Computer Vision & Image Processing CSE 473 / 573

Instructor - Kevin R. Keane, PhD

TAs - Radhakrishna Dasari, Yuhao Du, Niyazi Sorkunlu

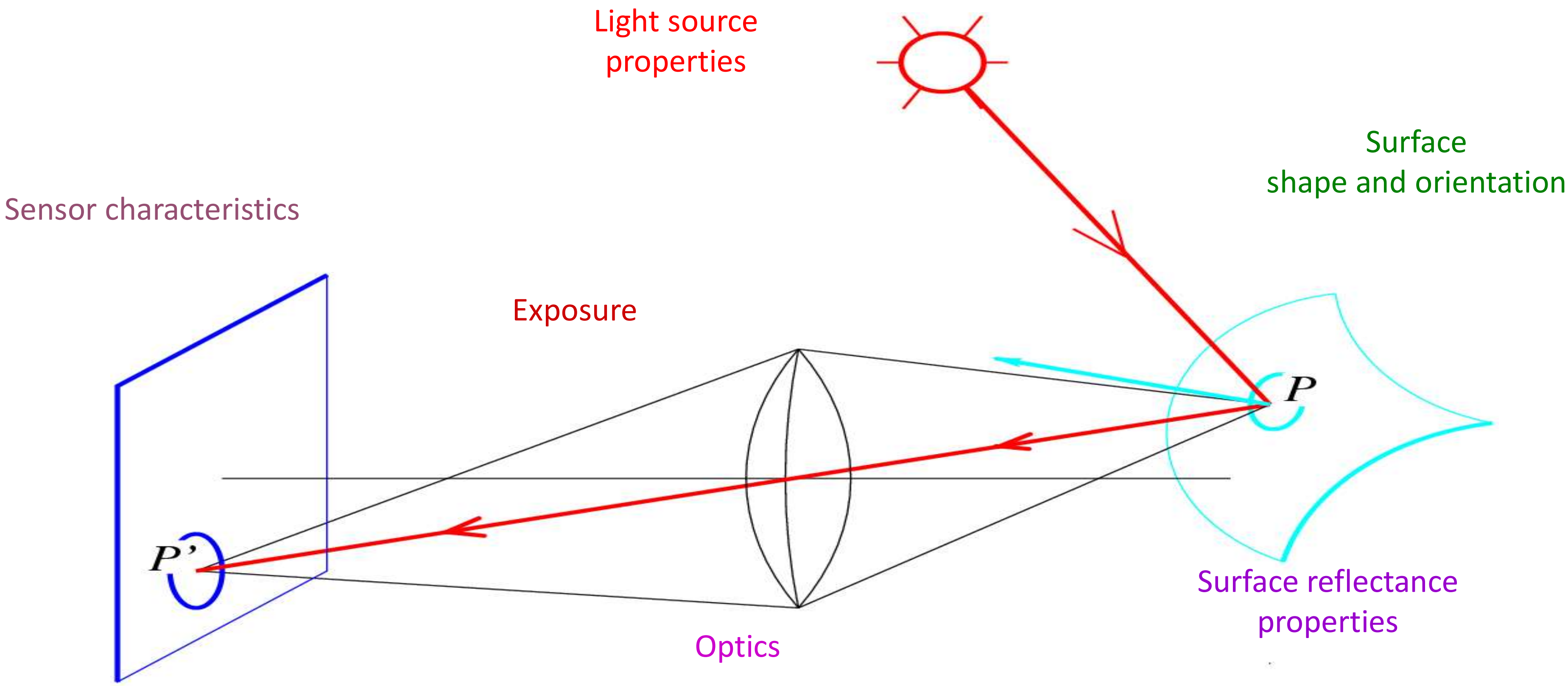
Lecture 4 – September 6, 2017

Physical parameters of image formation

- Photometric
  - Type, direction, intensity of light reaching sensor
  - Surfaces’ reflectance properties
  - Inference from shading

Image formation

- What determines the brightness of an image pixel?



Slide by L. Fei-Fei

Image formation - photometry

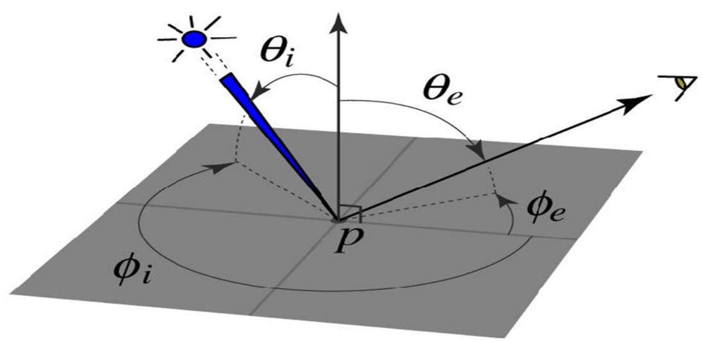
- The brightness of a pixel is a function of the brightness of the surface in the scene that projects to the pixel
- The brightness of the pixel is dependent on
  - How much light is incident on the surface and
  - The fraction of incident light that gets reflected
- We will now explore a few simple models of shading

Key issues

- Physical
  - what makes a pixel take its brightness values?
- Inference
  - what can we recover from the world using those brightness values?
- Human
  - What can people do?
    - which suggests problems we might be able to solve in computer vision

The interaction of light and surfaces

- What happens when a light ray hits a point on an object?
  - Some of the light gets **absorbed**
    - converted to other forms of energy (e.g., heat)
  - Some gets **transmitted** through the object
    - possibly bent, through refraction
    - or scattered inside the object (subsurface scattering)
  - Some gets **reflected**
    - possibly in multiple directions at once
  - Really complicated things can happen
    - fluorescence



Source: Steve Seitz

Model

- Light arrives at a surface
  - from a light source
  - from another surface
- It is reflected into the camera
  - many possible effects
- It arrives at a sensor at the back of the camera
  - a record is made
  - this could be a linear or a non-linear function of the amount of light

From light rays to pixel values

Pixel brightness depends on:

- Camera response
- Surface reflection
- Illumination

From light rays to pixel values

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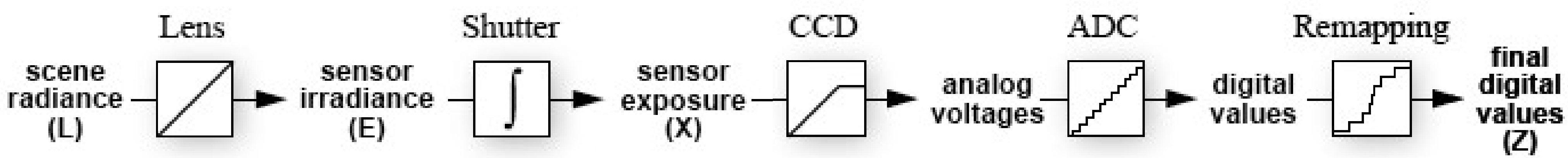
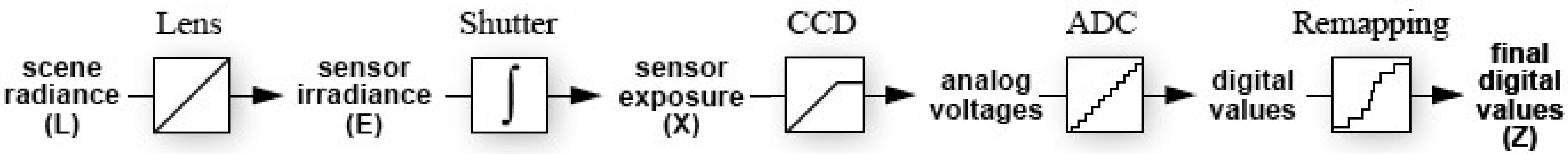
Camera response

- Film
  - Record is made by chemical processes in the film
  - These are non-linear; typically,
    - dark patches are lighter than they should be
    - light patches are darker than they should be
    - these ensure that detail is visible



Camera response

- CCD
  - Linear devices
    - with non-linearities produced by electronics to mimic film
- Calibration
  - Can be hard to find curves of camera response vs light input
  - Instead, use calibration algorithms (no covered in our course)



From light rays to pixel values

Pixel brightness depends on:

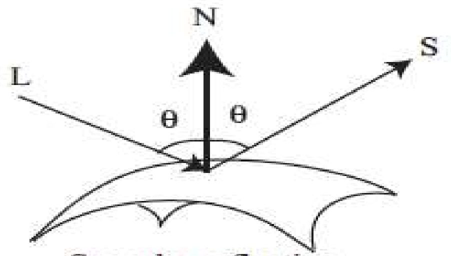
- Camera response
- Surface reflection
- Illumination

Surface reflection

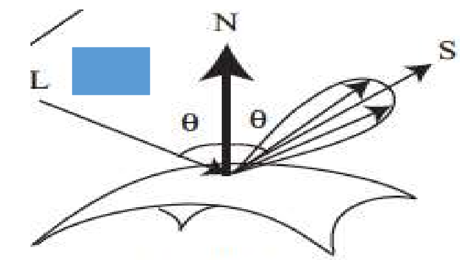
- Many effects can occur when light strikes a surface -- could be:
  - absorbed; transmitted; reflected; scattered
    - e.g. some people can see arteries, veins under their skin
      - because light is transmitted through skin, reflected at blood vessel, transmitted out
  - For simplicity, we assume that
  - surfaces don’t fluoresce
  - surfaces don’t emit light (i.e. are cool)
  - all the light leaving a point is due to that arriving at that point

The important reflection modes

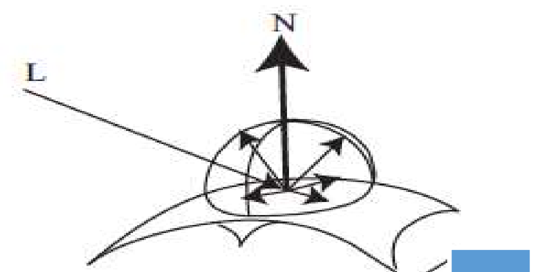
1. Specular reflection (mirror like)
    - Pure mirror:
        - incoming, outgoing directions and normal are coplanar
        - incoming, outgoing angles to normal are equal
    - Most specular surfaces:
        - some light leaves the surface along directions near to the specular direction as well
2. Diffuse reflection
    - Light leaves in equal amounts in each direction
        - so surface looks equally bright from each viewing direction



Specular reflection



Specularity



Diffuse reflection

Reflection modes

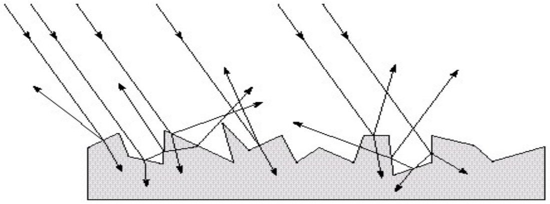
- The 2 most important reflection modes are
  - Diffuse reflection – incident light is spread evenly over the whole hemisphere of out going directions
  - Specular reflection – reflected light is concentrated in a single direction
    - Specular direction $\mathbf{S}$ is coplanar with the normal $\mathbf{N}$ and source direction $\mathbf{L}$
    - Incident angle = reflection angle = θ

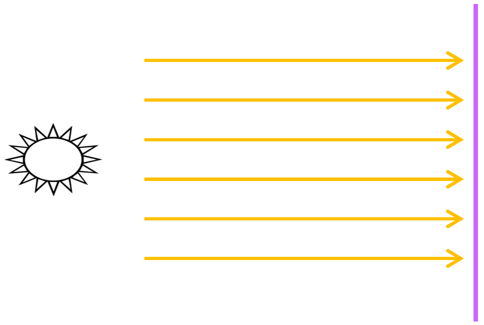
Diffuse reflection

- Light leaves the surface evenly in all directions
  - e.g. cotton cloth, carpets, matte paper, matte paints, most “rough” surfaces
- Described by one parameter: albedo
  - percentage of light arriving that leaves
  - range 0-1 practical range is smaller
- Light leaving is *albedo x light arriving*
  - Ambiguity: A surface could be dark because
    - It reflects a small percentage of the light arriving
    - There isn’t very much light arriving

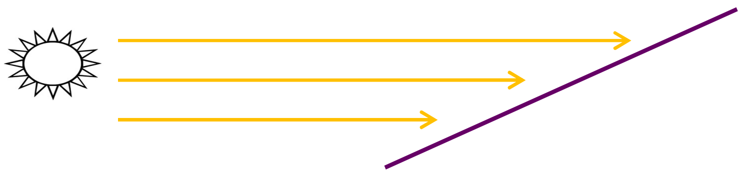
Diffuse reflection

- Light is reflected equally in all directions
  - Dull, matte surfaces like chalk or latex paint
  - Microfacets scatter incoming light randomly
  - Effect is that light is reflected equally in all directions
- Brightness of the surface depends on the incidence of illumination





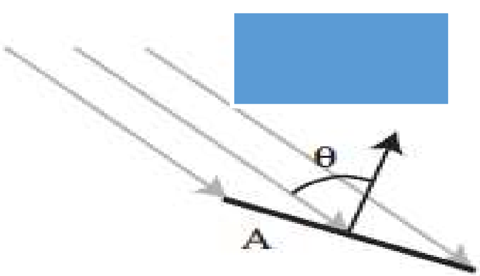
brighter



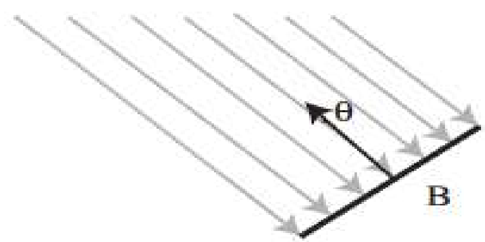
darker

How much light arrives?

- Assume source is far away
  - So light travels in parallel rays
  - (Light arriving) is proportional to (number of rays striking surface)
  - Surface A below receives less light than surface B
- Drawing yields
  - (number of rays striking surface) proportional to cos(θ)
    - where θ is angle between normal and direction of travel
- Shadows
  - If point can't see the light source, it is in shadow

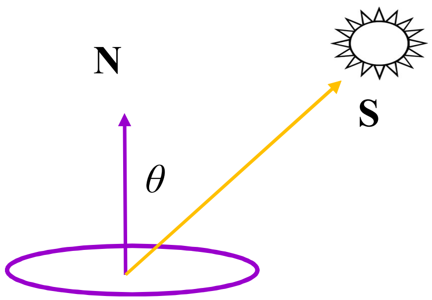


Diffuse reflection, dark

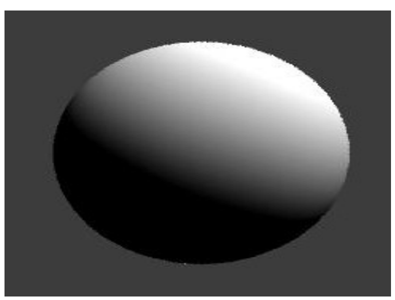


Diffuse reflection, bright

Diffuse reflection: Lambert's law

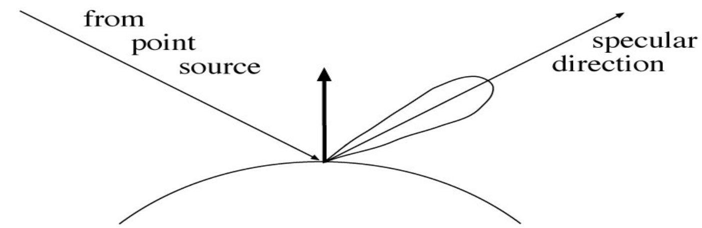


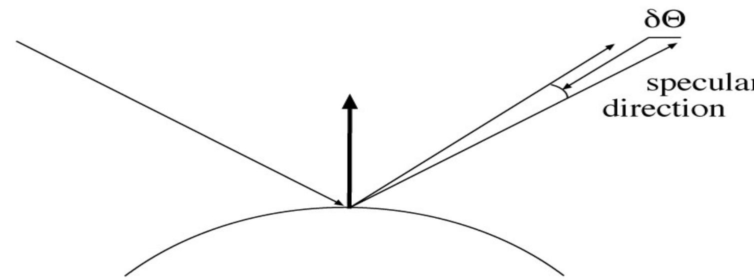
$$B = \rho(\mathbf{N} \cdot \mathbf{S})$$
$$= \rho \left\|\mathbf{S}\right\| \cos\theta$$



B: radiosity (total power leaving the surface per unit area)
ρ: albedo (fraction of incident irradiance reflected by the surface)
N: unit normal
S: source vector (magnitude proportional to intensity of the source)

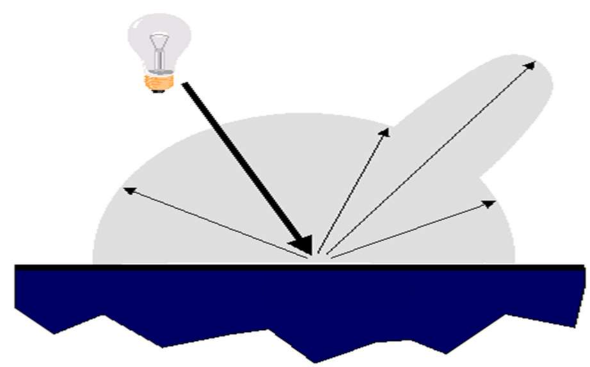
Specular reflection



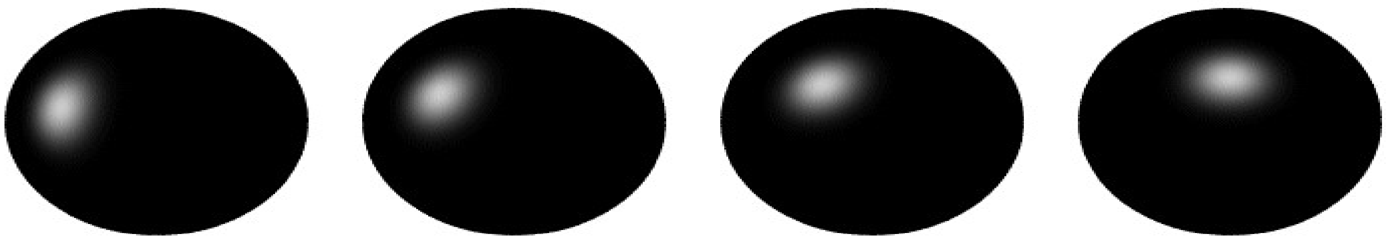


- Radiation arriving along a source direction leaves along the specular direction (source direction reflected about normal)
- Some fraction is absorbed, some reflected
- On real surfaces, energy usually goes into a lobe of directions
- Phong model: reflected energy falls of with
- Lambertian + specular model: sum of diffuse and specular term

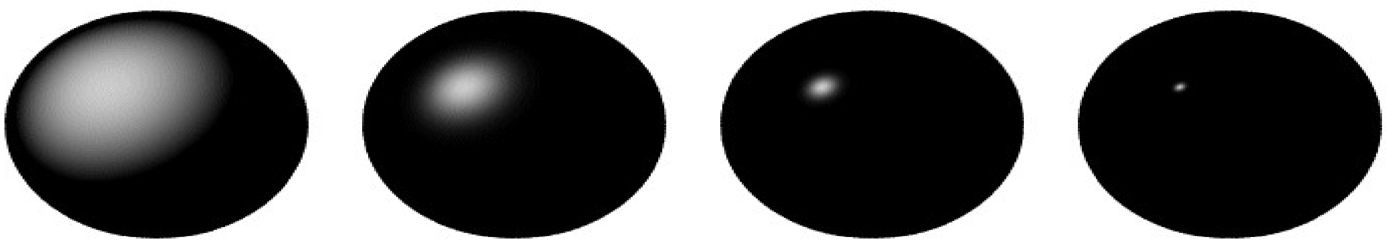
$$\cos^n(\delta\theta)$$



Specular reflection



Moving the light source



Changing the exponent

Diffuse + Specular model

- Most surfaces can be modeled as diffuse + specular
  - surface parameters:
    - diffuse albedo,
    - specular albedo,
- This justifies the following strategy for many analyses
  - Find and remove specularities
    - which are small, and bright
    - More sophisticated specularity finders use color information
  - Ignore the missing points, and treat the rest of the image as diffuse

Diffuse + Specular model cont'd

Choose the source effects to model:

- Simplest case is the local shading model
  - assume light comes from the source, no interreflections
  - Assume source is at an infinitely distance
- Again we are working with $\boldsymbol{N}(x)$ and $\boldsymbol{S}(x)$ and p(x) is albedo at x.
- Let $\mathrm{Vis}(\mathbf{S},\mathbf{x})$ be a function that is 1 when $\mathbf{x}$ can see the source, and 0 otherwise
- Then the intensity at $\mathbf{x}$ is given as:

$$I(\mathbf{x}) = \rho(\mathbf{x})(\mathbf{N} \cdot \mathbf{S}) Vis(S, \mathbf{x}) + \rho(\mathbf{x}) A + M$$

Image Intensity

Diffuse term

Ambient term

Specular mirror-like term

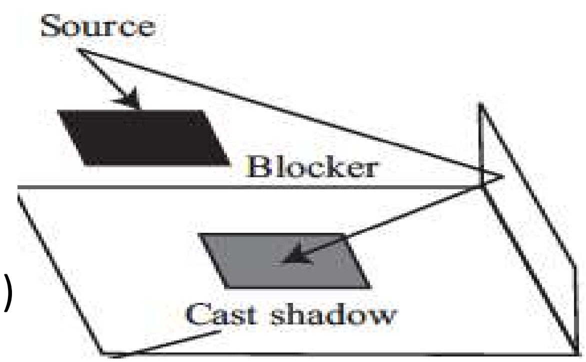
From light rays to pixel values

Pixel brightness depends on:

- Camera response
- Surface reflection
- Illumination

Shadows

- Most shadows aren’t dark
  - because shadow points get light from other surfaces, not just light source
- Area sources
  - Large, bright areas
  - e.g. diffuser boxes, the sky
  - Yield smooth, blurry shadows
    - Points that can see the whole source are brighter
    - Points that can see only part of the source are darker (penumbra)
    - Points that can see no part of the source are darkest (umbra)



- Other surfaces behave like area sources
  - Smooth, blurry shadows are common (and sometimes too faint to see)

How much light arrives?

- Orientation of surface affects how much light the surface gathers
- Patch A is tilted from the source with θ close to 90^o collects less energy (it cuts fewer rays per unit surface area)
- Patch B is facing the source with θ close to 0^o so it appears brighter
- The darker surfaces are turned away from the illumination direction

Area sources

Area sources generate complex shadows with smooth boundaries

- The surface patch sees the source disappearing slowly behind the occluder
- Patch A is darker than B
  - Shadowing effect but no clear boundary (instead is a smooth gradient)
- Chair leg casts a complex shadow with 2 distinct regions
  - **Umbra** – no source is seen at all
  - **Penumbra** – source is partially seen

Light and shading - Crucial points

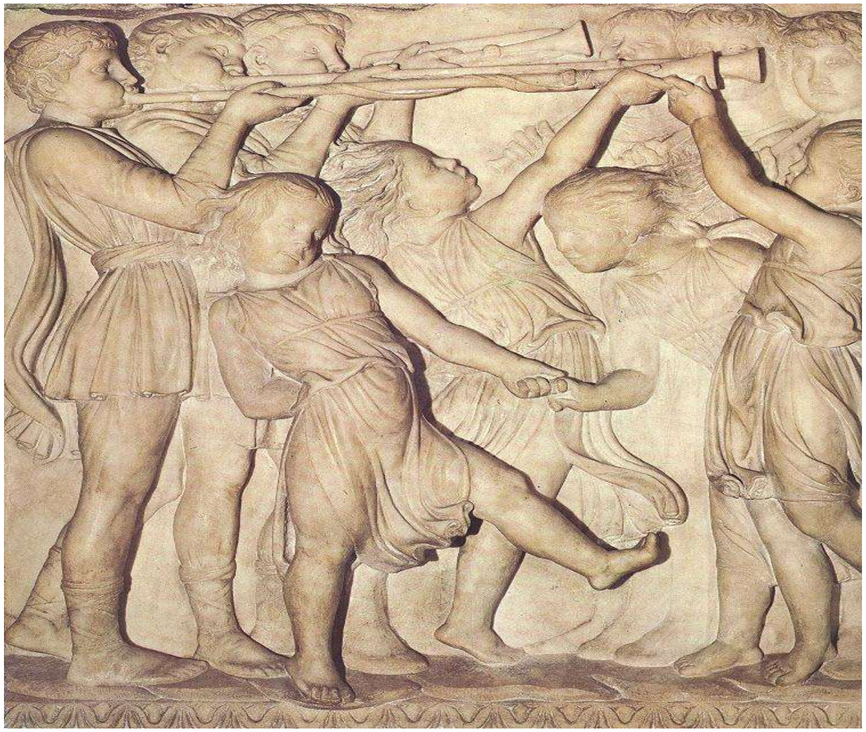
- Image brightness is affected by
  - amount of light arriving at surface
  - surface type (diffuse, specular) and amount reflected at surface
  - camera sensitivity
- There are significant ambiguities
  - eg low albedo surface in bright light
    - vs high albedo surface in low light
  - each might reflect about the same amount
- Most surfaces can be modeled as diffuse + specular
  - generally, find and remove specularities
  - treat the rest as diffuse
- Shadows occur when a light source is obstructed by an object.
  - occupies all of the space behind the opaque object with light in front of it.

Inference from shading

- Radiometric calibration and high dynamic range images
- The shape of specularities
- Inferring lightness and illumination
- Photometric stereo: shape from multiple shaded images

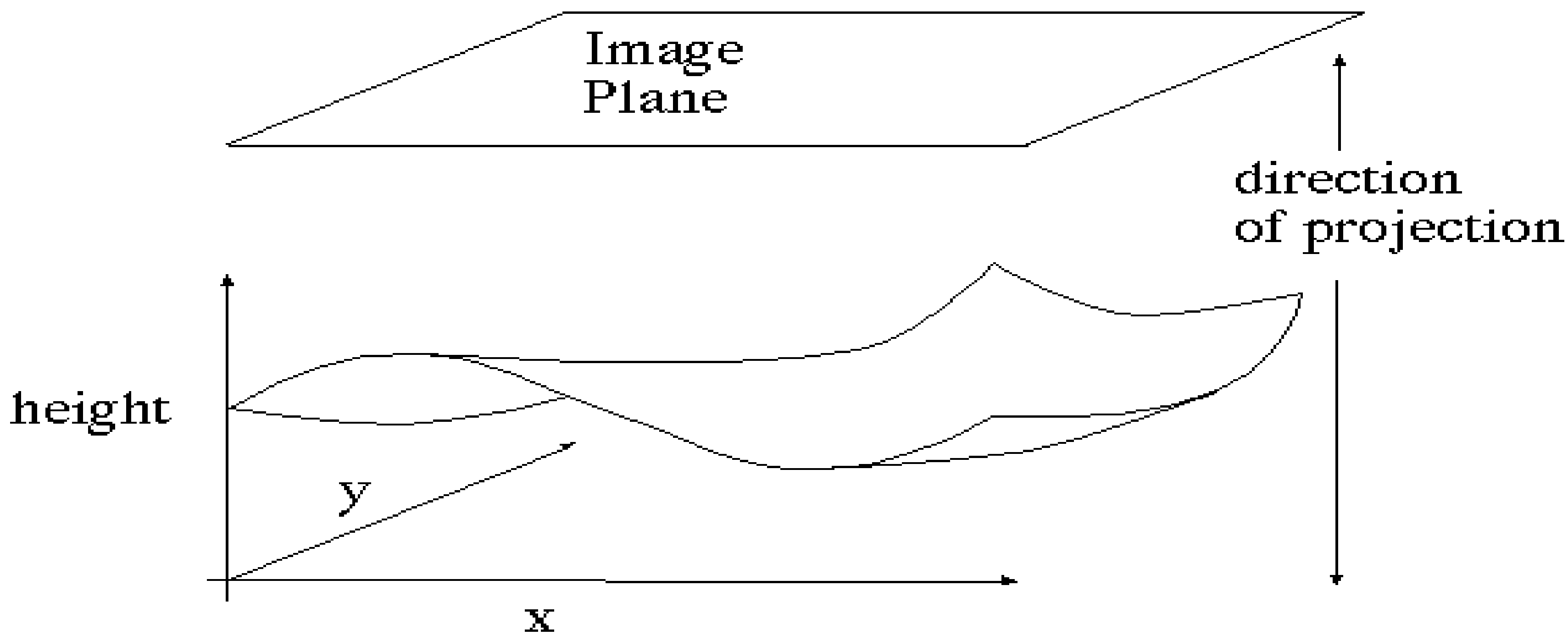
Photometric stereo
(shape from shading)

- Can we reconstruct the shape of an object based on shading cues?



Luca della Robbia,
Cantoria, 1438

Surface model: Monge patch



A Monge patch is a representation of a piece of surface as a height function. An orthographic camera, that maps (x,y,z) to (x,y) in the camera is viewing a Monge patch, i.e. the shape of the surface is represented a function of position in the image

Surface model continued

- Photometric stereo is a method for recovering a representation of the Monge patch from image data
  - Reason about image intensity for different images of the surface under different illumination conditions
  - Recover height of surface at each image pixel
  - Fix the positions of the camera and surface
    - Illuminate using faraway source (local shading model)

$$B(\mathbf{x}) = \rho(\mathbf{x})\mathbf{N}(\mathbf{x})\mathbf{S}(\mathbf{x})$$

  - The intensity value of a pixel at (x,y) is now

$$I(x, y) = kB(\mathbf{x})$$

Image model

- **Known:** source vectors $\mathbf{S}_j$ and pixel values $I_j(x,y)$
  - j is the index of the illumination source
- **Unknown:** surface normal $\mathbf{N}(x,y)$ and albedo $\rho(x,y)$
- Assume that the response function of the camera is a linear scaling by a factor of k
- Lambert's law:

$$
\begin{aligned}
I_j(x,y) &= kB(\mathbf{x}) \\
&= kB(x,y) \\
&\quad k\,\rho(x,y)\big(\mathbf{N}(x,y)\cdot\mathbf{S}_j\big) \\
&= \big(\rho(x,y)\mathbf{N}(x,y)\big)\cdot(k\,\mathbf{S}_j) \\
&= \mathbf{g}(x,y)\cdot\mathbf{V}_j
\end{aligned}
$$

Image model cont'd

- g(x,y) describes the surface
- Vj is a property of the illumination and camera
- We can have a dot product between the vector field g(x,y) and the vector Vj
- So for n sources (if n is sufficently large), we can stack up the known Vj into a matrix V
- For each point in the image, we stack up the intensity measurement from each of the n sources

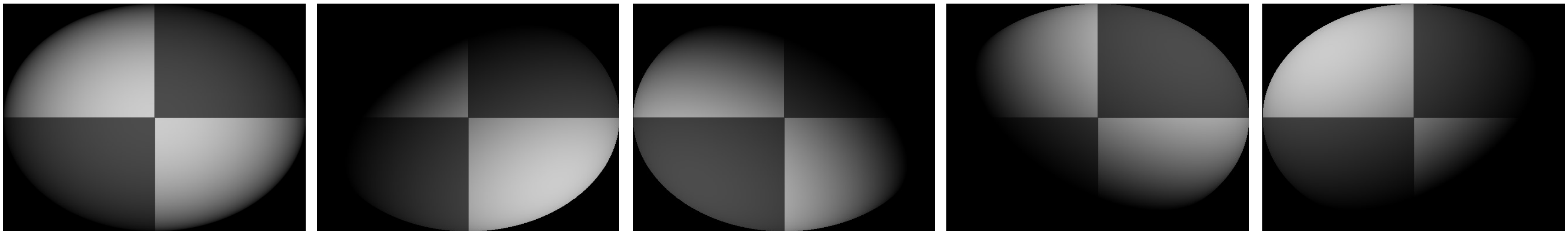
Least squares problem

- For each pixel, set up a linear system:
- Obtain least-squares solution for $\mathbf{g}(x,y)$ (which we defined as $\mathbf{N}(x,y)\ \rho(x,y)$)
- Since $\mathbf{N}(x,y)$ is the unit normal, $\rho(x,y)$ is given by the magnitude of $\mathbf{g}(x,y)$
- Finally, $\mathbf{N}(x,y) = \mathbf{g}(x,y) \,/\, \rho(x,y)$

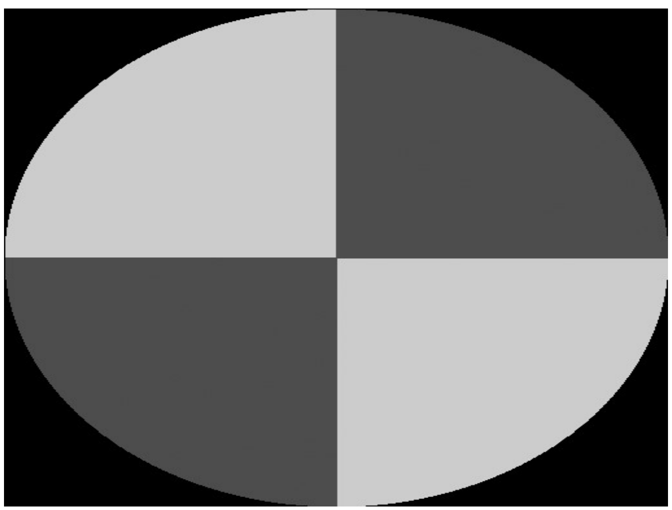
$$\underbrace{\begin{bmatrix} I_1(x,y) \\ I_2(x,y) \\ \vdots \\ I_n(x,y) \end{bmatrix}}_{\substack{(n \times 1) \\ \text{known}}} = \underbrace{\begin{bmatrix} \mathbf{V}_1^T \\ \mathbf{V}_2^T \\ \vdots \\ \mathbf{V}_n^T \end{bmatrix}}_{\substack{(n \times 3) \\ \text{known}}} \underbrace{\mathbf{g}(x,y)}_{\substack{(3 \times 1) \\ \text{unknown}}}$$

F&P 2nd ed., sec. 2.2.4

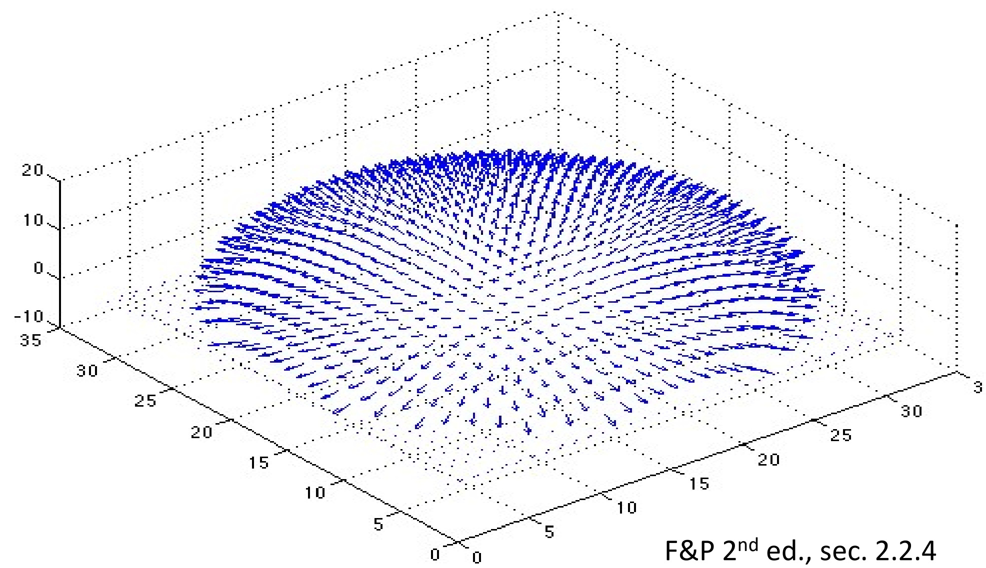
Example



Recovered albedo

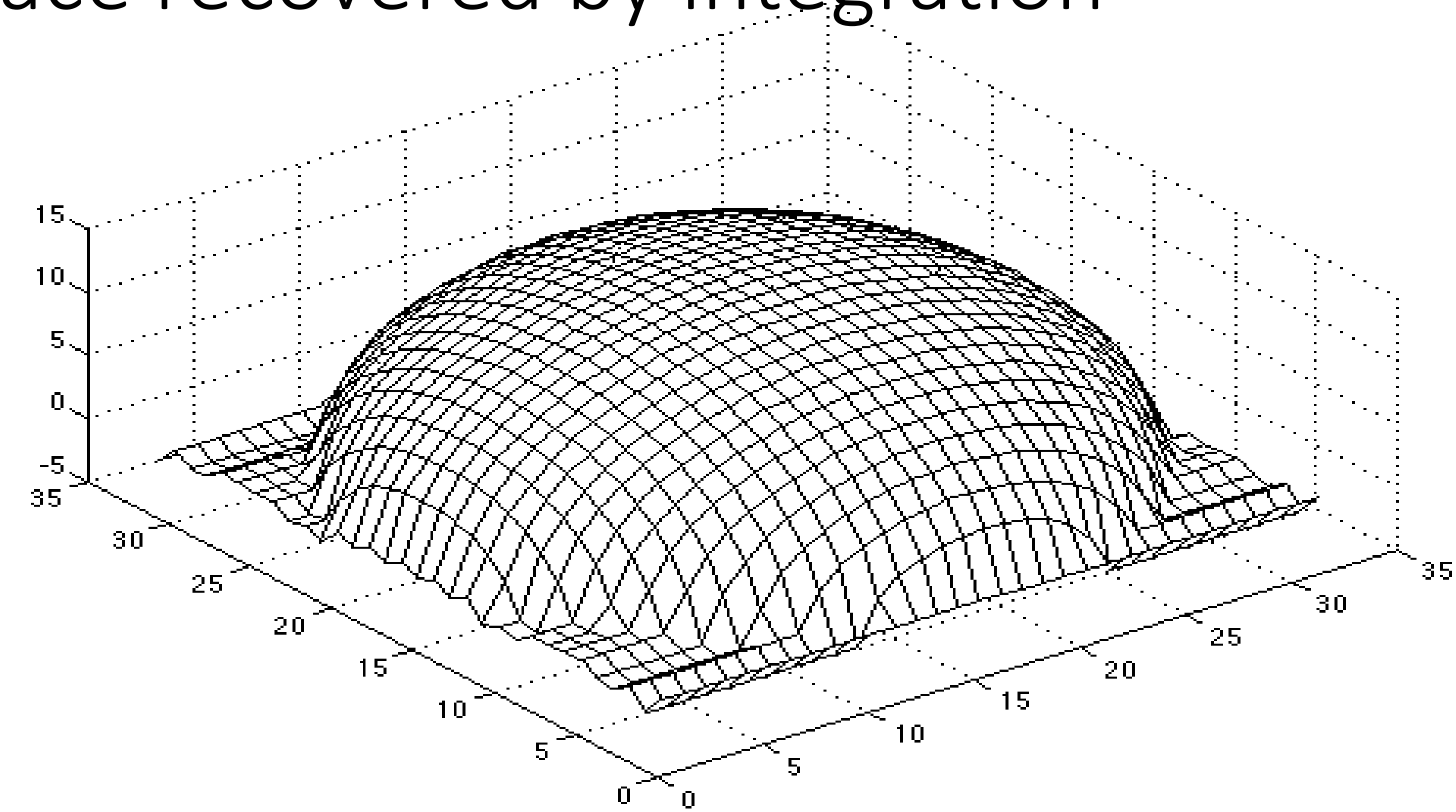


Recovered normal field



F&P 2nd ed., sec. 2.2.4

Surface recovered by integration



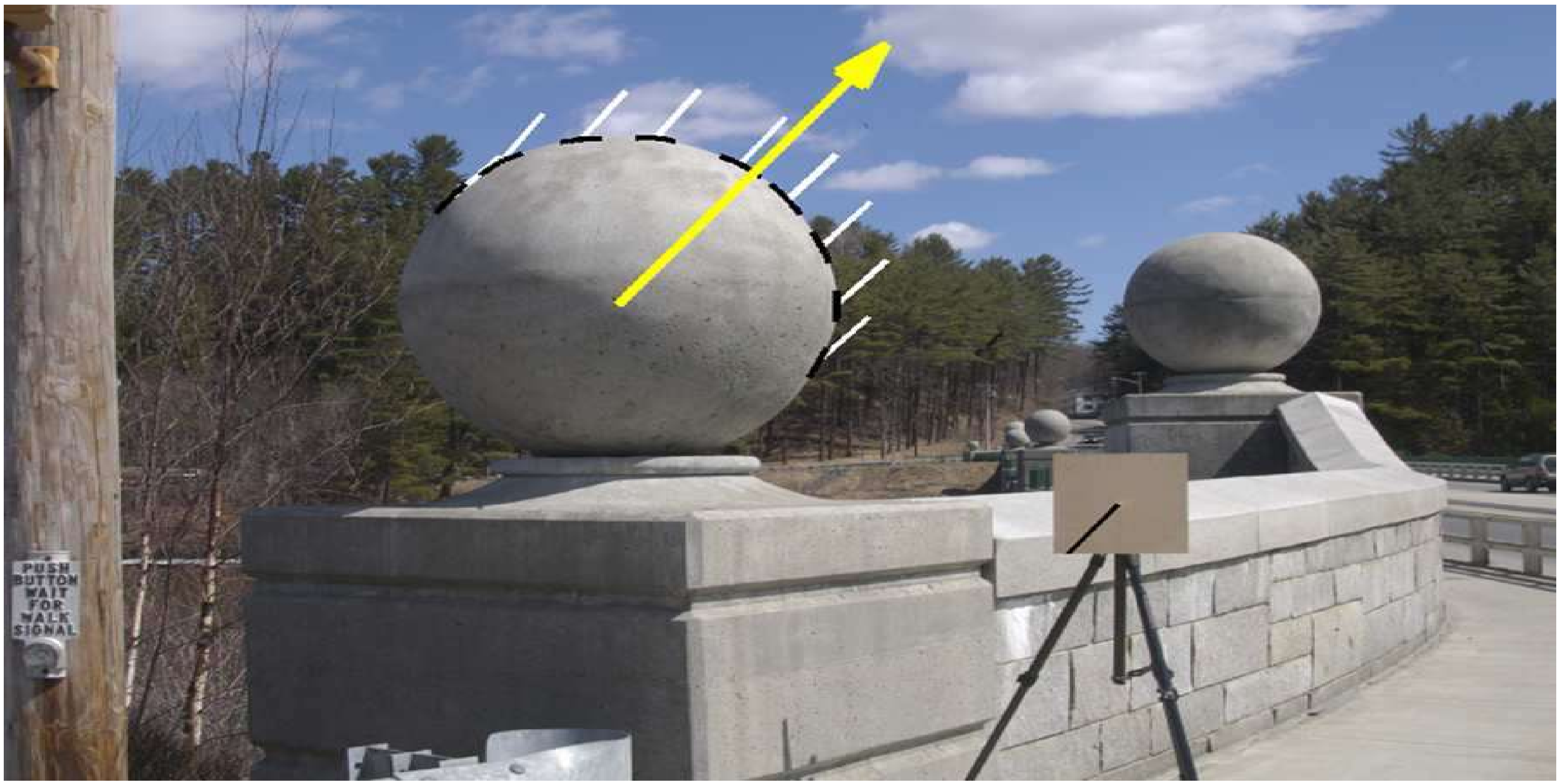
F&P 2nd ed., sec. 2.2.4

Limitations

- Orthographic camera model
- Simplistic reflectance and lighting model
- No shadows
- No inter-reflections
- No missing data
- Integration is tricky

Computer vision application

Finding the direction of light source



P. Nillius and J.-O. Eklundh, “Automatic estimation of the projected light source direction,” CVPR 2001

Computer vision application

Detecting composite photos:

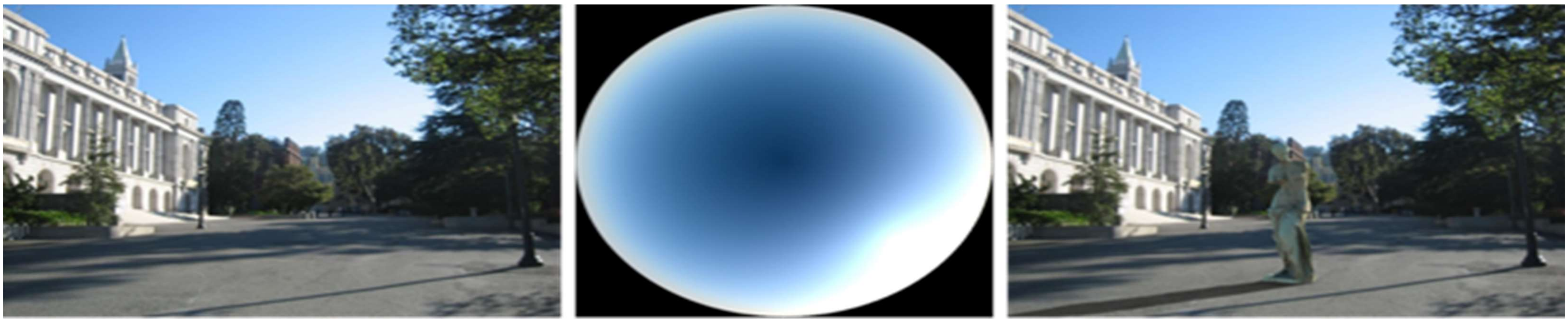
Fake photo

Real photo

M. K. Johnson and H. Farid, [Exposing Digital Forgeries by Detecting Inconsistencies in Lighting](), ACM Multimedia and Security Workshop, 2005.

Computer vision application

Estimating natural illumination from a single outdoor image:



From a single image (left), they estimate the most likely sky appearance (middle) and insert a 3-D object (right). Illumination estimation was done entirely automatically

J-F. Lalonde, A. A. Efros and S G. Narasimhan, Estimating Natural Illumination from a Single Outdoor Image, International Journal on Computer Vision, 98(2):123-145, 2012.

Slide Credits

- David A. Forsyth - UIUC
- Svetlana Lazebnik – UIUC

Next class

- Color
- Readings for next lecture:
  - Forsyth and Ponce Chapter 3; Szeliski 2.3.2 (optional)
- Readings for today:
  - Forsyth and Ponce 2.1, 2.2.4; Szeliski 2.2 (optional)

Questions