Light & Computational Illumination

Most slides stolen by David Jacobs from Marc Levoy
CS478 Winter 2012

Outline

- measures of light
  - radiometry versus photometry
  - luminous intensity of a point light
  - luminance leaving an area light
  - luminance arriving on a surface
  - illuminance on a surface
- reflection of light
  - diffuse
  - specular
  - goniometric diagrams
- flash
- paper parade!

Radiometry versus photometry

- *radiometry* is the study of light w/o considering humans
  - spectroradiometer - power as a function of wavelength
  - radiometer - total power, integrating over all wavelengths
  - measurements include
    - radiant intensity, radiance, irradiance
- *photometry* is the study of light as seen by humans
  - spectrophotometer - power we see as a function of wavelength
  - photometer, a.k.a. photographic light meter
  - measurements include
    - luminous intensity, luminance, illuminance

Relationship to tristimulus theory

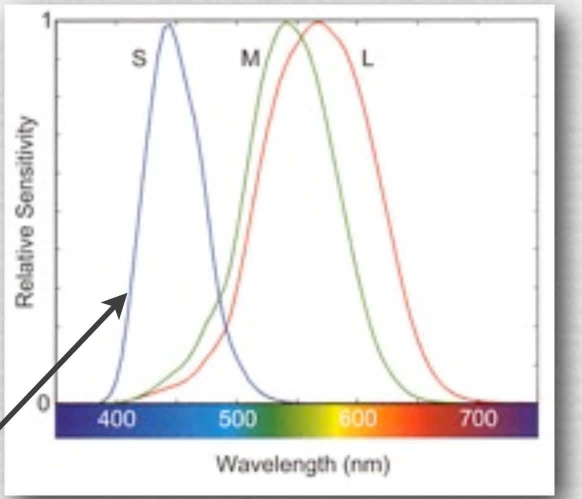
- the response of the human visual system to a spectrum is

$$(\rho,\gamma,\beta) = \left(\int_{400nm}^{700nm} L_e(\lambda)\,\rho(\lambda)\,d\lambda,\ \int_{400nm}^{700nm} L_e(\lambda)\,\gamma(\lambda)\,d\lambda,\ \int_{400nm}^{700nm} L_e(\lambda)\,\beta(\lambda)\,d\lambda \right)$$

radiance

luminance

(Stone)



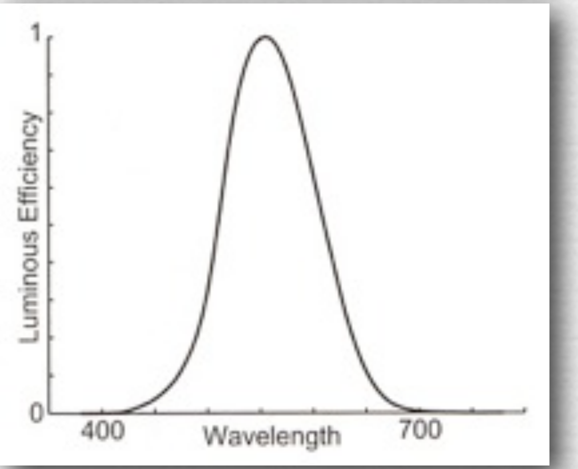
- the total response can be expressed as

$$L = \rho + \gamma + \beta = \int_{400nm}^{700nm} L_e(\lambda)\,V(\lambda)\,d\lambda$$

- where

$$V(\lambda) = \rho(\lambda) + \gamma(\lambda) + \beta(\lambda)$$

S is actually much lower than M or L

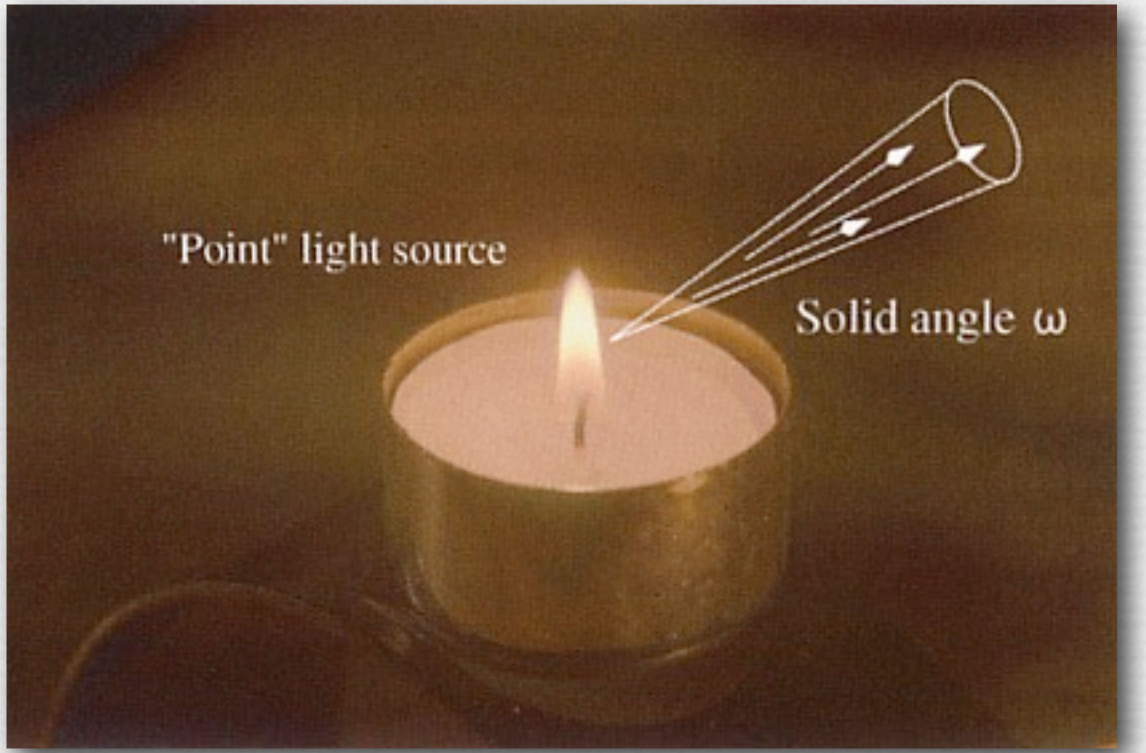


V(λ), or luminous efficiency curve

Luminous intensity of a point light

- power given off by the light per unit solid angle

$$I = \frac{P}{\Omega} \qquad \left(\frac{\text{lumens}}{\text{steradian}}\right)$$

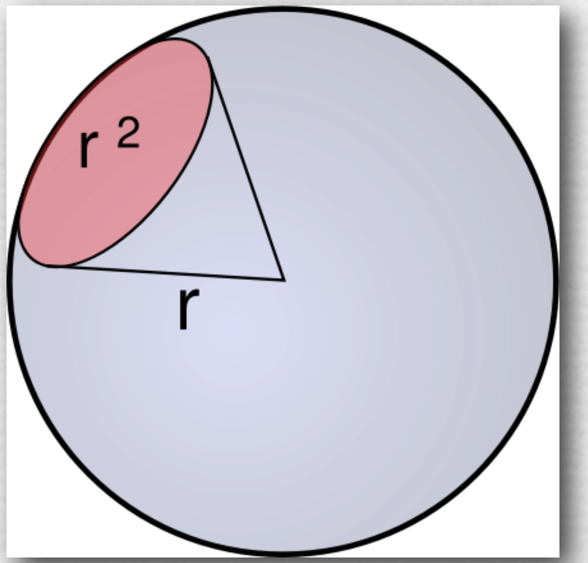


(Reinhard)

- related radiometric quantity
  - radiant intensity (watts/steradian)

Steradian as a measure of solid angle

- 1 steradian (sr) is the solid angle such that the area subtended by that solid angle on the surface of a sphere is equal to the sphere's radius^2
  - area of a sphere is $4 \pi r^2$, so $1 \text{ sr} = r^2 / 4\pi r^2 \approx 1/12$ of the sphere's surface



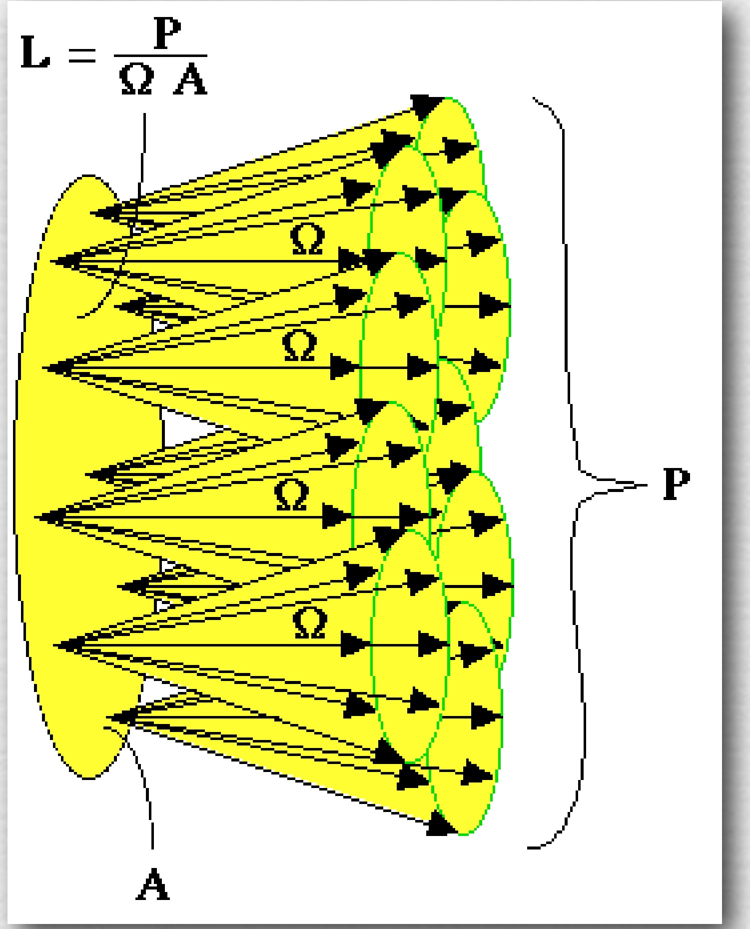
(http://www.handprint.com/HP/WCL/color3.html)

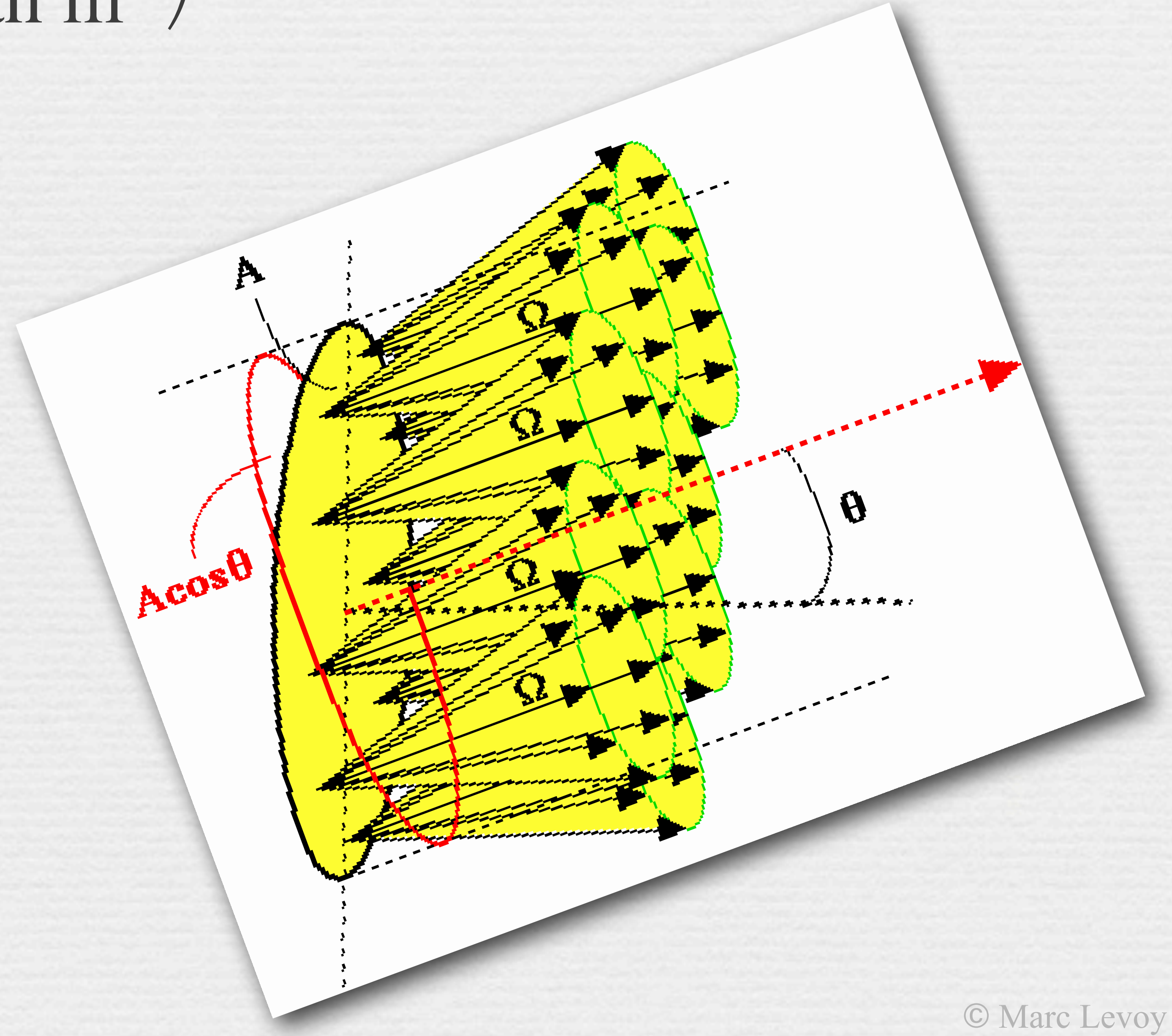
- examples
  - circular aperture 65° in subtended diameter
  - square aperture 57° on a side
  - a circle 12.7' in diameter cast by a streetlight 10' high

Luminance leaving an area light

- power given off by the light per unit solid angle per unit area, viewed at a declination of θ relative to straight-on

$$L = \frac{P}{\Omega A \cos\theta} \qquad \left(\frac{\text{lumens}}{\text{steradian m}^2}\right)$$



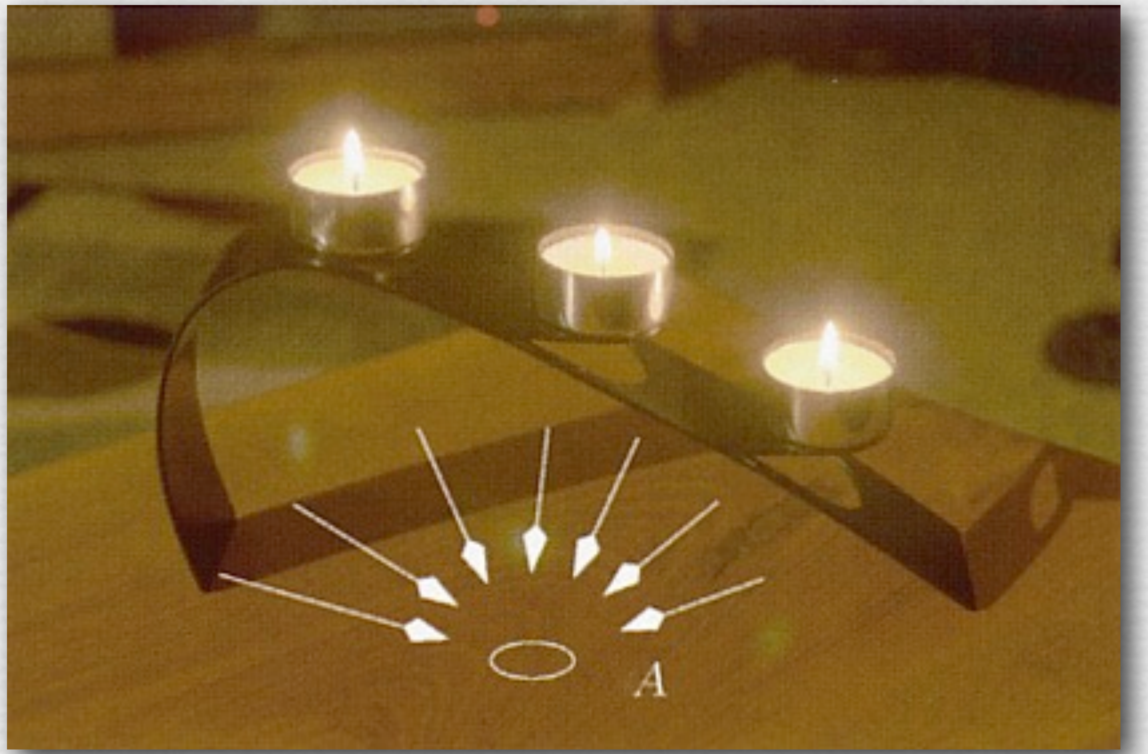


(http://omlc.ogi.edu/classroom/ece532/class1/radiance.html)

Illuminance on a surface

- power accumulating on a surface per unit area, considering light arriving from all directions

$$E = \frac{P}{A} \qquad \left(\frac{\text{lumens}}{\text{m}^2}\right)$$

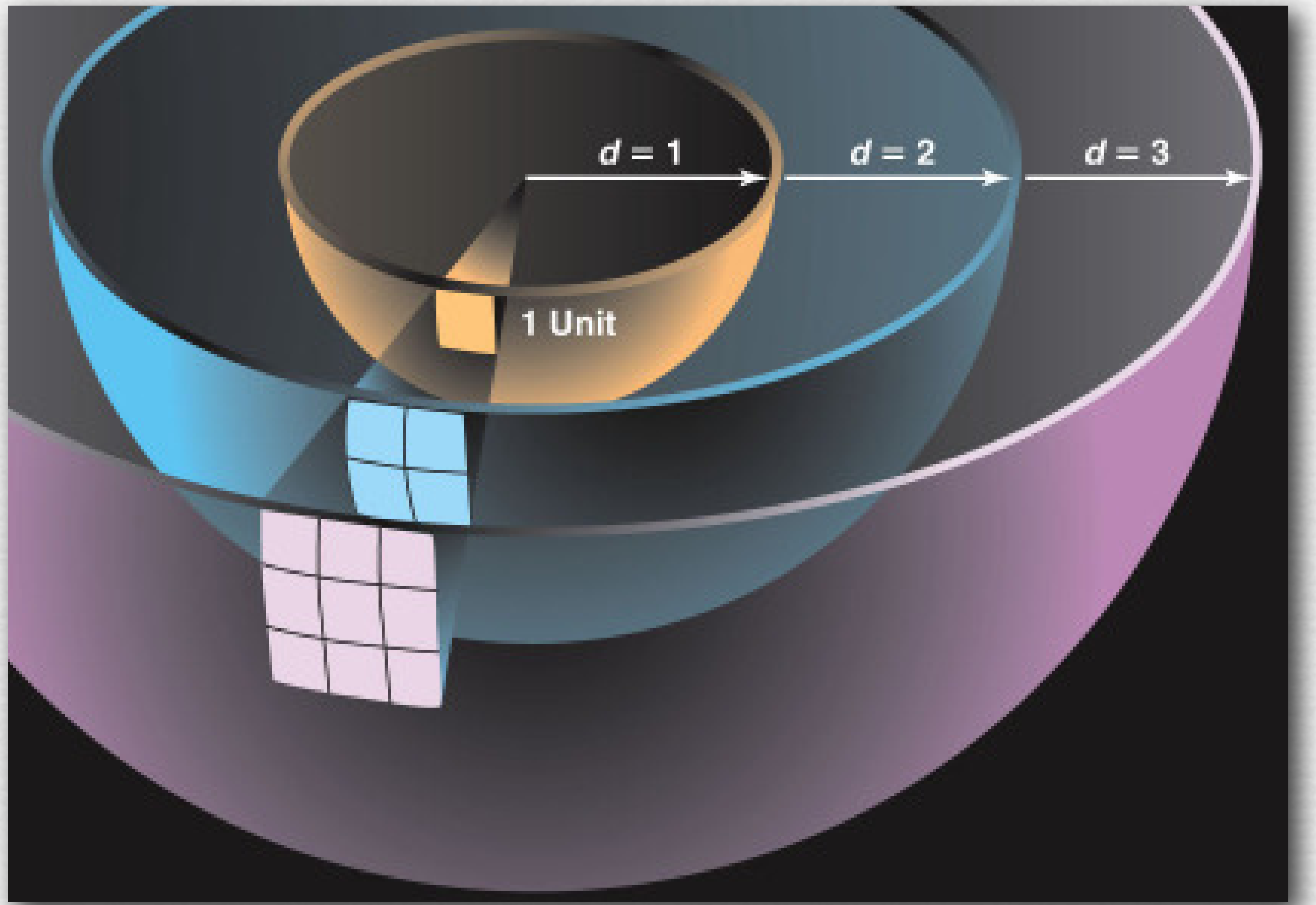


(Reinhard)

The effect of distance to the subject

Georges de La Tour
The Carpenter, 1640

(Thomson)



- for a point light, illuminance on a surface falls as d^2

Q. How does illuminance change with distance from an area light?

Recap

- to convert *radiometric* measures of light into *photometric* measures, multiply the spectral power distribution as measured by a spectroradiometer wavelength-by-wavelength by the human *luminous efficiency curve* $V(\lambda)$
- useful measures of light are the *luminous intensity* emitted by a point source (power per solid angle), the *luminance* emitted by (or arriving at) an area source (power per solid angle per unit area), and the *illuminance* accumulating on a surface (power per unit area)

Questions?

Outline

- measures of light
  - radiometry versus photometry
  - luminous intensity of a point light
  - luminance leaving an area light
  - luminance arriving on a surface
  - illuminance on a surface
- reflection of light
  - diffuse
  - specular
  - goniometric diagrams
- flash
- paper parade!

Albedo

- fraction of light reflected from a diffuse surface
  - usually refers to an average across the visible spectrum

- examples
  - clouds 80%
  - fresh snow 80%
  - old snow 40%
  - grass 30%
  - soil 15%
  - rivers 7%
  - ocean 3%

equality explains "whiteout" in blizzards

not including mirror reflections of the sun

Reflection from diffuse surfaces

(Dorsey)

two viewpoints, same illumination

Johann Lambert
(1728-1777)

- rough surfaces reflect light uniformly in all directions
  - appearance is independent of viewing direction
  - if perfectly so, surface is called ideal diffuse ("Lambertian")

Reflection from shiny surfaces

(Dorsey)

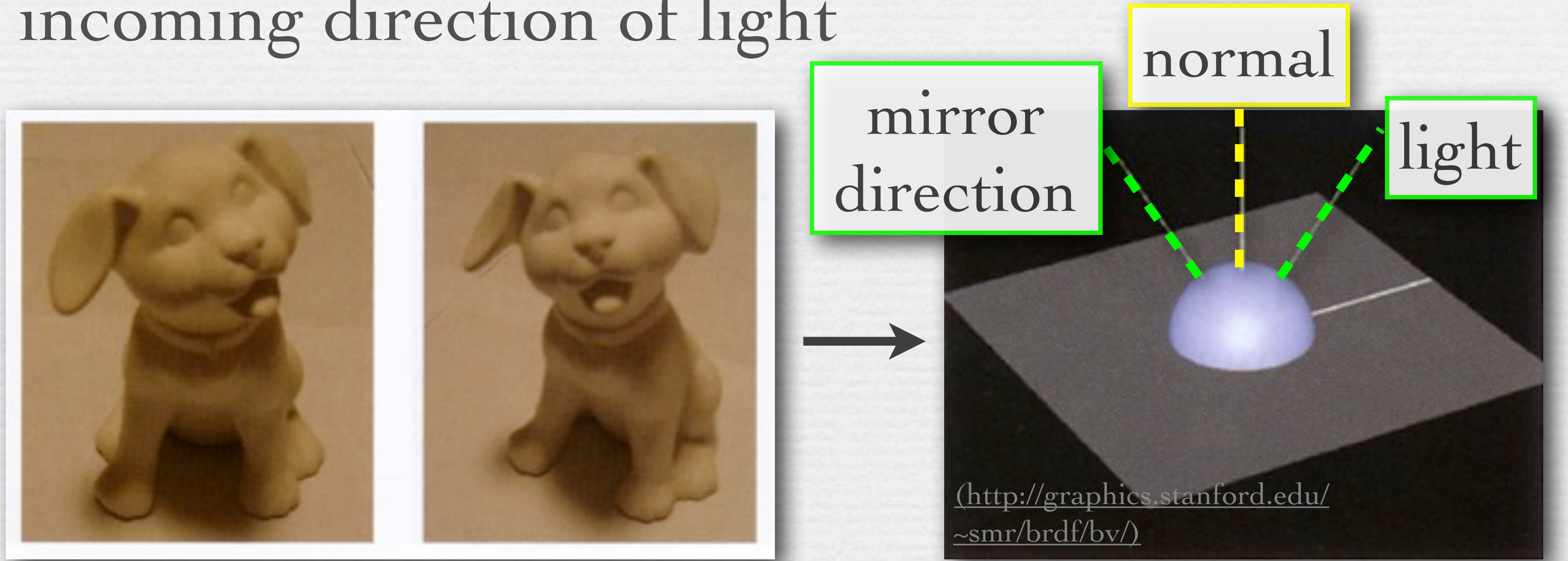
two viewpoints, same illumination (i.e. fixed to object)

- rough surfaces are composed of flat microfacets ("asperities" according to Bouguer)
  - the amount of variance in the orientation of the facets determines whether the surface is *diffuse* or *specular*
  - diffuse reflections look the same regardless of viewing direction
  - specular reflections move when the light or observer moves

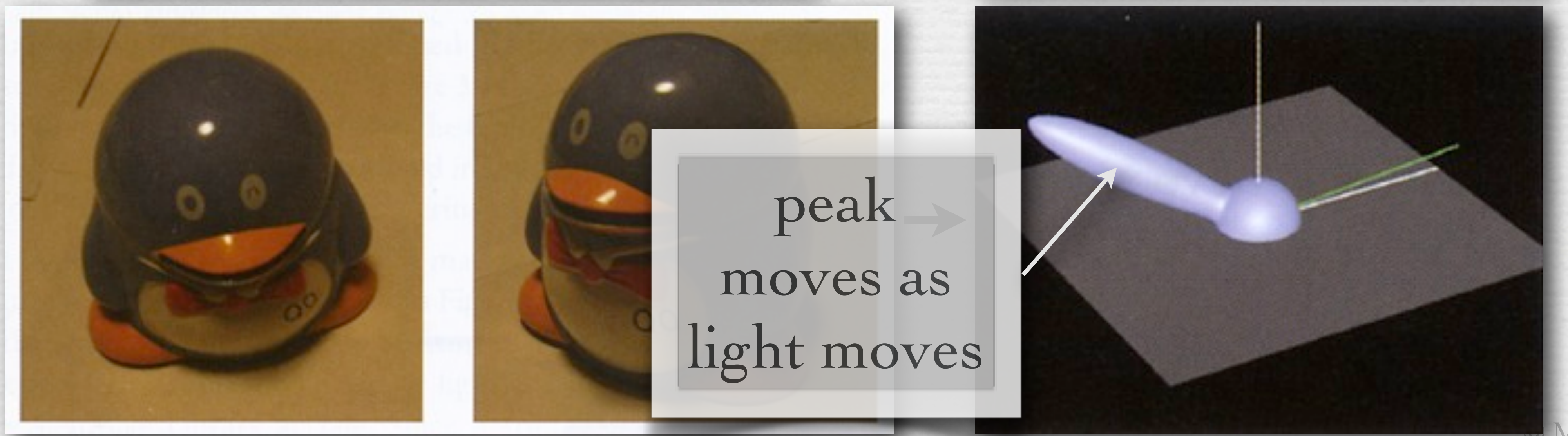
Goniometric diagram

- depiction of reflectance (fraction of light reflected) as a function of one of the relevant angles or directions
- shown here is reflectance as a function of viewing direction, for a fixed incoming direction of light

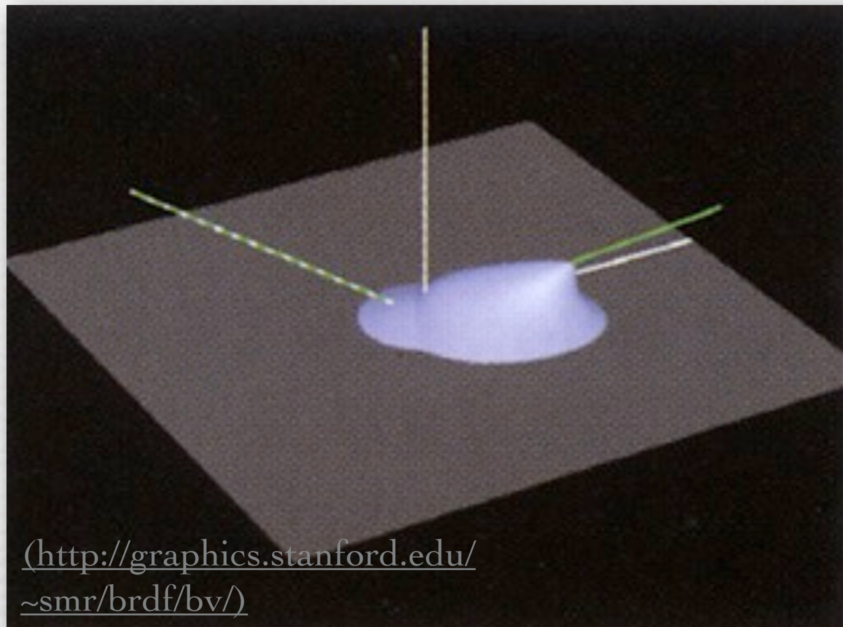
diffuse surface



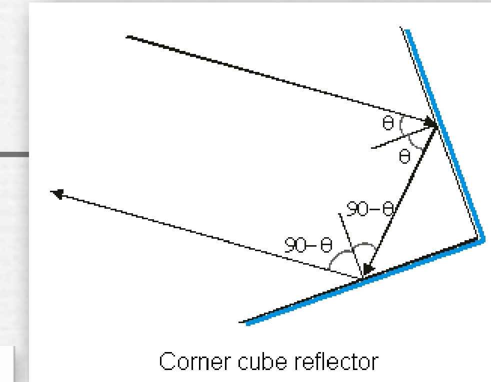
shiny surface



What unusual material property does this goniometric diagram depict?



(http://graphics.stanford.edu/~smr/brdf/bv/)

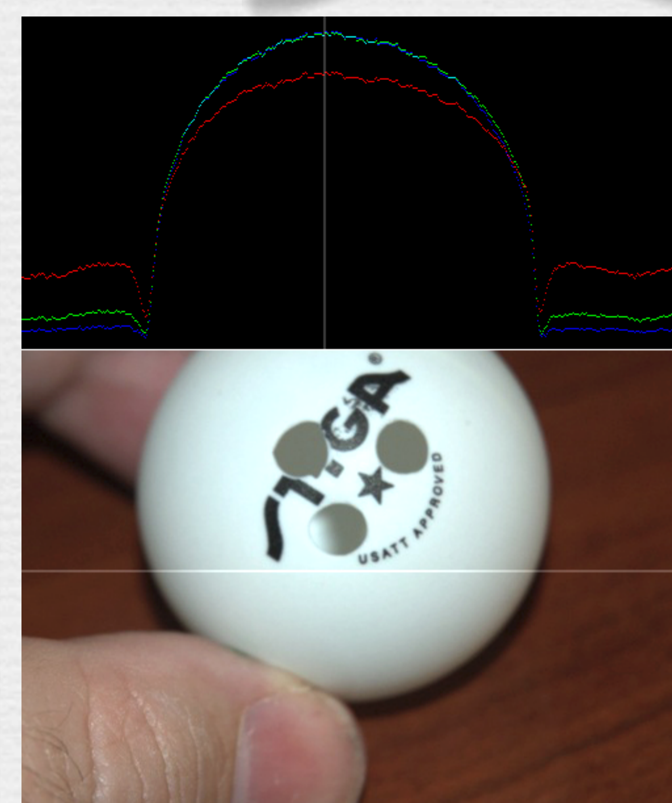


a full moon is roughly lit from the camera's viewpoint

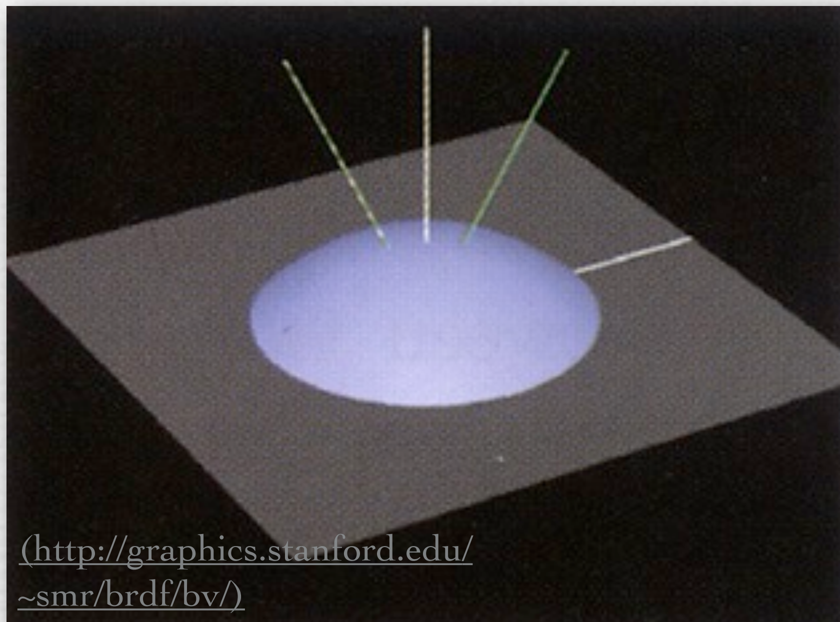
so is a flash photograph

- A. retroreflectivity
- the maria of the moon is retroreflective and gray
- a diffuse sphere, lit from the camera's viewpoint, falls as cos θ or cos $\sqrt{1-x^2}$

(NASA)

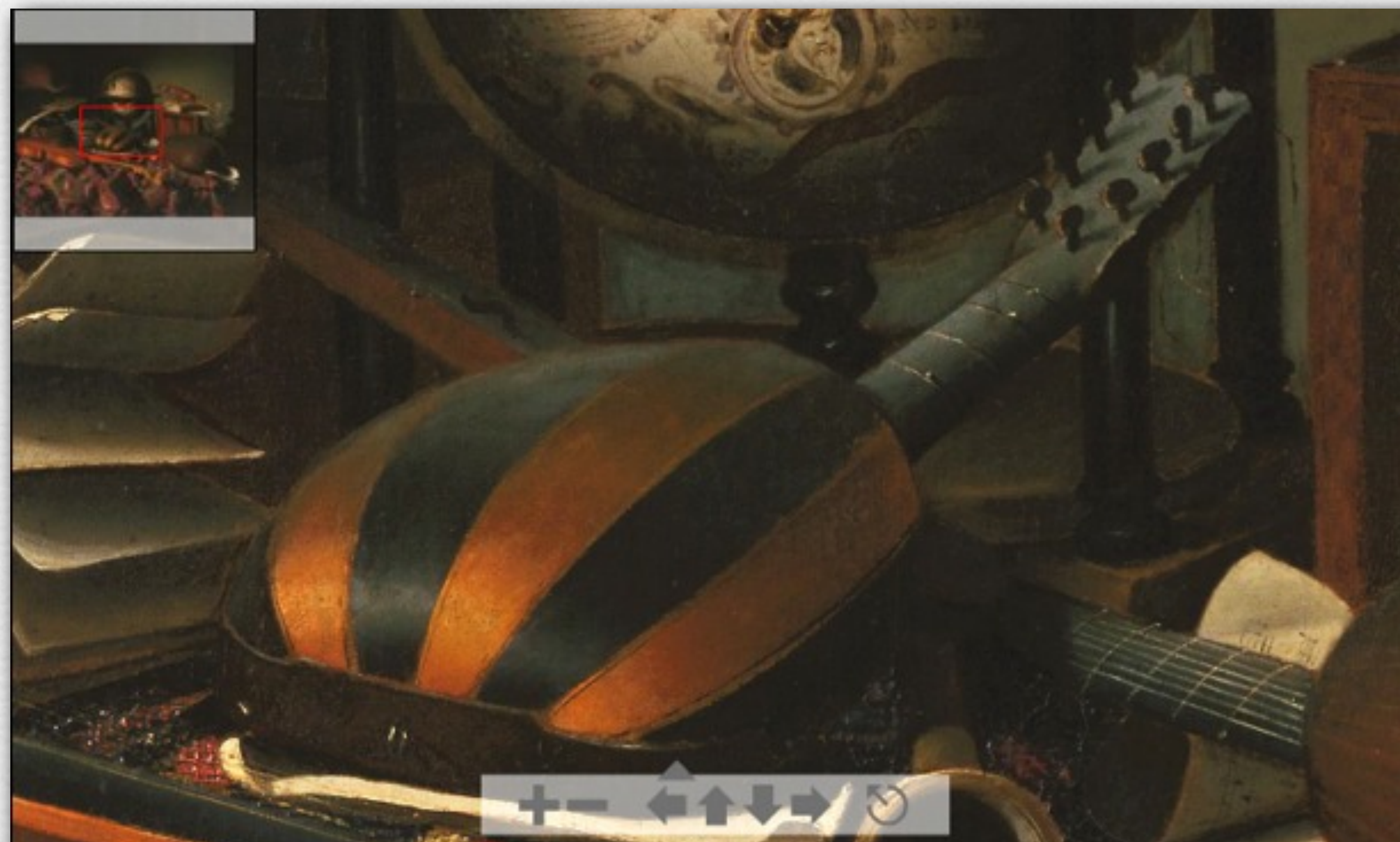


What unusual material property does this goniometric diagram depict?



- A. dusty scatterer
- appears brighter as the viewer moves to grazing angles

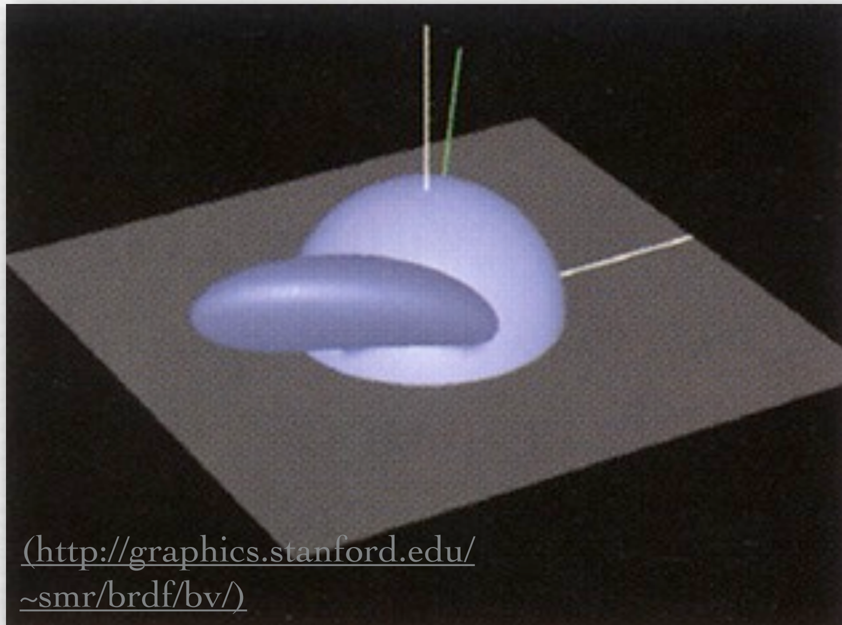
(famsf.org)

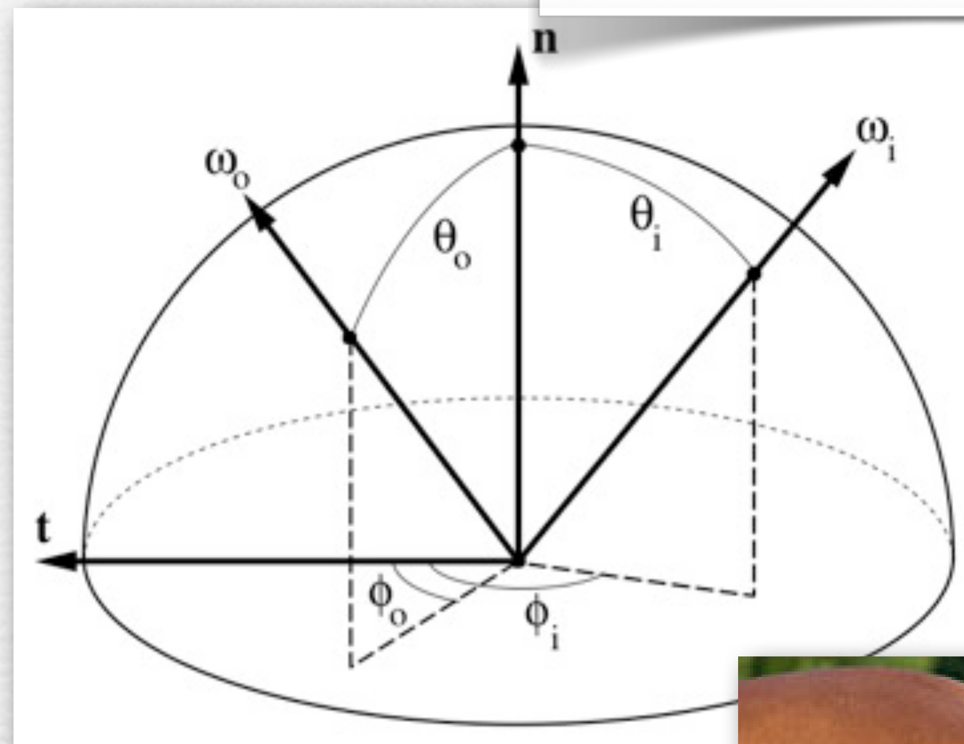


Bartolomeo Bettera,
Still Life with Musical Instruments,
17th century

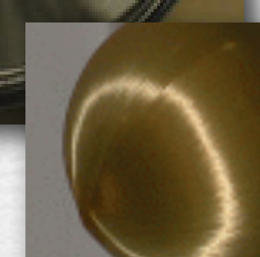
And this goniometric diagram?

θ's denote declination;
ϕ's denote azimuth


(http://graphics.stanford.edu/~smr/brdf/bv/)



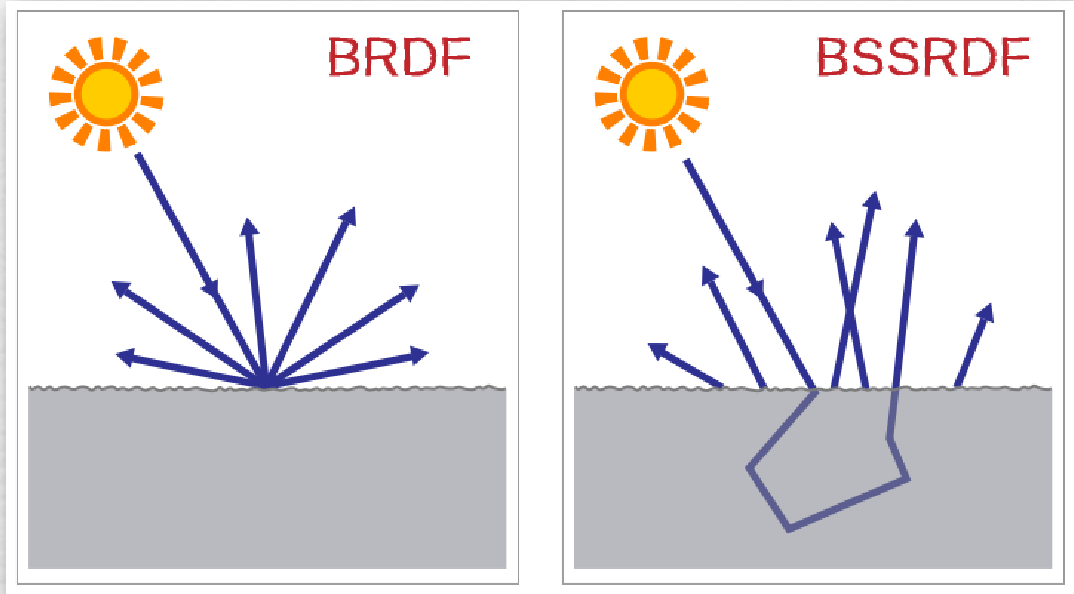
- A. anisotropic reflection
  - highlight not radially symmetric around mirror direction
- produced by grooved or directionally textured materials
  - highlight may depend on light direction ϕ_i and viewer direction ϕ_o (like the horse), or only on the difference $\phi_i - \phi_o$ between them (pot and Xmas tree ornament)

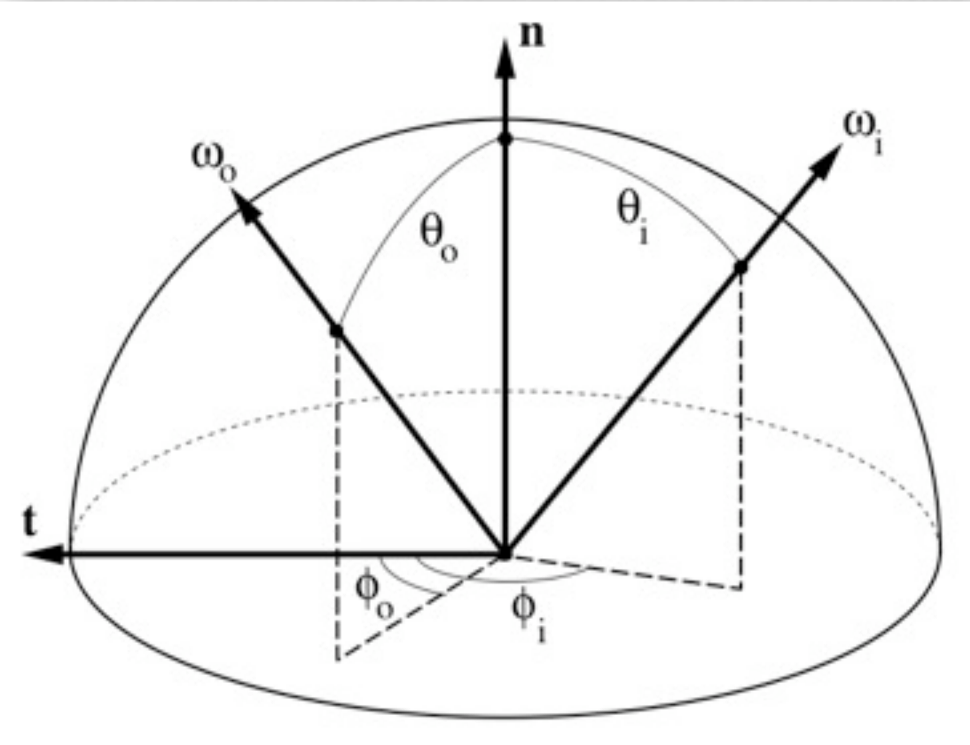



(horsemanmagazine.com)

BRDFs and BSSRDFs

(wikipedia)





(http://graphics.stanford.edu/~smr/brdf/bv/)

- Bidirectional Reflectance Distribution Function (BRDF, 4D function)

$$f_r(\theta_i, \phi_i, \theta_r, \phi_r) \qquad \left(\frac{1}{sr}\right)$$

- Bidirectional Surface Scattering Reflectance Distribution Function (BSSRDF, 8D function)

$$\rho(x_i, y_i, \theta_i, \phi_i, x_r, y_r, \theta_r, \phi_r) \qquad \left(\frac{1}{sr}\right)$$

BRDFs versus BSSRDFs

(Henrik Wann Jensen)

BRDF

BSSRDF

- subsurface scattering is critical to the appearance of human skin
  - cosmetics hide blemishes, but they also prevent subsurface scattering

Slide credits

- Stone, M., *A Field Guide to Digital Color*, A.K. Peters, 2003.
- Dorsey, J., Rushmeier, H., Sillion, F., *Digital Modeling of Material Appearance,* Elsevier, 2008.
- Reinhard et al., *High Dynamic Range Imaging*, Elsevier, 2006.
- Minnaert, M.G.J., *Light and Color in the Outdoors*, Springer-Verlag, 1993.

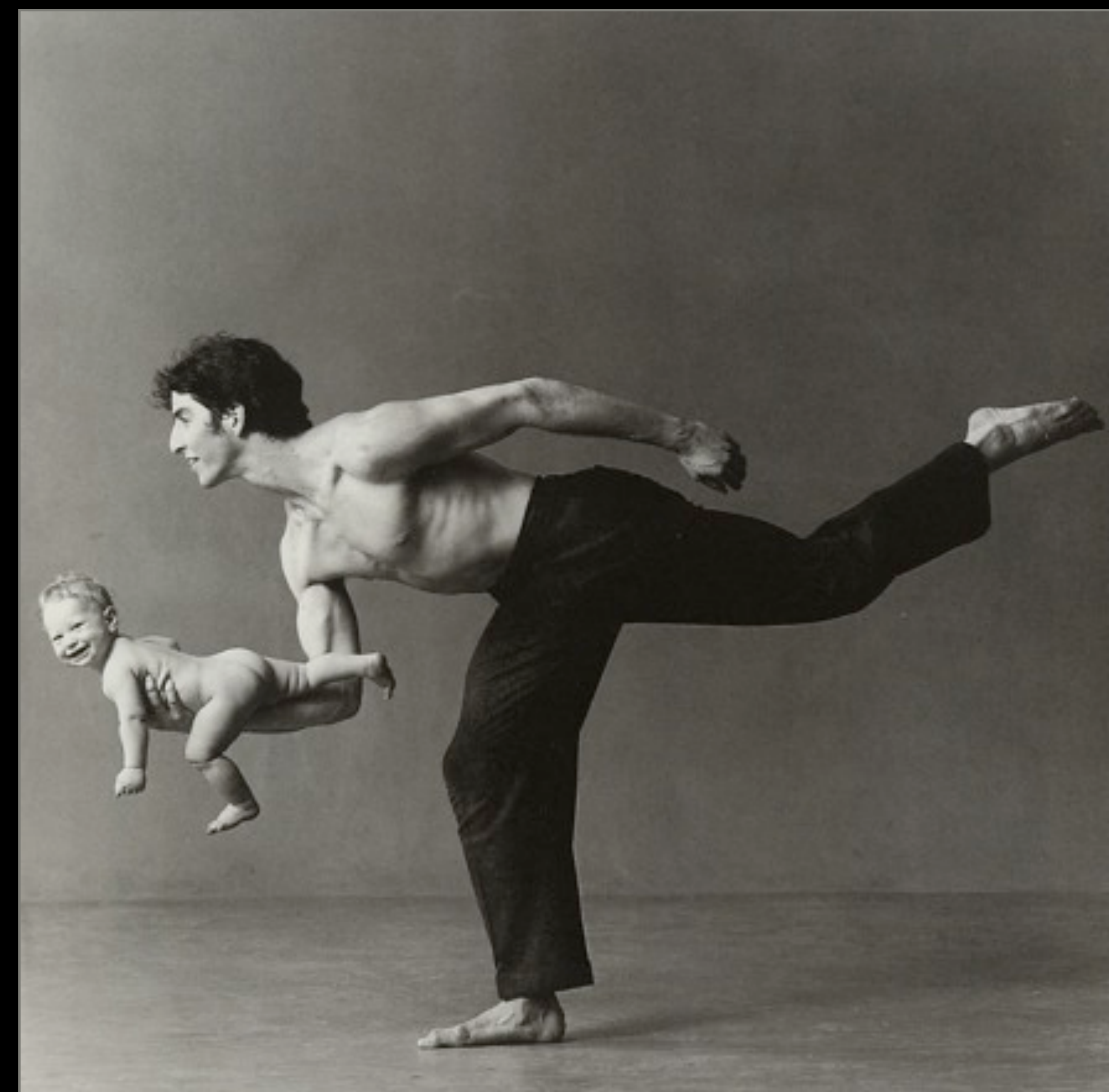
Outline

- measures of light
  - radiometry versus photometry
  - luminous intensity of a point light
  - luminance leaving an area light
  - luminance arriving on a surface
  - illuminance on a surface
- reflection of light
  - diffuse
  - specular
  - goniometric diagrams
- flash
- paper parade!

When to use flash?

- freezing the action
- fill-flash
- flash-plus-ambient
- flash as a fill light
- ways to avoid using flash

Lois Greenfield,
dance photography,
1983-1988



Lois Greenfield,
dance photography,
1983-1988

Fill-flash (for brightly lit backdrops)

(London)

exposed for foreground

exposed for background

exposed for background, with fill flash

- shorten exposure, then add flash
- could instead use HDR, but that requires multiple shots

Flash-plus-ambient (in low light)

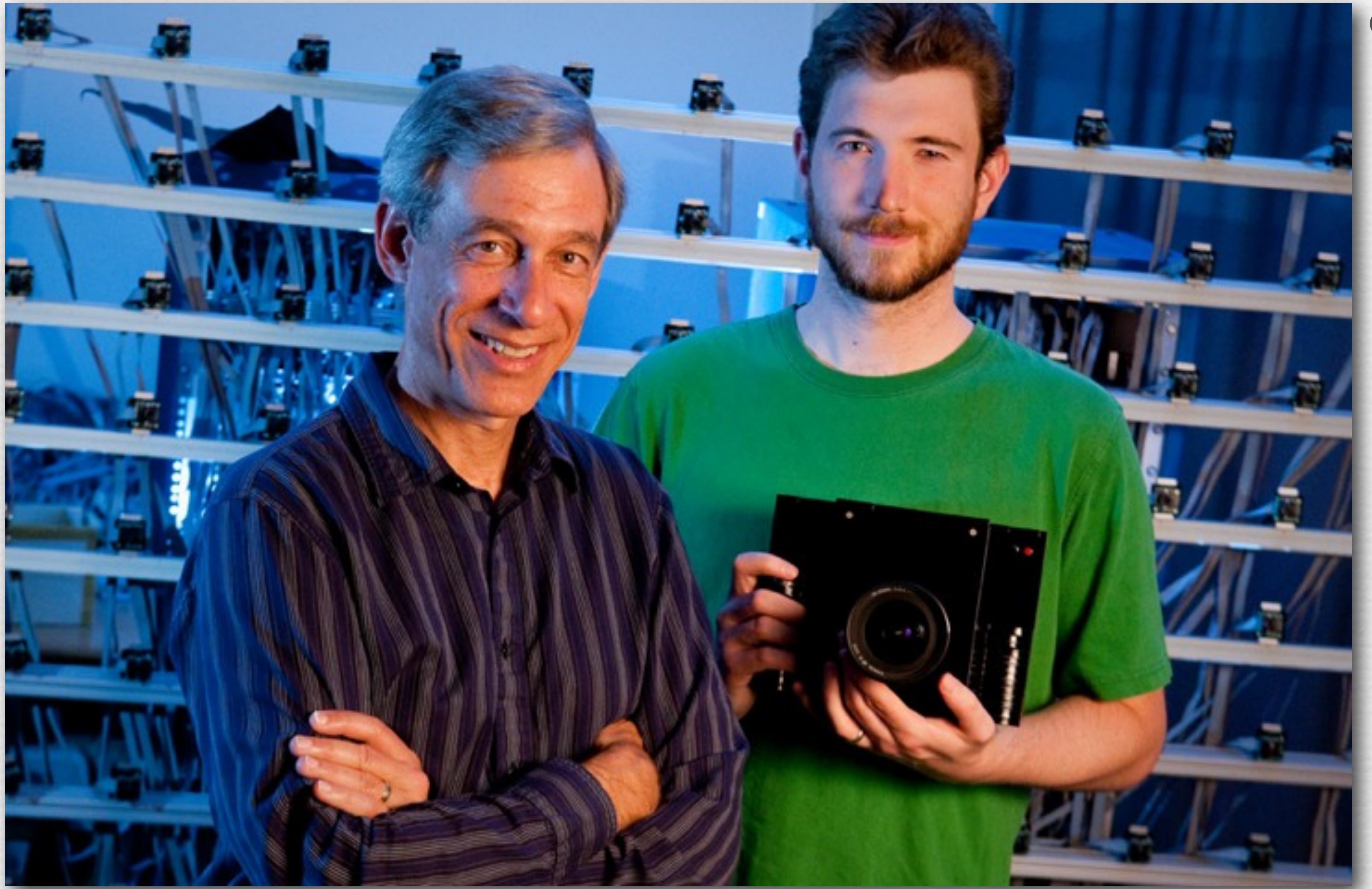
(Ang)

standard flash
exposure

1/4 second
with flash

- use flash, and lengthen exposure
- avoids isolating the foreground from its background

How was this shot lit?

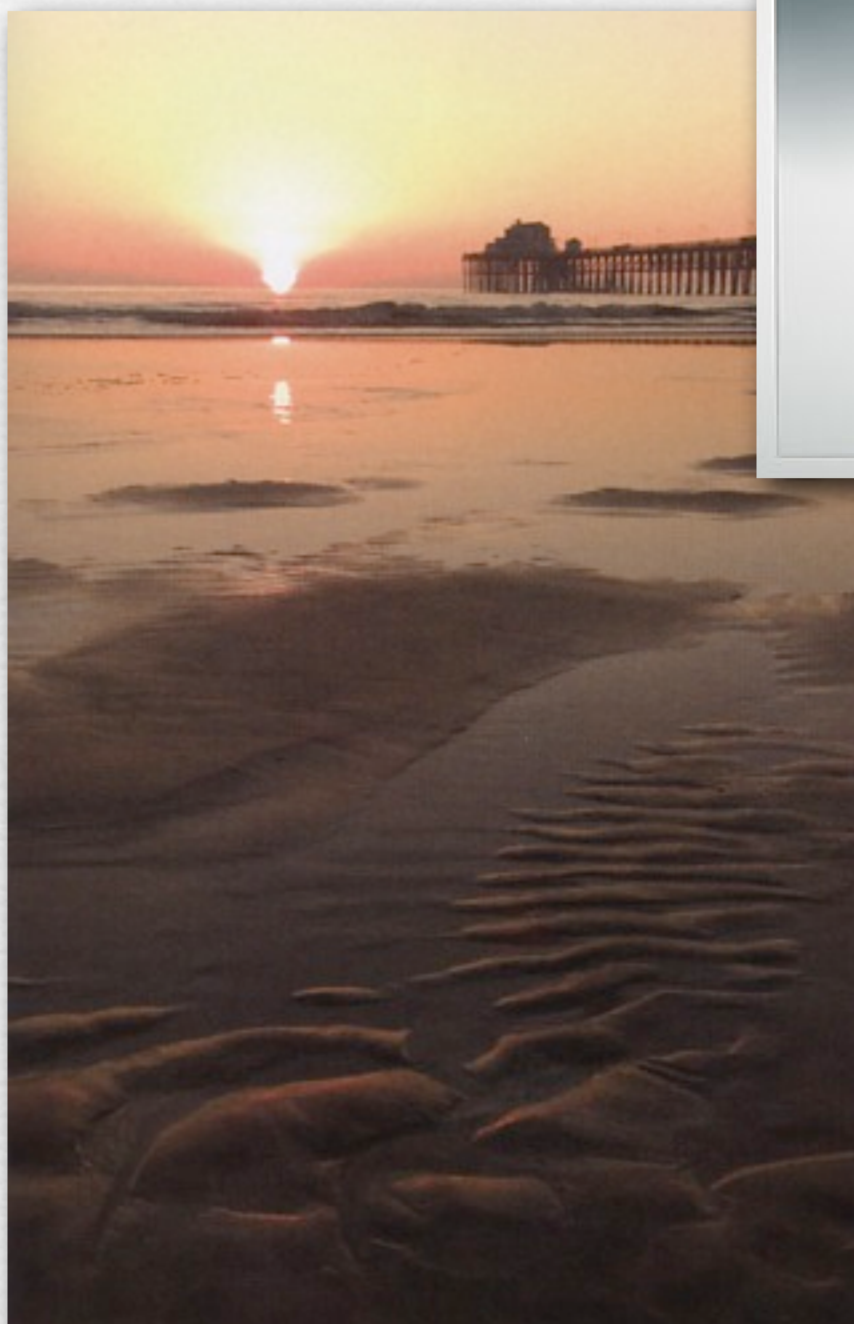


(Linda Cicero)

- key flash (on right side of scene) with orange gel & umbrella
  + fill flash (extreme left side of scene) with no gel or diffuser
  + background flash (pointed at back wall) with blue gel

Avoiding flash

(Peterson)

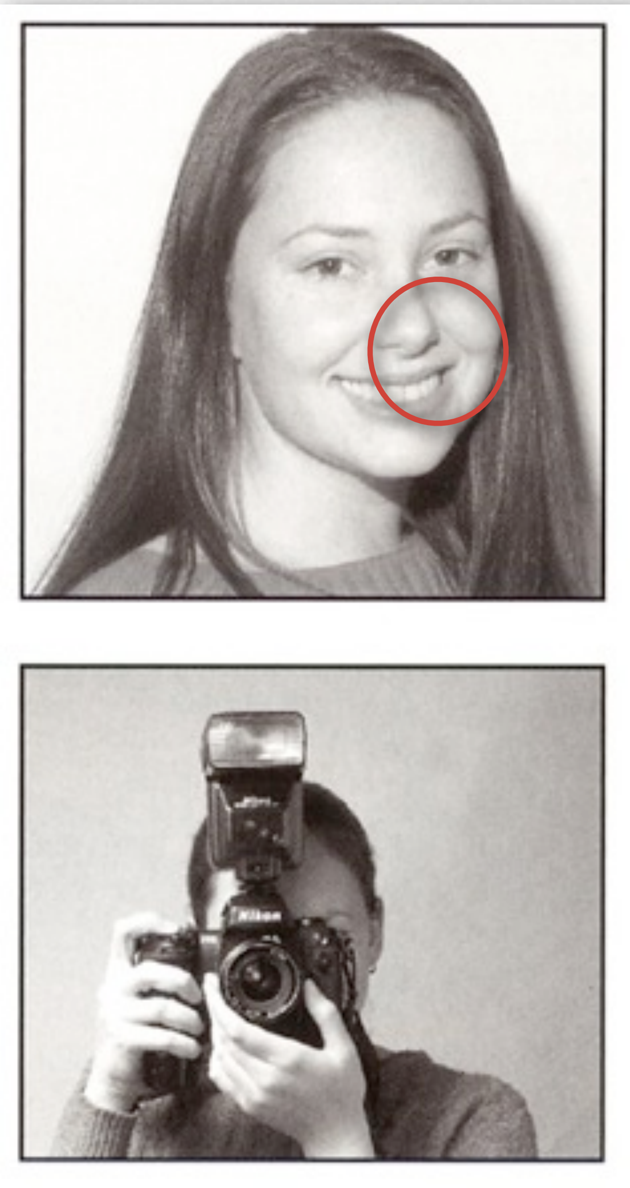


straight shot

with graduated neutral-density filter

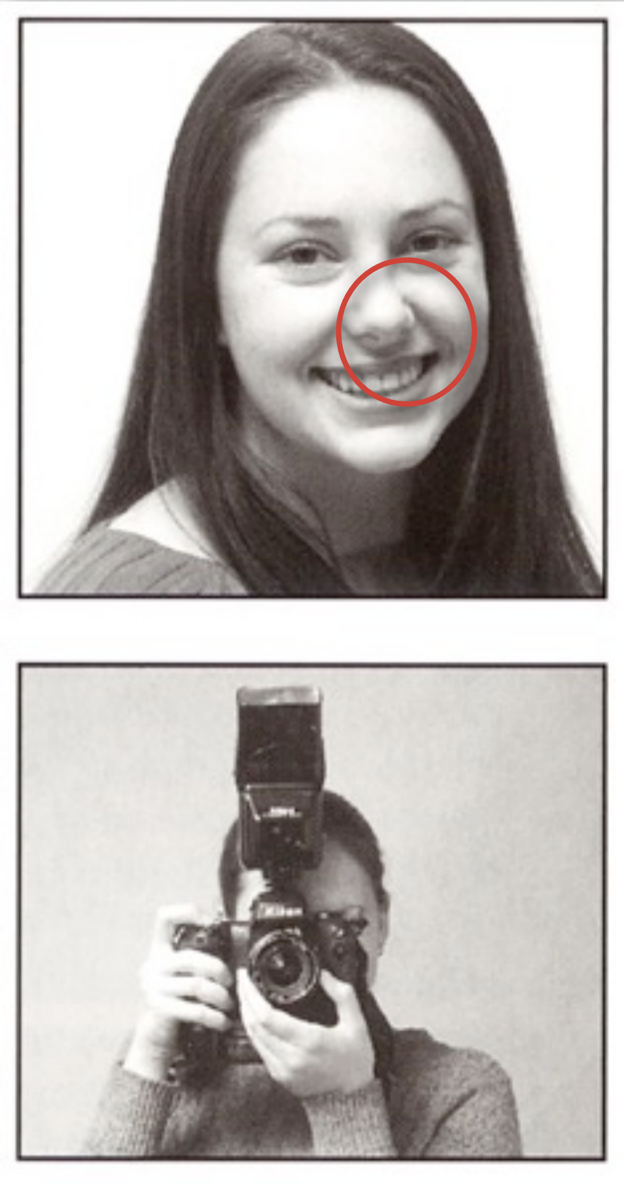
Flash placement

(London)

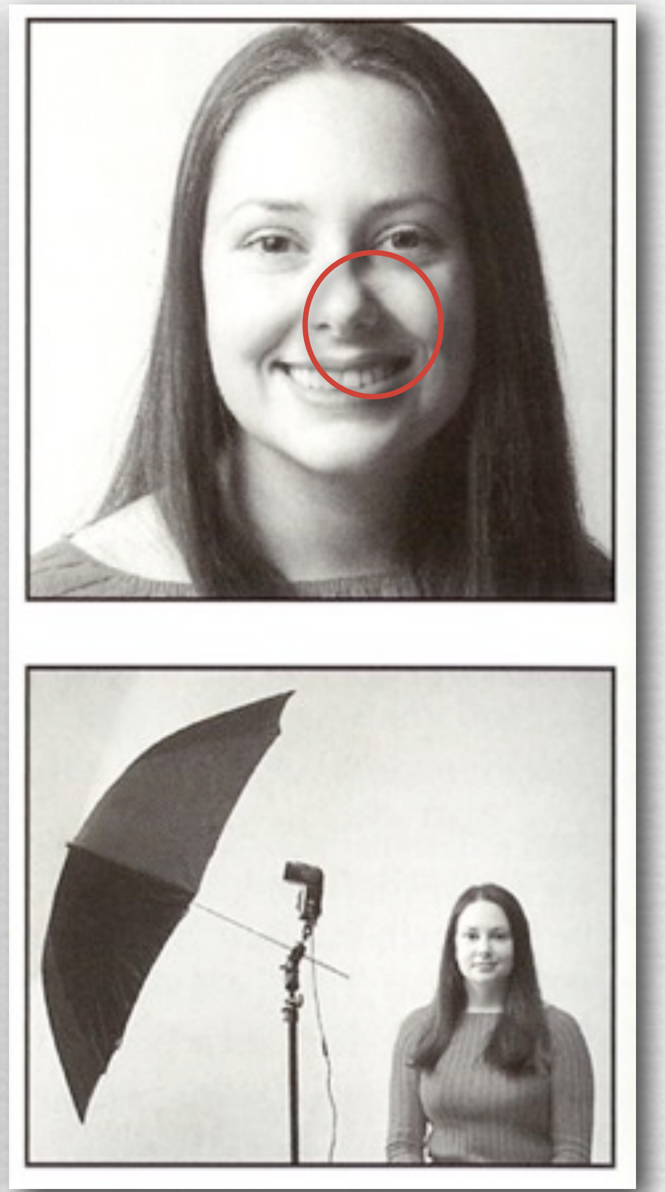


direct flash,
on camera

direct flash,
off camera



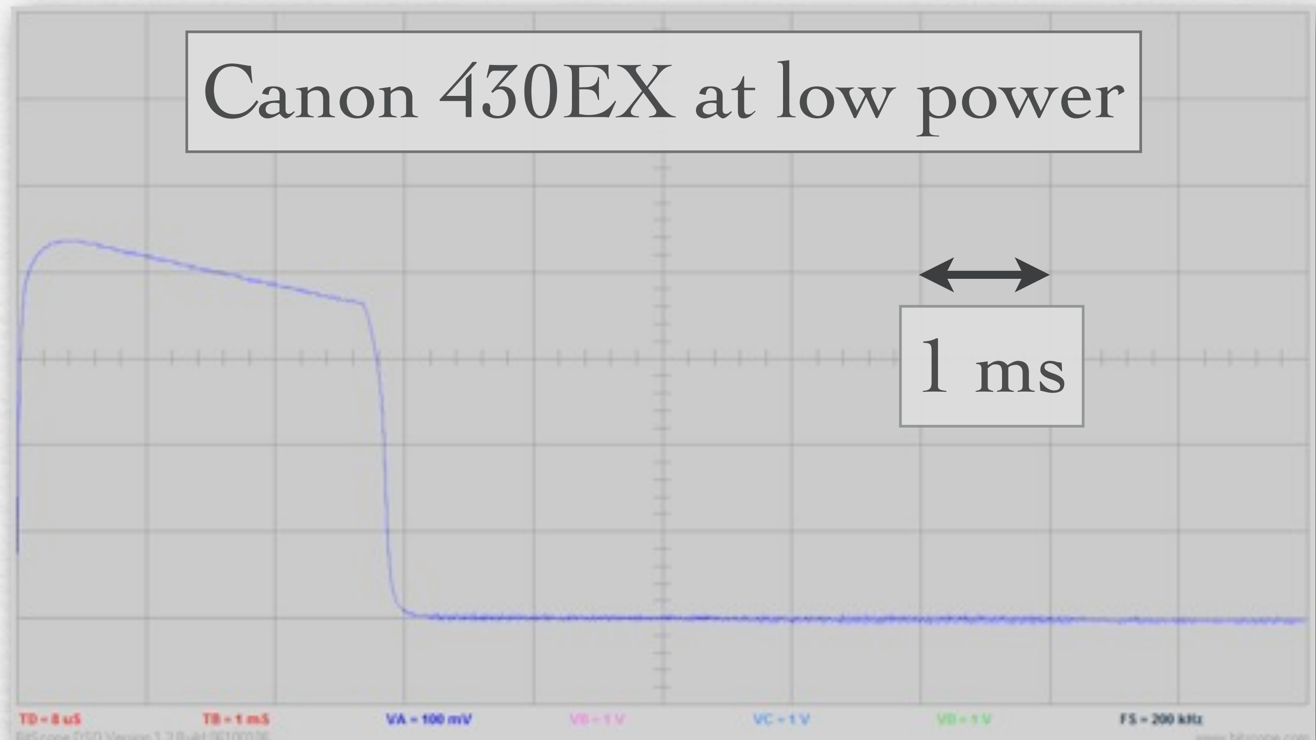
bounce flash,
from above

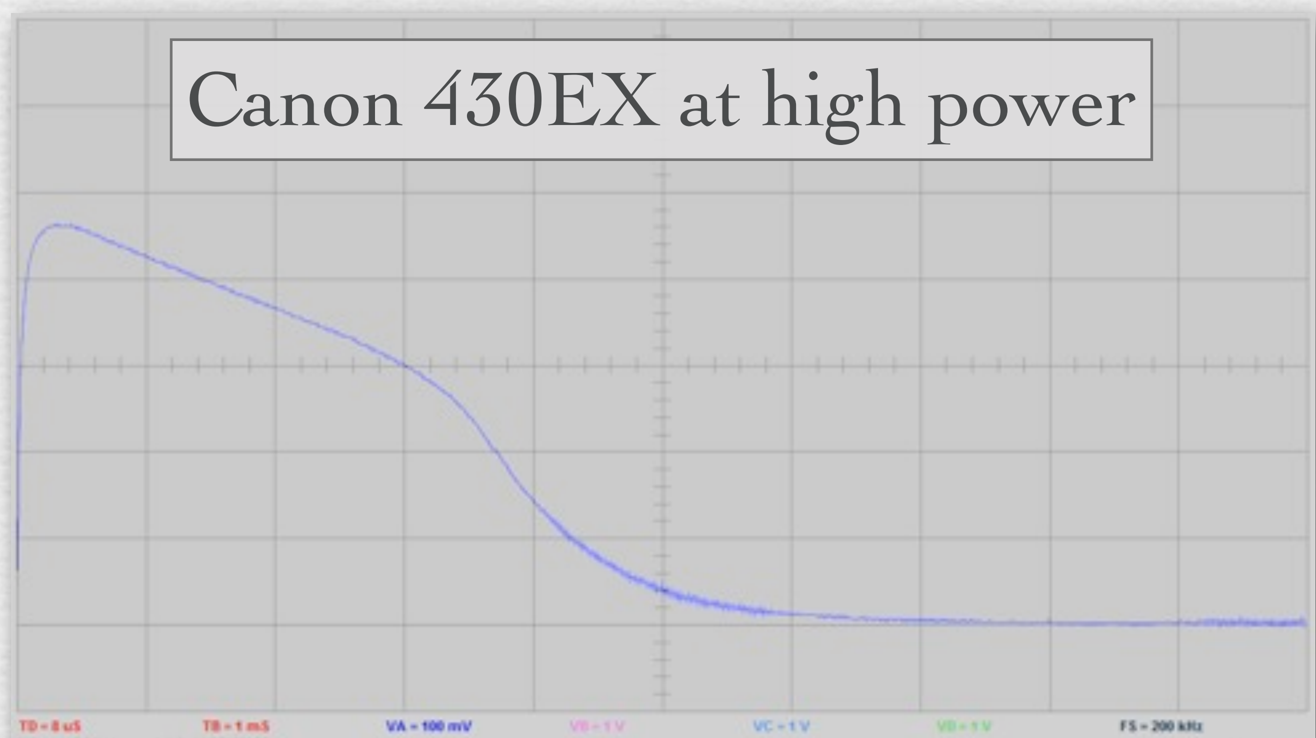


bounce flash,
from the side

Controlling exposure in flash photography

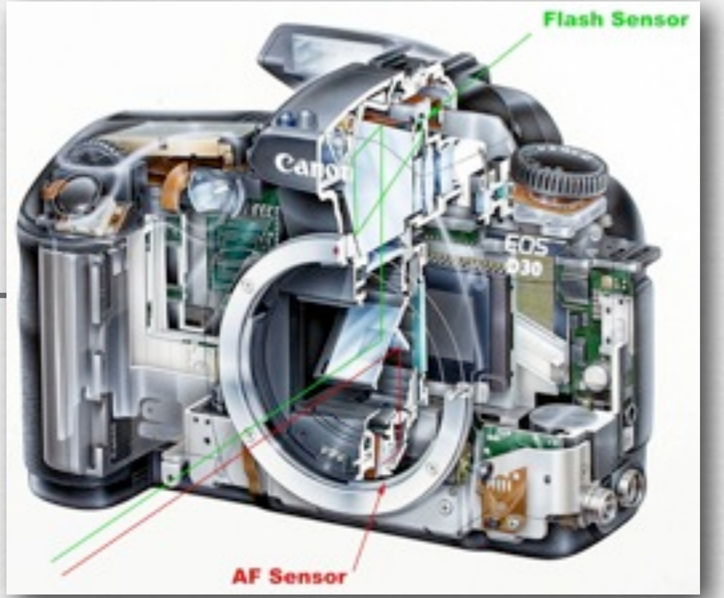
- the luminous intensity of a particular xenon flash tube is fixed
- flash is briefer than the shutter, so you can't use shutter speed to control illuminance on sensor
  - you can still use it to control ambient light
- aperture and ISO affects recording of both flash and ambient light
- instead, adjust duration of the flash pulse



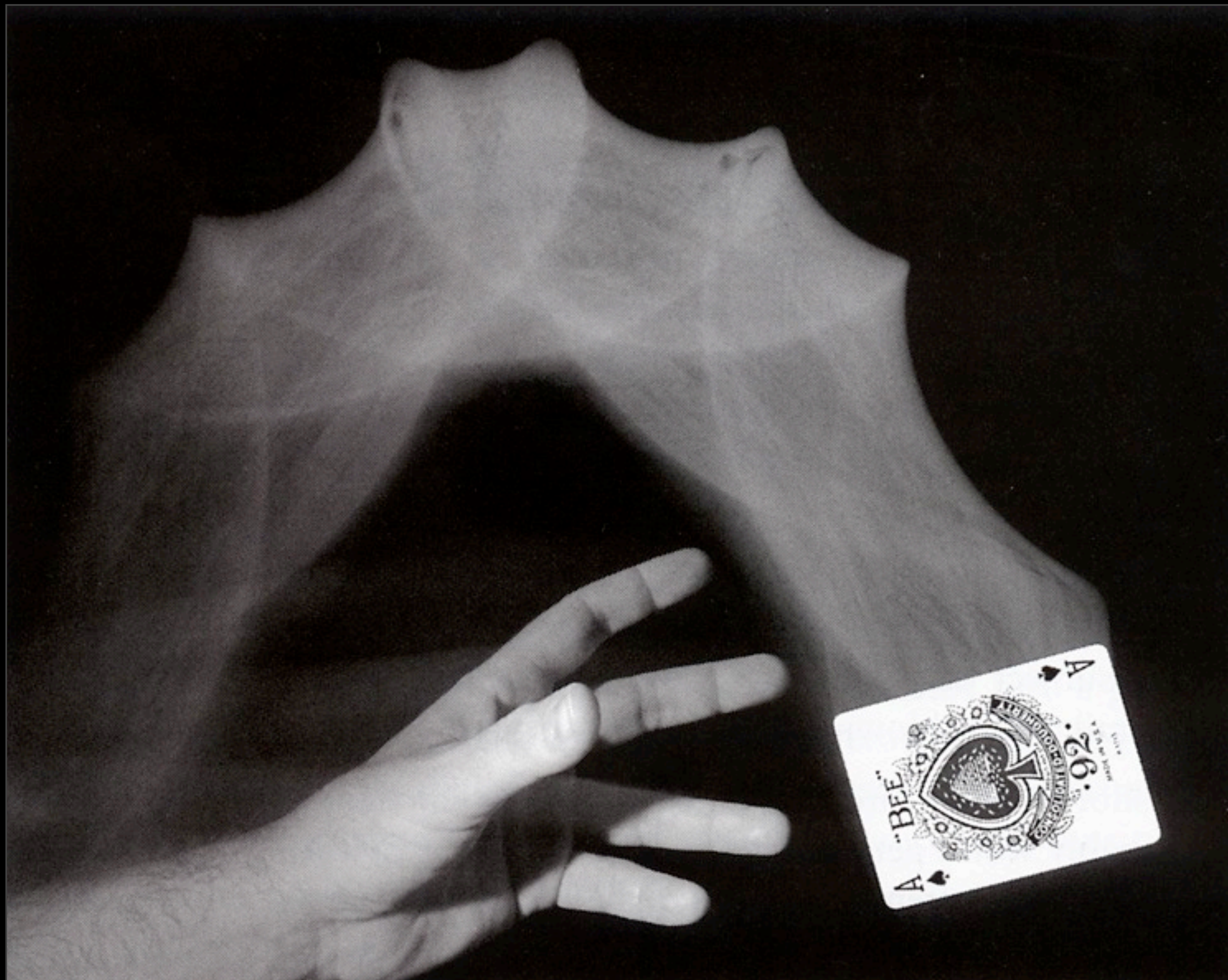


Metering for flash photography

(Canon E-TTL or Nikon iTTL, including Nikon D40)



- on shutter half-press, focus under ambient light (or AF assist light) and meter for ambient light
- on shutter press, fire weak preflash and record on flash sensor
- compute some combination of aperture, flash duration, and ISO
  - decision uses multi-point metering of ambient light, multi-point autofocusing, shooting mode, etc.
- flip up mirror, open shutter, and fire flash
- drawbacks
  - fooled by specular objects, scenes that fool metering and focusing,...
  - delay between pre-flash and flash is long enough to cause some people to blink, especially if using 2nd curtain sync



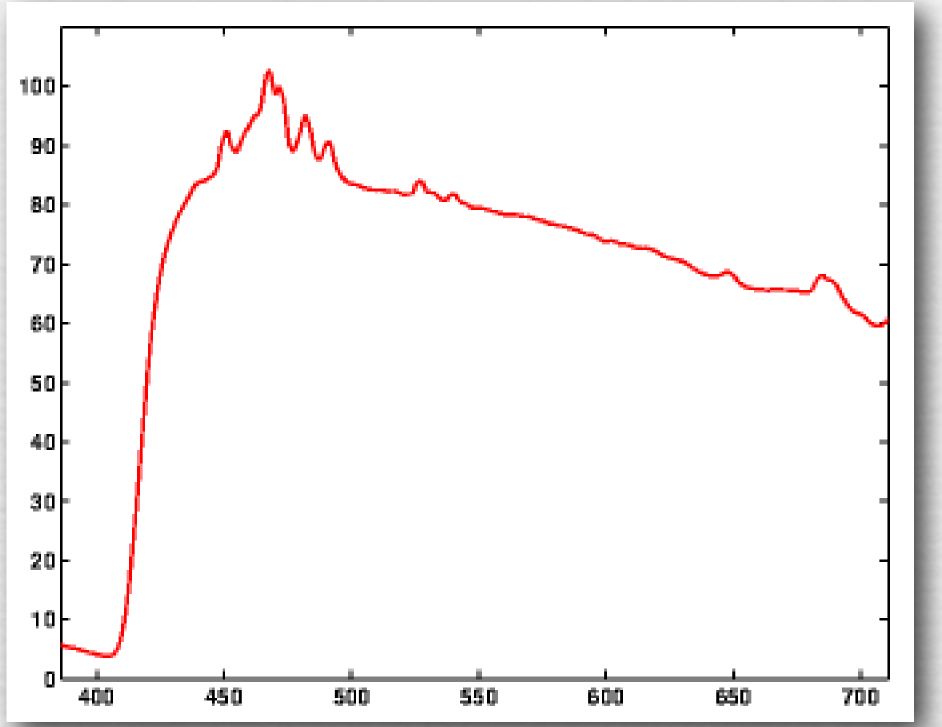
Derrick Story, card flip using second-curtain flash

Stanford programmable Frankencamera with 2 flash heads attached

- Canon 430EX (smaller flash) strobed continuously
- Canon 580EX (larger flash) fired once at end of exposure

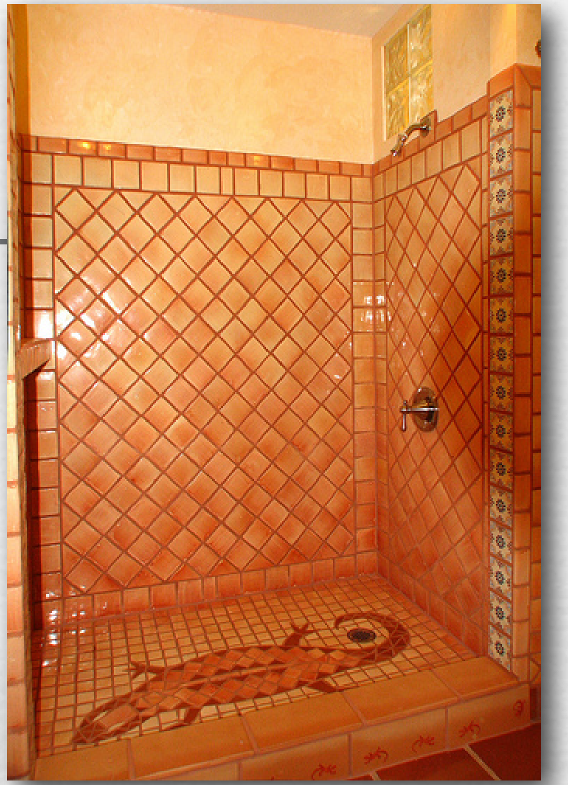
Color temperature of xenon flash

(graphics.cornell.edu)



- broad spectrum, approximates daylight (6500°K, i.e. D65)
- if mixed with ambient tungsten light, flash will look blue if WB is Tungsten, or background will look orange if WB is Flash
  - can compensate with color correction filter on the flash
  - filters are enumerated in °K of correction
  - filters reduce effective flash power

Problems with flash



- power falls as distance squared
  - subject is too bright
  - background is too dark
- in-camera flash is too close to lens
  - no shadows on subject
  - shadow of lens in wide-angle view
- red-eye
  - worse with in-camera flash
  - worse in low light (pupils are wide open)
  - pre-flash to shrink pupils, which looks better anyway
- shutter speed must be low enough that shutter is completely open
  - 1/90 - 1/250 sec on Canon EOS cameras ("flash synch speed")
  - limits the range of shutter speeds for fill-flash
- don't shoot perpendicularly into glass

Outline

- measures of light
  - radiometry versus photometry
  - luminous intensity of a point light
  - luminance leaving an area light
  - luminance arriving on a surface
  - illuminance on a surface
- reflection of light
  - diffuse
  - specular
  - goniometric diagrams
- flash
- paper parade!

Digital Photography with Flash and No-Flash Image Pairs

Georg Petschnigg   Maneesh Agrawala   Hugues Hoppe
Richard Szeliski   Michael Cohen   Kentaro Toyama
Microsoft Corporation

Orig. (top)   Detail Transfer (bottom)   Flash   No-Flash   Detail Transfer with Denoising

Figure 1: This candlelit setting from the wine cave of a castle is difficult to photograph due to its low light nature. A flash image captures the high-frequency texture and detail, but changes the overall scene appearance to cold and gray. The no-flash image captures the overall appearance of the warm candlelight, but is very noisy. We use the detail information from the flash image to both reduce noise in the no-flash image and sharpen its detail. Note the smooth appearance of the brown leather sofa and crisp detail of the bottles. For full-sized images, please see the supplemental DVD or the project website http://research.microsoft.com/projects/FlashNoFlash.

[Petschnigg 2004]

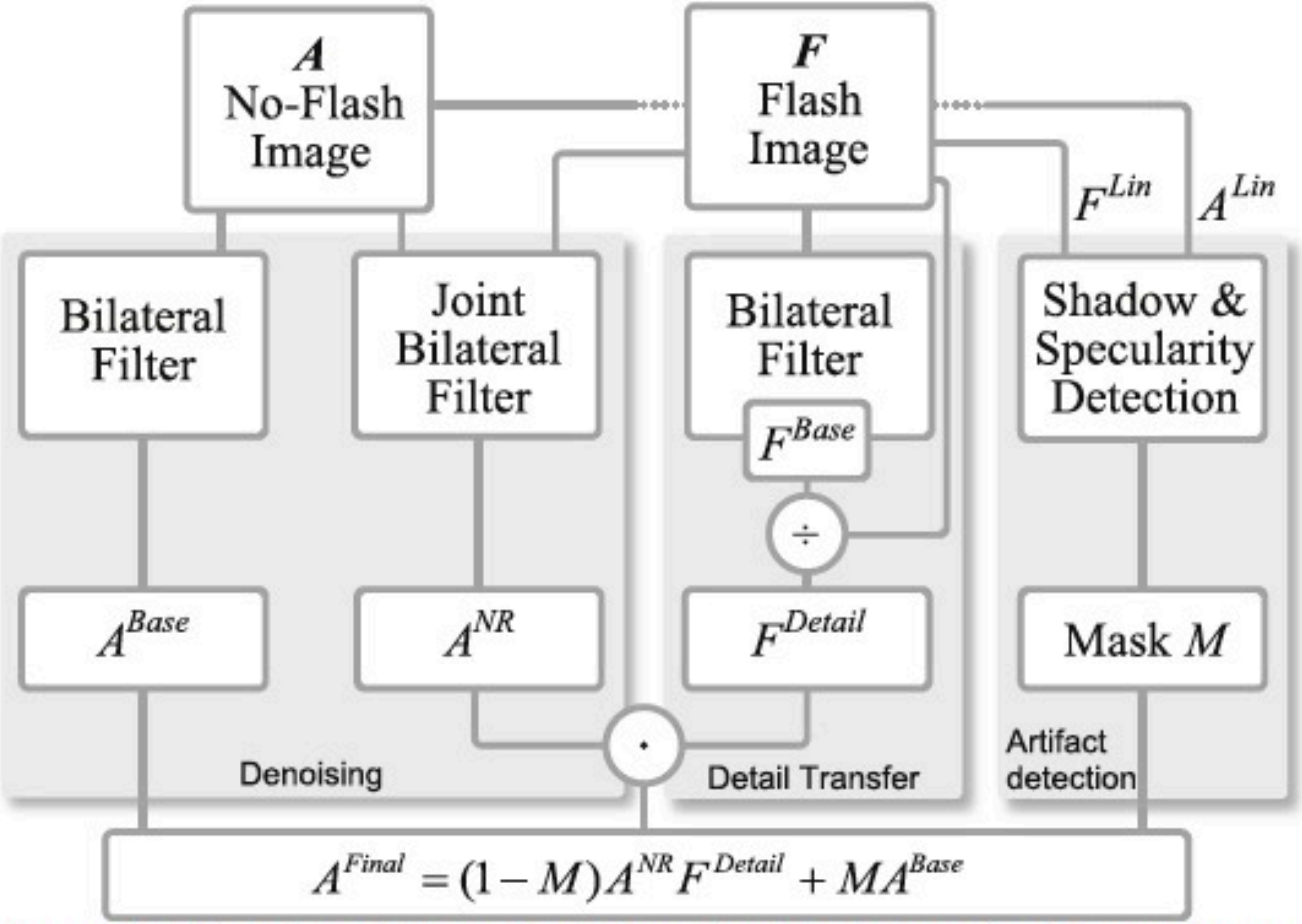
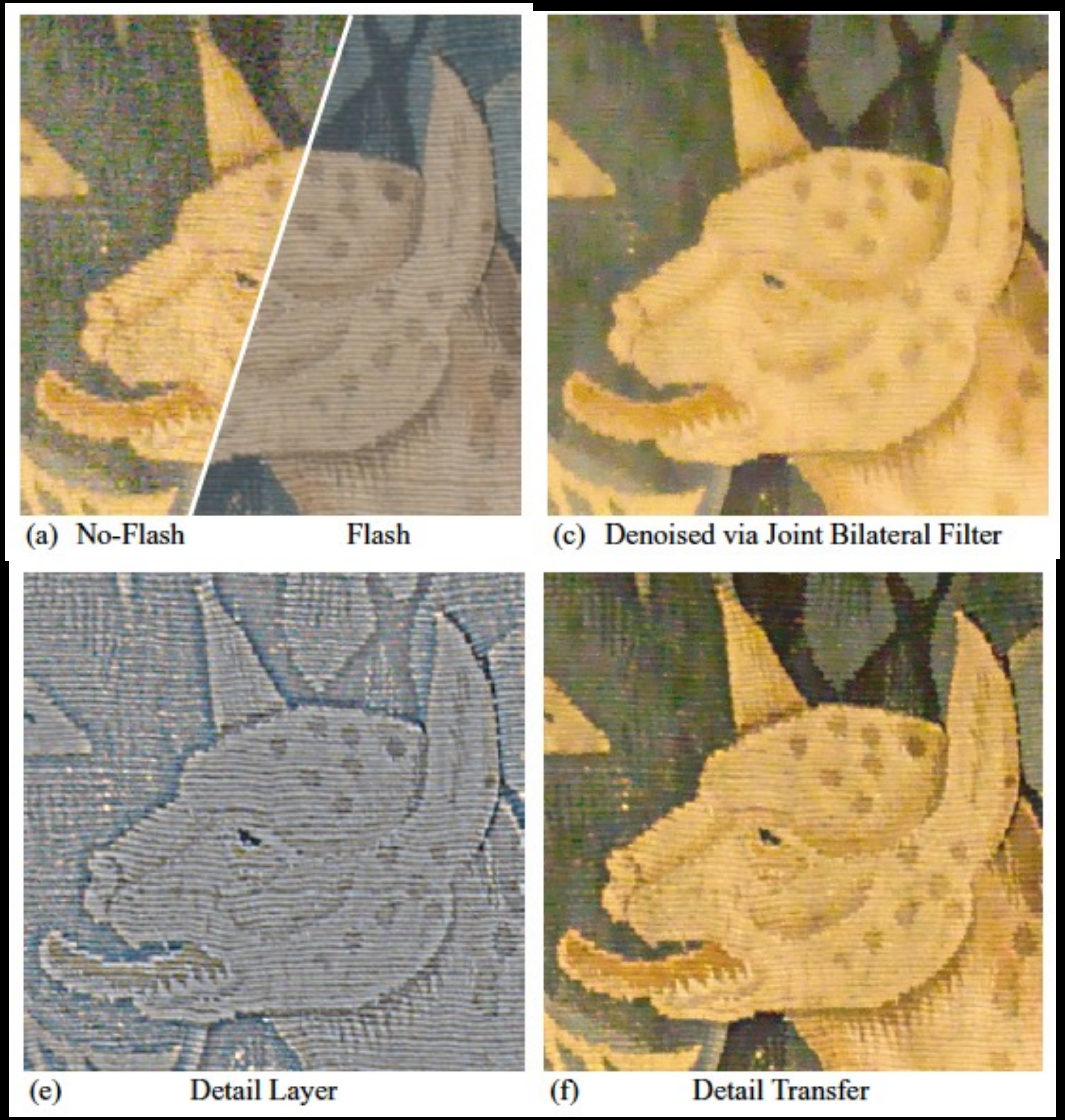
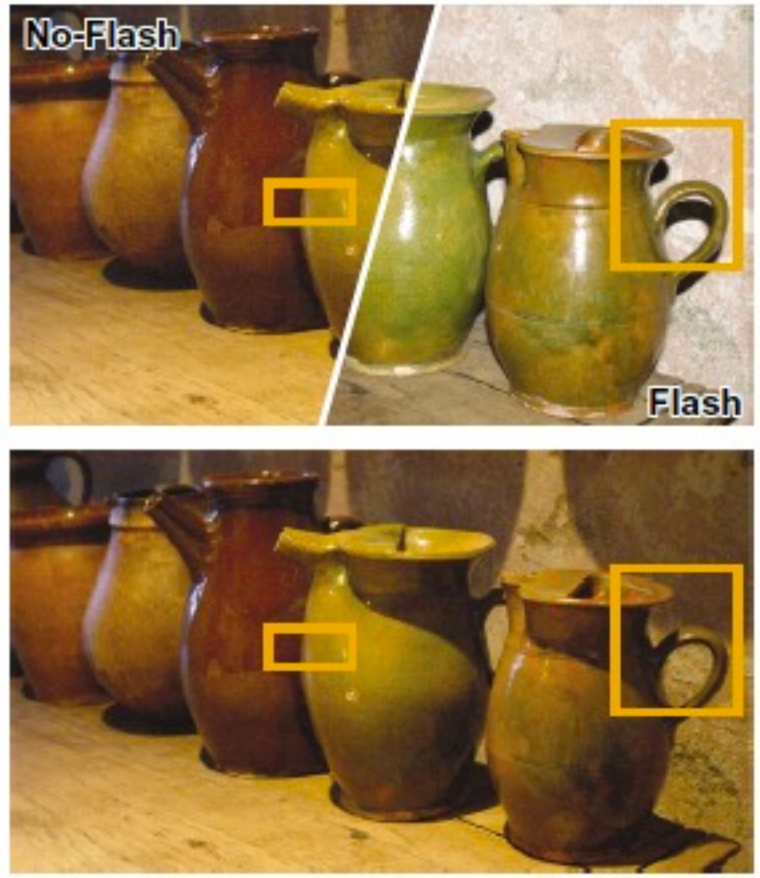


Figure 3: Overview of our algorithms for denoising, detail transfer, and flash artifact detection.

$$F^{Detail} = \frac{F + \varepsilon}{F^{Base} + \varepsilon},$$





Orig. (top) Detail Transfer (bottom)

Detail Transfer without Mask

Shadow and Specularity Mask

Detail Transfer using Mask

Dark Flash Photography

Dilip Krishnan* Rob Fergus

Dept. of Computer Science, Courant Institute, New York University

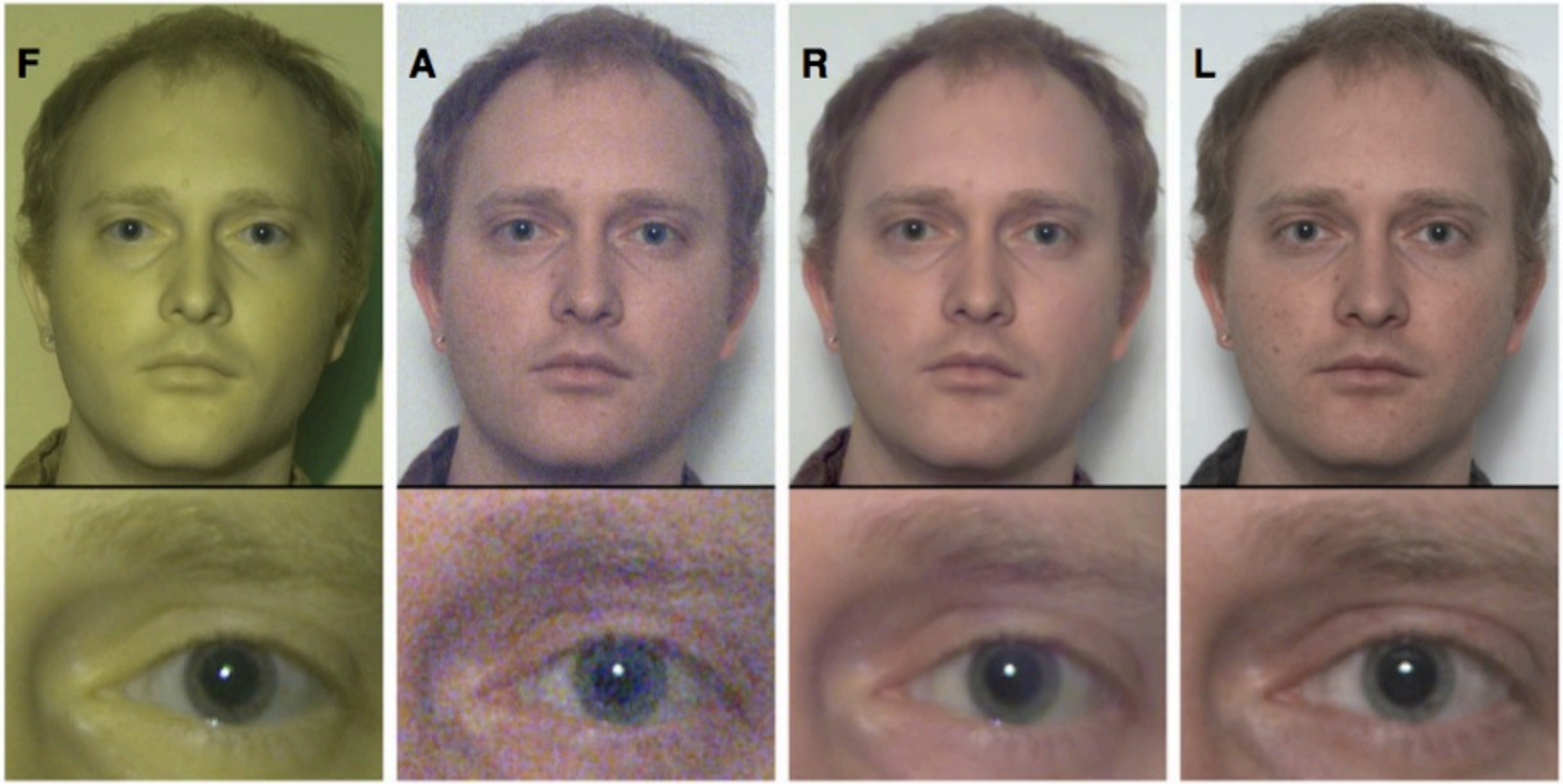
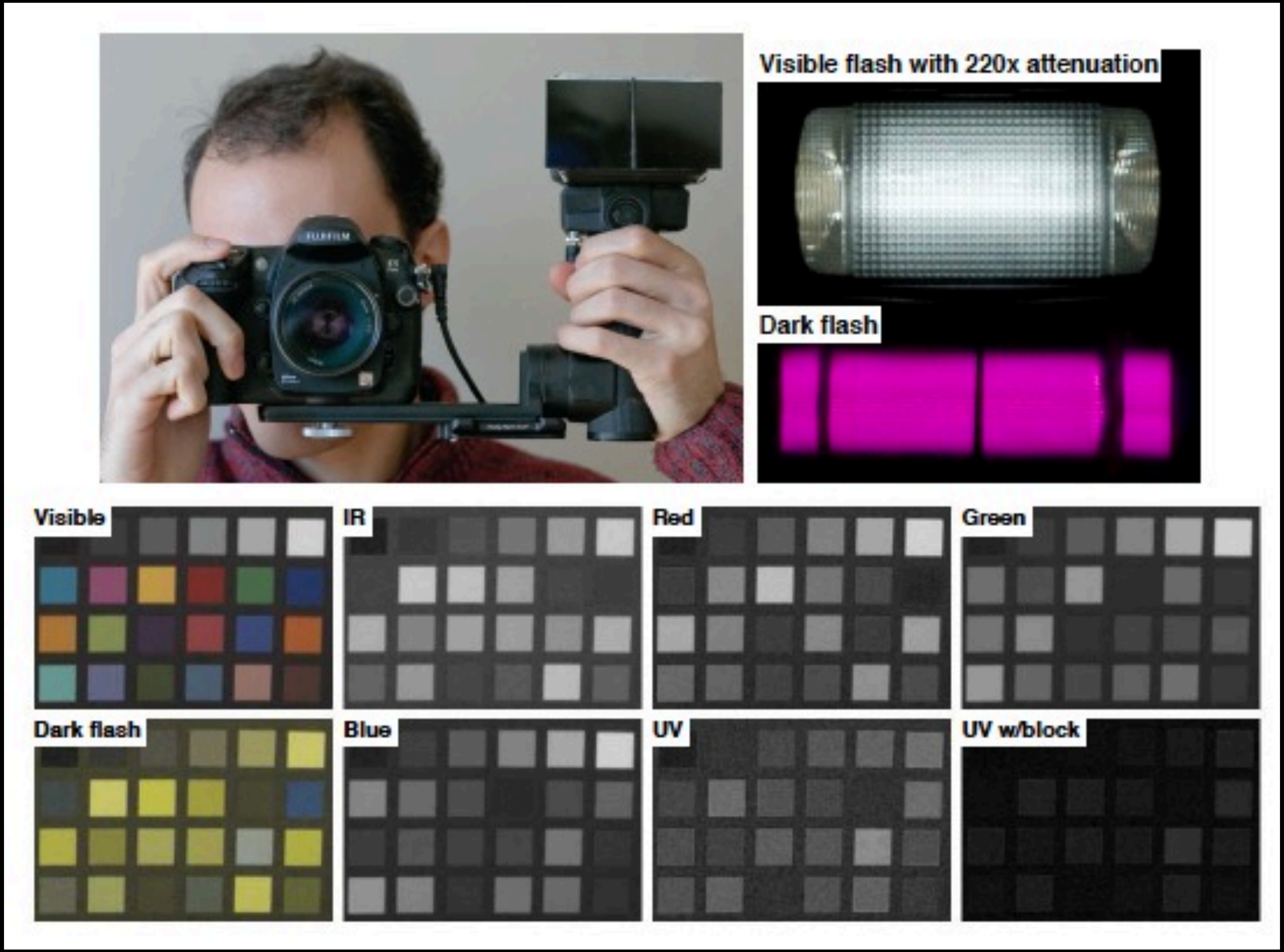
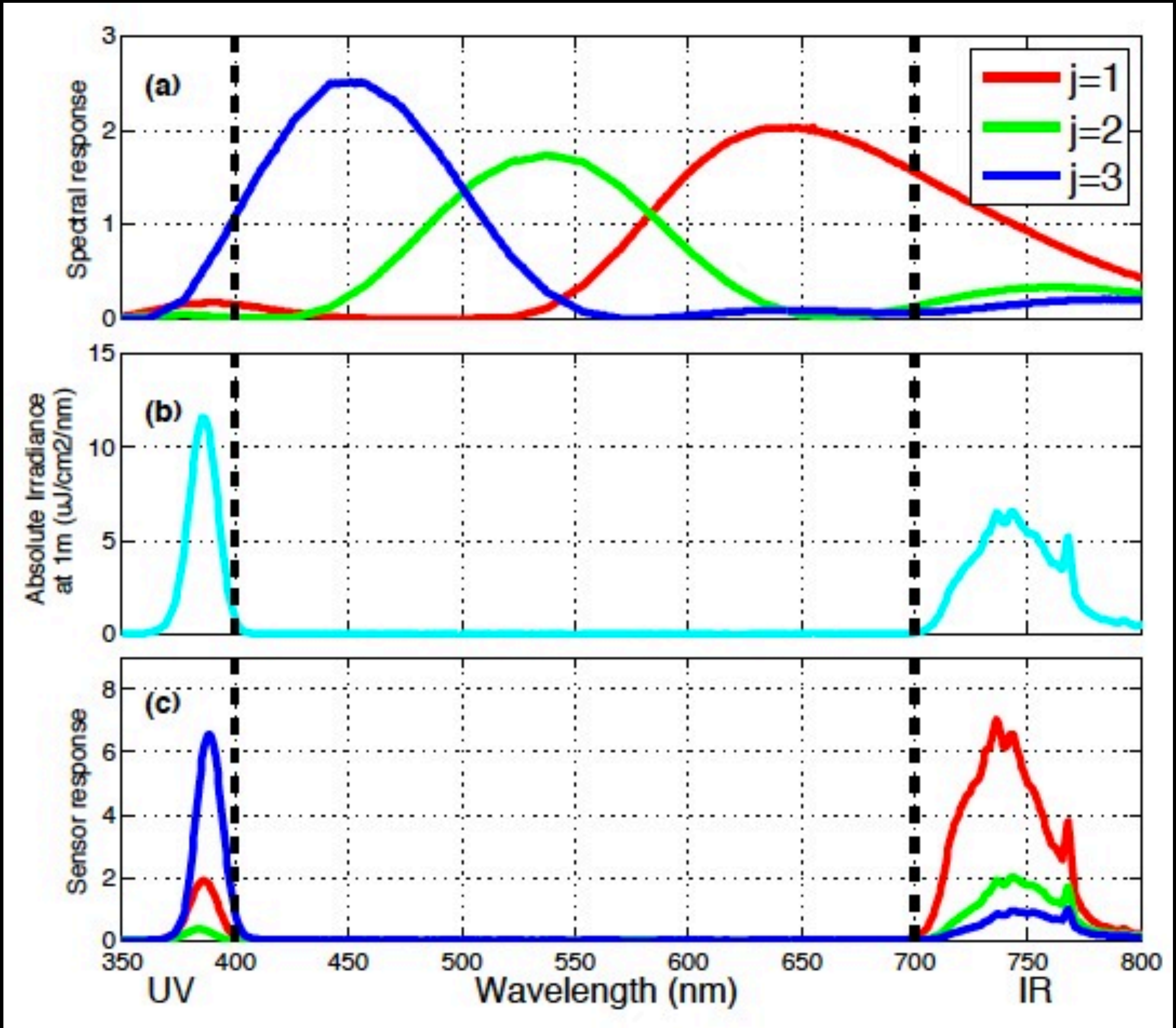


Figure 1: *Our camera and flash system offers dazzle-free photography by hiding the flash in the non-visible spectrum. A pair of images are captured at a blur-free shutter speed, one using a multi-spectral flash (F), the other using ambient illumination (A) which in this case is 1/100th of that required for a correct exposure. The pair are combined to give an output image (R) which is of comparable quality to a reference long exposure shot (L). The figures in this paper are best viewed on screen, rather than in print.*

[Krishnan 2009]


Visible flash with 220x attenuation
Dark flash
Visible
IR
Red
Green
Dark flash
Blue
UV
UV w/block



(a)
Spectral response
j=1
j=2
j=3
(b)
Absolute Irradiance at 1m (uJ/cm2/nm)
(c)
Sensor response
350
400
450
500
550
600
650
700
750
800
UV
Wavelength (nm)
IR

Non-photorealistic Camera: Depth Edge Detection and Stylized Rendering using Multi-Flash Imaging

Ramesh Raskar* Kar-Han Tan
Mitsubishi Electric Research Labs (MERL)

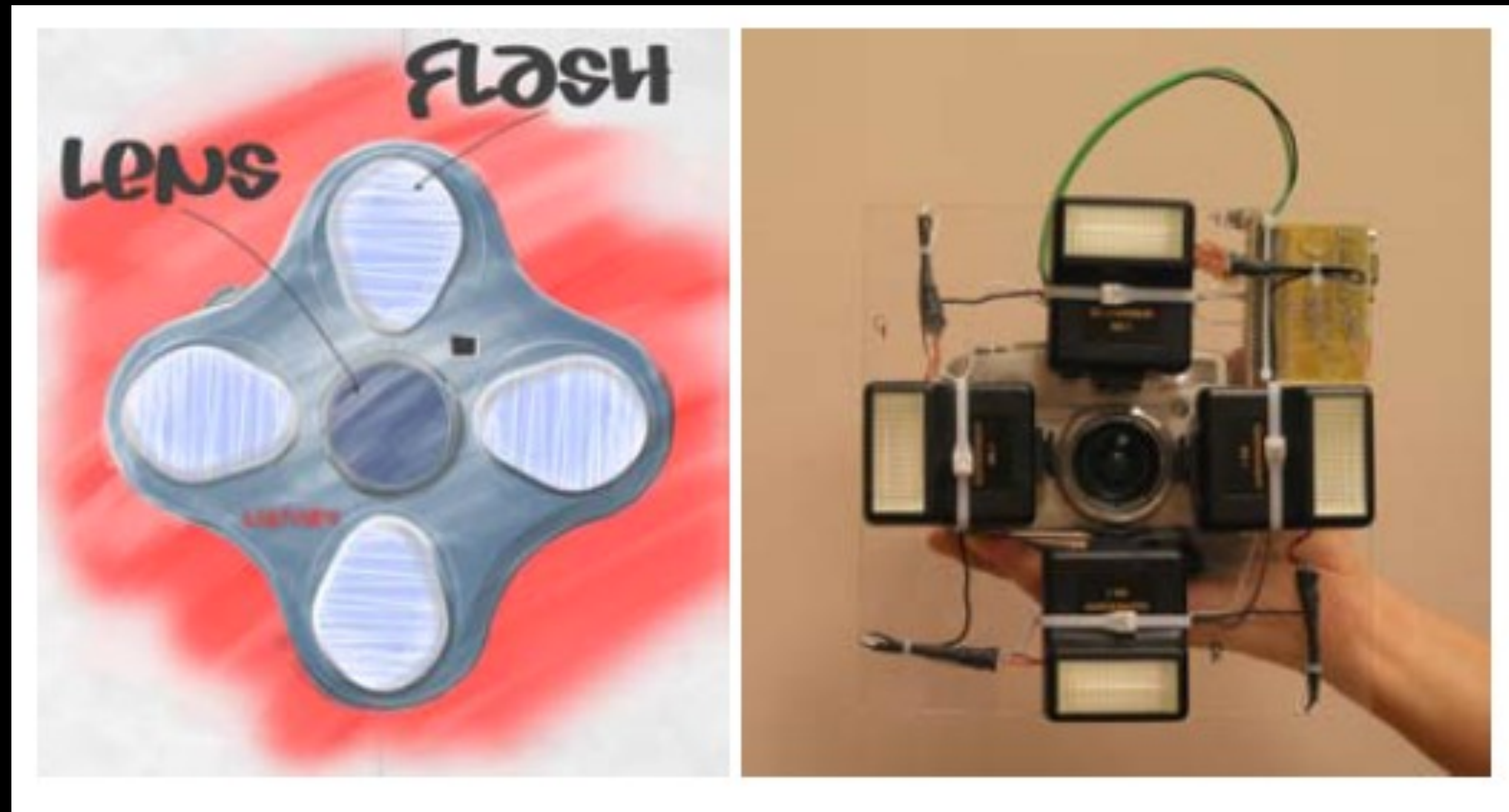
Rogerio Feris
UC Santa Barbara

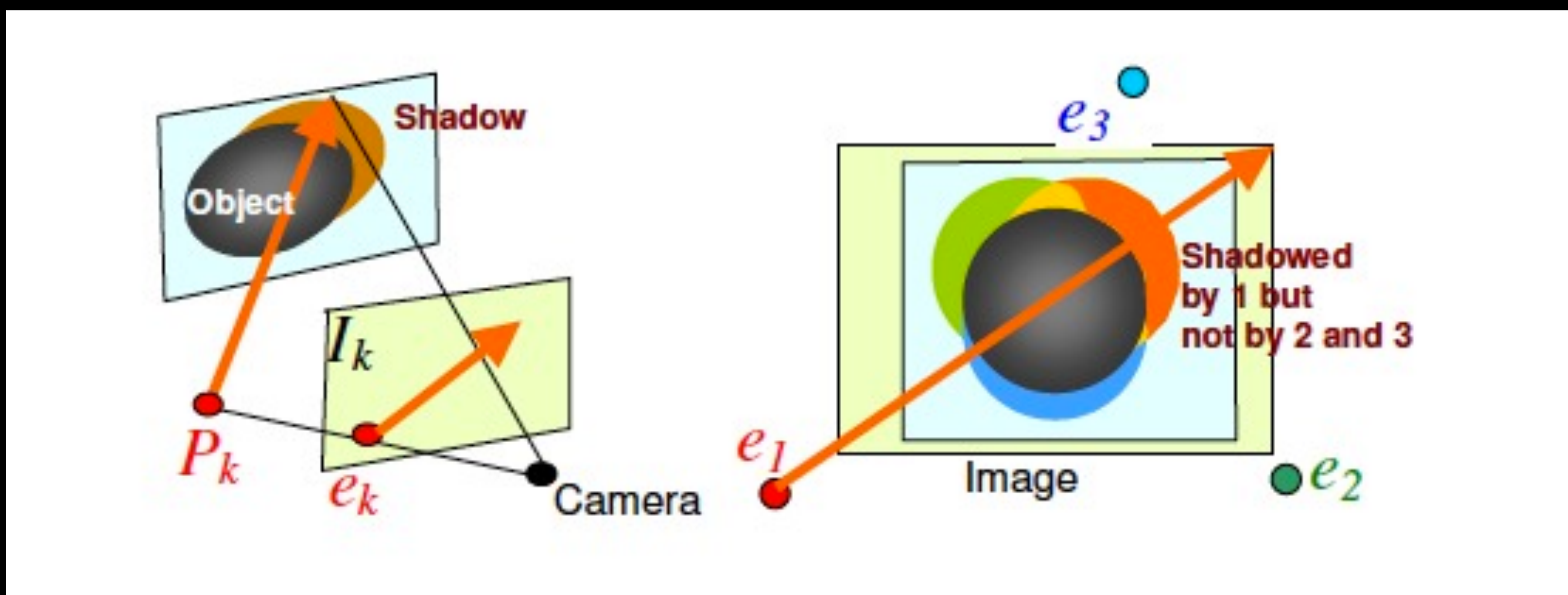
Jingyi Yu†
MIT

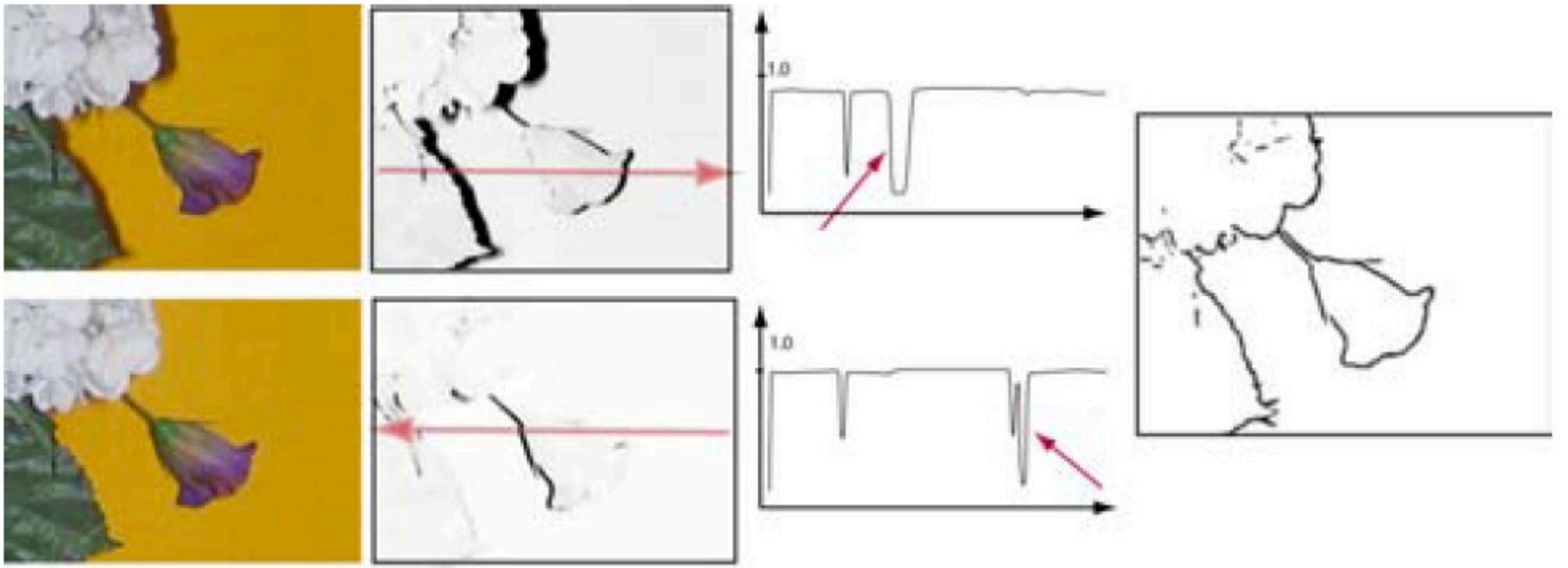
Matthew Turk
UC Santa Barbara

Figure 1: *(a) A photo of a car engine (b) Stylized rendering highlighting boundaries between geometric shapes. Notice the four spark plugs and the dip-stick which are now clearly visible (c) Photo of a flower plant (d) Texture de-emphasized rendering.*

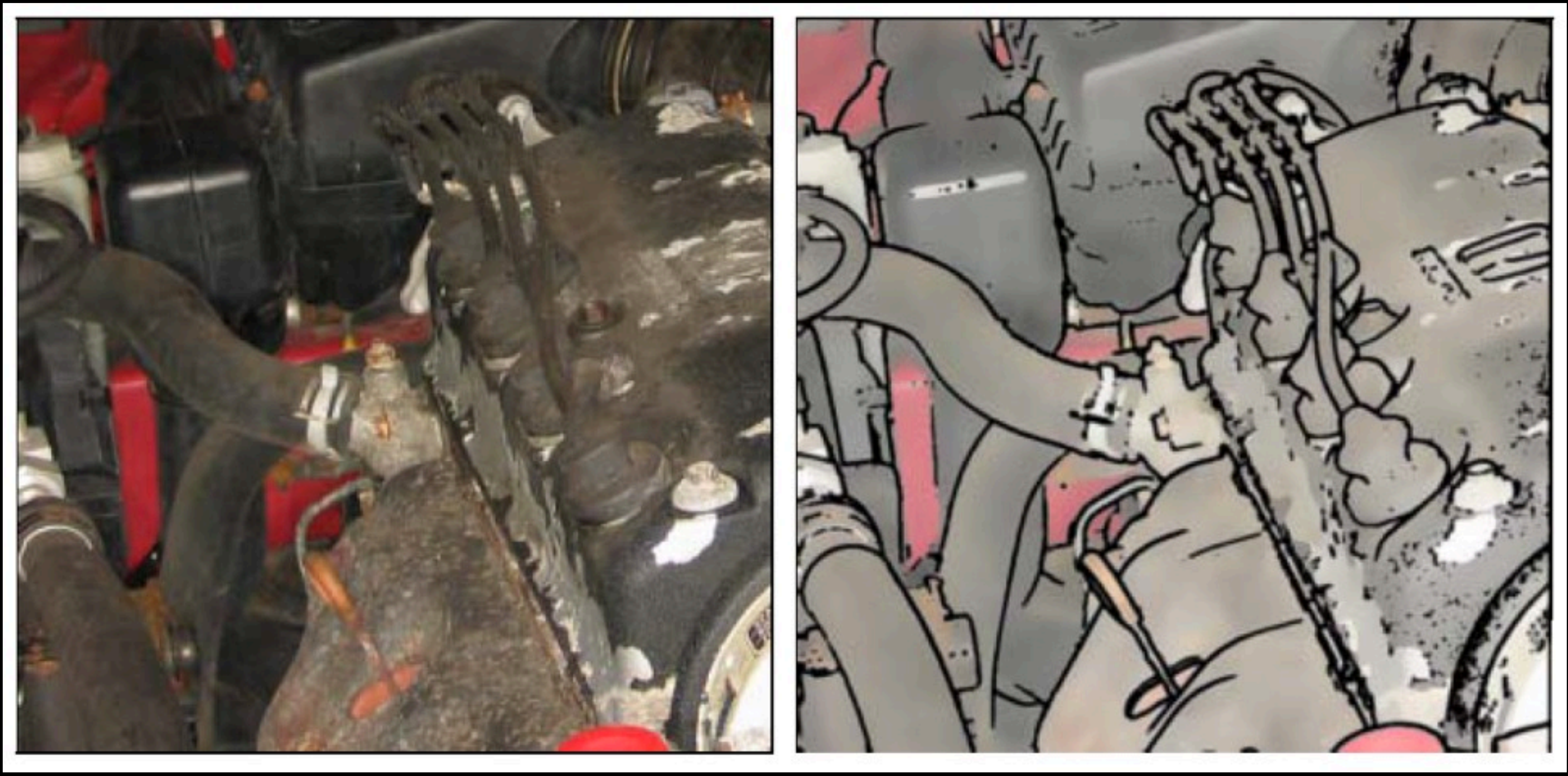
[Raskar 2004]


LENS
FLASH


Shadow
Object
I_k
P_k
e_k
Camera
e_3
Shadowed
by 1 but
not by 2 and 3
e_1
Image
e_2



1.0
1.0



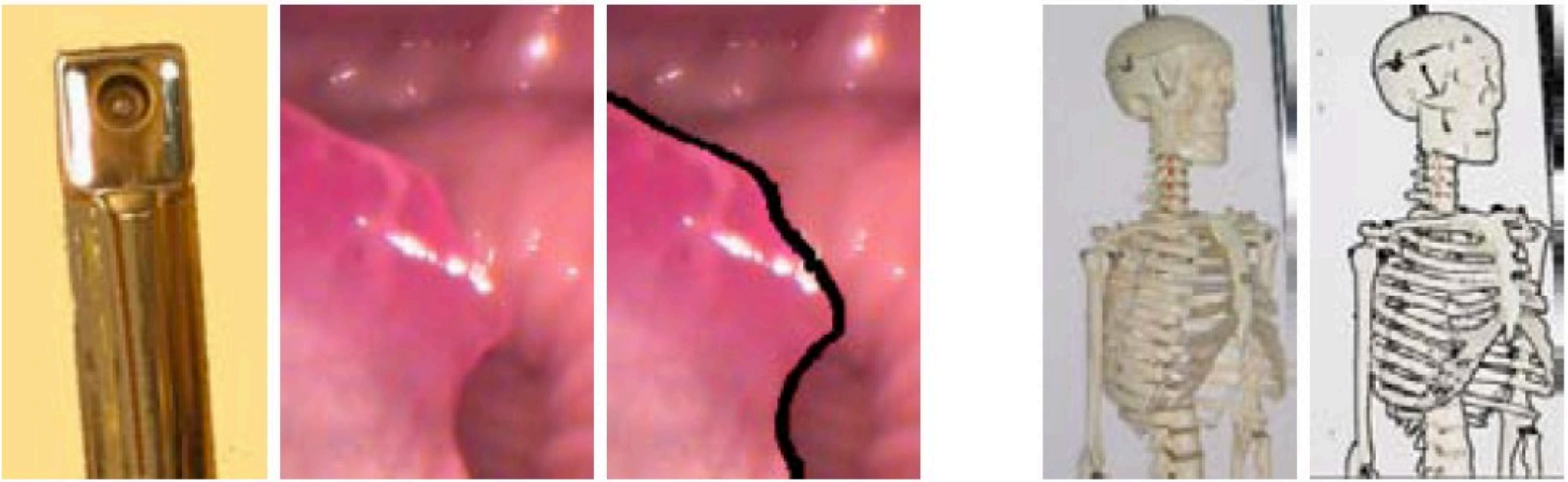


Figure 16: (Left) Enhanced endoscope, with only left lights turned on; input image and depth edge superimposed image. (Right) Skeleton and depth edge superimposed image.

Light Mixture Estimation for Spatially Varying White Balance

Eugene Hsu[1] Tom Mertens[2] Sylvain Paris[3] Shai Avidan[3] Frédo Durand[1]

[1]Massachusetts Institute of Technology, Computer Science and Artificial Intelligence Laboratory
[2]Hasselt University – tUL – IBBT, Expertise Centre for Digital Media, Belgium [3]Adobe Systems, Inc.

(a) Original image (b) Traditional white balance (c) Our result

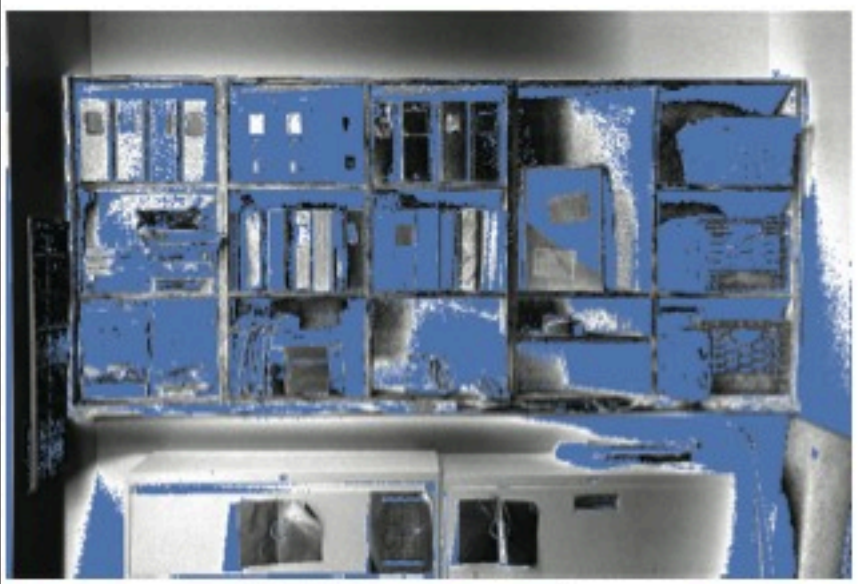
Figure 1: Image (a) shows a photograph under mixed flash and indoor lighting. Traditional white balance (b) produces unnatural results because it cannot deal with spatially varying light color. Here, the yellow color cast is still visible, and parts of the face have a blue cast. By estimating the relative contribution of lights at each pixel, our technique is able to reproduce colors more faithfully (c).

[Hsu 2008]

(a) Input (tungsten and daylight)

(b) Voting (white material color)

(c) Voting (brown material color)



(d) Mixture constraints

(e) Interpolated mixture

(f) Our result

Figure 2: An overview of our approach. Given an input image (a), we extract dominant material colors using a voting technique. Here, it identifies pixels corresponding to white (b) and brown (c) material colors. This information is used to estimate the local relative contributions of each light (d). The voting scheme only labels reliable pixels. The unreliable pixels, shown in blue, are inferred using an interpolation scheme (e). The mixture information can then be used to compute a visually pleasing white balance (f).

(a) Our result (b) Dim exterior (c) Dim interior

(d) Input image (e) Our result (f) Color change

Figure 5: We can achieve additional postprocessing effects. Using the mixture, lights can be dimmed (b,c) and colored (f) separately.

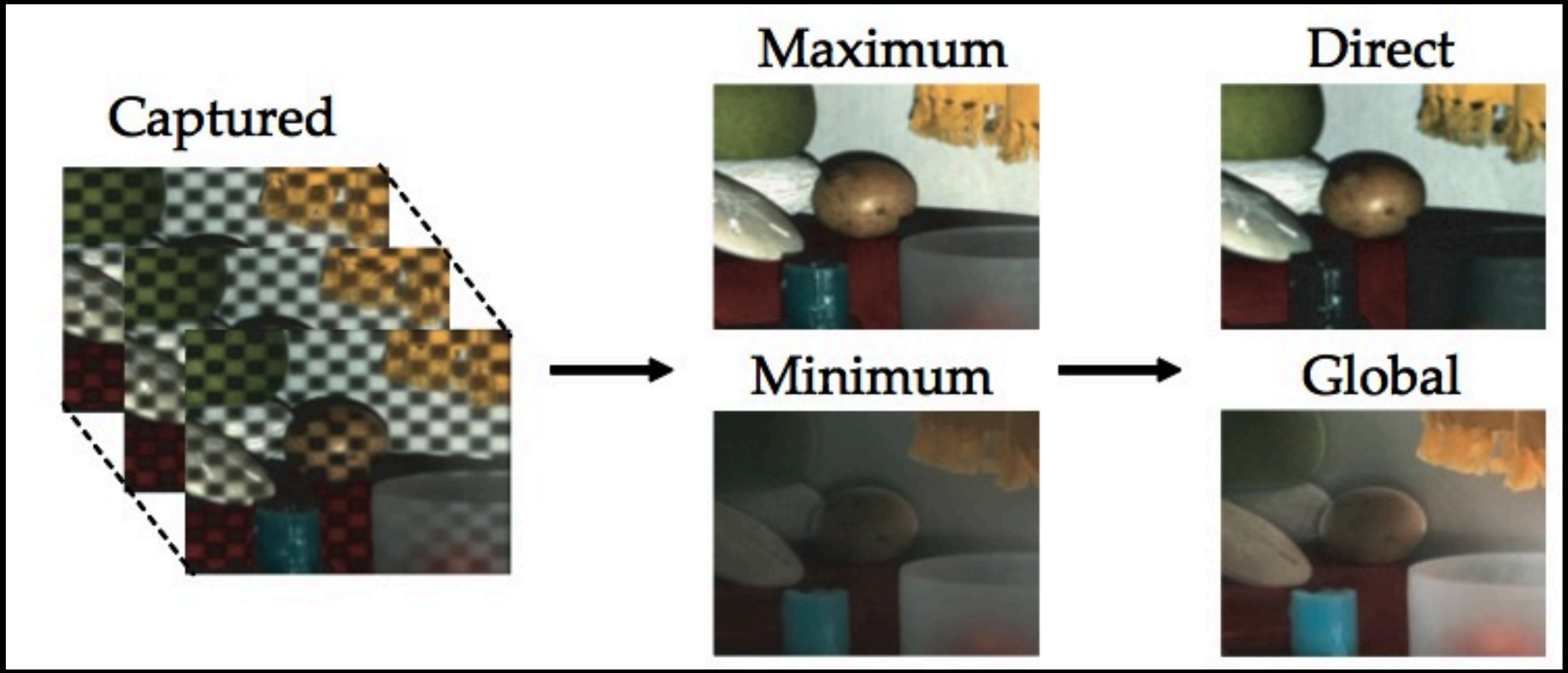
Fast Separation of Direct and Global Components of a Scene using High Frequency Illumination

Shree K. Nayar* Columbia University
Gurunandan Krishnan† Columbia University
Michael D. Grossberg‡ City University of New York
Ramesh Raskar§ MERL

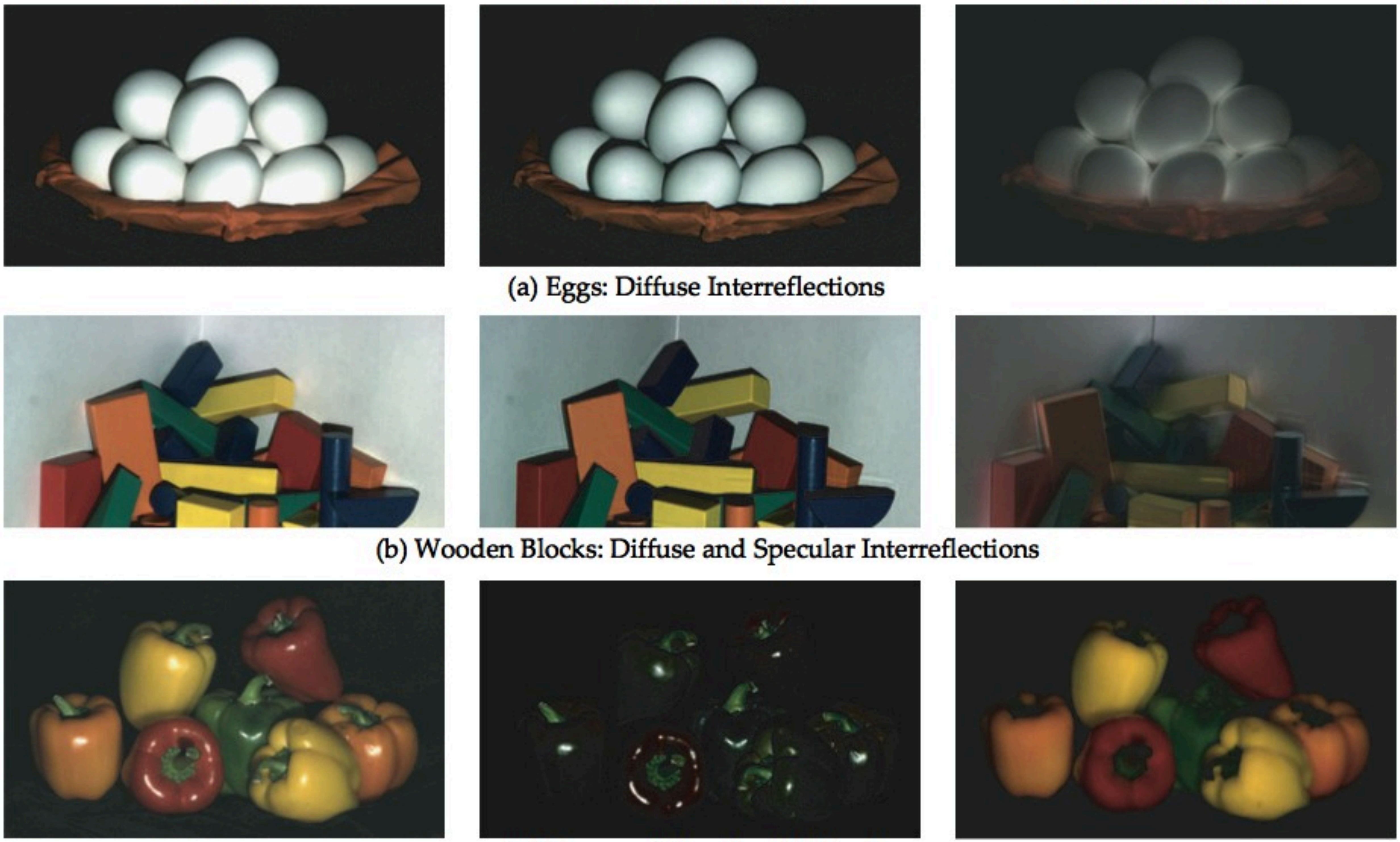
(a) Scene (b) Direct Component (c) Global Component

Figure 1: (a) A scene lit by a single source of light. The scene includes a wide variety of physical phenomena that produce complex global illumination effects. We present several methods for separating the (b) direct and (c) global illumination components of the scene using high frequency illumination. In this example, the components were estimated by shifting a single checkerboard pattern 25 times to overcome the optical and resolution limits of the source (projector) and sensor (camera). The direct and global images have been brightness scaled by a factor of 1.25. In theory, the separation can be done using just 2 images. When the separation results are only needed at a resolution that is lower than those of the source and sensor, the separation can be done with a single image.

[Nayar 2006]


Captured
Maximum
Minimum
Direct
Global

Scene | **Direct Component** | **Global Component**



(a) Eggs: Diffuse Interreflections

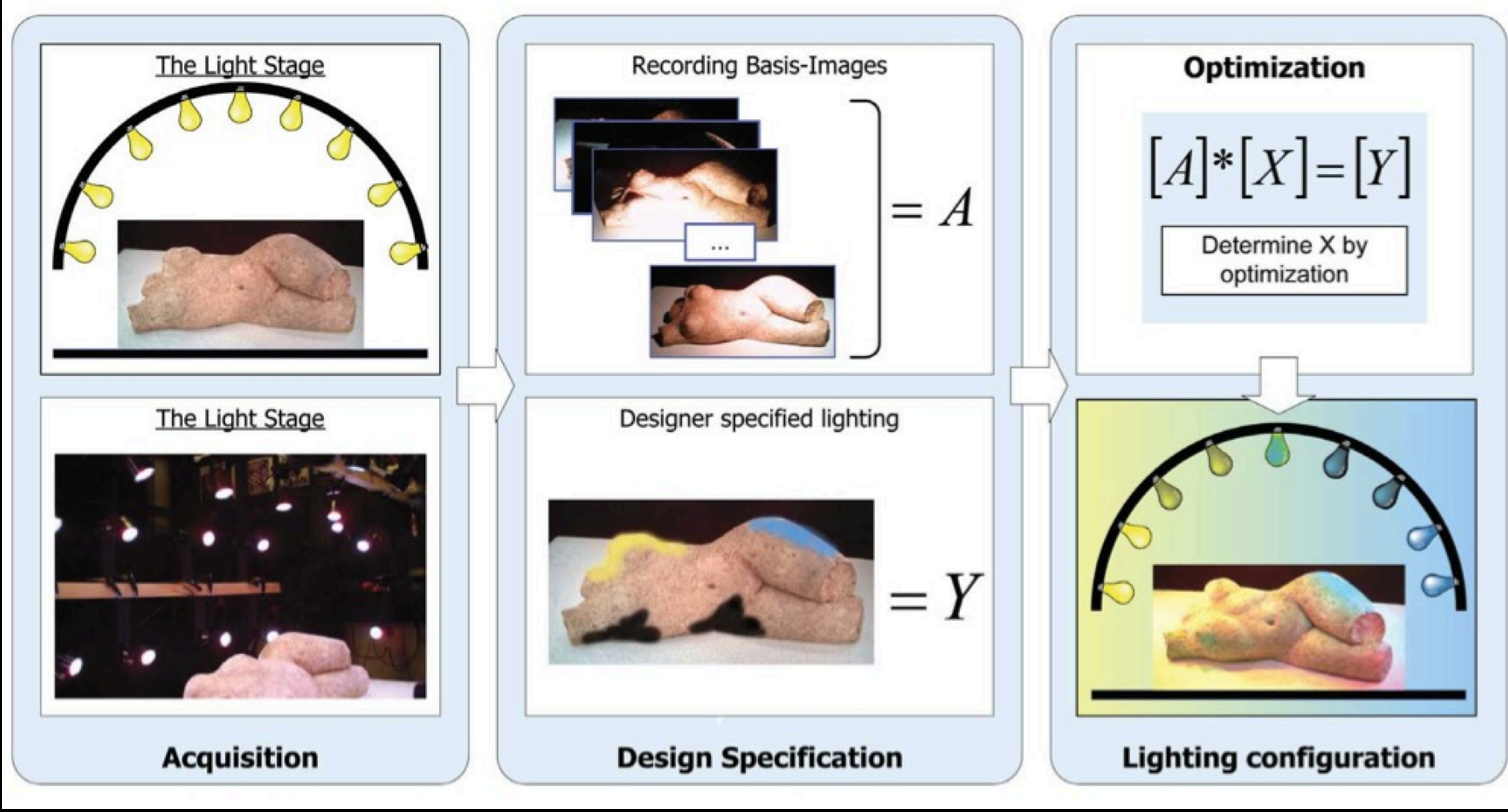
(b) Wooden Blocks: Diffuse and Specular Interreflections

(c) Peppers: Subsurface Scattering

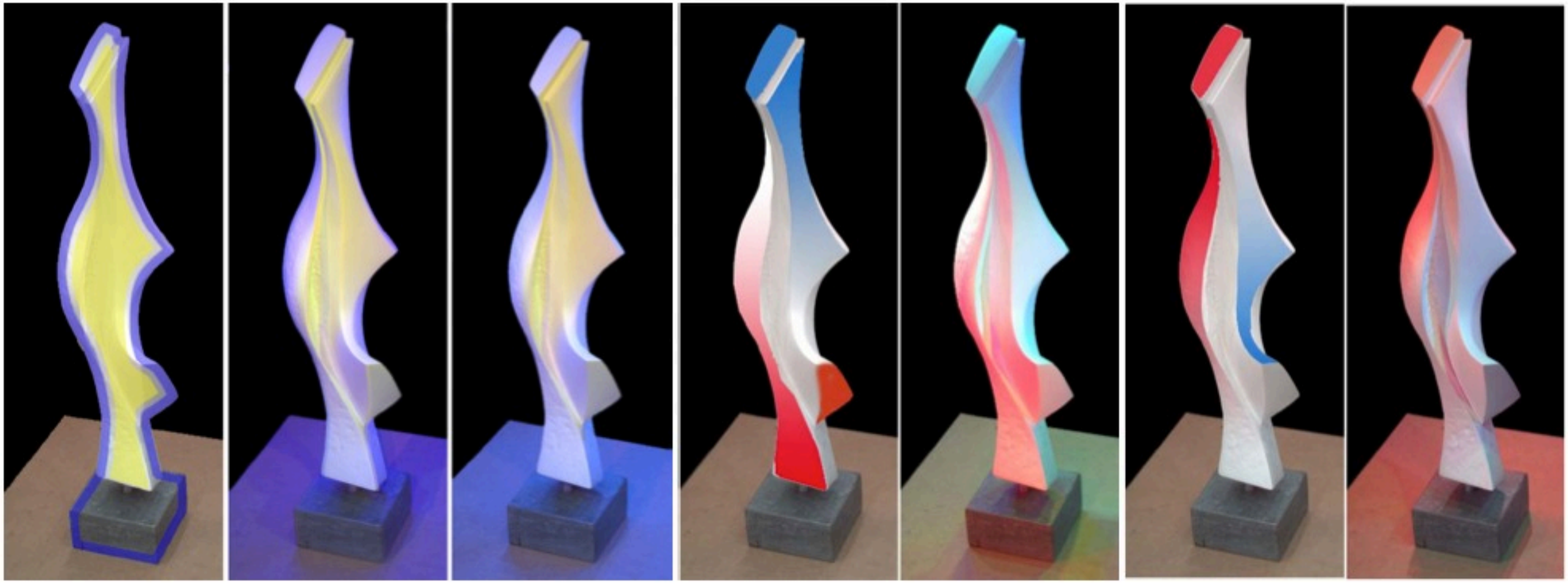
IMAGE-BASED LIGHTING DESIGN

Frederik Anrys
Department of Computer Sience
Katholieke Universiteit Leuven
Leuven, Belgium
email: Frederik.Anrys@cs.kuleuven.ac.be

Philip Dutré
Department of Computer Sience
Katholieke Universiteit Leuven
Leuven, Belgium
email: Philip.Dutre@cs.kuleuven.ac.be



[Anrys 2004]



Dual Photography

Pradeep Sen* Billy Chen* Gaurav Garg* Stephen R. Marschner†
Mark Horowitz* Marc Levoy* Hendrik P. A. Lensch*

*Stanford University †Cornell University

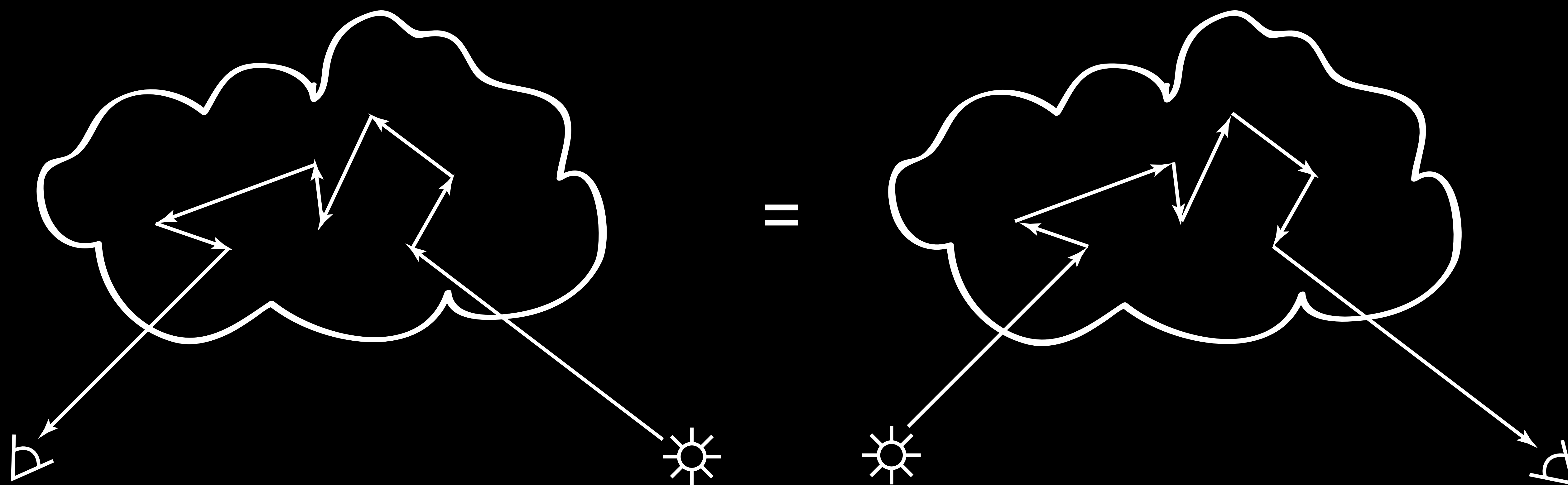
(a) (b) (c) (d)

Figure 1: (a) Conventional photograph of a scene, illuminated by a projector with all its pixels turned on. (b) After measuring the light transport between the projector and the camera using structured illumination, our technique is able to synthesize a photorealistic image from the point of view of the projector. This image has the resolution of the projector and is illuminated by a light source at the position of the camera. The technique can capture subtle illumination effects such as caustics and self-shadowing. Note, for example, how the glass bottle in the primal image (a) appears as the caustic in the dual image (b) and vice-versa. Because we have determined the complete light transport between the projector and camera, it is easy to relight the dual image using a synthetic light source (c) or a light modified by a matte captured later by the same camera (d).

[Sen 2005]

Helmholtz Reciprocity

- Light transport is symmetric
  - Interchanging the roles of light source and detector yields the same reading, regardless of transport path



Dual Photography

Pradeep Sen* Billy Chen* Gaurav Garg* Stephen R. Marschner†
Mark Horowitz* Marc Levoy* Hendrik P.A. Lensch*

*Stanford University †Cornell University

SIGGRAPH2005