

Surface Curvature

Justin Solomon
MIT, Spring 2017

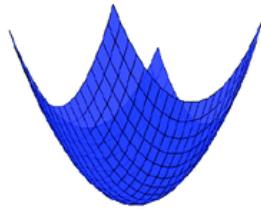


Today's Goal

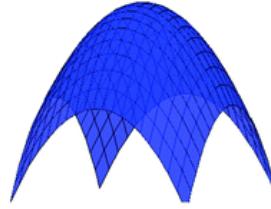
Quantify how a surface
bends.

Curvature.

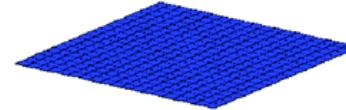
High-Level Questions



(a) $KG > 0, KH > 0$
elliptic concave



(b) $KG > 0, KH < 0$
elliptic convexe



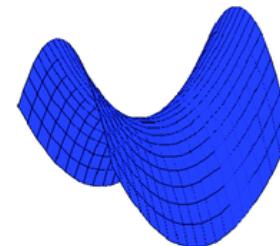
(c) $KG = 0, KH = 0$
plane



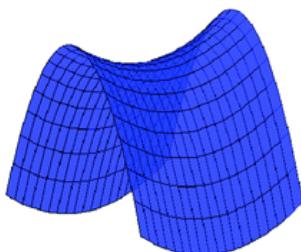
(d) $KG = 0, KH > 0$
parabolic concave



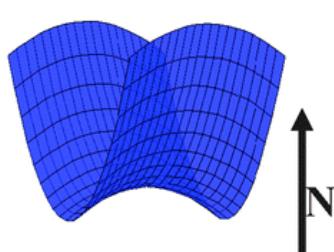
(e) $KG = 0, KH < 0$
parabolic convexe



(f) $KG < 0, KH = 0$
saddle (hyperbolic)



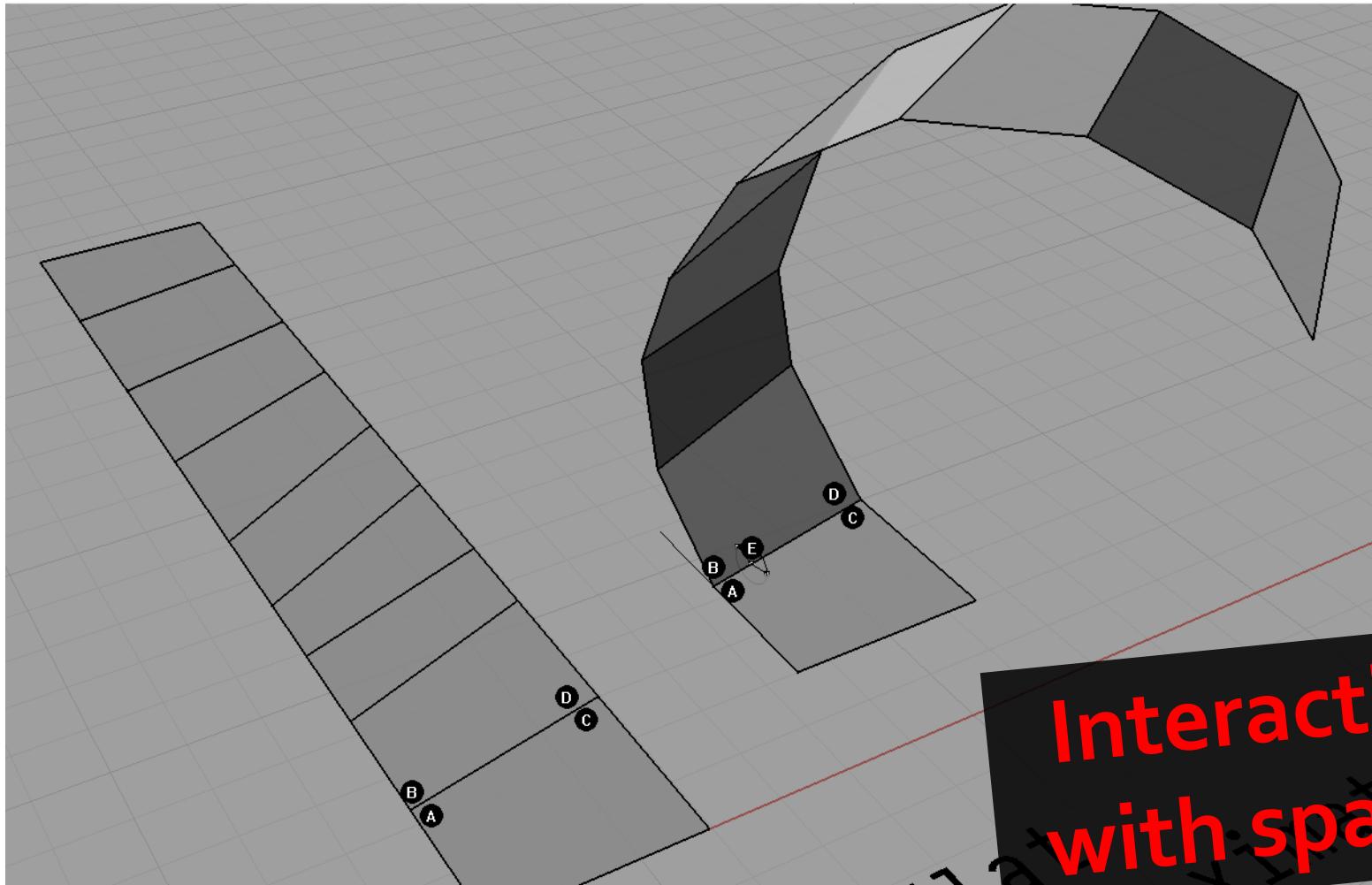
(g) $KG < 0, KH < 0$
hyperbolic-like



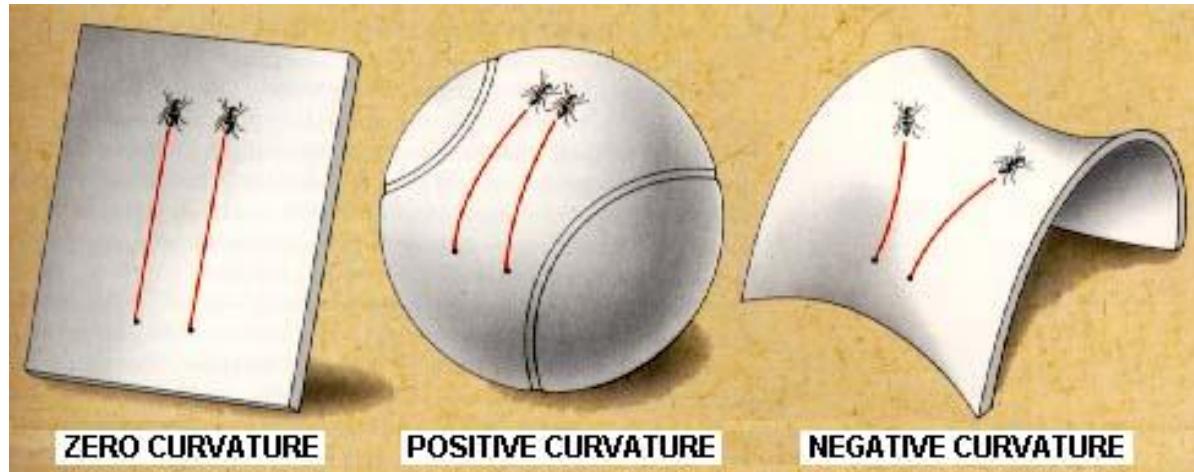
(h) $KG < 0, KH > 0$
hyperbolic-like

How to
distinguish?

High-Level Questions



High-Level Questions



Does
surrounding
space matter?

Practical Application

The Best Way to Eat Pizza, According to Science, Means You Probably Have Been Doing It Wrong



Bend It Like Gauss:



f Share this

By LUCIA PETERS Oct 10 2014

Congratulations, New Yorkers: Here's proof that you are apparently

<https://www.bustle.com/articles/43697-the-best-way-to-eat-pizza-according-to-science-means-you-probably-have-been-doing-it>

Recall:

Frenet Frame: Curves in \mathbb{R}^3

$$\frac{d}{ds} \begin{pmatrix} T \\ N \\ B \end{pmatrix} = \begin{pmatrix} 0 & \kappa & 0 \\ -\kappa & 0 & \tau \\ 0 & -\tau & 0 \end{pmatrix} \begin{pmatrix} T \\ N \\ B \end{pmatrix}$$

- **Binormal:** $T \times N$
- **Curvature:** In-plane motion
- **Torsion:** Out-of-plane motion

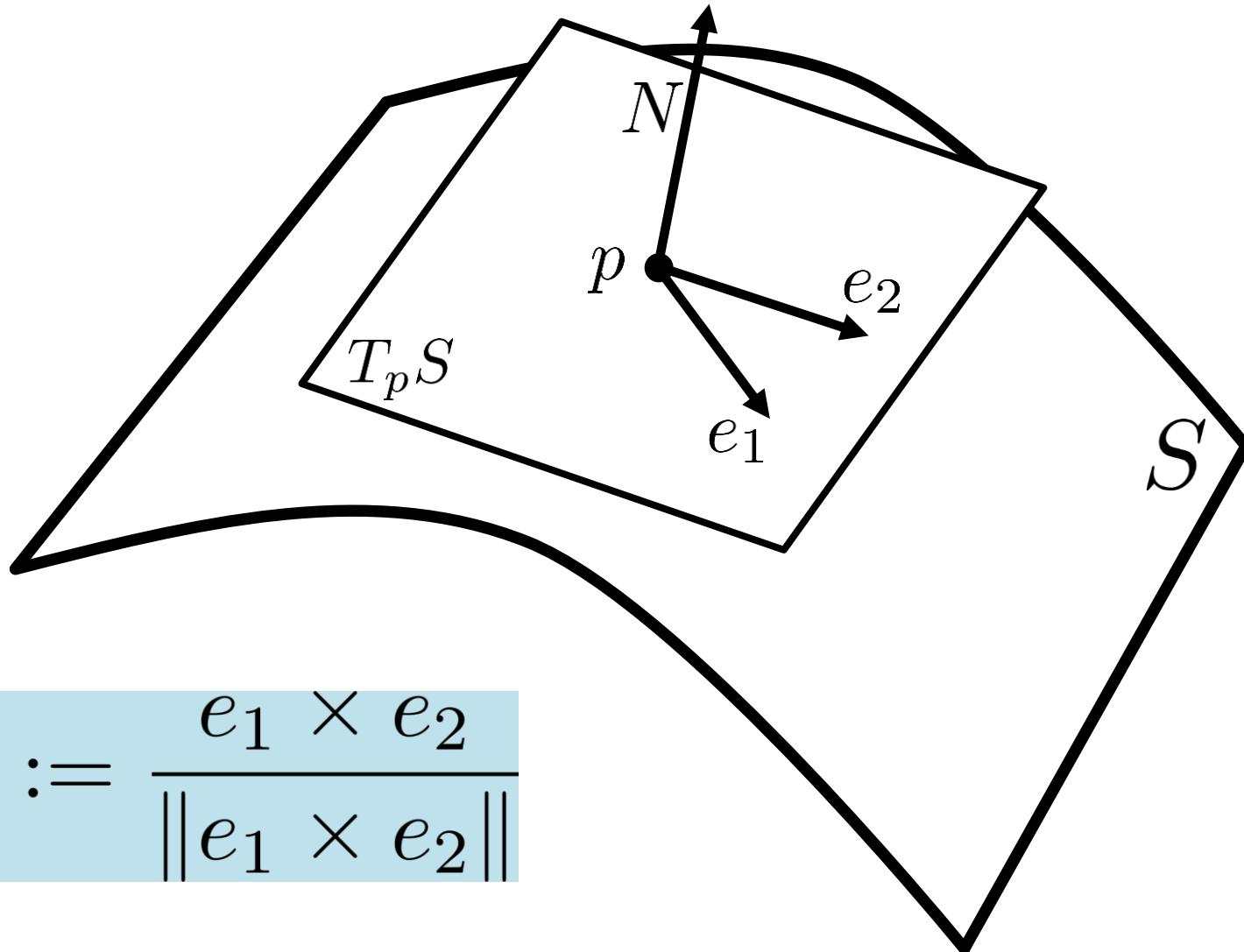
Theorem:

Curvature and torsion determine geometry of a curve up to rigid motion.



Can curvature/torsion
of a curve help us
understand **surfaces**?

Unit Normal

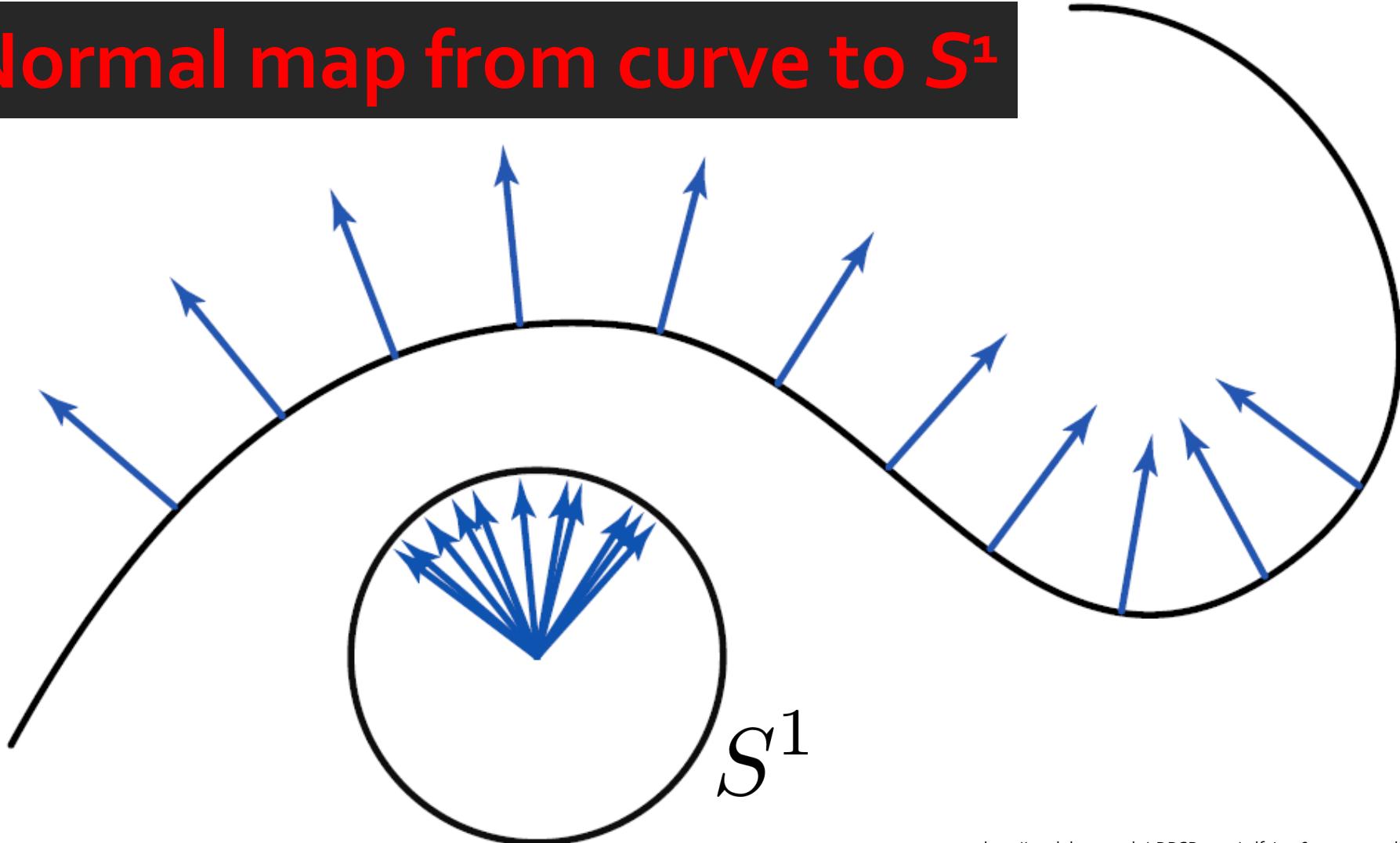


$$N := \frac{e_1 \times e_2}{\|e_1 \times e_2\|}$$

Recall:

Gauss Map

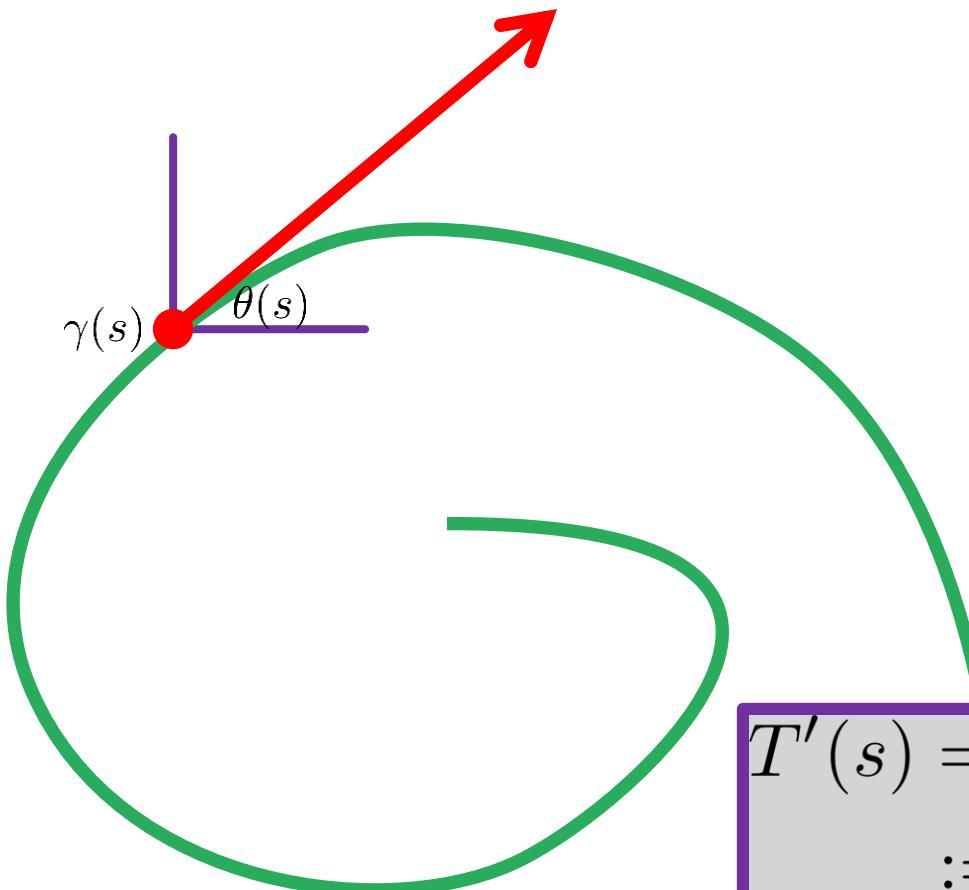
Normal map from curve to S^1



Recall:

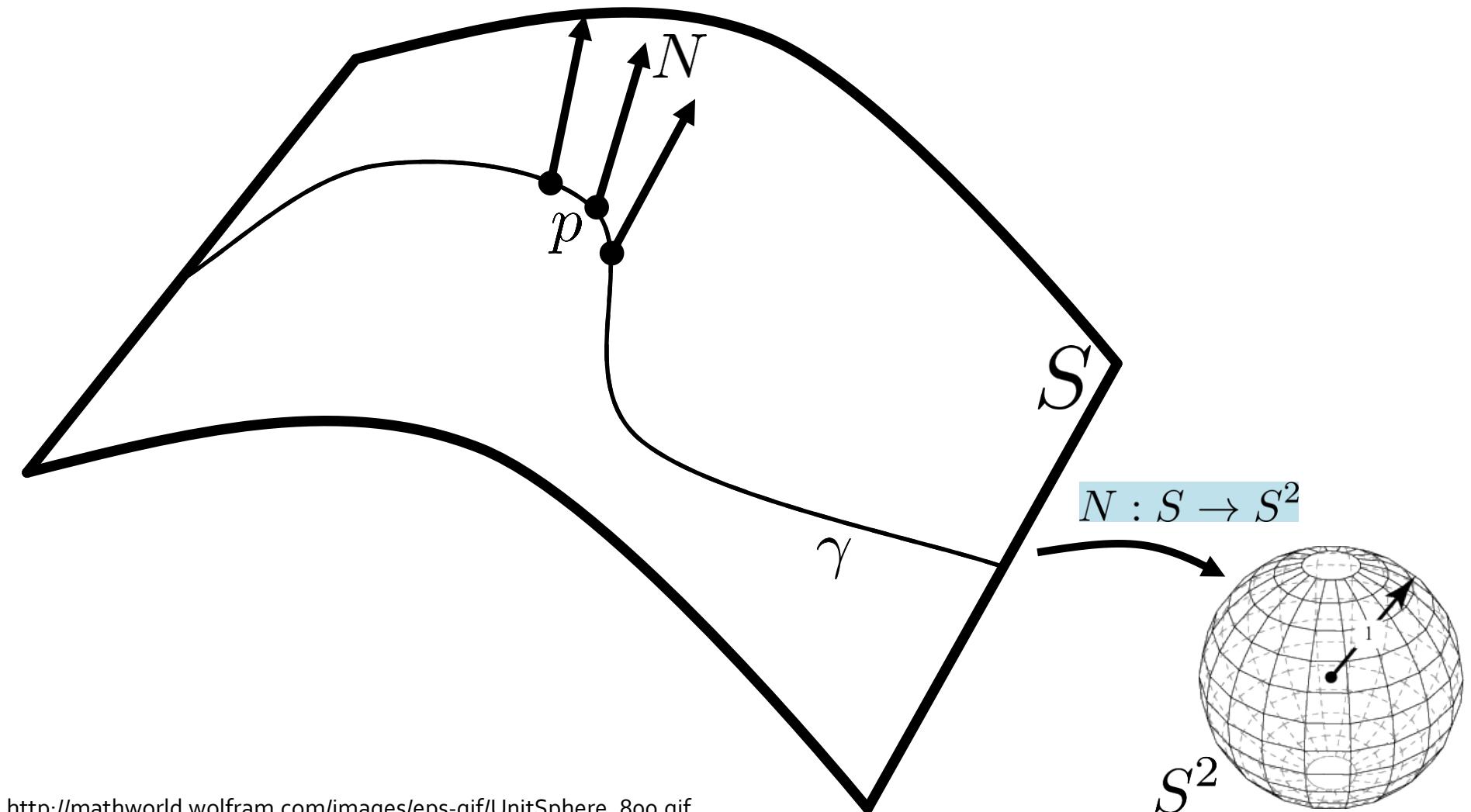
Signed Curvature on Plane Curves

$$T(s) = (\cos \theta(s), \sin \theta(s))$$



$$\begin{aligned} T'(s) &= \theta'(s)(-\sin \theta(s), \cos \theta(s)) \\ &:= \kappa(s)N(s) \end{aligned}$$

Gauss Map for Surface



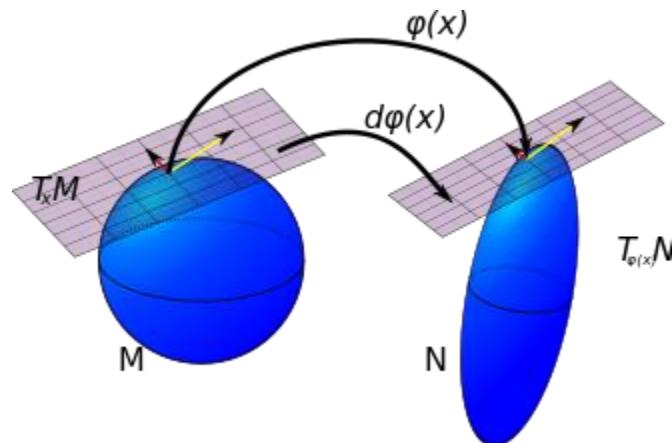
Differential of a Map

$$\varphi : M \rightarrow N$$

$$\implies d\varphi_p : T_p M \rightarrow T_{\varphi(p)} N$$

Linear map of tangent spaces

$$d\varphi_p(\gamma'(0)) := (\varphi \circ \gamma)'(0)$$



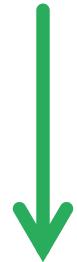
Calculation on Board

Where is the
derivative of N?

Spoiler alert: $T_p S$

Second Fundamental Form

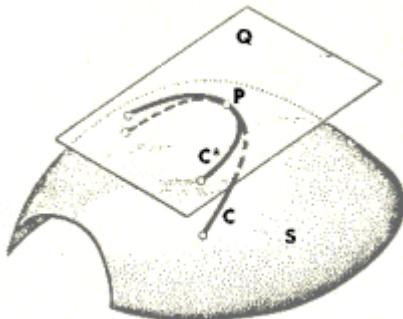
$$DN_p : T_p S \rightarrow T_p S$$



$$A_p(V, W) := -\langle DN_p(V), W \rangle$$

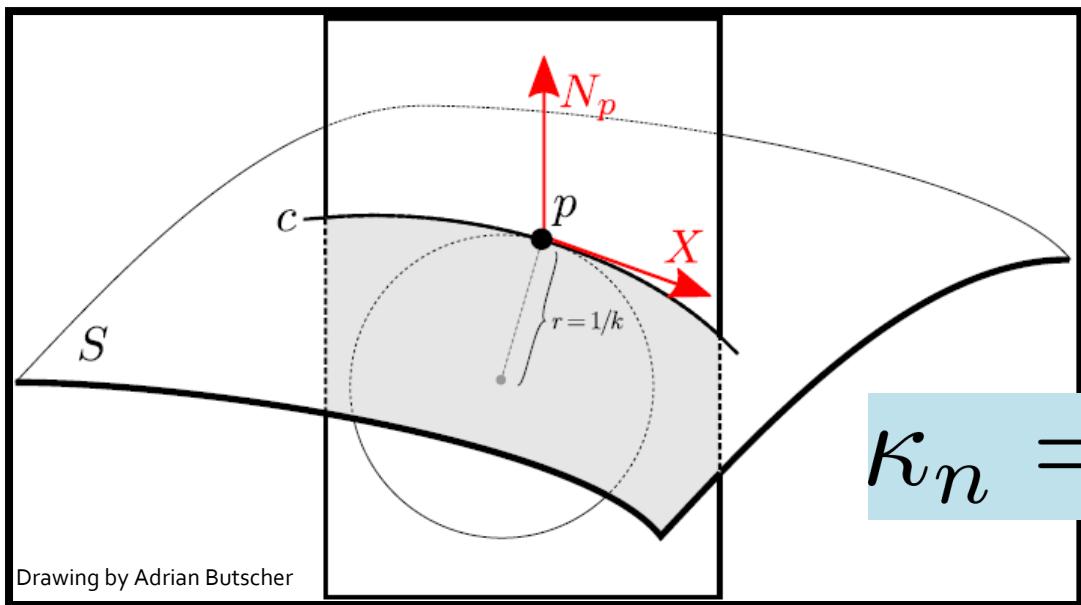
“Shape operator”

Relationship to Curvature of Curves



<http://www.solitaryroad.com/c335.html>

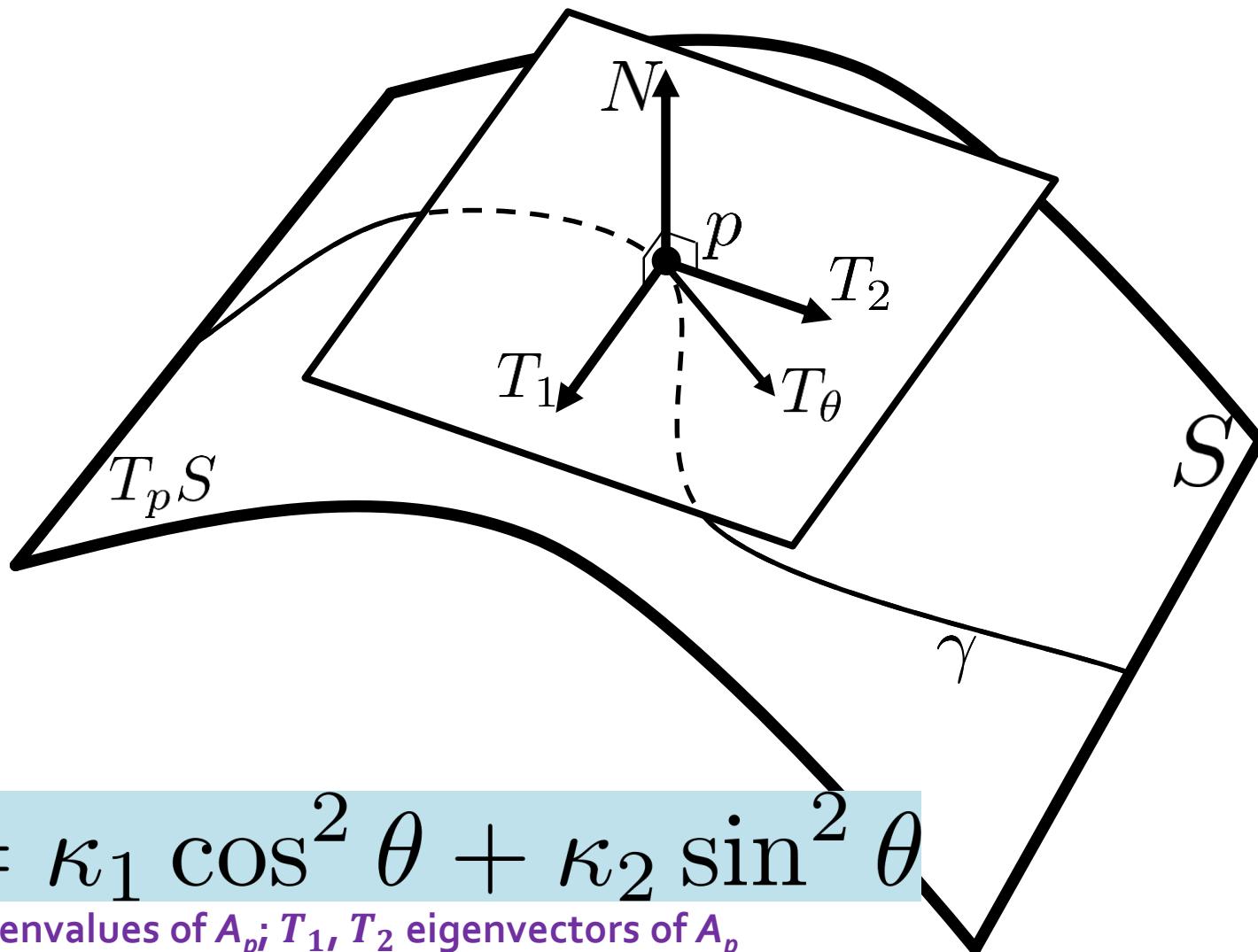
$$\kappa_g := \vec{\kappa} \cdot (\vec{N} \times \vec{T})$$



A_p is Self-Adjoint

(on board)

Principal Directions and Curvatures



$$\kappa_\theta = \kappa_1 \cos^2 \theta + \kappa_2 \sin^2 \theta$$

κ_1, κ_2 eigenvalues of A_{pi} ; T_1, T_2 eigenvectors of A_p

Principal Curvatures

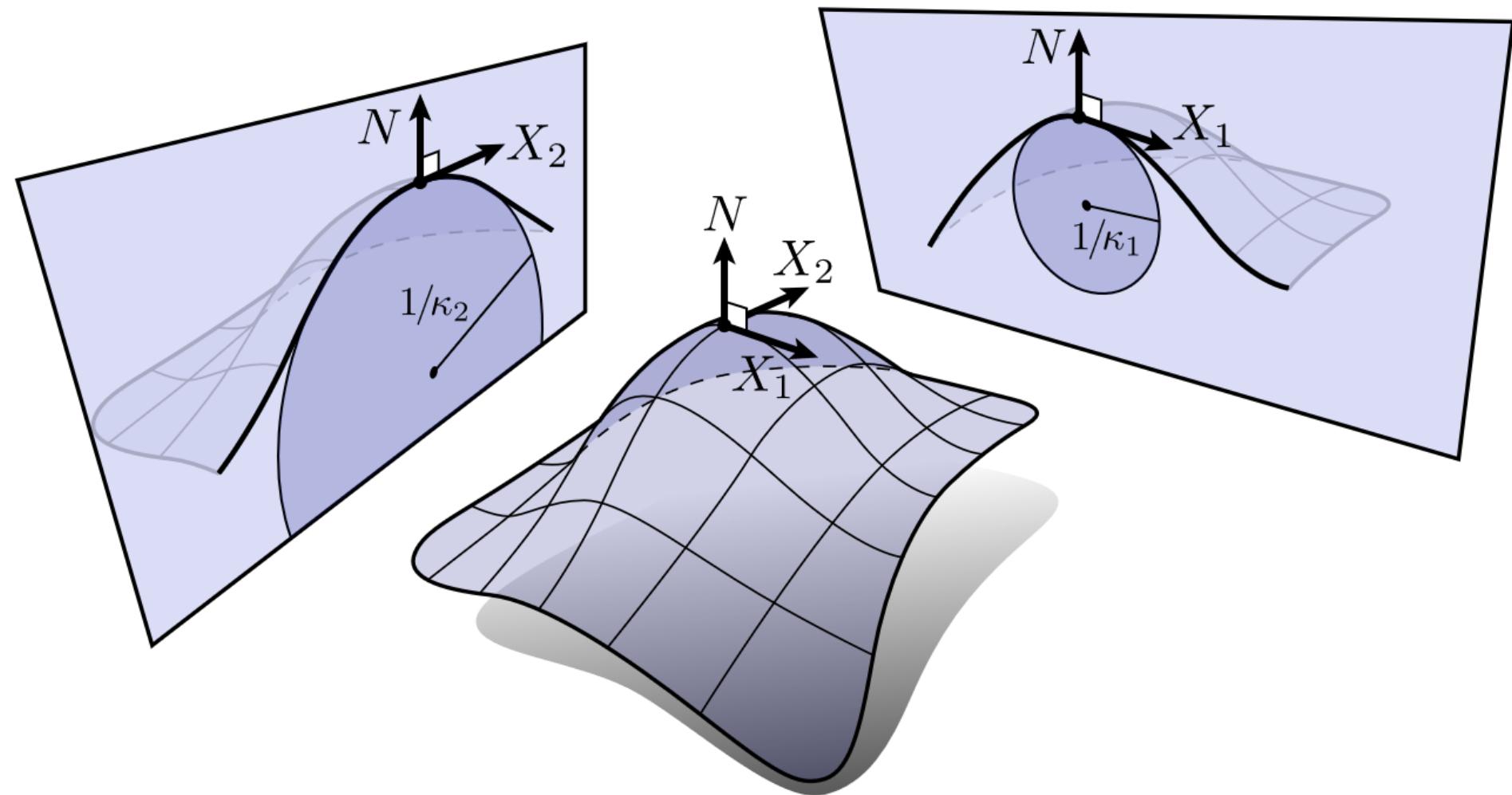
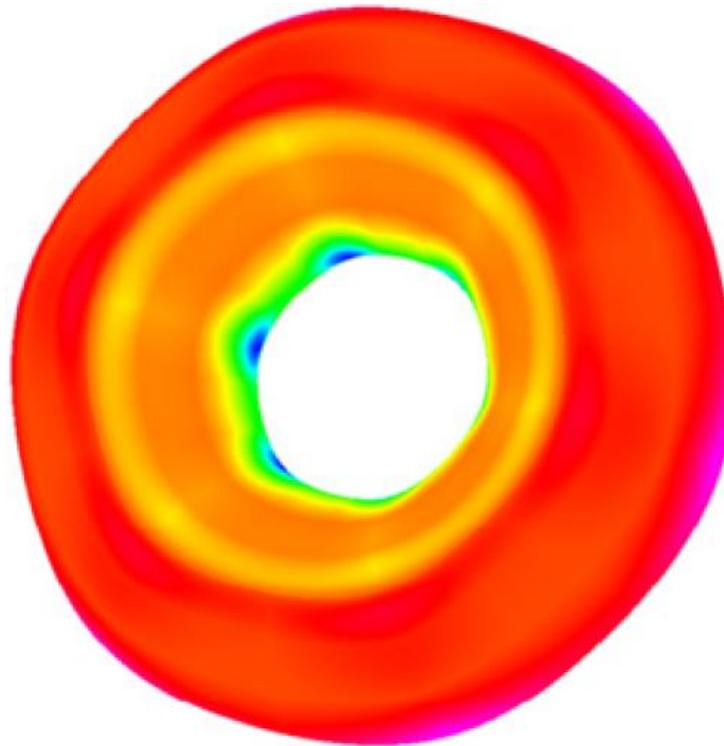


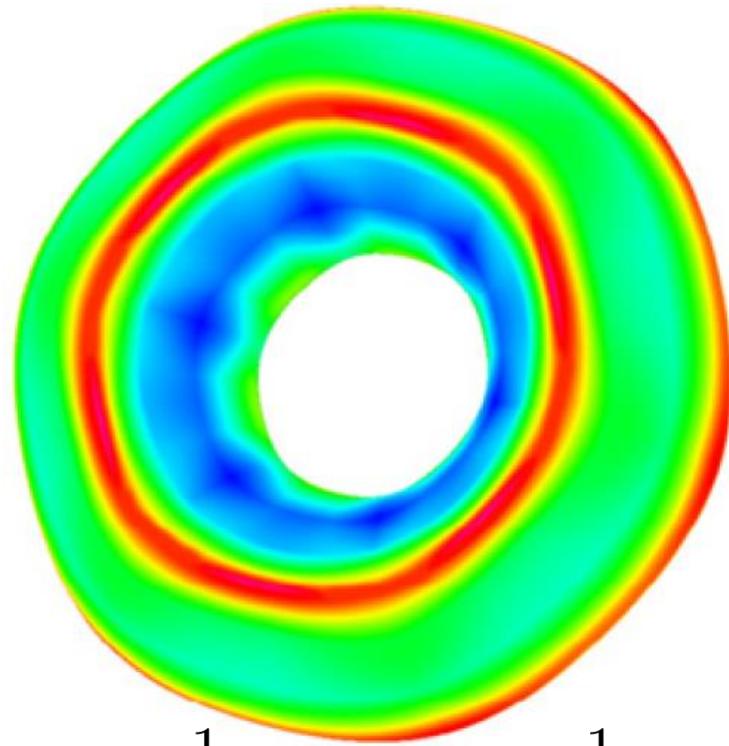
Image courtesy K. Crane, CMU

Extrinsic Curvature

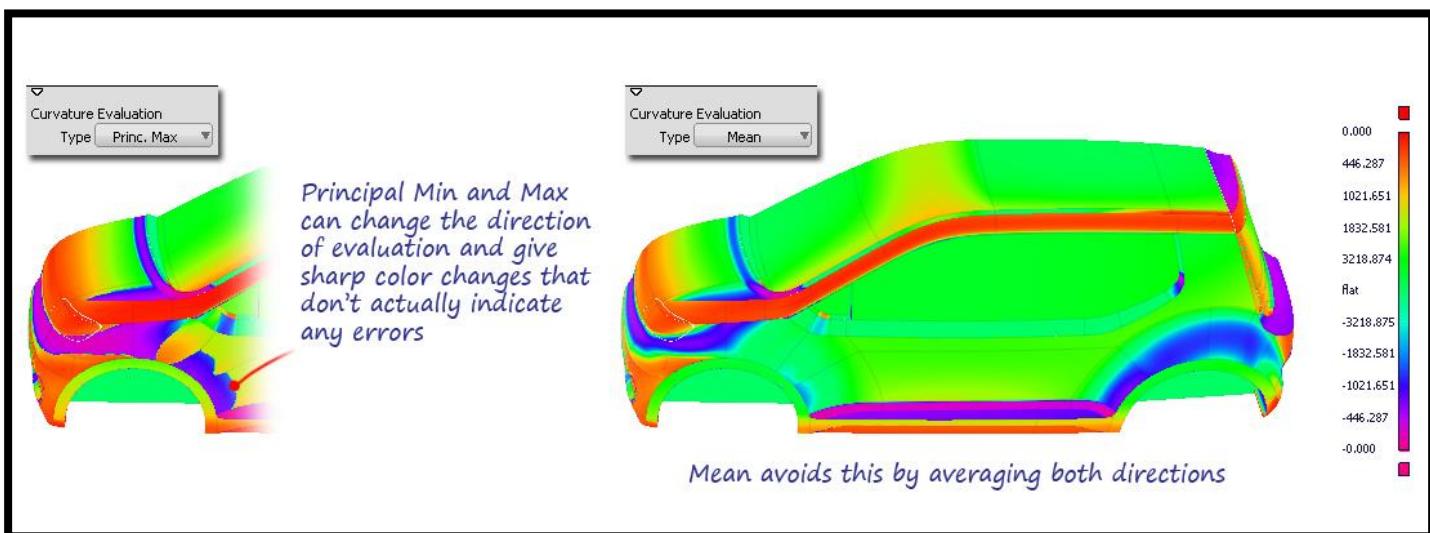
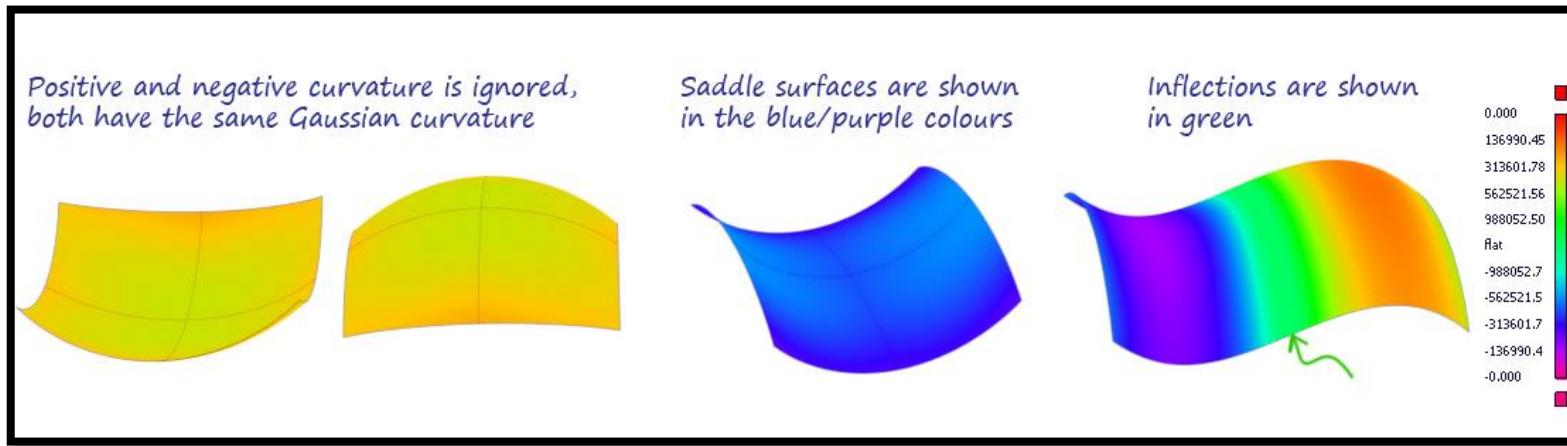


$$K := \kappa_1 \kappa_2 = \det \mathbb{II}$$

$$H := \frac{1}{2}(\kappa_1 + \kappa_2) = \frac{1}{2}\text{tr } \mathbb{II}$$



Interpretation



Uniqueness Result

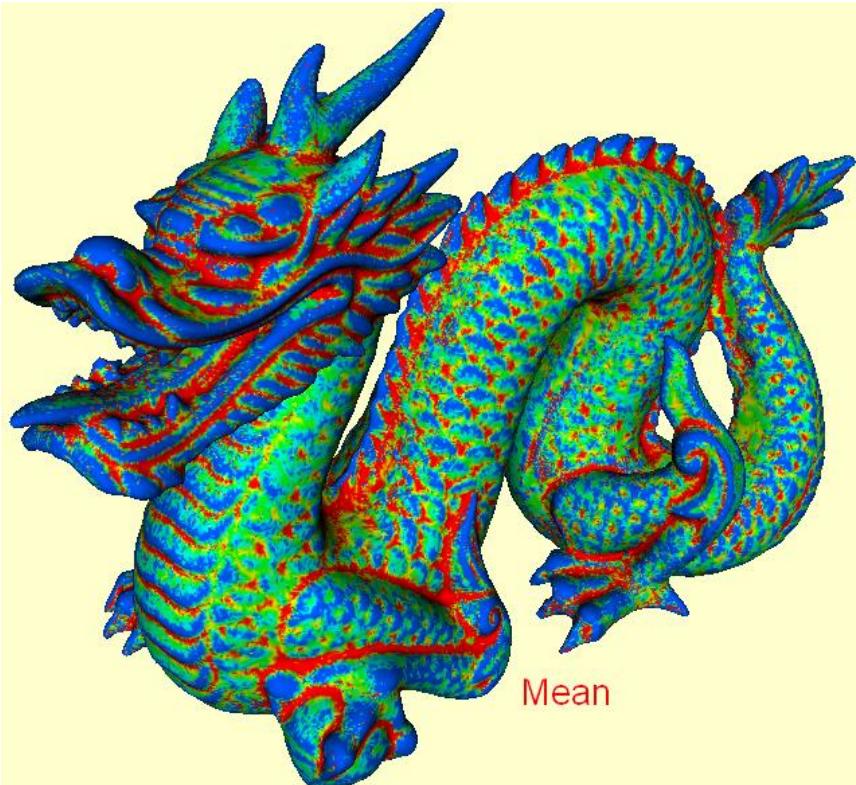
Theorem:

A smooth surface is determined up to rigid motion by its first and second fundamental forms.

Who Cares?

Curvature
completely determines
local surface geometry.

Use as a Descriptor



Smoothing and Reconstruction

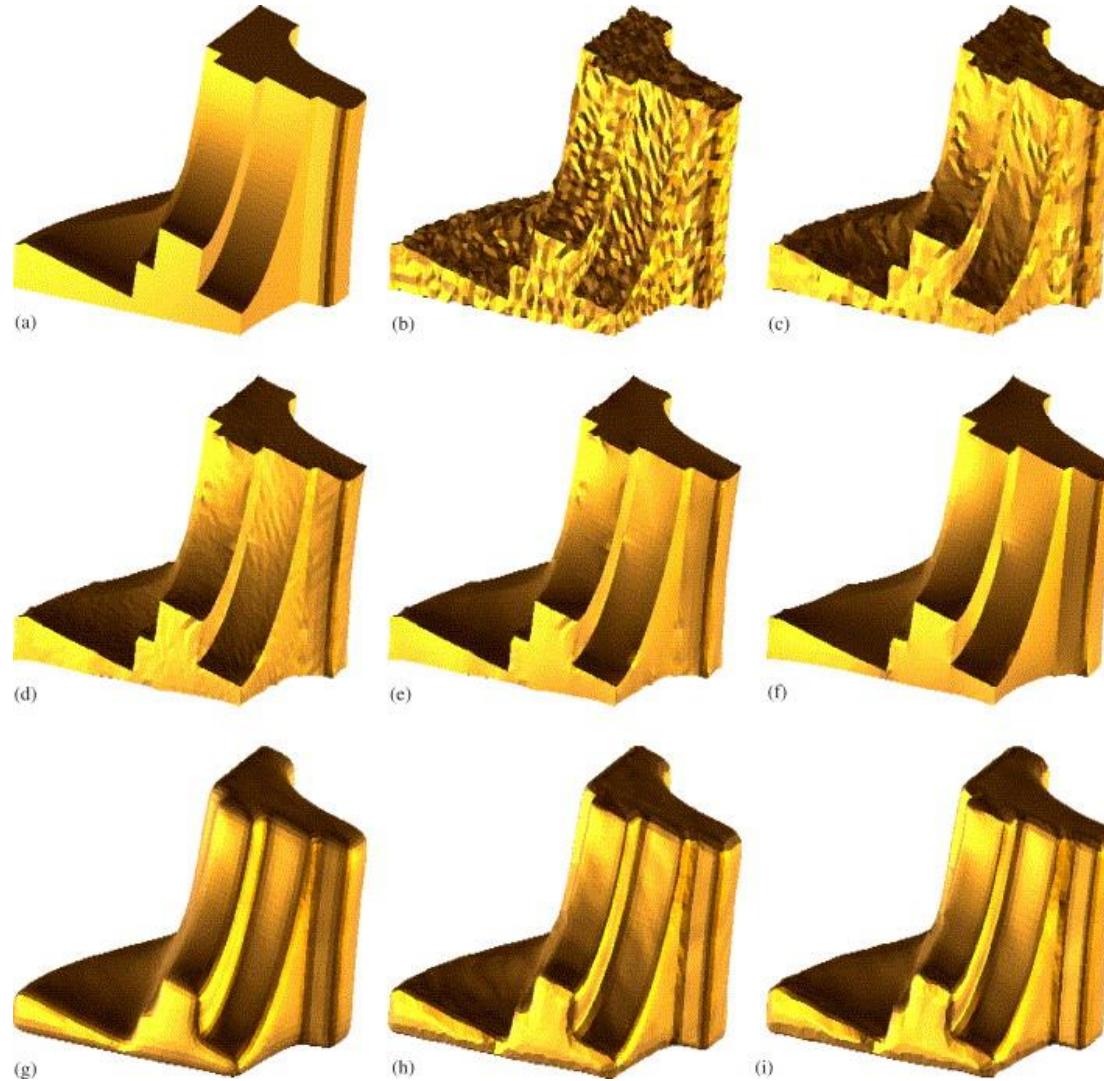


Linear Surface Reconstruction from Discrete Fundamental Forms on Triangle Meshes

Wang, Liu, and Tong

Computer Graphics Forum 31.8 (2012)

Fairness Measure



Triangular Surface Mesh Fairing via
Gaussian Curvature Flow

Zhao, Xu

Journal of Computational and Applied Mathematics 195.1-2 (2006)

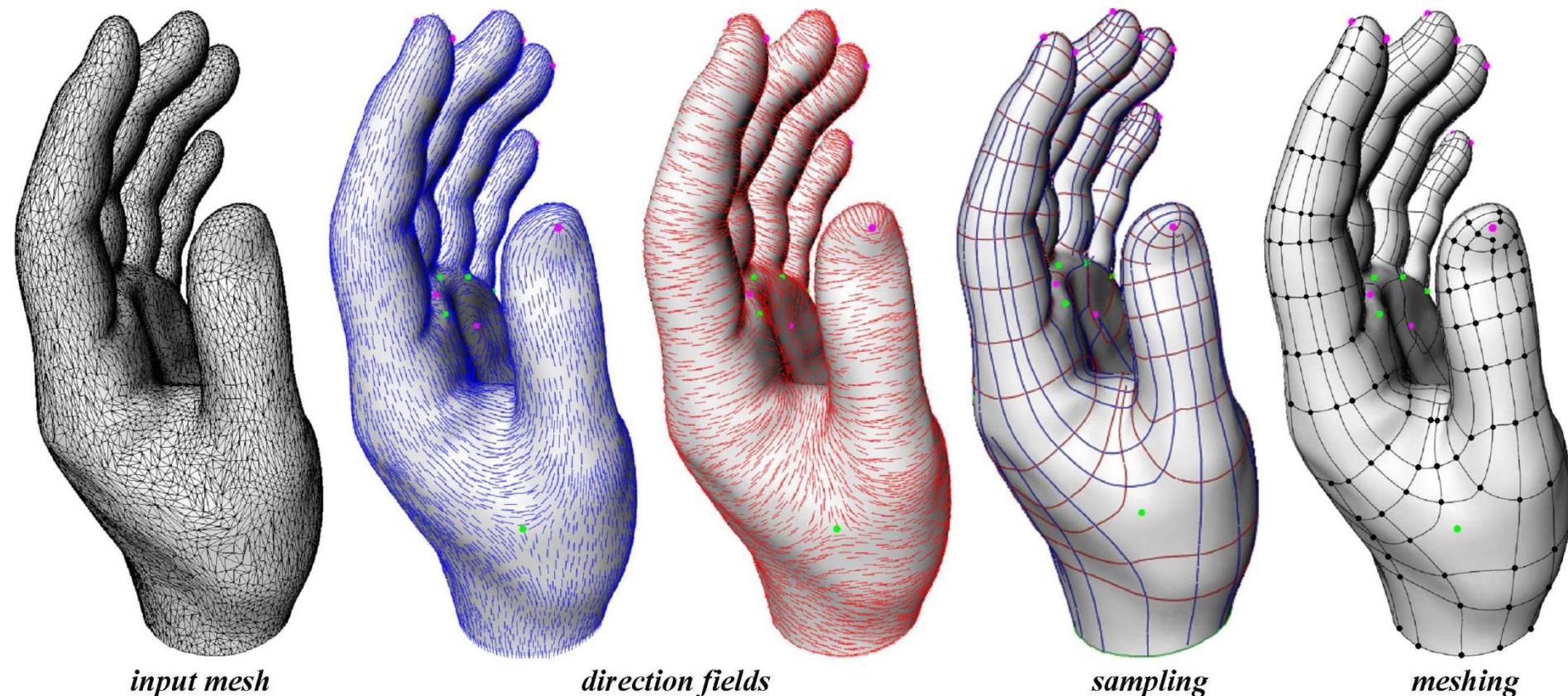
...and many more

Guiding Rendering



Highlight Lines for Conveying Shape
DeCarlo, Rusinkiewicz
NPAR (2007)

Guiding Meshing



Anisotropic Polygonal Remeshing

Alliez et al.

SIGGRAPH (2003)

Special Topic for Me...

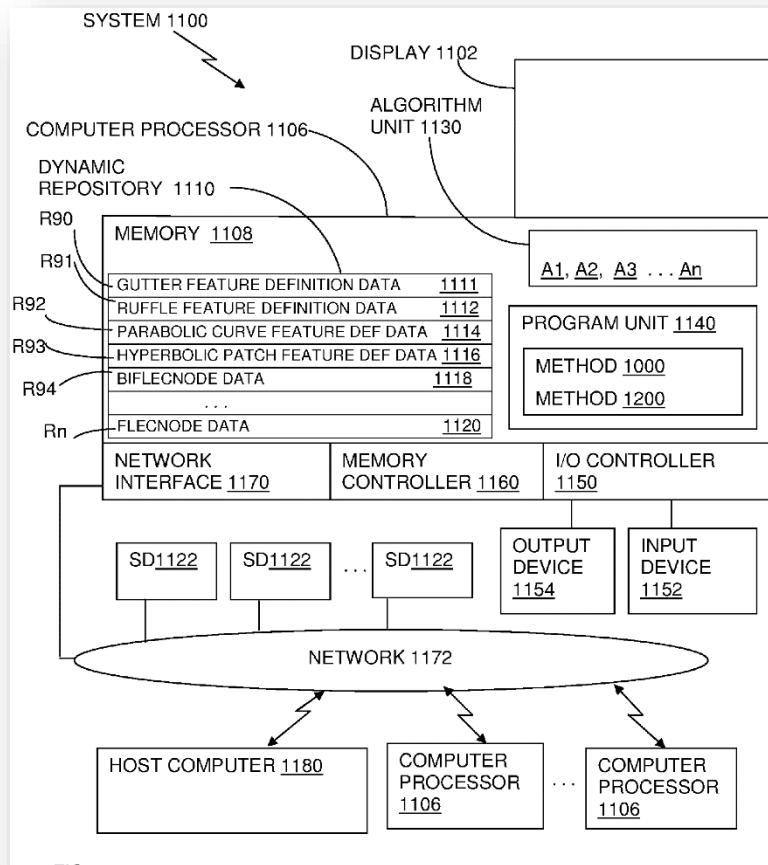
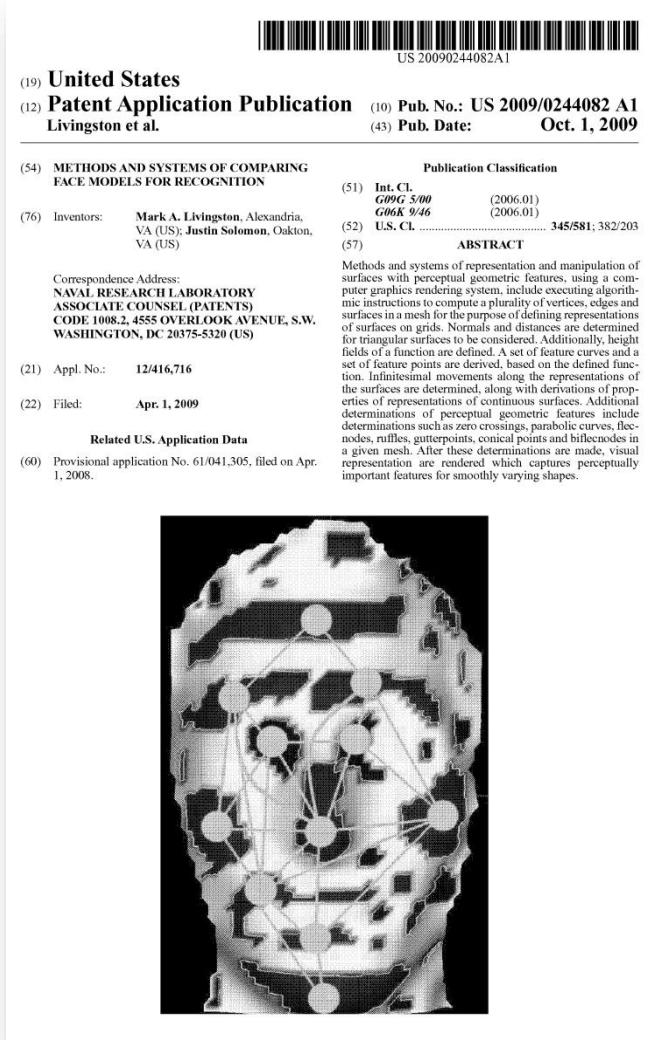
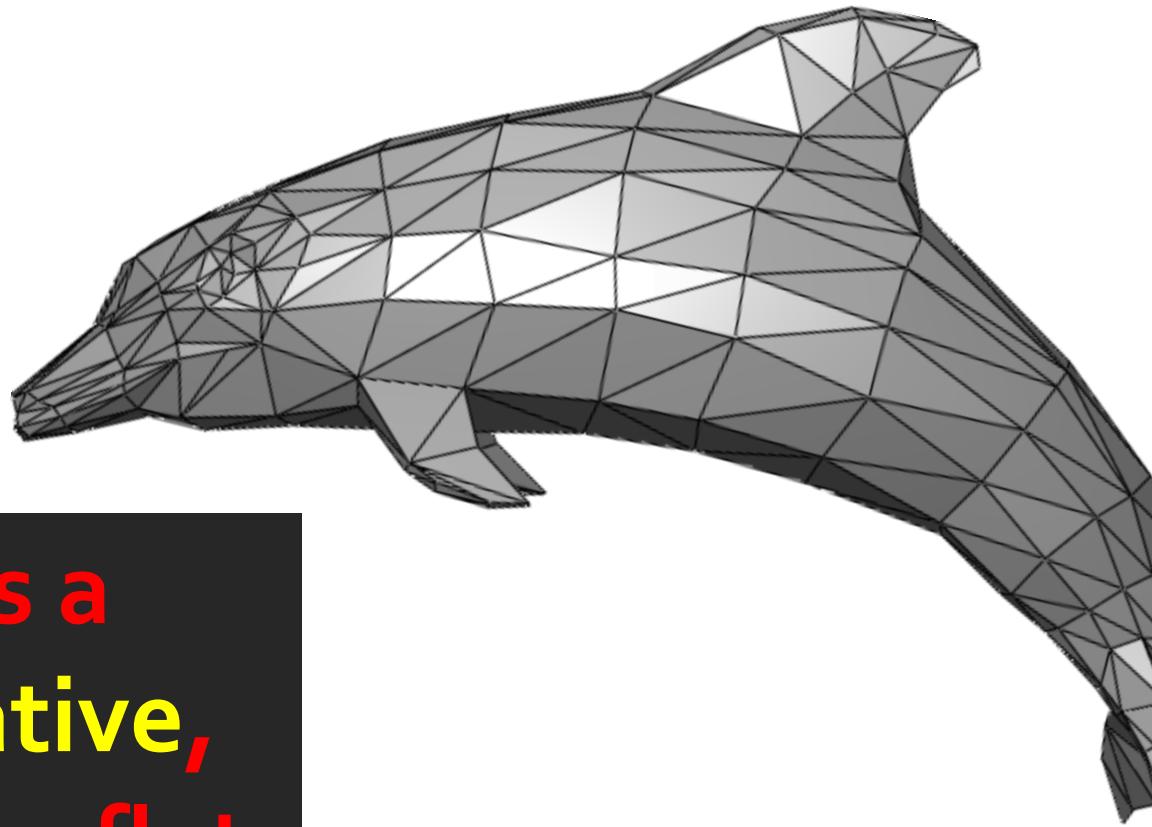


FIG. 11

Challenge on Meshes



**Curvature is a
second derivative,
but triangles are flat.**

Standard Citation

ESTIMATING THE TENSOR OF CURVATURE OF A SURFACE FROM A POLYHEDRAL APPROXIMATION

Gabriel Taubin

ICCV 1995

IBM T.J.Watson Research Center
P.O.Box 704, Yorktown Heights, NY 10598
taubin@watson.ibm.com

Abstract

Estimating principal curvatures and principal directions of a surface from a polyhedral approximation with a large number of small faces, such as those produced by iso-surface construction algorithms, has become a basic step in many computer vision algorithms. Particularly in those targeted at medical applications. In this paper we describe a method to estimate the tensor of curvature of a surface at the vertices of a polyhedral approximation. Principal curvatures and principal directions are obtained by computing in closed form the eigenvalues and eigenvectors of certain 3×3 symmetric matrices defined by integral formulas, and

mate principal curvatures at the vertices of a triangulated surface. Both this algorithm and ours are based on constructing a quadratic form at each vertex of the polyhedral surface and then computing eigenvalues (and eigenvectors) of the resulting form, but the quadratic forms are different. In our algorithm the quadratic form associated with a vertex is expressed as an integral, and is constructed in time proportional to the number of neighboring vertices. In the algorithm of Chen and Schmitt, it is the least-squares solution of an overdetermined linear system, and the complexity of constructing it is quadratic in the number of neighbors.

2. The Tensor of Curvature

Taubin Matrix

$$M := \frac{1}{2\pi} \int_{-\pi}^{\pi} \kappa_\theta T_\theta T_\theta^\top d\theta$$

$$\kappa_\theta := \kappa_1 \cos^2 \theta + \kappa_2 \sin^2 \theta$$

$$T_\theta := T_1 \cos \theta + T_2 \sin \theta$$

Taubin Matrix

$$M := \frac{1}{2\pi} \int_{-\pi}^{\pi} \kappa_\theta T_\theta T_\theta^\top d\theta$$

- Eigenvectors are N , T_1 , and T_2
- Eigenvalues are $\frac{3}{8}\kappa_1 + \frac{1}{8}\kappa_2$ and $\frac{1}{8}\kappa_1 + \frac{3}{8}\kappa_2$

Prove at home!

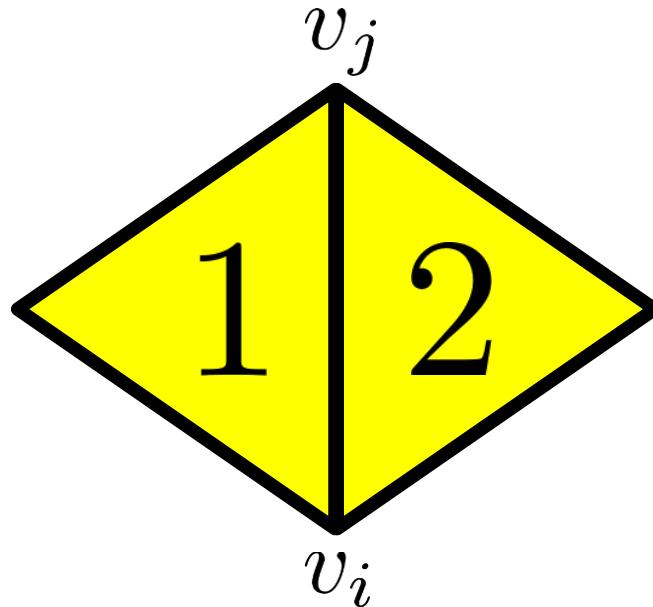
Taubin's Approximation

$$M := \frac{1}{2\pi} \int_{-\pi}^{\pi} \kappa_\theta T_\theta T_\theta^\top d\theta$$



$$\tilde{M}_{v_i} := \sum_{v_j \sim v_i} w_{ij} \kappa_{ij} T_{ij} T_{ij}^\top$$

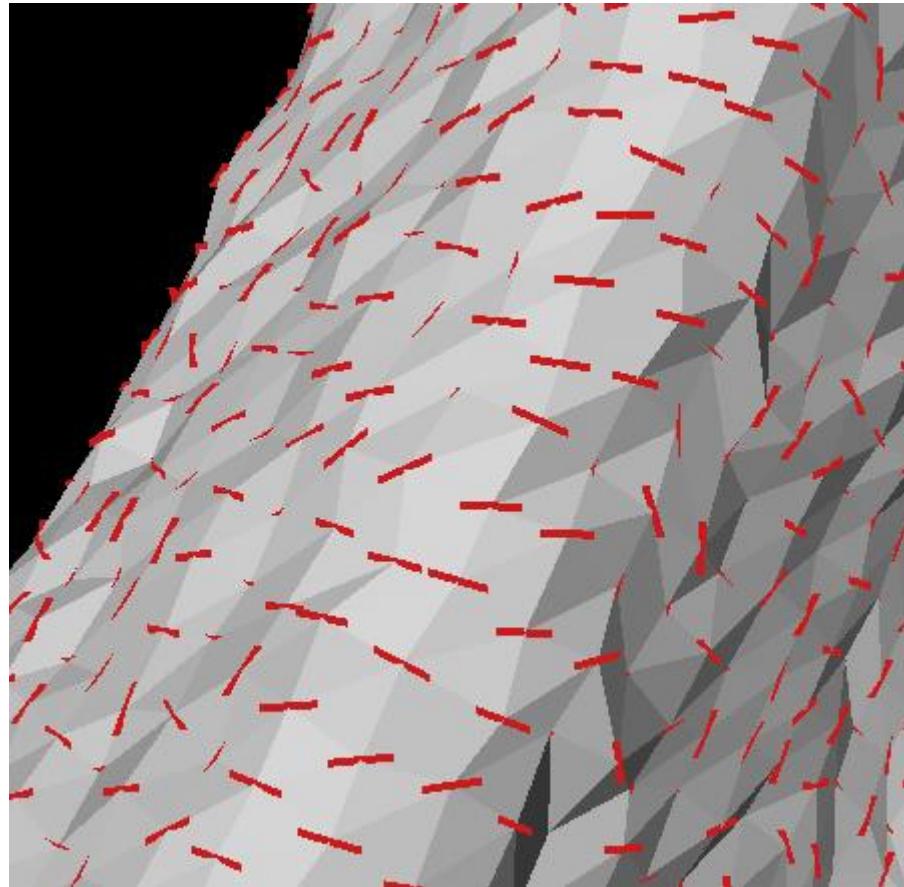
Taubin's Approximation



Divided difference
approximation

$$\tilde{M}_{v_i} := \sum_{v_j \sim v_i} w_{ij} \kappa_{ij} T_{ij} T_{ij}^\top$$

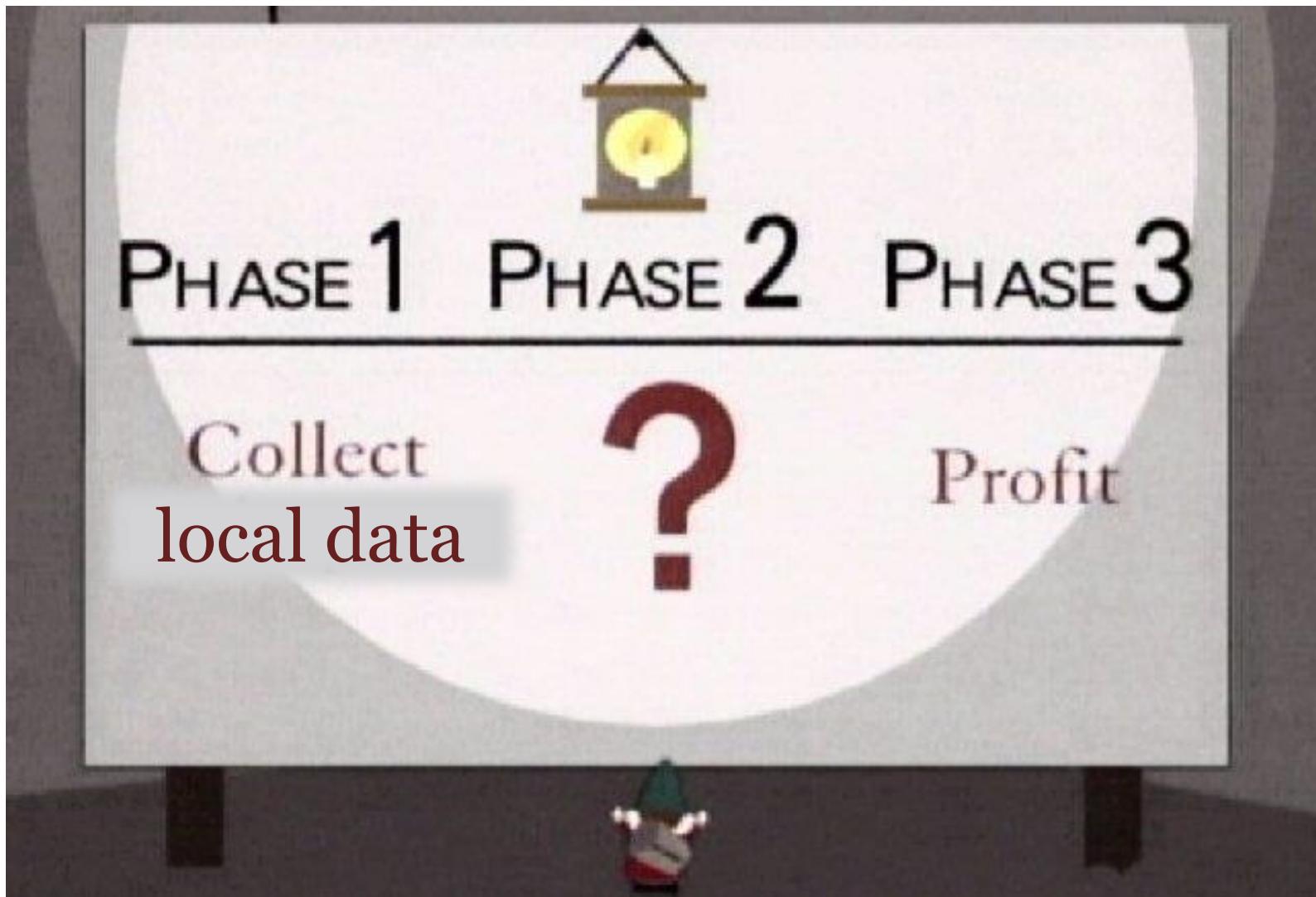
Problem



<http://iristown.engr.utk.edu/~koschan/paper/CVPR01.pdf>

Local estimates are noisy

General Strategy



⚠ WARNING



**ENGINEERING
DISGUISED AS
MATH**

Main Take-Away

**Use application to motivate
choice of curvature.**

*Simulation, smoothing, analysis, meshing,
nonphotorealistic rendering, ...*

Another Example

Estimating Curvatures and Their Derivatives on Triangle Meshes

Szymon Rusinkiewicz
Princeton University

3DPVT '04

Abstract

The computation of curvature and other differential properties of surfaces is essential for many techniques in analysis and rendering. We present a finite-differences approach for estimating curvatures on irregular triangle meshes that may be thought of as an extension of a common method for estimating per-vertex normals. The technique is efficient in space and time, and results in significantly fewer outlier estimates while more broadly offering accuracy comparable to existing methods. It generalizes naturally to computing derivatives of curvature and higher-order surface differentials.

1 Introduction

As the acquisition and use of sampled 3D geometry become more widespread, 3D models are increasingly becoming the focus of analysis and signal processing techniques previously applied to data types such as audio, images, and video. A key component of algorithms such as feature detection, filtering, and indexing, when applied to both geometry and other data

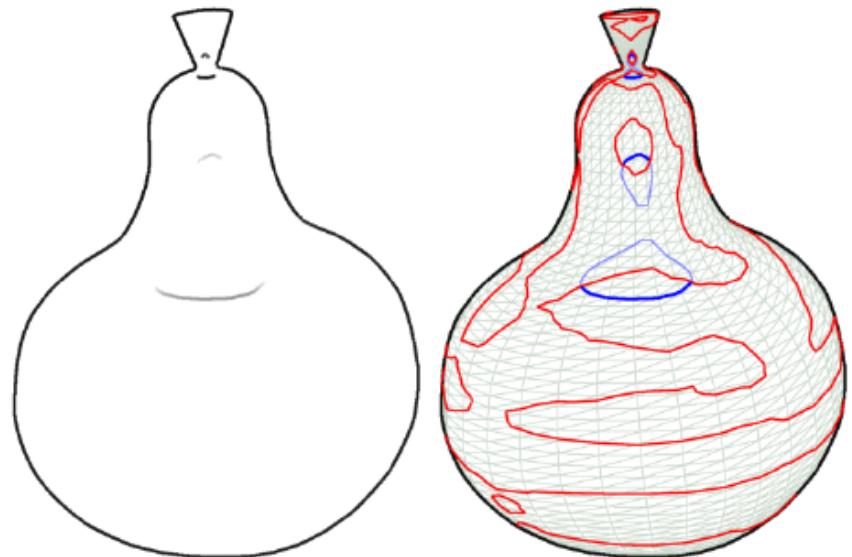


Figure 1: Left: suggestive contours for line drawings [DeCarlo et al. 2003] are a recent example of a driving application for the estimation of curvatures and derivatives of curvature. Right: suggestive contours are drawn along the zeros of curvature in the view direction, shown here in blue, but only where the derivative of curvature in the view direction is positive (the curvature derivative is negative in the other direction). This example illustrates how

Second Fundamental Form Matrix

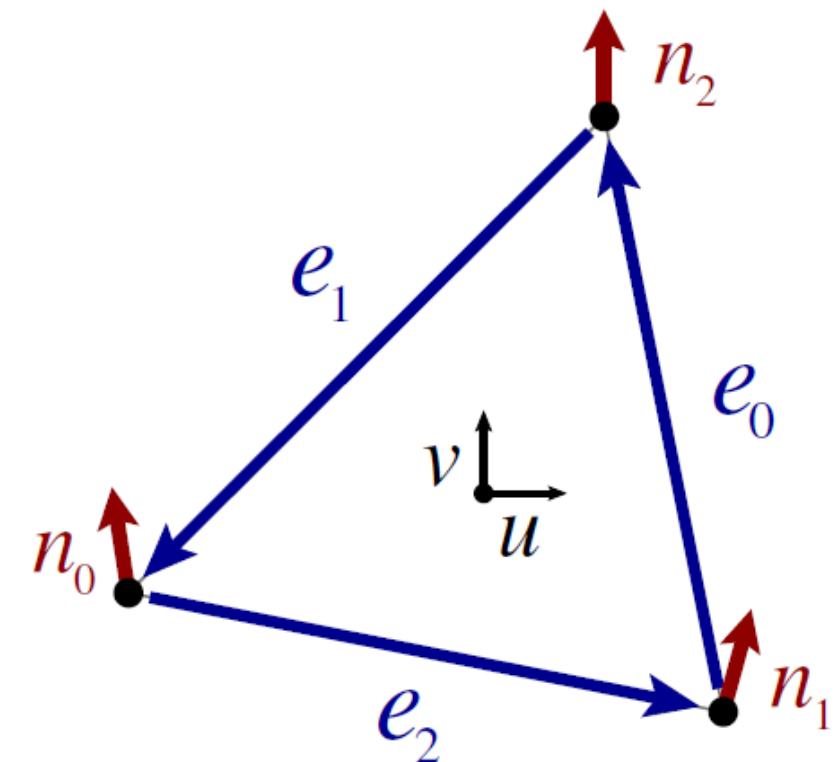
$$\begin{aligned} II &:= \begin{pmatrix} D_u N & D_v N \end{pmatrix} \\ &= \begin{pmatrix} \frac{\partial N}{\partial u} \cdot \vec{u} & \frac{\partial N}{\partial v} \cdot \vec{u} \\ \frac{\partial N}{\partial u} \cdot \vec{v} & \frac{\partial N}{\partial v} \cdot \vec{v} \end{pmatrix} \end{aligned}$$

Assume u, v are orthogonal

Second Fundamental Form Matrix

$$\vec{s} = c_1 \vec{u} + c_2 \vec{v}$$
$$\implies II \begin{pmatrix} c_1 \\ c_2 \end{pmatrix} = D_{\vec{s}} N$$

Finite Difference Per-Face



$$\text{II } \begin{pmatrix} e_0 \cdot u \\ e_0 \cdot v \end{pmatrix} = \begin{pmatrix} (n_2 - n_1) \cdot u \\ (n_2 - n_1) \cdot v \end{pmatrix}$$
$$\text{II } \begin{pmatrix} e_1 \cdot u \\ e_1 \cdot v \end{pmatrix} = \begin{pmatrix} (n_0 - n_2) \cdot u \\ (n_0 - n_2) \cdot v \end{pmatrix}$$
$$\text{II } \begin{pmatrix} e_2 \cdot u \\ e_2 \cdot v \end{pmatrix} = \begin{pmatrix} (n_1 - n_0) \cdot u \\ (n_1 - n_0) \cdot v \end{pmatrix}$$

Figure from the paper

Least-squares

Average for Per-Vertex

- **Rotate tangent plane about cross product of normals**
- **Average using Voronoi weights**

Completely Different Formula

Consistent Computation of First- and Second-Order Differential Quantities for Surface Meshes

Xiangmin Jiao*

Dept. of Applied Mathematics & Statistics
Stony Brook University

Hongyuan Zha†

College of Computing
Georgia Institute of Technology

Abstract

Differential quantities, including normals, curvatures, principal directions, and associated matrices, play a fundamental role in geometric processing and physics-based modeling. Computing these differential quantities *consistently* on surface meshes is important and challenging, and some existing methods often produce inconsistent results and require *ad hoc* fixes. In this paper, we show that the computation of the gradient and Hessian of a height function provides the foundation for consistently computing the differential quantities. We derive simple, *explicit* formulas for the transformations between the first- and second-order differential quantities (i.e., normal vector and curvature matrix) of a smooth surface and the first- and second-order derivatives (i.e., gradient and Hessian) of its corresponding height function. We then investigate a general, flexible numerical framework to estimate the derivatives of the height function based on local polynomial fittings formulated as weighted least squares approximations. We also propose an iterative fitting

often require *ad hoc* fixes to avoid crashing of the code, and their effects on the accuracy of the applications are difficult to analyze.

The ultimate goal of this work is to investigate a mathematically sound framework that can compute the differential quantities *consistently* (i.e., satisfying the intrinsic constraints) with provable *convergence* on general surface meshes, while being flexible and easy to implement. This is undoubtedly an ambitious goal. Although we may have not fully achieved the goal, we make some contributions toward it. First, using the singular value decomposition [Golub and Van Loan 1996] of the Jacobian matrix, we derive explicit formulas for the transformations between the first- and second-order differential quantities of a smooth surface (i.e., normal vector and curvature matrix) and the first- and second-order derivatives of its corresponding height function (i.e., gradient and Hessian). We also give the explicit formulas for the transformations of the gradient and Hessian under a rotation of the coordinate system. These transformations can be obtained without forming the shape operator and the associated computation of its eigenvalues or eigenvectors. We

Completely Different Formula

Consistent Computation of First- and Second-Order Differential Quantities for Surface Meshes

Xiangmin Jiao*

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Abstract

Differential quantities, including normals, curvatures, principal directions, and associated matrices, play a fundamental role in geo-

often require *ad hoc* fixes to avoid crashing of the code, and their effects on the accuracy of the applications are difficult to analyze.

The ultimate goal of this work is to investigate a mathematically sound framework that can compute the differential quantities

Theorem 3 *The mean and Gaussian curvature of the height function $f(u) : \mathbb{R}^2 \rightarrow \mathbb{R}$ are*

$$\kappa_H = \frac{\text{tr}(\mathbf{H})}{2\ell} - \frac{(\nabla f)^T \mathbf{H} (\nabla f)}{2\ell^3}, \text{ and } \kappa_G = \frac{\det(\mathbf{H})}{\ell^4}. \quad (16)$$

corresponding height function. We then investigate a general, flexible numerical framework to estimate the derivatives of the height function based on local polynomial fittings formulated as weighted least squares approximations. We also propose an iterative fitting

give the explicit formulas for the transformations of the gradient and Hessian under a rotation of the coordinate system. These transformations can be obtained without forming the shape operator and the associated computation of its eigenvalues or eigenvectors. We

Conserved Quantity Approach

Discrete Differential-Geometry Operators for Triangulated 2-Manifolds

Mark Meyer¹, Mathieu Desbrun^{1,2}, Peter Schröder¹, and Alan H. Barr¹

¹ Caltech

² USC

Visualization and Math. III

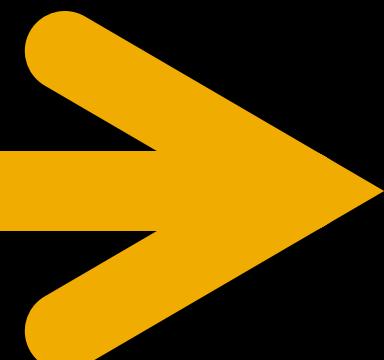
Summary. This paper proposes a unified and consistent set of flexible tools to approximate important geometric attributes, including normal vectors and curvatures on arbitrary triangle meshes. We present a consistent derivation of these first and second order differential properties using *averaging Voronoi cells* and the mixed Finite-Element/Finite-Volume method, and compare them to existing formulations. Building upon previous work in discrete geometry, these operators are closely related to the continuous case, guaranteeing an appropriate extension from the continuous to the discrete setting: they respect most intrinsic properties of the continuous differential operators. We show that these estimates are optimal in accuracy under mild smoothness conditions, and demonstrate their numerical quality. We also present applications of these operators, such as mesh smoothing, enhancement, and quality checking, and show results of denoising in higher dimensions, such as for tensor images.

Recall:

Structure preservation

[struhk-cher pre-zur-vey-shuhn]:

Keeping properties from the continuous abstraction exactly true in a discretization.



Gauss-Bonnet Theorem

$$\int_M K \, dA + \int_{\partial M} k_g \, ds = 2\pi\chi(M)$$

Gaussian
curvature



Geodesic curvature
(curvature projected
on tangent plane)

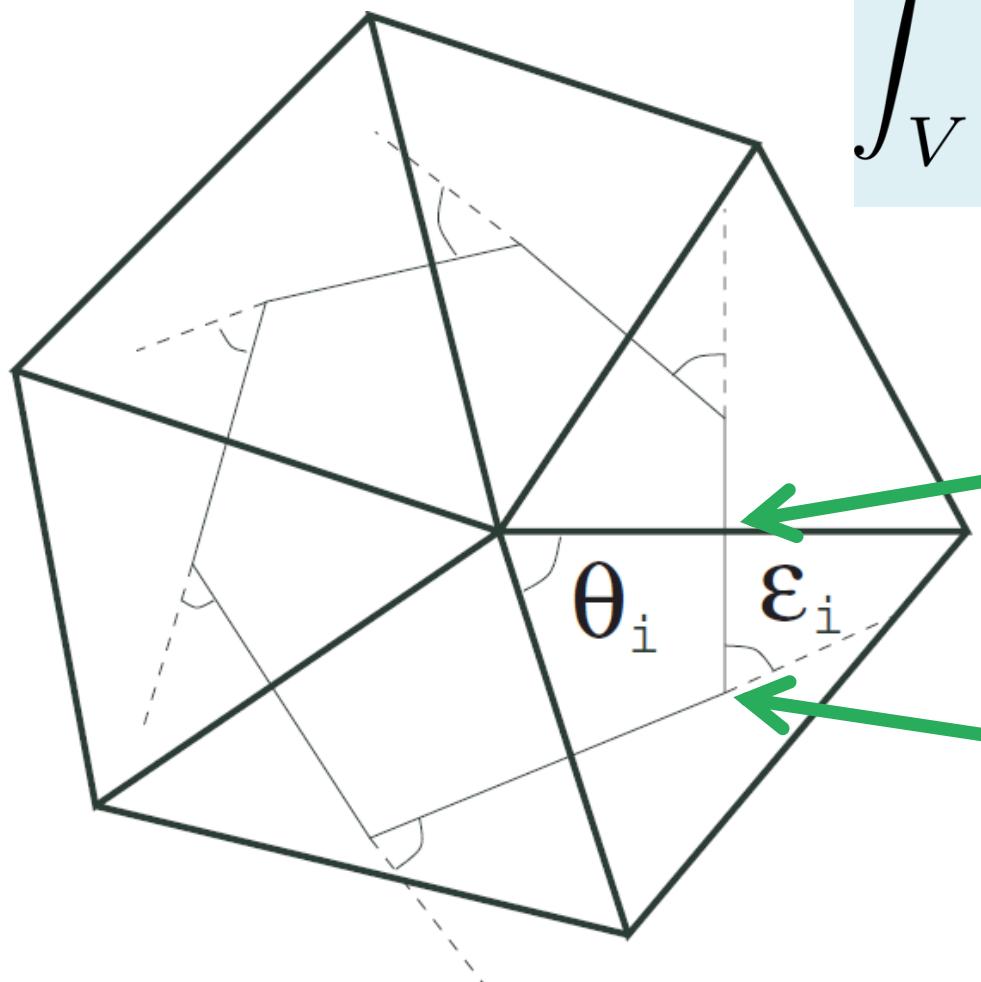


\omit{proof}

2-2g

For Polygonal Cells

$$\int_V K dA = 2\pi - \sum_j \varepsilon_j$$

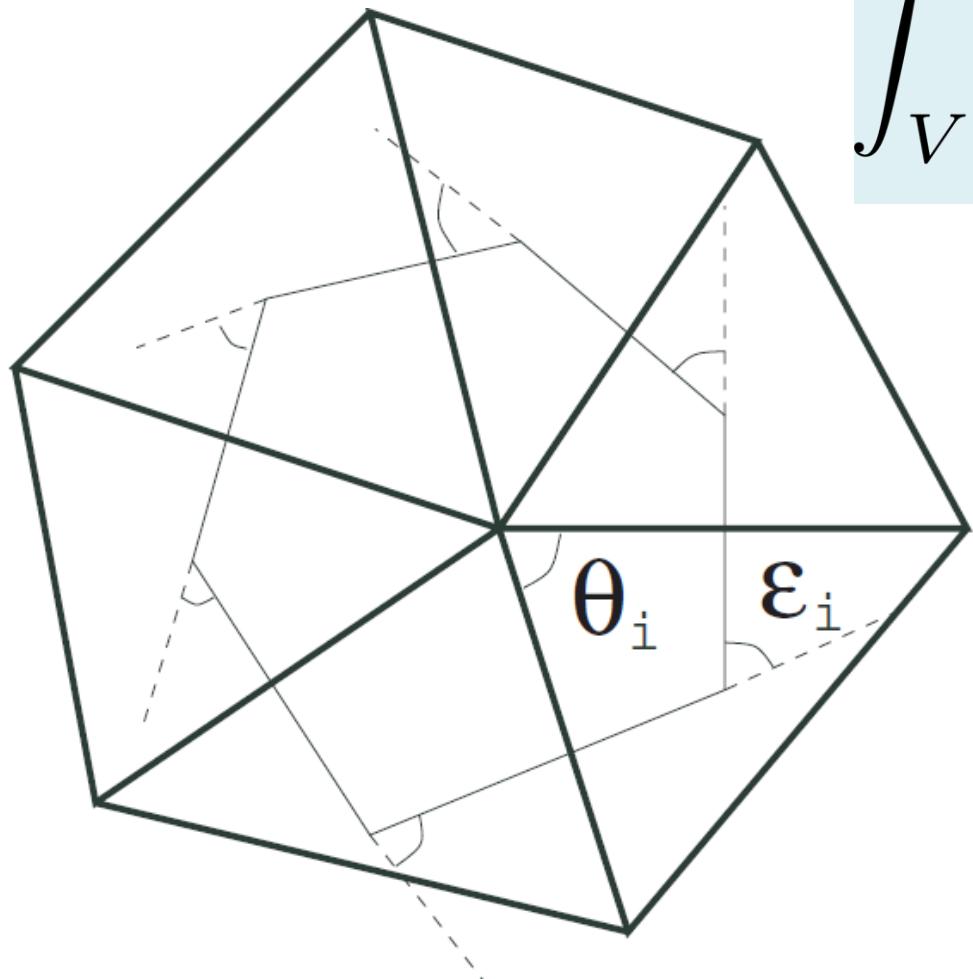


Change is in
normal
direction

Turning angle
integrated
curvature

For Voronoi Cells

$$\int_V K \, dA = 2\pi - \sum_j \theta_j$$



Homework!

Flip Things Backward

DEFINITION:

Gaussian curvature integrated over region V
is given by

$$\int_V K dA = 2\pi - \sum_j \theta_j$$

Divide by area for curvature estimate

Recall:

Euler Characteristic

$$V - E + F := \chi$$

$$\chi = 2 - 2g$$



$$g = 0$$



$$g = 1$$



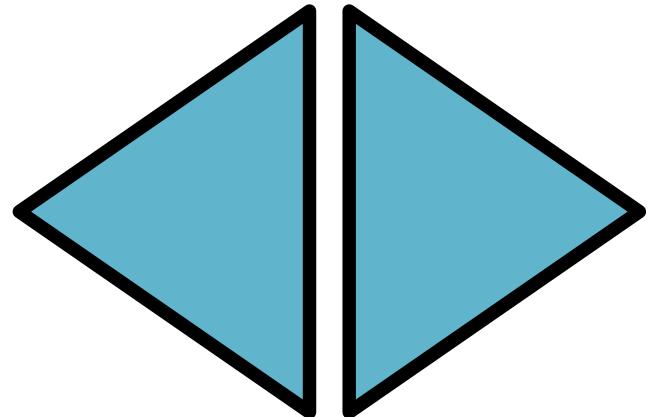
$$g = 2$$

Recall:

Consequences for Triangle Meshes

$$V - E + F := \chi$$

“Each edge is adjacent to two faces. Each face has three edges.”



$$2E = 3F$$

Closed mesh: Easy estimates!

Discrete Gauss-Bonnet

$$\int_M K \, dA = \sum_i \int_{V_i} K \, dA$$

Partition the surface

Discrete Gauss-Bonnet

$$\begin{aligned}\int_M K \, dA &= \sum_i \int_{V_i} K \, dA \\ &= \sum_i \left(2\pi - \sum_j \theta_{ij} \right)\end{aligned}$$

Apply our definition

Discrete Gauss-Bonnet

$$\begin{aligned}\int_M K \, dA &= \sum_i \int_{V_i} K \, dA \\ &= \sum_i \left(2\pi - \sum_j \theta_{ij} \right) \\ &= 2\pi V - \sum_{ij} \theta_{ij}\end{aligned}$$

Pull out constants

Discrete Gauss-Bonnet

$$\begin{aligned}\int_M K \, dA &= \sum_i \int_{V_i} K \, dA \\ &= \sum_i \left(2\pi - \sum_j \theta_{ij} \right) \\ &= 2\pi V - \sum_{ij} \theta_{ij} \\ &= 2\pi V - \pi F\end{aligned}$$

Consider sum over triangles

Discrete Gauss-Bonnet

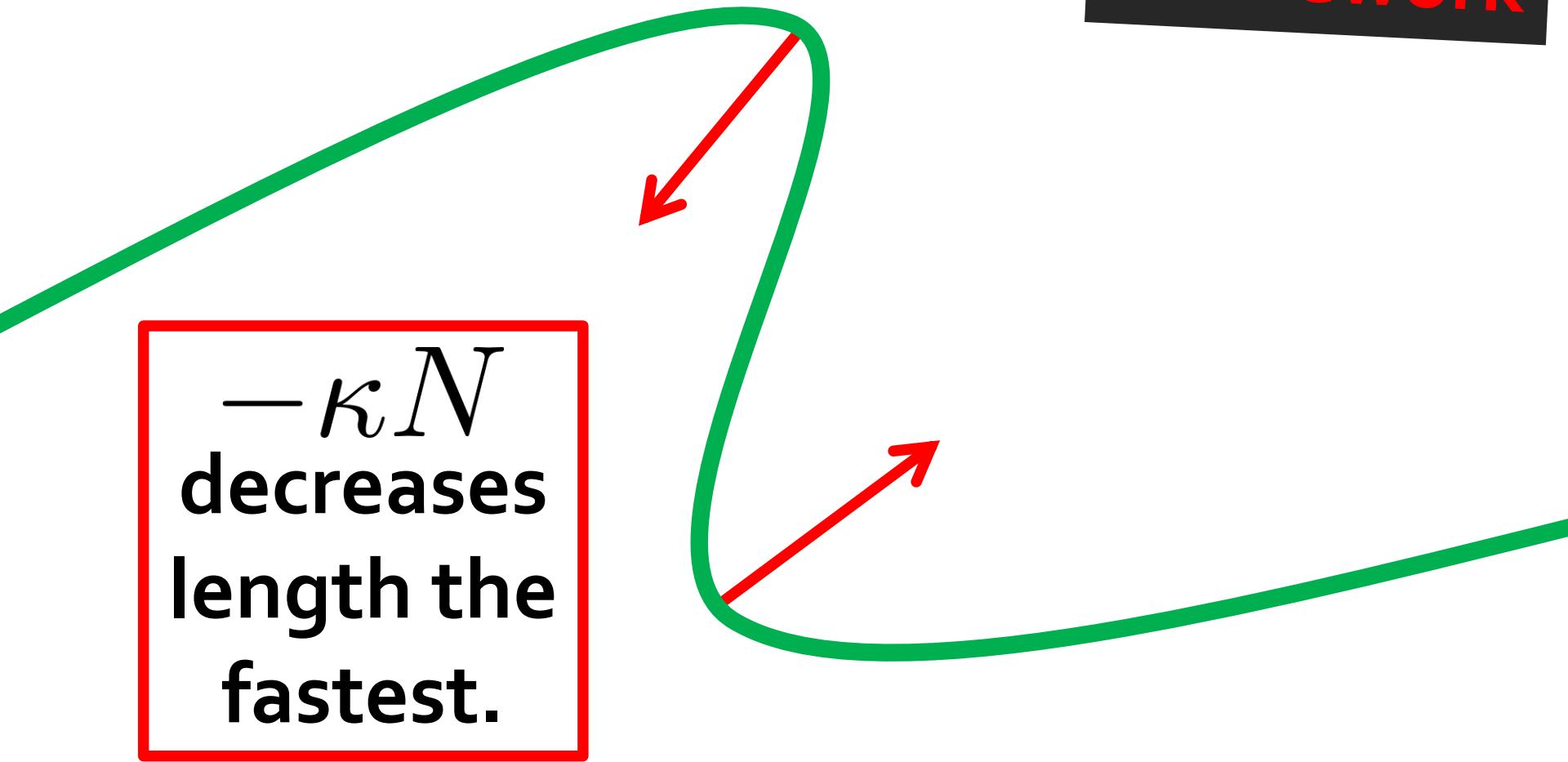
$$\begin{aligned}\int_M K dA &= \sum_i \int_{V_i} K dA \\&= \sum_i \left(2\pi - \sum_j \theta_{ij} \right) \\&= 2\pi V - \sum_{ij} \theta_{ij} \\&= 2\pi V - \pi F \\&= \pi(2V - F) \\&= 2\pi\chi \quad \text{}$$

By definition

Recall:

Alternative Definition

Homework

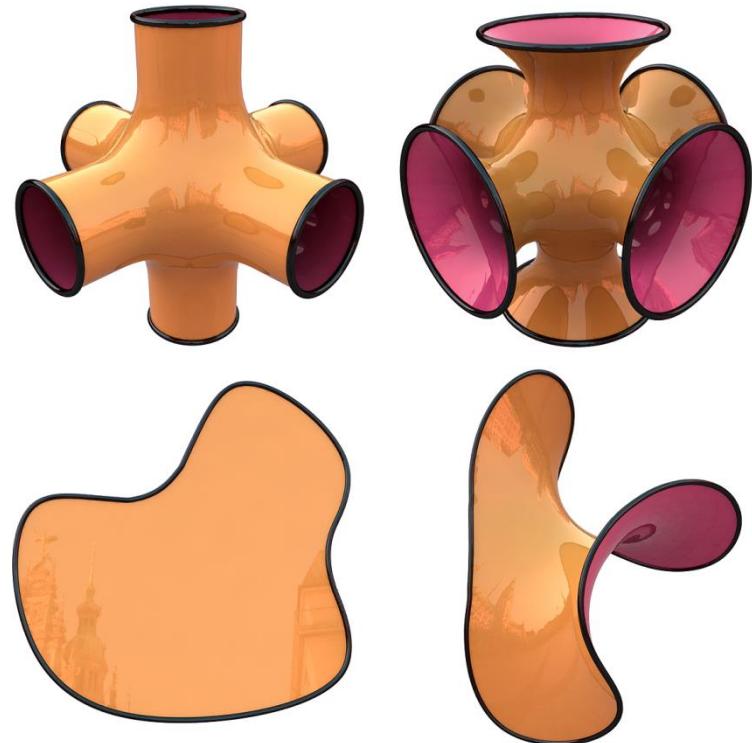


Mean Curvature Normal

$$E(M) = \text{Area}(M)$$

$$\nabla E(p) = H\vec{n}$$

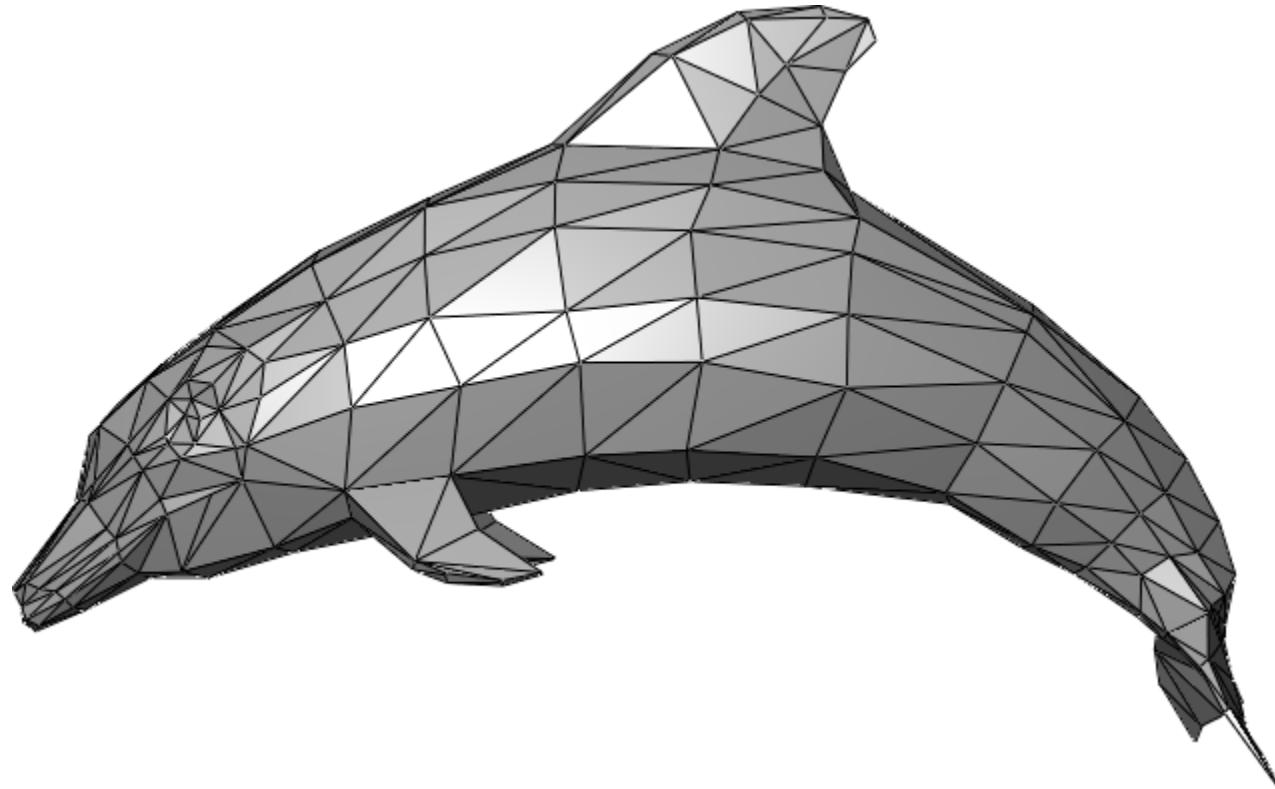
“Variational derivative”



$$\nabla E(p) \equiv 0 \quad \forall p \in \text{int } M$$

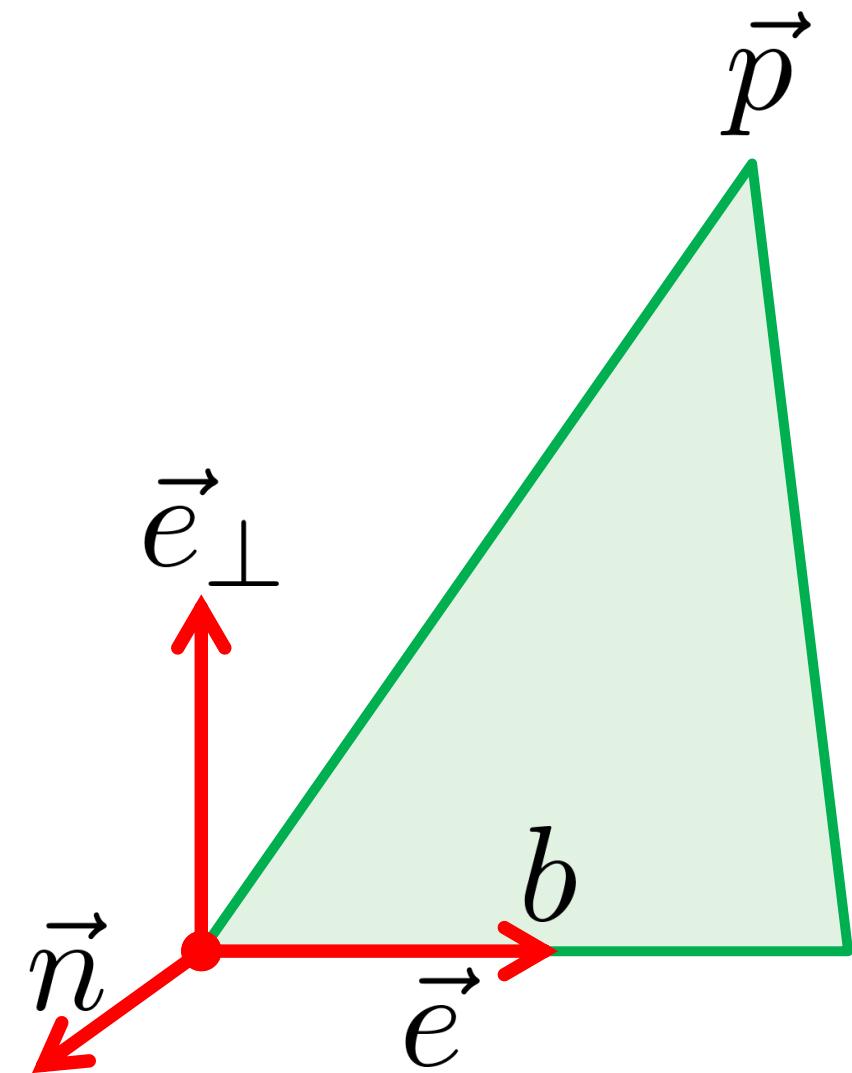
Minimal surfaces

Area Functional for Meshes



$$\text{Area} : \mathbb{R}^{3V} \rightarrow \mathbb{R}$$

Single Triangle



$$\vec{p} = p_n \vec{n} + p_e \vec{e} + p_\perp \vec{e}_\perp$$

$$A = \frac{1}{2} b \sqrt{p_n^2 + p_\perp^2}$$

As a function of \vec{p}

Single Triangle: Derivatives

$$\vec{p} = p_n \vec{n} + p_e \vec{e} + p_\perp \vec{e}_\perp$$

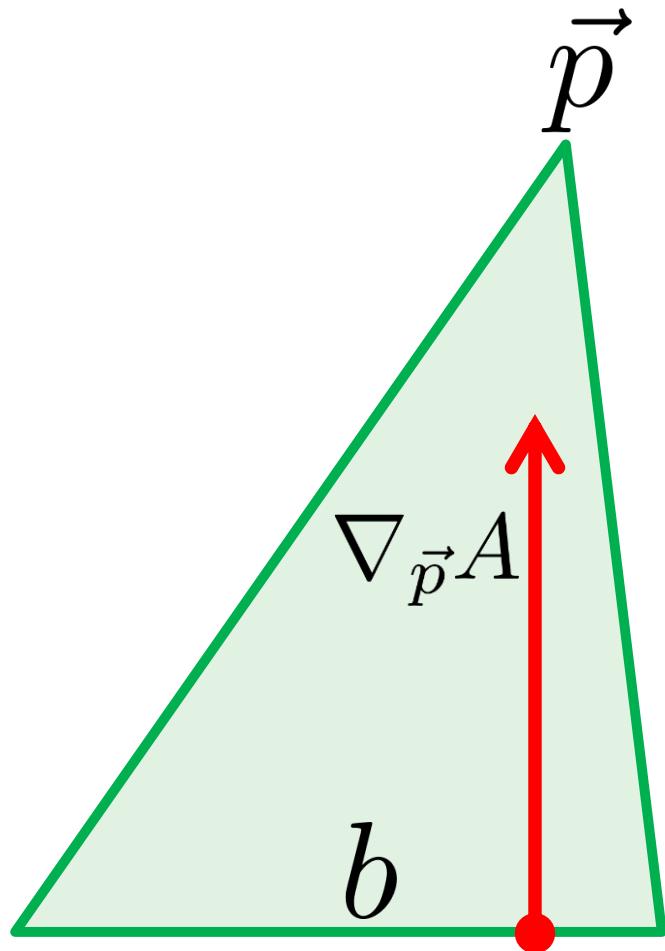
$$A = \frac{1}{2} b \sqrt{p_n^2 + p_\perp^2}$$

$$\frac{\partial A}{\partial p_e} = 0$$

$$\frac{\partial A}{\partial p_n} = \frac{bp_n}{2\sqrt{p_n^2 + p_\perp^2}} = 0 \implies \nabla_{\vec{p}} A = \frac{1}{2} b \vec{e}_\perp$$

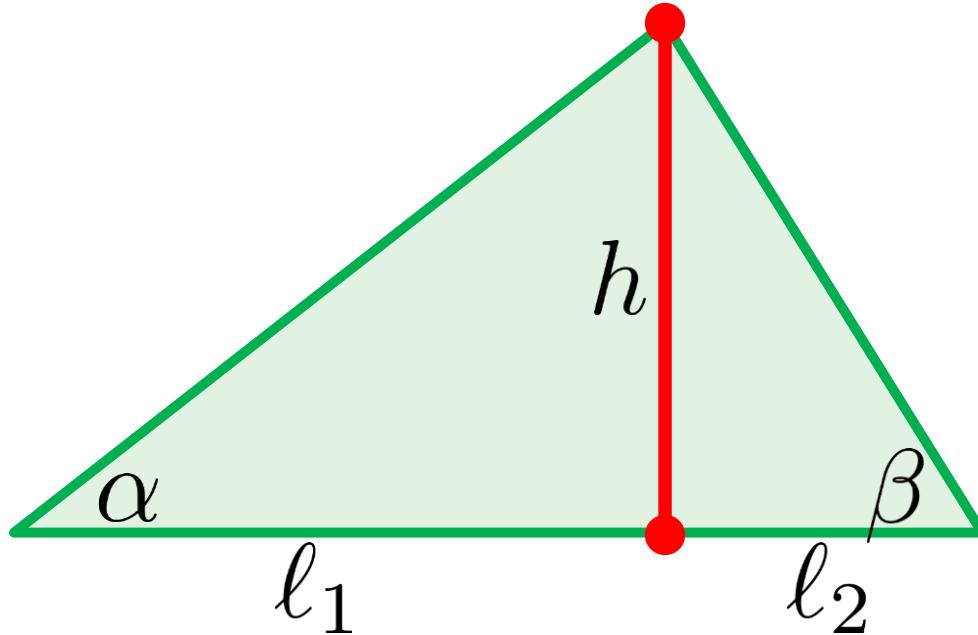
$$\frac{\partial A}{\partial p_\perp} = \frac{bp_\perp}{2\sqrt{p_n^2 + p_\perp^2}}$$

Single Triangle: Complete



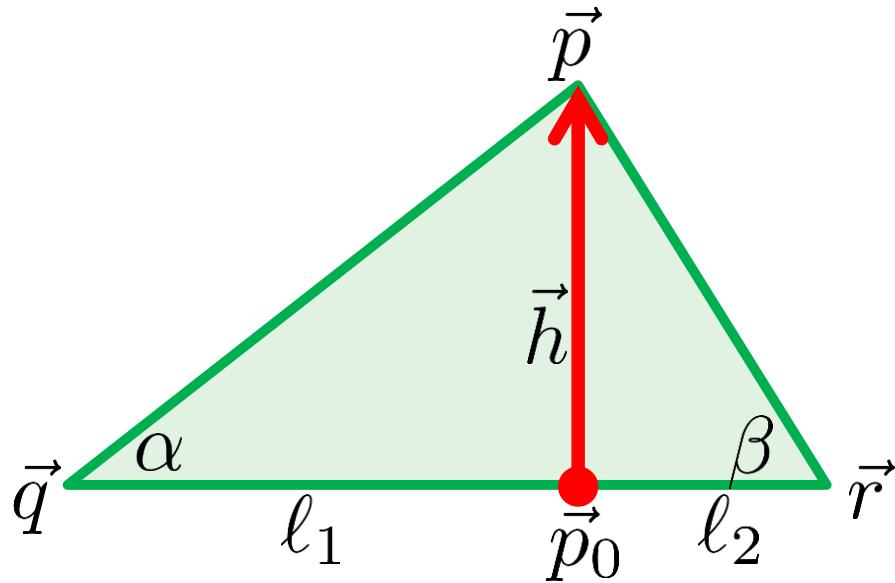
$$\vec{p} = p_n \vec{n} + p_e \vec{e} + p_\perp \vec{e}_\perp$$
$$A = \frac{1}{2} b \sqrt{p_n^2 + p_\perp^2}$$
$$\nabla_{\vec{p}} A = \frac{1}{2} b \vec{e}_\perp$$

Ratio of Base to Height



$$\frac{b}{h} = \frac{\ell_1 + \ell_2}{h} = \frac{\ell_1}{h} + \frac{\ell_2}{h} = \cot \alpha + \cot \beta$$

Height Vector



$$\vec{h} = \vec{p} - \vec{p}_0 = \vec{p} - (\vec{r} - \vec{q}) \frac{\tan \alpha}{\tan \alpha + \tan \beta}$$

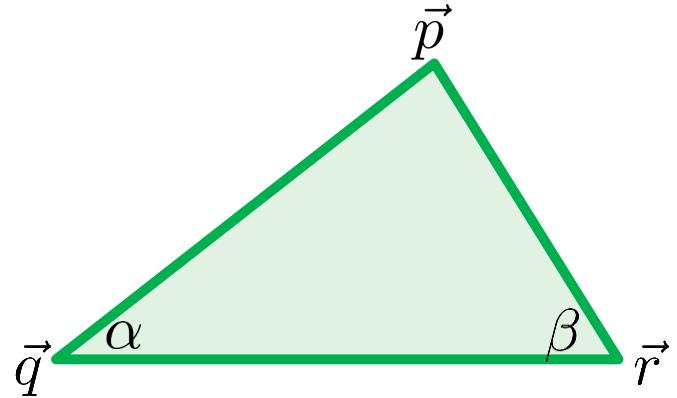
Alternative Gradient Formula

$$\nabla_{\vec{p}} A = \frac{1}{2} b \vec{e}_\perp$$

$$= \frac{1}{2} \frac{b}{\|\vec{h}\|} \vec{h}$$

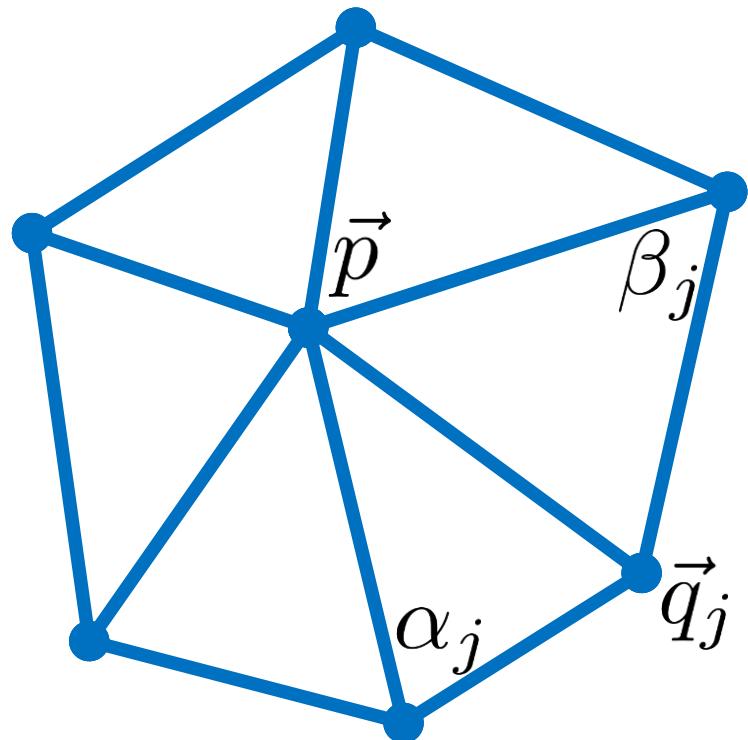
$$= \frac{1}{2} (\cot \alpha + \cot \beta) \left[\vec{p} - (\vec{r} - \vec{q}) \frac{\tan \alpha}{\tan \alpha + \tan \beta} \right]$$

$$= \frac{1}{2} ((\vec{p} - \vec{r}) \cot \alpha + (\vec{p} - \vec{q}) \cot \beta)$$



Summing Around a Vertex

$$\nabla_{\vec{p}} A = \frac{1}{2} \sum_j (\cot \alpha_j + \cot \beta_j) (\vec{p} - \vec{q}_j)$$



$$\nabla_{\vec{p}} A = \frac{1}{2} ((\vec{p} - \vec{r}) \cot \alpha + (\vec{p} - \vec{q}) \cot \beta)$$

Vanishes as you
refine the mesh

Integrated Mean Curvature Normal

DEFINITION:

The mean curvature normal integrated over region V is given by

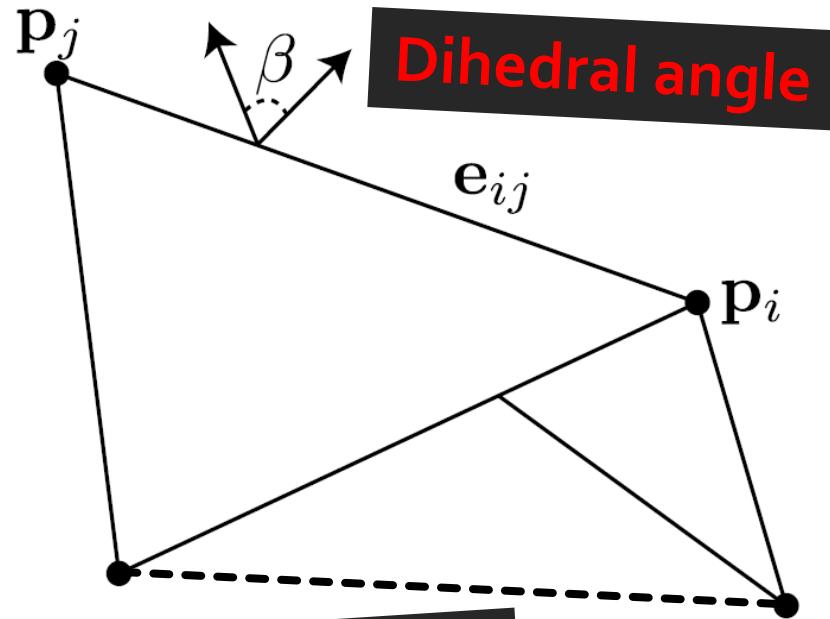
$$\nabla_{\vec{p}} A = \frac{1}{2} \sum_j (\cot \alpha_j + \cot \beta_j) (\vec{p} - \vec{q}_j)$$

Divide by area for curvature estimate

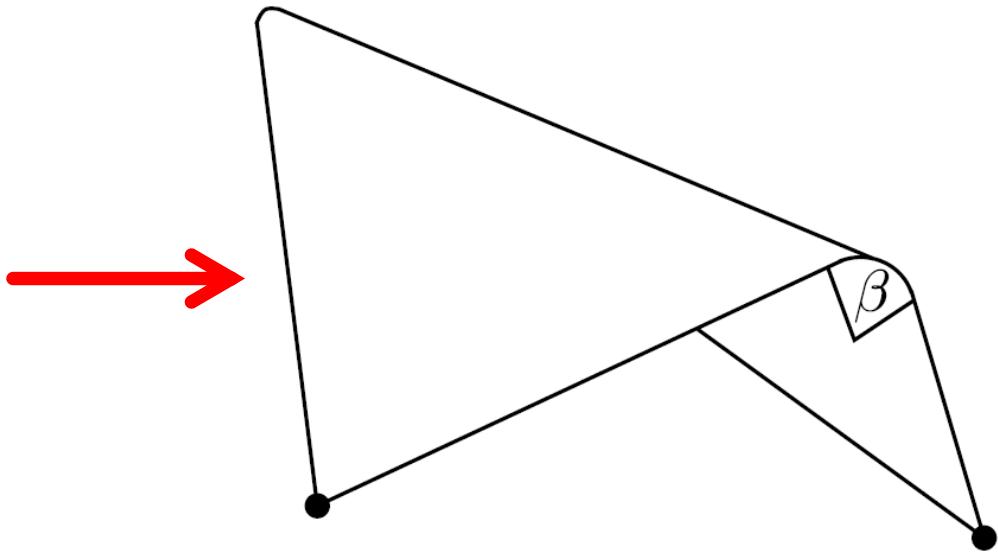
Pipeline

- Compute integrated H, K
- Divide by **area of cell** for estimated value

Another Mean Curvature



Same vertices,
lower curvature



$$\int_B H = \frac{1}{2} \beta \|e\|$$

J.A. Bærentzen et al., *Guide to Computational Geometry Processing* (2012)

Used for triangulation applications

Tuned for Variational Applications

Computing discrete shape operators on general meshes

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Abstract

Discrete curvature and shape operators, which can be computed on general meshes, are essential in a variety of applications: simulation, geometric data processing, In many of these applications, existing approaches for formulating curvature operators are based on expensive methods used in engineering applications or on methods from computer graphics.

We propose a simple and efficient formulation for computing discrete shape operators on meshes with degrees of freedom associated with normals. Our formulation produces results for all curvature operators commonly used in graphics; it is simple, efficient, and produces consistent results for different types of meshes.

Cotan



Theirs



Tuned for Robustness

Eurographics Symposium on Geometry Processing (2007)
Alexander Belyaev, Michael Garland (Editors)

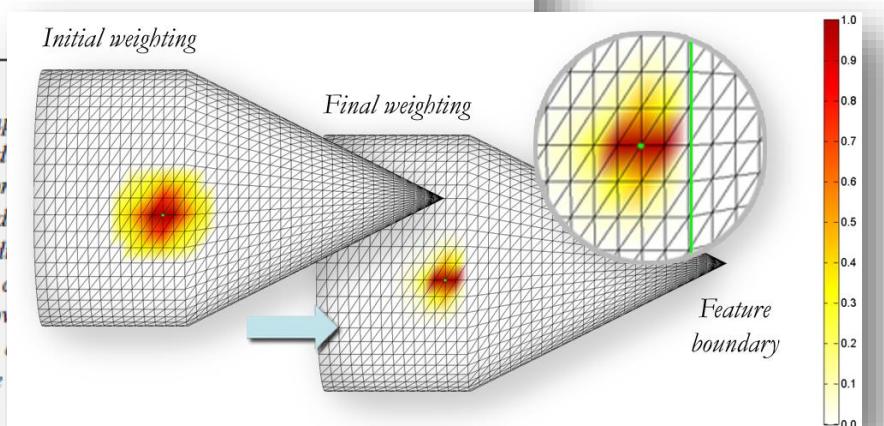
Robust statistical estimation of curvature on discretized surfaces

Evangelos Kalogerakis, Patricio Simari, Derek Nowrouzezahrai and Karan Singh

Dynamic Graphics Project, Computer Science Department, University of Toronto

Abstract

A robust statistics approach to curvature estimation on discretely sampled point clouds, is presented. The method exhibits accuracy, stability and robustness on sampled surfaces with irregular configurations. Within an M-estimation framework, it handles noise and structured outliers by sampling normal variations in an adaptive manner around each point. The algorithm can be used to reliably derive higher order derivatives of surface normals while preserving the fine features of the normal and curvature fields. The proposed method is compared with state-of-the-art curvature estimation methods and shown to improve the quality of curvature estimation across ground truth test surfaces under varying tessellation densities and levels of noise. Finally, the benefits of a robust statistical estimation of curvature are demonstrated in applications of mesh segmentation and suggestive contour rendering.



Categories and Subject Descriptors (according to ACM CCS): I.3.5 [Computational Geometry and Object Modeling]: Geometric algorithms, languages, and systems; curve, surface, solid, and object representations.

Alternative Strategies

- **Locally fit** a smooth surface

What type of surface? How to fit?

- Different **formula**

Function of curvature? Where on mesh?

Convergence of approximation?

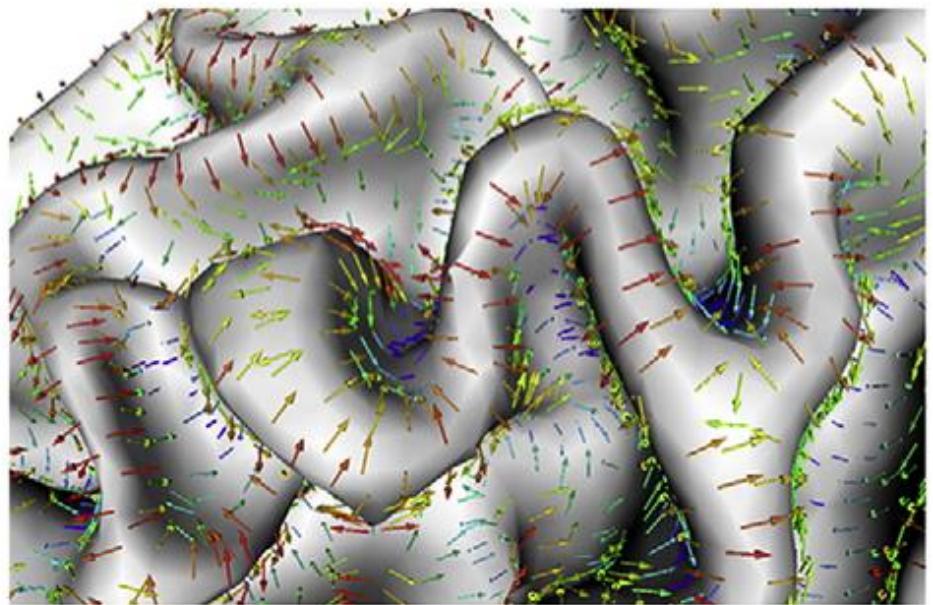
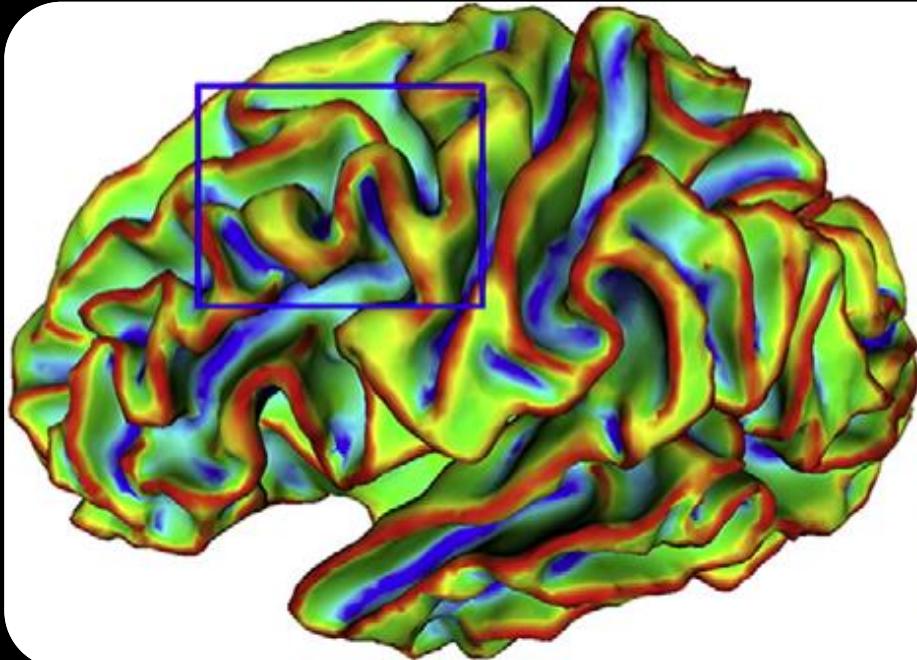
- **Learn curvature computation**

Tune for application? Training data?

Practical Advice

Try as many as you can.

Most are easy to implement!



Surface Curvature

Justin Solomon
MIT, Spring 2017

