Fabricating Microgeometry for Custom Surface Reflectance

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Acquiring & Fabricating Geometry

Wikimedia Common

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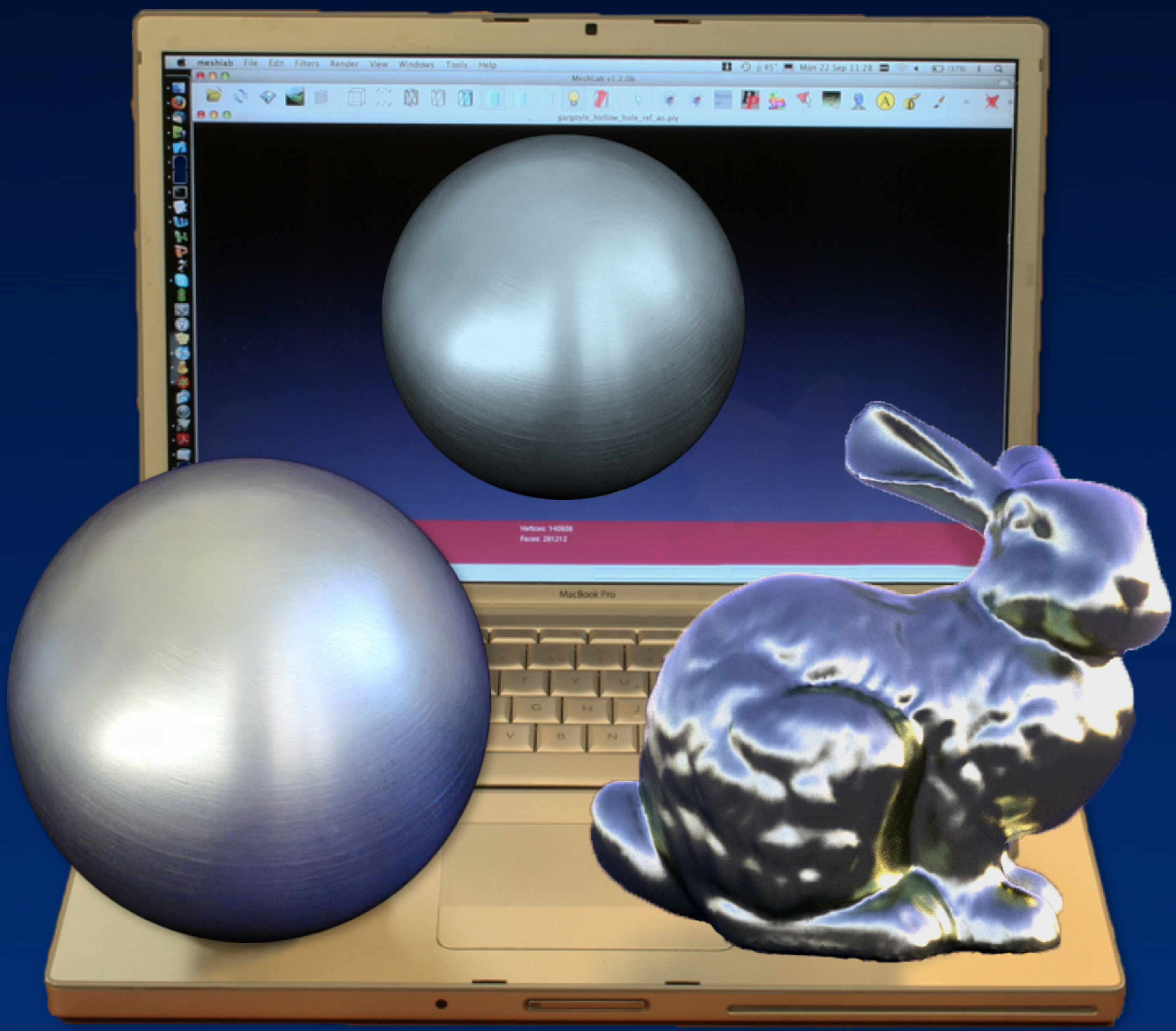
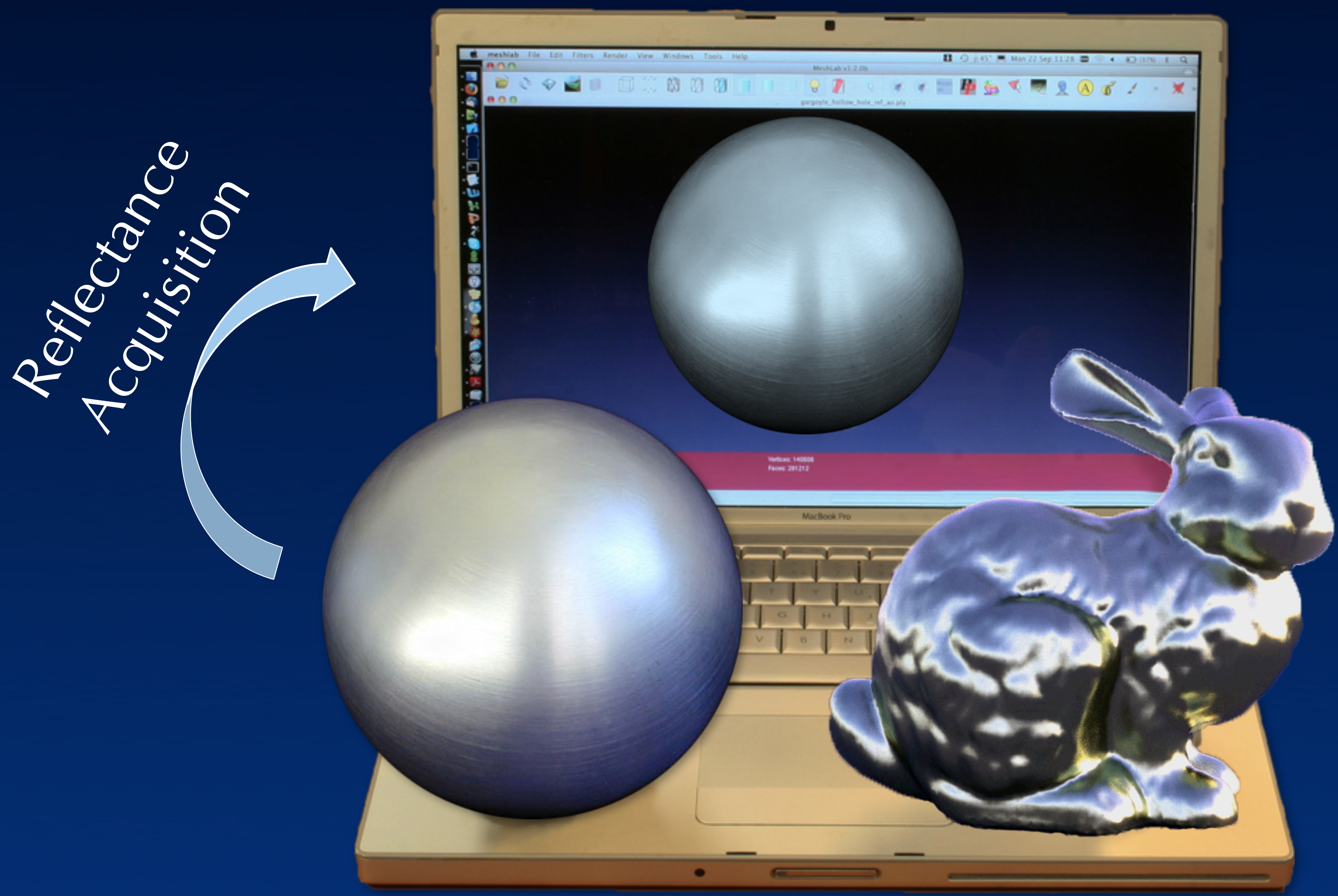
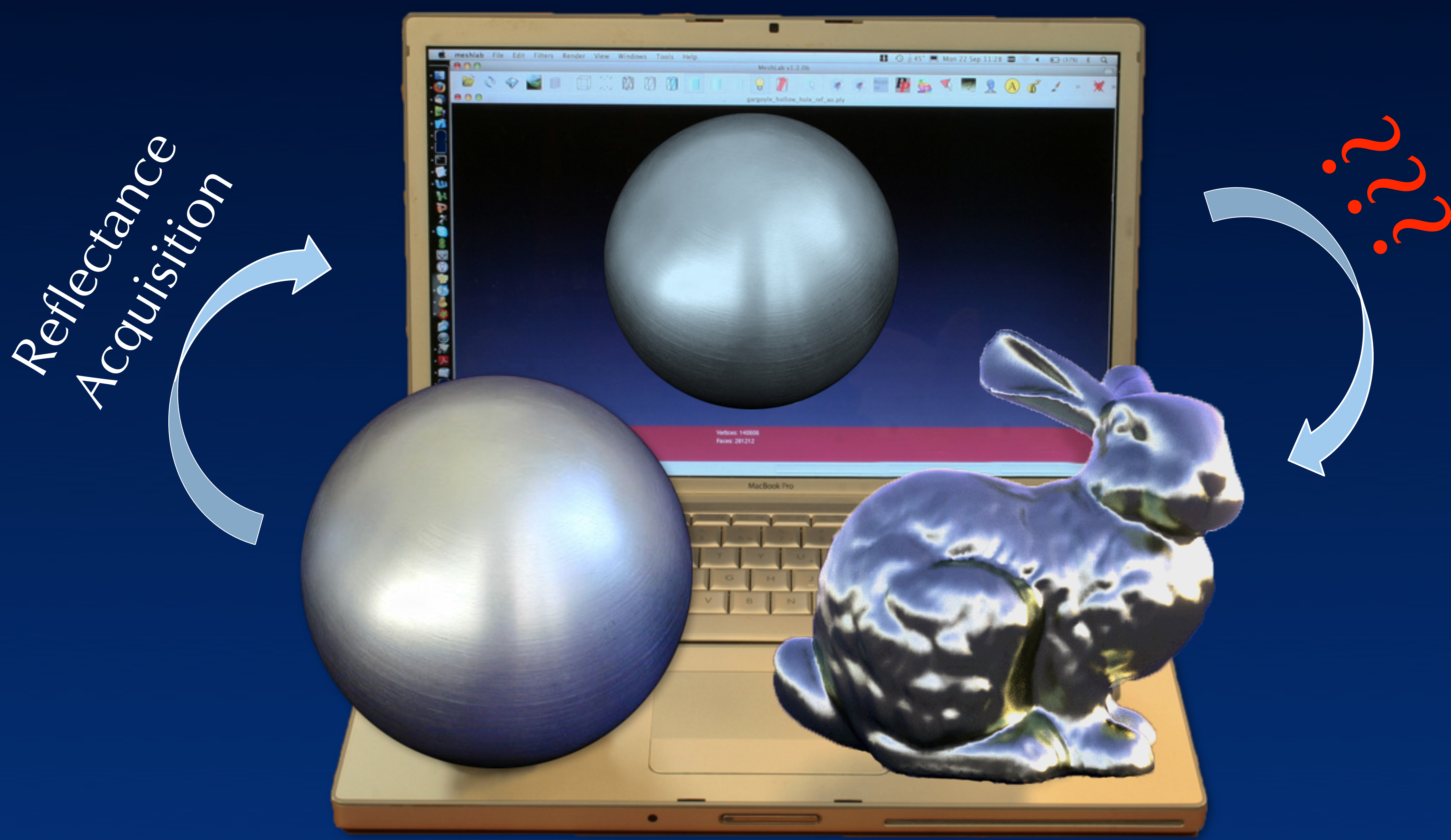
Acquiring & Fabricating Reflectance?



Acquiring & Fabricating Reflectance?



Acquiring & Fabricating Reflectance?



Microfacet Theory

- Reflectance as a result of microgeometry
  - Surface modelled by tiny mirrors (*microfacets*)
    [Torrance and Sparrow 1967]

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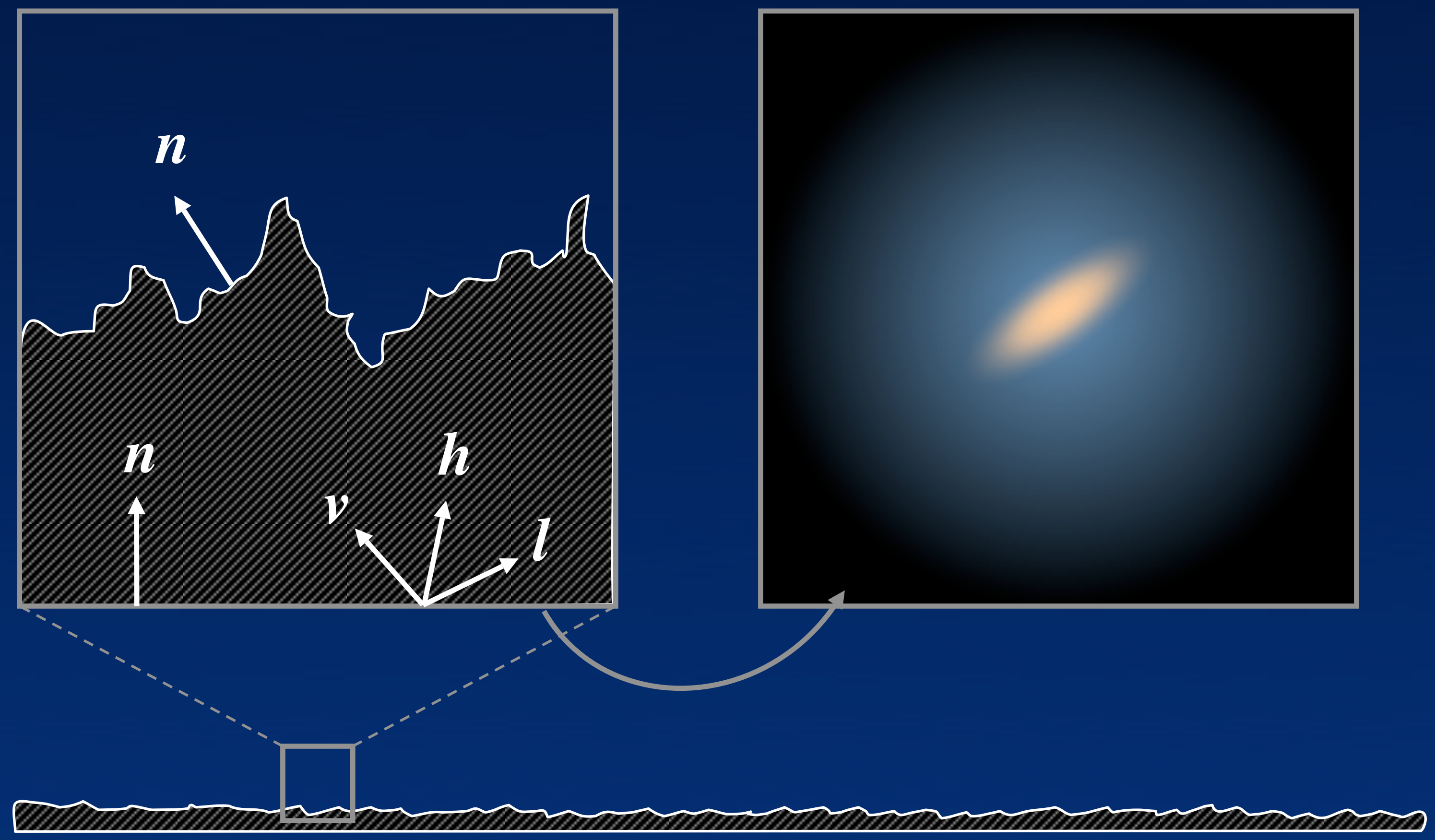

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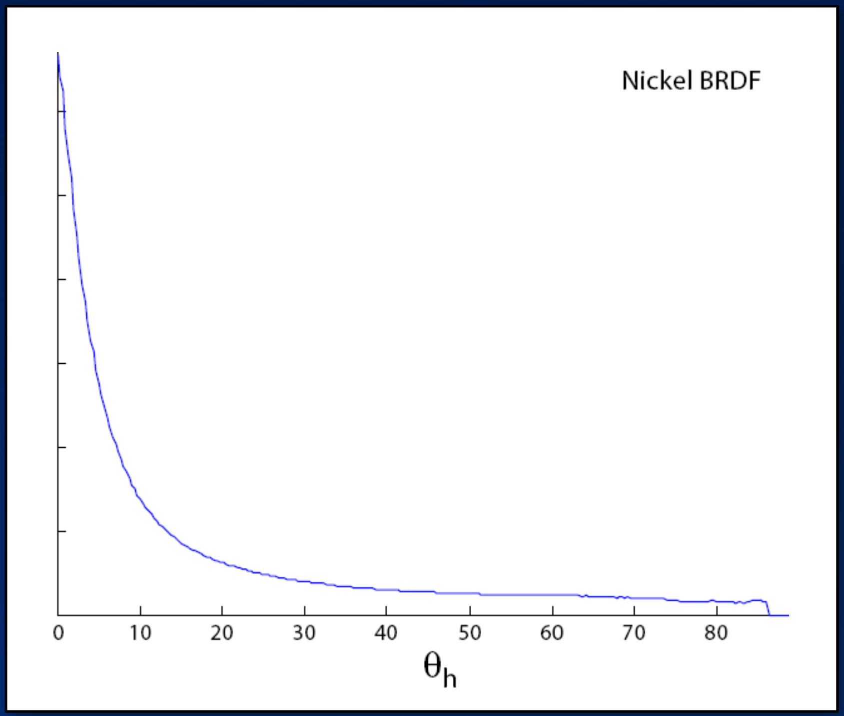
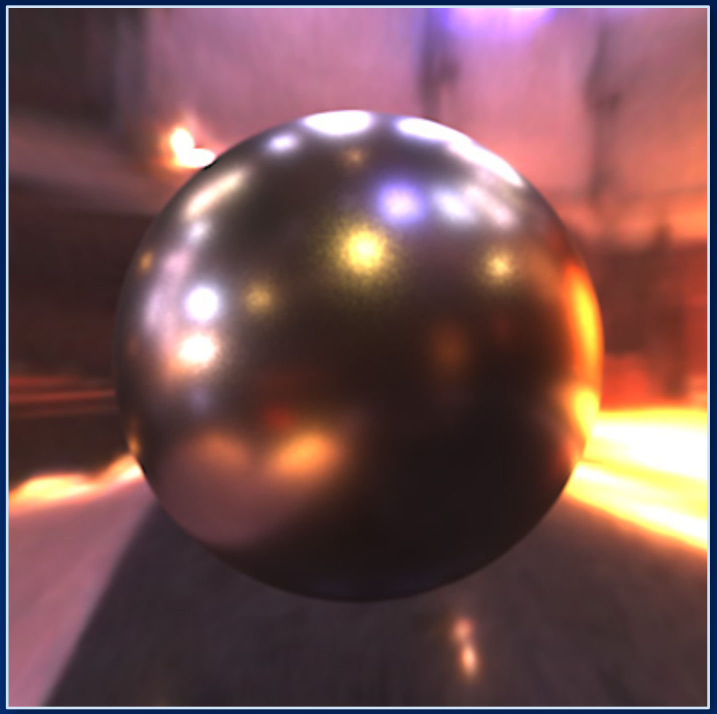


1-D Microfacet Distribution



Appearance

Microfacet Theory

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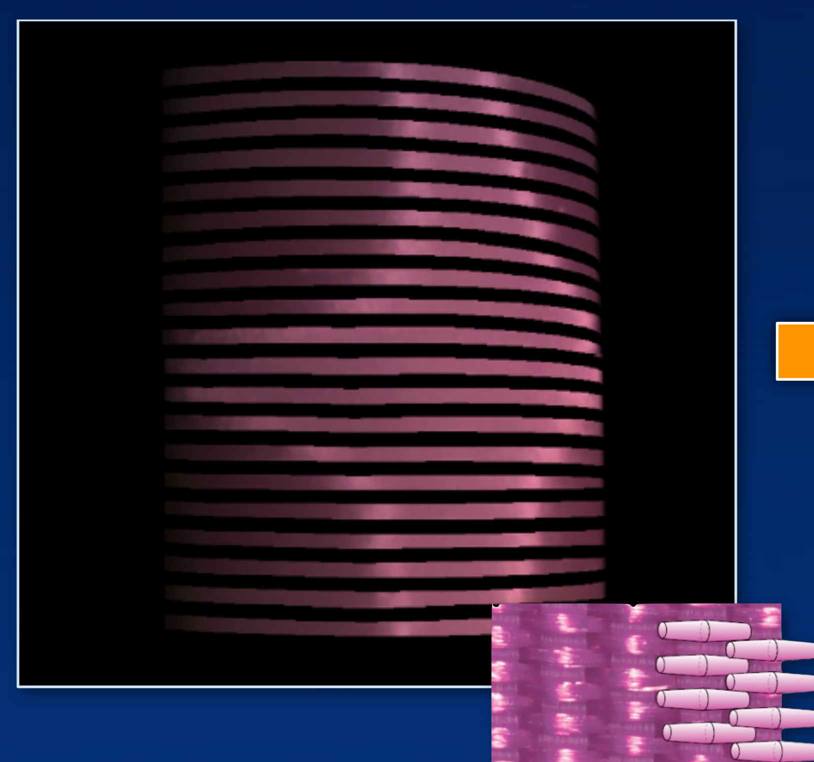
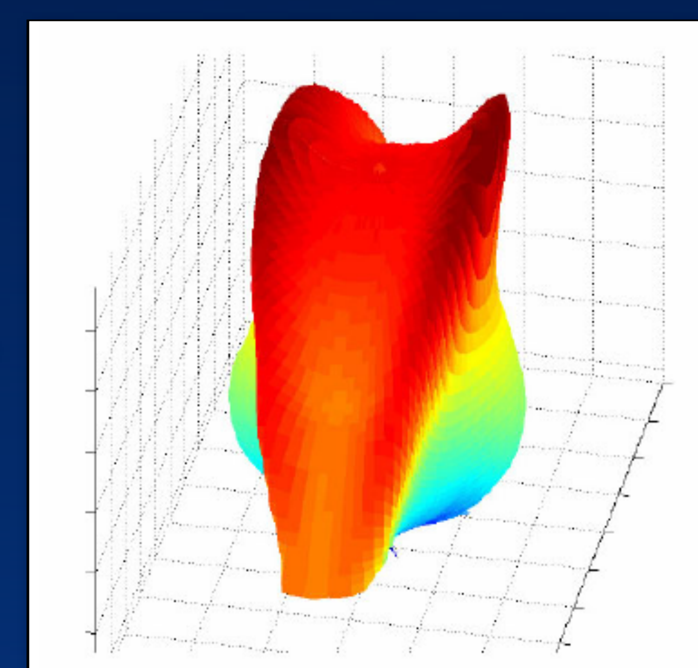
  - Net effect described by *microfacet distribution* (MFD)
- MFD can be estimated from measured data [NGAN ET AL. 2005]





[NGAN ET AL. 2005]

Microfacet Theory

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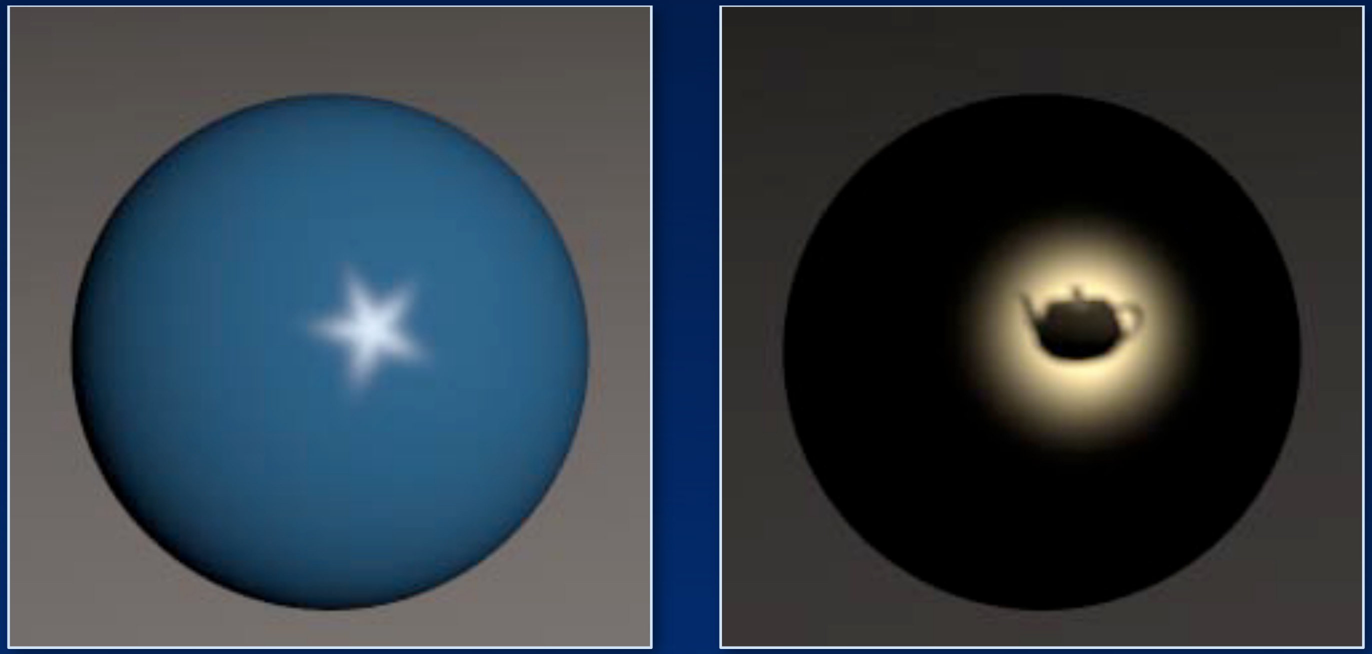
  - Surface modelled by tiny mirrors (*microfacets*) [Torrance and Sparrow 1967]
  - Net effect described by *microfacet distribution* (MFD)
- MFD can be estimated from measured data [Ngan et al. 2005]
- Our goal:

  fabricating microgeometry from an MFD

Previous Work

- Material design and editing
  - Aggregate BRDF from arbitrary microgeometry or MFD [Westin et a. 1992; Ashikhmin et al. 2000]



[Ashikhmin et al. 2000]

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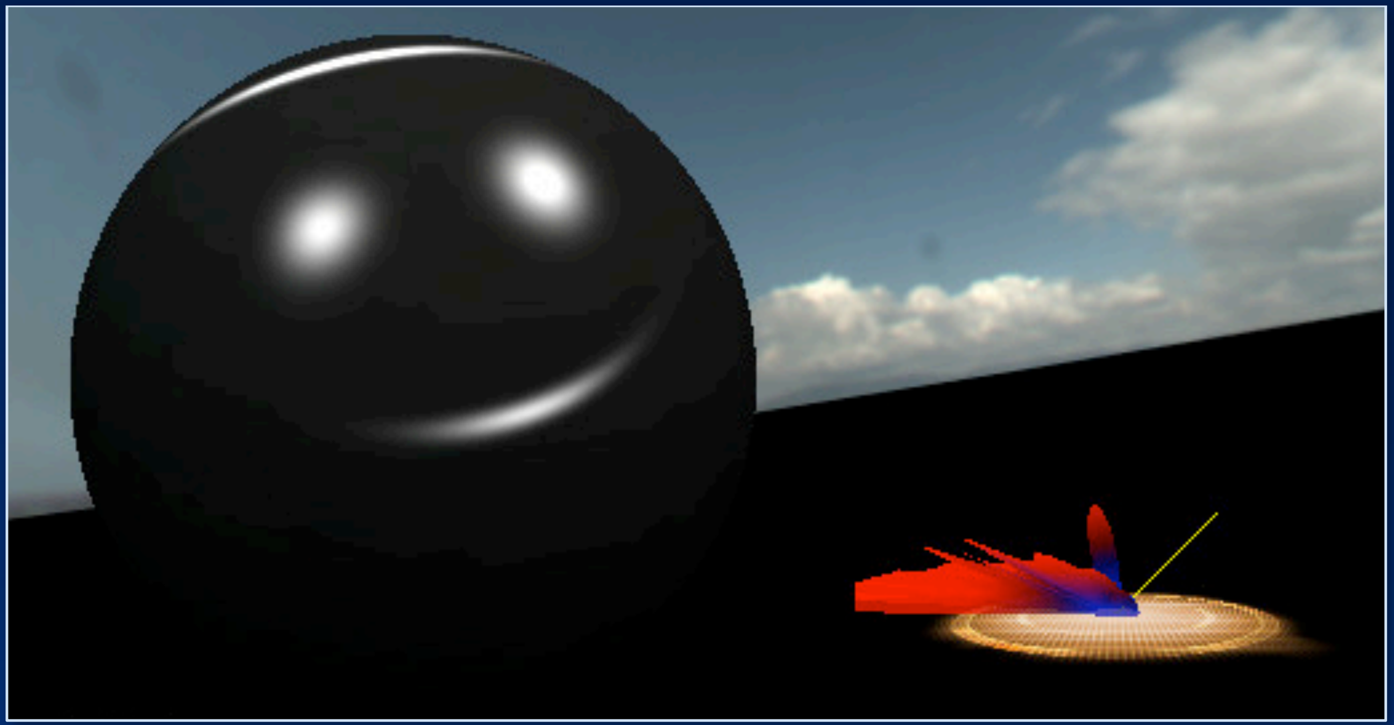
  - BRDF design by drawing highlights [COLBERT ET AL. 2006]



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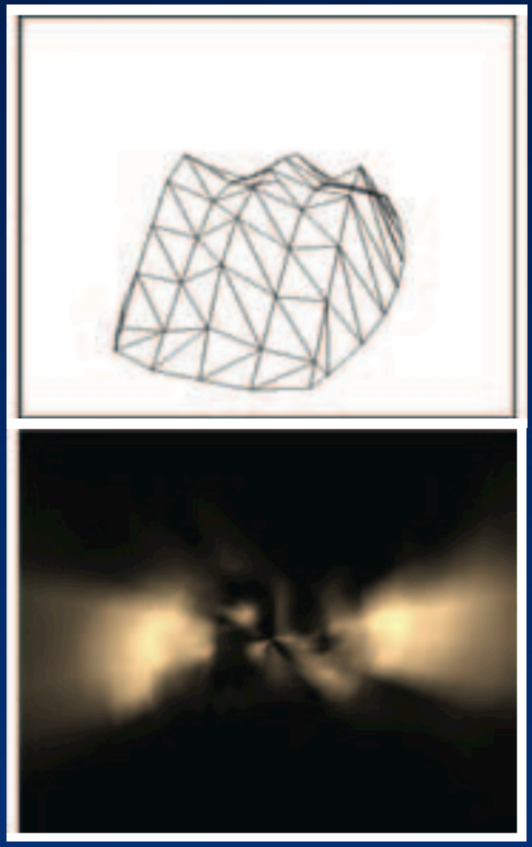
- Reflector design
  - Search for mirror geometry with target radiation [Patow and Pueyo 2005; Patow et al. 2007]



[Patow and Pueyo. 2005]

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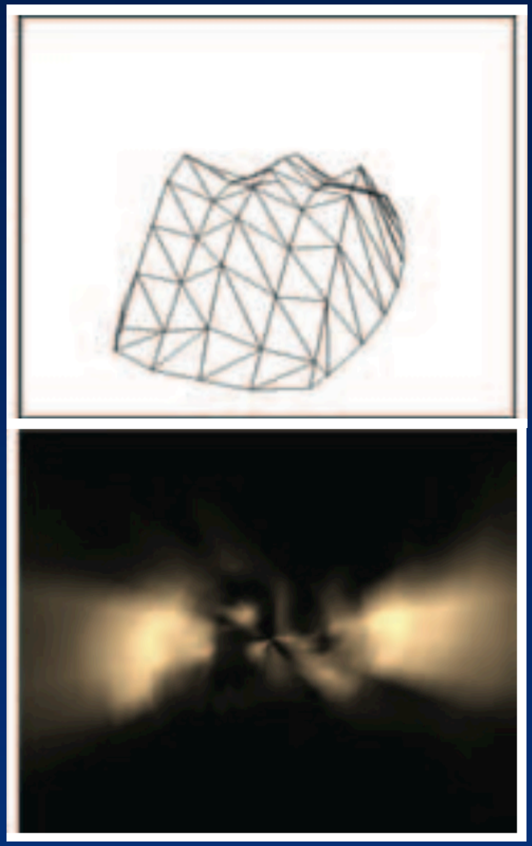
  - But fixed light source position and not planar



[Patow and Pueyo. 2005]

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- Physical appearance output
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Previous Work

- Physical appearance output
  - 3-D printing of artistic geometry [Séquin 2000]
  - Bas-relief sculpture outputs macroscopic appearance [Cignoni et al. 1997; Weyrich et al. 2007; Song et al. 2007; Kerber et al. 2007]
  - But no user-defined reflectance output

[Séquin 2005]

[Weyrich et al. 2007]

Problem Definition

- BRDF specification by microfacet distribution (MFD)
- Find microgeometry that
  - has normals that satisfy MFD
  - is a height field
  - is tileable (for efficiency)

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  - has normals that satisfy MFD
  - is a height field
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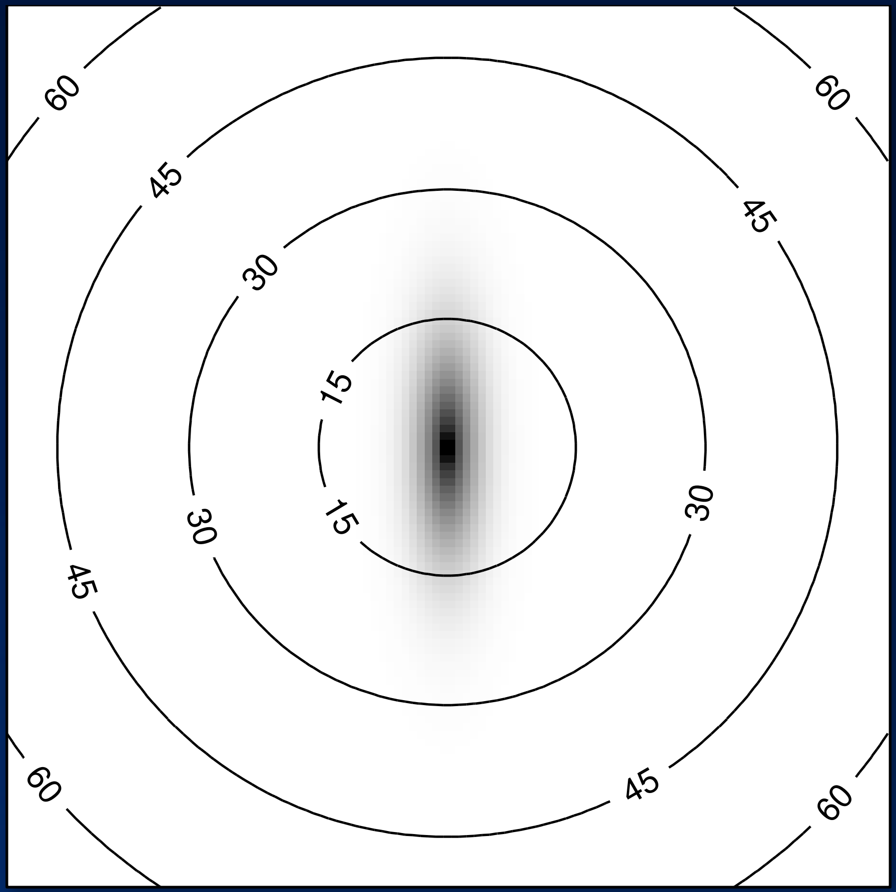
- In a sense, MFD integration problem
- Related to Poisson problem
  - except that gradient *locations* not known

Approach

Desired Highlight Shape (MFG)

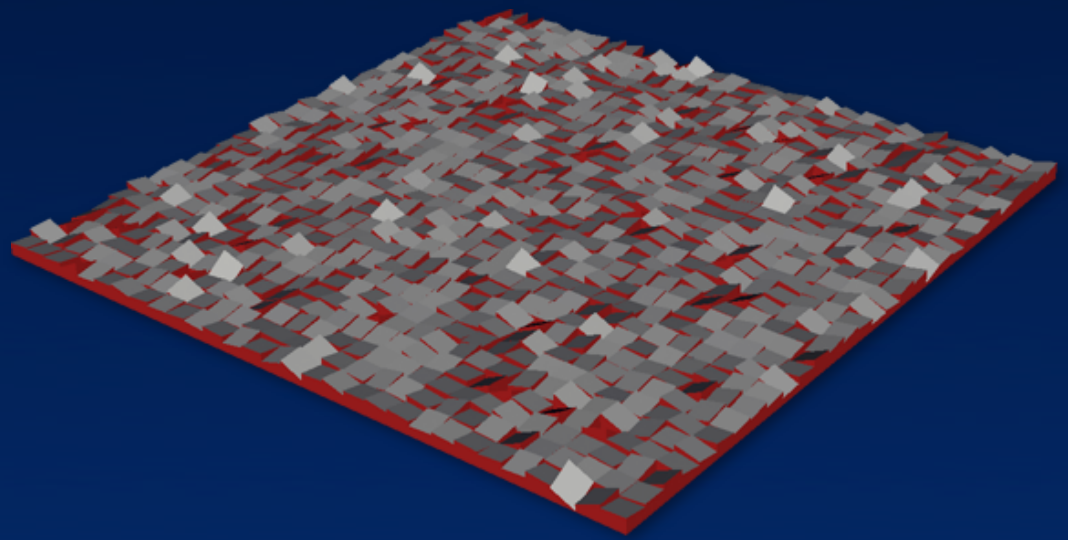


Approach

Desired Highlight Shape (MFG)

Low-Discrepancy Sampling

Sampled MF Orientations



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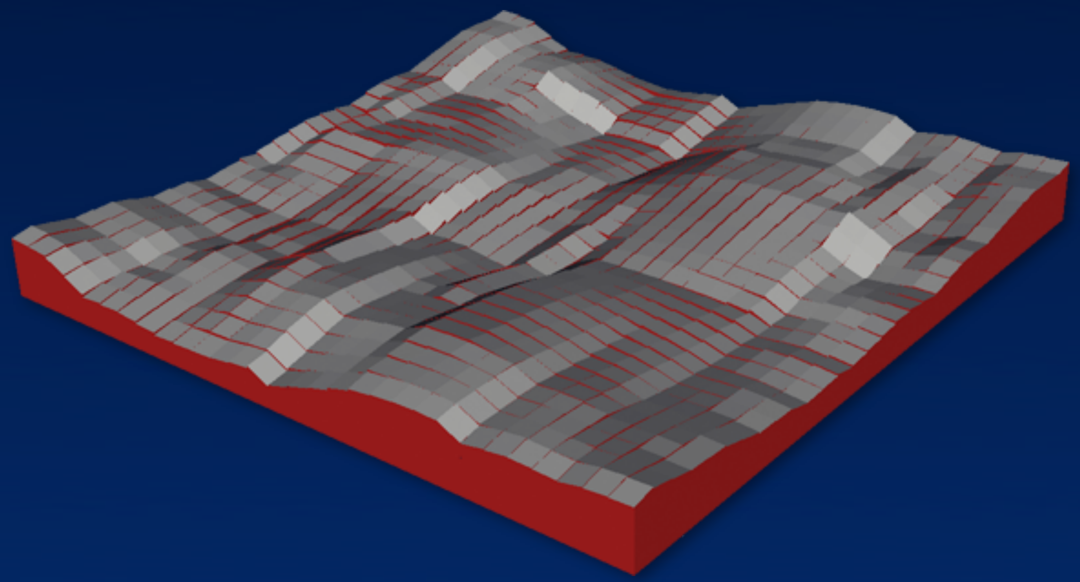
Simulated Annealing / Poisson Equation

Continuous Height Field



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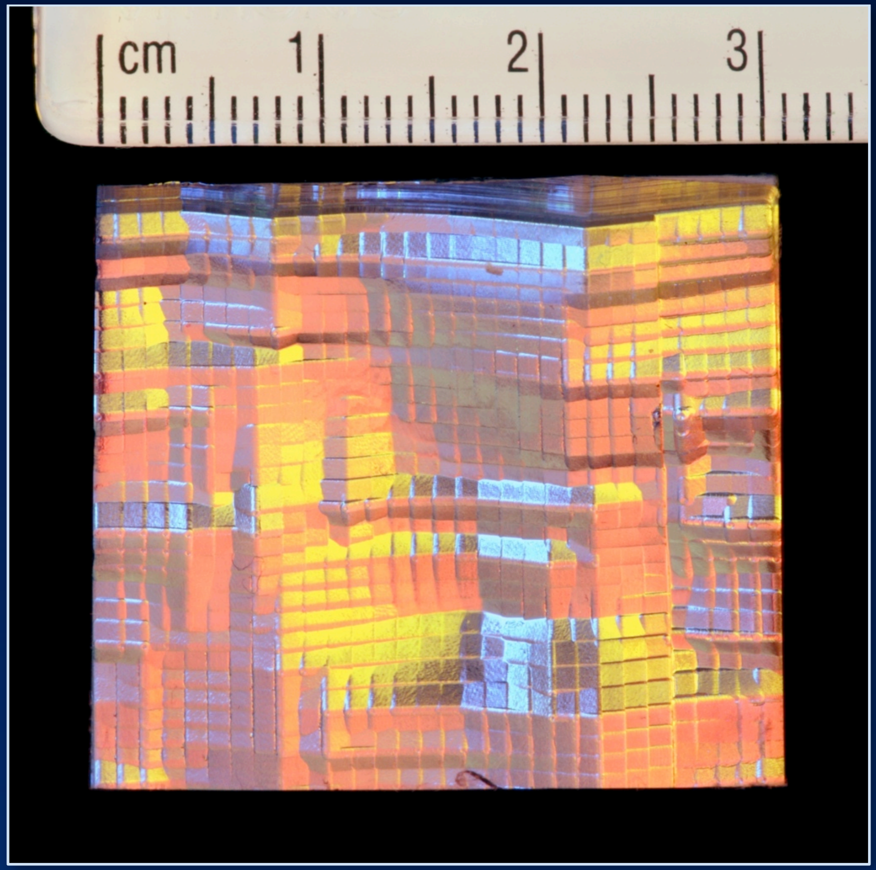
Computer-Controlled Milling

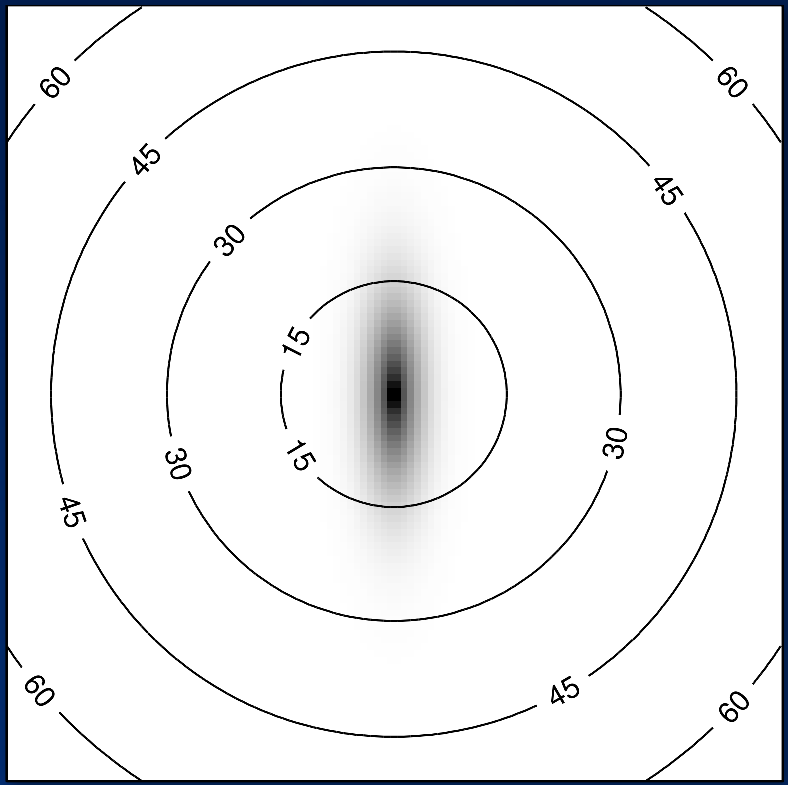
Milled Surface



Reflectance Specification

- Target BRDF assumptions
  – Spatially homogeneous
  – Purely specular (describable by MFD)

- Hemispherical MFD
  – Defined by highlight under frontal illumination
  – 2-D representation in parabolic mapping



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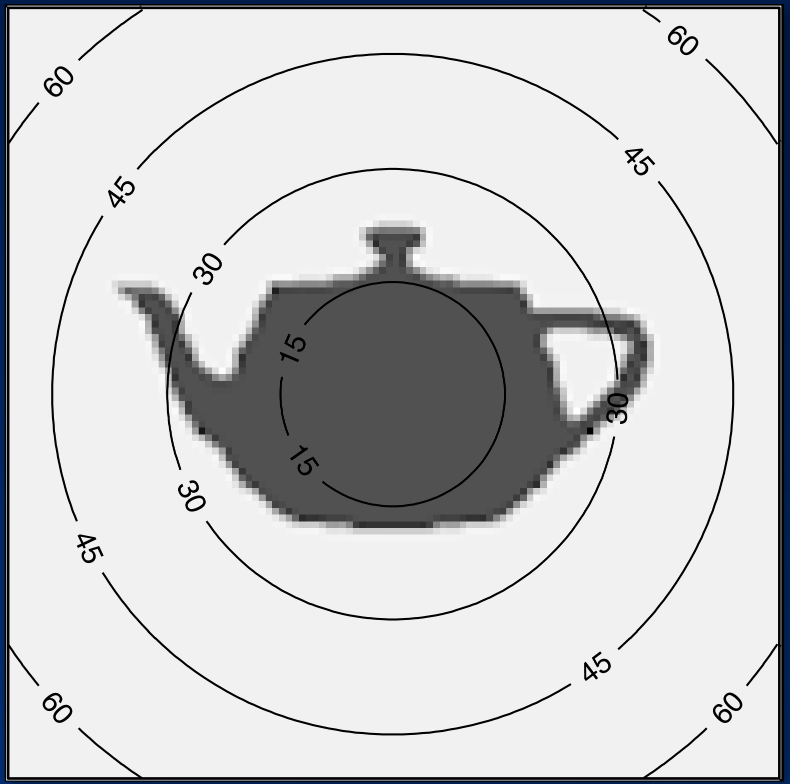

Reflectance of Base Material

- Substrate exhibits its own, base BRDF

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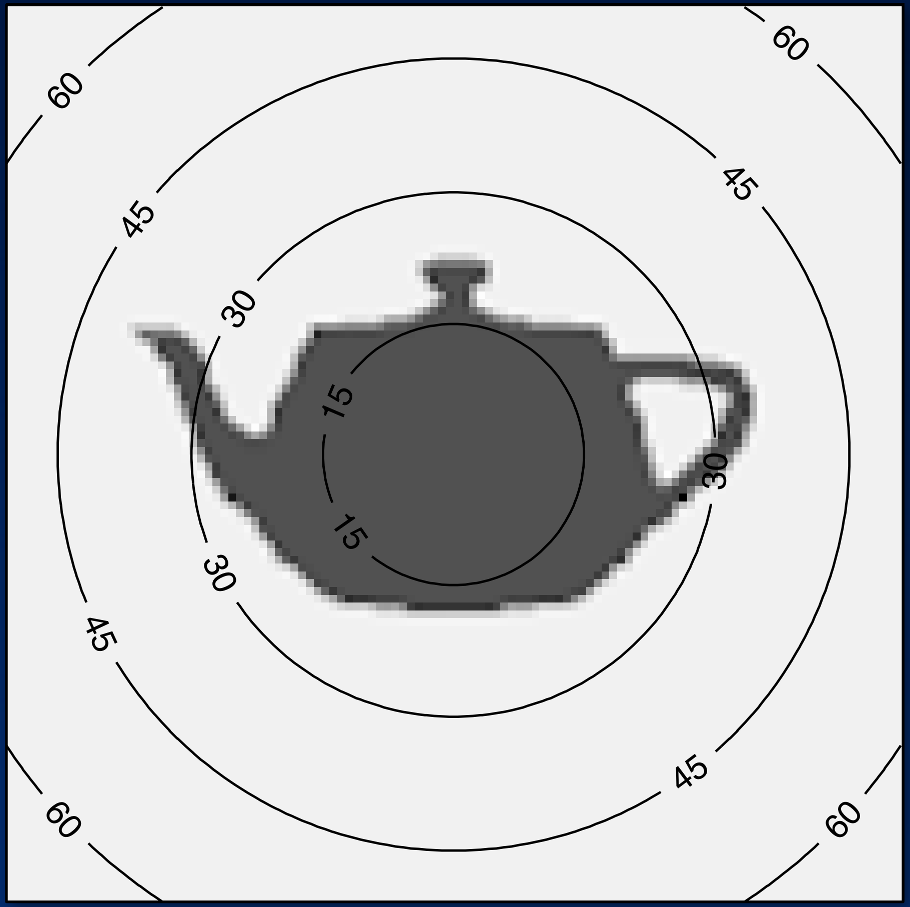
- Net BRDF is *convolution of MFD by base BRDF*

- Goal:

  Shaping base material to exhibit aggregate target BRDF

Accounting For Base BRDF

- Deconvolving Target MFD by Base BRDF
  - Lucy-Richardson deconvolution algorithm



Target MFD

Accounting For Base BRDF

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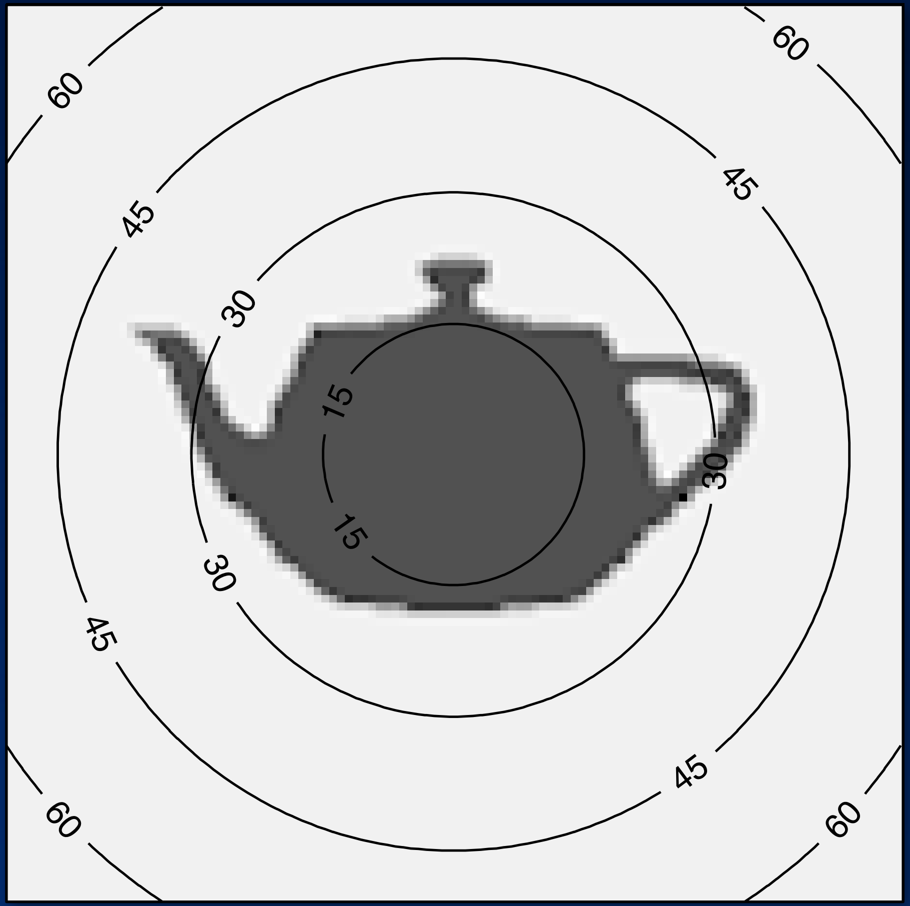
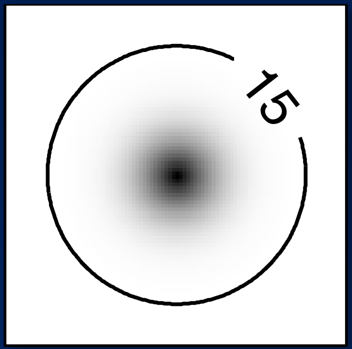


Target MFD



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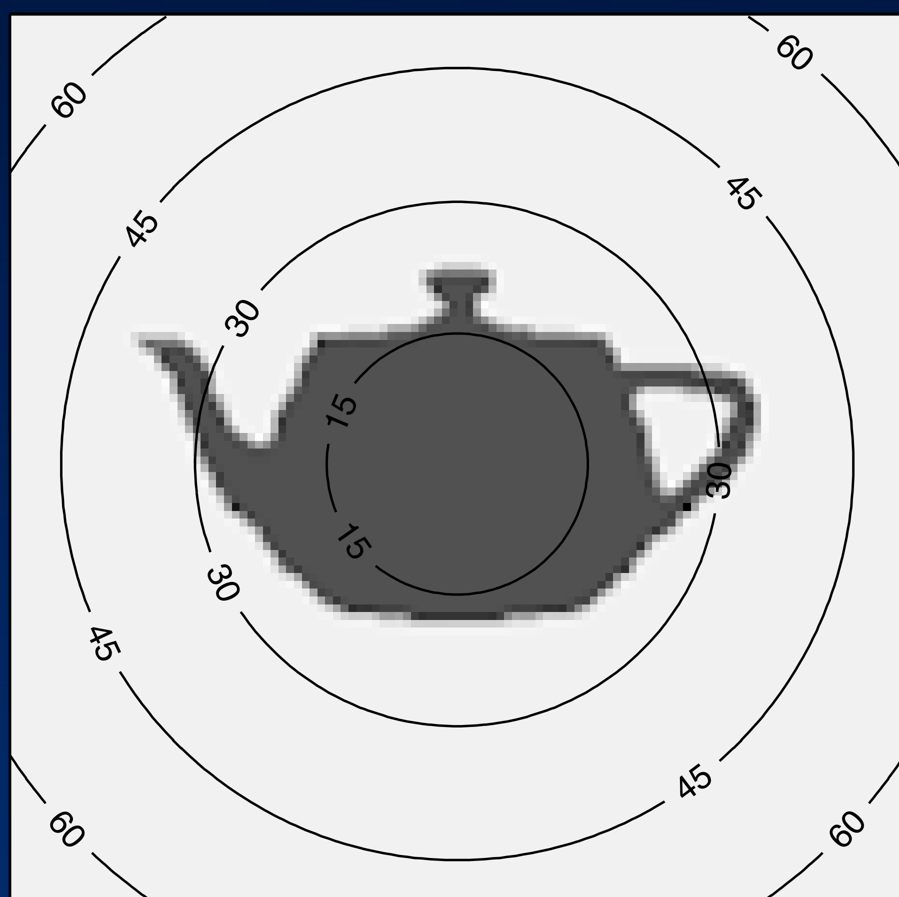
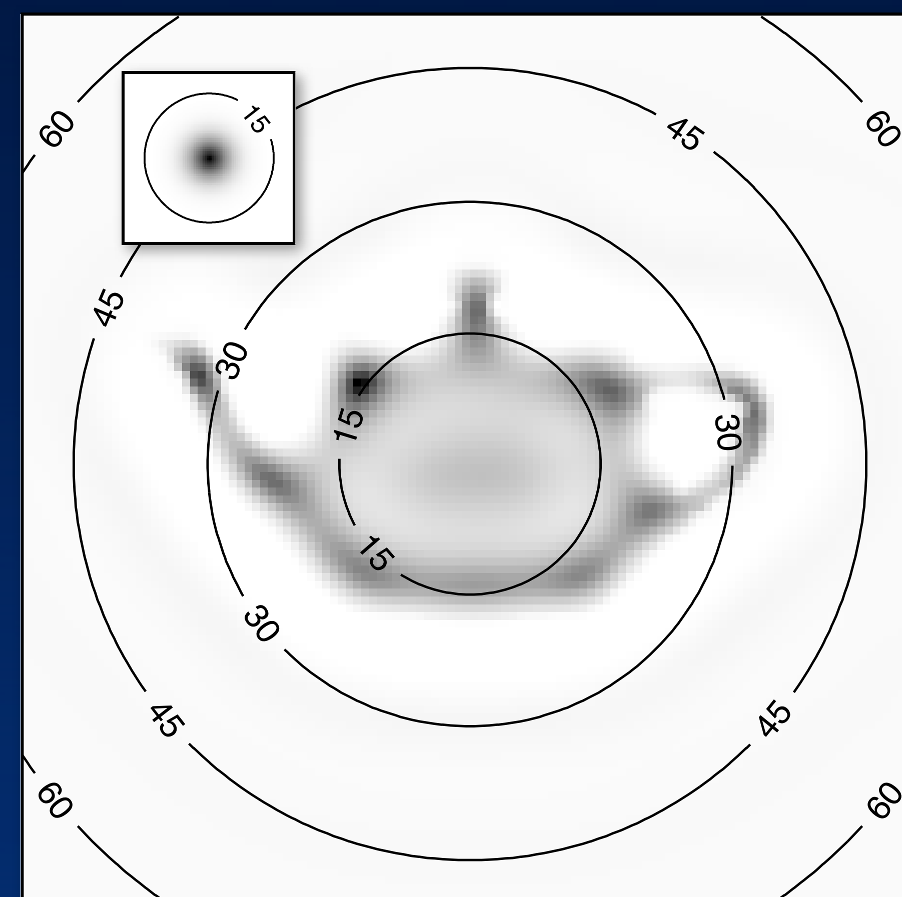
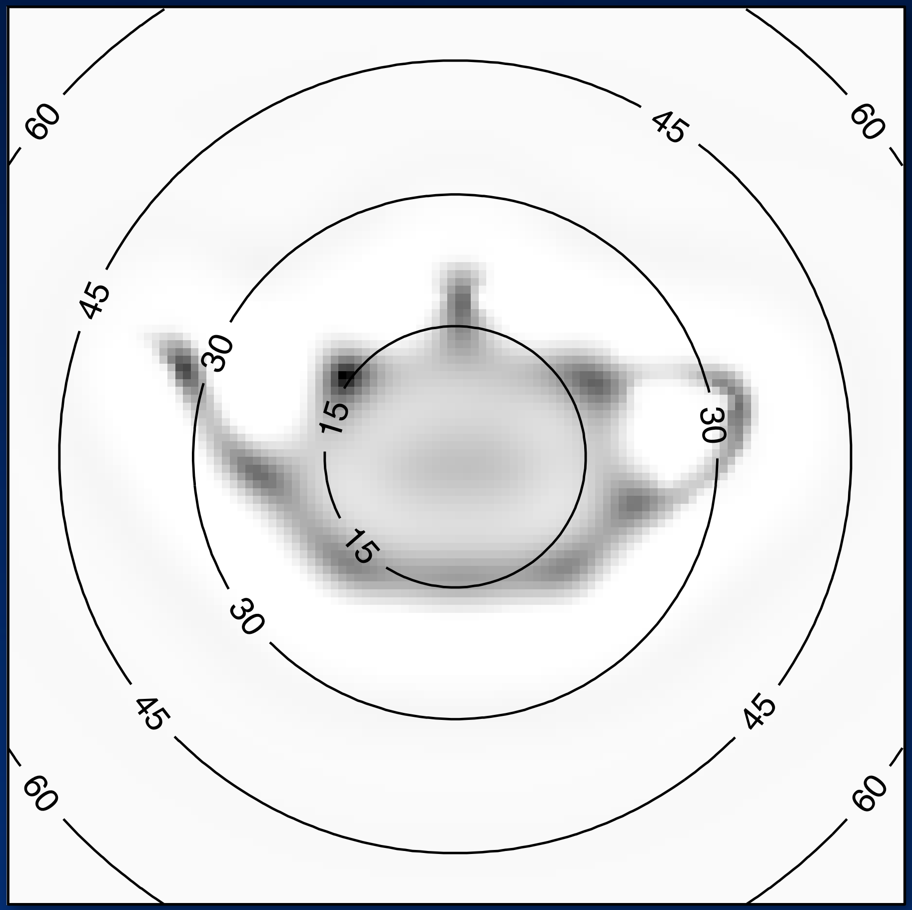


Target MFD



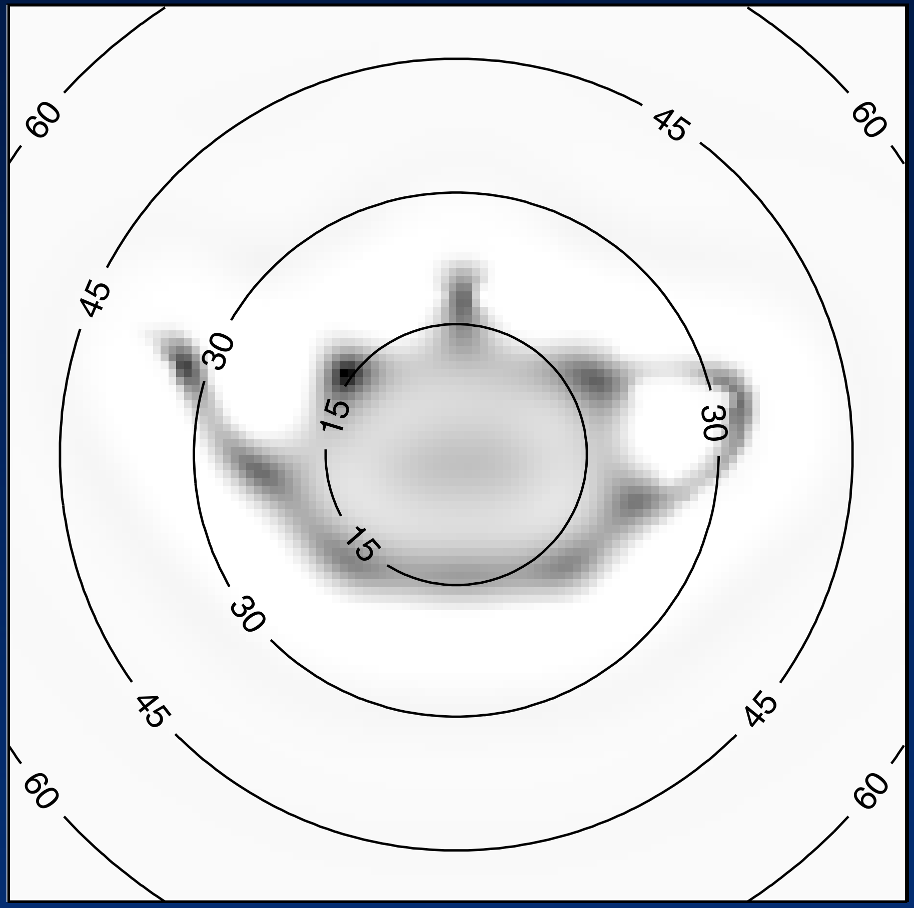
Deconvolved by base MFD

Accounting For Base BRDF



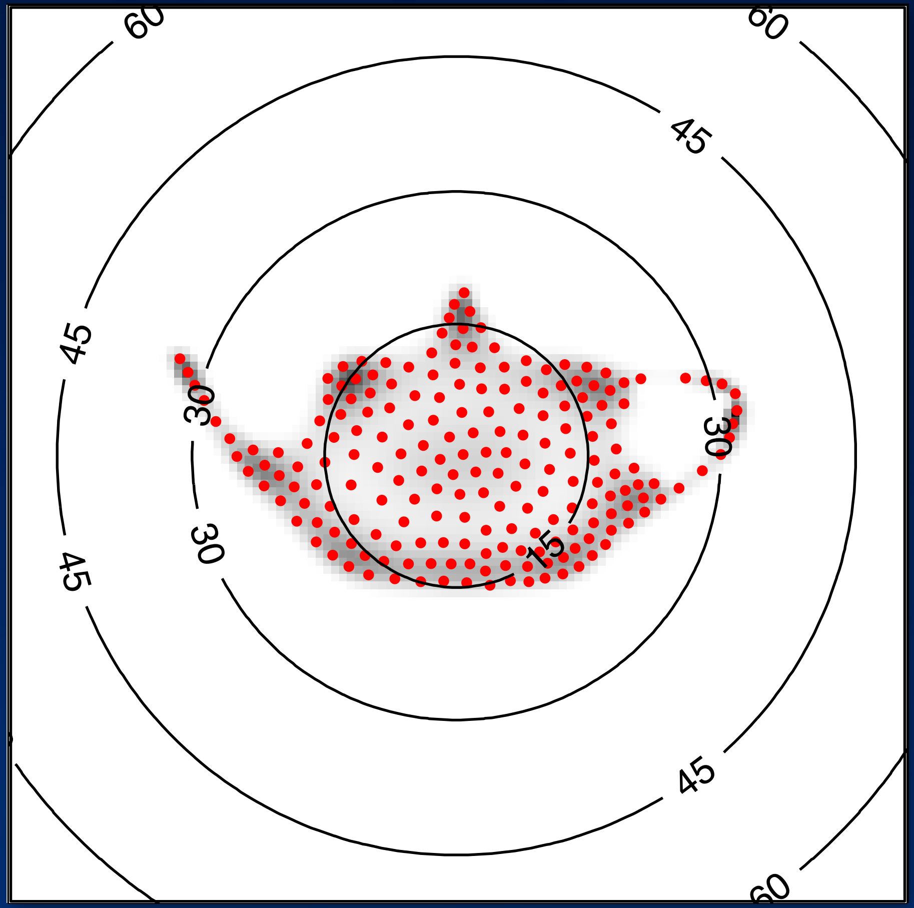
Sampling the MFD

- Microfacets cannot control "brightness" of a reflection



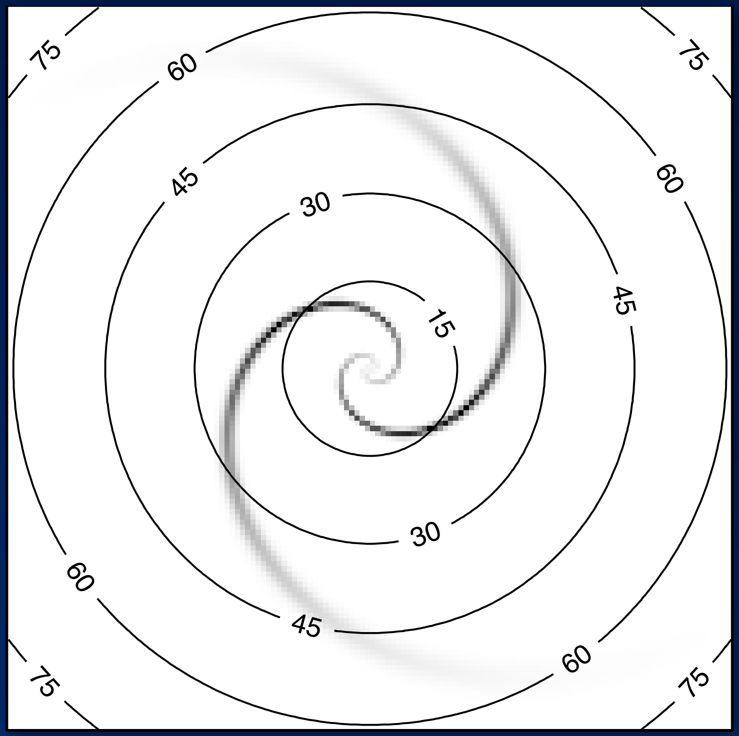
Sampling the MFD

- Microfacets cannot control “brightness” of a reflection
- “Stippling” instead: drawing discrete facets from MFD

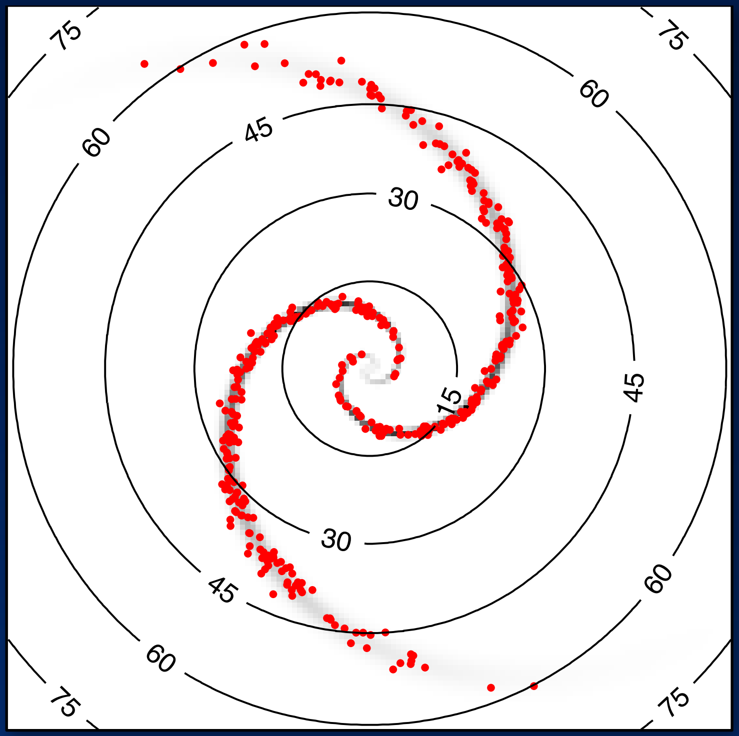


Sampling the MFD

- Low-discrepancy sampling required



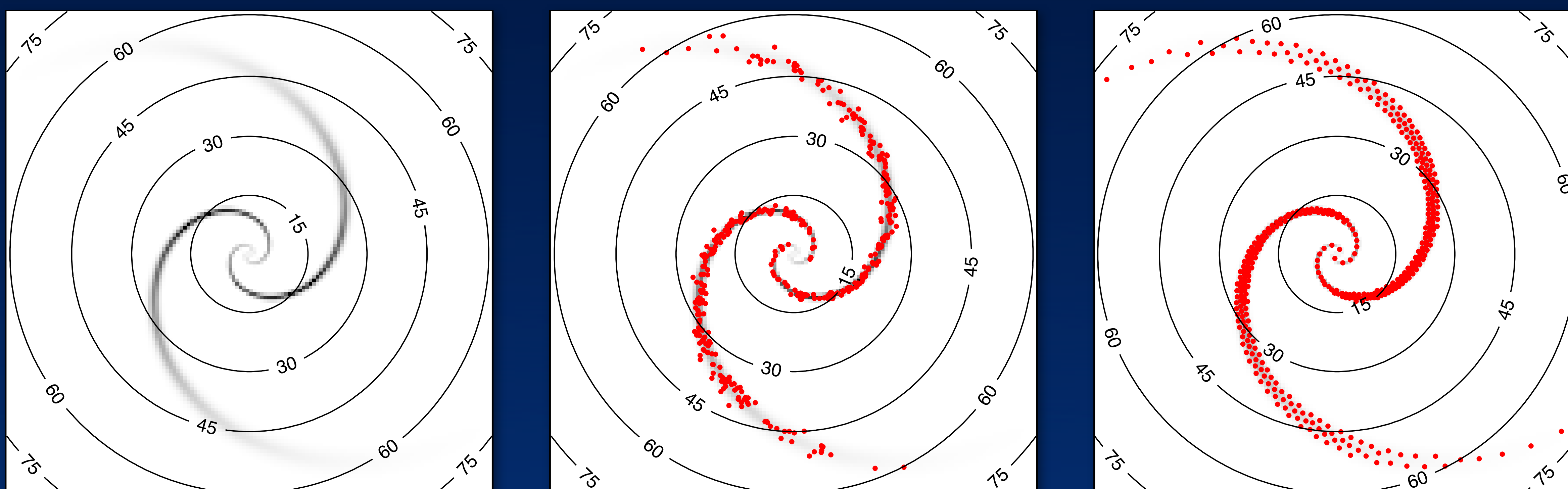
Target MFD



Random Sampling

Sampling the MFD

- Low-discrepancy sampling required
- We use centroidal Voronoi tesselation [Secord 2002]

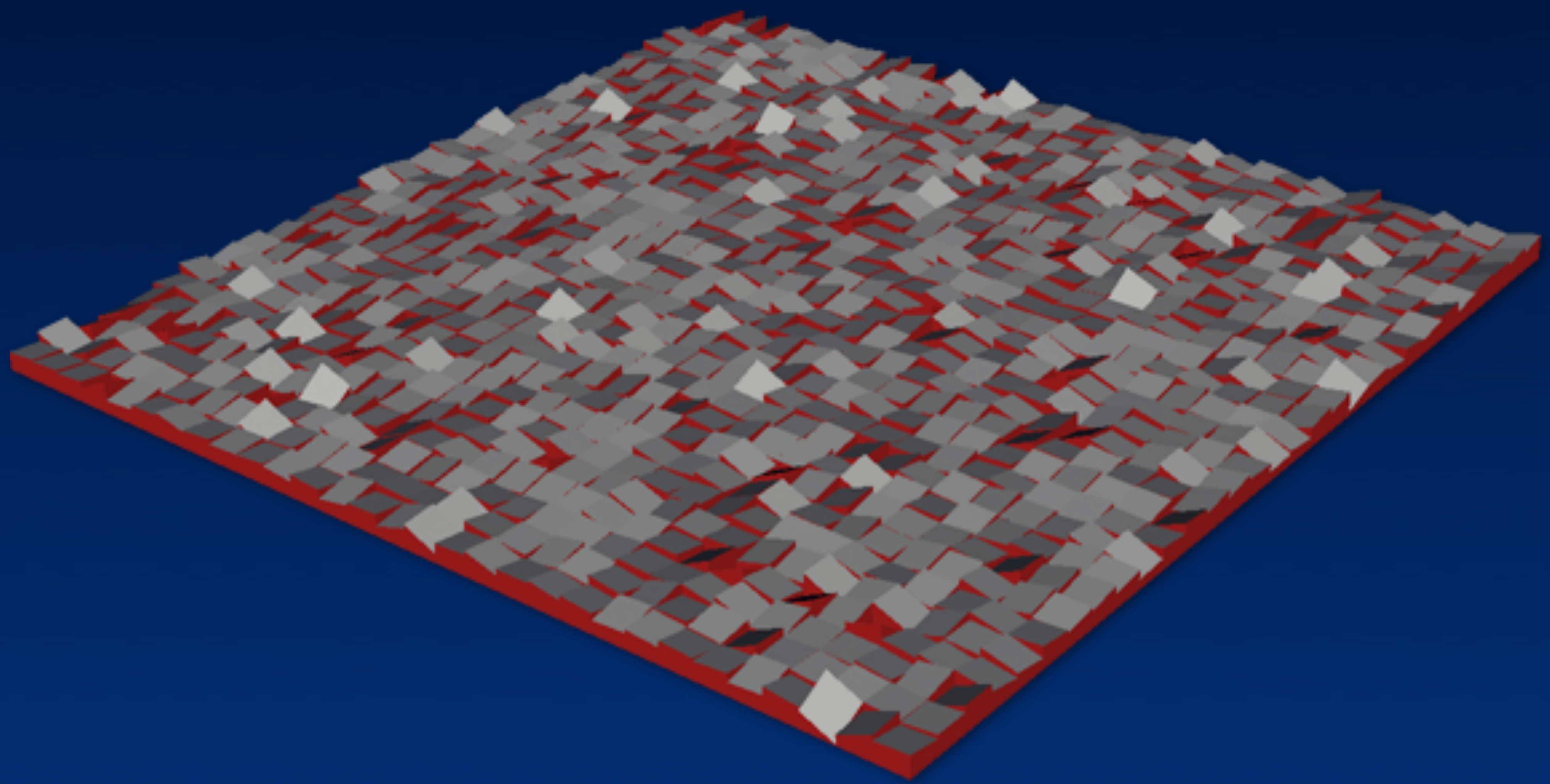


Target MFD

Random Sampling

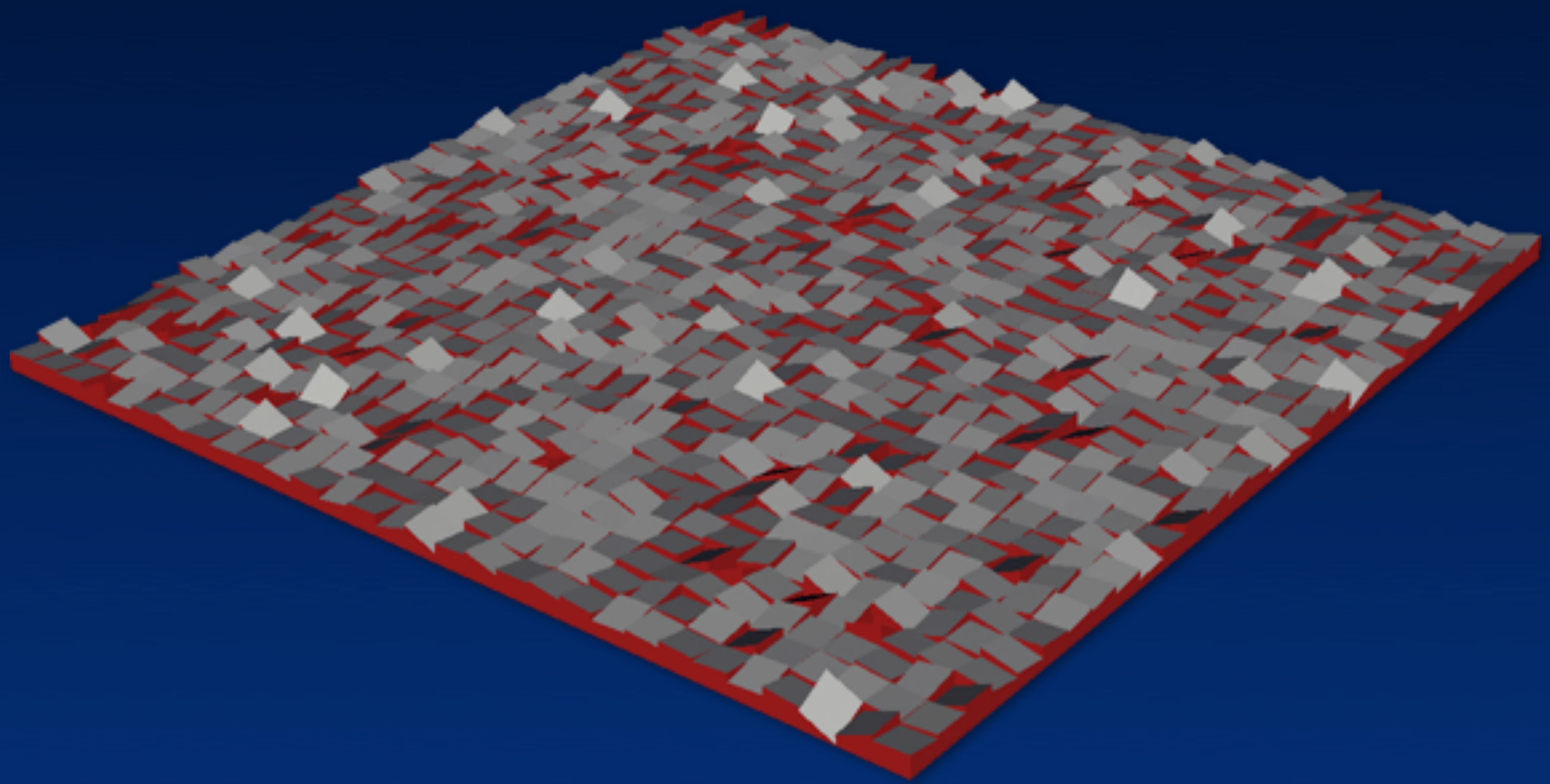
Low-discrepancy Sampling

Result of MF Sampling



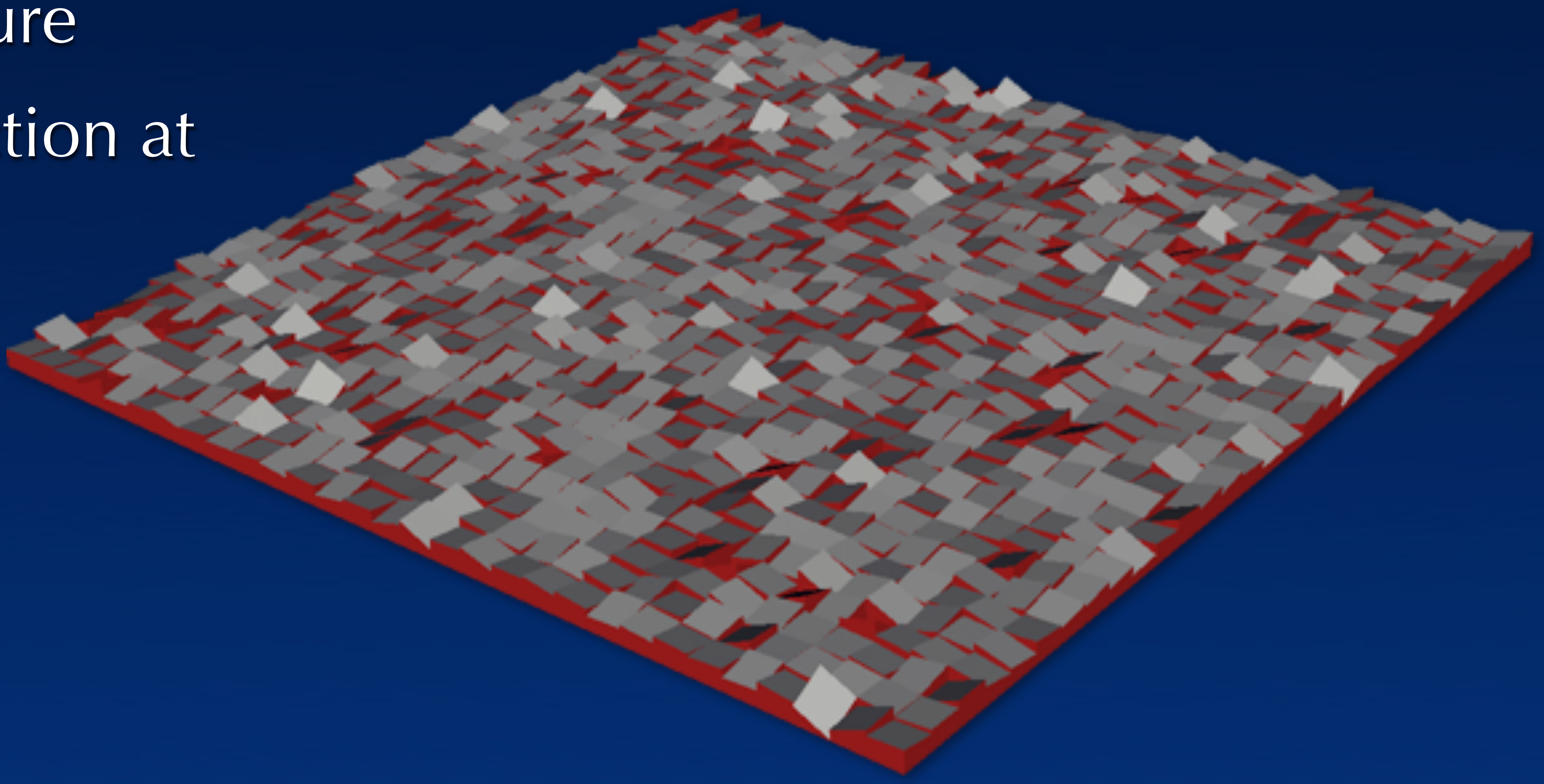
Result of MF Sampling

- Should exhibit desired aggregate reflectance…



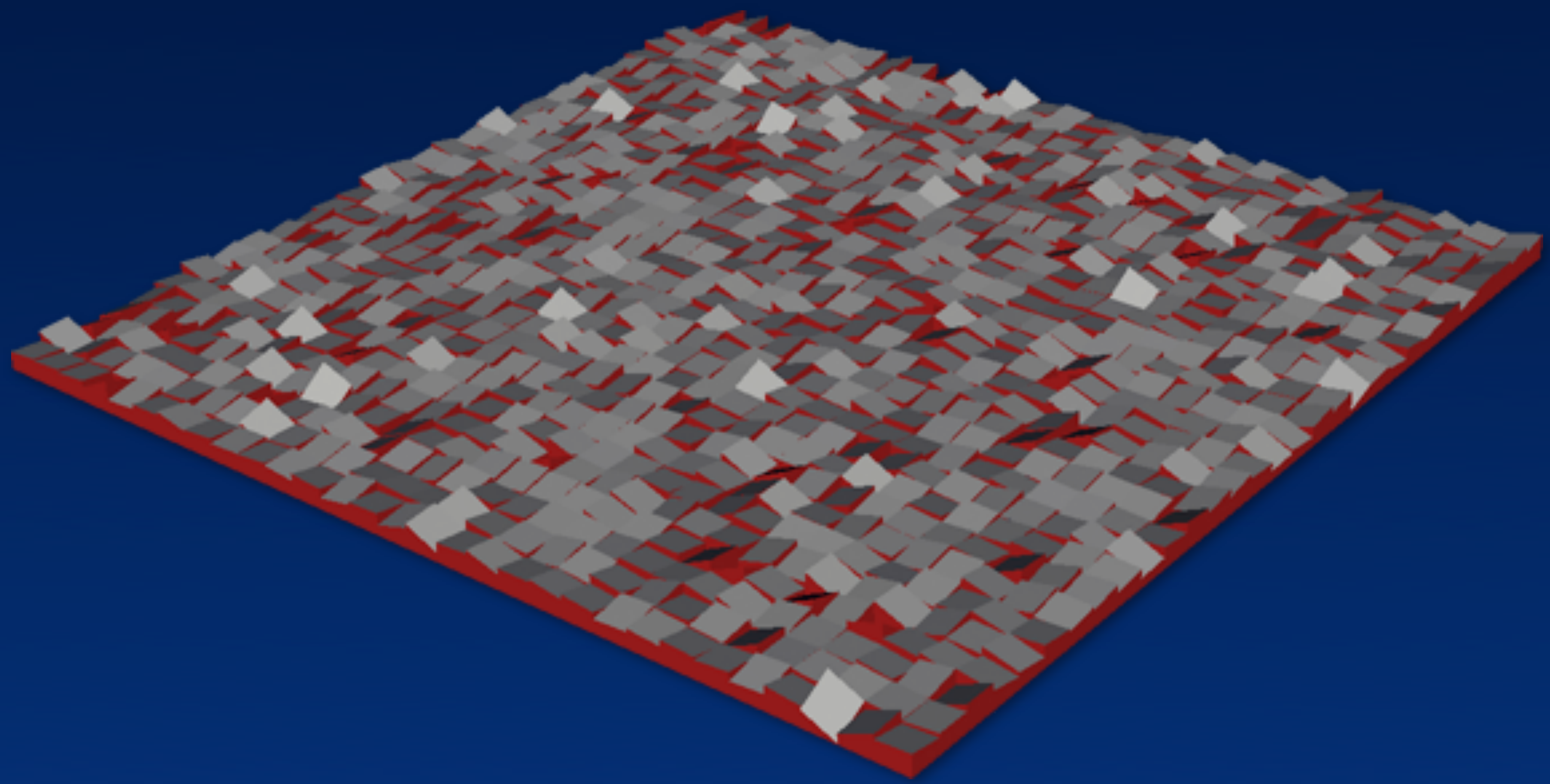
Result of MF Sampling

- Should exhibit desired aggregate reflectance…
- … but:
  - Discontinuities hard to manufacture
  - Interreflection at verticals



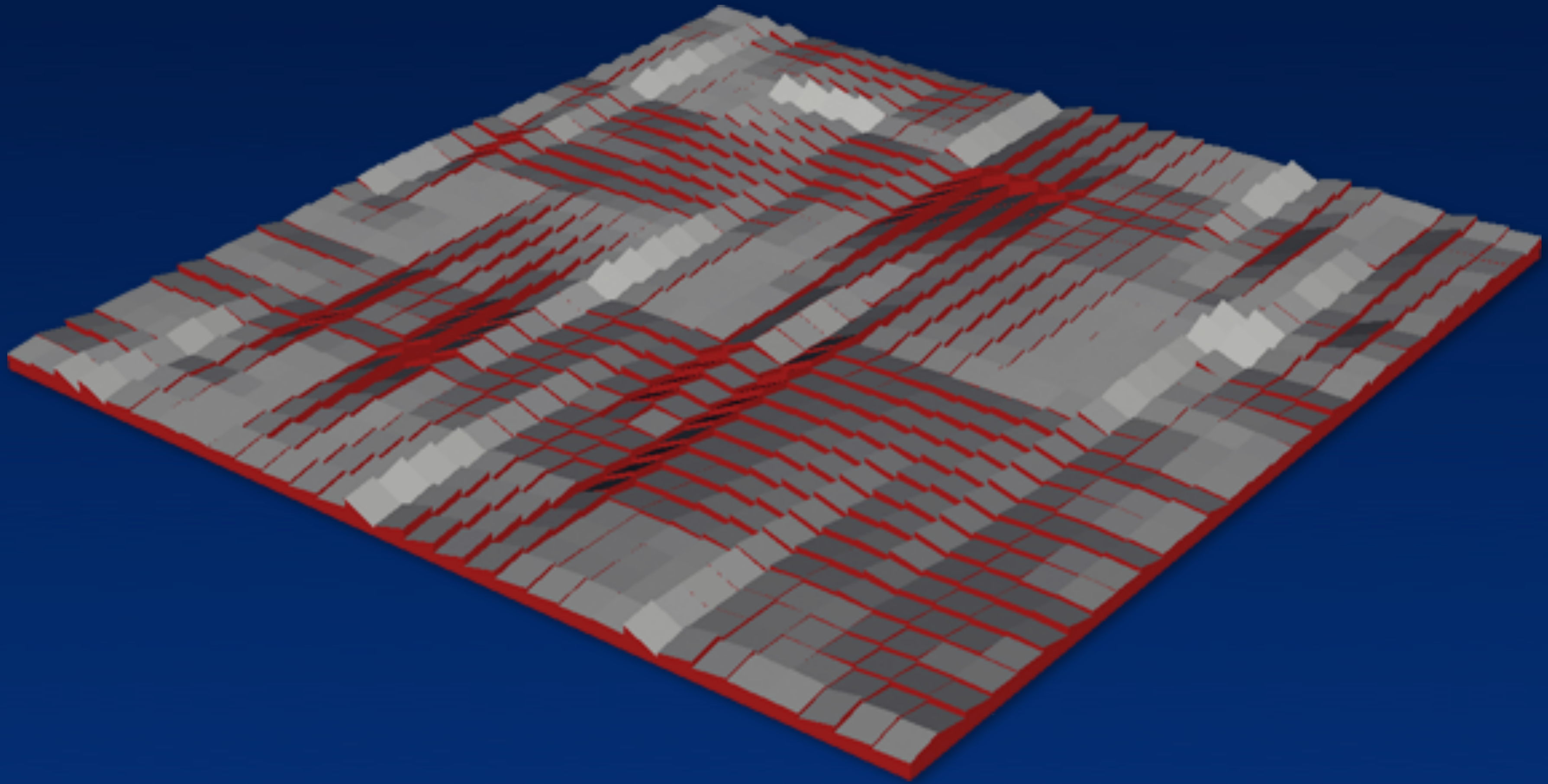
Height Field Optimization

- Maximize continuity and integrability



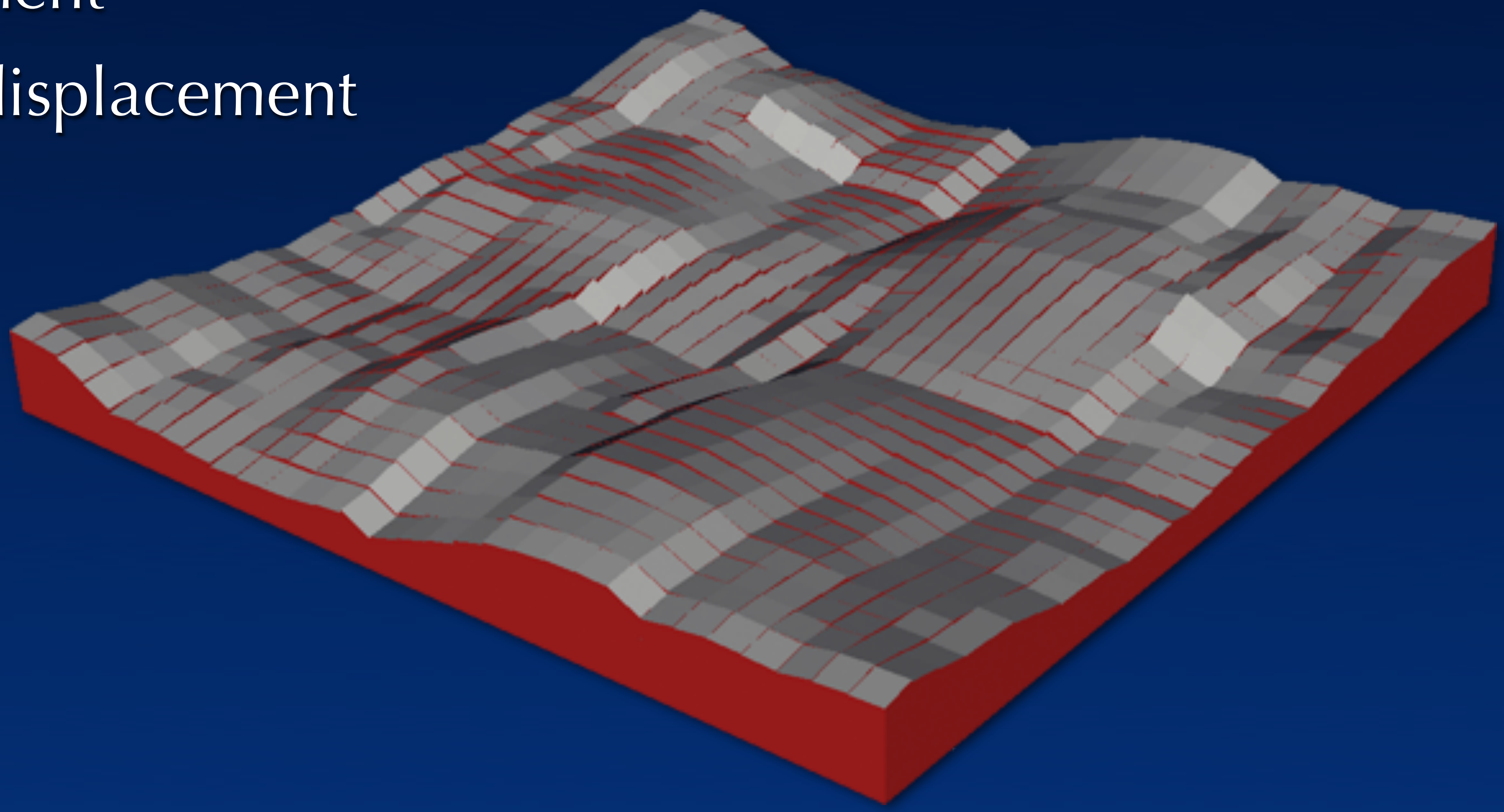
Height Field Optimization

- Maximize continuity and integrability
- Two-stage procedure
  1. Arrangement



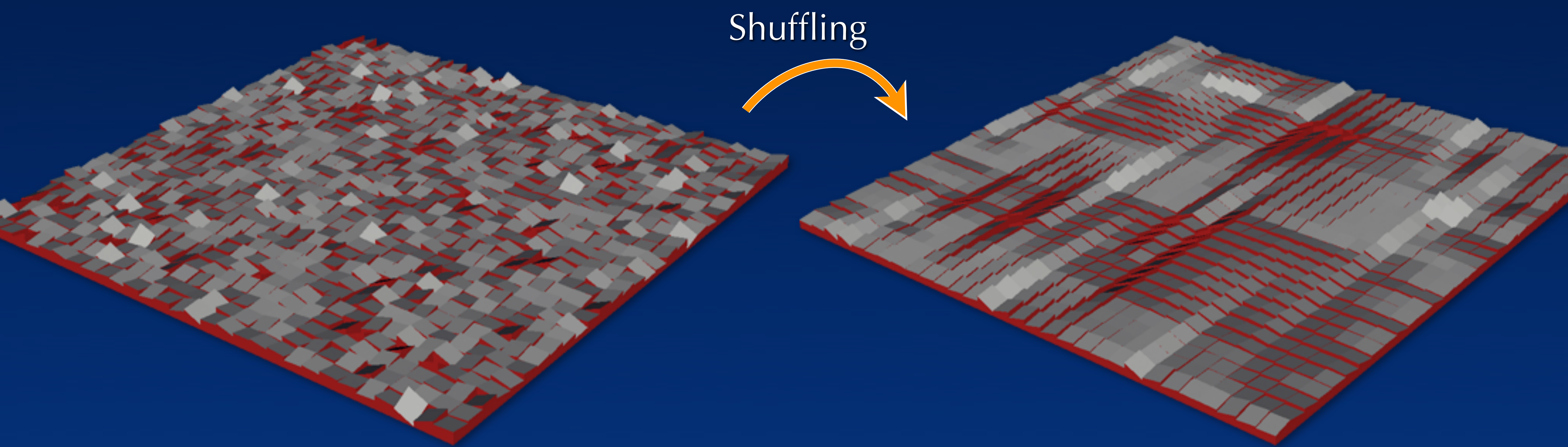
Height Field Optimization

- Maximize continuity and integrability
- Two-stage procedure
    1. Arrangement
    2. Vertical displacement



Arrangement Optimization

- Shuffling facets to optimize:



Arrangement Optimization

- Shuffling facets to optimize:
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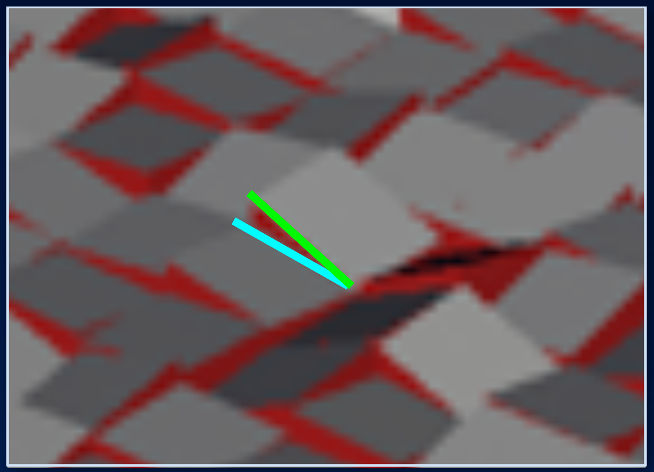

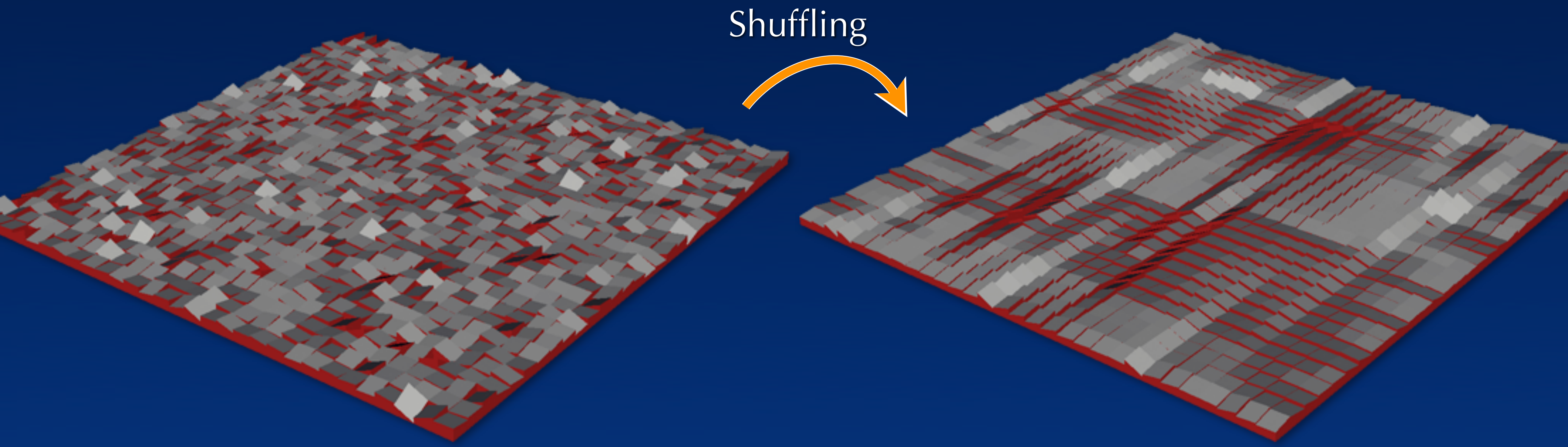

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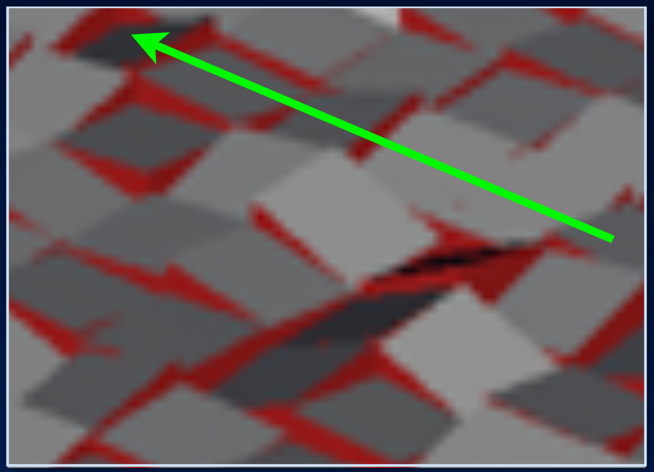
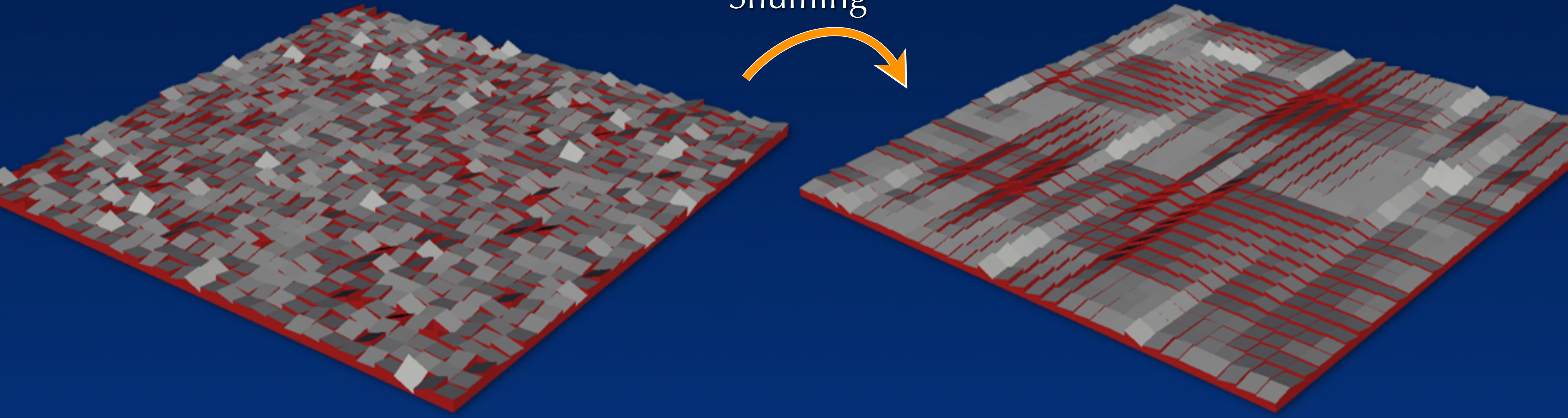
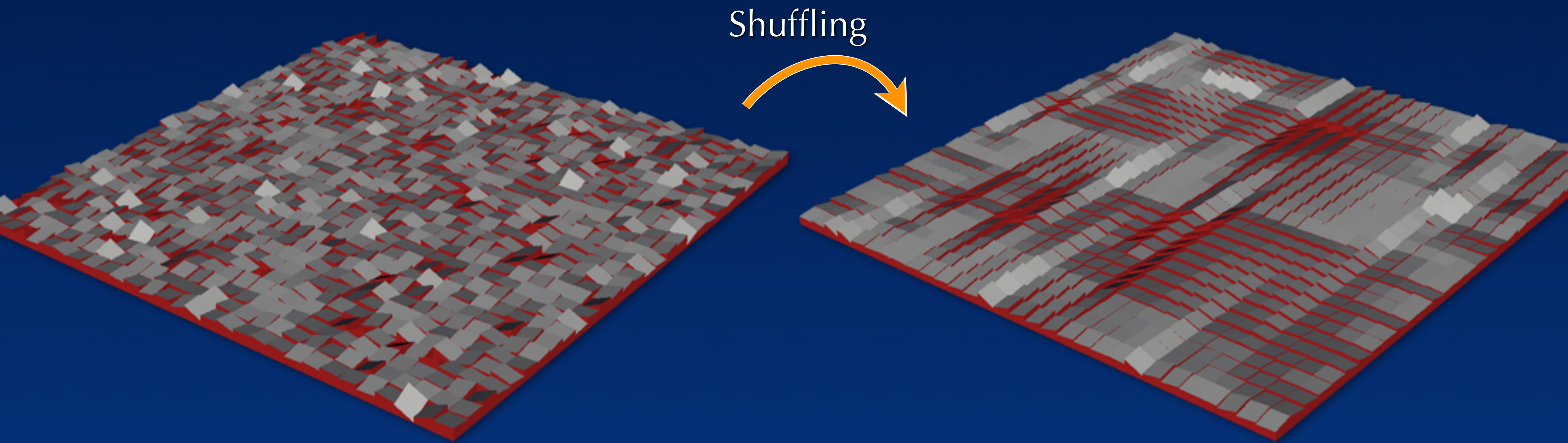




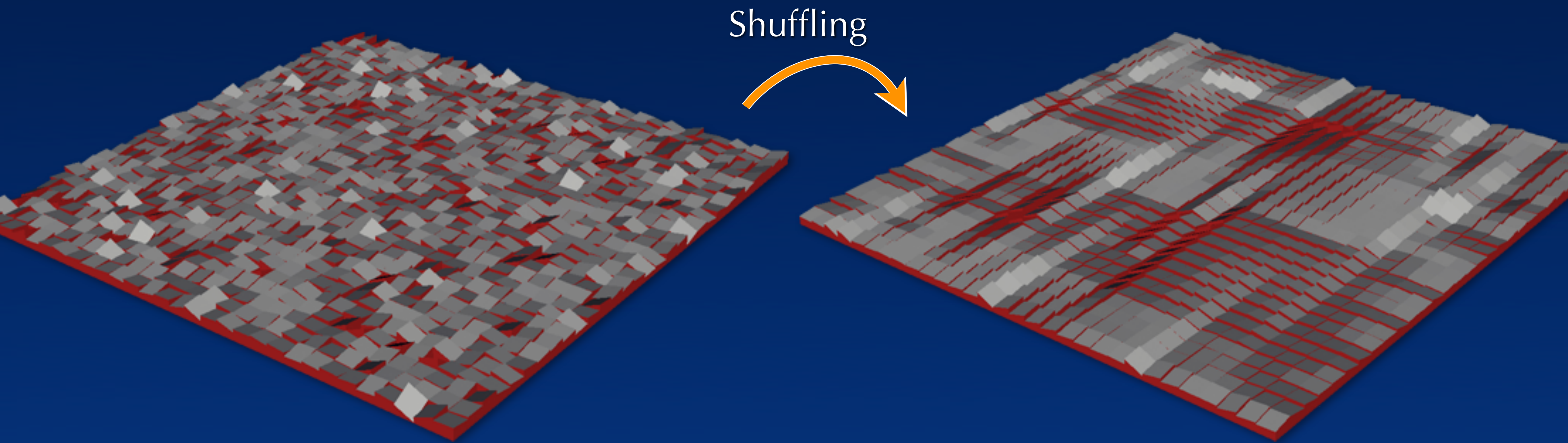
Arrangement Optimization

- Shuffling facets to optimize:
  - Compatibility of neighboring slopes
  - Mean-free rows and columns
  - Minimize "valleys" in end result
    (physical process causes horizontal flats at concavities)



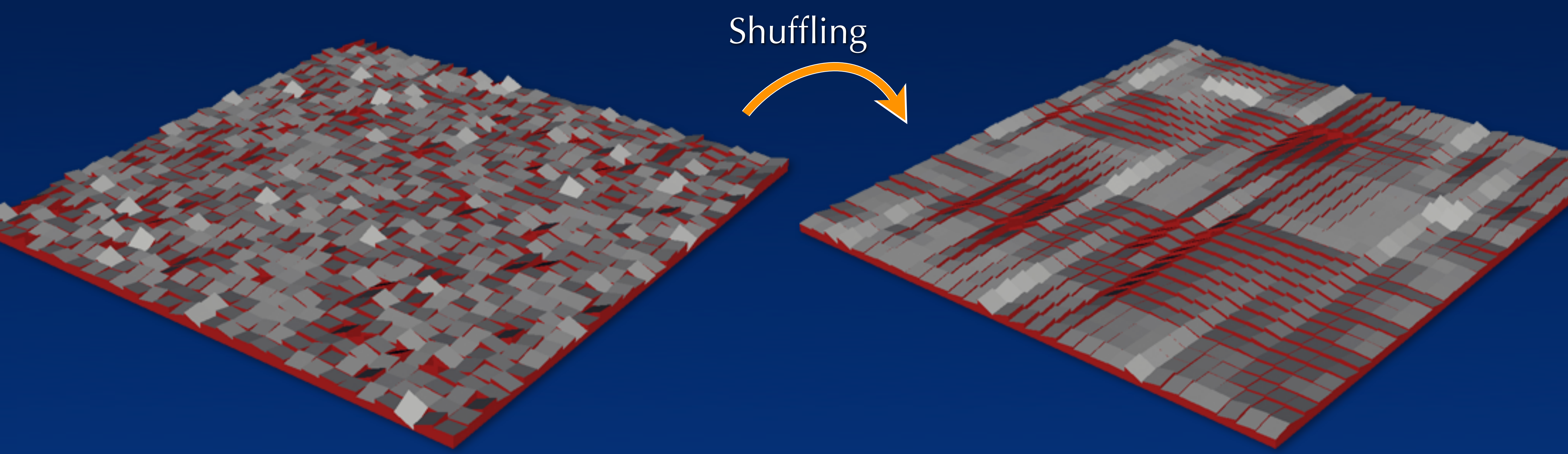
Arrangement Optimization

- Shuffle using simulated annealing optimization

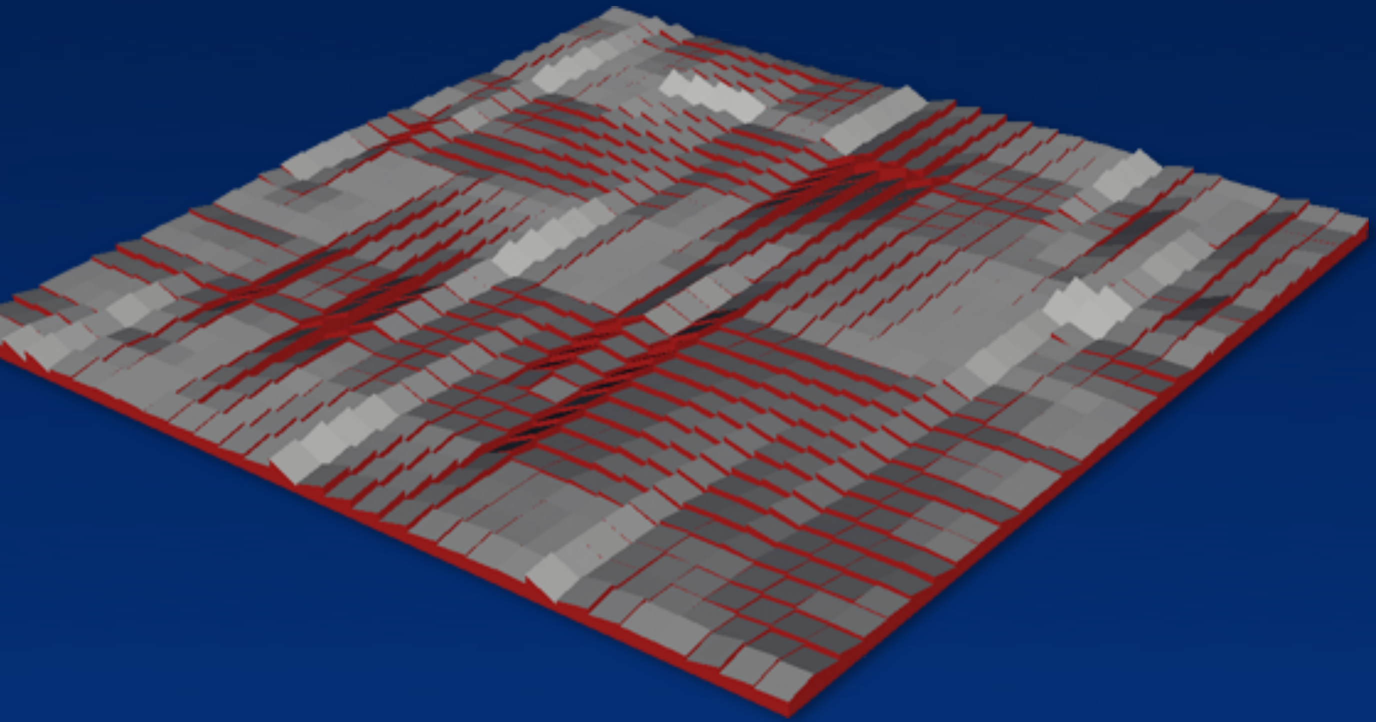


Arrangement Optimization

- Shuffle using simulated annealing optimization
  - Global penalty function
  - Pair-wise facet swaps
  - Logarithmic annealing schedule

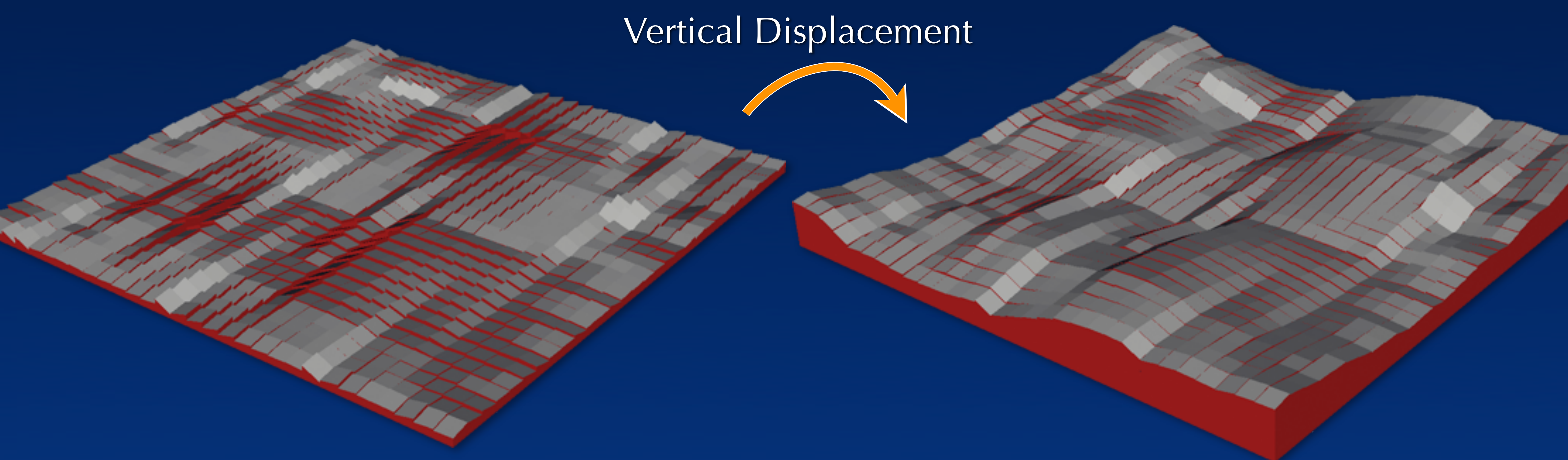


Arrangement Optimization



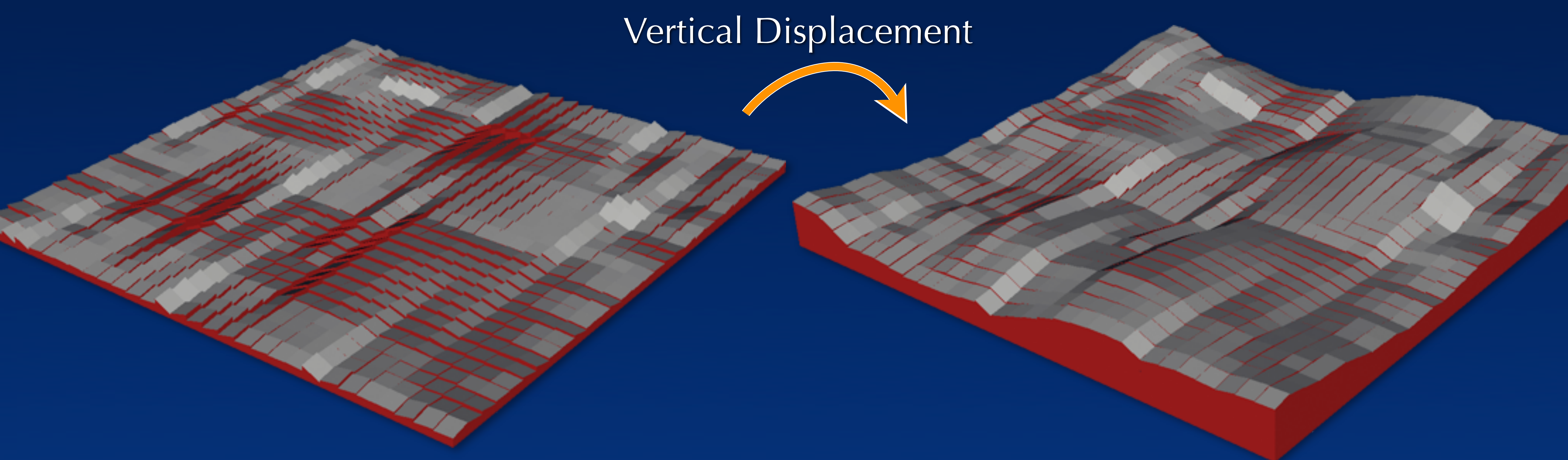
Displacement Optimization

- Vertical displacement to minimize discontinuities

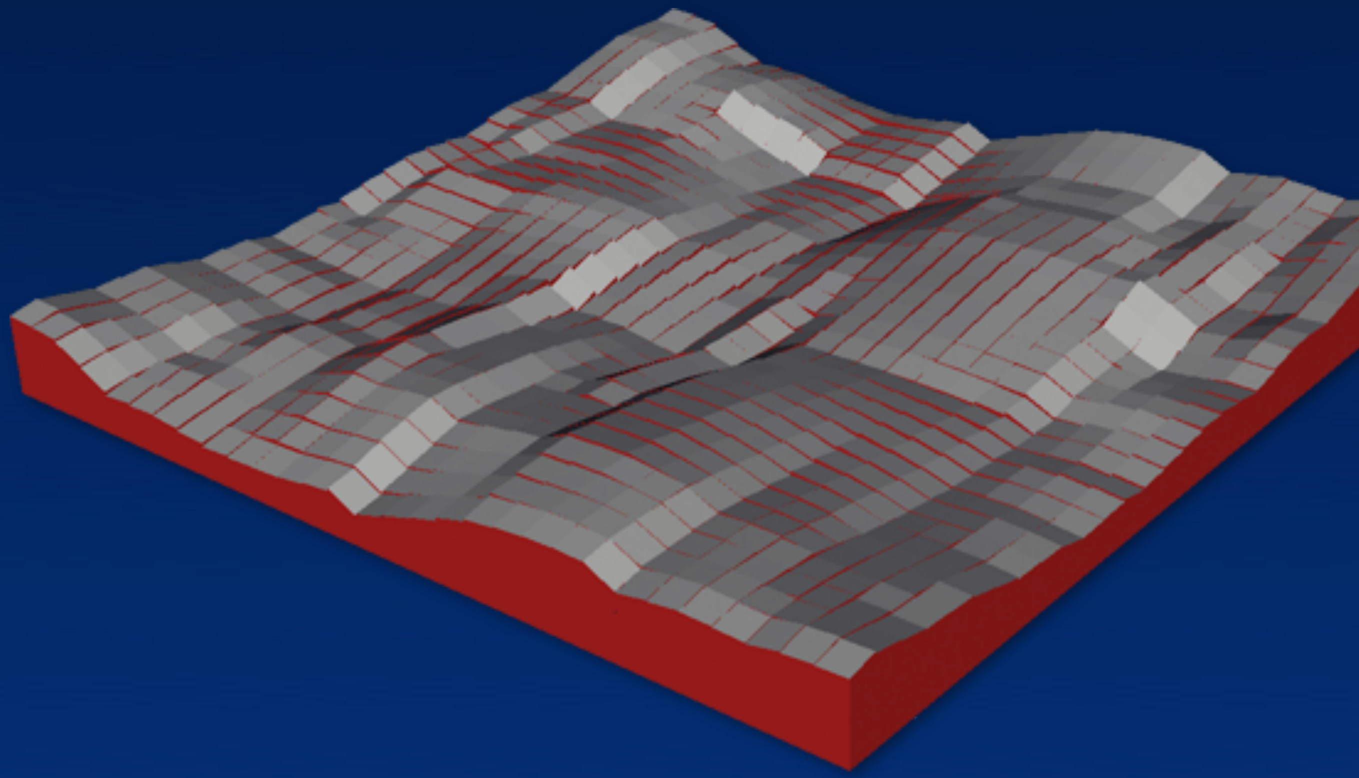


Displacement Optimization

- Vertical displacement to minimize discontinuities
- Maps to Poisson problem
  - Facets determine local gradients
  - Cyclic connectivity for tileability

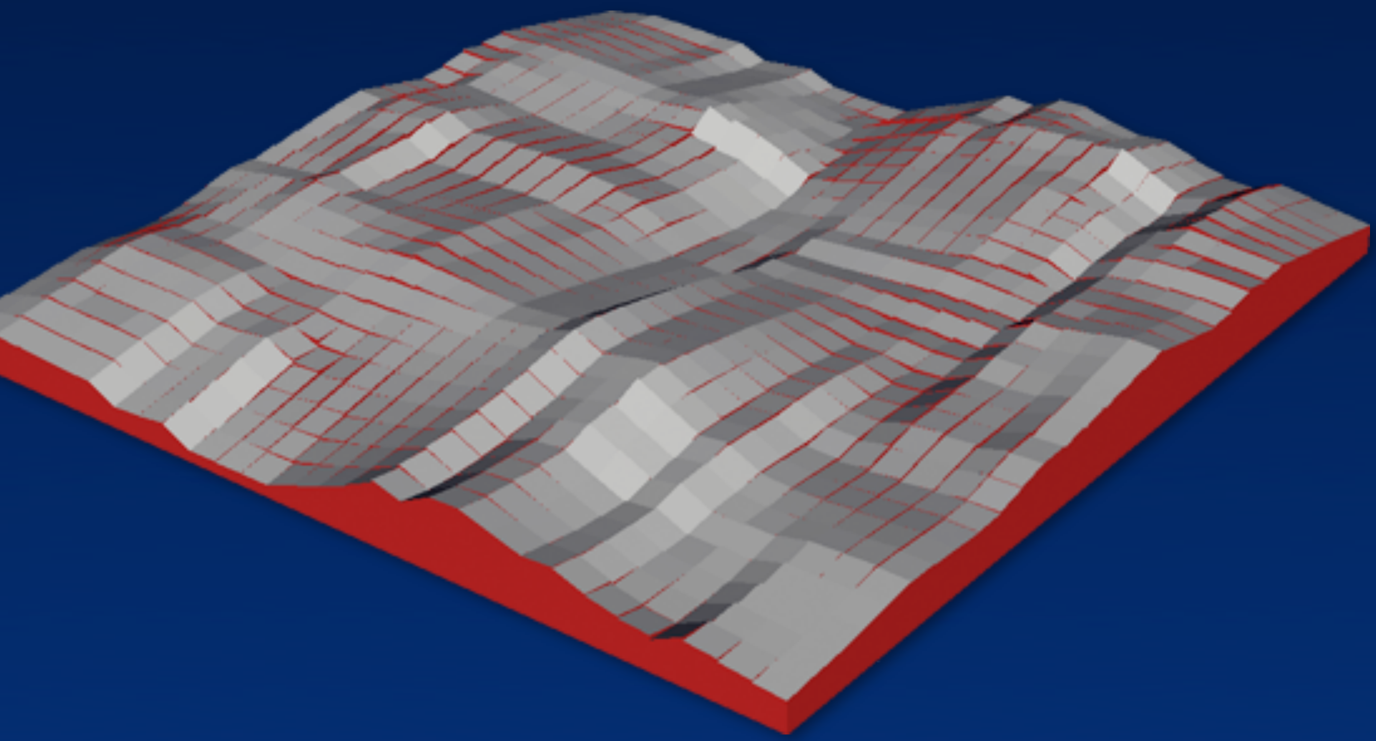


Displacement Optimization

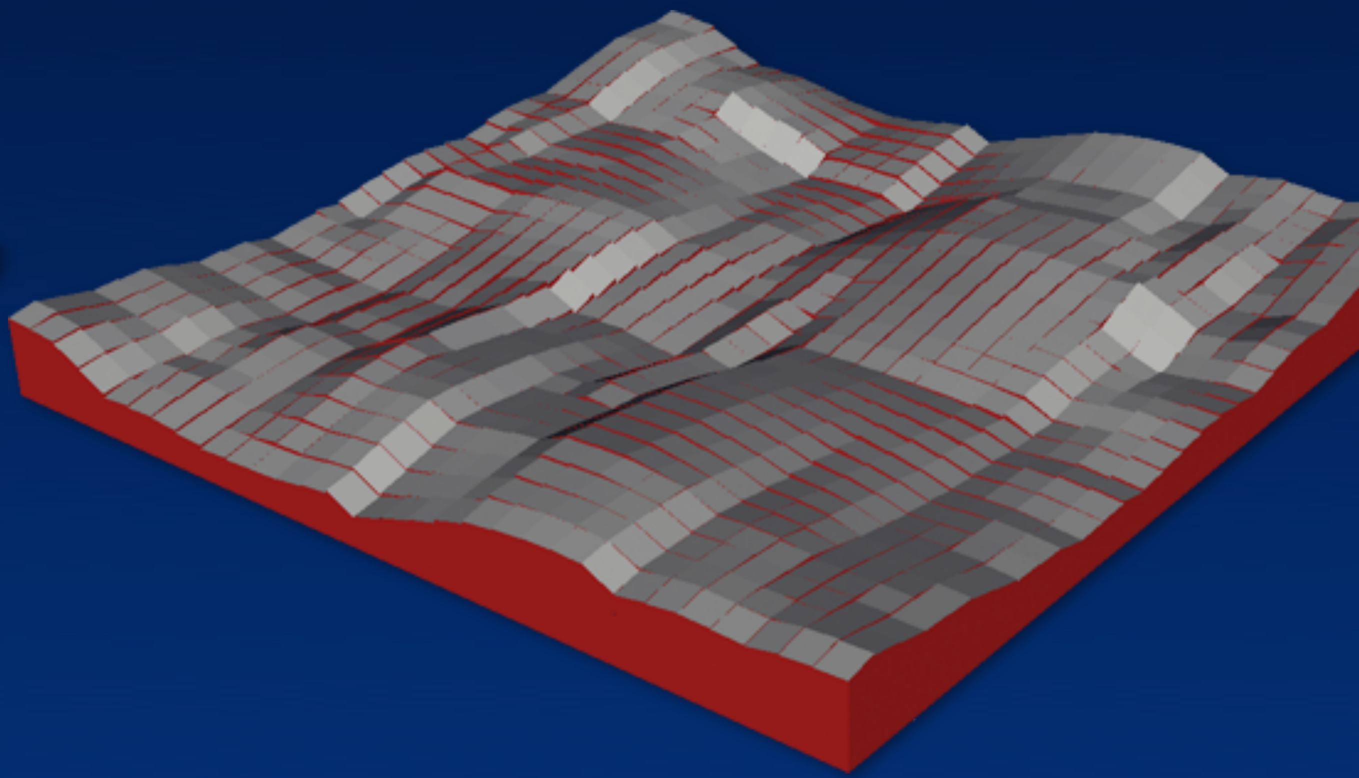


Effect of Valley Optimization

- Halves horizontal areas
- Preserves continuity



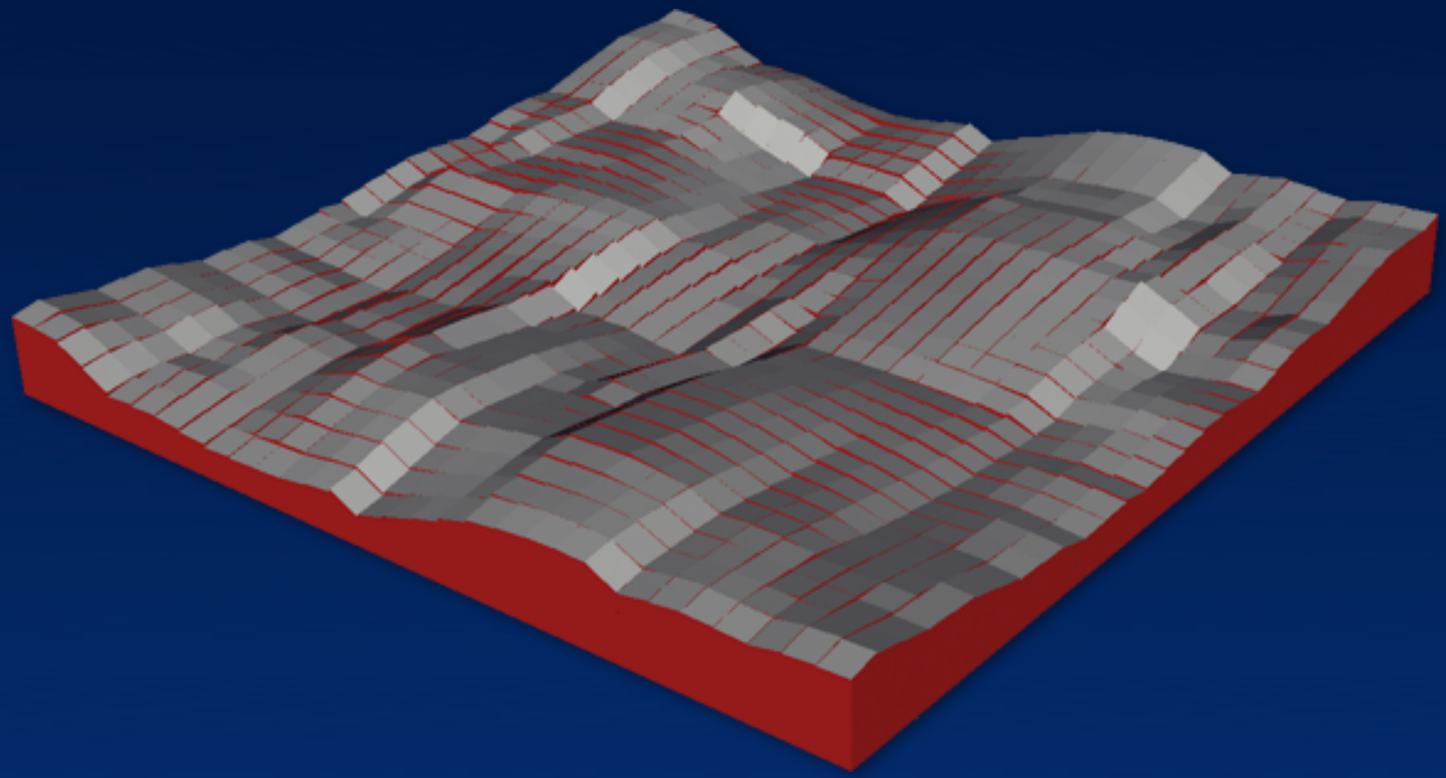
Unoptimized: 918 Concave Edges



418 Concave Edges

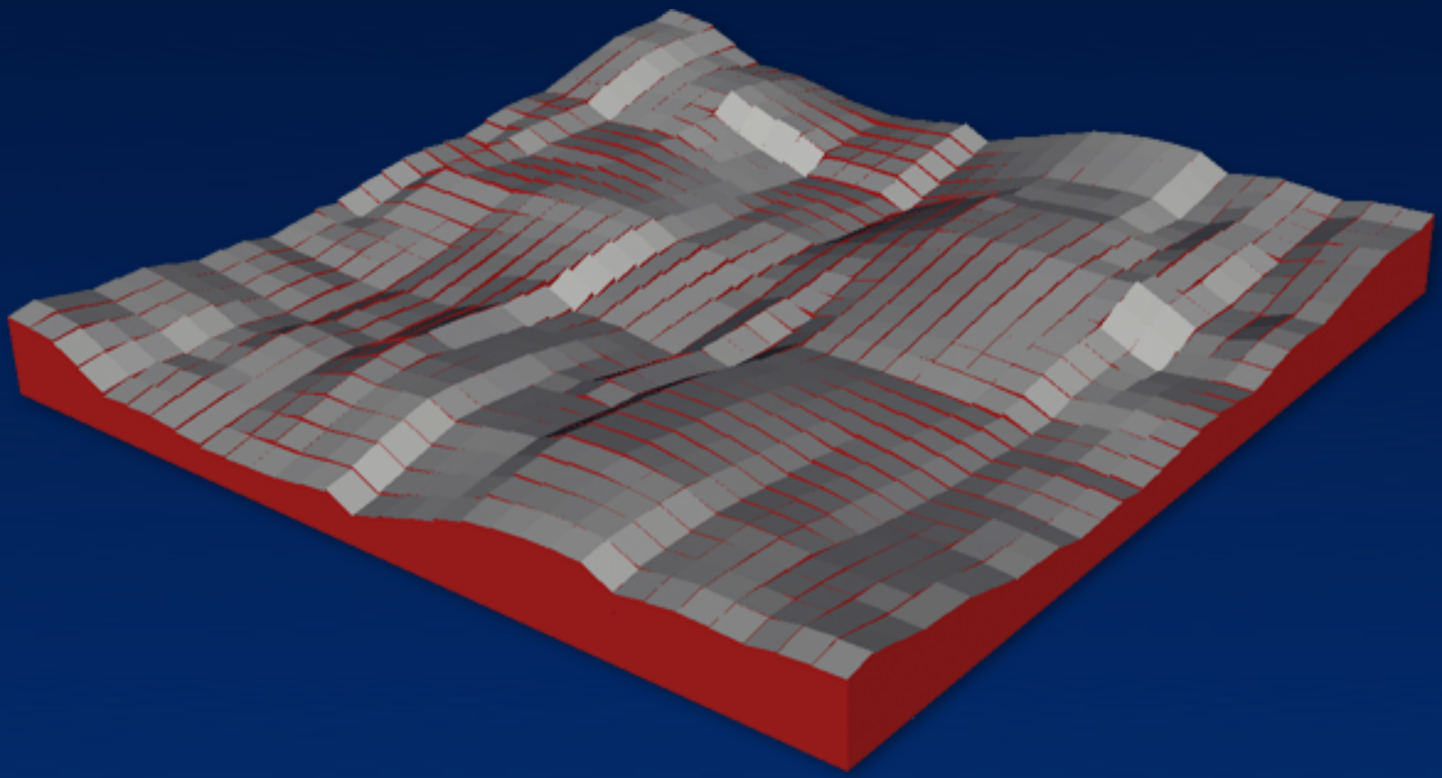
Fabricating Microgeometry

- Requires shaping glossy materials



Fabricating Microgeometry

- Requires shaping glossy materials
- Many processes exist
  - Milling
  - Etching
  - Cutting
  - Minting
  - …



Our Prototype Process

- Prototype fabrication
  - Base material: aluminum
  - Computer-controlled mill

Our Prototype Process

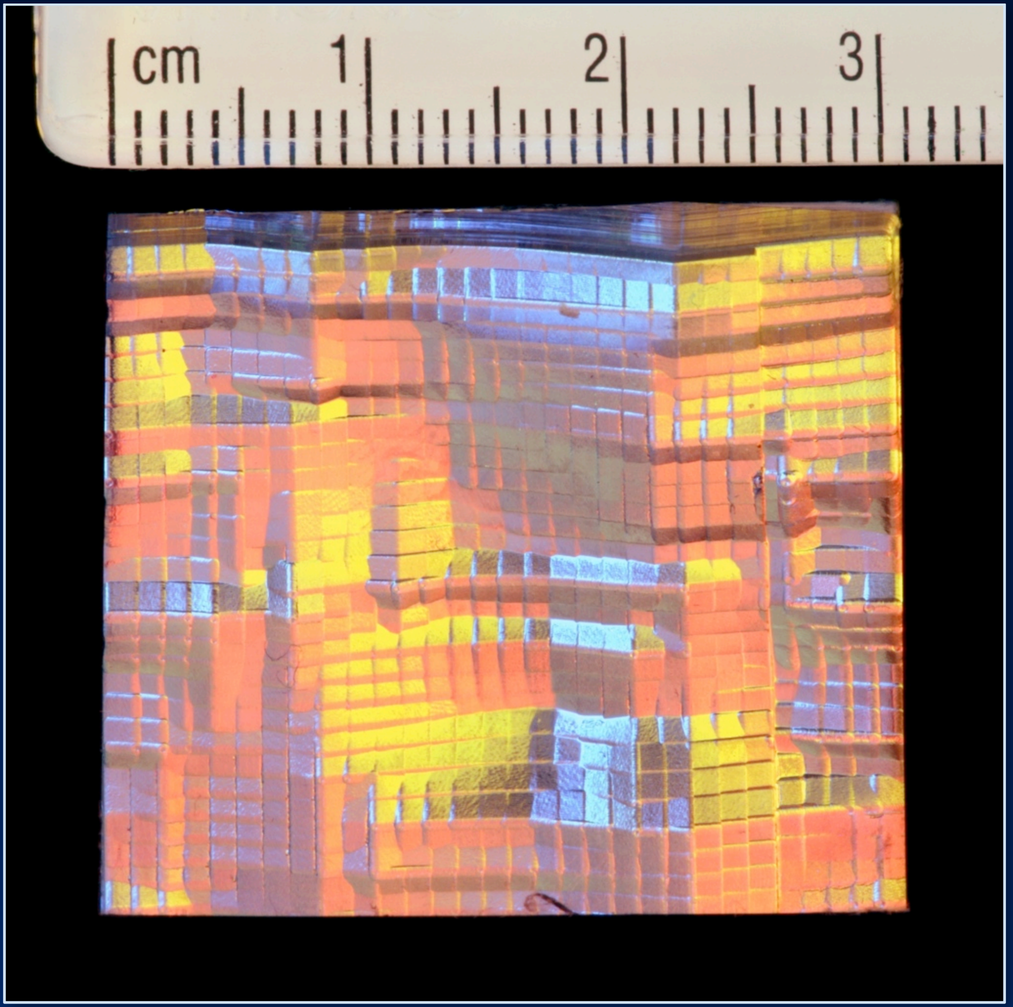
- Prototype fabrication
  - Base material: aluminum
  - Computer-controlled mill
- Practical challenges
  - Drill bit tip has finite extent
  - Milling creates grooves
  - Milling speed

Our Prototype Process

- Process Details
  - Milling at 0.001-inch resolution
  - Milling *x*- and *y*-scanlines

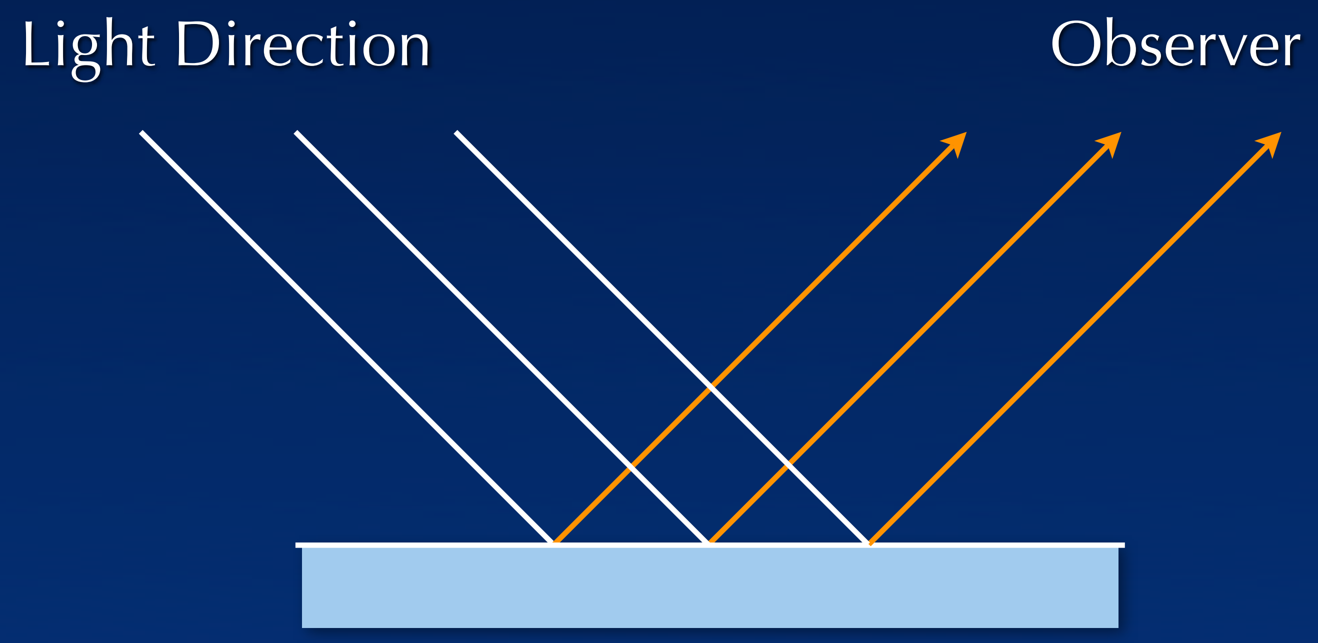
Our Prototype Process

- Process Details
  - Milling at 0.001-inch resolution
  - Milling *x*- and *y*-scanlines
- Sample size
  - 30×30-height field
  - ca. 1mm^2 facets
  - Overall milling time: 5.5 hours



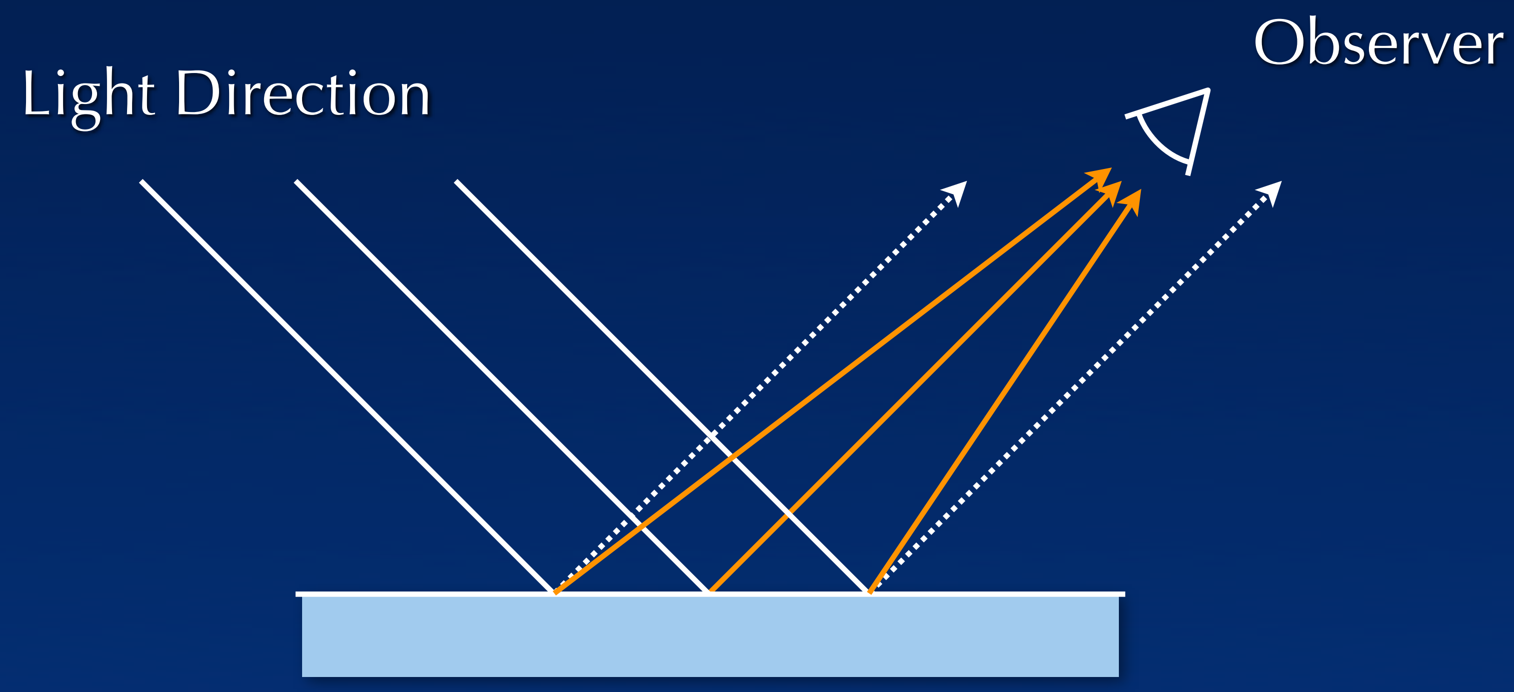
Highlight Observation

- Distant light source + distant observer
  - Mirror reflection where facet orientations match
  - No visible highlight



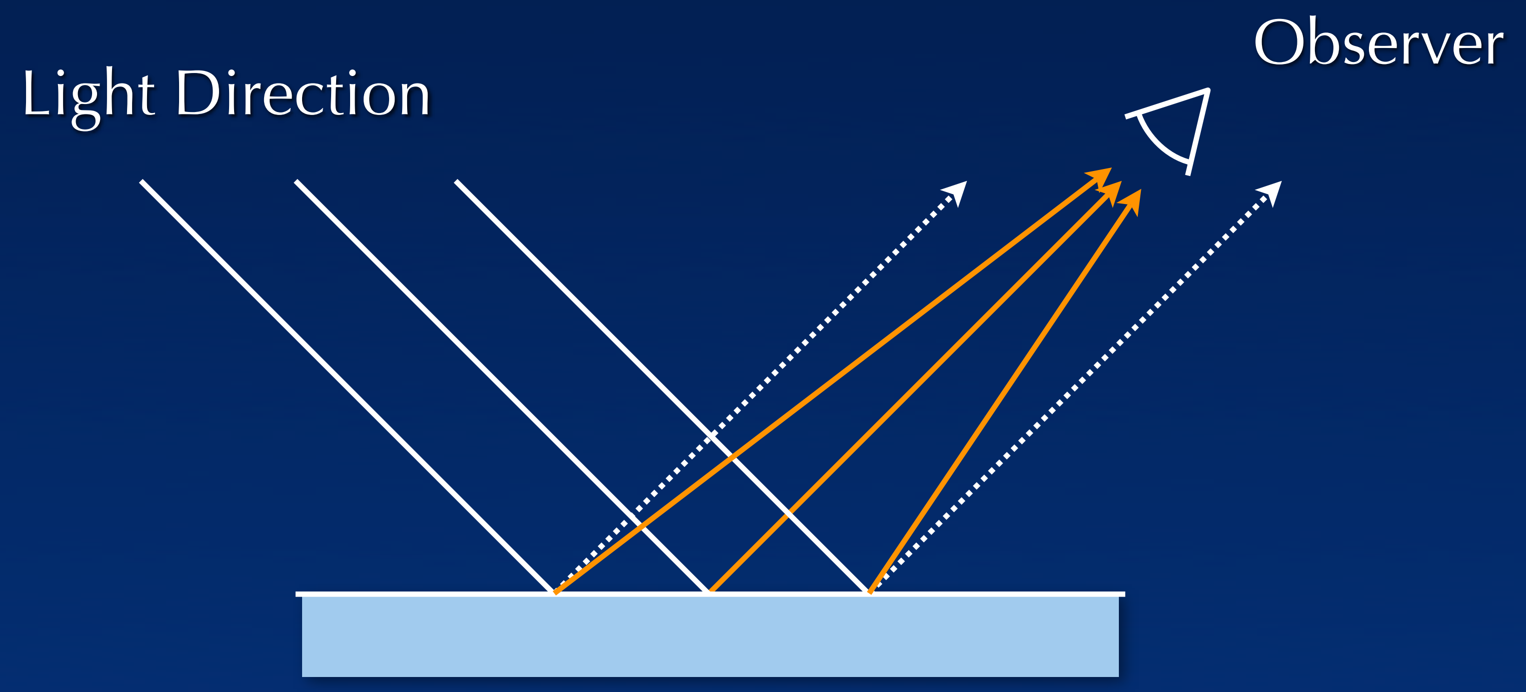
Highlight Observation

- Distant light source + local observer
  - Multiple off-specular observations
  - Visible highlight formation



Highlight Observation

- Distant light source + local observer
  - Multiple off-specular observations
  - Visible highlight formation
- Requires tiled material



Evaluation

- Imaging reflectance lobe

Evaluation

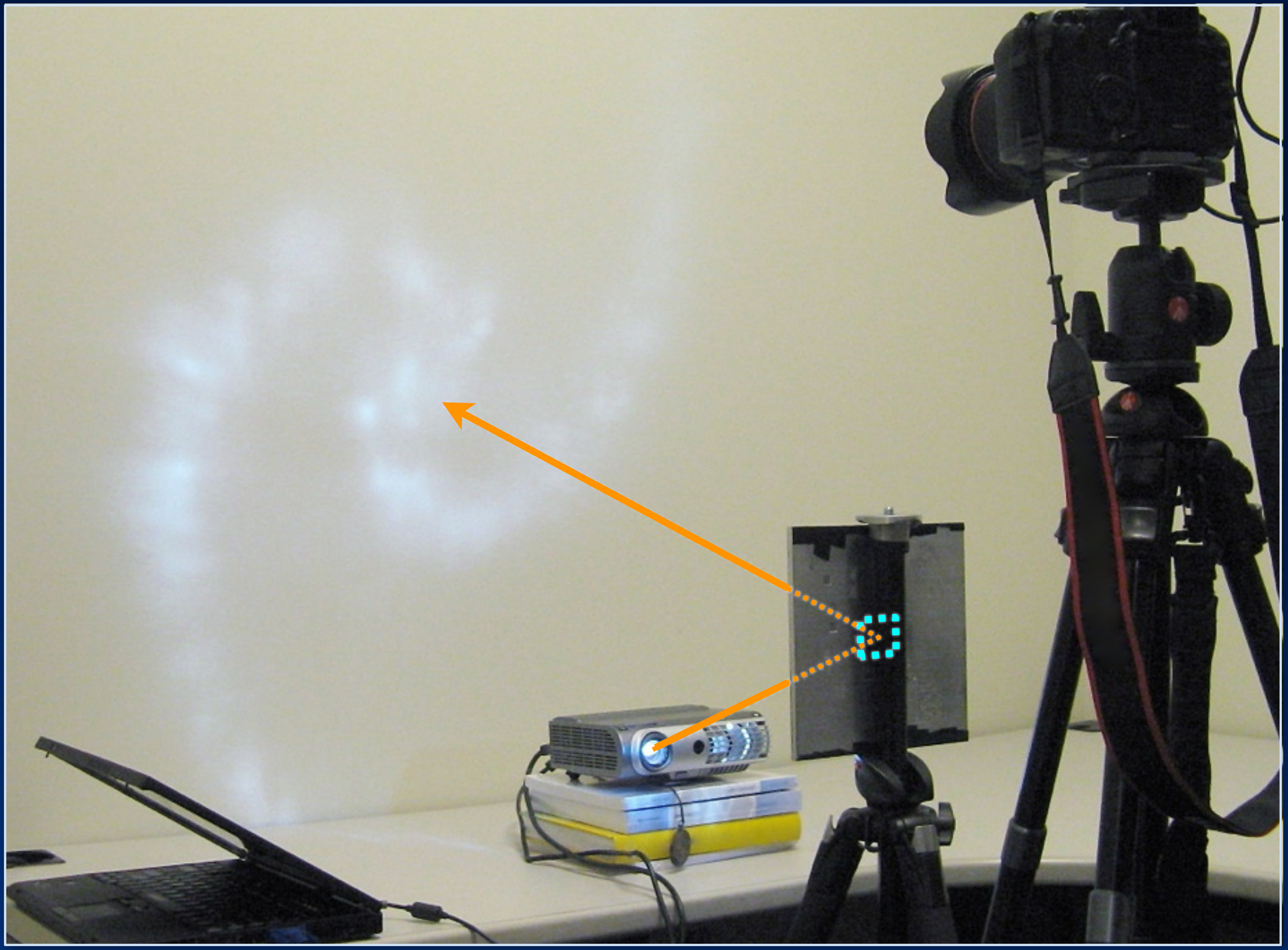
- Imaging reflectance lobe
- Experimental setup:

Evaluation

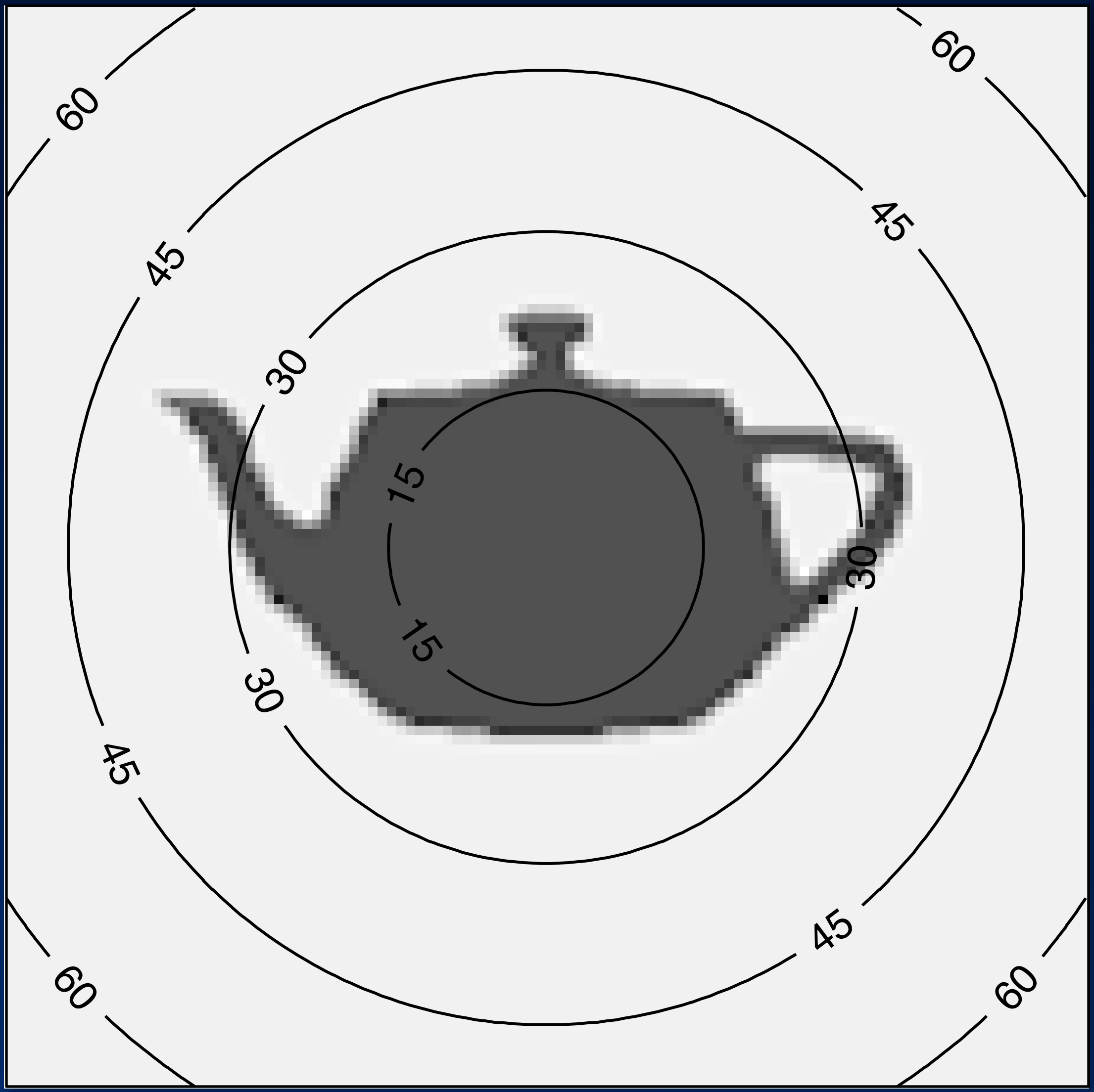
- Imaging reflectance lobe
- Experimental setup:

Evaluation

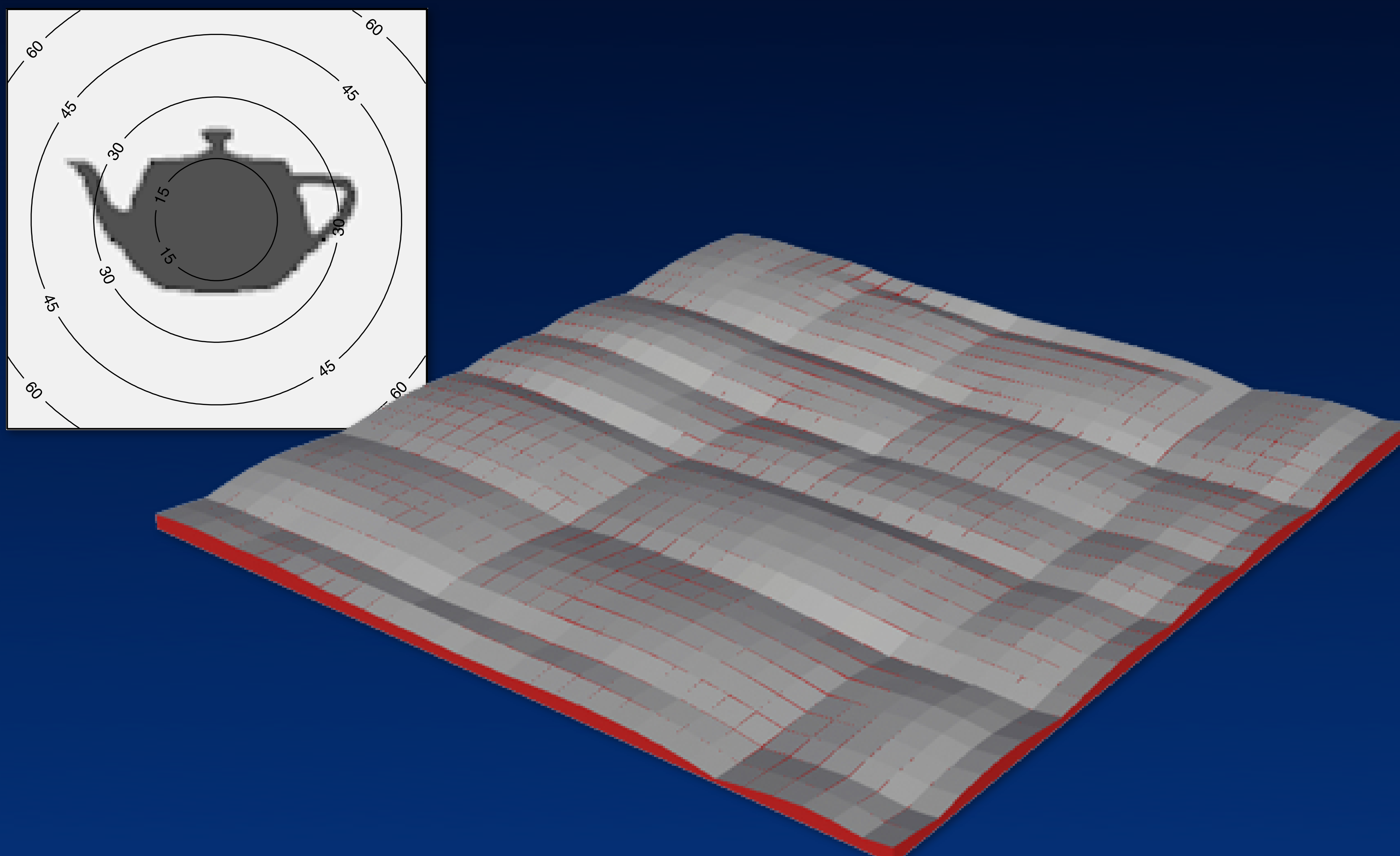
- Imaging reflectance lobe
- Experimental setup:



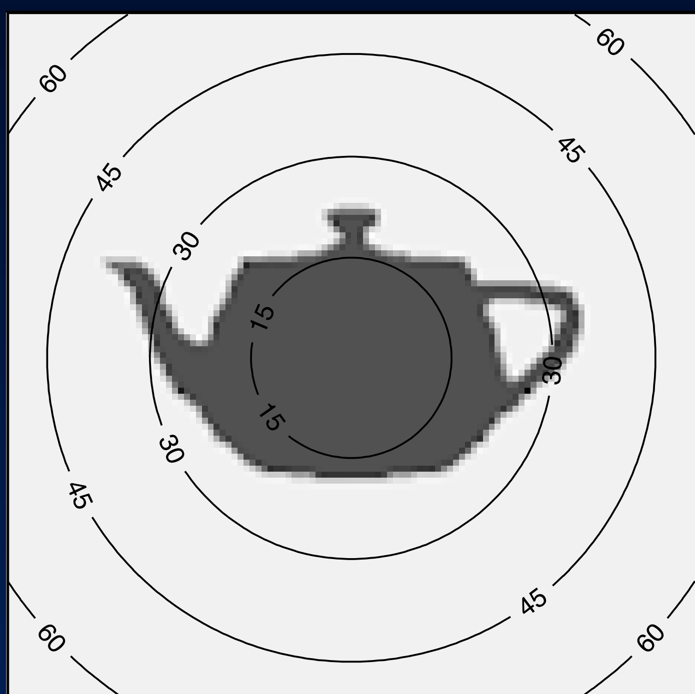
Results

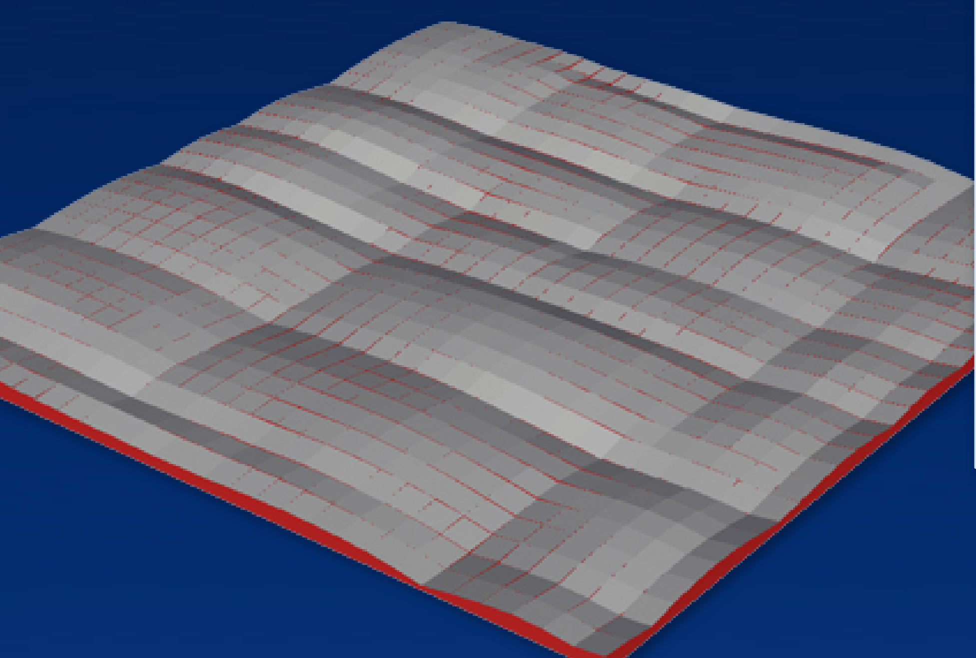


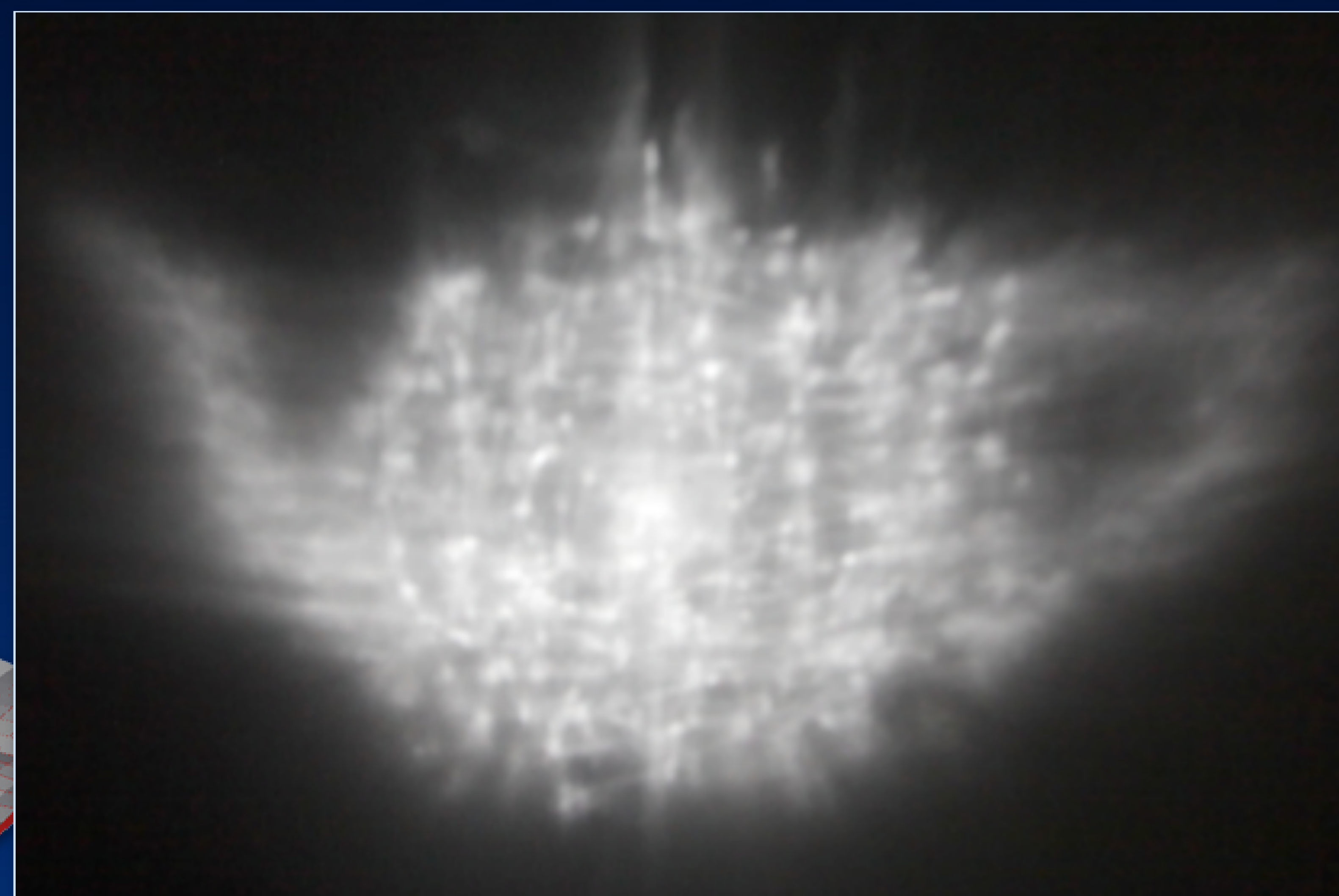
Results



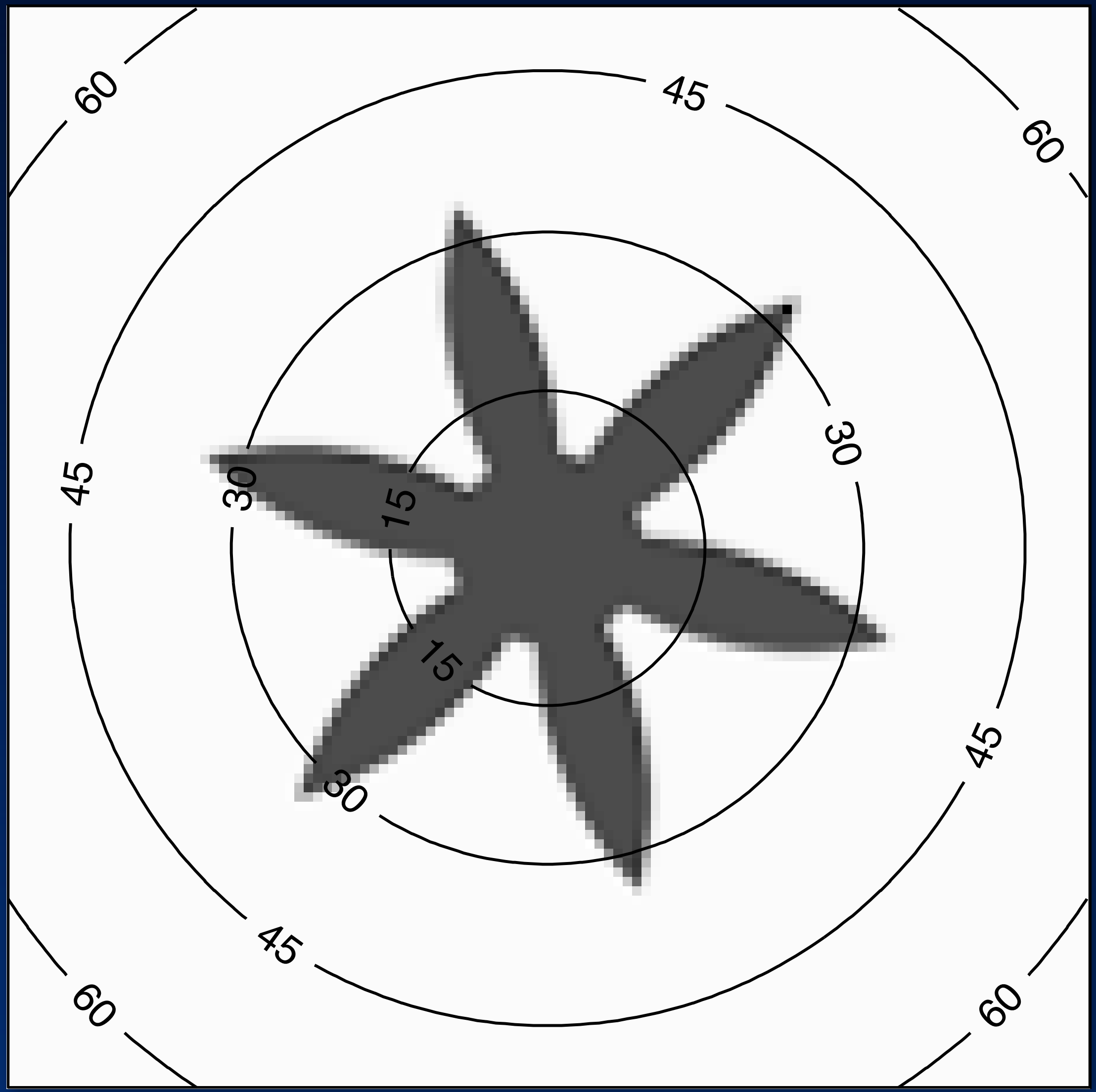
Results



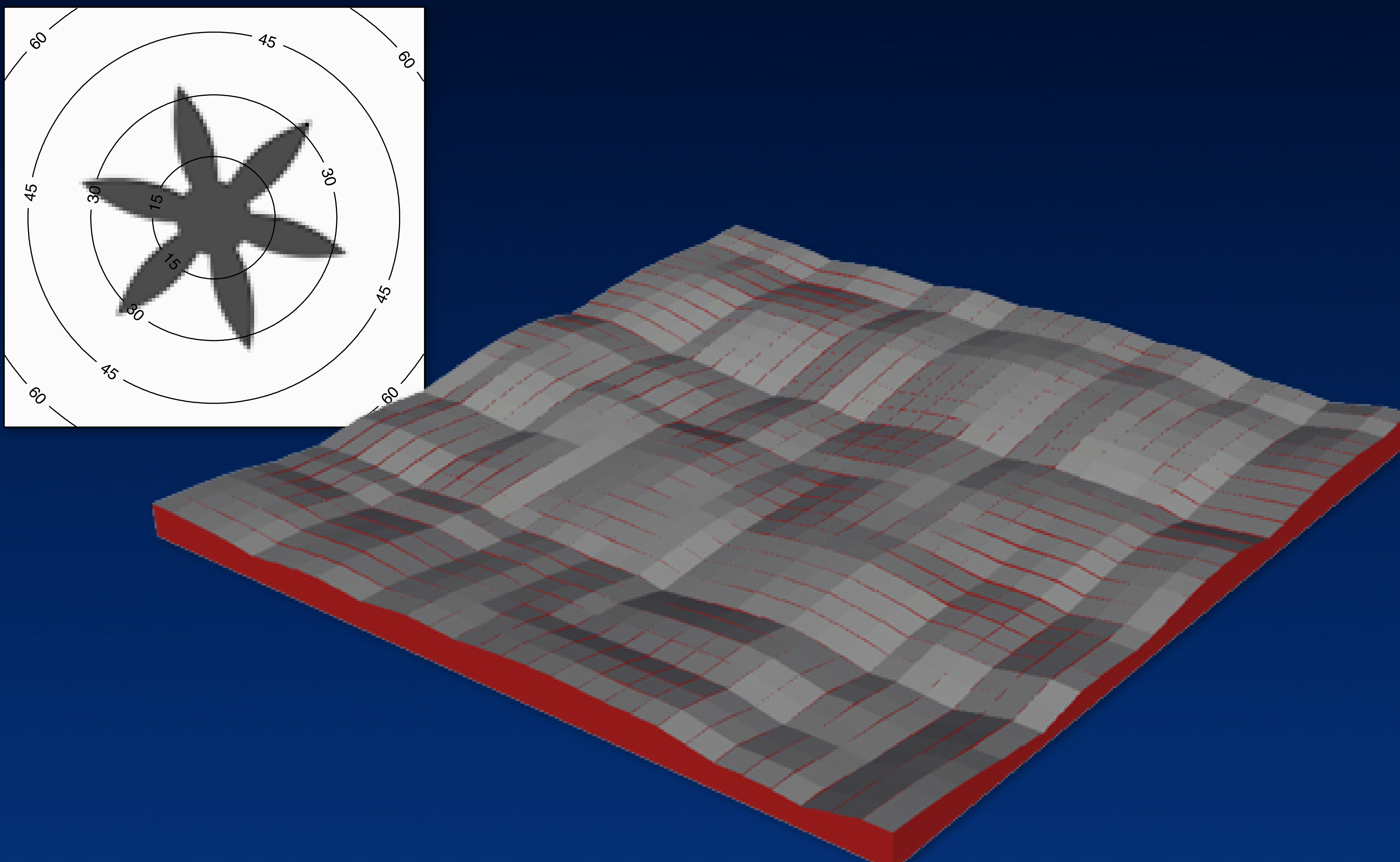




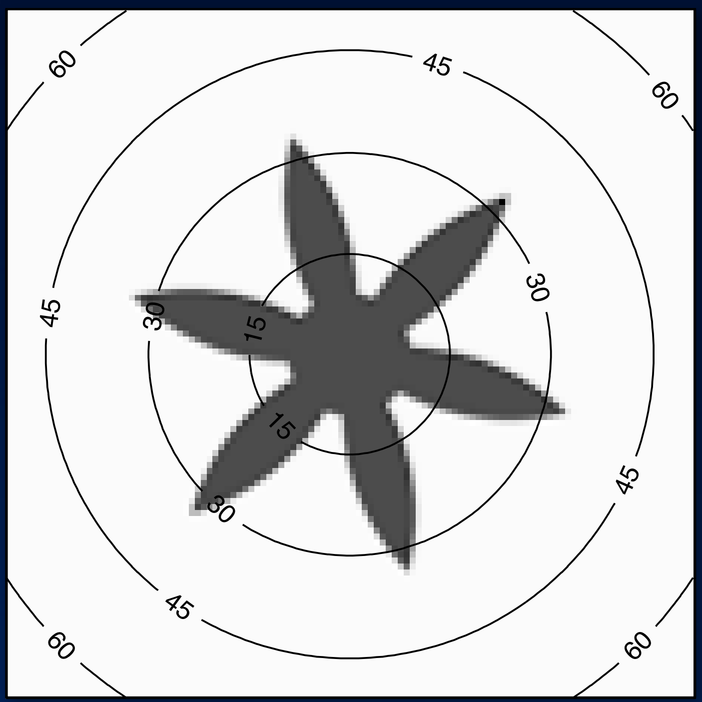
Results

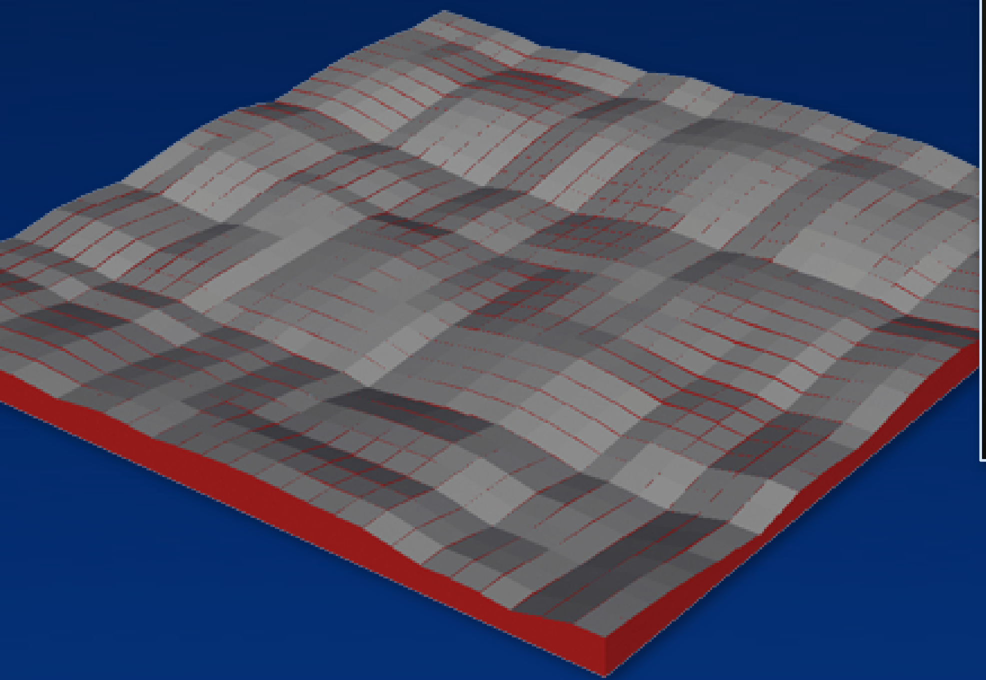


Results



Results





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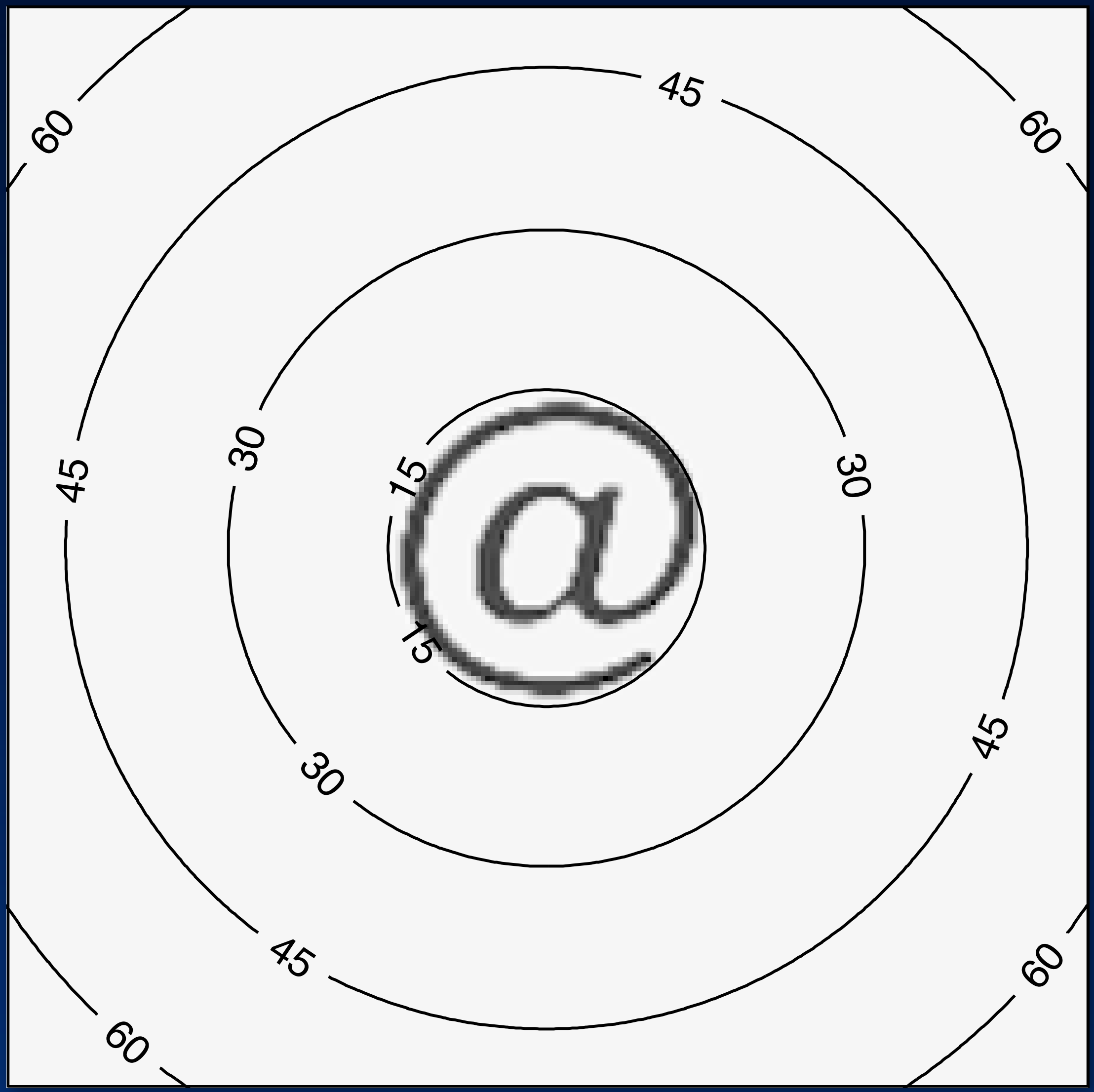

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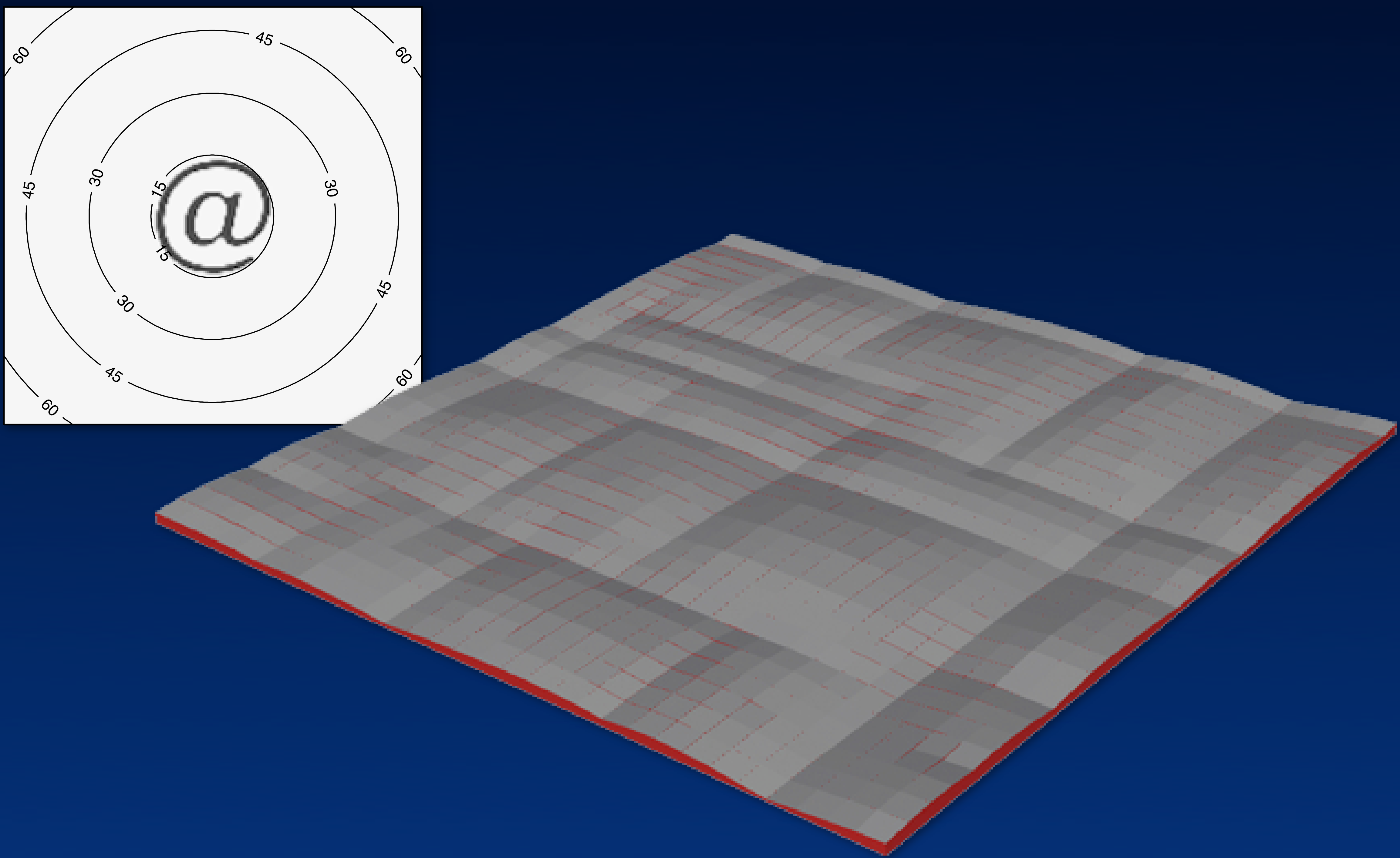
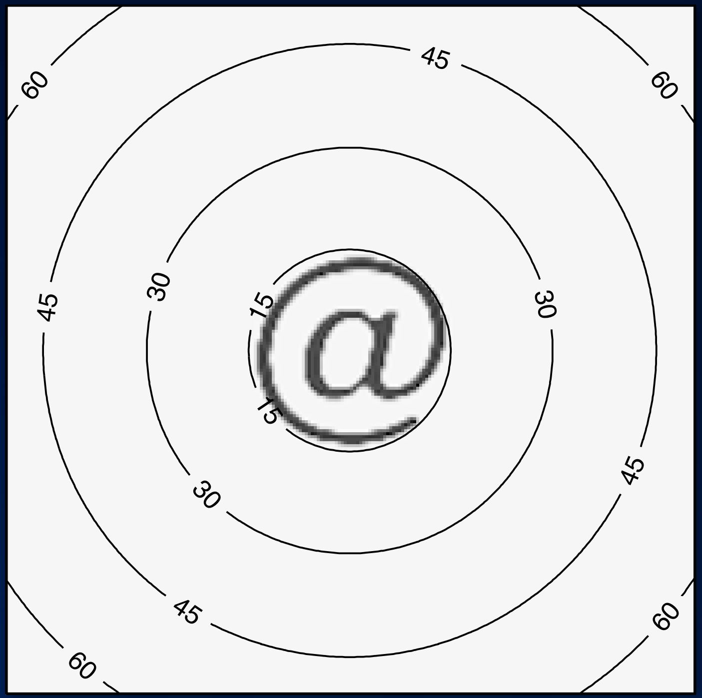
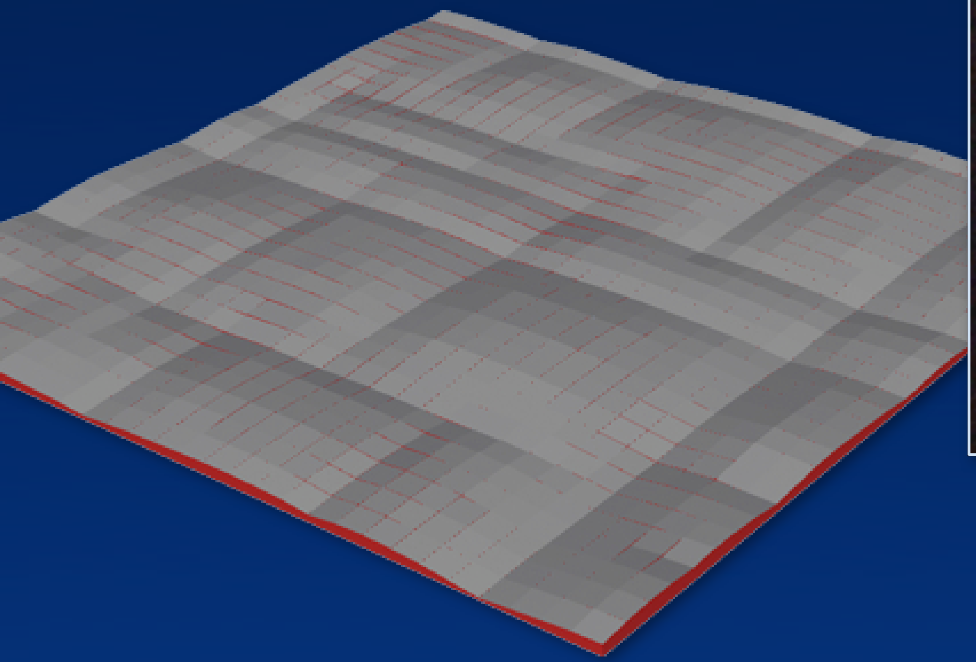
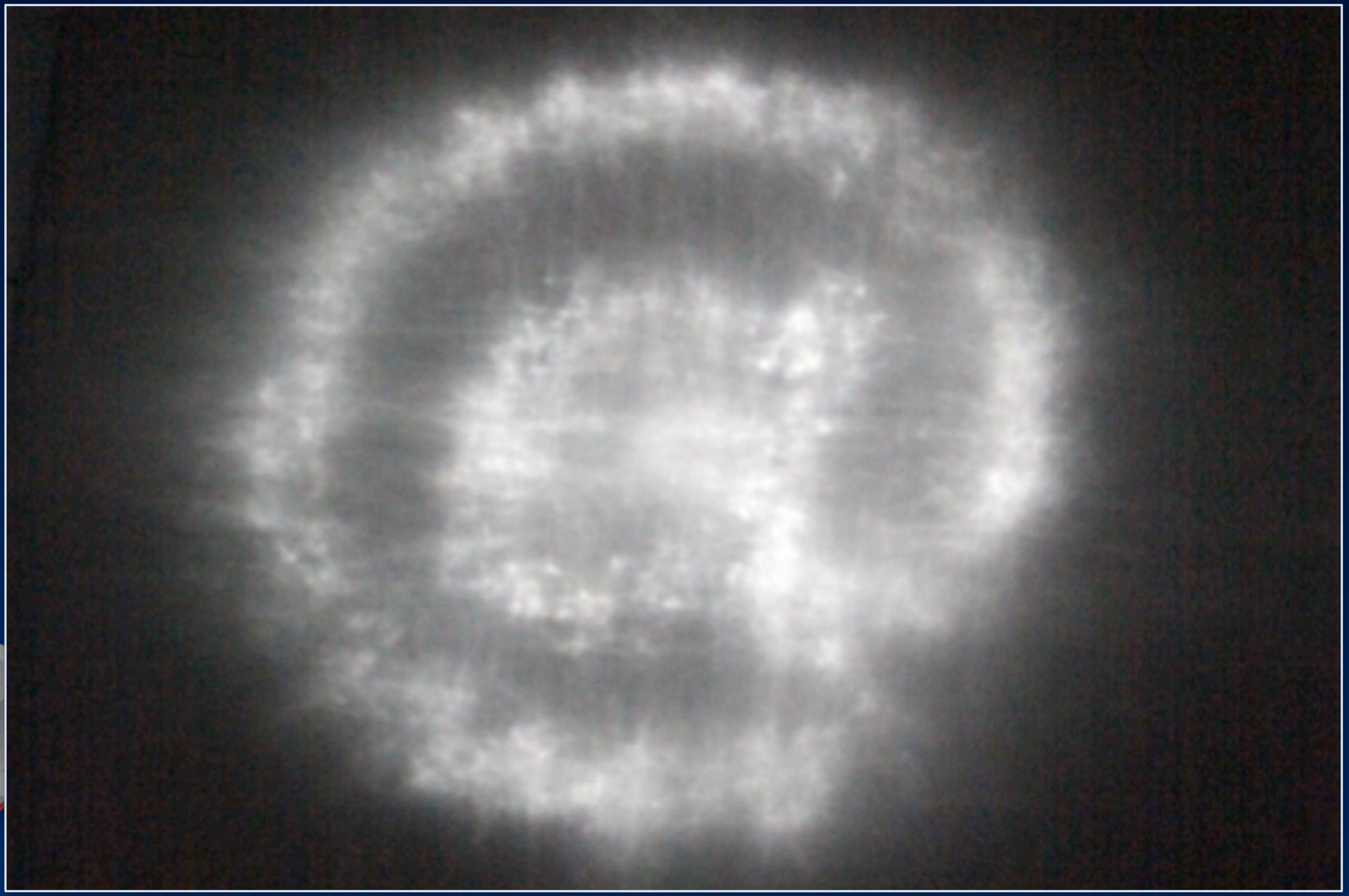


Results







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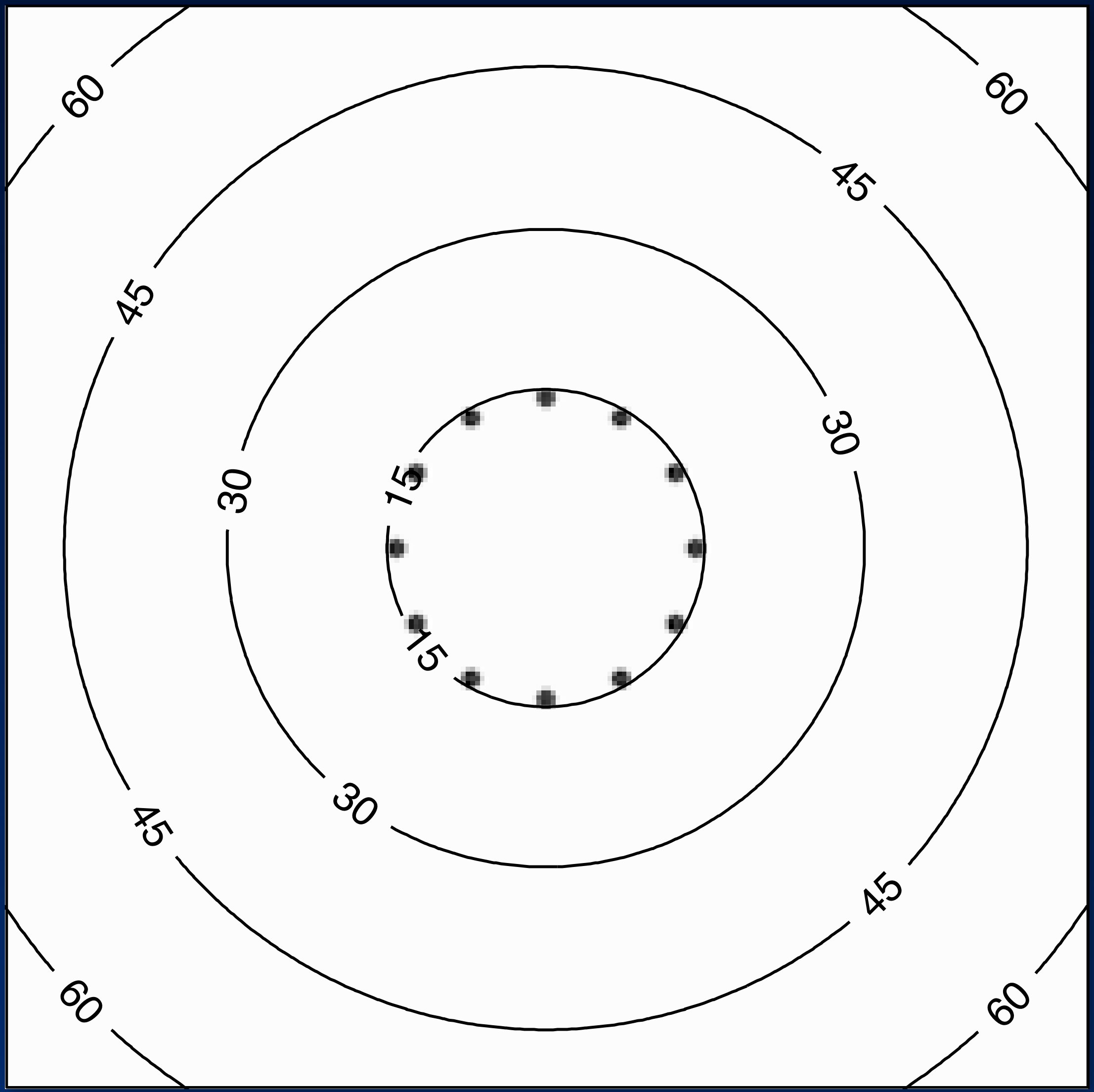

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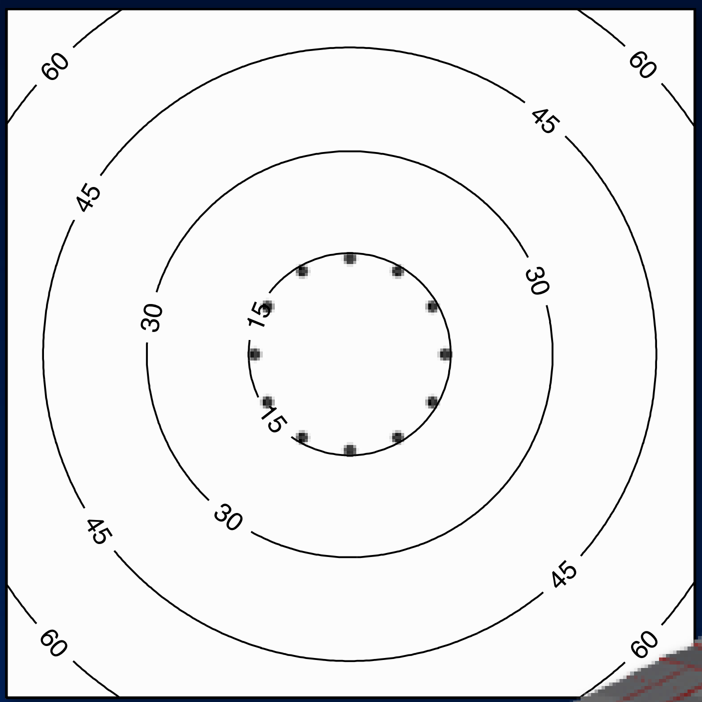
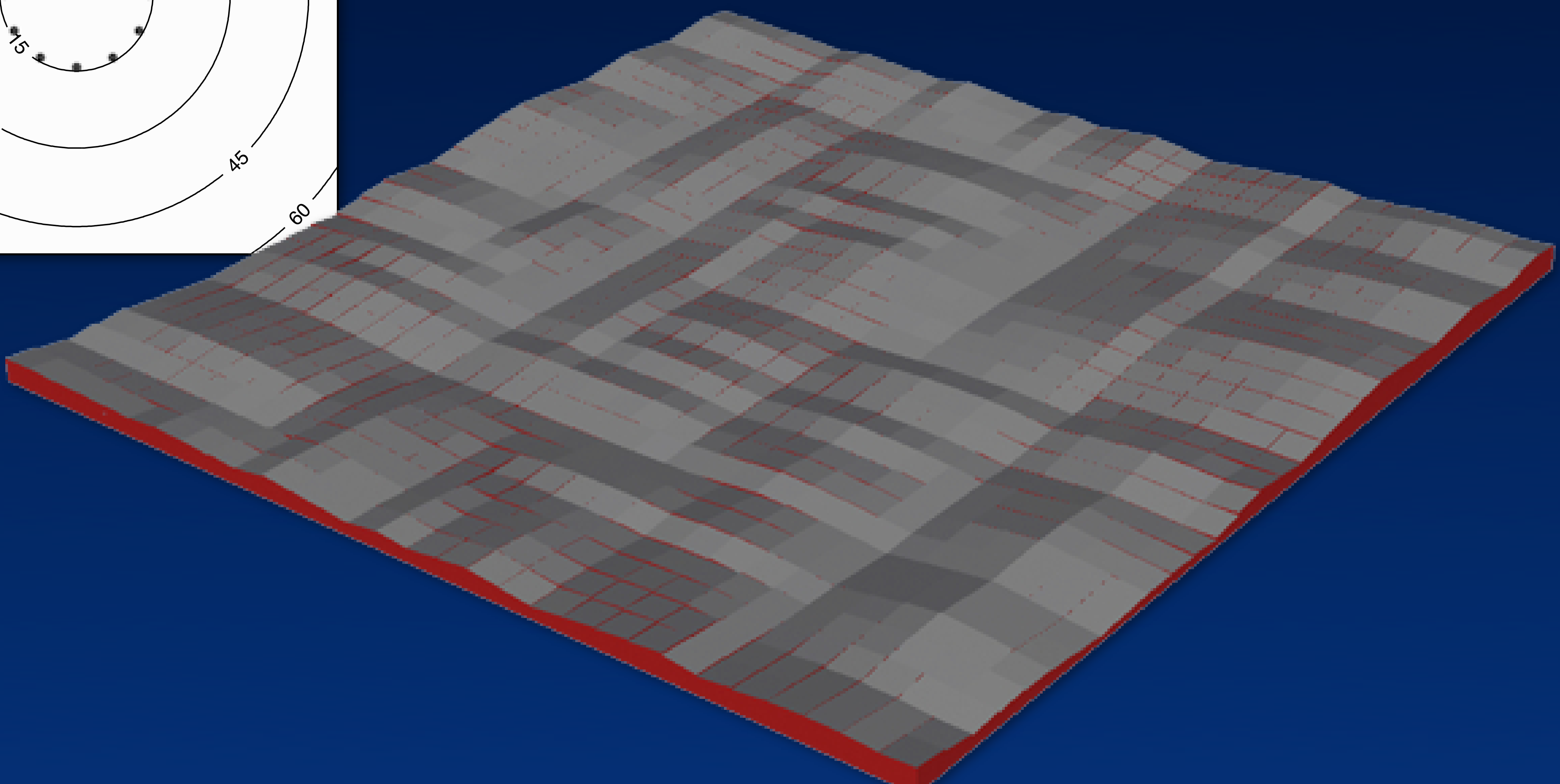
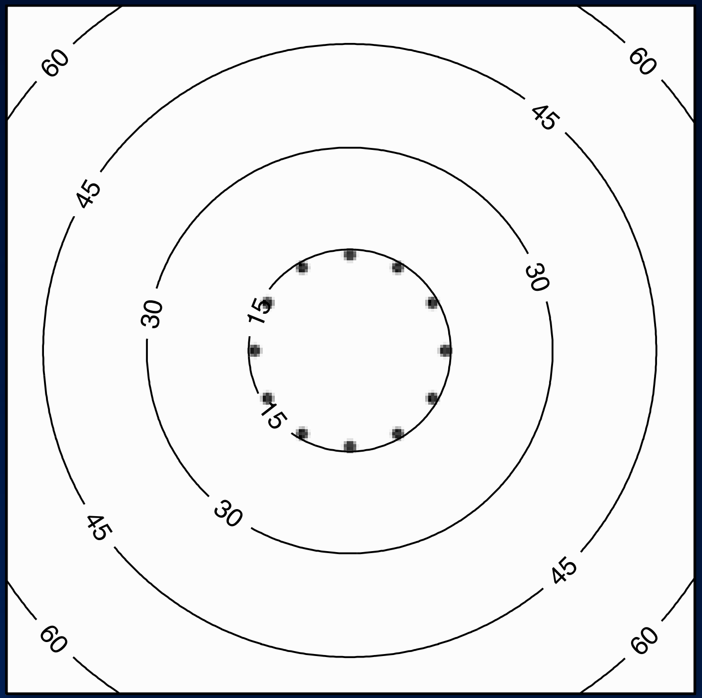
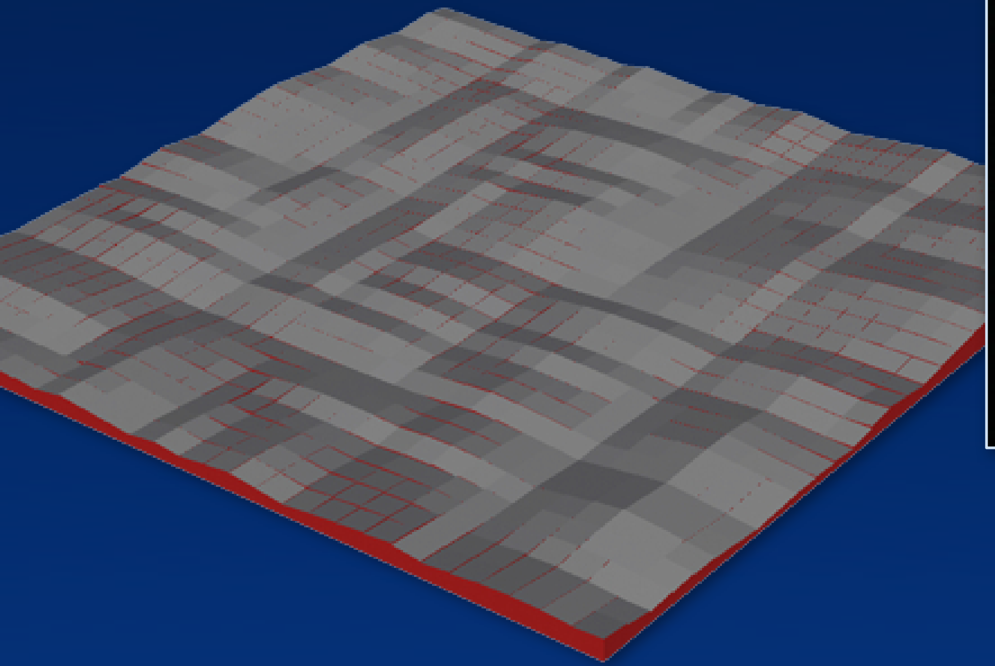
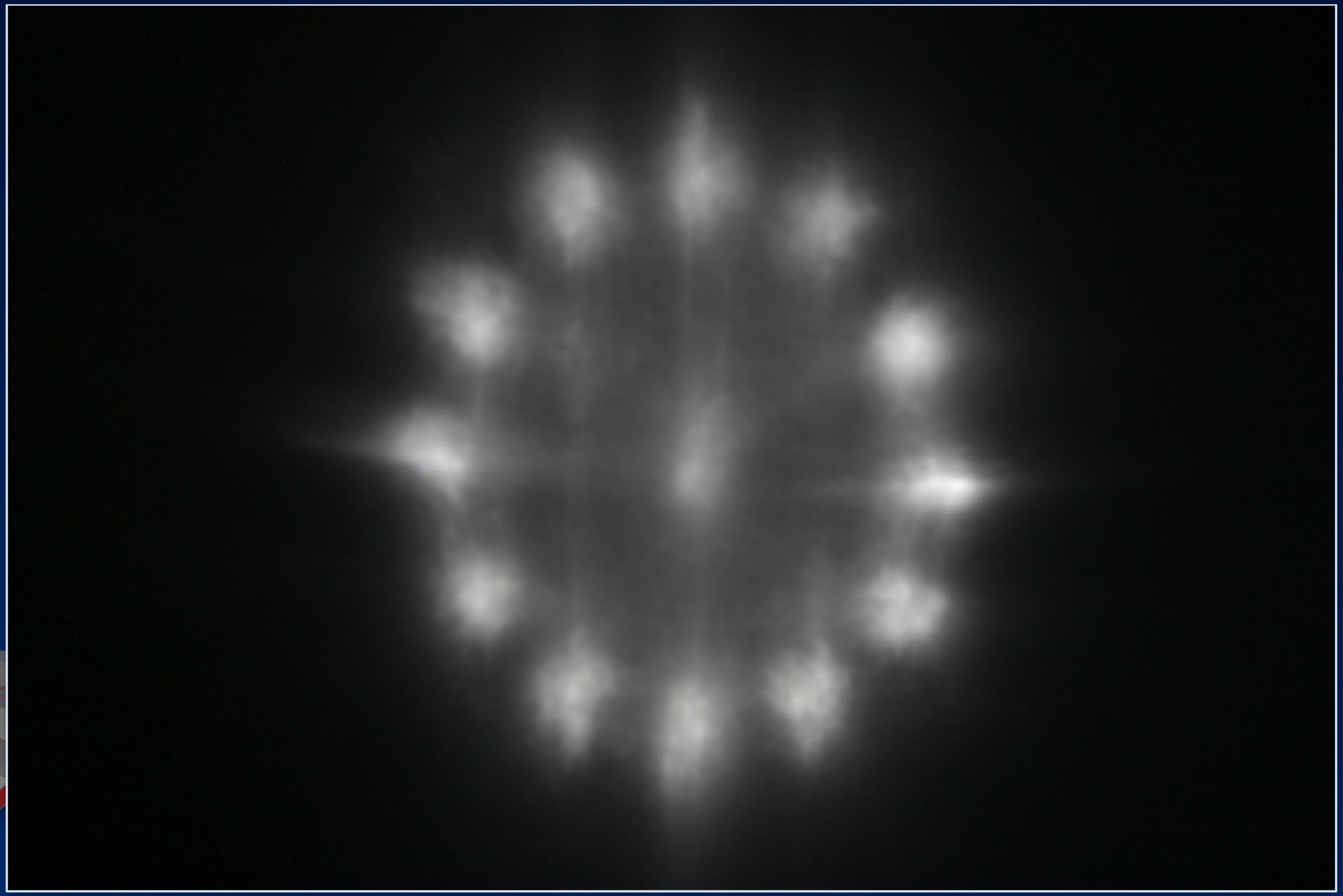




Results







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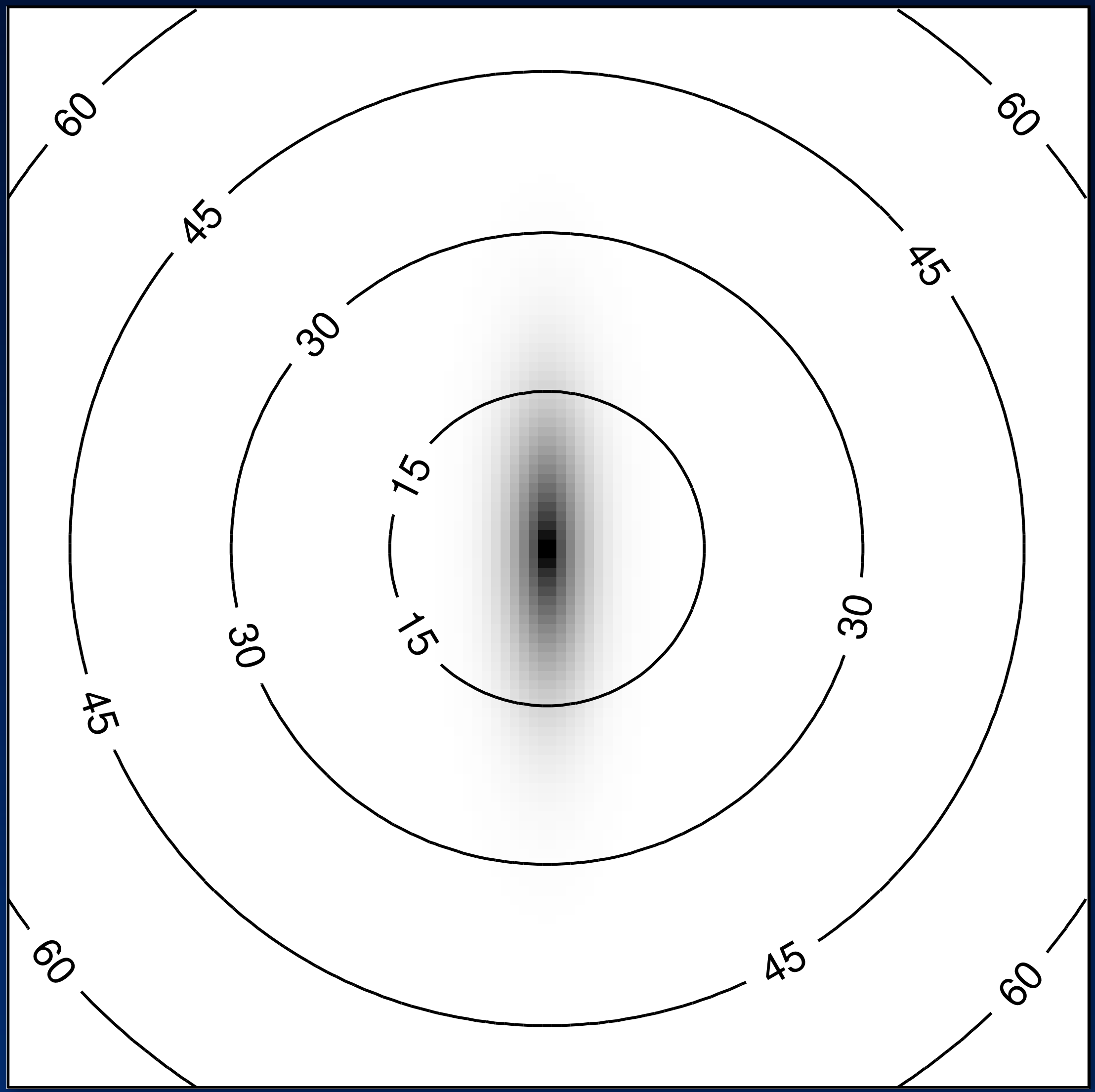
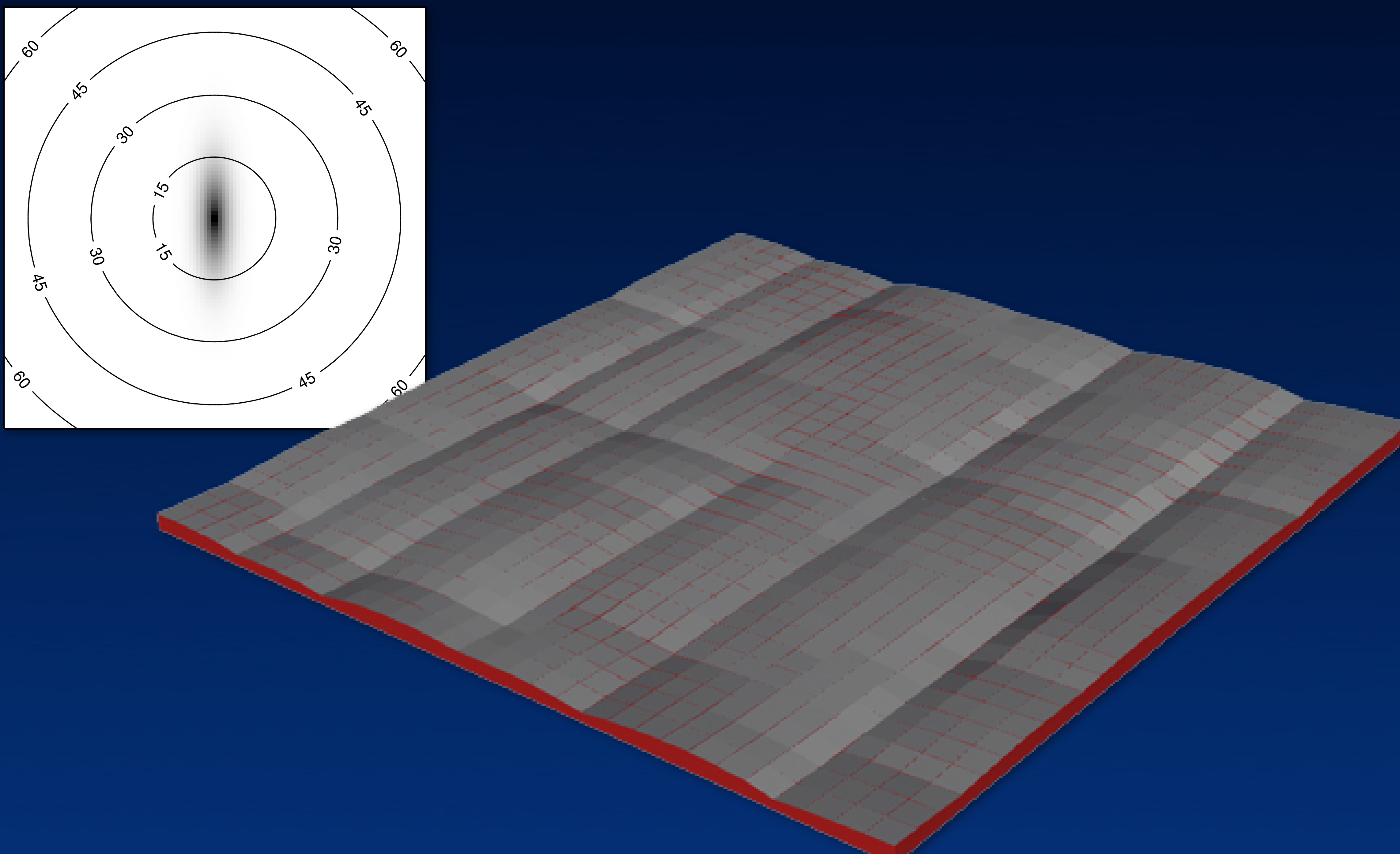
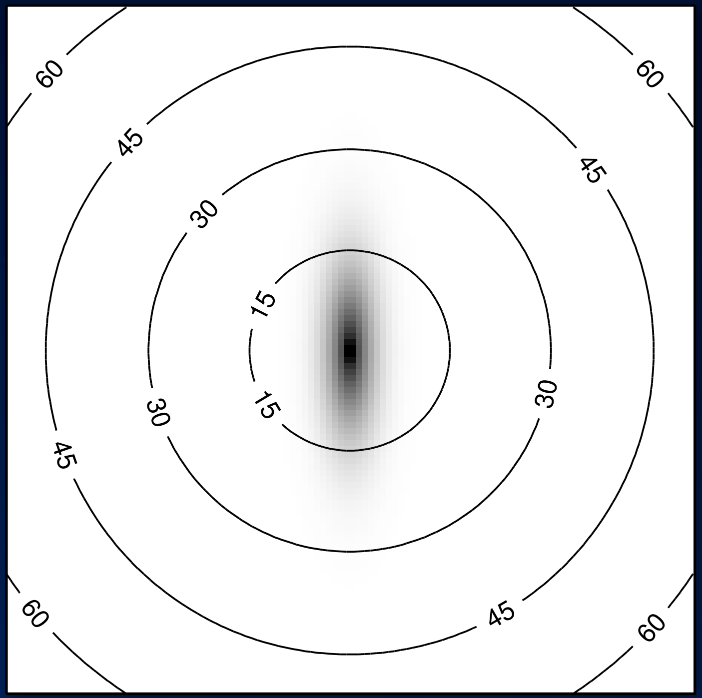
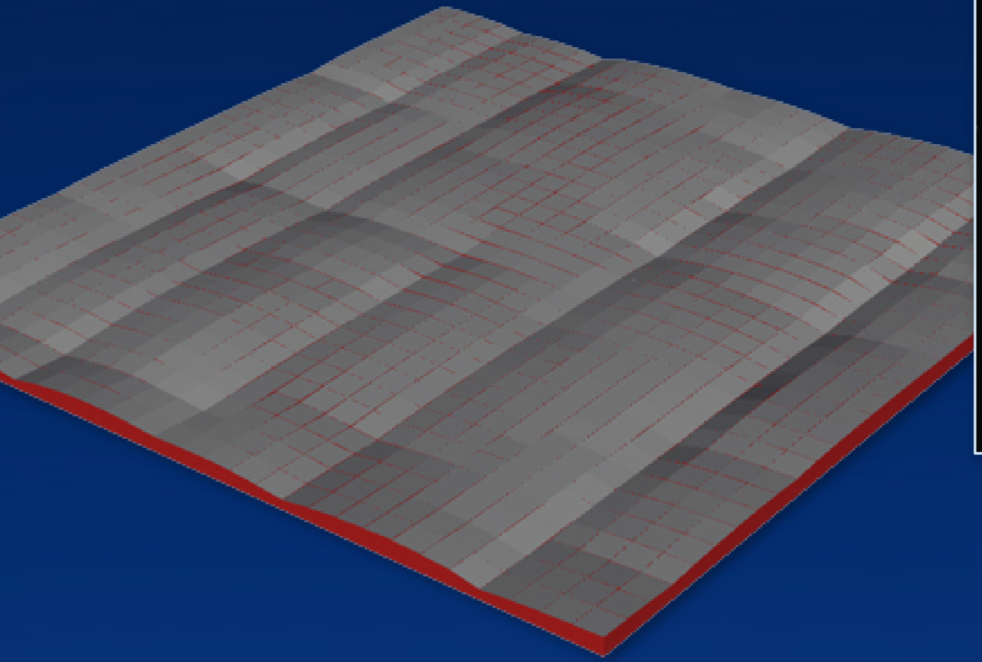


Results



Results





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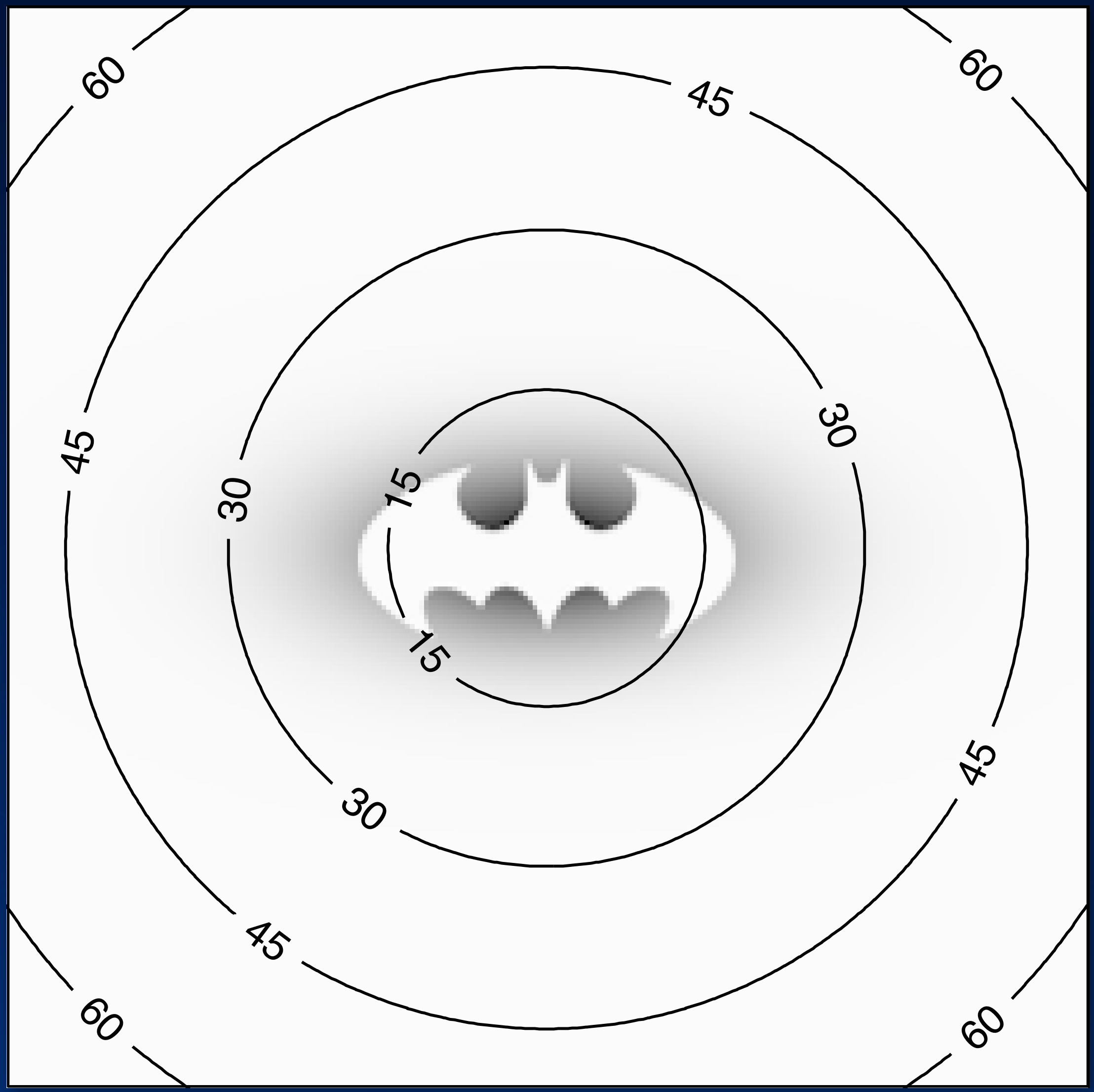

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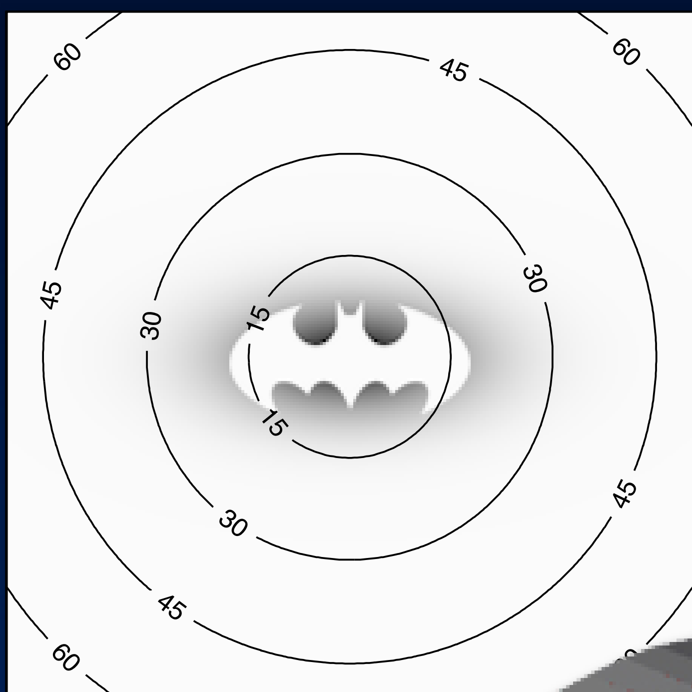
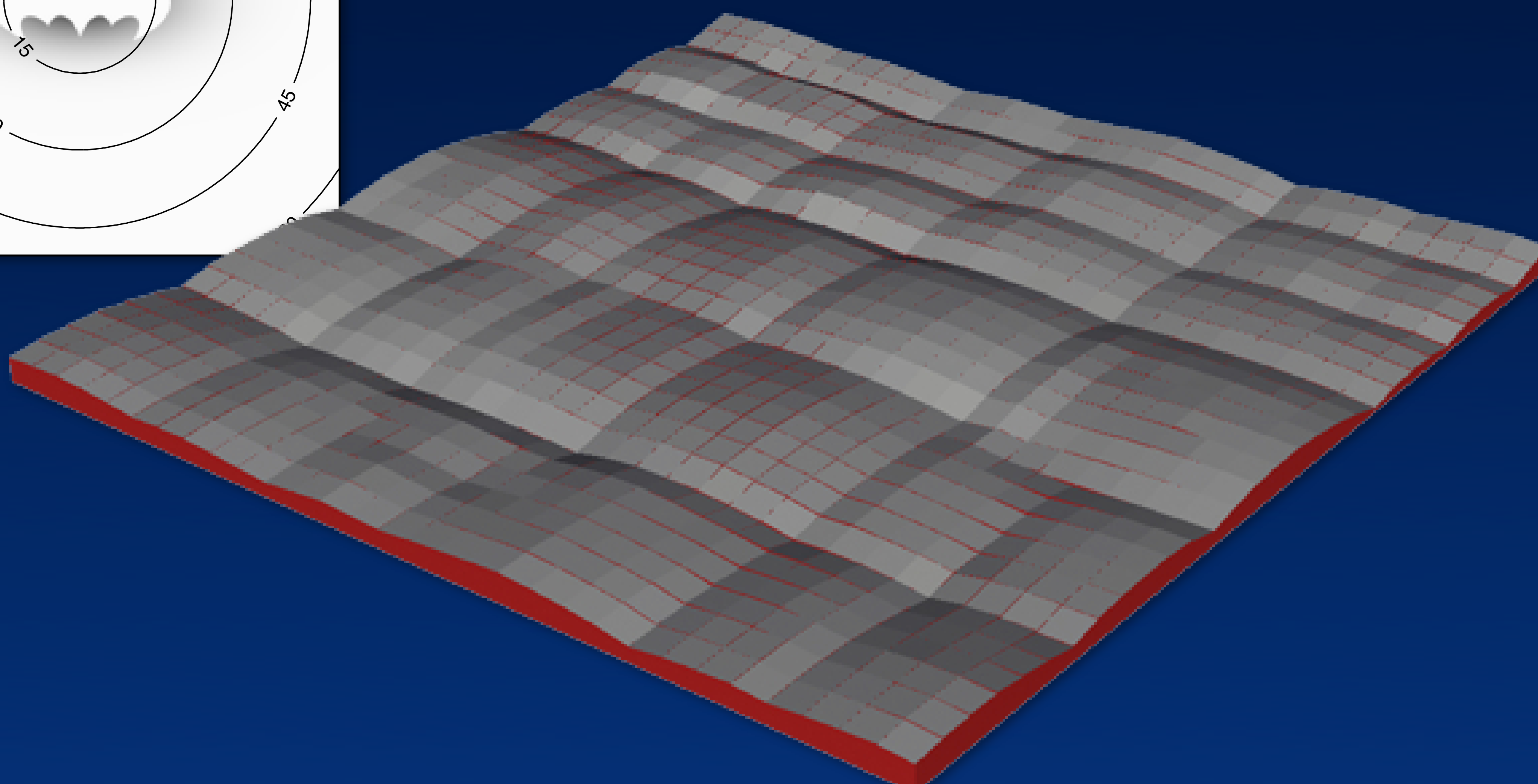
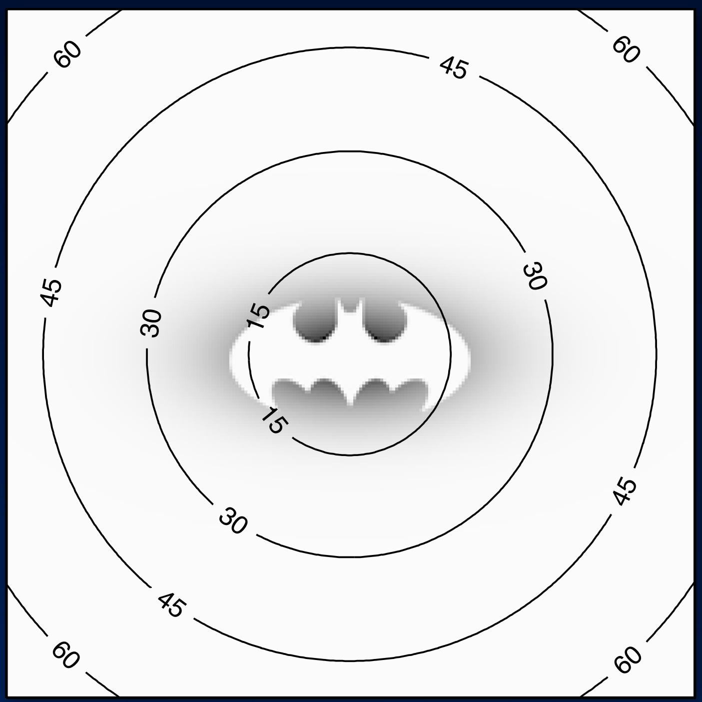
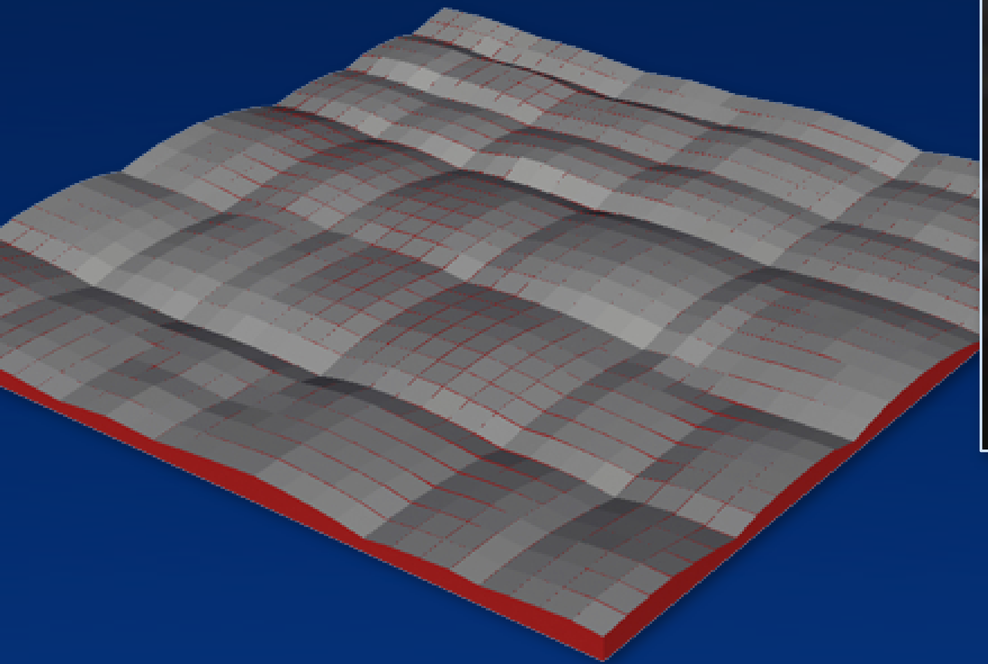
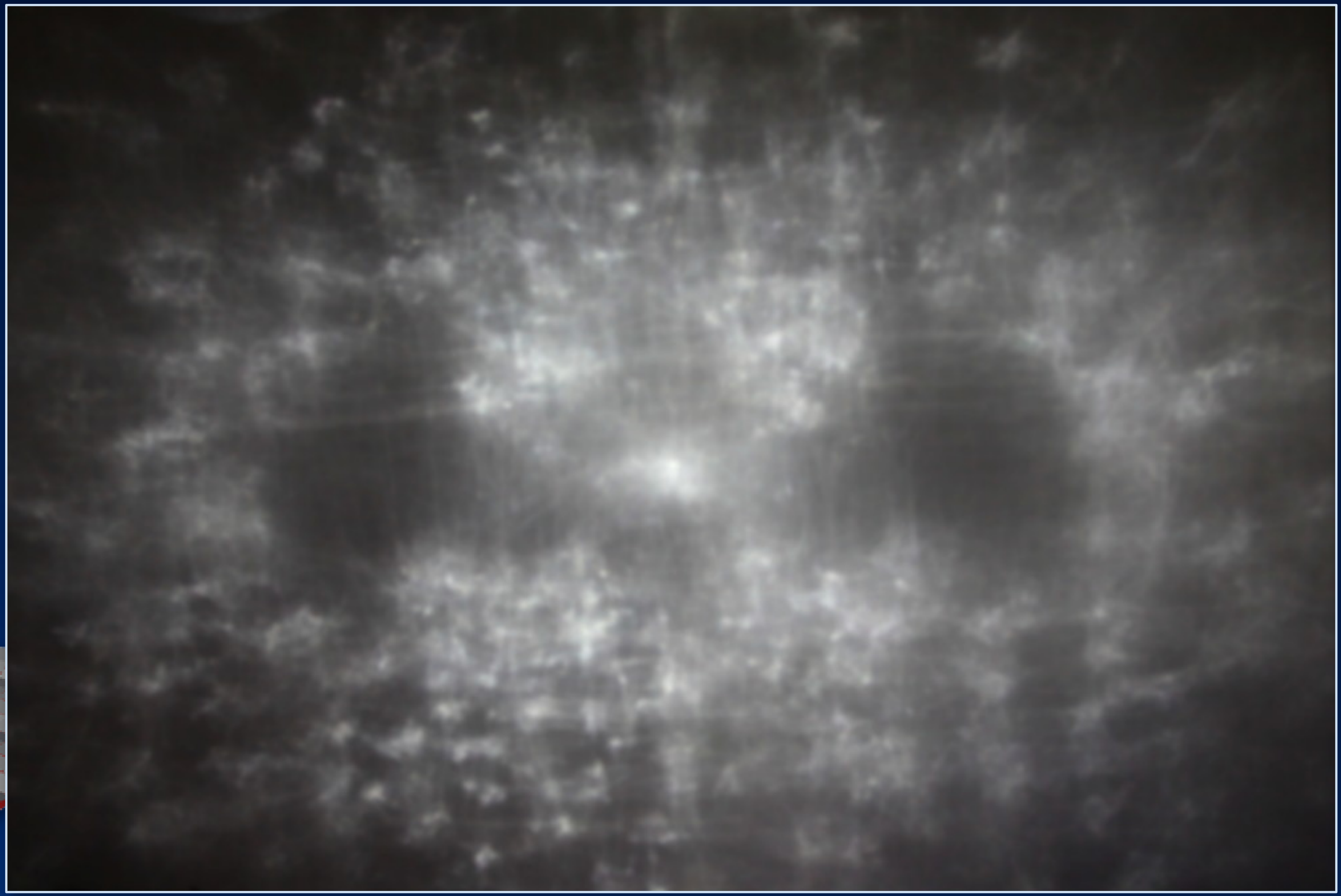




Results

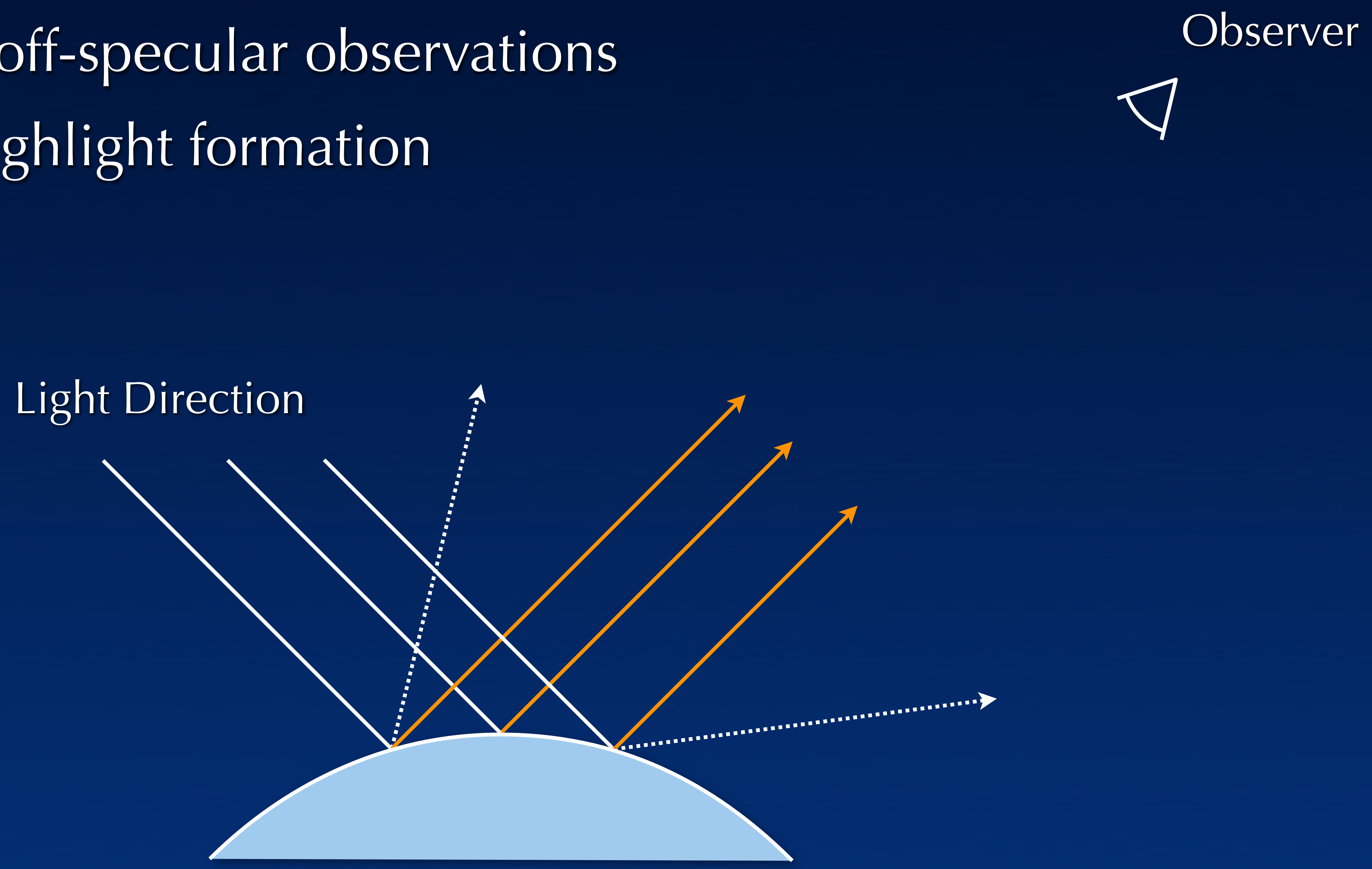






Curved Surfaces

- Curved surface + general observer
  - Multiple off-specular observations
  - Visible highlight formation



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(Simulation)

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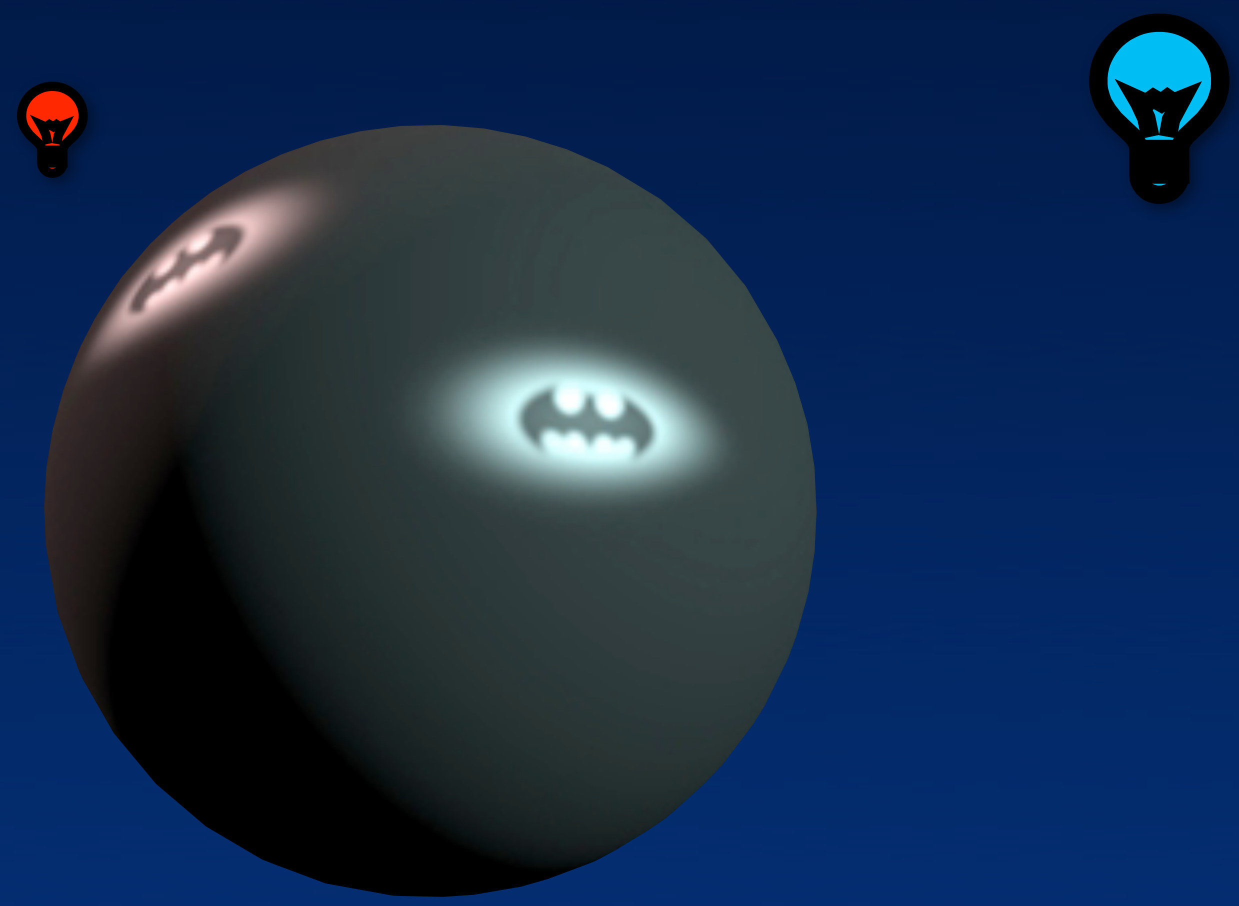

(Simulation)

Constraints

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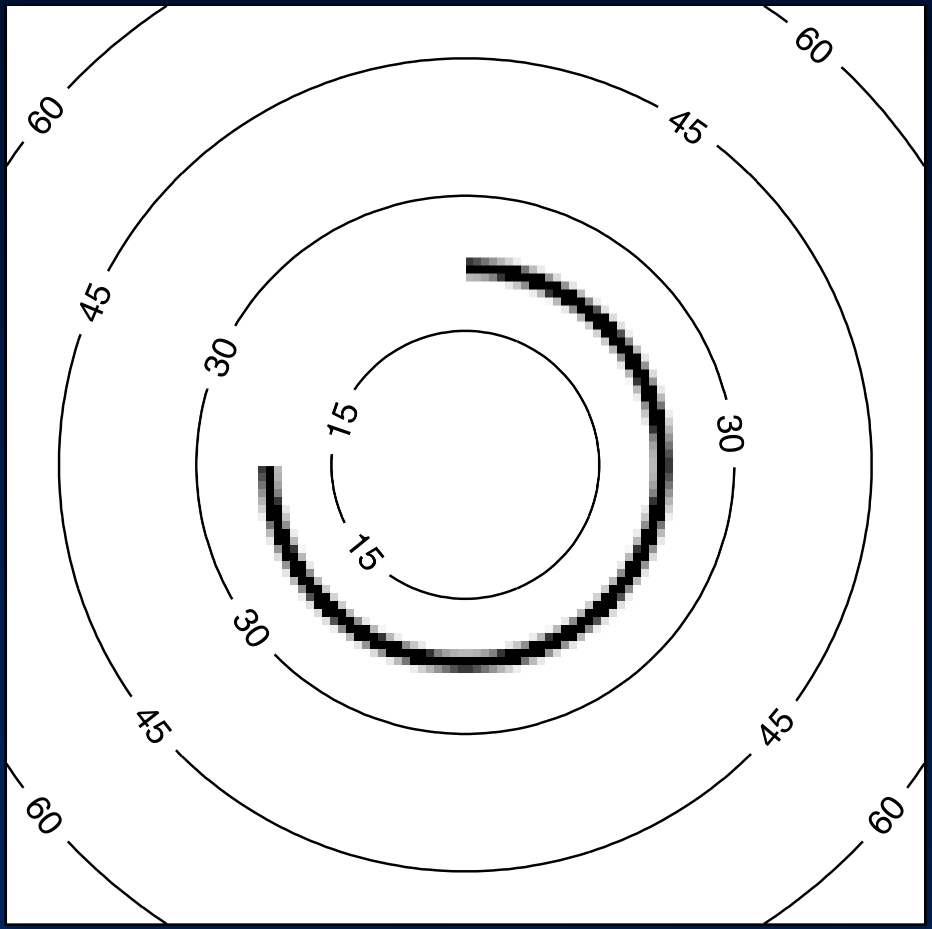
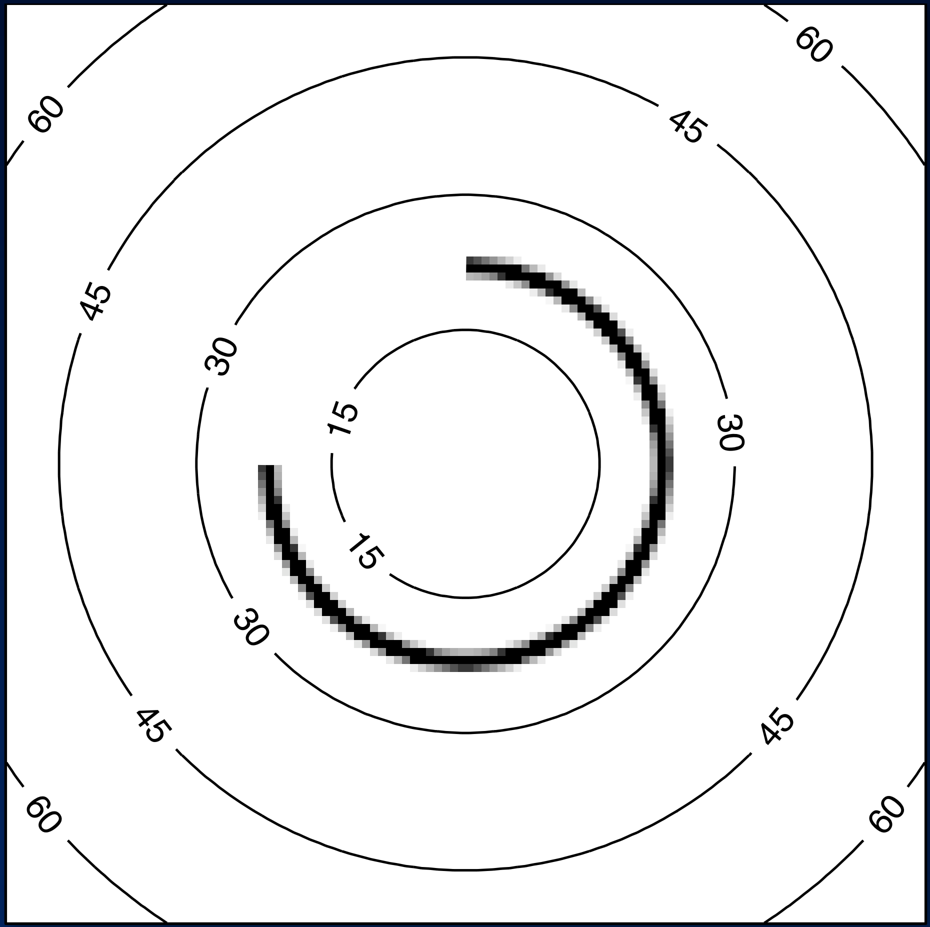


Constraints

- Only integrable MFDs
  - Barycenter along surface normal
  - “What goes up has to go down”
- Purely specular reflectance



Constraints

- Only integrable MFDs
  - Barycenter along surface normal
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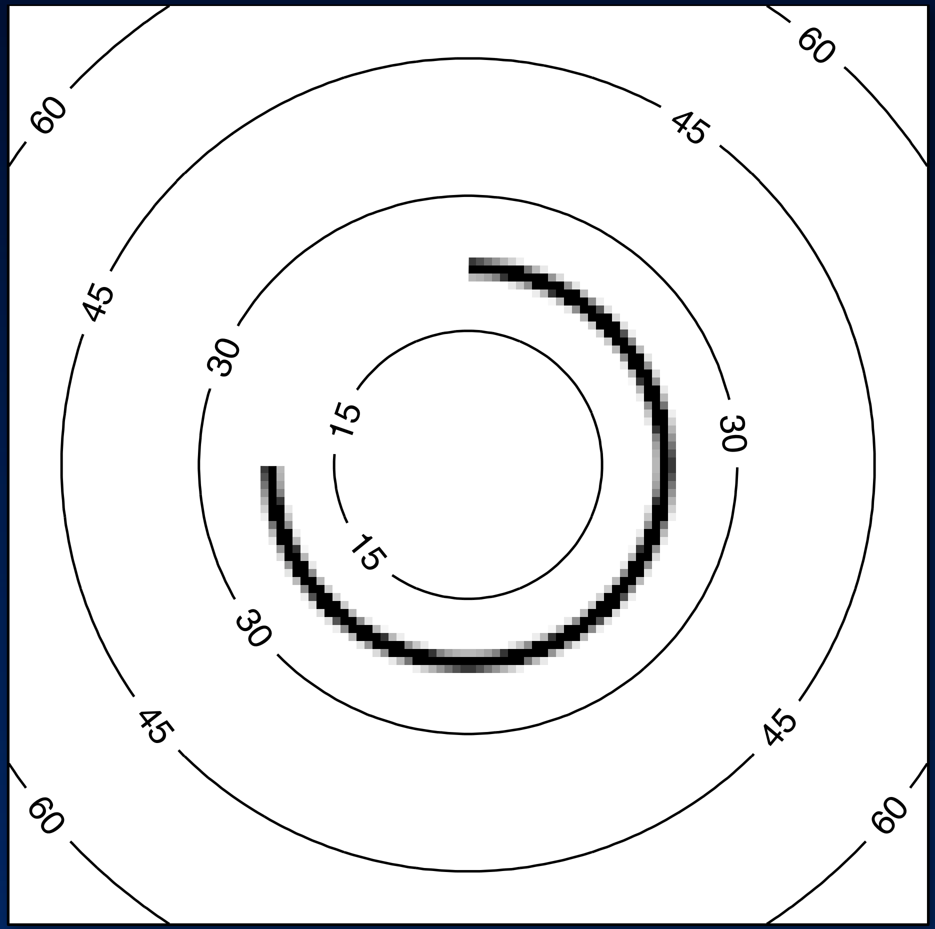
- Purely specular reflectance
- Shadowing term implicit



Practical Scenarios

- Various application scenarios exist
  - Architectural decorations

Courtesy by charlienin @ Panormaio

Practical Scenarios

- Various application scenarios exist
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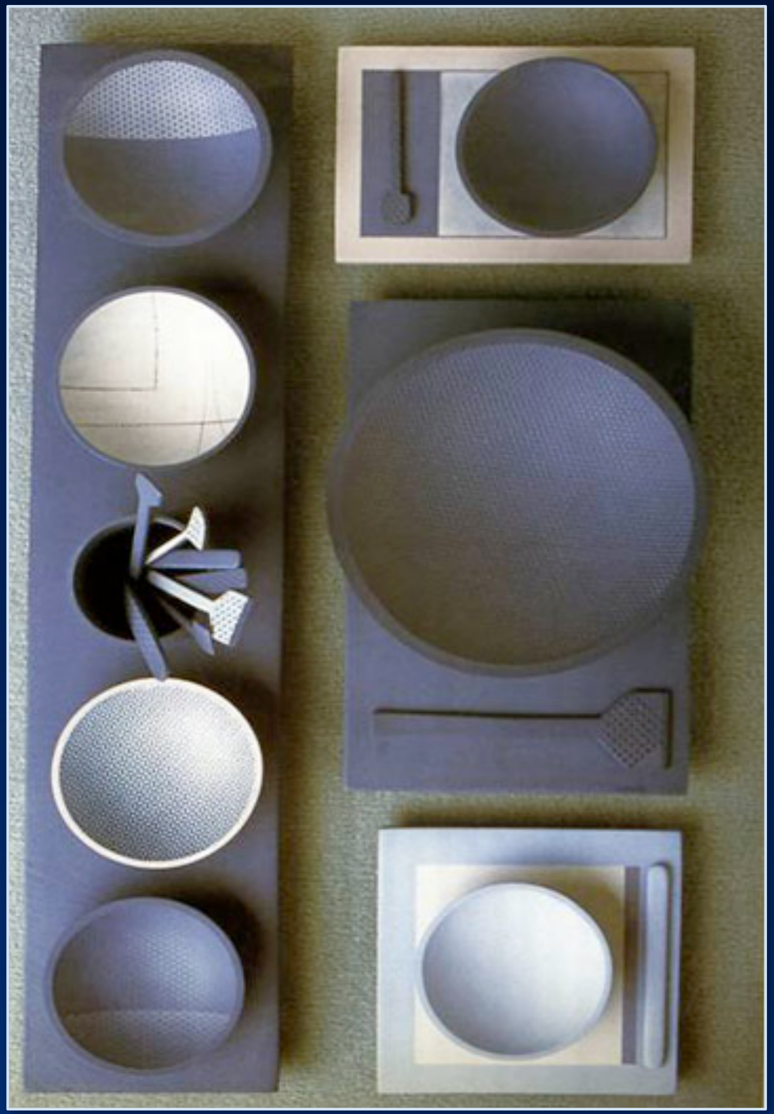
  - Material *design* (not *selection*)



Courtesy by Vicky Shaw

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With permission © Studio Make Light

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Courtesy by Kent Quirk

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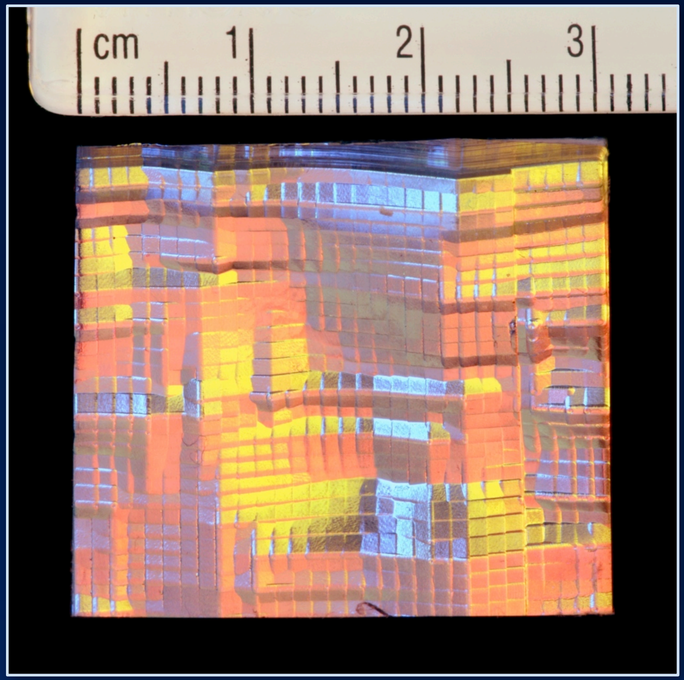

- Manufacturing methods are application-dependent

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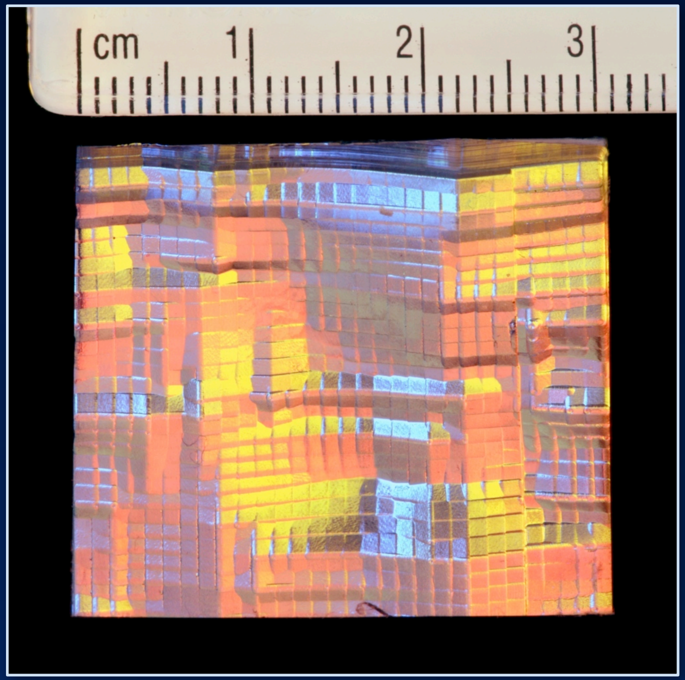

- Manufacturing methods are application-dependent
- Microgeometry computation remains general

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- University of Southern California Office of the Provost

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