



DTU Compute
Department of Applied Mathematics and Computer Science

DTU Mechanical Engineering
Department of Mechanical Engineering



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Microstructure Control and Material Appearance

Presenter: Jeppe Revall Frisvad
 Technical University of Denmark (DTU)
 September 2020



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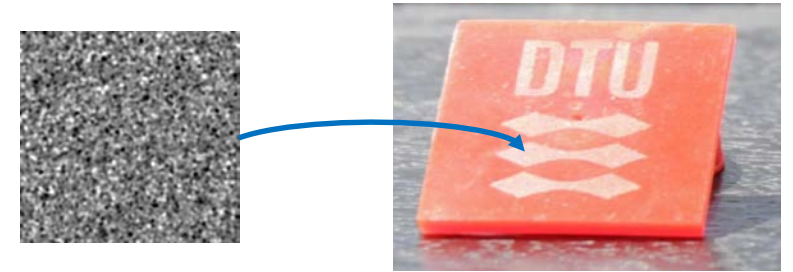
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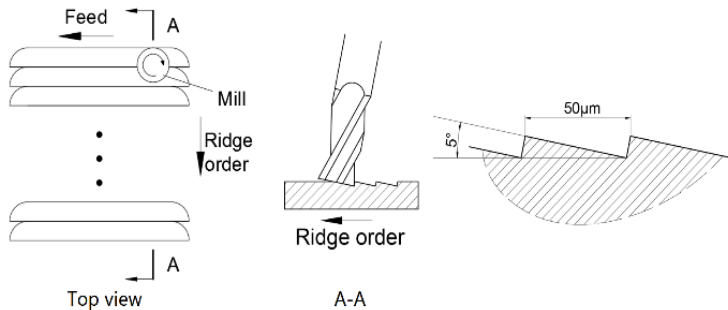
Why microstructure control?

- Microstructure relates to optical and mechanical material properties.
 - Product appearance: design, specification, and quality assessment.
 - Product fingerprinting for tracability. (*)
 - Fluid flow control.
 - Influence on sliding friction.
 - Engineering of optical materials (LEDs, lasers, waveguides, sensors, solar cells, etc.)



- Needed for integrated control of appearance in additive manufacturing.

(*)



<https://www.rel8.dk/>



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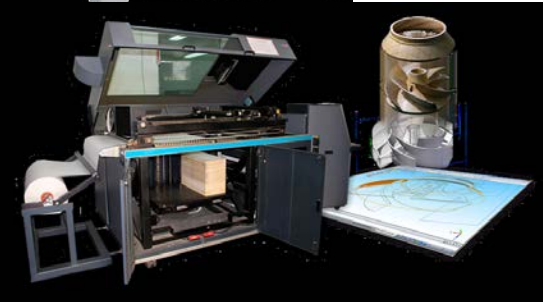
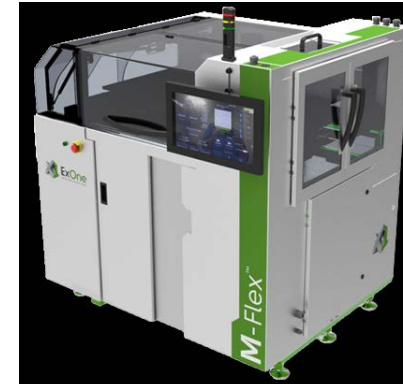
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A selection of 3D printers

- Material Extrusion: fused deposition modelling (FDM), direct writing assembly (DWA), . . . ;
- Powder: binder jetting, selective laser sintering, . . . ;
- Lamination: laminated object manufacturing (LOM), selective deposition lamination (SDL), . . . ;
- Photopolymerization: stereolithography (SLA), direct light processing (DLP), . . . ;





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Slicing an object for 3D printing

- Triangle mesh representation.
- Horizontal cross sections aligned with the print layers.
- This sampling of cross sections leads to aliasing.
- Antialiasing is done by averaging many samples.
- But how to use the resulting grayscale values?





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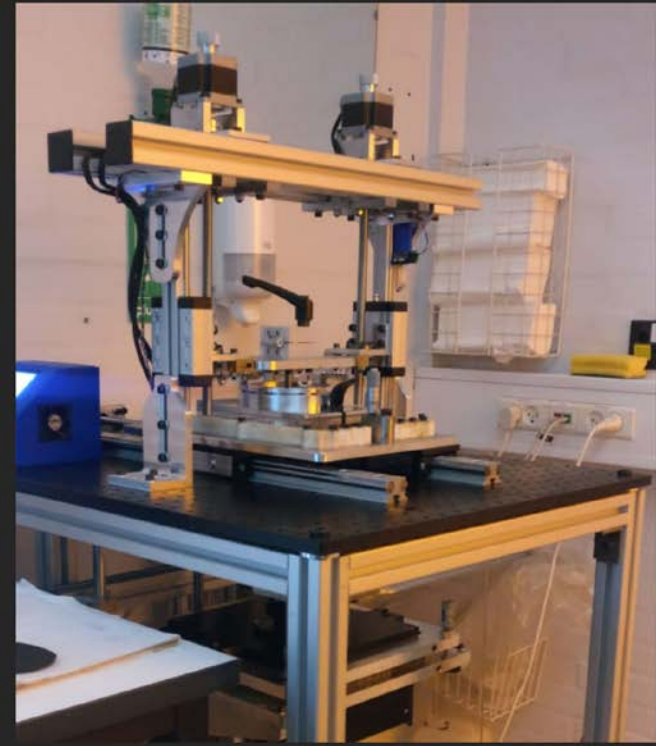
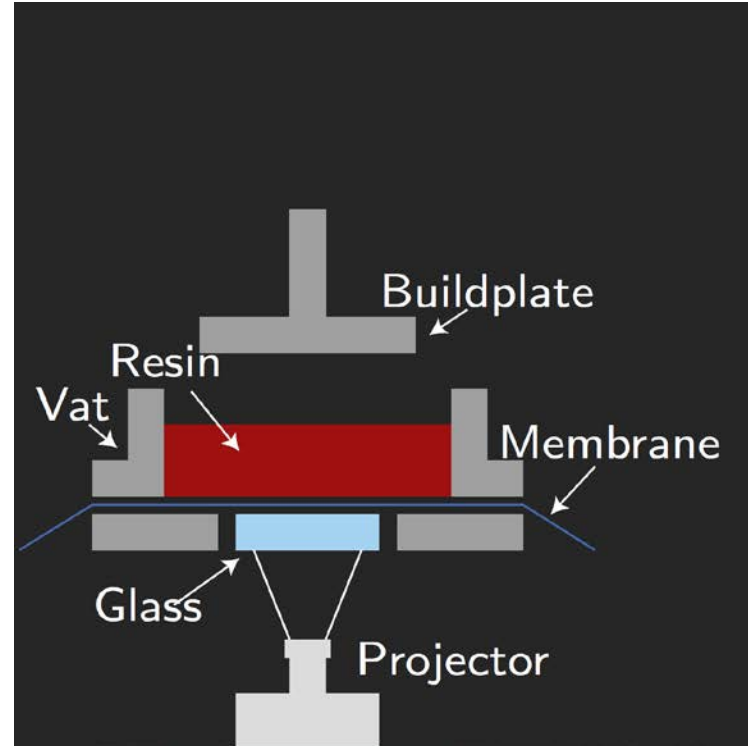
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What is a DLP printer?

- Photopolymer (resin).
- Vat.
- Building platform (step precision: $1 \mu\text{m}$).
- DLP UV-projector (2560 × 1600 micro-mirrors, pixel pitch of $7.54 \mu\text{m}$).
- Membrane (optional).

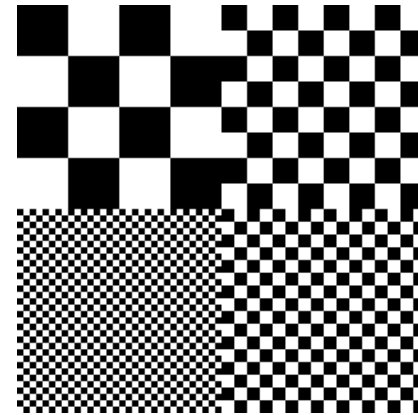


- The projector can project grayscale images, but what is the effect?



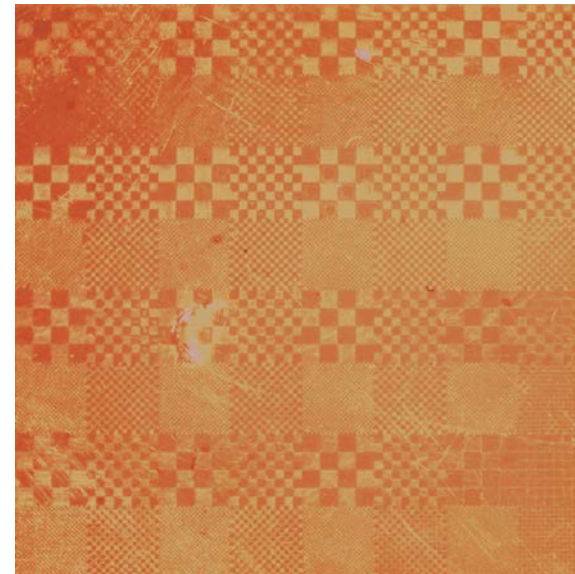
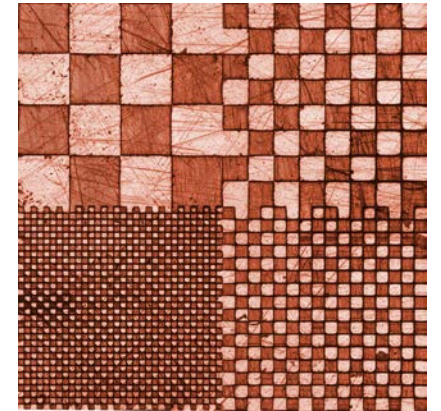
Calibration of print parameters

- Projector calibration:
 - fix exposure time;
 - print calibration sample with increasing intensity;
 - fix intensity;
 - print calibration sample with increasing exposure time;
- Layer thickness: $18 \mu\text{m}$;
- UV LED amplitude: 230;
- Exposure time: 3 s;



projected pattern

print result in microscope



repeated print of pattern with different parameter settings



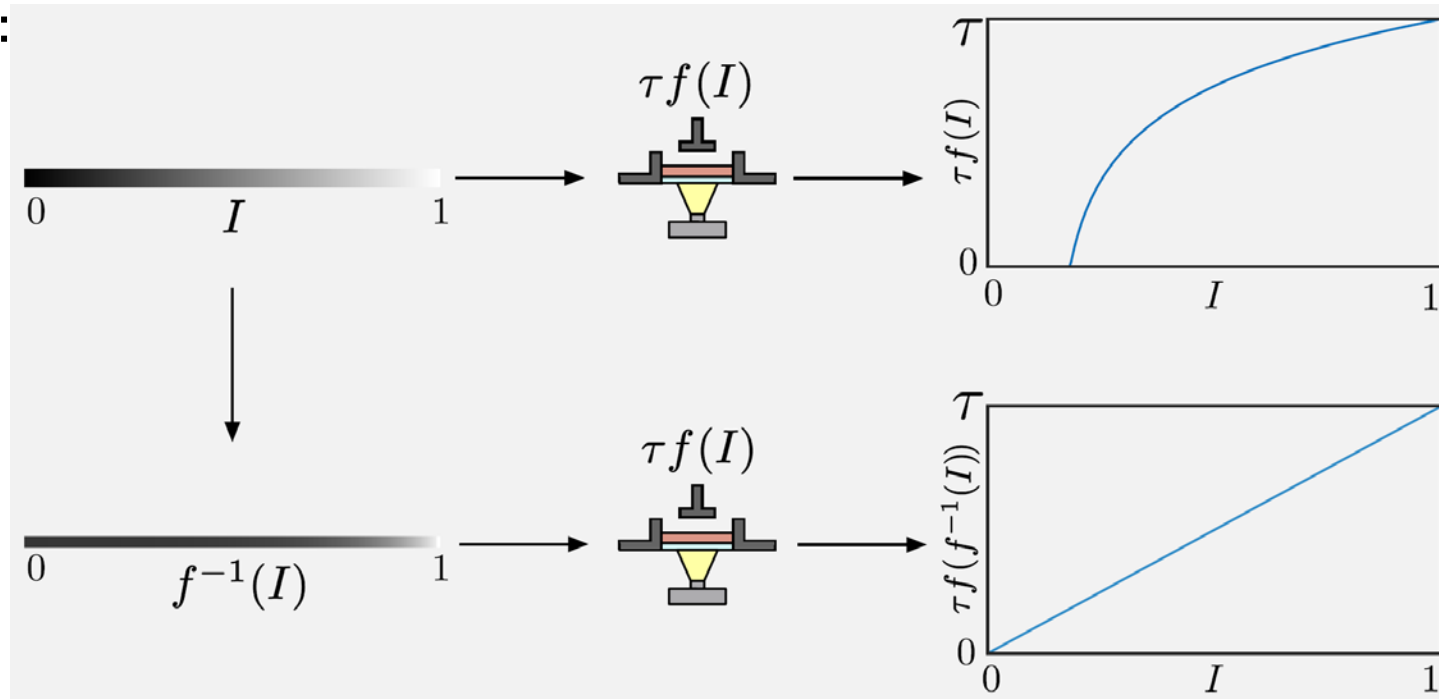
Subvoxel growth control

- The curing process is non-linear:

$$\tau f(I) = \begin{cases} \alpha + \beta \log(I - \gamma), & \text{for } I > e^{-\alpha/\beta} + \gamma \\ 0, & \text{for } I \leq e^{-\alpha/\beta} + \gamma \end{cases}$$

- If we find α , β , and γ , we can correct:

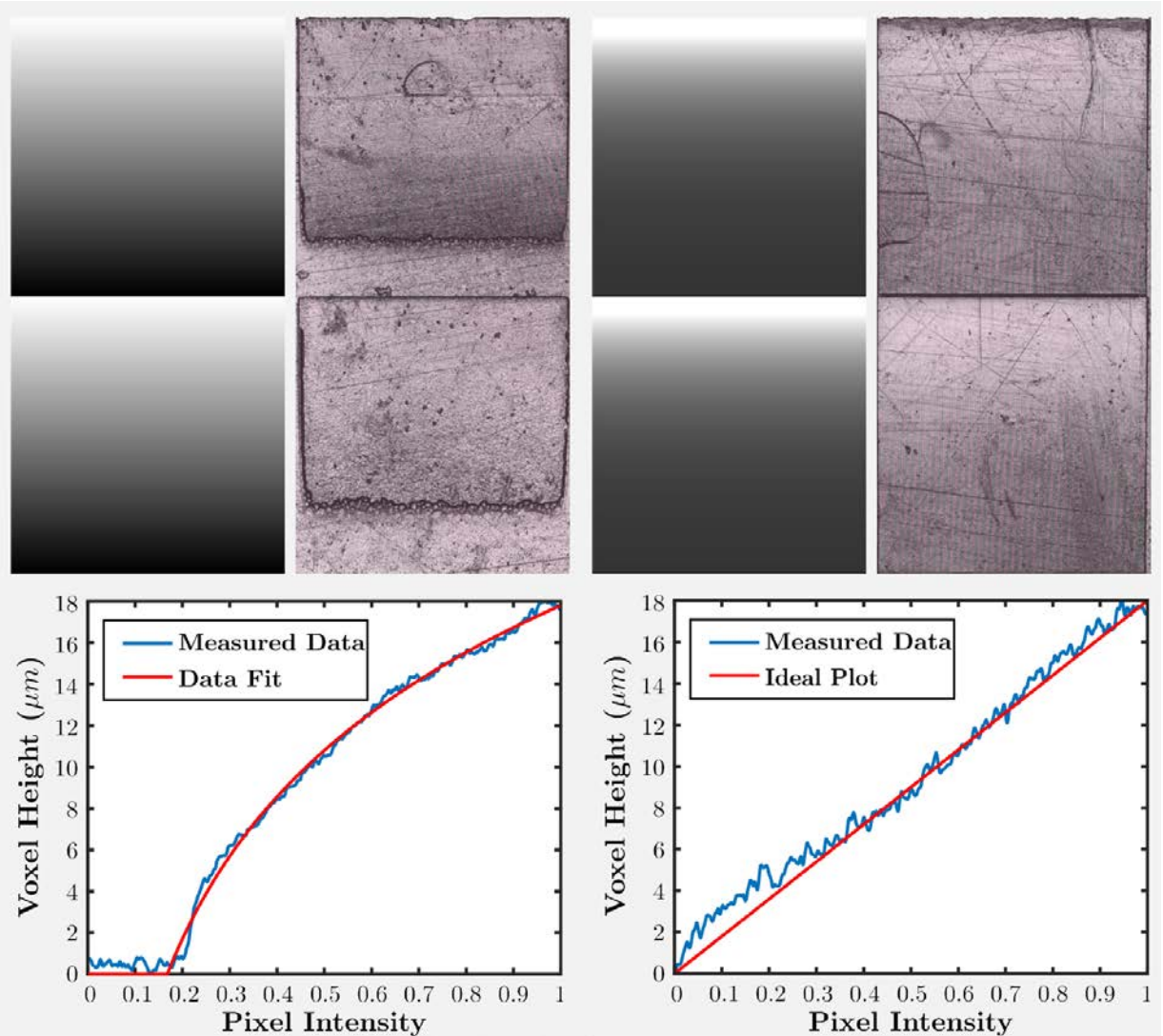
$$f^{-1}(I) = \begin{cases} e^{\frac{\tau I - \alpha}{\beta}} + \gamma, & \text{for } I > 0 \\ 0, & \text{for } I = 0 \end{cases}$$





Subvoxel height measurements

- To estimate α , β , and γ :
 - print linear gradient;
 - measure the surface height with a resolution of $0.4 \mu\text{m}$;
 - find a fit and estimate the parameters;
- $\alpha = 17.71 \mu\text{m}$,
- $\beta = 10.24 \mu\text{m}$,
- $\gamma = -0.01$





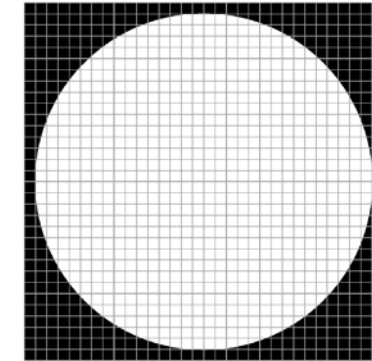
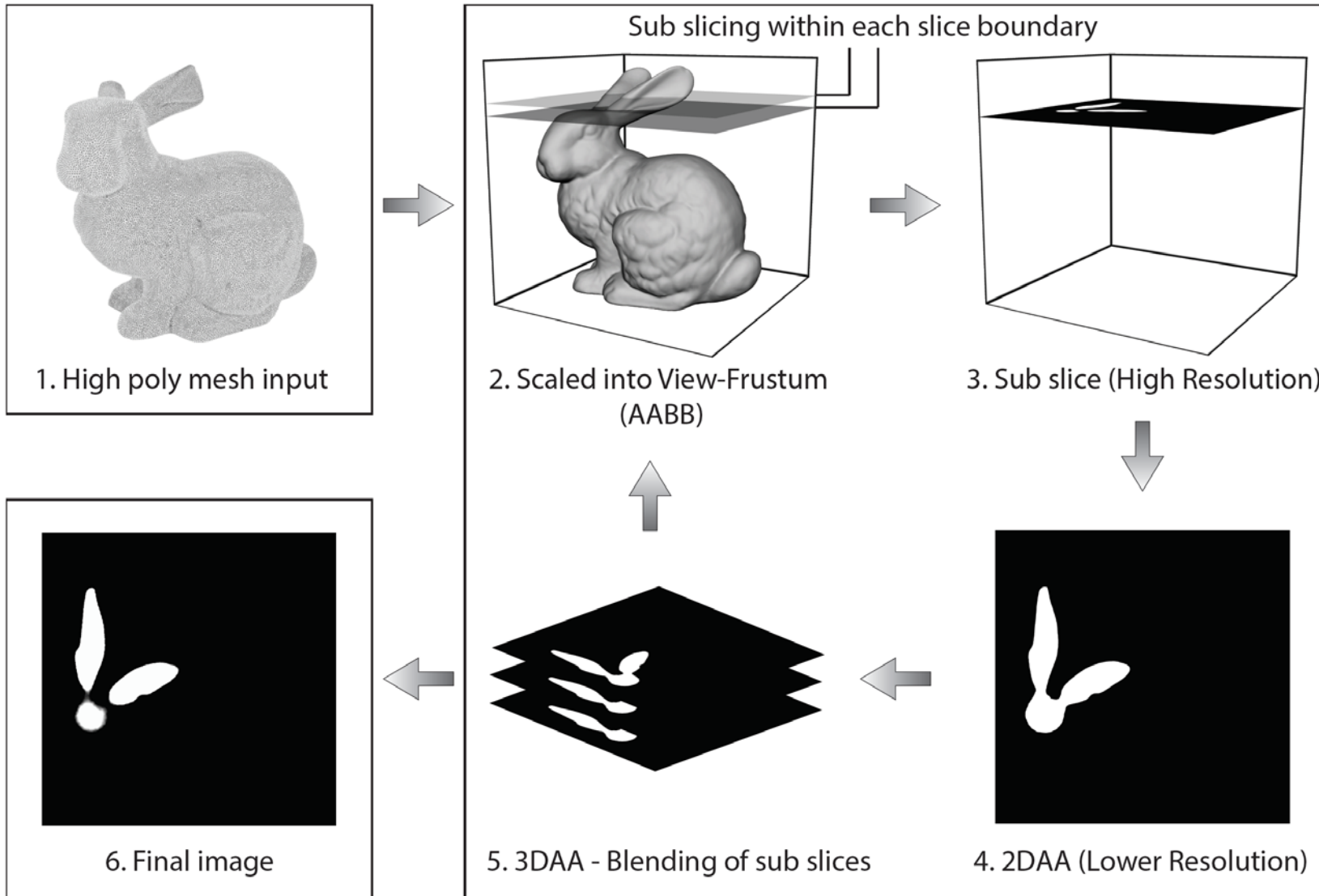
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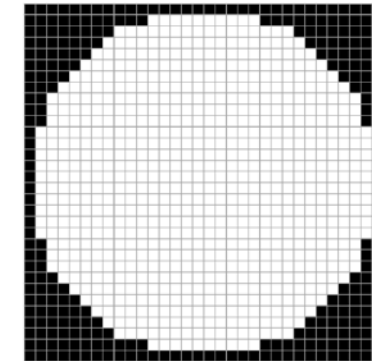
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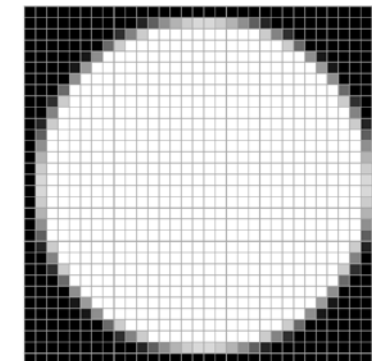
Antialiasing in the slicer



slice of a sphere



aliased cross section



after anti-aliasing

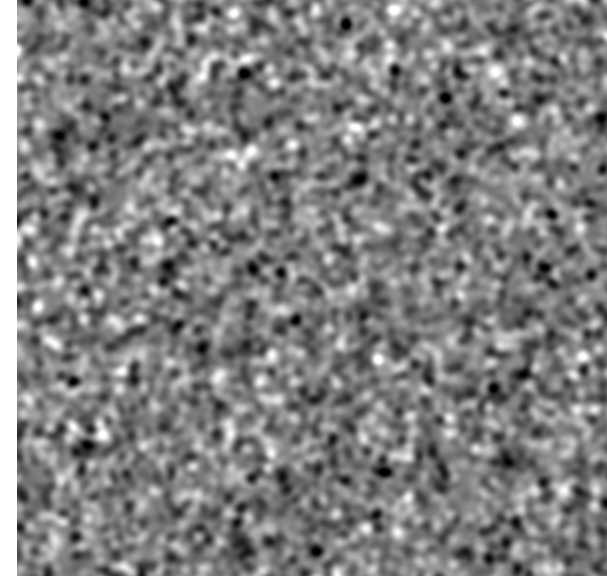




Microstructure control using DLP grayscale values

- Using a smooth noise function to modify surface roughness by controlling noise amplitude A and frequency B .

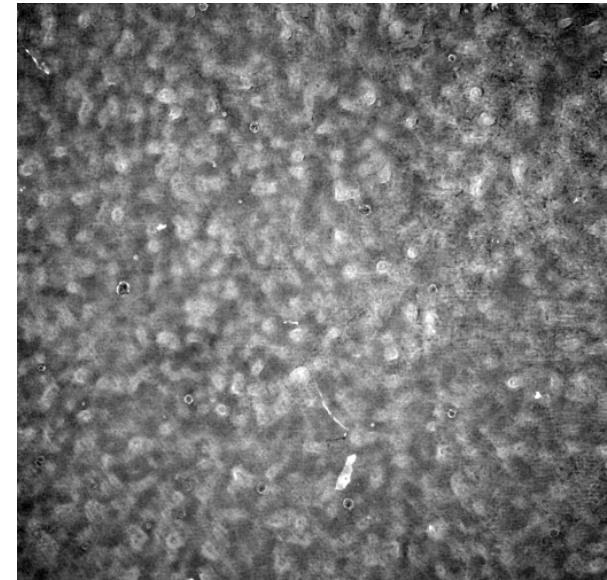
Example of noise used as projector pattern.



| | $A = 0.625$ | $A = 2$ | $A = 3$ | |
|-------------------------|-------------|---------|---------|----------|
| S_q (μm) | 2.82 | 4.20 | 6.94 | $B = 16$ |
| S_q (μm) | 3.64 | 5.71 | 10.10 | $B = 32$ |

S_q is the root mean square height of a surface area.

Printed output as observed in microscope.





Noise

■ Noise explorer:

<https://people.compute.dtu.dk/jerf/code/noise/>

■ Sparse convolution noise

- Convolution of randomly placed $(\mathbf{x}_{i,j})$ impulses of random value $(\alpha_{i,j})$.
- Use a filter kernel with compact support and insert a regular grid (cell vertices \mathbf{q}_i).

$$\text{cubic}(\mathbf{v}) = \begin{cases} (1 - 4 \mathbf{v} \cdot \mathbf{v})^3 & \text{for } \mathbf{v} \cdot \mathbf{v} < \frac{1}{4} \\ 0 & \text{otherwise} \end{cases}$$

- Use a seeded RNG: $\text{rnd}(t)$
- Choose a number of impulses per cell (N).

$$\text{noise}(\mathbf{p}) = \frac{4}{5\sqrt[3]{N}} \sum_{i=0}^7 \sum_{j=1}^N \alpha_{i,j} \text{cubic}(\mathbf{x}_{i,j} - \mathbf{p})$$

$$\mathbf{x}_{i,j} = \mathbf{q}_i + \boldsymbol{\xi}_{i,j}$$

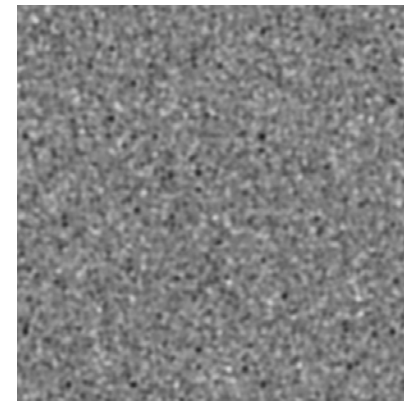
$$\alpha_{i,j} = \text{rnd}(t_{n_{i,j}}) (1 - 2(j \bmod 2))$$

$$\boldsymbol{\xi}_{i,j} = \left(\text{rnd}(t_{n_{i,j}+1}), \text{rnd}(t_{n_{i,j}+2}), \text{rnd}(t_{n_{i,j}+3}) \right)$$

$$n_{i,j} = 4(N\mathbf{q}_i \cdot \mathbf{a} + j)$$

$$\mathbf{q}_i = \left\lfloor \mathbf{p} - \left(\frac{1}{2}, \frac{1}{2}, \frac{1}{2} \right) \right\rfloor + \left(i \bmod 2, \left\lfloor \frac{i}{2} \right\rfloor \bmod 2, \left\lfloor \frac{i}{4} \right\rfloor \bmod 2 \right)$$

My choice: $N = 30$ and $\mathbf{a} = (1, 1000, 576)$



$$0.5 (A \text{ noise}(B \mathbf{p}) + 1)$$

$A = 1, B = 1$





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Control of surface roughness in 3D

- The noise function accepts a 3D positions as input, so we can directly use it in our slicer and control the roughness of a 3D surface.



no grayscale



$A = 0.625$



$A = 2$



$A = 3$





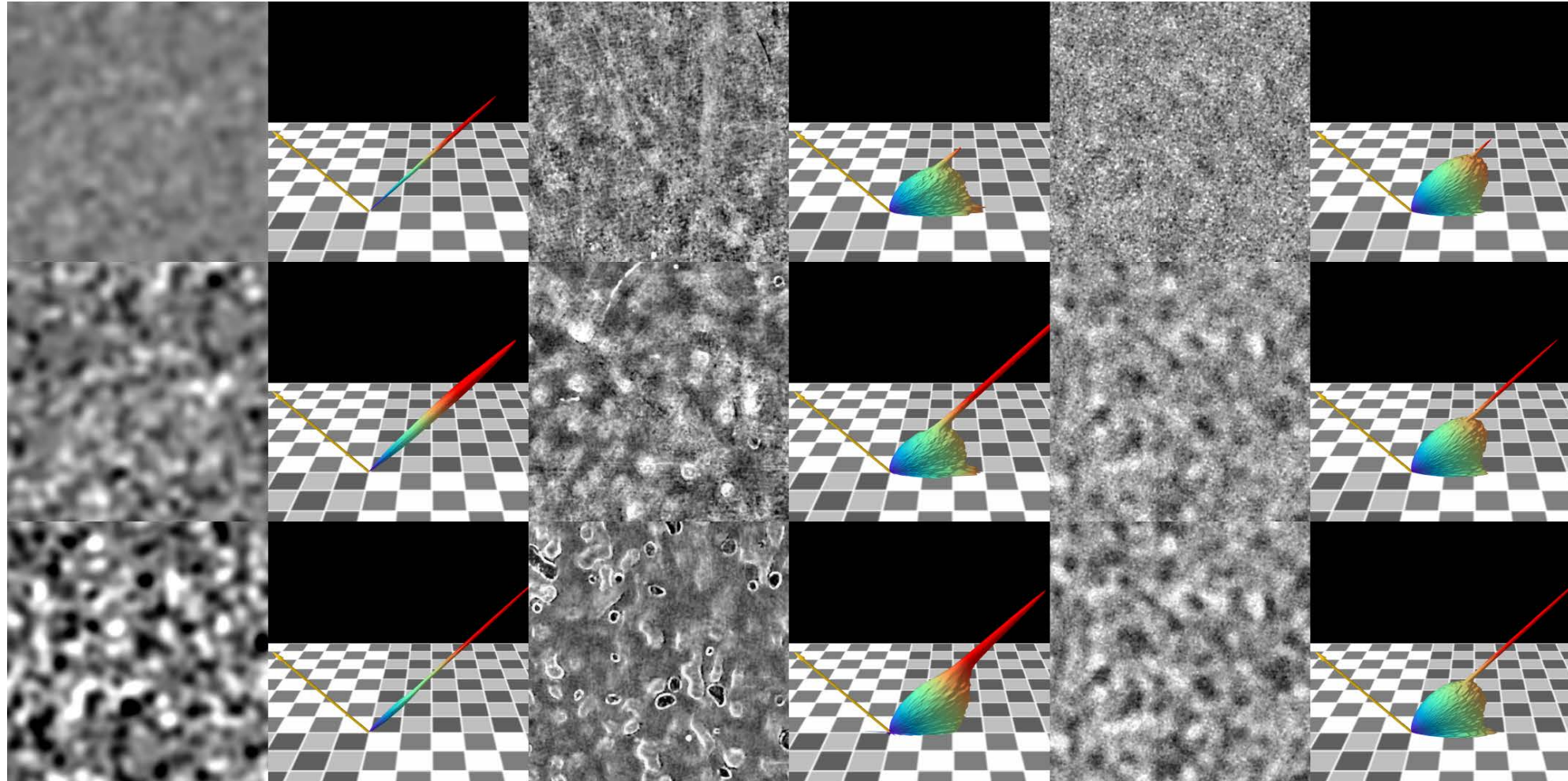
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BRDF and printer ground noise



(a) input

(b) input BRDF

(c) measured

(d) printed BRDF

(e) input + ground

(f) model BRDF

$$\text{ground}(\mathbf{p}) = \frac{2}{3} \text{noise} \left(\frac{\mathbf{p}}{50 \mu\text{m}} \right) + \frac{1}{9} \text{noise} \left(\frac{\mathbf{p}}{25 \mu\text{m}} \right) + \frac{1}{12} \text{noise} \left(\frac{\mathbf{p}}{2 \mu\text{m}} \right)$$





Noise-based modeling

■ Noise with octaves

- Number of octaves $\Omega \geq 1$
- Lacunarity $\ell > 1$
- Fractional increment (roughness) $H \in (0,1]$

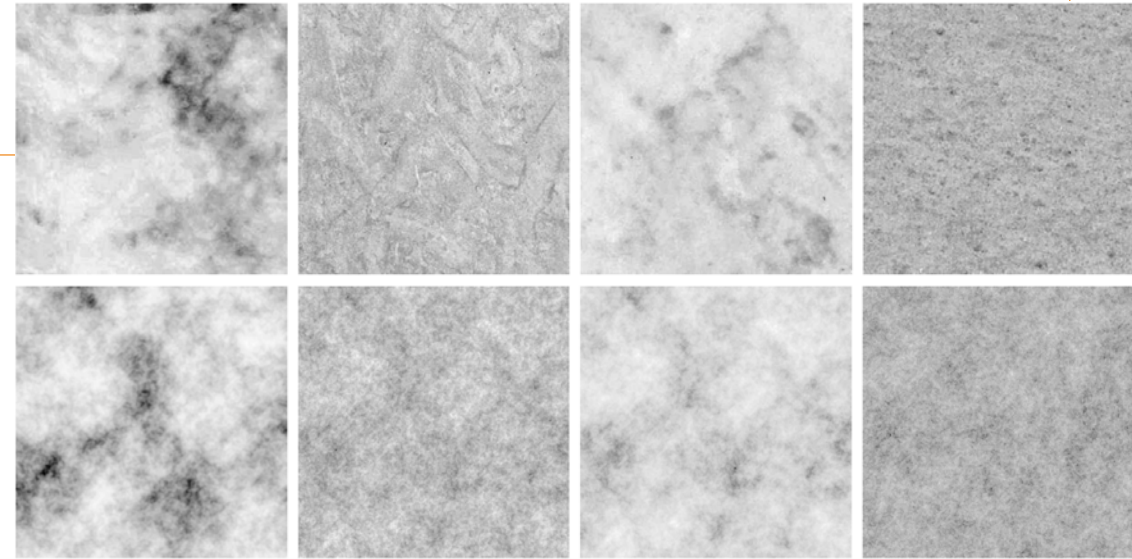
$$\text{fBm}(\mathbf{p}) = \sum_{i=0}^{\Omega-1} \ell^{-Hi} \text{noise}(\mathbf{p} \ell^i)$$

- $H = 1$ is a monofractal (same fractal dimension everywhere)

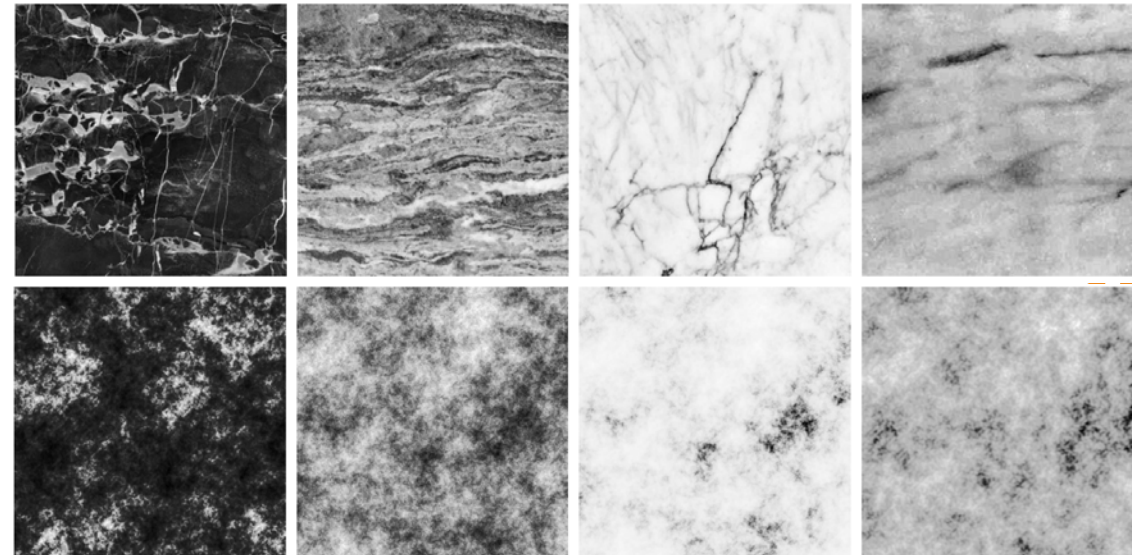
■ Absolute value for sharp edges

$$\text{turbulence}(\mathbf{p}) = \sum_{i=\Omega_{\text{low}}}^{\Omega_{\text{high}}} \frac{1}{2^i} |\text{noise}(2^i \mathbf{p})|$$

Top rows: input from marble images



Kim Harder Fog. Noise-based texture synthesis by analysis of image examples. MSc thesis, Technical University of Denmark, 2017.

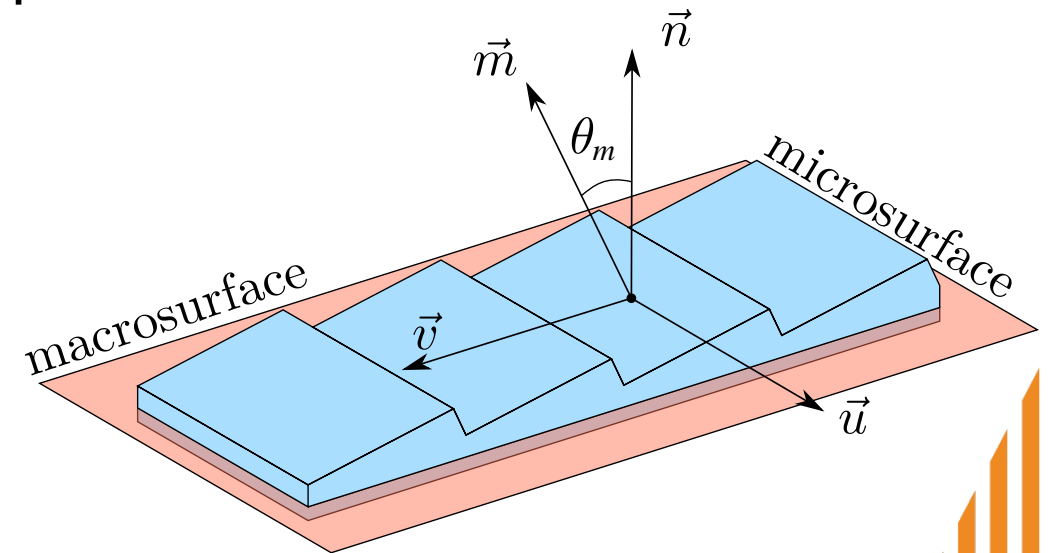


Bottom rows: fBm fit



Anisotropic surface reflectance

- Random rough surfaces produce isotropic reflections.
- Scattering is independent of sample orientation.
- Structured surfaces can produce anisotropic reflections.
- Example: ridged surface



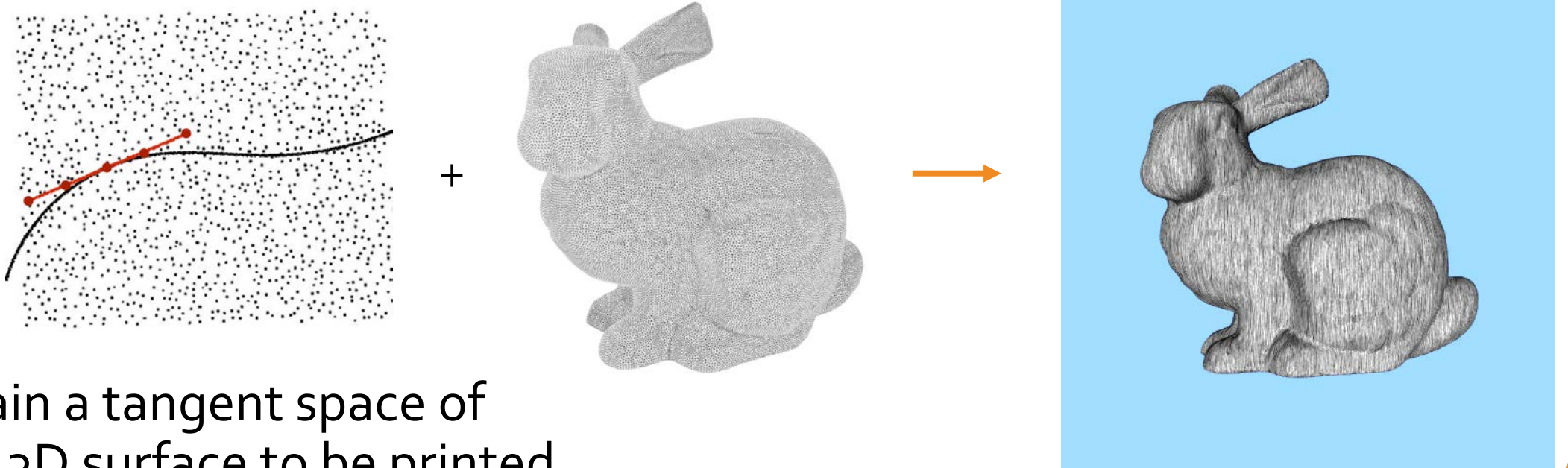
Identical 2x2 cm² samples.
Every ridge is 50 μm.
Slope angle is $\theta_m = 5^\circ$.
Two samples have been rotated 90°
as compared with the other two.

[Luongo et al. Modeling the anisotropic reflection of surfaces with microstructure engineered to produce visible contrast after rotation. ICCVW 2017]



Line integral convolution

- Given a 3D noise function like sparse convolution noise:
 - For each pixel take the integral along a line.



- Obtain a tangent space of your 3D surface to be printed.

<https://people.compute.dtu.dk/jerf/code/hairy/>

References:

- Battke, H., Stalling, D., Hege H.-C. Fast line integral convolution for arbitrary surfaces in 3D. In *Visualization and Mathematics*, pp. 181-195. Springer, 1997.
- Frisvad, J. R. Building an orthonormal basis from a 3d unit vector without normalization. *Journal of Graphics Tools* **16**(3):151-159, August 2012.



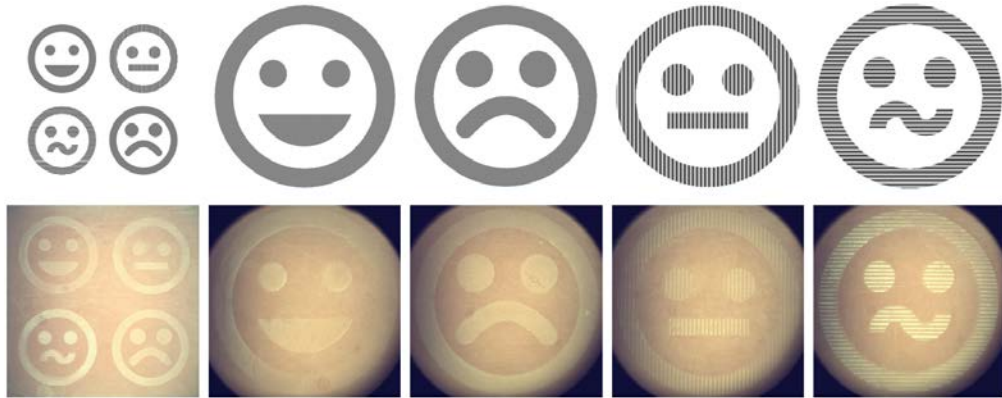
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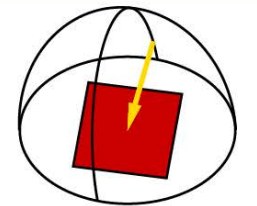
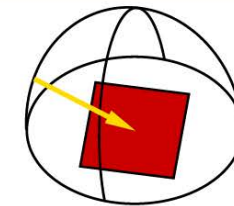
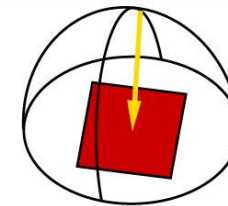
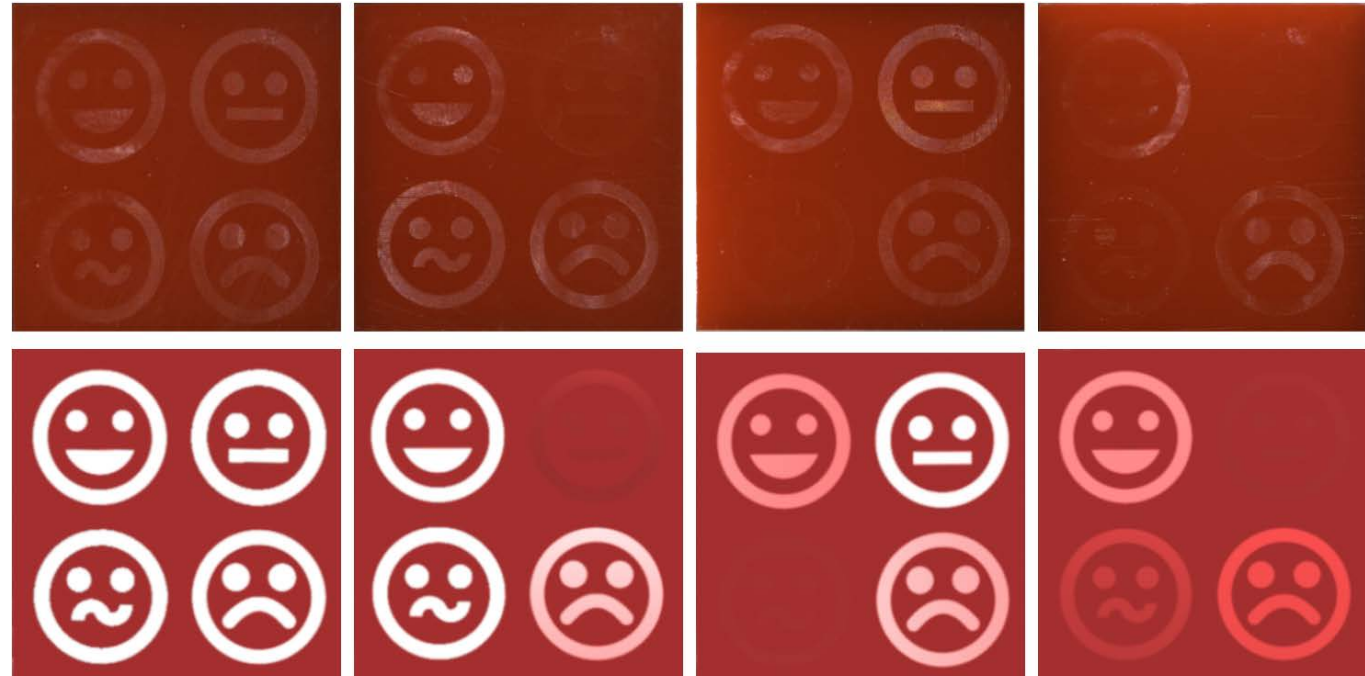
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Anisotropic smileys (ridges and sinusoids)



Input texture and microscope images.



Top row:
Middle row:
Bottom row:

3D printed
computed
direction of incidence





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Print results





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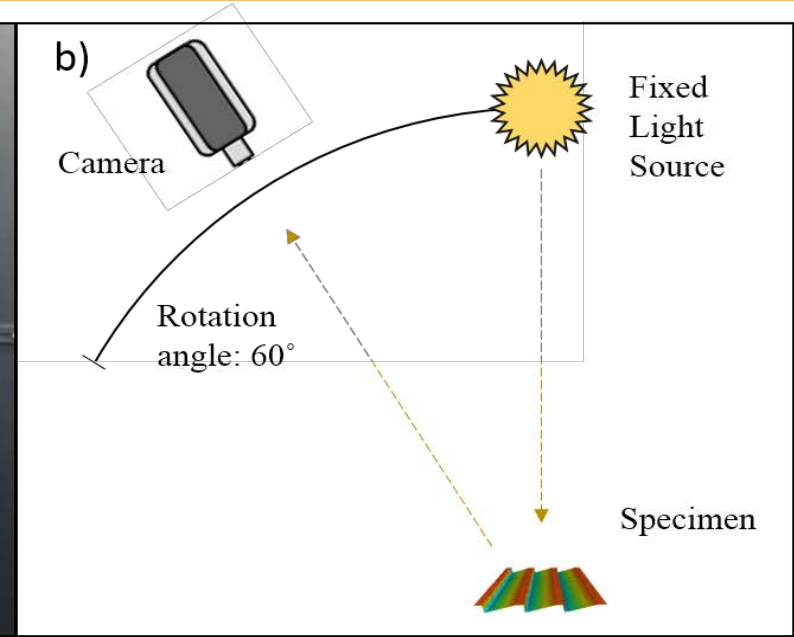
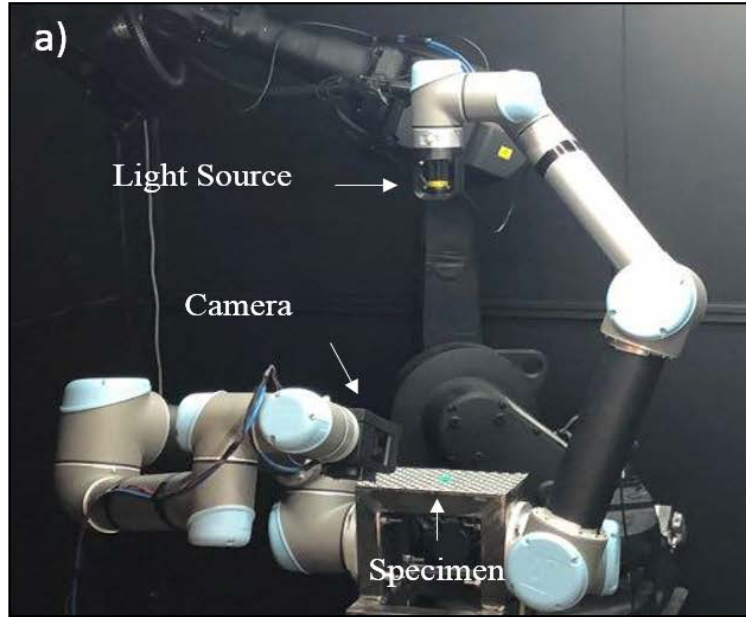
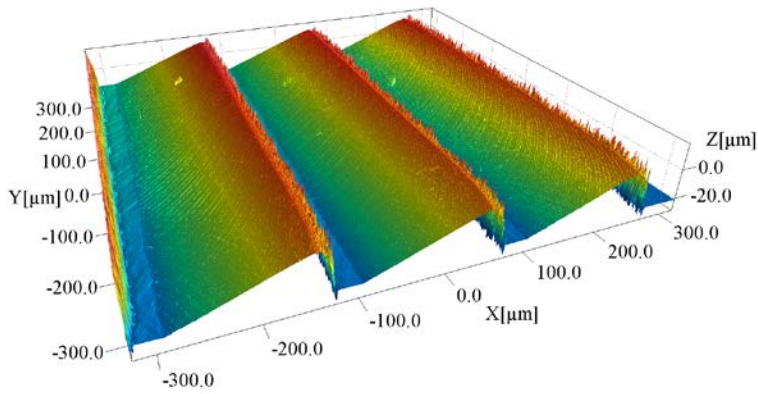
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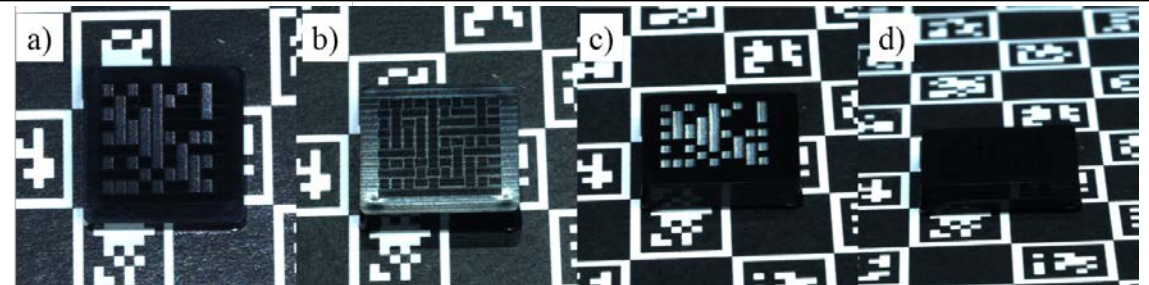
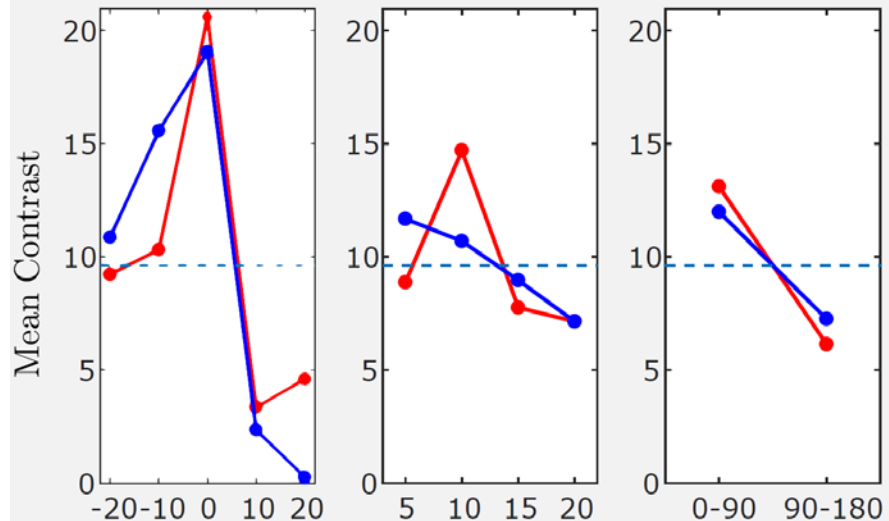
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Testing the optical function of an engineered surface

Confocal microscope image



Camera angle, θ_c Ridge angle, θ_r Surface angle, ϕ_s



- Red: measured.
- Blue: predicted by analytic model.



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Measuring surface microgeometry

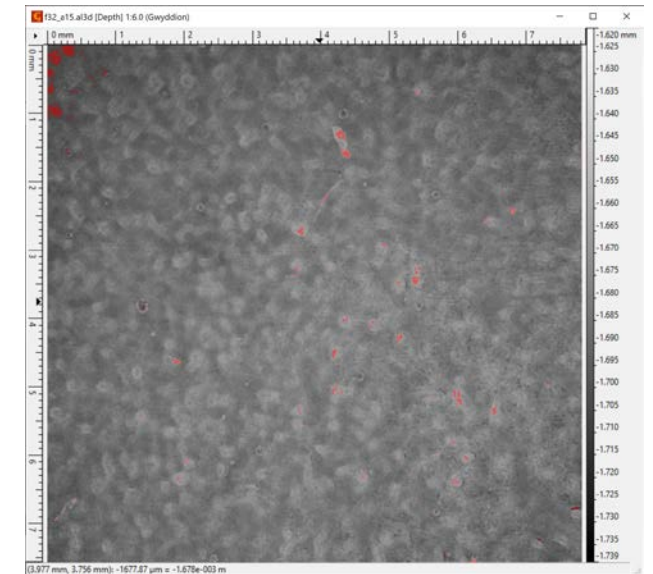
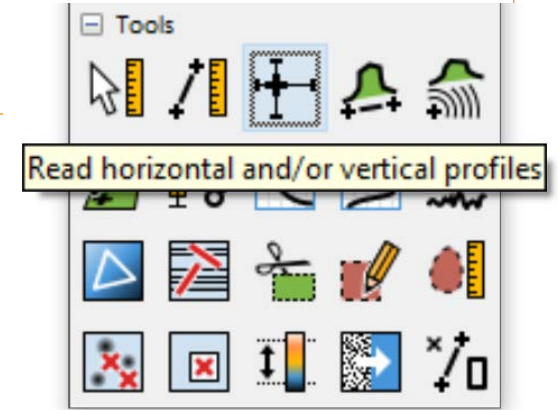
- Alicona Infinite Focus
 - Non-contact
 - Optical
 - Depth by focus-variation
 - Vertical resolution depending on choice of magnification
 - From x2.5: 2300 nm
 - Down to x100: 10 nm
 - Min. measurable roughness:
 - S_a : 3.5 down to 0.015 (arithmetic average height)
 - Output: xxx.al3d file





Inspecting and correcting the data

- Free tool for analysis of height fields obtained by microscopy
Gwyddion: <http://gwyddion.net/>
- File→Open... (it opens .al3d files)
- Data inspection: Tools – Read horizontal and/or vertical profiles
Mode: cross / horizontal / vertical (click the image to extract a profile)
- Data correction (outlier removal and adjustment of base):
 - Data Process→Correct Data→Mask of Outliers
Data Process→Correct Data→Remove Data Under Mask
Data Process→Mask→Remove Mask
 - Data Process→Level→Flatten Base
- Process: Remove outliers, flatten base, remove outliers
- File→Save as... (store processed data as a .gwy file)





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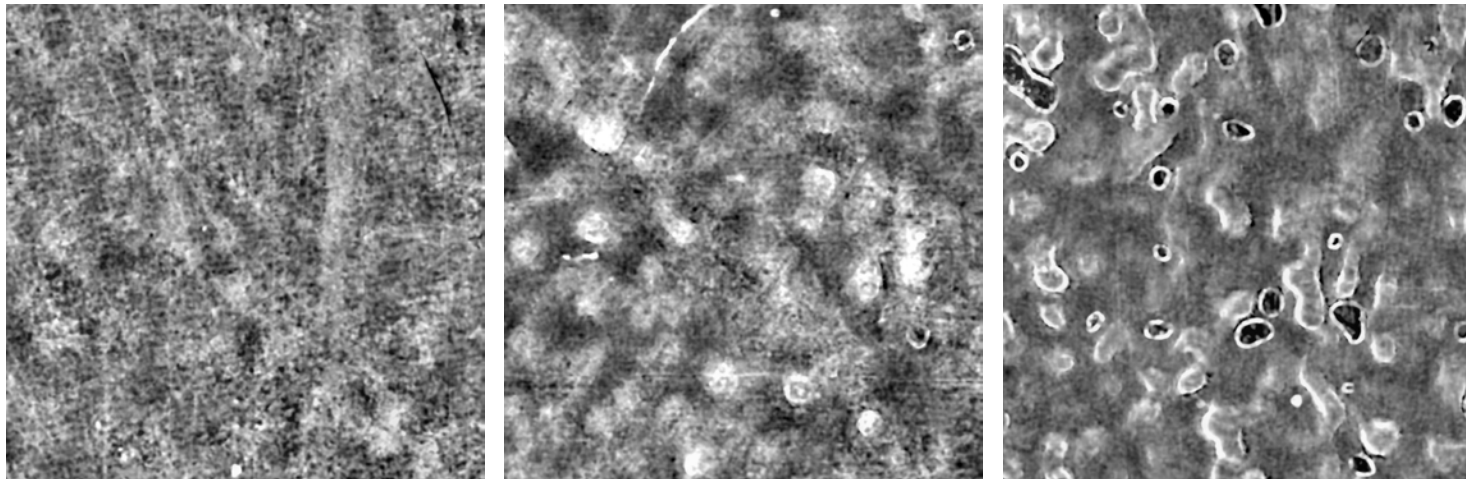
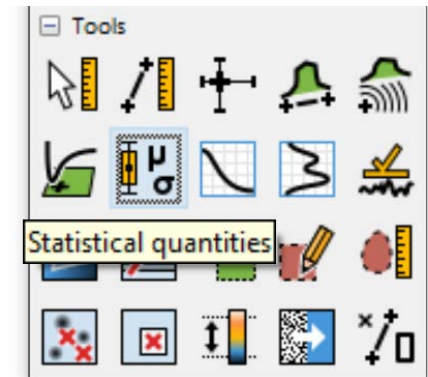
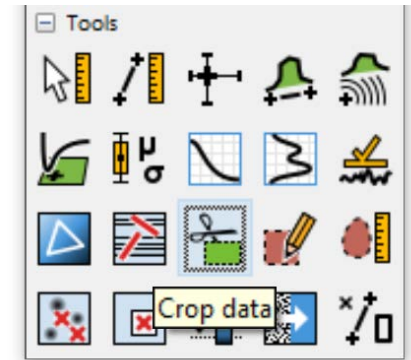
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Profilometry and data export


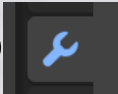
- Cutout: Use the Crop data tool with Create new image checked
- Roughness measurement along a line:
Use the Calculate roughness parameters tool
- Surface roughness: Use the Statistical quantities tool
- Export using File→Save as...
Choose an image file type (.png, for example)
Remove decorations (Value scale, Lateral scale, frame, etc.)



Note the **physical width** of the image and the **physical depth** that the grayscale values correspond to. These are available from the Statistical Quantities tool.



Height map to mesh by displacement mapping

- We can use Blender for this task <https://www.blender.org/>
- Following a tutorial <https://johnflower.org/tutorial/make-mountains-blender-heightmaps>
 - Open Blender and delete the default cube (press del)
 - Add→Mesh→Grid (increase X Subdivisions and Y Subdivisions in Add Grid)
 - Import the height map as a texture 
 - Apply texture to grid as a displacement map 
 - Set Strength to **physical depth** divided by **physical width**
 - Set shading to smooth (right click and select Shade Smooth)
 - File→Export→Wavefront (.obj) [you can uncheck Include UVs]
 - This produces xxx.obj and xxx.mtl
 - Edit xxx.mtl (set illum 4 and Ni 1.5)
 - Ni is the assumed index of refraction

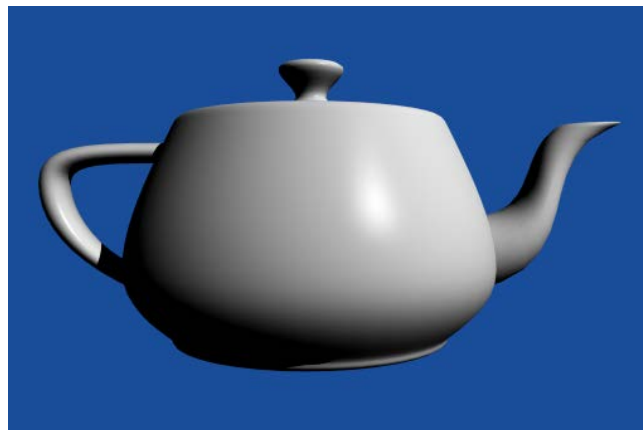
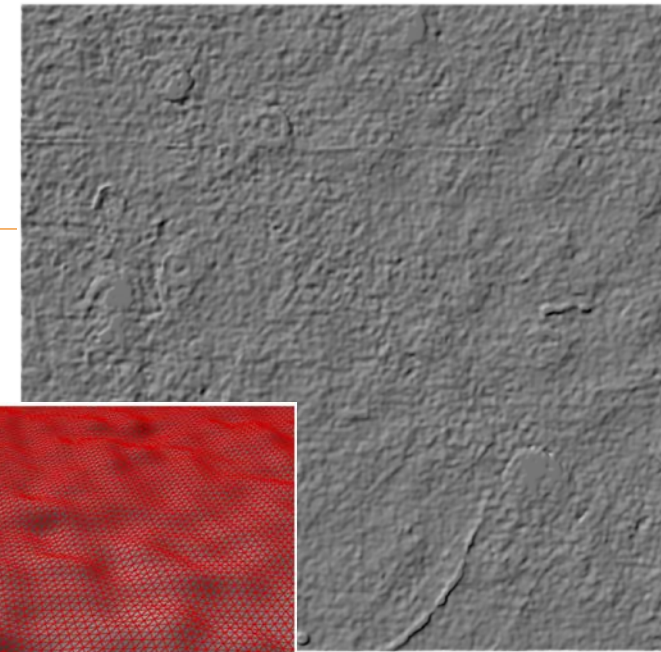
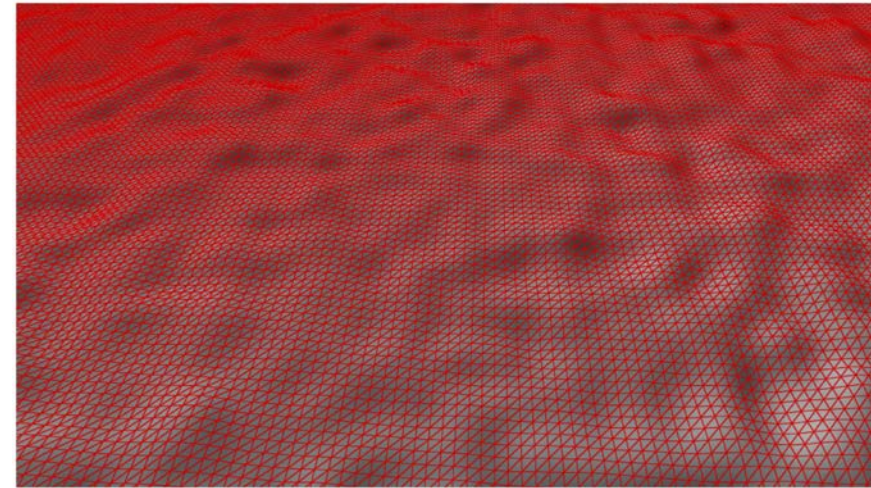
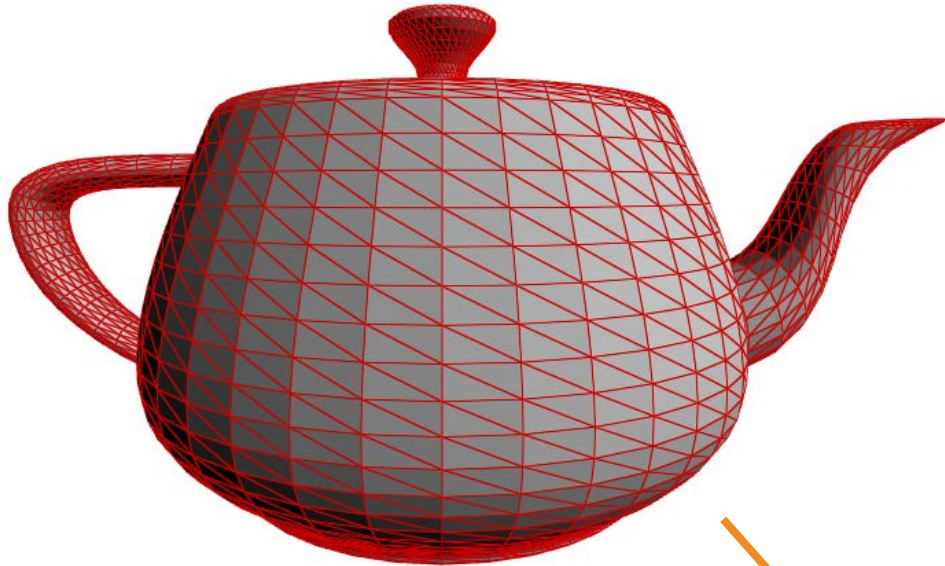
f32_a15.mtl - Notepad 2e x64

File Edit View Settings ?

```
1# Blender MTL File: 'None'
2# Material Count: 1
3
4newmtl None
5Ns 0
6Ka 0.000000 0.000000 0.000000
7Kd 0.8 0.8 0.8
8Ks 0.8 0.8 0.8
9d 1
10Ni 1.5
11illum 4
12
```



Two meshes – how to combine?

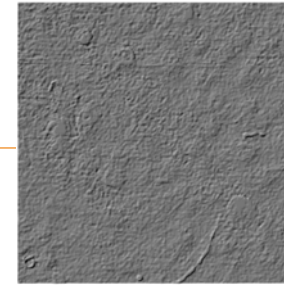




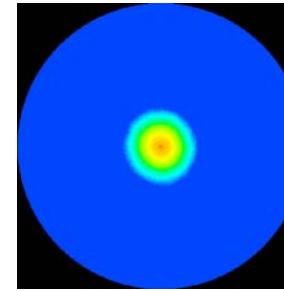
Models at different scales

- We divide the microscopic scale into
 - Nano/micro: models considering explicit microgeometry.
 - Micro/milli: models using particle size or microfacet normal distribution functions.
- We divide the macroscopic scale into
 - BSSRDF: models where the points of incidence and emergence are different.
 - BRDF/BTDF: local models for opaque/thin objects.

microsurface

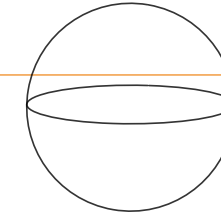


profilometry

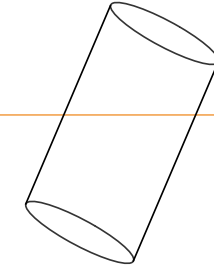


normal distribution

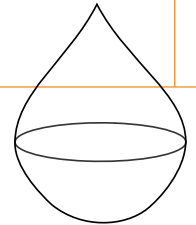
particles



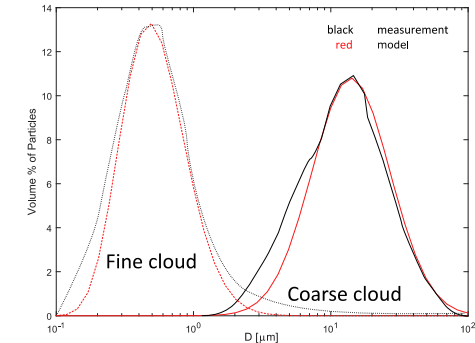
sphere



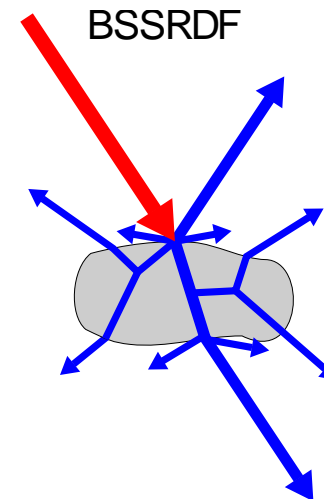
cylinder



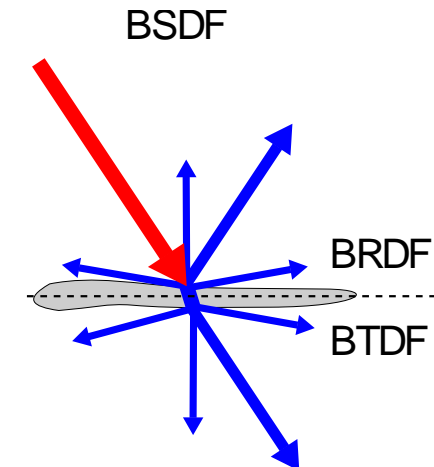
raindrop



particle size distribution



BSSRDF



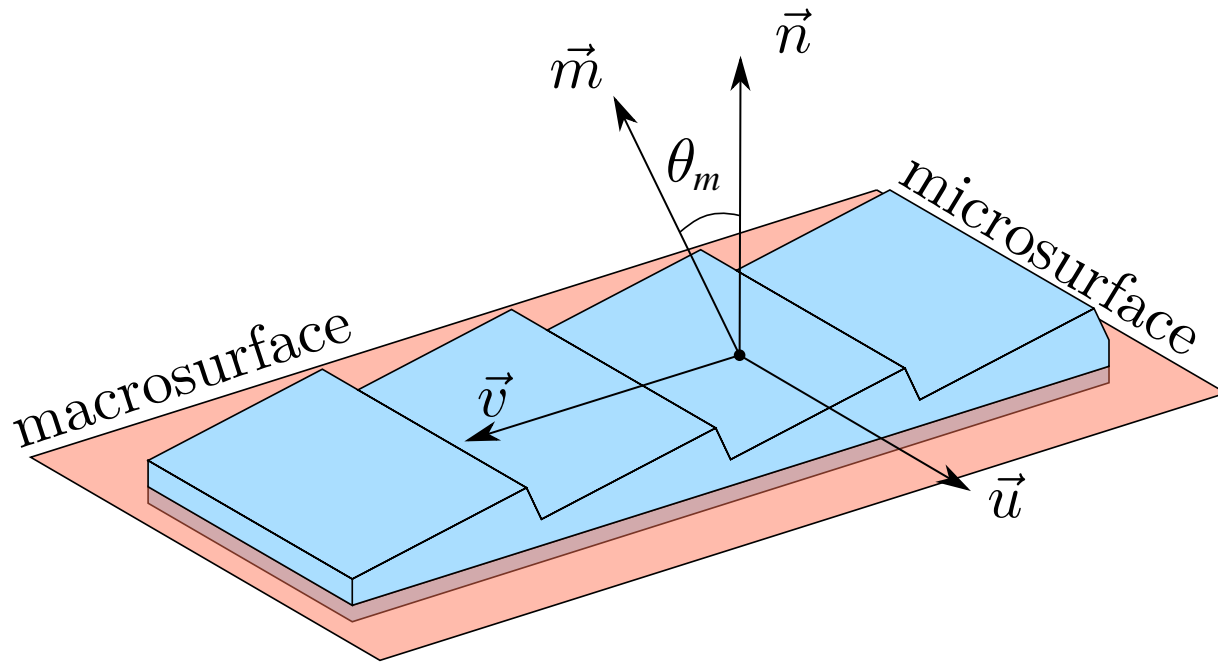
BSDF

BRDF

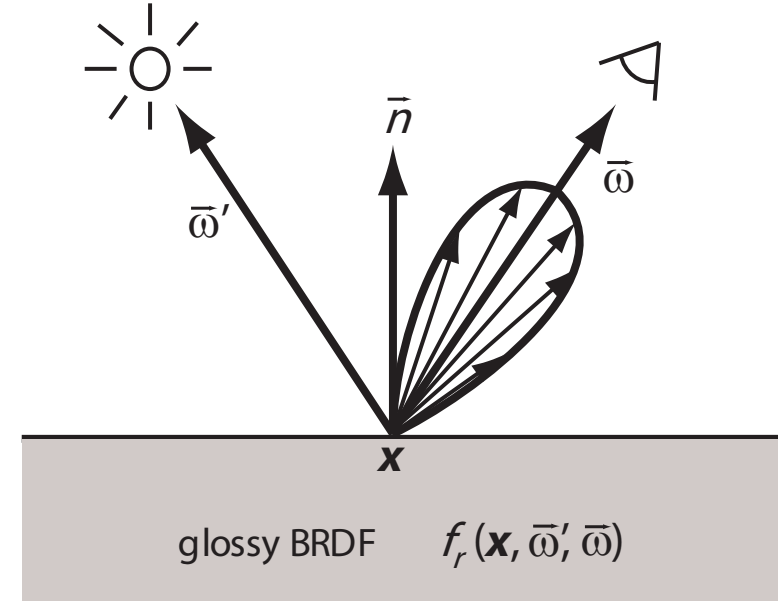
BTDF



Macro and micro surface



The microsurface defines the geometry of a differential area dA at a position \mathbf{x} on the macrosurface.

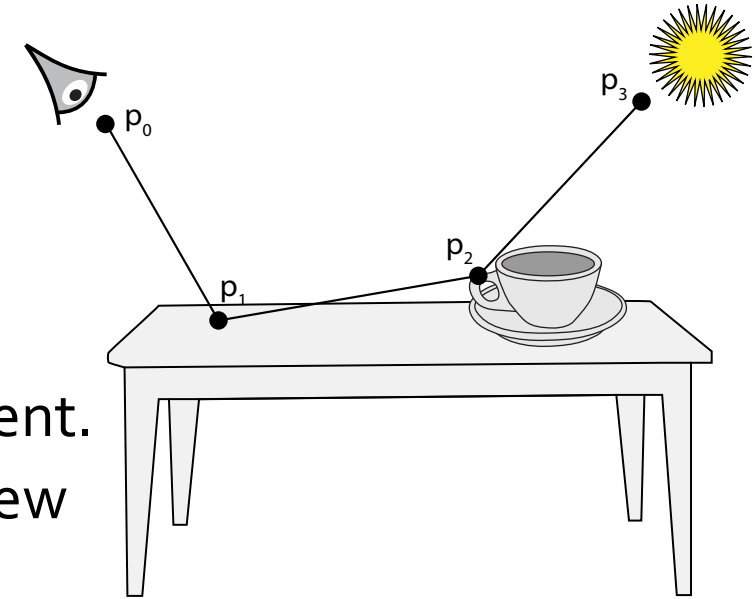


- The BSDF defines the ratio of light incident in a surface point \mathbf{x} from a direction $\vec{\omega}'$ that scatters into another direction $\vec{\omega}$.
- The BRDF f_r is the reflectance part of the BSDF.



Progressive unidirectional path tracing

1. **Generate rays** from the camera through pixel positions.
 2. **Trace the rays** and evaluate a measurement equation for each ray.
 3. **Randomize the position** within the pixel area to Monte Carlo integrate (measure) the radiance arriving in a pixel.
- Noise is reduced by **progressive updates** of the measurement.
 - Update the rendering result in a pixel L_j after rendering a new frame with result L_{new} using
$$L_{j+1} = \frac{L_{\text{new}} + jL_j}{j + 1}$$
 - Progressive (stop and go) rendering is convenient for several reasons:
 - No need to start over.
 - Result can be stored and refined later if need be.
 - Convergence can be inspected during progressive updates.



<http://www.pbr-book.org/>

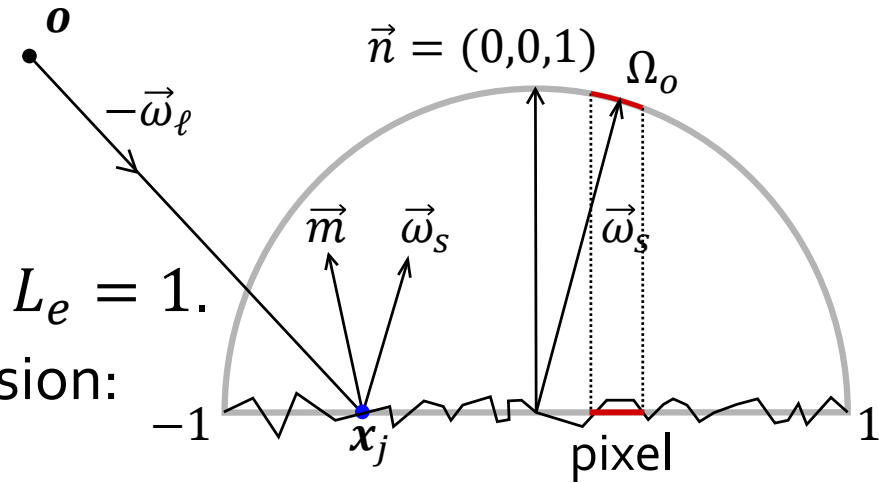


Computing a surface BSDF from microgeometry

- One randomly placed sample per pixel (jitter sampling):

$$N = WH, \quad \text{pdf}(\mathbf{x}_j) = \frac{1}{A}, \quad \Omega_r \cos \Theta_r \approx \frac{4}{WH}$$

- Since the constant emitted radiance cancels out, we set $L_e = 1$.
- Suppose we always choose either reflection or transmission:
 - Russian roulette with $R(\vec{m}, \vec{\omega}_i)$ as the probability of reflection.



- The Monte Carlo estimator is then

$$f_s(\mathbf{x}, \vec{\omega}_\ell, \Omega_r) = \frac{1}{4|\vec{\omega}_\ell \cdot \vec{n}|} \sum_{j=1}^N L_{o,j} |\vec{\omega}_o \cdot \vec{m}| [\vec{\omega}_o \in \Omega_o]$$

- $\xi \in [0,1]$ is a continuous, uniform, random variable.
- We compute $L_{o,j}$ by **path tracing the microsurface** (see Falster et al. [2020]).
- For translucent materials, we need to combine this with subsurface scattering.



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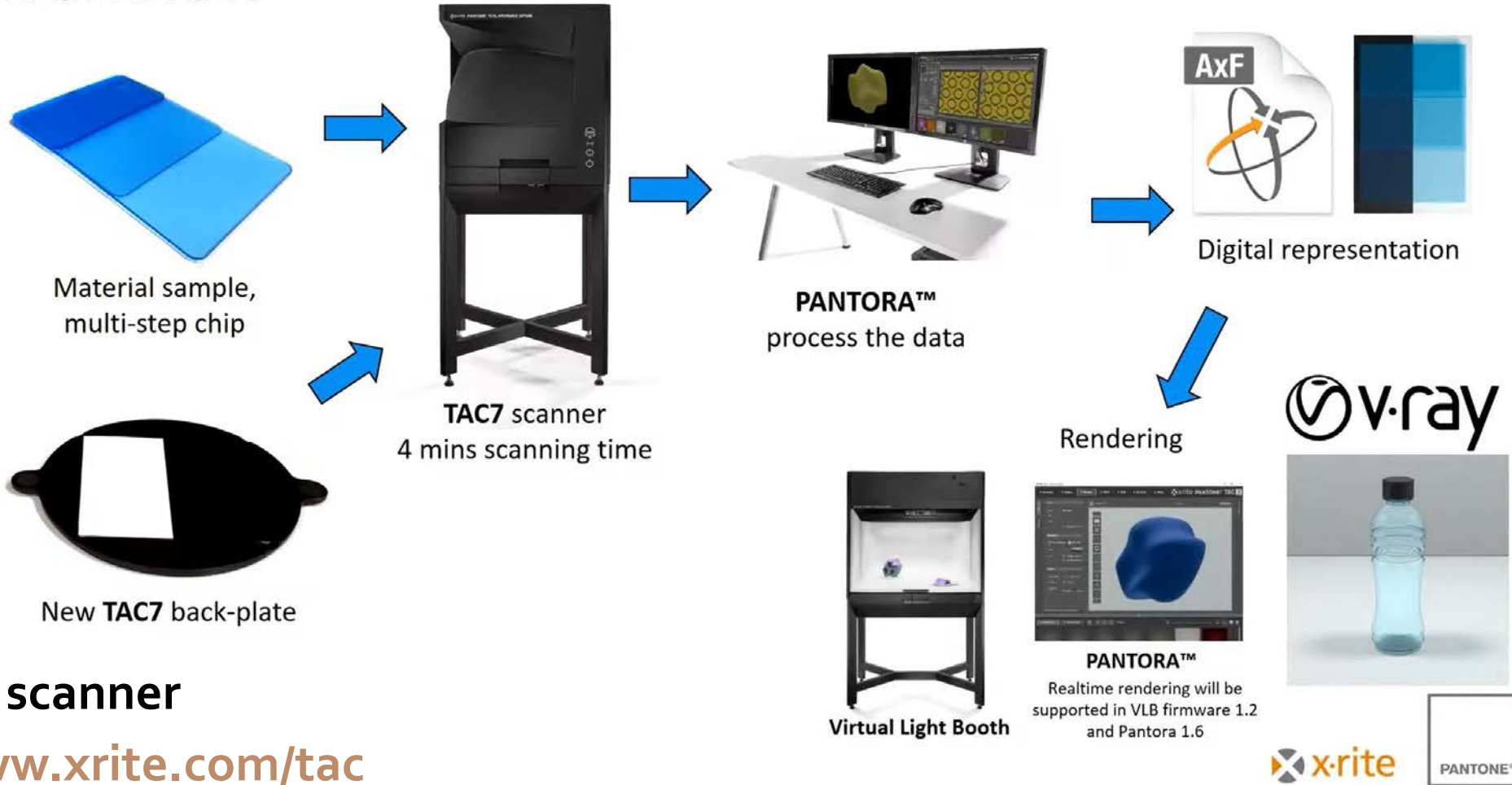
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Appearance acquisition and specification

Workflow



xrite TAC7 scanner

<https://www.xrite.com/tac>



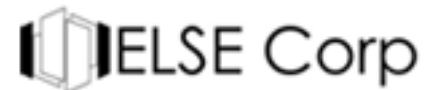
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Appearance Exchange Format





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Rendering material appearance



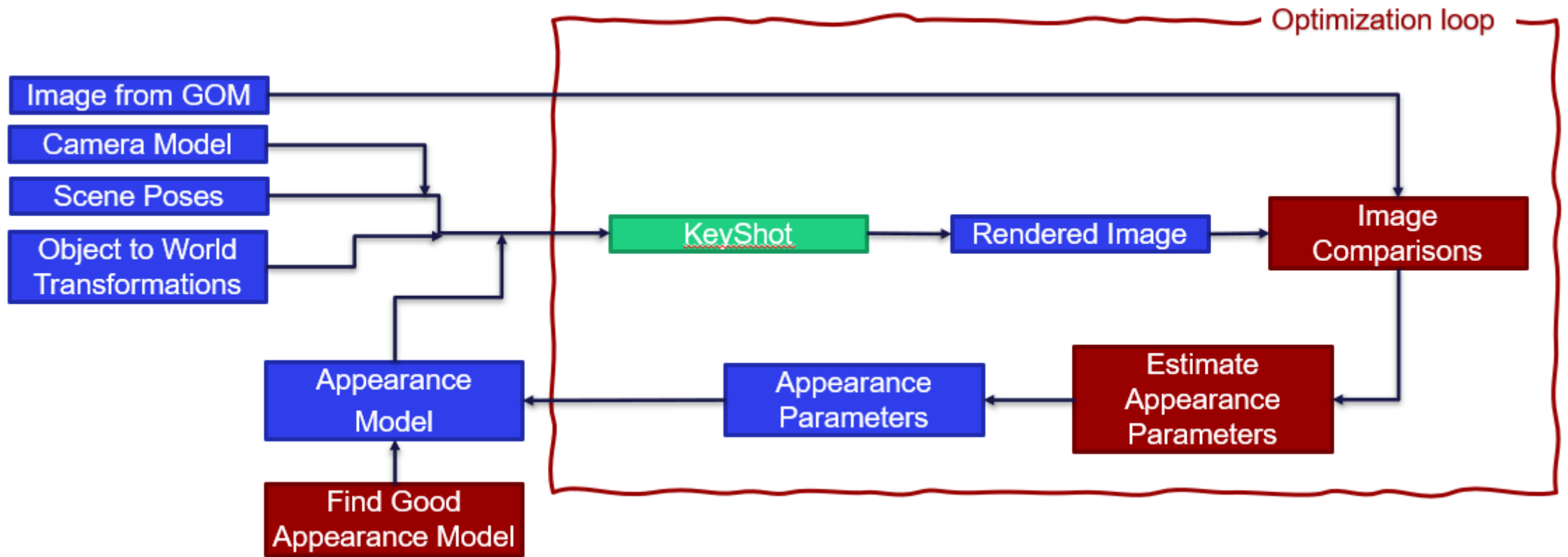
<https://luxion.com/>

The new 'Translucent Medium' material in KeyShot 9.2. Model: [DK - LEGO Architect London](#)



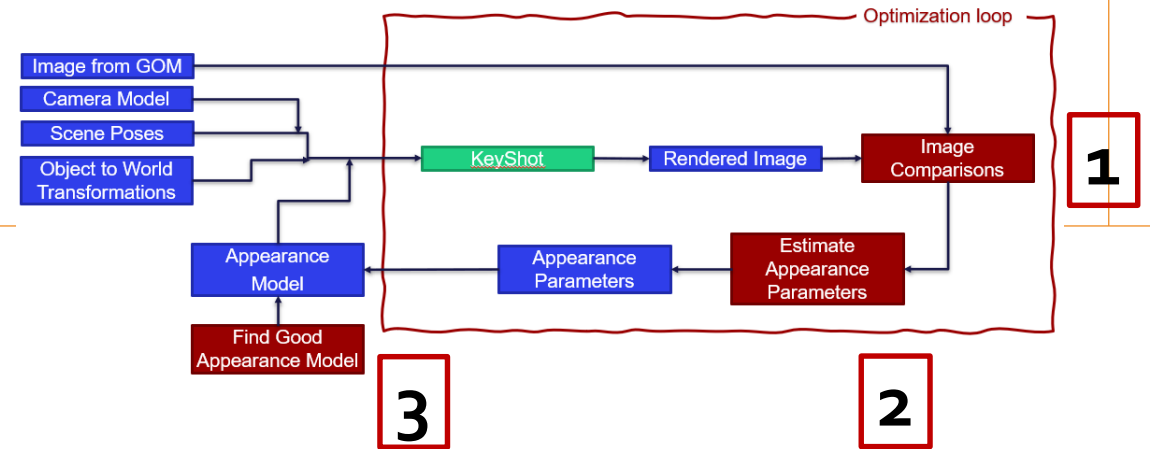
Appearance assessment

- Suggested pipeline to generate digital master





1. Image comparison
[Stets et al. 2017; Hannemose et al. 2020]
2. Estimate appearance parameters
[Stets et al. 2017; Regi et al. 2019; Luongo et al. 2020; Hannemose et al. 2020]
3. Find good appearance model
[Luongo et al. 2017; Luongo et al. 2020; Falster et al. 2020; Hannemose et al. 2020]



Stets, J. D., Dal Corso, A., Nielsen, J. B., Lyngby, R. A., Jensen, S. H. N., Wilm, J., Doest, M. B., Gundlach, C., Eiriksson, E. R., Conradsen, K., Dahl, A. B., Bærentzen, J. A., Frisvad, J. R., and Aanæs, H. [Scene reassembly after multimodal digitization and pipeline evaluation using photorealistic rendering](#). *Applied Optics* 56(27):7679-7690, September 2017.

Luongo, A., Falster, V., Doest, M. B., Li, D., Regi, F., Zhang, Y., Tosello, G., Nielsen, J. B., Aanæs, H., and Frisvad, J. R. [Modeling the anisotropic reflectance of a surface with microstructure engineered to obtain visible contrast after rotation](#). In *Proceedings of IEEE International Conference on Computer Vision Workshop (ICCVW 2017)*, pp. 159-165. October 2017.

Regi, F., Doest, M. B., Loaldi, D., Li, D., Frisvad, J. R., Tosello, G., and Zhang, Y. [Functionality characterization of injection moulded micro-structured surfaces](#). *Precision Engineering* 60, pp. 594-601. November 2019.

Luongo, A., Falster, V., Doest, M. B., Ribo, M. M., Eiriksson, E. R., Pedersen, D. B., and Frisvad, J. R. [Microstructure control in 3D printing with digital light processing](#). *Computer Graphics Forum* 39(1), pp. 347-359. February 2020.

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Hannemose, M., Doest, M. B., Gregersen, S. K. S., Wilm, J., and Frisvad, J. R. [Alignment of rendered images with photographs for testing appearance models](#). *Applied Optics*. Submitted. 2020.



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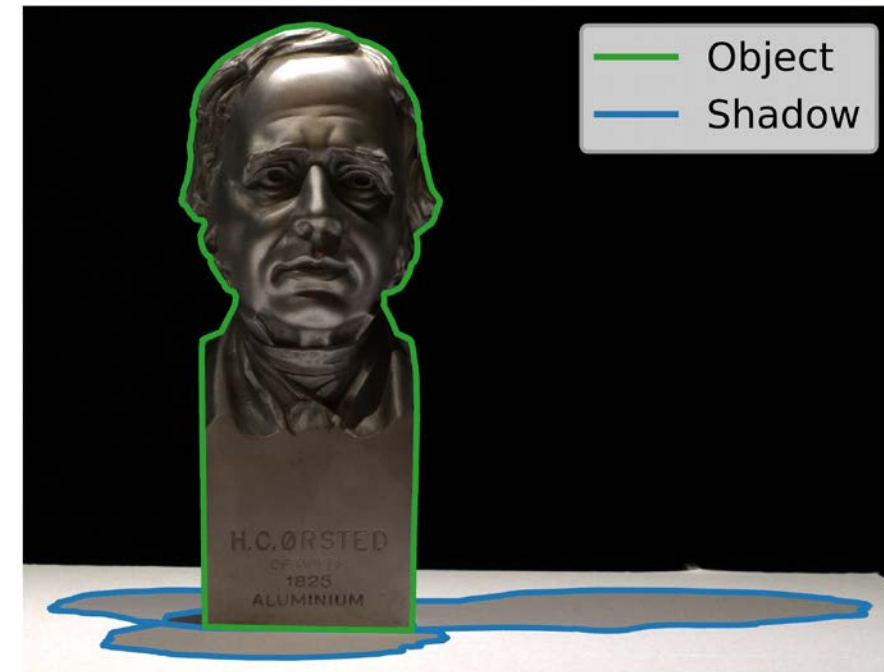
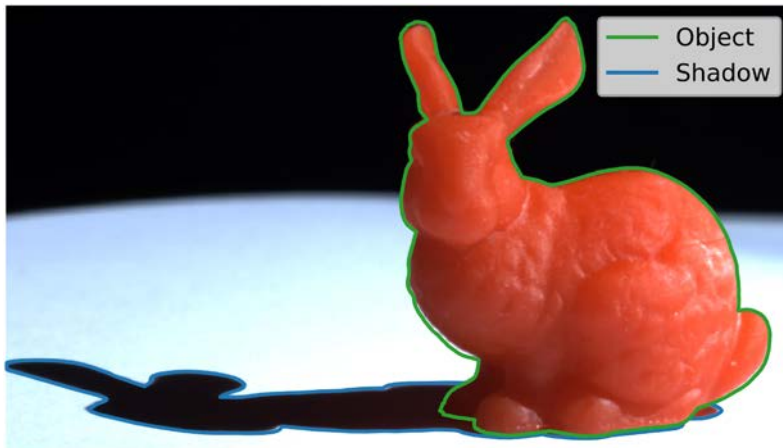
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Photo-render alignment method

■ Requirements:

- Images of the object of interest.
- Camera calibration.
- Segmentation of images into object, background, and shadow.
- CAD model (polygon mesh).





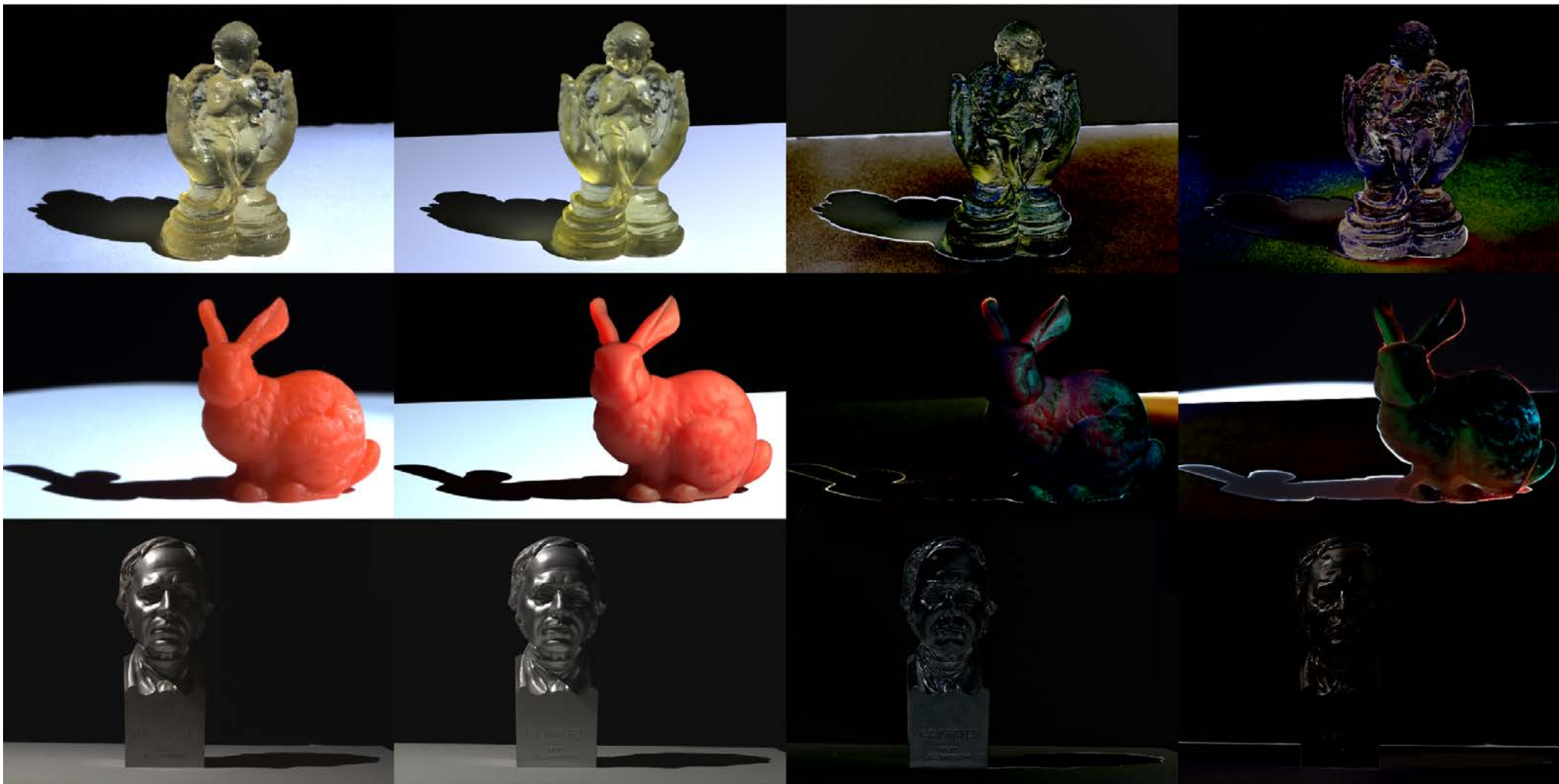
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Photo-render alignment and appearance models



photograph (x)

rendering (y)

$2 \max(y - x, 0)$

$2 \max(x - y, 0)$



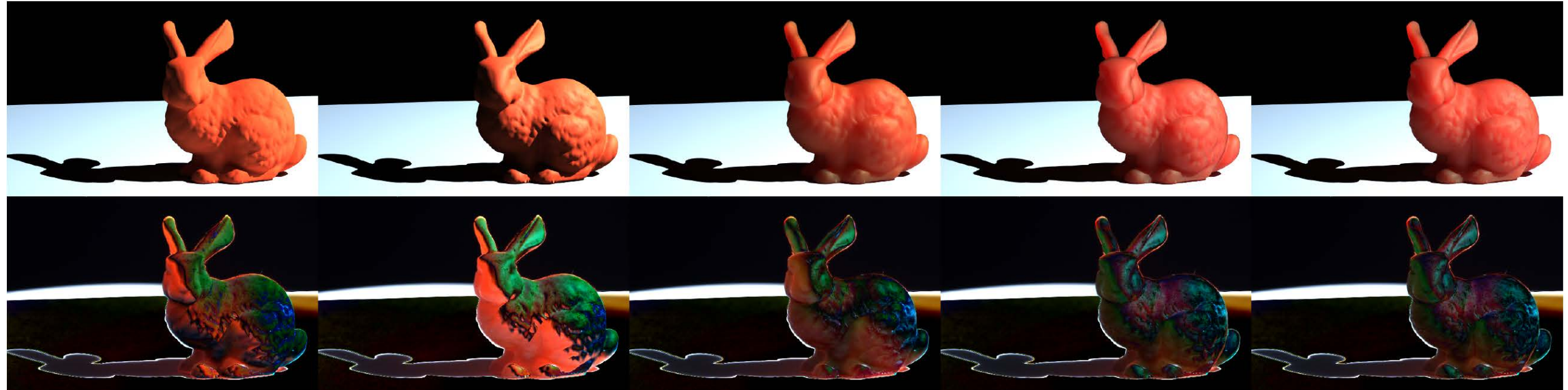
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Developing appearance models



RMSE: 0.1152
SSIM: 0.8108
Lambertian

RMSE: 0.1237
SSIM: 0.7931
interfaced

RMSE: 0.1136
SSIM: 0.8145
standard SSS

RMSE: 0.1127
SSIM: 0.8177
directional SSS

RMSE: 0.1124
SSIM: 0.8180
SV roughness

- The Stanford bunny printed by the described DLP printer.



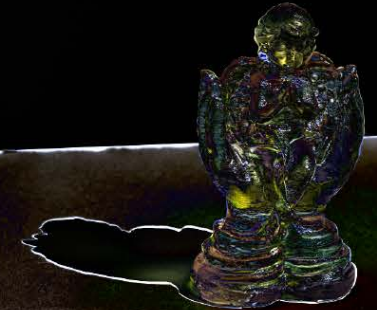
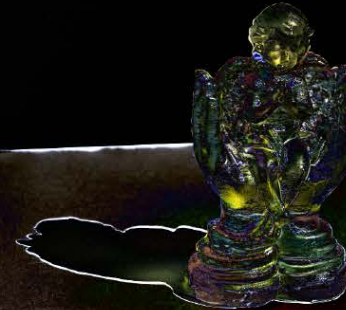
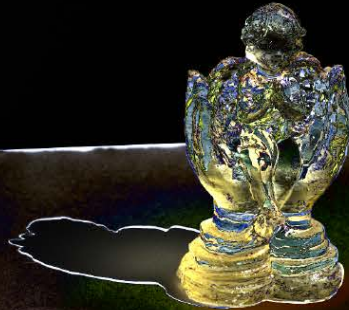
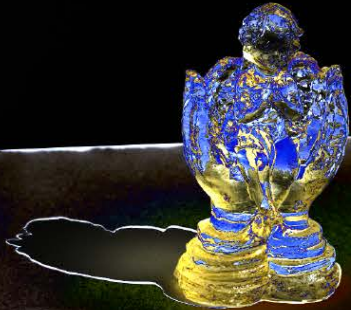
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Developing appearance models



RMSE: 0.1267
SSIM: 0.7699
glass

RMSE: 0.1135
SSIM: 0.8051
absorbing

RMSE: 0.0741
SSIM: 0.8876
rough

RMSE: 0.0733
SSIM: 0.8870
SV roughness

RMSE: 0.0730
SSIM: 0.8858
layered

- Cupped angel printed using a commercial SLA printer (Peopoly Moai) and a transparent resin by AddiFab.



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Developing appearance models



RMSE: 0.0311
SSIM: 0.9339
metallic

RMSE: 0.0159
SSIM: 0.9693
rough

RMSE: 0.0134
SSIM: 0.9713
SV roughness



$0.5 + \mathbf{H} \cdot \vec{n}$



$|\mathbf{H} \cdot \vec{n}|$



α_g

- 3D scanned aluminium bust (depicting H. C. Ørsted).
- Model for spatially varying roughness α_g based on the mean curvature normal \mathbf{H} and the surface normal \vec{n} .

Thank you

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