Computational Photography

Independent Study Presentation 1:

Introduction to Computational Photography and Optics

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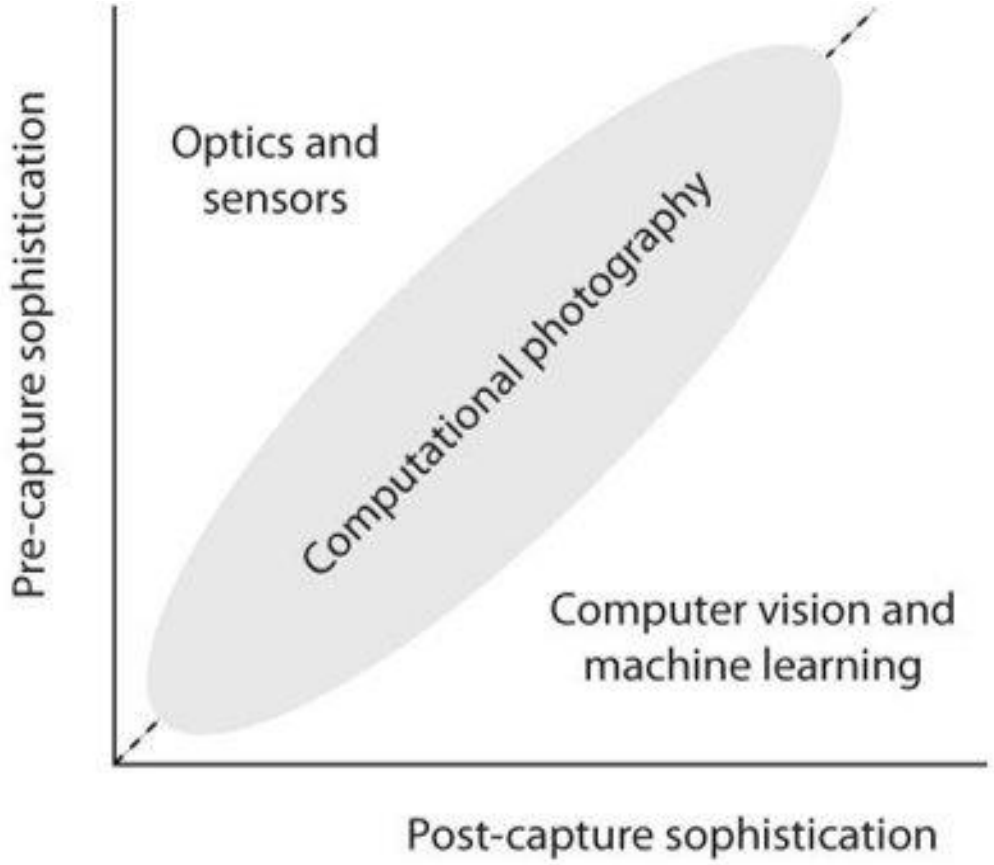
Overview of the Presentation

Introduction to Computational Photography	Components of Computational Photography Stages of Computational Photography
Understanding Light	Wave and Particle Nature of light
Defining Optical System with Rays	Measuring the light rays-Radiometry and Photometry Interaction of Light and Matter
Understanding Lenses and Digital cameras*	Optics of Lens and Ray bending Lens and Digital Camera Parameters and Trade-Offs
Conclusion	Future of Computational Photgraphy References

Introduction to Computational Photography

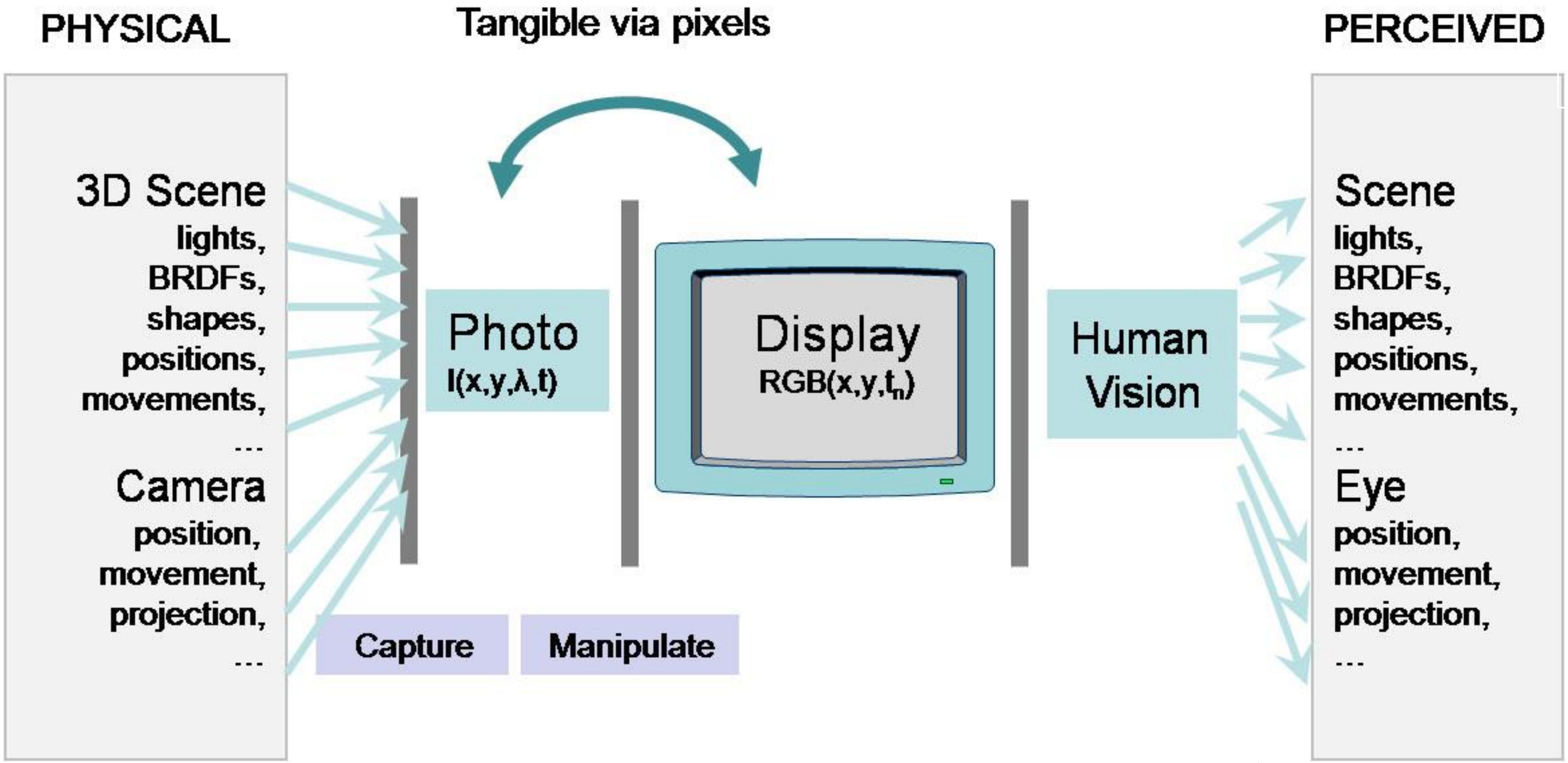
Definition and Origin of Computational Photography



Computational Photography captures a machine-readable representation of the physical world, allowing us to hyper-realistically synthesize the essence of our visual experience.

Image Credit: Raskar Tumblin Computational Photography

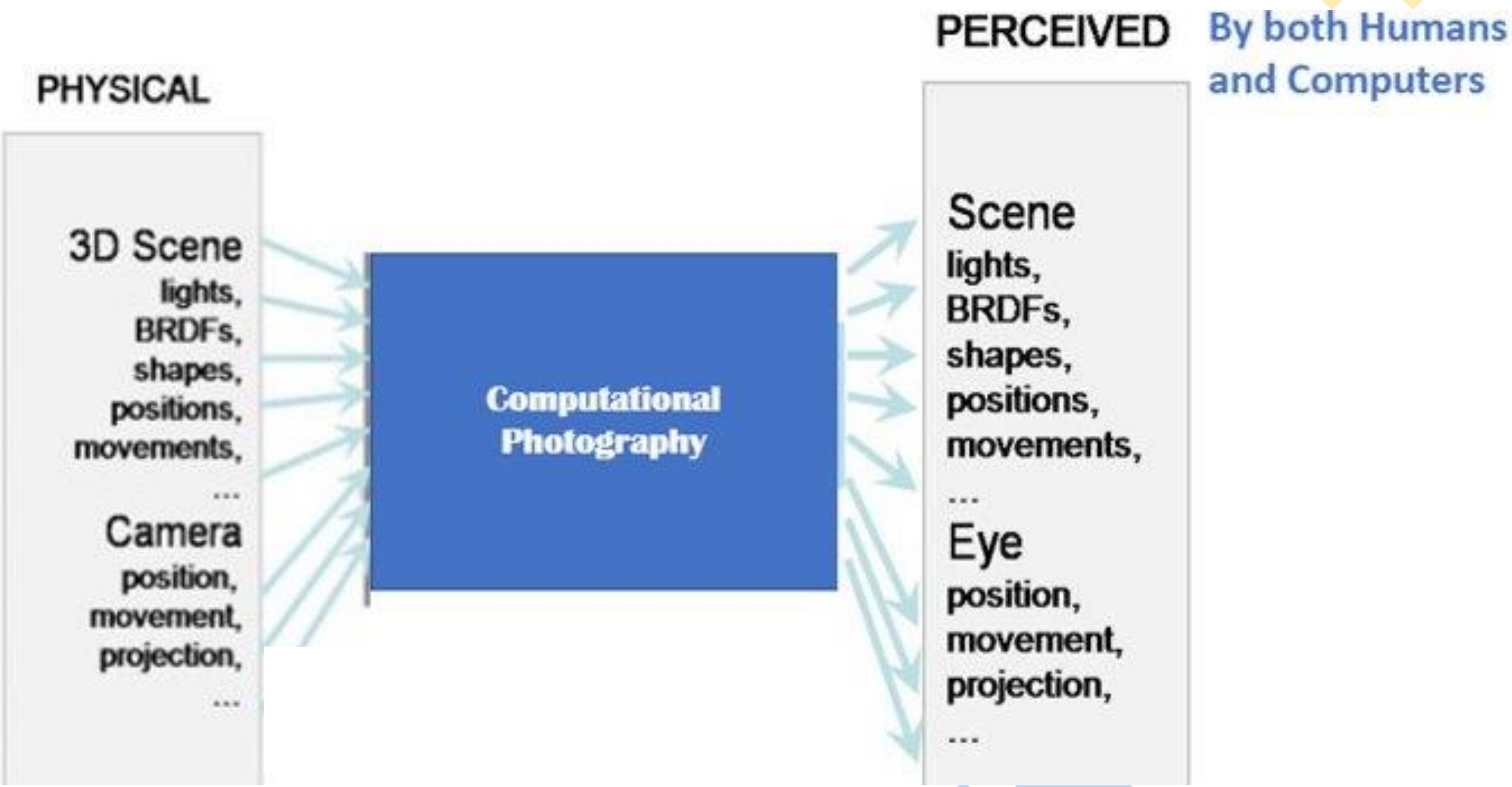
Digital Photography



Only by the humans

Image Credit: Raskar Tumblin Computational Photography

Computational Photography



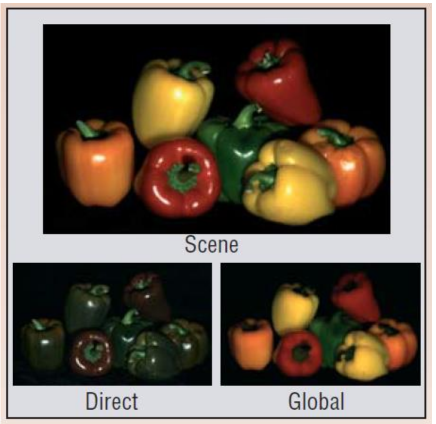
What Computational Photography Enables:

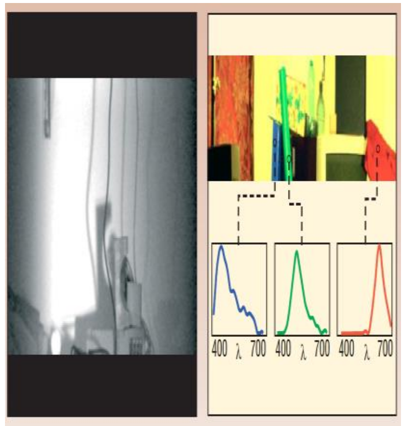
To Create New Visual Information from a given scene e.g. Creating Global and Direct Component of a scene

To Construct New Visual Information e.g. 360 degree view from a single point and single camera

To Measure already present Visual Information e.g. Observing multiple EM frequencies present in the scene

To Manipulate Visual Information e.g. Relighting the images and Creating the new viewpoints





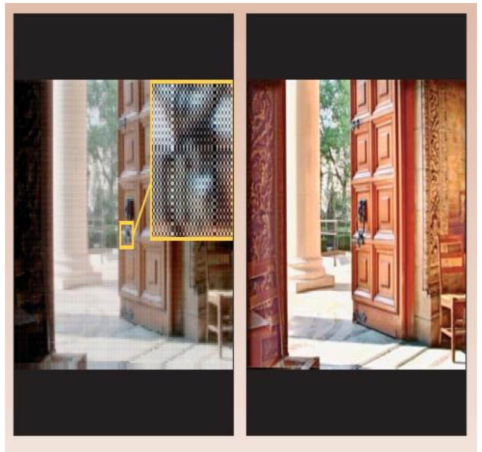
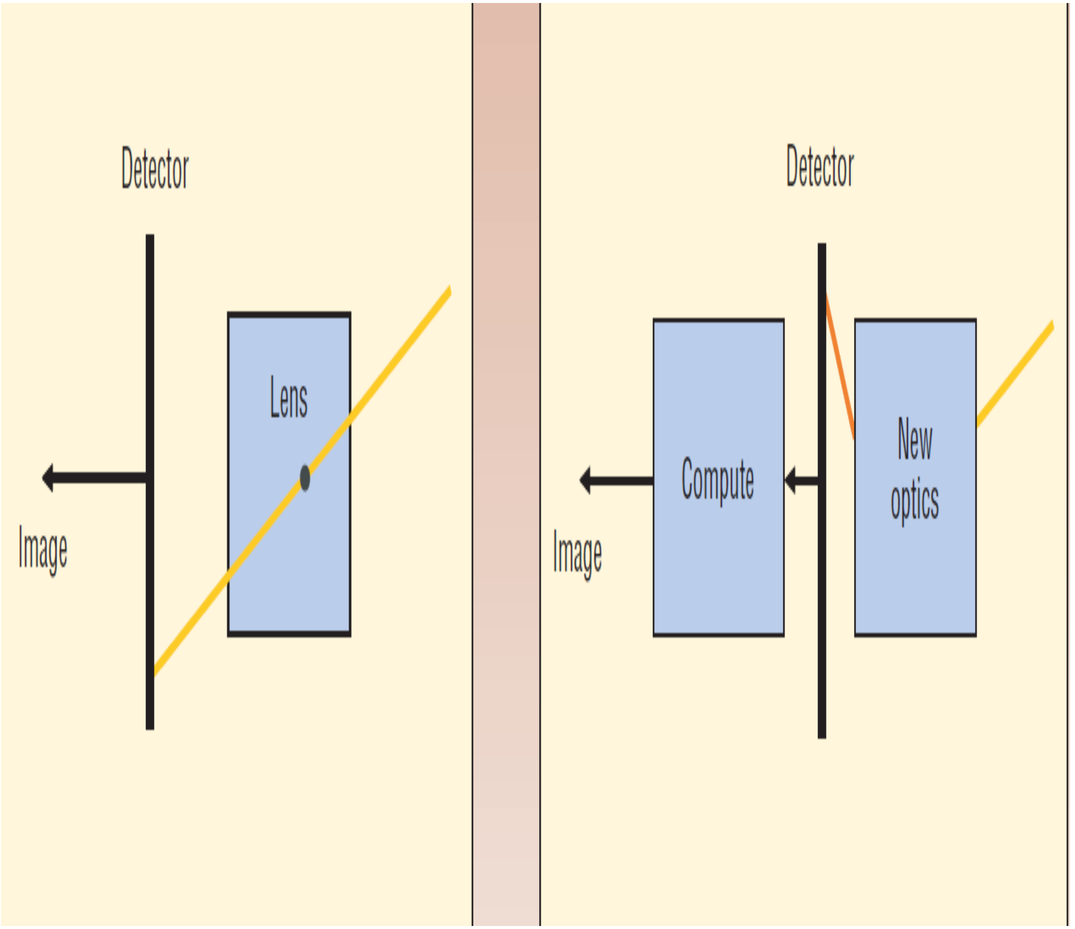


Image Credit: Computational Cameras, Shree K Nayar

How Computational Photography Does so?



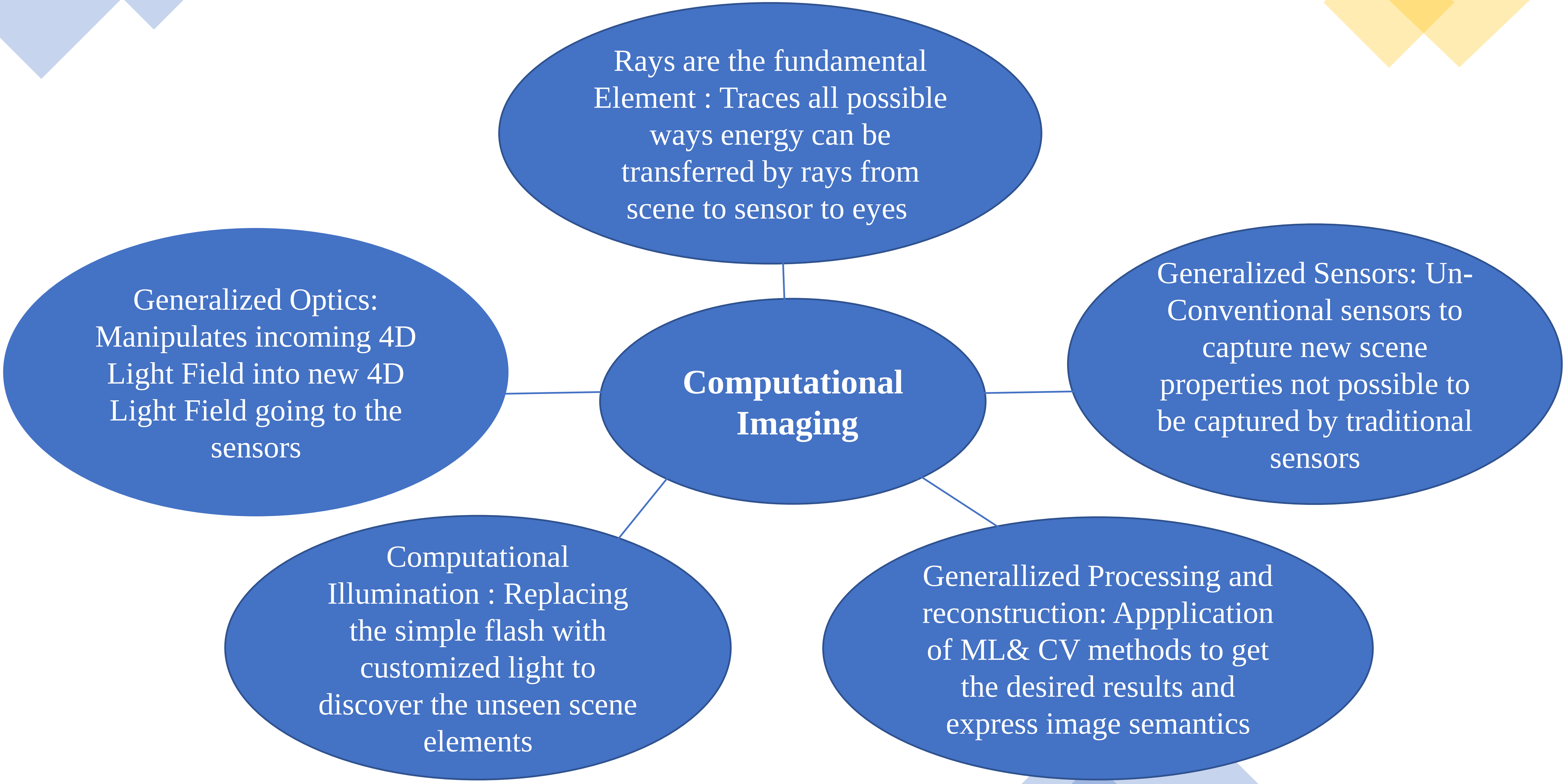
Digital Photography **Computational Photography**

It replaces the

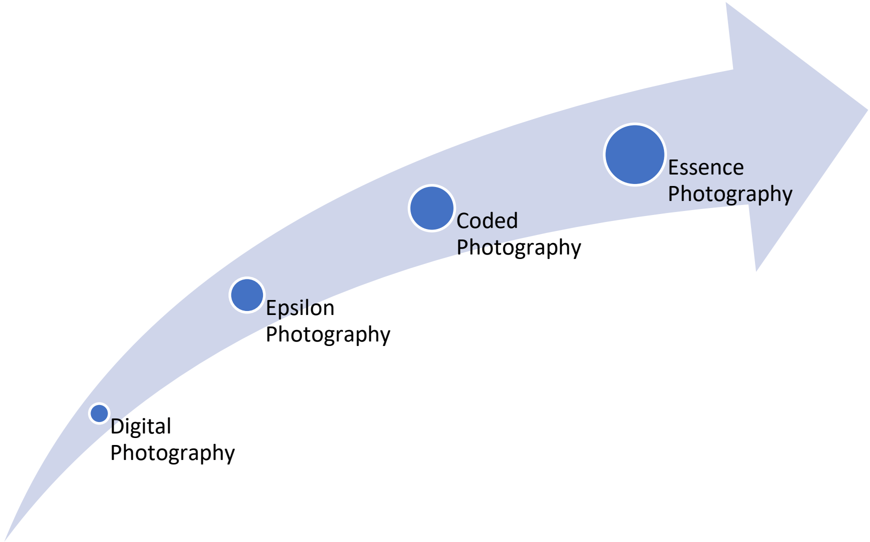
- Lens with Generalized Optics
- Sensor with Generalized sensor
- Natural Light and Flashlight with Programmable Illumination
- Incorporates Processing Computational Algorithm before giving out the final Image.

Image Credit: Computational Cameras, Shree K Nayar

Components of Computational Photography



Stages of Computational Photography



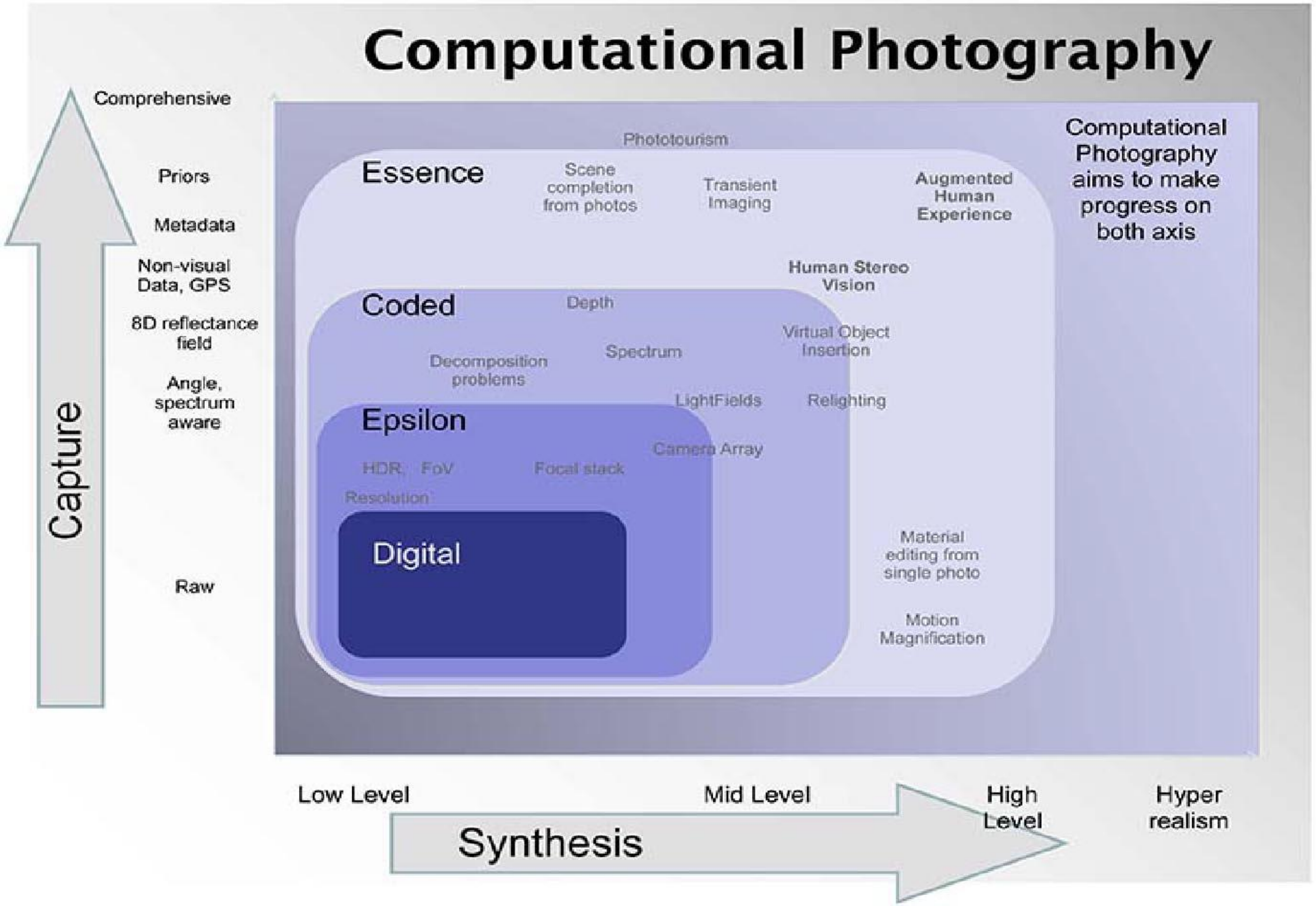


Image Credit: Raskar Tumblin Computational Photography

Film-like Digital Photography

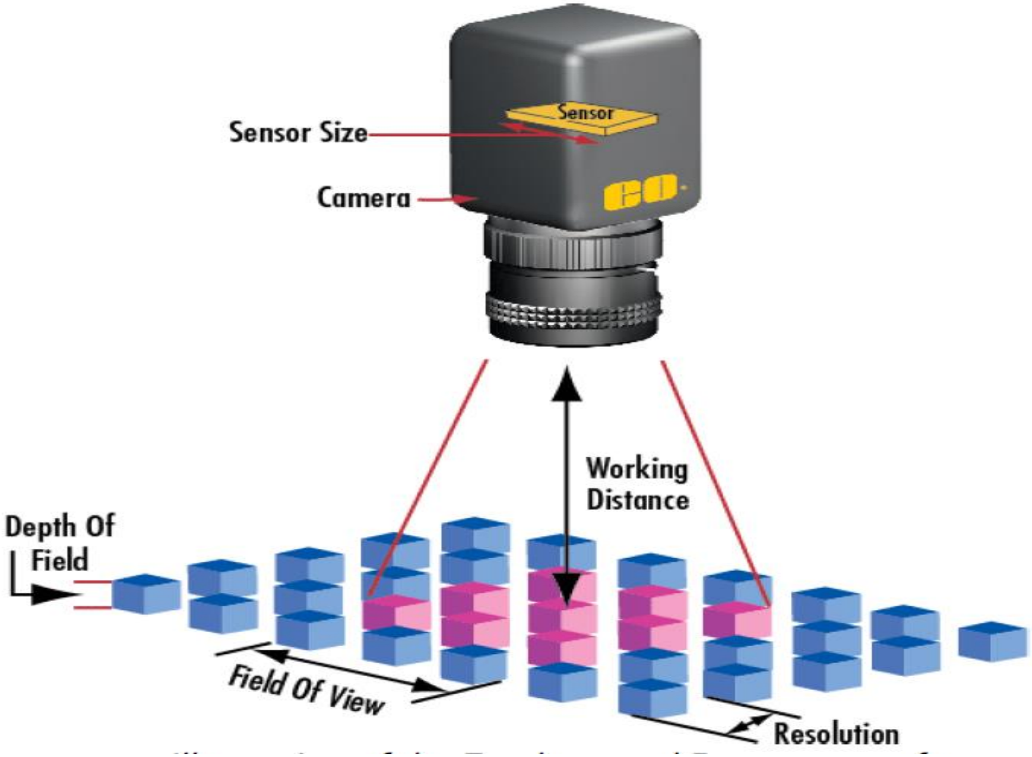
Basic Structure and Components

Component	Purpose
Camera Obscura Structure	To admit light in a dark box and forming image on a plane inside the box
Lens	To control aperture ,focus distance and focal length
Sensor	To control light sensitivity, latitude and color sensing
Camera Box	To control moment of exposure, location and orientation
Auxiliary Lighting	To control position, intensity and timing of illumination

Film-like Digital Photography

Parameters to be decided while clicking a Digital Photograph

- Field of View
- Exposure & Dynamic Range
- Depth of Field
- Spatial Resolution
- Temporal Resolution
- Wavelength Resolution



Digital Camera and Trade-Offs

Larger the focal length larger the PMAG but smaller the field of view

Shorter the focal length larger the field of view but more distortions and cost of lens

Larger the Focal Length and aperture more is the light admitted for dimly lit scene but smaller the FOV

Increasing Depth of Focus requires smaller aperture hence increased exposure time and higher sensor sensitivity leading to higher noise

Higher the Spatial resolution smaller the pixel size larger the data storage requirements

Exposure time too large moving objects appear blurred and when too short then less amount of light gets captured

Higher the spatial resolution poorer is Depth of Focus

Larger lens apertures gather more light, but reduce the depth of focus in the image

A longer exposure time, additional scene lighting, or greater sensitivity makes brighter pictures. But a longer exposure time can increase blur, additional lighting can disrupt scene appearance, and greater sensitivity results in increased noise.

Epsilon Photography

It improves a given image by recording multiple images each varying one or more camera parameter by some small amount epsilon.

Each epsilon setting allows partial information of the scene which is combined to give a better scene representation.

This stage involves low level processing of pixels and localized scene features.

Goal: To enhance the performance of traditional parameters of the camera and go beyond their mutual trade-offs

How Epsilon Photography improves the Digital Camera Parameters

Field of View

- It can be enhanced by creating image panorama by stitching images of overlapping regions

Exposure & Dynamic Range

- Can be improved by Exposure bracketting and calculating normalized pixel value

Depth of Field

- Can be enhanced by combining images with different plane of focus

Spatial Resolution

- Higher Spatial resolution can be obtained tiling multiple cameras and assembling spatially varying mosaic form

Temporal Resolution

- High speed imaging is attained by staggering the exposure time of multiple low frame rate camera

Wavelength Resolution

- Expands wavelength resolution by successively changing the color filter in front of the camera during exposure

Coded Photography

Coded Photography tries to go beyond the Digital Camera capabilities

Unlike Epsilon Photography Coded Photography captures mid-level cues like shape,boundary,depth etc along with pixels

Goal: To estimate scene properties that are not directly visible and are critical for post capture manipulation and synthesis

Coded Photography is an out of box photgraphic method in which individual ray sample or data set may not be comprehensible without further re-binning decoding and reconstruction

Some Examples of Coded Photography

Decomposition of Scene in meaningful components such as Global Direct Component ,Foreground and background Components etc.

Coded Exposure Technique to capture fast moving object which otherwise appears blurry

Gradient Camera for higher Dynamic Range

Confocal Synthetic Aperture to see through murky water

Coded Aperture Technique to re-focus the out of focus region by preserving the high spatial frequencies of light

Techniques to recover the glare by capturing selected ray through a calibrated grid

Using Multiple flashes to distinguish b/w geometric and reflectance boundaries of the object

Essence Photography

In this photography measurements goes beyond radiometric quantities of the scene.

Goal: To capture the essence of a scene and scruitinize its perceptually critical components.

A camera equipped with essence photography may-

- Measure Geographical location coordinates of the scene
- Identifies Scene Contents
- Recognizes Gestures
- Can perform non-photorealistic synthesis like motion exaggeration, beautification of photographs etc.

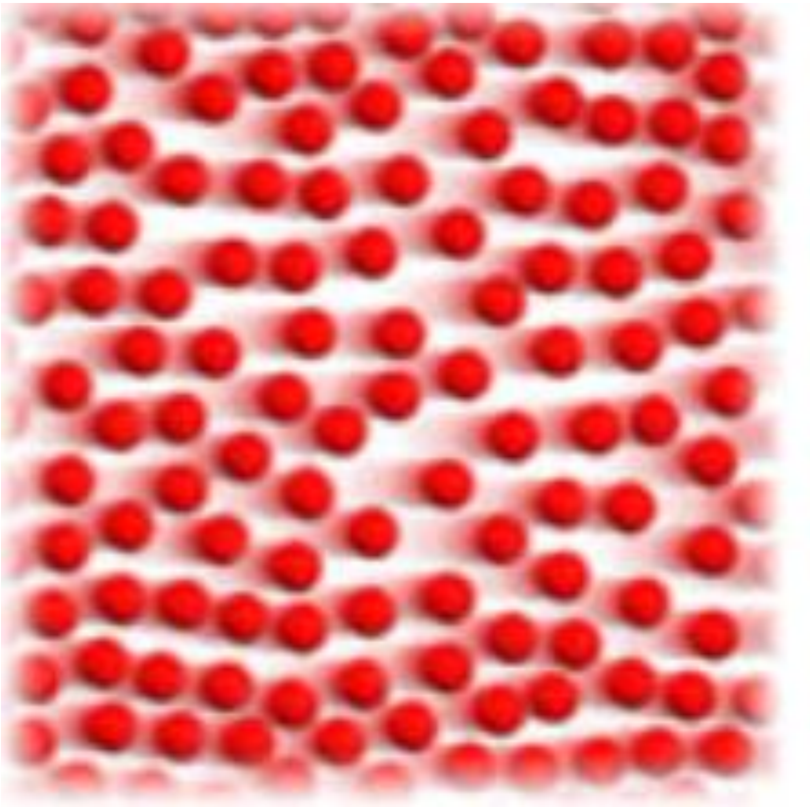
Hence, Computational Photography enables us to capture what we want to capture rather than what we can capture!!!

Understanding Light

Scientific Theories about the Nature of the Light

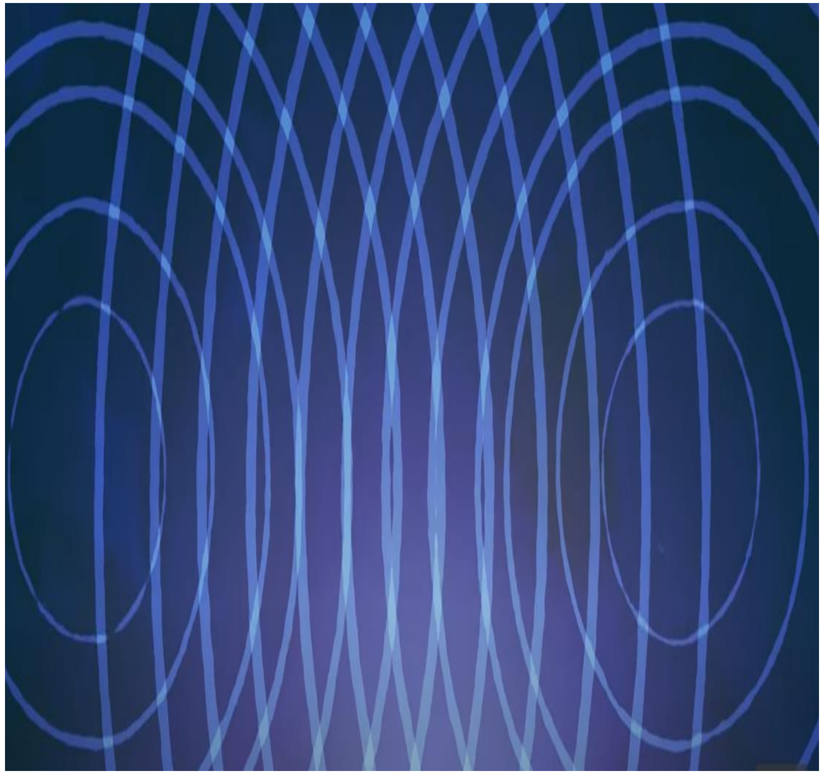
Two Conflicting Approaches:

Light is made up of Particles

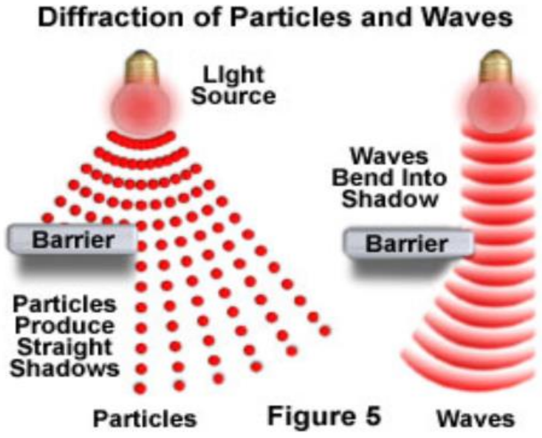


VS

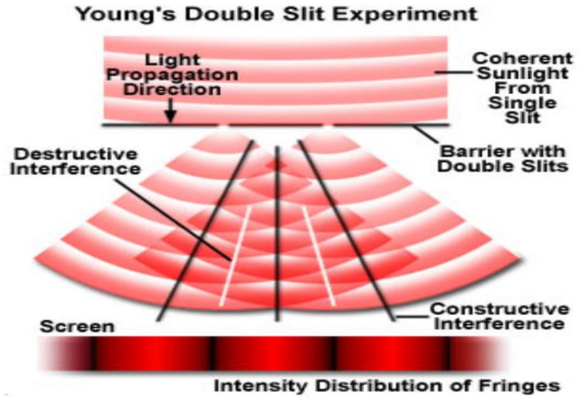
Light is made up of Waves



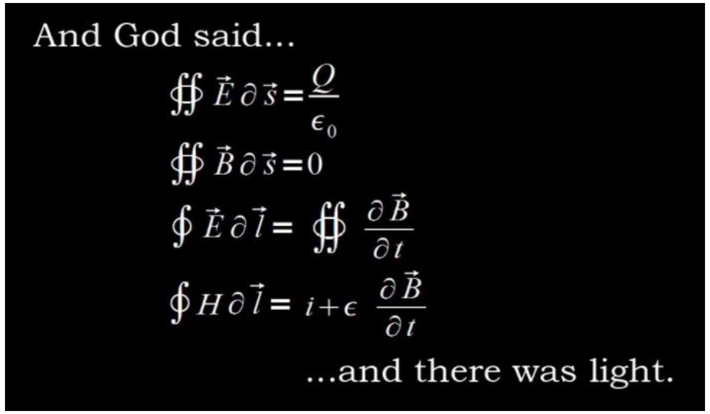
Phenomena and Experiments Demonstrating Wave Nature of Light



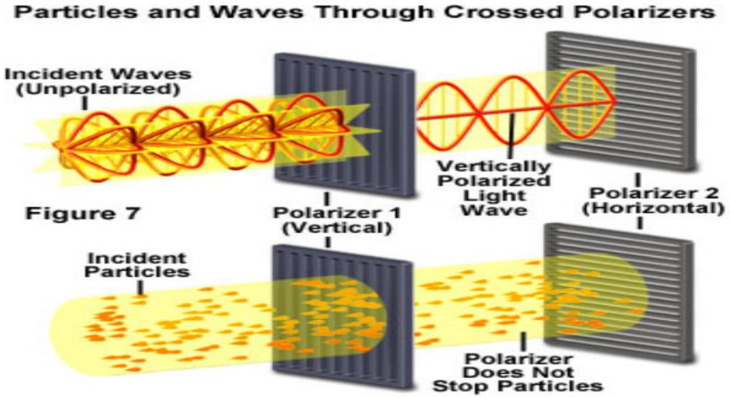
Diffraction of Light



Interference of Light as Waves

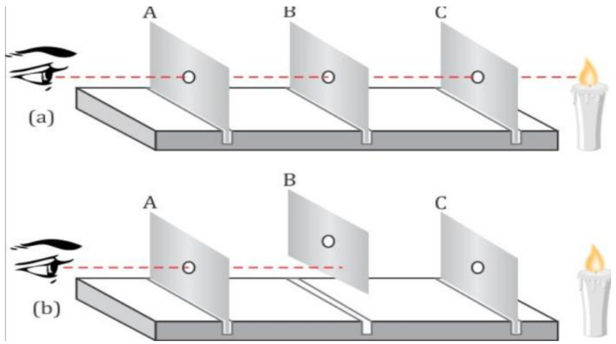


Maxwell's Equation for Wave Propagation

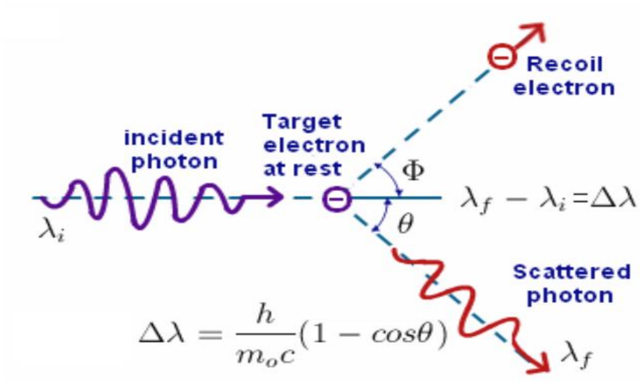


Polarizers filtering the Light

Phenomena and Experiments Demonstrating Particle Nature of Light

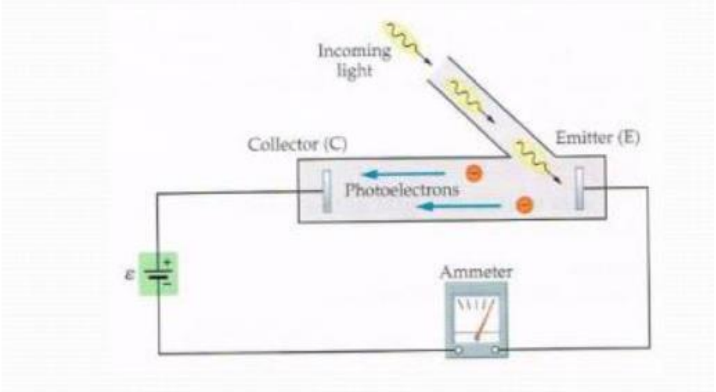


Light travels in a straight-line path



Compton Scattering

Black body radiation explanation



Photoelectric Effect

Conclusions about the Nature of the Light

Light exhibits wave-particle duality

Light behaves as a wave at macroscopic scales, but it behaves as a particle at atomic scales.

Maxwell's equations are sufficient when there are many photons, and quantum theory is necessary when there are only a few photons.

Light propagates as a wave, but it interacts with matter as a particle when the matter is of comparable size as the wavelegth of the wave.

Defining Optical System with Rays

Understanding the Ray Space

What is a Ray intuitively?

- It is a 2-way tracing through space which a single photon might leave behind as it propagates
- It is a simplified model of wave nature,representing wave as a straight line

Formal Definition of Ray Space

- We define Ray Space/Plenoptic 4D position-angle function to identify every ray in 3D space
- **2 dimensions for position on the plane** it is being imaged **and 2 dimensions for the** incidence angle.
- Other dimensions such as polarization and wavelngth etc. Characterizing the ray can be added

Why Rays?

- Helps explore complex Optical System locally
- Decomposition of every optical operation as a ray bending event
- Ray paths are exactly reversible, so ray tracing helps to characterize any physical space.

Challenges and Solution for Ray based measurements

What is the basic challenge in measuring the rays?

- One single ray doesn't exist in isolation and carries non-measurable amount of Light.
- Its angular extent is zero and it comes from a single point on source with zero area.

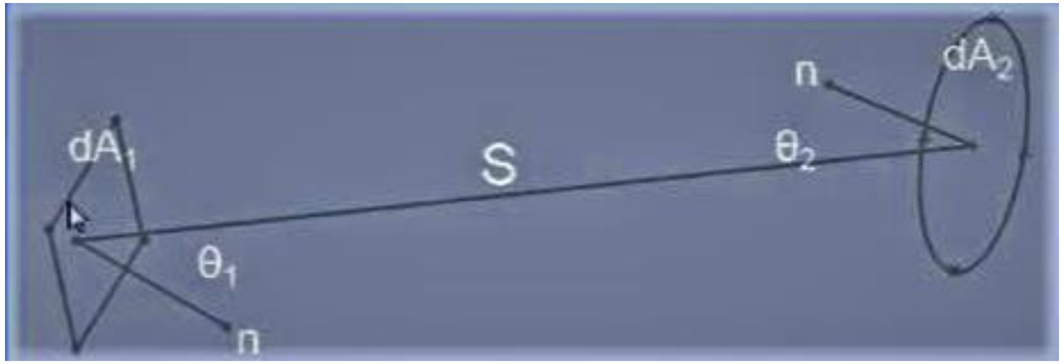
Solution

- We can measure the strength of the Light carried by bundle of rays instead of dealing with single ray
- Strength of Light can be measured in terms of Power and Energy leaving the source and reaching the destination in terms of rays
- This field which measures the Light Rays are referred as Radiometry and Photometry.

Radiometry

Radiometry is the process of measuring the EM radiation which includes visible range also
While
Photometry is the process of measuring the visible light radiations as experienced by human eyes. It's a normalized form of Radiometry for human vision.

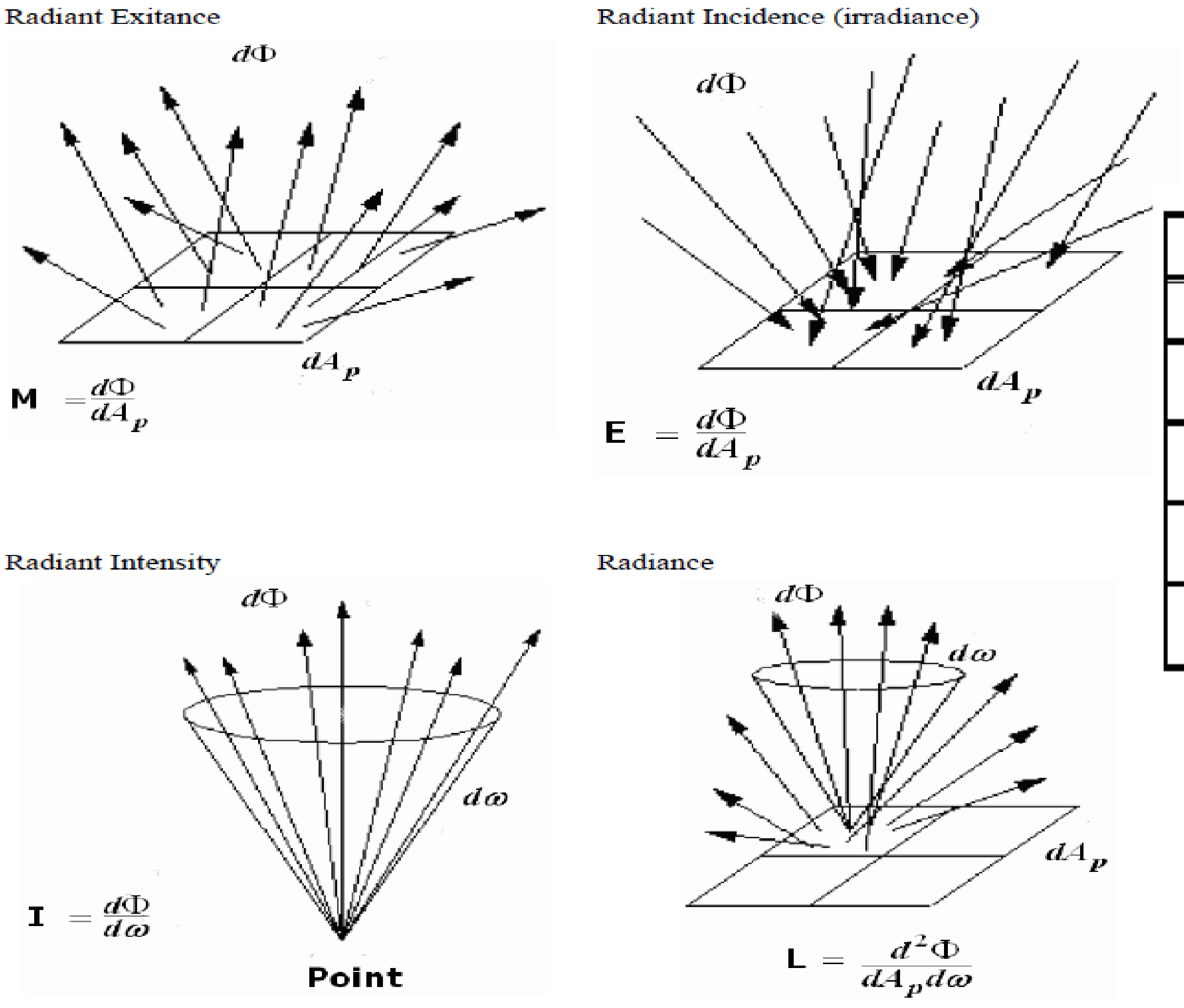
What we want to measure is How much energy from source area dA1 was captured by destination area dA2 per second



Fundamental Law of Radiative Transfer

$$\Phi = \int_{A_1}\int_{A_2} \frac{L}{S^2} dA_1 \cos\theta_1 \, dA_2 \cos\theta_2$$

Parameters of Radiometry



Radiometric			Photometric		
Quantity	Symbol	Units	Quantity	Symbol	Units
Radiant Power	Φ_e	W	Luminous Flux	Φ_v	lumens (lm)
Radiant Intensity	I_e	W/sr	Luminous Intensity	I_v	lm/sr
Irradiance	E_e	W/m^2	Illuminance	E_v	lm/m^2
Radiance	L_e	W/m^2-sr	Luminance	L_v	lm/m^2-sr

"e" = "energetic"

"v" = "visual"

Image Credit: Breault Research Organization

Parameters of Radiometry

$$E(x,y) = \frac{d\Phi}{dA}\left(W/m^2\right)$$

$$L(x,y,\theta,\varphi) \equiv \frac{d^2\Phi}{dA\cos\theta d\Omega}\left(W/(m^2\cdot sr)\right)$$

$$I(\theta,\varphi) = \frac{d\Phi}{d\omega}(W/sr)$$

Irradiance **Radiance** **Radiant Intensity**

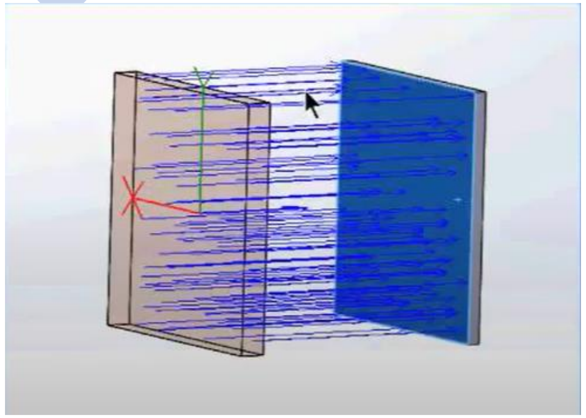
Inter-Dependence among the parameters

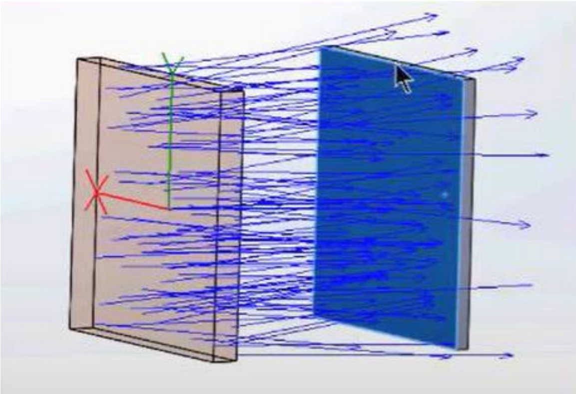
$$E(\theta,\varphi) = \int_{\pi} L d\Omega$$

$$\Phi = \int L dA d\omega = \int E dA = \int I d\omega$$

$$I(\theta,\varphi) = \int_{A} L dA$$

Significance of Parameters of Radiometry





By measuring the power of ray bundles we want to measure and characterize rays which can’t be measured in isolation

Irradiance basically localizes the position of rays on the incidence plane by measuring the power transferred to unit area

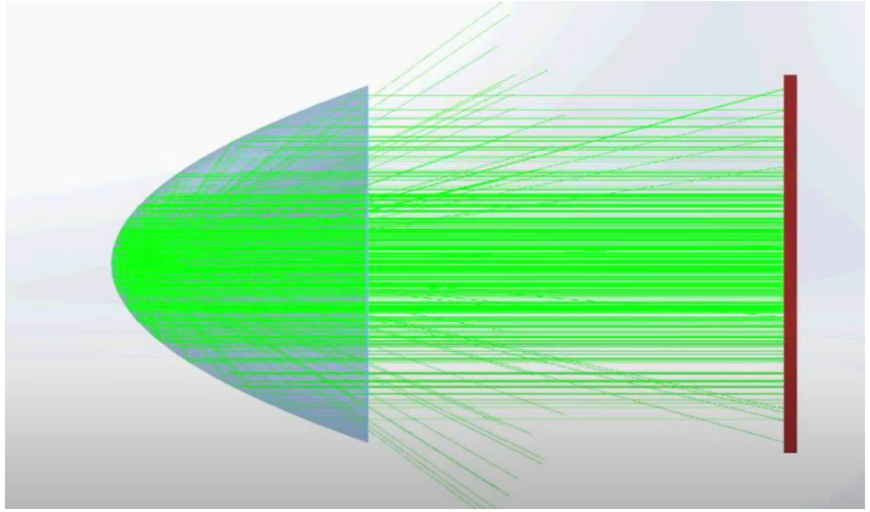
Radiant intensity localizes the incidence angle of the rays by measuring the power transferred to unit solid angles

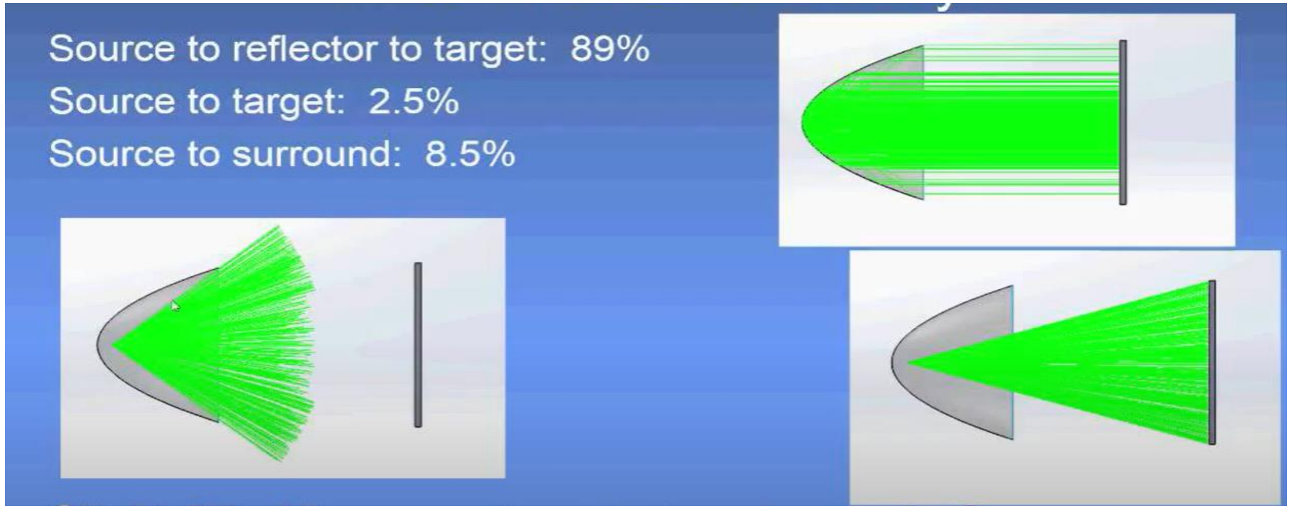
Irradiance and Radiant intensity talk about the power distribution on the destination

Radiance is power corresponding to a single ray; this is what our eyes can measure. Radiance identifies a single ray completely as it remains constant throughout the propagation in a lossless medium.

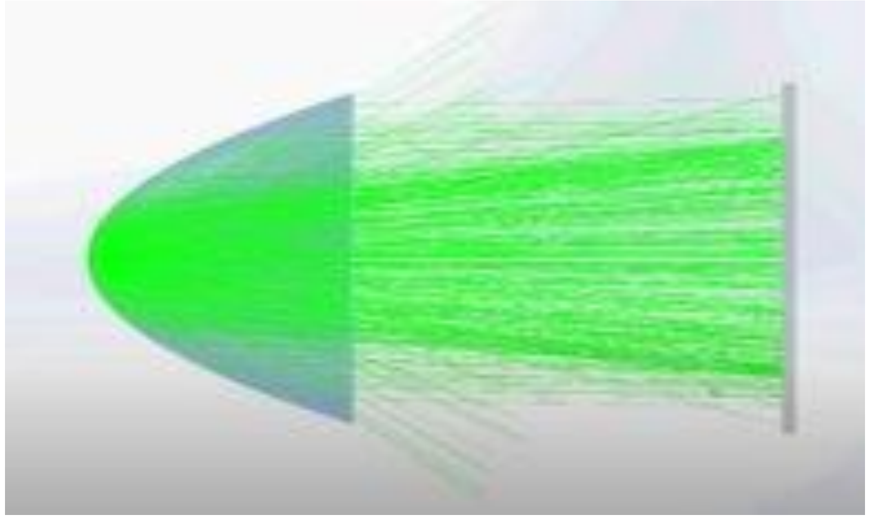
Understanding the Parameters with a Ray Tracing simulation result

Case1





Case2



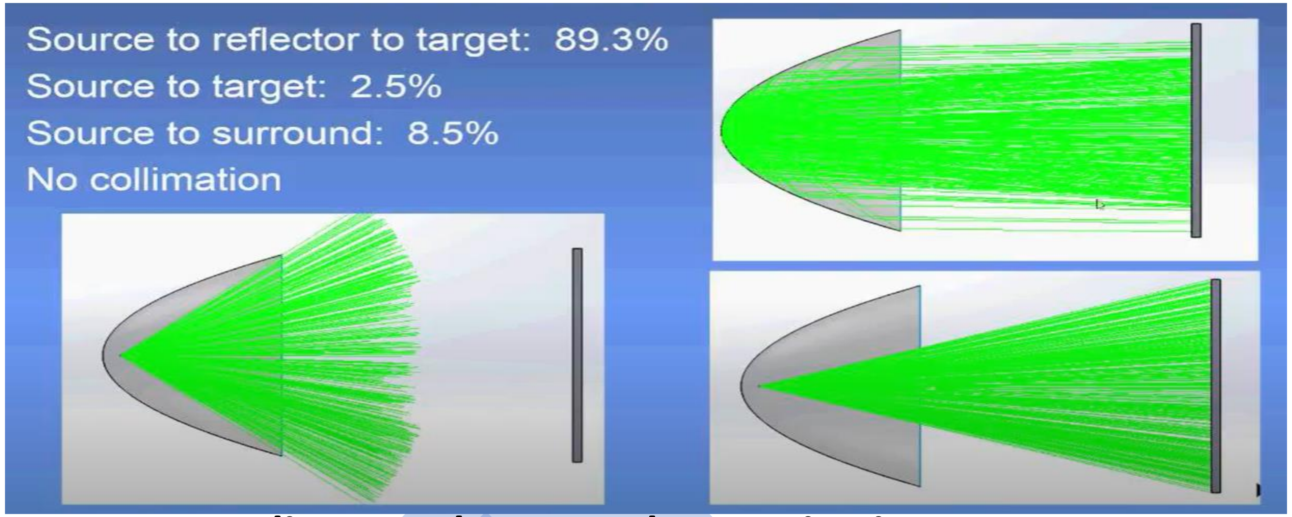
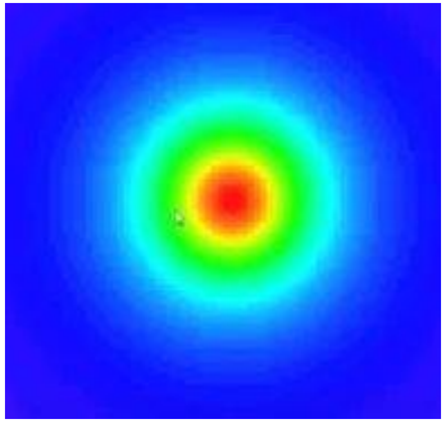
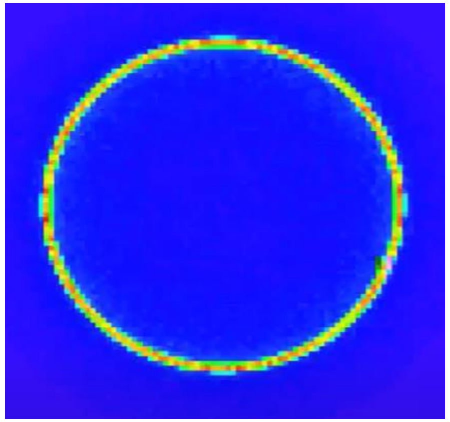


Image Credit: Breault Research Organization

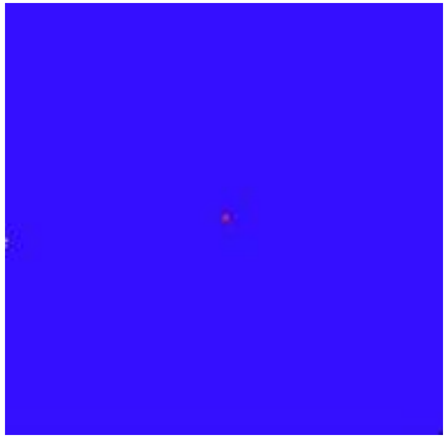
Understanding the Parameters with a Ray Tracing simulation result



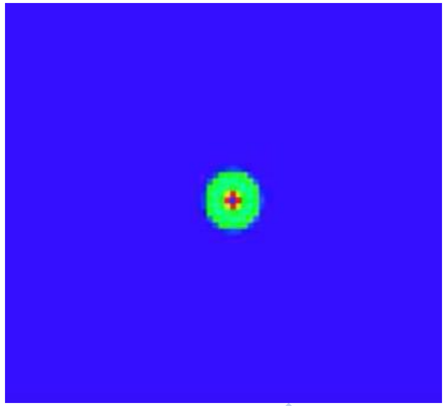
Irradiance Pattern for Case1



Irradiance Pattern for Case2



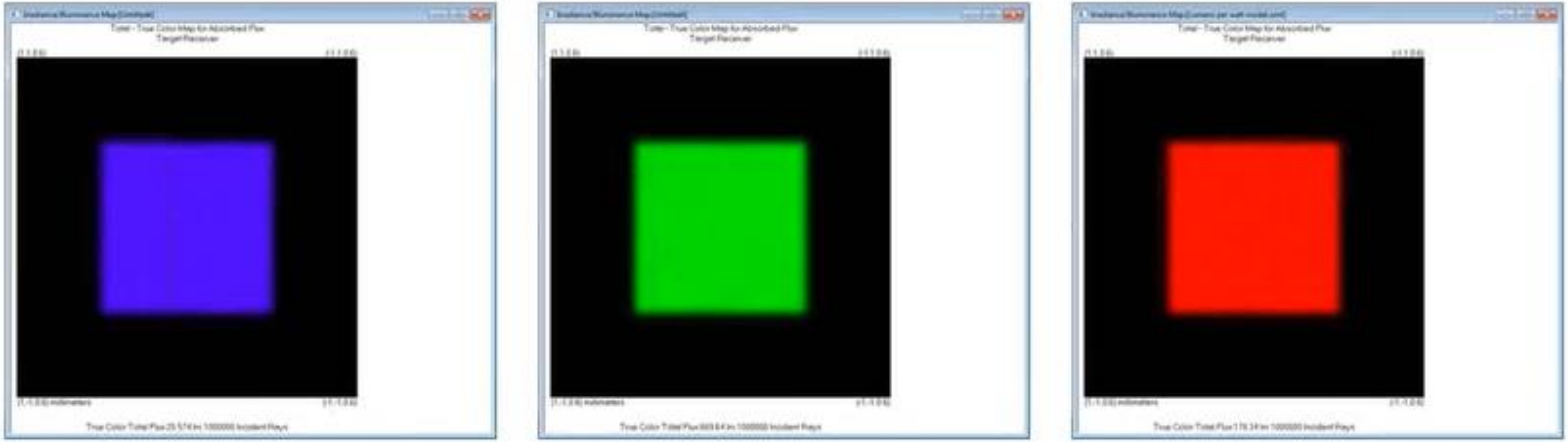
Radiant Intensity angle variation for Case1



Radiant Intensity angle variation for Case2

Image Credit: Breault Research Organization

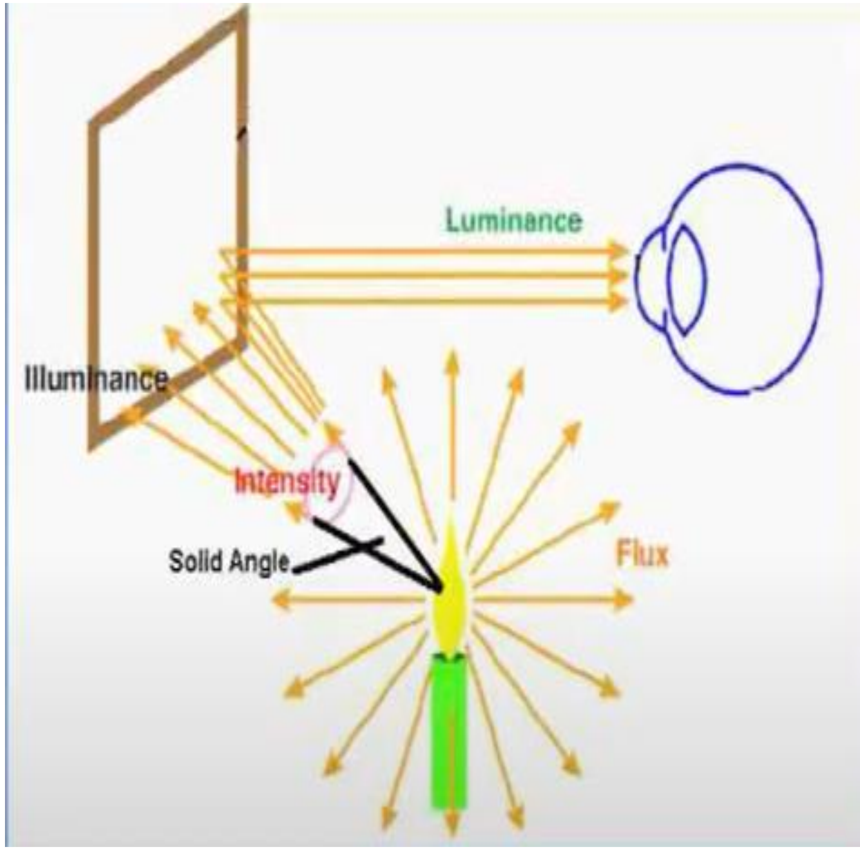
Why do we need Photometry if we already have Radiometry



λ= 0.45um 1 watt ≈ 25.5 lumens	λ= 0.55um 1 watt ≈ 670 lumens	λ= 0.63um 1 watt ≈ 178 lumens

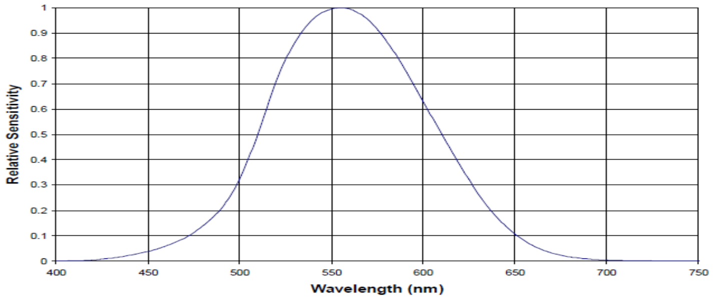
Image Credit: Lambda Research Corporation

Conversion from Radiometric to Photometric Quantities



- Power (Watts) is converted to luminous flux (lumens) via the relation:

$$\Phi_v = K \int_{380}^{780} P_e(\lambda) V(\lambda) d\lambda$$

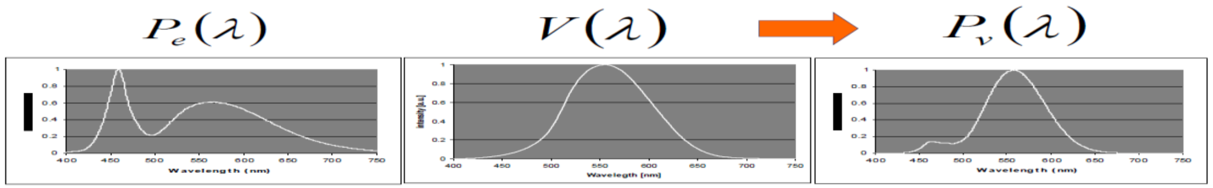


Φ_v = flux (lumens)

P_e = Power

V = photopic response function of the human eye

K = constant (683 lm/W for photopic)



$$\Phi_v = K \int_{380}^{780} P_e(\lambda) V(\lambda) d\lambda$$

Image Credit: Osram Opto-Semiconductors

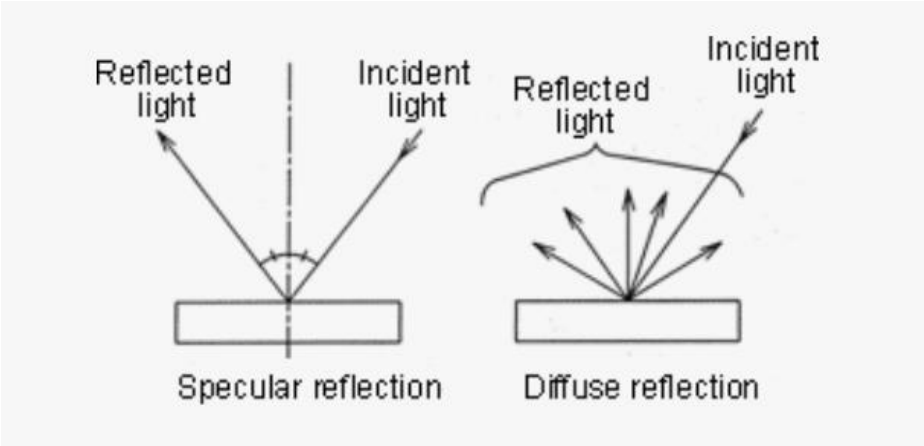
Spectral Distribution and Luminous Efficacy

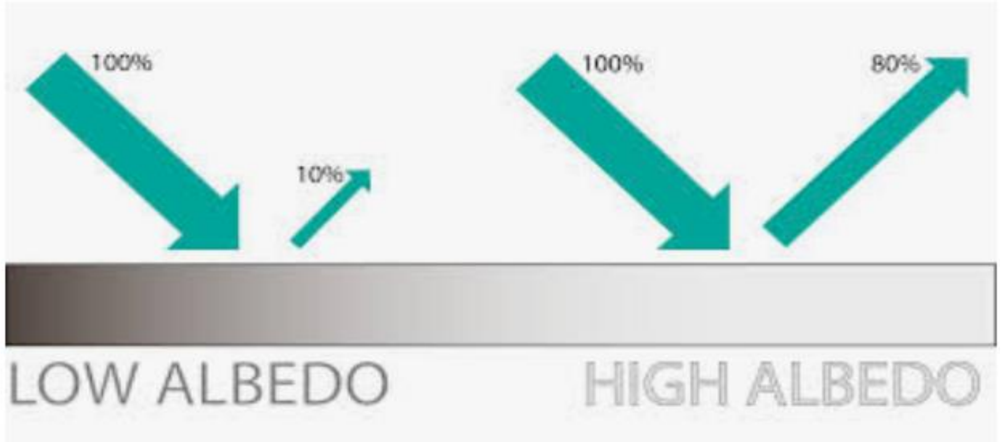
- Photopic response of Light is the plot between Spectral Radiant Flux and the wavelength
- Spectral Efficacy is a measure of how much lumens are obtained per watt of Radiant Flux
- 1 Watt converts to 683 lumens at 555 nm wavelength.
- The maximum Luminous efficacy of 100% is obtained as 683 lumens/watt at 555 nm
- There is no direct correlation between Radiant flux and Luminous flux
- Even if a white light source has Radiant spectral exactly same as the photopic curve the maximum efficacy is 240 lumens/watt

Interaction of Light and Materials

Albedo

The ratio of amount of radiant flux leaving a surface to the amount of radiant flux incident on the surface.





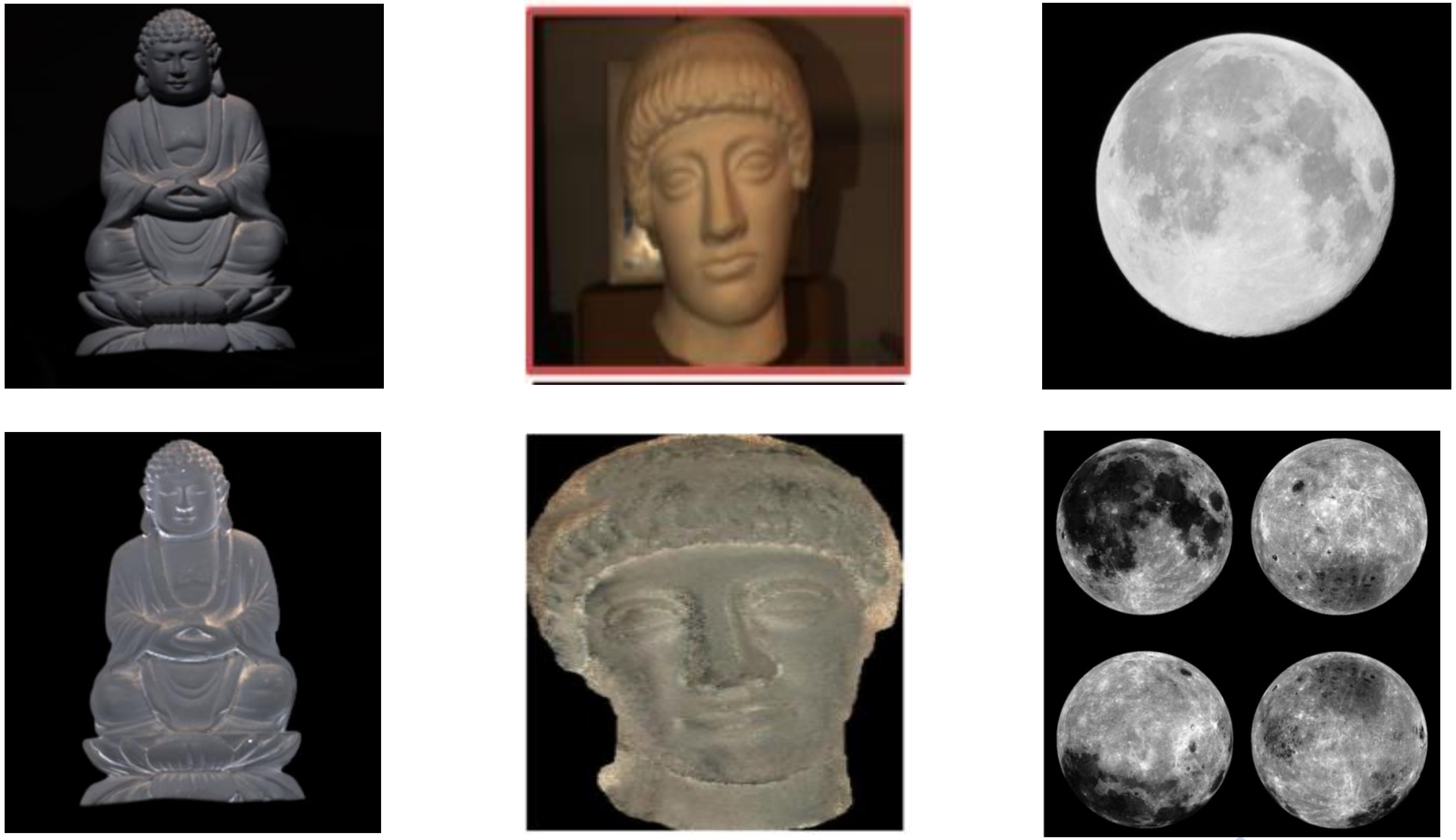
For perfectly diffuse surfaces

$$\Phi_r = E_i A \rho = \pi L_r A \rho$$

$$1 \geq \Phi_r / \Phi_i \geq 0$$

Interaction of Light and Materials

Example of Albedo Map



Objects and their corresponding albedos

Interaction of Light and Materials

BRDF

The Bidirectional Reflectance Distribution Function (BRDF), measured at a single point x on a surface, is the ratio of outgoing radiance Li to incoming irradiance Ei, where irradiance is received from just one direction.

$$BRDF = f_r(x, \lambda, \theta_i, \phi_i, \theta_r, \phi_r) = dL_r/dE_i$$

The reflectance of the material varies with the illumination direction and the viewing direction. BRDF, which describes what portion of the incident light from one direction will leave in another given direction.

Interaction of Light and Materials

Properties of BRDF

1
- Incoming and outgoing directions cover all directions both above and below the surface, thus enabling BRDF to describe refection and transmission combined.

2
- The BRDF function is symmetric for all materials. Its value is identical if we swap the incoming and outgoing directions. This is known as Helmholtz Reciprocity.

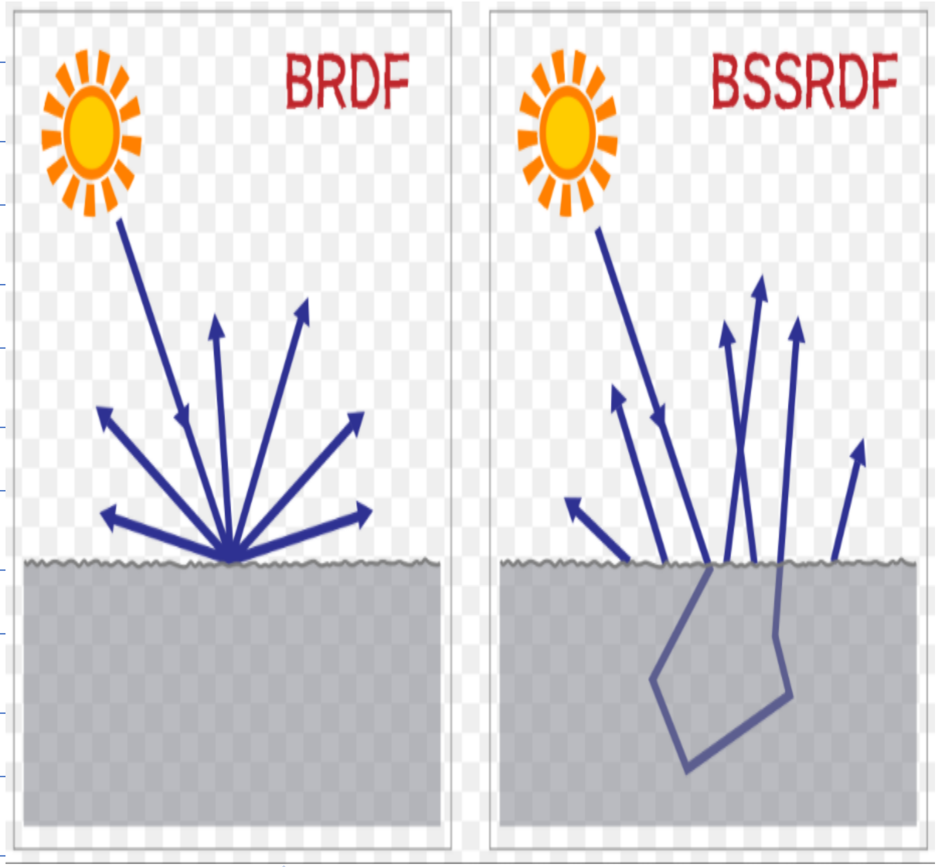
3
- It is not simply the ratio of incoming and outgoing radiance for two chosen rays, a ratio that would always fall between 0 and 1. It is the ratio of the outgoing ray's radiance Lr to the irradiance E from only one direction.
- Thus a perfect difuse reflector has a BRDF value of 1 and not the value of $1/\pi$ you might initially expect.

4
- The 5 input dimensions of BRDF namely the 4 angles(incoming,outgoing) and wavelength makes it tidious to calculate.
- Though BRDF databases for different surfaces are present,usually we resort for parameterized BRDF models for the surface.

Interaction of Light and Materials

BSSRDF

- BSSRDF is Bi-Directional Sub-Surface Reflectance Distribution Function
- BRDF based models fail to model the surfaces which are translucent like human skin, marble, milk etc.
- BRDF assumes every material to be either opaque or transparent.
- BRDF assumes that ray changes occur only at surfaces not within the surface.
- That is, it does not acknowledge sub-surface scattering.
- BSSRDF is also calculated using predefined parametric surface models



- Using Radiometry and Photometry any source of light and its incidence on a surface can be measured.
- With the help of Albedo, BRDF and BSSRDF any material can be characterized for its interaction with light rays.

Hence, we can define an optical system with

RAYS

Understanding Lenses and Digital Cameras

What are Lenses

Any **ray-bending device** qualifies **as a lens, including mirrors, running water, and atmospheric** anomalies.

For imaging a **lens** is **any device that bends incoming rays into useful** patterns of **outgoing rays.**

Rays Define a vast set of Lenses in 9D space with each point defining a unique lens.

However, meaningful lenses for focused images fall on a 3D manifold of 9D space

Parameters we can control in Lens Design are

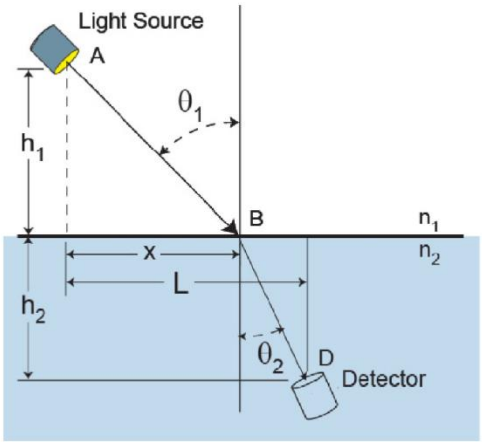
- Refractive Index
- Lens Shape

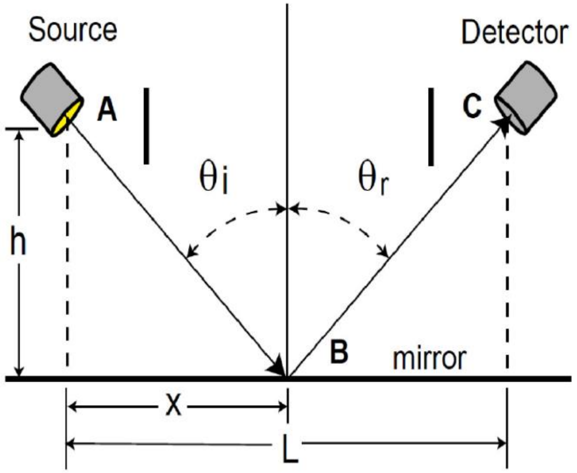
However,assessment of Lens Error is not done using 9D function calculation rather by assessing the images they form

Ray Bending

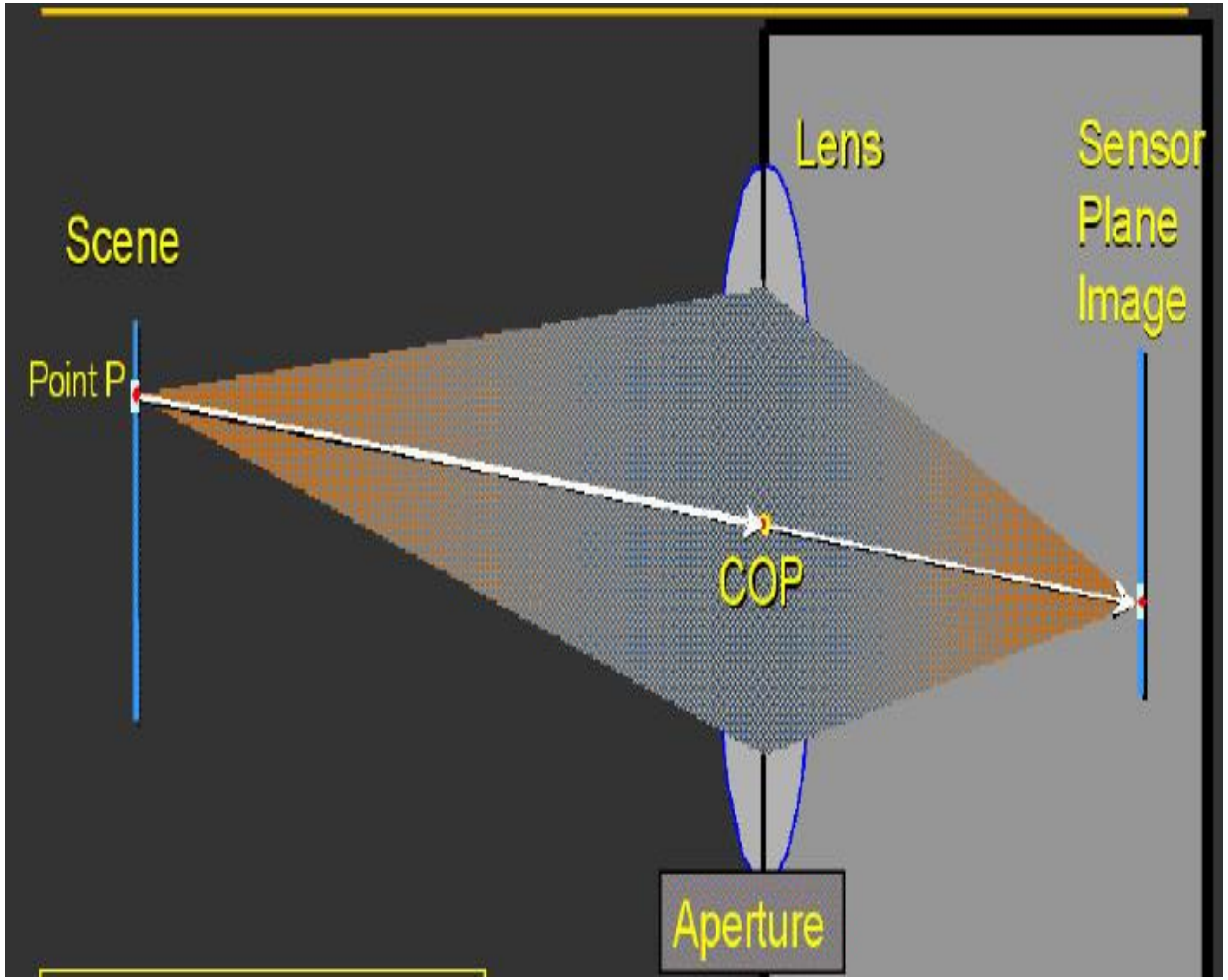
4 Laws of Ray bending in Optics

1. Light travels in a straight line path in a material of constant refractive index
2. The angle of incidence is same as the angle of reflection
3. The ray bending occurs when light propagates from one medium to other according to following equation $\eta_1 \sin\theta_1 = \eta_2 \sin\theta_2$
4. Rays and Refraction Laws are only valid for optical systems where diffraction doesn't occur. Diffraction odifies the path of the rays that pass through openings of size< 10*lambda





Ray Bending for Image formation

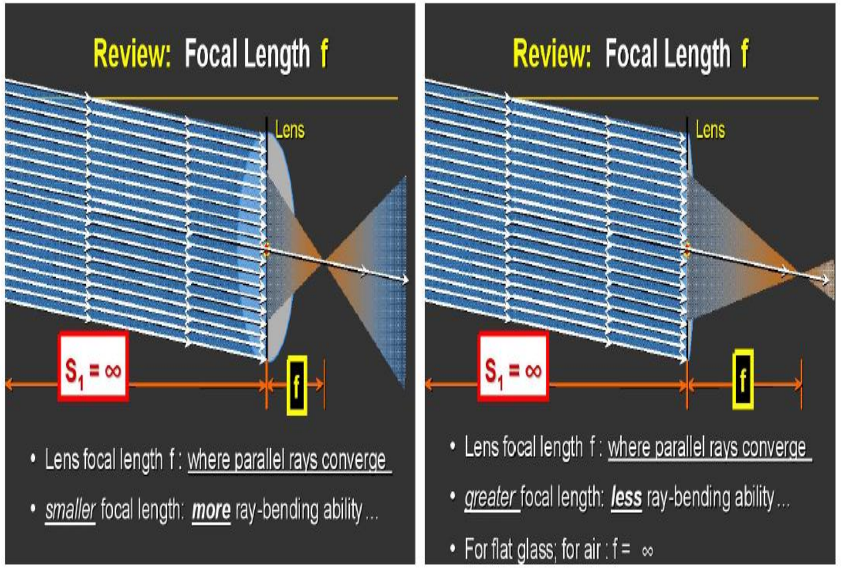


- Through the ray bundles some finite fraction of Radiant exitance M from scene point P becomes the radiance E on sensor
- However, every time calculating the E is cumbersome, so we model lenses as thin Lens for the practical purposes

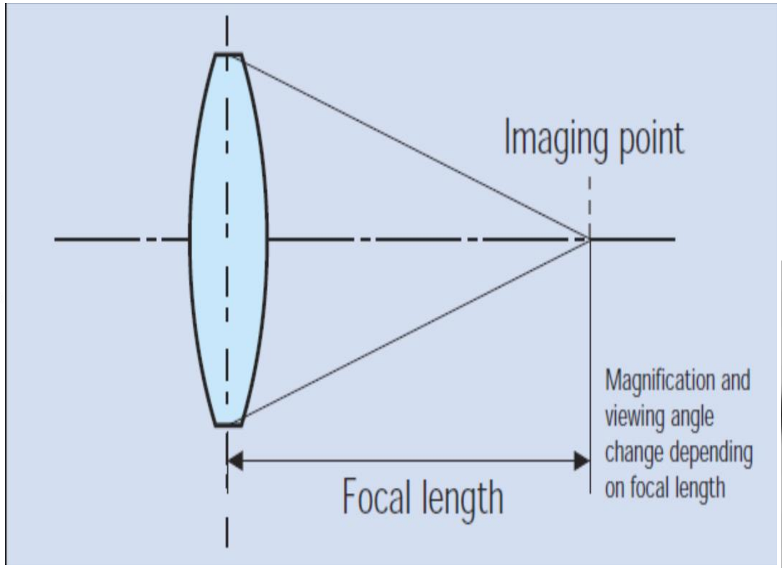
Ideal Thin Lens parameters

We have 3 parameters to choose from for defining Ideal Lens completely

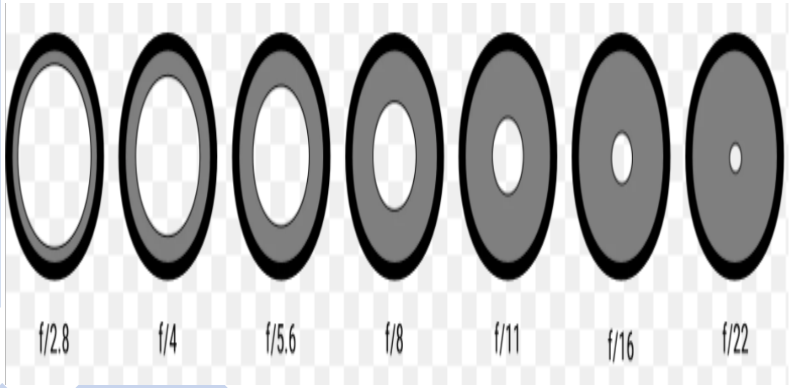
Focal Length



Aperture Diameter



Lens Speed or f-number



Digital Camera Parameters

Field of View

Working Distance

Depth of Field

Resolution

Sensor Size

PMAG

PMAG = Sensor Size [mm] / Field of View[mm]

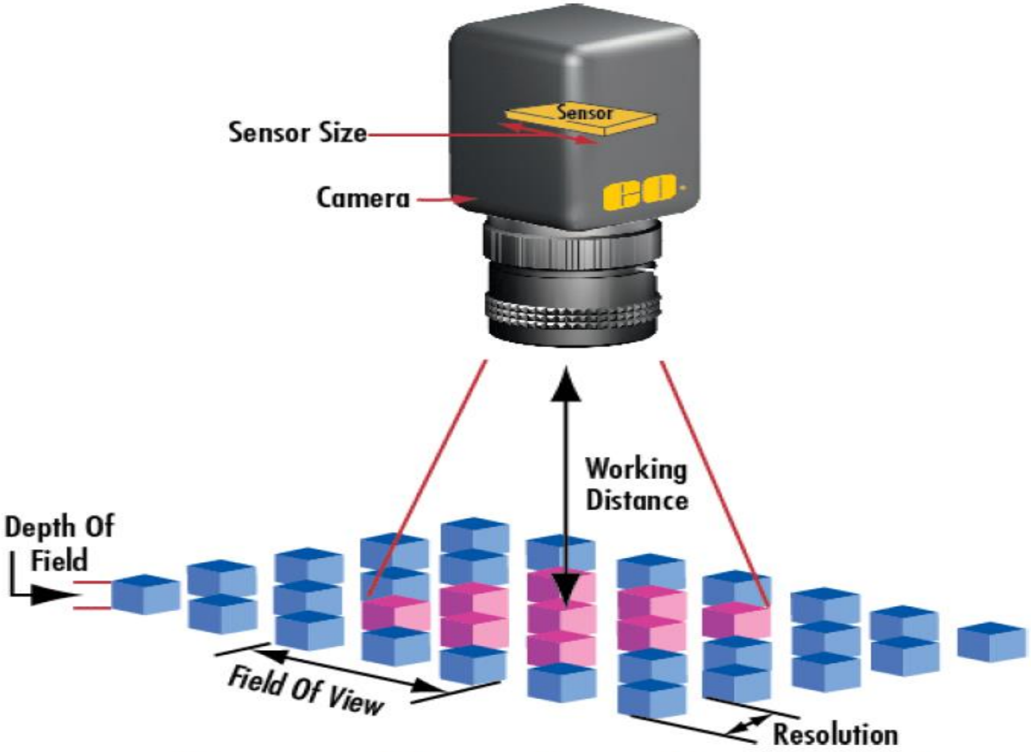
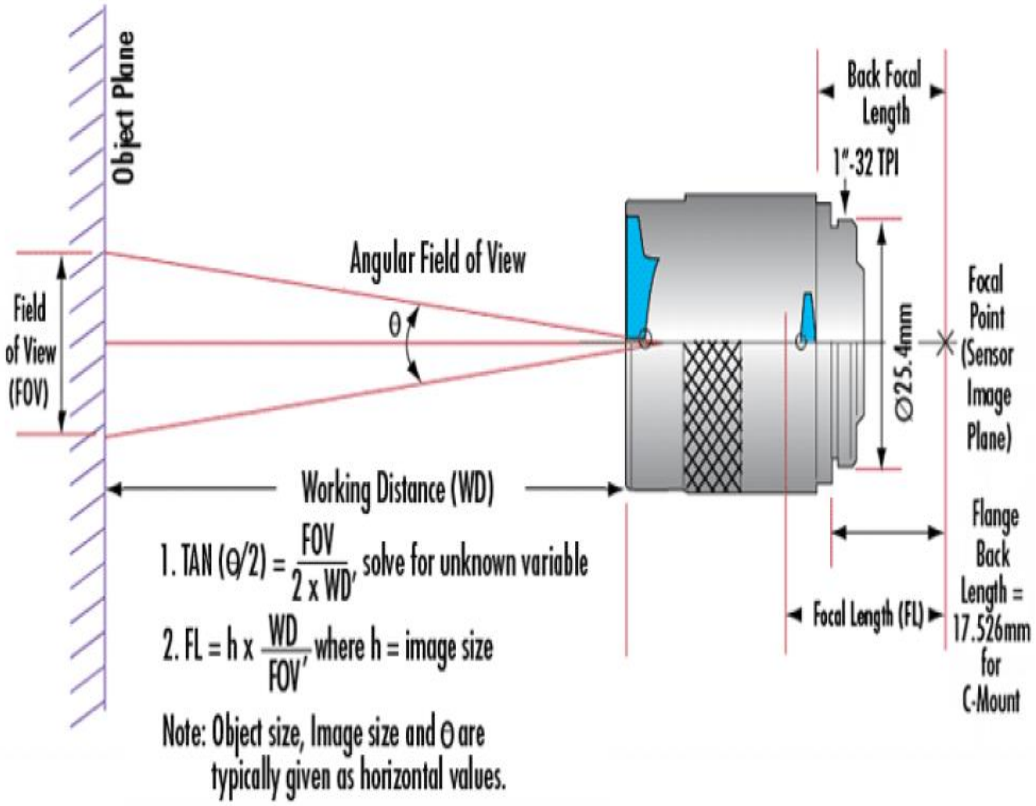


Image Credit: Edmund Optics

Focal Length and Field of View



$$\mathrm{AFOV}\,[^\circ] = 2 \times \tan^{-1}\left(\frac{h}{2f}\right)$$

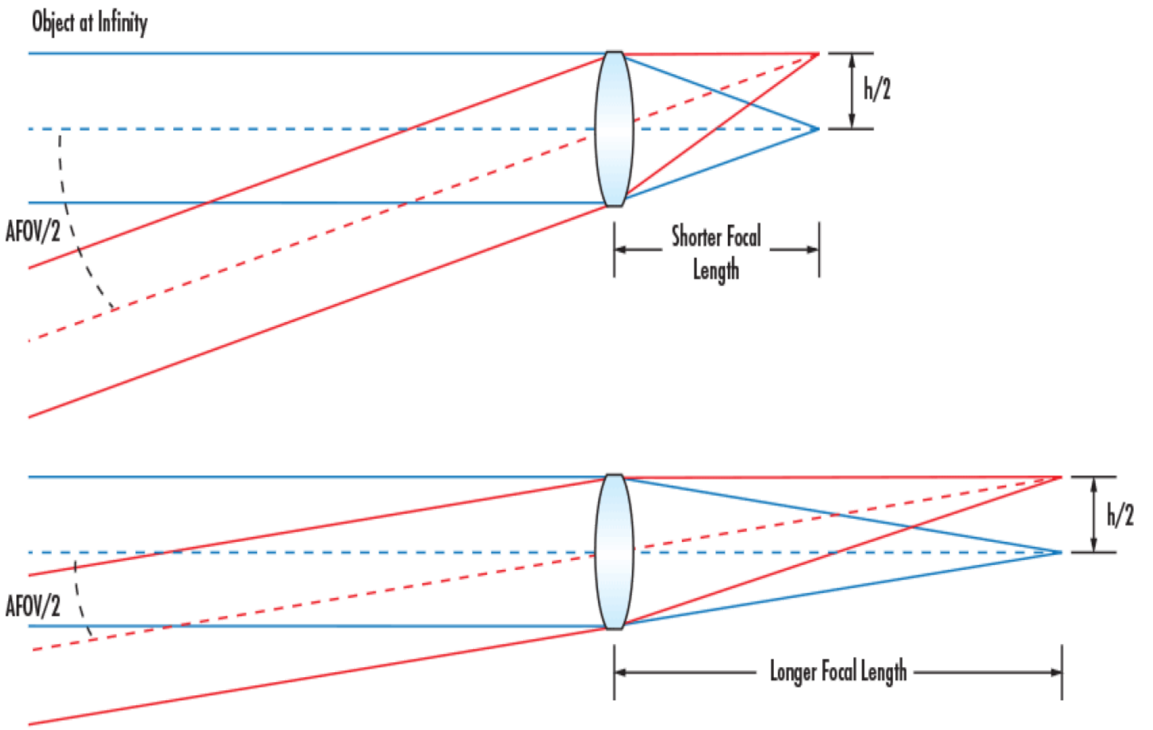


Image Credit: Edmund Optics

Resolution

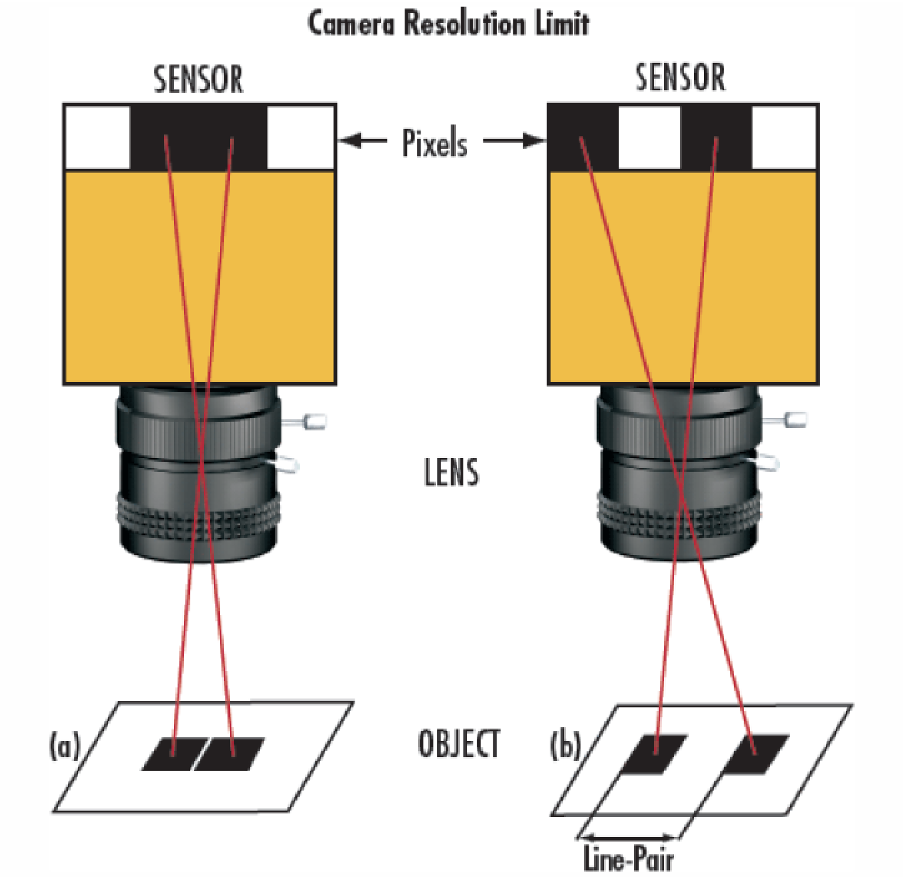


Figure 1: *Resolving Two Squares. If the space between the squares is too small (a) the camera sensor will be unable to resolve them as separate objects*

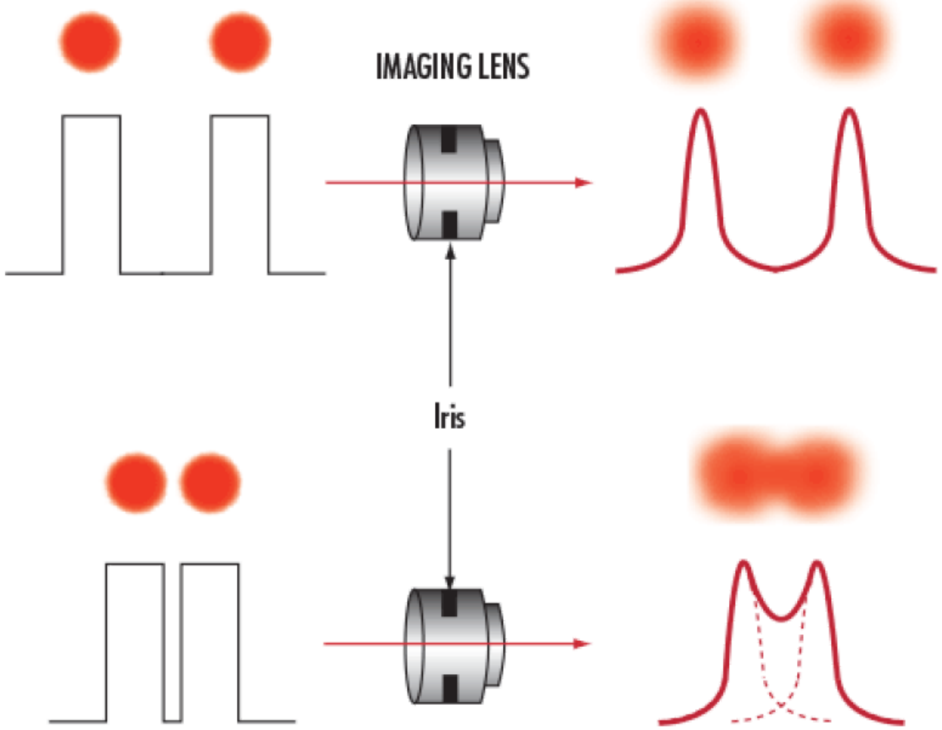
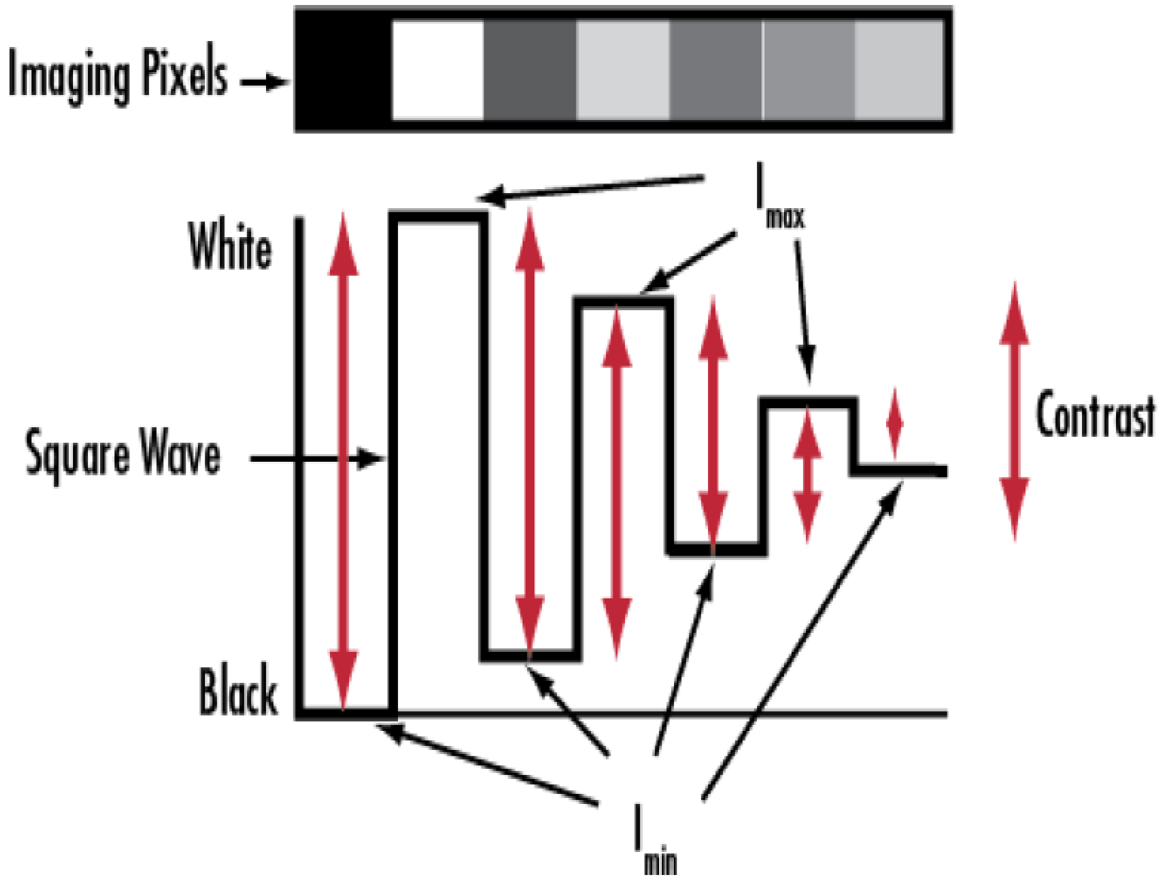


Figure 2: *Two spots Being Imaged by the Same Lens. The Top Lens is Imaging Objects at a Low Frequency, the Bottom Lens is Imaging Objects at a Higher Frequency*

Image Credit: Edmund Optics

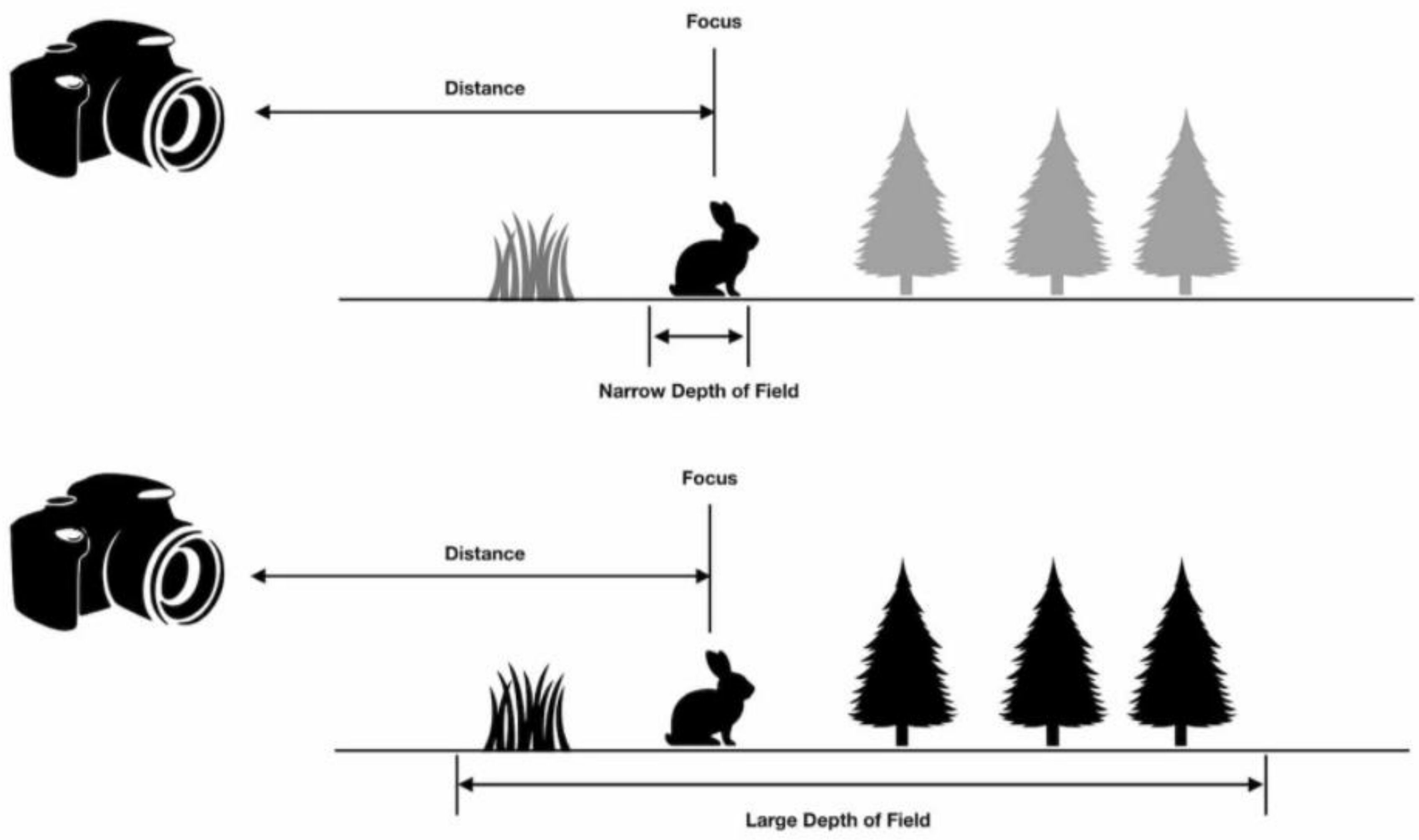
Contrast



$$\% \text{ Contrast} = \left[\frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}\right]$$

Image Credit: Edmund Optics

Depth of Field



Digital Camera and Thin Less Trade-Offs

Larger the focal length larger the PMAG but smaller the field of view

Shorter the focal length larger the field of view but more distortions and cost of lens

Larger the Focal Length and aperture more is the light admitted for dimly lit scene but smaller the FOV

Increasing Depth of Focus requires smaller aperture hence increased exposure time and higher sensor sensitivity leading to higher noise

Higher the Spatial resolution smaller the pixel size larger the data storage requirements

Exposure time too large moving objects appear blurred and when too short then less amount of light gets captured

Higher the spatial resolution poorer is Depth of Focus

Larger lens apertures gather more light, but reduce the depth of focus in the image

A longer exposure time, additional scene lighting, or greater sensitivity makes brighter pictures. But a longer exposure time can increase blur, additional lighting can disrupt scene appearance, and greater sensitivity results in increased noise.

Conclusion

Future Impact of Computational Photography

Still many unanswered questions remain in-front of Computational Photography few of them are-

- What will the future of photography look like?
- What will a camera look like in ten years? In twenty years? In fifty years?
- How will powerful new movie-making capabilities change the nature of photography?
- Will photography as we know it disappear into a soup of unlimited media possibilities?
- How will online photo collections transform visual social computing?
- How will a billion portable networked cameras change the social culture?

But Overall,

Computational photography, in which photographs of the future will be computed rather than recorded, has already started to change the work-flow of imaging and give us new and expanded opportunities for seeing.

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Thank You!!!