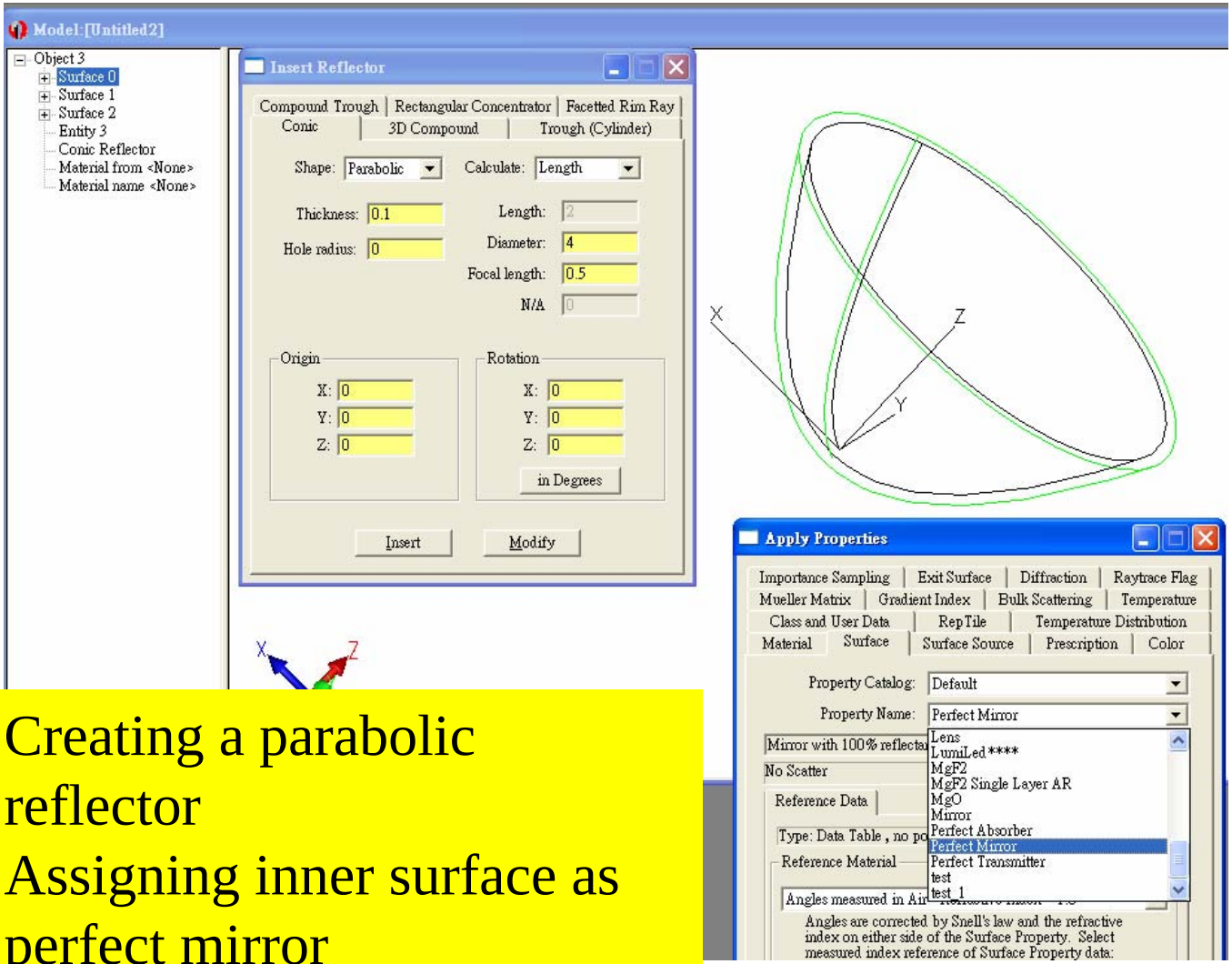


Select surface 0
Apply property with “surface source” and take Lambertian

Making ray tracing

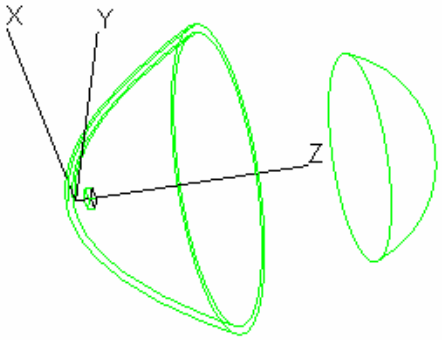


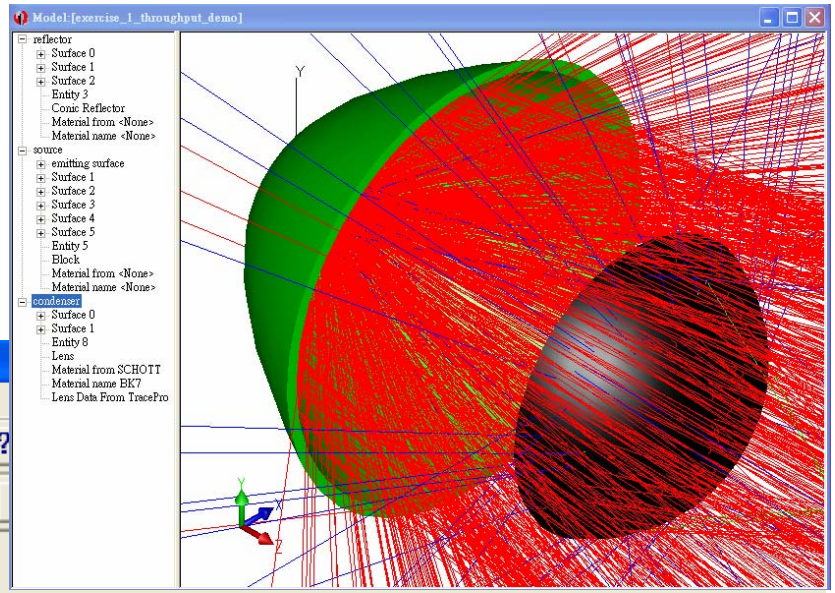
Creating reflector

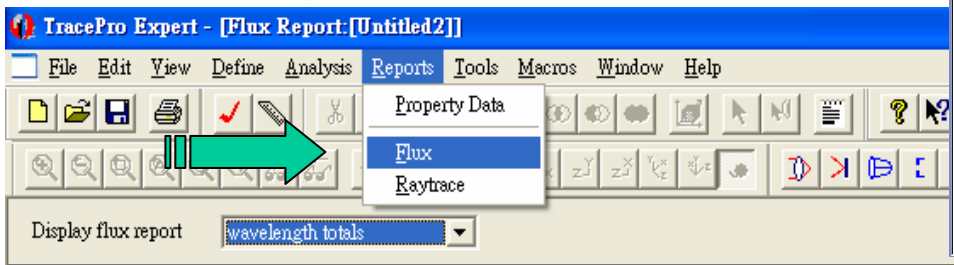


1. Creating a parabolic reflector
2. Assigning inner surface as perfect mirror

Checking flux







Object Name	Material Catalog	Material Property	Surface Area	Number	Incident	Absorbed	Lost (All Types)	Lost->Escaped Model	Lost->Flux Threshold
Surface Name	Surface Catalog	Surface Property	[sq mm]	of rays	[watts]	[watts]	[watts]	[watts]	[watts]
reflector	<None>	<None>			0.47791184451227	0			
Surface 0	Default	Perfect Mirror	21.322213025211	486	0.47699659269073	0	0.44167167698845	0.44167167698845	0
Surface 1	Default	<None>	1.4475424176074	1	0.00091525182154121	0	0	0	0
Surface 2	Default	<None>	23.69216680507	1	0.00091525182154121	0	0.00091525182154121	0.00091525182154121	0
source	<None>	<None>			0.0035039375588962	0			
emitting surface	Default	<None>	0.04	8	0.0025880716722543	0	0.43861011368147	0.43861011368147	0
Surface 1	Default	<None>	0.04	5	0.0021061310914817	0	0	0	0
Surface 2	Default	<None>	0.02	1	0.00013985352544042	0	0	0	0
Surface 3	Default	<None>	0.02	2	0.0010943836559224	0	0	0	0
Surface 4	Default	<None>	0.02	1	0.00016341079257113	0	0	0	0
Surface 5	Default	<None>	0.02	1	0.00091602438012238	0	0	0	0
condenser	SCHOTT	BK7			0.13954531202327	4.2839648963904e-005			
Surface 0	Default	<None>	9.4247779607694	253	0.18859552492956	0	0.099261182935288	0.096169504328478	0.0030916786068102
Surface 1	Default	<None>	6.2831853071796	207	0.18035971271638	0	0.01949893492429	0.01235398492792	0.00714494999637

How to work on “design”

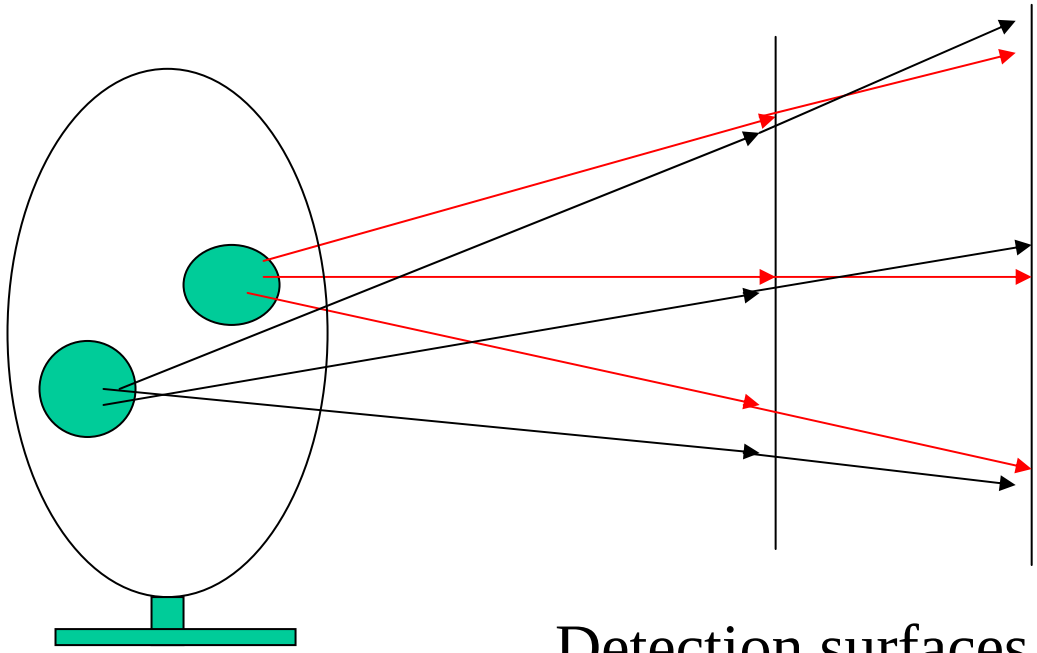
- Never forget your handy calculator
  - Try to use simple geometry and etendue to get some estimate and even develop your program
  - Mathematica is generally very helpful
- Know very well, at least, one software, e.g.,
  - ASAP (script)
  - TracePro (macro: scheme)

  (for verification)
- Keep track of SPIE/SID and patents
- Focus on your work
  - Keep progress/growing with your job
  - If you are a student, then do your homework solidly

Illumination considerations on source space for design

- **What information should we have?**
  - Source
    - Spatial distribution
      - size
    - Temporal characteristics

    → Intensity and power (flux)
    - Polarization
    - Coherence



Detection surfaces

Only one surface data is not enough, in general.

→ Candela (distribution) plot

Unless, you are considering a point source only!!

Illumination consideration on image space for design

- What information should we have?
  - Irradiance requirement
    - Flatness
  - Detection schemes
    - responses

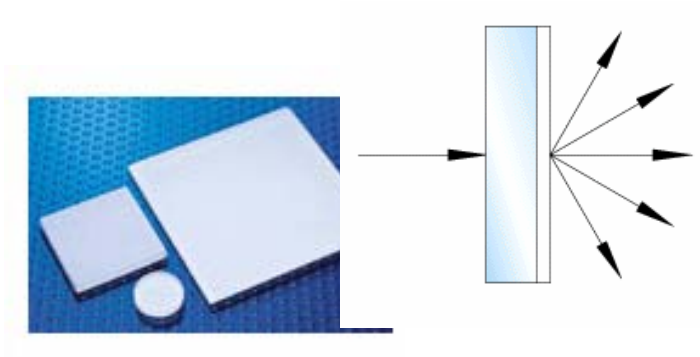
Seen by eyes
Seen by CCD detector
Seen by detector

Characterization:

how to characterize effectively may be most crucial

Illumination consideration on optics for design

- What information should we have?
  - Unlike typical lens system, scattering may be another very crucial factor
  - Good knowledge of lens design is still helpful
  - Good knowledge of reflective surface (geometry) is very helpful

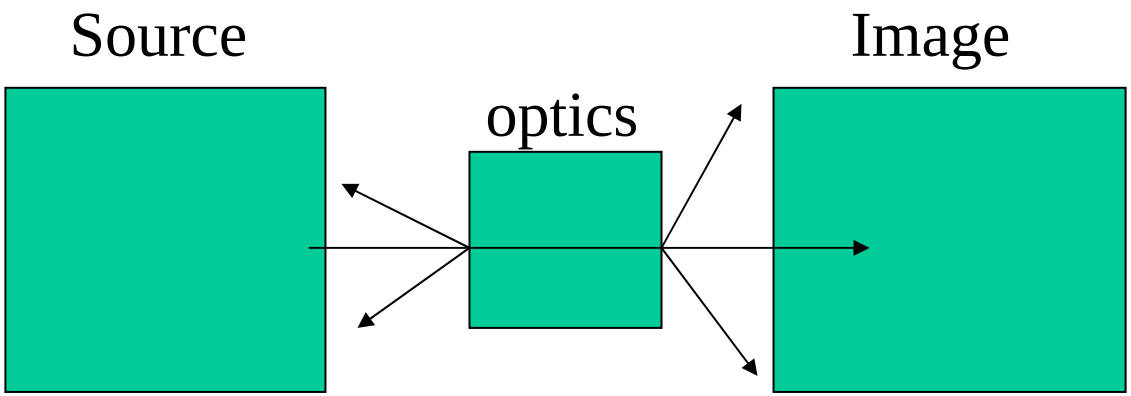


Opal glass
(ground glass)

Commercial condenser

(From Edmund)

In terms of “Module”

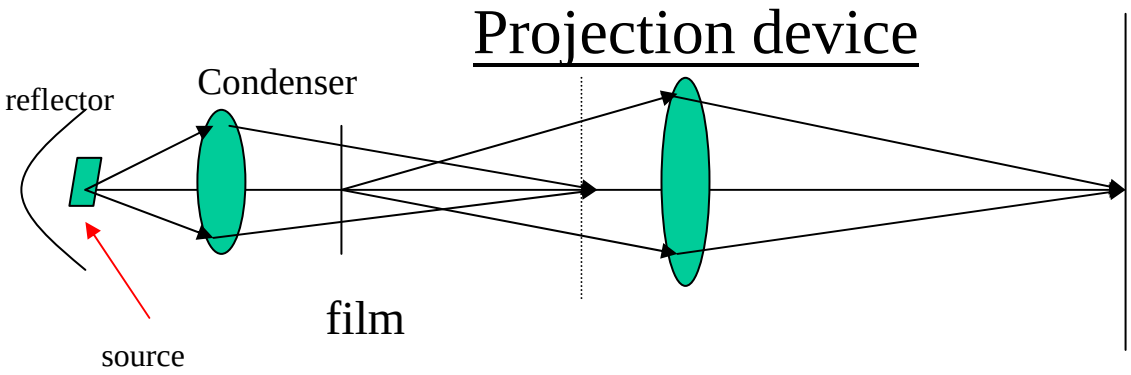


Numerical aperture
FOV
Acceptance angle

Throughput consideration:
(1) Input port
(2) Exit port

Check carefully about pupils

Calculation example



$$M = \frac{h_{screen}}{h_{film}} = \frac{d_{screen}}{d_{film}}$$

Illumination based on Kohler scheme

Source brightness (luminance): B
Source area: A

$$\frac{1}{d_{screen}} + \frac{1}{d_{film}} = \frac{1}{f_{projection\ lens}}$$

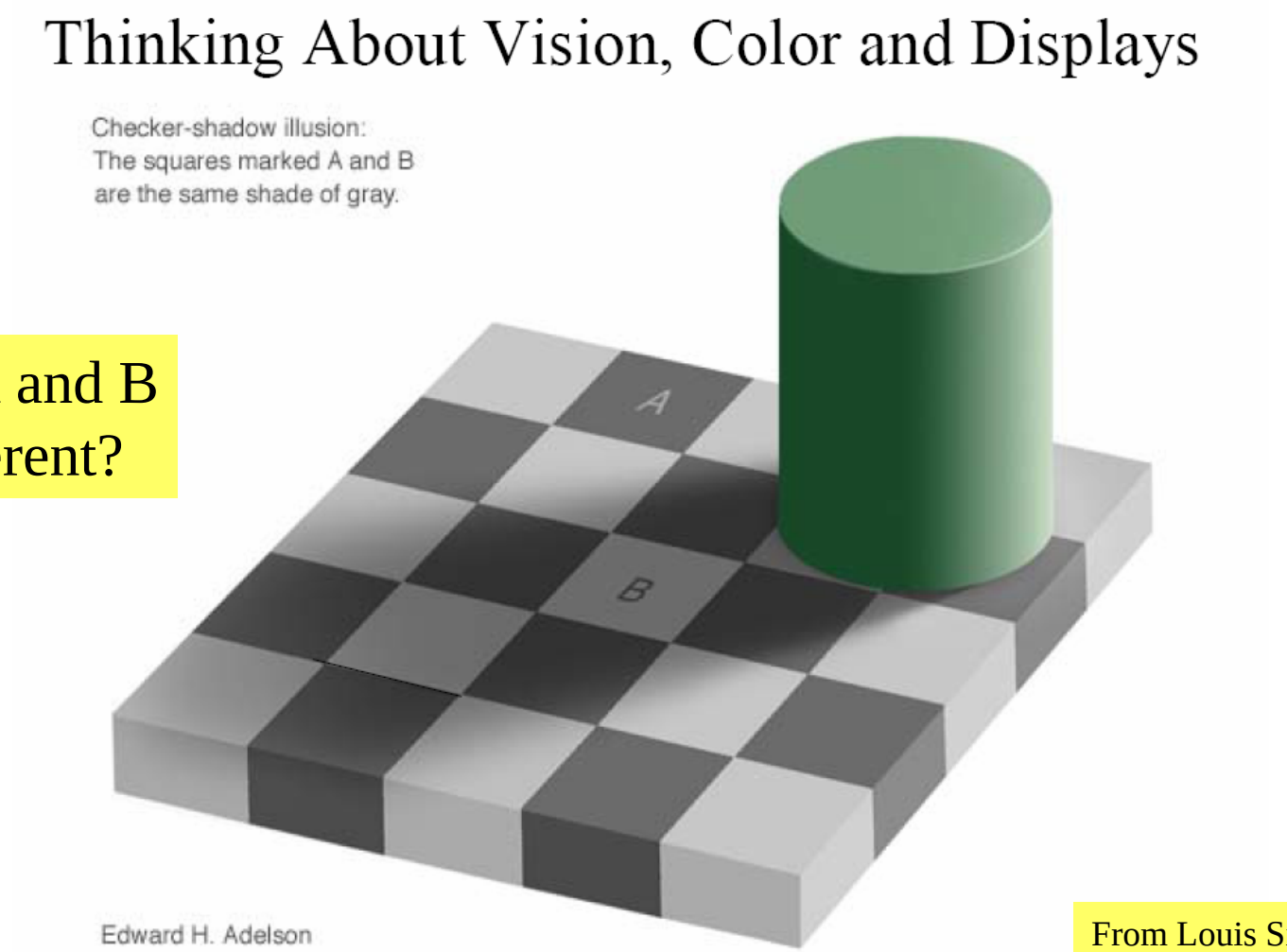
Throughput consideration

1. Why reflector is necessary?
2. What cause throughput loss?

Conclusions

- There remains a lot of issues in radiometry and photometry; but a summary of useful tools has been illustrated here.
- Most important thing is to learn how to estimate throughput
- As an ending of this first lecture, it may be useful to remind you one thing that often mixed with illumination – “vision”
  - Hopefully, you can see the world is larger than you expect

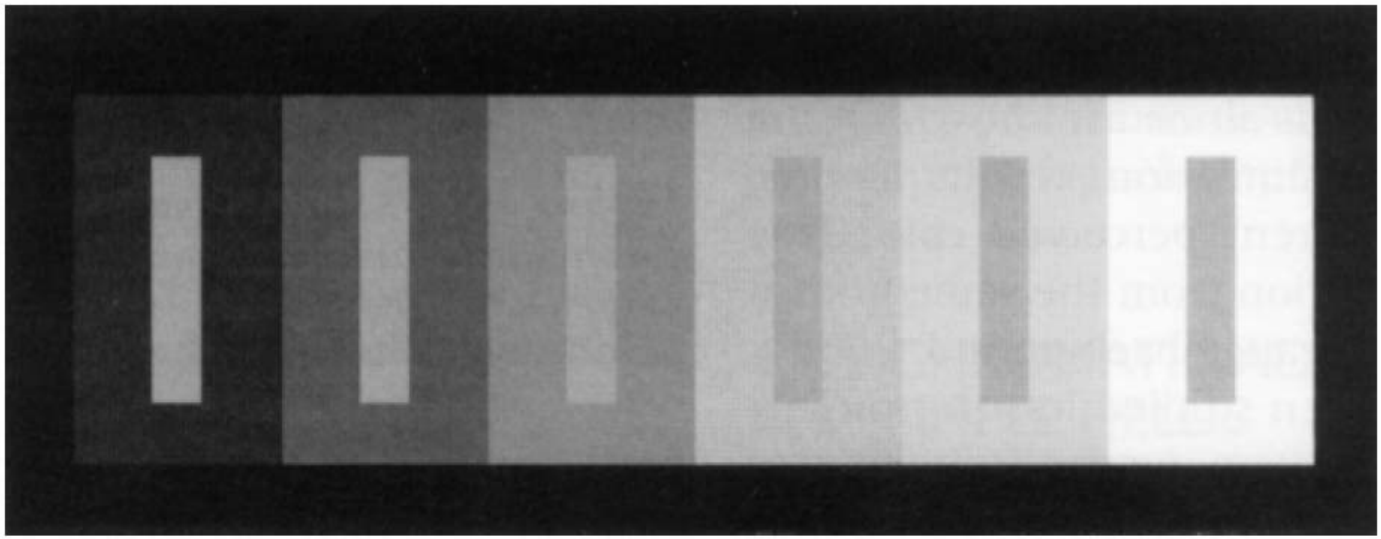
Something beyond illumination



Look at A and B
How different?

From Louis Silverstein

Cont'd 1

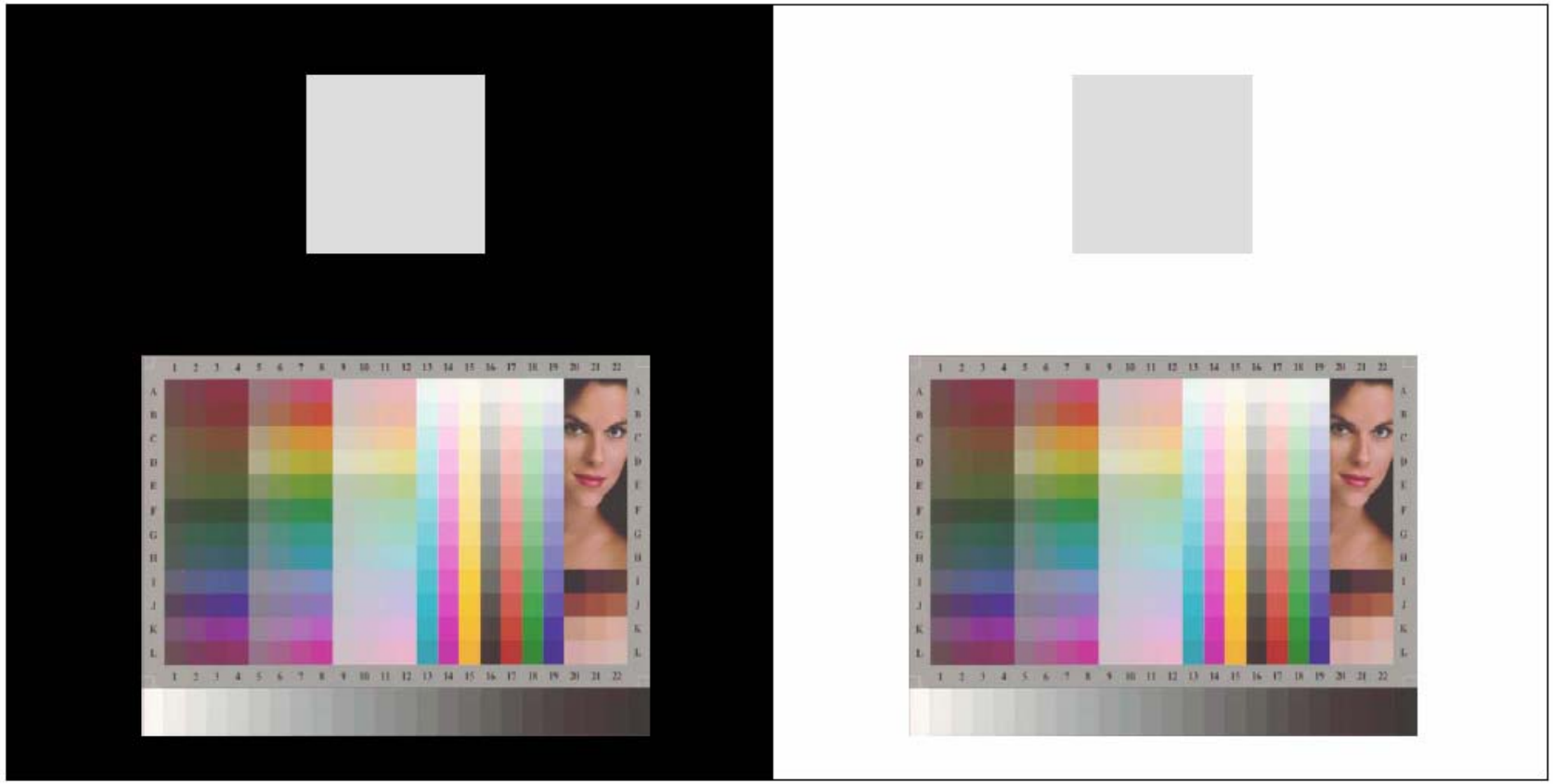


Look at the inside bar

Simultaneous Contrast – The Effects of the Visual Surround on Perceived Brightness

From Louis Silverstein

Cont'd 2



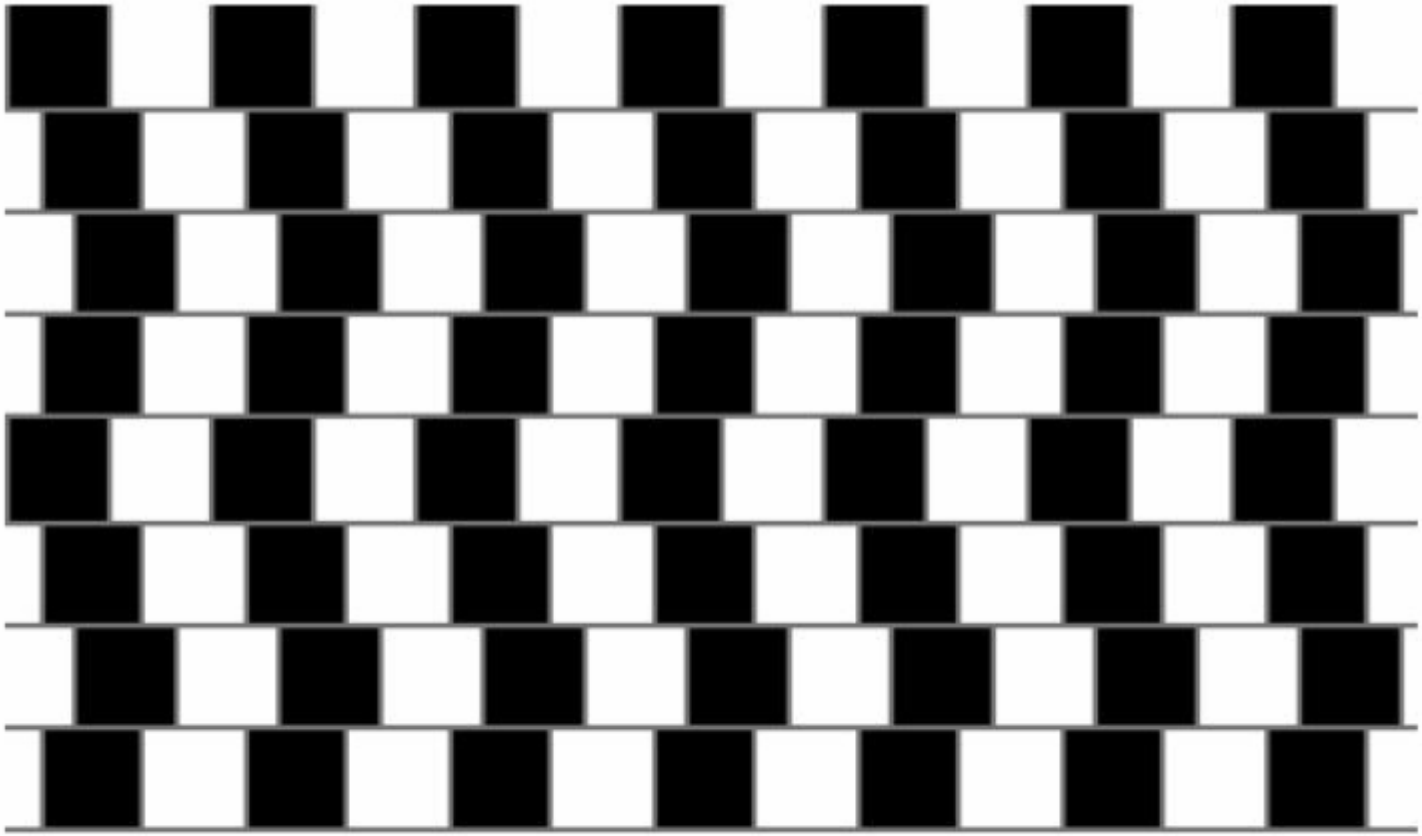
Look at the pattern

Simultaneous Contrast – The Effects of the Visual Surround on Perceived Brightness

From Louis Silverstein

Cont'd 3

Look at lines

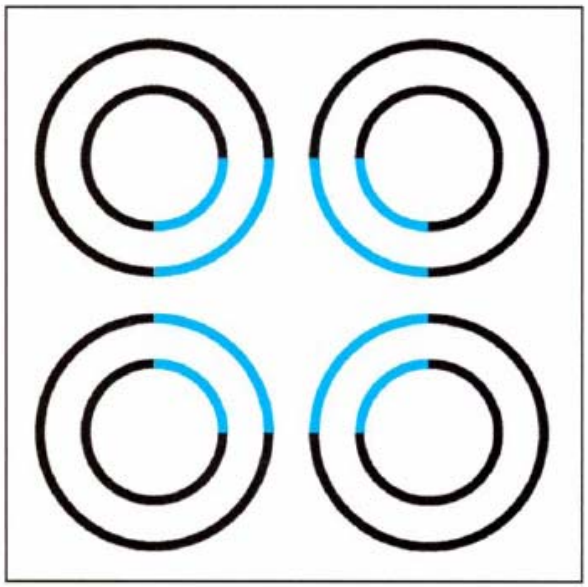


Are the horizontal lines parallel or do they slope?

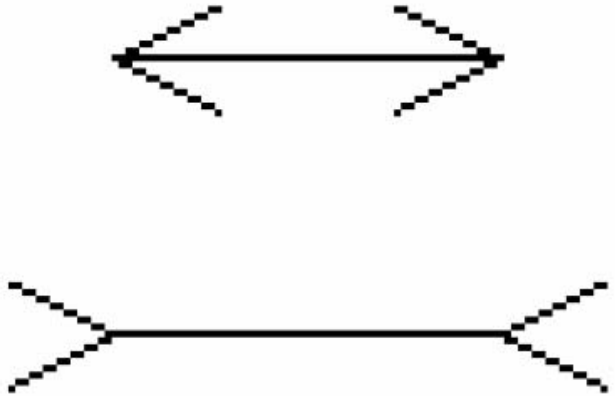
From Louis Silverstein

Cont'd 4

Look at the circles and arrows



Illusory Blue Square

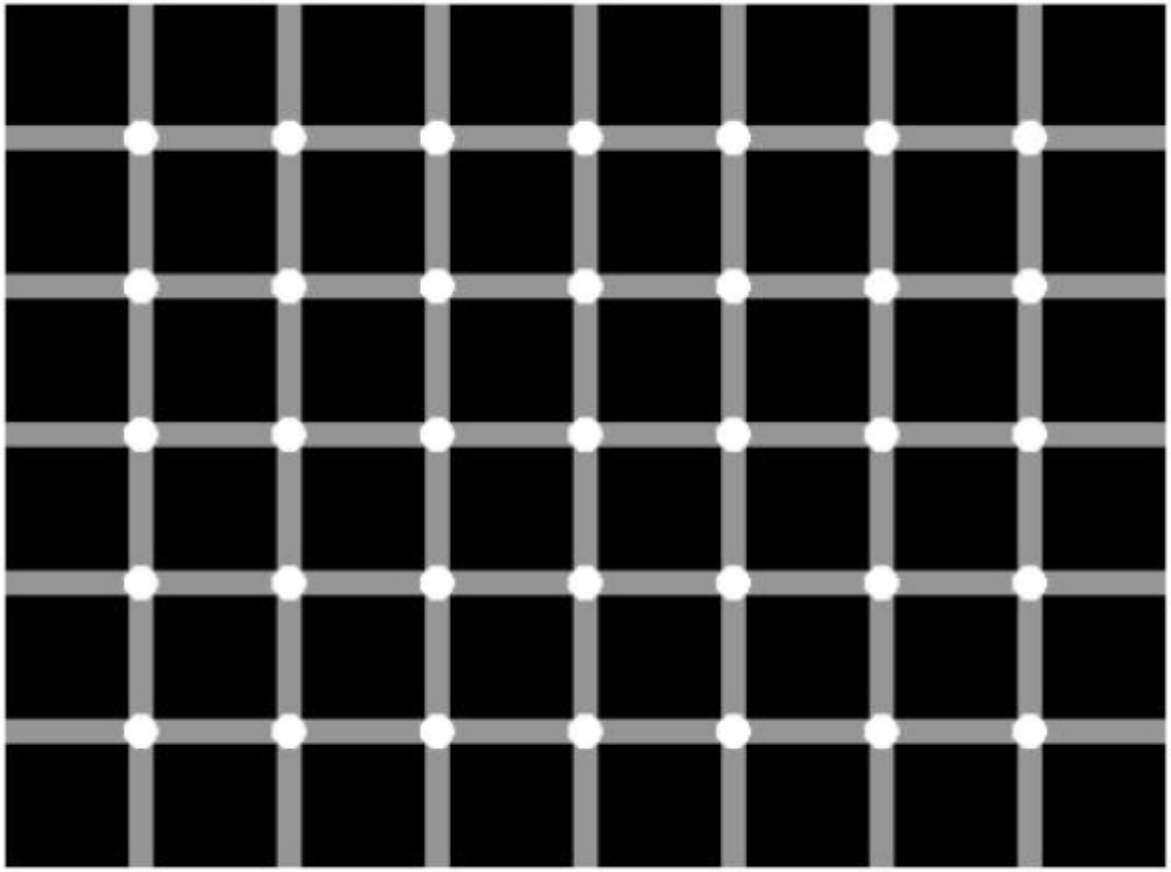


Muller-Lyre Illusion

From Louis Silverstein

Cont'd 5

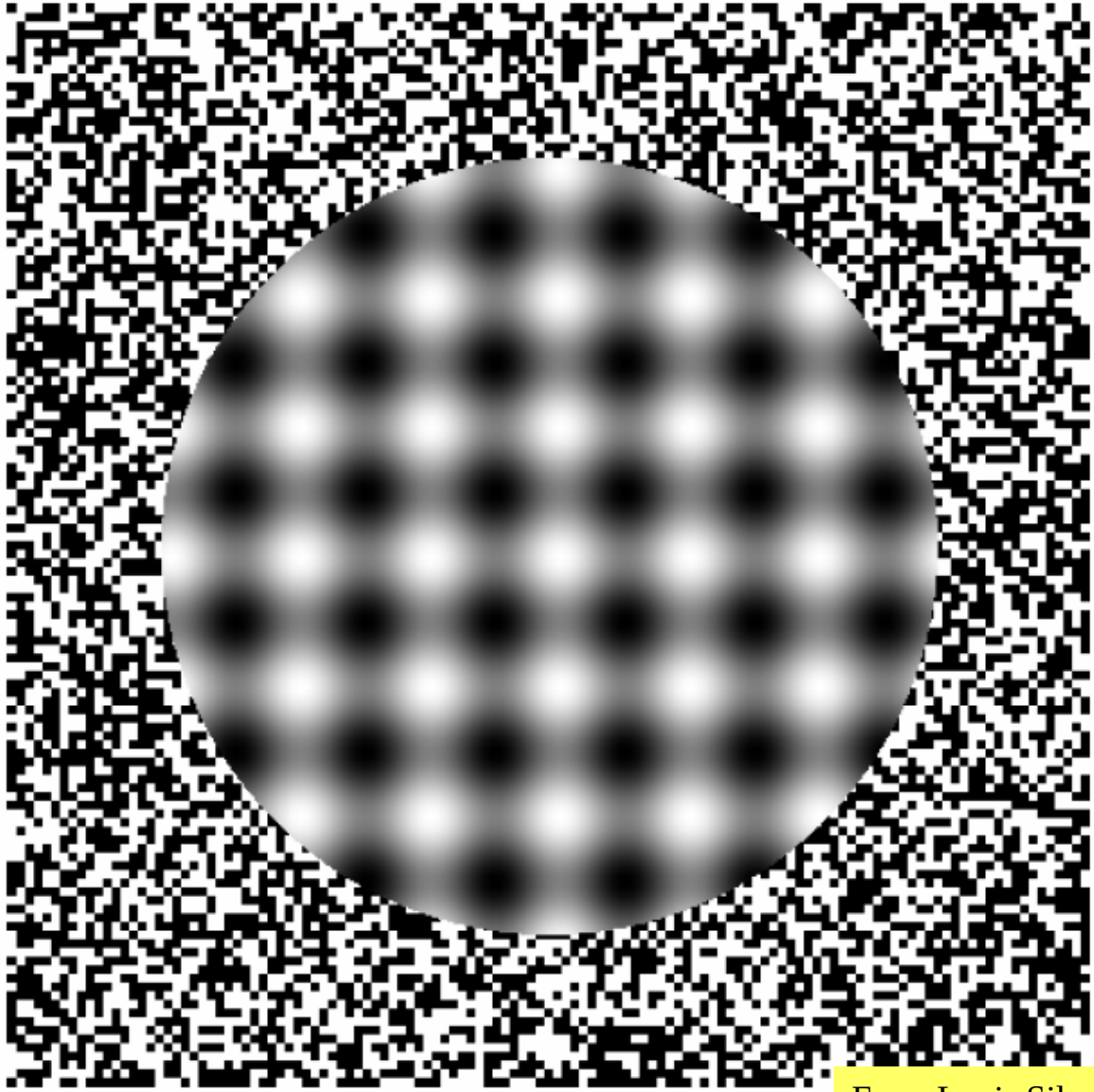
Look at white dots inside



Count The Black Dots

From Louis Silverstein

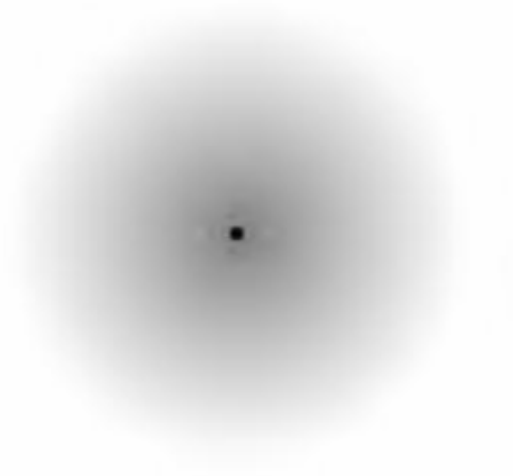
Cont'd 6



Look at how background being separated What is inside

From Louis Silverstein

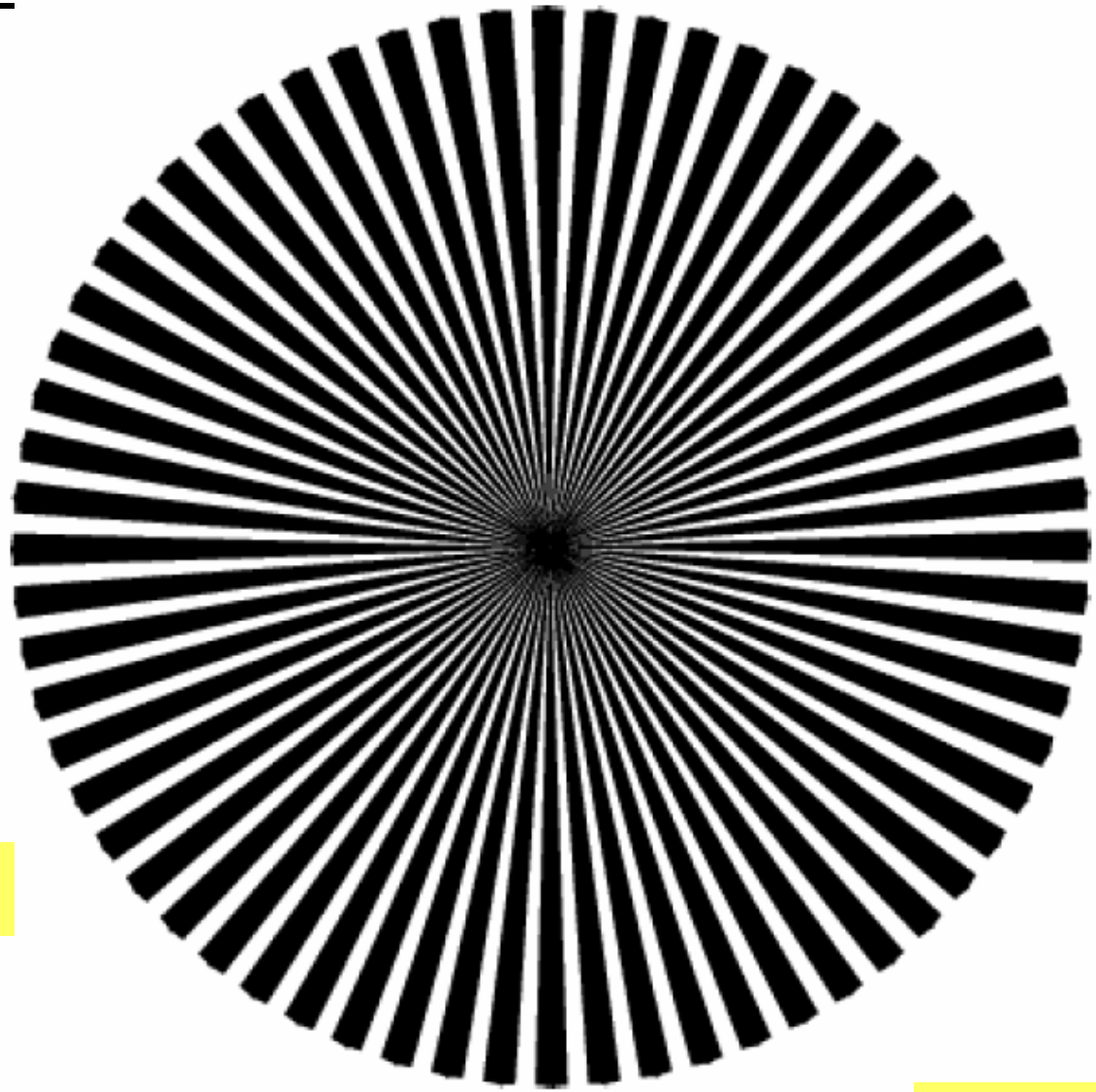
Cont'd 7



Keep staring at the black dot. After a while the gray haze around it will appear to shrink.

From Louis Silverstein

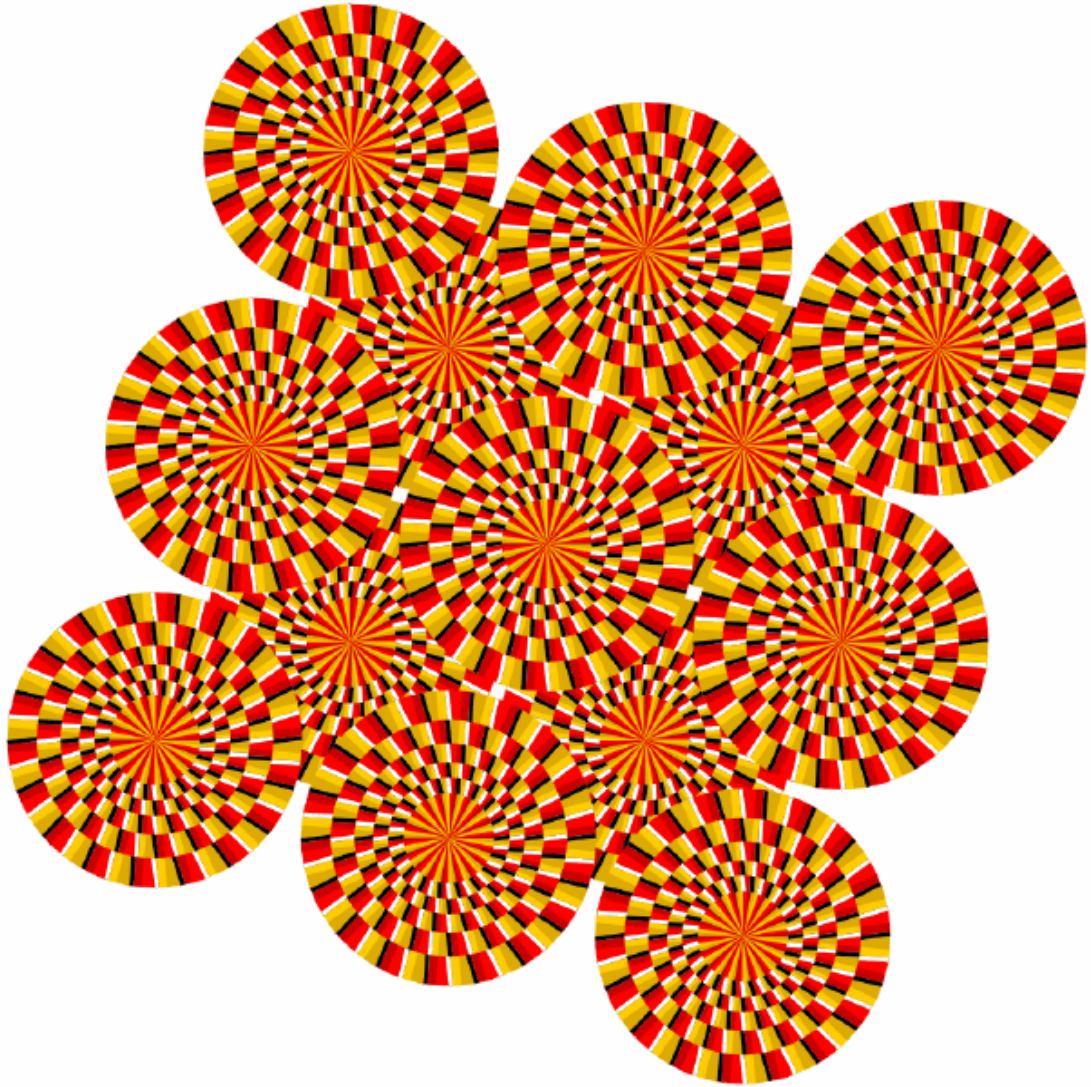
Cont'd 8



Look at inside

From Louis Silverstein

Cont'd 9



Look at the pattern

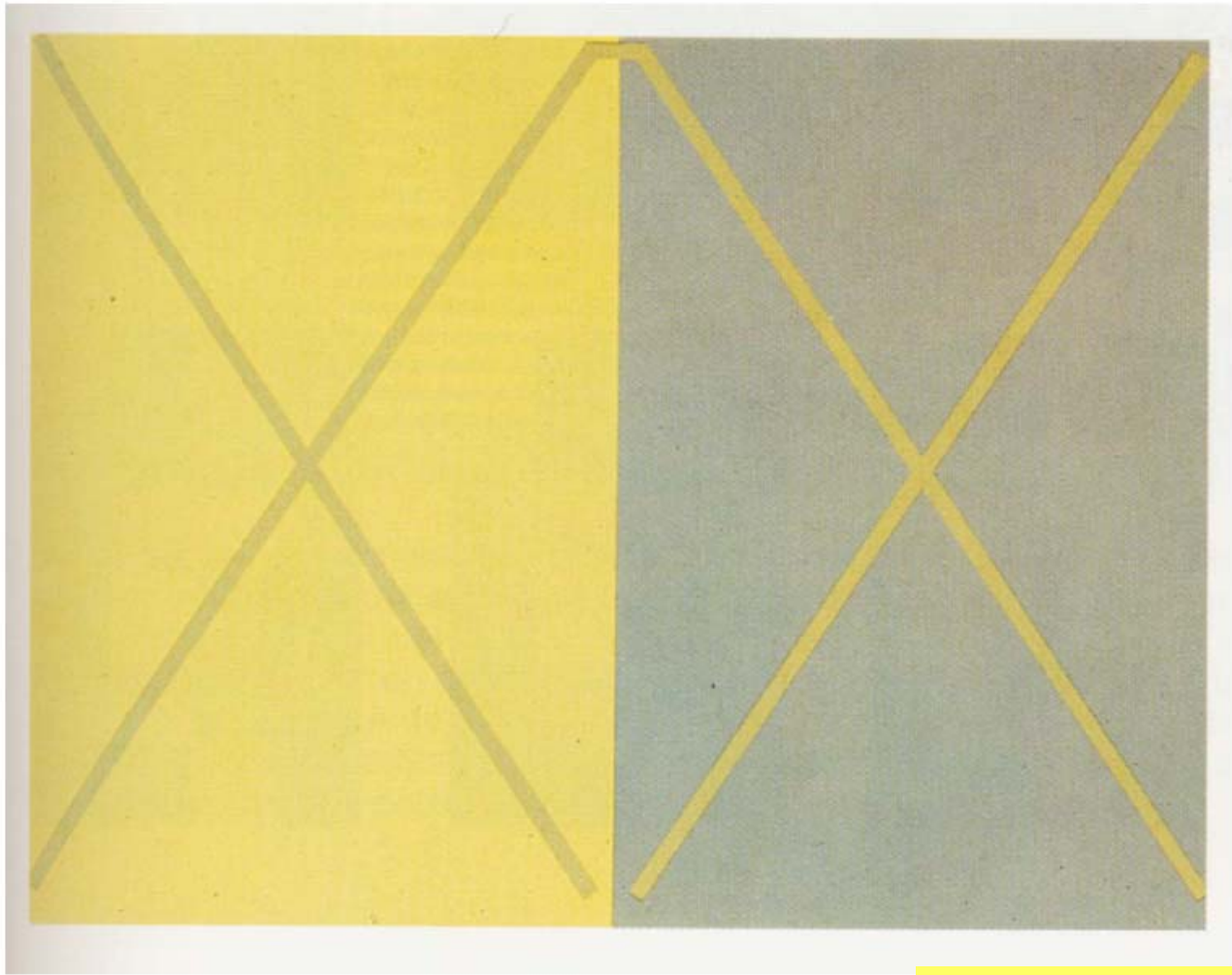
From Louis Silverstein

Cont'd 10

Look at the pattern

From Louis Silverstein

Cont'd 11

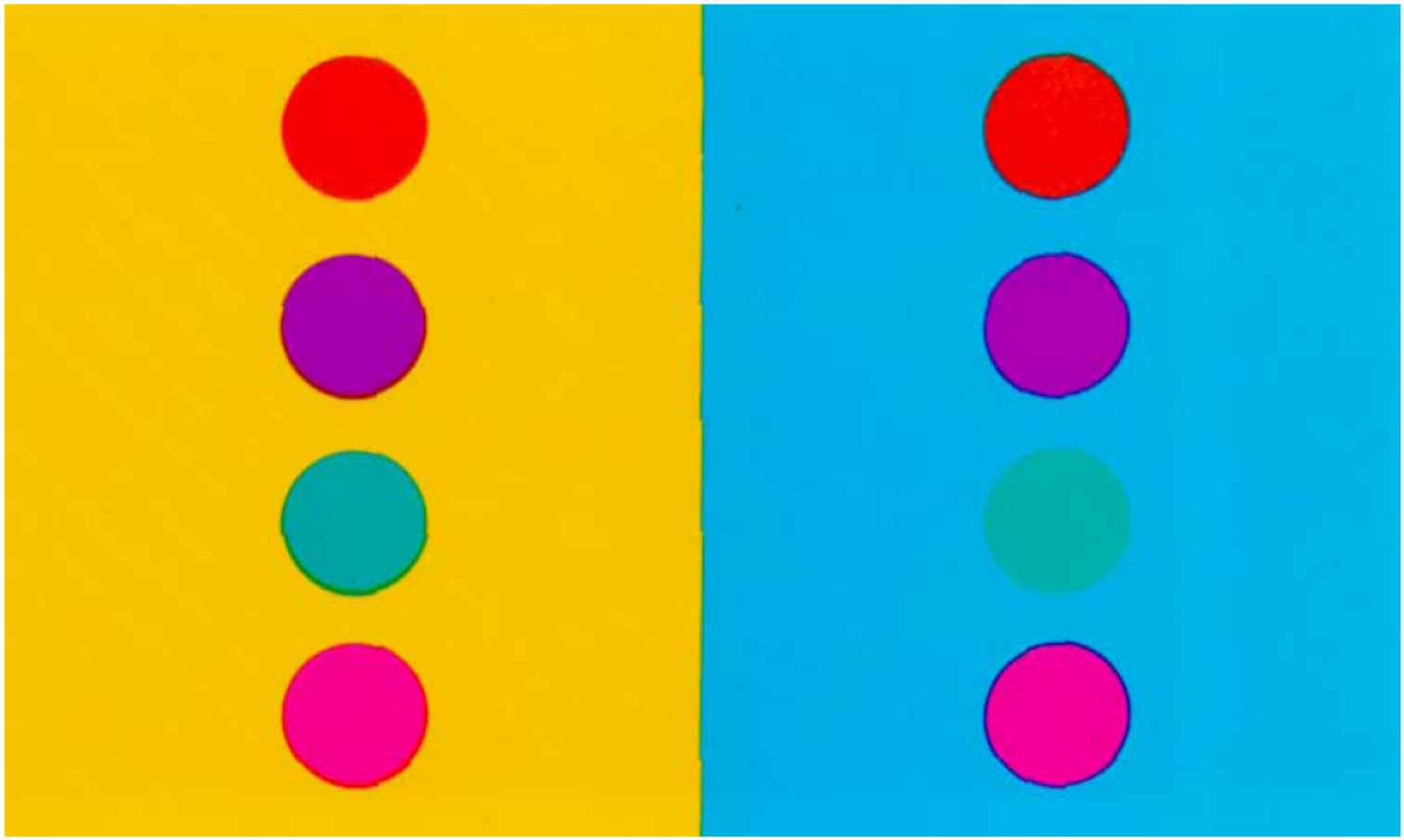


Look at the line

From Louis Silverstein

Cont'd 12

Look at the circles



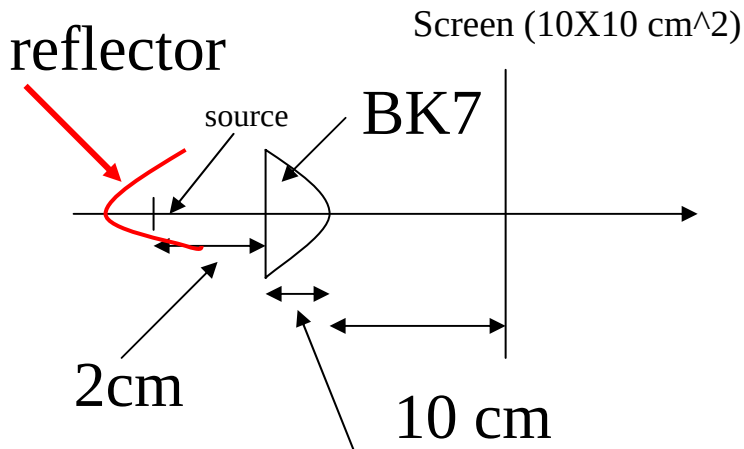
From Louis Silverstein

References:

- Useful literatures can be found from
  - Handbook of applied photometry,edited by C. DeCusatis, (AIP Press, 1997)
- If you want to know more basics, then try
  - G. Brooker, “Optical practicalities: etendue, interferometry, fringe localization,” chapter 11, “Modern Classical Optics,” (Oxford, 2003)
- Classical literature should be referred to
  - R. Kingslake, “Illumination in optical images” chapter 5 in volume II of “Applied Optics and Optical Engineering,” ed. by R. Kingslake
    - This is a very old reference but useful.

Homework 1

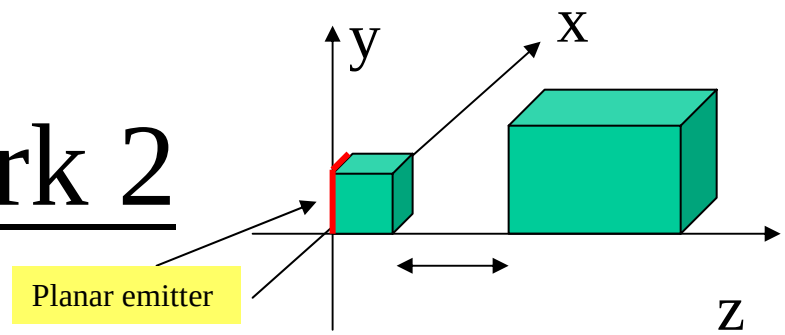
1. Select a commercial condenser
   - ➢ If not available, set the following lens
2. Set a Lambertian source, 1 mm X 1mm
3. Calculate the throughput efficiency of the lens
4. Try to employ a reflector to improve the efficiency
   - ❑ Only a specular reflector is considered here
     - ❑ Perfect reflector
5. Verify by TracePro simulation



CT: 1.5 cm
(CT: center thickness)
R: 1.5 cm
(R: radius of curvature)
CA: 2.54 cm
(CA: clear aperture)

$$\phi = \frac{1}{f} = (n-1)[\frac{1}{r_1} - \frac{1}{r_2} + \frac{t(n-1)}{r_1 r_2 n}]$$

Homework 2



- Consider two tubes as with the following specification
  - 1.0X1.0X1.0 cm^3 (a cube) (wall thickness 0.1 mm)
  - 2.0X2.0X5.0 cm^3 (a rectangular tube) (wall thickness 0.1 mm)
    - Assume all walls with 1.0% absorption loss
  - Assume that the two tubes are away from 2 cm and one planar Lambertian light source (1X1 cm^2) right on the surface of the first cube with total 1.0W emission power
    - ❑light emitting area can reflect rays but with 30% loss
  - ❑You are asked to estimate the throughput right after first cube
  - ❑You are asked to figure out at least three different ways of coupling solution such that the light can be relay to second tube and then estimate the throughput right after the second tube

Homework 3

- This homework is rather advanced
- In the book of G. Brooker, a lengthy discussion, that illustrated in several exercises and even several sections, shows how to extend the concept of etendue to physical optics and to improve the design of interferometer . It is known that a light beam can be decomposed into longitudinal and transverse modes. You are asked to deduce the following relation:

$$\text{(number of transverse modes occupied)} = \frac{etendue}{\lambda^2}$$

G. Brooker, Modern classical optics, Oxford, (2003)
See chapter 11