Radiometry

CMPSCI 670: Computer Vision

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February 6, 2024

College of
INFORMATION AND
COMPUTER SCIENCES

UMASS
AMHERST

Administrivia

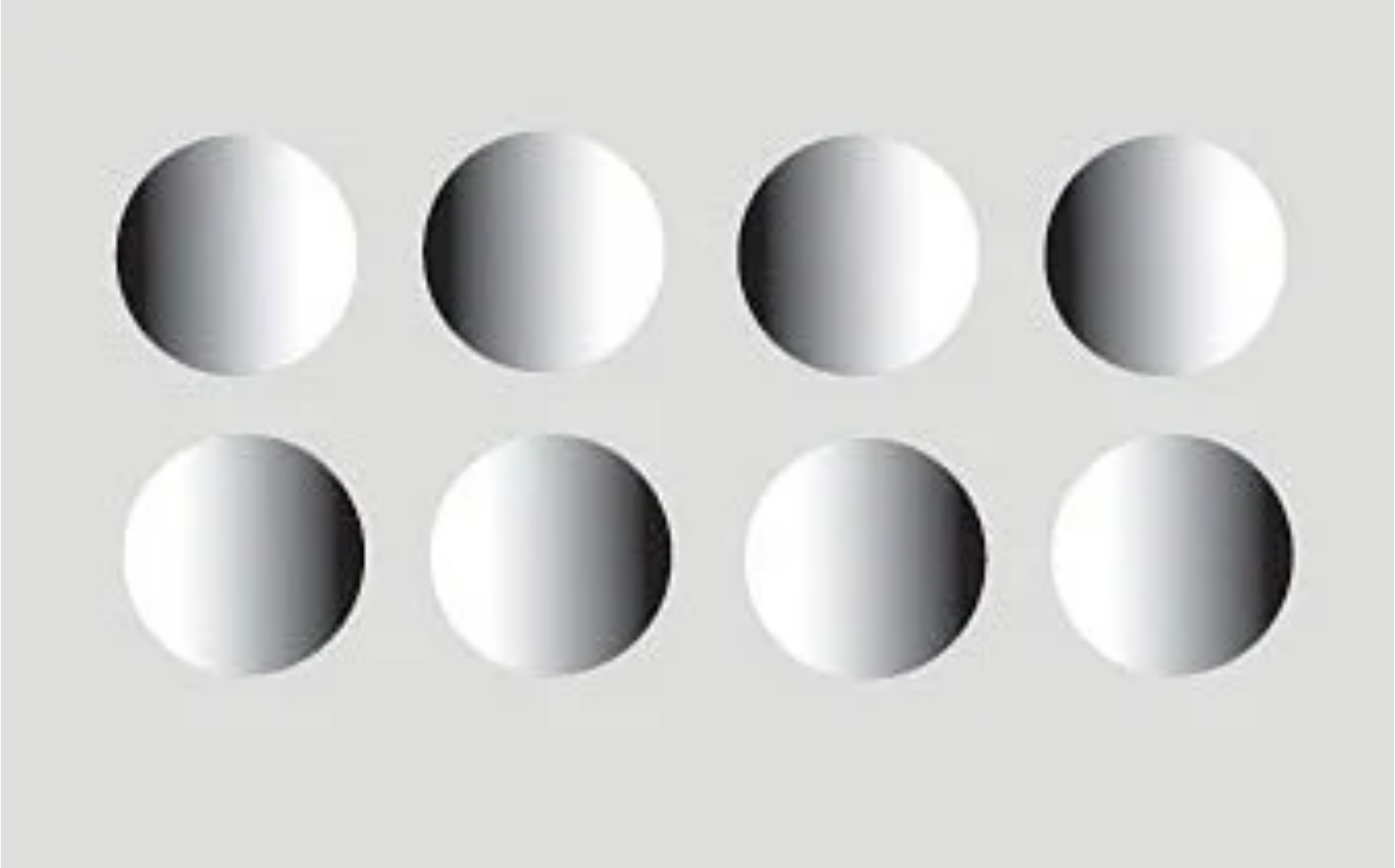
Homework 1 will be released today

Python tutorial — Friday 2/9, 2 - 3 pm, CS 150/151

TAs will cover python basics (e.g. numpy, matplotlib, scipy, skimage)

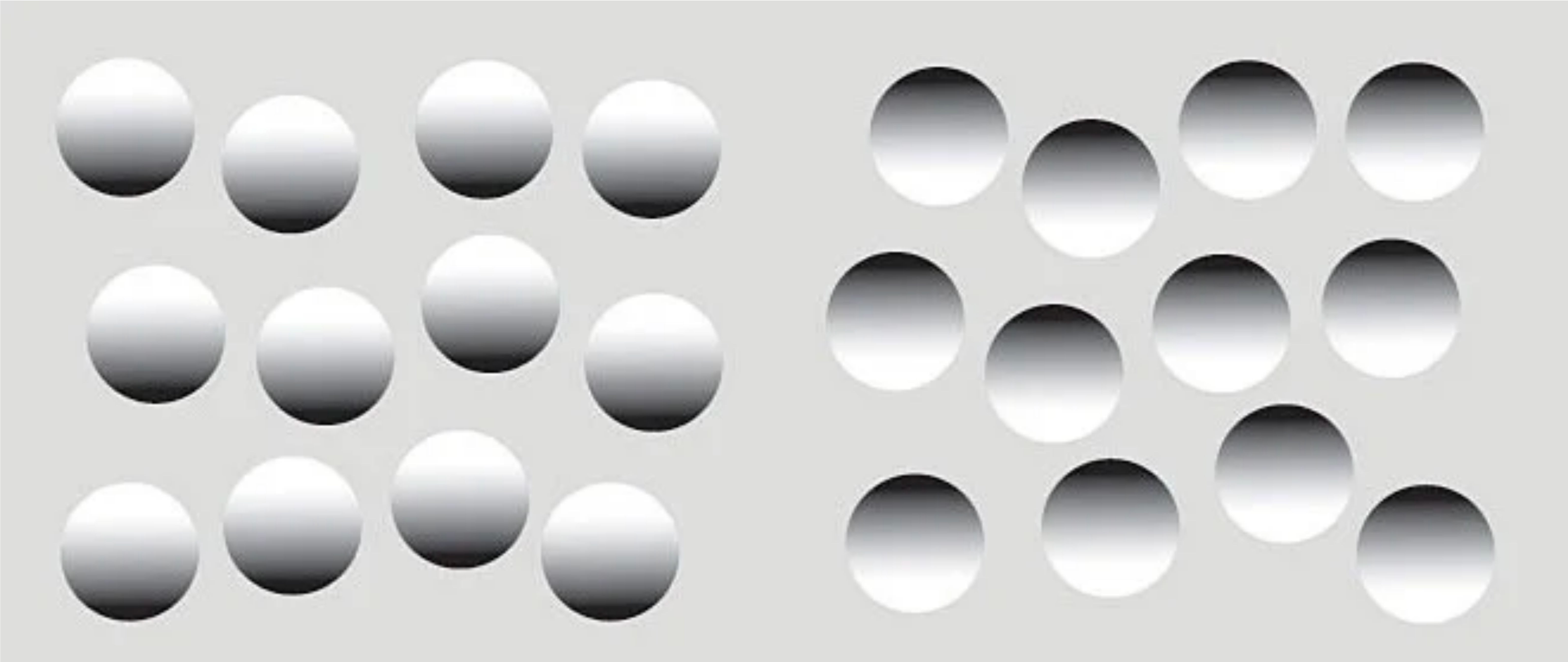
Project Poster Presentation May 10th, 2-4pm, LGRC A112.

Your Perception



Figures from: https://www.scientificamerican.com/article/seeing-is-believing-aug-08/

Your Perception



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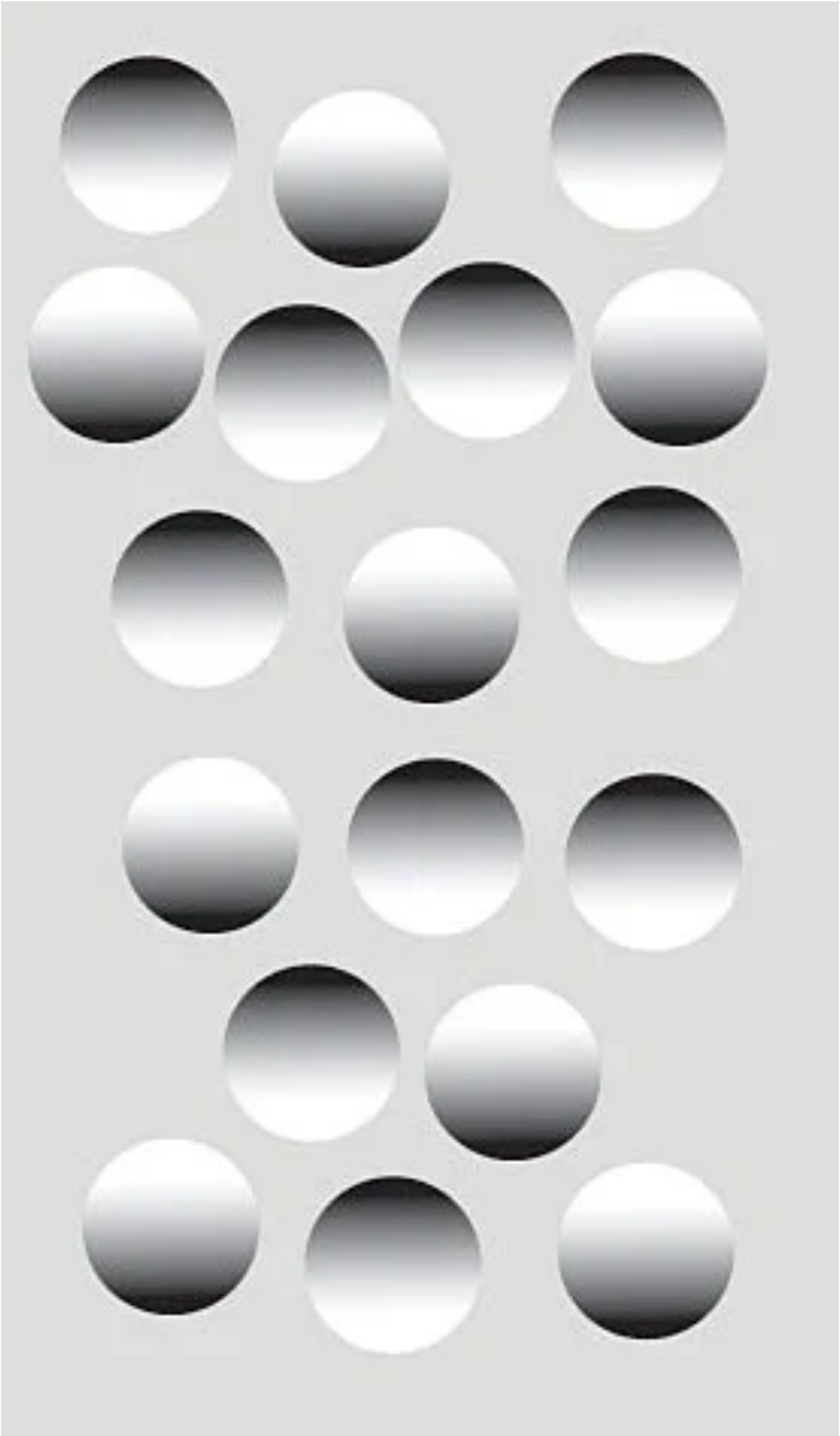

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Your Perception

https://macaulaylibrary.org/asset/557939521

Your Perception

https://macaulaylibrary.org/asset/424082941

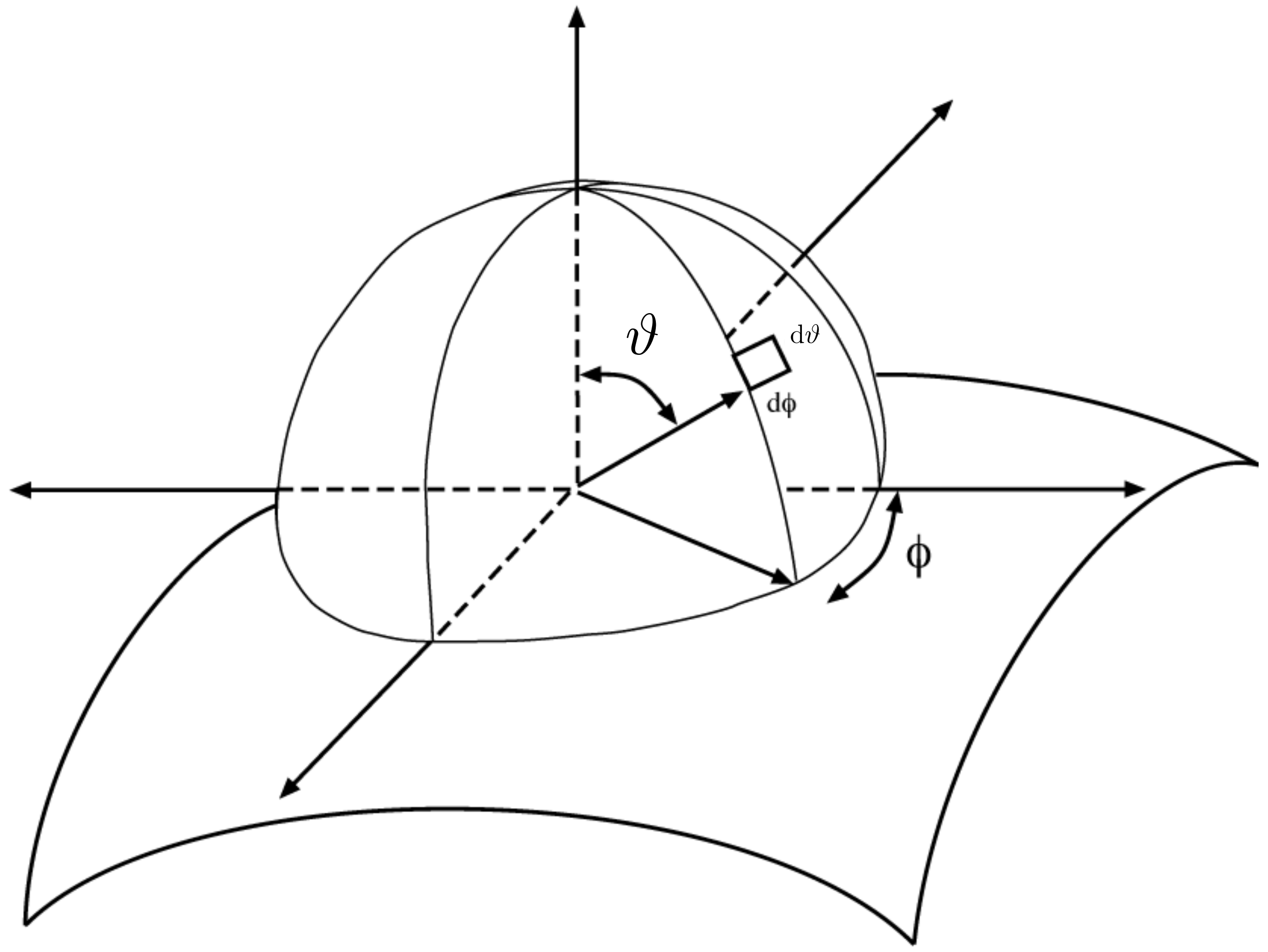
Radiometry

Questions:

- How “bright” will surfaces be?
- What is “brightness”?
    - measuring light
    - interactions between light and surfaces

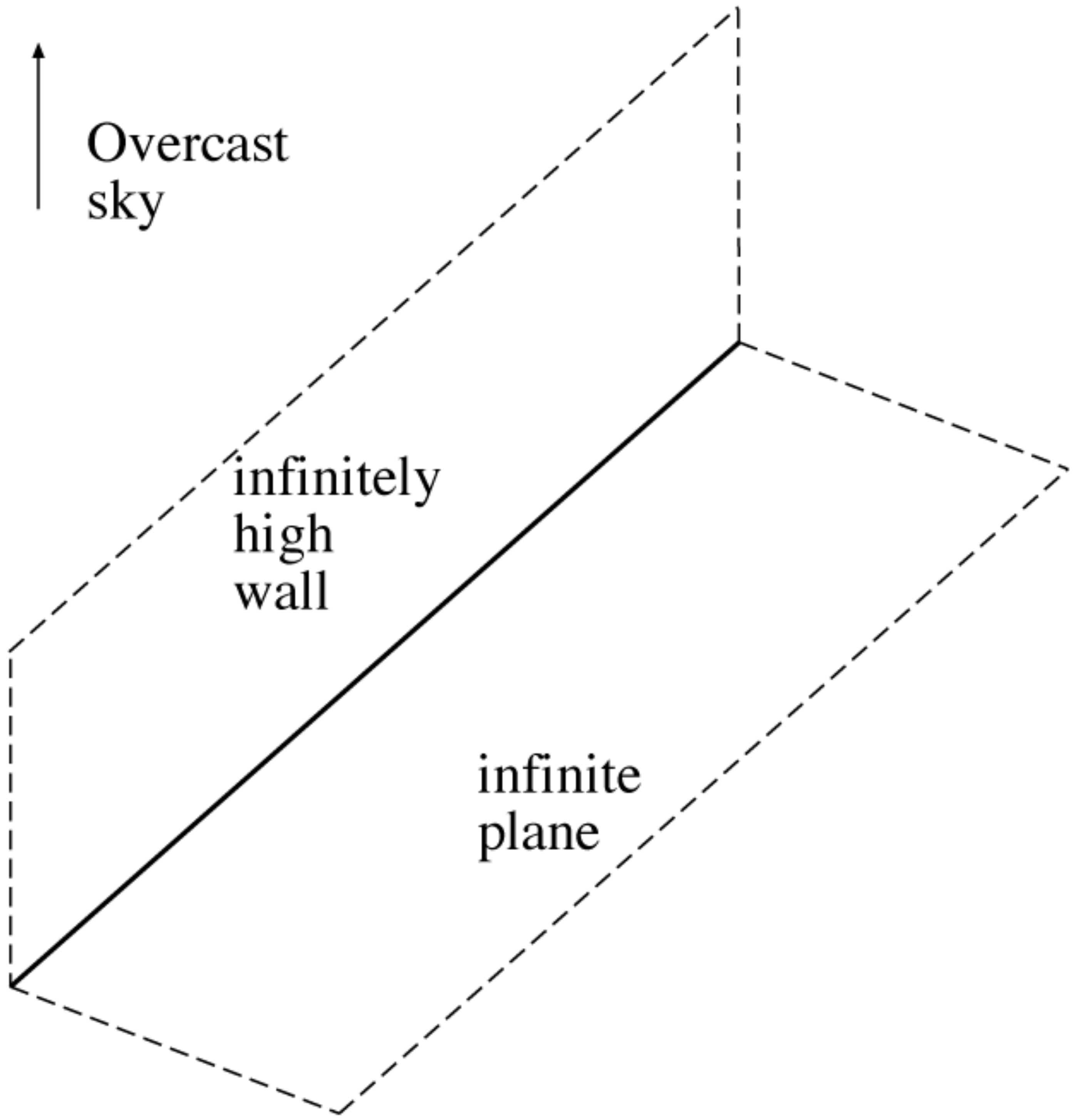
Core idea — think about light arriving at a surface around any point is a hemisphere of directions

Simplest problems can be dealt with by reasoning about this hemisphere



Computer Vision - A Modern Approach
Set: Radiometry
Slides by D.A. Forsyth

Lambert's wall



What is the distribution
of brightness on the ground?

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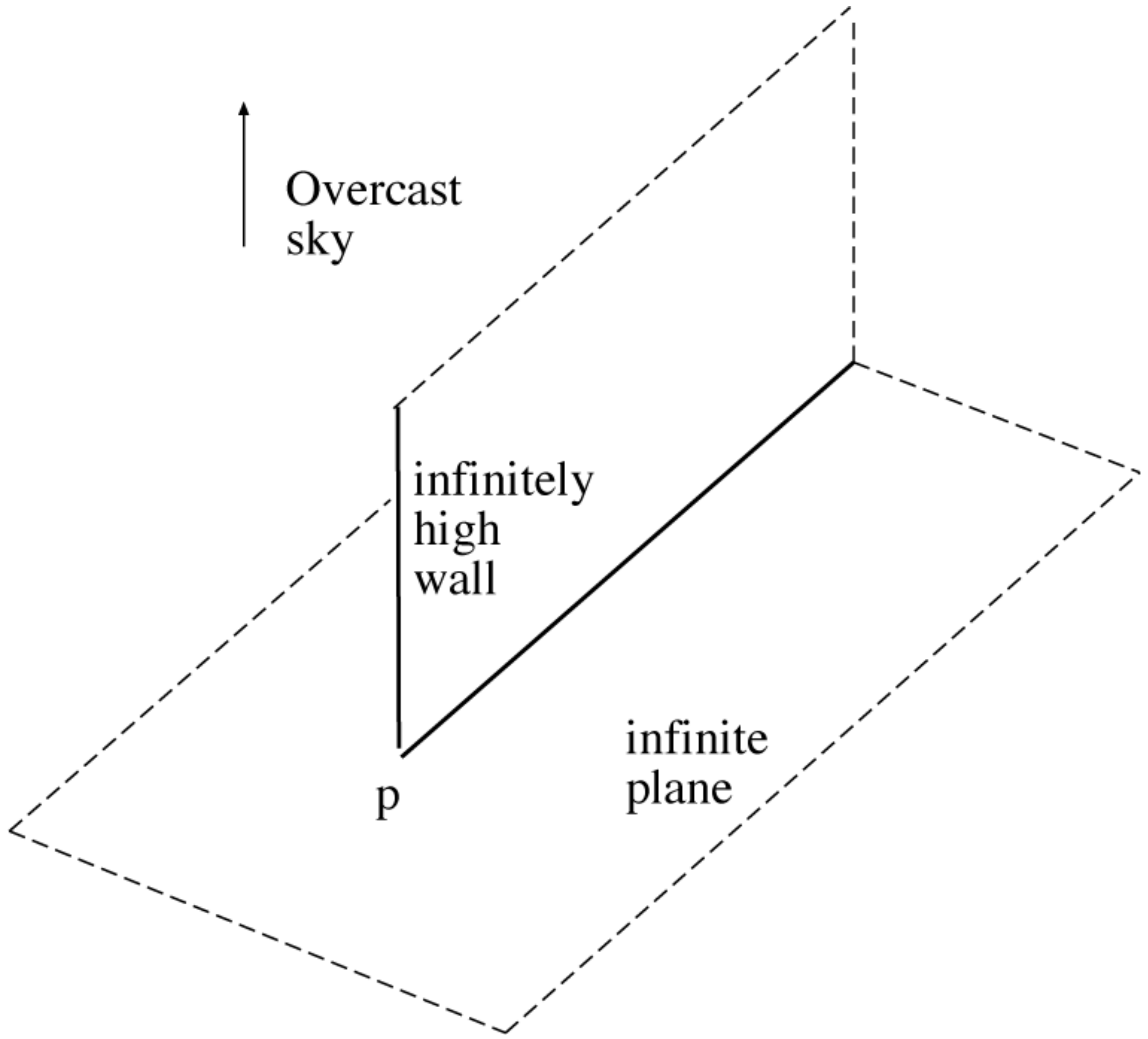
More complex wall



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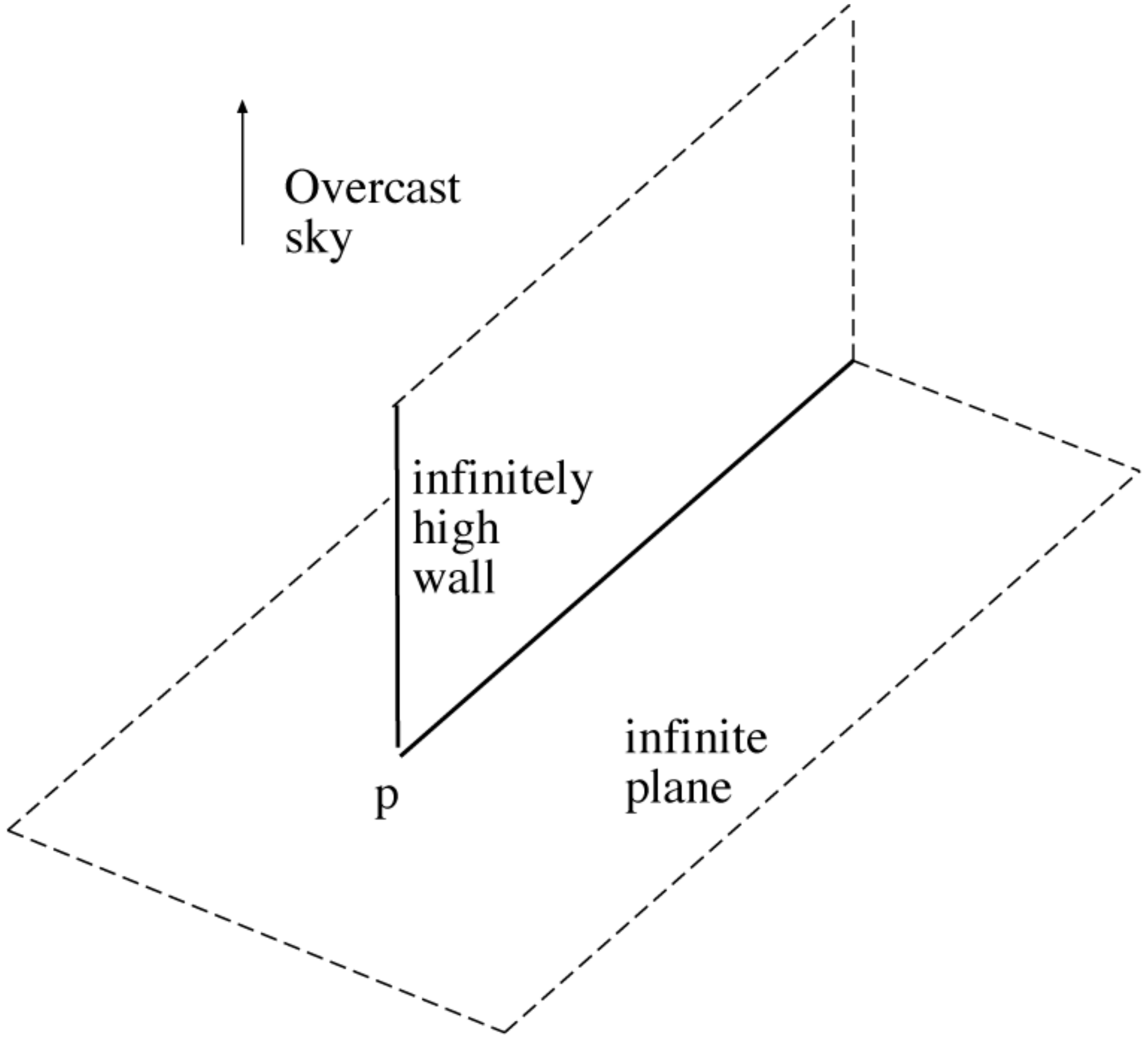

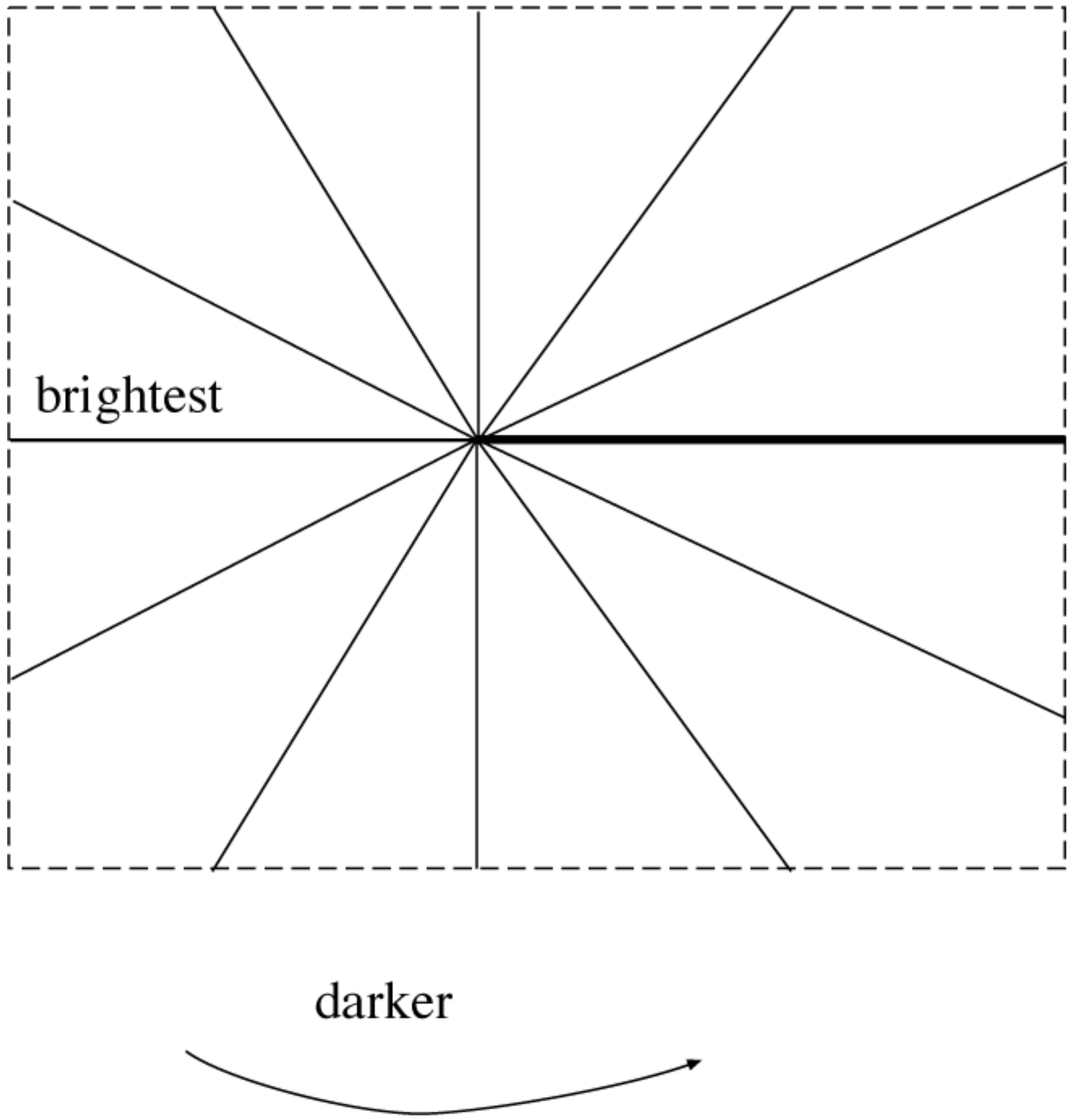

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Light at surfaces

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

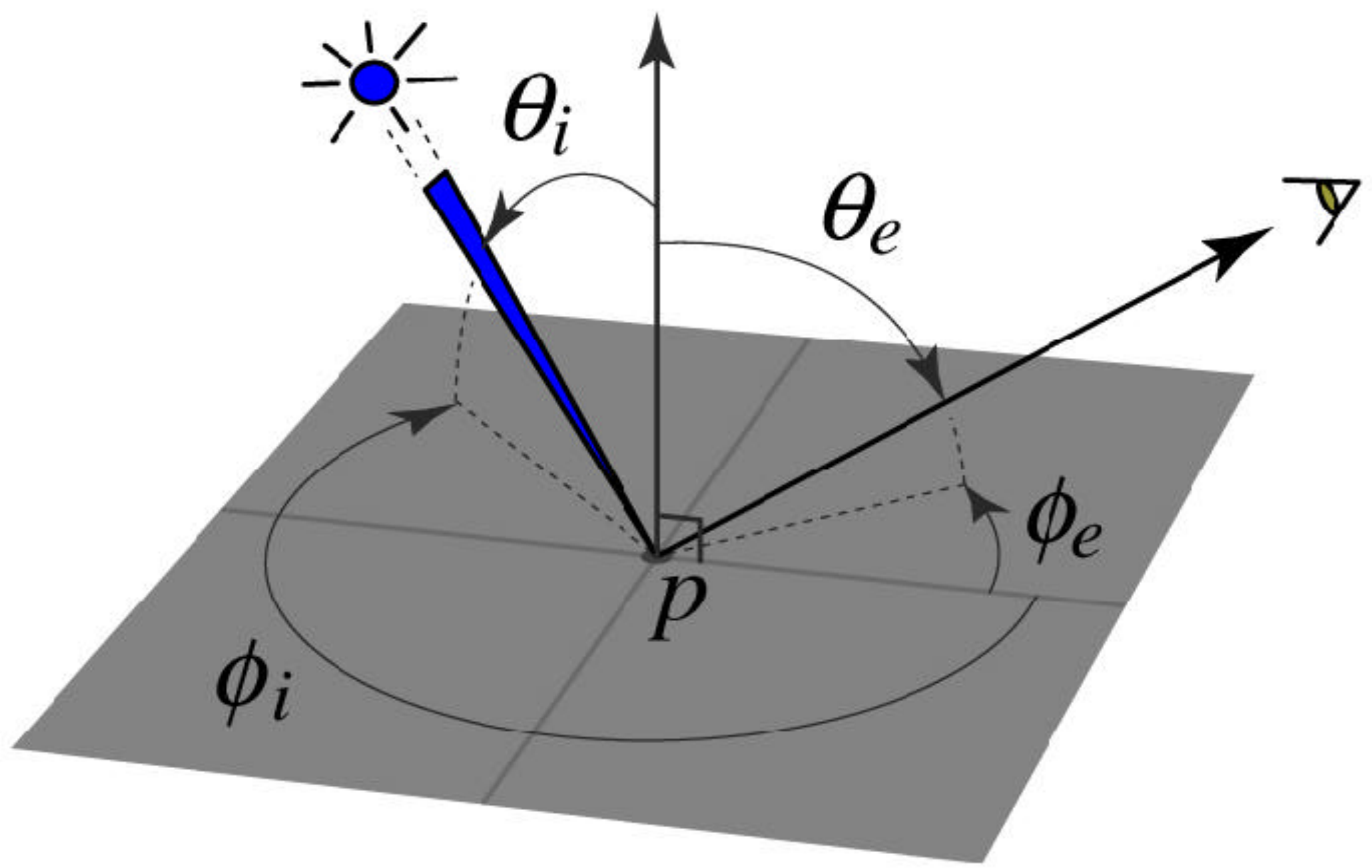
Fluorescence

Modeling surface reflectance

Bidirectional reflectance distribution function (BRDF)

- How bright a surface appears when viewed from one direction when light falls on it from another
- **Definition**: ratio of the radiance in the emitted direction to irradiance in the incident direction

$$\rho(p, \theta_i, \phi_i, \theta_e, \phi_e) = \frac{L(p, \theta_e, \phi_e)}{L(p, \theta_i, \phi_i) \cos \theta_i d\omega}$$



Simplifying assumptions
locality, no fluorescence, does not generate light

Source: Steve Seitz

Gonioreflectometer

The University of Virginia spherical gantry, an example of a modern image-based gonioreflectometer

BRDFs can be incredibly complicated…

Suppressing the angles in the BRDF

BRDF is a very general notion

- some surfaces need it (underside of a CD; tiger eye; etc)
- very hard to measure — illuminate from one direction, view from another, repeat
- very unstable — minor surface damage can change the BRDF
  - e.g. ridges of oil left by contact with the skin can act as lenses

- However, for many surfaces, light leaving the surface is largely independent of exit angle
  - surface roughness is one source of this property

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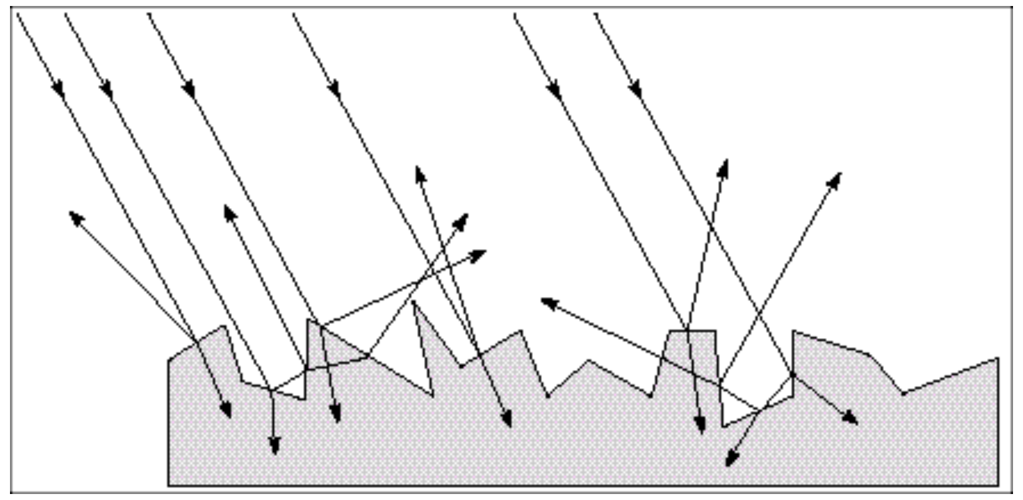
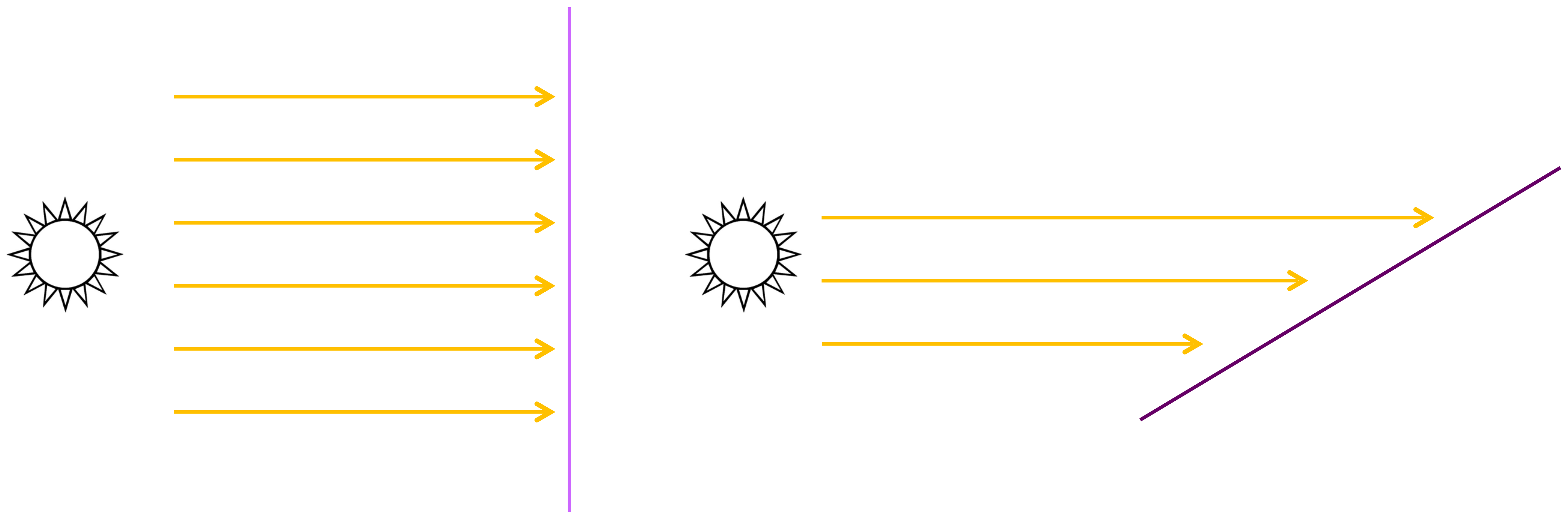
Special cases: Diffuse reflection

Light is reflected equally in all directions

- Dull, matte surfaces like chalk or cotton cloth
- Microfacets scatter incoming light randomly
- Effect is that light is reflected (approximately) equally in all directions

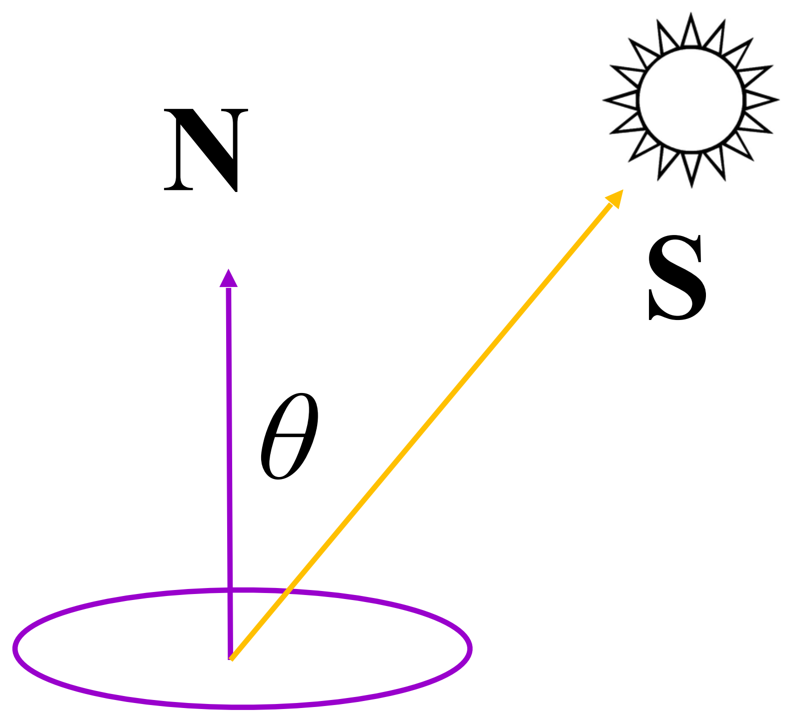
Brightness of the surface depends on the incidence of illumination



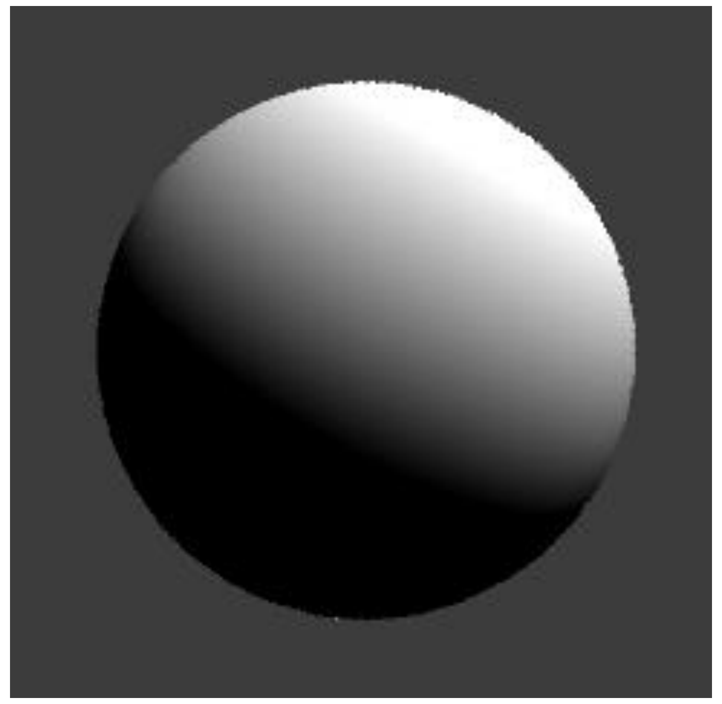


brighter darker

Diffuse reflection: Lambert's law



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



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)

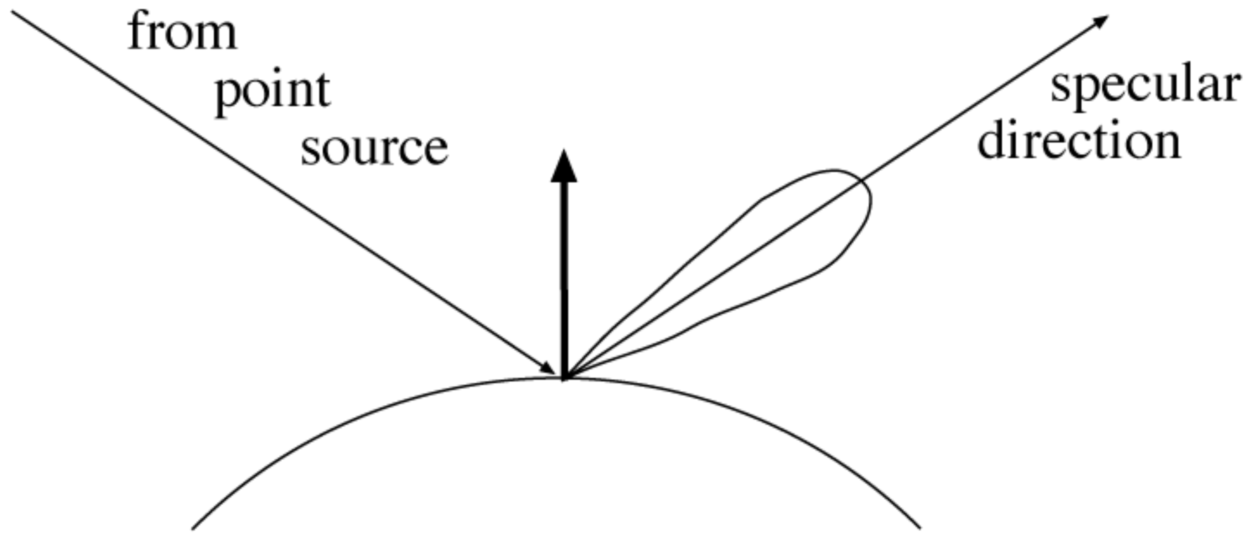
Some fraction is absorbed, some reflected

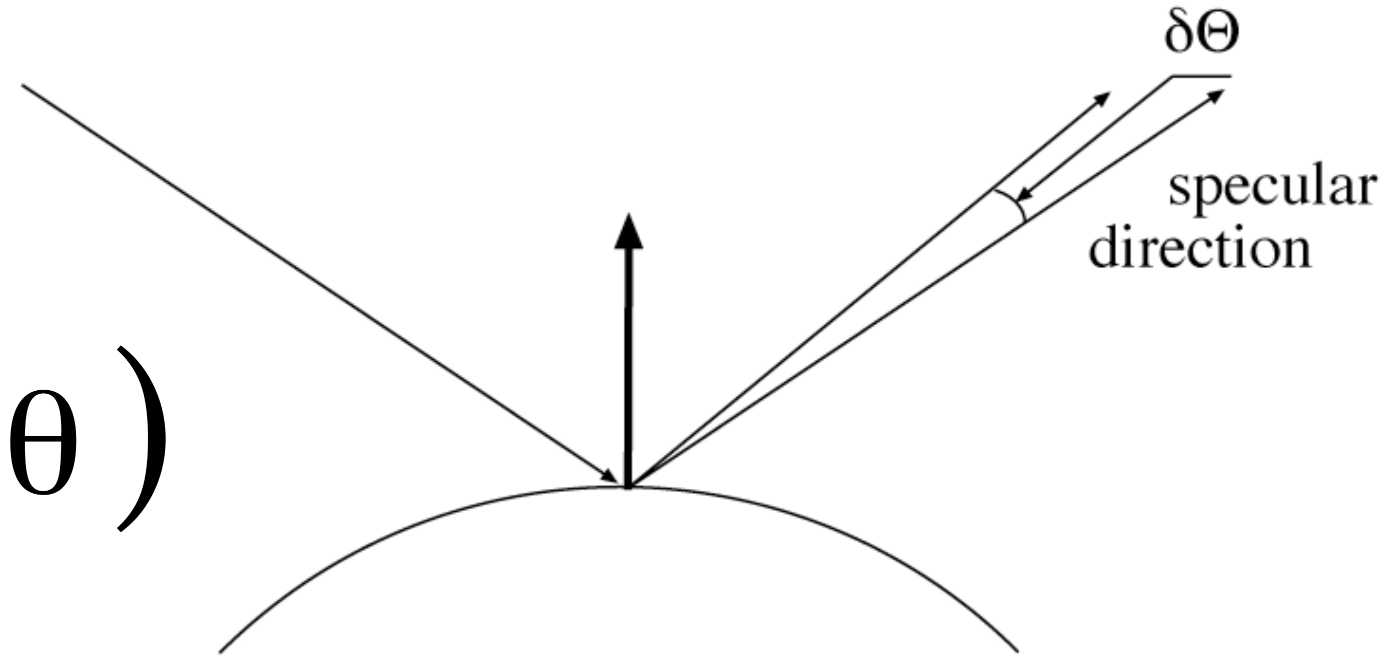
On real surfaces, energy usually goes into a lobe of directions

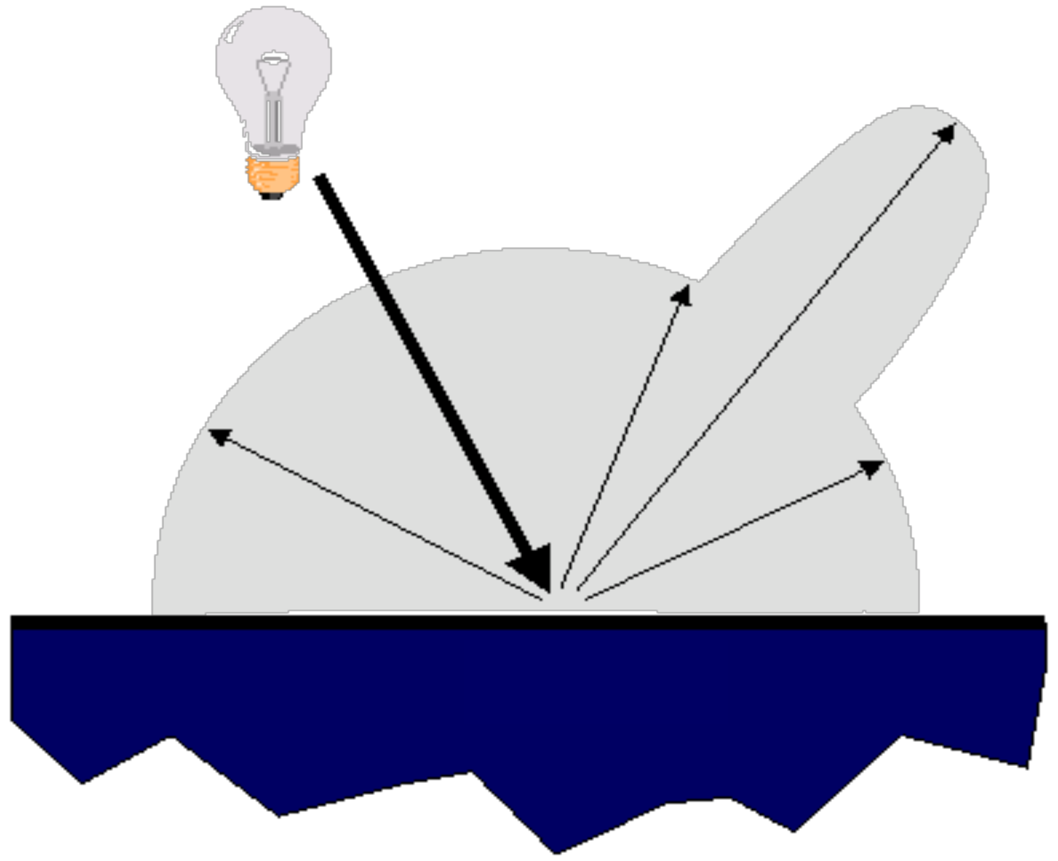
Phong model: reflected energy falls of with $\cos^n(\delta\theta)$

Lambertian + specular model: sum of diffuse and specular term

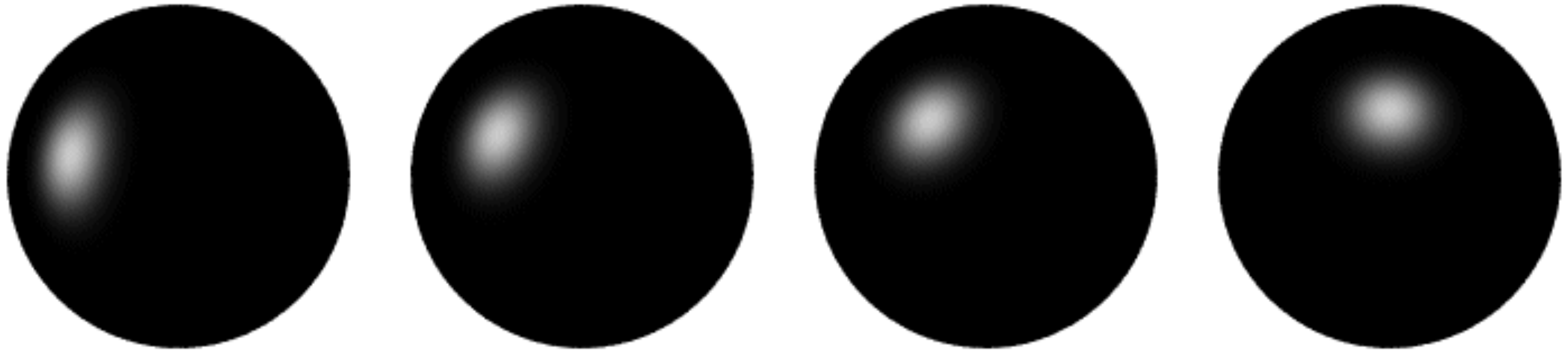
- a reasonable approximation to lot of surfaces we see



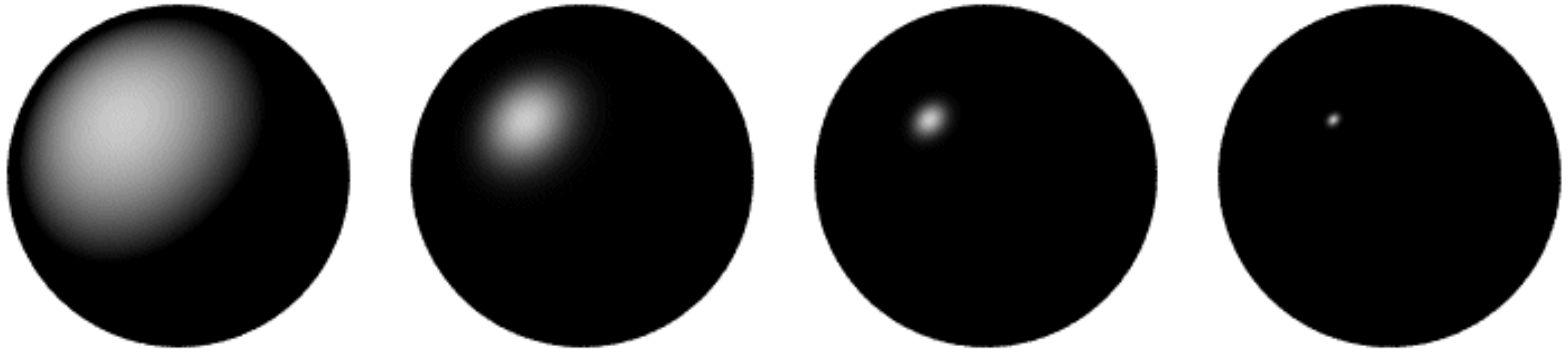




Specular reflection



Moving the light source



Changing the exponent

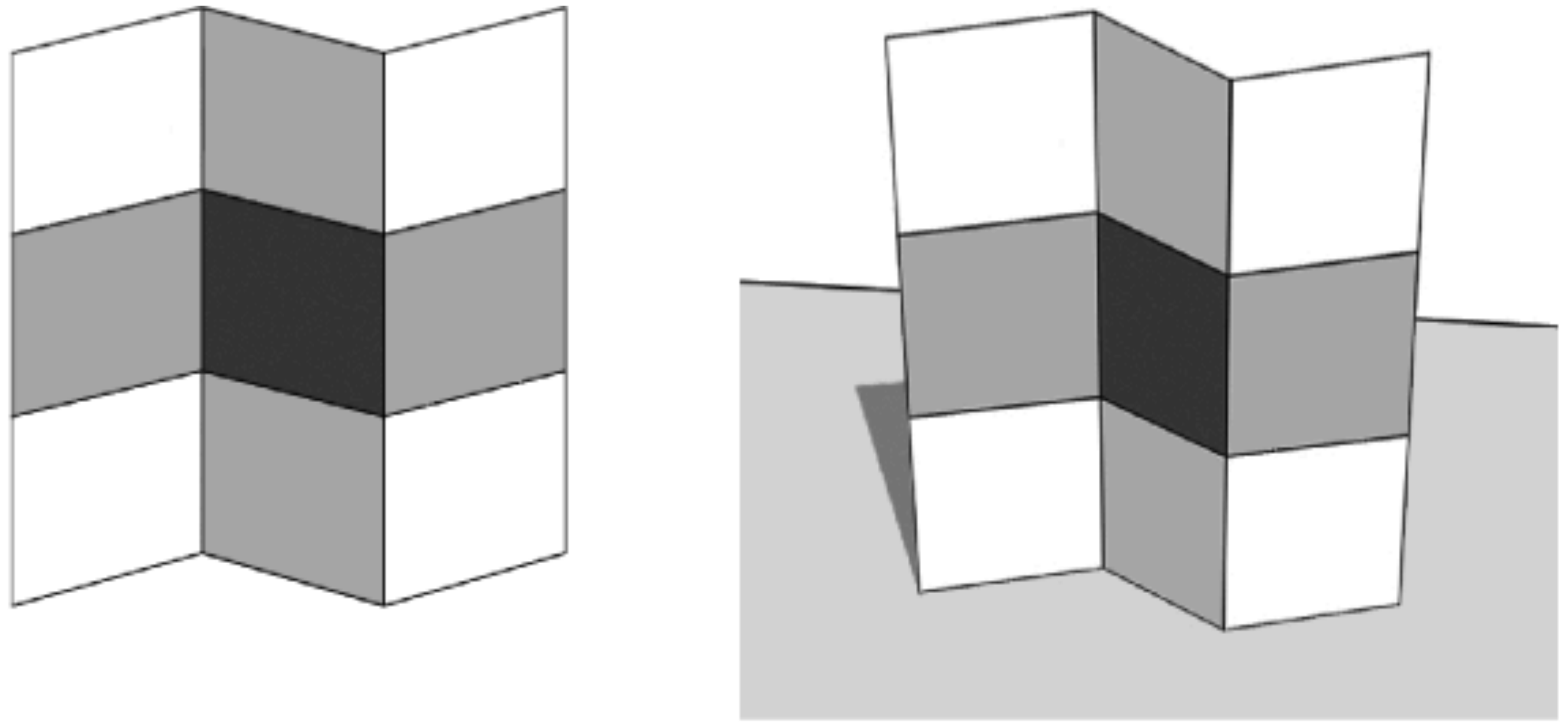
$$\cos^n(\delta\theta)$$

Photometric stereo

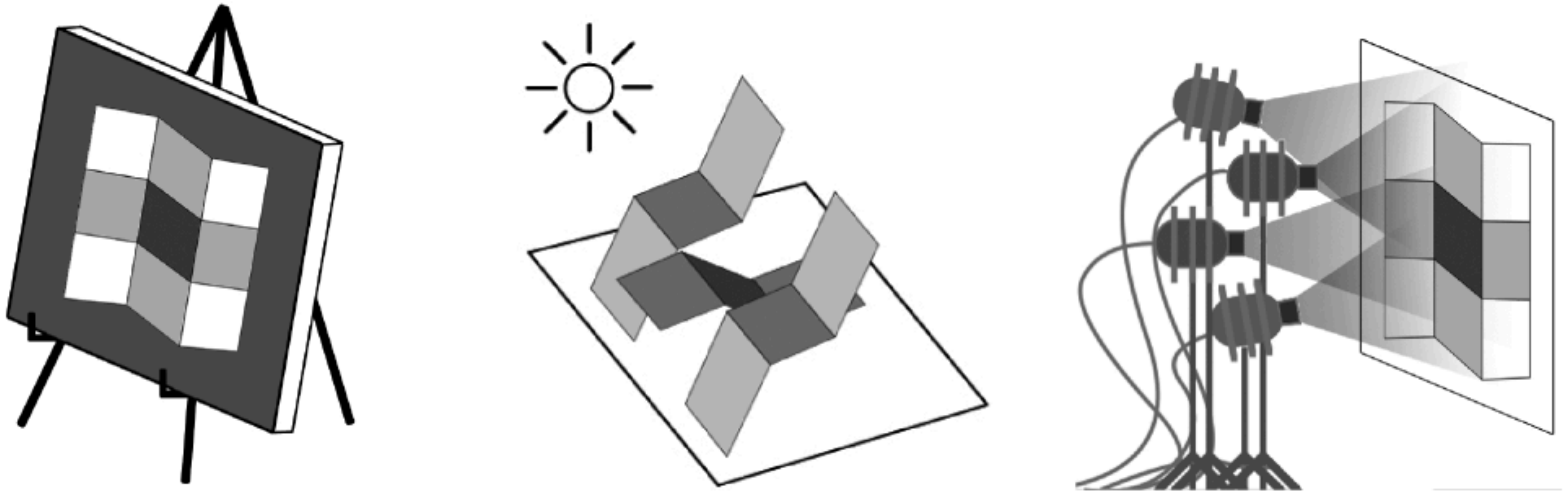
Can we reconstruct the shape of an object based on shading cues?

Luca della Robbia,
Cantoria, 1438

Ambiguities in shape and shading



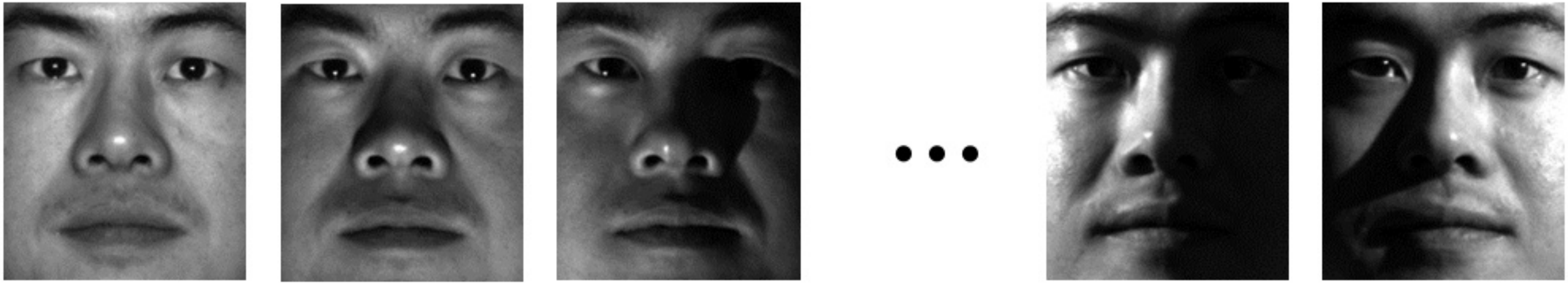
(a) an image (b) a likely explanation



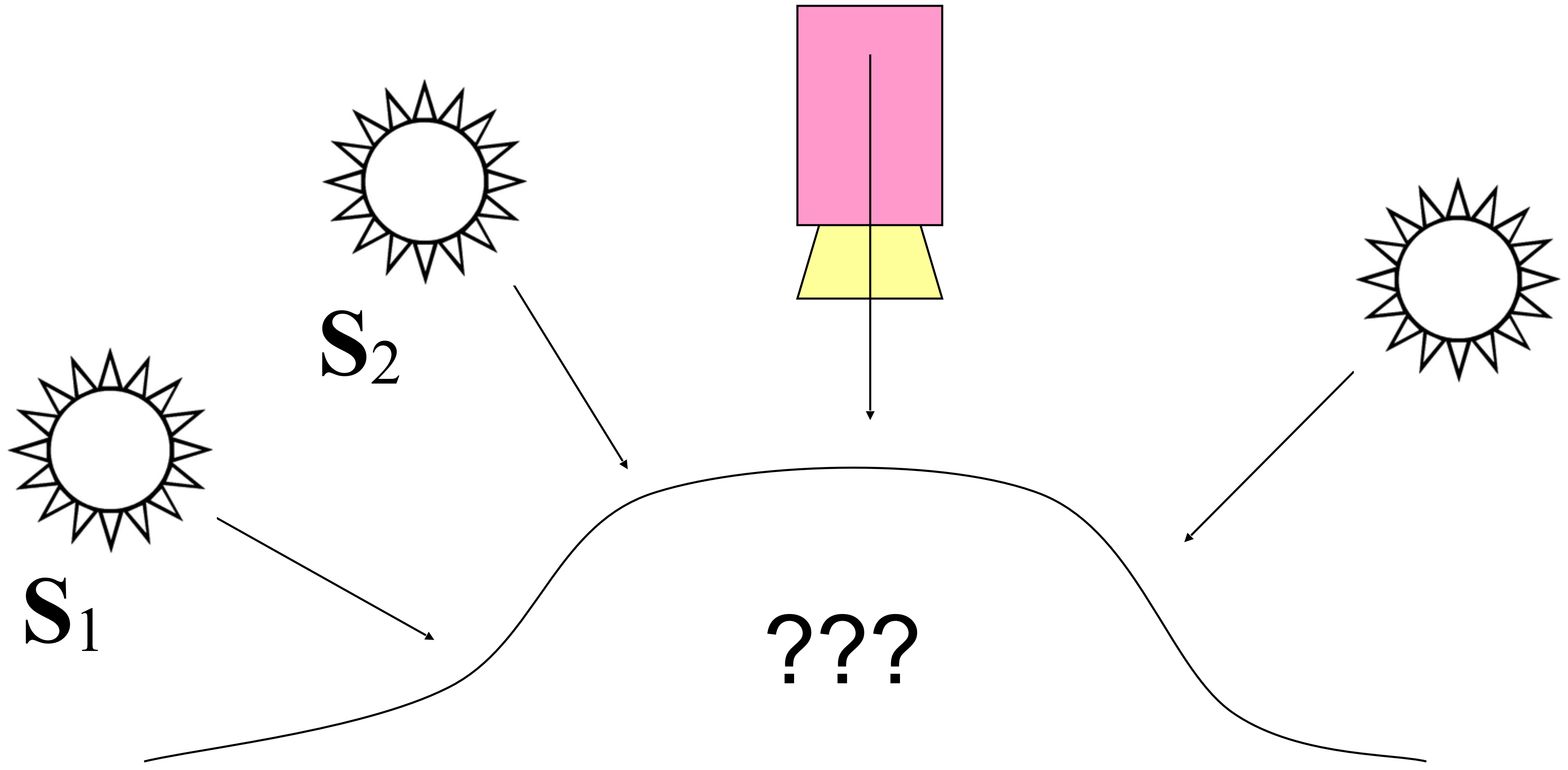
(c) painter's explanation (d) sculptor's explanation (e) gaffer's explanation

The workshop metaphor from Adelson and Pentland, 1996

Photometric stereo



S_1 S_2 S_3 S_n

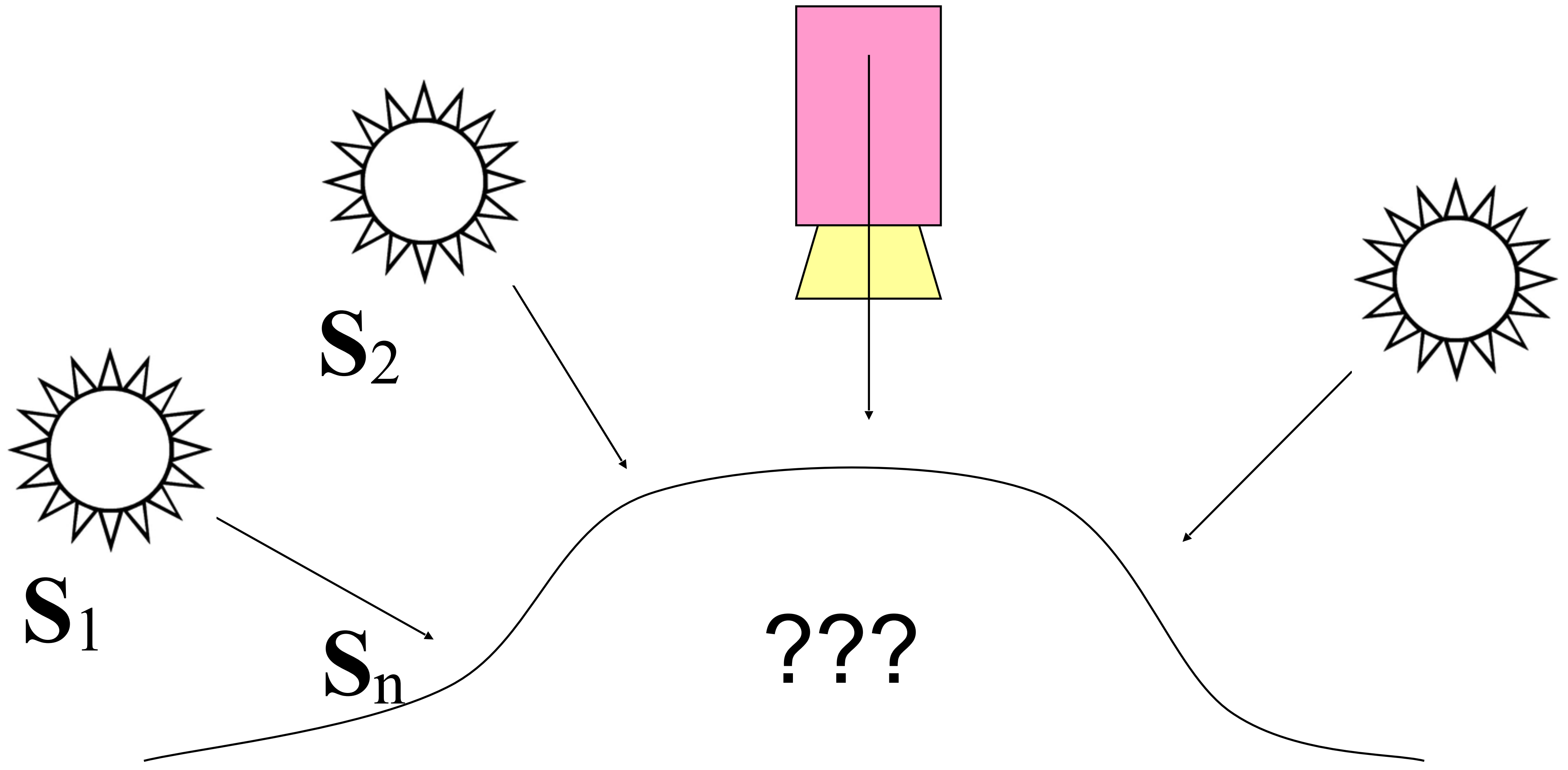


Photometric stereo

Assume:

- A **Lambertian** object
- A **local shading model, i.e.,** each point on a surface receives light only from sources visible at that point
- A set of **known** light source directions
- A set of **pictures** of an object, obtained in exactly the same camera and object configuration but using different sources
- Orthographic projection

Goal: reconstruct object shape and albedo



F&P 2nd ed., sec. 2.2.4

Surface model: Monge patch

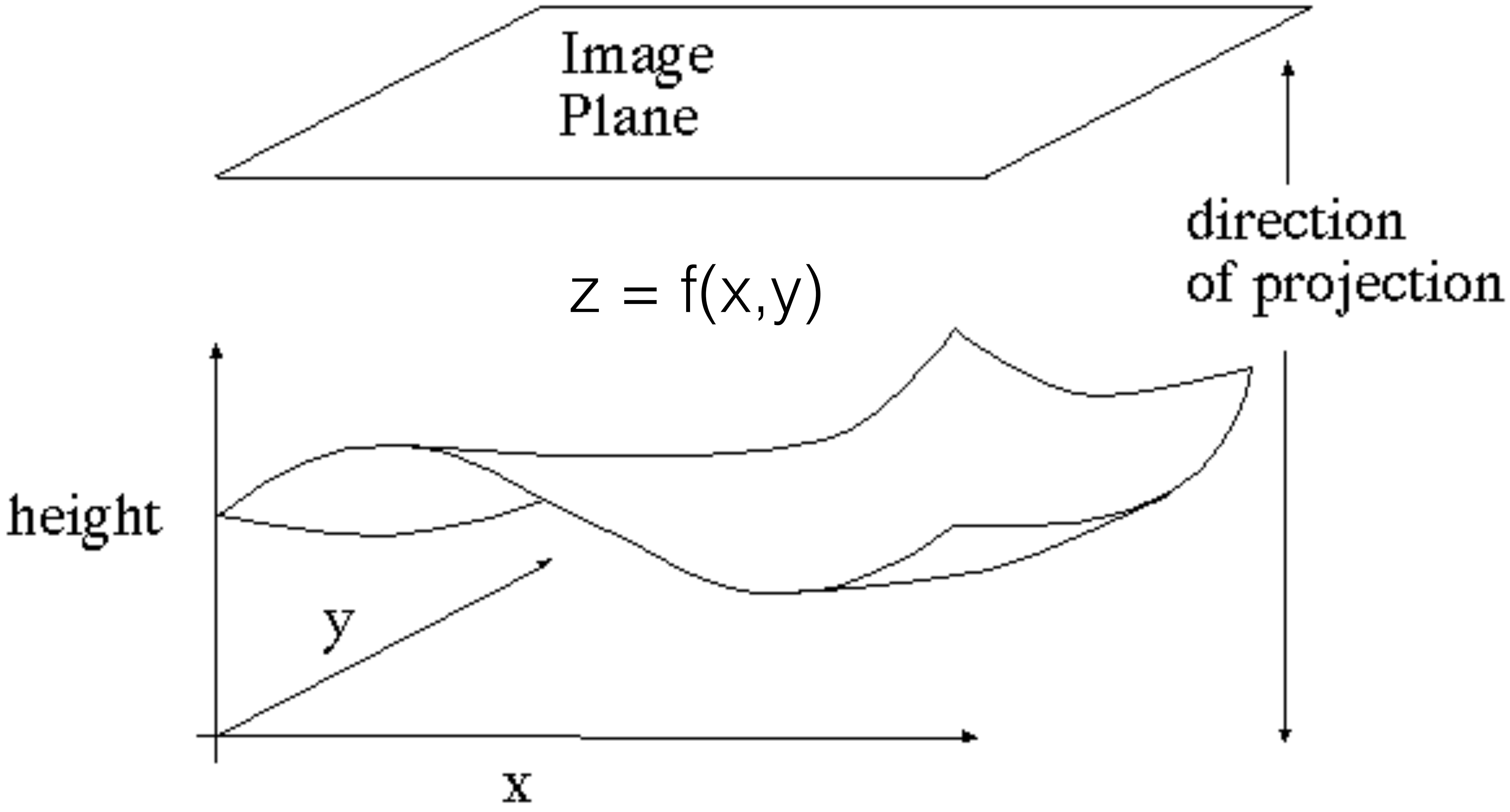


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Image model

Known: source vectors $\mathbf{S}_j$ and pixel values $I_j(x,y)$

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:

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

F&P 2nd ed., sec. 2.2.4

Least squares problem

- For each pixel, set up a linear system:

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

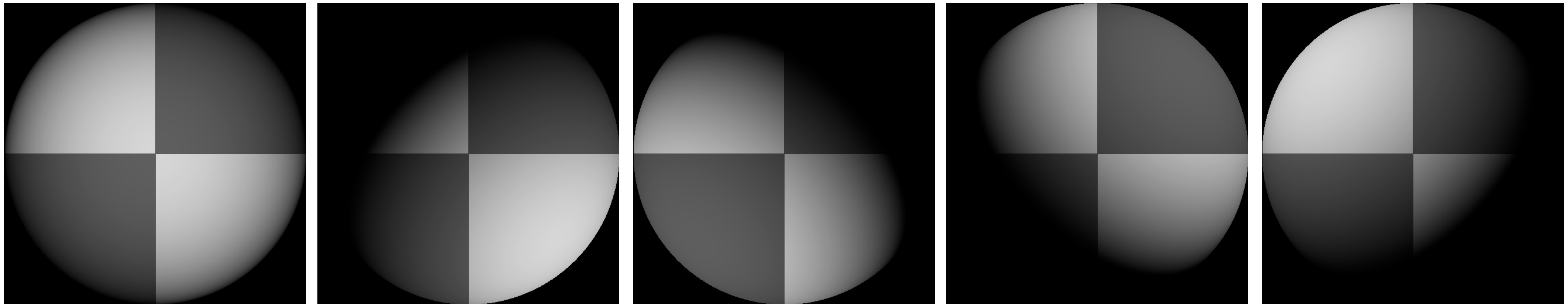
Obtain least-squares solution for $\mathbf{g}(x,y)$ defined as $\mathbf{N}(x,y)\ \rho(x,y)$

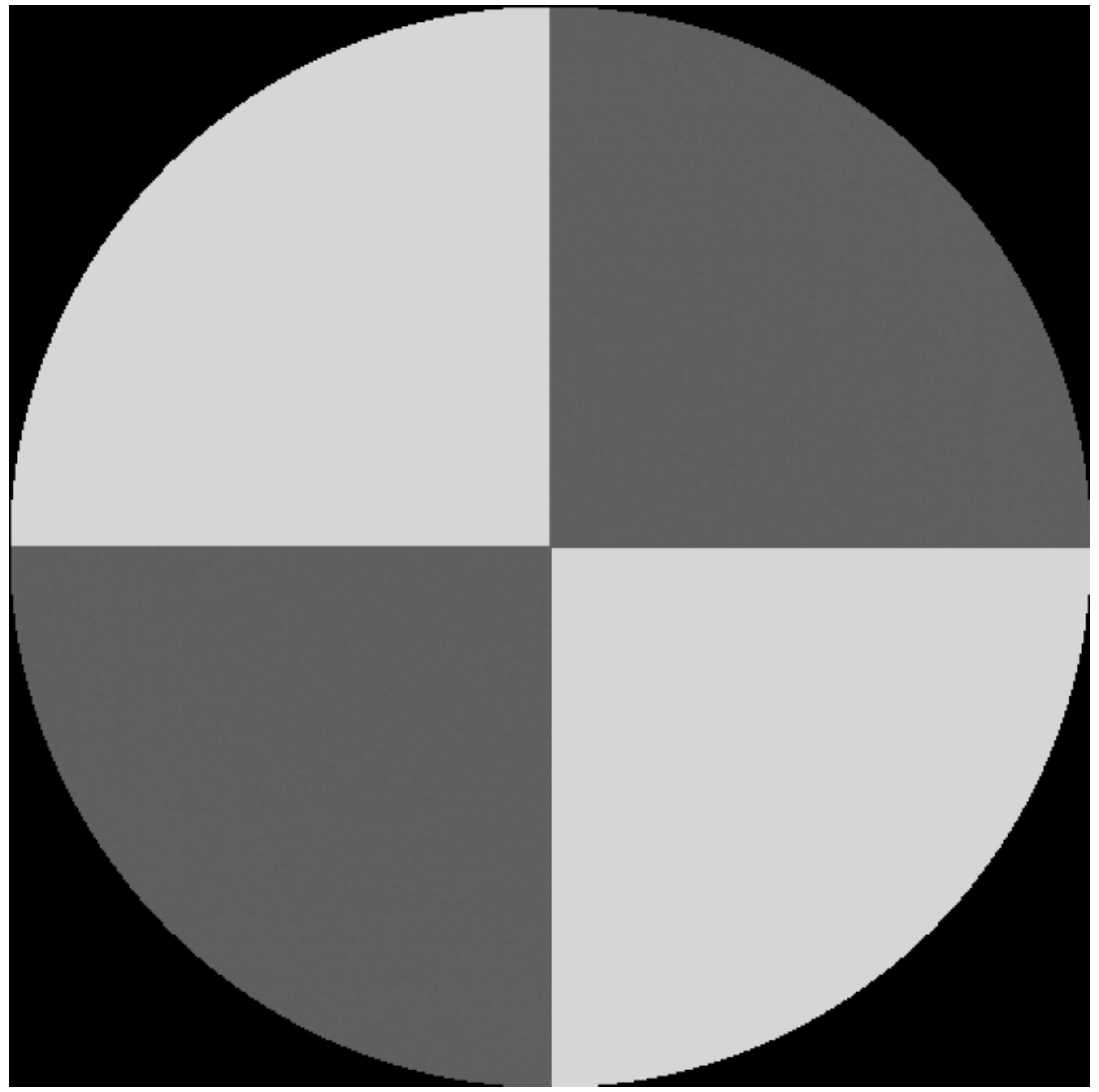
Since $\mathbf{N}(x,y)$ is the unit normal, $\rho(x,y)$ is given by the magnitude of $\mathbf{g}(x,y)$

Finally, $\mathbf{N}(x,y) = \mathbf{g}(x,y) / \rho(x,y)$

F&P 2nd ed., sec. 2.2.4

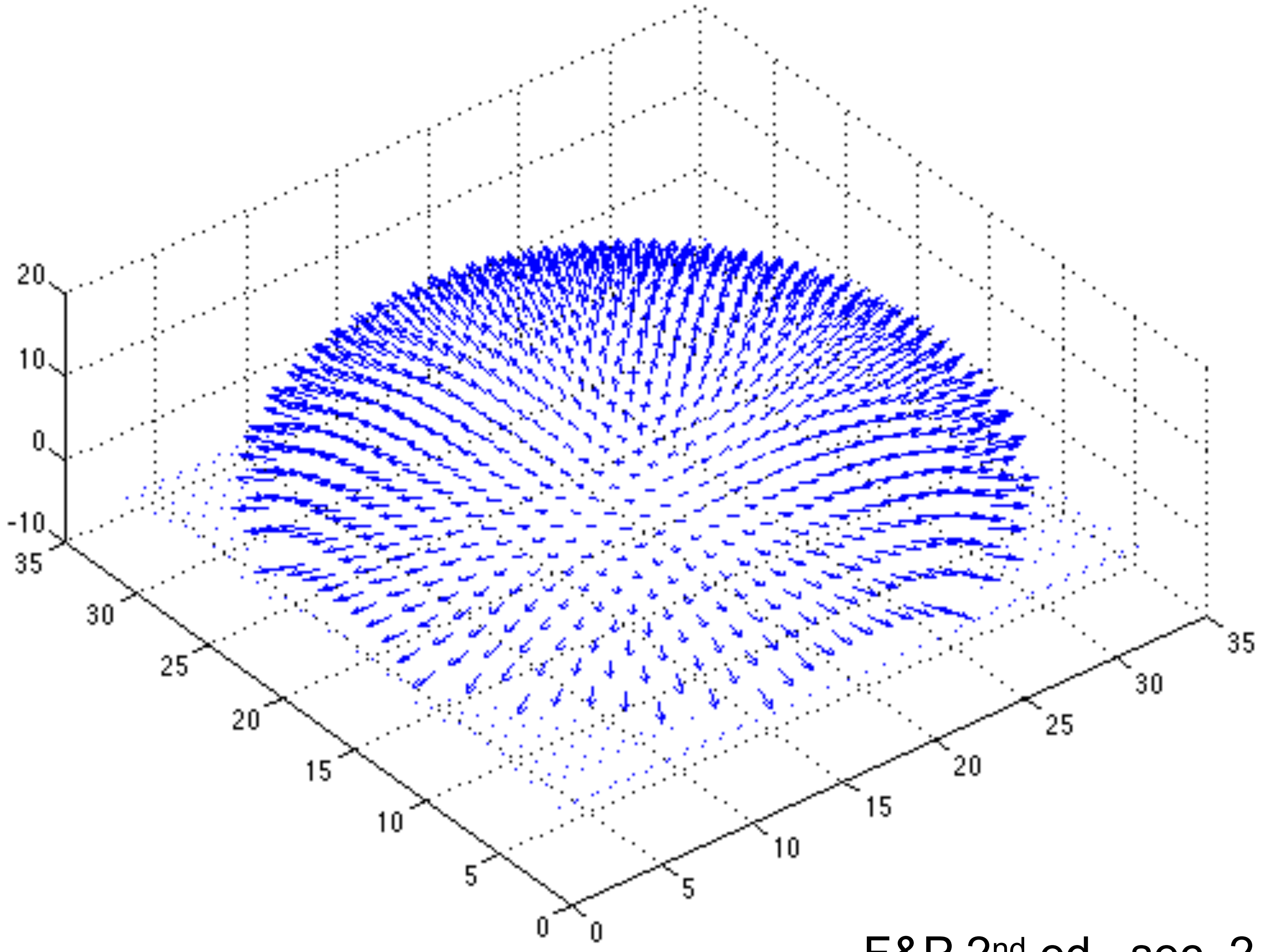
Example





Recovered albedo

Recovered normal field



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Recovering a surface from normals

Recall the surface is written as

$$(x, y, f(x, y))$$

This means the normal has the form:

$$\mathbf{N}(x, y) = \frac{1}{\sqrt{f_x^2 + f_y^2 + 1}} \begin{pmatrix} f_x \\ f_y \\ 1 \end{pmatrix}$$

If we write the estimated vector *g* as

$$\mathbf{g}(x, y) = \begin{pmatrix} g_1(x, y) \\ g_2(x, y) \\ g_3(x, y) \end{pmatrix}$$

Then we obtain values for the partial derivatives of the surface:

$$f_x(x, y) = g_1(x, y) / g_3(x, y)$$
$$f_y(x, y) = g_2(x, y) / g_3(x, y)$$

F&P 2nd ed., sec. 2.2.4

Recovering a surface from normals

Integrability: for the surface f to exist, the mixed second partial derivatives must be equal:

$$\frac{\partial^2 f}{\partial x \partial y} = \frac{\partial^2 f}{\partial y \partial x} \quad \text{i.e.,}$$

$$\frac{\partial}{\partial y}(g_1(x,y) / g_3(x,y)) =$$

$$\frac{\partial}{\partial x}(g_2(x,y) / g_3(x,y))$$

In practice, they should be similar

We can now recover the surface height at any point by integration along some path

$$f(x,y) = \oint_C \left(\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y} \right) \cdot d\boldsymbol{l} + c$$

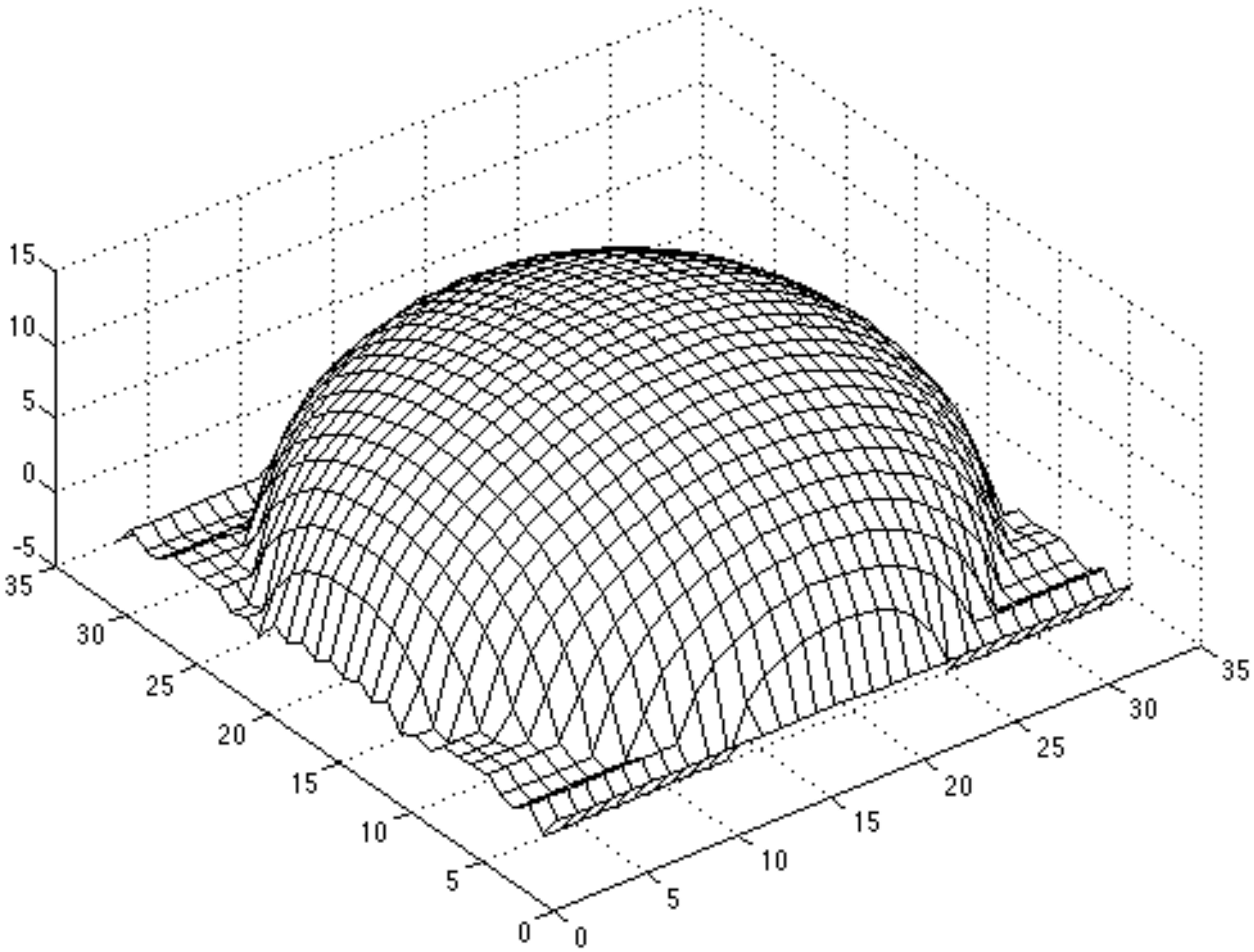
For example:

$$f(u,v) = \int_0^v \frac{\partial f}{\partial y}(0,y)dy + \int_0^u \frac{\partial f}{\partial x}(x,v)dx + c$$

For robustness, take integrals over many different paths and average the results

F&P 2nd ed., sec. 2.2.4

Surface recovered by integration



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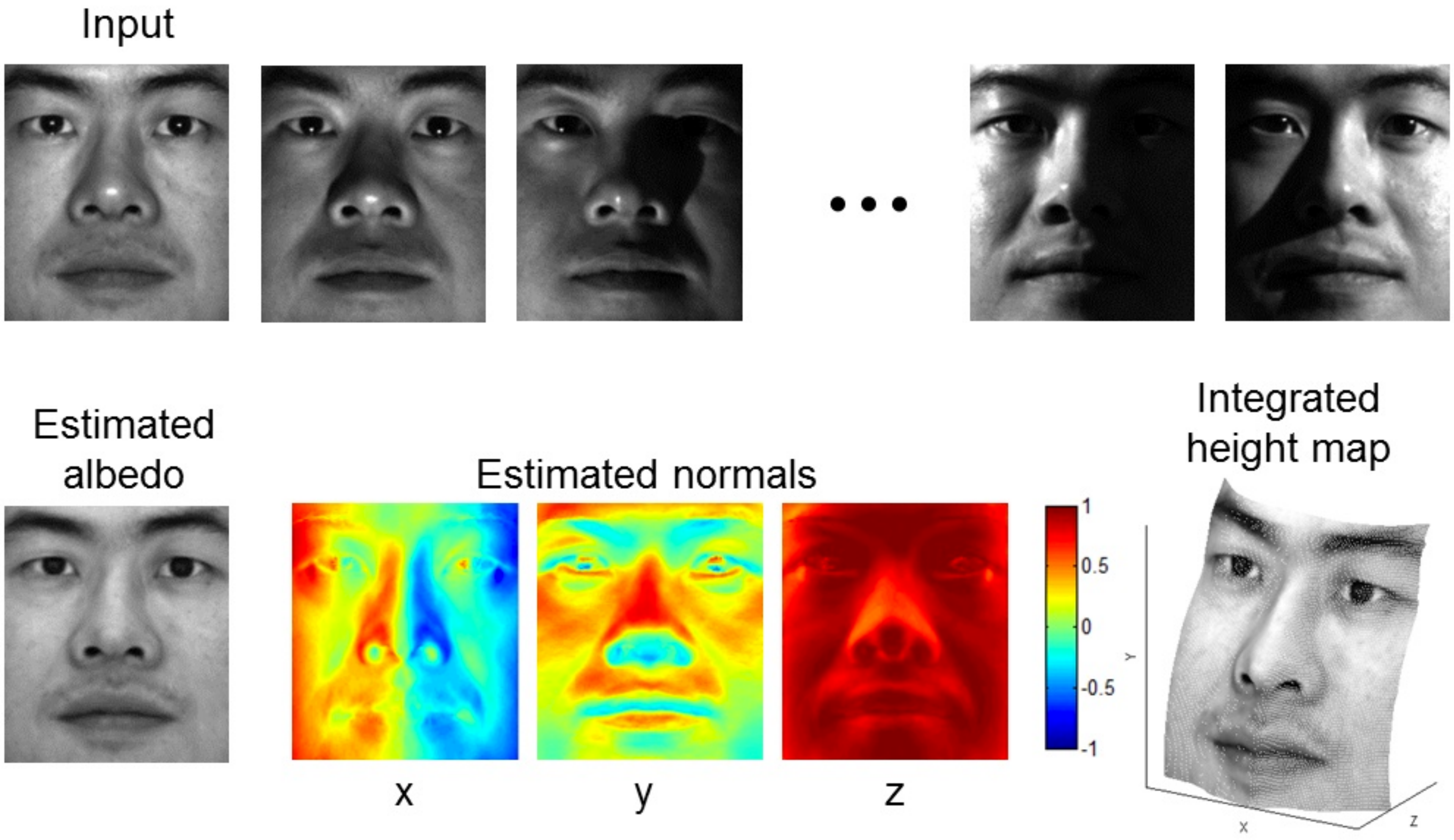
Works for more complicated surfaces



Limitations

Orthographic camera model

Simplistic reflectance and lighting model

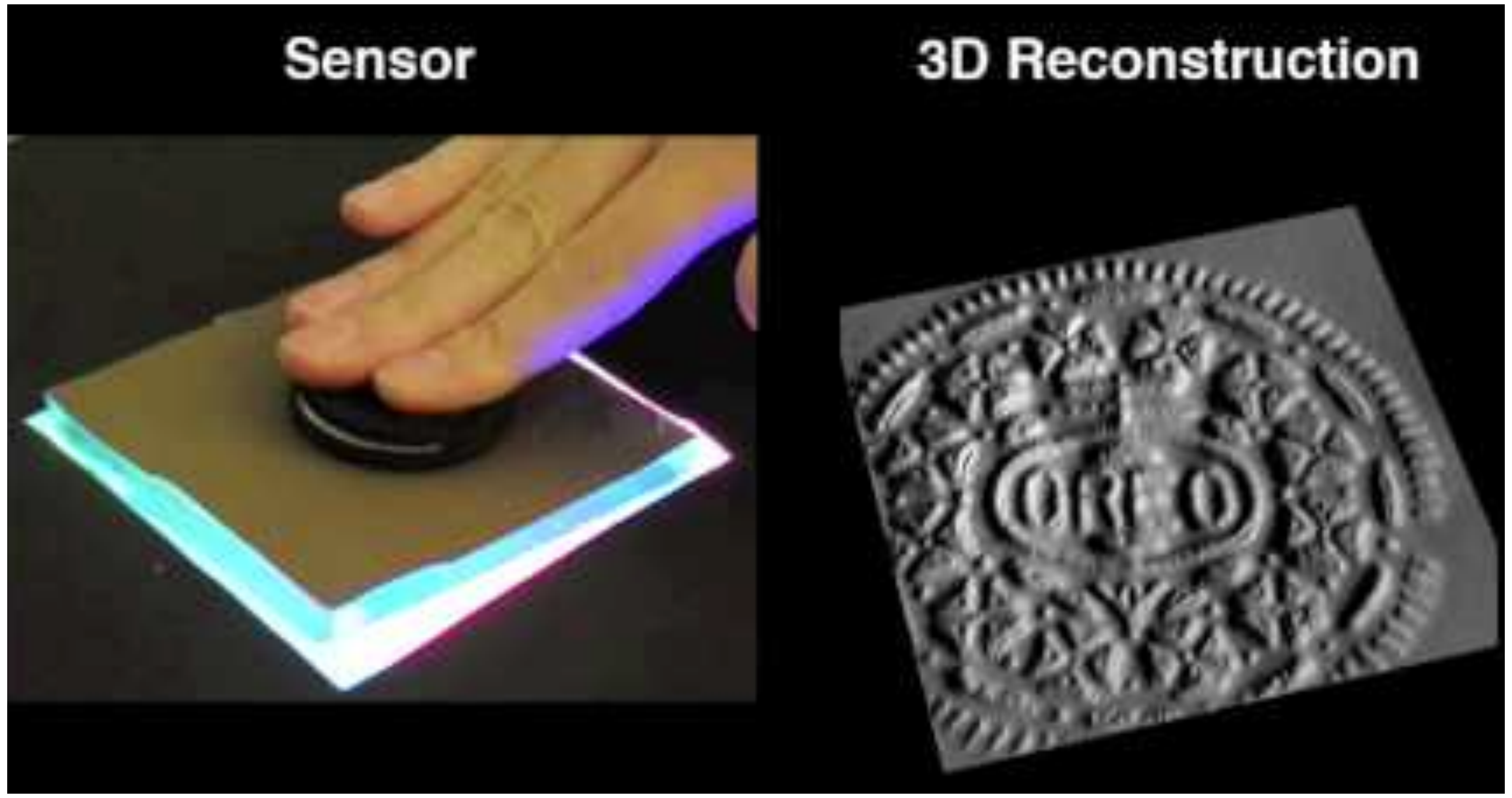
No shadows

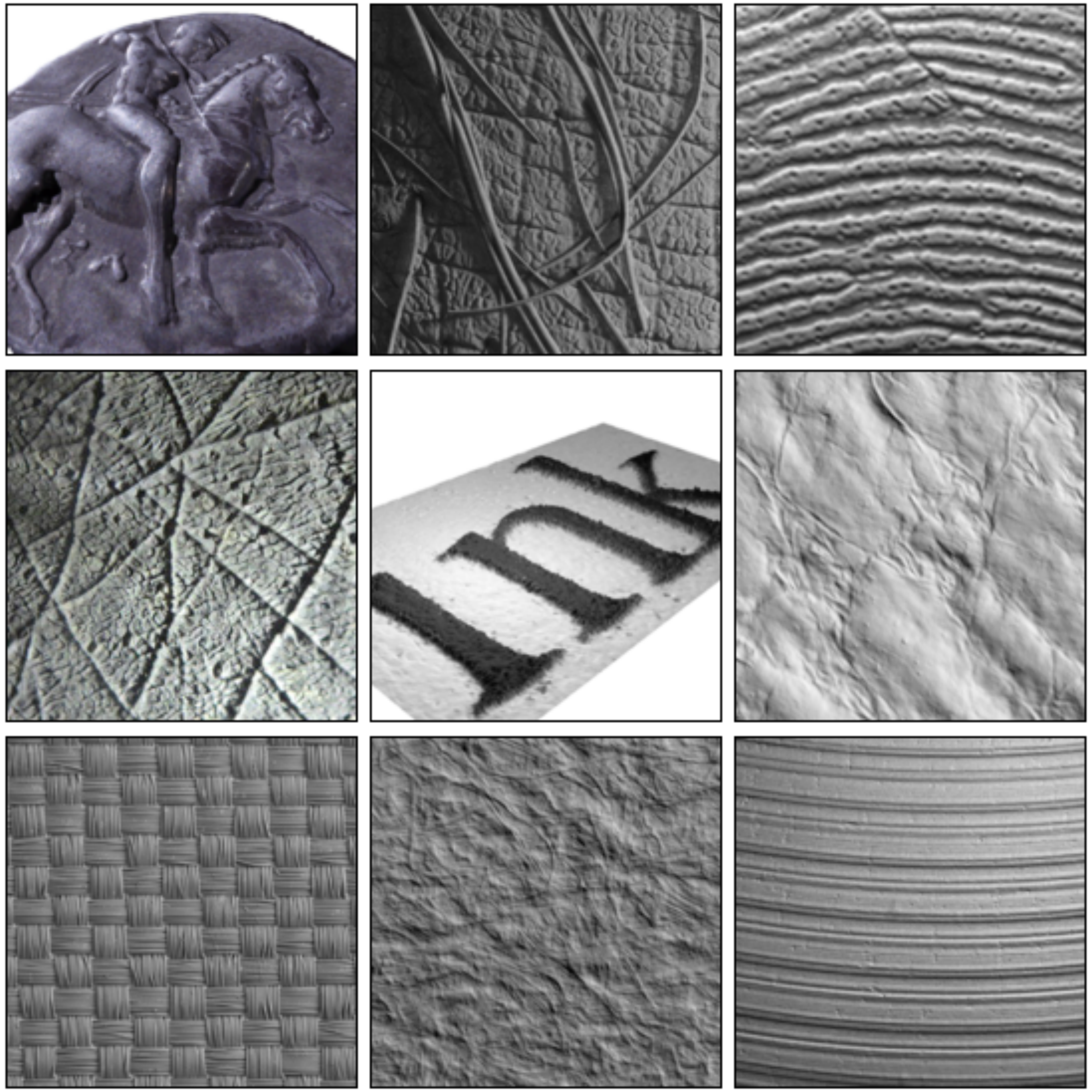
No inter-reflections

No missing data

Integration is tricky

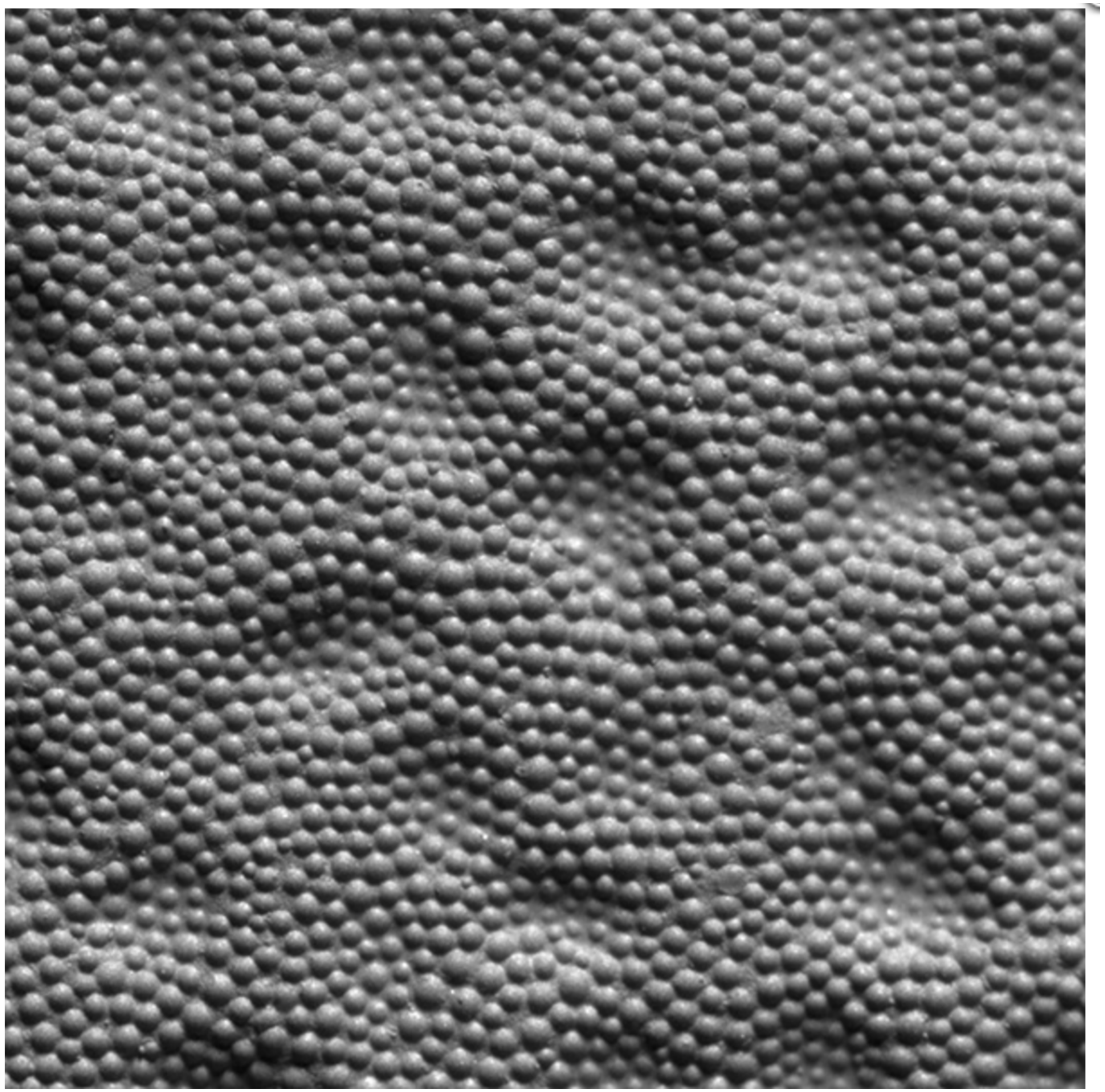
GELSIGHT





https://www.youtube.com/watch?v=S7gXih4XS7A

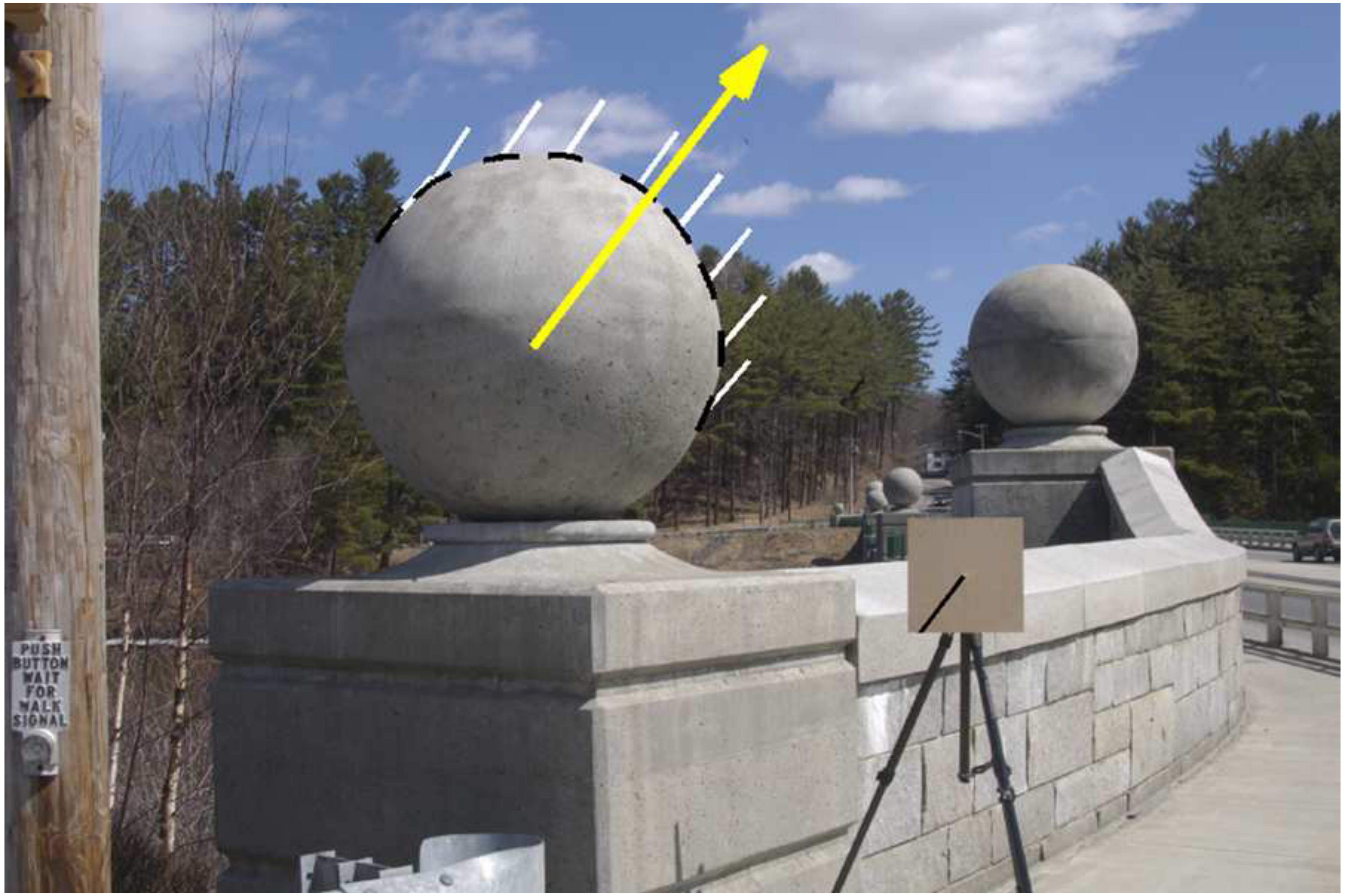
GELSIGHT



Retro-reflective fabric. Raw image using GelSight.

A fingerprint with visible pores. Raw image using GelSight.

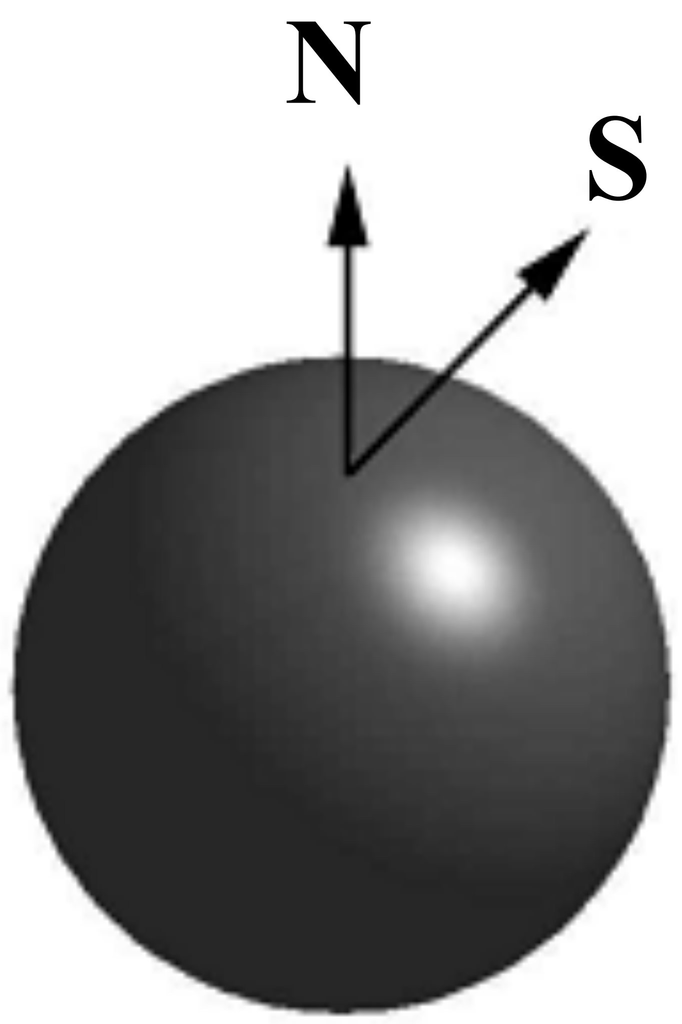
Finding the direction of the light source



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

Finding the direction of the light source

$$\boxed{I(x,y) = \mathbf{N}(x,y) \cdot \mathbf{S}(x,y) + A}$$



For points on the *occluding contour*:

$$\begin{pmatrix} N_x(x_1,y_1) & N_y(x_1,y_1) & 1 \\ N_x(x_2,y_2) & N_y(x_2,y_2) & 1 \\ \vdots & \vdots & \vdots \\ N_x(x_n,y_n) & N_y(x_n,y_n) & 1 \end{pmatrix} \begin{pmatrix} S_x \\ S_y \\ A \end{pmatrix} = \begin{pmatrix} I(x_1,y_1) \\ I(x_2,y_2) \\ \vdots \\ I(x_n,y_n) \end{pmatrix}$$

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

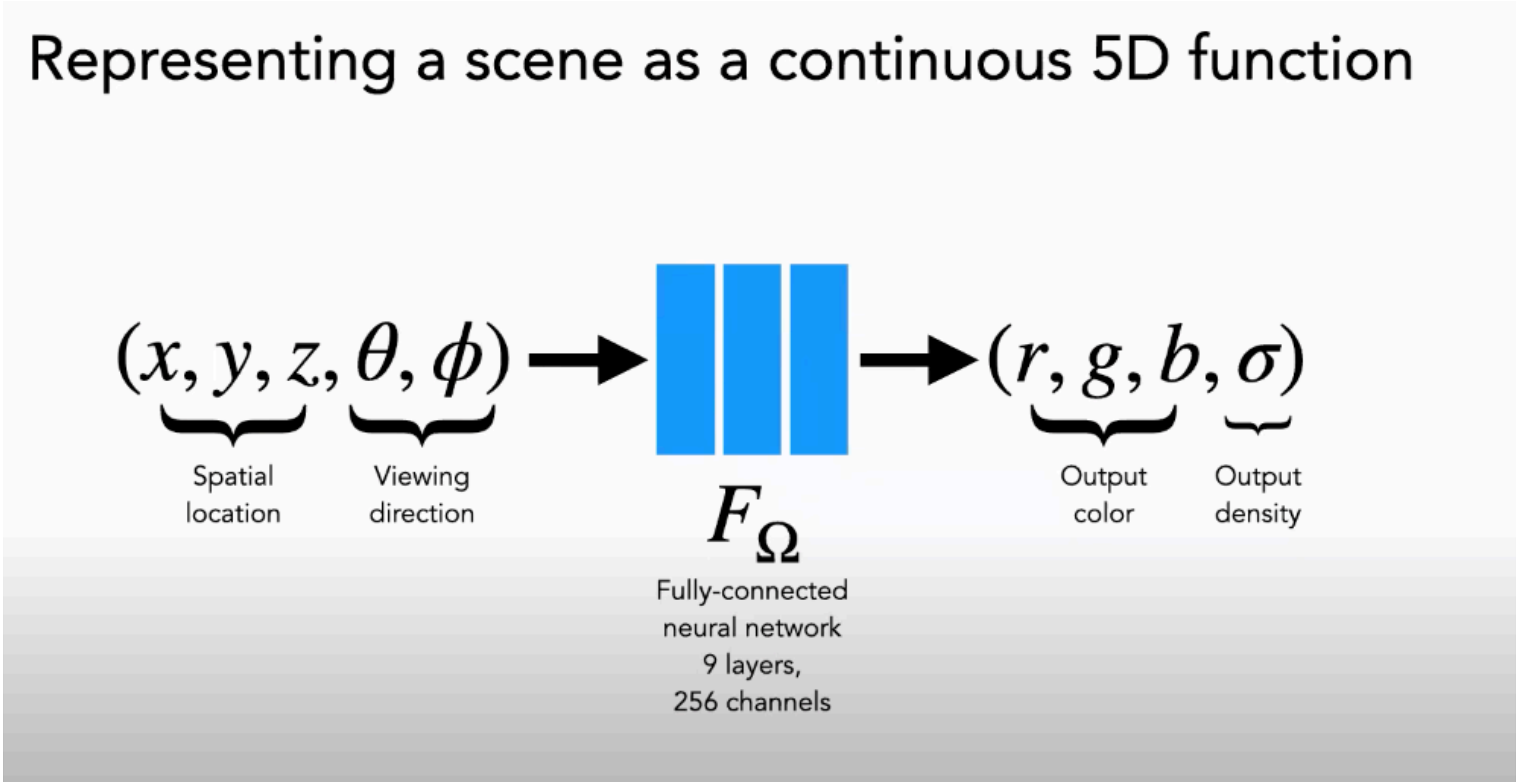
Detecting composite photos

Fake photo

Real photo

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

Neural radiance fields (NeRF)



Neural radiance fields (NeRF)