Real-world illumination and the perception of surface reflectance properties

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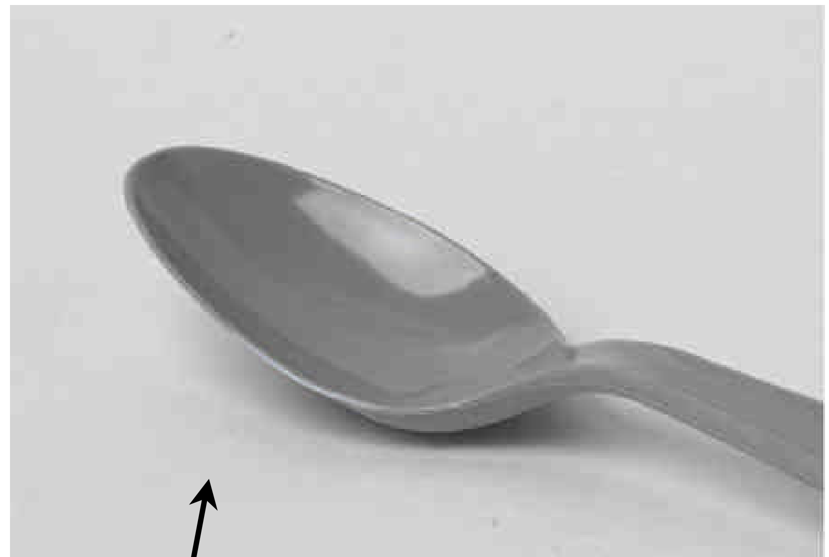
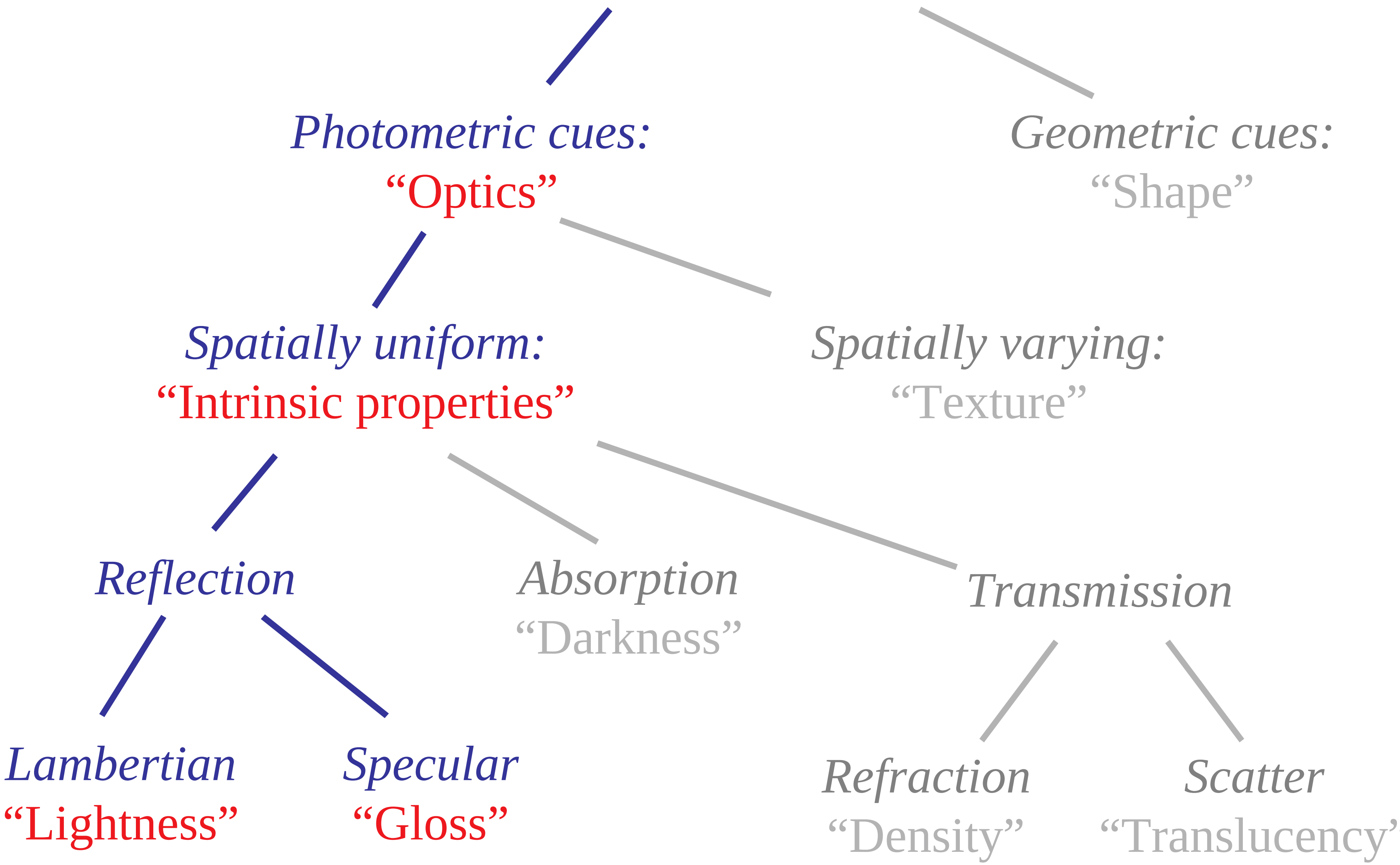
Material Recognition



Similar objects,
different *materials*

Perception of Material Properties



Surface Reflectance

- These spheres look different because they have different **surface reflectance properties**, e.g. *lightness* and *gloss*
- We are interested in **how humans estimate surface reflectance**

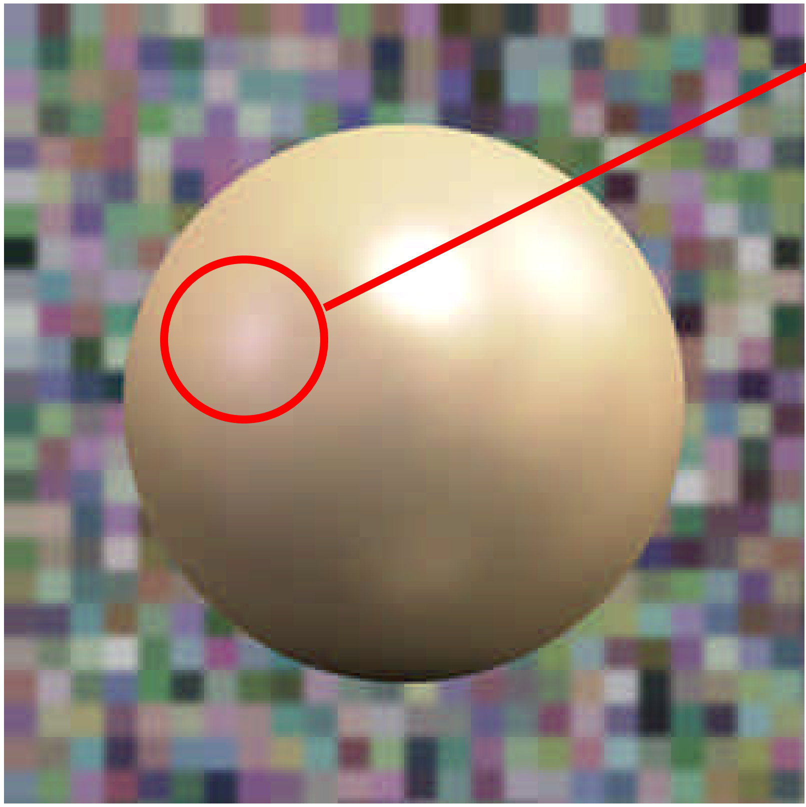
Confounding Effects of Illumination

- Identical materials can lead to very different images
- Different materials can lead to very similar images

Our Hypothesis

Humans exploit *statistical regularities of real-world illumination* in order to eliminate unlikely image interpretations

Eliminating unlikely interpretations



Blurry feature

2 interpretations:

- Sharp reflection, blurry world
- Blurry reflection, sharp world

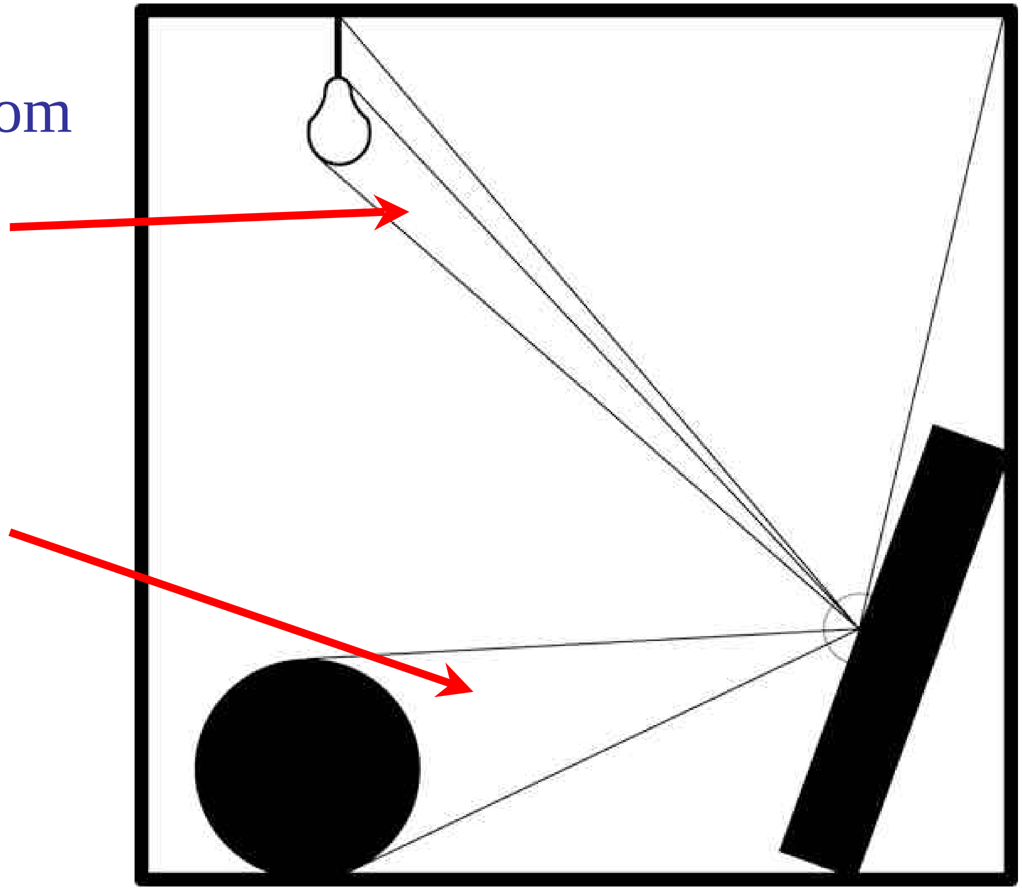
But the world *usually* isn't blurry!

Therefore it is probably a blurry *reflection*

Real-world Illumination

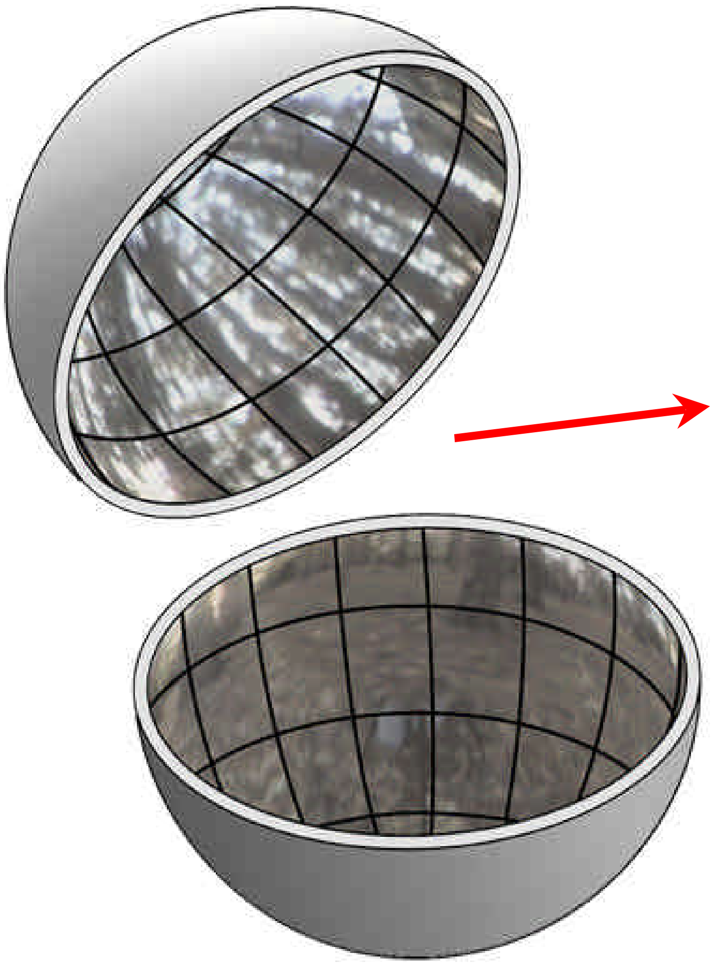
Directly from luminous sources

Indirectly, reflected from other surfaces



Illumination (at a point in space) = spherical image that would be acquired by a camera that looks in every direction from that point

Photographically captured illumination maps (Debevec *et al*., 2000)



Panoramic projection of illumination map

Illuminations from the real world have characteristic statistics

Some statistics that are well-conserved

- Properties based on raw luminance values
  - High dynamic range
  - Pixel histogram heavily skewed towards low intensities
- Quasi-local and Non-local properties
  - Nearby pixels are correlated in intensity (roughly 1/f amplitude spectrum)
  - Distributions of wavelet coefficients are highly kurtotic (i.e. significant wavelet coefficients are sparse)
  - Approximate scale invariance (i.e. distributions of wavelet coefficients are similar at different scales)
- Global and Non-stationary properties
  - Dominant direction of illumination
  - Presence of recognizable objects such objects and trees
  - Cardinal axes (due to ground plane and perpendicular structures erected thereupon).

Observations

- Subjects should be able to estimate surface reflectance reliably across real-world illuminations
- Subjects should be poor at estimating surface reflectance properties when their assumptions about the statistics of the illumination are infringed, *i.e.* under illuminations with atypical statistics, surface reflectance estimation should be poor.

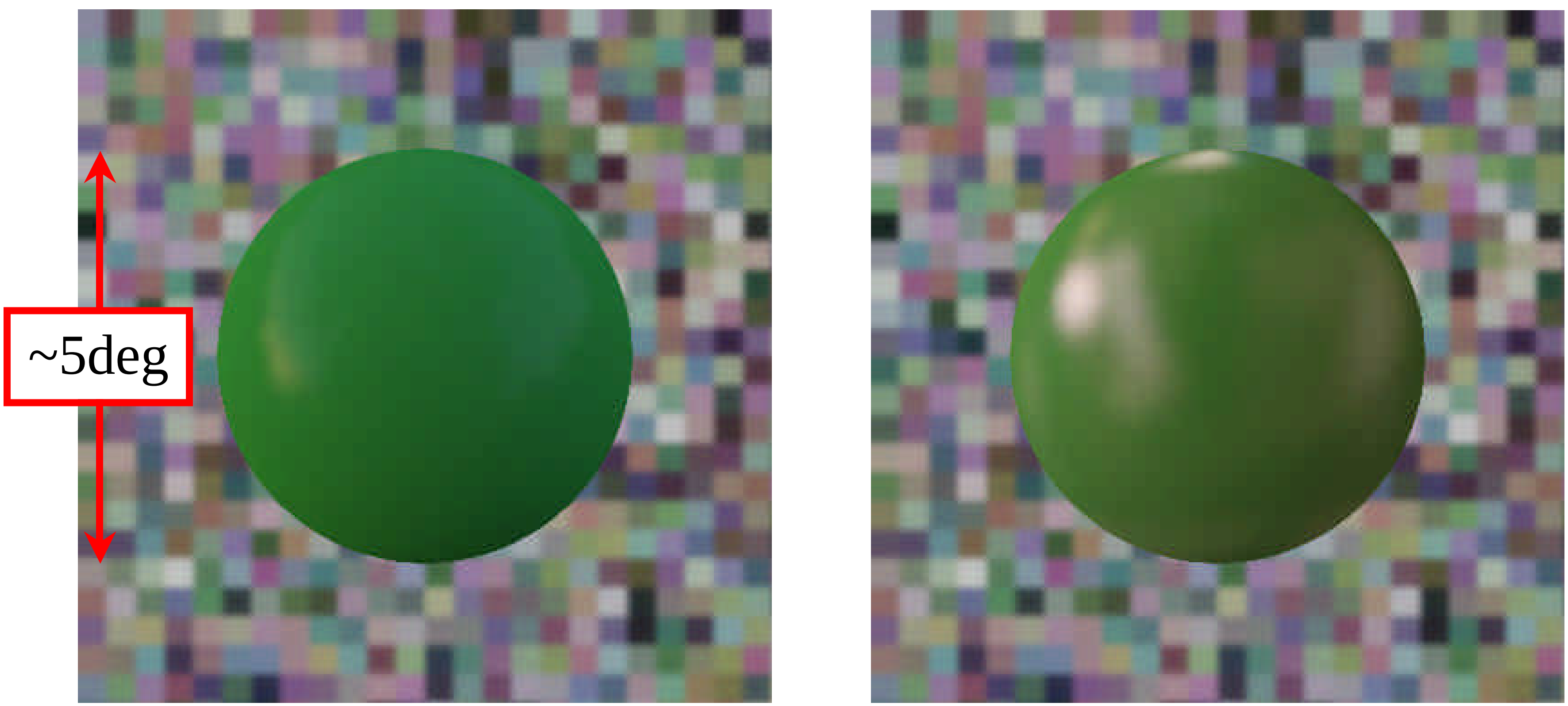
Observations

- Context has little effect on surface reflectance estimation

METHOD

Surface Reflectance Matching

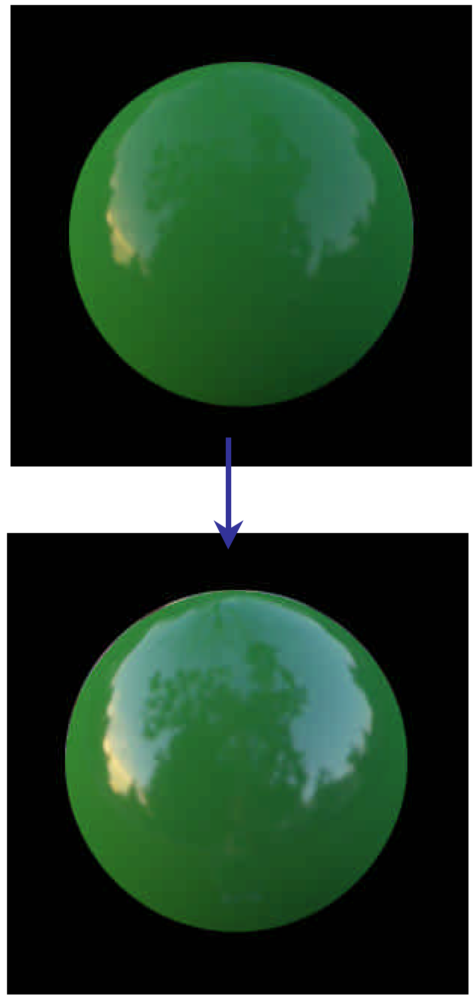
Test **Match**



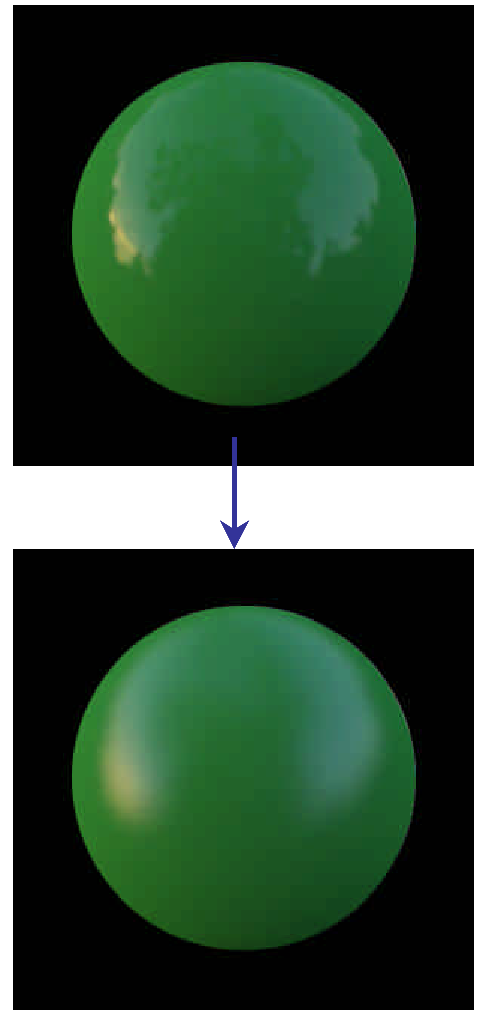
The Phong/Ward Reflectance Model

Diffuse reflectance

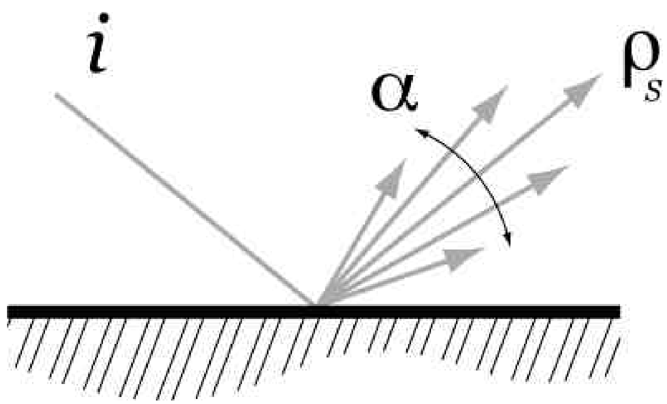
Specular reflectance

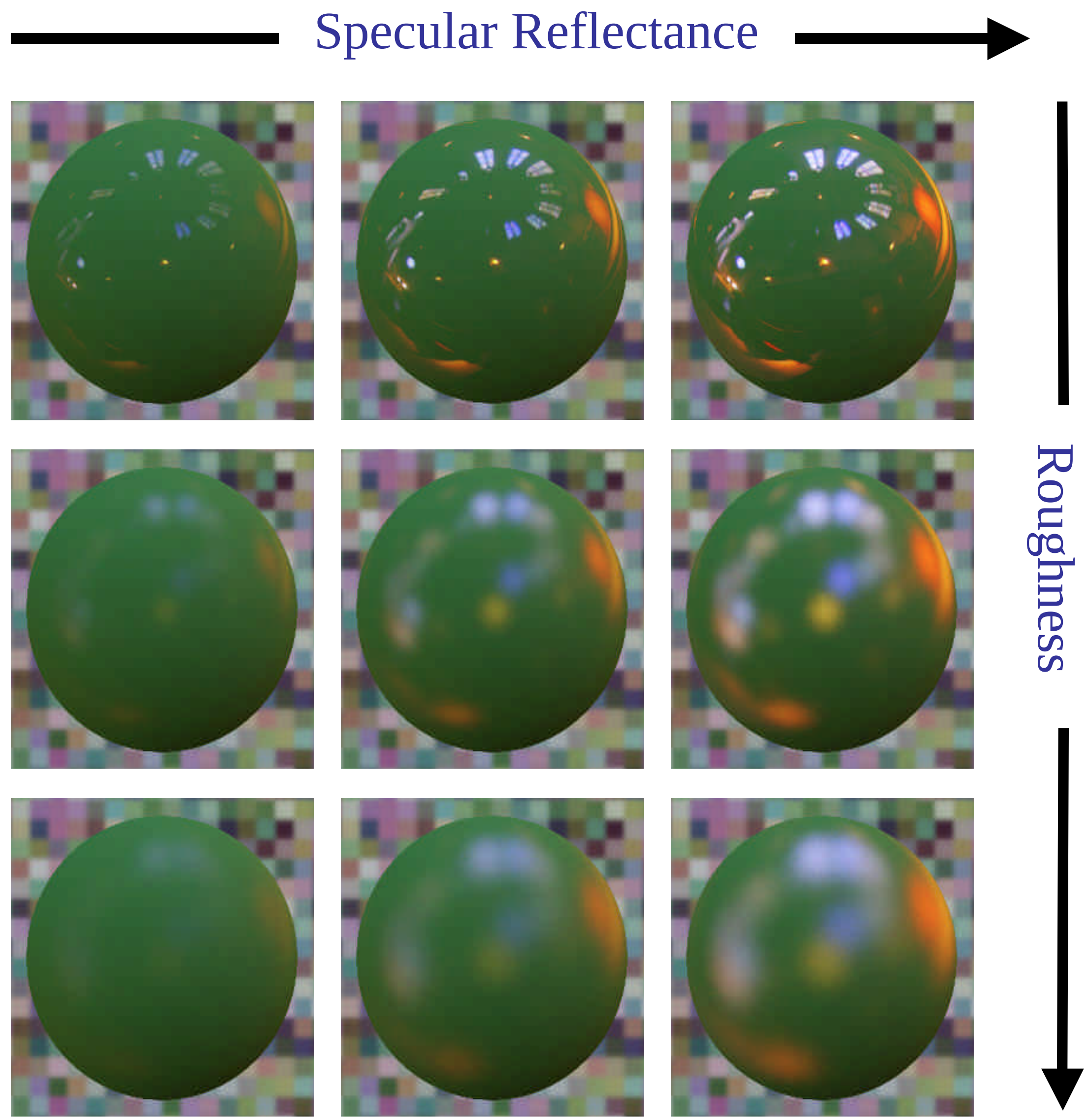


Roughness



Parameters of Specular Reflection



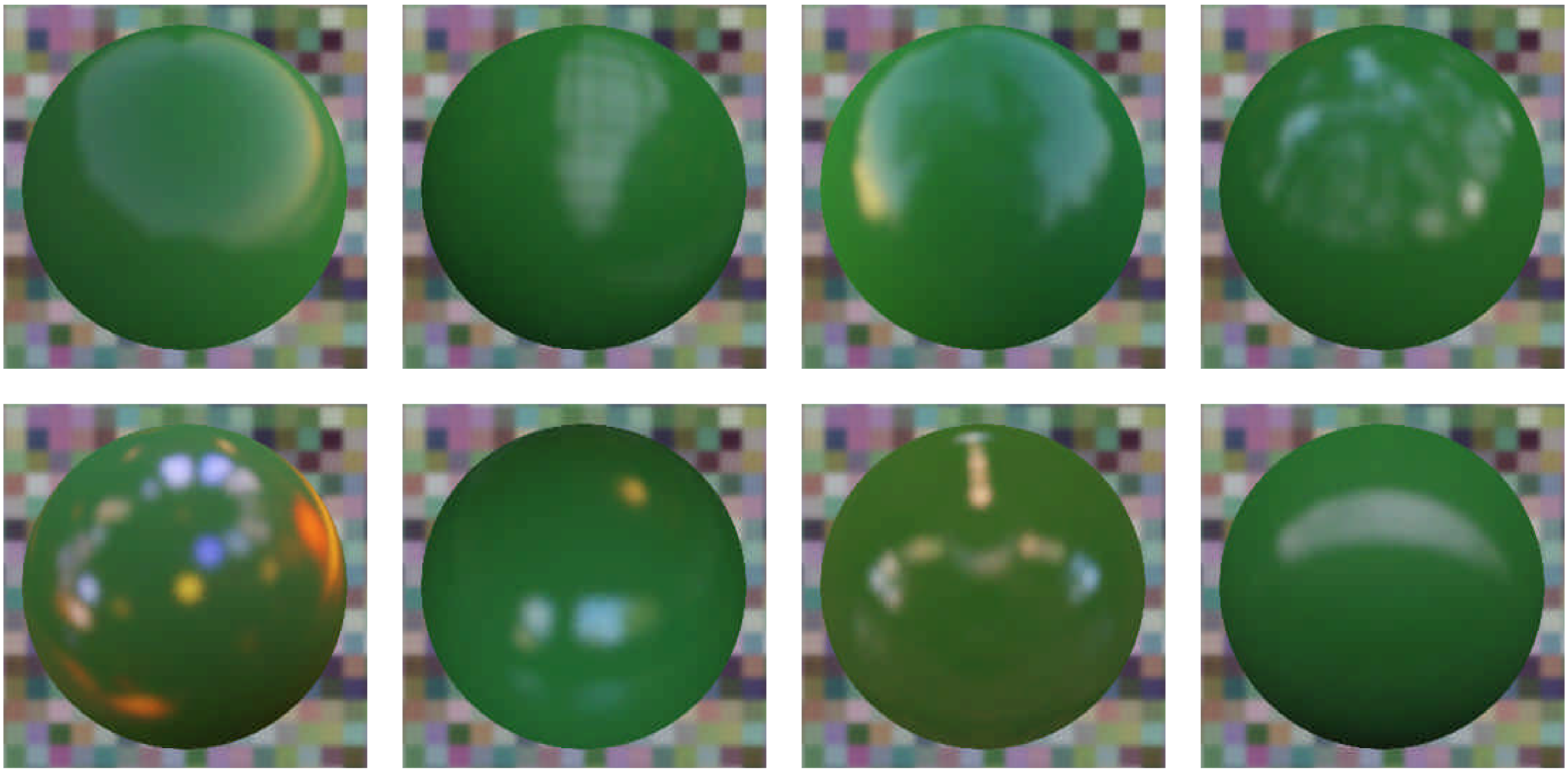


- Specular Reflectance
  - *matte to glossy*
- Roughness
  - *crisp to blurred*
- Axes rescaled to form a psychophysically uniform space
  - (Pellacini *et al*. 2000)

Real-world Illuminations

Illuminations downloaded from: http//graphics3.isi.edu/~debevec/Probes

Beach Building Campus Eucalyptus

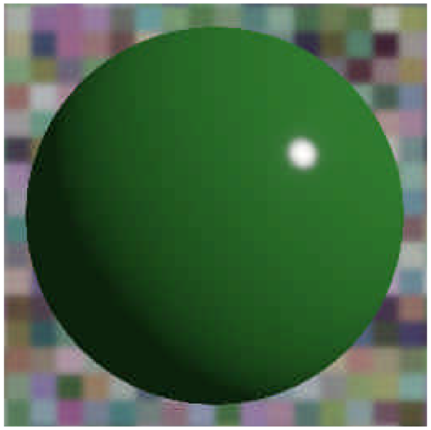


Grace Kitchen St. Peter’s Uffizi

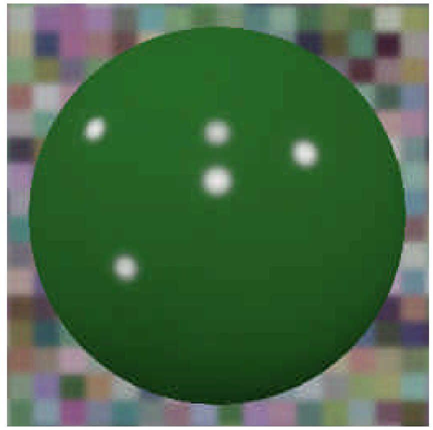
Match Illumination

Galileo

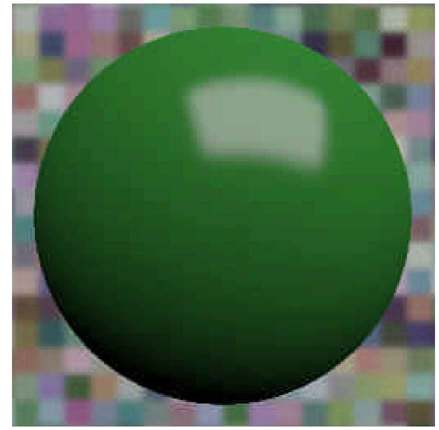
Artificial Illuminations



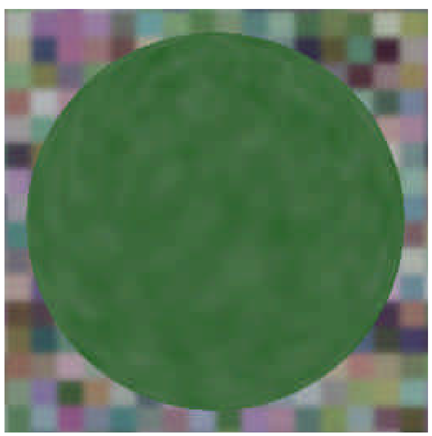
Single point source



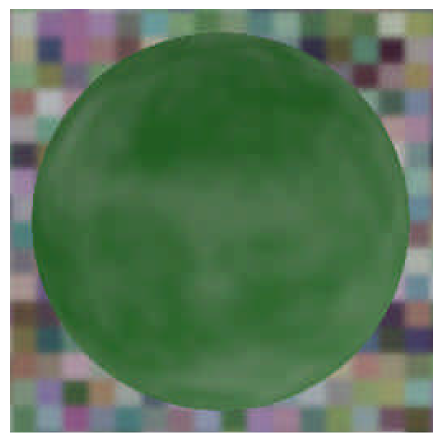
Multiple point sources



Extended source



Gaussian White Noise

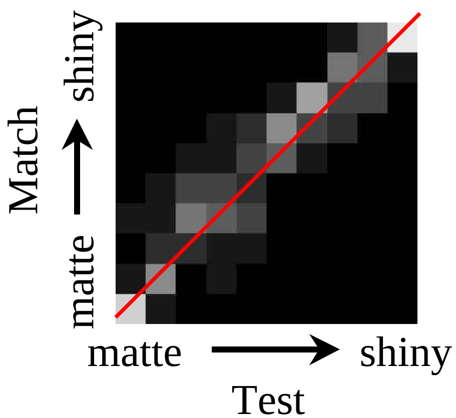


Gaussian Pink Noise

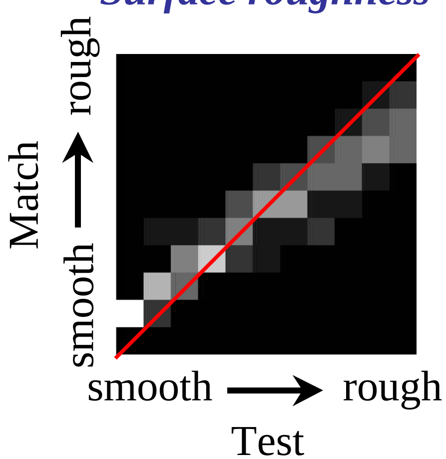
Subjects can match surface reflectance

Subject: **RF.** *(110 observations)*
Illumination: **“St. Peter’s”.**

Specular reflectance

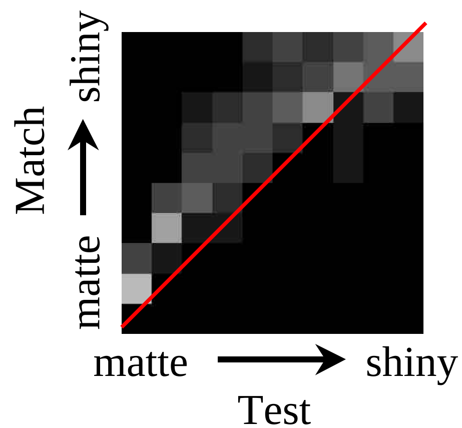


Surface roughness

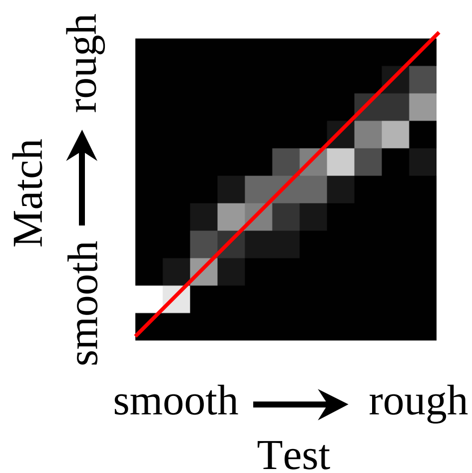


Subject: **MS.** *(110 observations)*
Illumination: **“Grace”.**

Specular reflectance

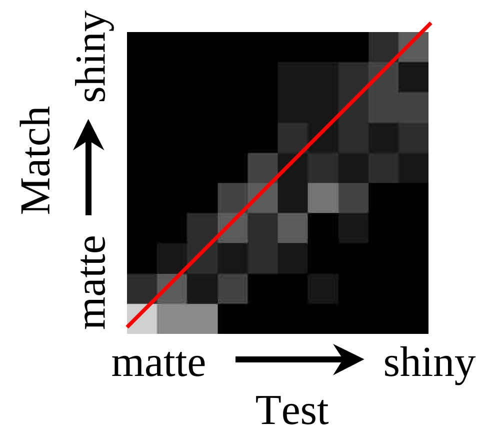


Surface roughness

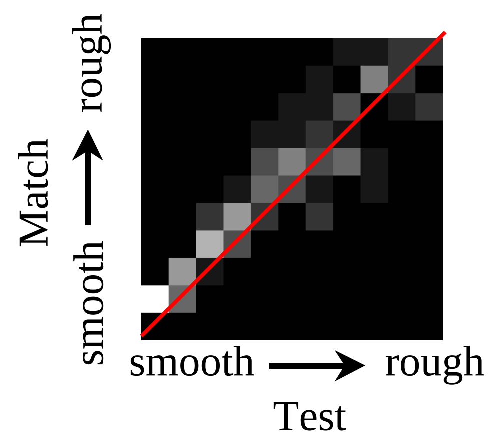


Subject: **RA.** *(110 observations)*
Illumination: **“Eucalyptus”.**

Specular reflectance

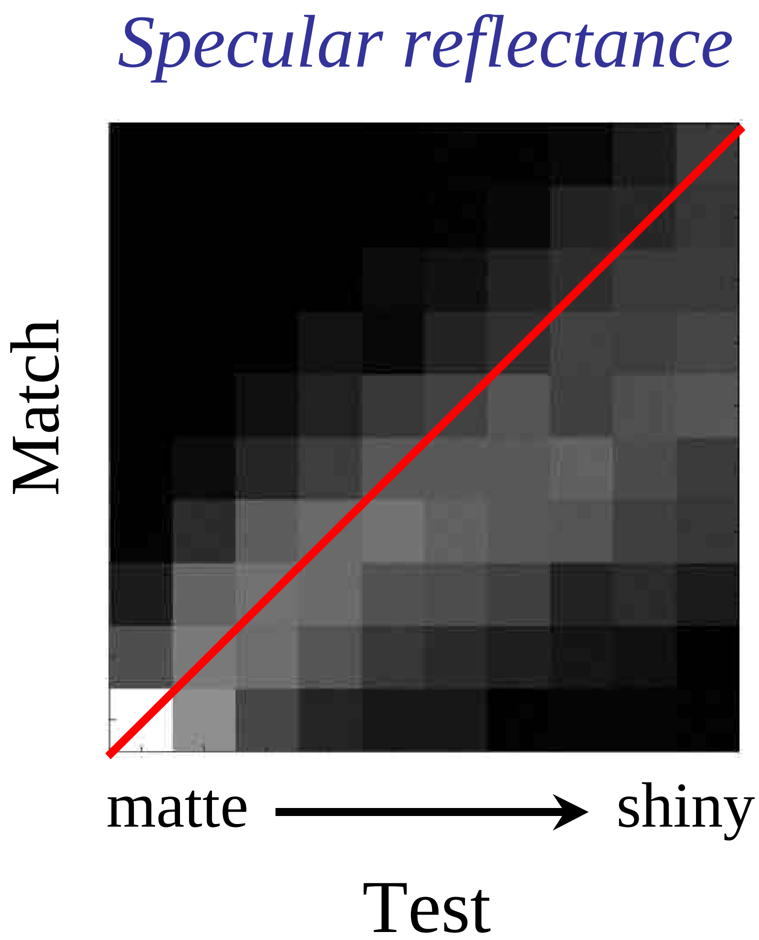


Surface roughness

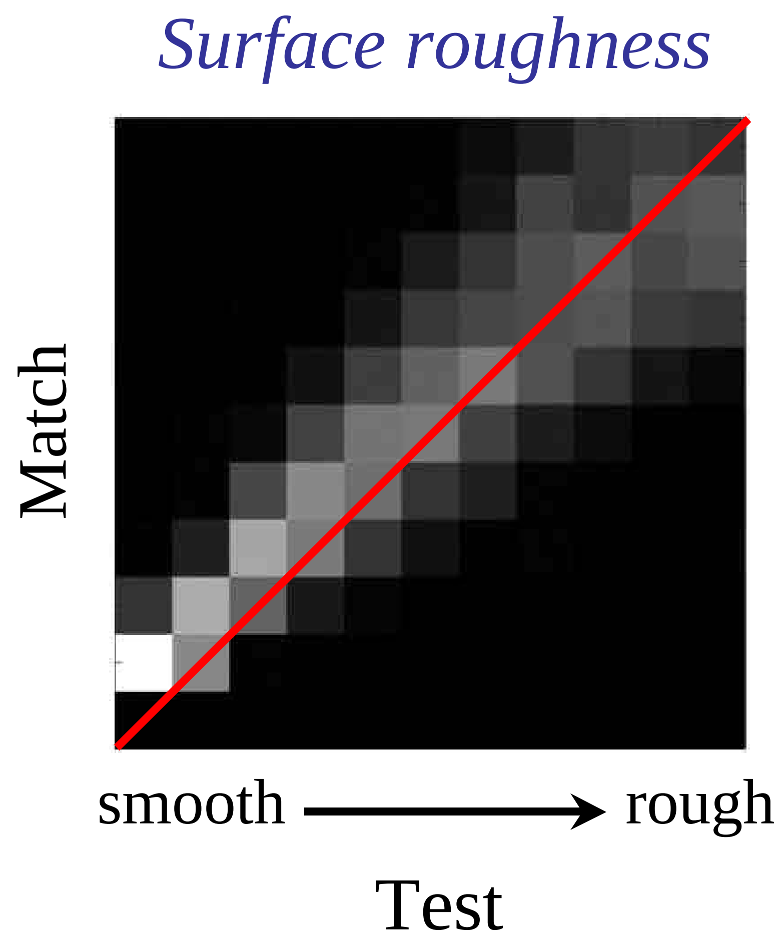


Subjects can match surface reflectance

Data pooled across all subjects and all real-world illuminations

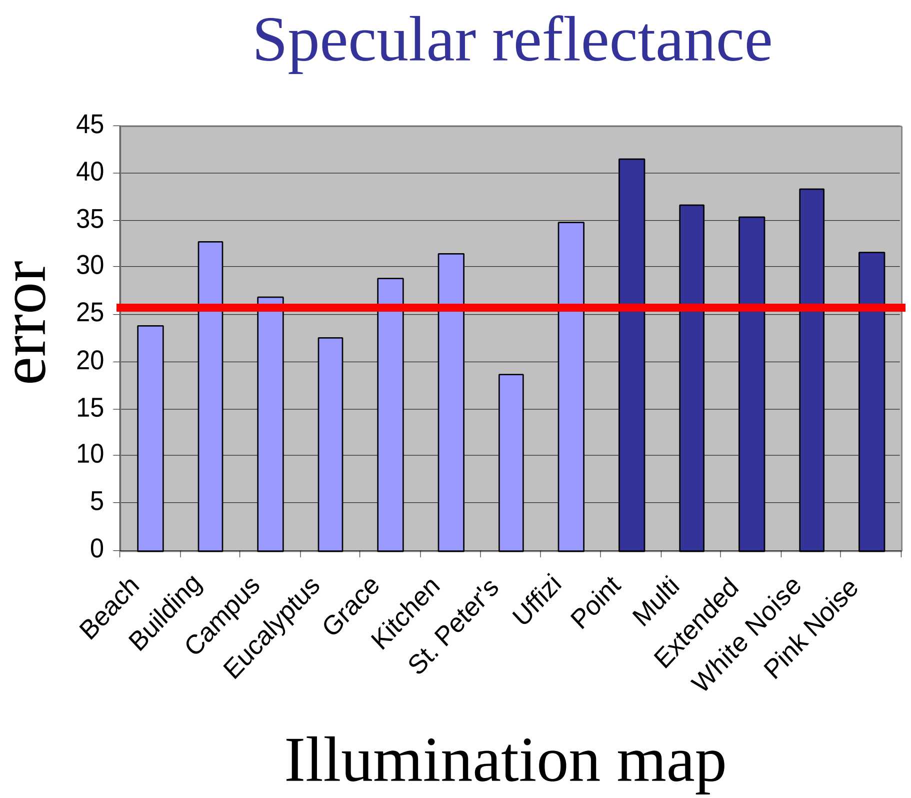


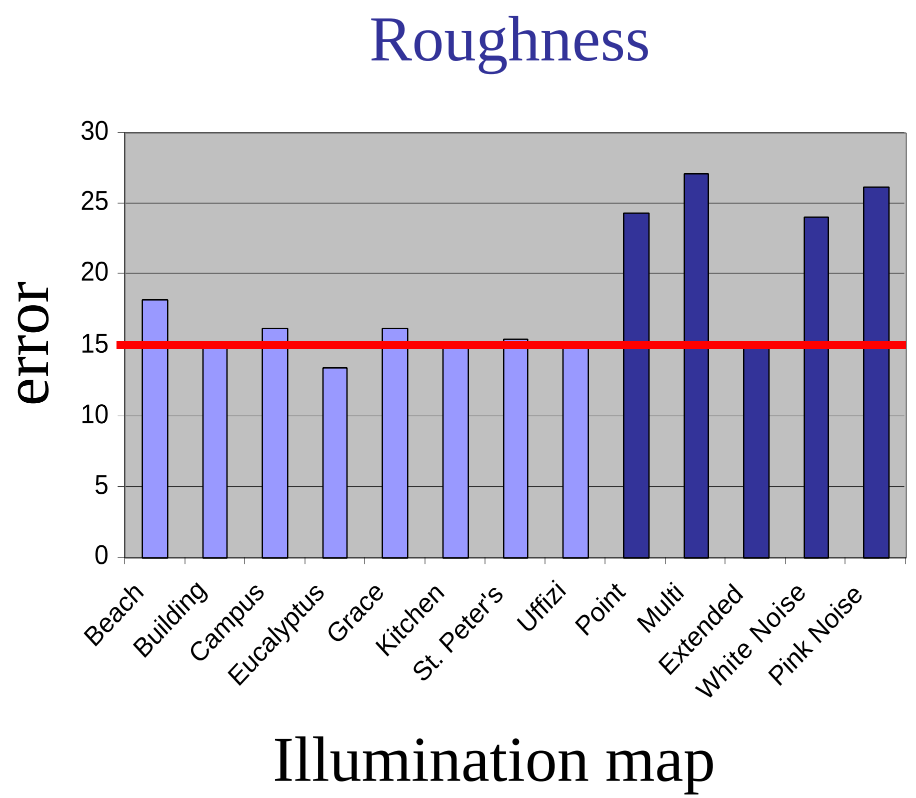
r.m.s. error = 28% of range



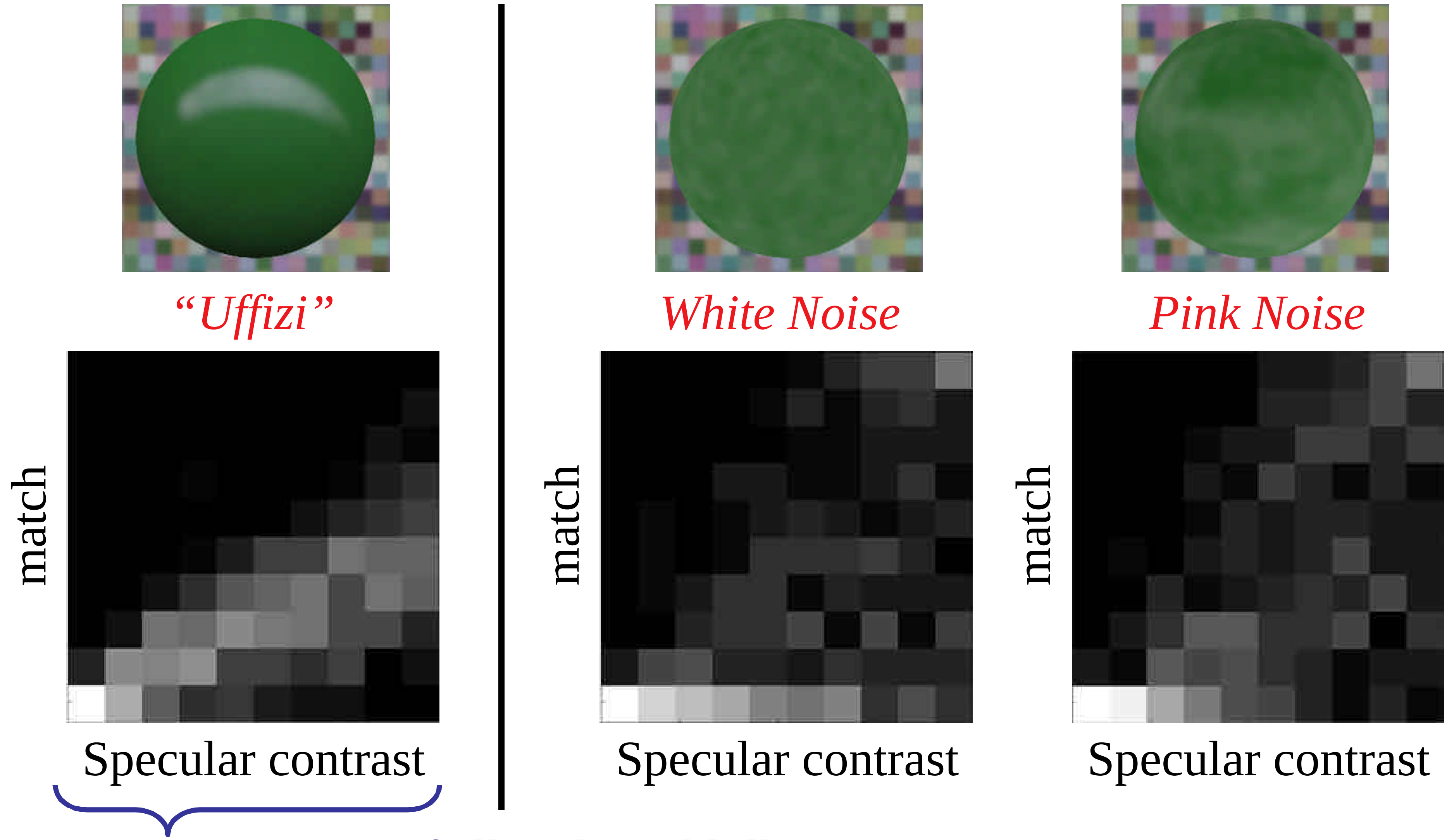
r.m.s. error = 16% of range

Real-world *vs* Artificial Illumination





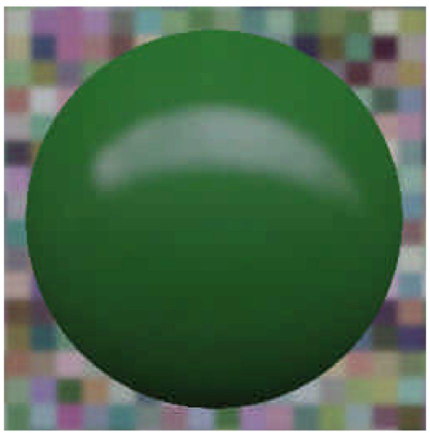
Noise is unlike real-world illumination



Least accurate of all real-world illuminations

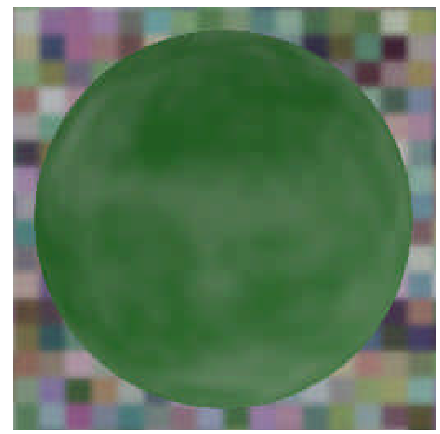
What are the relevant statistics?

Real

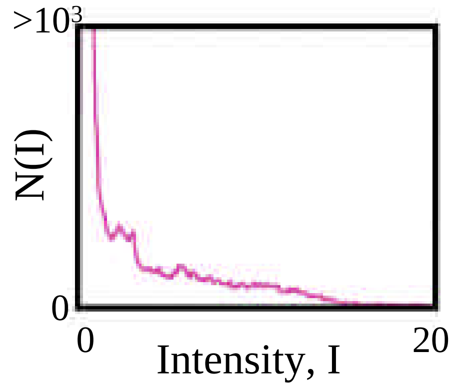


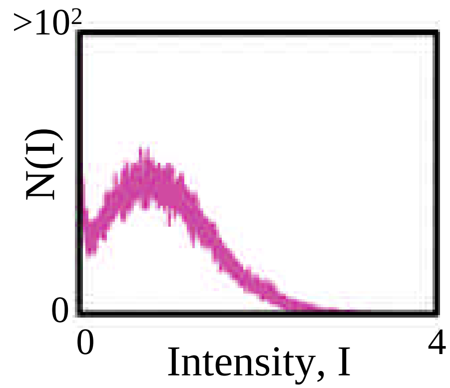
Extended

1/f Noise

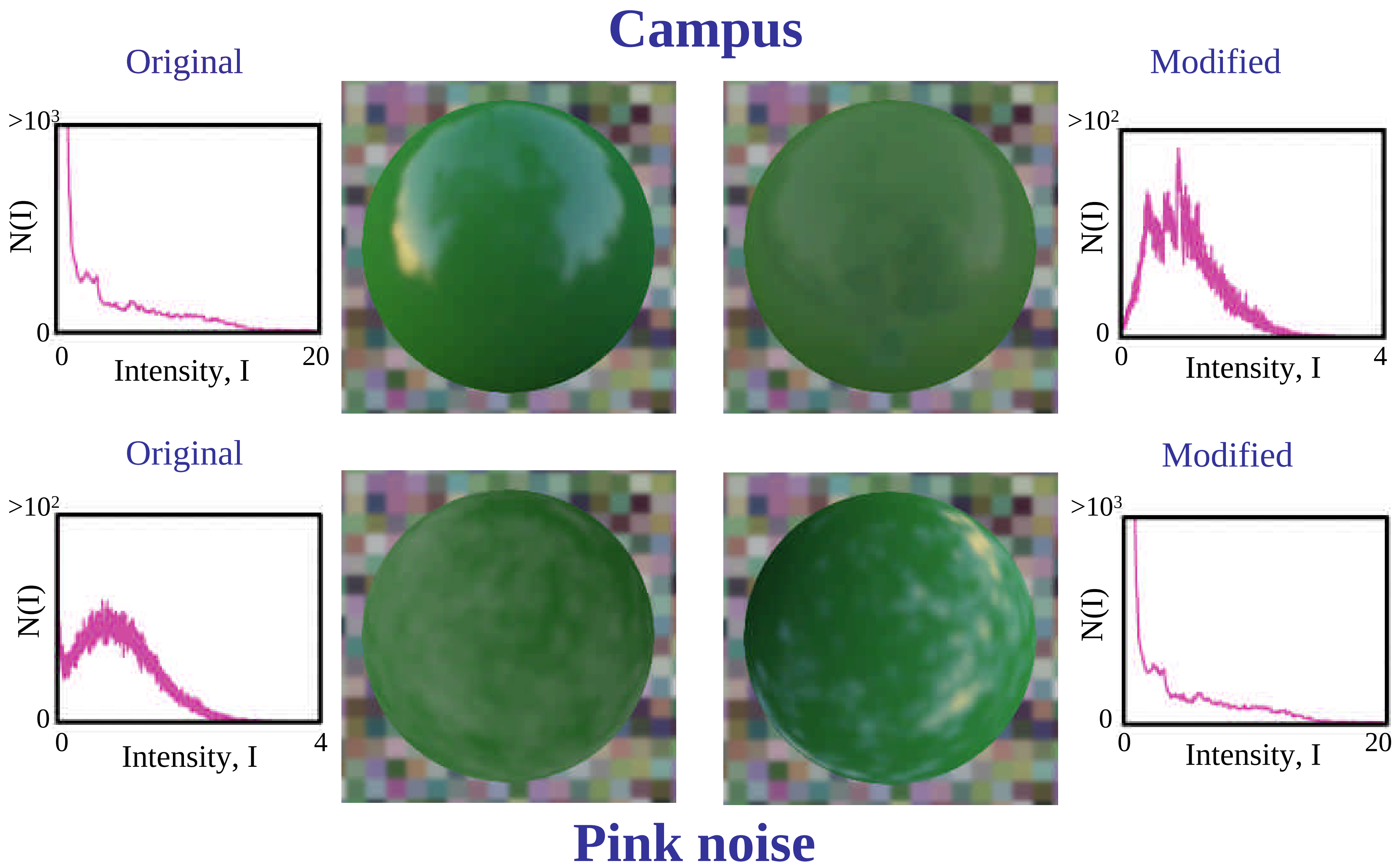


Illuminations have skewed pixel histograms



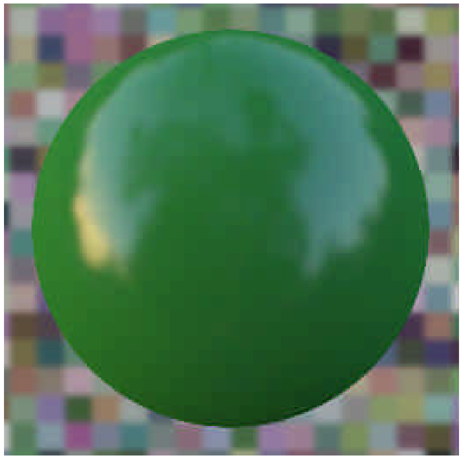


Illumination histograms are important

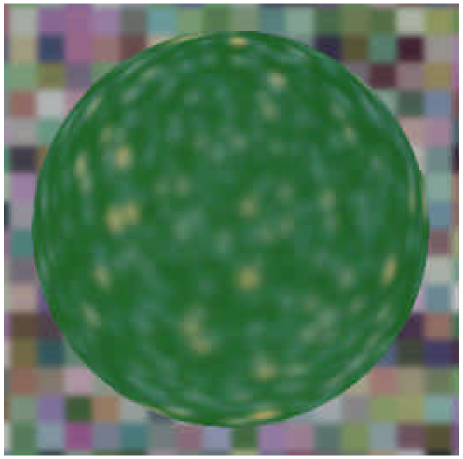


Histograms aren't everything

Campus original



White noise with histogram of campus



Heeger-Bergen texture synthesis

Input texture

Synthesized texture

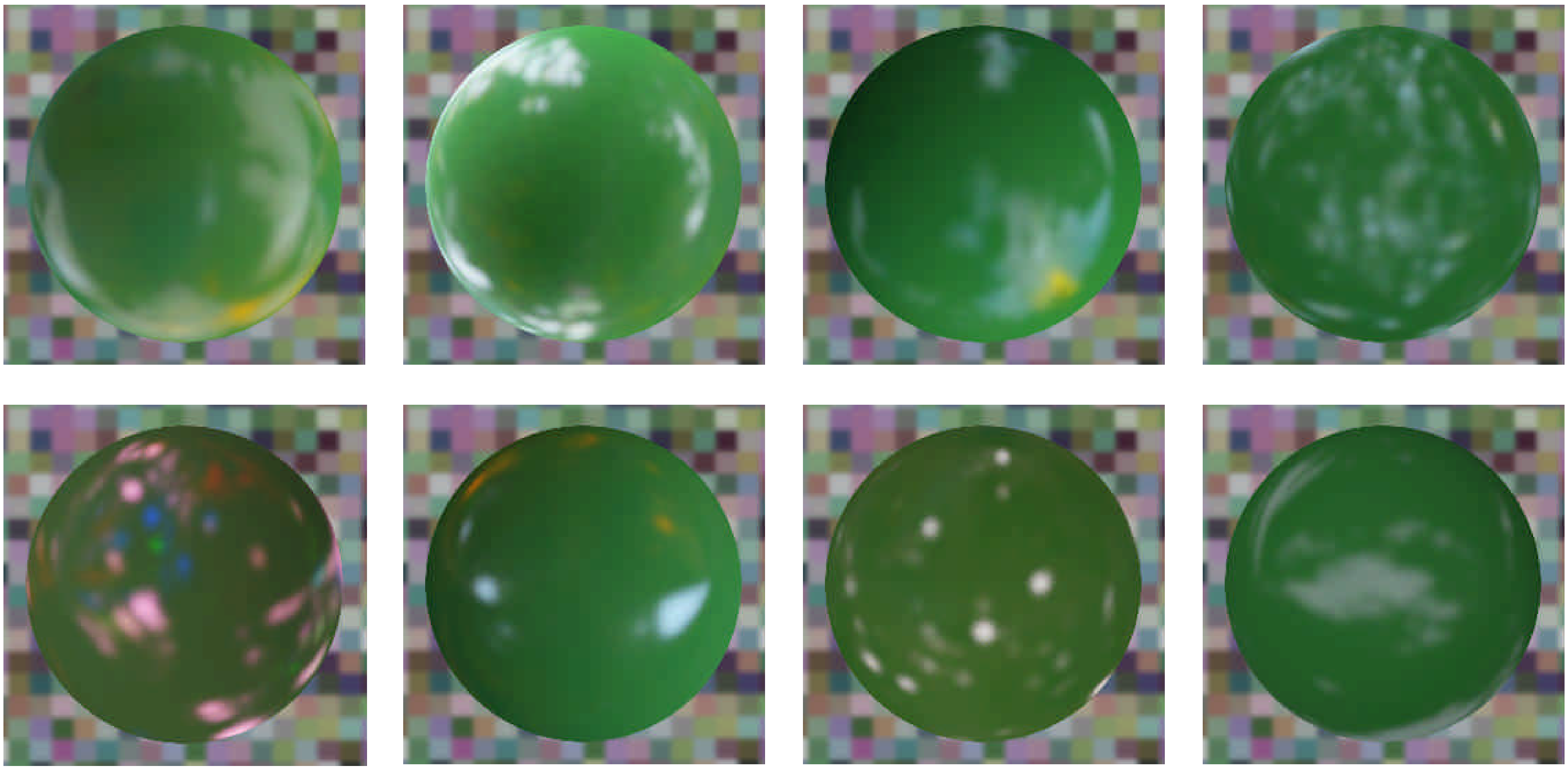
Taken from *Pyramid-Based Texture Analysis/Synthesis*

Treat illumination maps as if they are stochastic texture

Wavelet Statistics

Synthetic illuminations with same wavelet statistics as real-world illuminations

Beach Building Campus Eucalyptus



Grace Kitchen St. Peter’s Uffizi

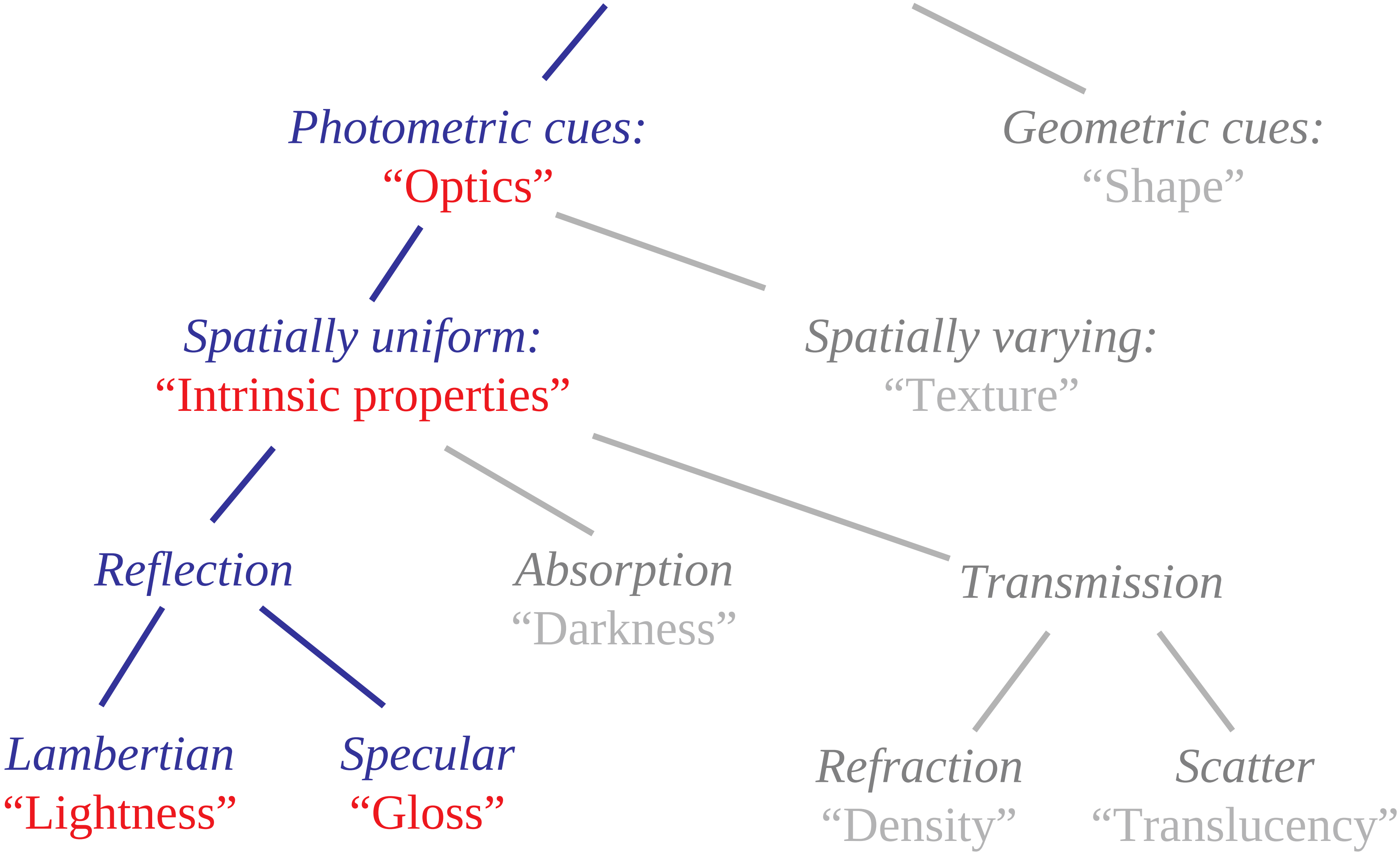
Summary and Conclusions

- Reflectance estimation under unknown illumination is hard because:
  - identical materials can lead to very different images and
  - different materials can lead to the identical images.
- Subjects can match reflectance properties reliably and accurately
  - across illuminations
  - in the absence of context
- Performance is better for real-world illuminations than for artificial illuminations with atypical statistics
- Subjects can exploit statistical regularities of real-world illumination to perform the task

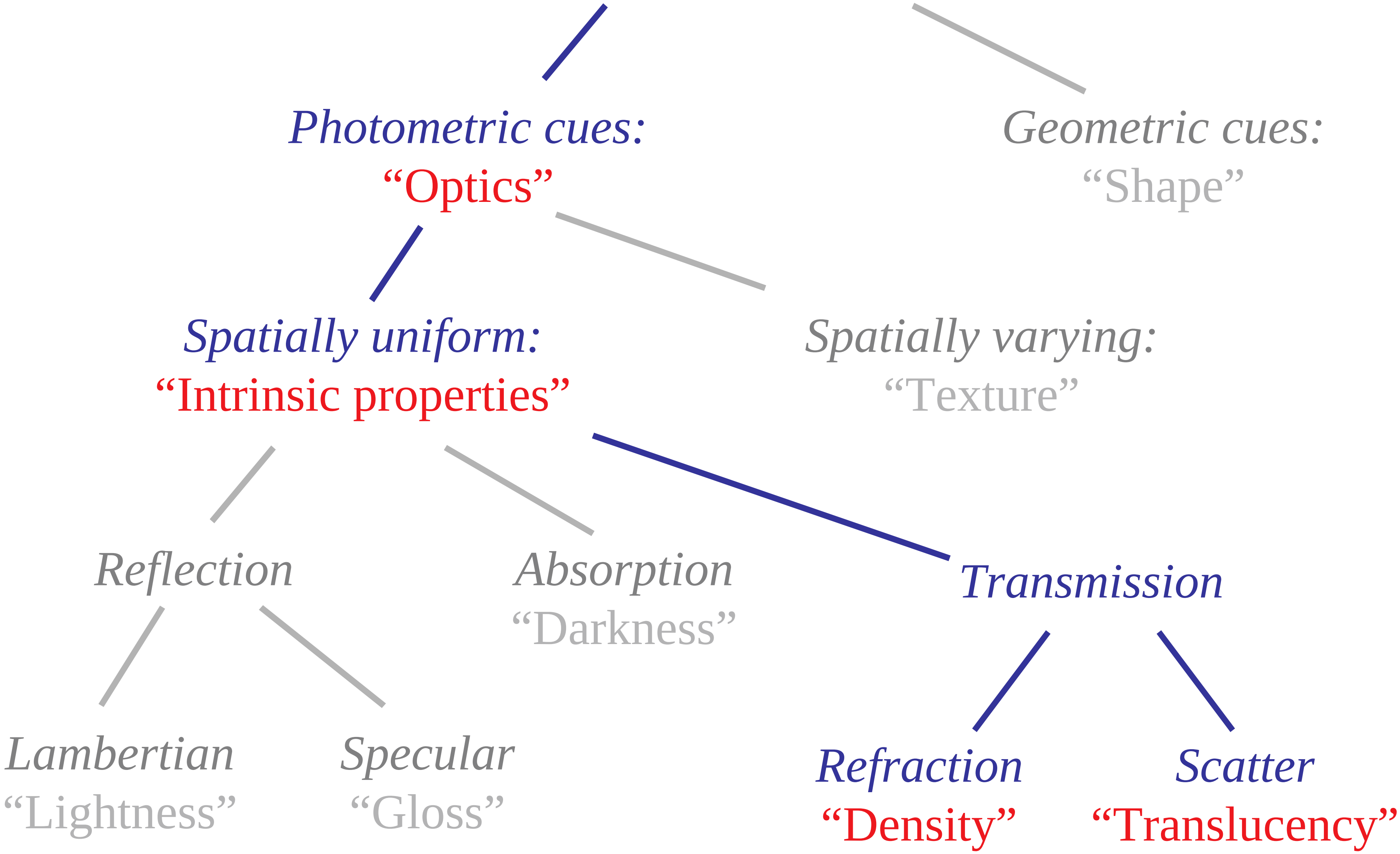
Summary and Conclusions

- We now have some ideas about important properties of illuminations
  - *Extended edges help*
  - *Dominant direction of illumination may be important*
  - *Power spectrum is insufficient alone*
  - *Heavily skewed pixel histogram*
  - *Wavelet statistics*

Perception of Material Properties



Perception of Material Properties

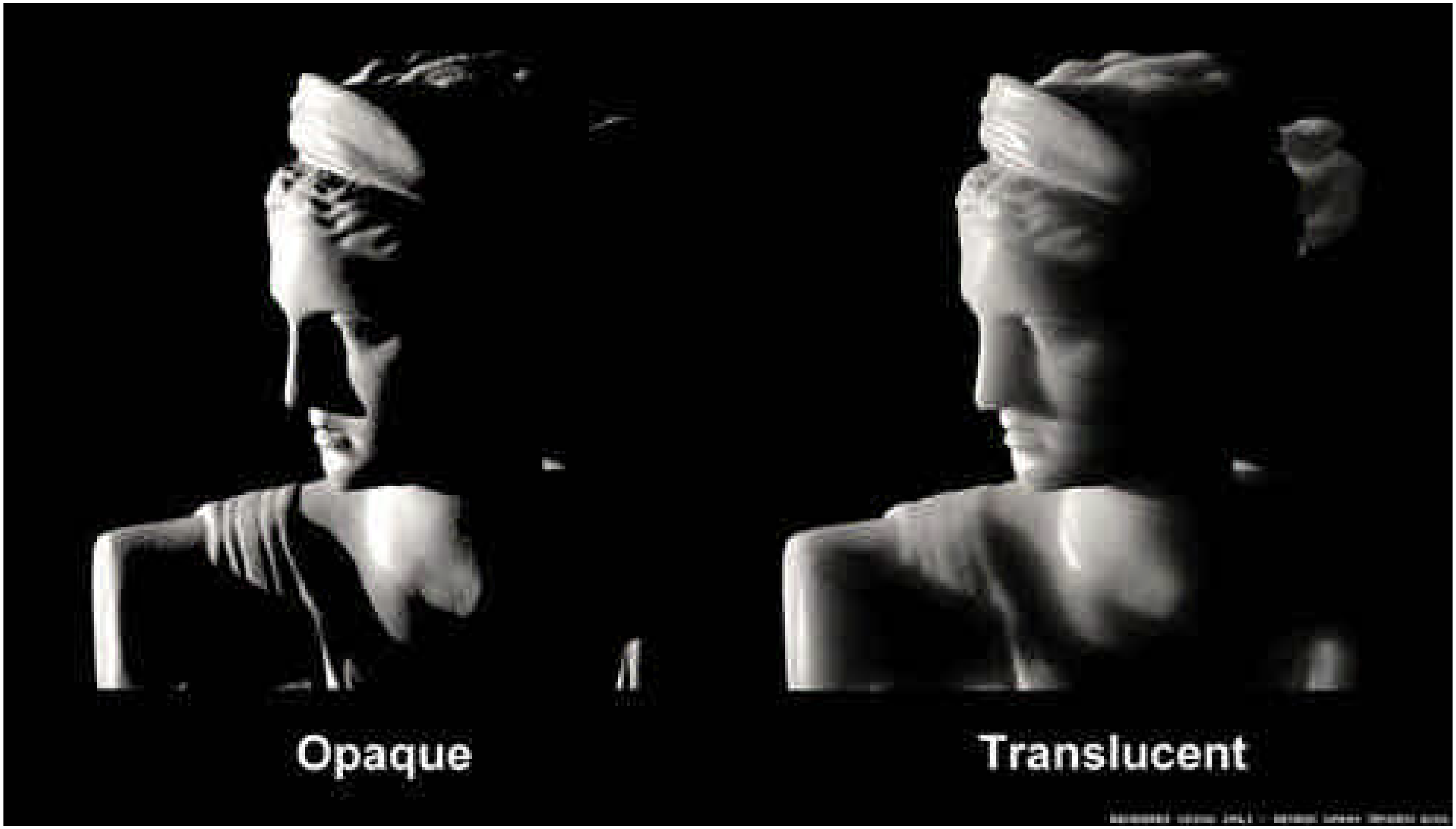


Refractive Index

R.I. = 1.2

R.I. = 1.8

Translucency



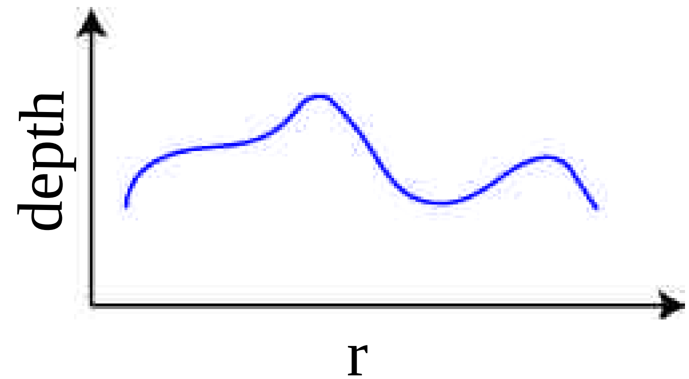
Rendered using photon mapping by Henrik Wann Jensen

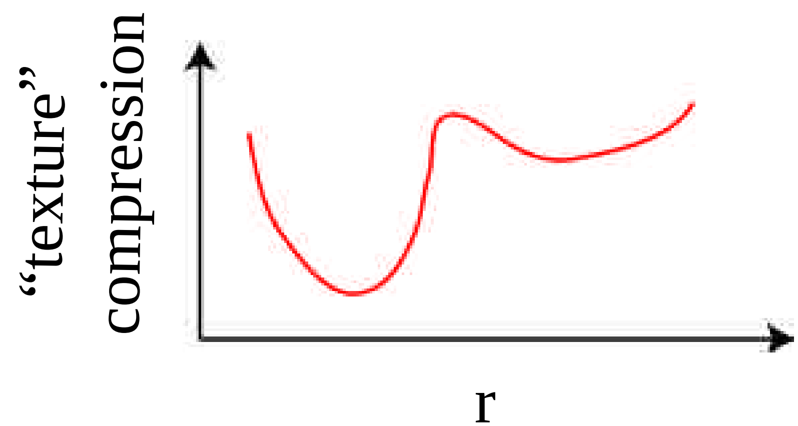
Role of illumination statistics in the perception of shape

Real-world illumination

Synthetic illumination

“Texture” Trajectories

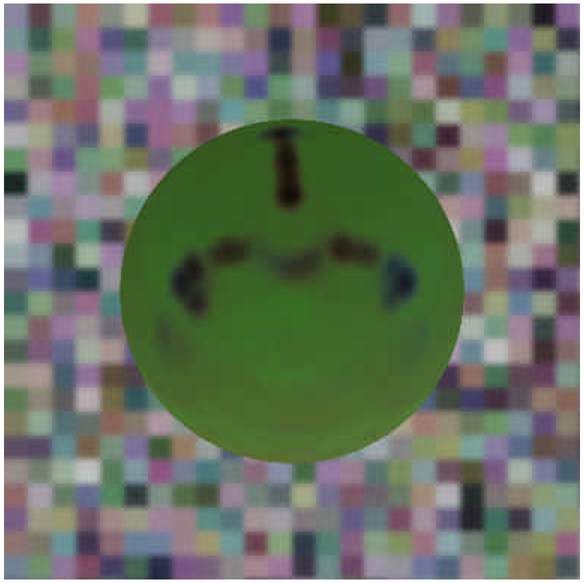


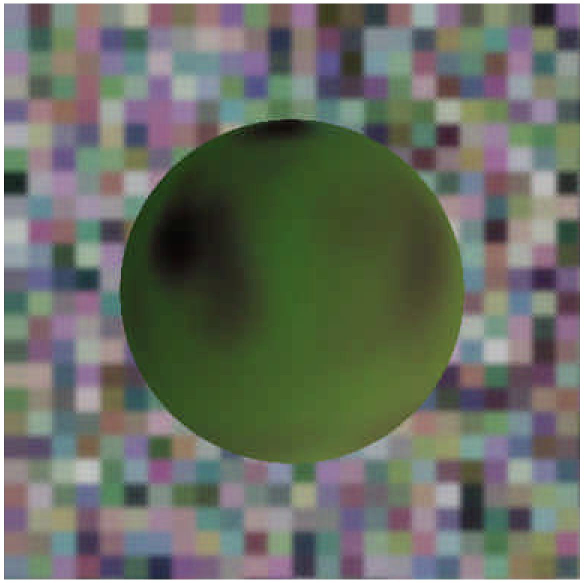


Thank you

What cues are subjects using?

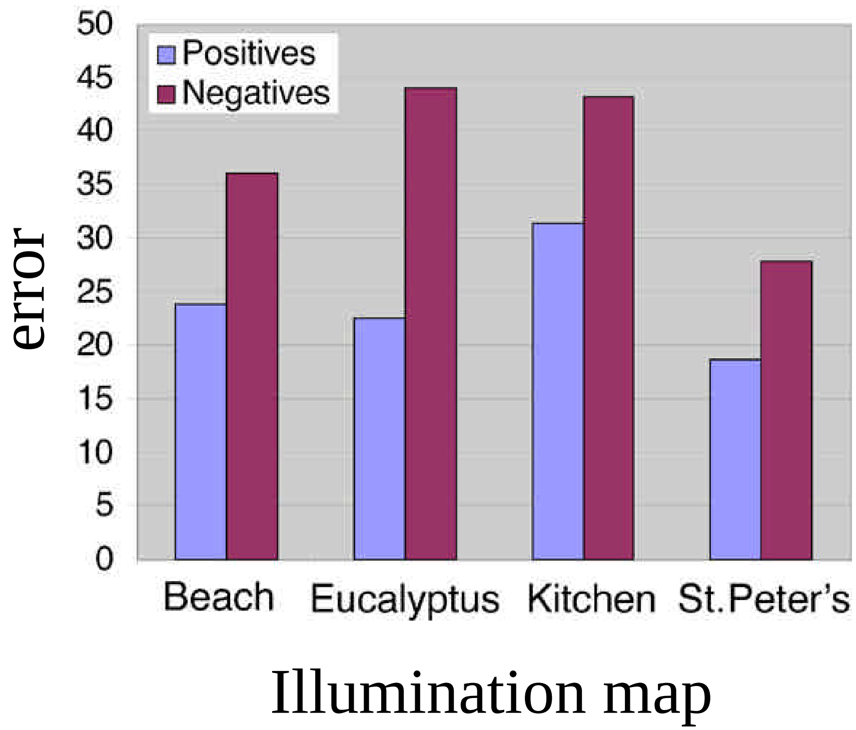
- Photographic Negatives of original real-world illuminations
  - Similar low-level image statistics to originals
  - Incoherent/non-uniform percept of surface reflectance qualities





What cues are subjects using?

Specular contrast



Surface roughness