Digital Bas-Relief From 3D Scenes

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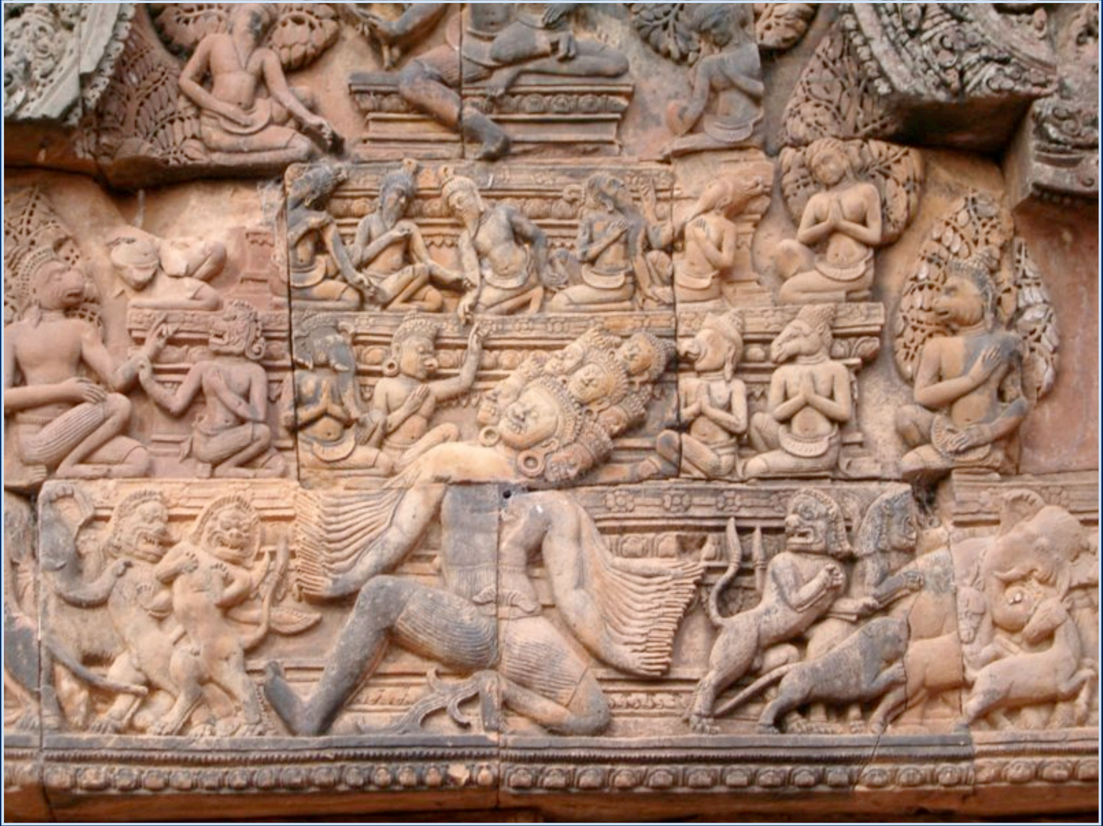
Szymon Rusinkiewicz Adam Finkelstein

Princeton University

Relief In Sculpture

- Sculpture in limited depth
- Bridges 3D and 2D media



Ch. Archambault

Banteya Srei, Cambodia, 10th c. AD

Relief In Sculpture

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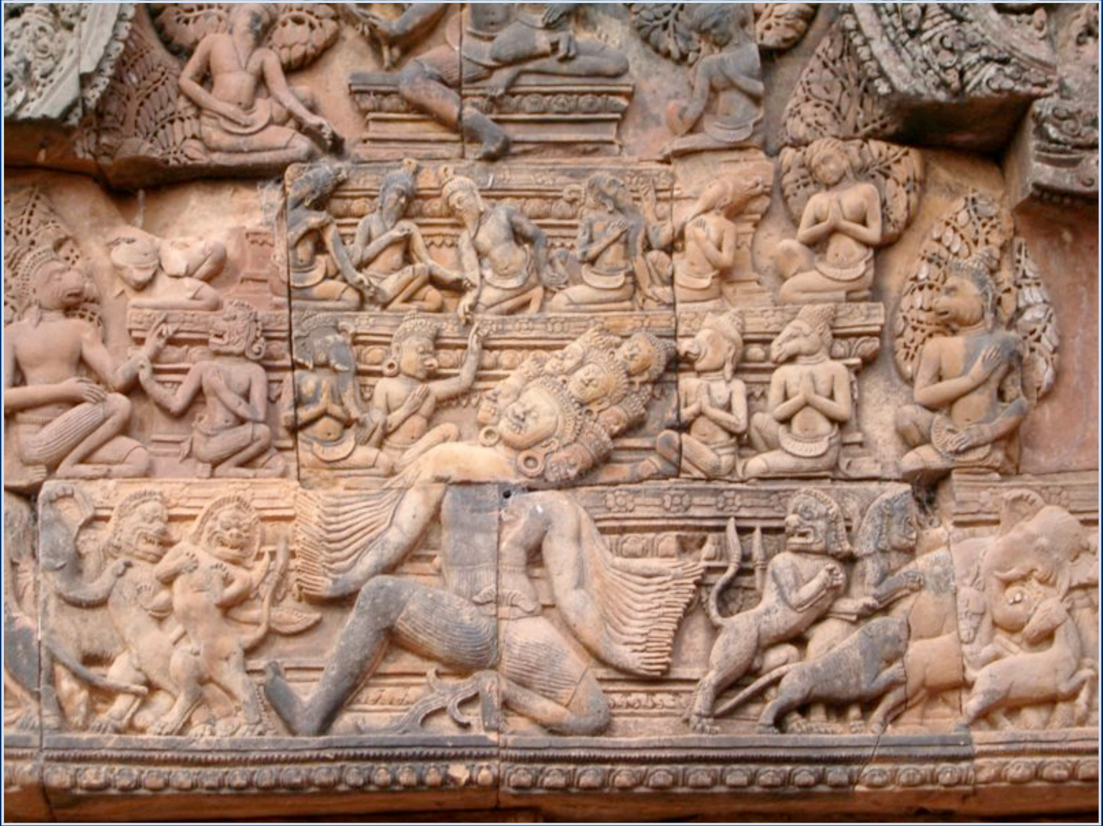
High relief
(*alto relievo*)

Low relief
(*basso relievo,*
bas-relief)



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Traditional Bas-Relief

Assyrian Bas-Relief, (9th c. BC)

Greek Elgin Marbles (5th c. BC)

Wikipedia

Historic Glass Bottles

U.S. Dep. BLM

Coins

Wikipedia

Digital Bas-Relief From 3D Scenes

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Input Scene

Output Relief

Contributions

- Automated technique for relief generation
  - From arbitrary input scenes
  - Depth-range compression
  - Preservation of visual cues
  - For a wide range of physical materials

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- Automated technique for relief generation
  - From arbitrary input scenes
  - Depth-range compression
  - Preservation of visual cues
  - For a wide range of physical materials
- Gradient-domain editing framework
- Promotion of bas-relief as a digital medium

Outline

- Problem statement
- Related work
- Automated bas-relief generation
- Results & Applications

Bas-Relief's Constraints

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- Limited height range
  - Relief resembles scene geometry
  - Possible because of the *bas-relief ambiguity* [Belhumeur et al. 1999]
- Pure height field (no "undercuts")
- No depth discontinuities

Guidelines For The Sculptor

- *Depth Illusion:* mainly by 2D perspective

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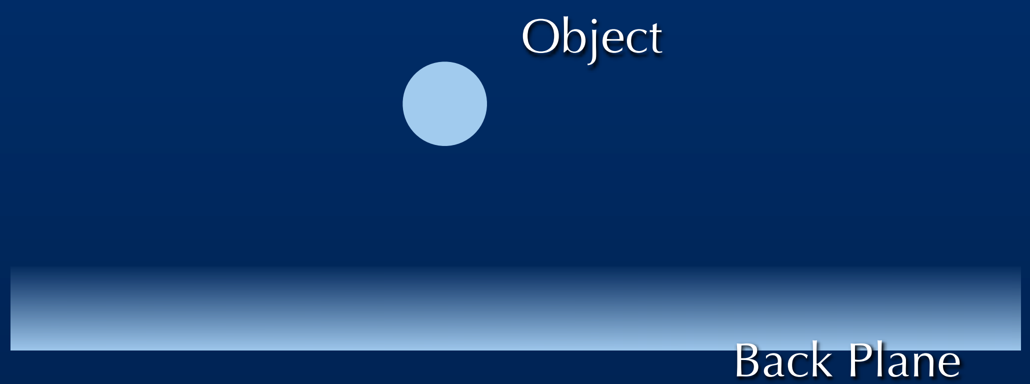
- *Depth Compression*



Guidelines For The Sculptor

- *Depth Illusion:* mainly by 2D perspective
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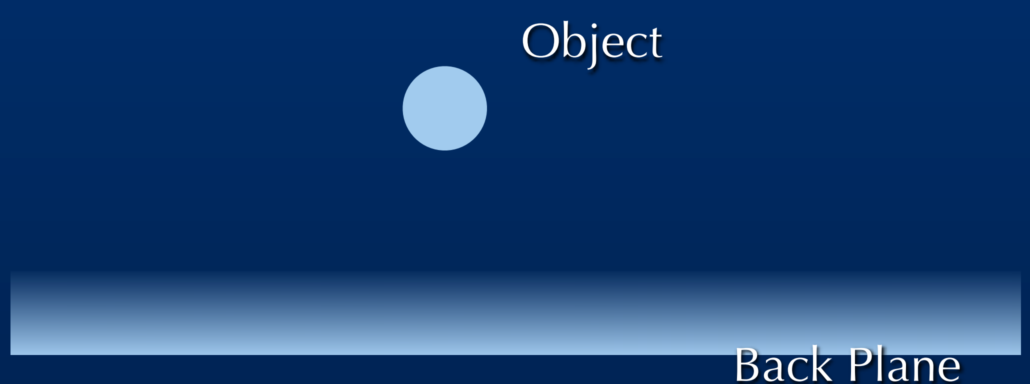
  - Shape compression



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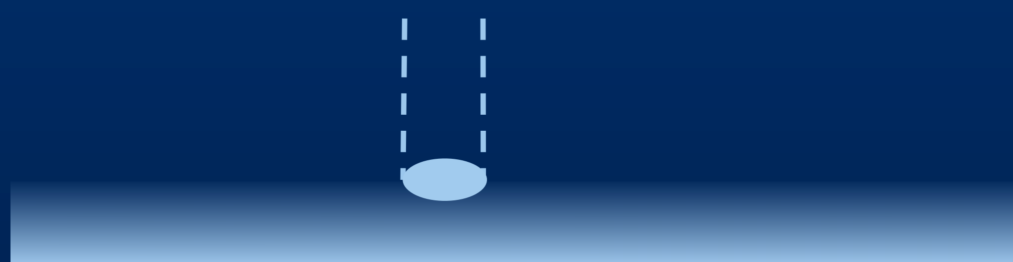

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- *Object Order:* preserve where objects overlap

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- *Object Order:* preserve where objects overlap

- These goals may be conflicting
- Trade-offs have to be found

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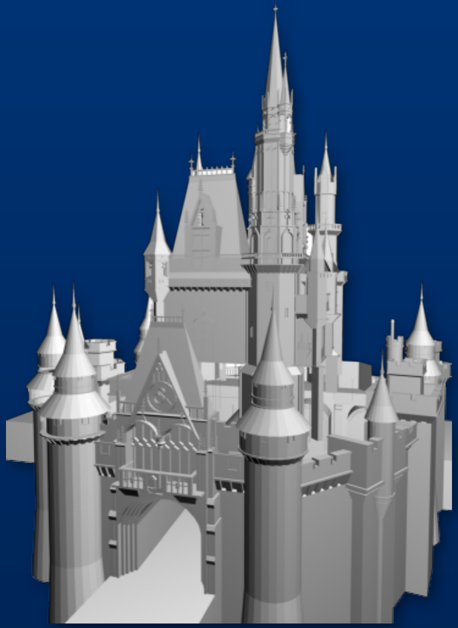
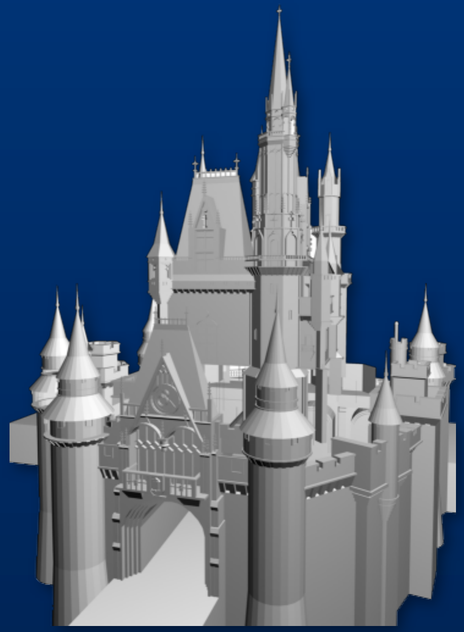
Objective



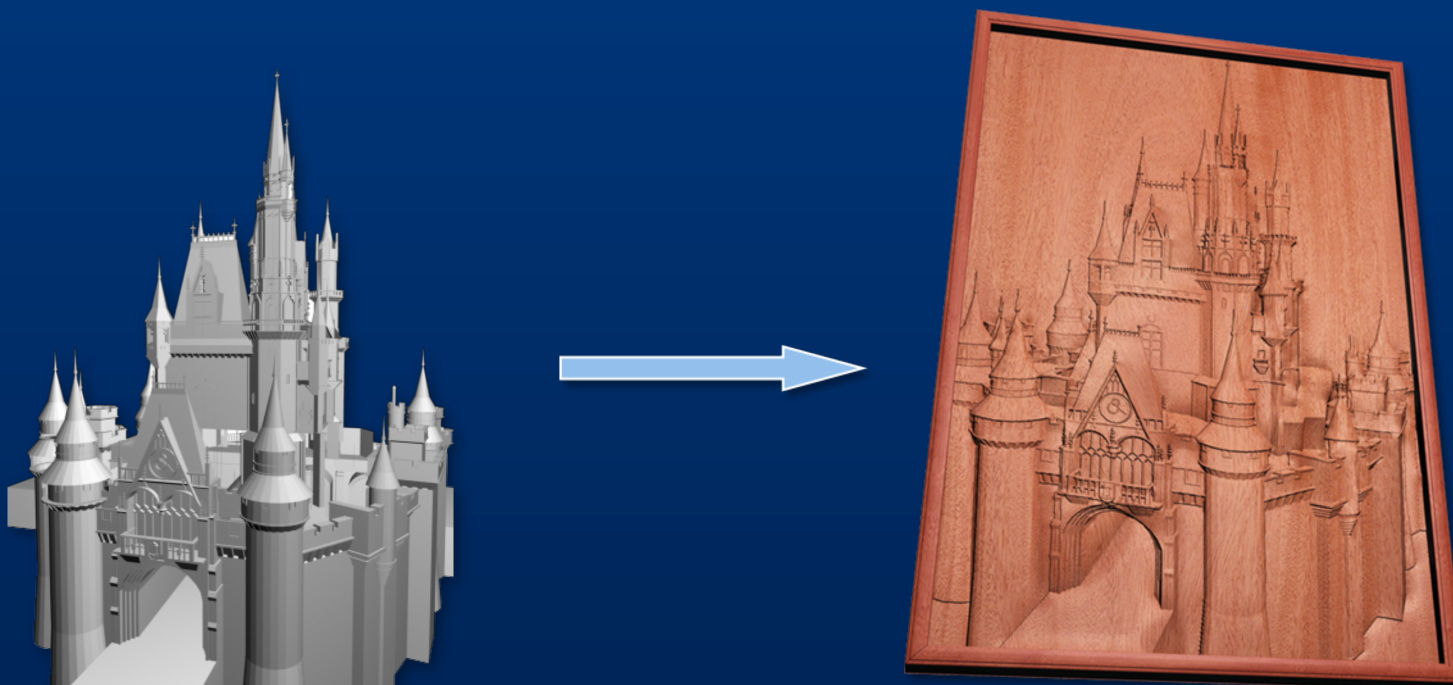
Objective

- Given a 3D scene + camera settings



Objective

- Given a 3D scene + camera settings
- Automated generation of bas-relief geometry



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Bas-Relief

- From a technical point of view:
  - Dynamic-range compression
  - Perceptual preservation

Bas-Relief

- From a technical point of view:
  - Dynamic-range compression
  - Perceptual preservation
- Both aspects relate to tone-mapping and high-dynamic-range (HDR) compression

Related Work

- Range compression in images
  - Global tone-reproduction curves (TRC), e.g., histogram adjustment [Larson et al. 1997]
  - Local tone-reproduction operators (TRO) [Tumblin and Turk 1999], [Ashikhmin 2002], [Durand and Dorsey 2002], [Fattal et al. 2002]

Related Work

- Range compression in images
  - Global tone-reproduction curves (TRC), e.g., histogram adjustment [Larson et al. 1997]
  - Local tone-reproduction operators (TRO) [Tumblin and Turk 1999], [Ashikhmin 2002], [Durand and Dorsey 2002], [Fattal et al. 2002]
- Not trivially applicable to relief height-fields
  - Global techniques cannot collapse silhouettes
  - Local operators preserve steps at silhouettes
  - Designed for image intensities, not surface shading

Related Work

- Bas-relief
  - Initial steps in bas-relief generation [Cignoni et al. 1997]
  - Simulation of 3D sculpting tools [Sourin 2001]
  - Concurrent work [Kerber et al. 2007]

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The Algorithm

- Formulation on height fields

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- Framework: non-linear gradient-domain compression
  - Similar to use in tone mapping [Fattal et al. 2002]
  - Compresses shape, not intensities

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- Formulation on height fields
- Framework: non-linear gradient-domain compression
  - Similar to use in tone mapping [Fattal et al. 2002]
  - Compresses shape, not intensities
- Gradient-domain operators
  - Depth compression and silhouette collapse
  - Artistic editing operations

The Algorithm

Four-step procedure:

The Algorithm

Four-step procedure:

1. Depth image from input scene

The Algorithm

Four-step procedure:

1. Depth image from input scene
2. Gradient-domain depth compression

The Algorithm

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3. *Optionally*: Further gradient editing

The Algorithm

Four-step procedure:

1. Depth image from input scene
2. Gradient-domain depth compression
3. *Optionally*: Further gradient editing
4. Integration yields final relief heights

Input Depth Image

- Depth buffer part of most rendering systems
- Homogeneous mapping ("perspective z")

$$z_{\text{buf}} = C + \frac{D}{z}$$

- Intrinsic properties desirable for relief
  - Plane preservation
  - Range attenuation of distant features

Input Depth Image

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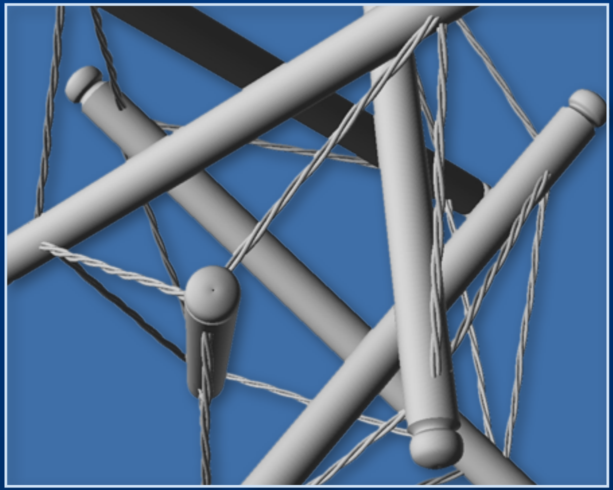

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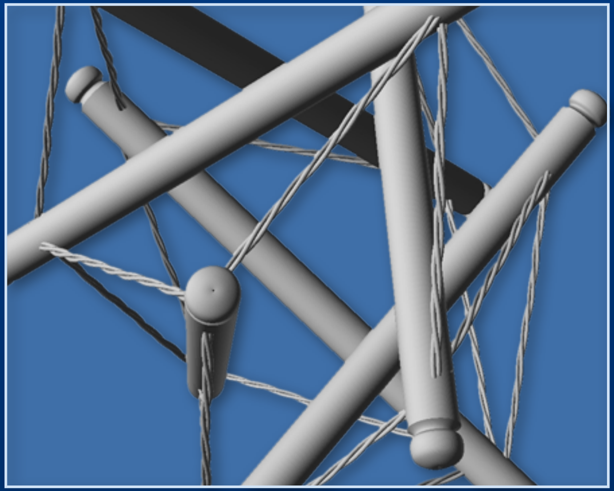
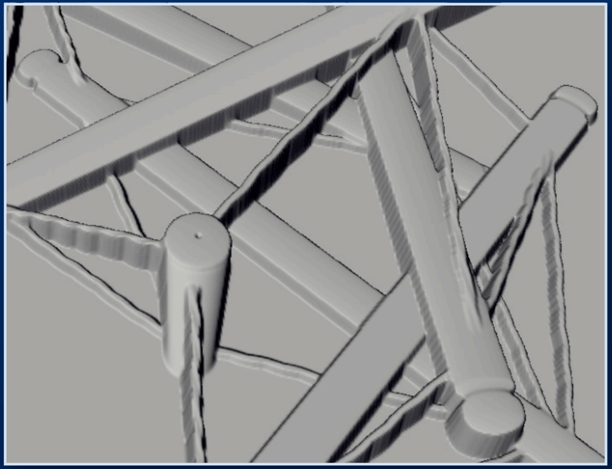
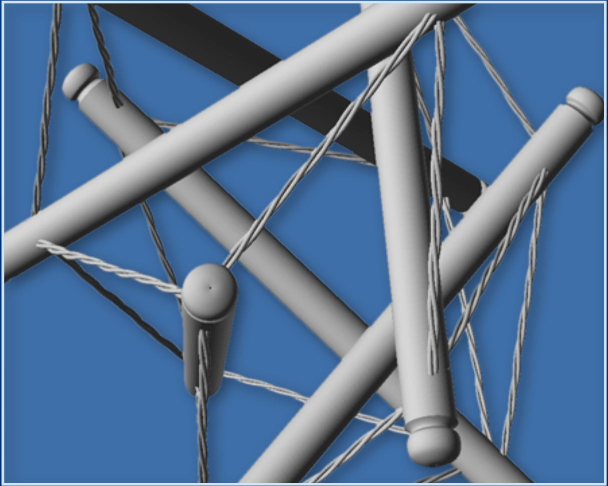
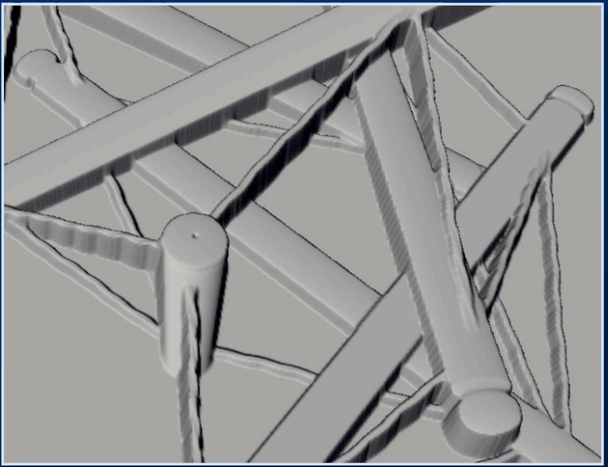




Input Depth Image

- Input depths may already be interpreted as a relief
- Linear scale to meet range constraints?
  [Cignoni et al. 1997]
- Disadvantages:
  - Linear scale flattens features
  - Depth discontinuities persist





Gradient-Domain Compression

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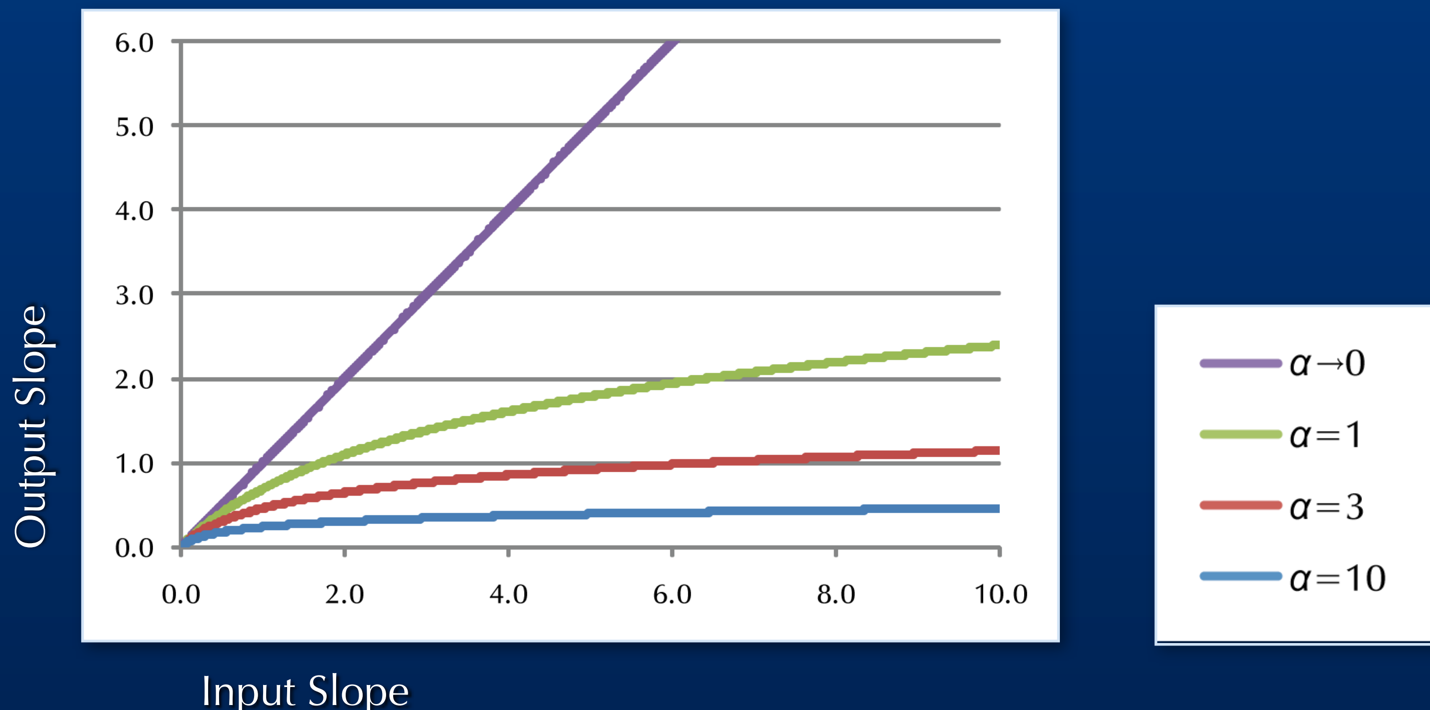
- Derive gradients $\nabla h(x,y)$ from scene depth-map
- Fix gradient direction to preserve shape cues
- Non-linear compression of gradient magnitudes
  - Shape compression by attenuating large slopes
  - Silhouette collapse by eliminating depth discontinuities
- Implemented as a mapping $C(x)$ applied to $\|\nabla h(x,y)\|$

Shape Compression

$$C(x) = \frac{1}{\alpha}\log(1+\alpha x), \quad \alpha > 0$$



Silhouette Collapse

- Elimination of depth discontinuities by thresholding $\|\nabla h(x,y)\|$:

$$s(x,y) = \begin{cases} C(\|\nabla h\|), & 0 \leq \|\nabla h\| < \vartheta_{\text{sil}}\,, \\ 0 & \vartheta_{\text{sil}} \leq \|\nabla h\| \end{cases}$$

- Treats large input gradients as silhouettes
- For high sampling rates: clear discrimination from large surface slopes

Integration

- Modified gradient field g' describes relief
- In general, g' is not integrable
- Optimization for height field h' that matches

$$h' = \arg\min_h \iint \|\nabla h - g'\|^2 \, \mathrm{d}x \, \mathrm{d}y \, ,$$

by solving Poisson equation

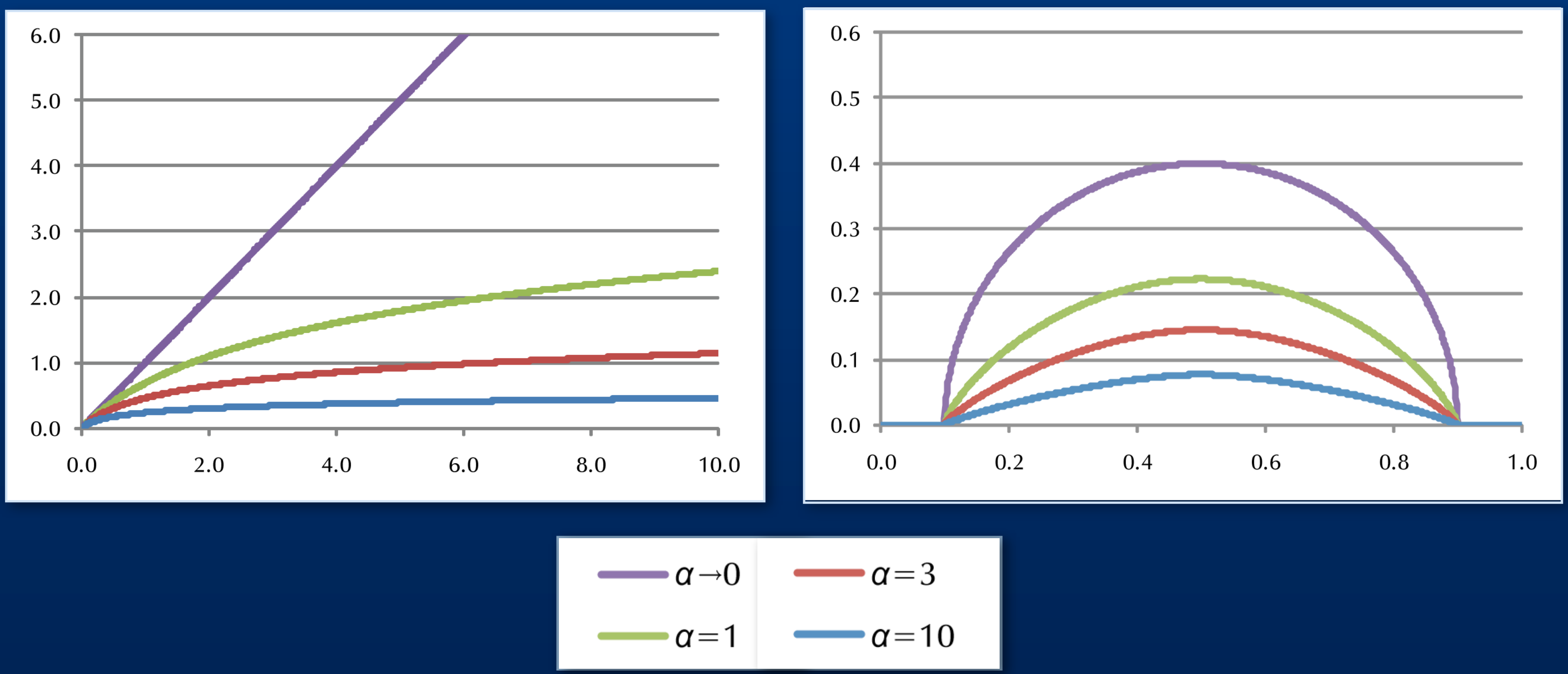
$$\nabla^2 h = \operatorname{div} g' \, .$$

Compression Results

1D example: Cylinder cross-section

Compression Functions

Integration Results



Compression Results

2D example:

complex input depth-map

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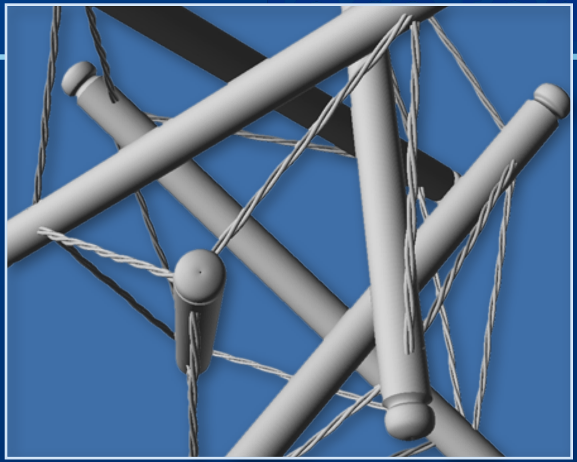
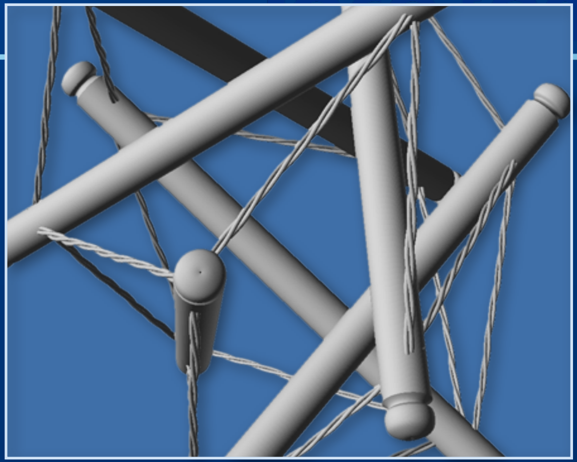
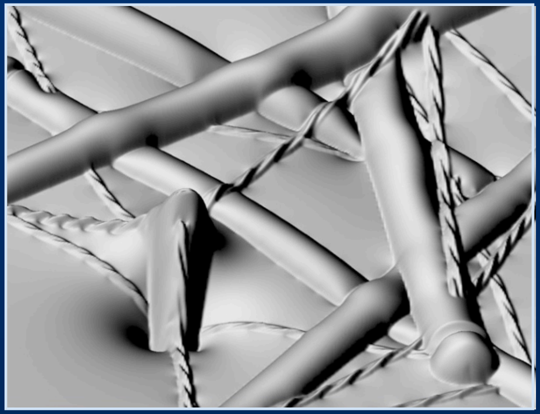


Compression Results

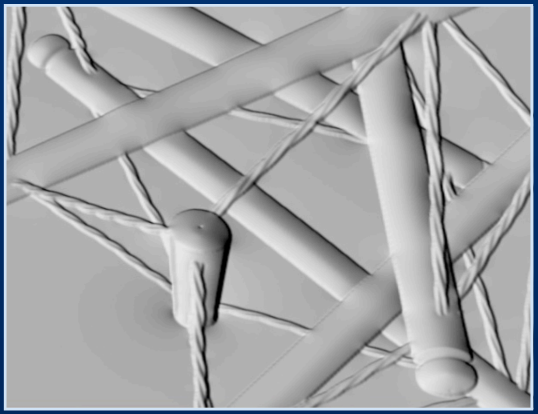
2D example:
complex input depth-map





No Compression
$\alpha \longrightarrow 0.0$

Compression
$\alpha = 1.0$



Compression
$\alpha = 10.0$

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Relief From Complex Scenes

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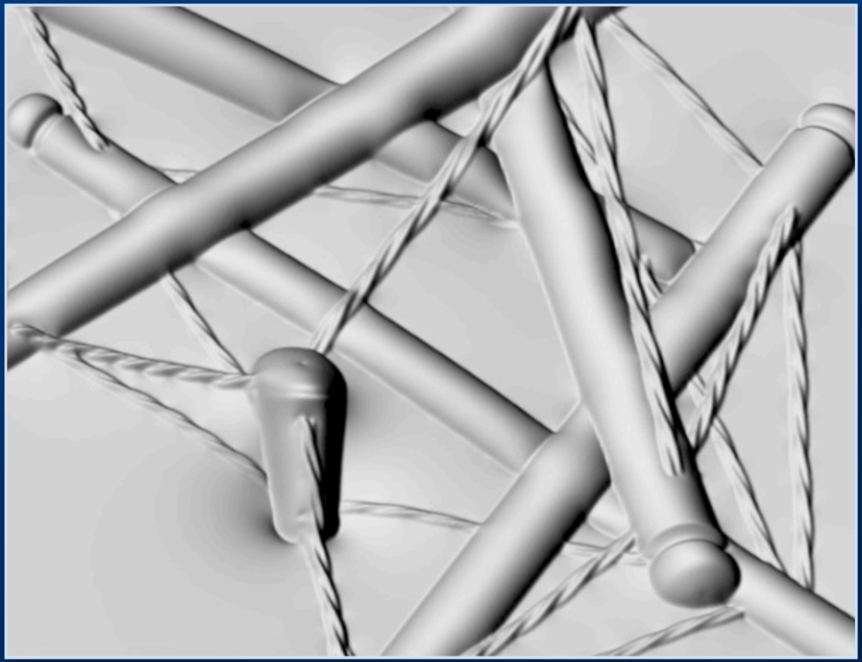
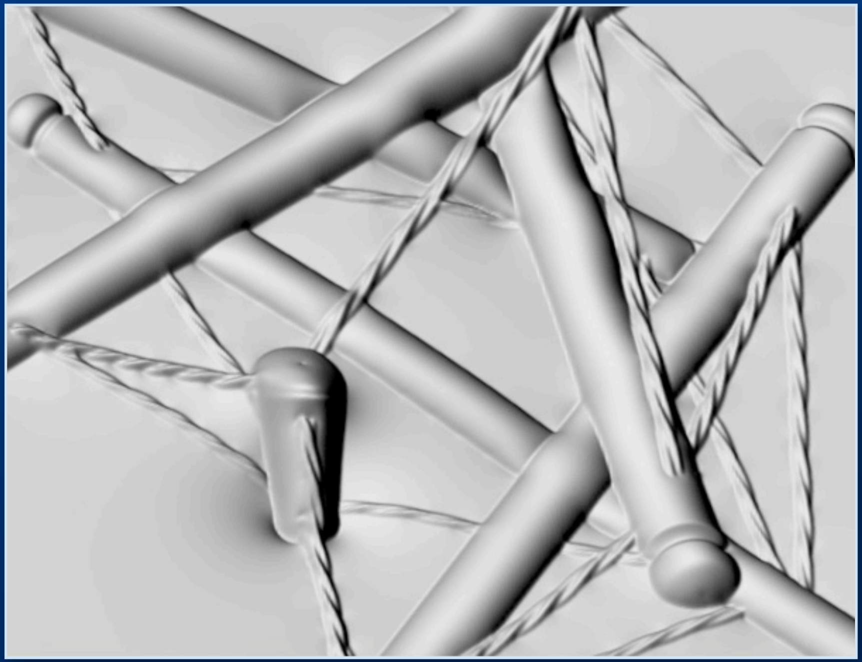
Silhouette Constraints



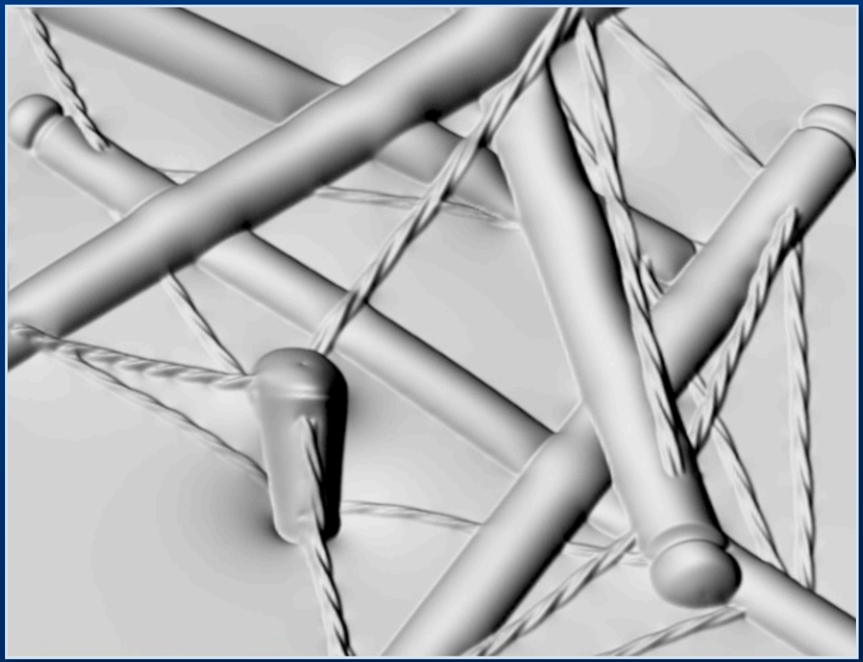
Silhouette Constraints

- Receding background emphasizes silhouettes



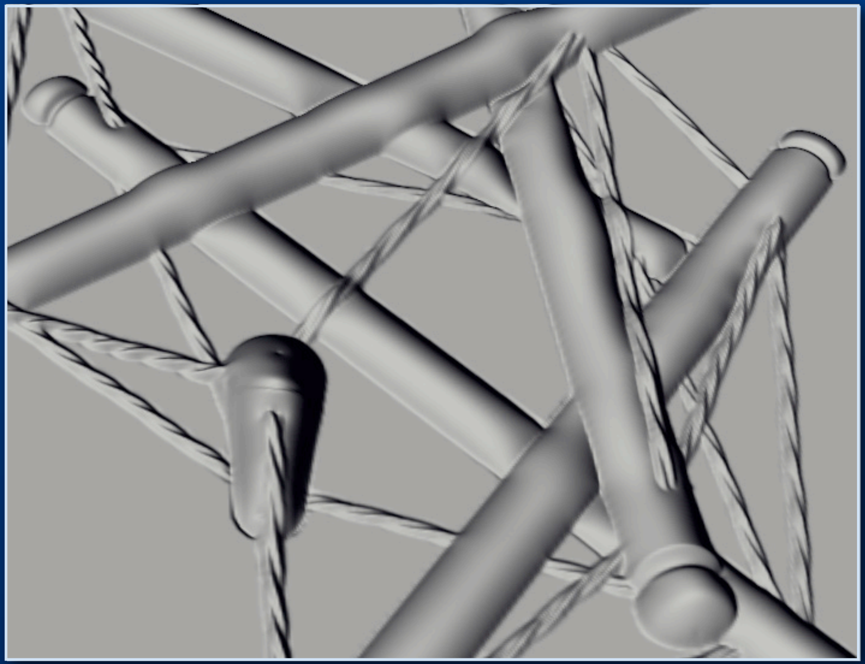
Silhouette Constraints

- Receding background emphasizes silhouettes
- Sometimes flat background desirable



Silhouette Constraints

- Receding background emphasizes silhouettes
- Sometimes flat background desirable
- Sea-level constraint at silhouettes flattens back pane



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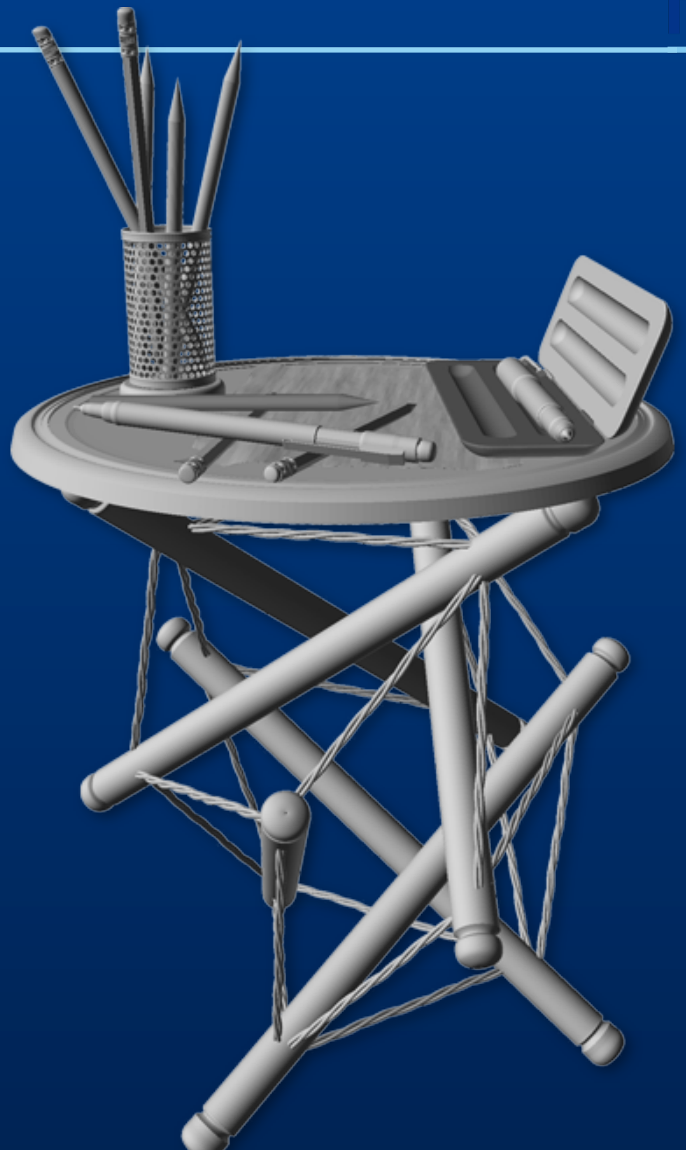

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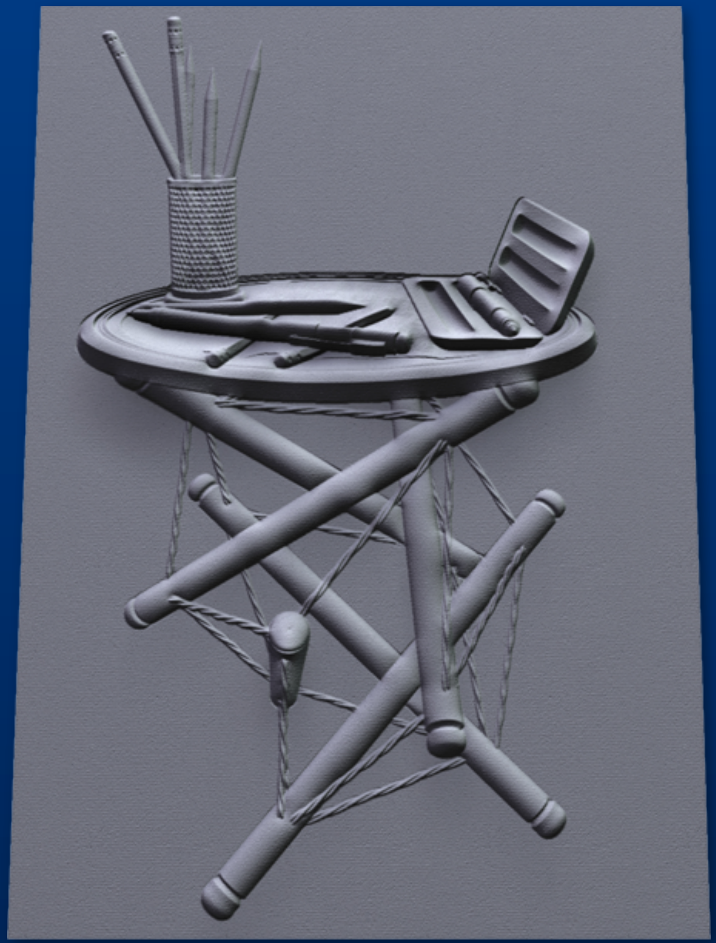

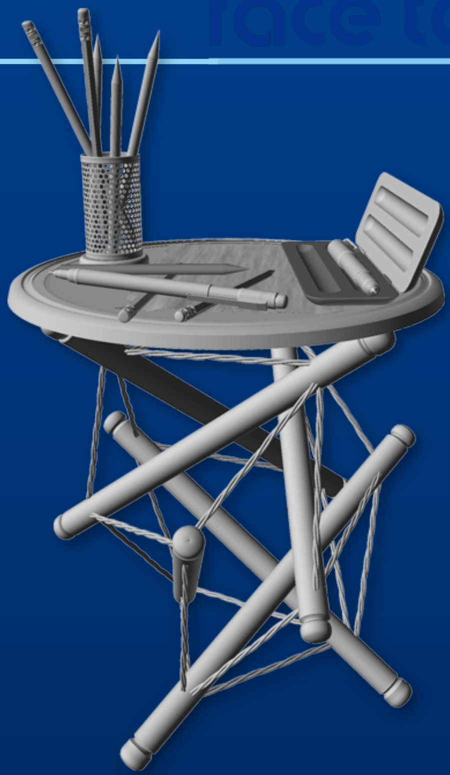

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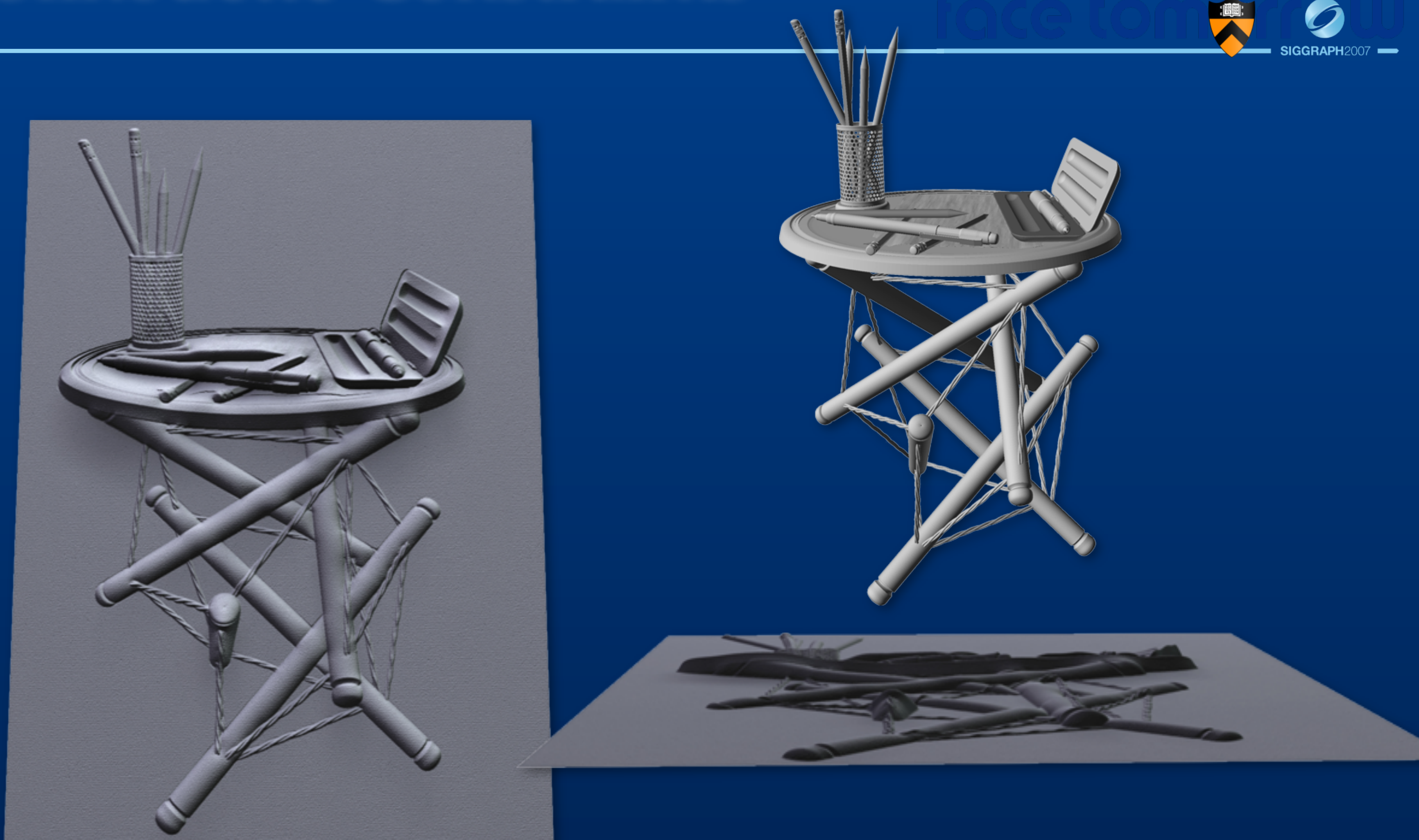
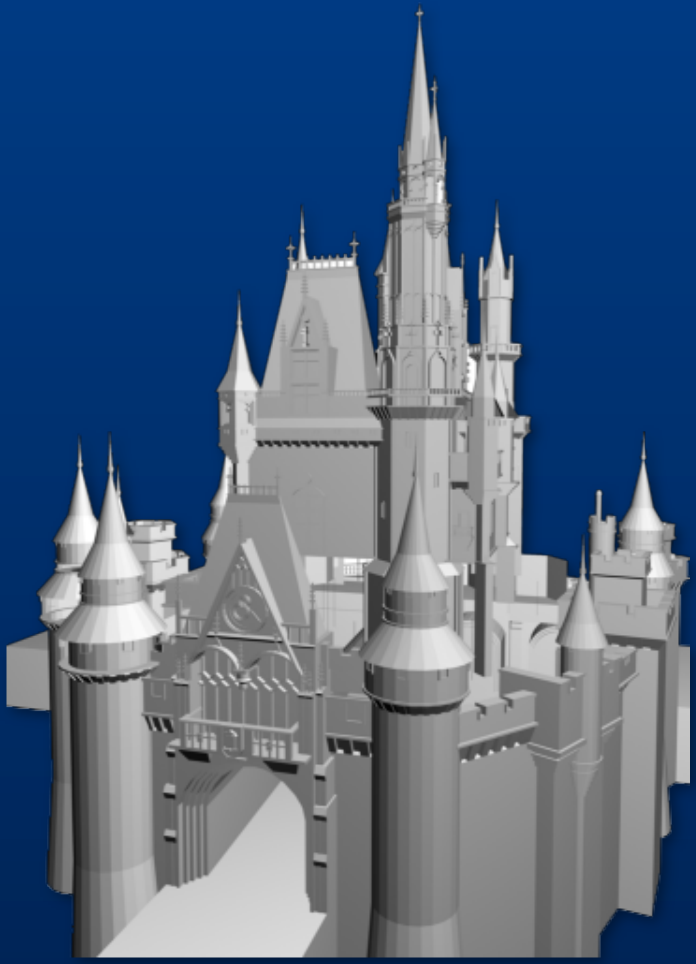


Material Dependence

- *Compression:* glossier materials allow for flatter relief
- *Detail:* must respect medium
(e.g., translucent media allow for less detail)
- *Steps:* to emphasize depth discontinuities

Material Dependence



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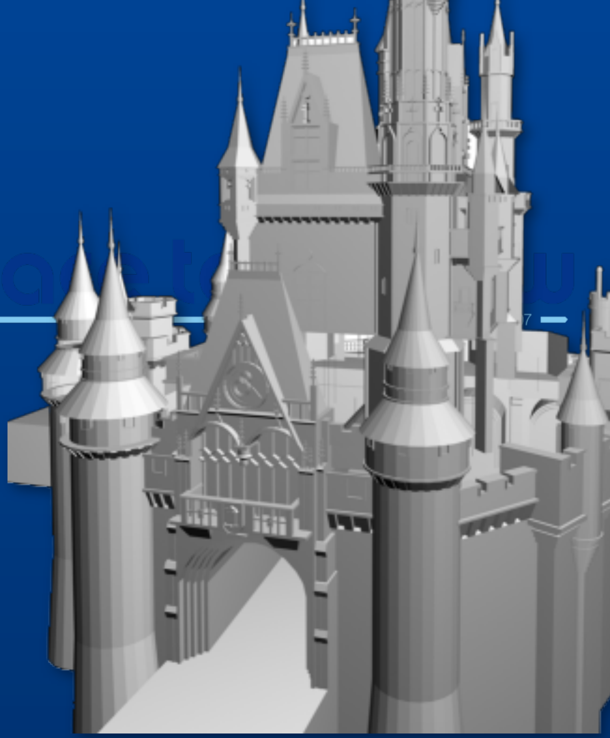
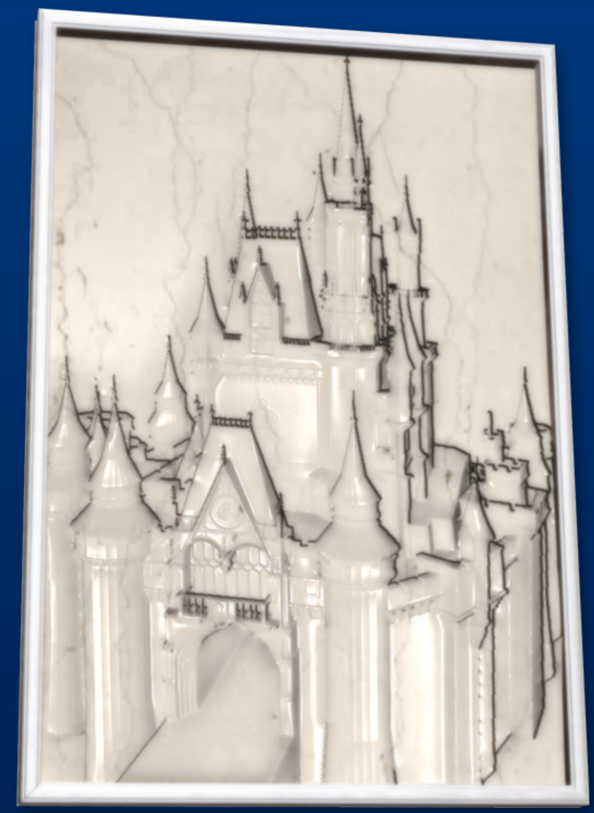


Material Dependence

100 : 3.2

100 : 0.88



100 : 4.2

Gradient-Domain Editing

- Frequency control
  - Independent scaling of frequency decomposition
  - Decomposition uses silhouette-respecting filter

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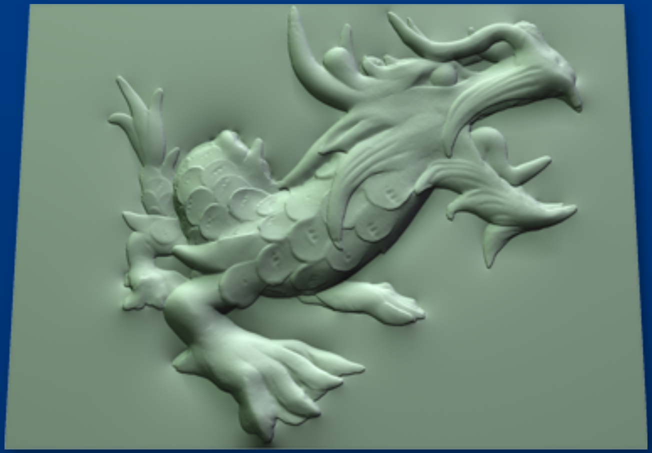

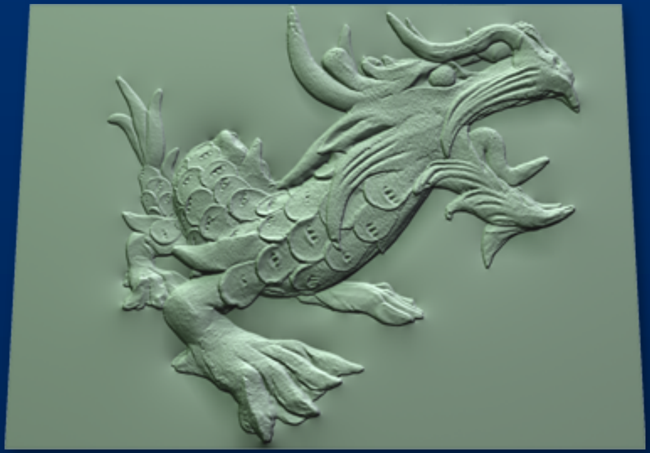

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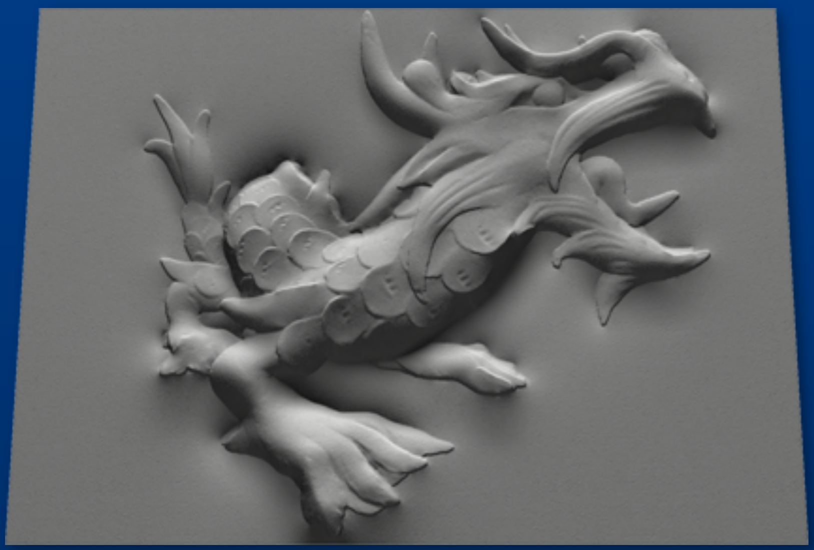
Physical Reliefs

- Previous results use realistic shaders and lighting
- Final evaluation using
  - A physical stone relief
  - Real coins showing a 3D scene

Physical Reliefs — Limestone



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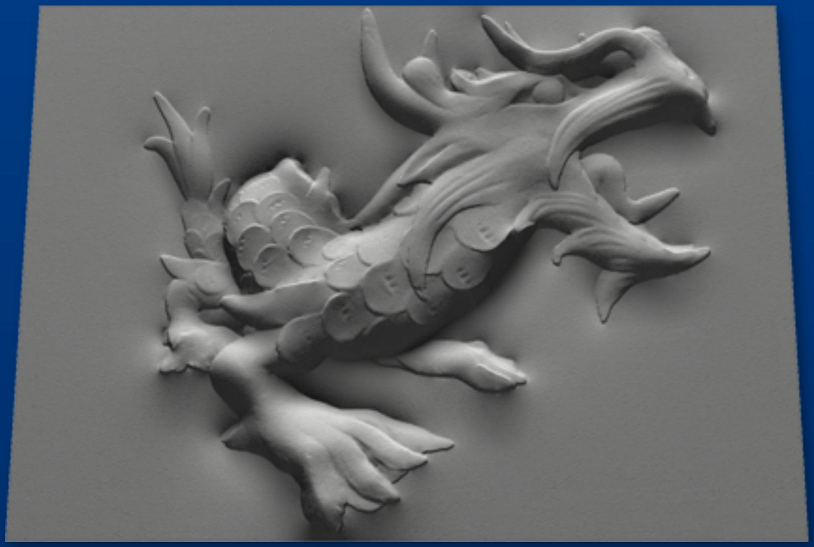
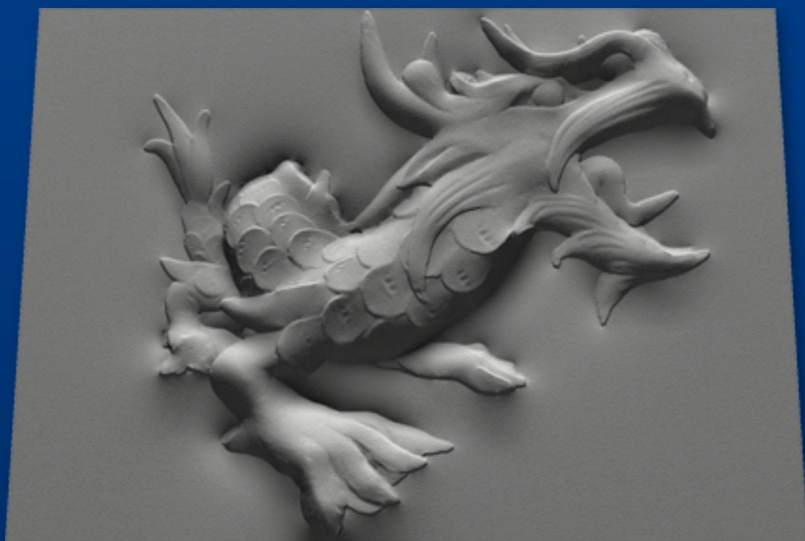
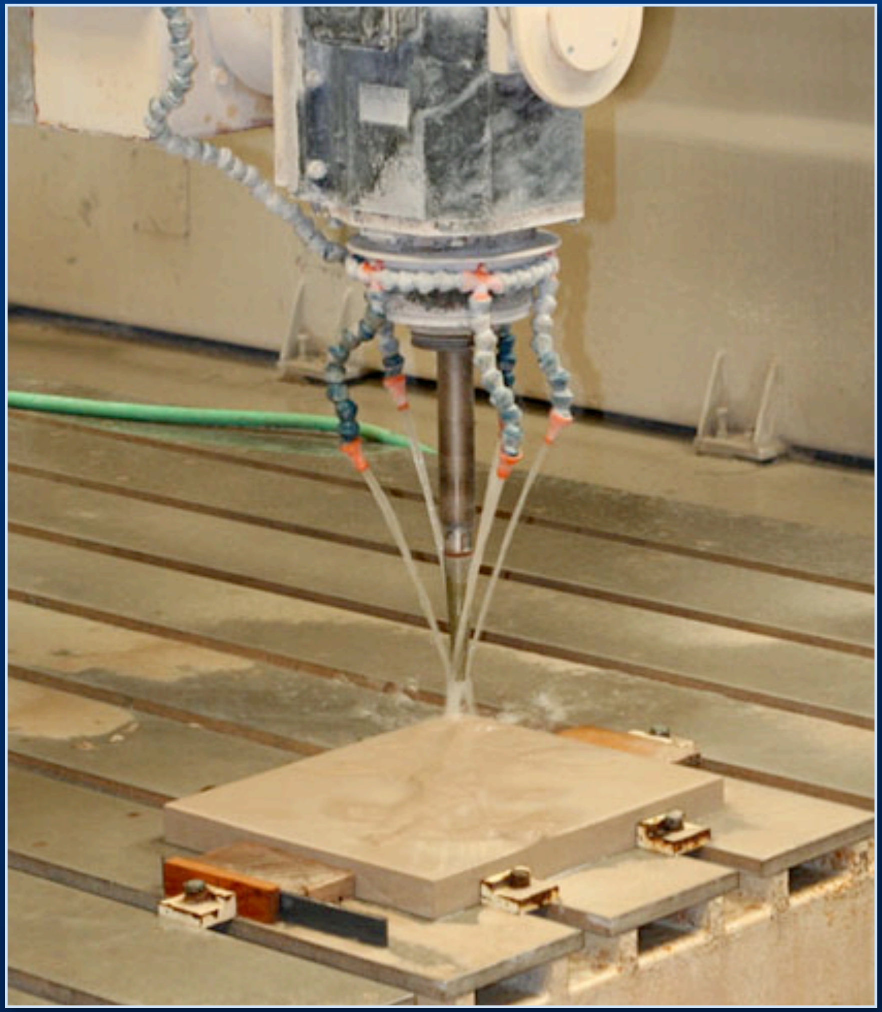


- Transferring height fields to a robotic mill

Physical Reliefs — Limestone





- Transferring height fields to a robotic mill
- Milling a relief from stone

Physical Reliefs — Coins

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- Limestone represents a very diffuse material

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- Second experiment on shiny materials: custom-made coins

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Physical Reliefs — Coins

- Limestone represents a very diffuse material
- Second experiment on shiny materials: custom-made coins
- Handed out after this session — first-come first served!

Conclusion

- Automated technique for relief generation
  – From arbitrary input scenes
  – Depth-range compression
  – Preservation of visual cues
  – For a wide range of physical materials
- Gradient-domain editing framework
- Promotion of bas-relief as a digital medium

Future Work

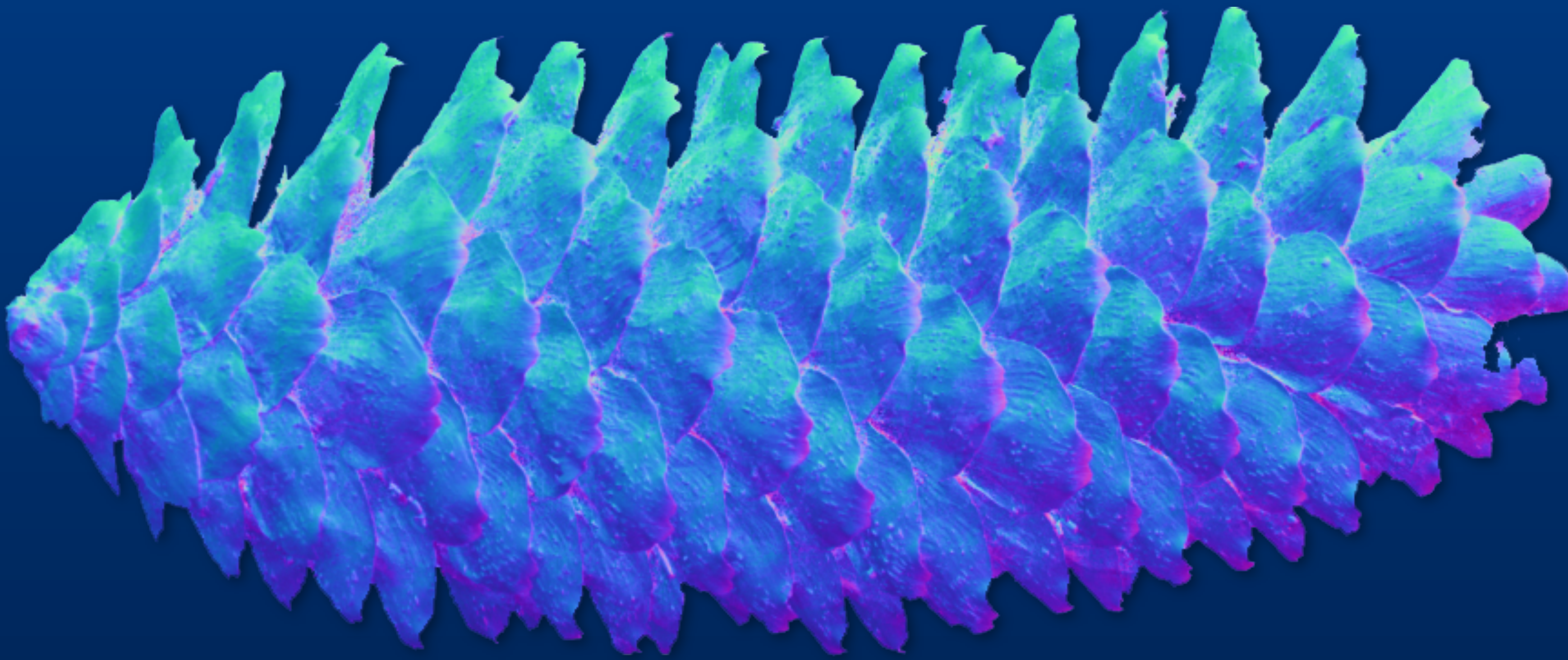
- Formal incorporation of material properties
- Higher-level editing operations
- Bas-relief over general geometry
- *Alto relievo*
- Additional sources of input

Additional Sources

- Scene input not limited to 3D sources
- Only requirements:
  - Gradient field
  - Silhouette locations
- Gradients obtainable from normals

Photometric Normals

Photometric Normals



Relief From Normals

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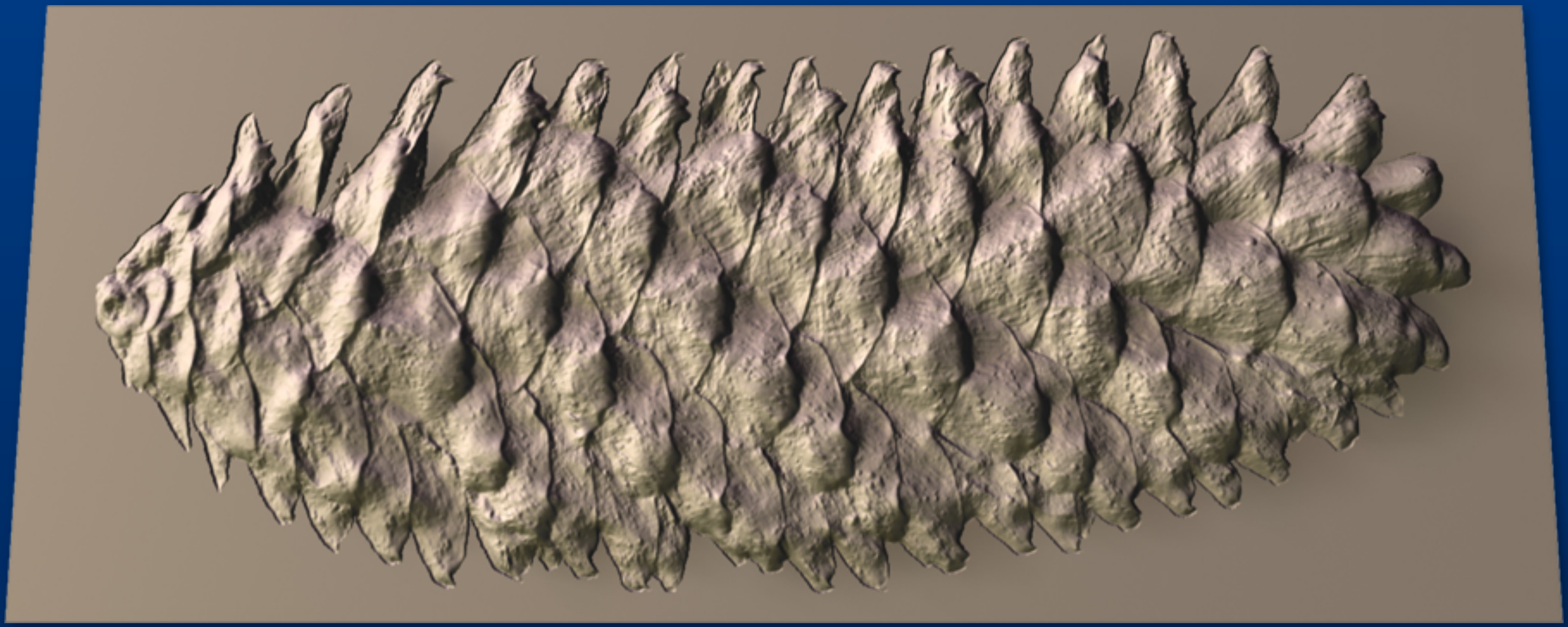

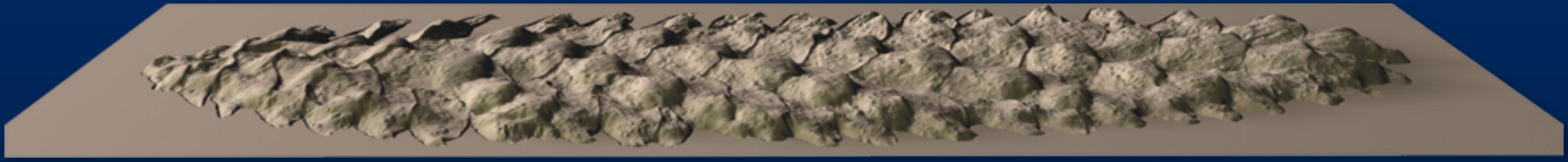

Acknowledgements

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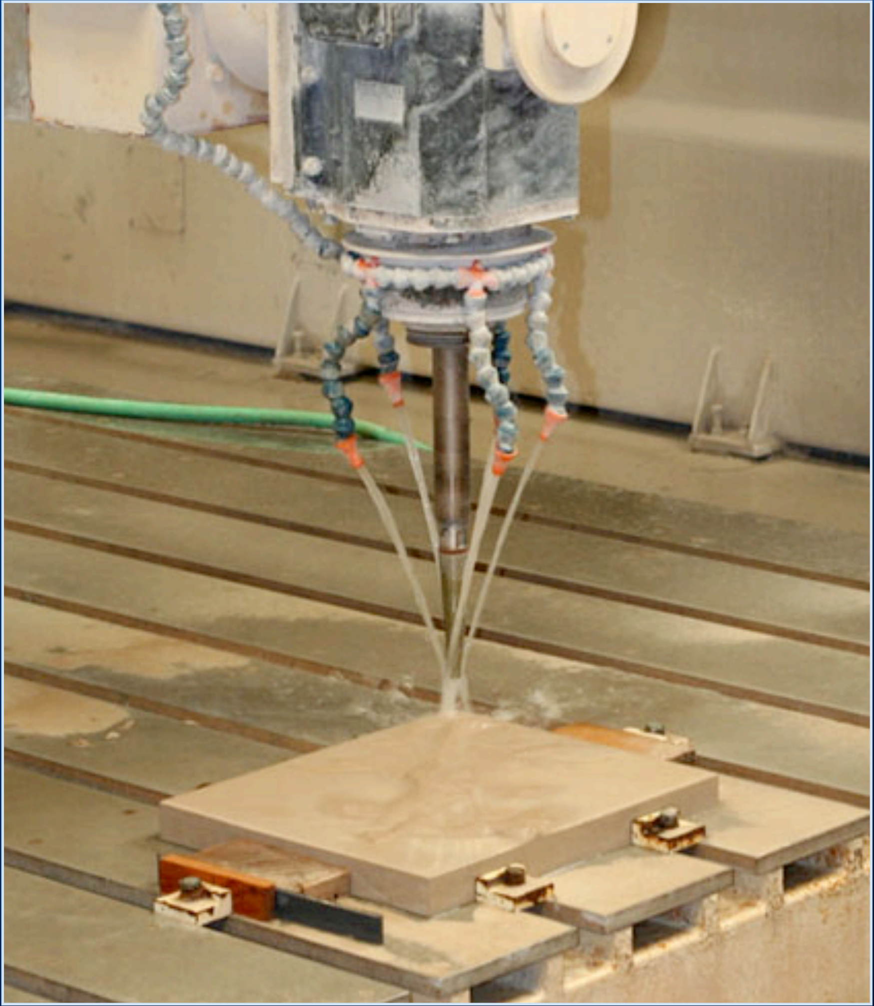

Limitations

- Conflicting goals of guidelines for bas-relief
  - Relative ordering
  - Continuity
  - Shape preservation
- Some scenes impose high strain on optimization
  - Such scenes are generally badly suited for bas-relief
  - Artists have to design scenes that minimize conflicts

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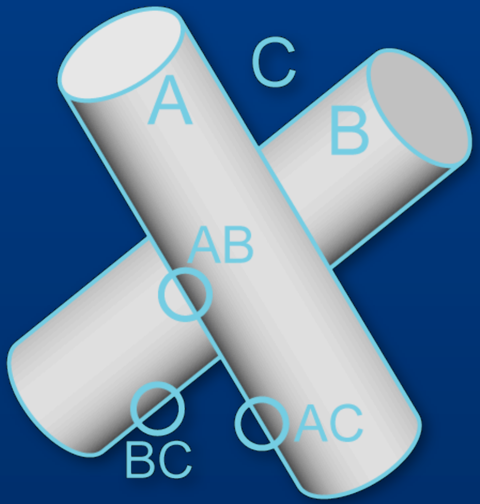

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