Perceptually Based Rendering

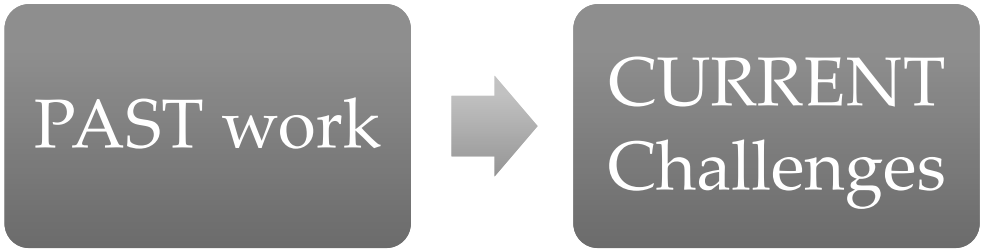
Holly Rushmeier
Department of Computer Science
Yale University

Perceptually Based Rendering

- What is perceptually-based rendering?
- History: Perception and Rendering
- Models: Transport and Input
- Hardware: 2D and 3D
- Experiments: Labs and Crowds

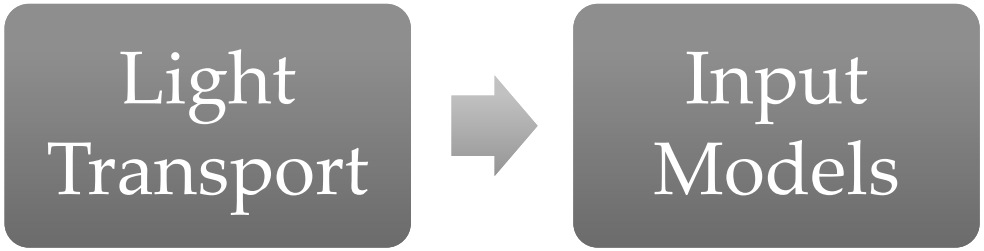
Perceptually Based Rendering

- What is perceptually-based rendering?
- History: Perception and Rendering
- Models: Transport and Input
- Hardware: 2D and 3D
- Experiments: Labs and Crowds



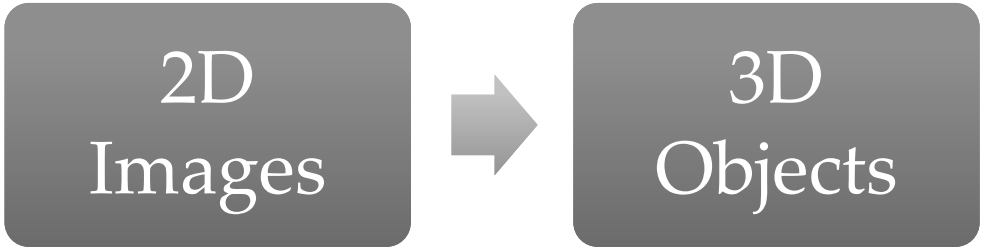
Perceptually Based Rendering

- What is perceptually-based rendering?
- History: Perception and Rendering
- Models: Transport and Input
- Hardware: 2D and 3D
- Experiments: Labs and CrowdS



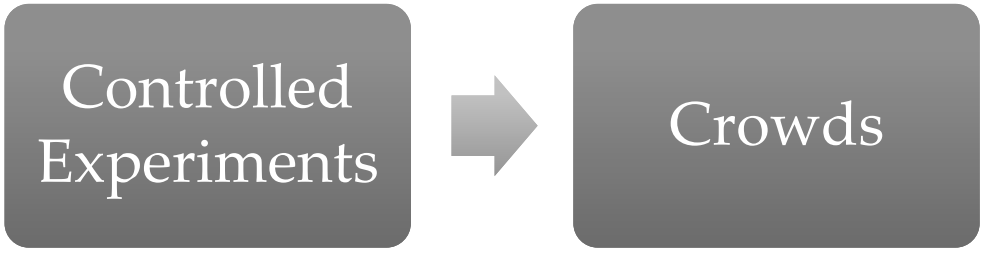
Perceptually Based Rendering

- What is perceptually-based rendering?
- History: Perception and Rendering
- Models: Transport and Input
- Hardware: 2D and 3D
- Experiments: Labs and Crowds



Perceptually Based Rendering

- What is perceptually-based rendering?
- History: Perception and Rendering
- Models: Transport and Input
- Hardware: 2D and 3D
- Experiments: Labs and Crowds

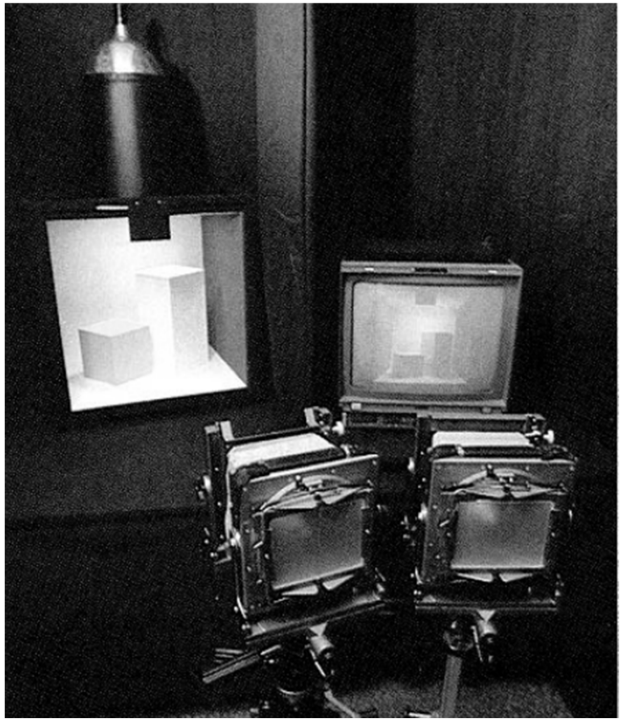


Perceptually Based Rendering

- What is perceptually-based rendering?
- History: Perception and Rendering
- Models: Transport and Input
- Hardware: 2D and 3D
- Experiments: Labs and Crowds

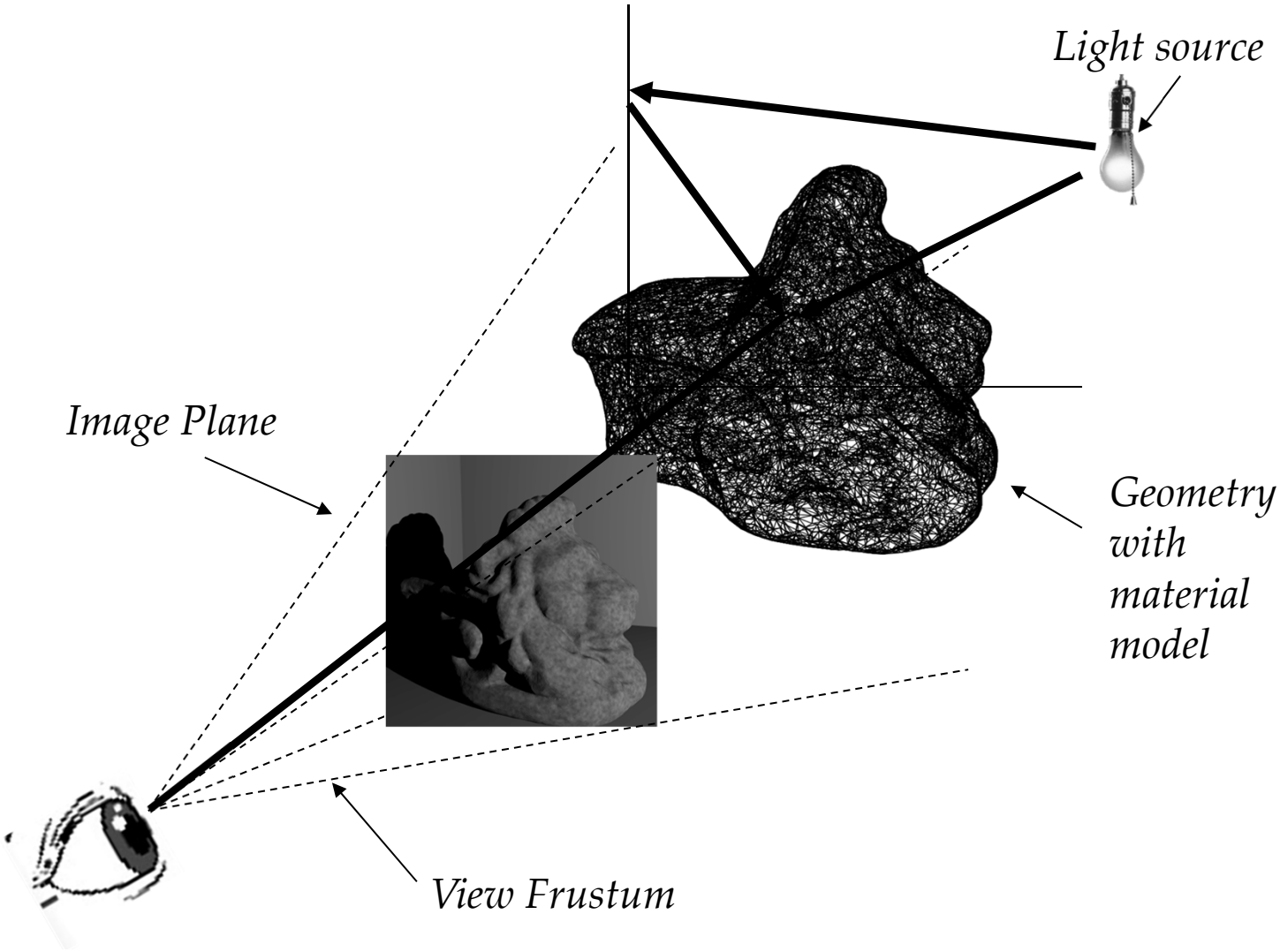
Perceptually Based Rendering

- Context: Realistic Rendering

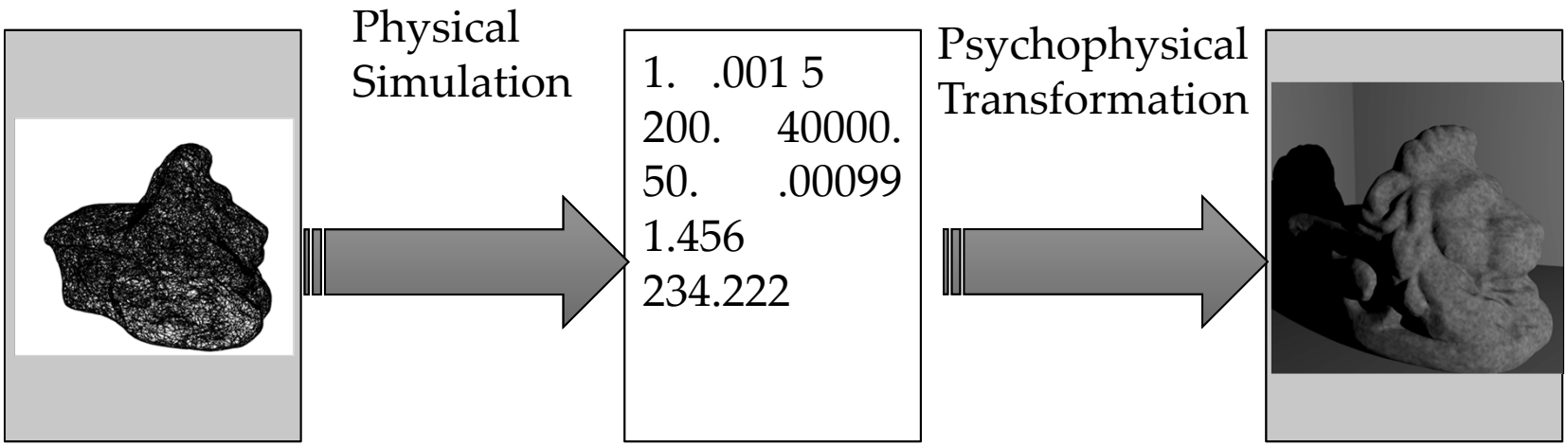


Meyer, Rushmeier, Cohen, Torrance and Greenberg, TOG 1986

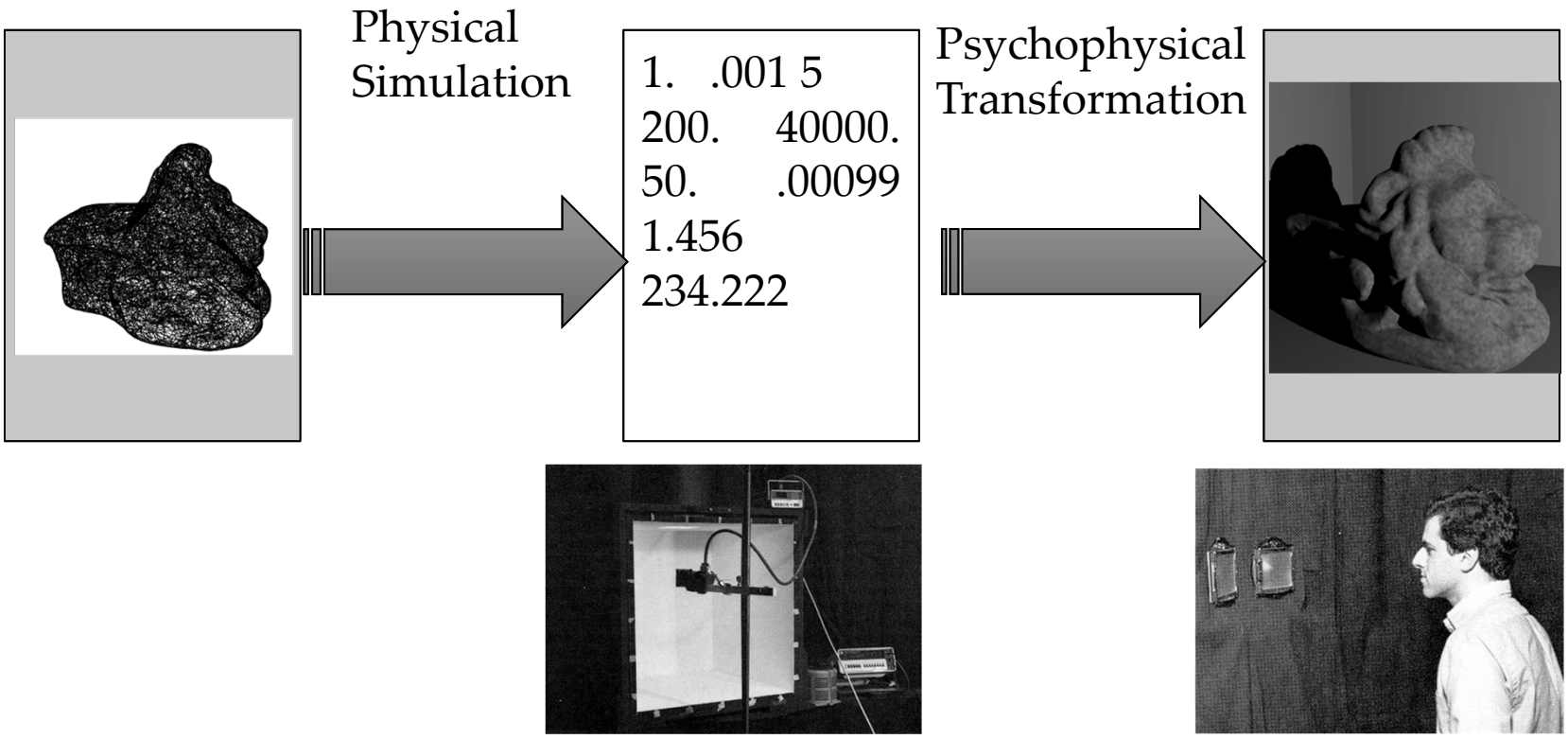
Perceptually Based Rendering



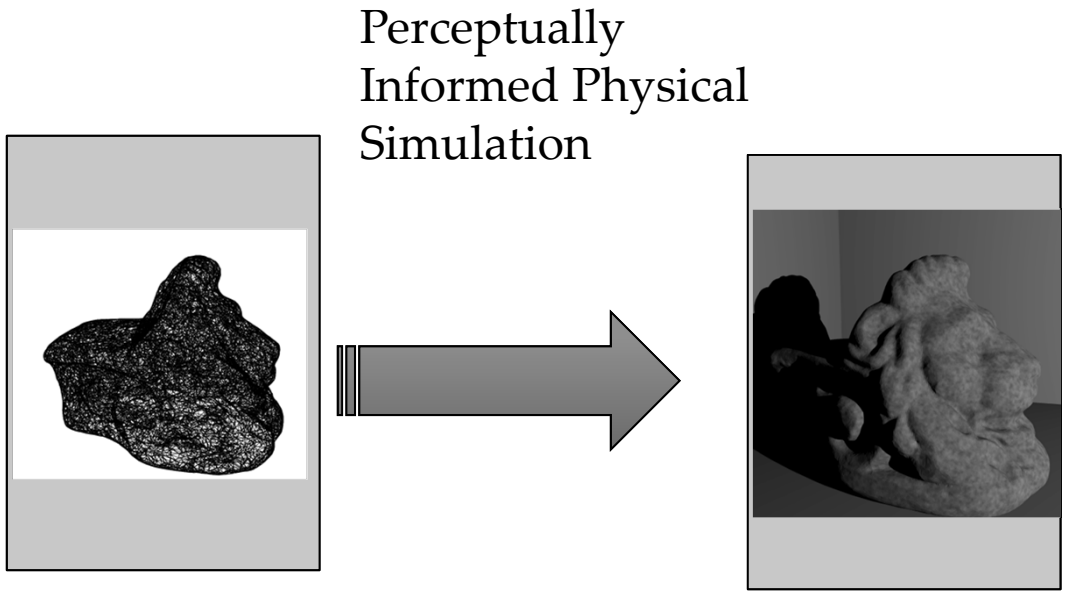
Perceptually Based Rendering



Perceptually Based Rendering



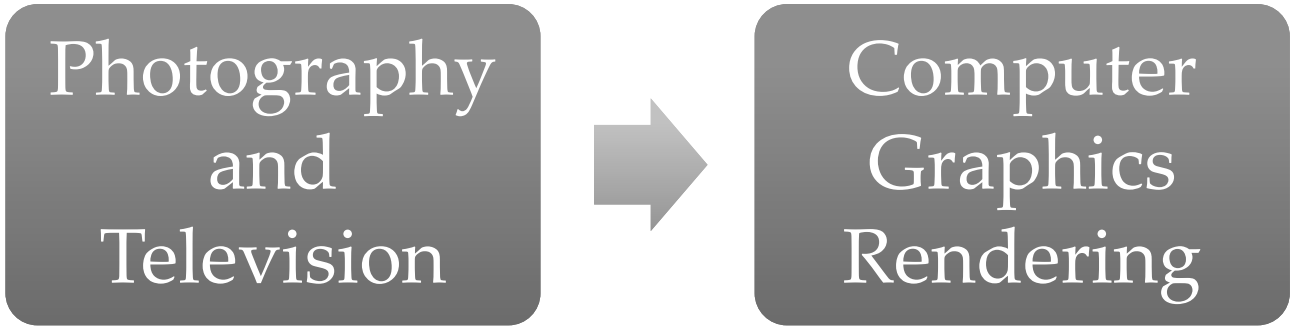
Perceptually Based Rendering



Perceptually Based Rendering

- What is perceptually-based rendering?
- History: Perception and Rendering
- Models: Transport and Input
- Hardware: 2D and 3D
- Experiments: Labs and Crowds

History



History: BCGR

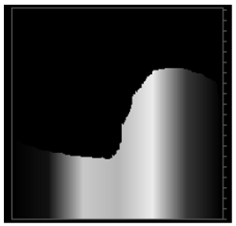
Before Computer Graphics Rendering

Sergei Mikhailovich Prokudin-Gorski
https://commons.wikimedia.org/wiki/File:Rzhev.jpg

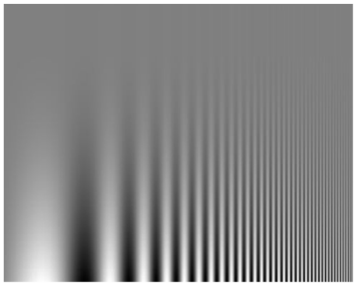
https://upload.wikimedia.org/wikipedia/commons/8/81/Tvwithantenna.jpg

Producing the same array of light isn't even possible

- Can't capture/display arbitrary spectra



- Can't produce a continuous image



Models of perception needed just to make photography and television even possible.

Perceptually Based Rendering

- What is perceptually-based rendering?
- History: Perception and Rendering
- Models: Transport and Input
- Hardware: 2D and 3D
- Experiments: Labs and Crowds

Light Transport

- Multiple reflections/interactions expensive to compute

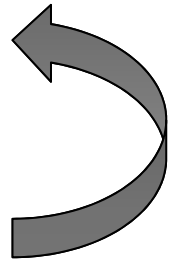
$$L_o(x,\omega_o) = L_e(x,\omega_o) + \int_\Omega f_r(x,\omega_i \rightarrow \omega_r) L_i(x,\omega_i) \cos\theta_i \, d\omega_i$$

Light Transport

- Multiple reflections/interactions expensive to compute

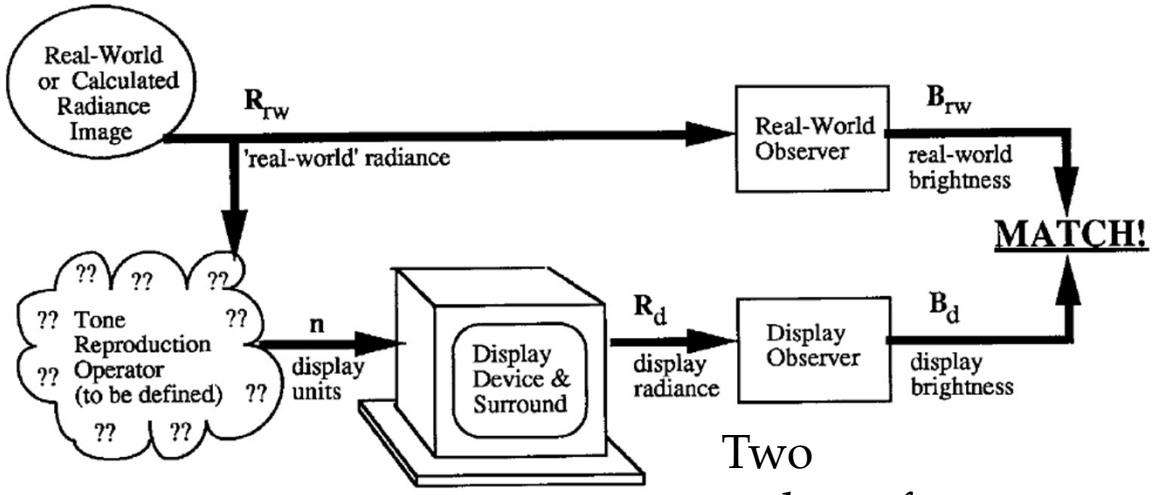
$$L_o(x,\omega_o) = L_e(x,\omega_o) + \int_\Omega f_r(x,\omega_i \rightarrow \omega_r) L_i(x,\omega_i) \cos\theta_i \, d\omega_i$$

- Formulate a solution technique with error bound (per pixel, per surface)
- Express error bound in terms of perceptual model



Tone Mapping

Many orders of magnitude



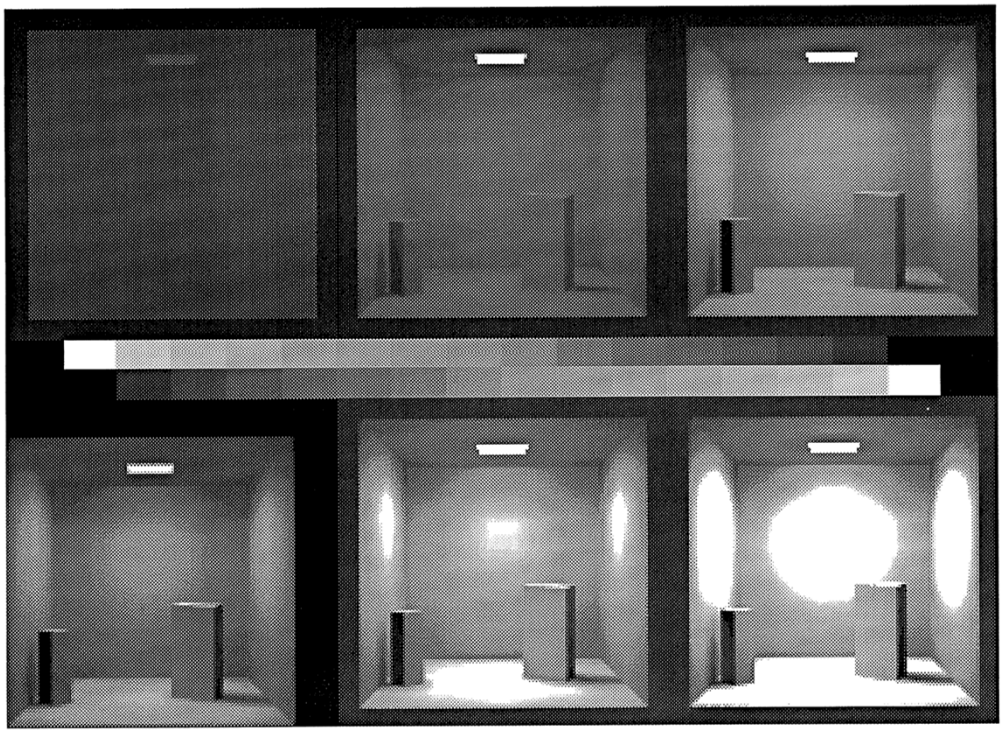
Two orders of magnitude

Tumblin and Rushmeier 1993
Larson(Ward), Rushmeier, and Piatko 1997

establishes ΔL_o

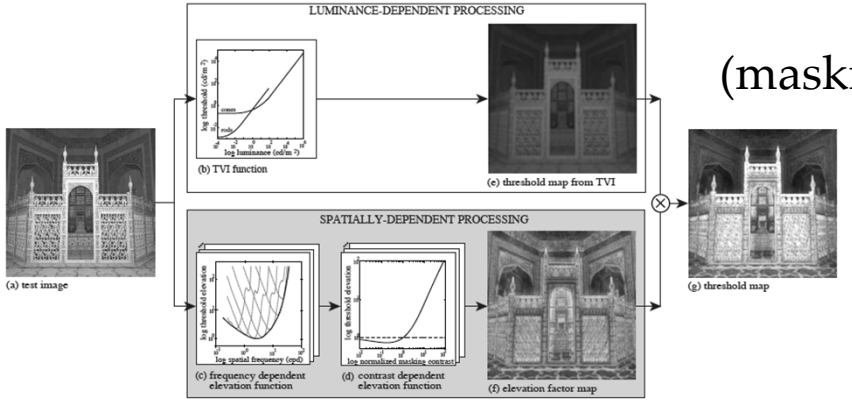
$$L_o(x,\omega_o) = L_e \int_{\Omega} f_r(x,\omega_i \rightarrow \omega_r) L_i(x,\omega_i) \cos\theta_i \, d\omega_i$$

$$n = \left[\left(\frac{L_{rw}^{\left(\frac{\alpha_{rw}}{\alpha_d}\right)}}{L_{d\,\max}} \right) 10^{\left[\frac{(\beta_{rw} - \beta_d)}{\alpha_d}\right]} - \left(\frac{1}{C_{\max}} \right) \right]^{\left(\frac{1}{\gamma_d}\right)}$$



Tumblin and Rushmeier, IEEE CGA 1993

Subsequent Work by Other Groups



(masking effects and indirect calculations)

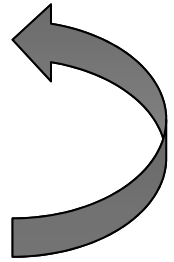
Ramasubramanian et al. 1999

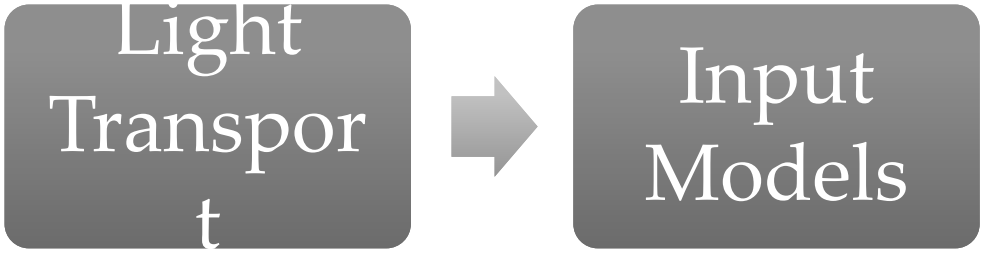
(visual attention)

Yee et al. 2001

Perceptually Efficient Light Transport Now Well Established Research Area

- Formulate a solution technique with error bound (per pixel, per surface)
- Express error bound in terms of perceptual model

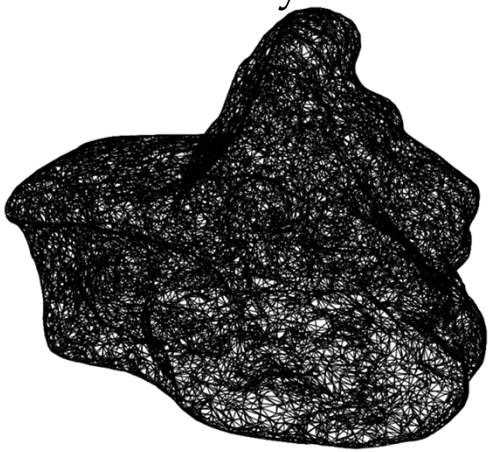




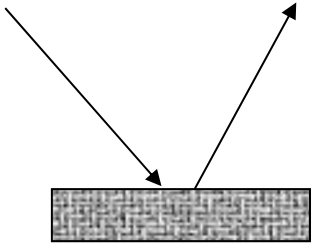
- Accuracy of transport depends on input
- Input defined independent of image, so can't apply the same models.

Rendering Input

Geometry



Material Model

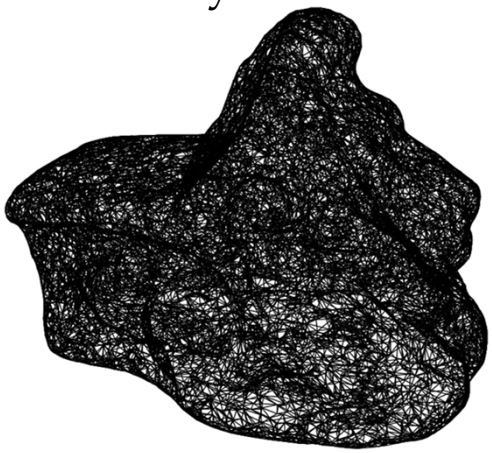


Source Illumination

Global Illumination

Rendering Input- Geometry

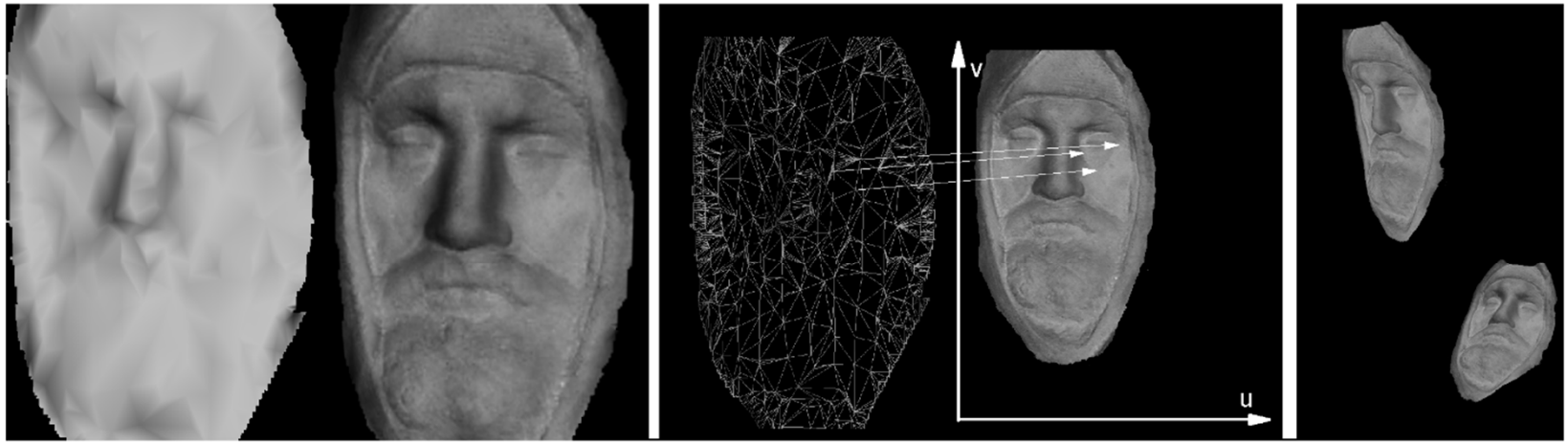
Geometry

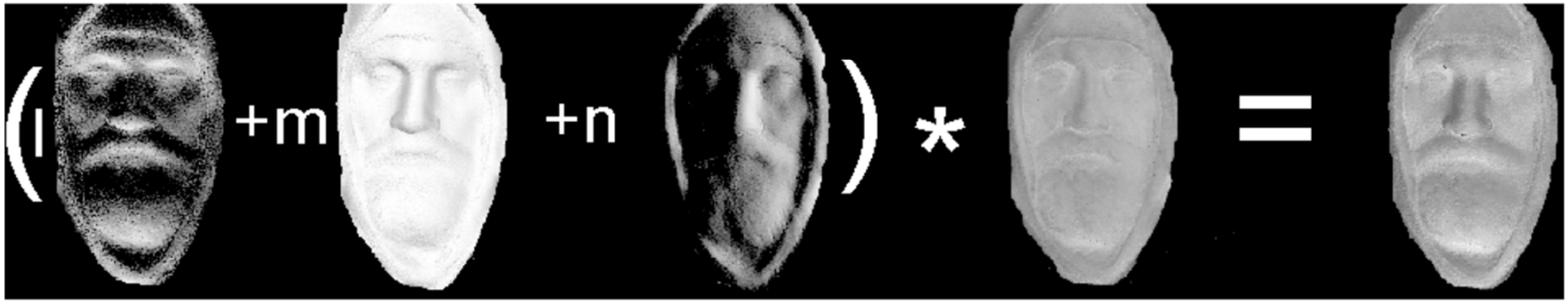


- Representation
- Level of Detail

Representation:

Trade-off triangles and texture maps

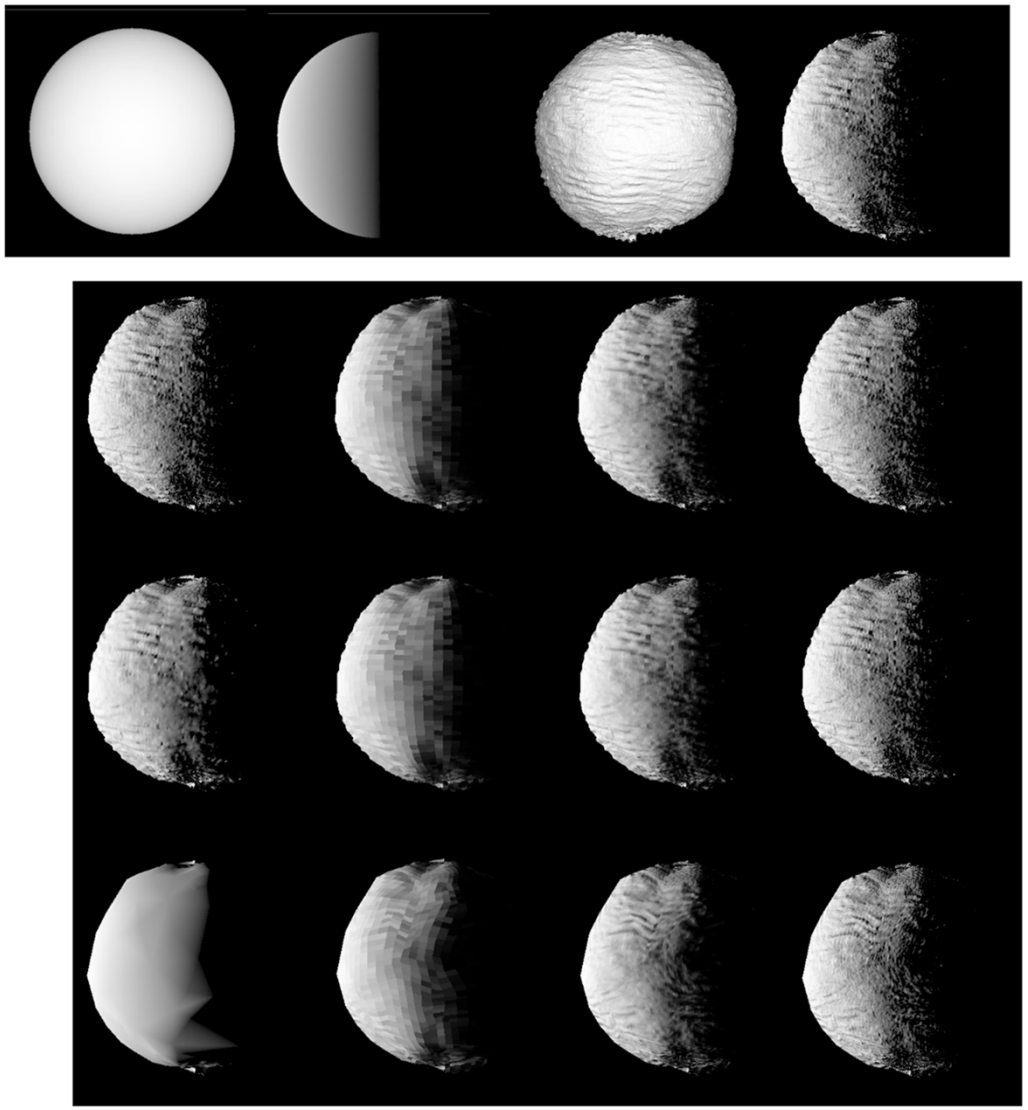


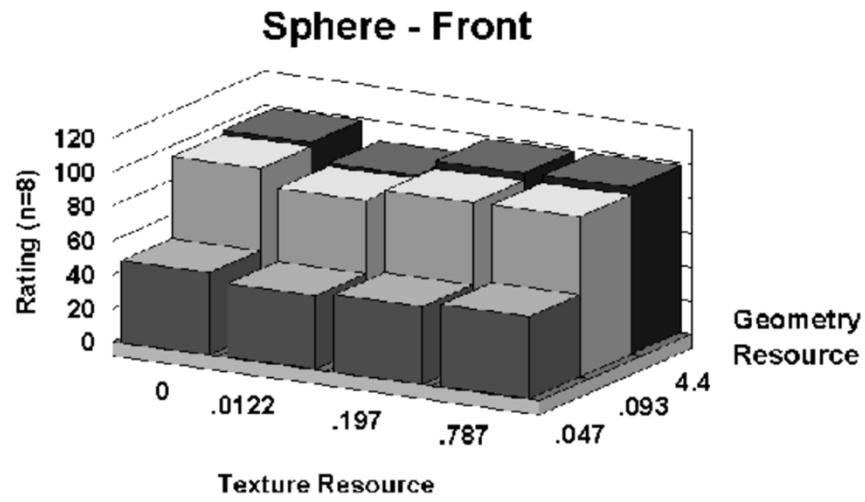


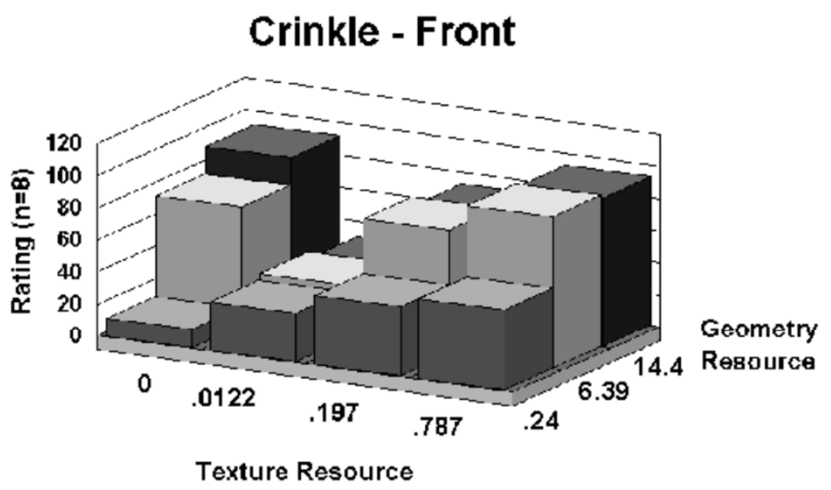
- Rushmeier, Rogowitz and Piatko, HVEI 2000

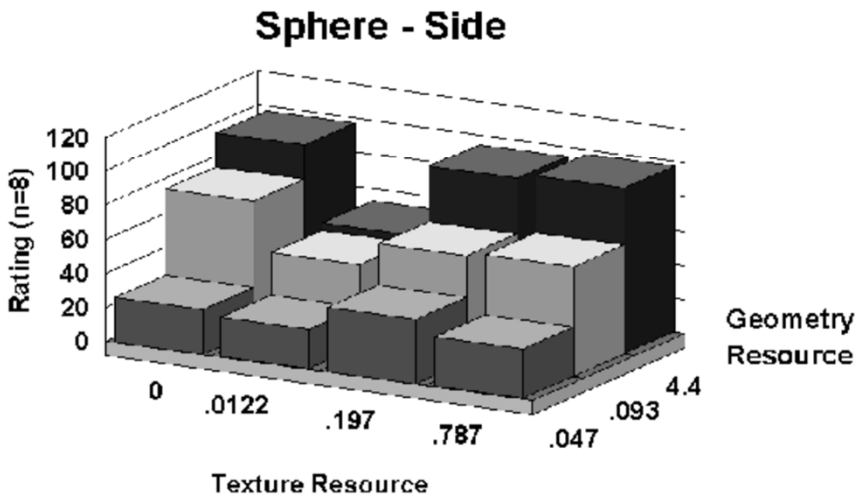
Representation:

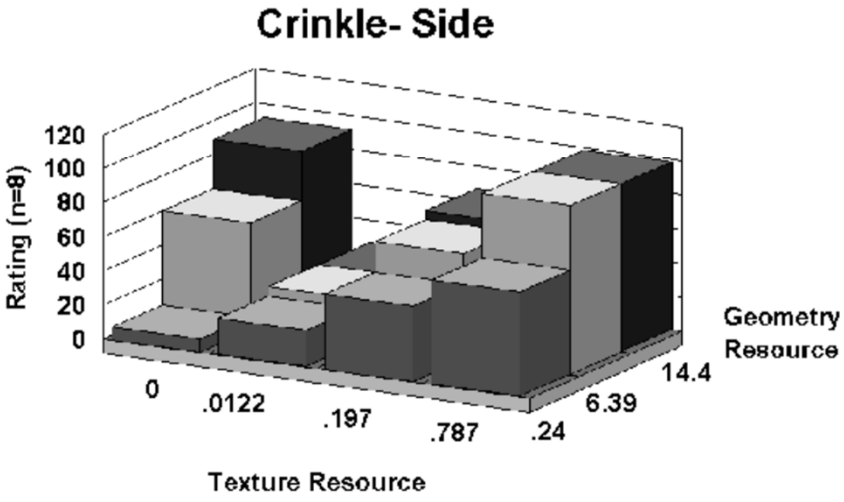
Trade-off triangles and texture maps




Sphere - Front
Rating (n=8)
120
100
80
60
40
20
0
0
.0122
.197
.787
.047
.093
4.4
Geometry Resource
Texture Resource

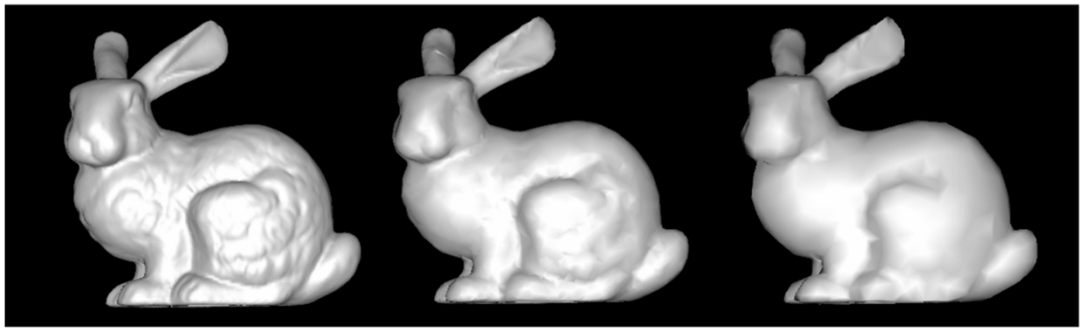

Crinkle - Front
Rating (n=8)
120
100
80
60
40
20
0
0
.0122
.197
.787
.24
6.39
14.4
Geometry Resource
Texture Resource

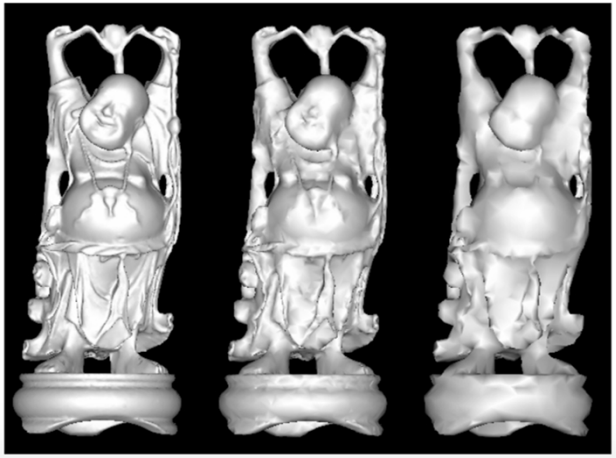

Sphere - Side
Rating (n=8)
120
100
80
60
40
20
0
0
.0122
.197
.787
.047
.093
4.4
Geometry Resource
Texture Resource


Crinkle- Side
Rating (n=8)
120
100
80
60
40
20
0
0
.0122
.197
.787
.24
6.39
14.4
Geometry Resource
Texture Resource

Geometry:

Can you evaluate in static image?

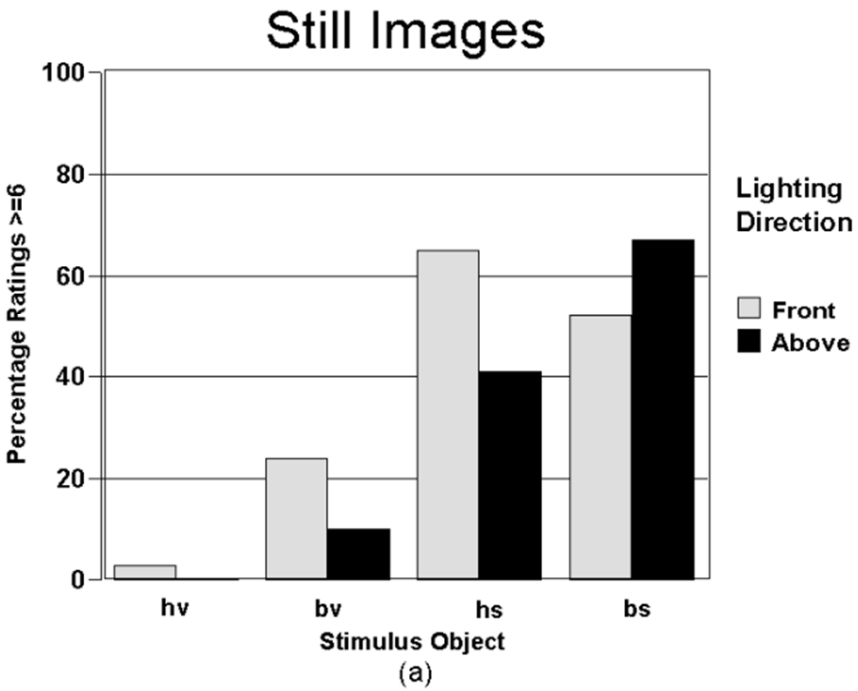


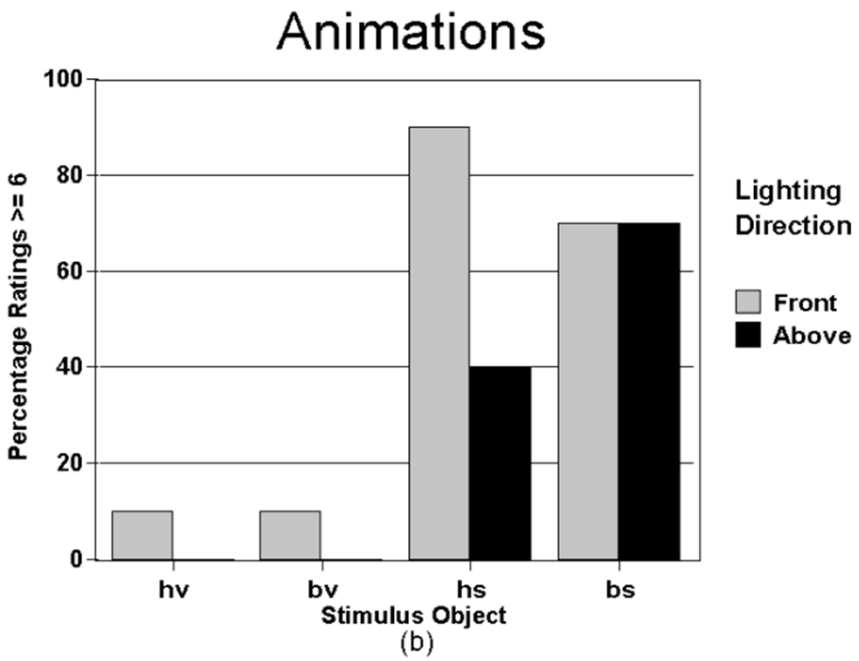


Rushmeier and Rogowitz, HVEI 2001

Still vs Rotating front to side view

Lit from above, lit from front

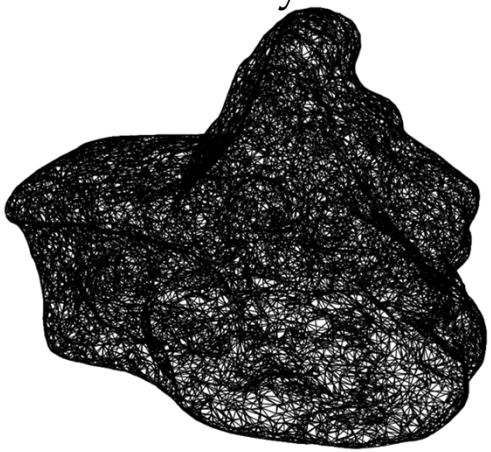




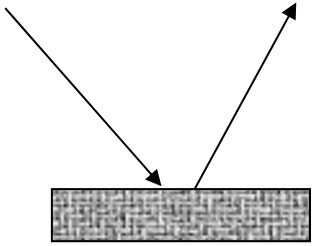
For all conditions, very simplified rated lower
For moderate simplification, animation higher ratings than still
For all but one case, front lit higher rated than lit from above.

Rendering Input

Geometry



Material Model

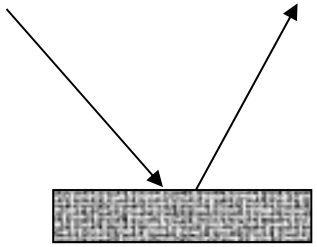


Source Illumination

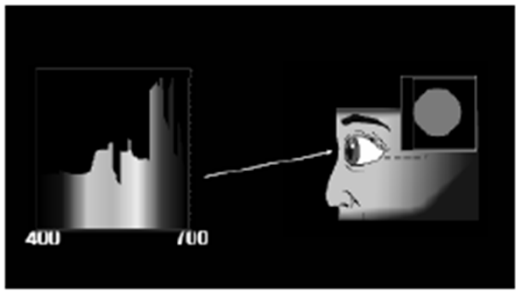
Global Illumination

Rendering Input: Material Model

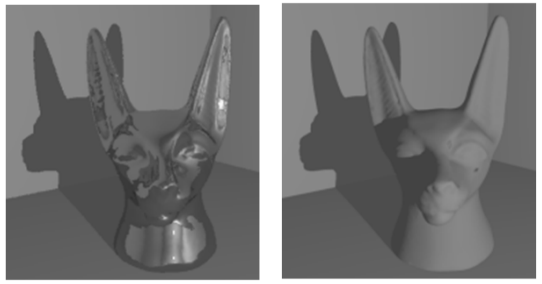
Material Model



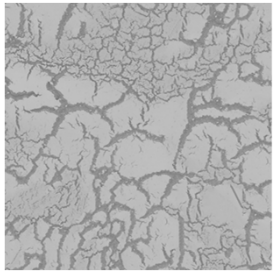
Spectral (color)



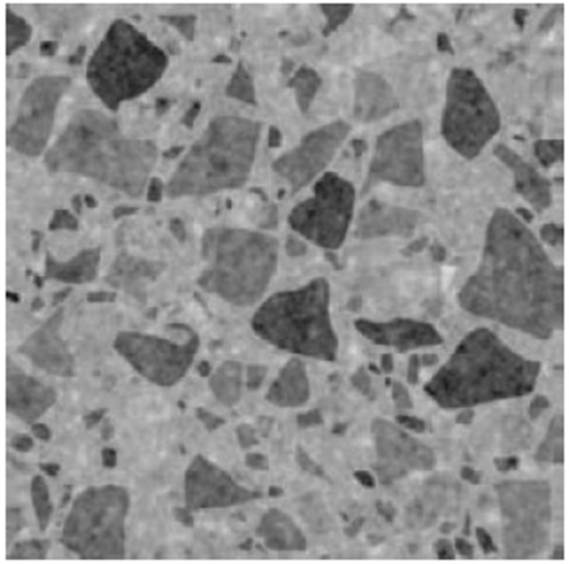
Directional (Shiny, matte, glossy, hazy)

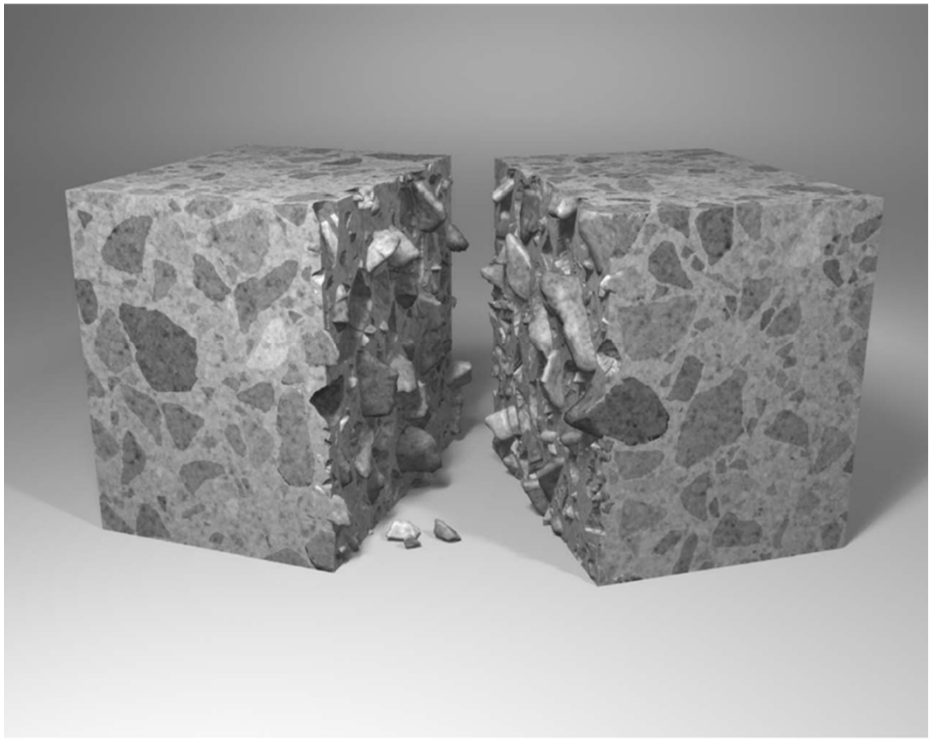


Spatial variation (texture)



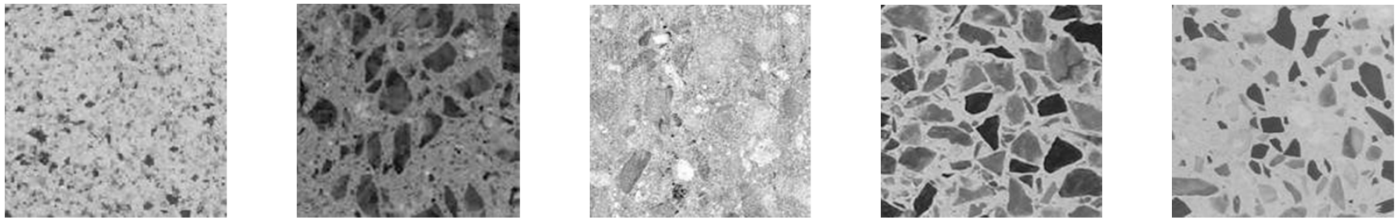
The Material Modeling Problem – Example

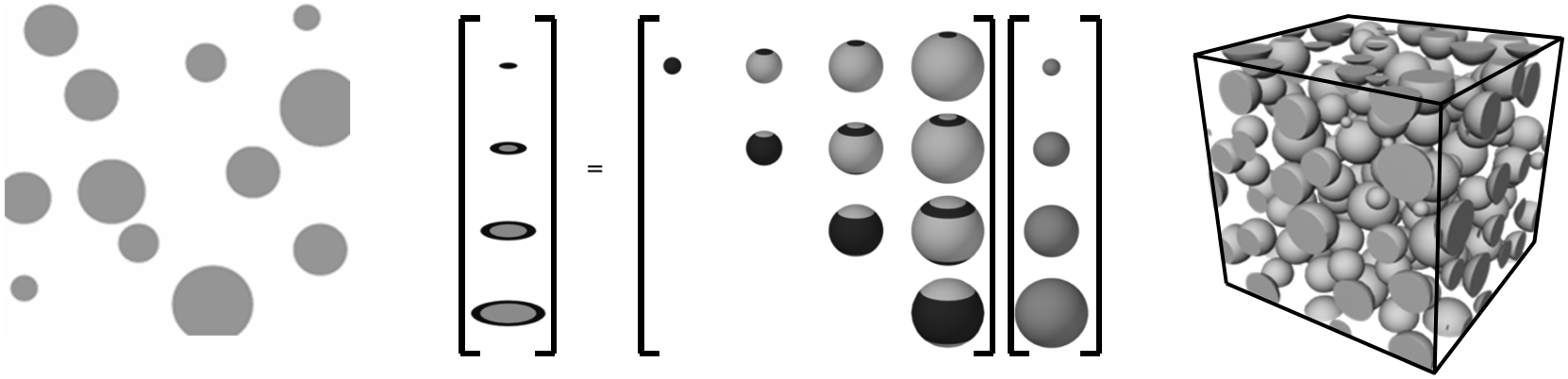




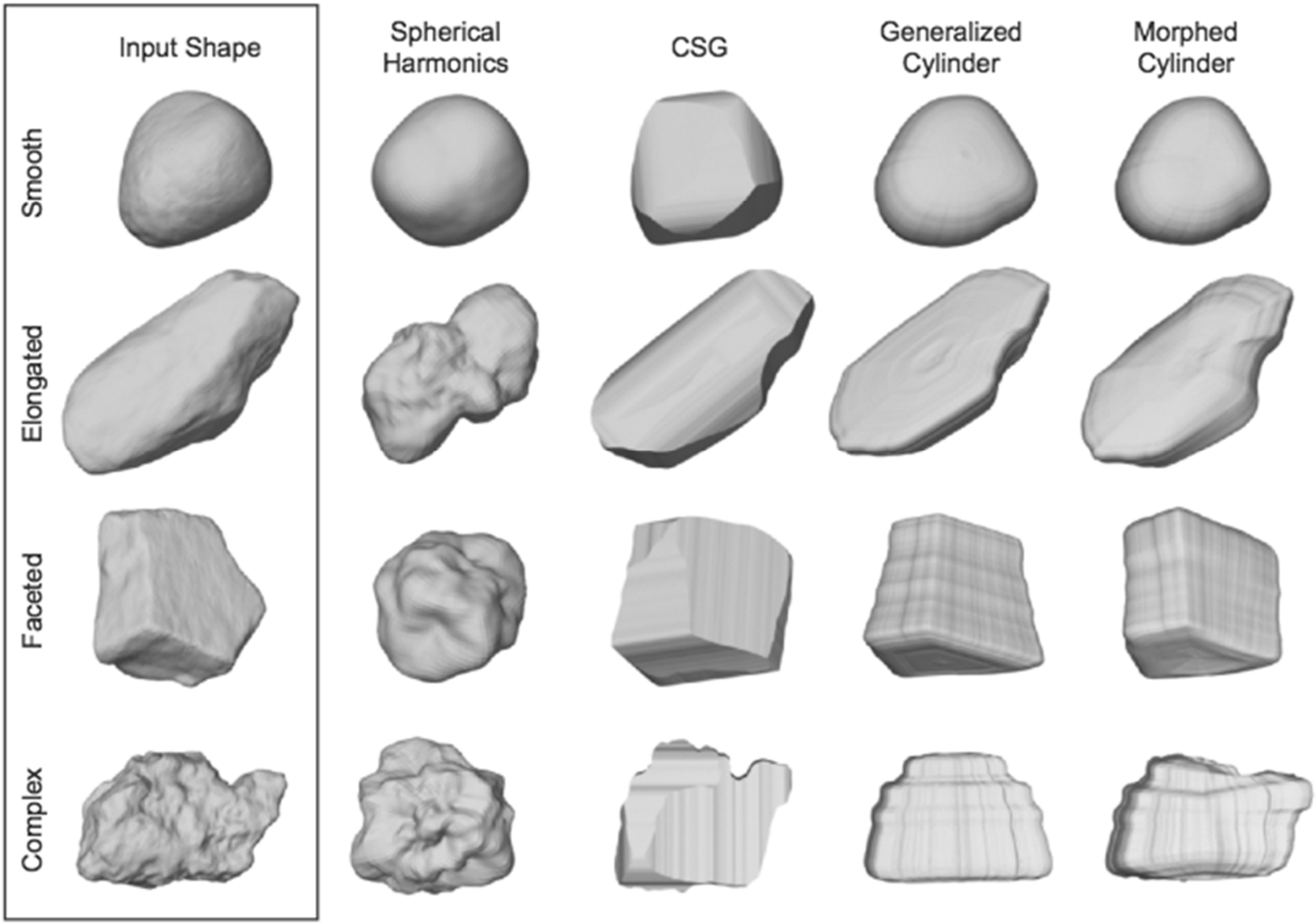
Same material?

Jagnow, Dorsey and Rushmeier, TOG 2004, TAP 2008

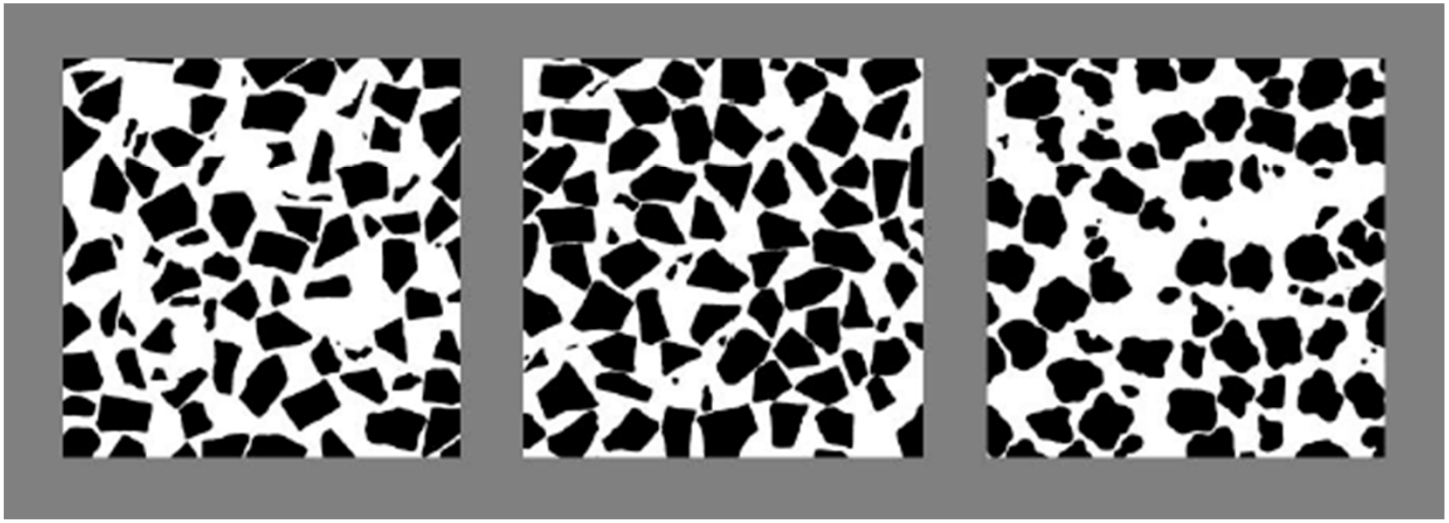




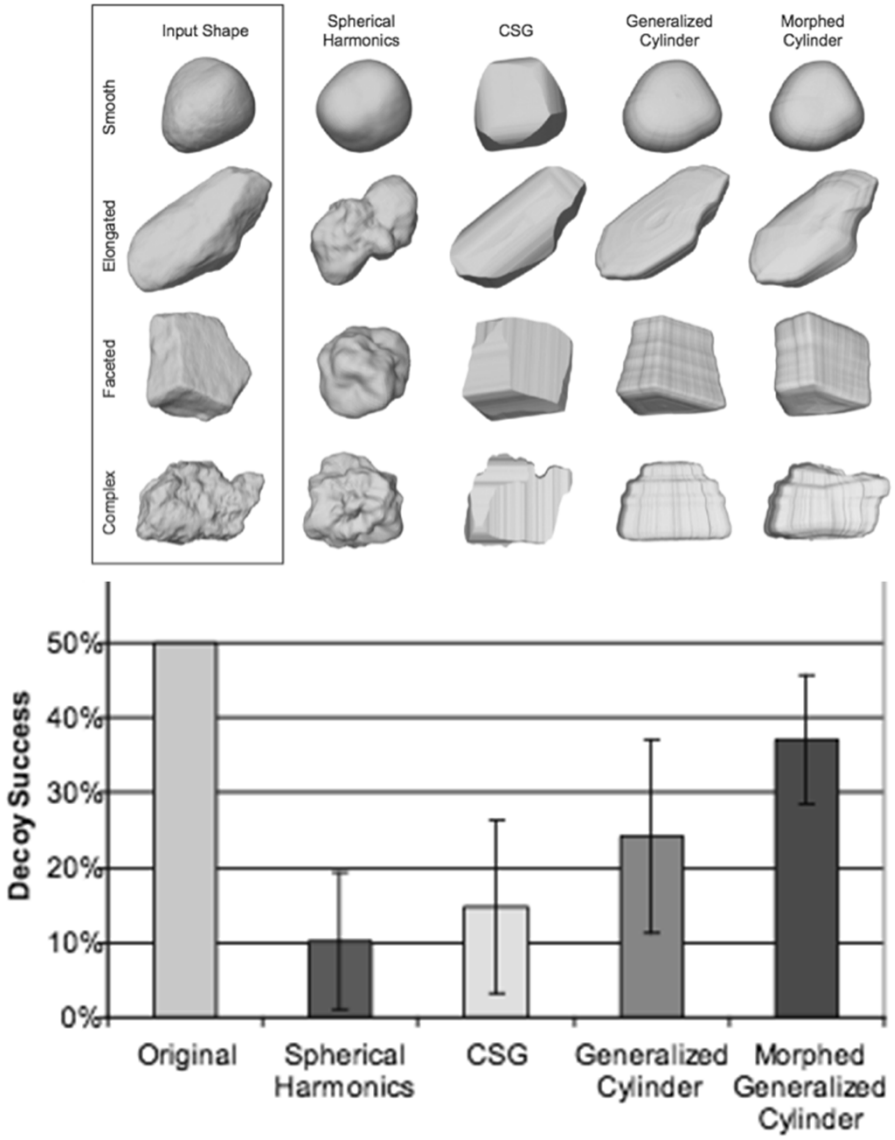
Size distribution can be estimated from classic stereology, but what about estimating non-spherical shape?


Input Shape
Spherical Harmonics
CSG
Generalized Cylinder
Morphed Cylinder
Smooth
Elongated
Faceted
Complex

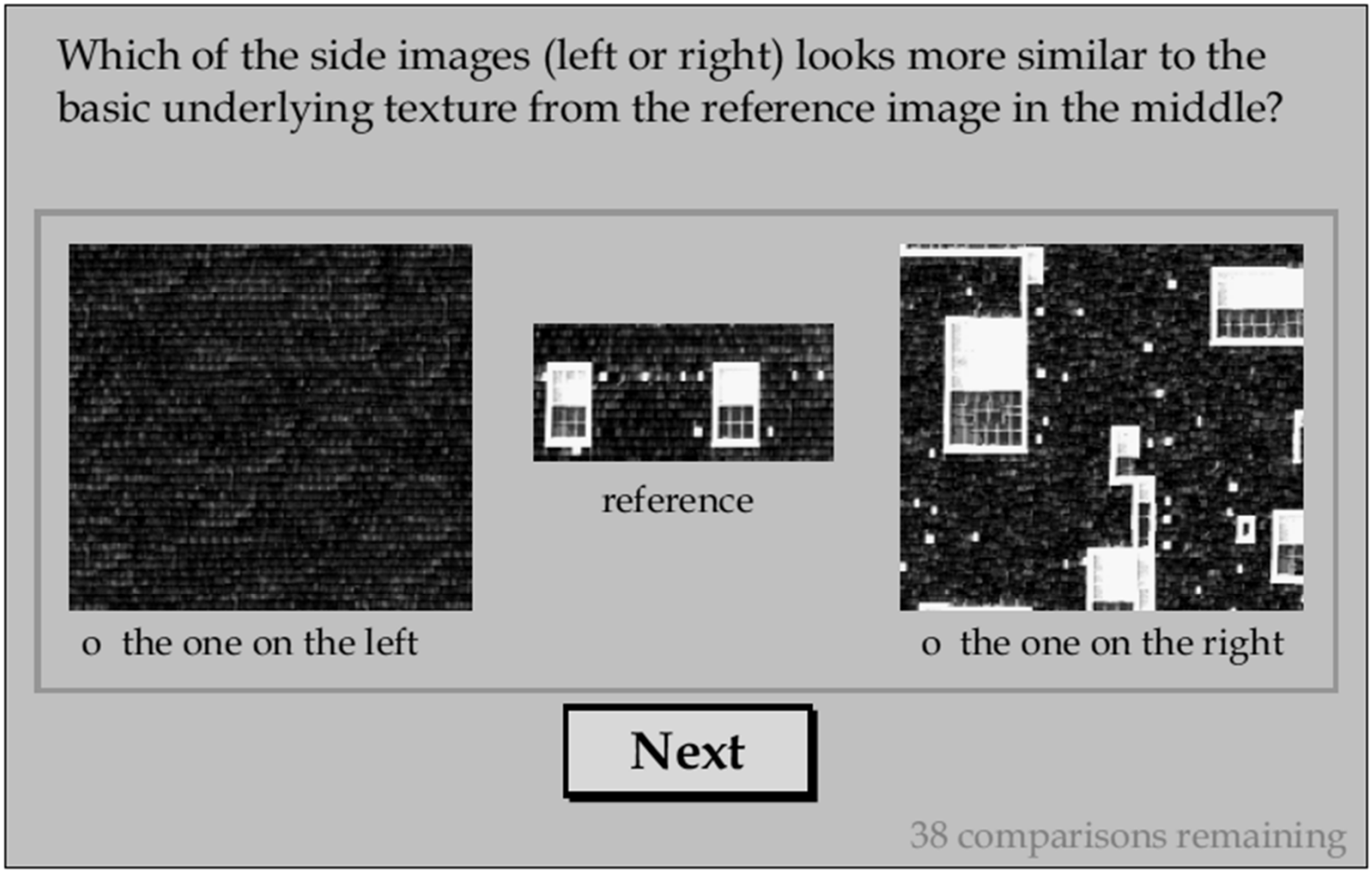
The Material Modeling Problem -- Example



Which is the slice through the same material shown in the center?


Input Shape
Spherical Harmonics
CSG
Generalized Cylinder
Morphed Cylinder
Smooth
Elongated
Faceted
Complex
Decoy Success
50%
40%
30%
20%
10%
0%
Original
Spherical Harmonics
CSG
Generalized Cylinder
Morphed Generalized Cylinder

Validating Input Models



Lu, Garr-Schulz, Dorsey and Rushmeier, SAP 2009

Validation Experiments

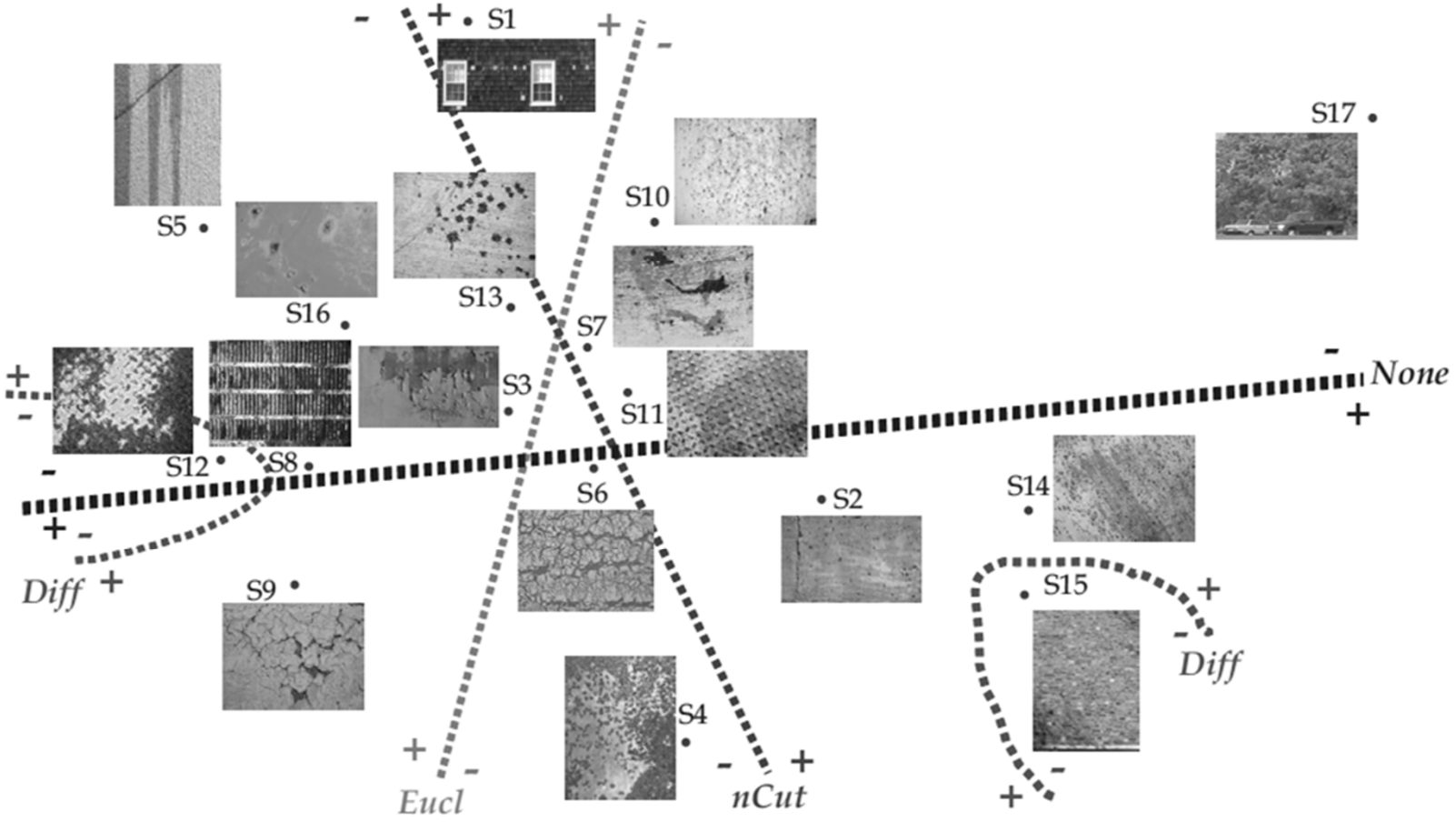
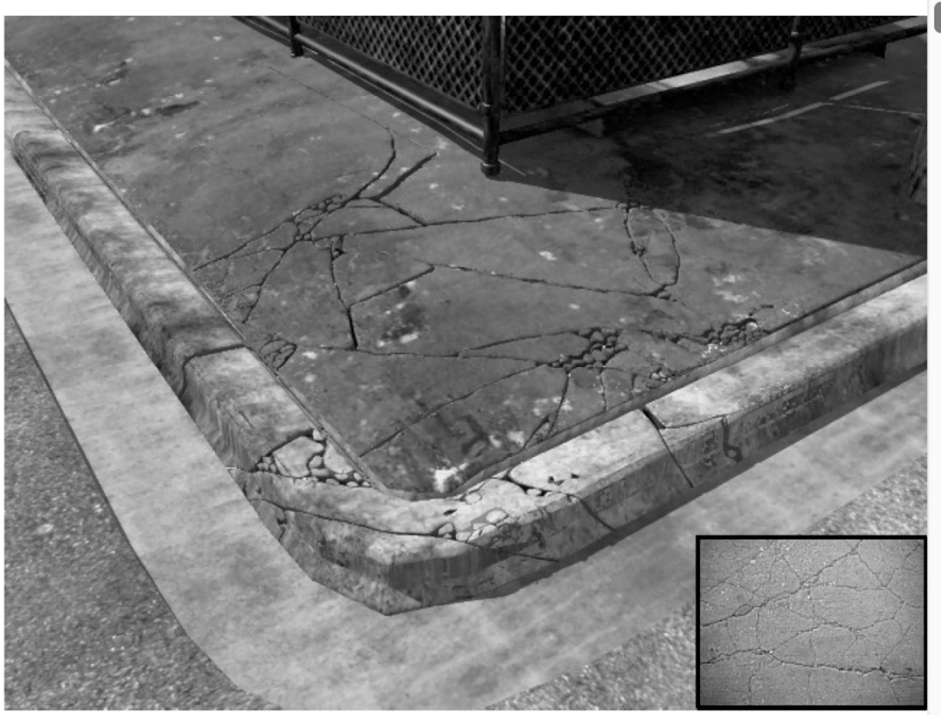


Image by Flicker user motiqua, under the Creative Common Attribution 2.0 Generic License
http://flic.kr/p/7TRX79

run	2-moments	5-moments	HOG Texture Space	Trivial Feature Space	Autocorrelation Feature Space
1	no participants approved of all tiles	5 of 8 participants approved of all the tiles	no participants approved of all tiles	no participants approved of all tiles	no participants approved of all tiles
2	no participants approved of all tiles	5 of 8 participants approved of all the tiles	no participants approved of all tiles	no participants approved of all tiles	no participants approved of all tiles

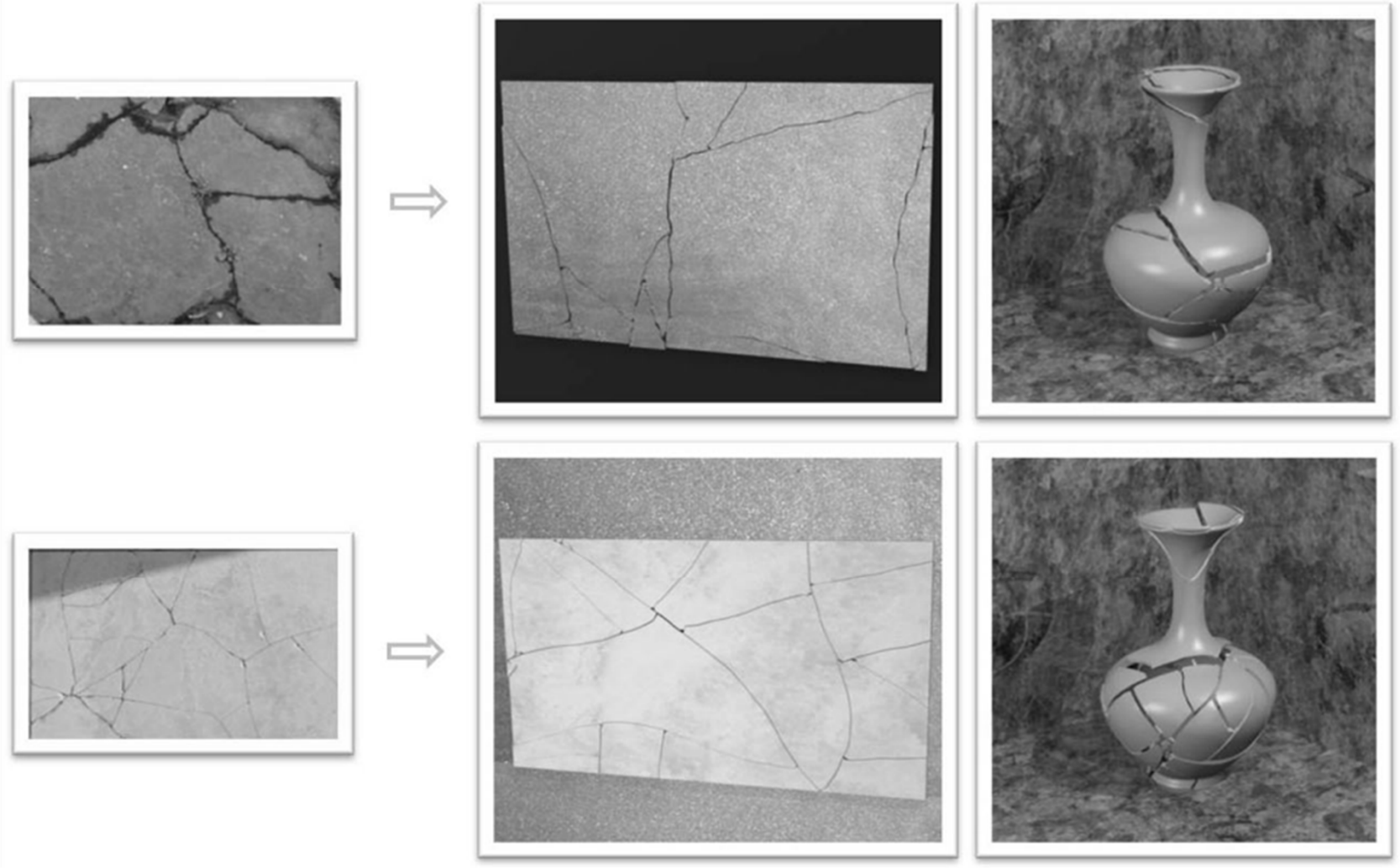
- Lockerman ,Xue ,Dorsey,Rushmeier, CAD/Graphics 2013

Example-Based Fractured Appearance

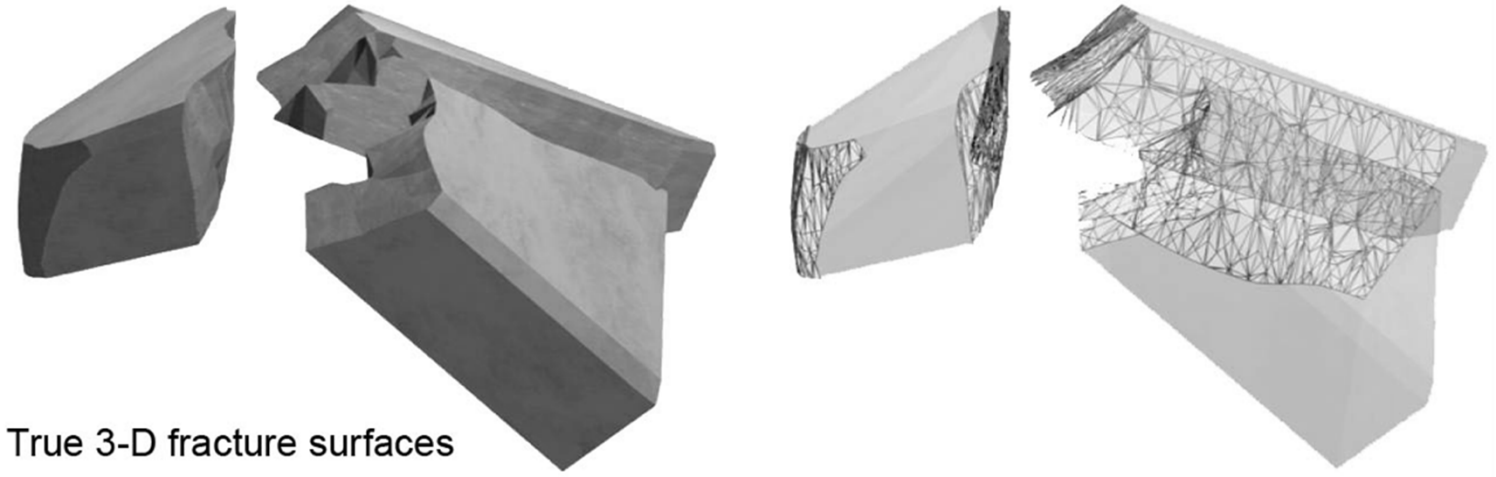


Glondu, Muguercia, Marchal, Bosch, Rushmeier, Dumont and Drettakis, EGSR 2012

Can we use exemplars and simulation for cracks?

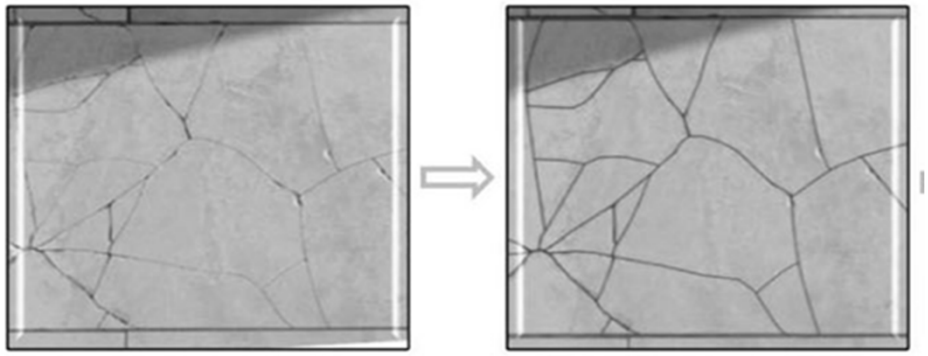


Previous work by Glondu and Marchal -- a fast accurate fracture model



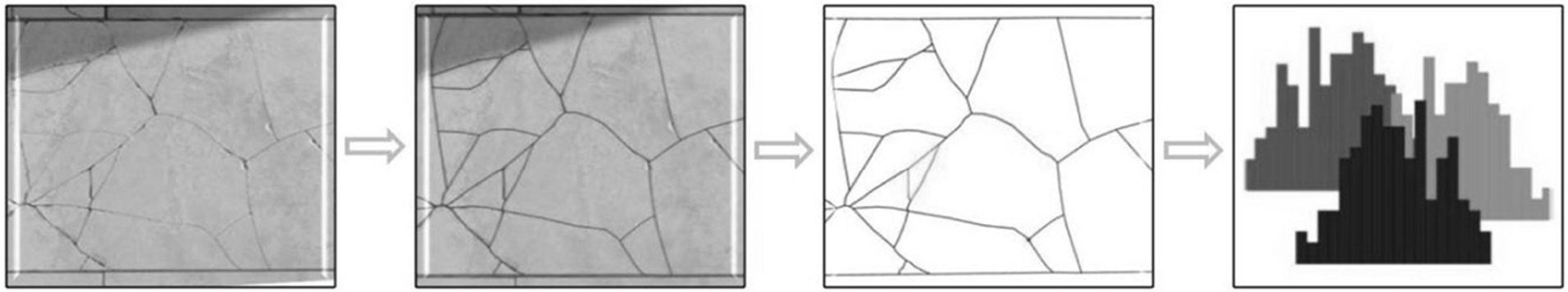
True 3-D fracture surfaces

But running simulation to match crack pattern is hopeless!



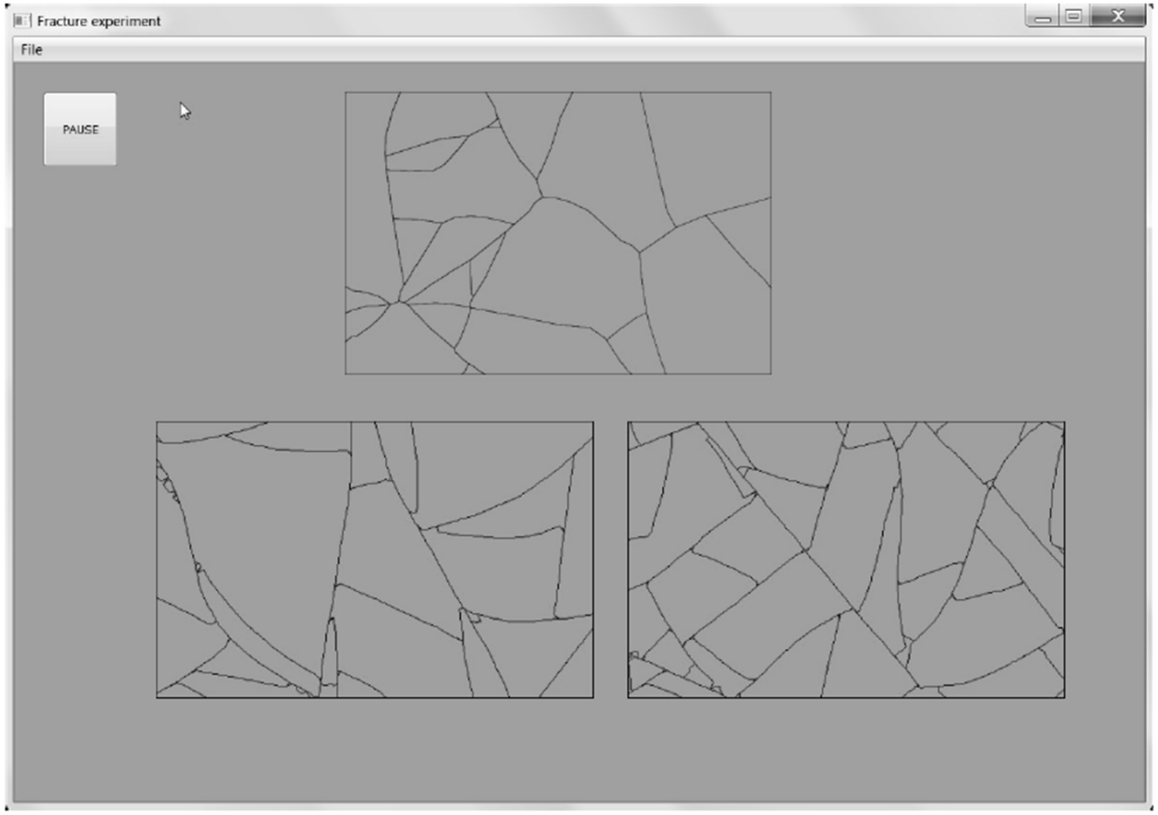
Photograph

Cracks



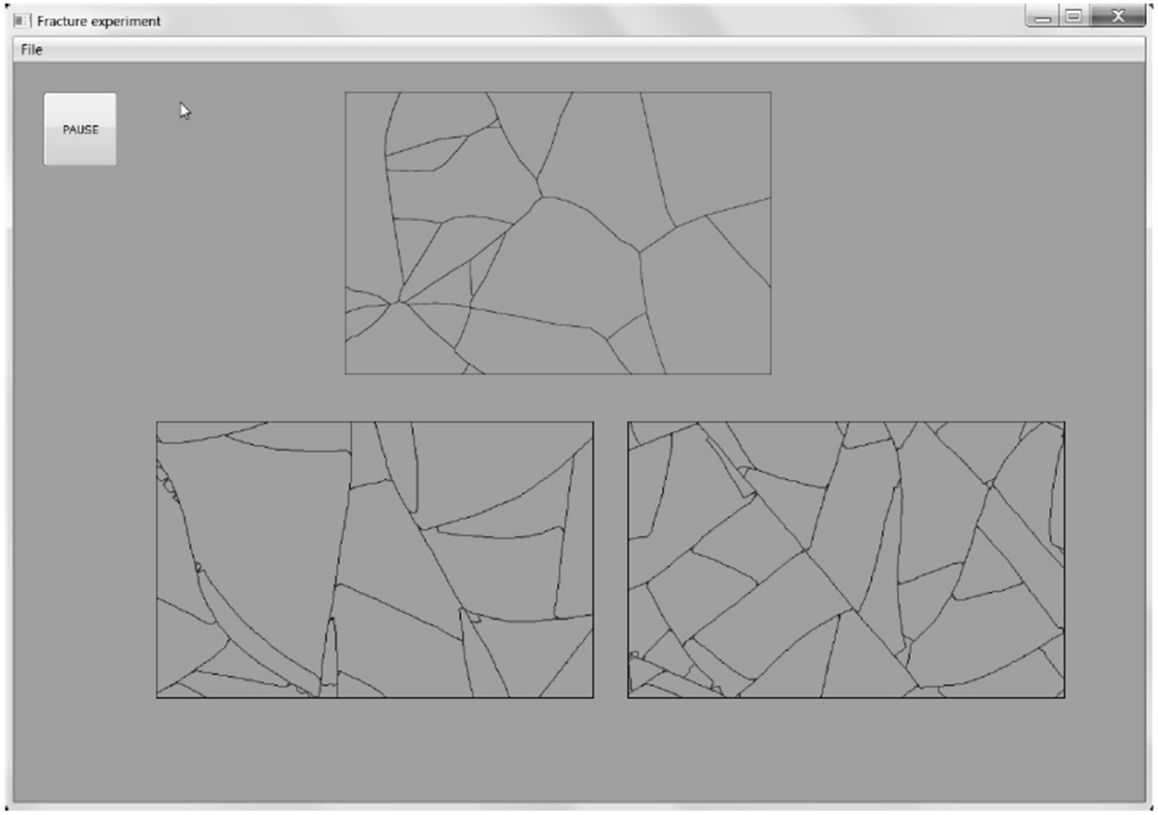
Since a person is choosing the example to match, the features that matter are perceptual.

New Experiments in Person



Studying crack pattern statistics
Glondu et al. 2012

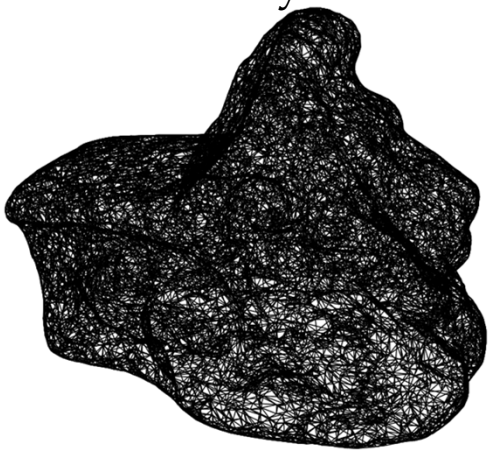
New Experiments in Person



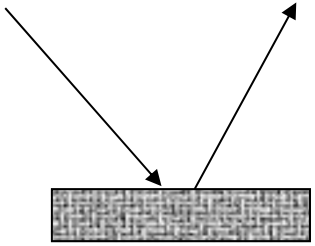
Studying crack pattern statistics
Glondu et al. 2012

Rendering Input

Geometry



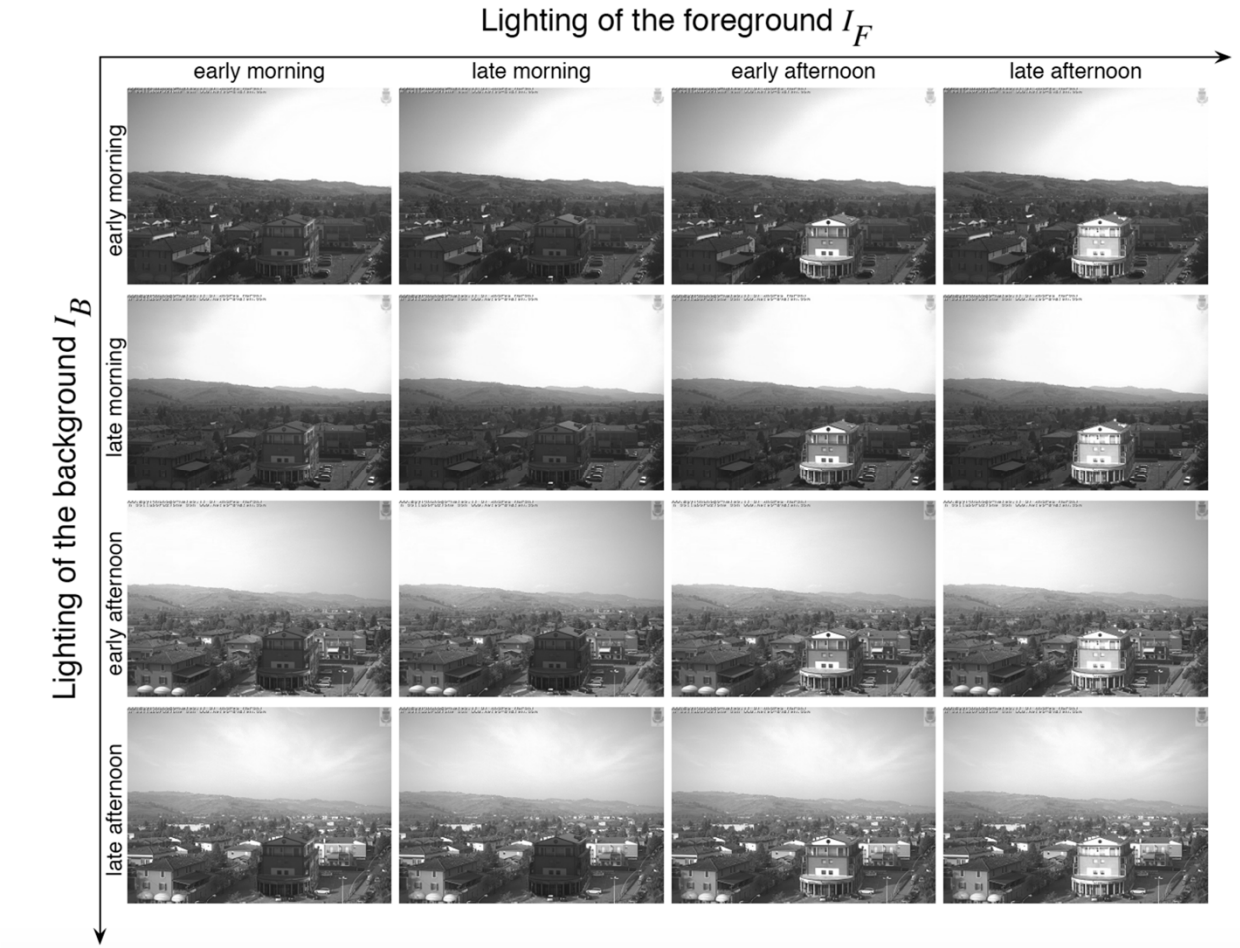
Material Model



Source Illumination

Global Illumination

Rendering Input: Light Source



Tan, Lalonde, Sharan, Rushmeier, O'Sullivan ,TAP 2015

(a) Campanile

(b) Street

(a) Montage 1

(b) Montage 2

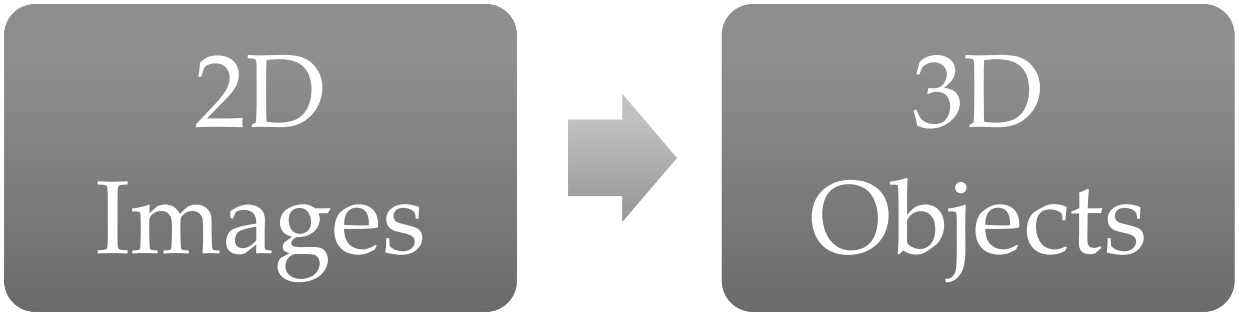
(c) Mask 1

(d) Mask 2

Perceptually Based Rendering

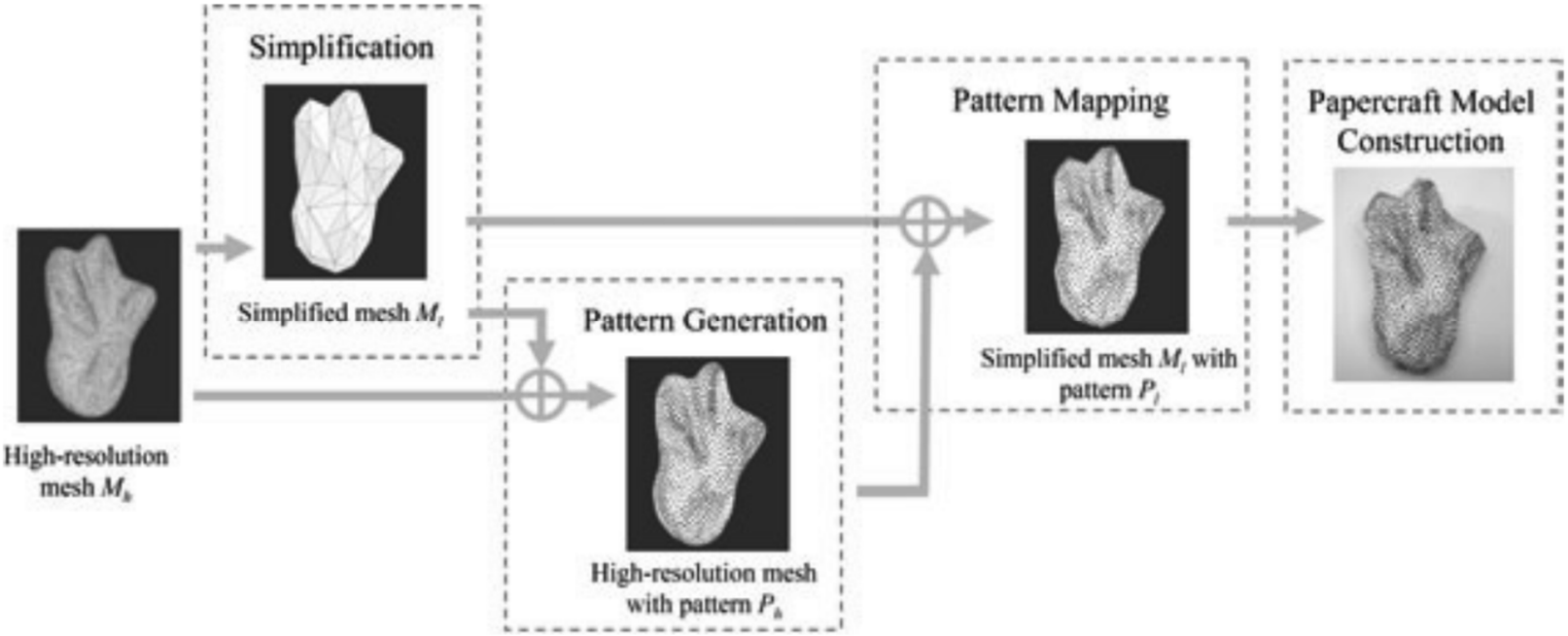
- What is perceptually-based rendering?
- History: Perception and Rendering
- Models: Transport and Input
- Hardware: 2D and 3D
- Experiments: Labs and Crowds

Perceptual Rendering an Object



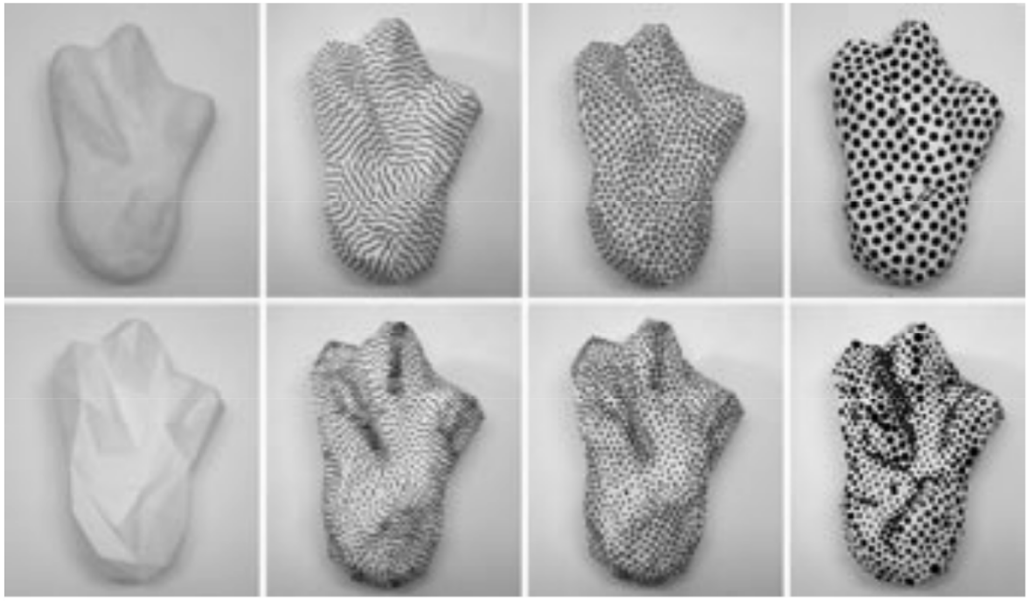
Sculptural, not just image rendering

Printed Patterns for Enhanced Shape Perception of Papercraft Models



Xue, Chen, Dorsey, and Rushmeier, 2010

Clay model in center, paper approximations on either side

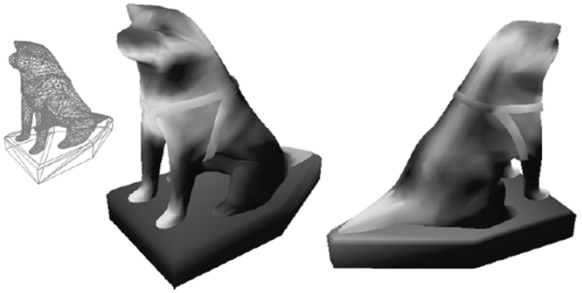


- uni-stroke: >blank
- modu-stroke: >blank, >uni-stroke, >uni-cross, >uni-dot
- uni-cross: >blank
- modu-cross: >blank, >uni-stroke, >uni-cross, >uni-dot
- uni-dot: >blank
- modu-dot: >blank, >uni-stroke, >uni-cross, >uni-dot

Tactile Mesh Saliency

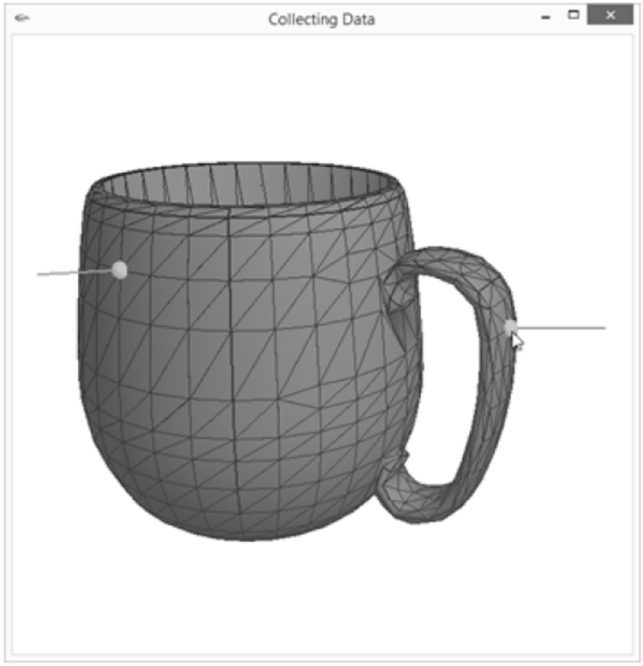
Grasp

Press



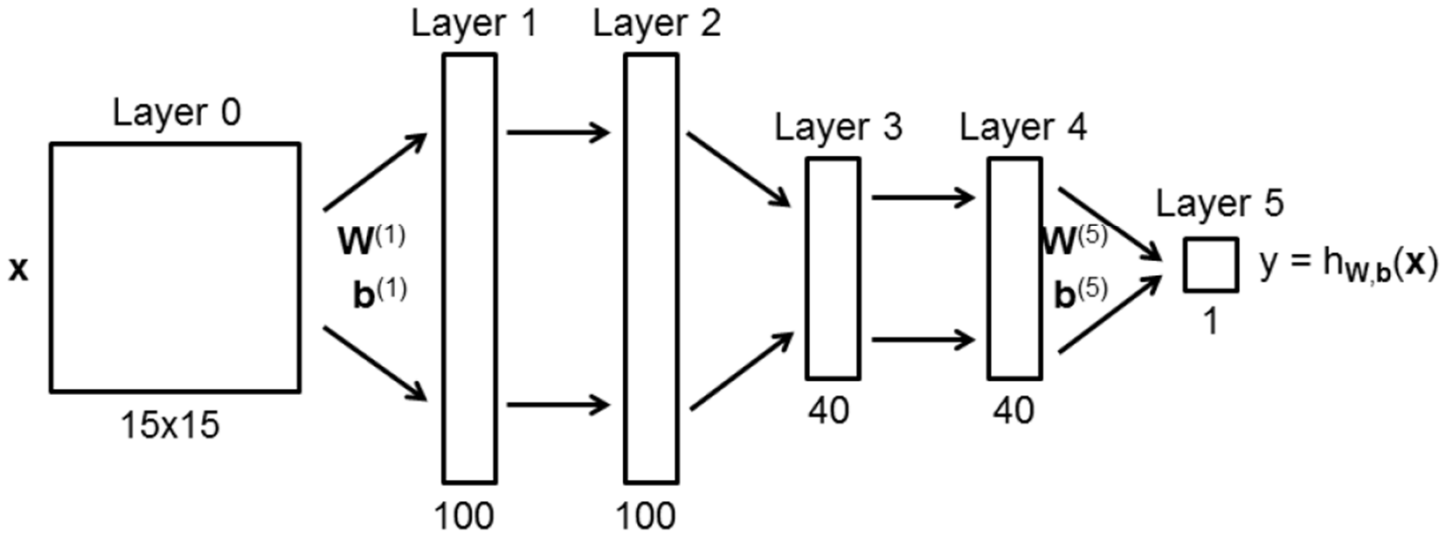
Touch

Lau, Dev, Shi, Dorsey and Rushmeier, SIGGRAPH 2016



which point is more salient?

learning to rank formulation



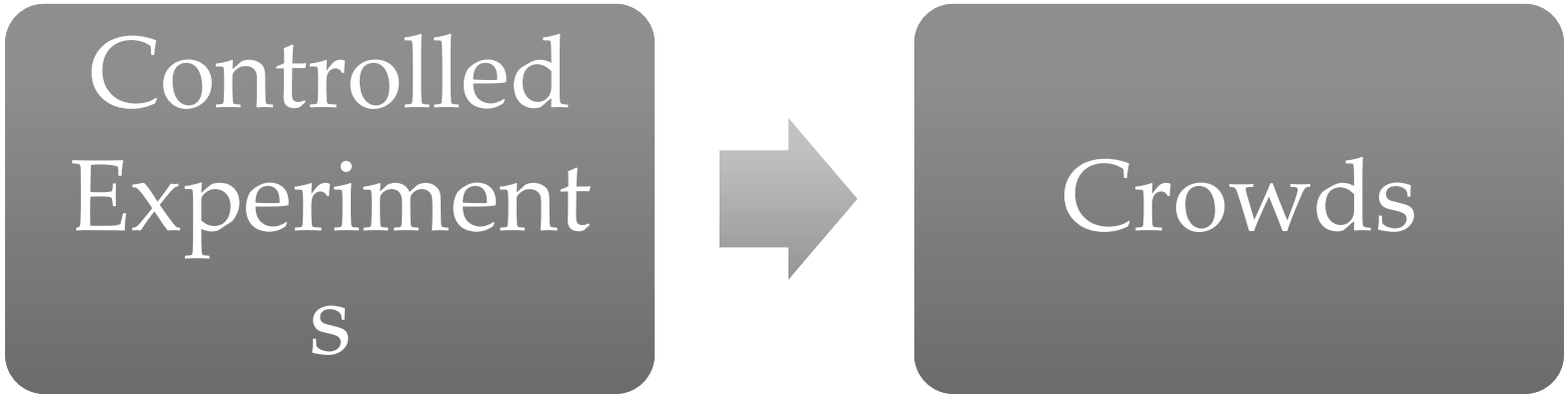
Rendering effect of wear

Reinforced 3D model

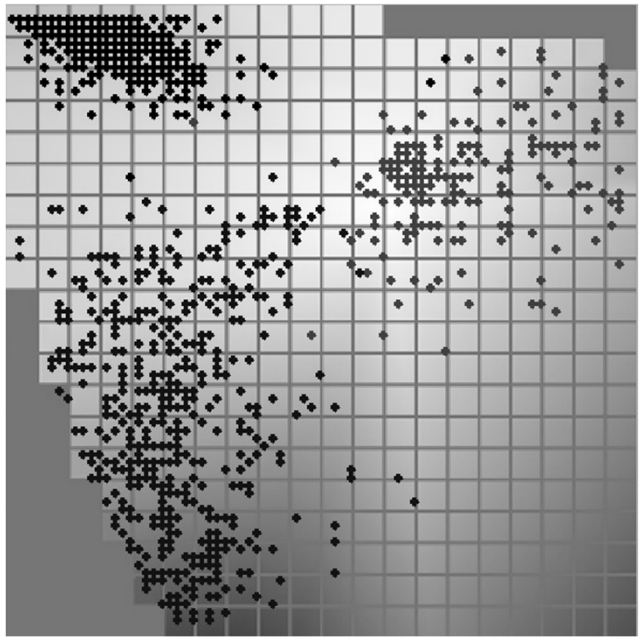
Perceptually Based Rendering

- What is perceptually-based rendering?
- History: Perception and Rendering
- Models: Transport and Input
- Hardware: 2D and 3D
- Experiments: Labs and Crowds

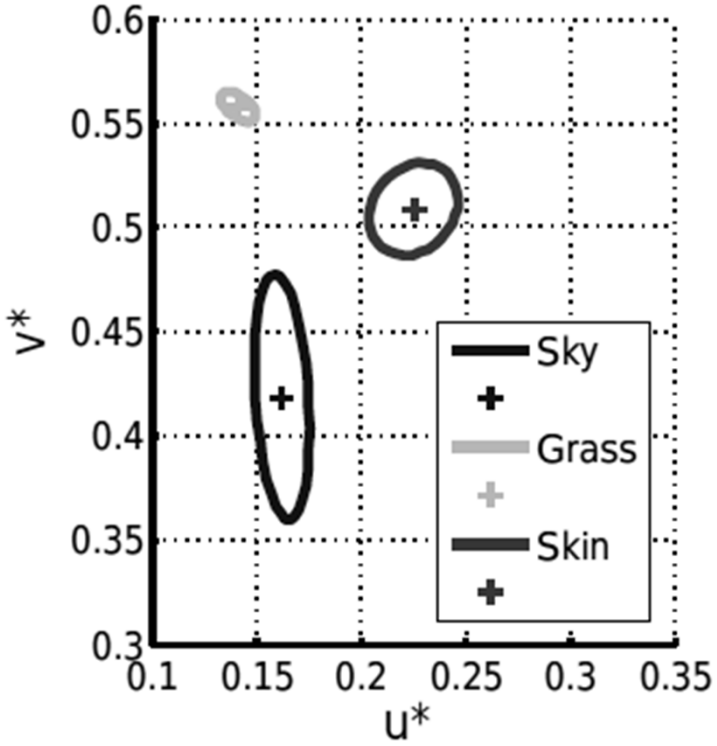
Crowd Sourcing



Crowd Sourcing



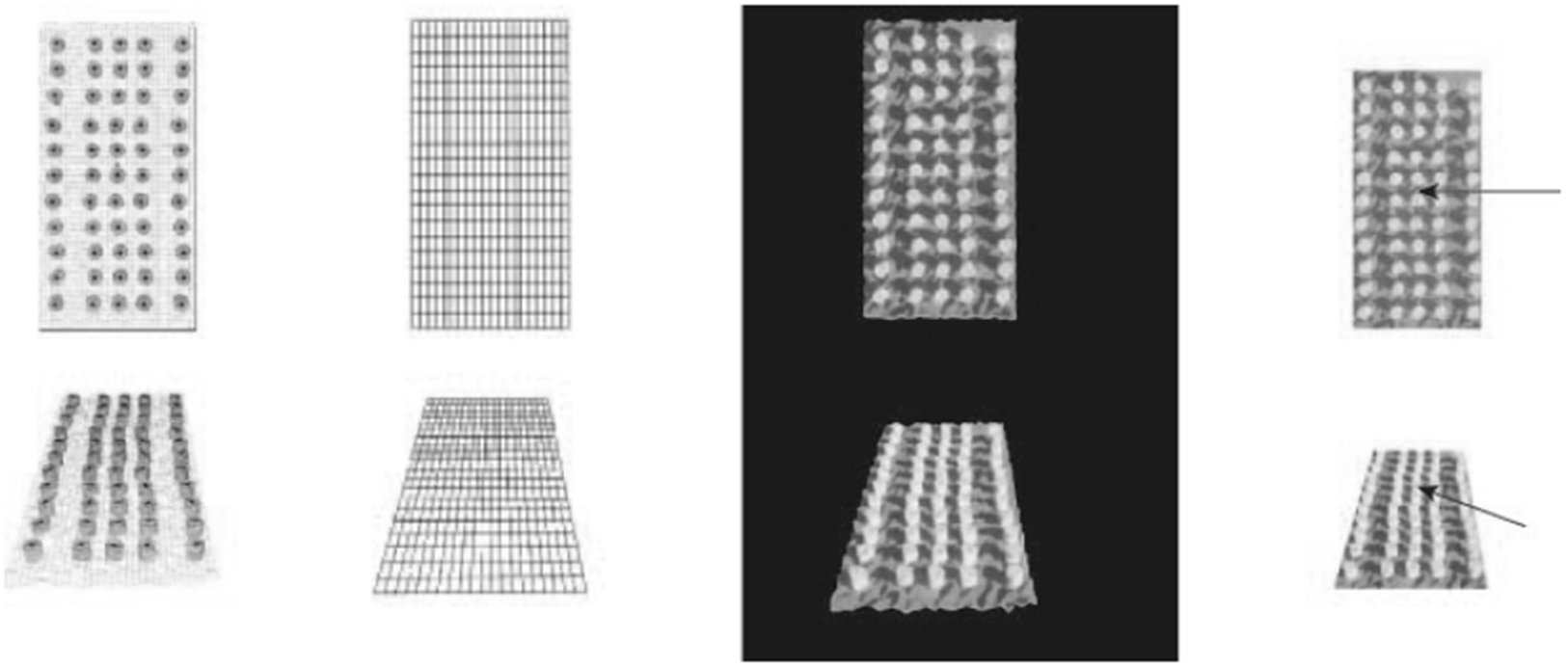
Memory Colors



- Xue, Tan, McNamara, Dorsey, and Rushmeier, HVEI2014

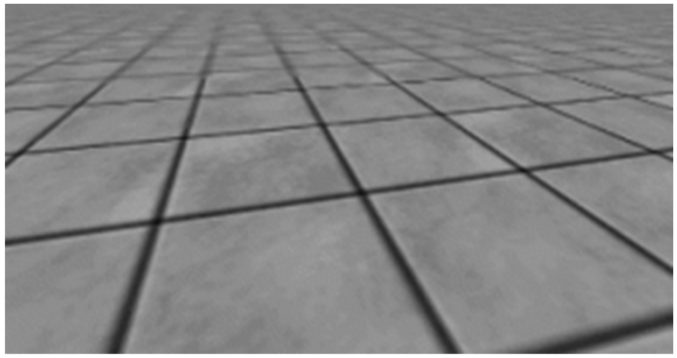
Editing images – adjusting towards memory colors

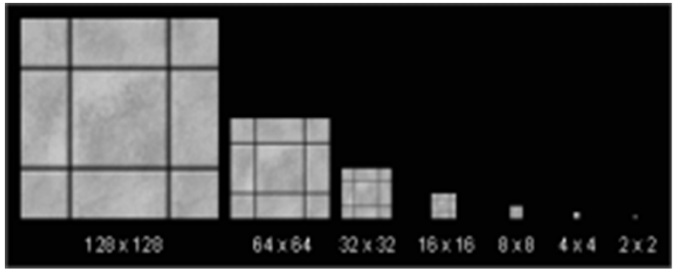
Bidirectional Texture Functions : Textures that encode variations with position and direction



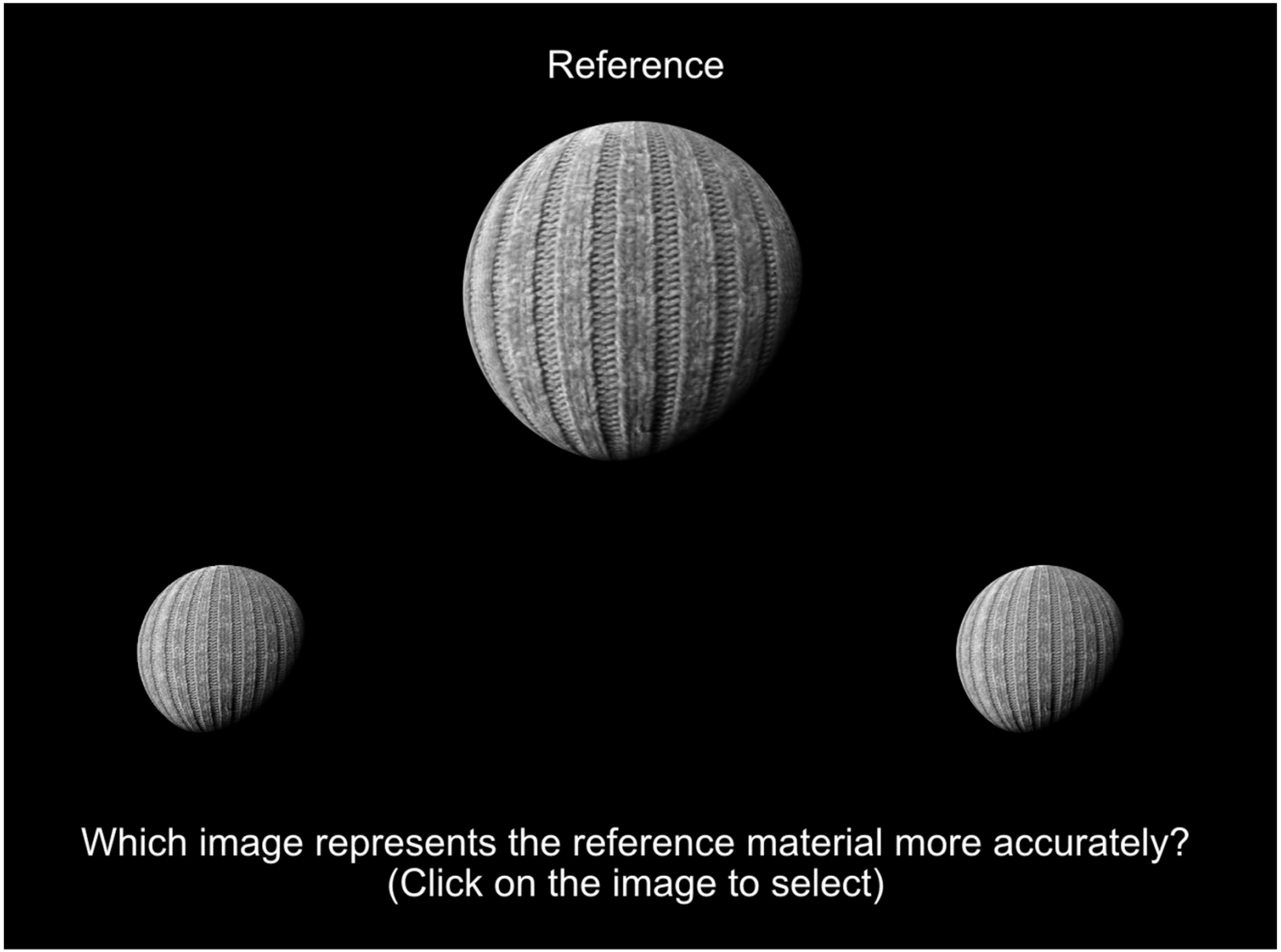
A flat image that looks different from different angles.

What about filtering for classic mipmapping?



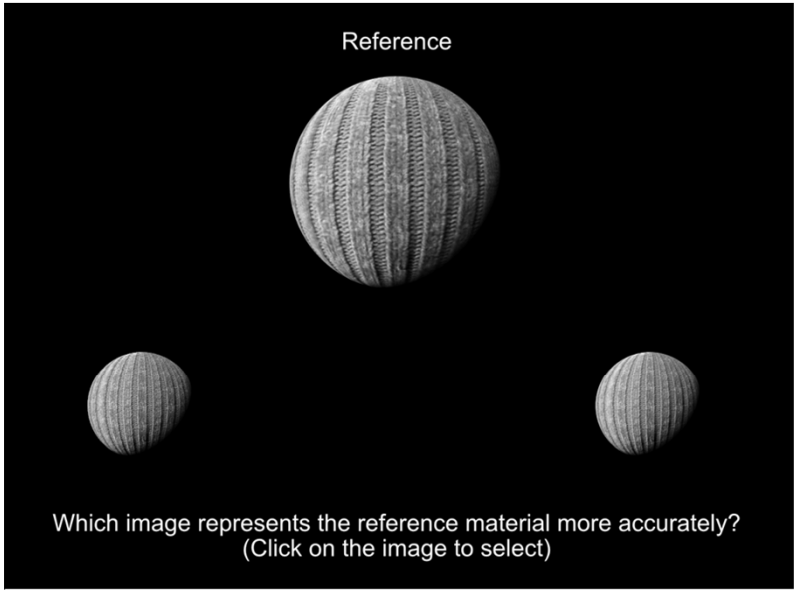


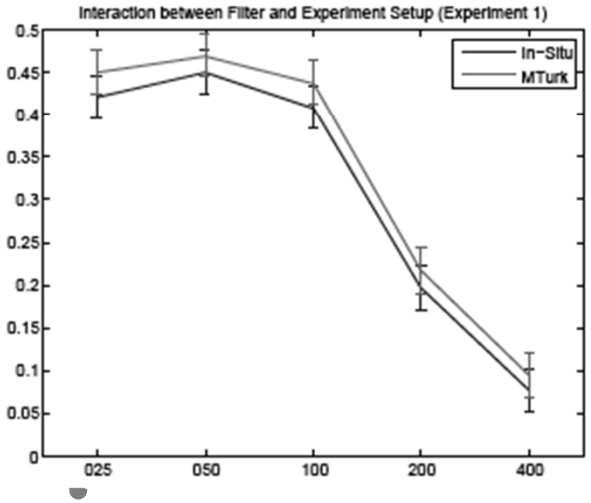
http://www.gamedev.net/page/resources/_/technical/directx-and-xna/mip-mapping-in-direct3d-r1233

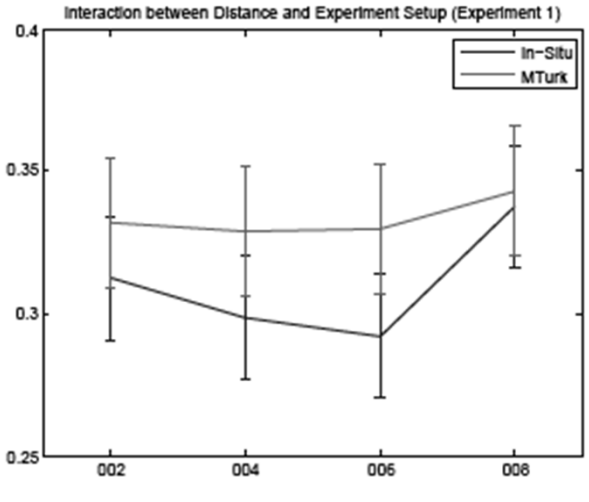


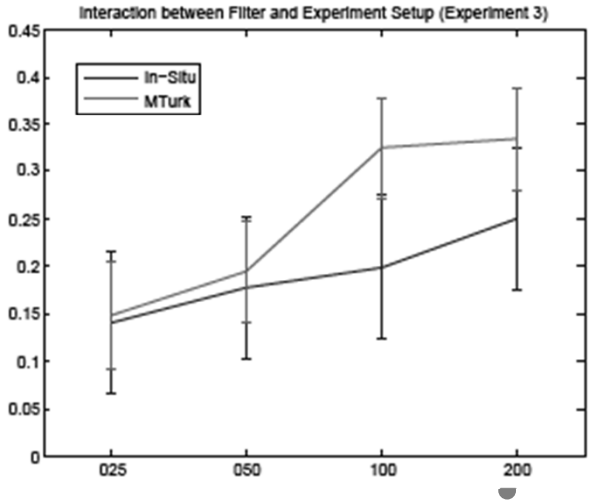
Jarabo, Wu, Dorsey, Rushmeier, Gutierrez, TVCG 2014

Crowd Sourcing

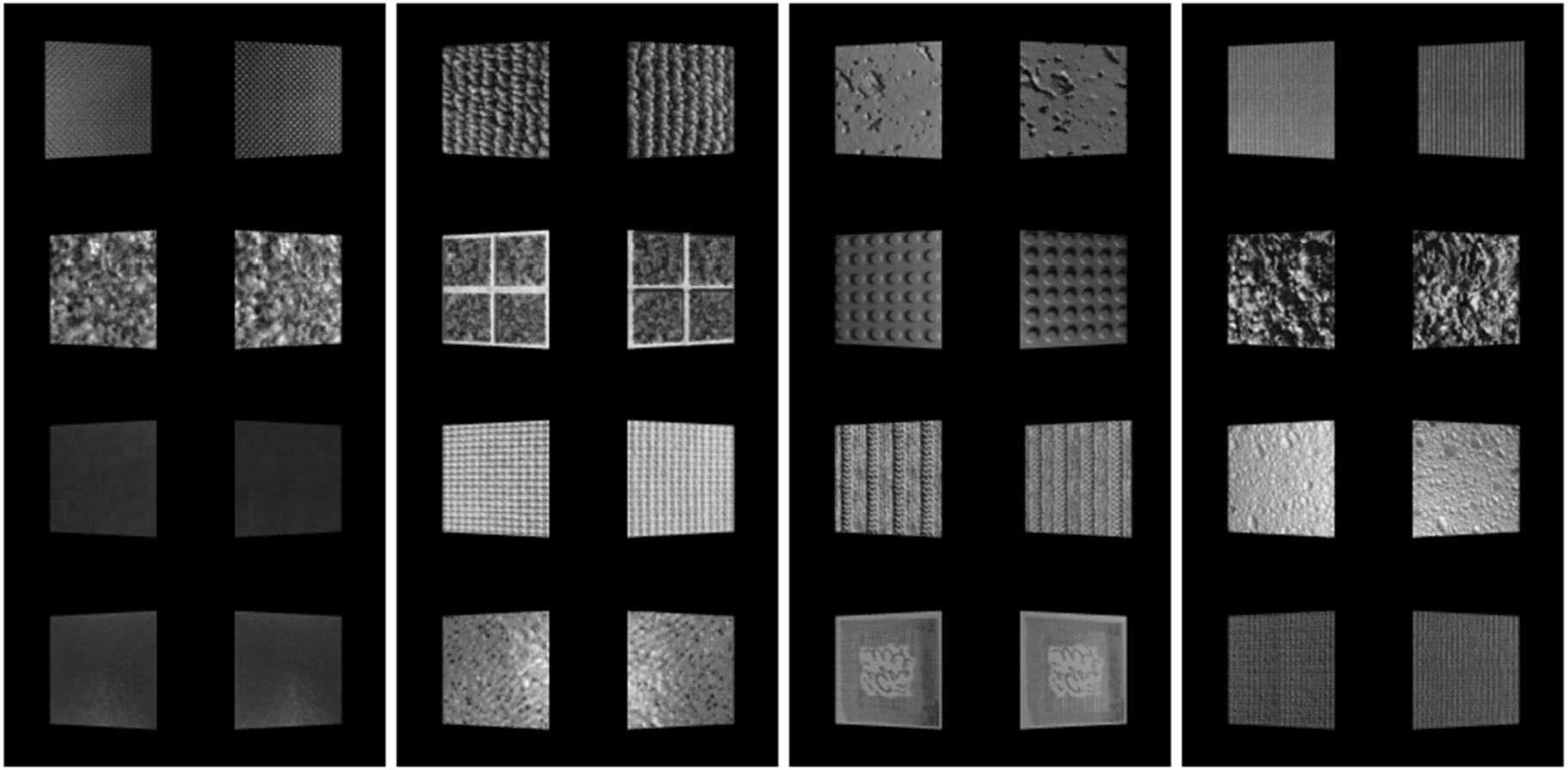








Categorization Experiment



Summary of the Future of Perceptually Based Rendering