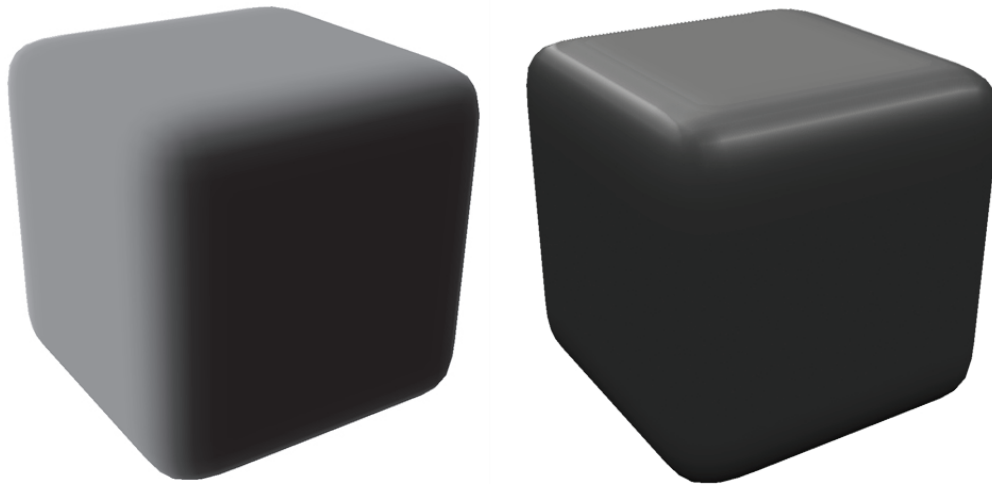


Apparent Ridges for Line Drawing

Tilke Judd, Frédo Durand, Edward Adelson

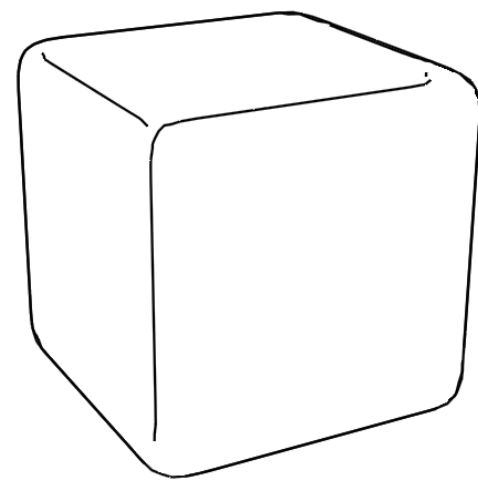
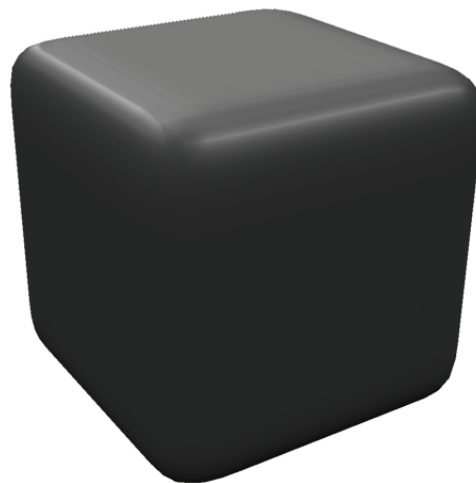
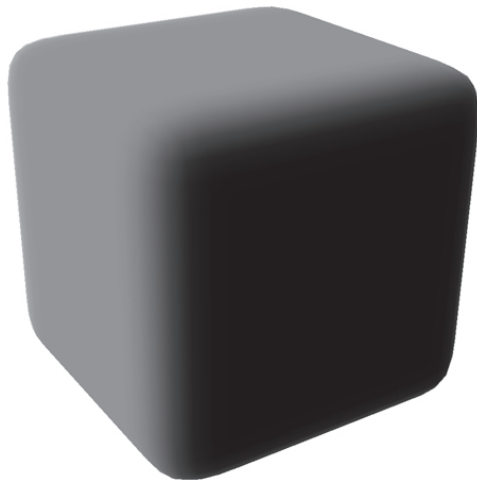
MIT Computer Science Artificial Intelligence Laboratory
MIT Dept of Brain and Cognitive Science Laboratory

Depict a shape



Our Goal

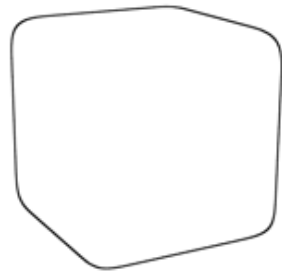
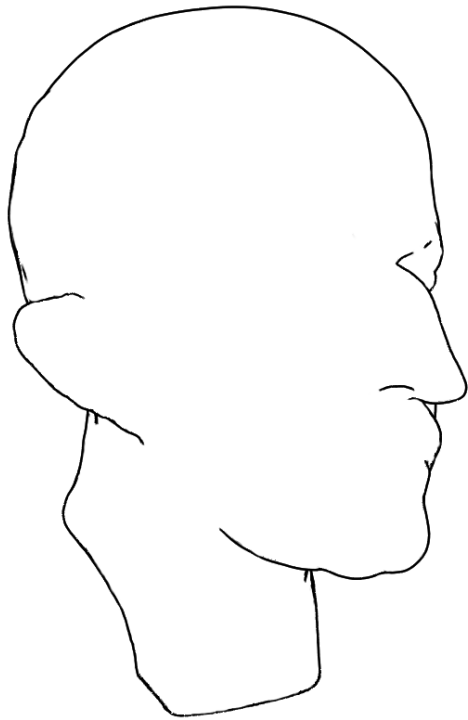
create a line drawing that best conveys an object's shape independent of lighting



Input: 3D model



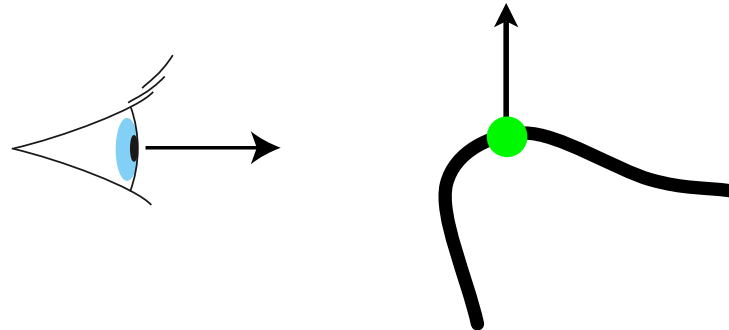
Previous work: Contours



Def: normal \perp view direction

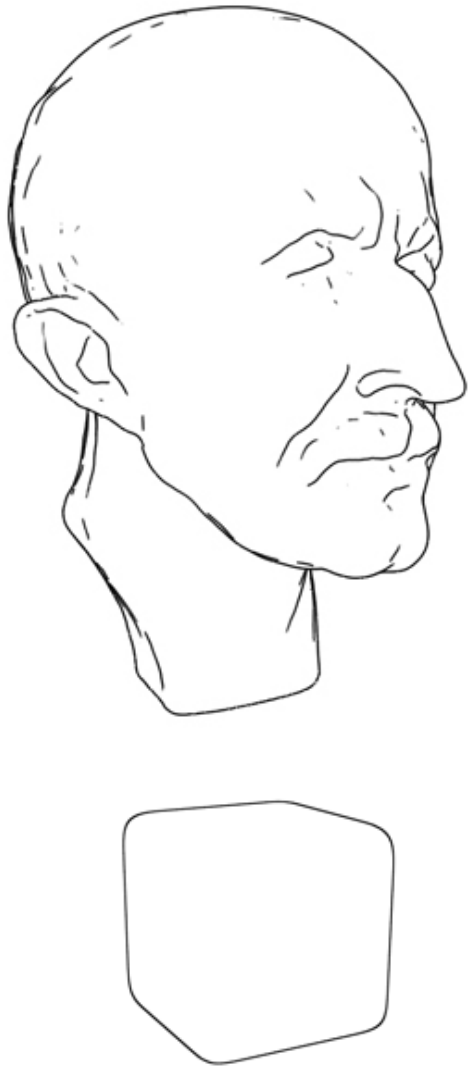
+ view dependent

- **not enough information**



Previous work: Suggestive Contours

[DeCarlo et al. 2003]

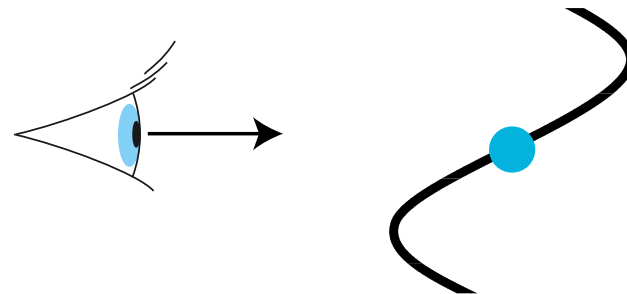


“contours in nearby views”

Def: curvature in view direction=0

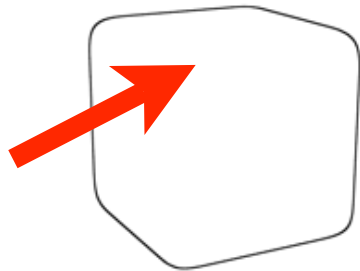
+ view dependent

- **no lines in convex regions**



Previous work: Suggestive Contours

[DeCarlo et al. 2003]

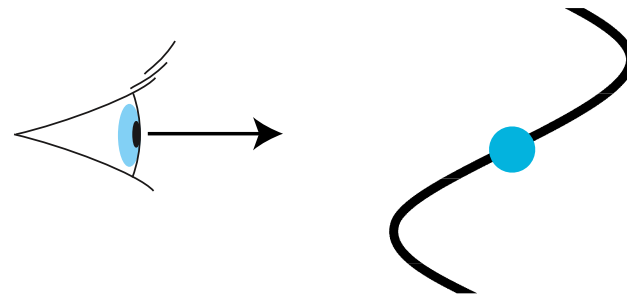


“contours in nearby views”

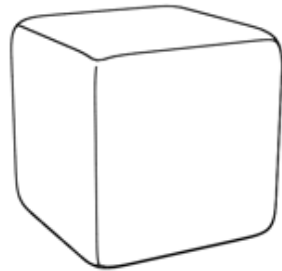
Def: curvature in view direction=0

+ view dependent

- **no lines in convex regions**



Previous work: Ridge & Valleys



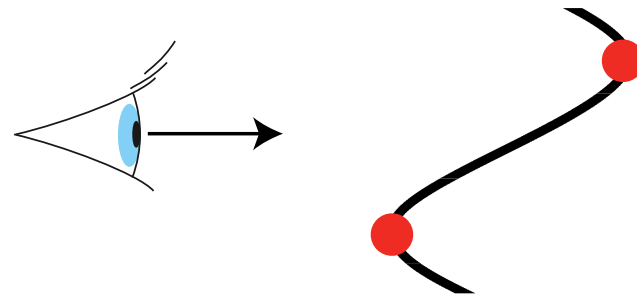
Def: locations of max curvature

+ capture change in normal

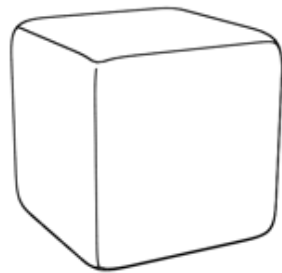
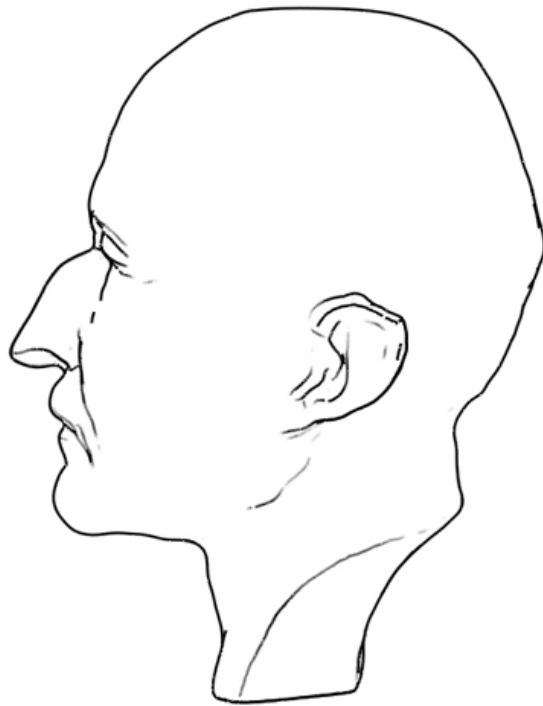
- view *independent*

- locked onto object

- **look overly sharp**



Previous work: Ridge & Valleys



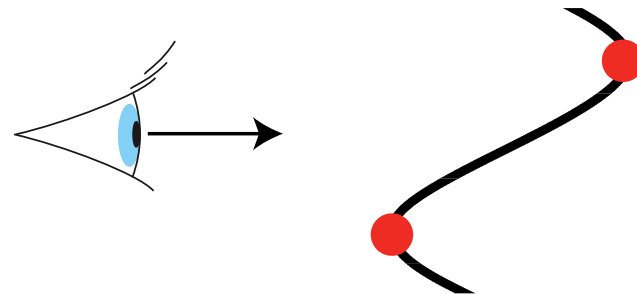
Def: locations of max curvature

+ capture change in normal

- view *independent*

- locked onto object

- **look overly sharp**



An Artist Drawing



includes
ridge- and valley-like lines

does not suggest lighting

Etched illustration for the poem
"La chevelure d'une flamme" by Matisse
copyright 2007 Succession H. Matisse, Paris / Artist Rights Society, New York

An Artist Drawing



includes
ridge- and valley-like lines

does not suggest lighting

=> *It is useful to define ridge-
and valley-like lines which are
illumination independent*

Etched illustration for the poem
"La chevelure d'une flamme" by Matisse
copyright 2007 Succession H. Matisse, Paris / Artist Rights Society, New York

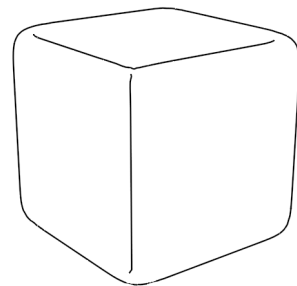
Our new lines: Apparent ridges



View dependent ridge- and valley-like features

Light & material independent

Based on perceptual motivations



Perceptual Motivation

Where to draw lines?

Perceptual Motivation

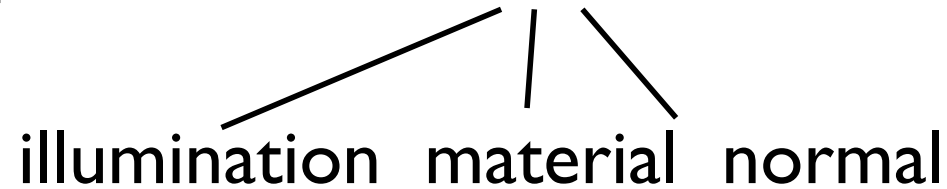
Where to draw lines?

At rapid variation of luminance in image

Perceptual Motivation

Where to draw lines?


At rapid variation of luminance in image



Perceptual Motivation

Where to draw lines?

At rapid variation of luminance in image



illumination material normal

*But we want illumination-
& material-independent lines!*

Perceptual Motivation

Where to draw lines?

At rapid variation of luminance in image

~~illumination~~ ~~material~~ normal

*But we want illumination-
& material-independent lines!*

Perceptual Motivation

Where to draw lines?

At rapid variation of luminance in image


~~illumination~~ ~~material~~ normal

*But we want illumination-
& material-independent lines!*

Perceptual Motivation

Where to draw lines?

At rapid variation of luminance in image

~~illumination~~ ~~material~~ normal

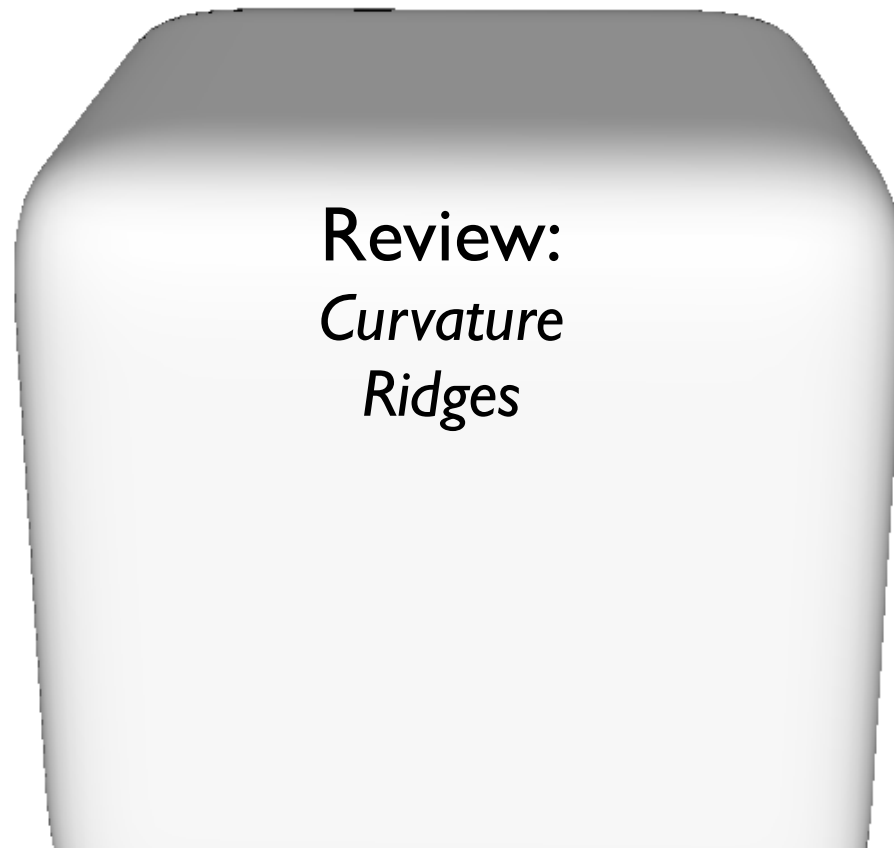
*But we want illumination-
& material-independent lines!*

Draw lines at rapid variation of normal
with respect to the image position

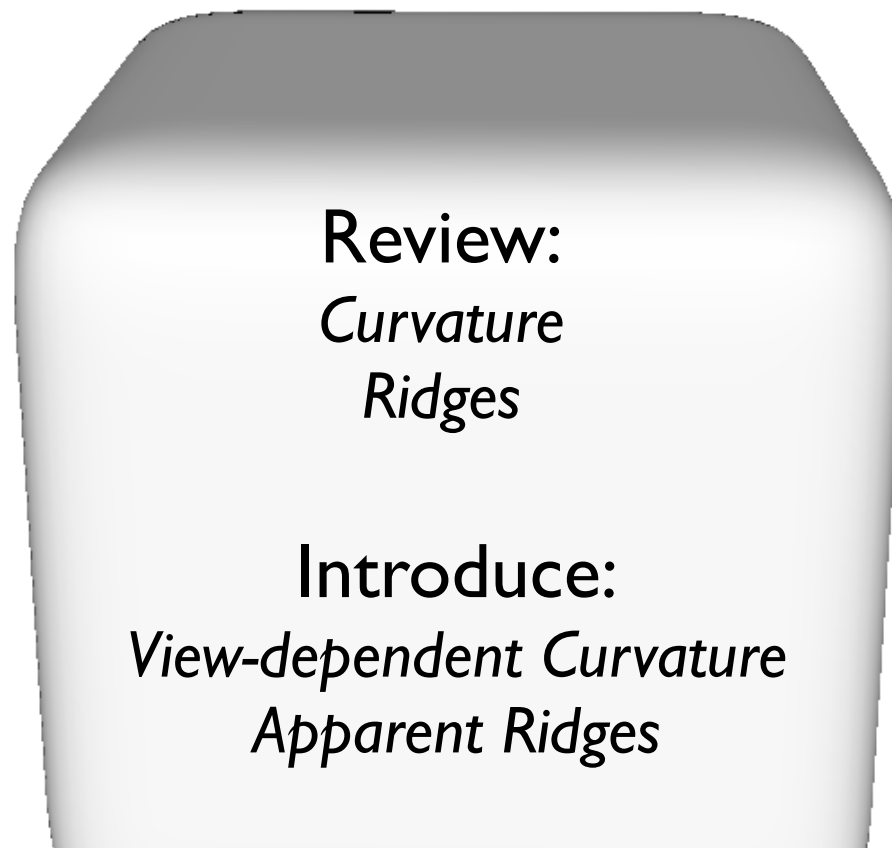
Example on 3D rounded cube



Example on 3D rounded cube



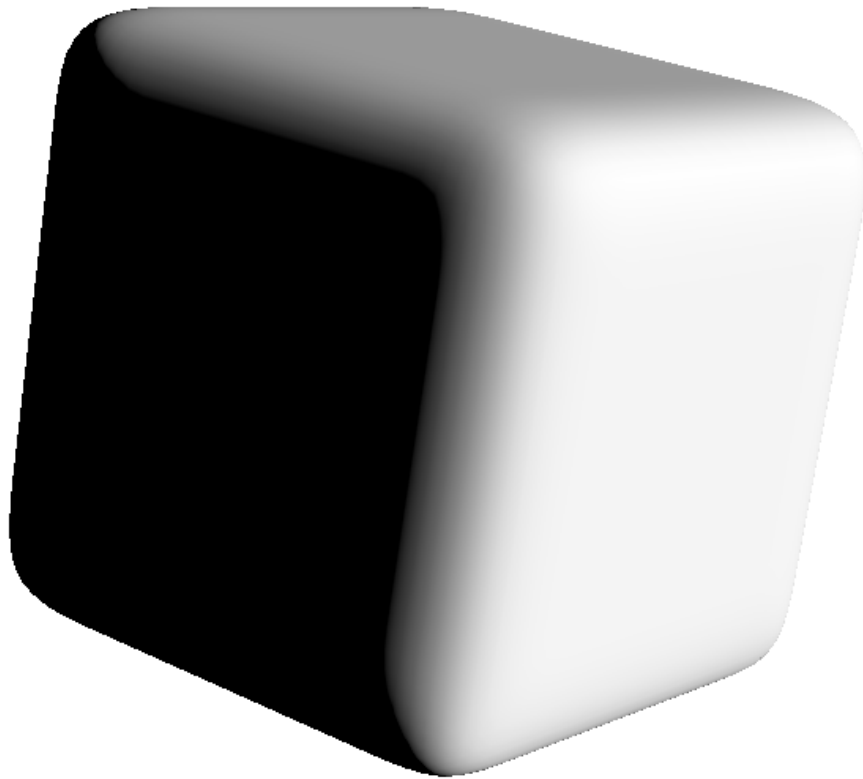
Example on 3D rounded cube



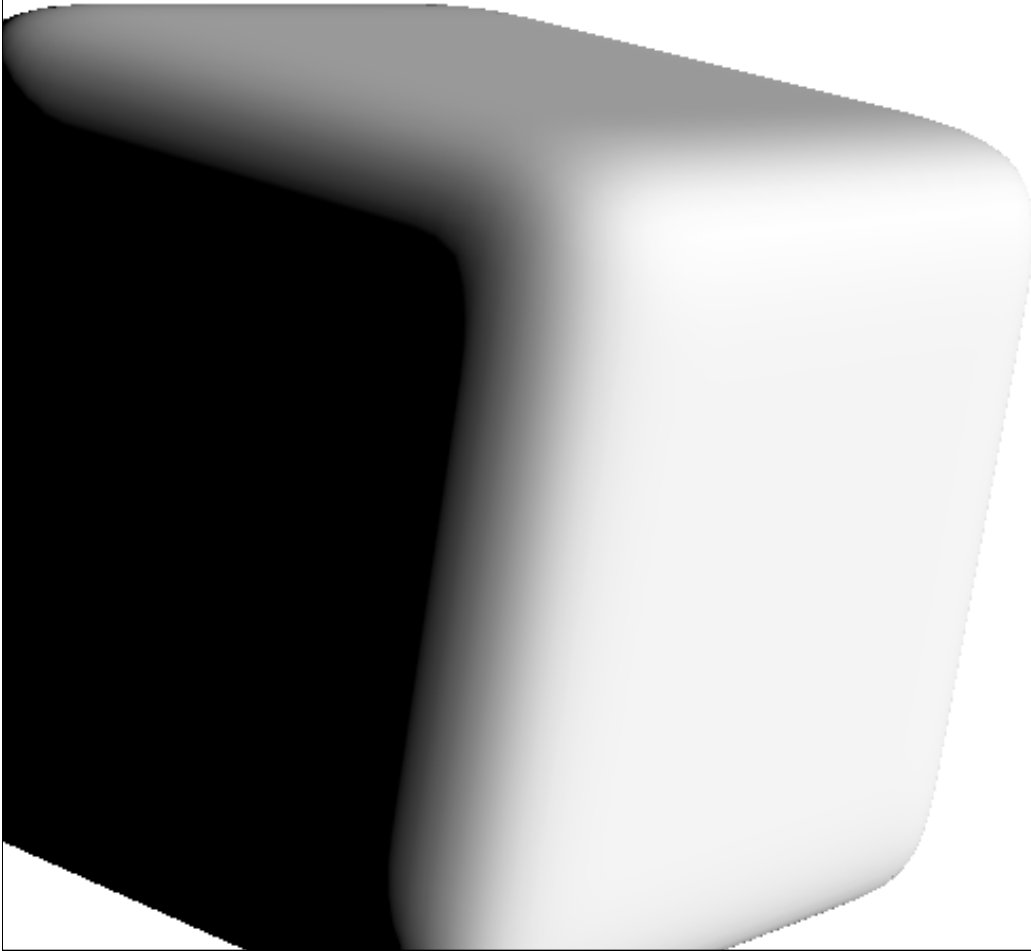
Example on 3D rounded cube



Example on 3D rounded cube



Example on 3D rounded cube



Curvature



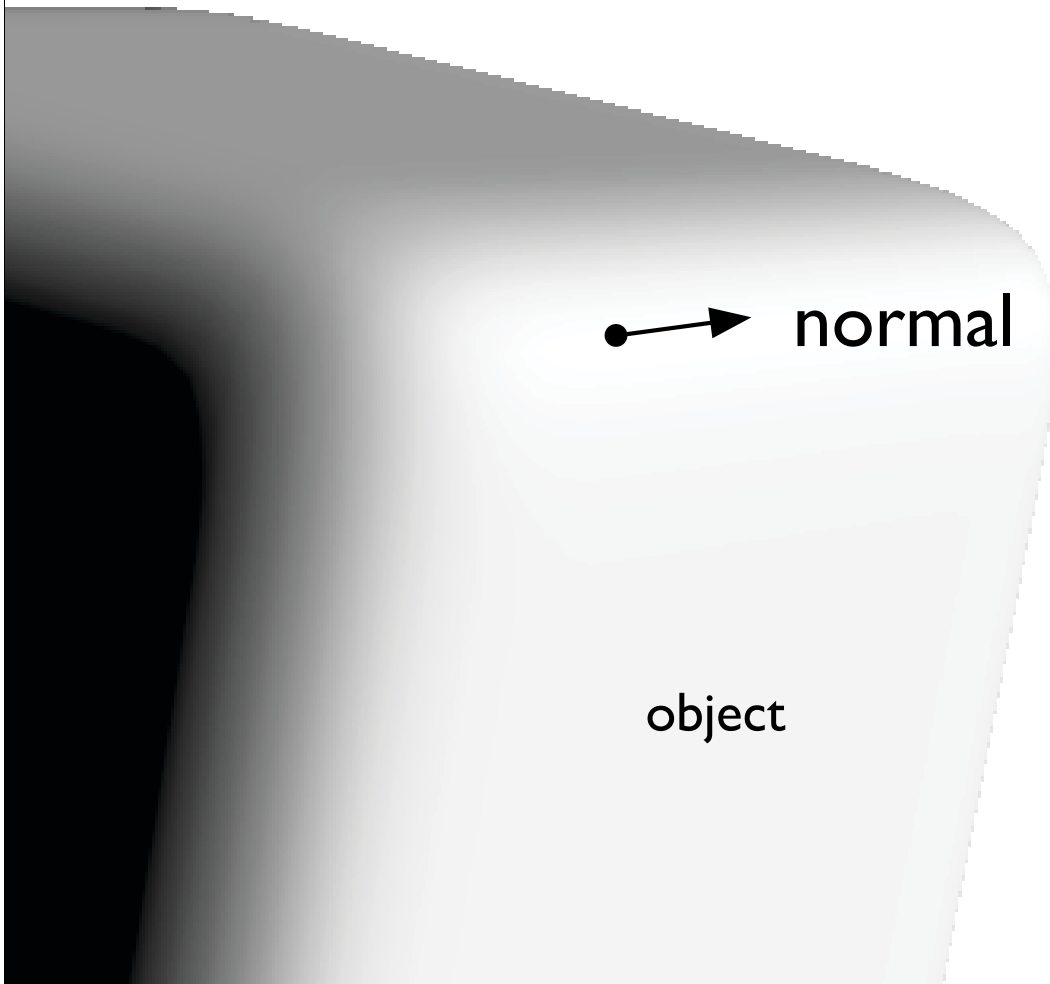
object

Curvature

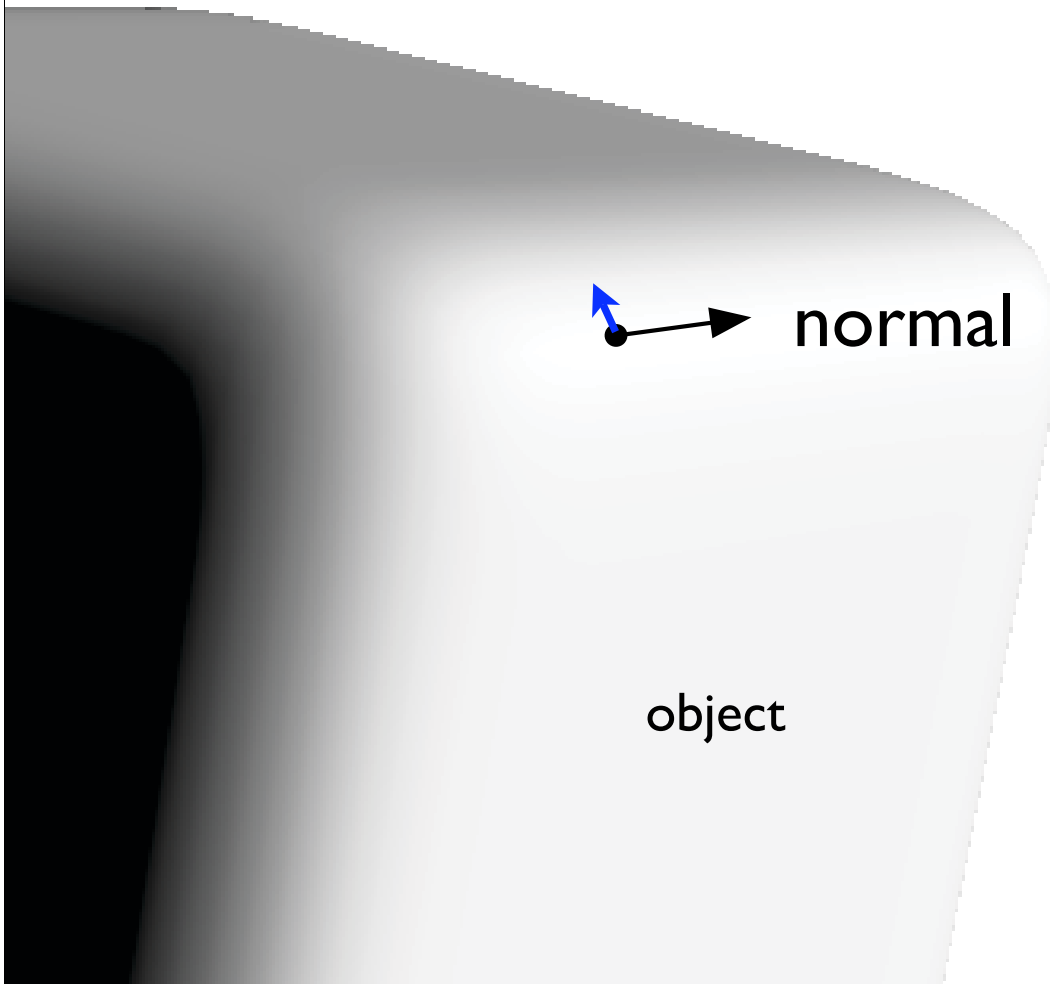


object

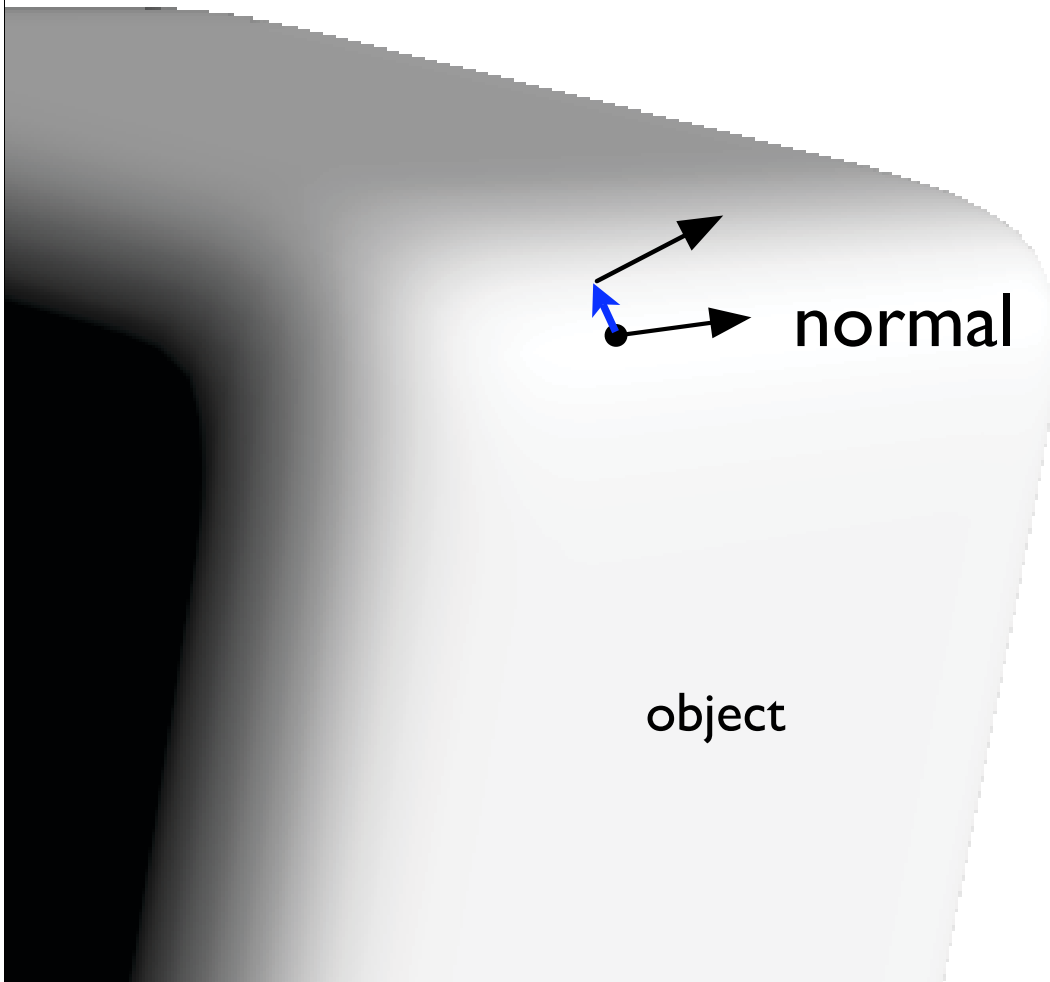
Curvature



Curvature



Curvature



Curvature

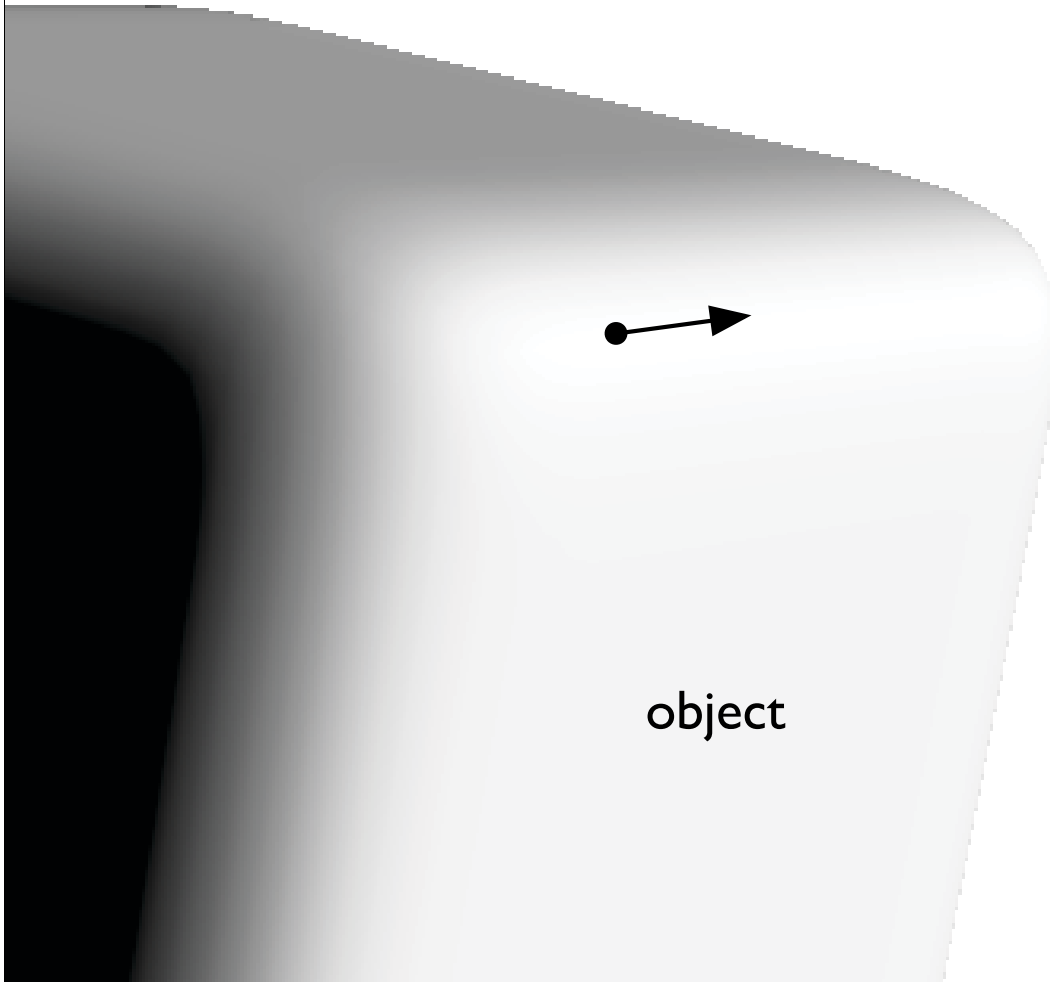
derivative of normal wrt object-space displacement
described by S (shape operator)



object

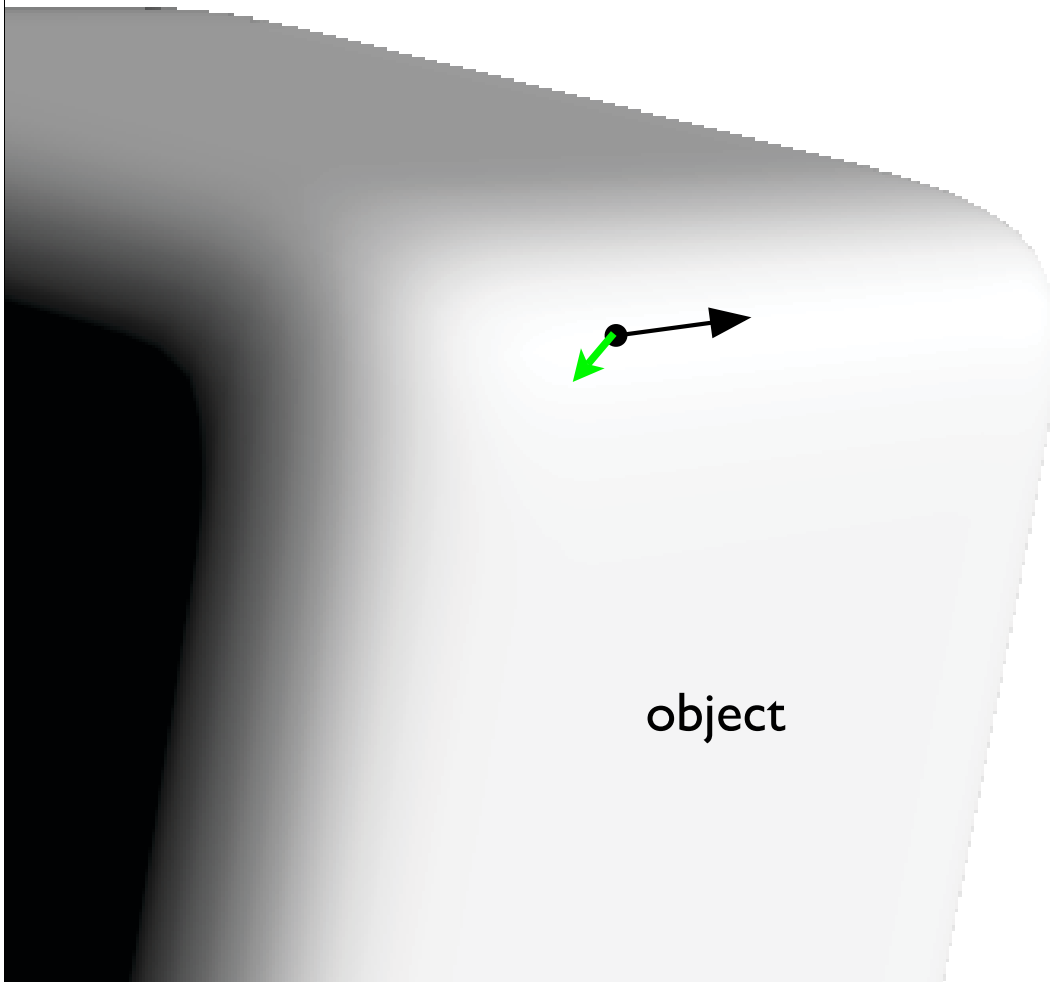
Curvature

derivative of normal wrt object-space displacement
described by S (shape operator)



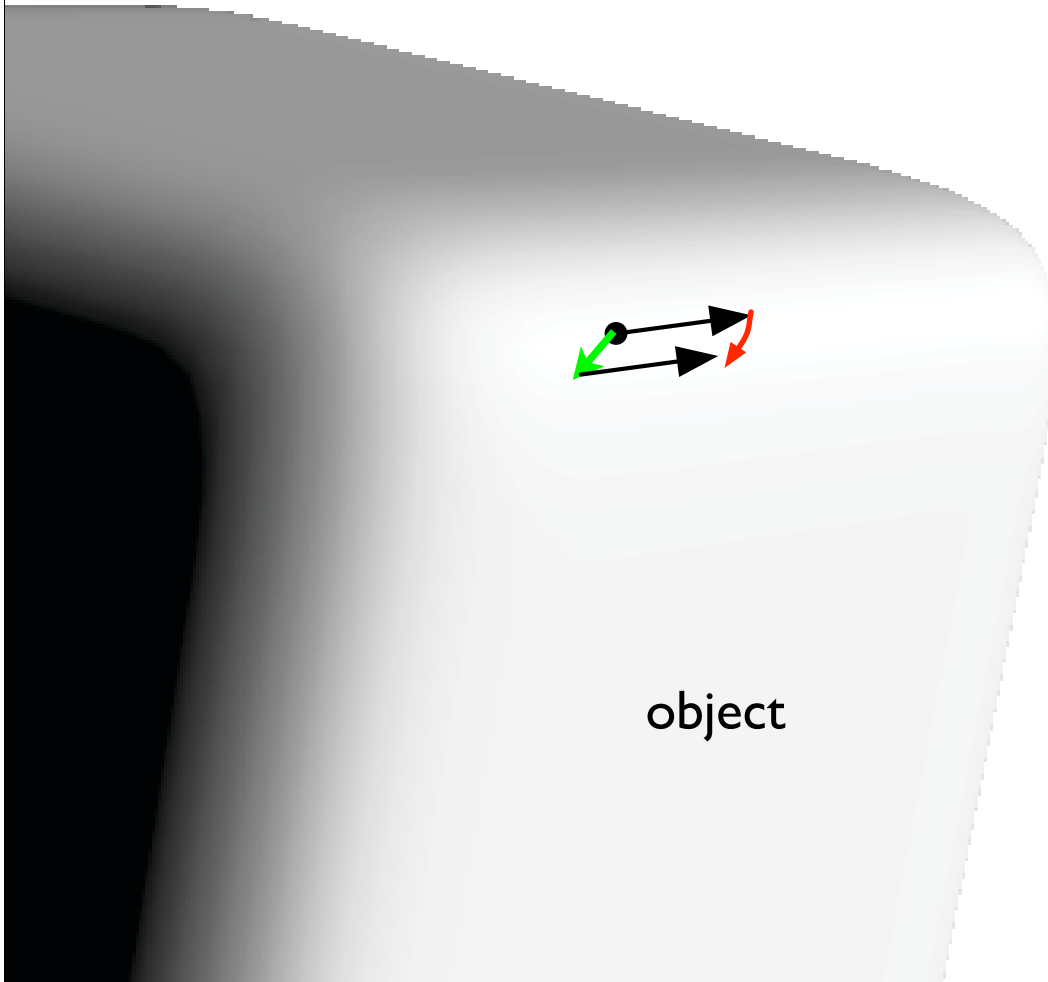
Curvature

derivative of normal wrt object-space displacement
described by S (shape operator)



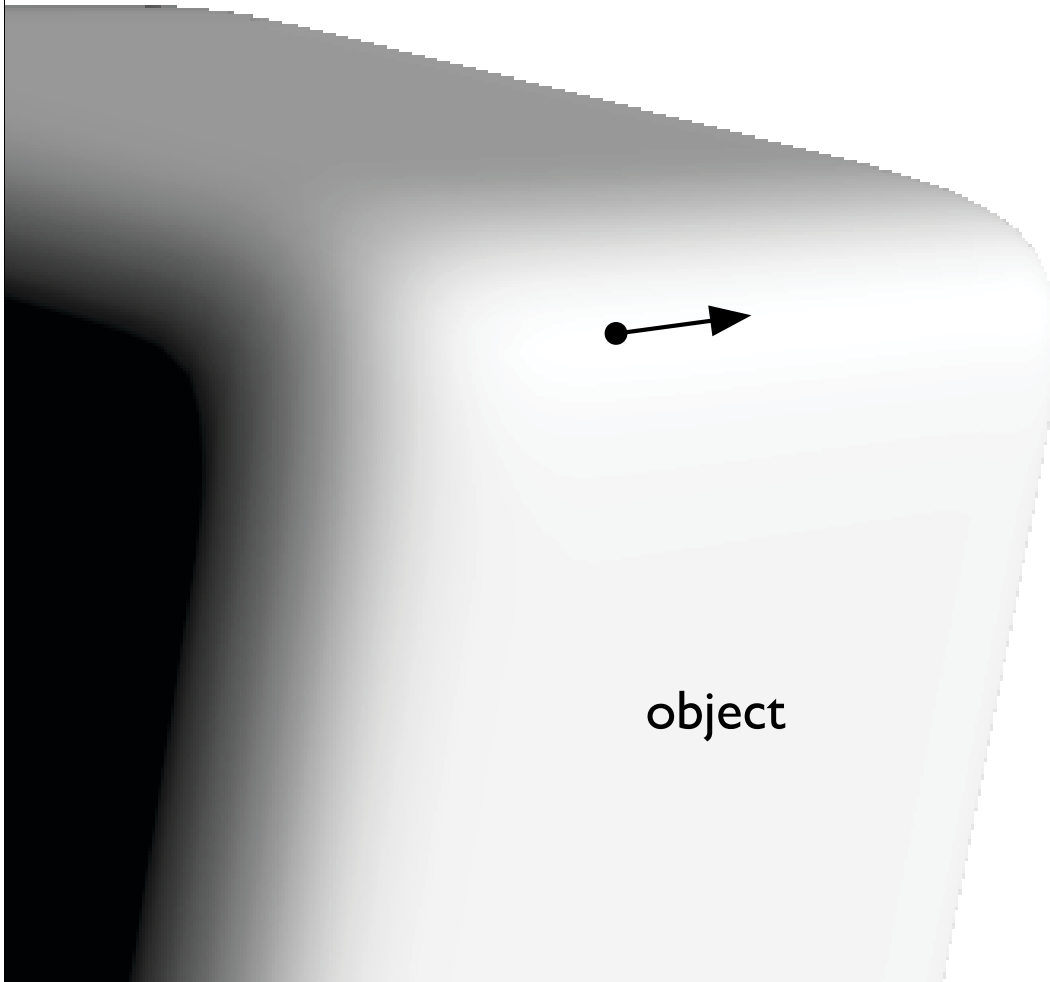
Curvature

derivative of normal wrt object-space displacement
described by S (shape operator)



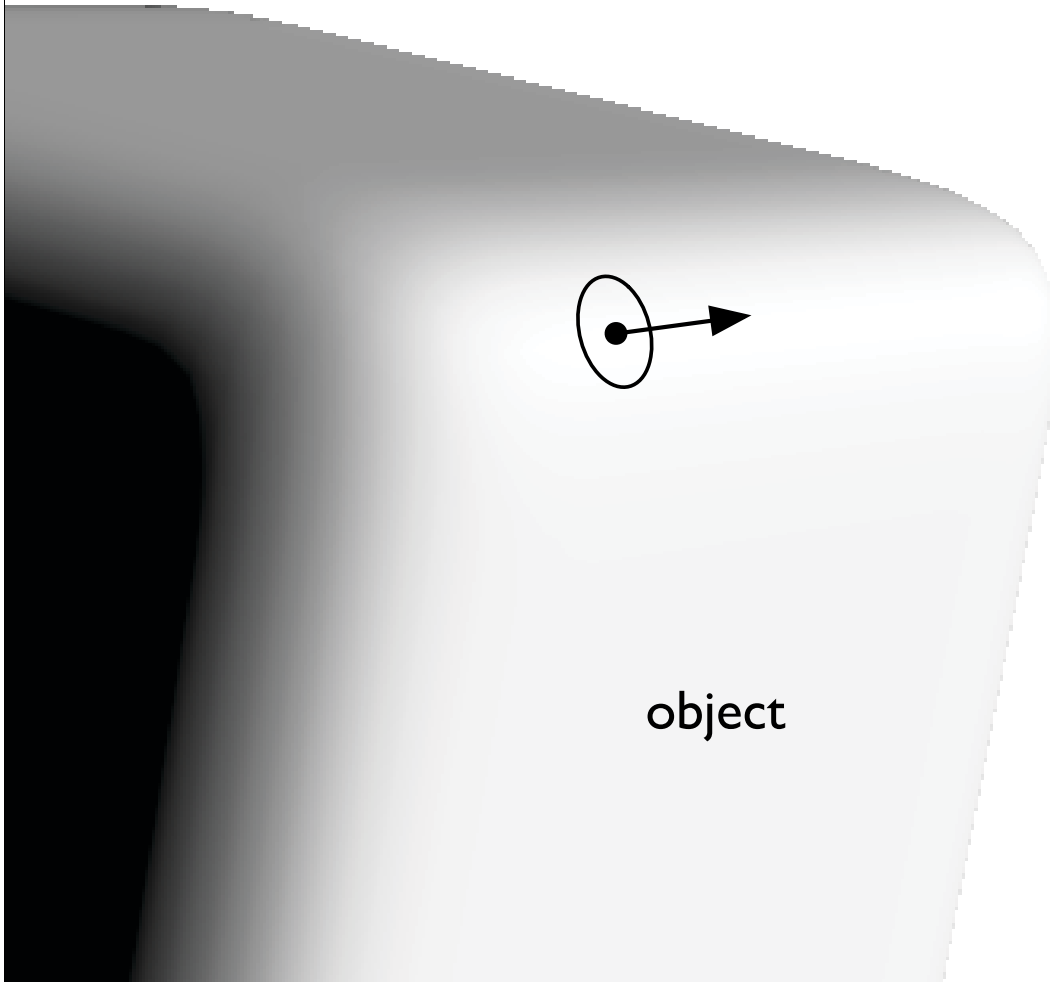
Curvature

derivative of normal wrt object-space displacement
described by S (shape operator)



Curvature

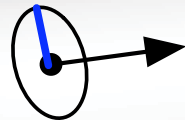
derivative of normal wrt object-space displacement
described by S (shape operator)



Curvature

derivative of normal wrt object-space displacement
described by S (shape operator)

maximum
principal direction

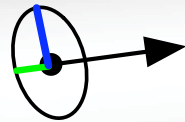


object

Curvature

derivative of normal wrt object-space displacement
described by S (shape operator)

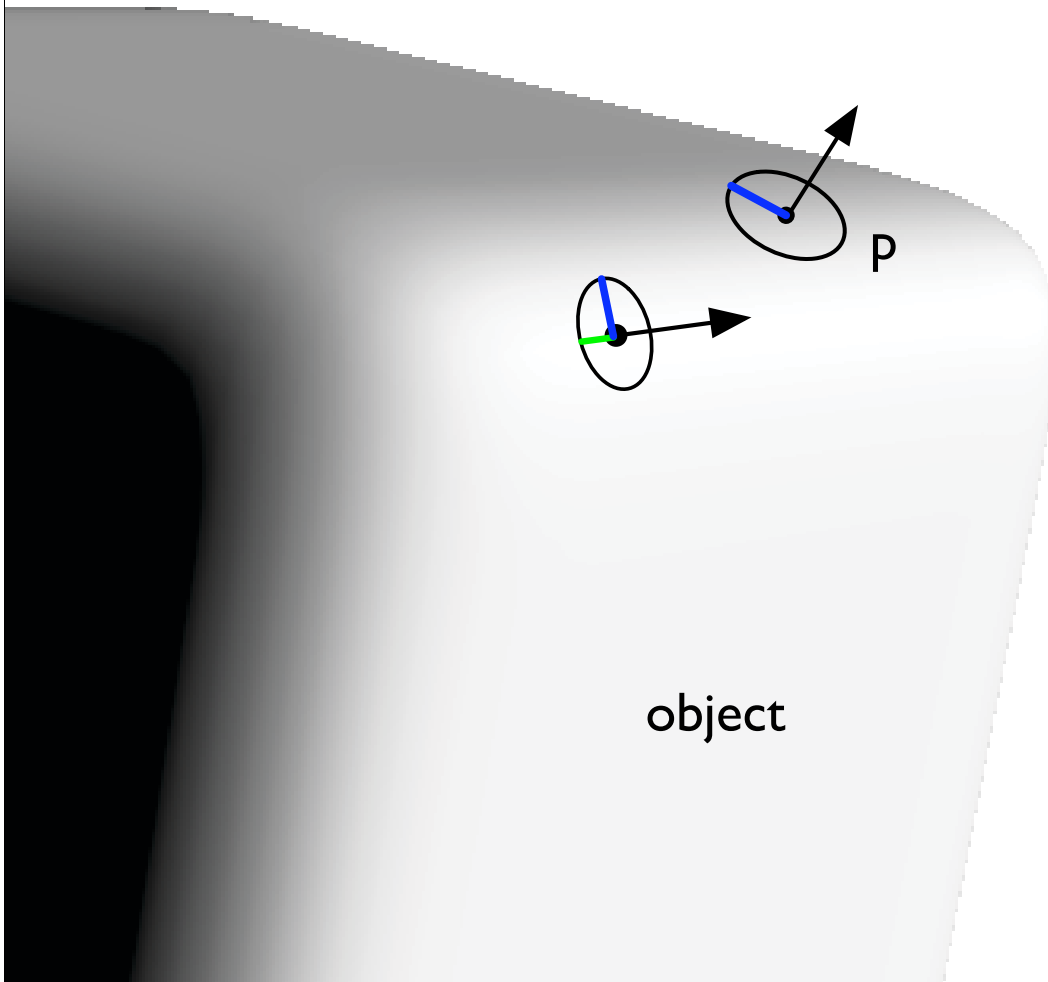
maximum
principal direction



object

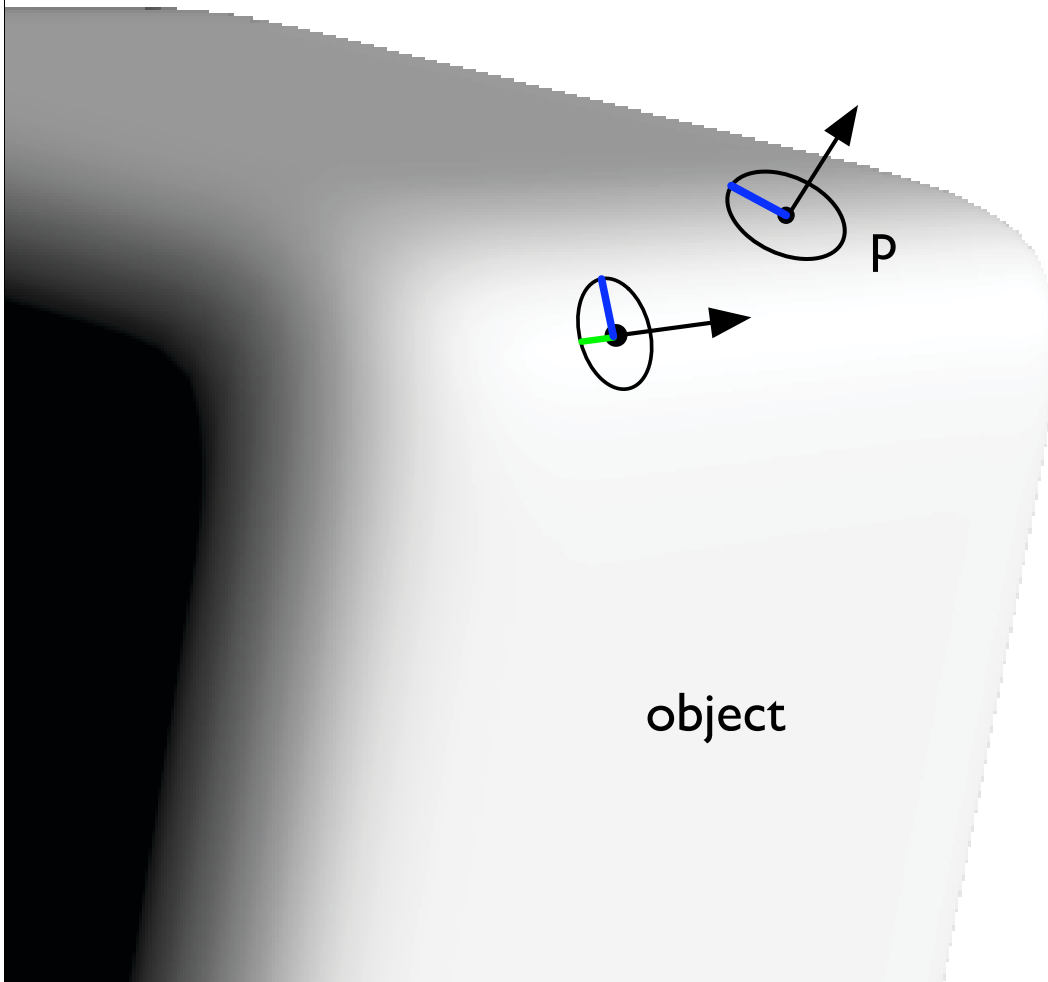
Curvature

derivative of normal wrt object-space displacement
described by S (shape operator)



Curvature

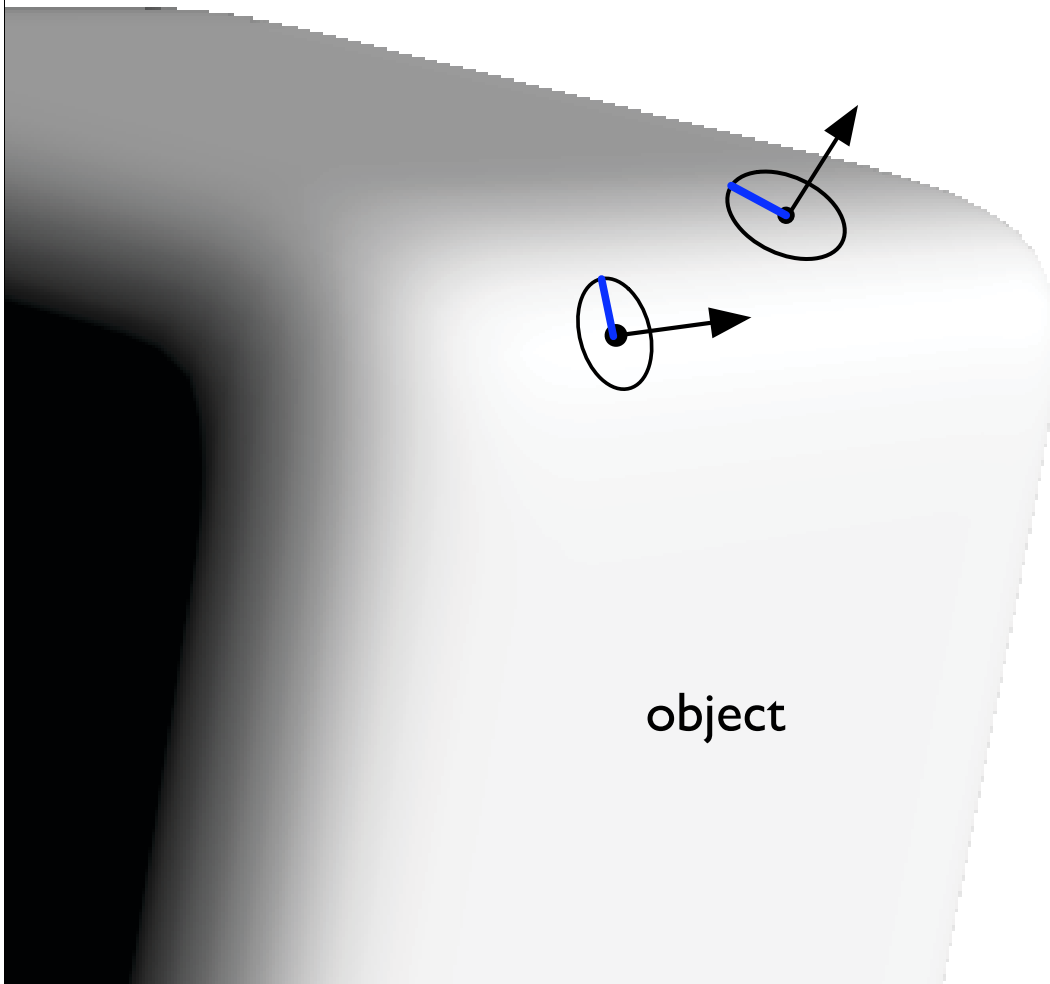
derivative of normal wrt object-space displacement
described by S (shape operator)



- Eigenvectors of $S(p)$:
principal directions at p
- Eigenvalues of $S(p)$:
max and min curvature at p

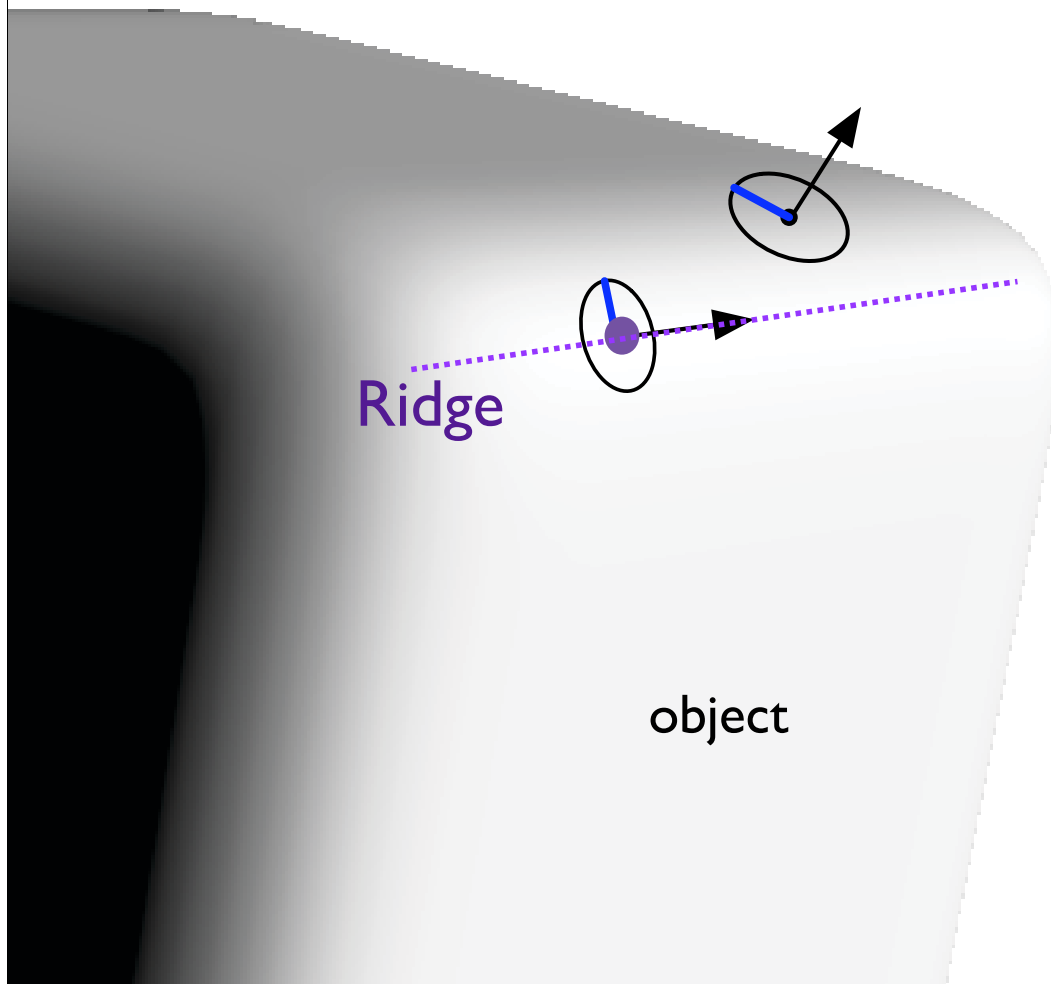
Ridges

extrema of max curvature in its principal direction



Ridges

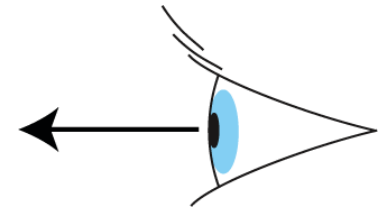
extrema of max curvature in its principal direction



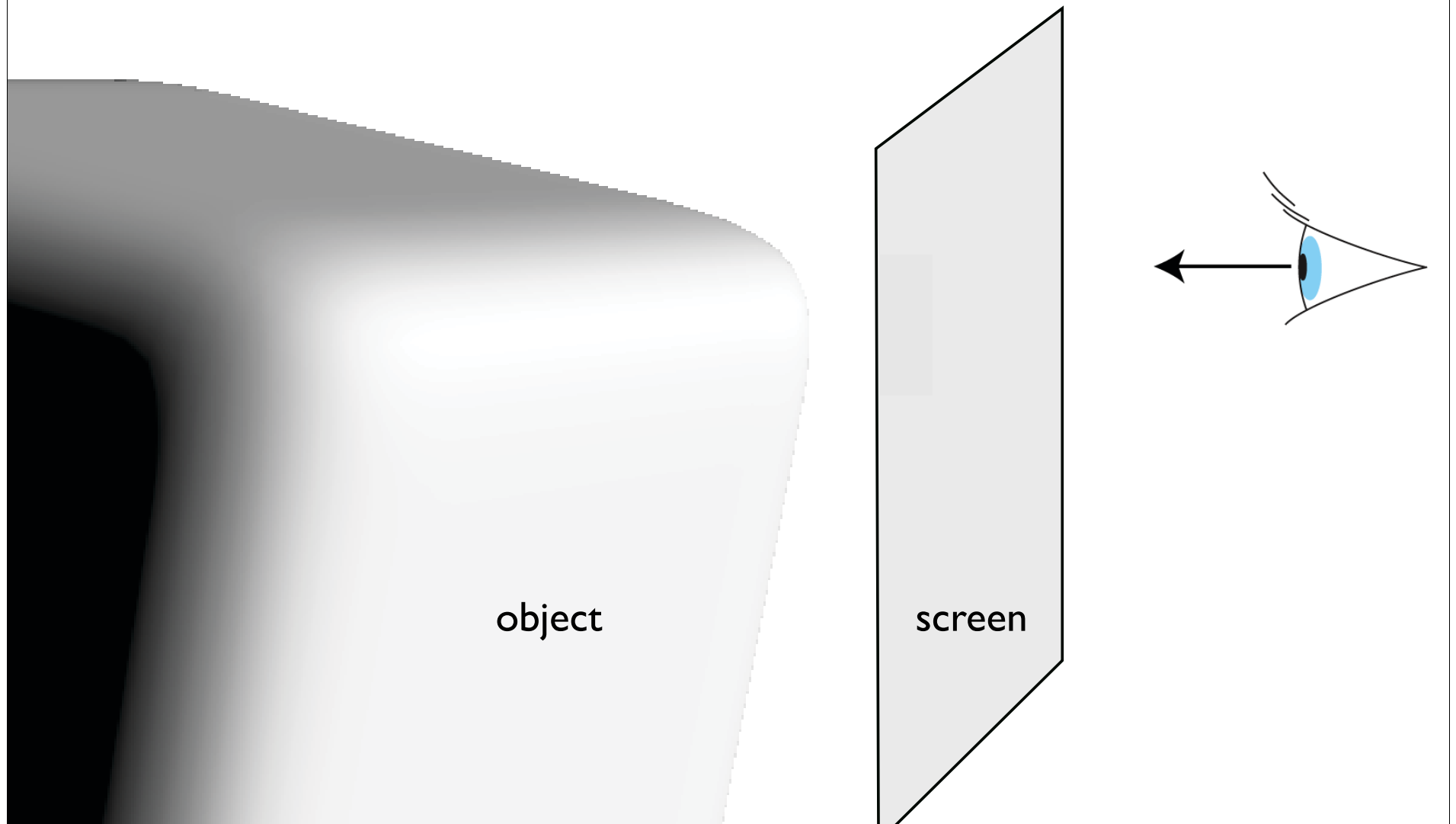
View-dependent Curvature



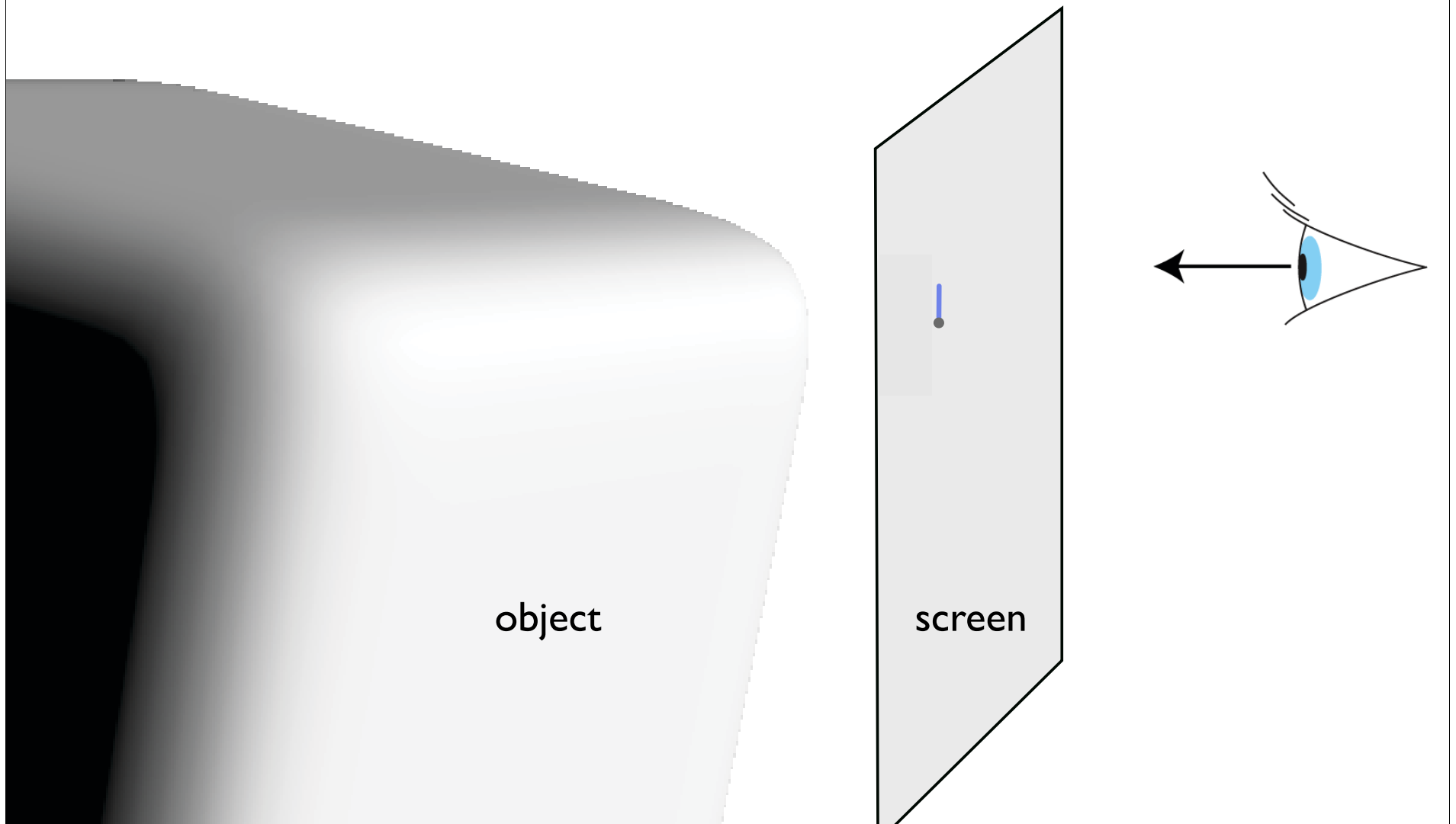
View-dependent Curvature



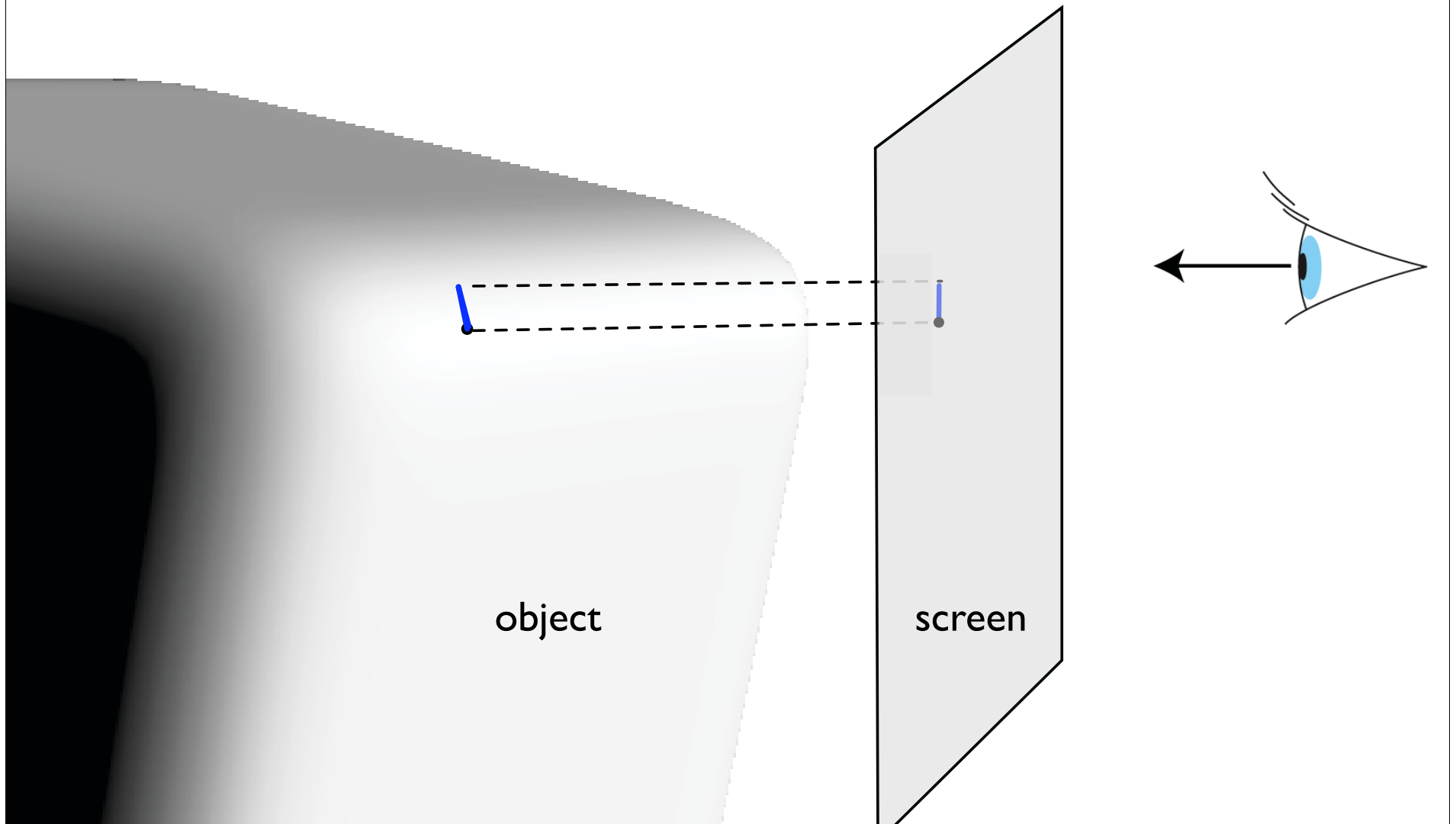
View-dependent Curvature



View-dependent Curvature

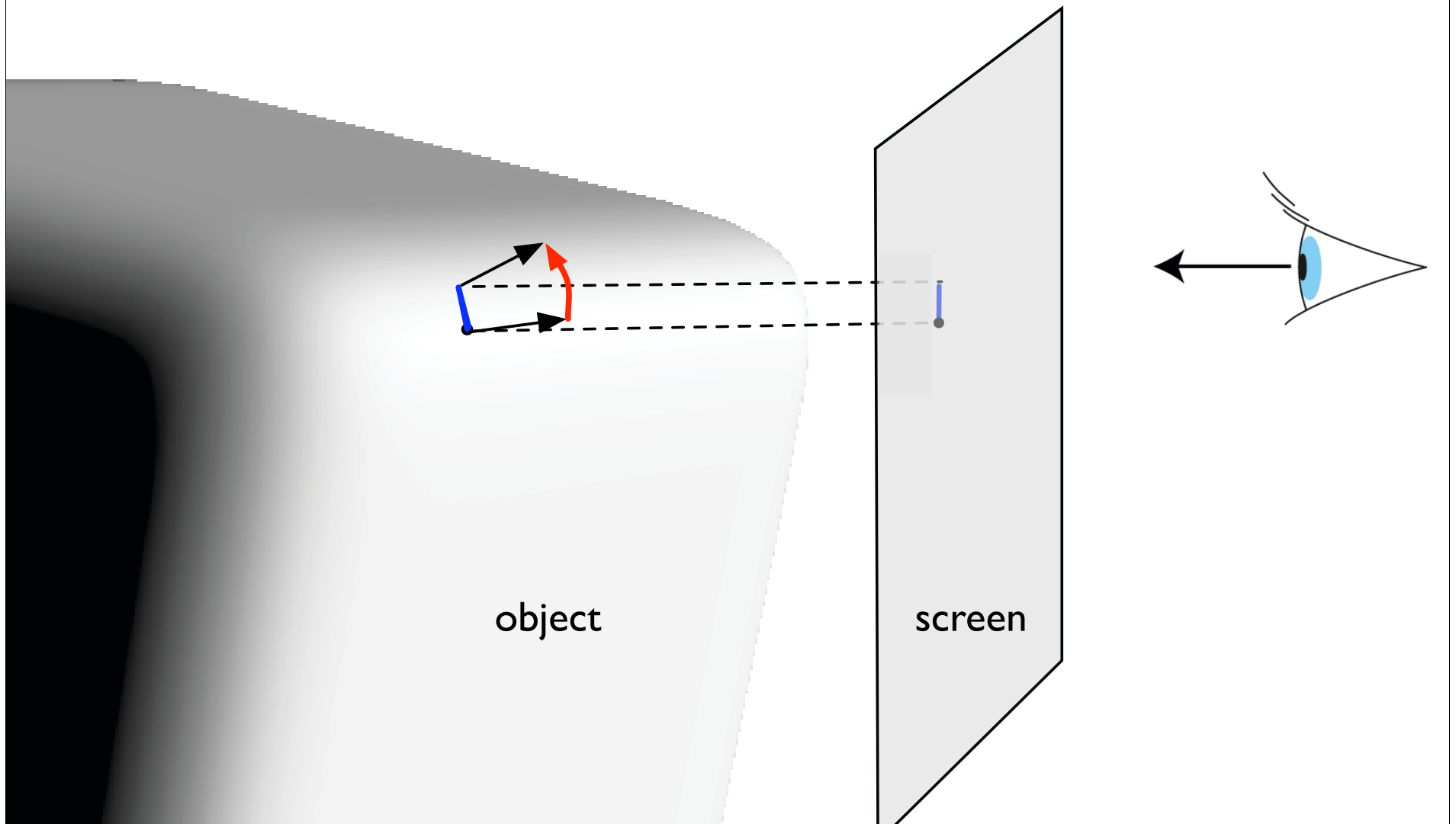


View-dependent Curvature



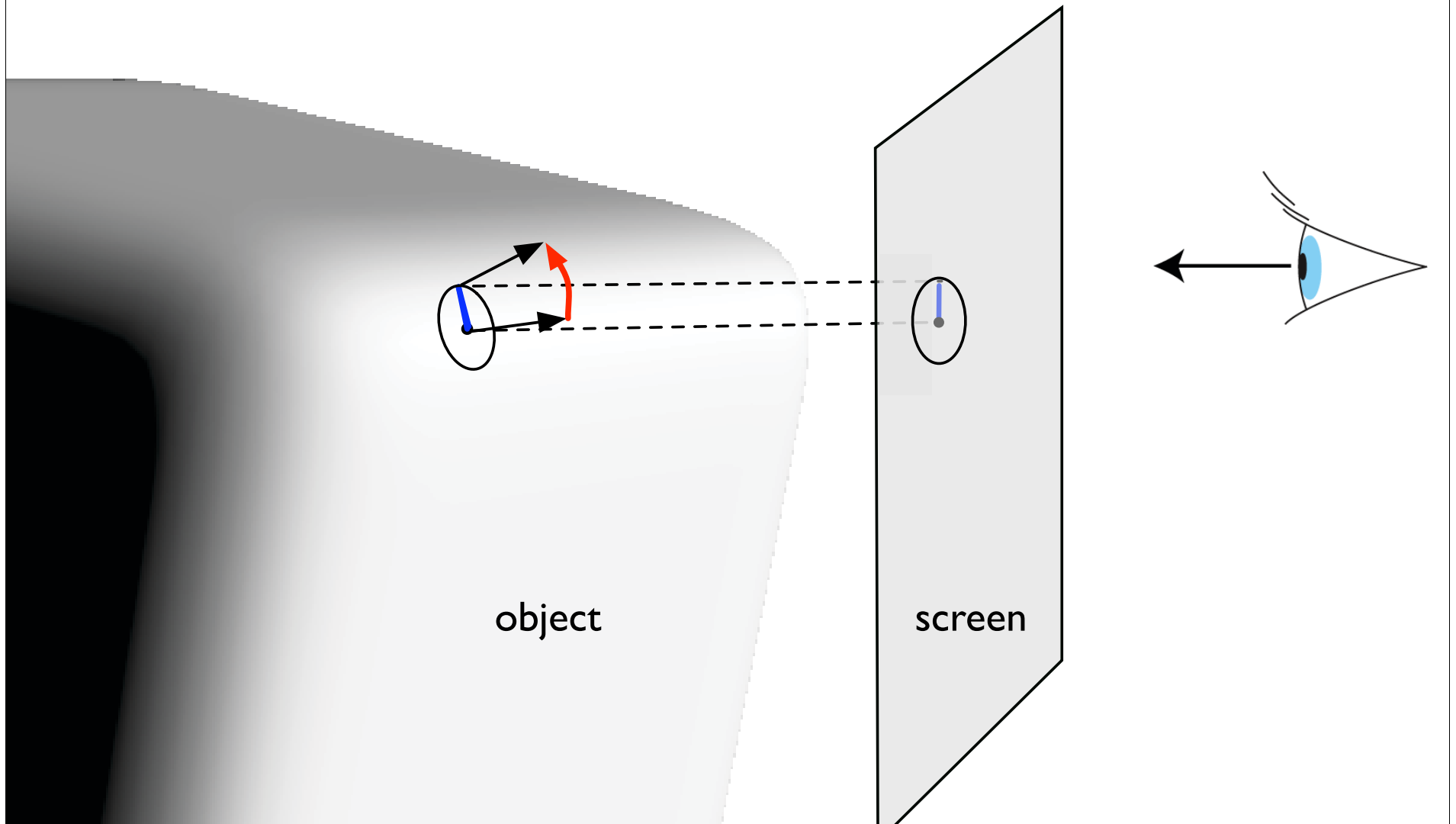
View-dependent Curvature

derivative of normal wrt screen displacement



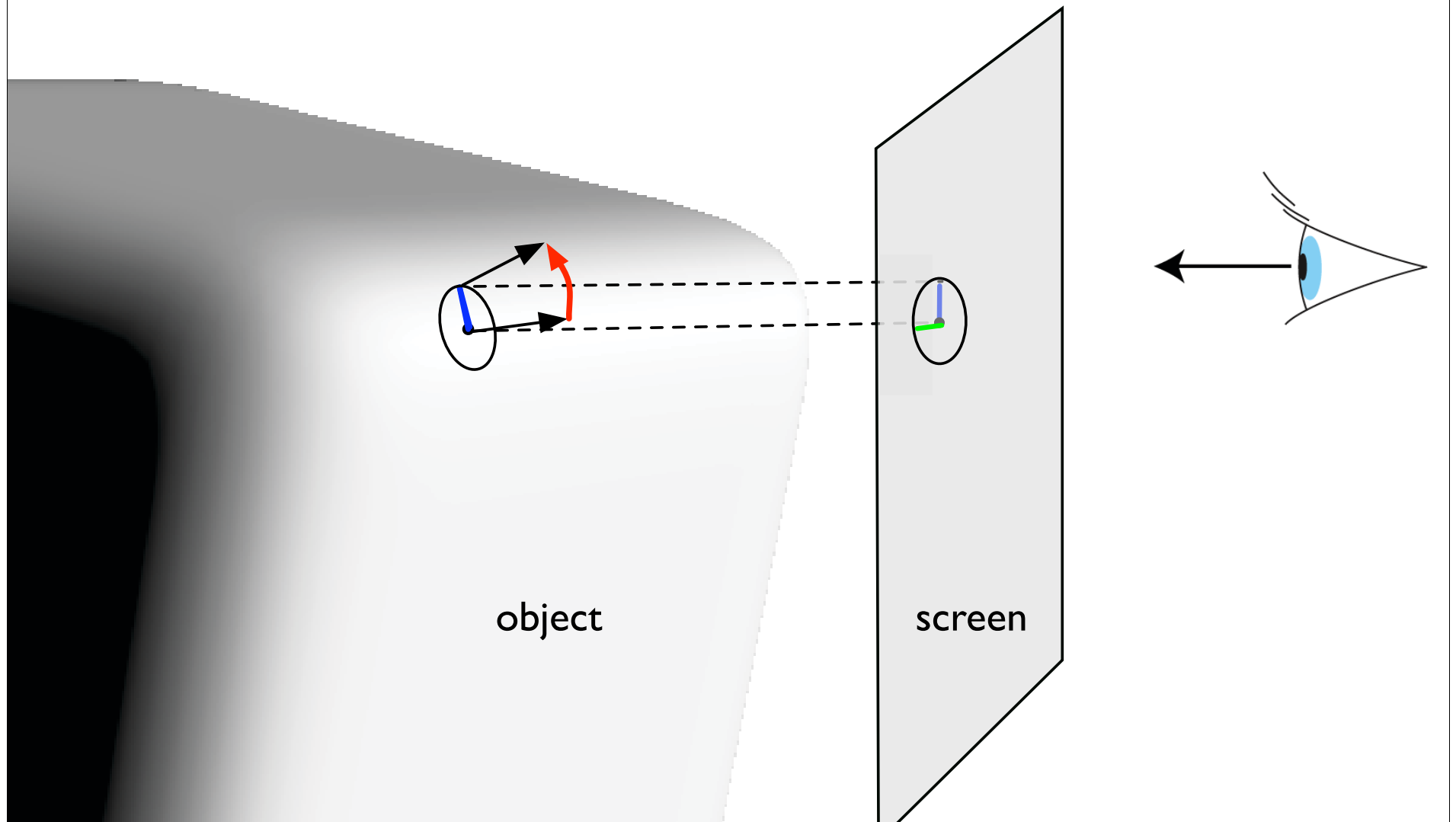
View-dependent Curvature

derivative of normal wrt screen displacement



View-dependent Curvature

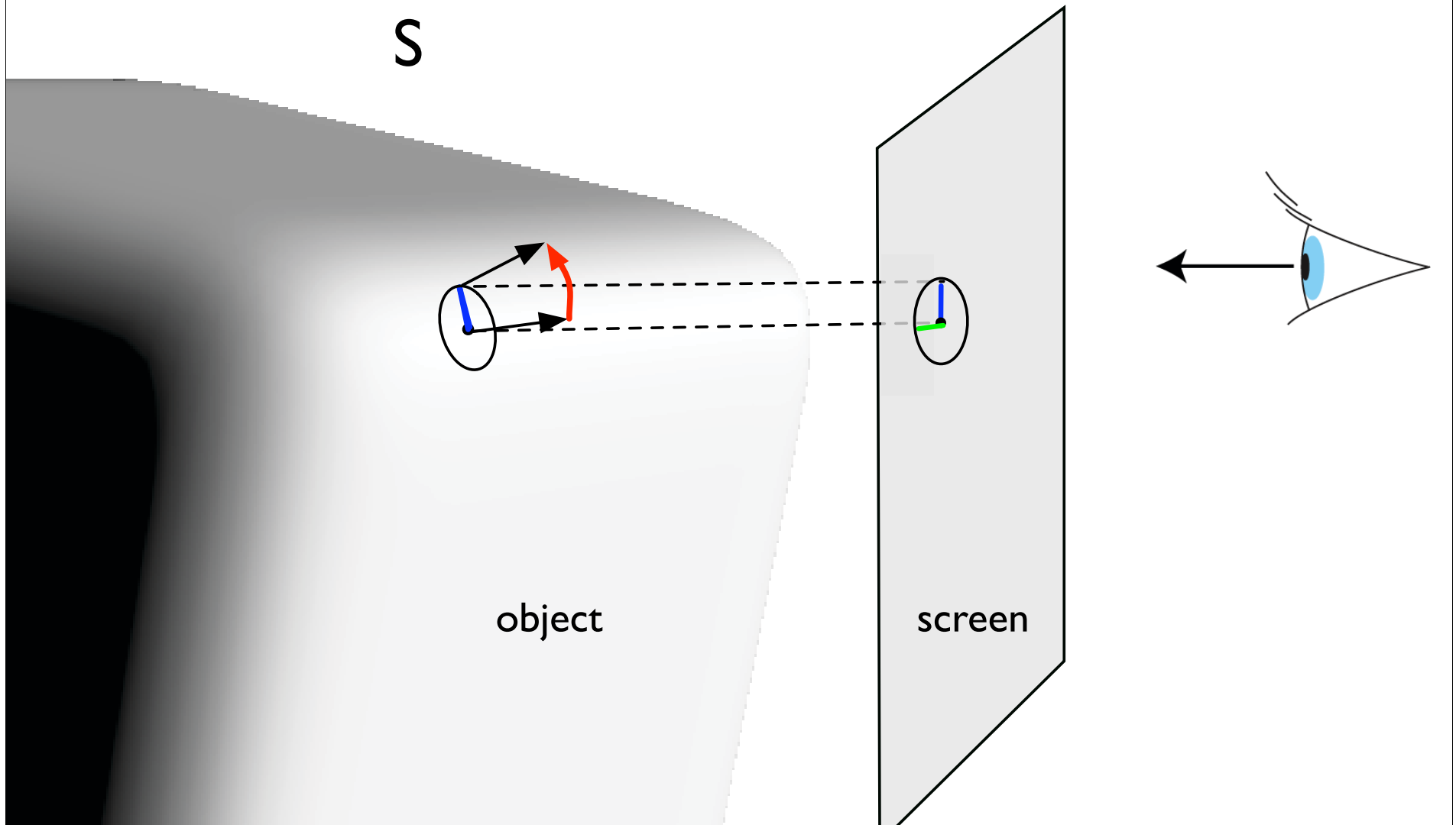
derivative of normal wrt screen displacement



View-dependent Curvature

derivative of normal wrt screen displacement

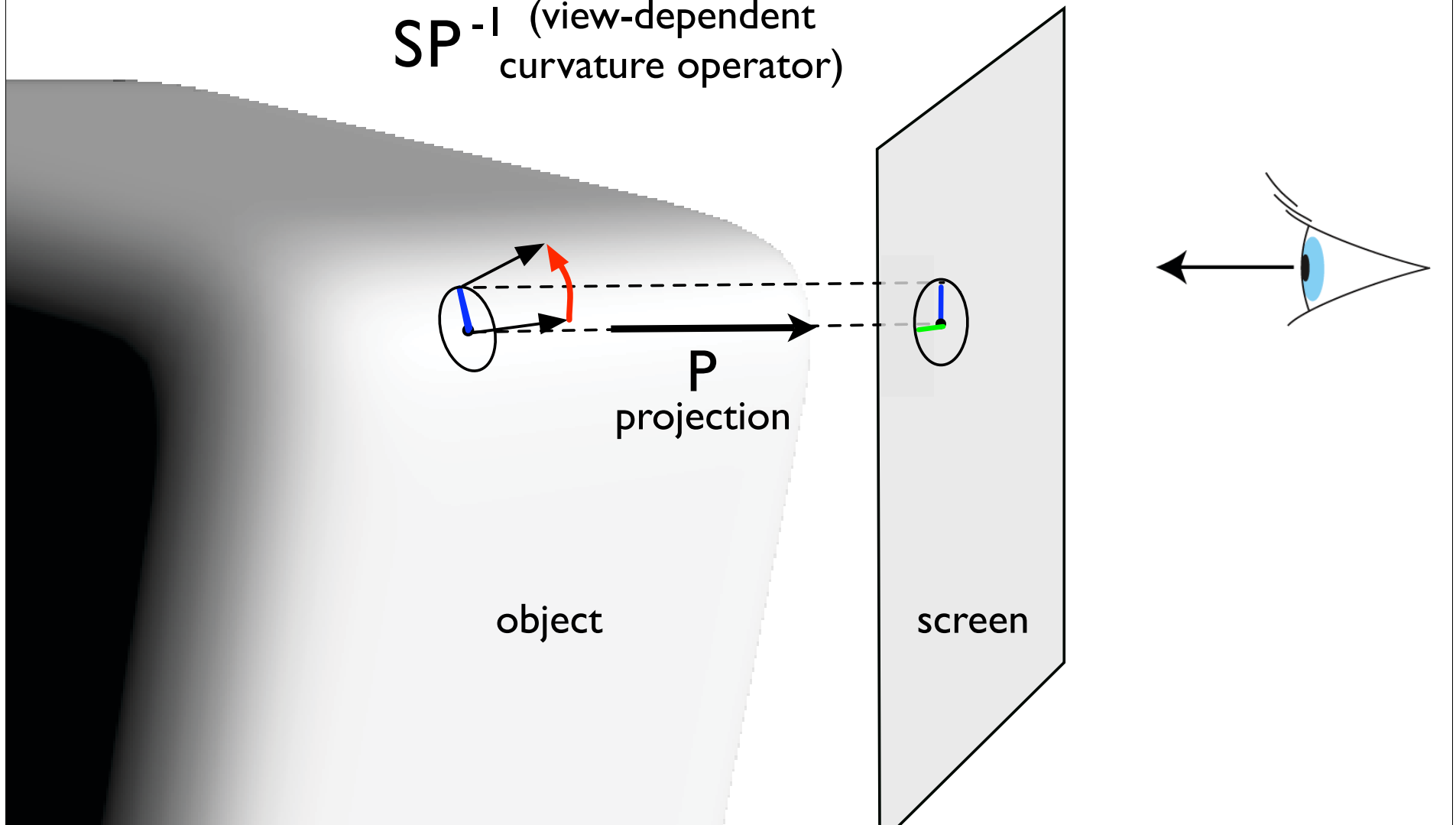
S



View-dependent Curvature

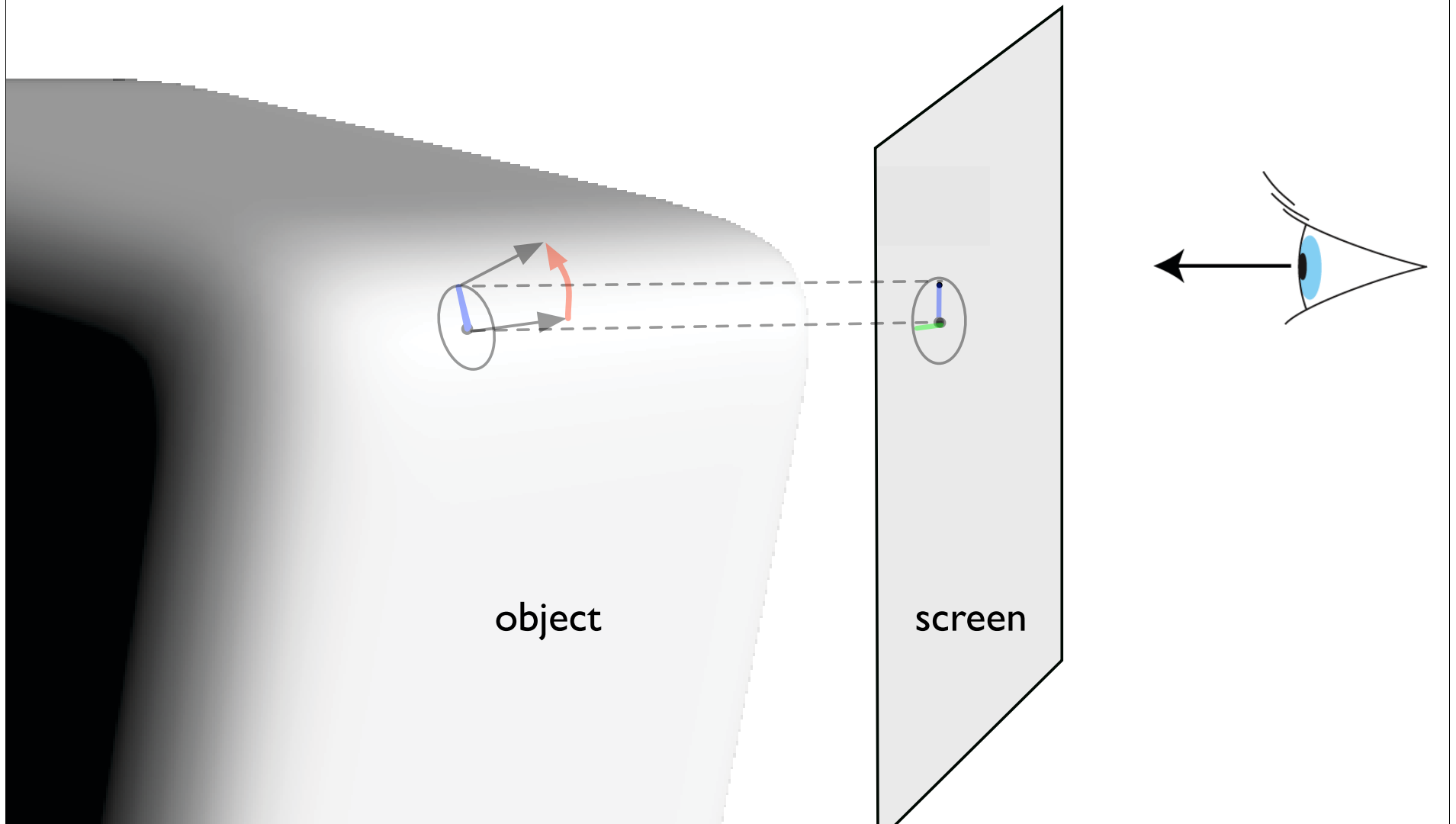
derivative of normal wrt screen displacement

SP^{-1} (view-dependent curvature operator)



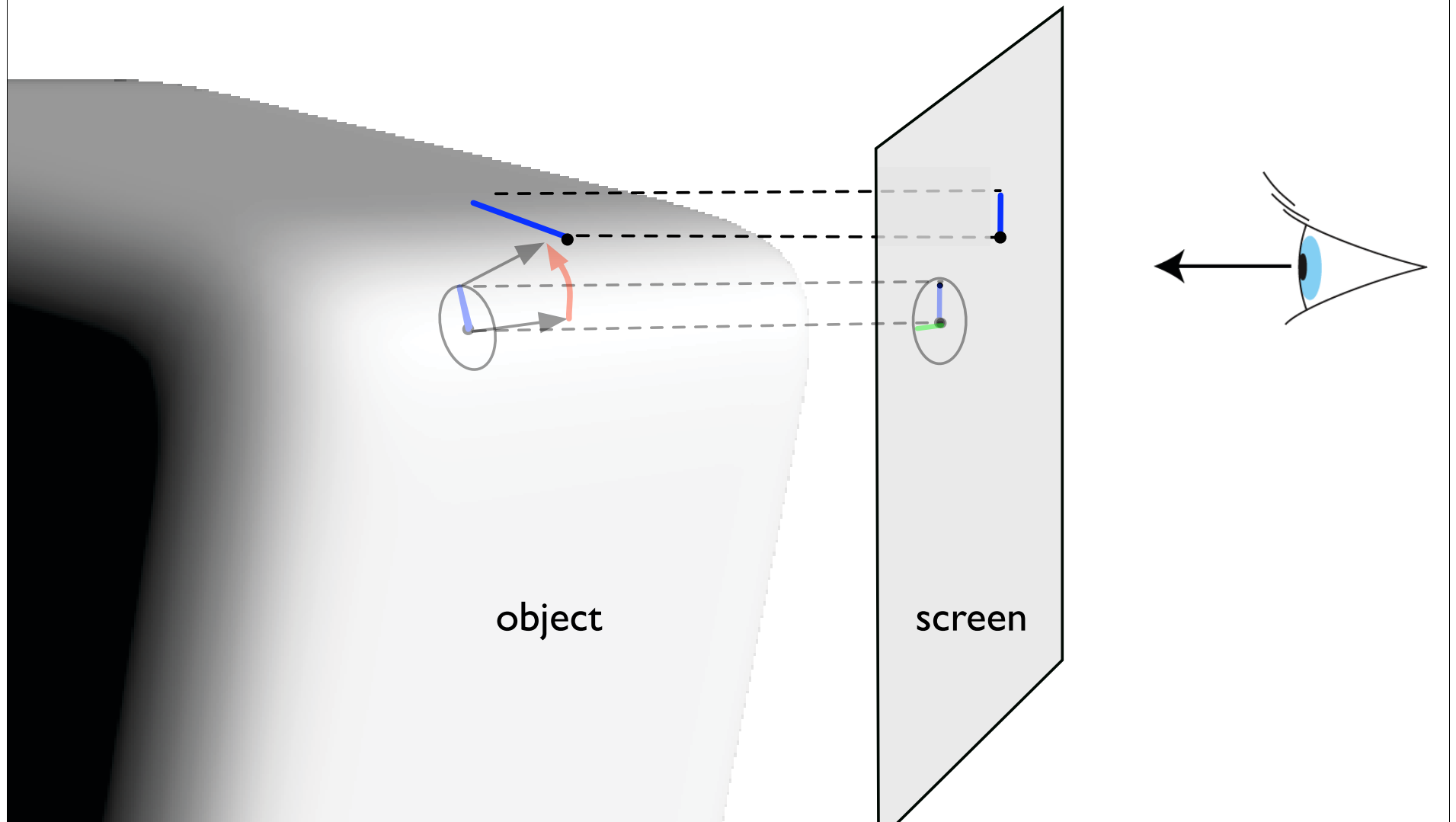
View-dependent Curvature

derivative of normal wrt screen displacement



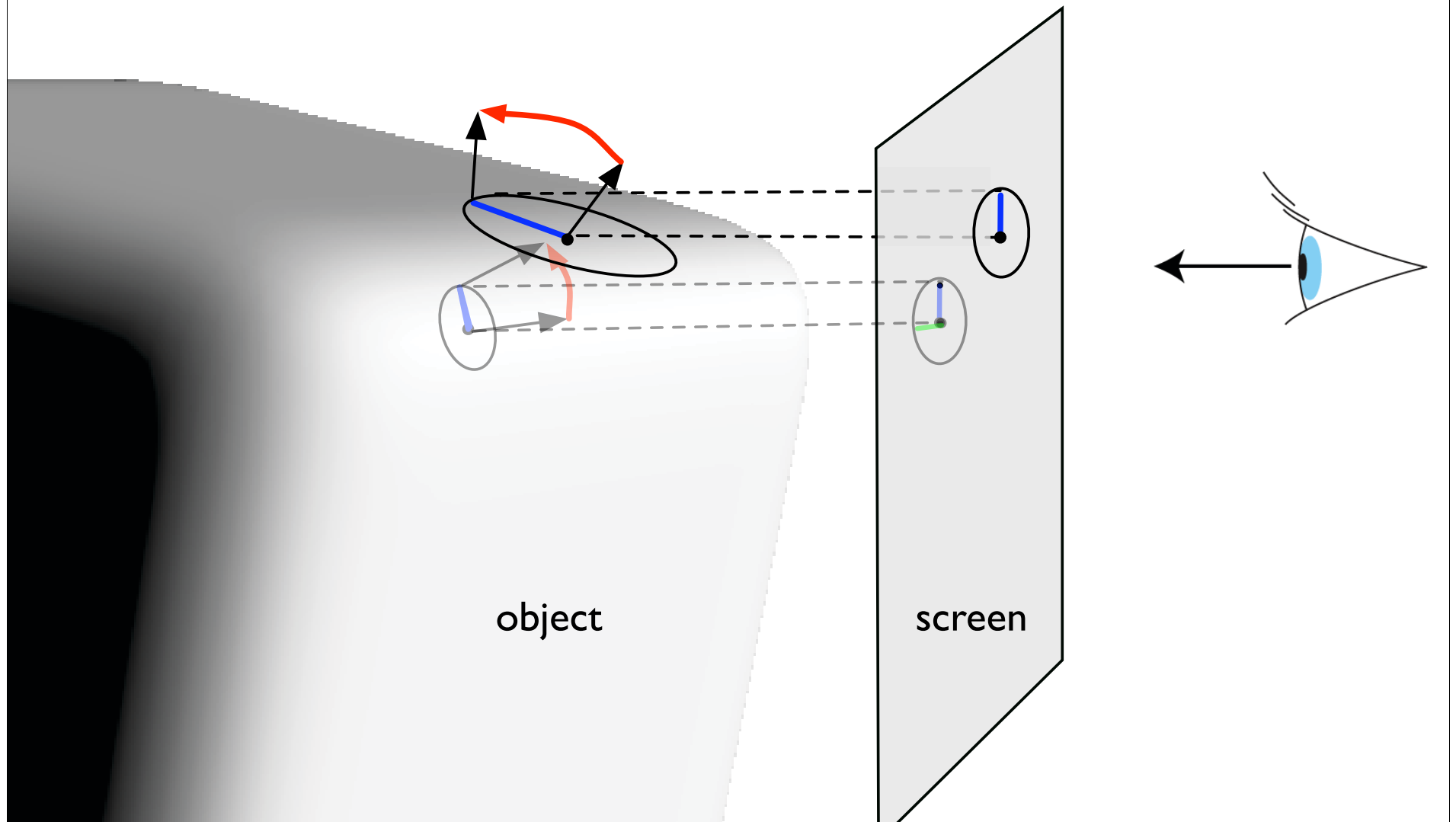
View-dependent Curvature

derivative of normal wrt screen displacement



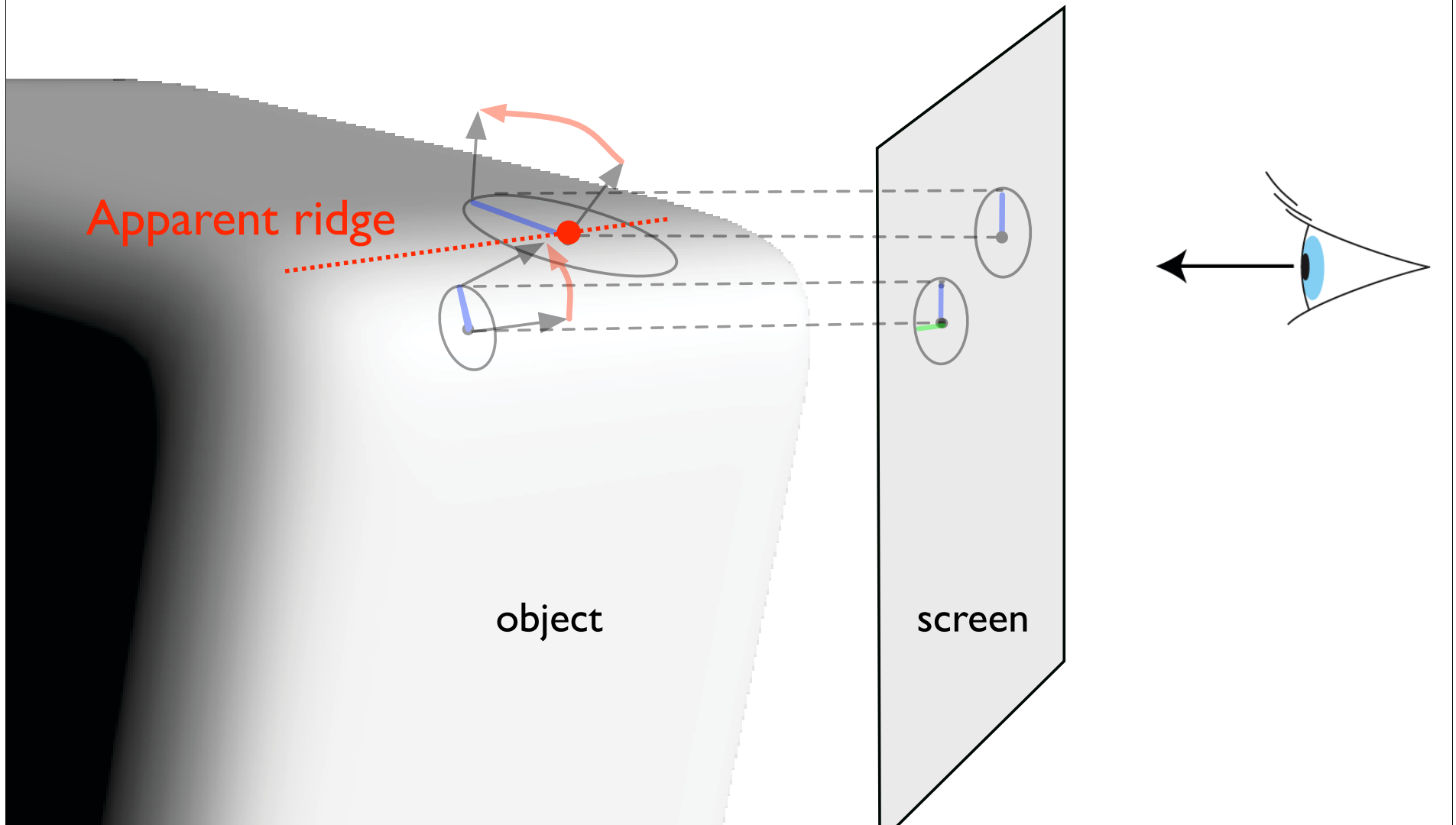
View-dependent Curvature

derivative of normal wrt screen displacement



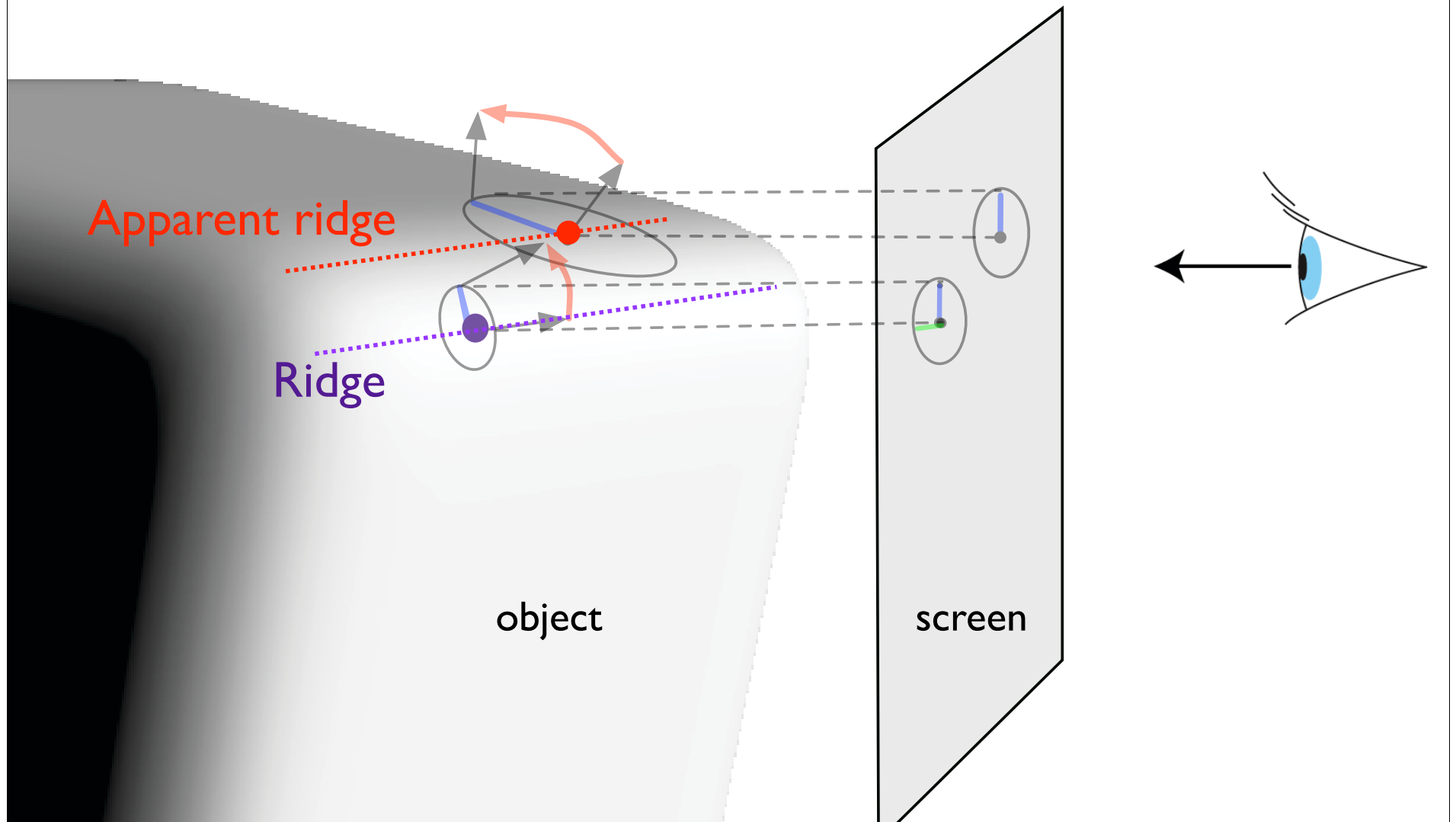
Apparent Ridges

extrema of max view-dependent curvature in its principal direction



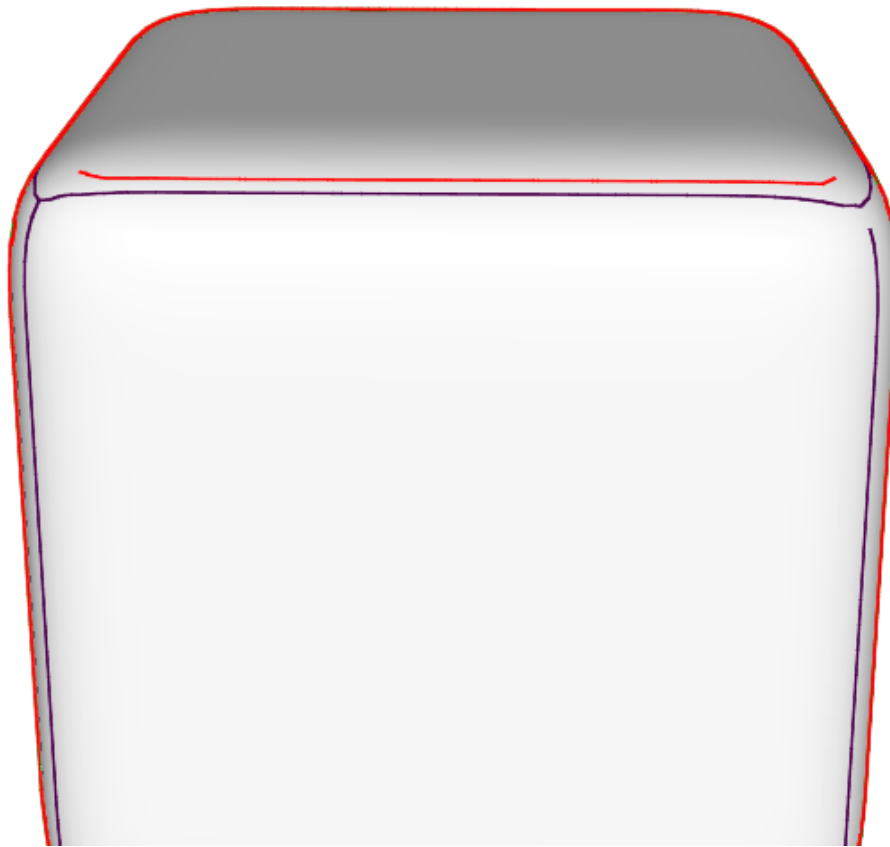
Apparent Ridges

extrema of max view-dependent curvature in its principal direction



Lines on 3D rounded cube

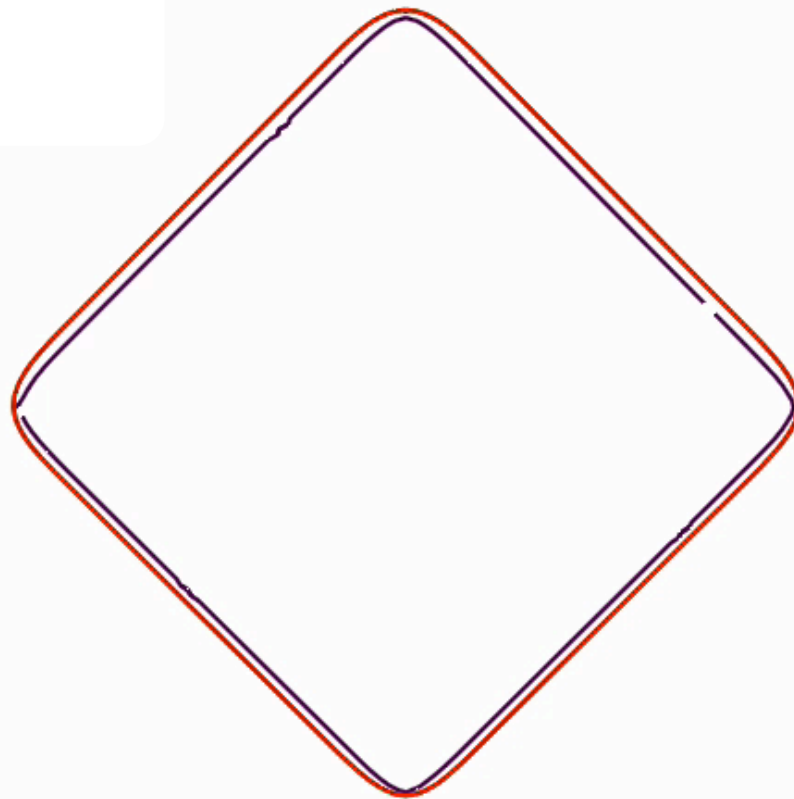
Apparent ridges
Ridges



Lines on 3D rounded cube

Apparent ridges

Ridges



Recap: Our New Definitions

View-dependent Curvature

variation of the surface normal with respect to the screen plane

Apparent Ridges

maximum of the maximum view-dependent curvature in its principal direction

Recap: Our New Definitions

View-dependent Curvature

variation of the surface normal with respect to the screen plane

Apparent Ridges

maximum of the maximum view-dependent curvature in its principal direction

Recap: Our New Definitions

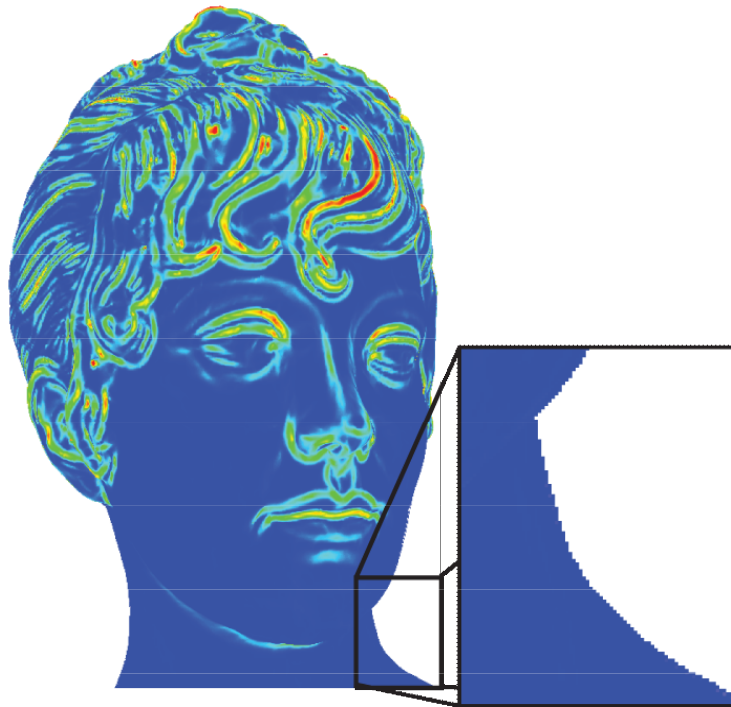
View-dependent Curvature

variation of the surface normal with respect to the screen plane

Apparent Ridges

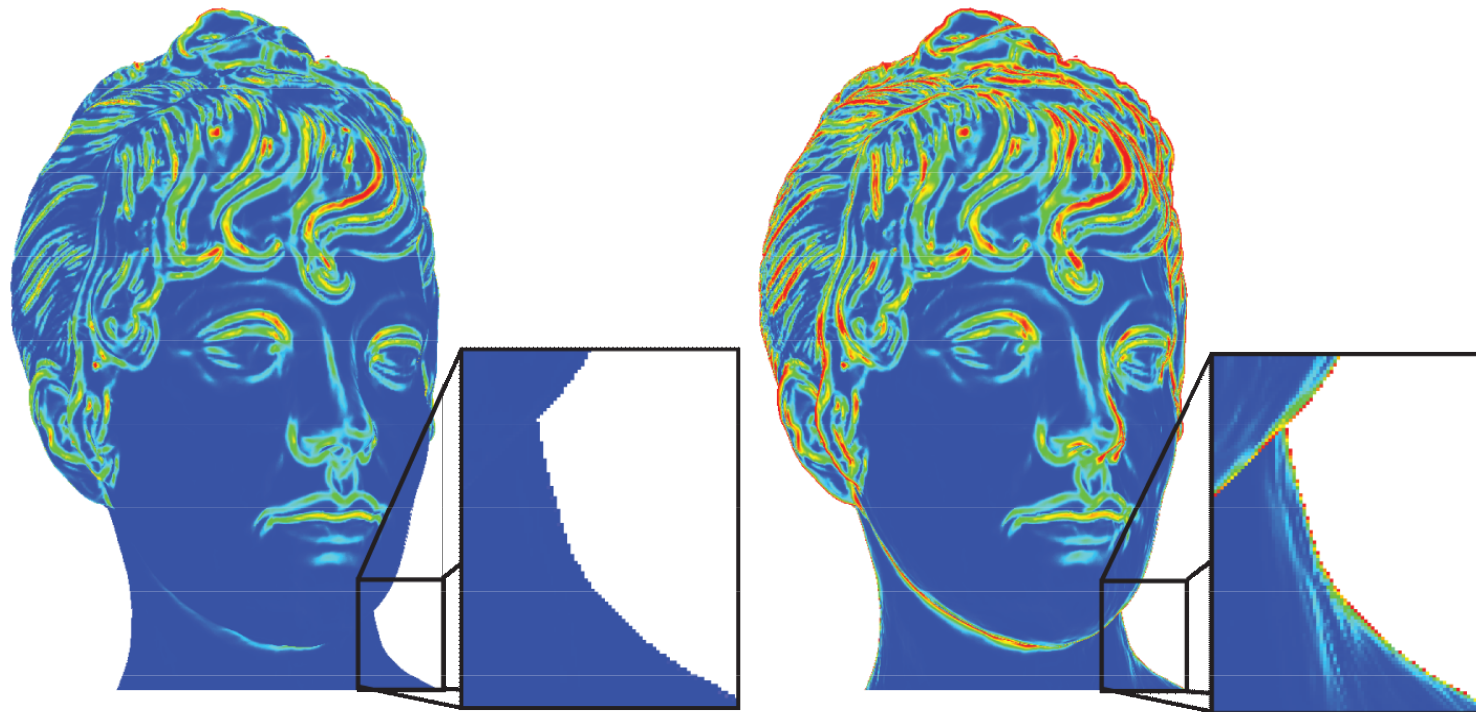
maximum of the maximum view-dependent curvature in its principal direction

Max Curvature



Traditional maximum
Curvature

Comparison



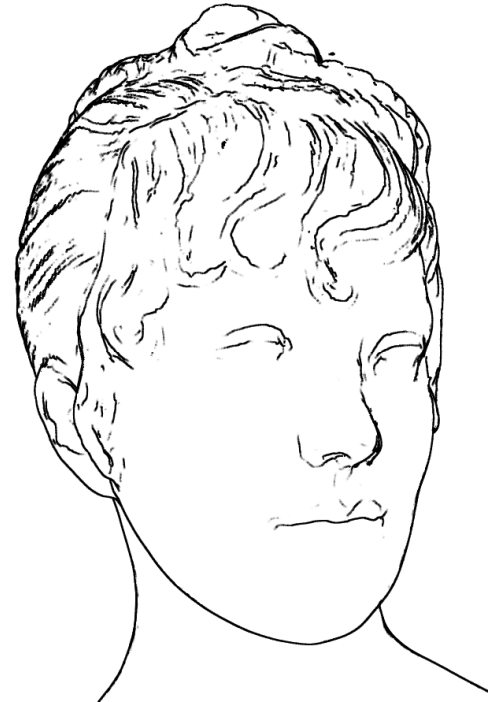
Traditional maximum
Curvature

Maximum
View-dependent Curvature
Larger at grazing angle

Line Comparison



Ridges & Valleys
extrema of curvature

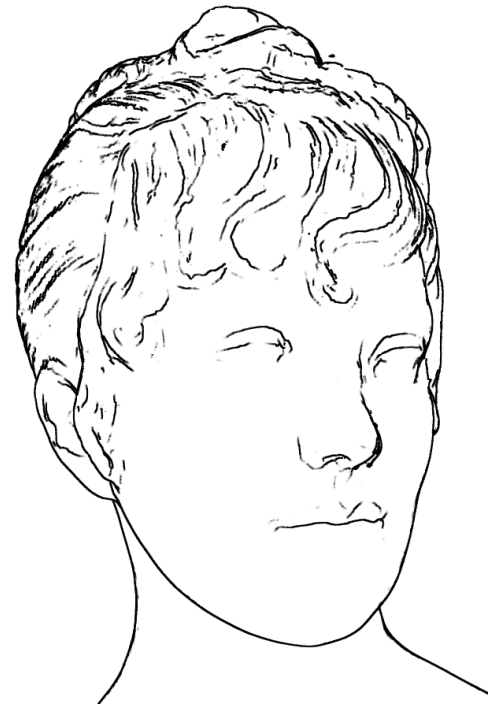


Apparent Ridges
extrema of view-dep curvature
Biased towards contour

Line Comparison



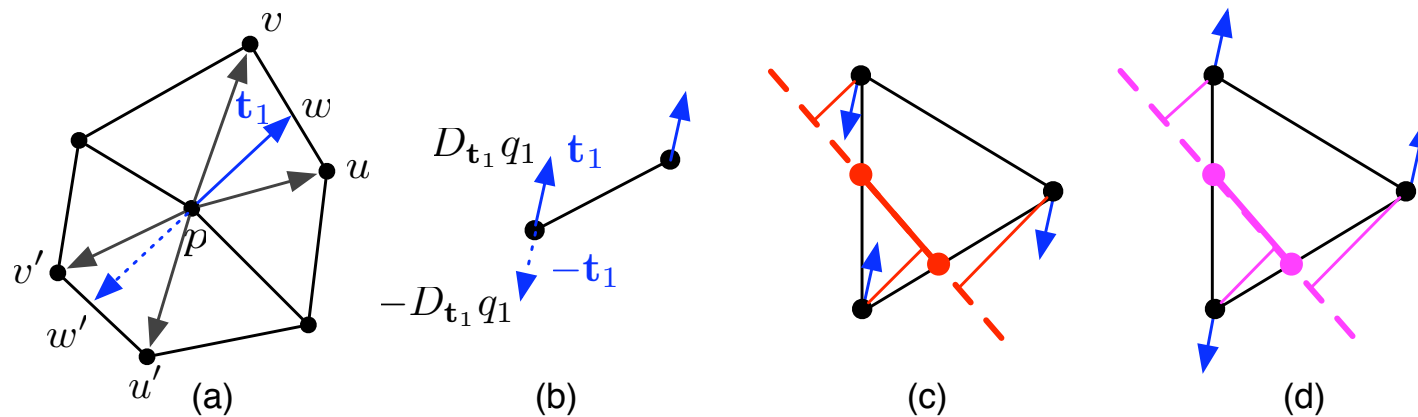
Ridges & Valleys
extrema of curvature



Apparent Ridges
extrema of view-dep curvature
Biased towards contour

Implementation

- Input: meshes
- combination of finite difference & orientation tests [Ohtake et al. 2004]
- See paper



Thresholding

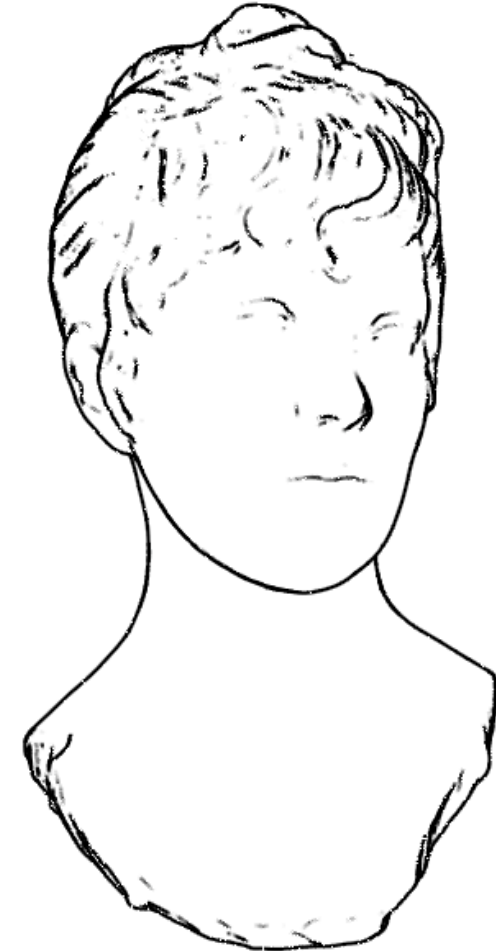
keep lines where view-dependent curvature $>$ threshold



Low threshold



Medium Threshold



High Threshold

Results

line drawing is a subjective study

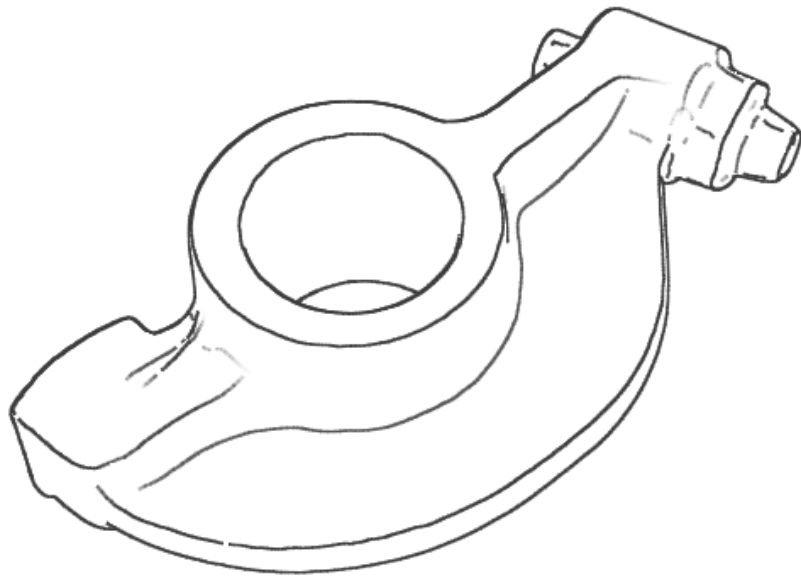
we choose threshold
to match amount of line

Results

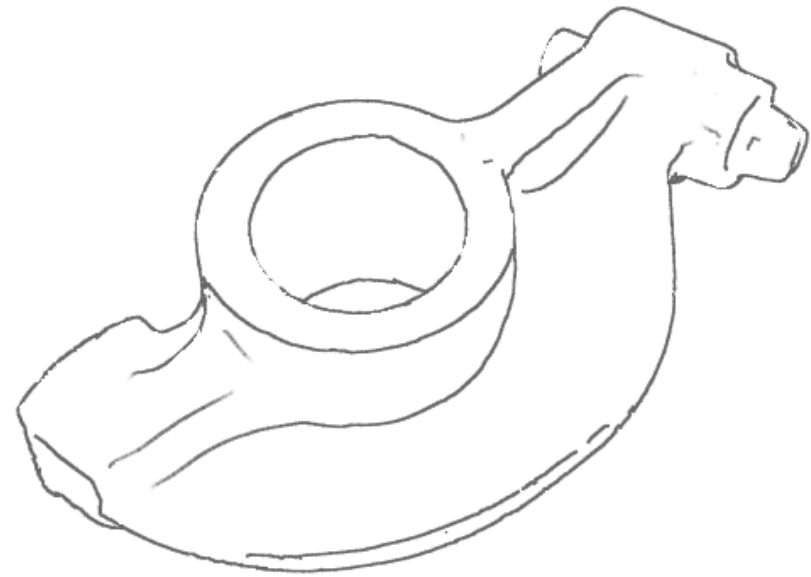
Apparent Ridges:

- include *contours*
- modify *ridges and valleys*
(*bias towards contour*)
- are different from *suggestive contours*

Comparison to Ridges and Valleys



Ridges & Valleys



Apparent Ridges

Where ridges and valleys do well, so do apparent ridges

Comparison to Ridges and Valleys



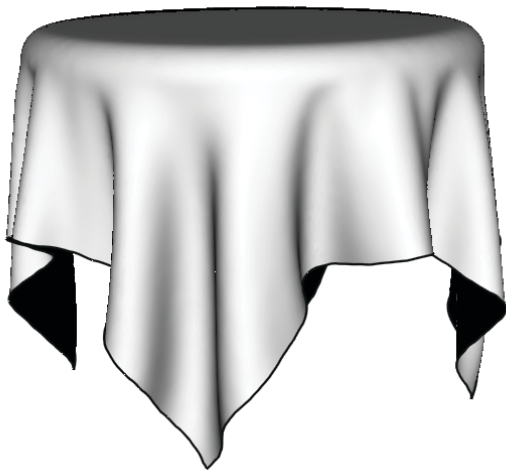
Ridges & Valleys



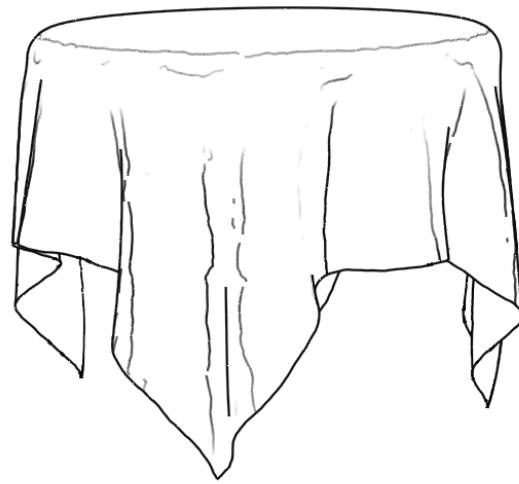
Apparent Ridges

Apparent ridges are less rigid and boxy

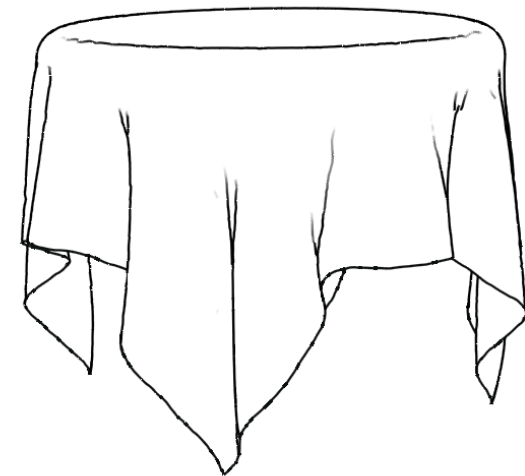
Comparison to Ridges and Valleys



Shaded view



Ridges & Valleys



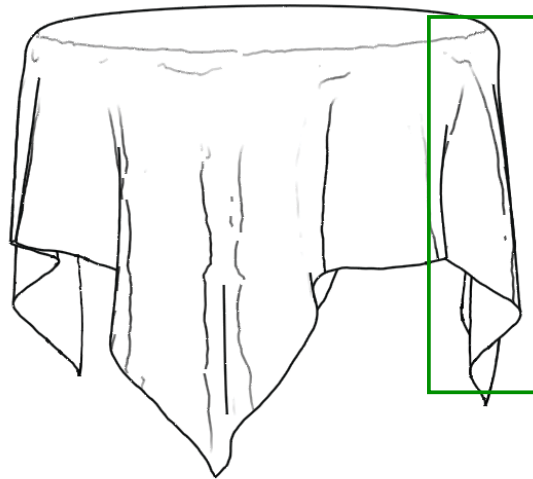
Apparent Ridges

Apparent ridges bias ridges and valleys towards the contour

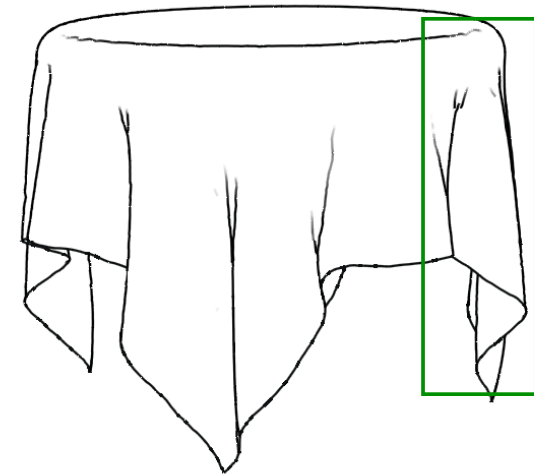
Comparison to Ridges and Valleys



Shaded view



Ridges & Valleys



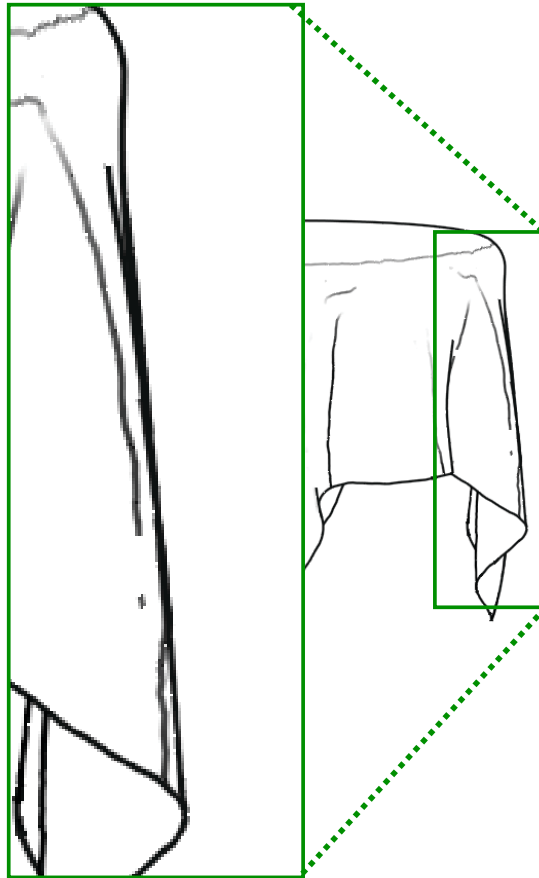
Apparent Ridges

Apparent ridges bias ridges and valleys towards the contour

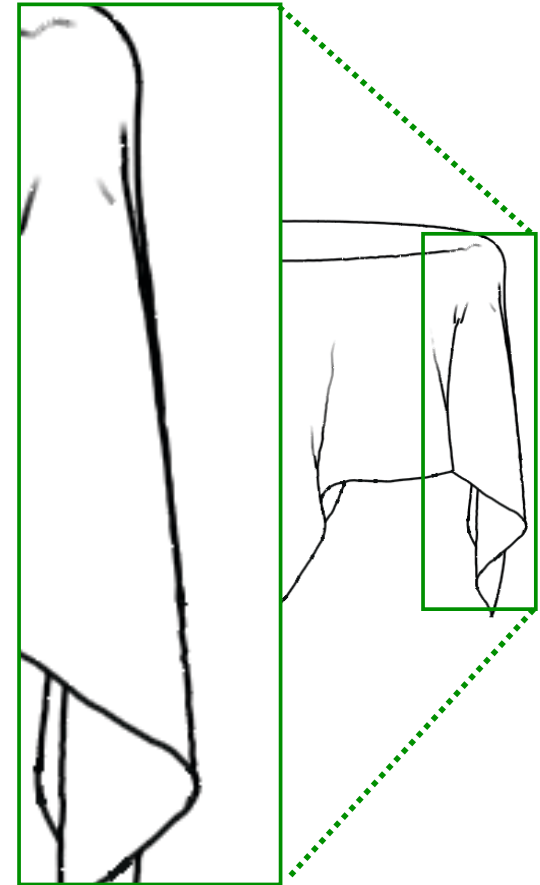
Comparison to Ridges and Valleys



Shaded view



Ridges & Valleys



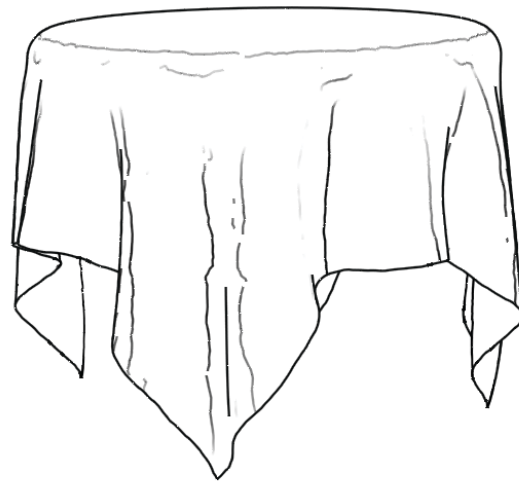
Apparent Ridges

Apparent ridges bias ridges and valleys towards the contour

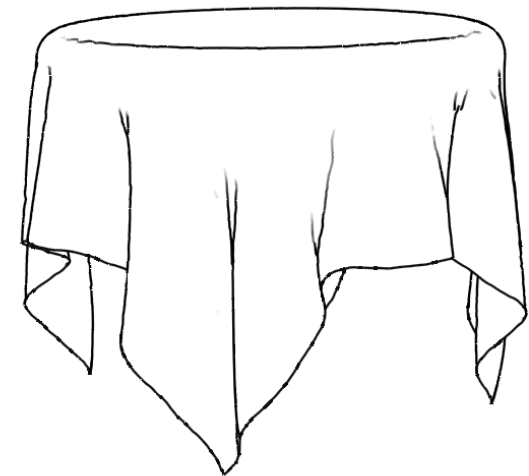
Comparison to Ridges and Valleys



Shaded view



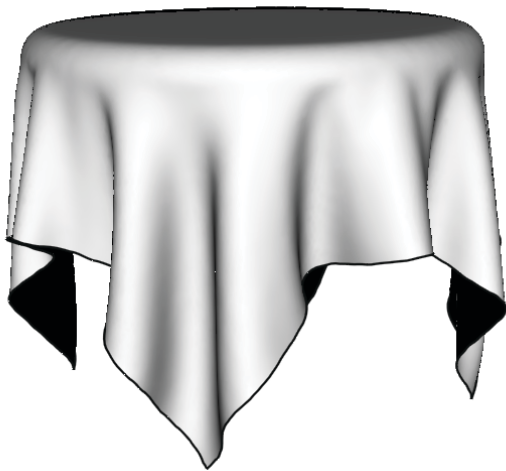
Ridges & Valleys



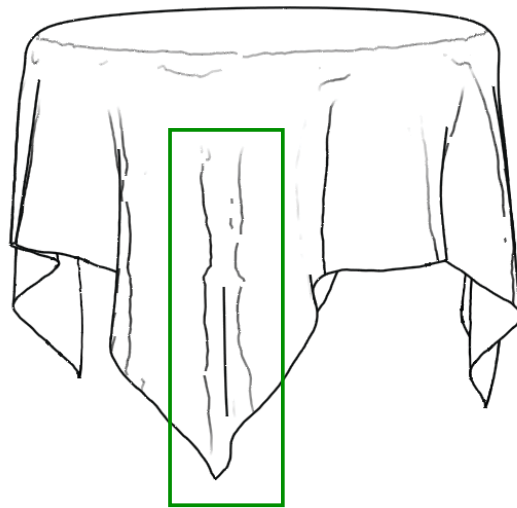
Apparent Ridges

Apparent ridges bias ridges and valleys towards the contour

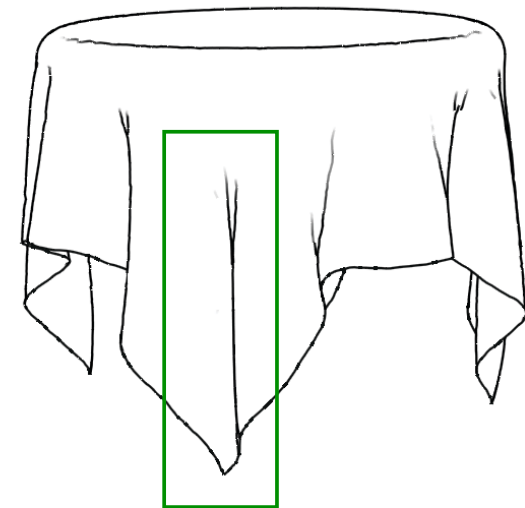
Comparison to Ridges and Valleys



Shaded view



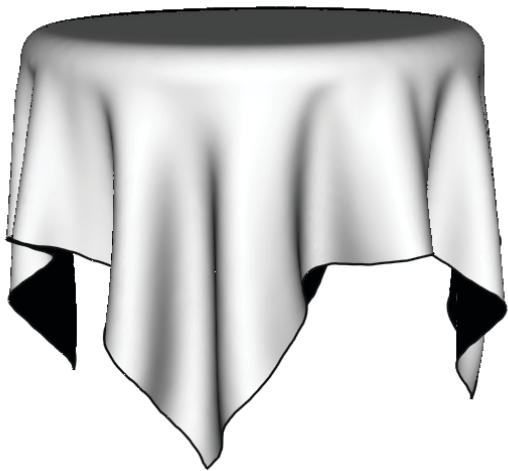
Ridges & Valleys



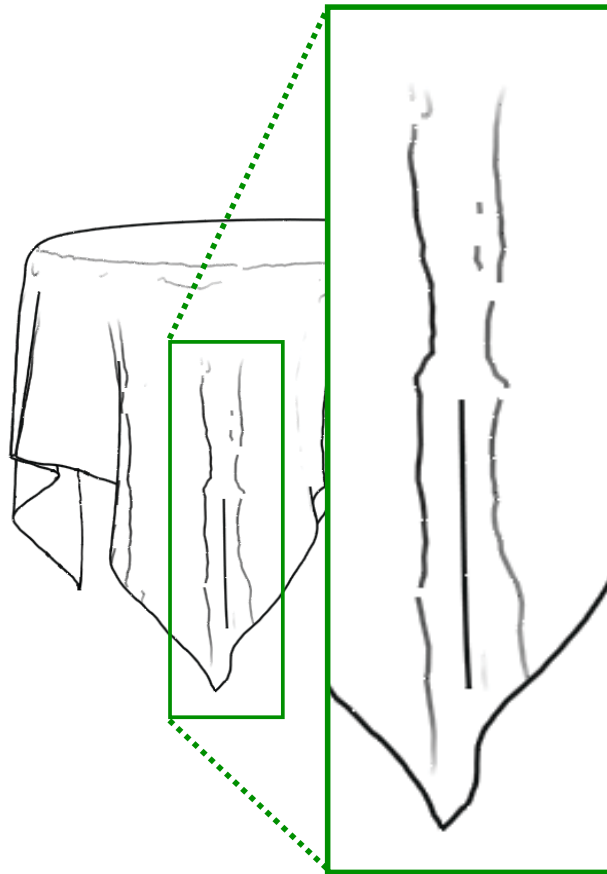
Apparent Ridges

Apparent ridges bias ridges and valleys towards the contour

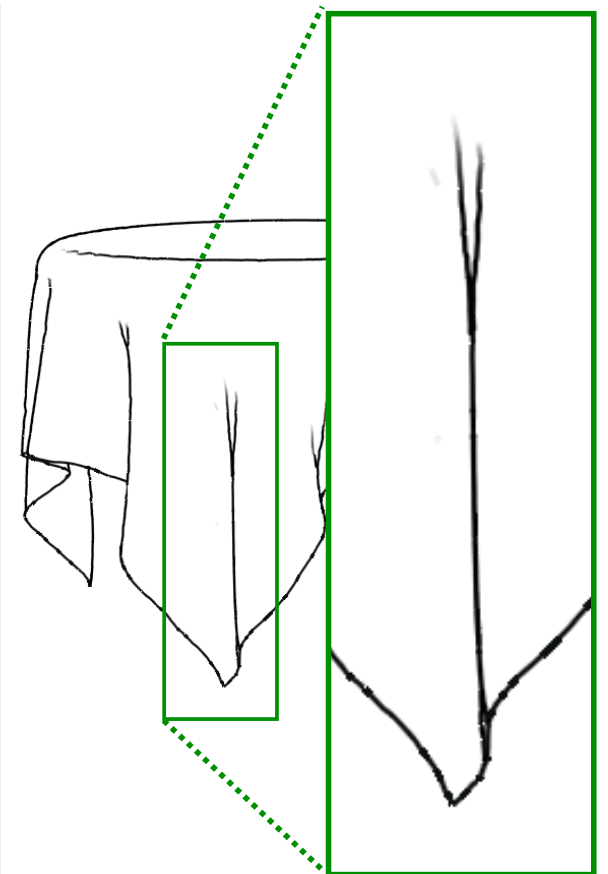
Comparison to Ridges and Valleys



Shaded view



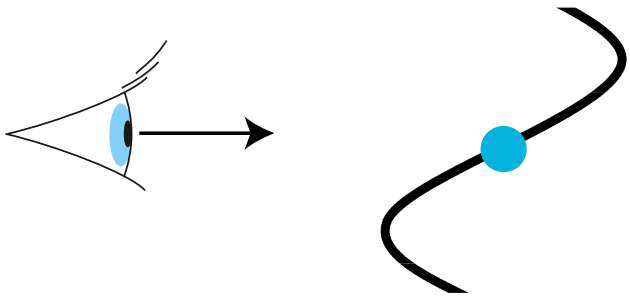
Ridges & Valleys



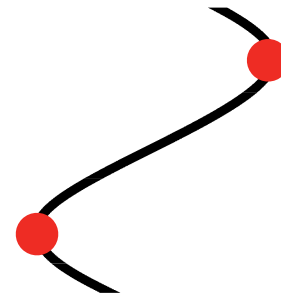
Apparent Ridges

Apparent ridges bias ridges and valleys towards the contour

Apparent Ridges are different from Suggestive Contours

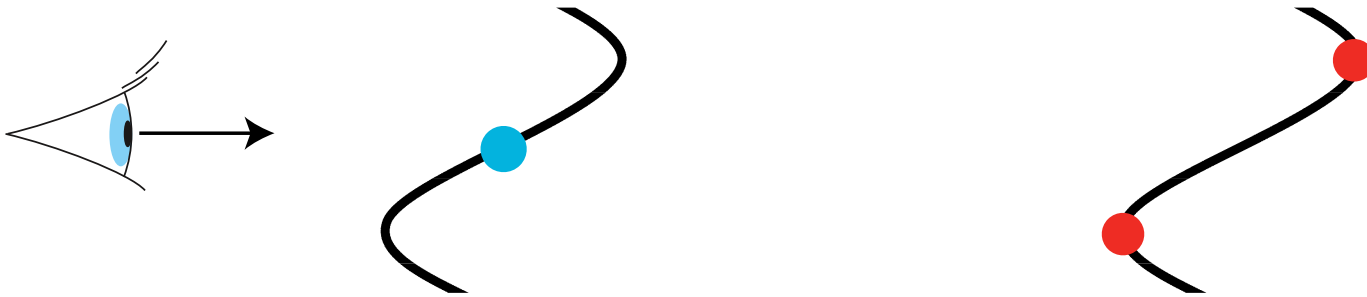


Suggestive Contours



Apparent Ridges

Apparent Ridges are different from Suggestive Contours



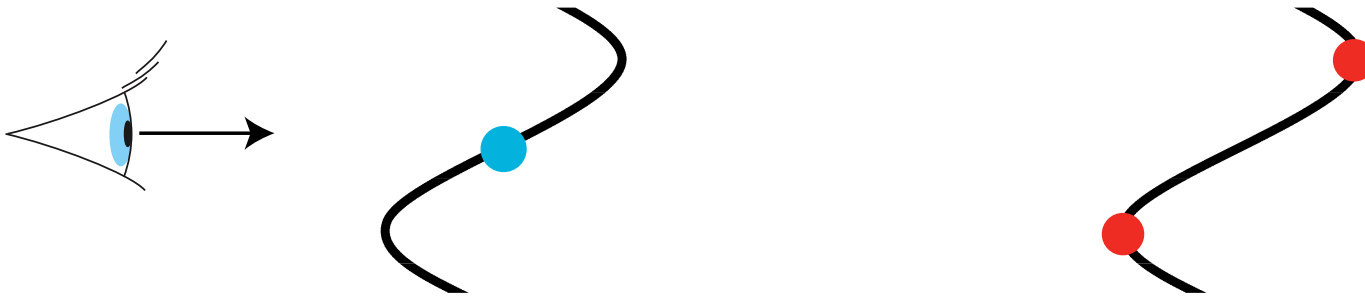
Suggestive Contours

variation of normal is 0

Apparent Ridges

variation of normal is *maximum*

Apparent Ridges are different from Suggestive Contours



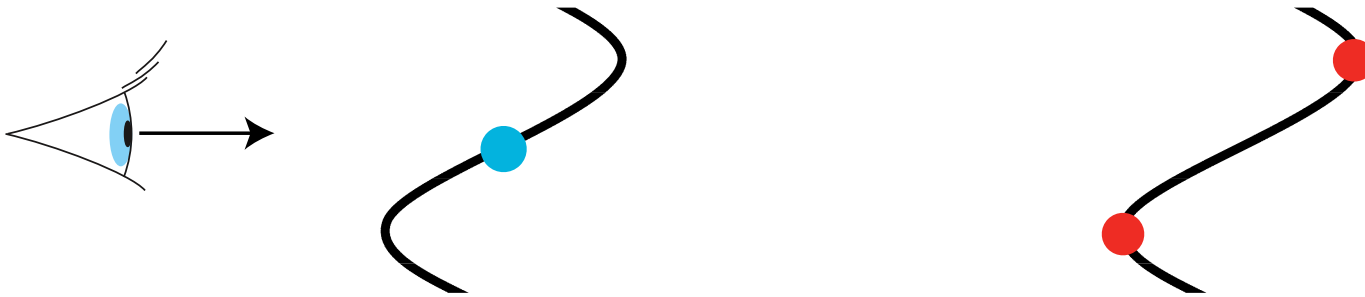
Suggestive Contours

variation of normal is 0
view direction

Apparent Ridges

variation of normal is *maximum*
max principal direction

Apparent Ridges are different from Suggestive Contours



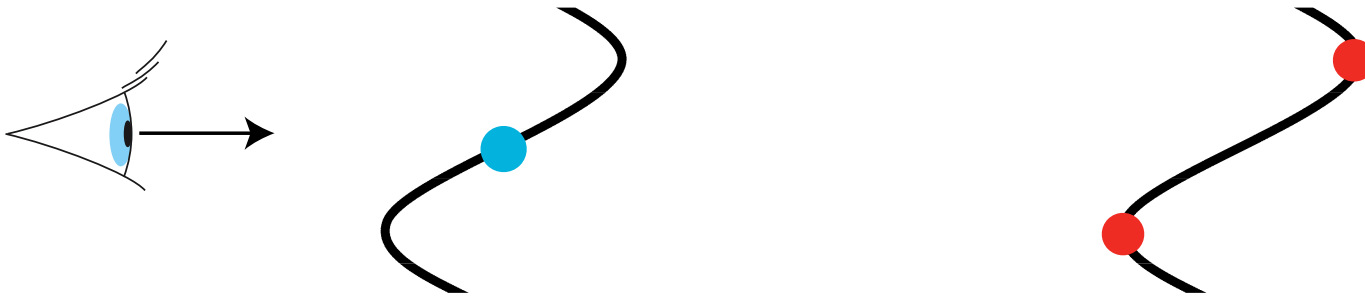
Suggestive Contours

variation of normal is 0
view direction
where image luminance is dark

Apparent Ridges

variation of normal is *maximum*
max principal direction
at rapid luminance variation

Apparent Ridges are different from Suggestive Contours



Suggestive Contours

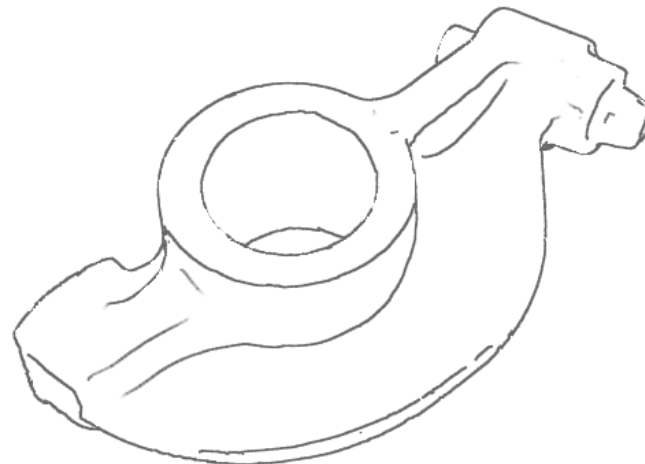
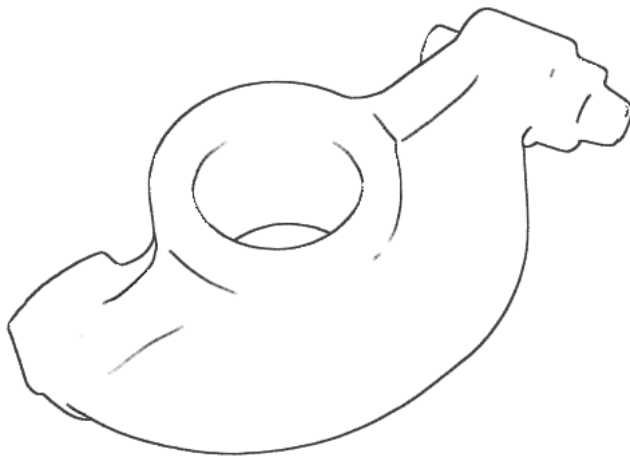
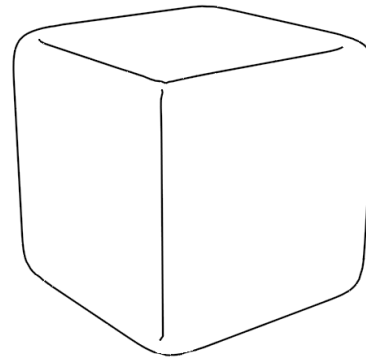
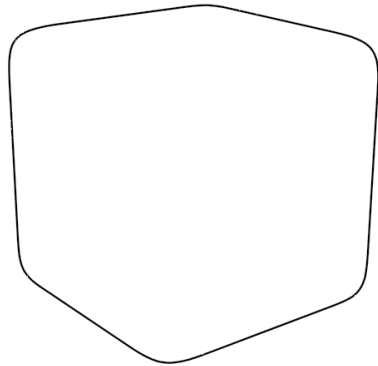
variation of normal is 0
view direction
where image luminance is dark

Apparent Ridges

variation of normal is *maximum*
max principal direction
at rapid luminance variation

both provide interesting set of lines

Comparison to Suggestive Contours

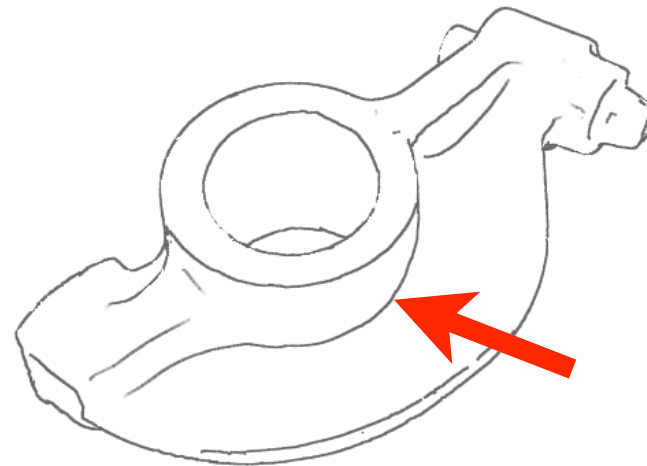
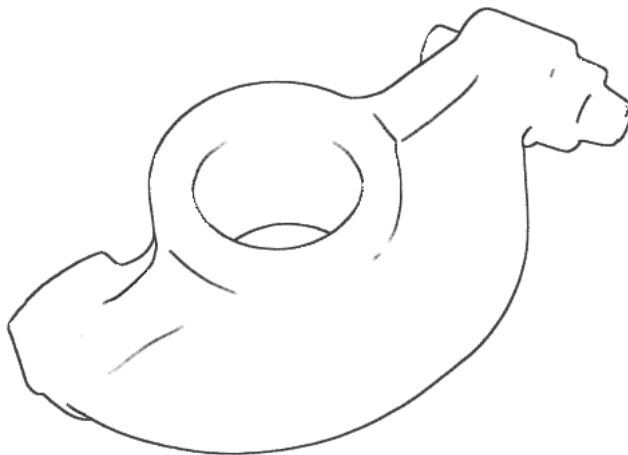
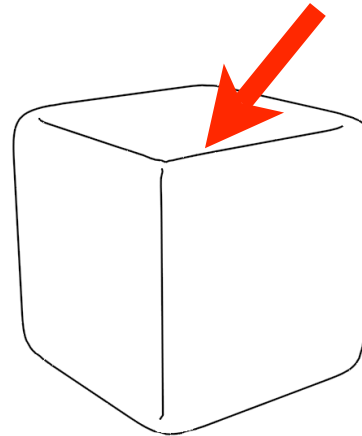
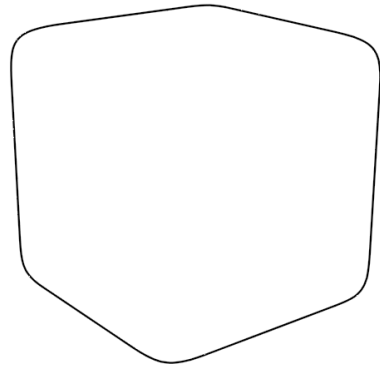


Suggestive Contours

Apparent Ridges

Apparent ridges exist in convex regions of the shape

Comparison to Suggestive Contours



Suggestive Contours

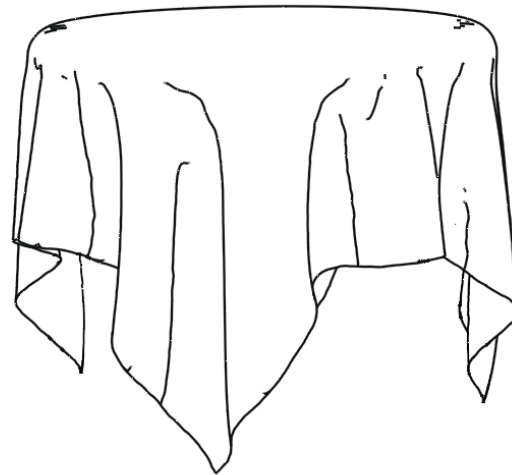
Apparent Ridges

Apparent ridges exist in convex regions of the shape

Comparison to Suggestive Contours

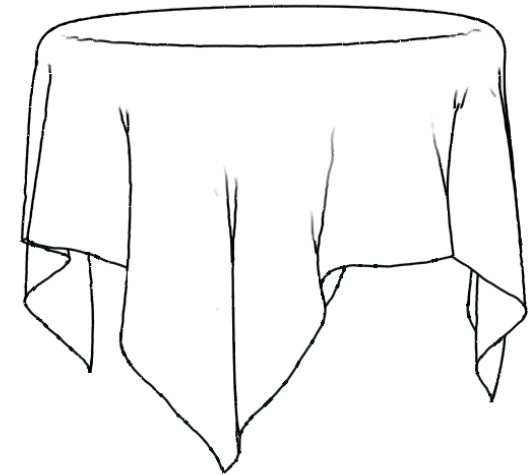


Shaded view



Suggestive Contours

where luminance
is dark



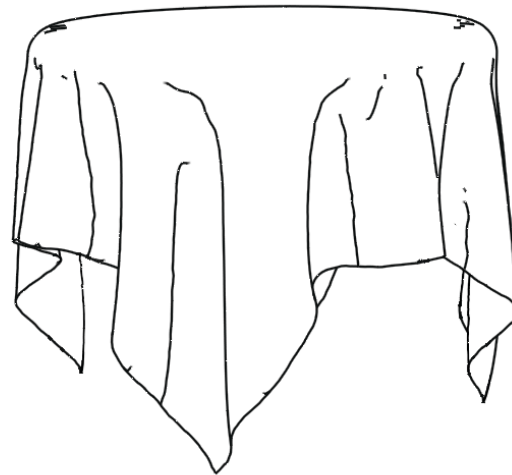
Apparent Ridges

at rapid change in
luminance

Comparison to Suggestive Contours

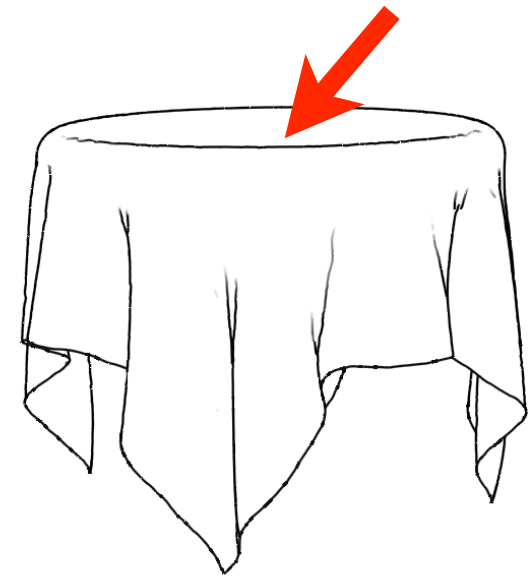


Shaded view



Suggestive Contours

where luminance
is dark



Apparent Ridges

at rapid change in
luminance

Comparison to Suggestive Contours



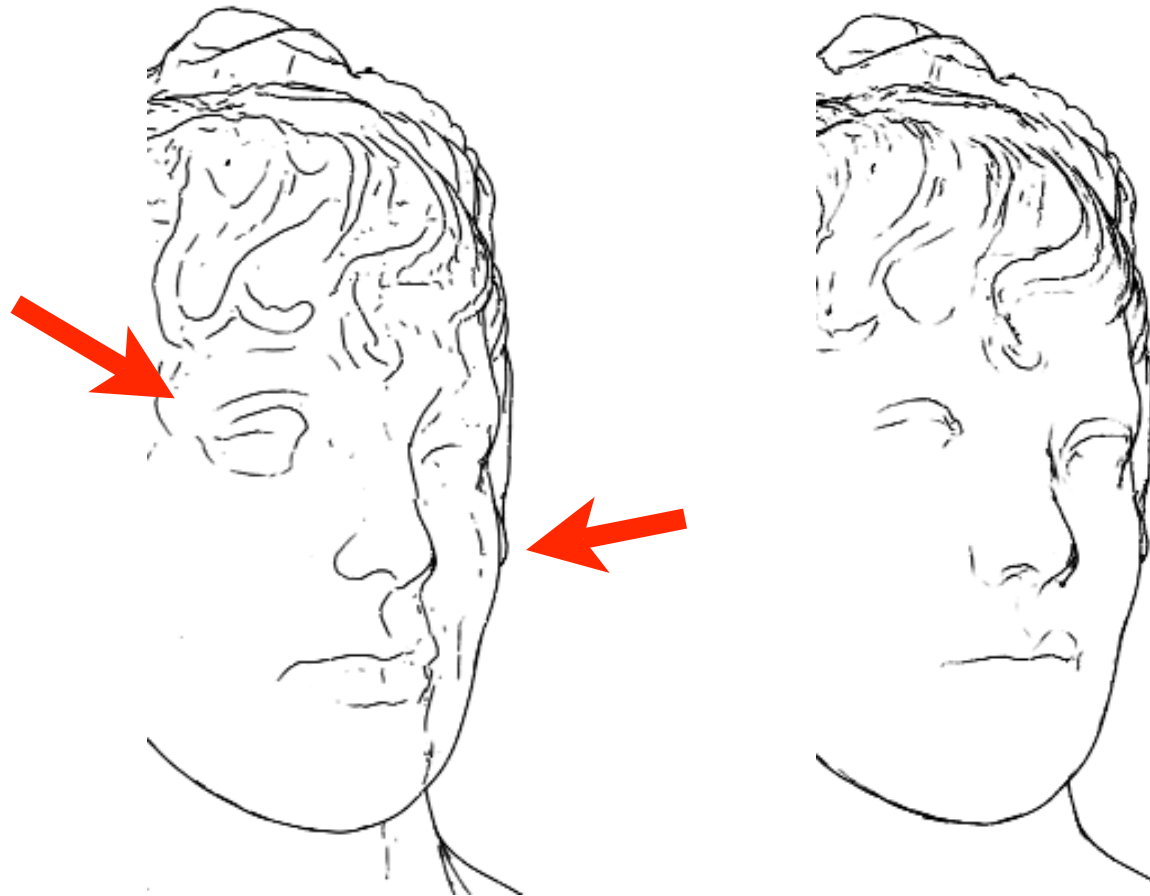
Suggestive Contours



Apparent Ridges

Apparent ridges create more natural images

Comparison to Suggestive Contours

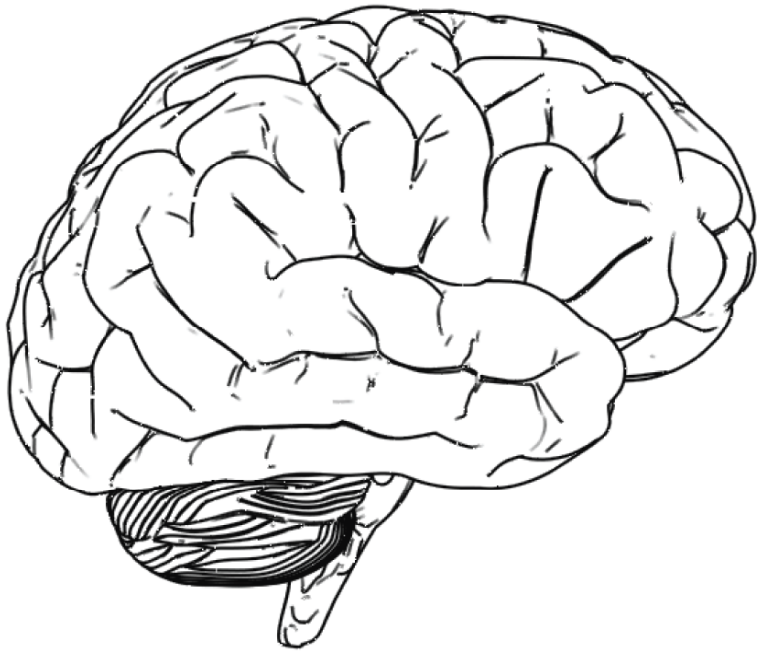


Suggestive Contours

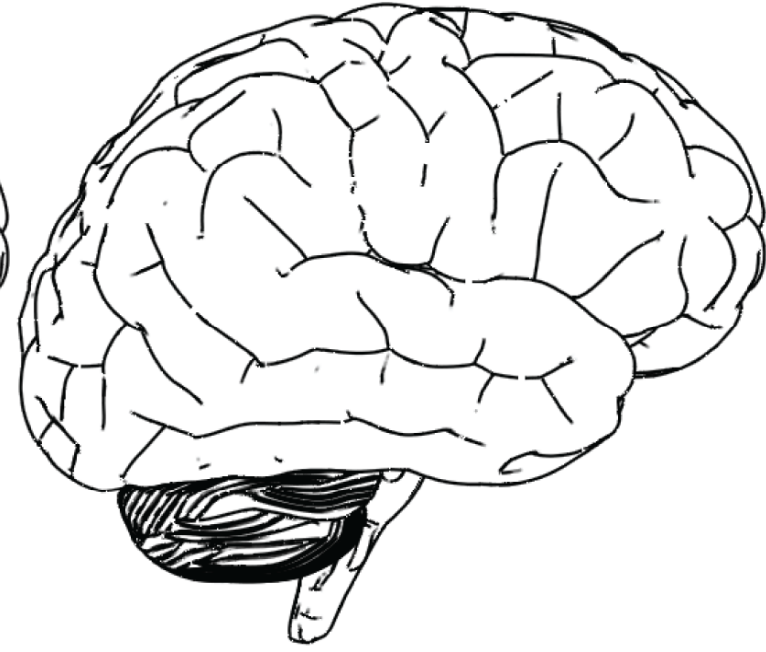
Apparent Ridges

Apparent ridges create more natural images

Comparison to Suggestive Contours



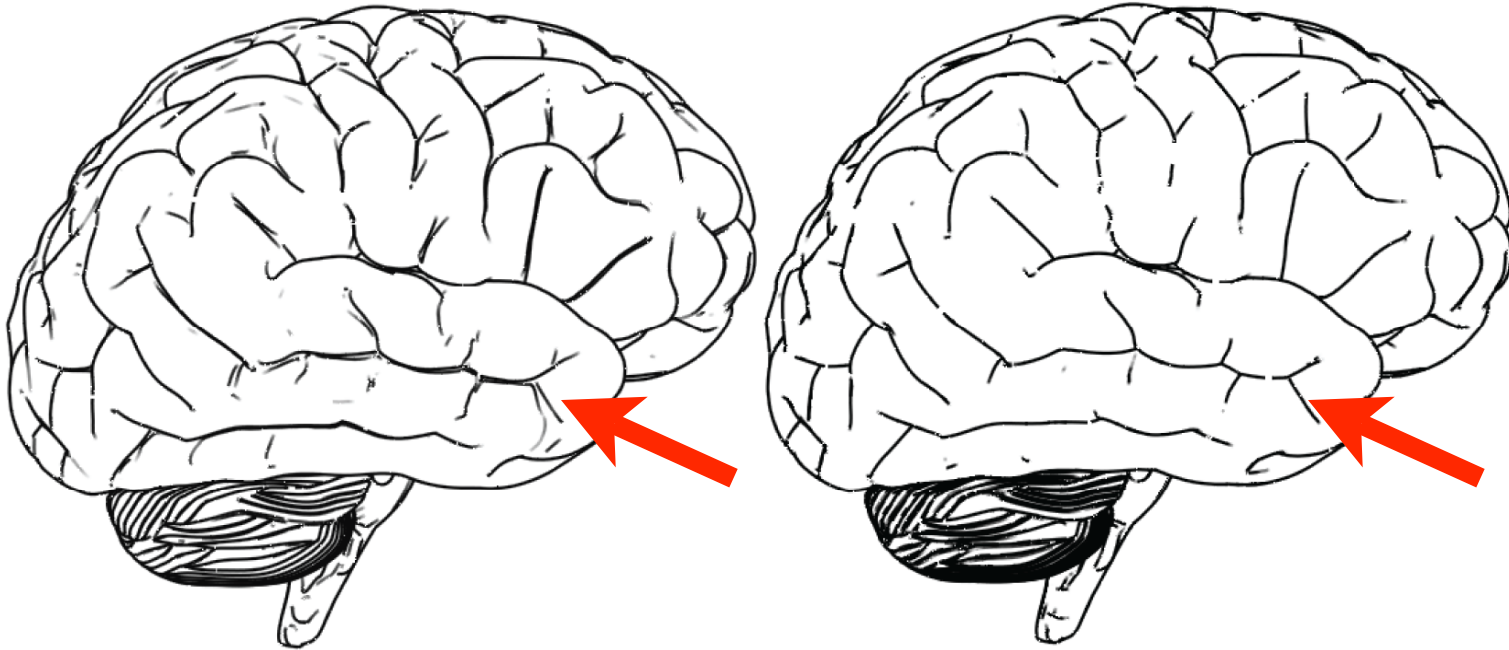
Suggestive Contours



Apparent Ridges

Trade situations where one or two lines are drawn

Comparison to Suggestive Contours

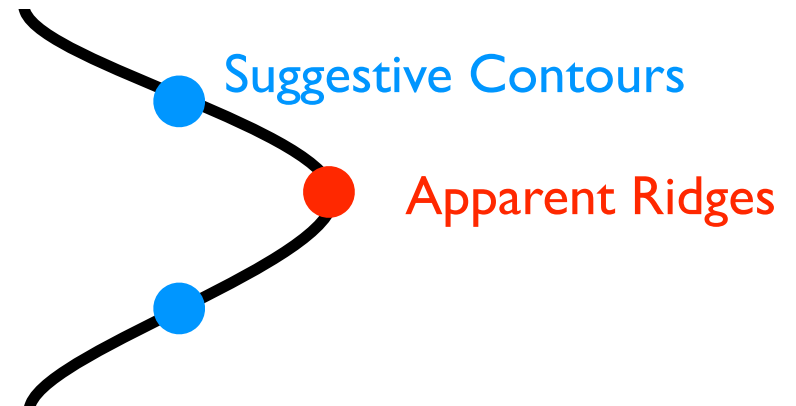
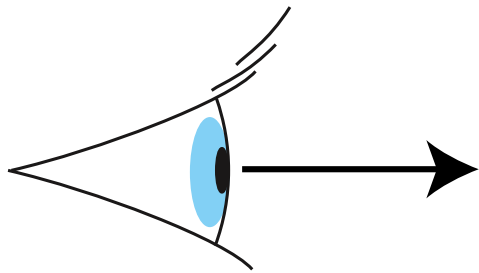


Suggestive Contours

Apparent Ridges

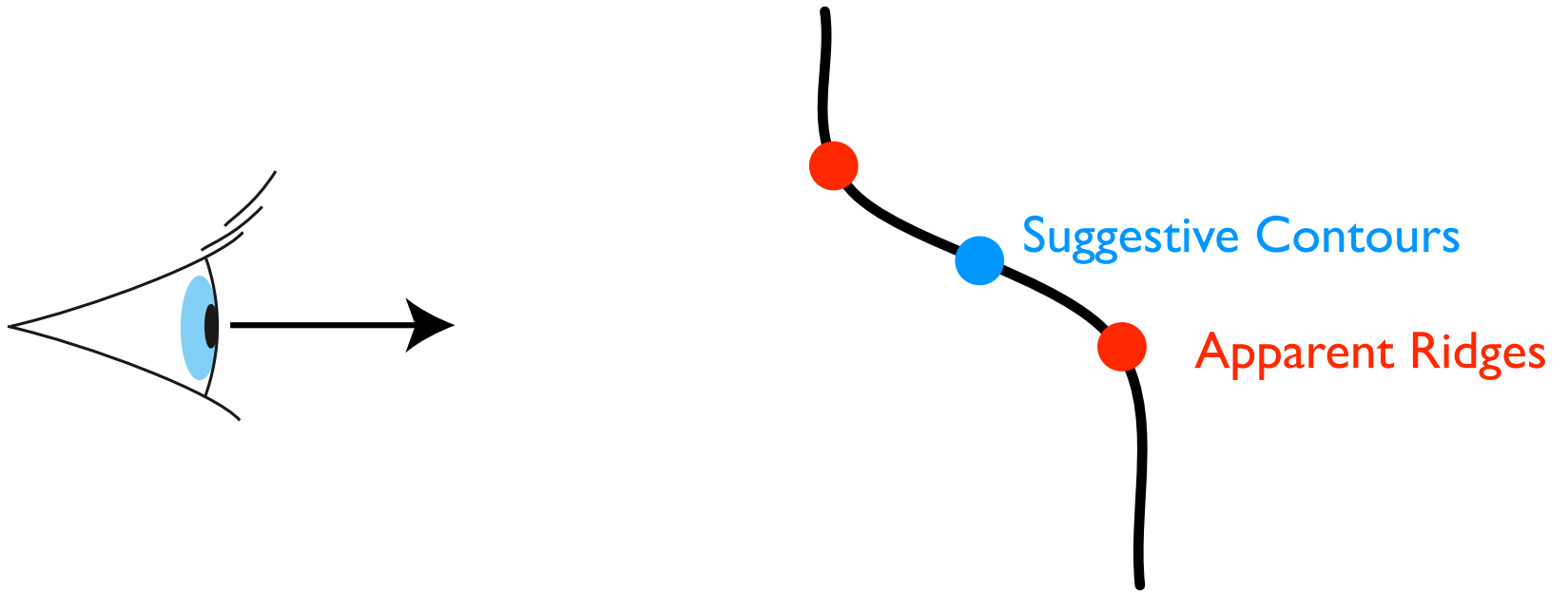
Trade situations where one or two lines are drawn

Comparison to Suggestive Contours



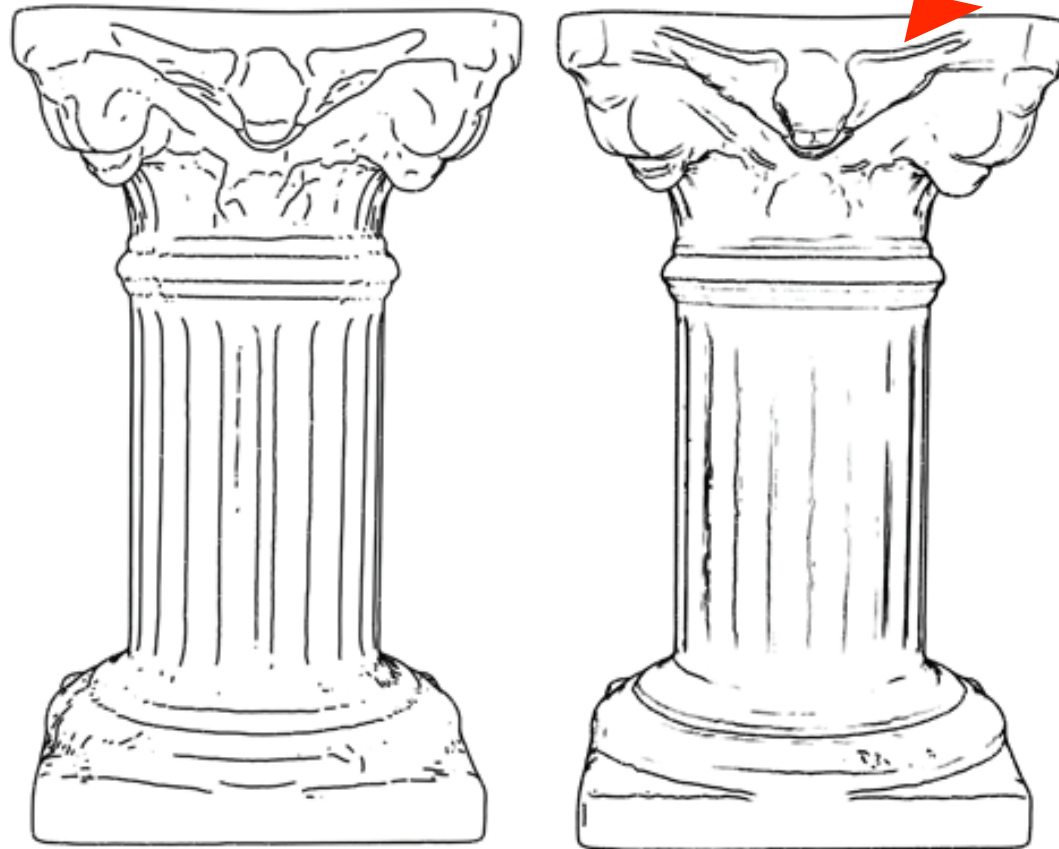
Trade situations where one or two lines are drawn

Comparison to Suggestive Contours



Trade situations where one or two lines are drawn

Comparison to Suggestive Contours

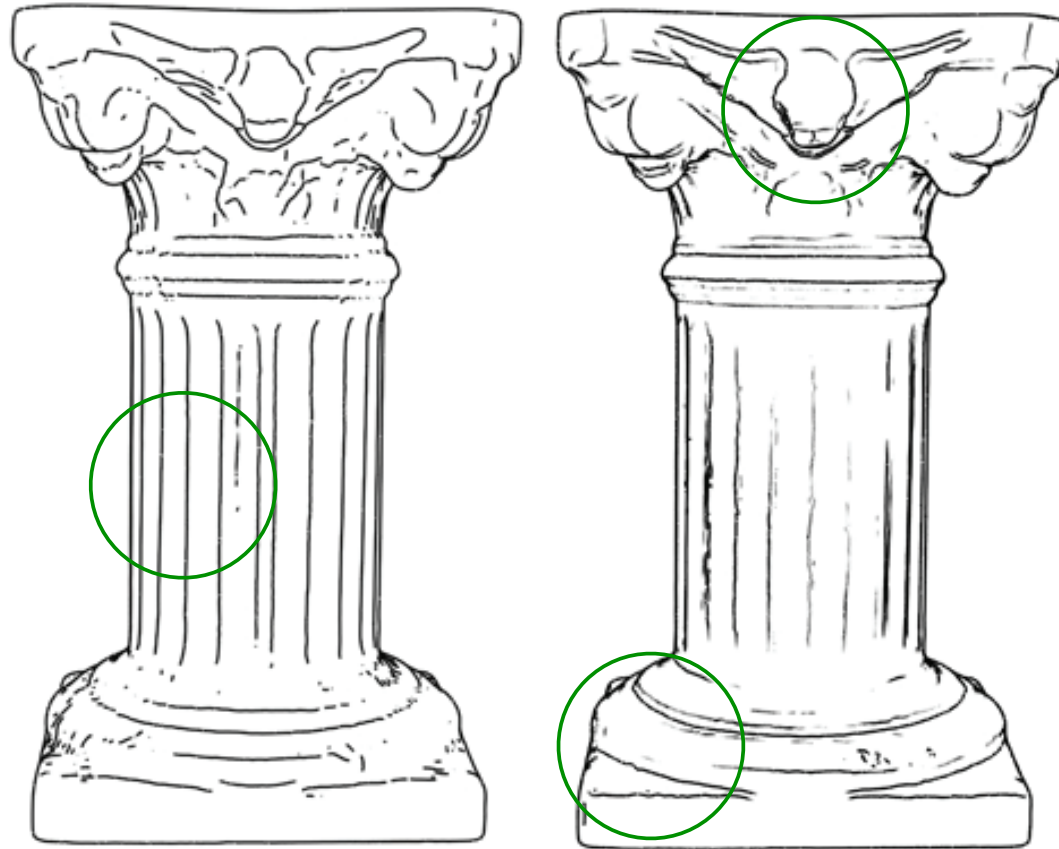


Suggestive Contours

Apparent Ridges

Trade situations where one or two lines are drawn

Comparison to Suggestive Contours

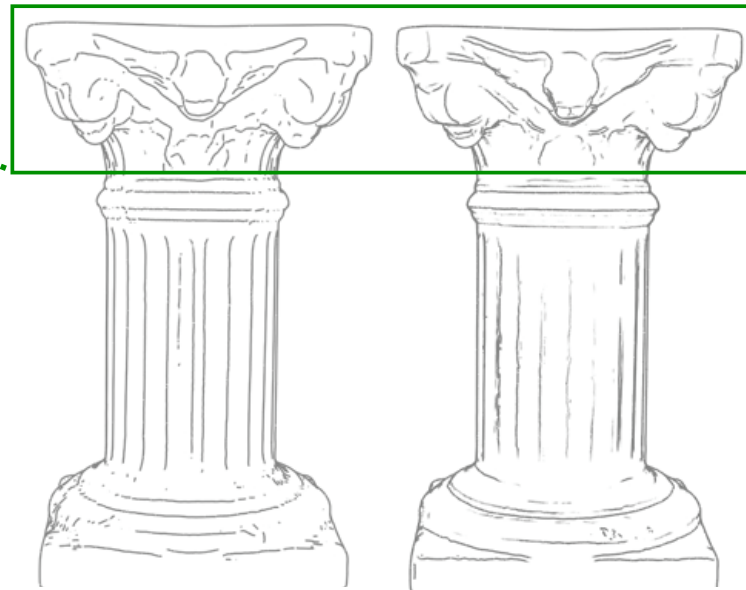
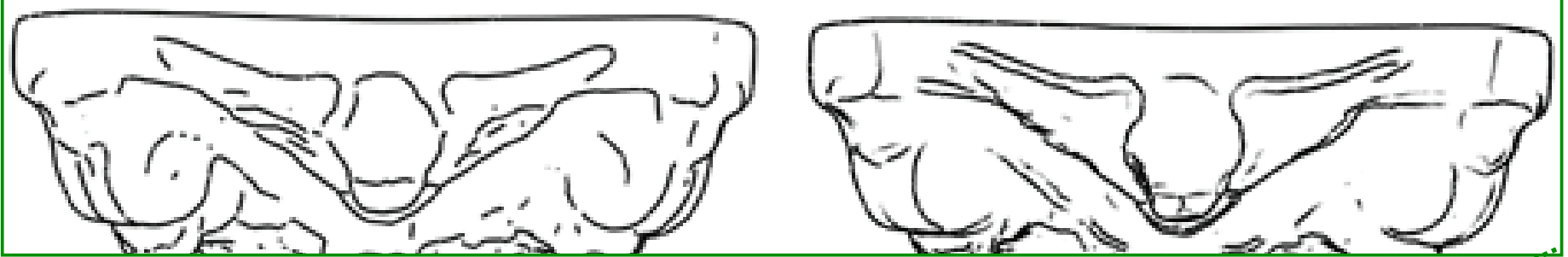


Suggestive Contours

Apparent Ridges

Sometimes difficult to say which is better

Comparison to Suggestive Contours

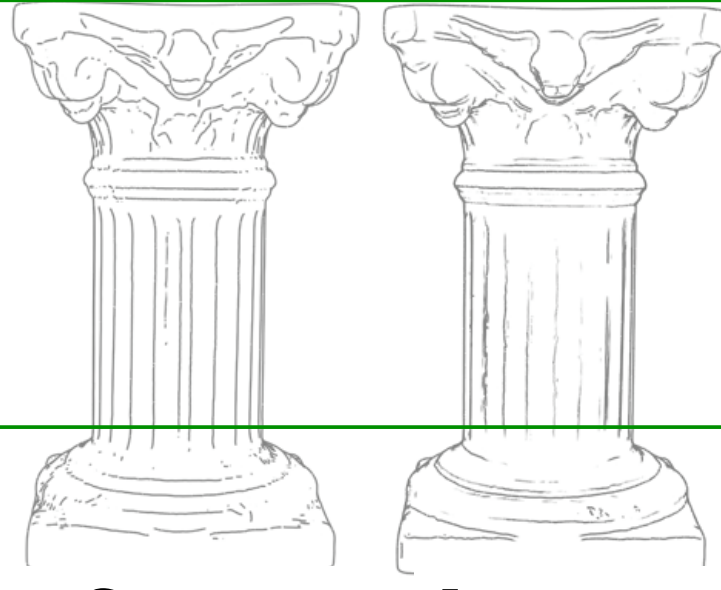
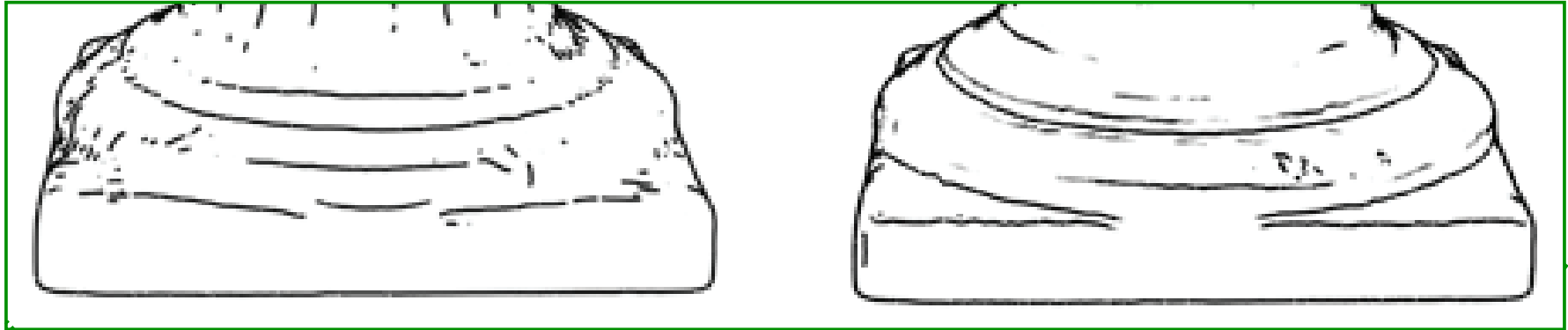


Suggestive Contours

Apparent Ridges

Sometimes difficult to say which is better

Comparison to Suggestive Contours

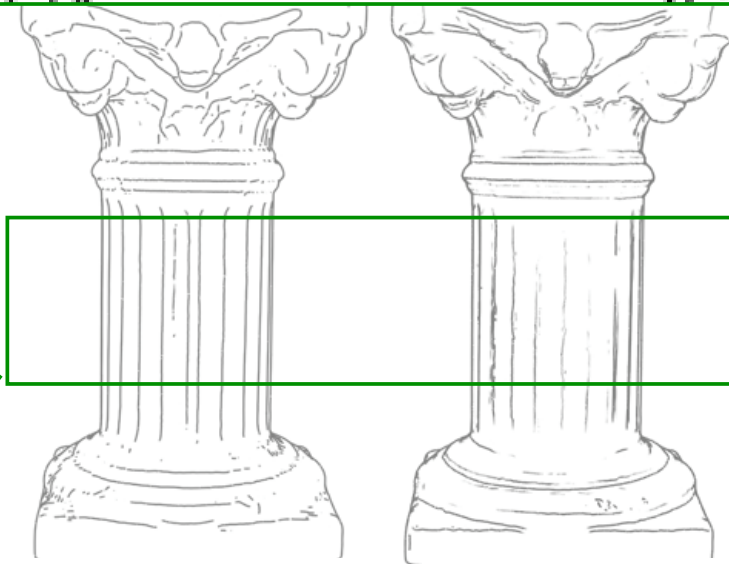


Suggestive Contours

Apparent Ridges

Sometimes difficult to say which is better

Comparison to Suggestive Contours

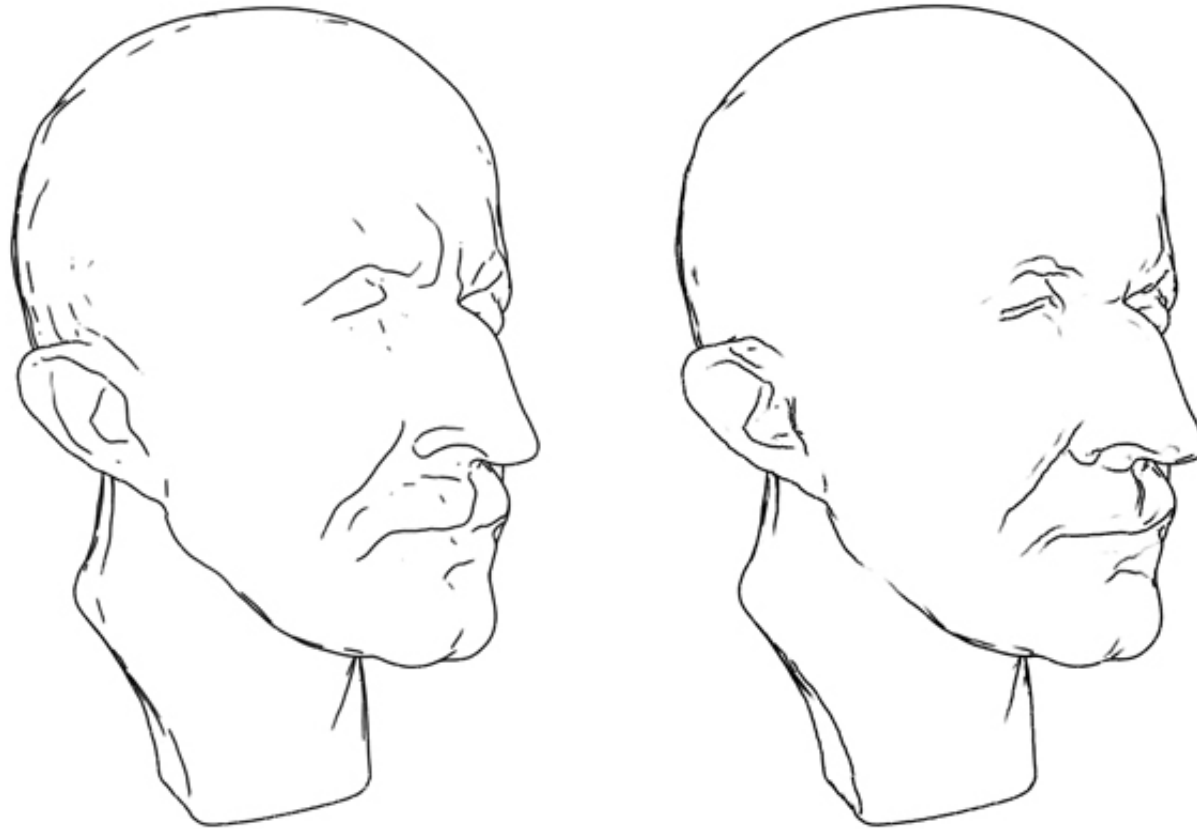


Suggestive Contours

Apparent Ridges

Sometimes difficult to say which is better

Comparison to Suggestive Contours

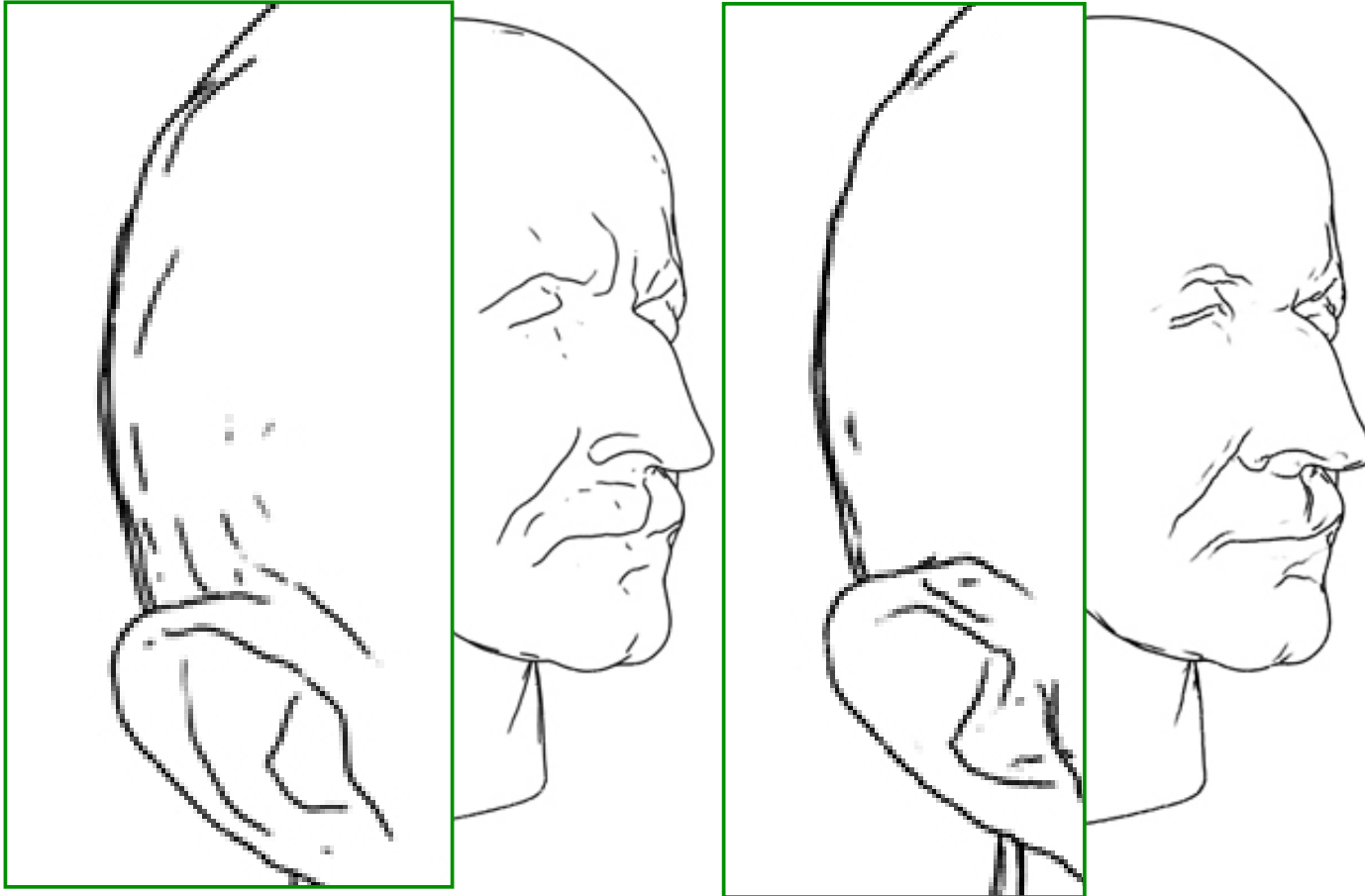


Suggestive Contours

Apparent Ridges

Sometimes difficult to say which is better

Comparison to Suggestive Contours

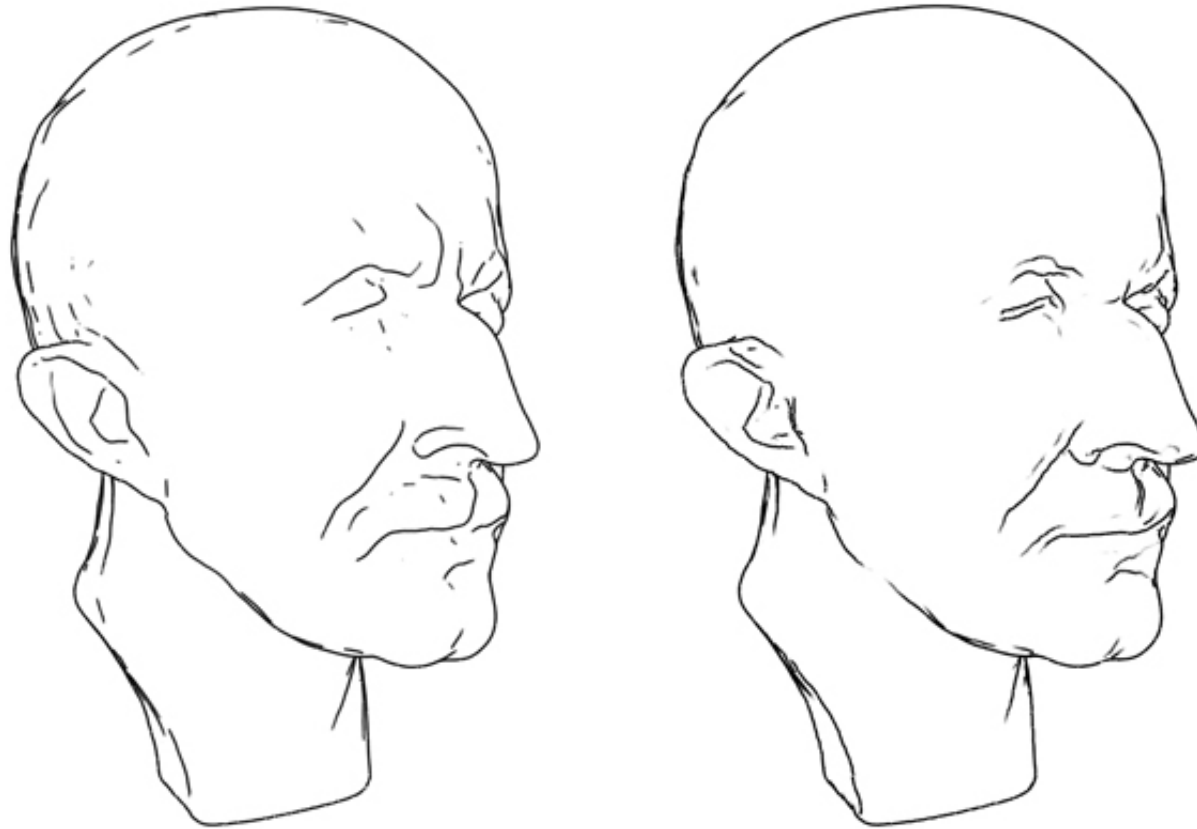


Suggestive Contours

Apparent Ridges

Sometimes difficult to say which is better

Comparison to Suggestive Contours

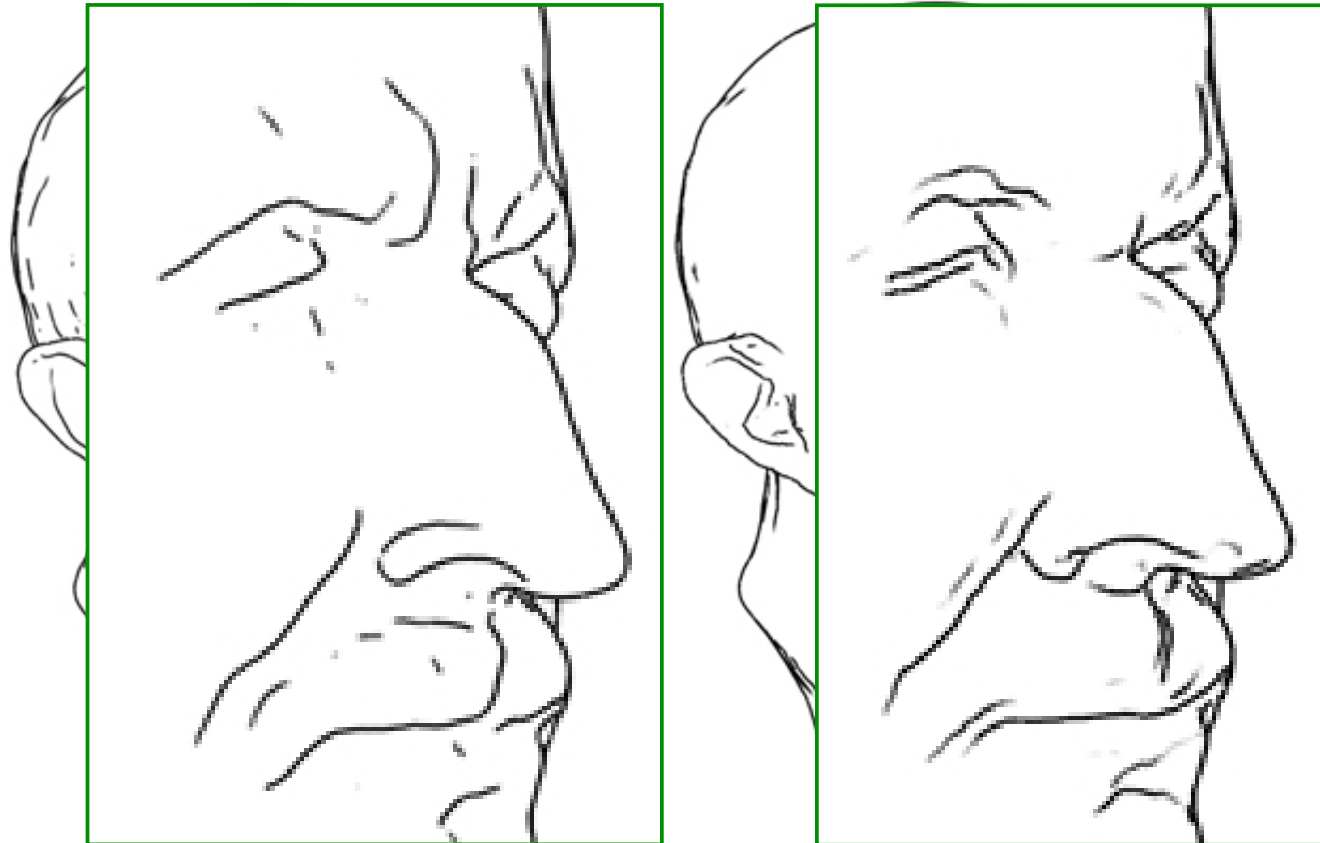


Suggestive Contours

Apparent Ridges

Sometimes difficult to say which is better

Comparison to Suggestive Contours



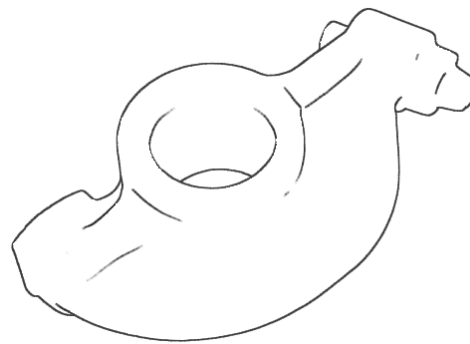
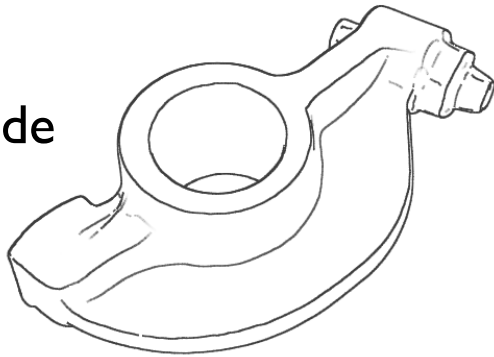
Suggestive Contours **Apparent Ridges**

Sometimes difficult to say which is better

Apparent Ridges are Versatile

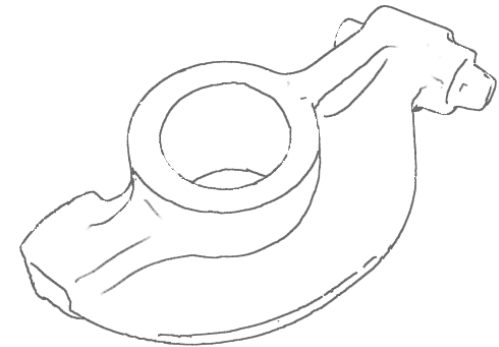
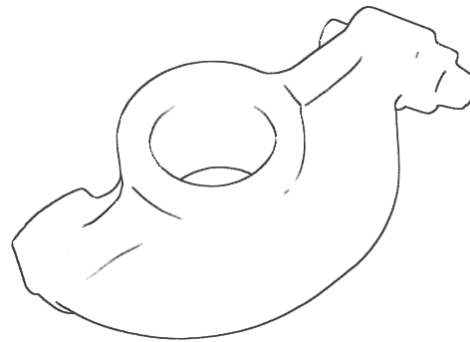
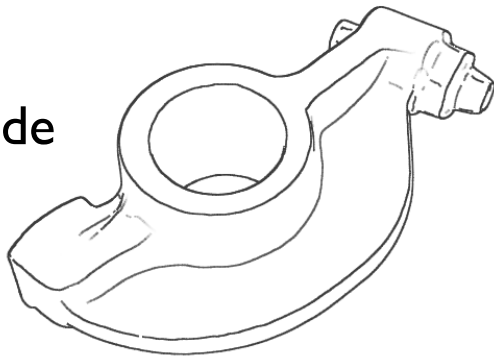
Apparent Ridges are Versatile

Man made



Apparent Ridges are Versatile

Man made



Natural



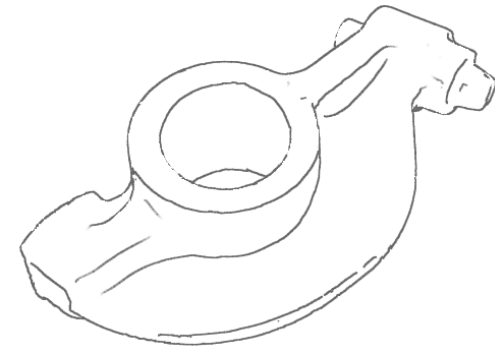
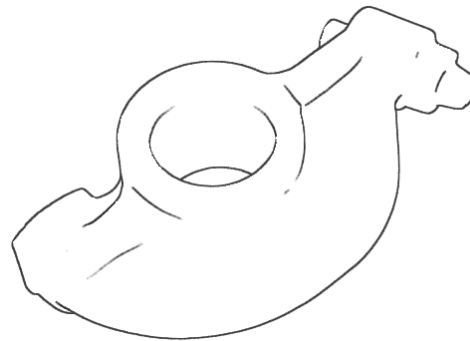
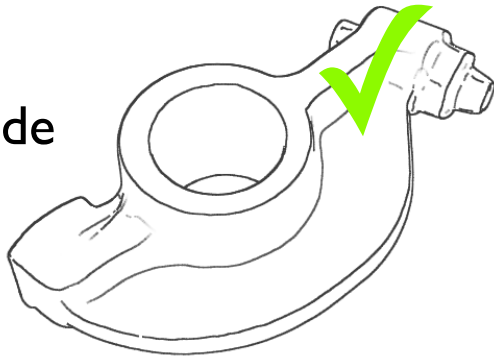
Ridges & Valleys

Suggestive Contours

Apparent Ridges

Apparent Ridges are Versatile

Man made



Natural



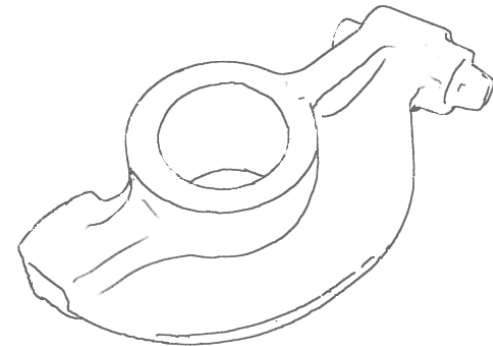
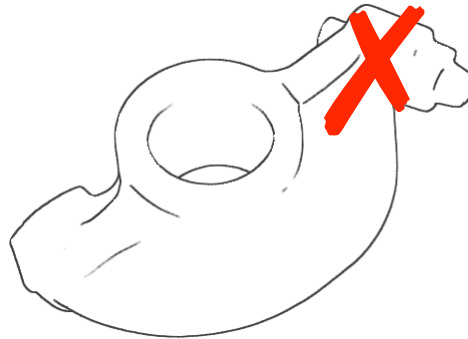
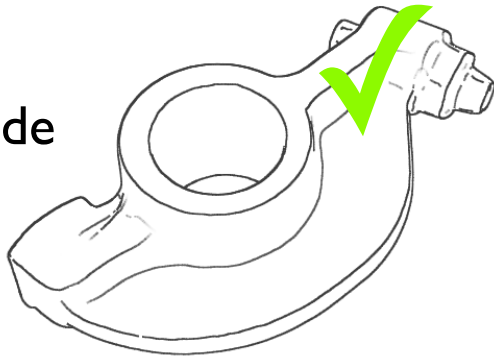
Ridges & Valleys

Suggestive Contours

Apparent Ridges

Apparent Ridges are Versatile

Man made



Natural



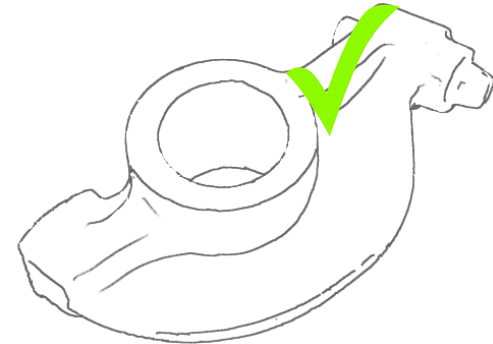
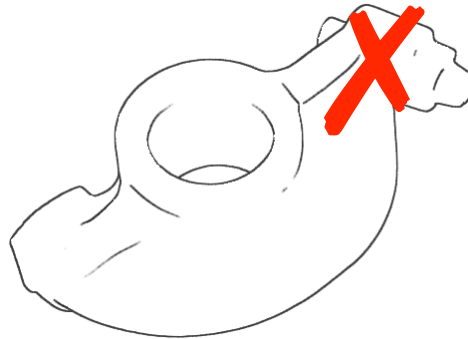
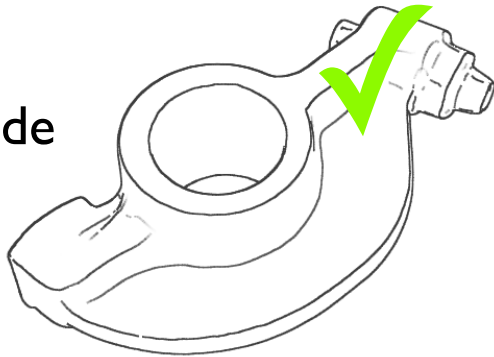
Ridges & Valleys

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Apparent Ridges

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Natural



Ridges & Valleys



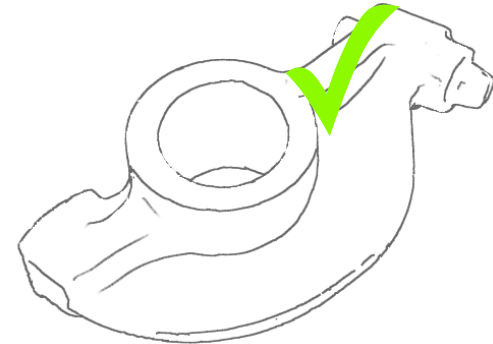
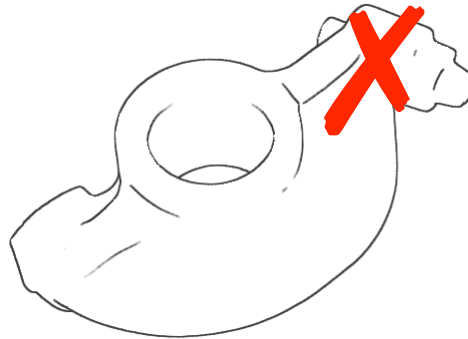
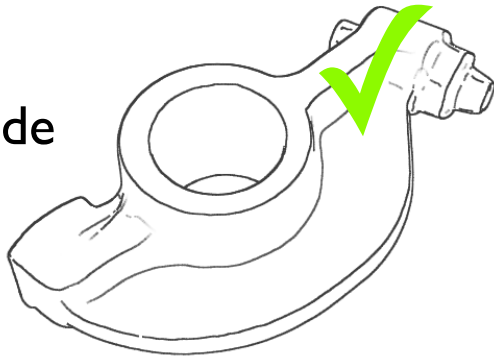
Suggestive Contours



Apparent Ridges

Apparent Ridges are Versatile

Man made



Natural



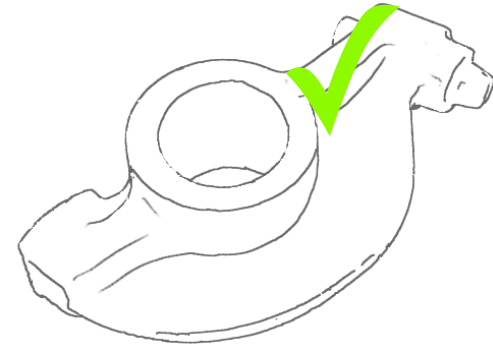
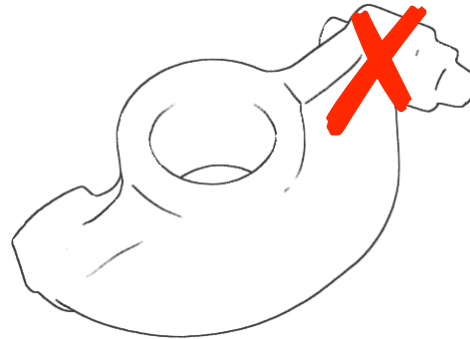
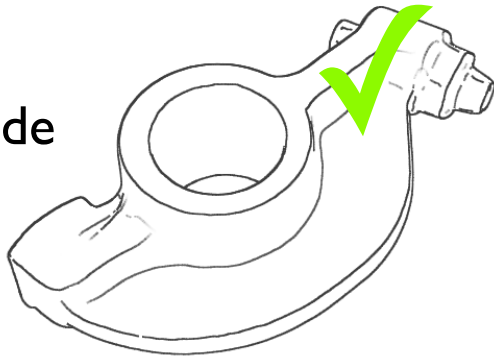
Ridges & Valleys

Suggestive Contours

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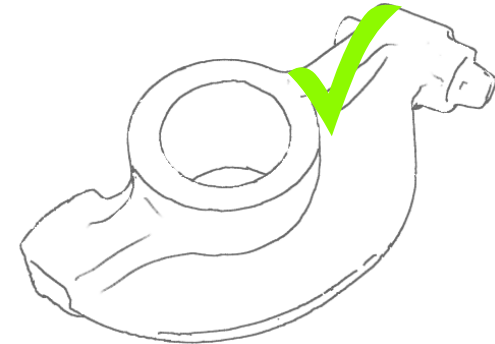
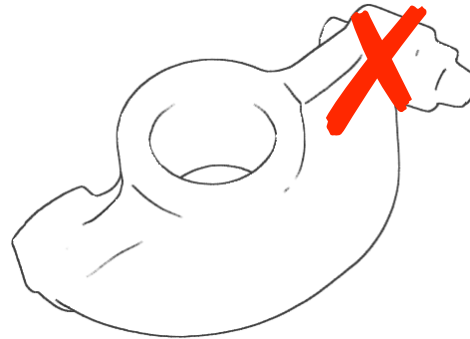
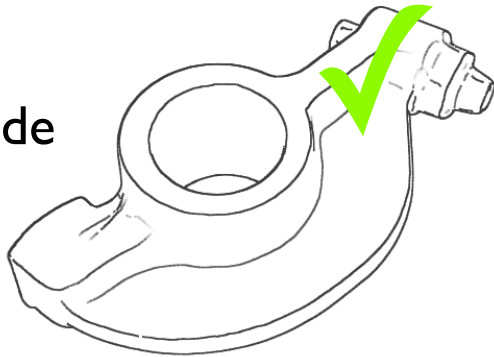
Ridges & Valleys

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Natural



Ridges & Valleys

Suggestive Contours

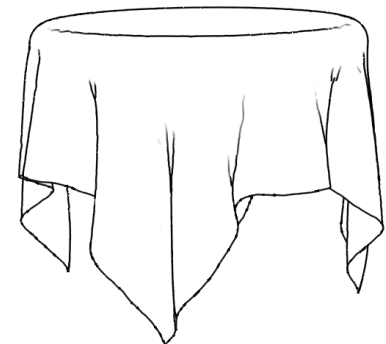
Apparent Ridges

Discussion & limitations

- Potentially noisy due to 2nd order derivative
- More costly than other lines
- Limitations shared with other lines
 - Thresholding sometimes eliminates good detail
 - Fair comparison is hard (user study)

Summary: Apparent Ridges

- Perceptual motivation:
rapid changes in luminance
- Simple change from ridges & valleys
 - variation of normal with respect to screen, not object space
 - bias towards contour
- Different from suggestive contours
 - higher order of derivative
 - rapid luminance variation vs dark regions
 - lines in convex regions
- Versatile



Questions?

Acknowledgments

NSF CAREER award 0447561

NSF Grant No. 0429739

Microsoft Research New Faculty Fellowship

Sloan Fellowship

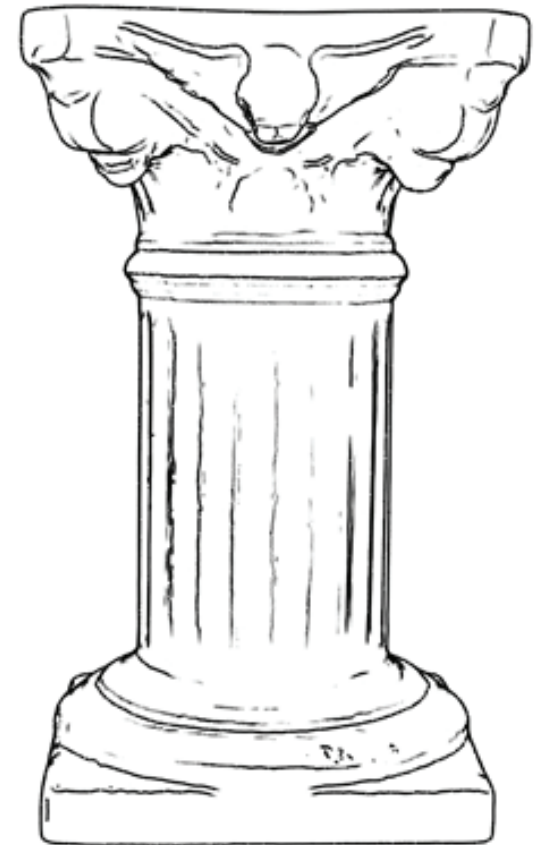
NSF graduate fellowship

Szymon Rusinkiewicz and Doug DeCarlo

for *rtsc* software

Yann LeTallec

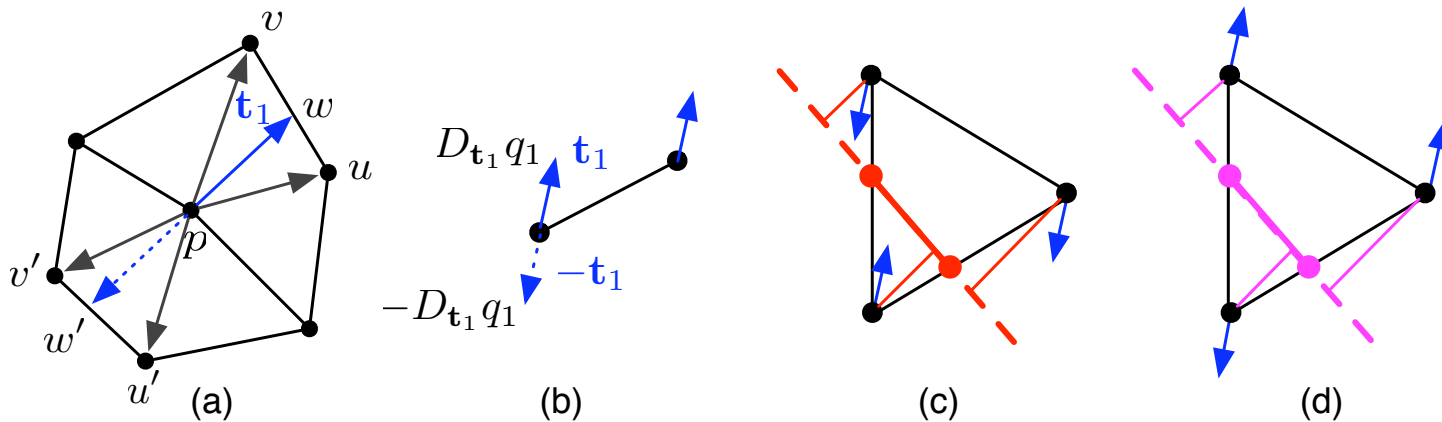
SIGGRAPH reviewers



Apparent Ridges

Computation on meshes

- Estimate view-dependent curvature SP^{-1}
- Estimate view dependent curvature derivative
- find consistent principal direction field
- Locate zero crossings
- Trim to eliminate minima
- Threshold



New lines

- Previous talk:
 - lighting dependent & image-based
- Suggestive & principal highlights:
 - work best in white
 - opposite behavior when viewpoint changes (they move away from contour)
 - lower order of derivative
(bright pixel vs. rapid variation)
 - extremum along view direction, not principal direction