Line Drawings of 3D Shapes

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COS 426
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April 24, 2014

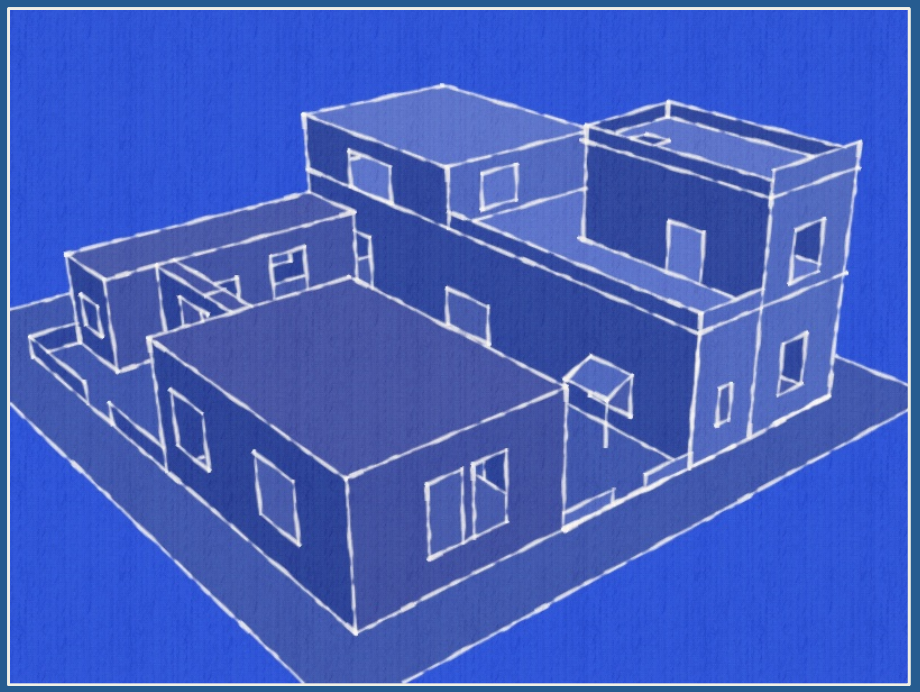
Line drawings

Convey most important features of a shape

Flaxman (1805)

Lines in 3D Scenes

- Aid comprehension
- Evoke hand-drawn style
- Allow abstraction



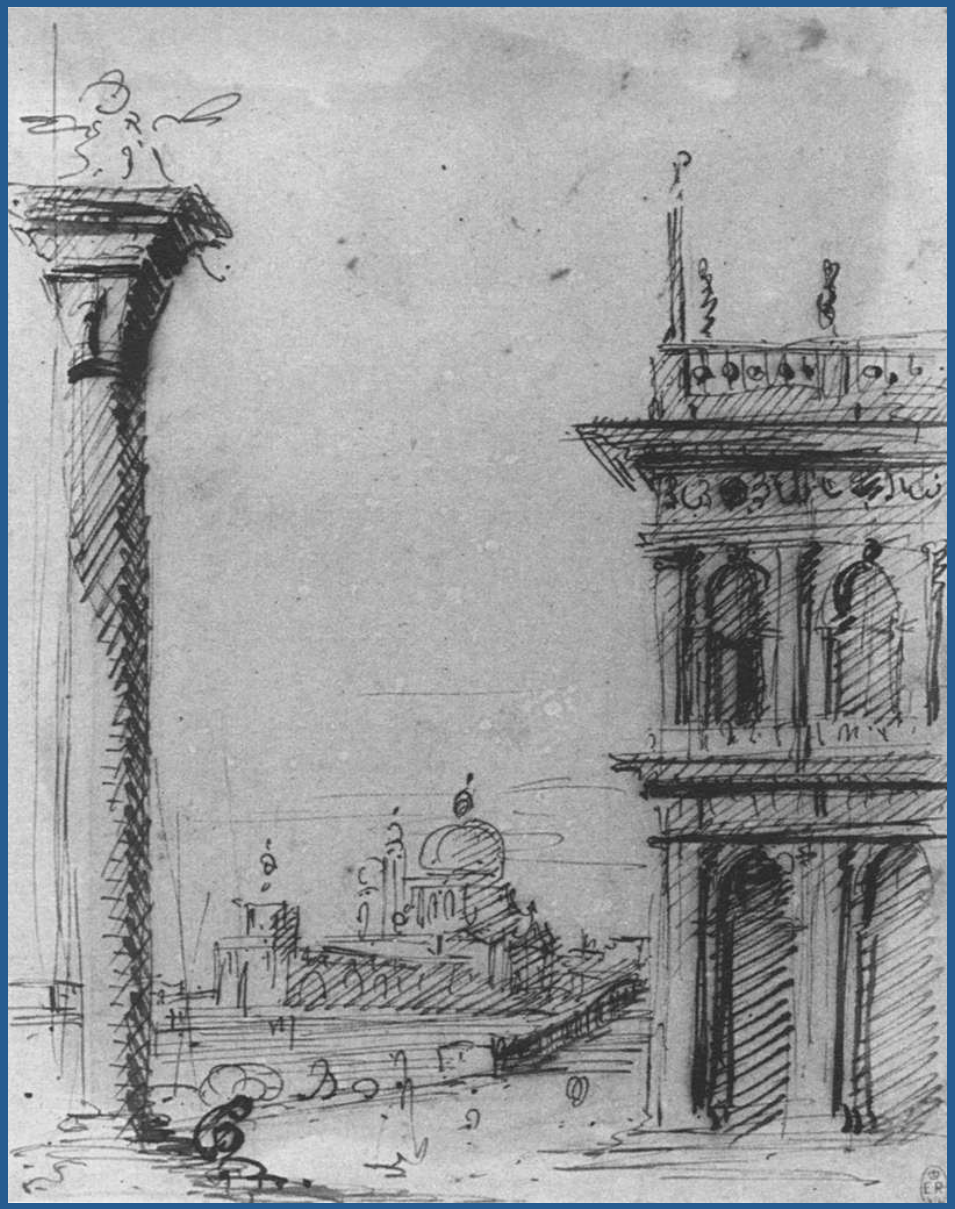
Computer-Generated Line Drawing

Artist's Rendering (Rembrandt)

Range of Line Drawings

- “Line drawing” is not a single style
- Immense range of approaches
  - Loose to controlled
  - Sparse to developed
  - Abstract to veridical
  - Emotional to explanatory

Loose vs. Controlled



Canaletto

Sparse vs. Developed

John Singer Sargent

Piranesi

Abstract vs. Veridical

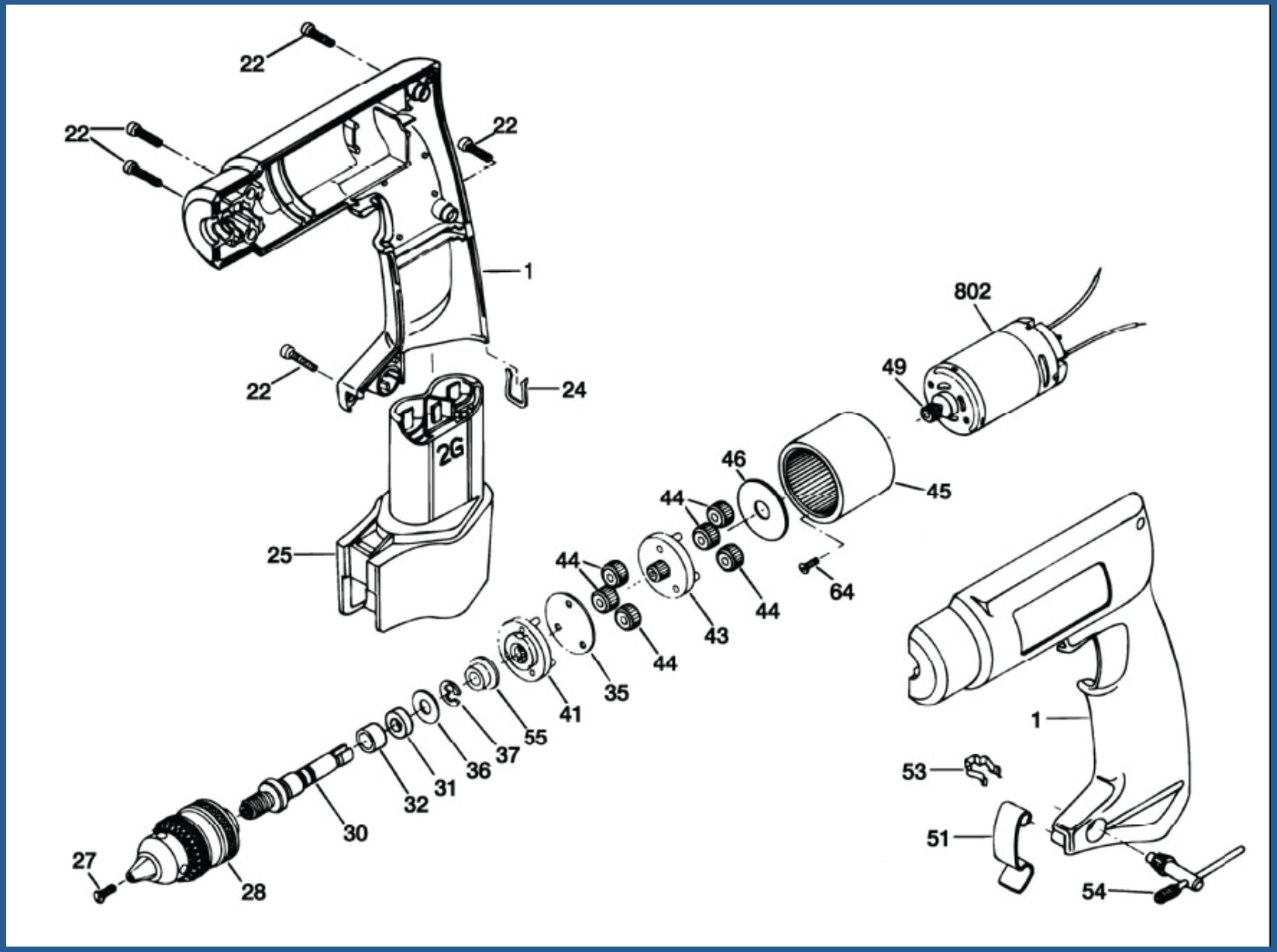
Picasso

Gustave Moreau

Emotional

Michelangelo

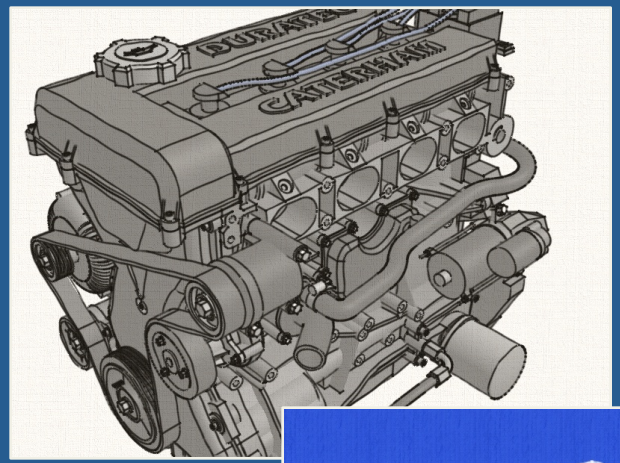
Explanatory

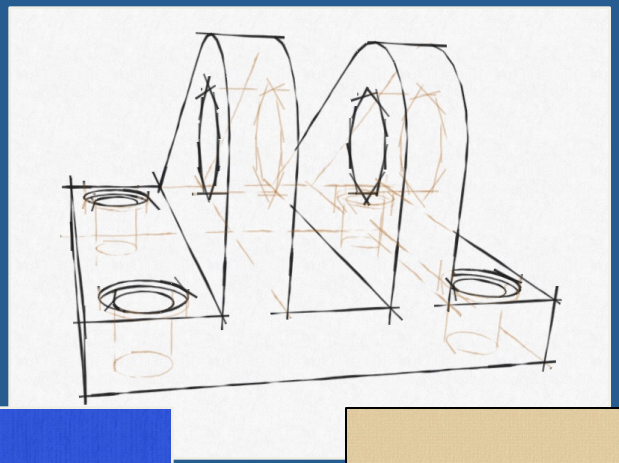


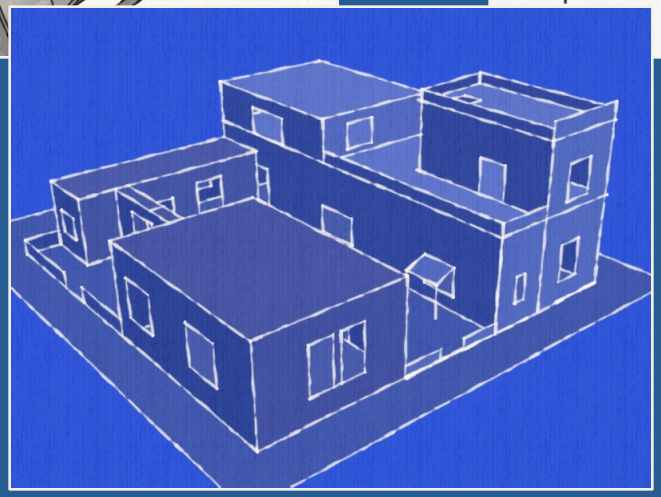
Bosch Tools Schematic (from [Li 2008])

CG Line drawings

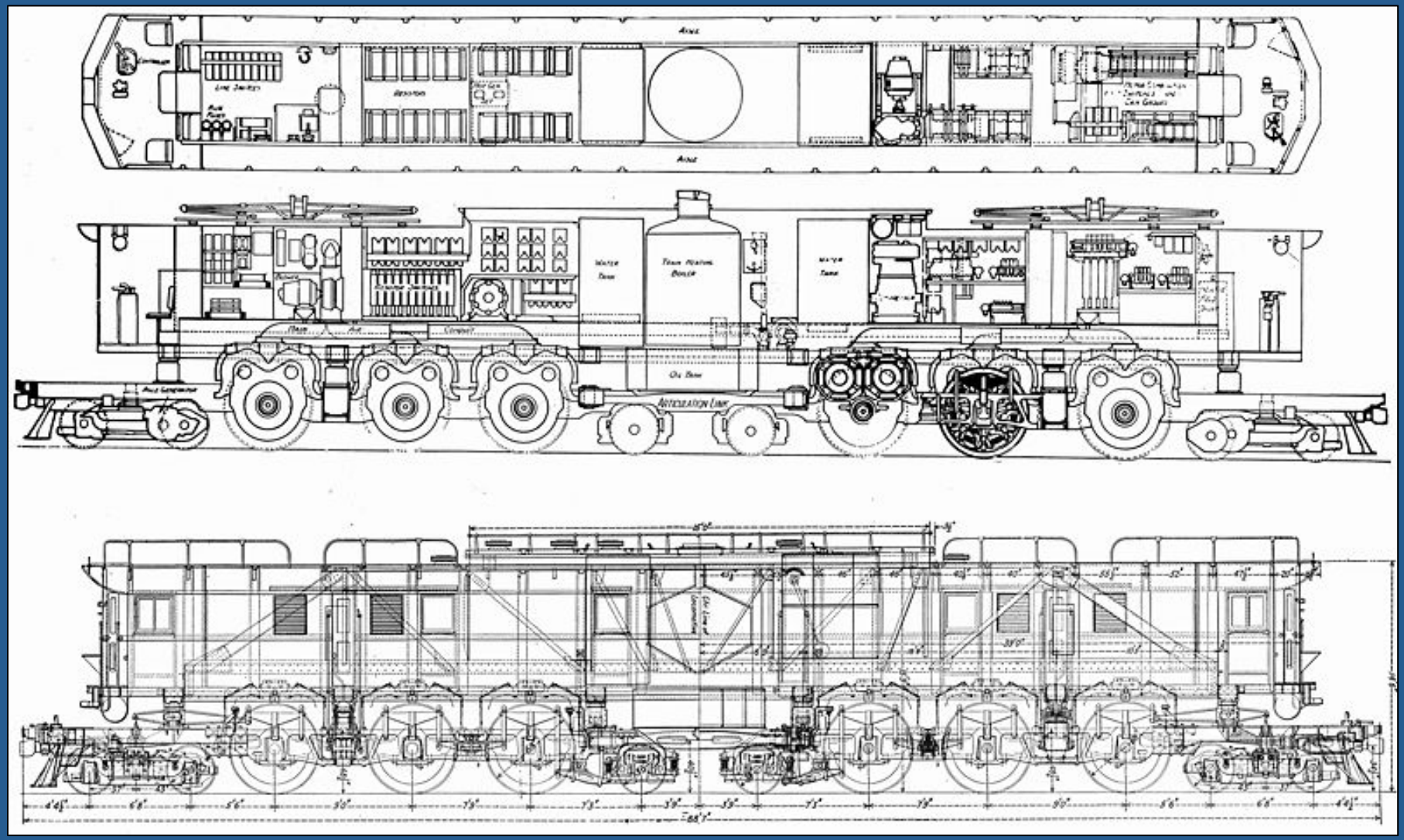
What styles can we understand & reproduce?





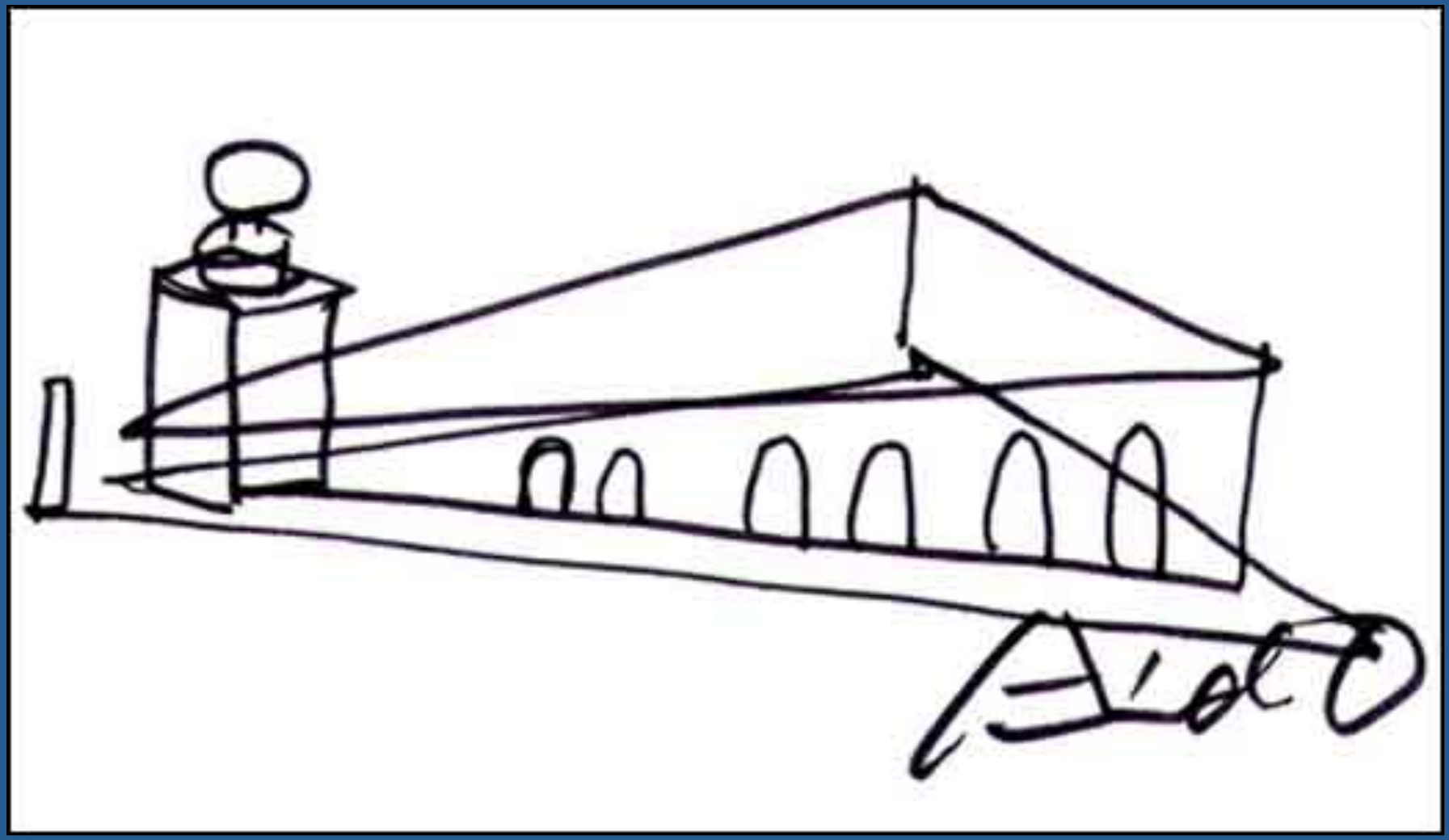


Pretty Easy



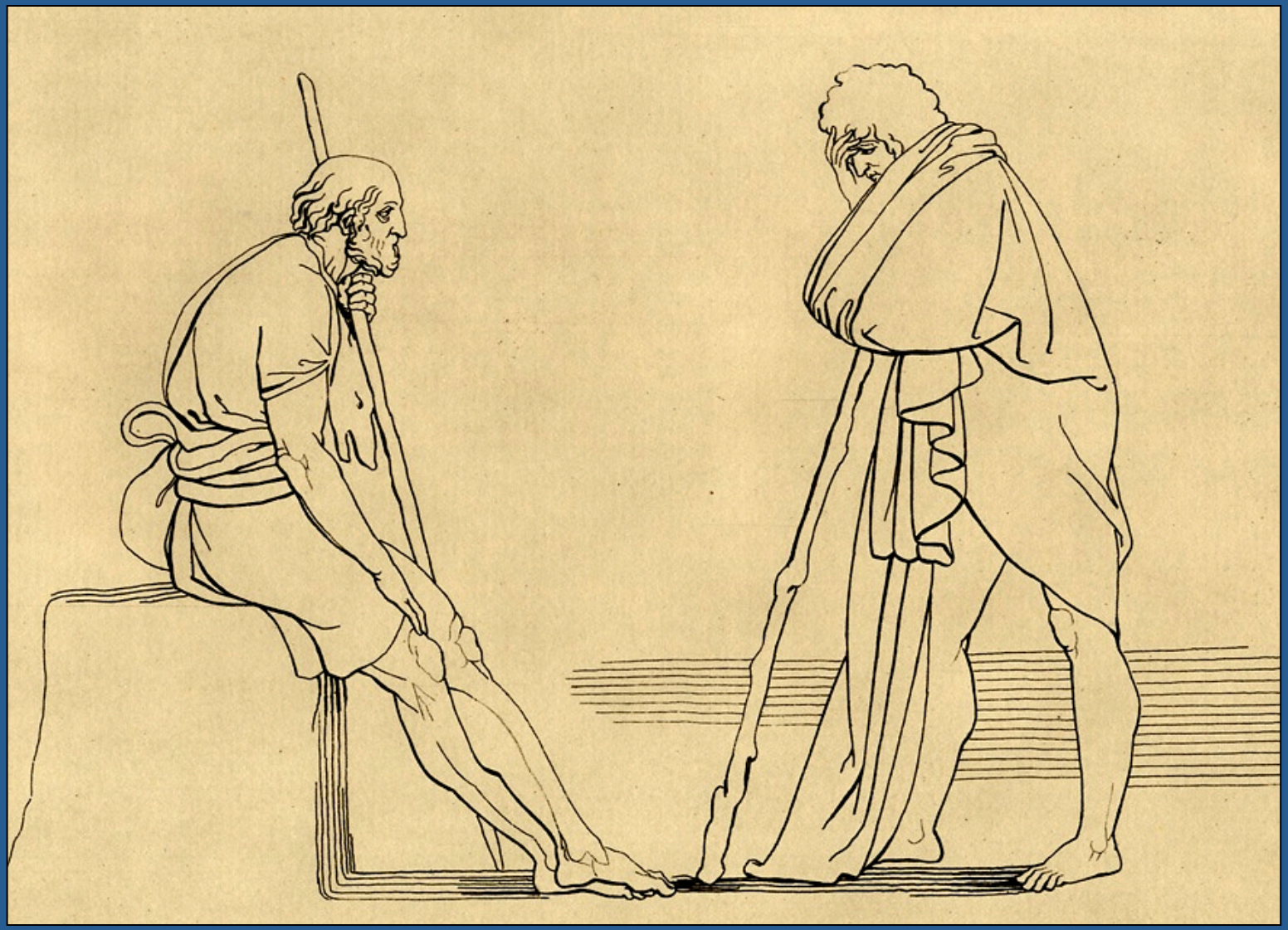
1922 Locomotive Cyclopedia

Hard



Tadao Ando

Harder

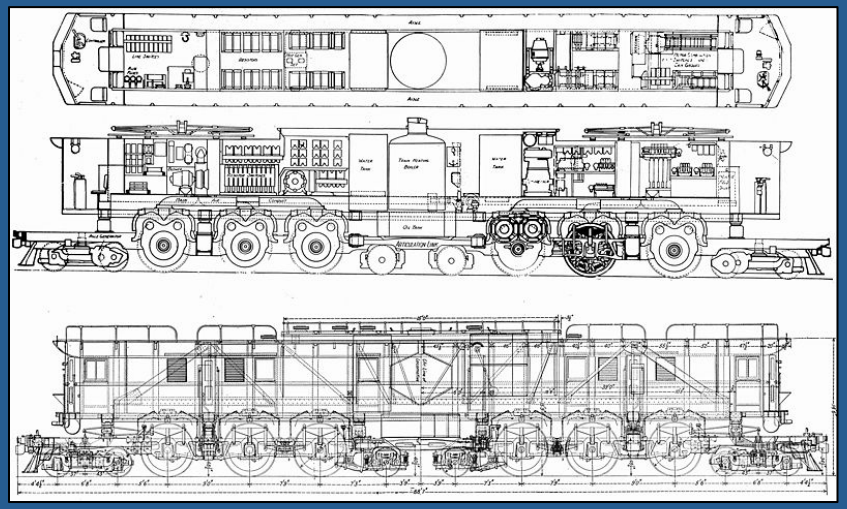


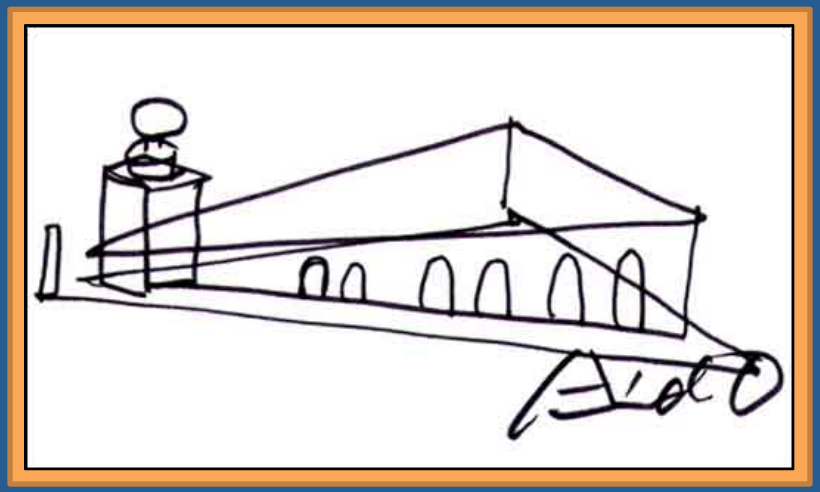
Flaxman

Really Hard

Picasso

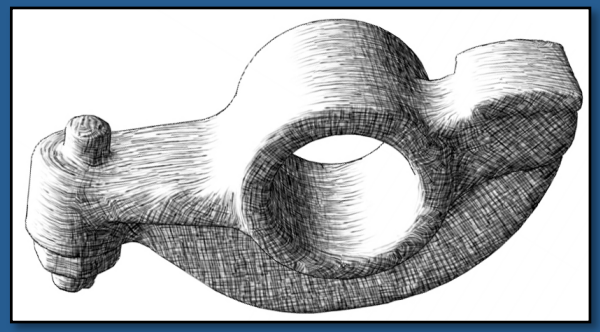
Just right?



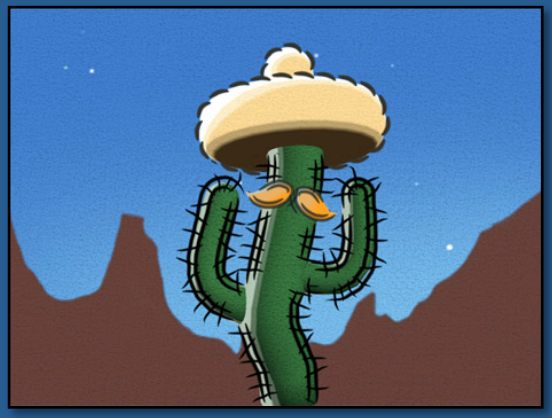


Research Challenges

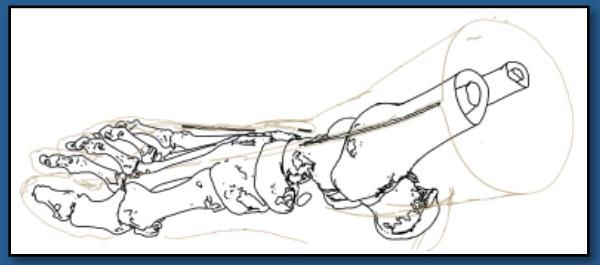
- Technical / Algorithmic:
  - Efficient shading, temporal coherence, extraction
  - Level of detail, stroke visibility, texturing
  - etc.



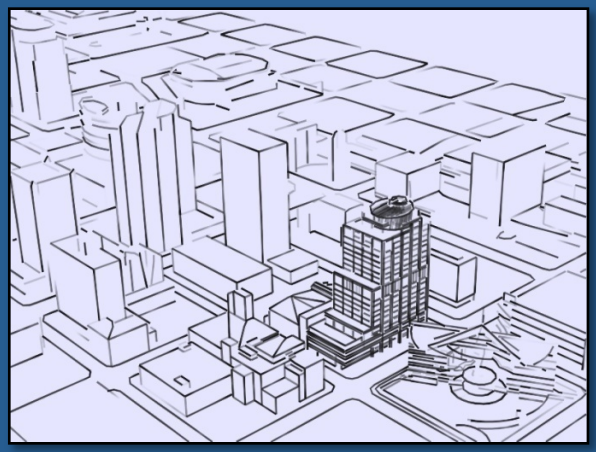
Real-Time Hatching
Emil Praun, Hugues Hoppe, Matthew Webb, and Adam Finkelstein
Proceedings of ACM SIGGRAPH 2001



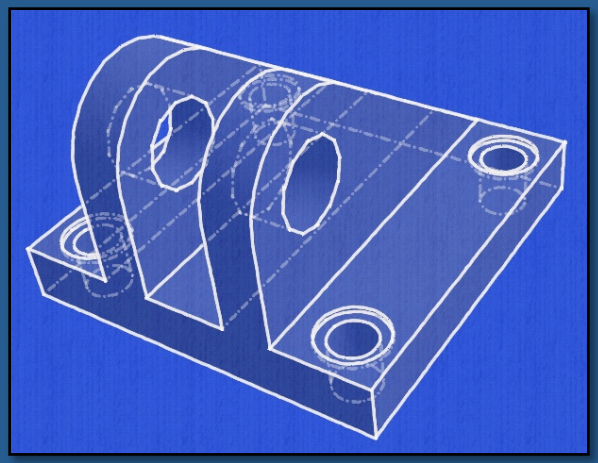
Coherent Stylized Silhouettes
Robert Kalnins, Philip L. Davidson, Lee Markosian, and Adam Finkelstein
ACM Transactions on Graphics 22(3) (SIGGRAPH 2003)



Line Drawings from Volume Data
Michael Burns, Janek Klawe, Szymon Rusinkiewicz, Adam Finkelstein, and Doug DeCarlo
ACM Transactions on Graphics 24(3) (SIGGRAPH 2005)



Directing Gaze in 3D Models with Stylized Focus
Forrester Cole, Doug DeCarlo, Adam Finkelstein, Kenrick Kin, Keith Morley, and Anthony Santella,
Eurographics Symposium on Rendering 2006



Fast High-Quality Line Visibility
Forrester Cole and Adam Finkelstein
Proceedings of i3D 2009

Self-Similar Texture for Coherent Line Stylization
Pierre Bénard, Forrester Cole, Aleksey Golovinskiy, and Adam Finkelstein
Proceedings of NPAR 2010

Research Challenges

- Technical / Algorithmic:
  - Efficient shading, temporal coherence, extraction
  - Level of detail, stroke visibility, texturing
  - etc.
- Theoretical:
  - What lines to draw?
  - How do artists make drawings?
  - How do people perceive drawings?

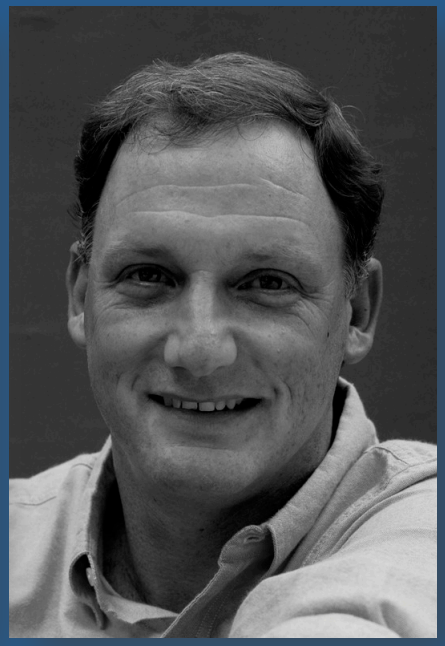
Overview

1. What lines to draw?
2. How do artists make drawings?
3. How do people perceive drawings?

Many collaborators, including…

Doug DeCarlo
Rutgers

Szymon Rusinkiewicz
Princeton



Tom Funkhouser
Princeton

Forrester Cole
Princeton

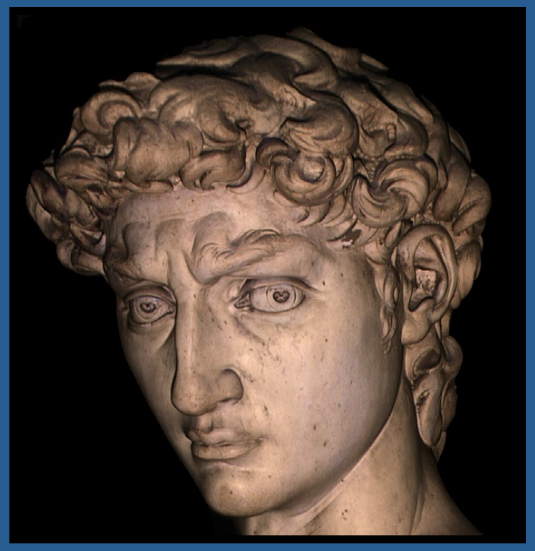
Part 1:
What lines to draw?

"Suggestive Contours for Conveying Shape"
Doug DeCarlo, Adam Finkelstein, Szymon Rusinkiewicz, Anthony Santella
ACM Transactions on Graphics 22(3), (Proc. SIGGRAPH 2003)

What lines to draw

Silhouettes:

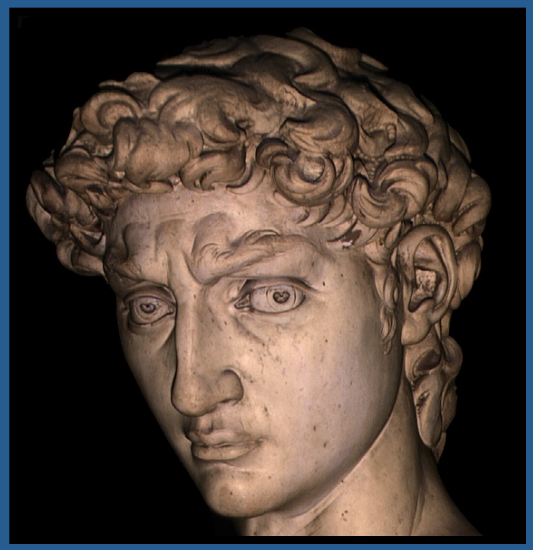
– boundary between object and background



What lines to draw

Contours:

- occlusion boundaries
- surface normal perpendicular to view direction

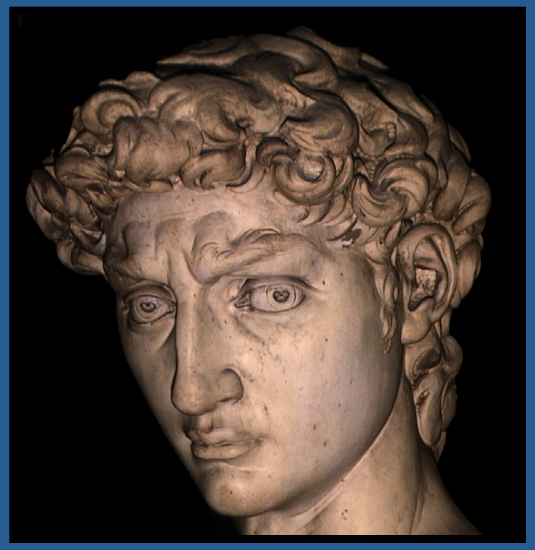


[Saito & Takahashi 90, Winkenbach & Salesin 94, Markosian et al 97, …]

What lines to draw

Ridges and valleys (crest lines)

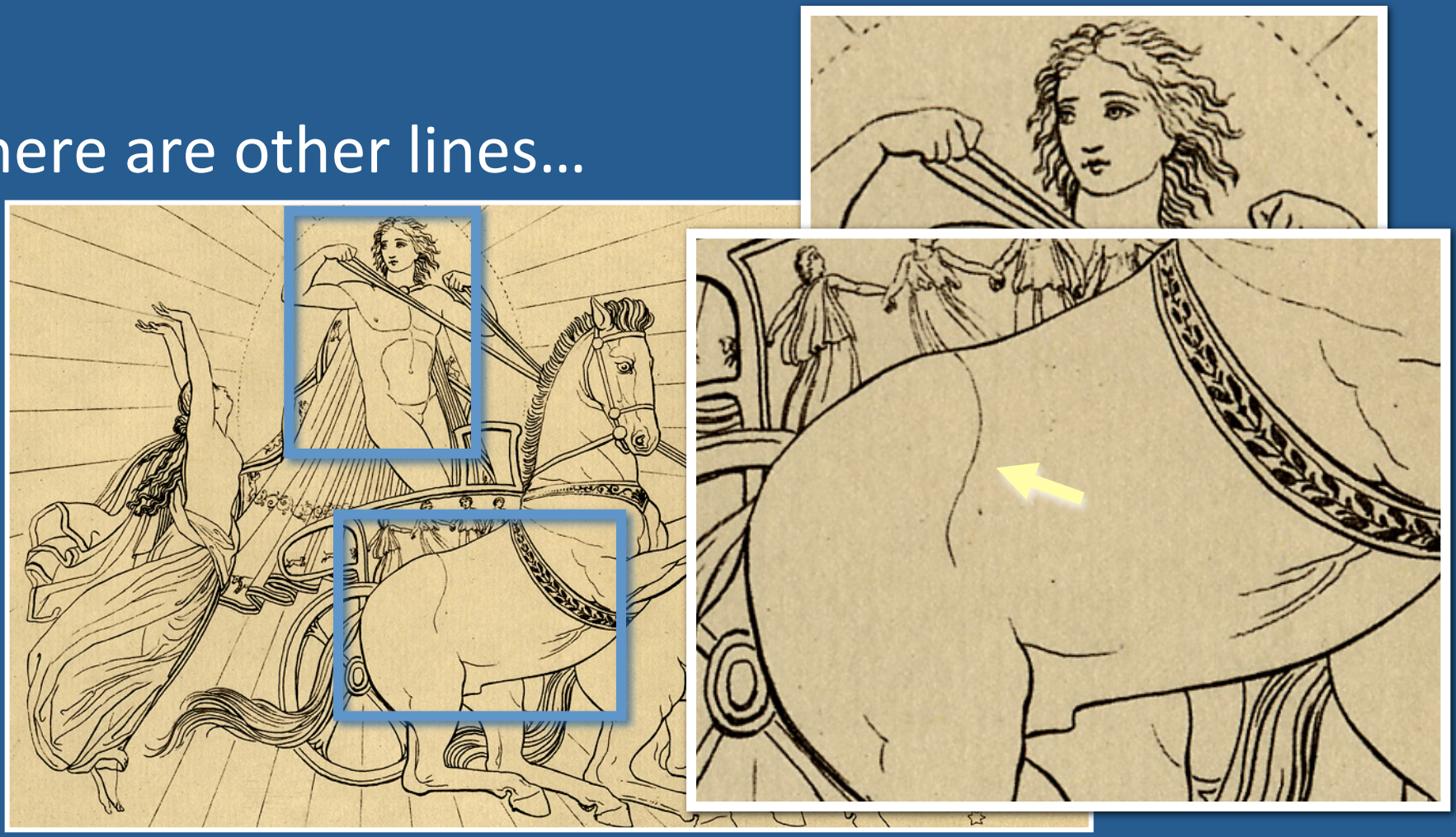
- local maxima of curvature
- creases: infinitely sharp folds



[Thirion & Gourdon 92, Interrante et al 95, Stylianou & Farin 00, Pauly et al 03, …]

What lines to draw

There are other lines…



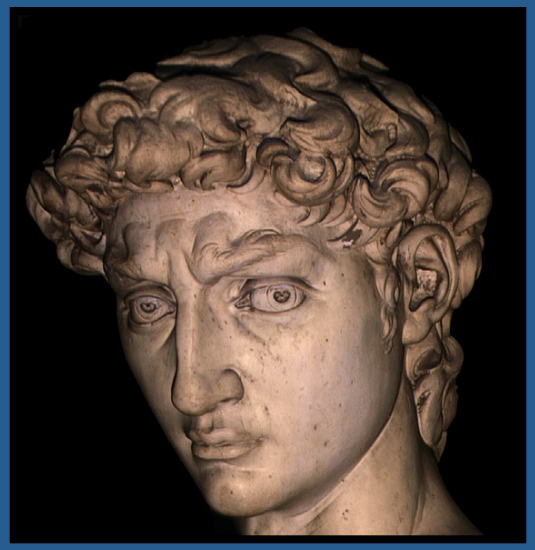
Flaxman (1805)

Hypothesis: some are “almost contours”

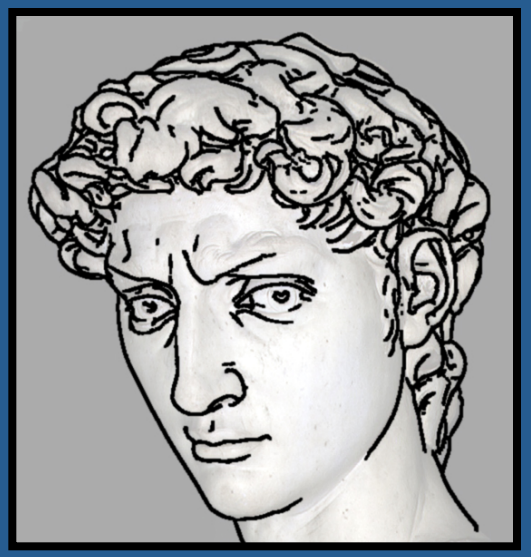
Suggestive contours

What does “almost contours” mean?

- points that become contours in nearby views



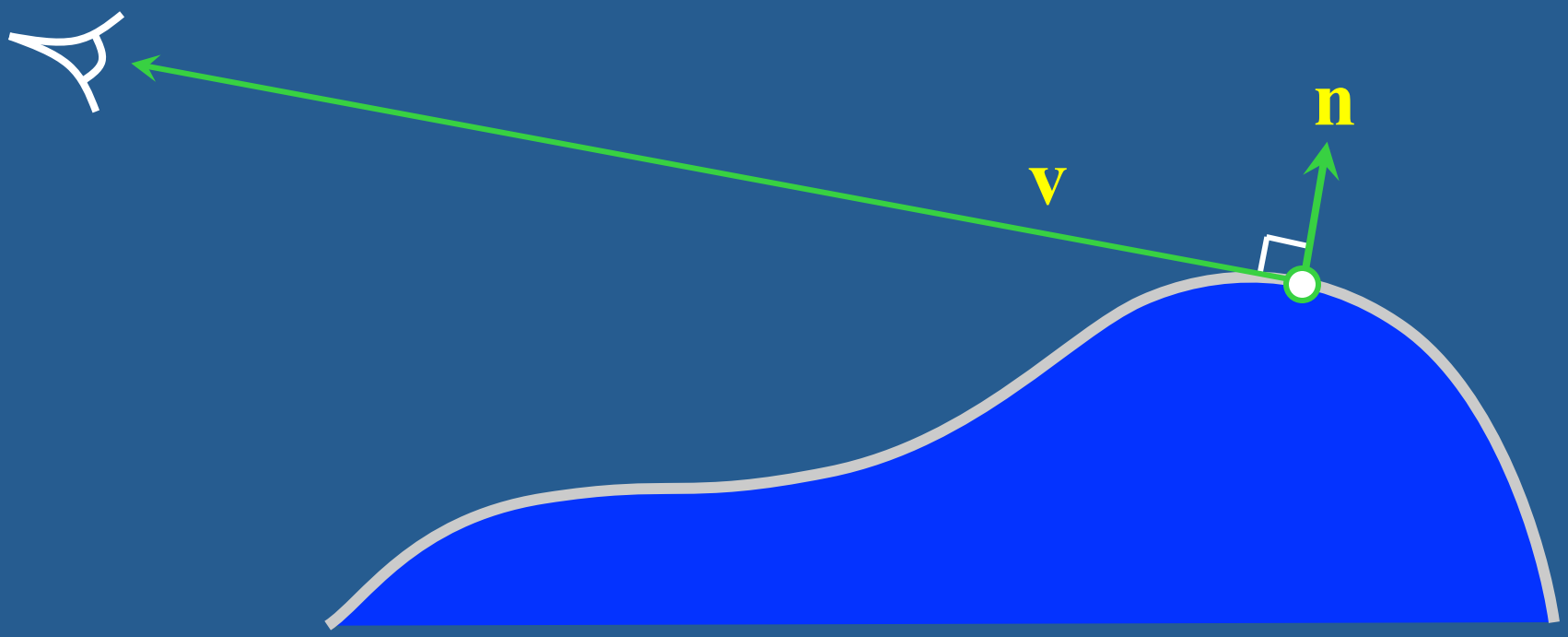
contours



contours +
suggestive contours

Contours

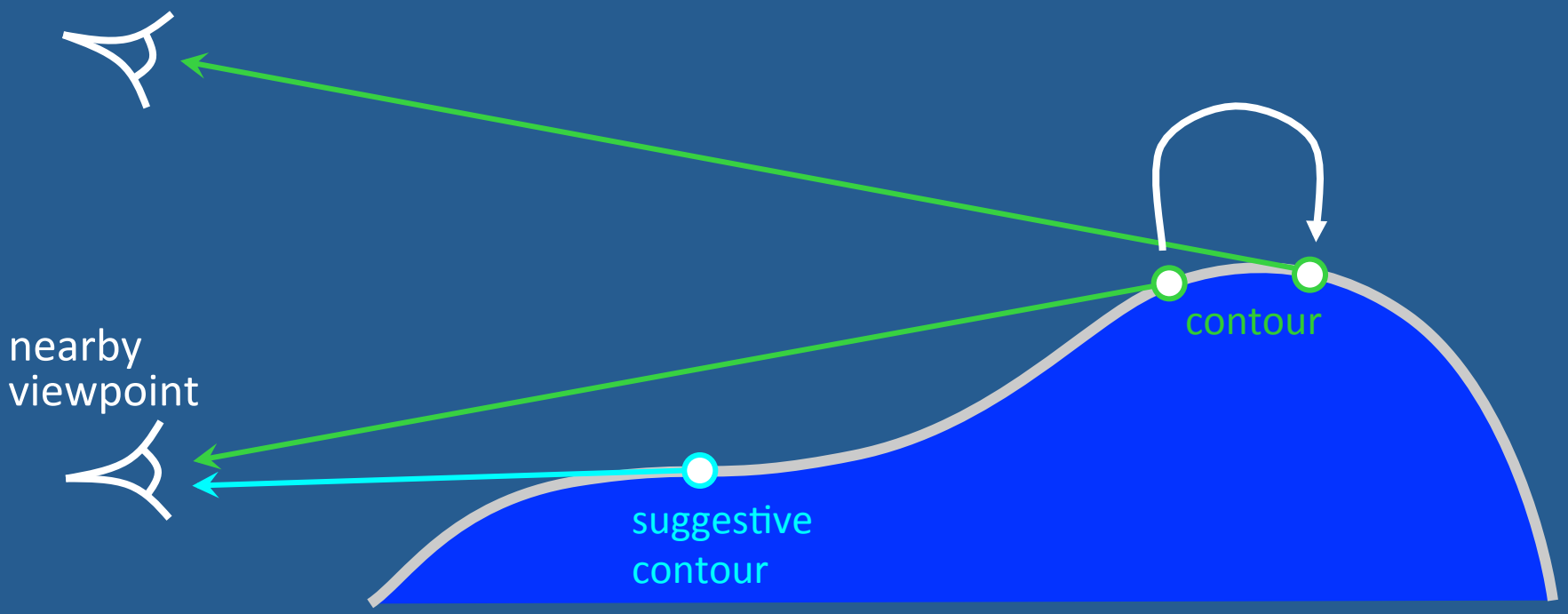
Points where $n \cdot v = 0$



Suggestive contours: definition 1

Contours in nearby viewpoints

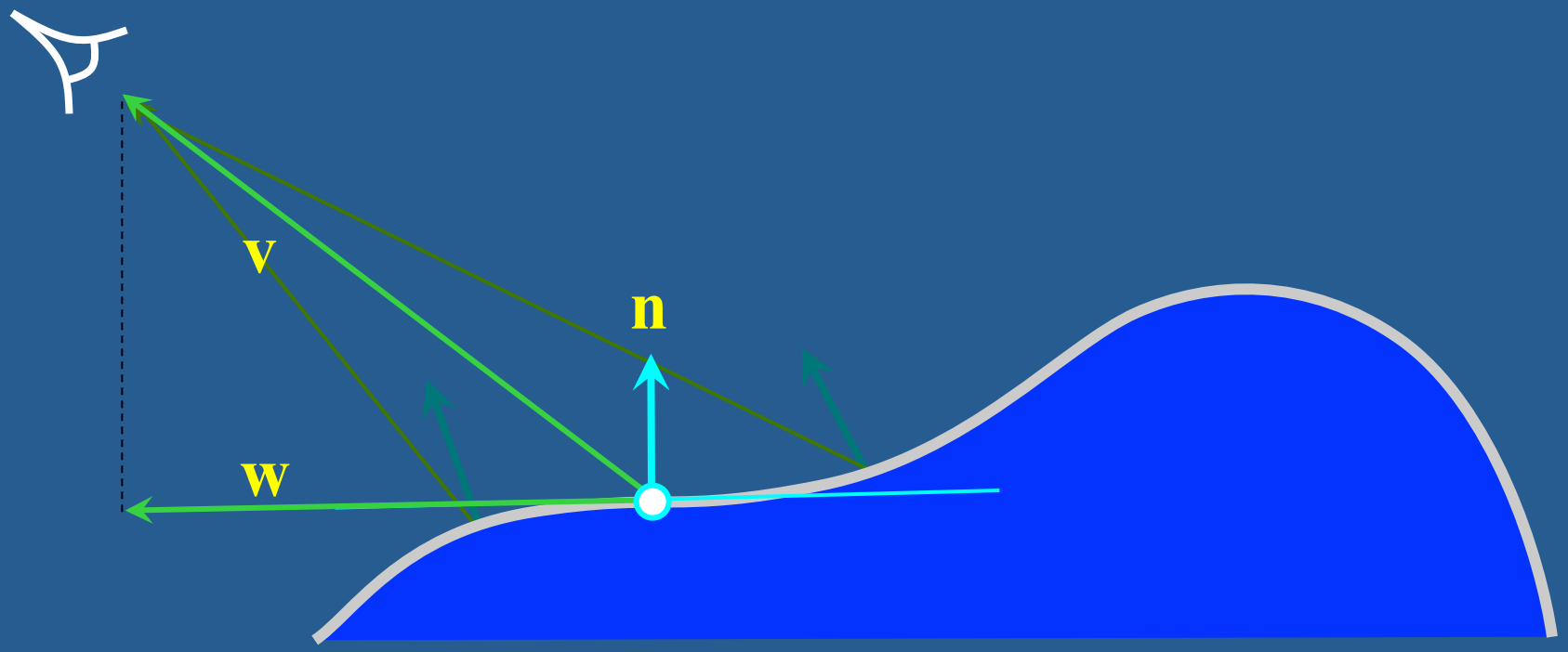
(not corresponding to contours in closer views)



Suggestive contours: definition 2

$n \cdot v$ not quite zero, but a local minimum

(in the direction of w)



Minima vs. zero crossings

Definition 2: Minima of $n \cdot v$

Finding minima is equivalent to:

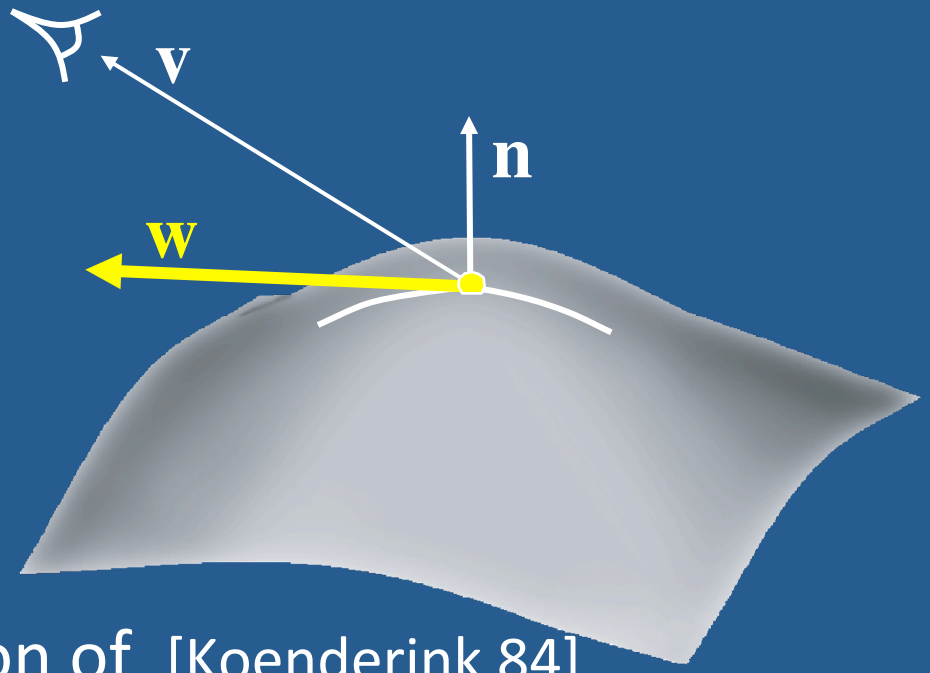
- finding zeros of the derivative
- checking that 2nd derivative is positive

This leads to definition 3.

Derivative of $n \cdot v$ is a form of curvature…

Radial curvature: κ_r

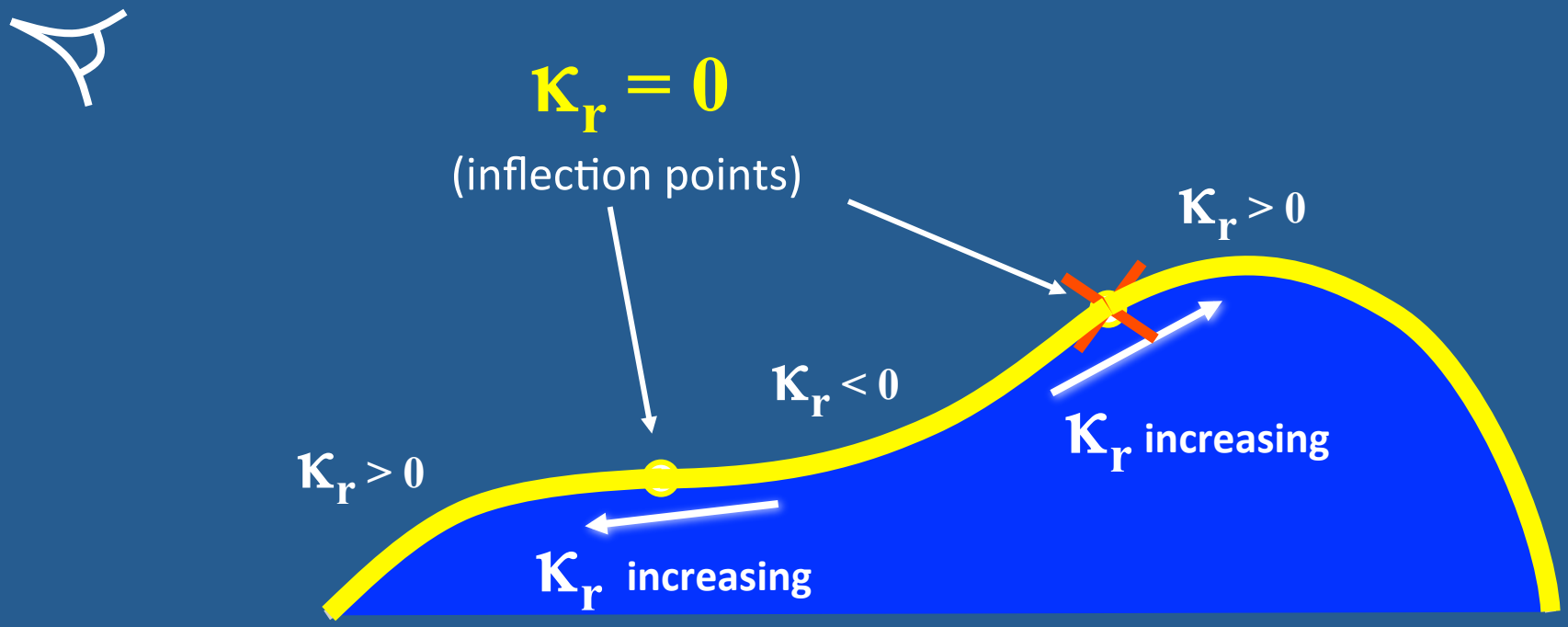
Curvature in projected view direction, w:



– Extension of [Koenderink 84]

Suggestive contours: definition 3

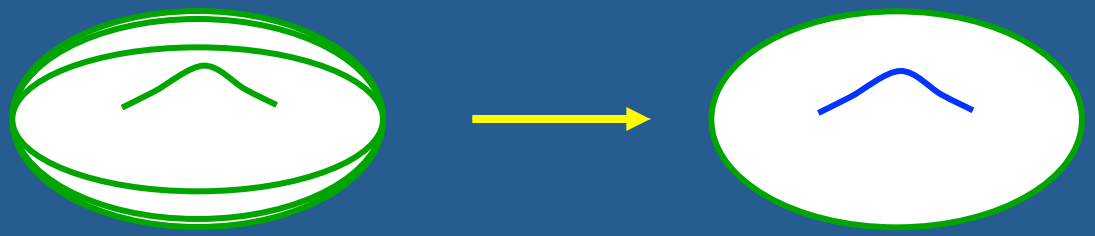
Points where $\kappa_r = 0$ and $D_w \kappa_r > 0$



Qualitative structure

Suggestive contours fall into two categories

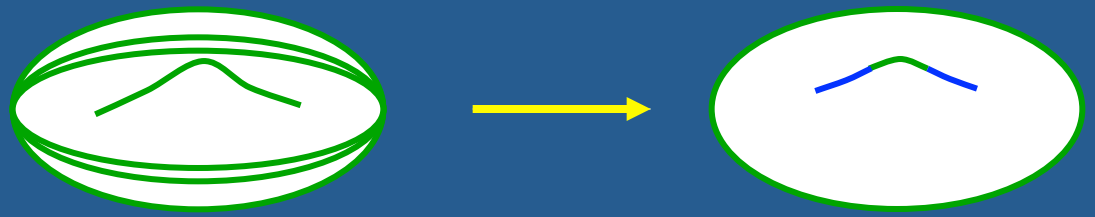
anticipation



contours only

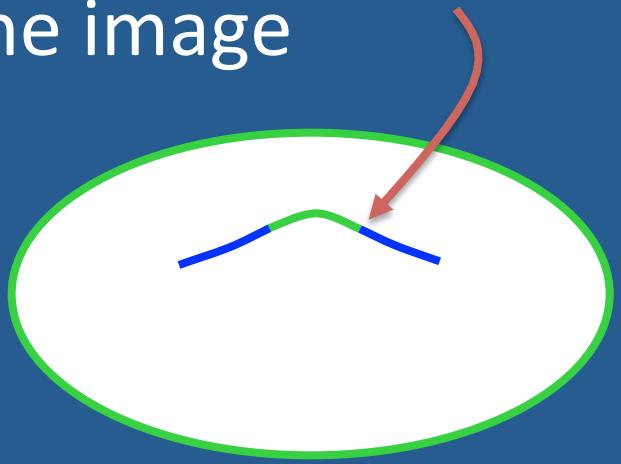
contours + suggestive contours

extension

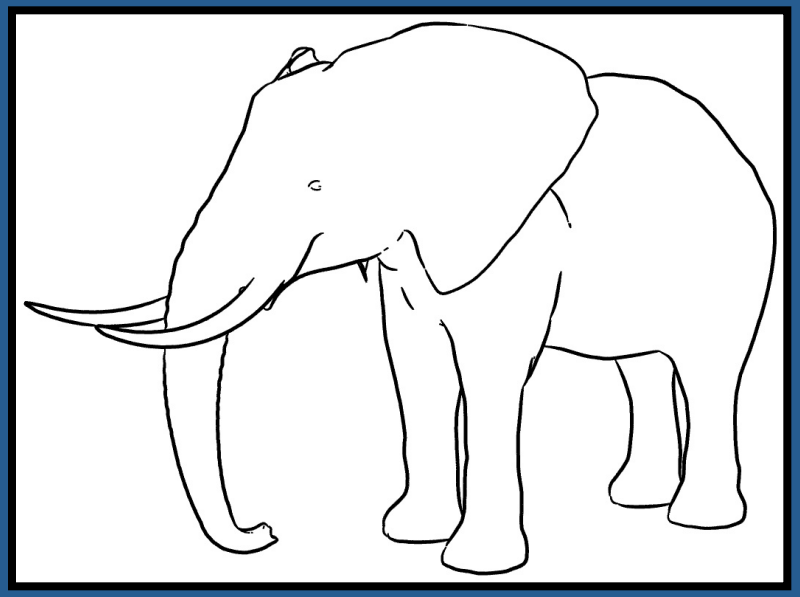


Continuity of extensions

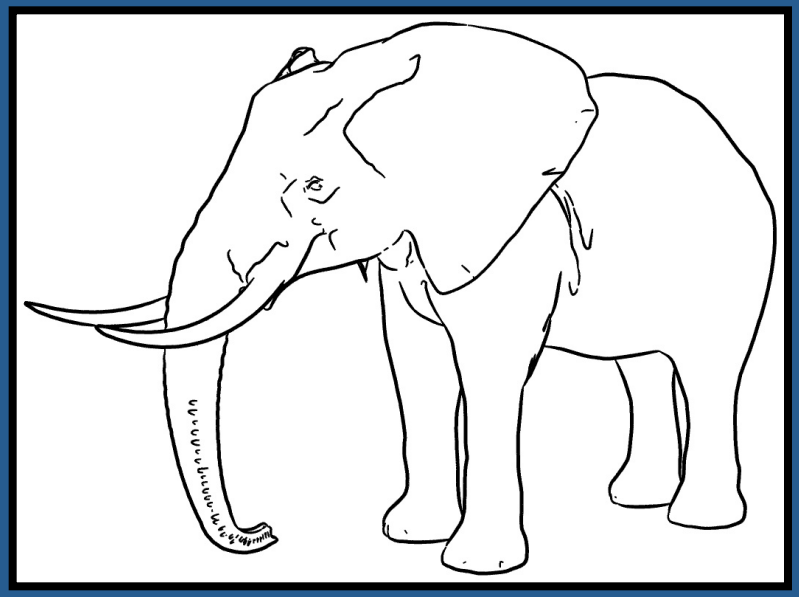
The suggestive contour lines up with the contour in the image



Results…

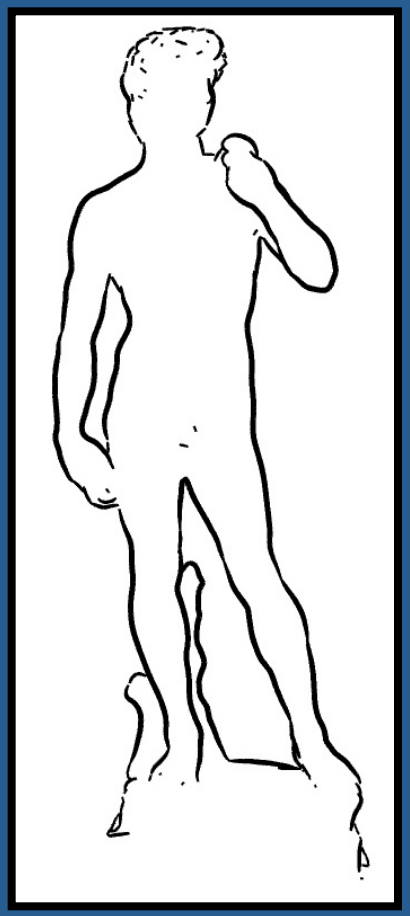


contours

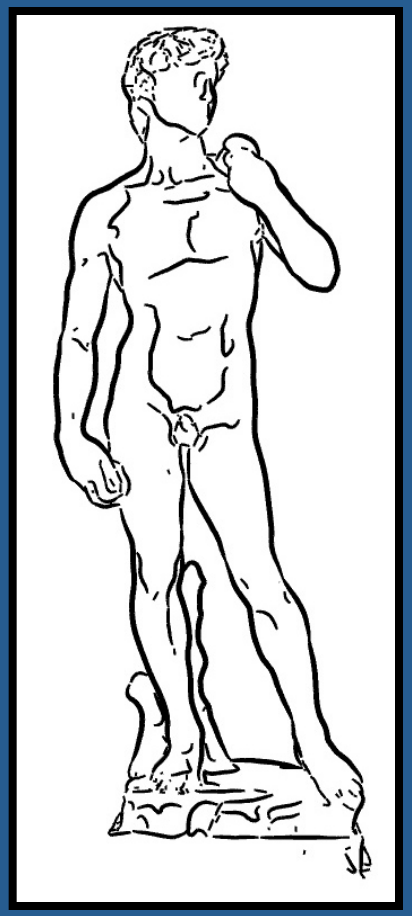


contours
+
suggestive contours

Results…

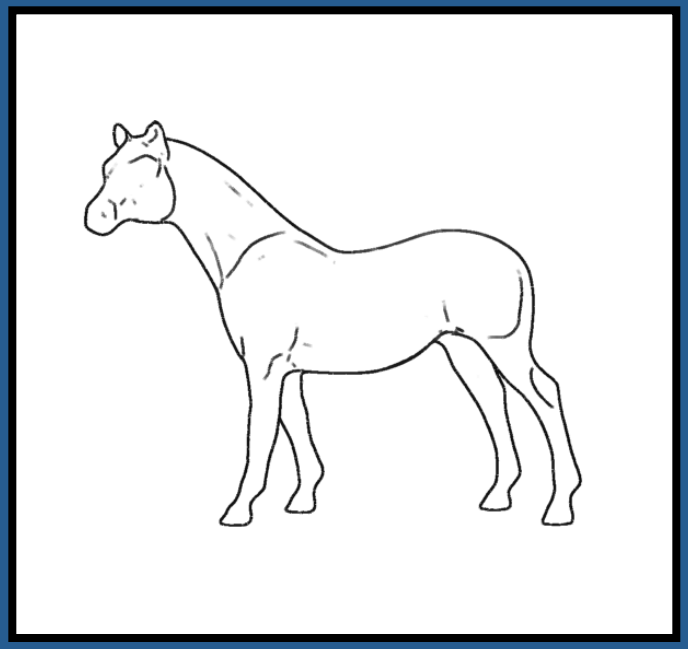


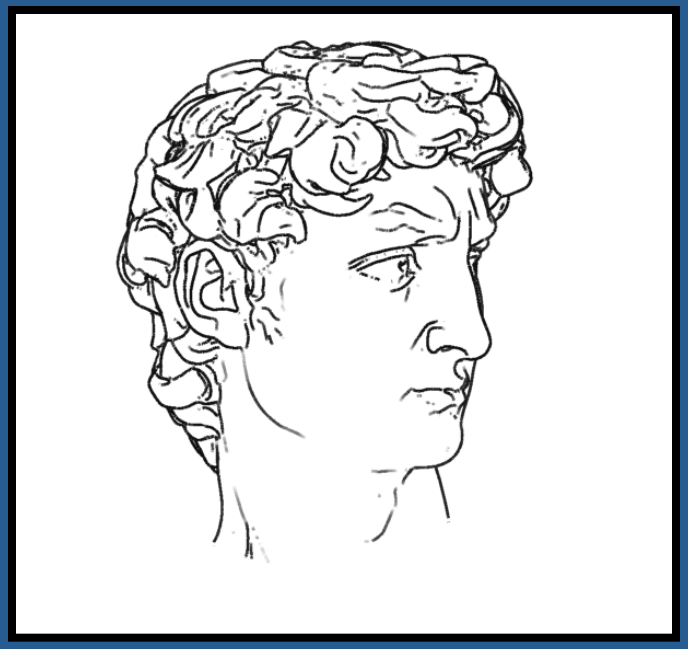
contours



contours
+
suggestive contours

Results…

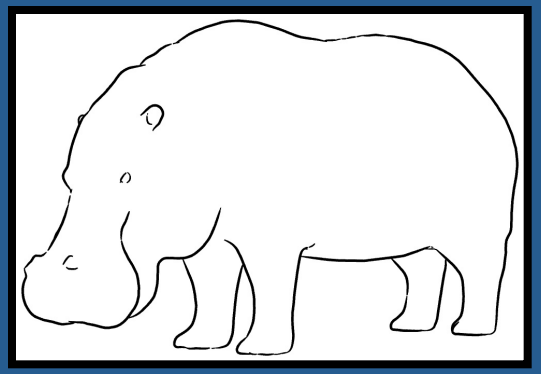




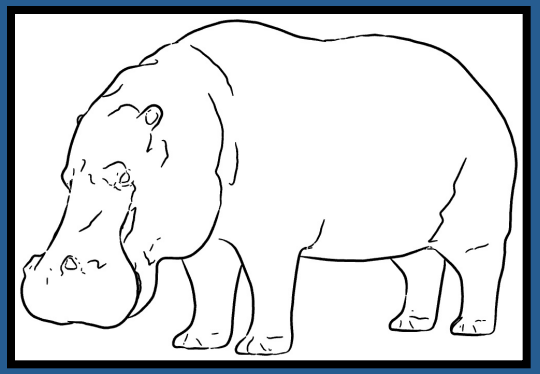
Summary

Suggestive contours:

- new family of lines for NPR
- improve perception of geometry
- naturally complement contours



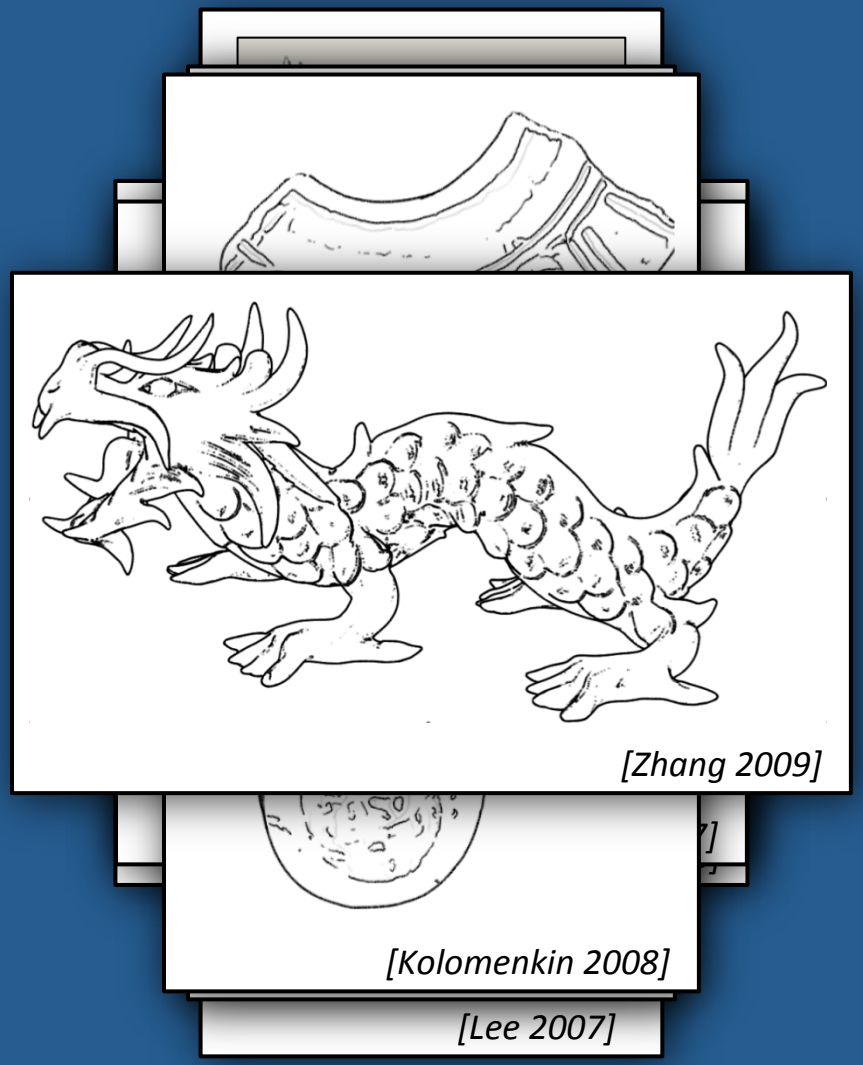
contours



contours + suggestive contours

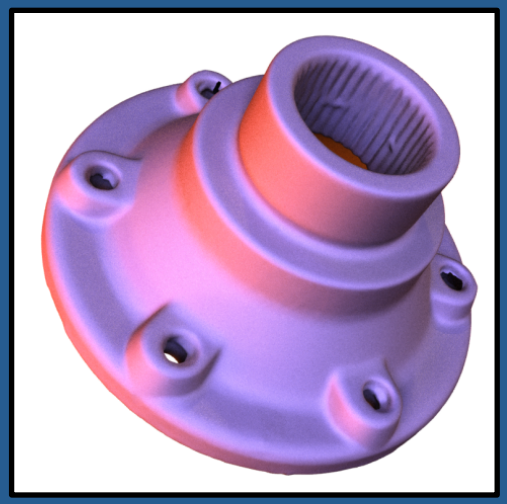
Algorithmic Line Drawing

- Occluding contours
- Ridges and valleys
- Suggestive contours
- Apparent ridges
- Abstracted shading
- Suggestive highlights
- Principal highlights
- Demarcating curves
- Laplacian lines

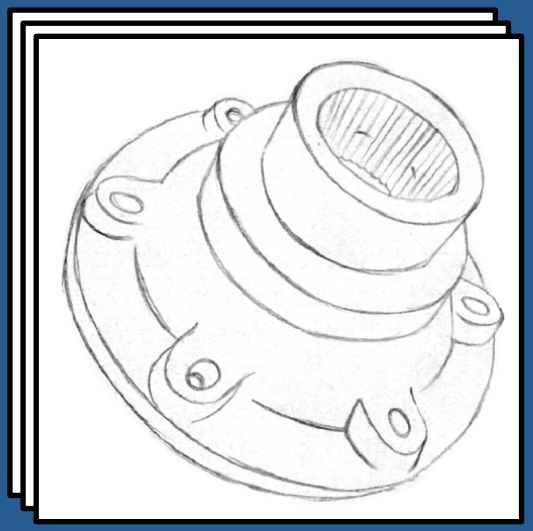


Part 2:
Where Do People Draw Lines?

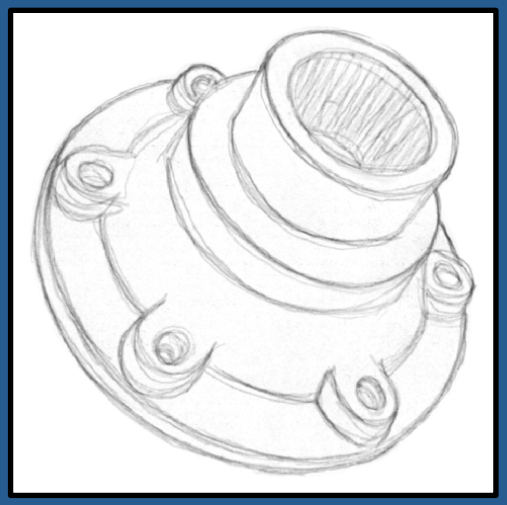
"Where Do People Draw Lines?"
Forrester Cole, Aleksey Golovinsky, Alex Limpaecher, Heather Stoddart Barros, Adam Finkelstein, Thomas Funkhouser, and Szymon Rusinkiewicz
ACM Transactions on Graphics 27(3), (Proc. SIGGRAPH 2008)



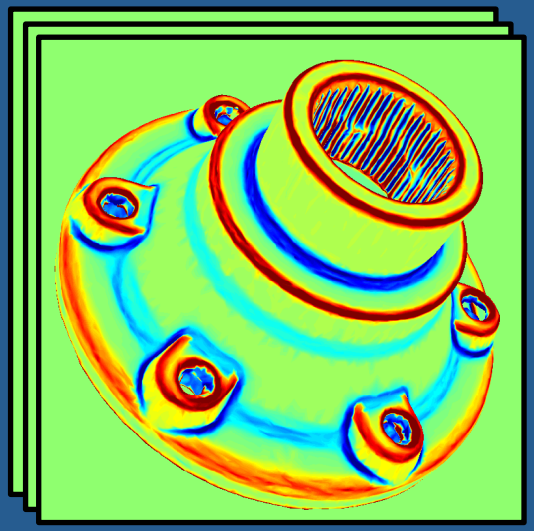
Prompt



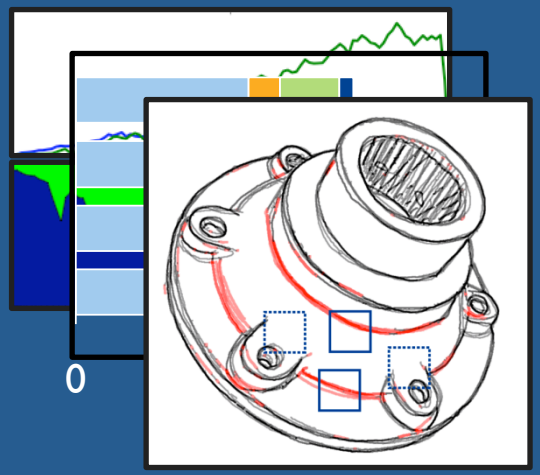
Drawings



Average Drawing



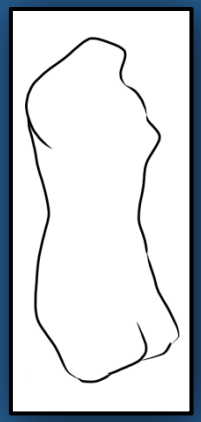
Shape Features



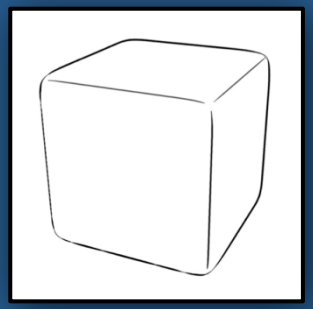
Mathematical Descriptions

Algorithmic Line Drawing

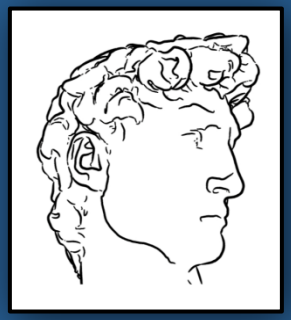
- We investigate four definitions:
  - Occluding Contours [Hertzmann 2000]
  - Geometric Ridges and Valleys [Ohtake 2004]
  - Suggestive Contours [DeCarlo 2003]
  - Apparent Ridges [Judd 2007]



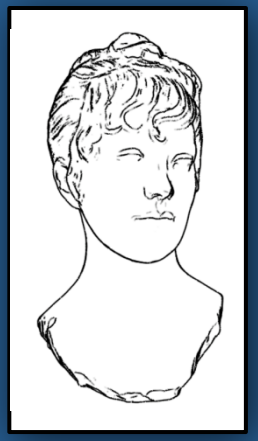
Occluding Contours



Ridges and Valleys

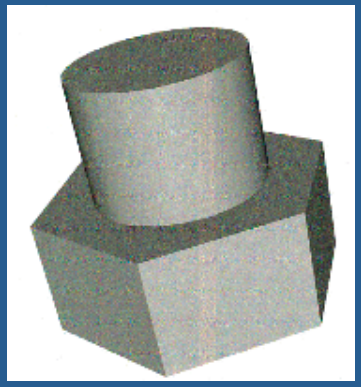


Suggestive Contours

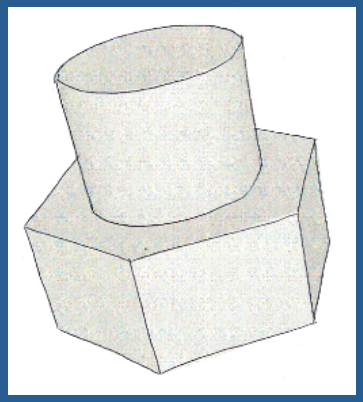


Apparent Ridges

Style: Pure Line Drawing

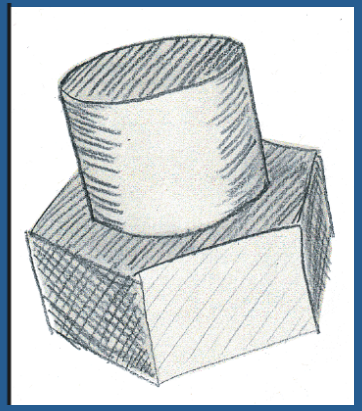


Prompt Image

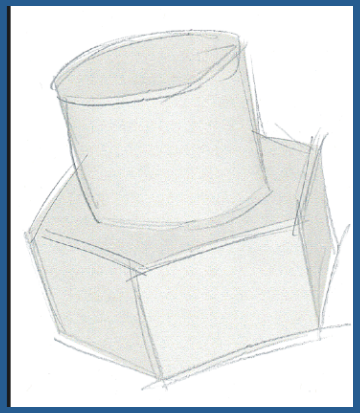


Solid, Smooth Feature Lines

Disallow:



Hatching and Shading

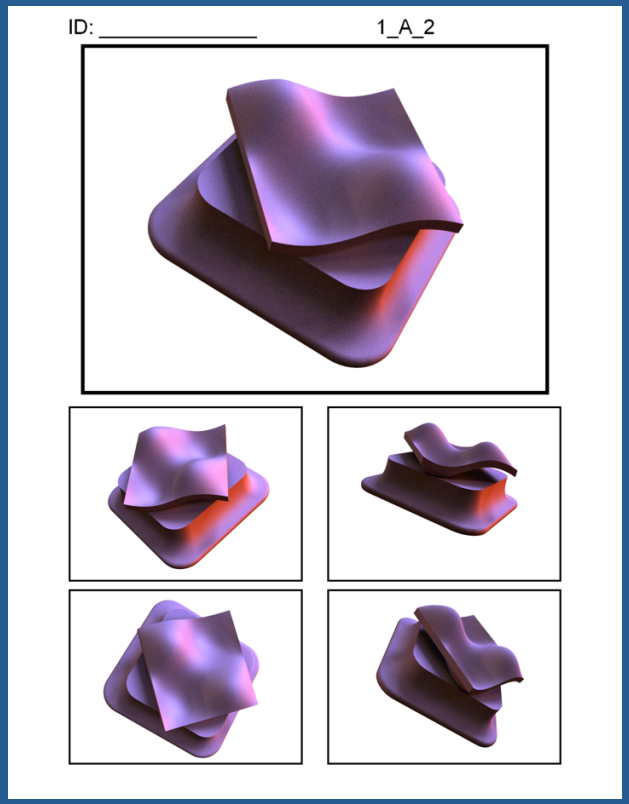


Sketchy Lines

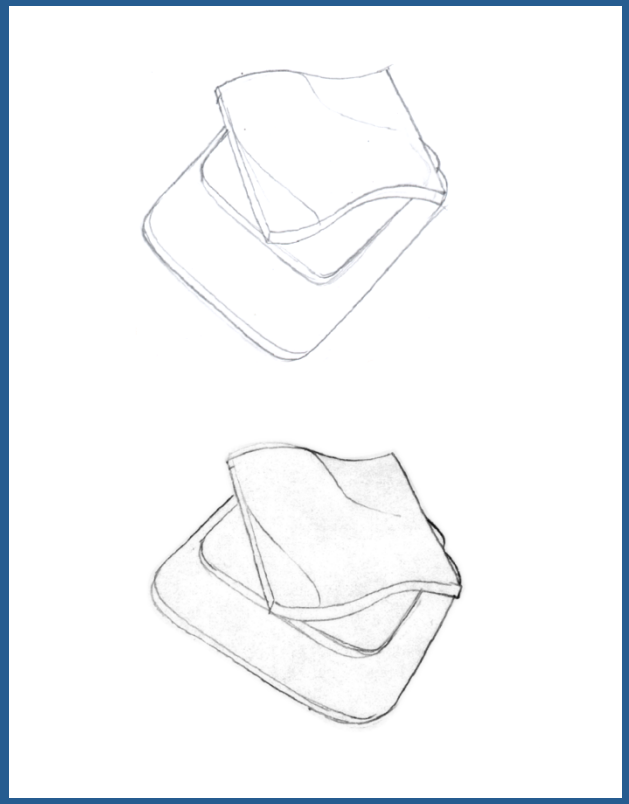
Study Protocol

Steps:

1. Fold
2. Draw
3. Unfold
4. Trace
5. Scan



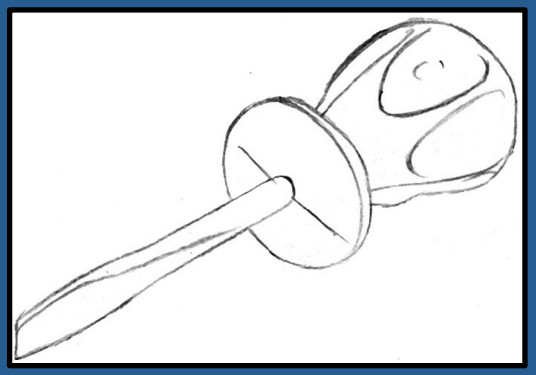
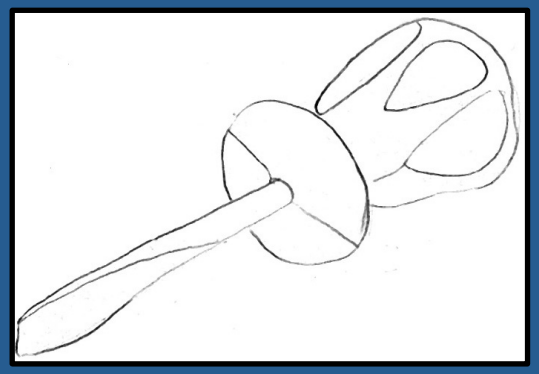
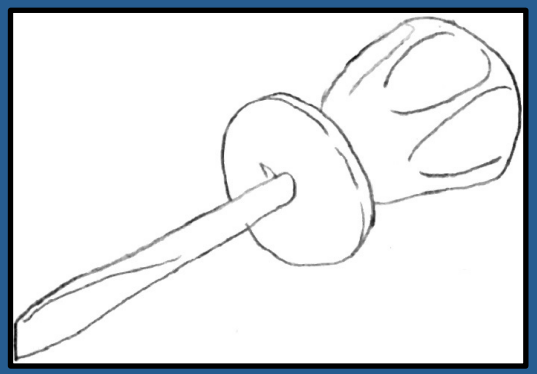
Prompt Page



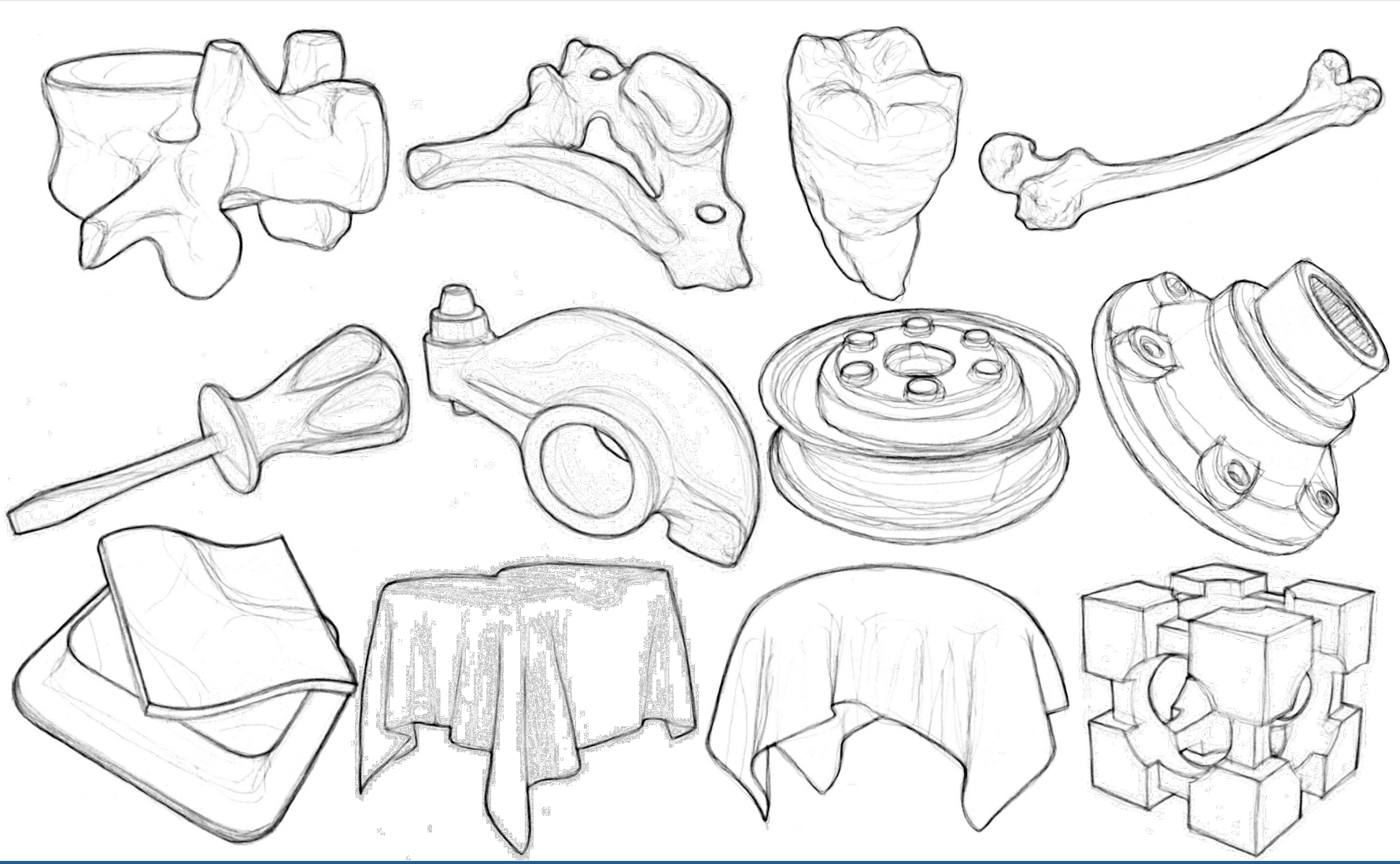
Drawing Page

Collection Results

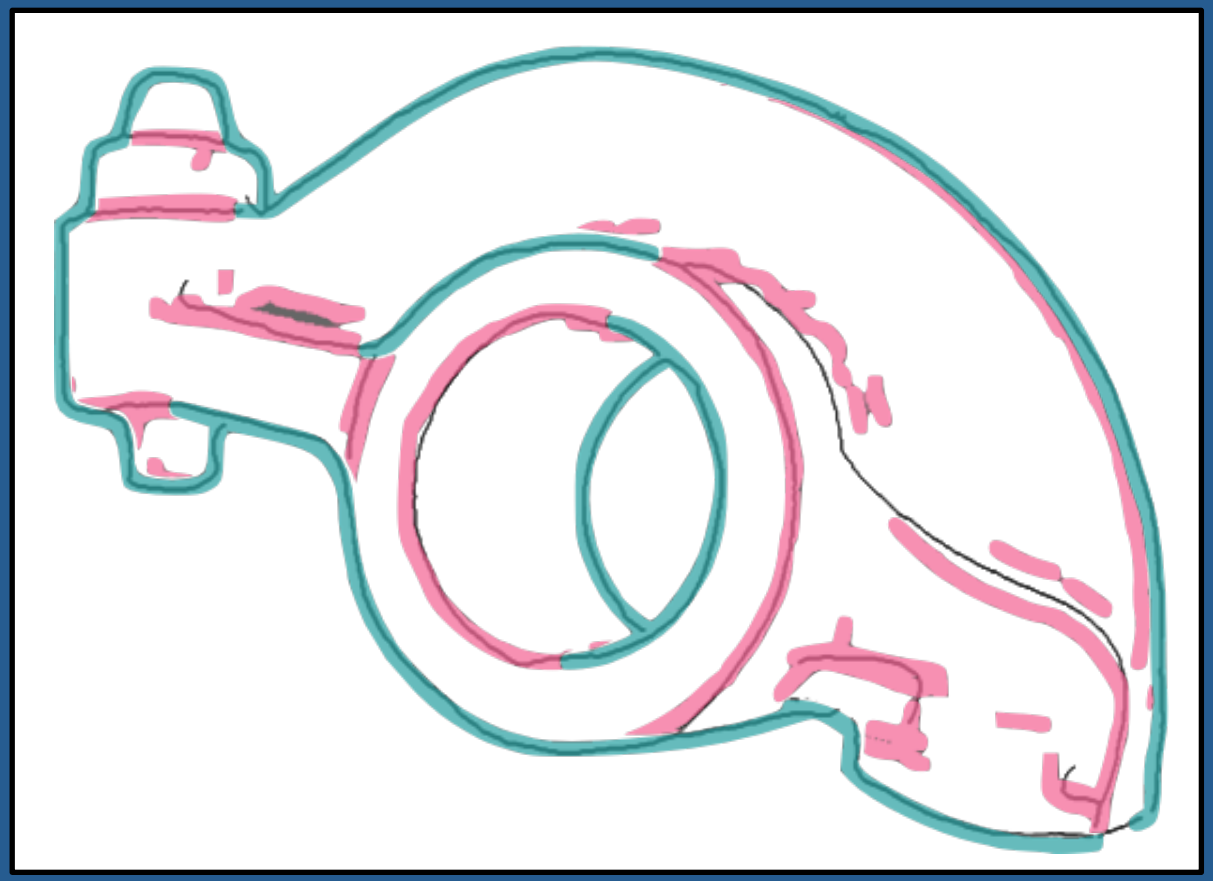
- 29 artists, art students and some professionals
- 208 drawings collected
- 170 “precise” drawings
  - Traced 90% of exterior silhouette within 1mm

Averaged Drawings

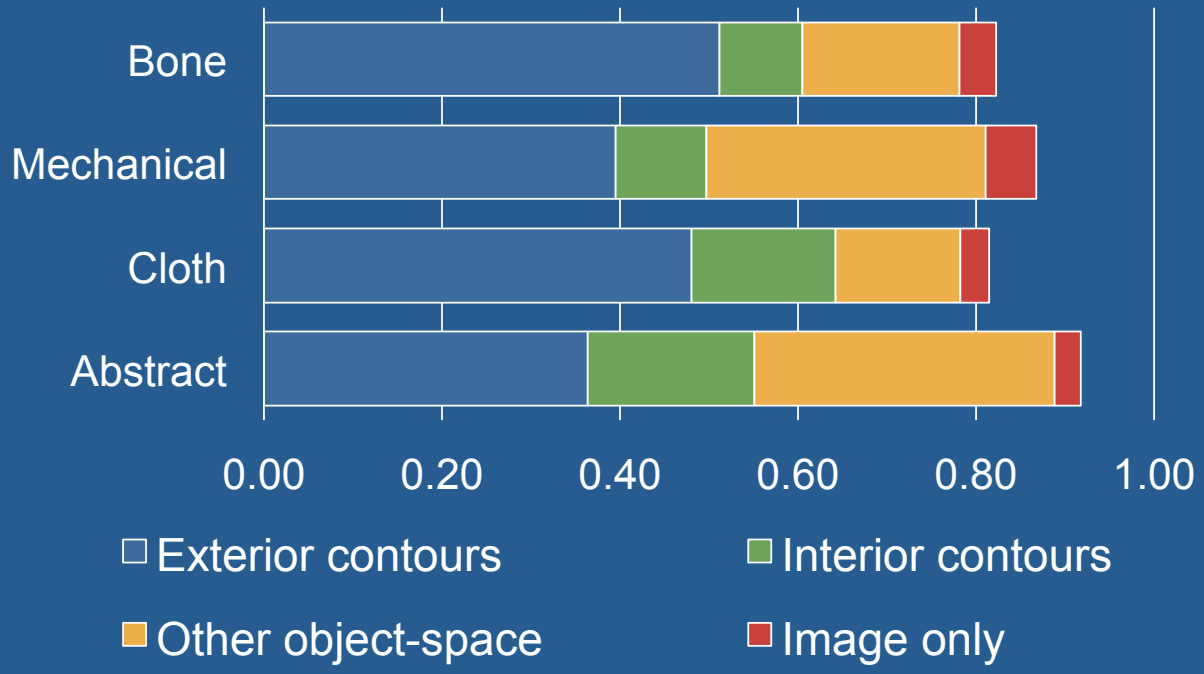


Matching CG Lines



Categorization of Lines

- Contours explain 50-65% of all lines
- Other object-space lines explain 15-30%
- Image features alone explain approx. 5%



Result:

Known definitions explain 80-90% of lines

Other Definitions

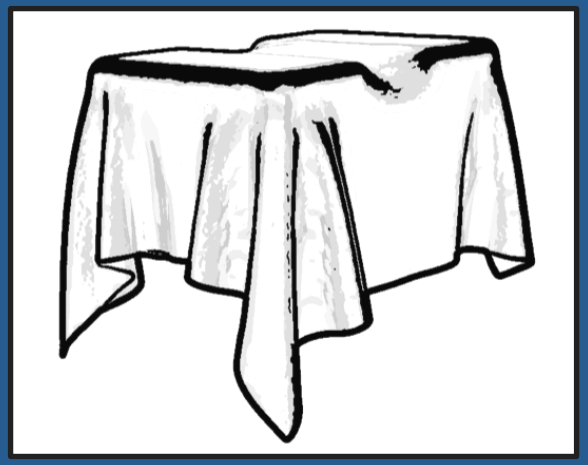
- All CG line def. based on 1-2 local features
- Could we combine more?

Image-Space	Object-Space	
	View-Dependent	View-Independent
`ImgGradMag`	`N·V`	`SurfMaxCurv`
`ImgMaxCurv`	`ViewDepCurv`	`SurfMaxCurvDeriv`
`ImgMinCurv`	`ViewDepCurvDeriv`	`SurfMinCurv`
`ImgLuminance`	`RadialCurv`	`SurfMeanCurv`
	`RadialCurvDeriv`	`SurfGaussianCurv`
	`RadialTorsion`	

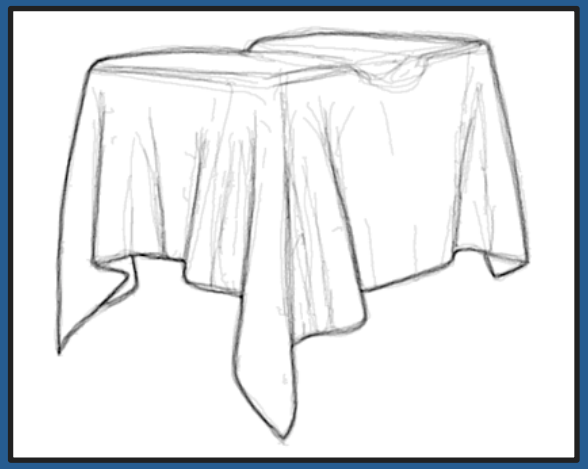
Features in Combination

Regression Tree Model:

```
ImgGradMag> 2433.08
| ImgGradMag> 4706.19
| | 0.181
| | 0.0341
| RadialCurvDeriv> 0.02
| | ViewDepCurvDeriv> 0.044
| | | 0.0455
| | | 0.0175
| | SurfGaussianCurv> -0.004
| | | ViewDepCurv> 0.076
| | | | N dot V > 0.782
| | | | | 0.0113
| | | | | 0.0252
| | | | SurfMaxCurvDeriv> 0.014
| | | | | SurfMinCurv> 0.022
| | | | | | 0.0044
| | | | | | 0.0125
| | | | | 0.0023
...
```



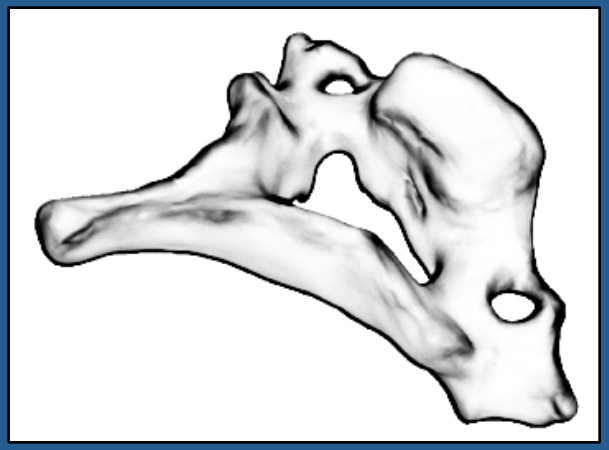
Predicted Probability



Artists' Average

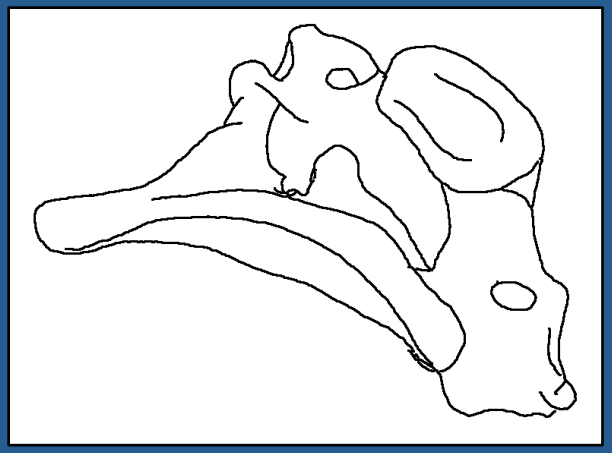
Synthesis Algorithm?

Find ridges in probability image



Probability Image

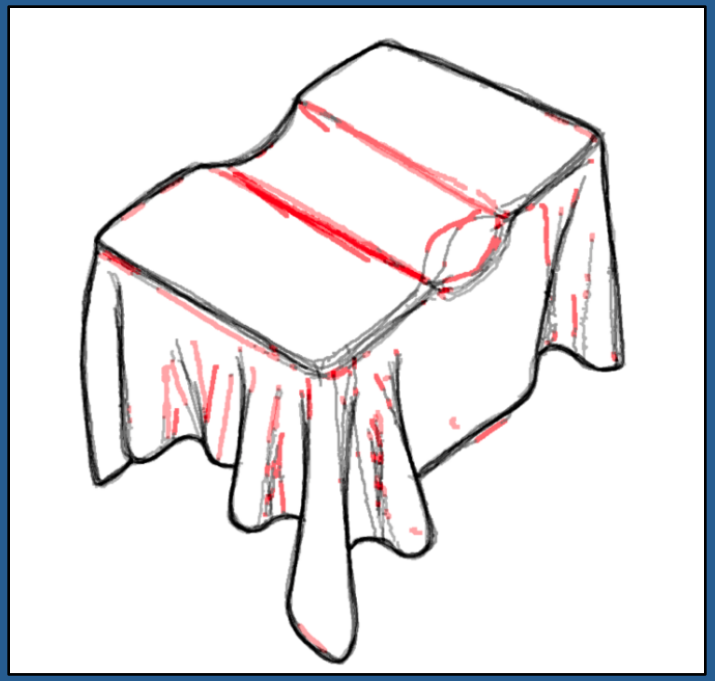
Synthesized Drawing

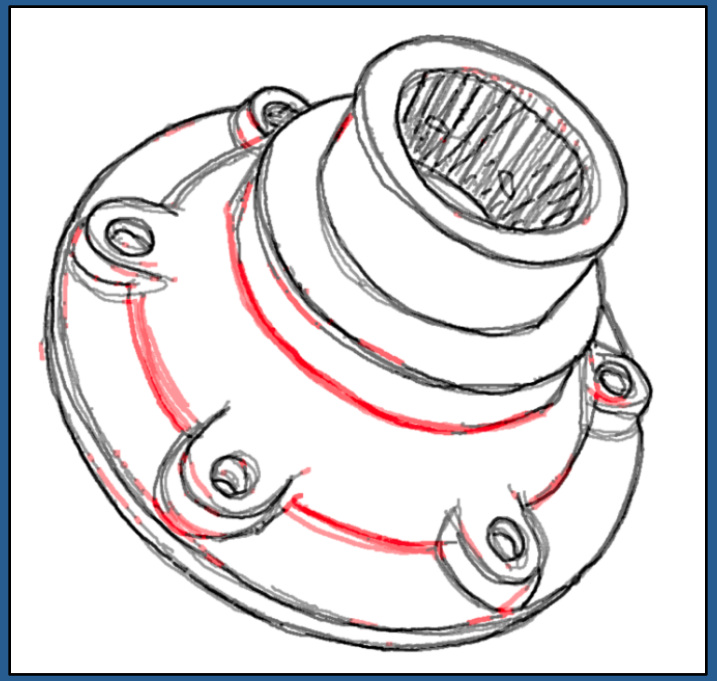


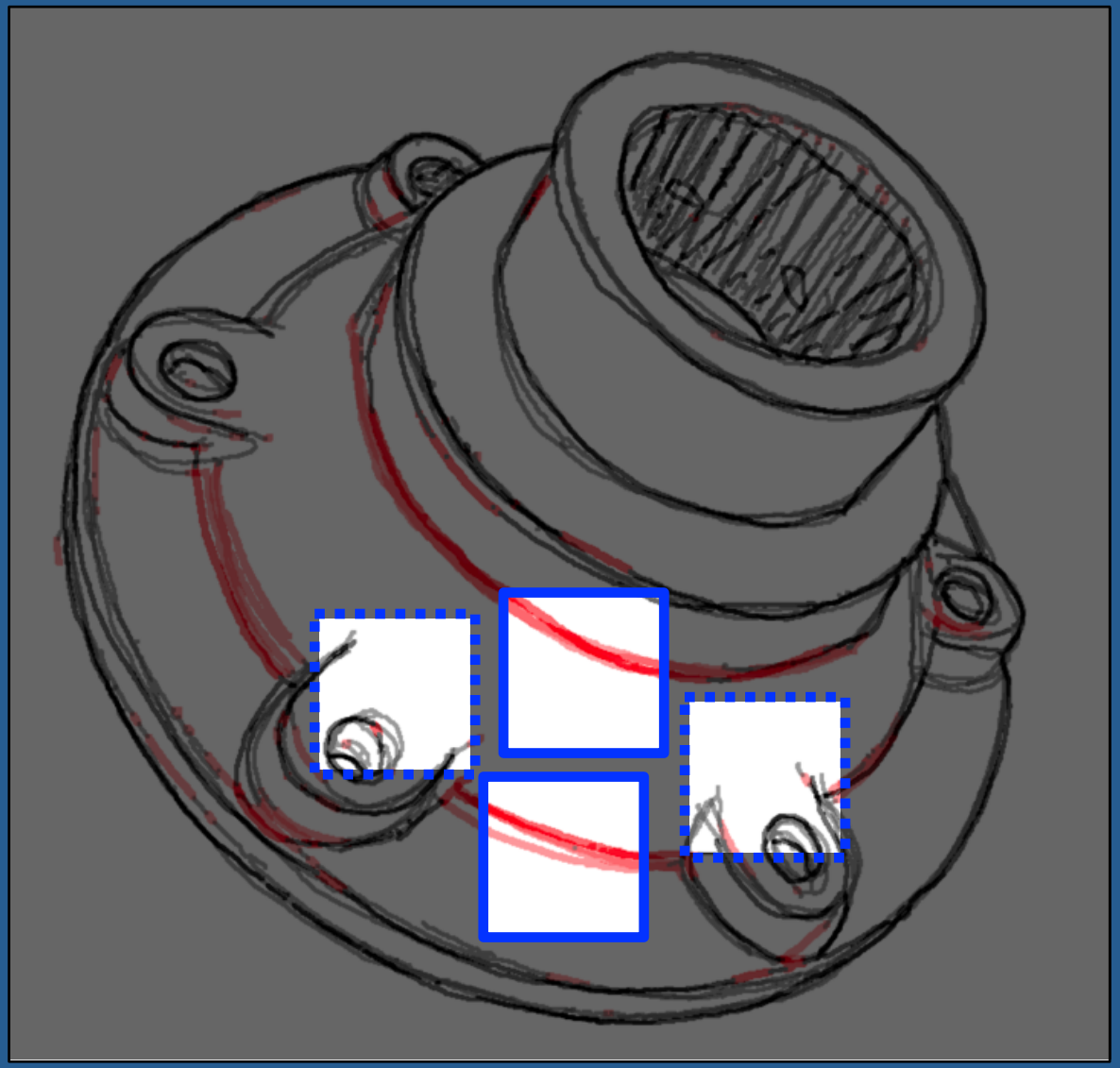
Artist's Drawing

Unexplained Lines

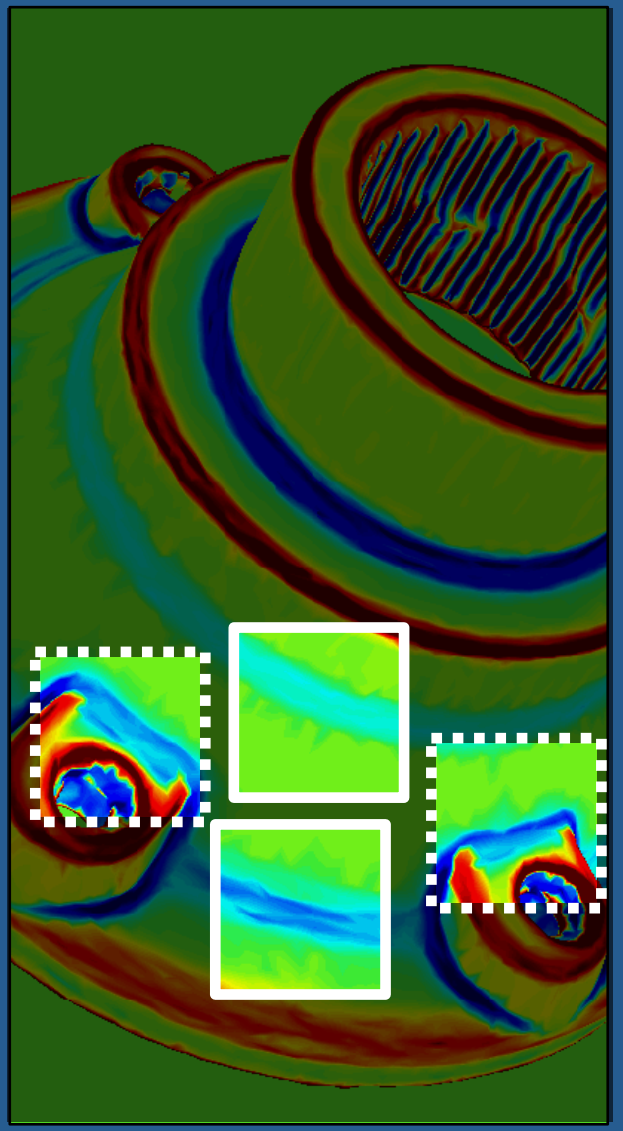
10-20% unexplained for reasonable thresholds





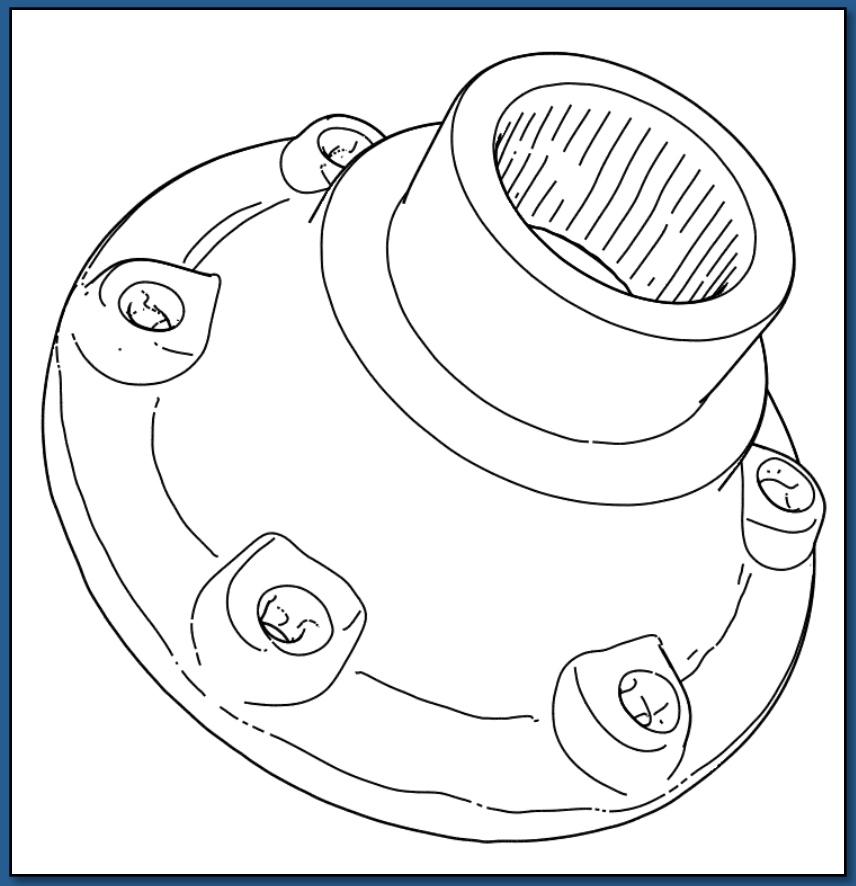


Composite Drawing

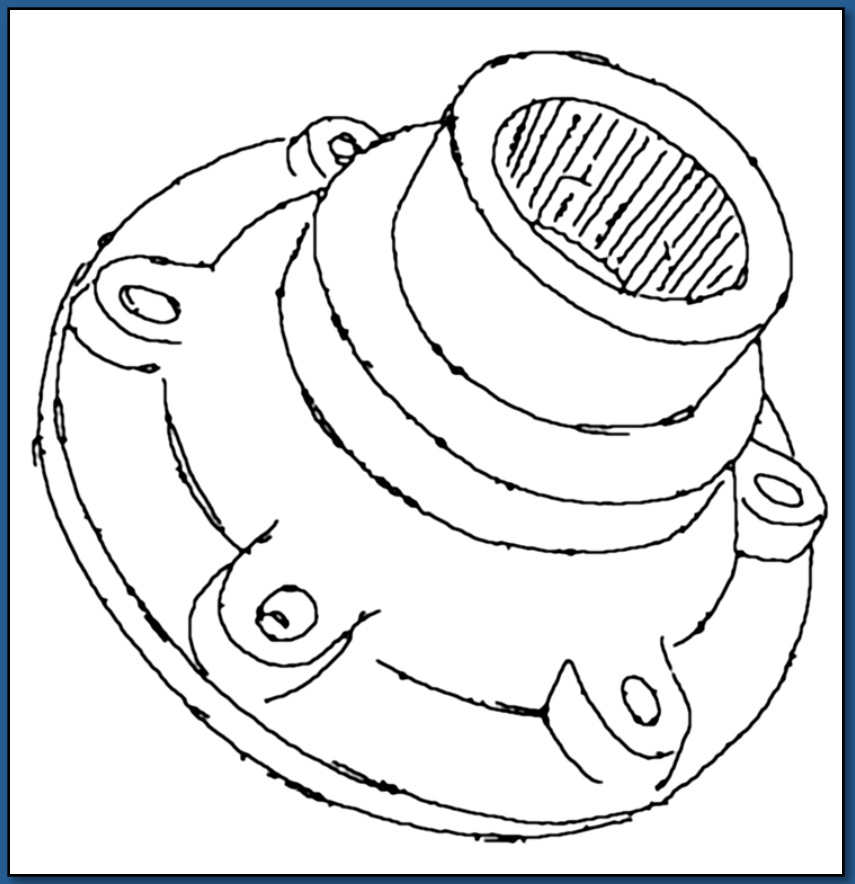


Maximum Curvature

Does it matter?



Ridges and Valleys



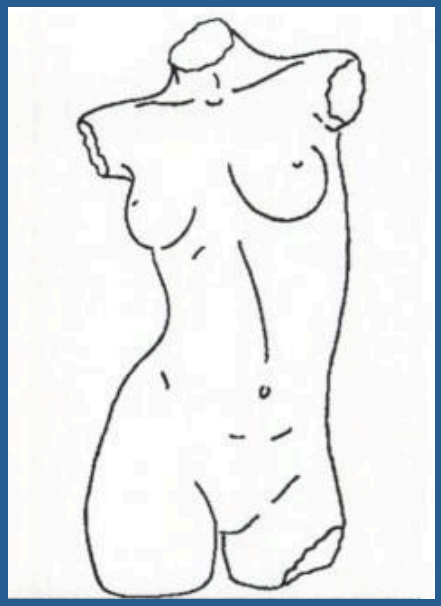
Artist's Drawing

Part 3:
How Well Do Line Drawings Depict Shape?

"How Well Do Line Drawings Depict Shape?"
Forrester Cole, Kevin Sanik, Doug DeCarlo, Adam Finkelstein,
Thomas Funkhouser, Szymon Rusinkiewicz, Manish Singh
ACM Transactions on Graphics 28(3) (Proc. SIGGRAPH 2009)

Previous Work

- Koenderink [1996] studied single drawing
- Conclusion: perception from drawing almost as good as from photograph



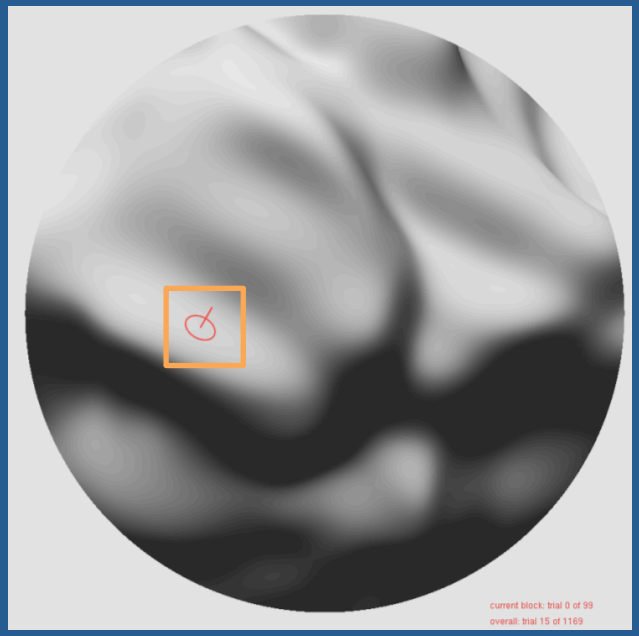
[Koenderink 1996]

Study Goals

- Measure percepts for unfamiliar shapes
- Compare human and CG drawings
- Compare accuracy/precision with ground truth

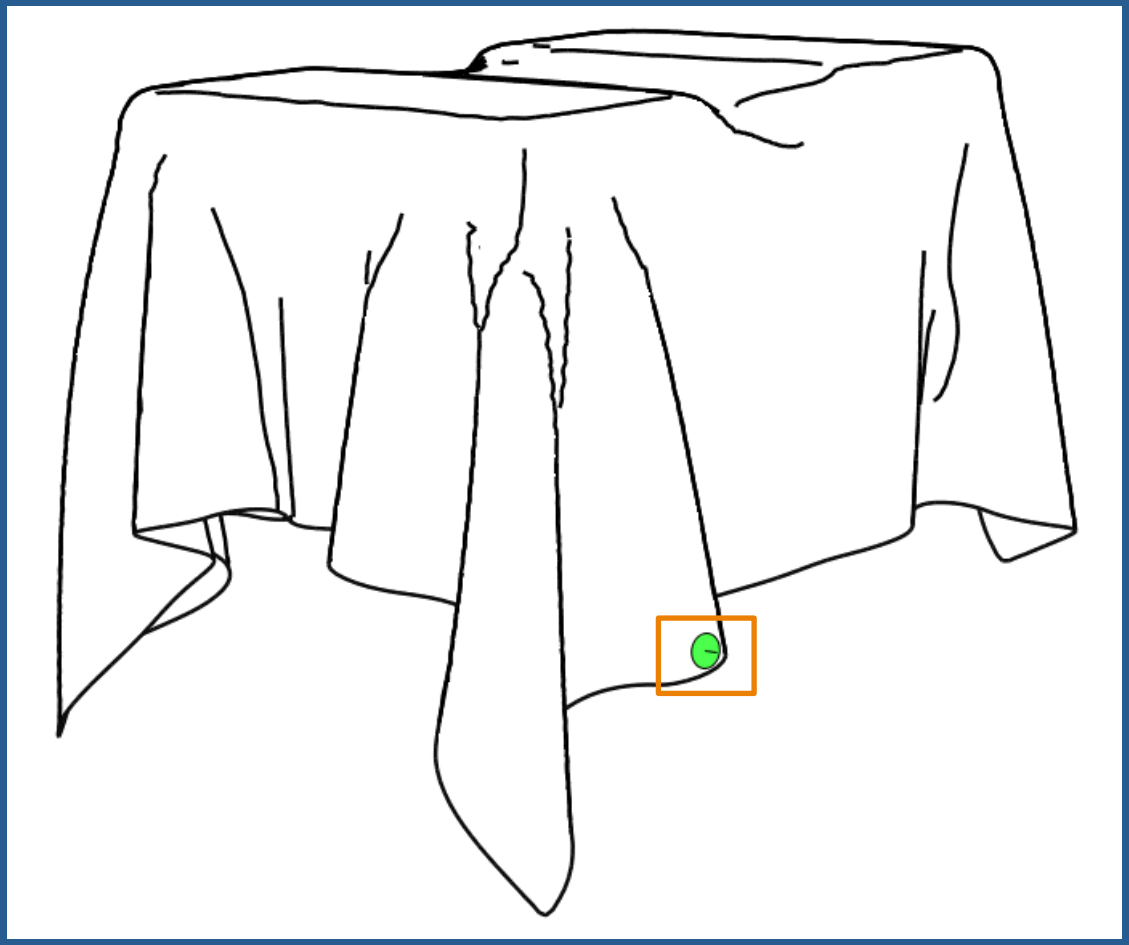
Measuring Shape Perception

- *Gauge figure* due to Koenderink [1992]
- Commonly used to analyze shaded imagery



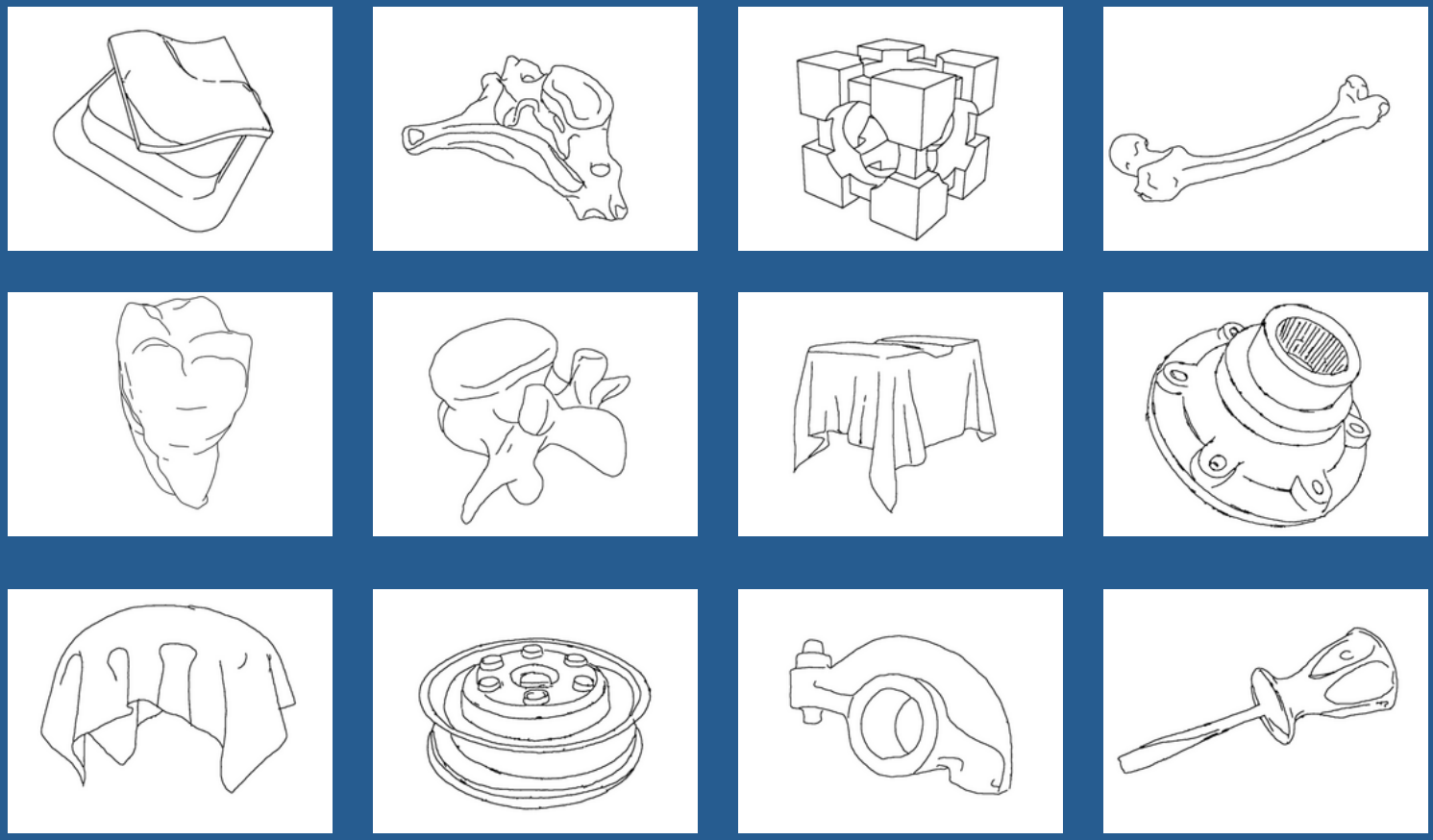
[O'Shea 2008]

Orienting a Gauge



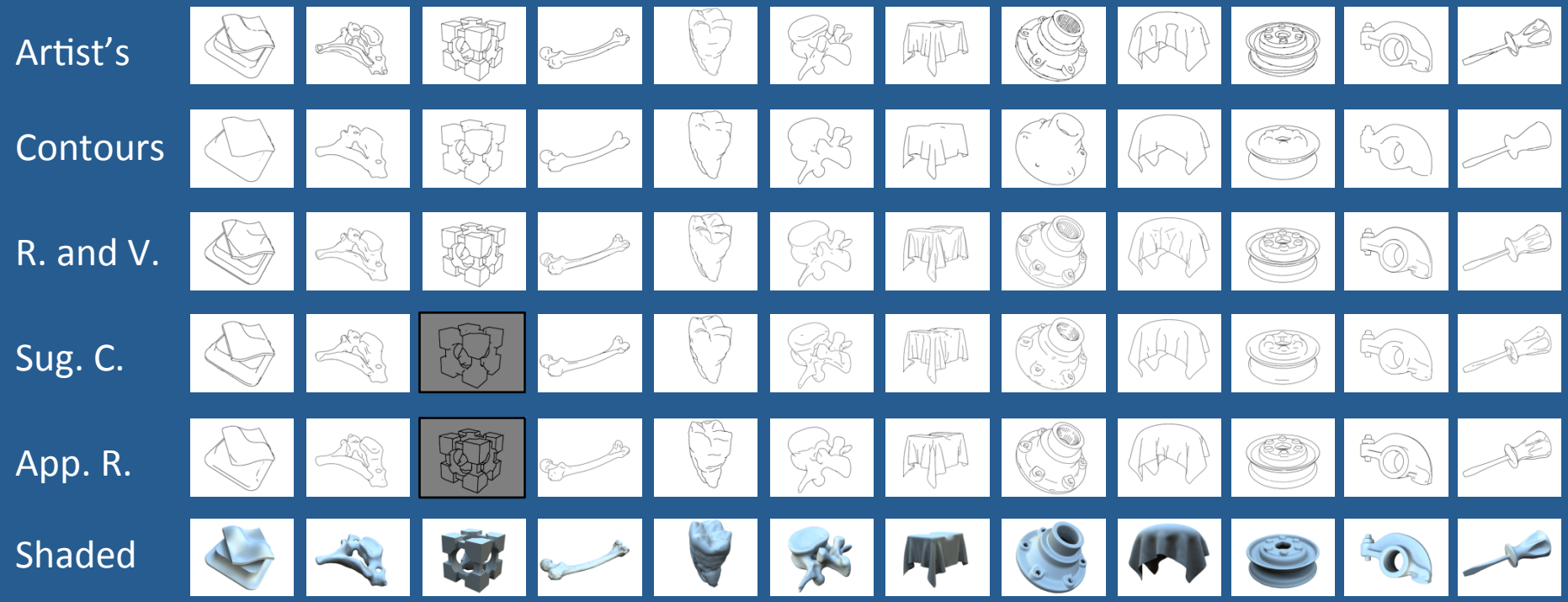
Study Setup

All 12 models from previous study

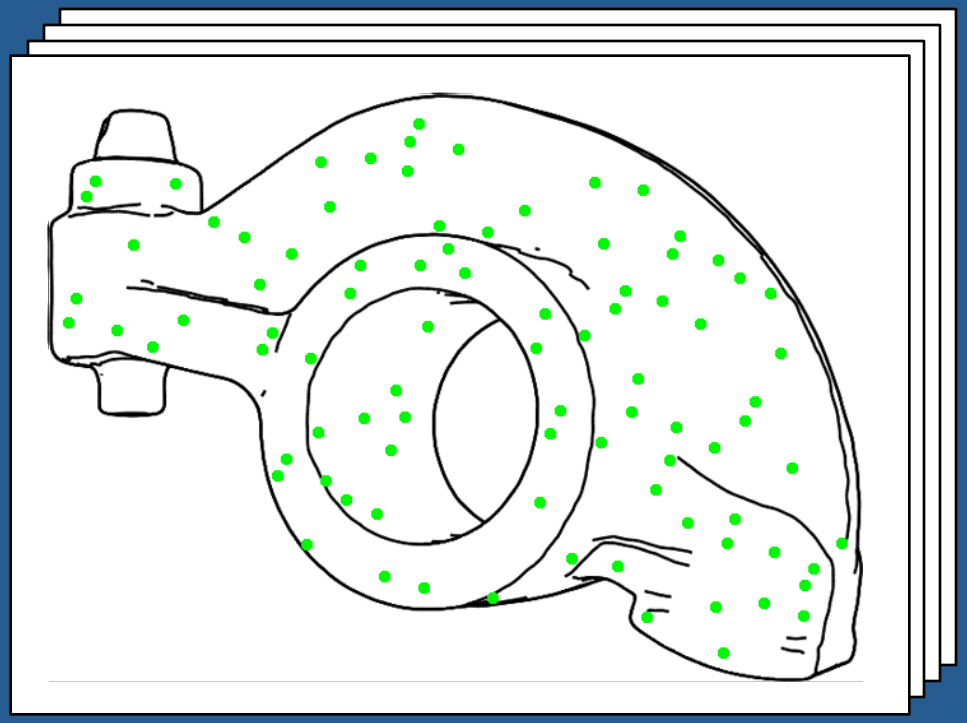


Study Setup

6 styles x 12 models - 2 duplicates = 70 prompts



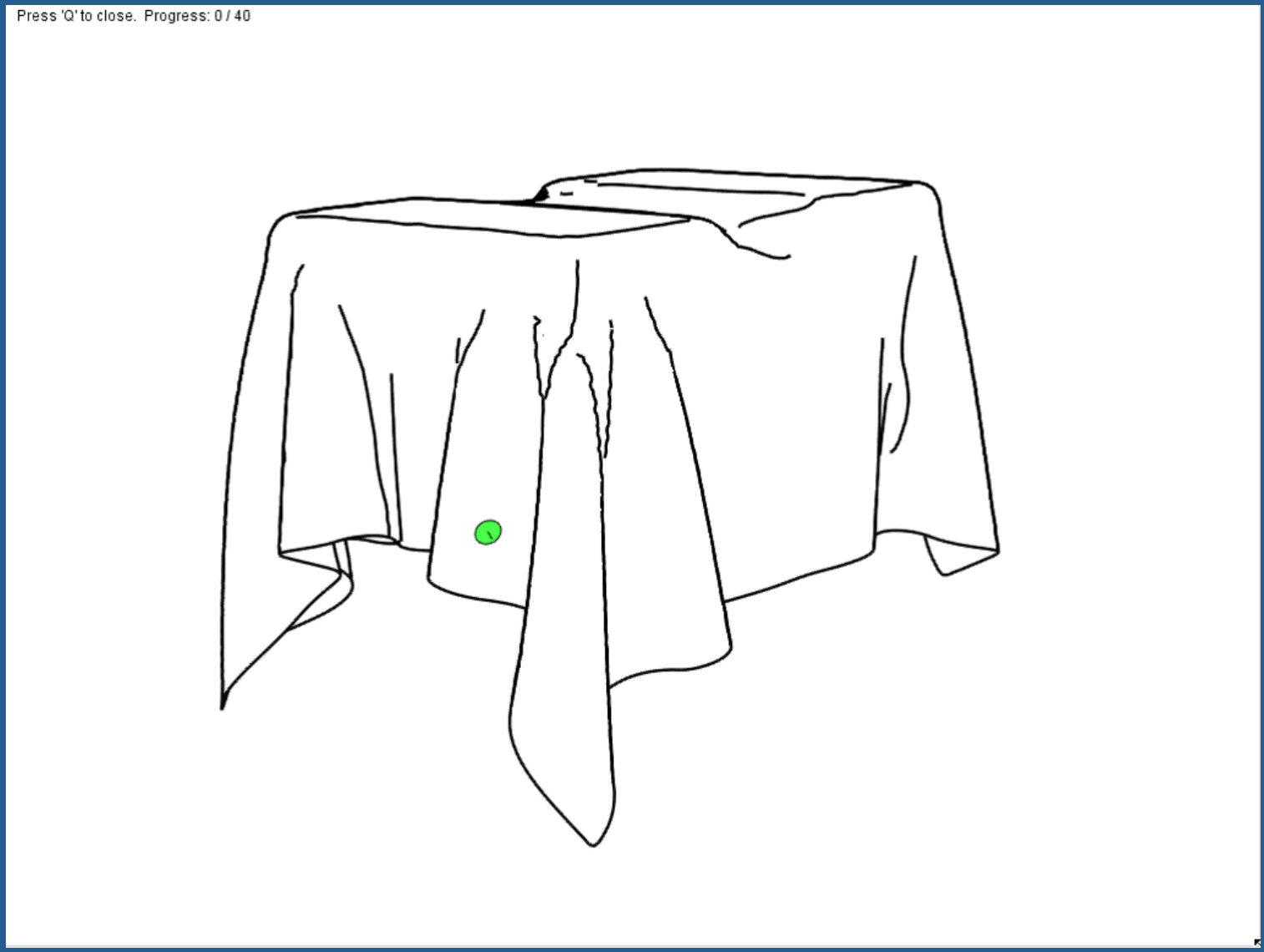
Study Setup



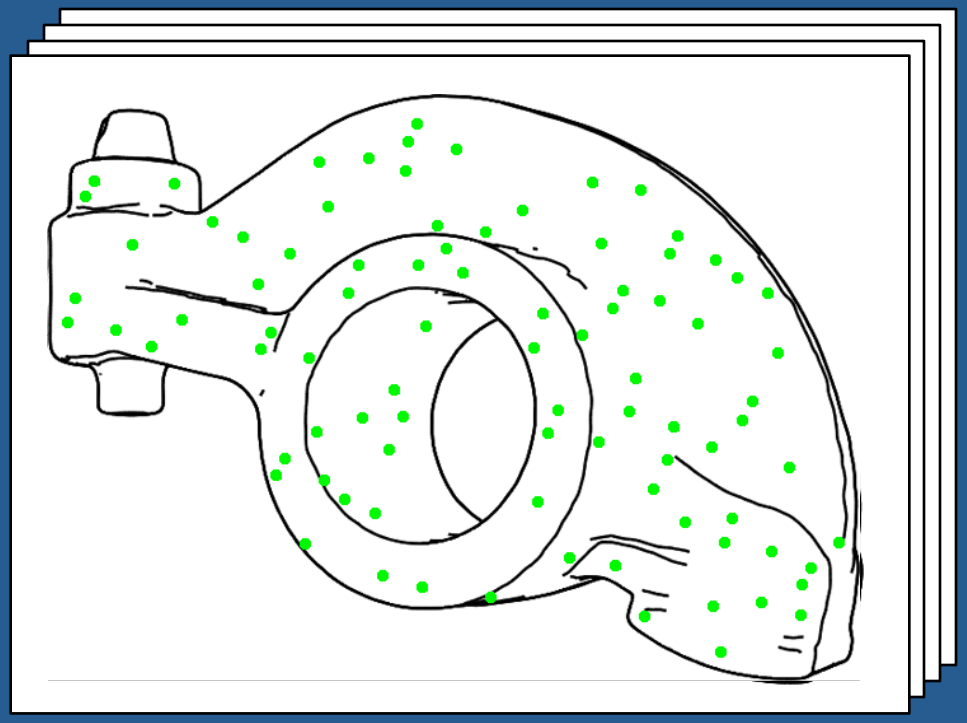
	70	prompts
x	90	gauges / prompt
x	8	opinions / gauge
x	2	settings / opinion

≈ 100,000 settings

Example Session



Study Setup



70 prompts
x 90 gauges / prompt
x 8 opinions / gauge
x 2 settings / opinion

≈ 100,000 settings
x 4 seconds / setting

---

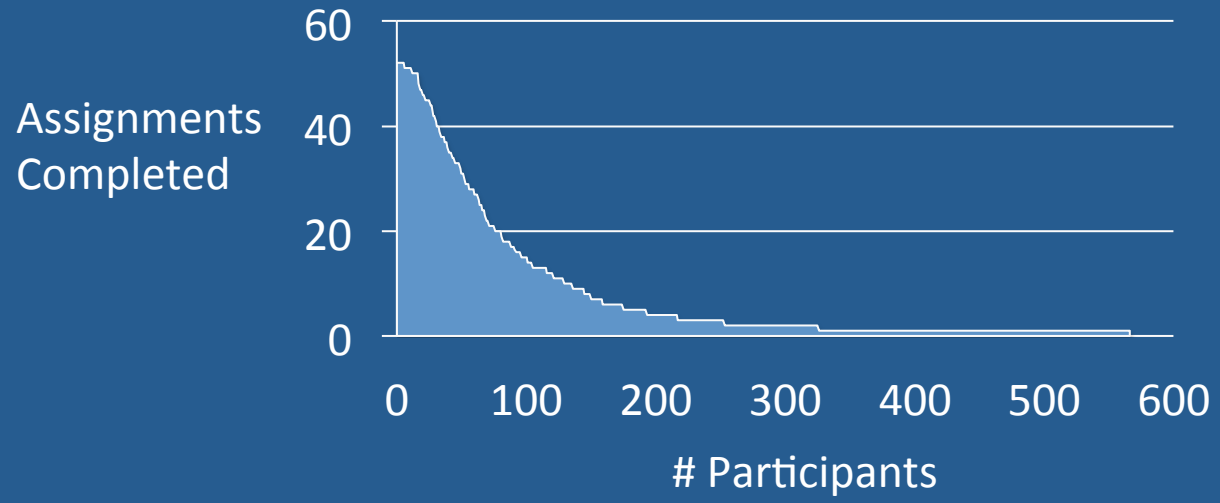
111 hours

So Much Data…

- Mechanical Turk to the rescue!
- Turker sets 60 gauges, gets paid $0.20
- Efficient even after throwing away garbage
  - "Garbage" is inconsistent data
  - About 80% of data is consistent

Data Collection

- 275,000 gauge settings
- 8 models x 90 gauges + 4 models x 180 gauges
- Each gauge 9 to 29 opinions, average 15
- 560 different people
- Most active 20% accounted for 75% of data



We made it this far.

Conclusions

- Most artists' lines explained by CG definitions
- Lines can depict shape as well as shading
- People have similar interpretations of drawings

Thanks

Princeton University

- Forrester Cole
- Thomas Funkhouser
- Aleksey Golovinsky
- Kenrick Kin
- Alex Limpaecher
- Keith Morley
- Szymon Rusinkiewicz

Rutgers University

- Doug DeCarlo
- Kevin Sanik
- Anthony Santella
- Manish Singh

Independent Artist

- Heather Barros