中国科学技术大学
University of Science and Technology of China

GAMES 102在线课程

几何建模与处理基础

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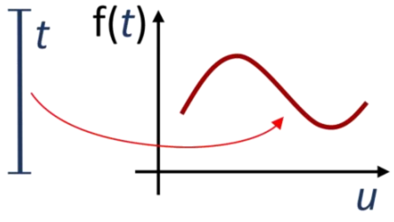
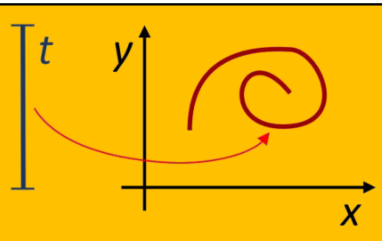
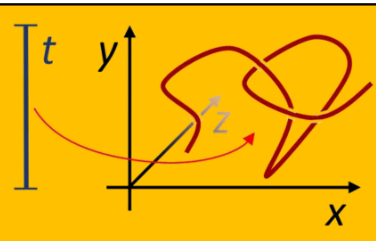
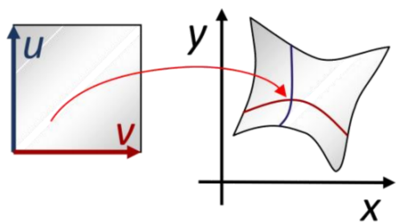
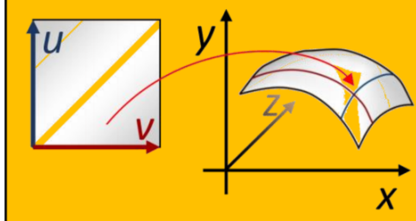
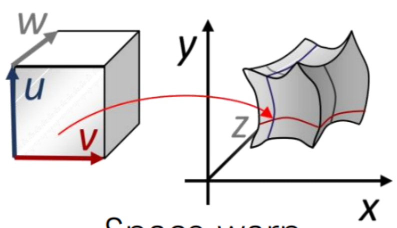
GAMES 102在线课程：几何建模与处理基础

曲面参数化

回顾：低维空间的参数曲线/曲面

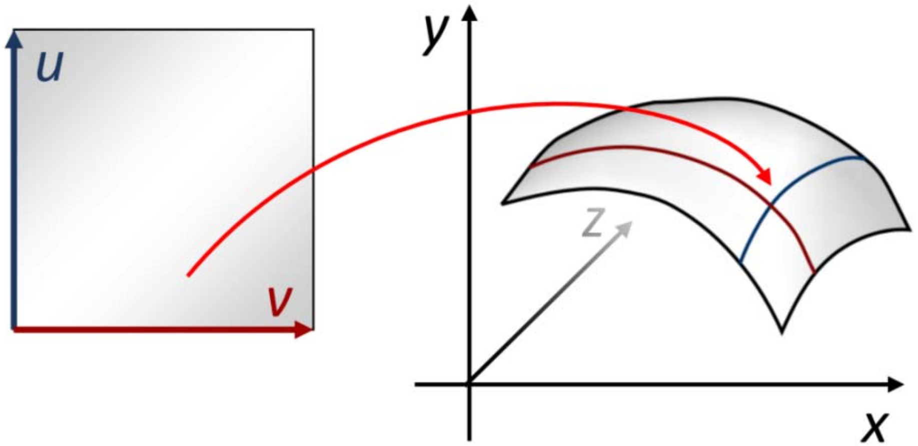
	Output: 1D	Output: 2D	Output: 3D
Input: 1D	 Function graph	 Plane curve	 Space curve
Input: 2D		 Plane warp	 Surface
Input: 3D			 Space warp

回顾：R^3中的参数曲面

- 本质是二维的（二维流形）
- 曲面的每个点对应与参数域上的一个点（称为参数）

$$f:\Omega \to S$$

$$(u,v) \mapsto \begin{cases} x = x(u,v), \\ y = y(u,v), \\ z = z(u,v), \end{cases}$$

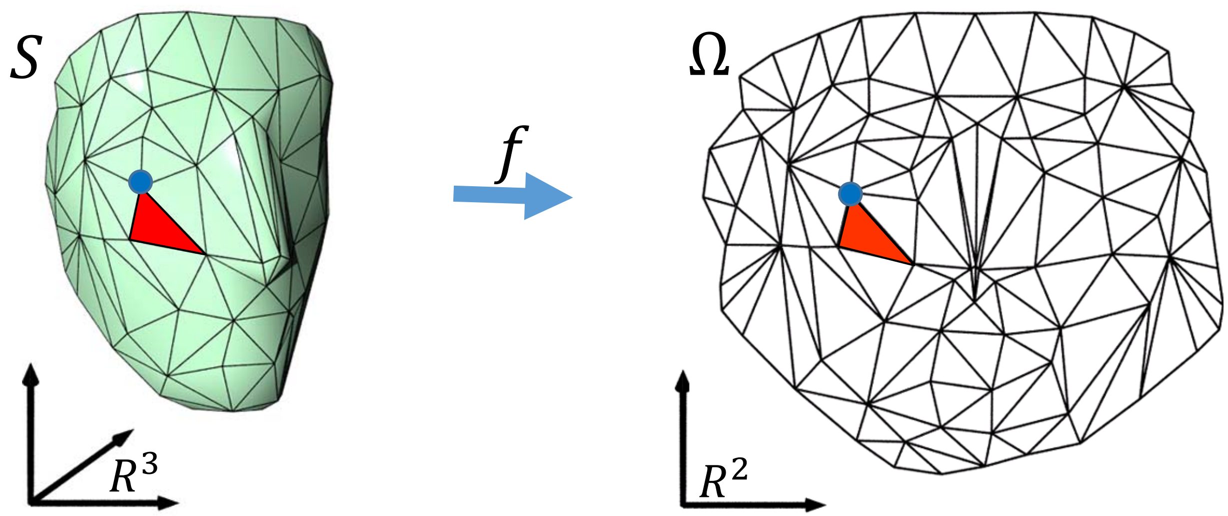


Parameter domain　　Embedded (ambient) space

逆问题：参数化(Parameterization)

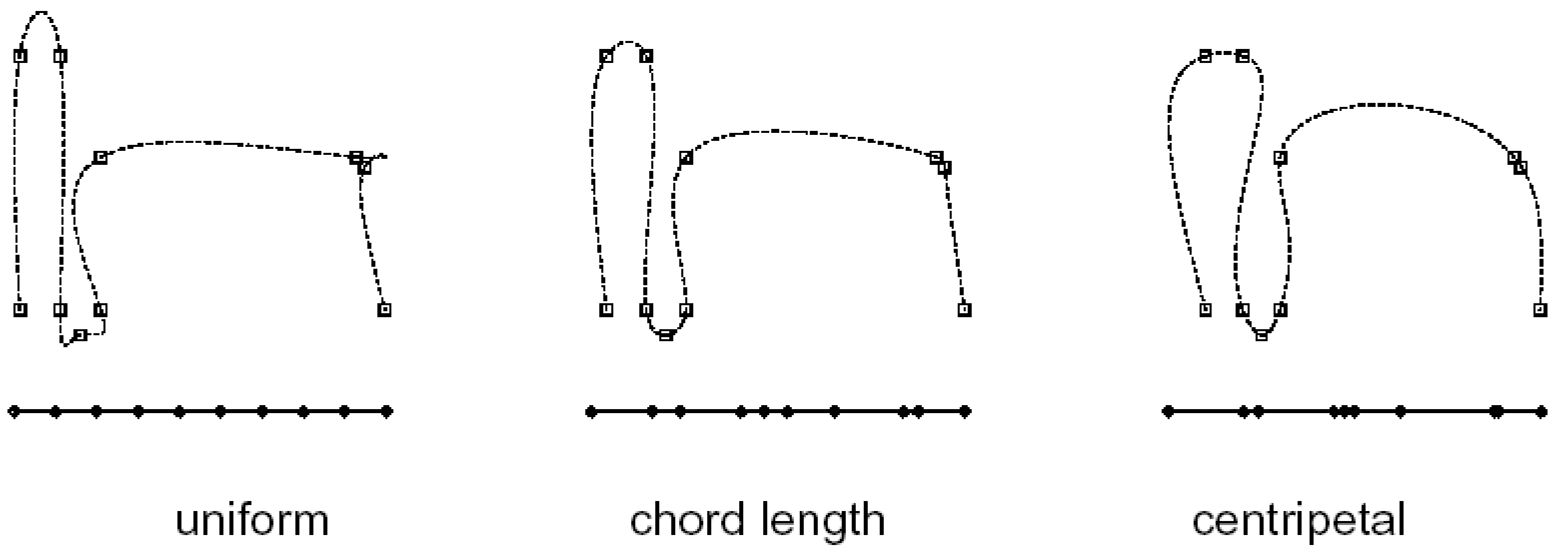
- 问题：给定一张曲面，如何找其二维的参数定义域？
- 又称为：曲面展开(flattening)

Find a mapping $f: S \subset R^3 \rightarrow \Omega \subset R^2$



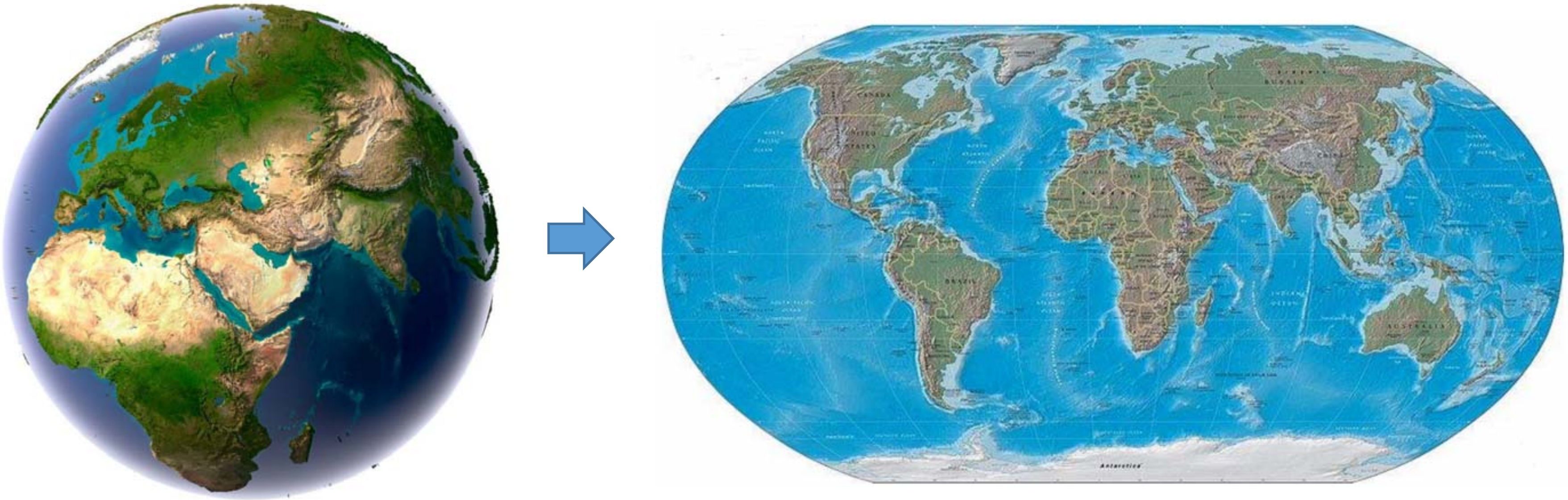
参数化的重要性

- 例子：B样条曲面拟合



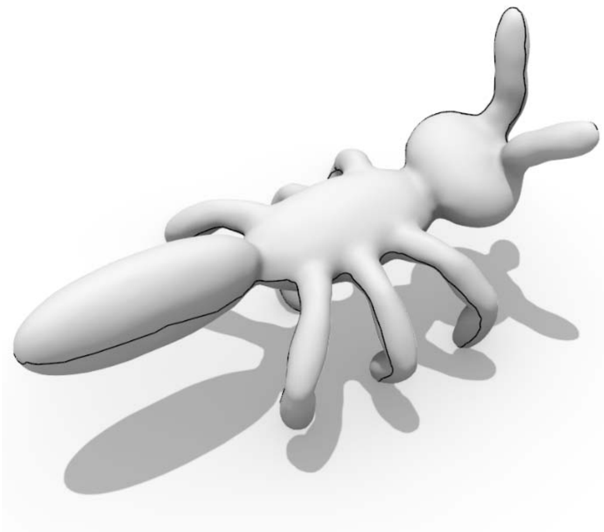
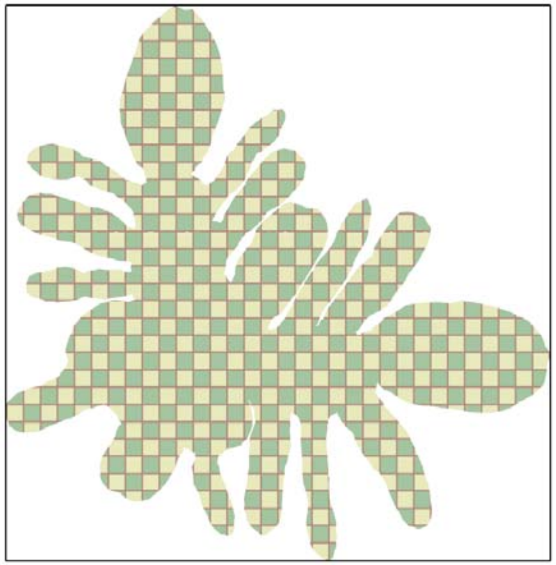
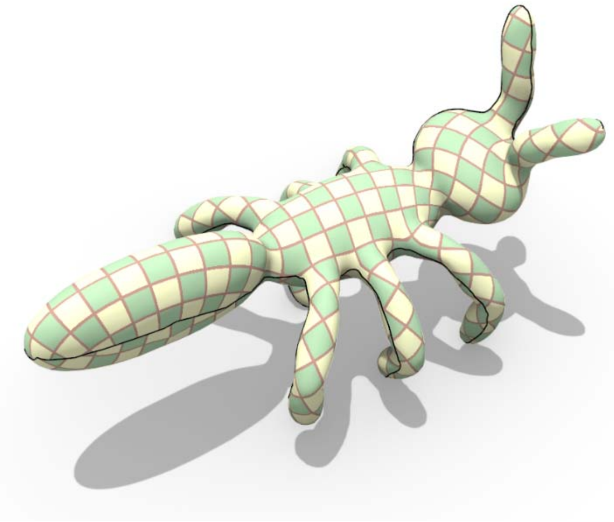
参数化的应用-1

- 地图绘制（地理学）



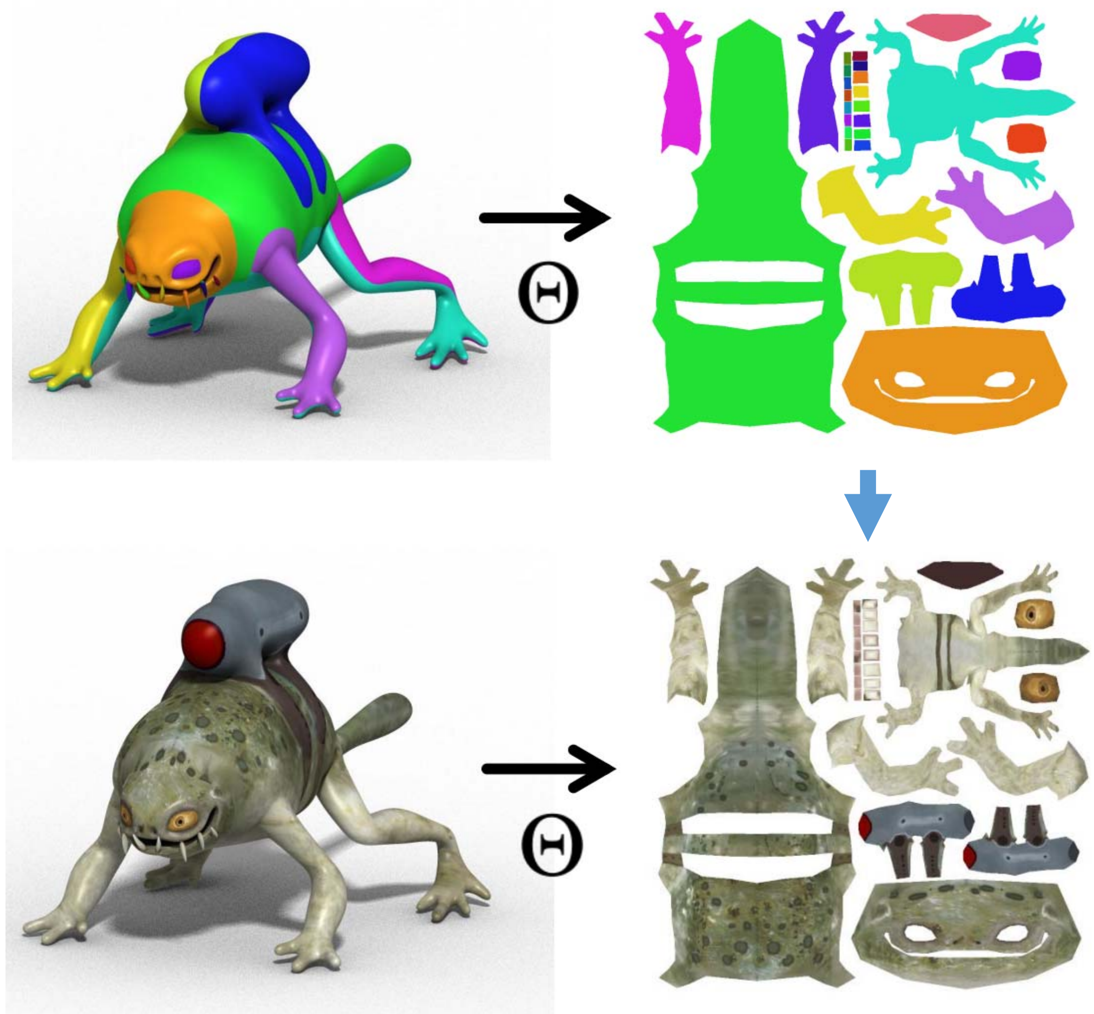
参数化的应用-2

- 纹理映射

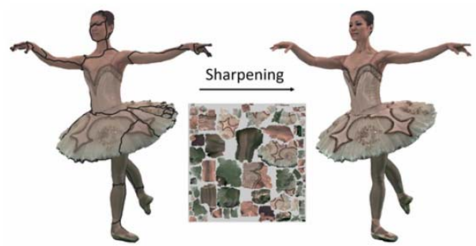
参数化的应用-3

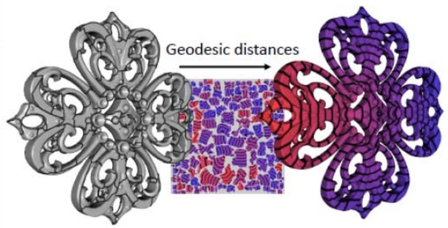
- 曲面绘画

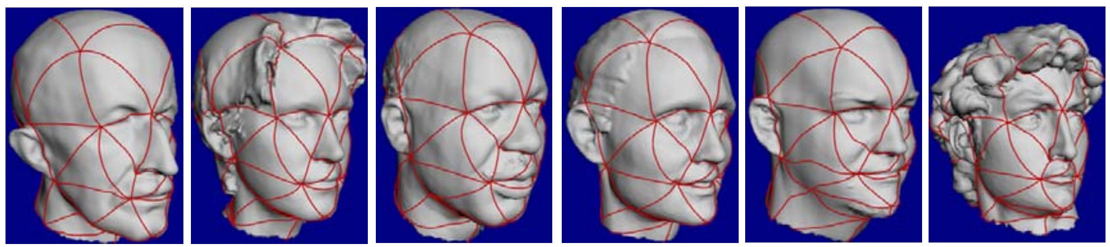


参数化的应用-4

- 大部分几何处理的基础（基本问题）
  - Visualization
  - Texture mapping
  - Matching
  - Compression
  - Remeshing
  - Reconstruction
  - Rendering
  - Animation
  - …







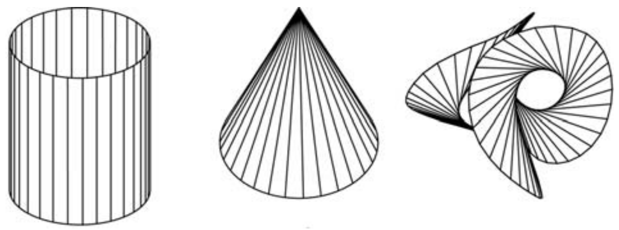
理想的参数化?

A: One that preserves all the basic geometry length, angles, area, …

➔ Isometric parameterization

- **But:** only for developable surfaces

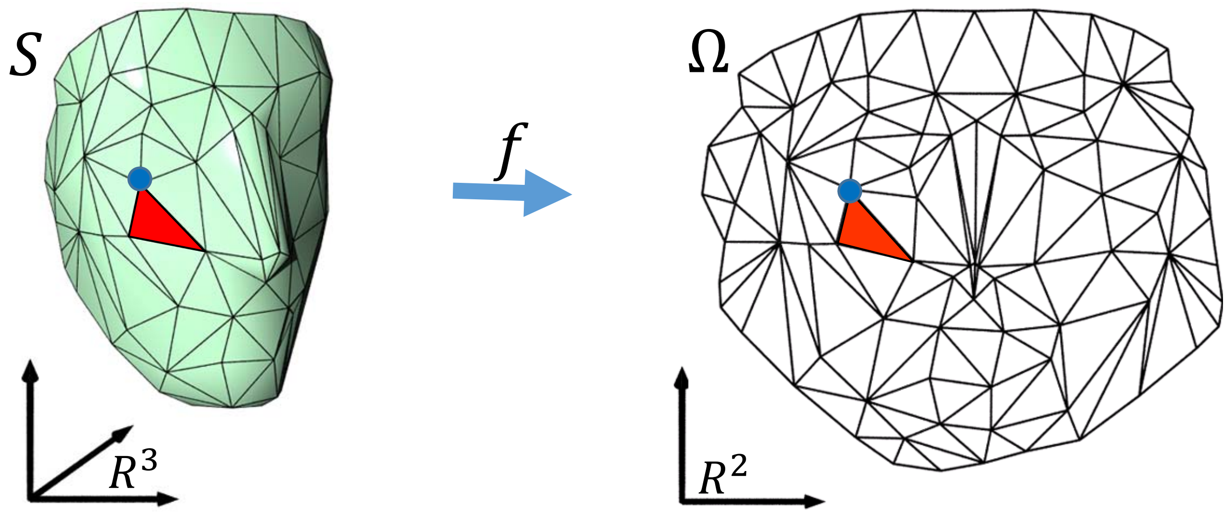
  i.e., there will always be distortions!



➔ Try to keep the distortion as small as possible

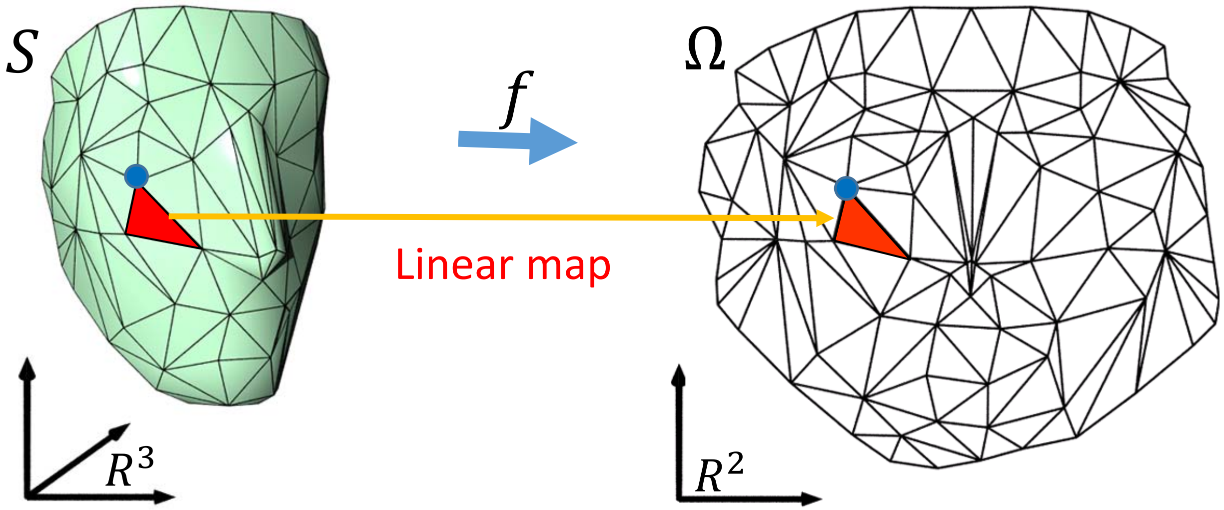
参数化期望保持的几何性质

- 保角映射(angle-preserving)： conformal （共形）
- 保面积映射(area-preserving)： authalic
- 等距映射(isometric)： conformal + authalic

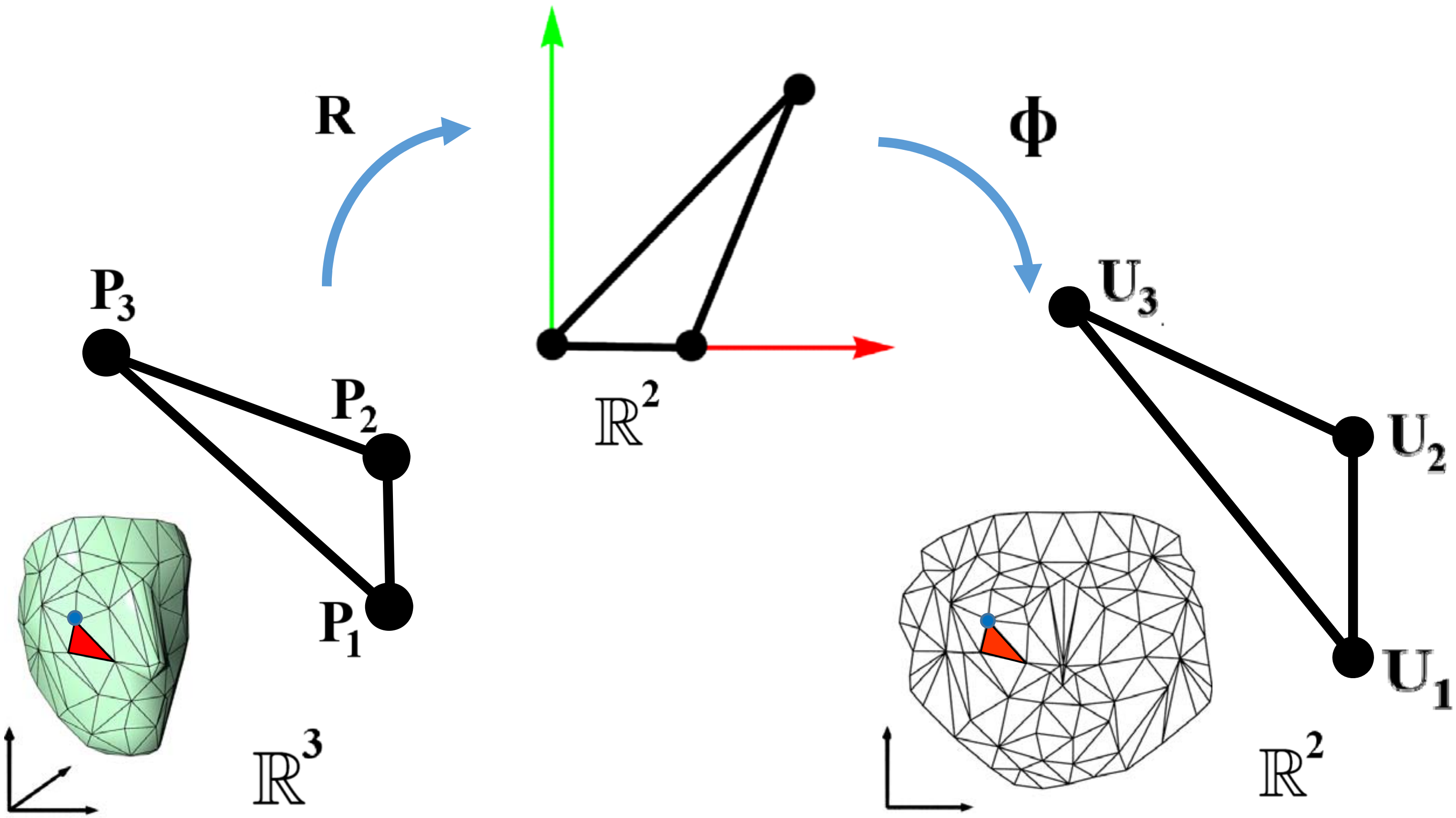


Metric of Distortion

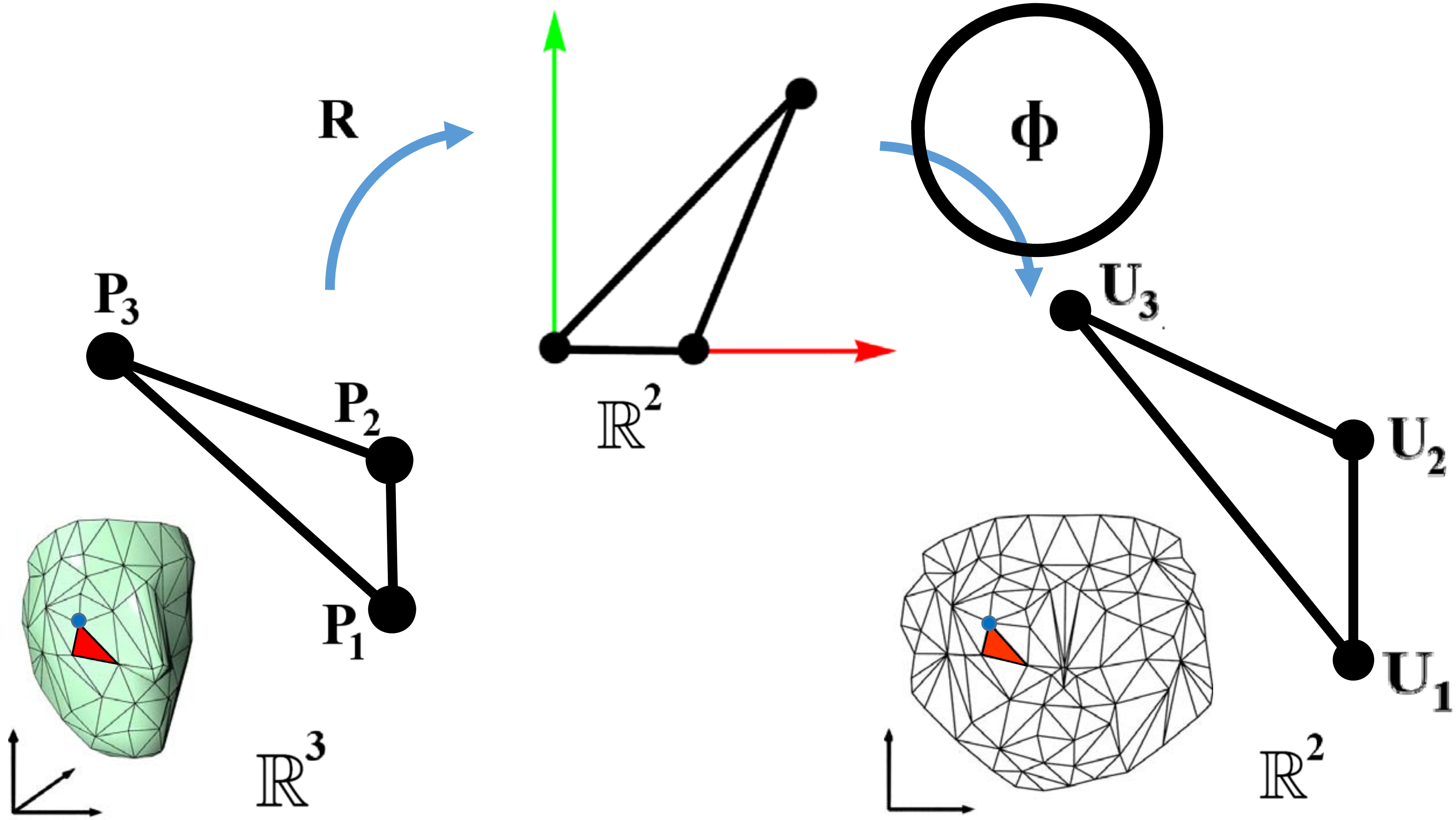
- f is approximated by piecewise linear maps between pairs of triangles



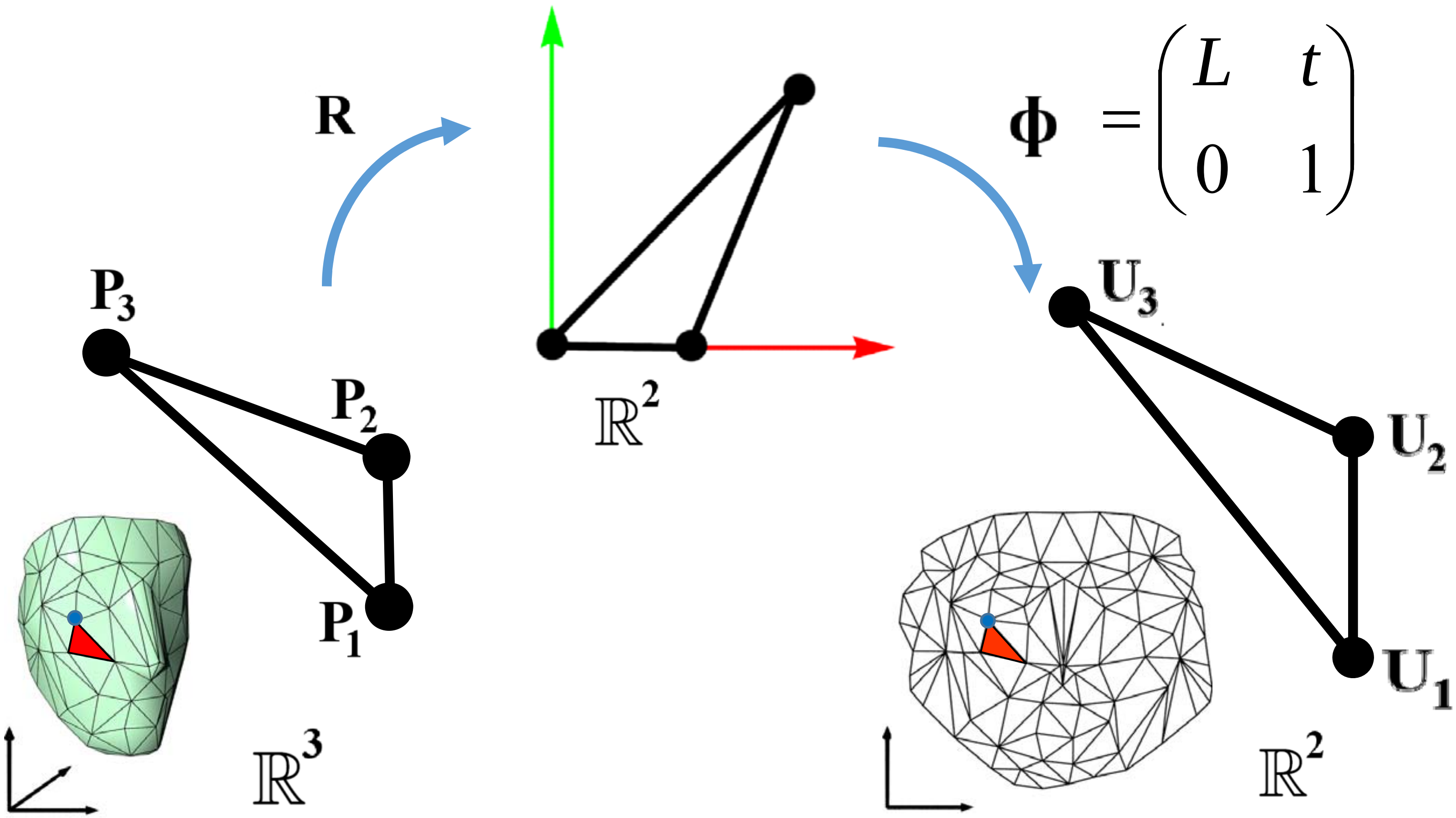
Isometric Flattening



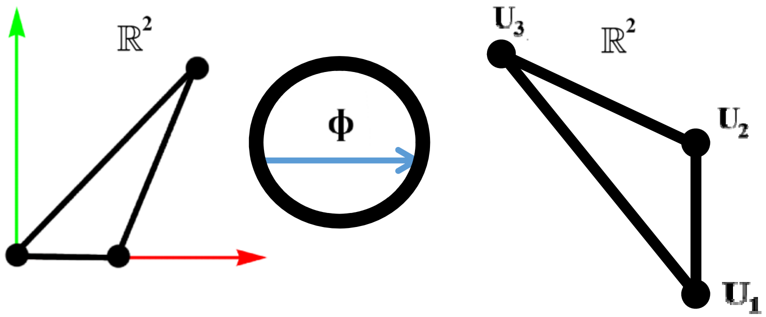
Isometric Flattening



Isometric Flattening

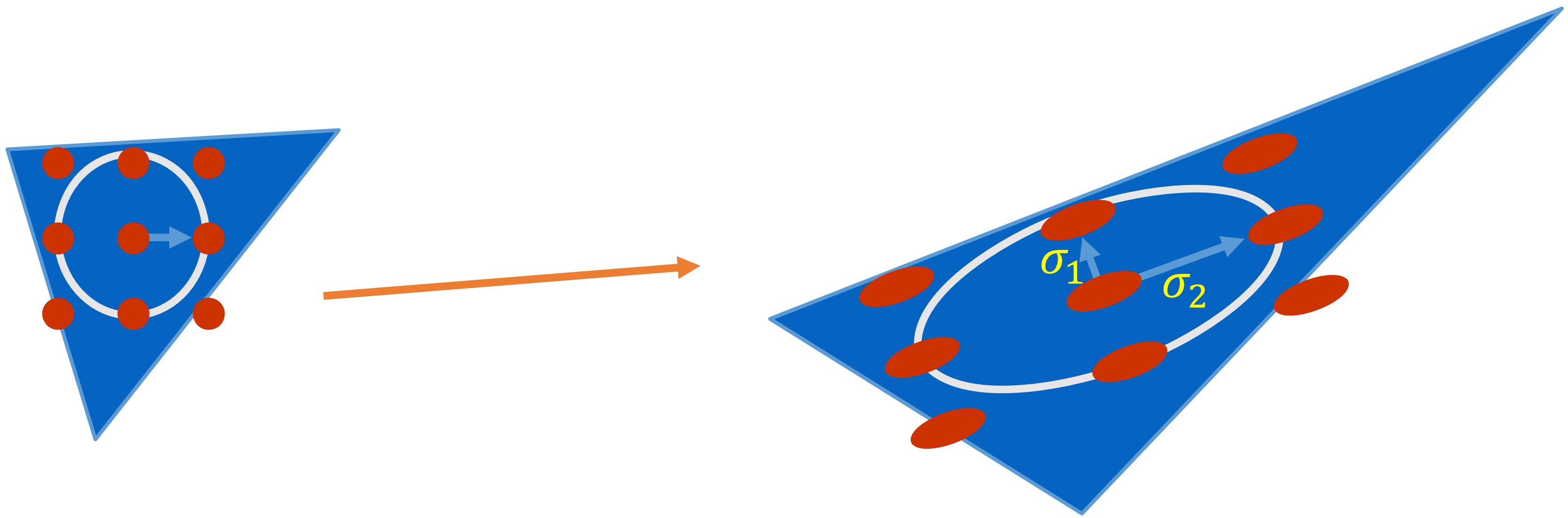


Distortion Measure

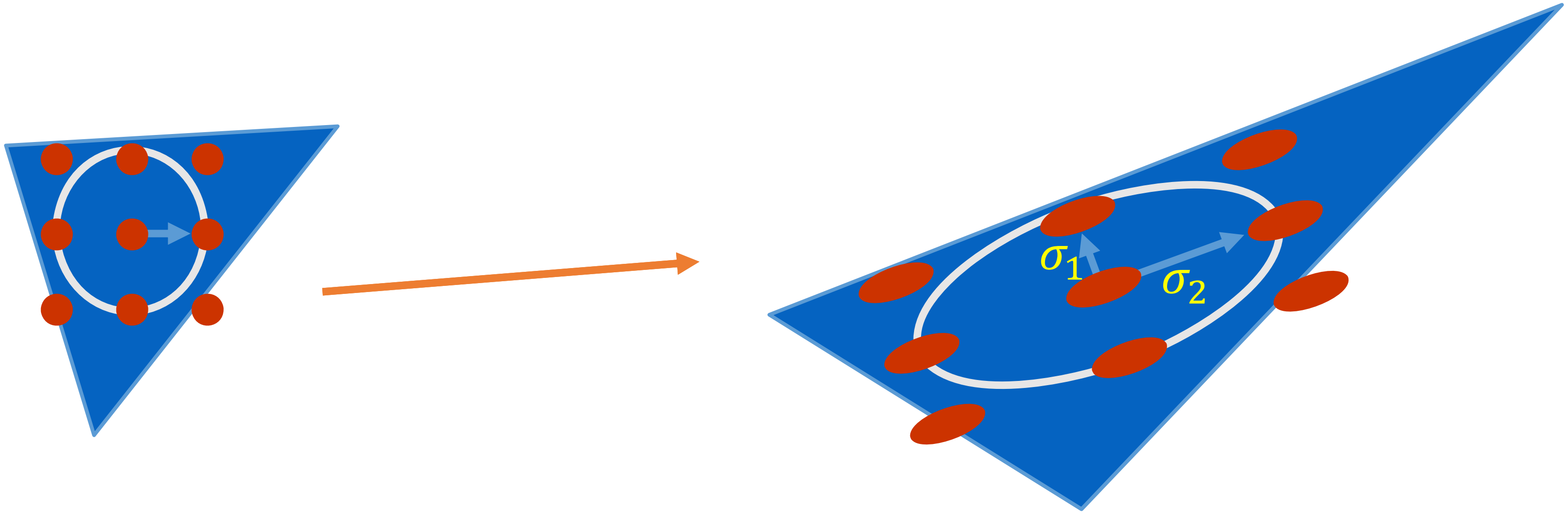


$$L = U\begin{pmatrix} \sigma_1 & 0 \\ 0 & \sigma_2 \end{pmatrix} V^*$$

$$\sigma_2 \geq \sigma_1$$

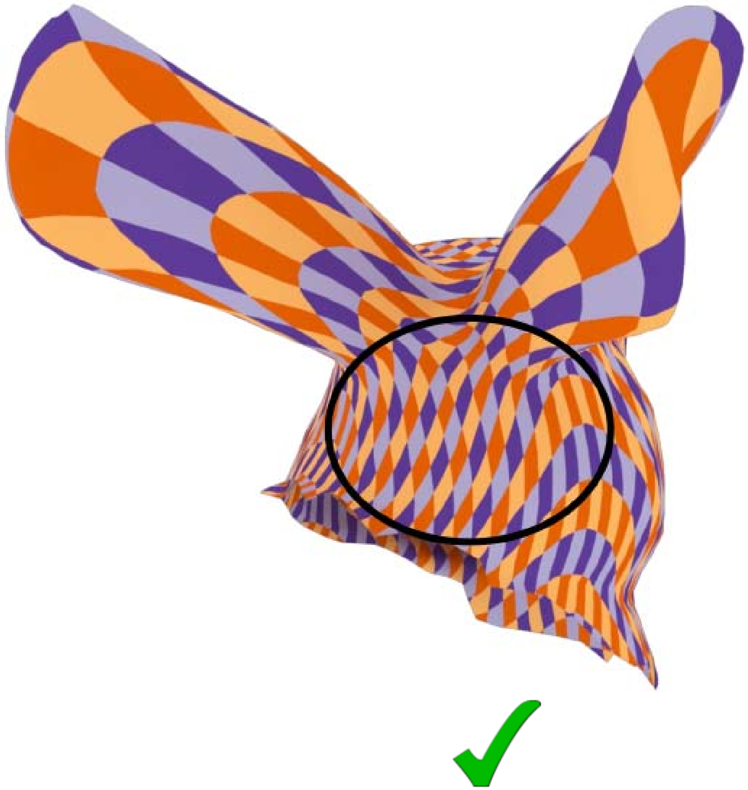


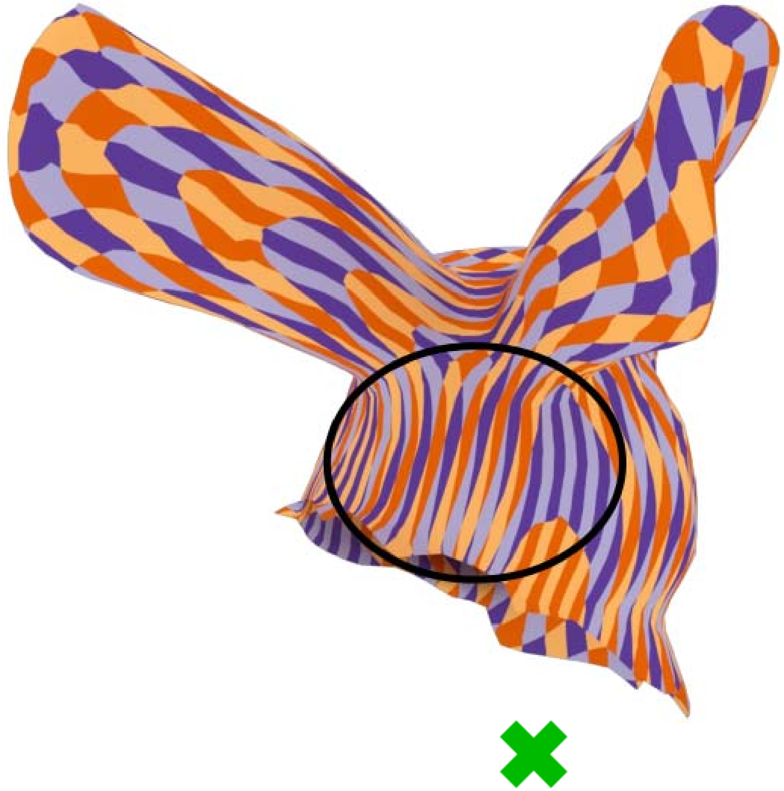
Distortion Measure



- angle-preserving (*conformal*) $\sigma_1 = \sigma_2$
- area-preserving (authalic) $\sigma_1 \sigma_2 = 1$
- length-preserving (*isometric*) $\sigma_1 = \sigma_2 = 1$

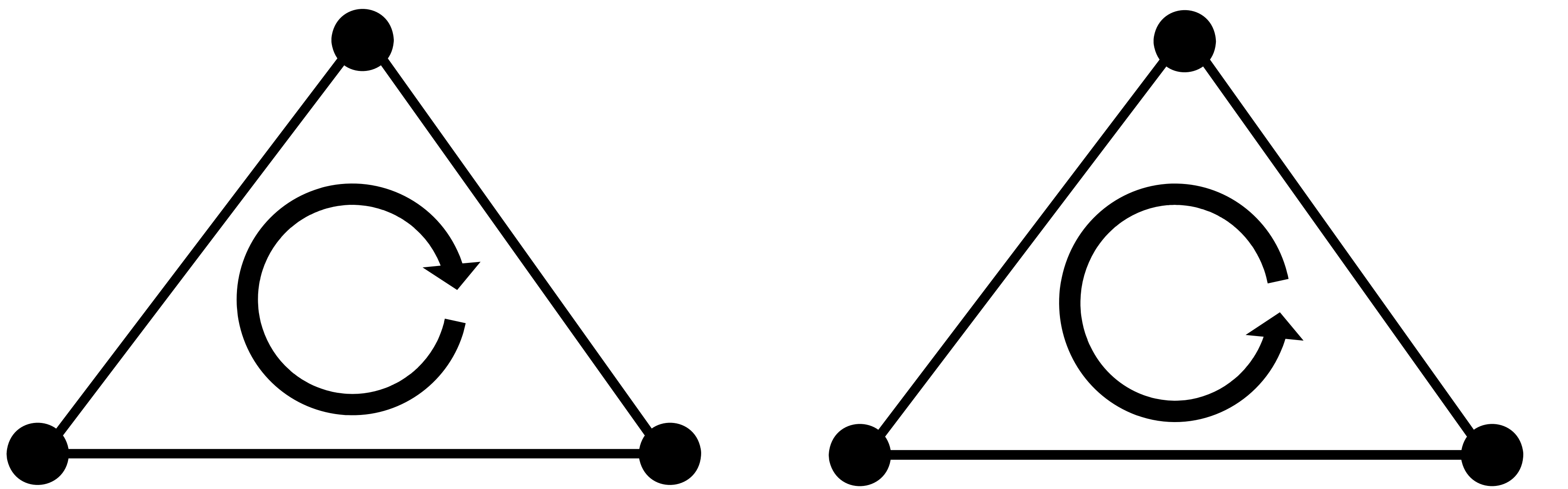
Desired Property: Low distortion



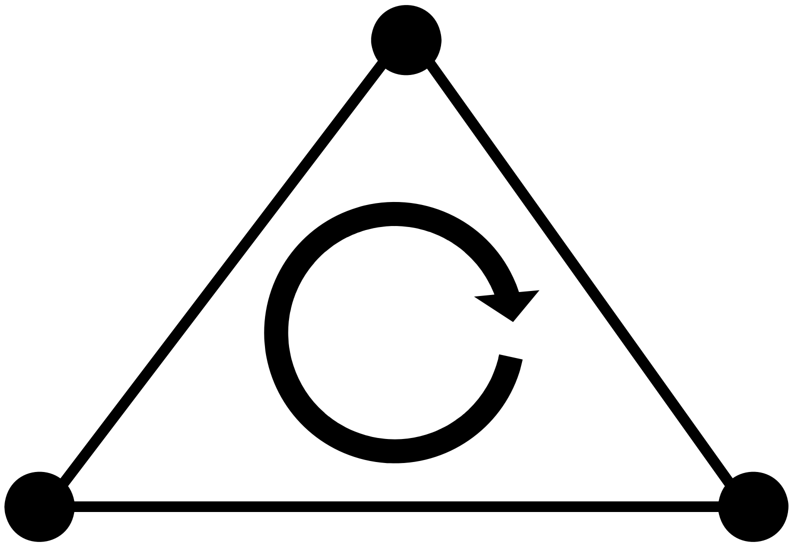


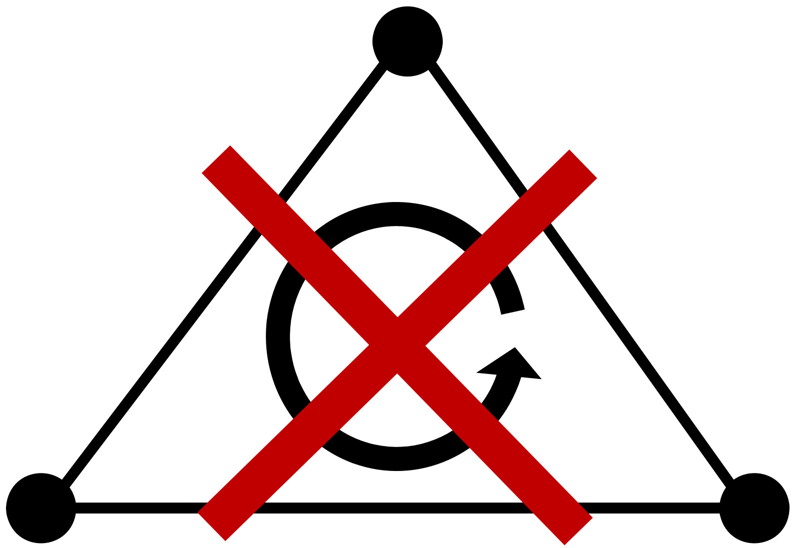
High distortion

Problem Local Injectivity



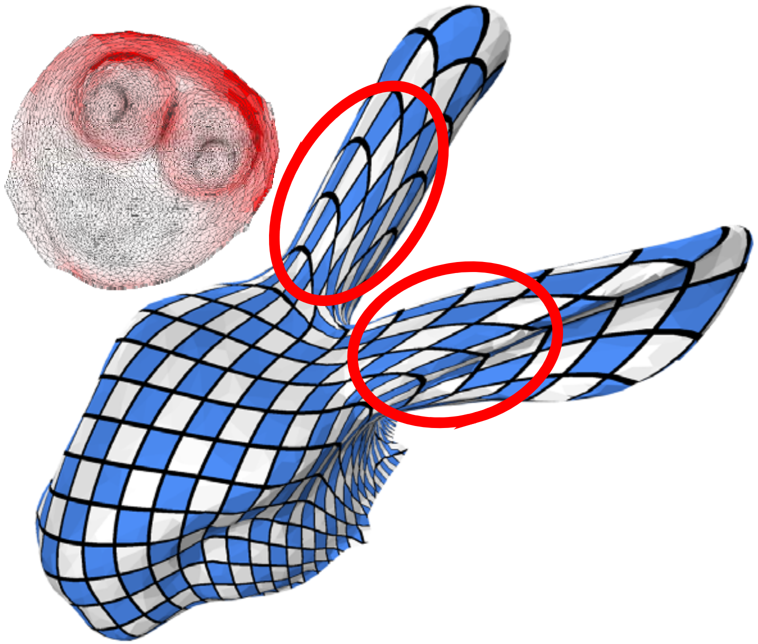
Problem Local Injectivity

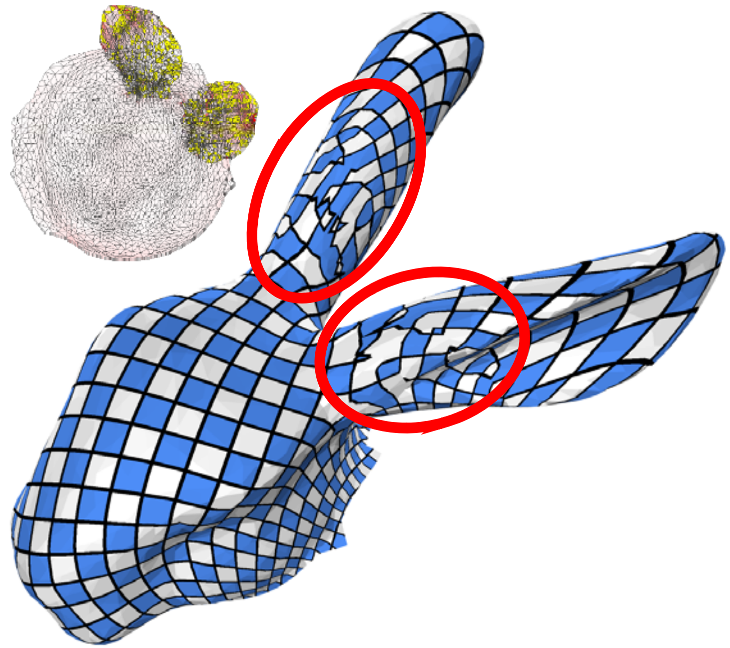




Flip / Foldover

Desired Property: Flip free triangles

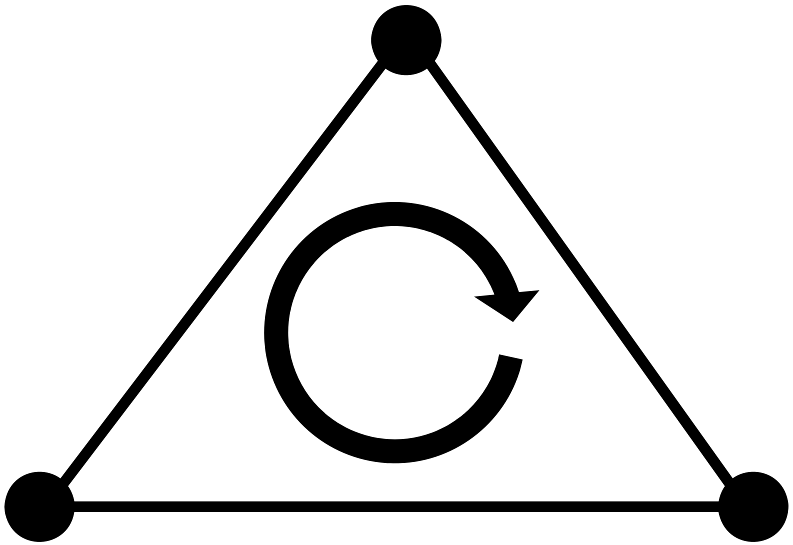


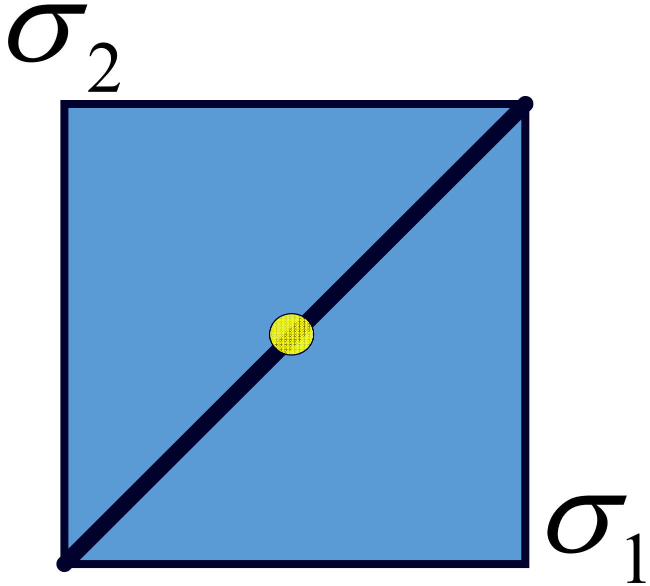


✓ ✗

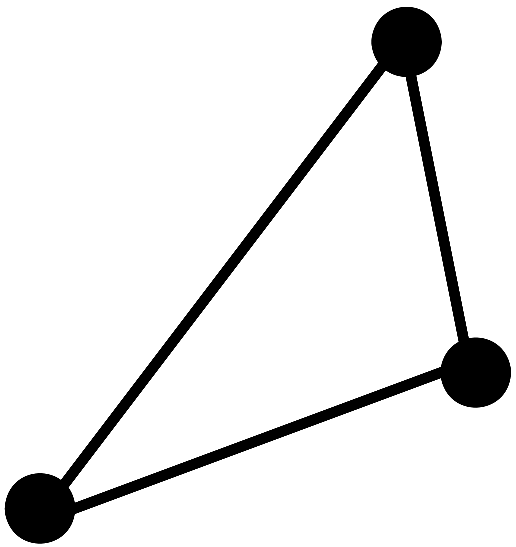
Flip/Foldover triangles

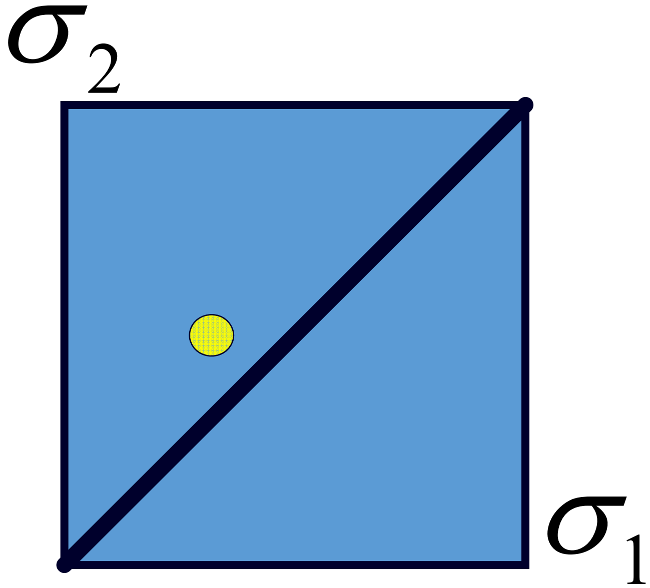
Distortion



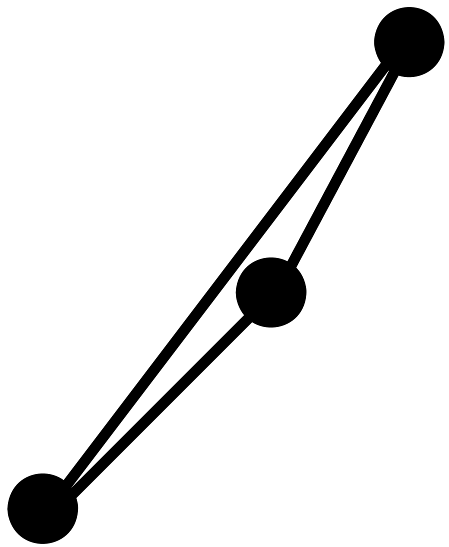


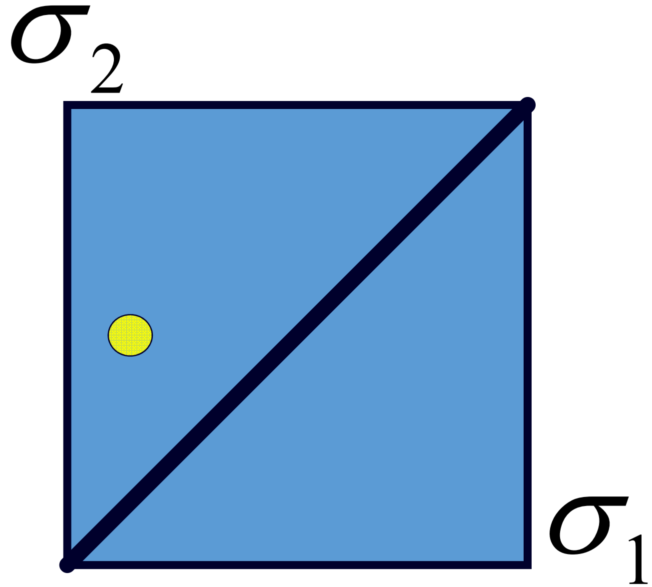
Distortion



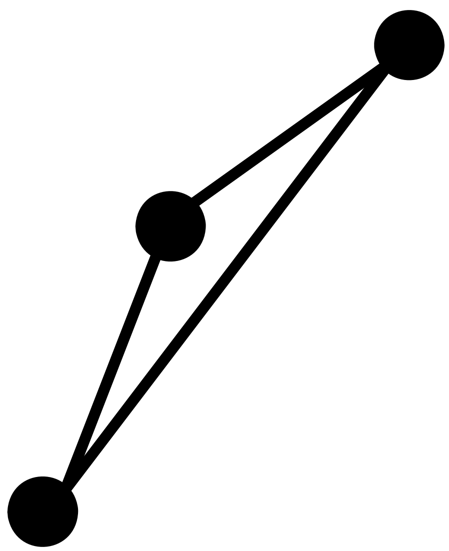


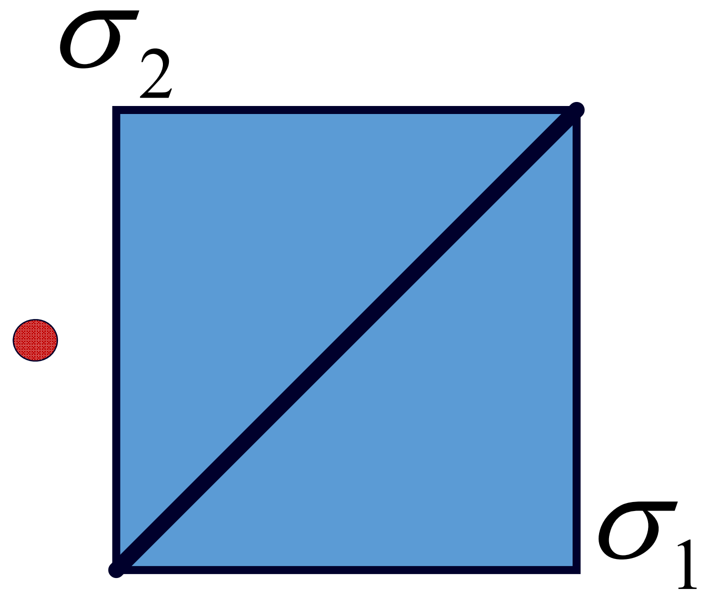
Distortion





Distortion (Flip/Foldover)





Methods of Mesh Parameterization

- Tutte’s method and its variants
  - Tutte’s method [Tutte 1963; Floater 1997, 2003]
  - Variants [Weber and Zorin 2014; Aigerman and Lipman 2015, 2016; Aigerman et al. 2017; Bright et al. 2017;]
- Geometry-based optimization methods
  - Representation based methods [Sheffer and Sturler 2001; Sheffer et al. 2005; Chien et al. 2016b; Fu and Liu 2016]
  - ARAP [Sorkine and Alex 2007; Liu et al. 2008]
  - Bounded distortion methods [Lipman 2012; Aigerman et al. 2014; Kovalsky et al. 2015]
- Foldover free guaranteed optimization methods
  - [Smith and Schaefer 2015; Kovalsky et al. 2016; Jiang et al. 2017; Claici et al. 2017; Rabinovich et al. 2017; Shtengel et al. 2017; Zhu et al. 2018]

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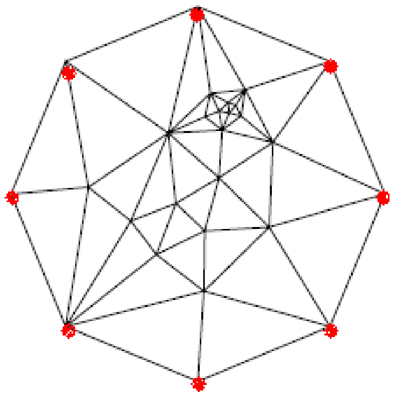
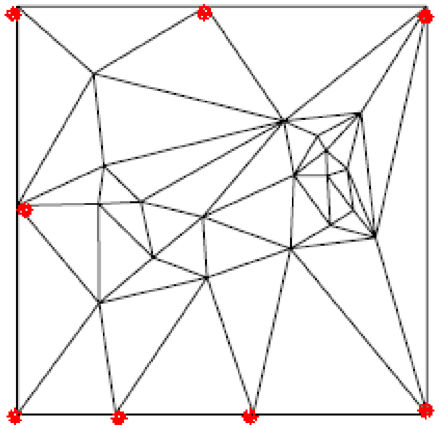
Tutte's embedding method

- ✓ Map the triangulation within a convex boundary by solving a sparse linear system





$$p_i = \sum_{\{j:(i,j)\in \text{edges}\}} \lambda_{i,j_k} p_k, \quad \sum_{k=1}^{d_i} \lambda_{i,j_k} = 1, \quad \lambda_{i,j_k} > 0$$

[Floater. Parametrization and smooth approximation of surfaces. CAGD 1997.]

Tutte's embedding method

✓Map the triangulation within a convex boundary by solving a sparse linear system

✓Foldover-free result with a theoretical guarantee

Theorem [Tutte,63], [Maxwel,1864] :

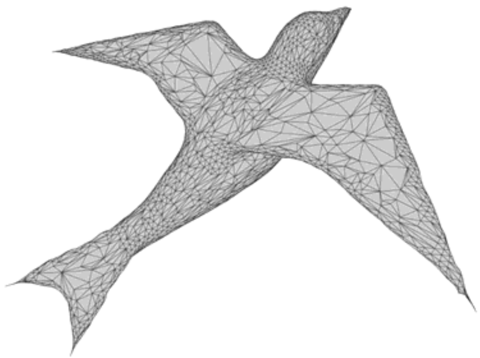
- If G=<V,E> is a 3-connected planar graph (triangular mesh) then any barycentric embedding provides a valid parameterization.

$$Wx = b_x \qquad Wy = b_y \qquad w_{ij} = \begin{cases} < 0 & (i,j) \in E \\ -\sum_{j \neq i} w_{ij} & (i,i) \\ 0 & otherwise \end{cases}$$

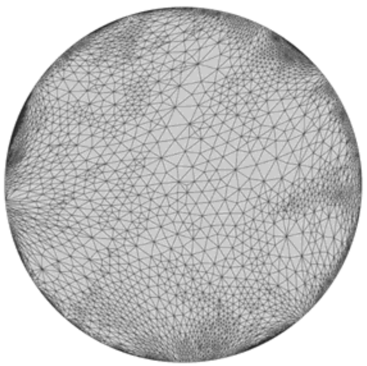
$$W \text{ is symmetric} : w_{ij} = w_{ji}$$

Tutte’s embedding method

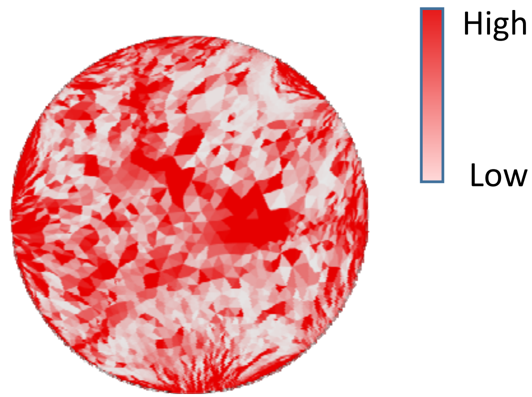
- ✓ Map the triangulation within a convex boundary by solving a linear system
- ✓ Foldover-free result with a theoretical guarantee
- ✓ Usually high distortion



[Tutte 1963; Floater 1997, 2003]



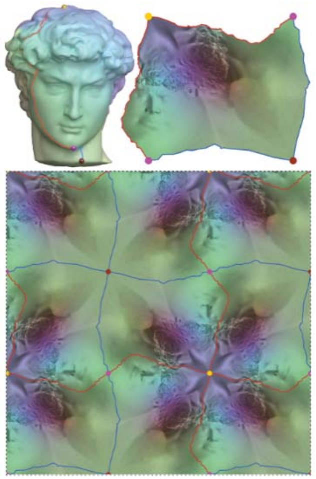
Convex boundary



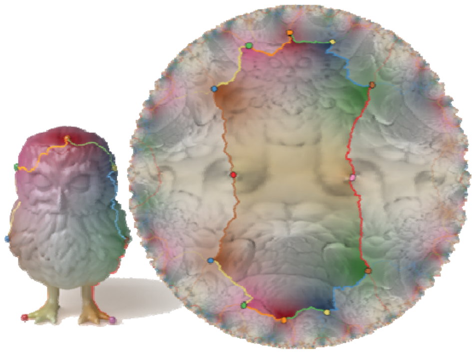
High distortion

Variants of Tutte's embedding method

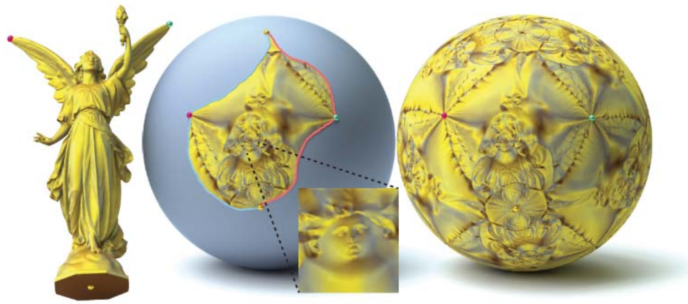
✓Foldover-free result with theoretical guarantees



Euclidean-orbifold
[Aigerman et al. 2015]



Hyperbolic-orbifold
[Aigerman et al. 2016]



Spherical-orbifold
[Aigerman et al. 2017]

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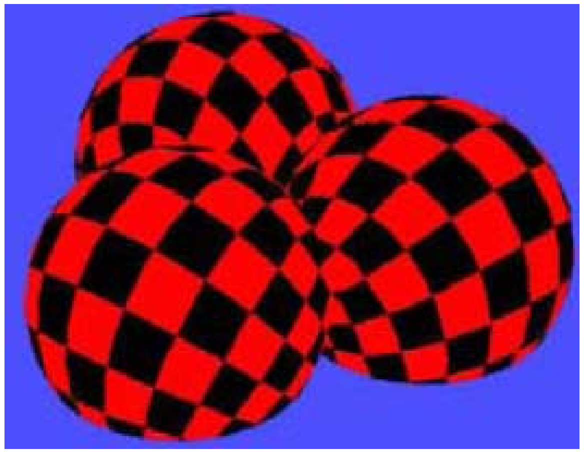
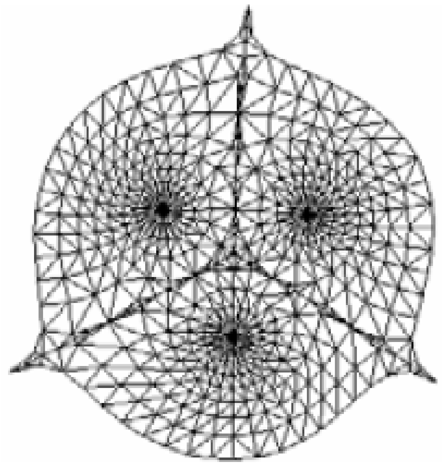
Angle Based Flattening (ABF) & ABF++

[Sheffer and Sturler 2001; Sheffer et al. 2005]

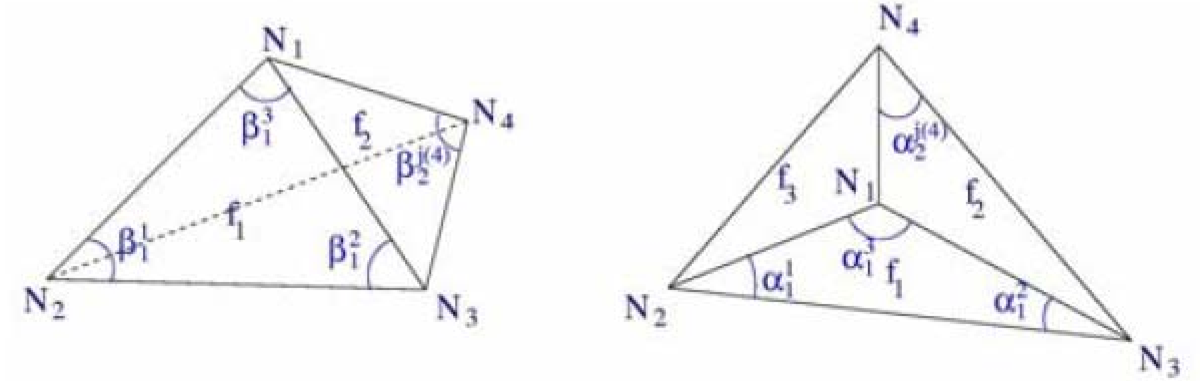
- Triangular 2D mesh is defined by its angles
  - Define problem in angle space
- Angle based formulation
  - Distortion as function of angles
  - Validity - set of angle constraints





Constrained Minimization

- Notations:



- Objective: minimize (relative) deviation of angles

$$F(\alpha) = \sum_{i,j} w_i^j (\alpha_i^j - \beta_i^j)^2$$

Initial choice for weights:

$$w_i^j = {\beta_i^j}^{-2}$$

Constraints

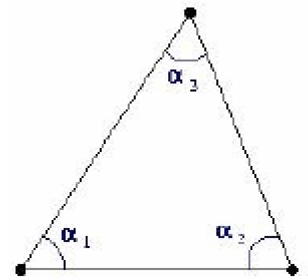
- To avoid flipped triangles

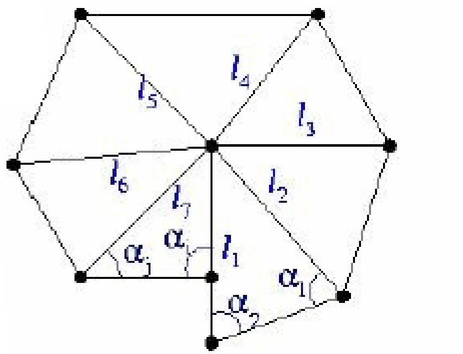
$$g^1(\alpha) \equiv \alpha_i^j \geqslant \varepsilon$$

$$g^2(\alpha) \equiv \alpha_i^1 + \alpha_i^2 + \alpha_i^3 = \pi$$

$$g^3(\alpha) \equiv \sum_k \alpha_i^j(k) = 2\pi$$

$$g^4(\alpha) \equiv \prod_k \sin(\alpha_i^{j(k)-1}) - \prod_k \sin(\alpha_i^{j(k)+1}) = 0$$





$$\frac{l_1}{l_2} = \frac{\sin(\alpha_1)}{\sin(\alpha_2)}$$

$$\frac{l_1}{l_2} \cdots \frac{l_7}{l_1} = \frac{\sin(\alpha_1)}{\sin(\alpha_2)} \cdots \frac{\sin(\alpha_i)}{\sin(\alpha_j)}$$

Solution

- Use Lagrange Multipliers

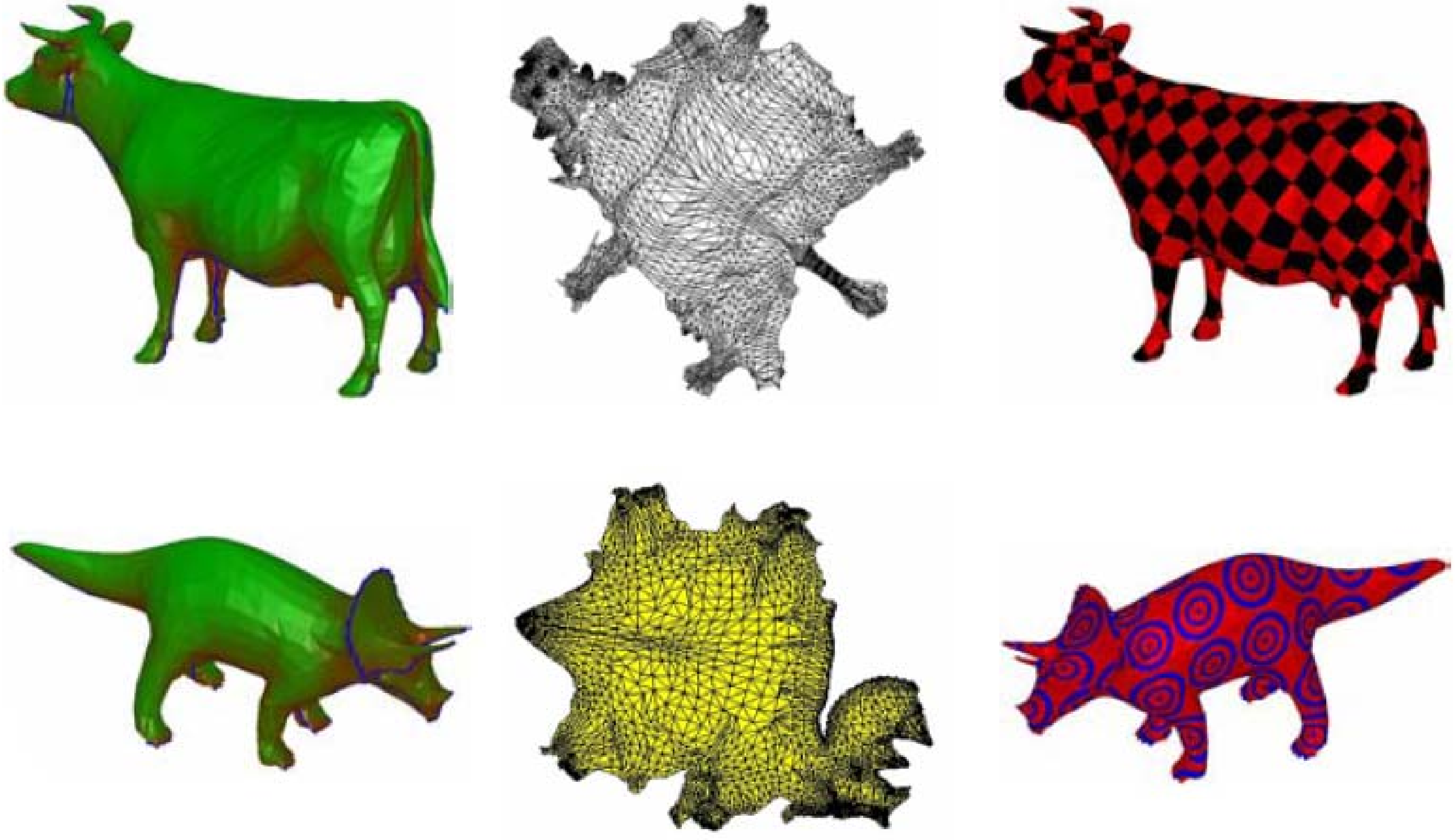
$$F^*(\alpha,\mu) = F(\alpha) + \mu_1 g^2(\alpha) + \mu_2 g^3(\alpha) + \mu_3 g^4(\alpha)$$

- Solve the min-max problem (minimum on α, maximum on μ)

$$\min_{\alpha} \max_{\mu} F^*(\alpha,\mu)$$

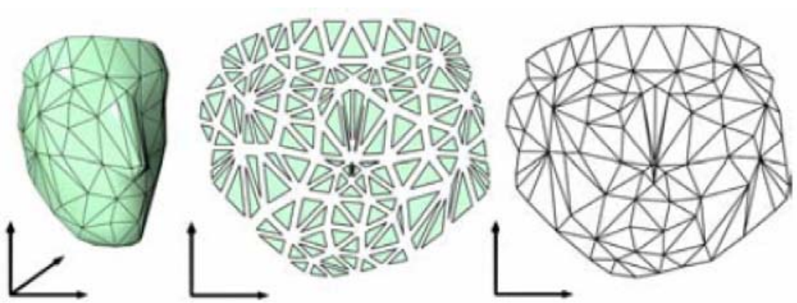
- Reached when all derivatives are zero
- Have non-linear system of equations
- Use Newton method to solve

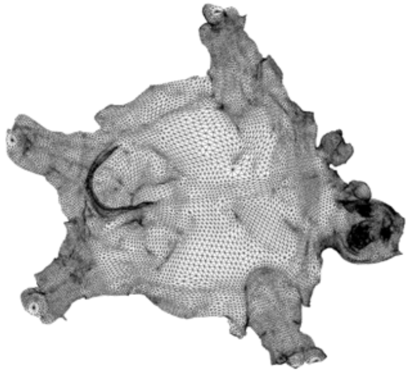
Examples



As-rigid-as-possible (ARAP) [Liu et al. 2008]

- Measuring the approximation between the linear mapping and the rigidity (the optimal rotation)
- Local/global optimization
  - Local: compute singular values
  - Global: solve linear systems
- No theoretically guaranteed to avoid foldovers

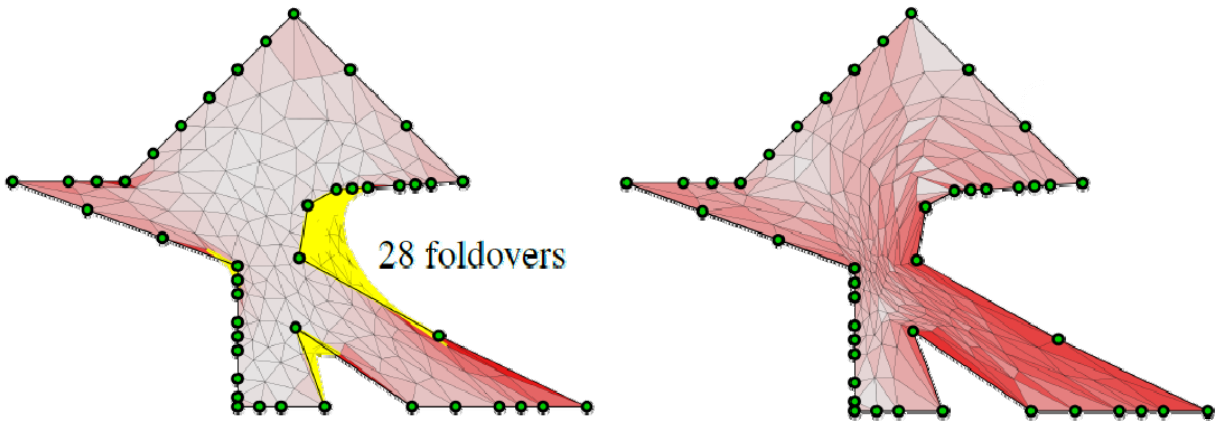




[Ligang Liu et al. A Local/Global Approach to Mesh Parameterization. SGP 2008.]

Simplex Assembly [Fu and Liu 2016]

- ✓Instead of vertex positions, treat the affine transformation as variables
- ✓Use a barrier function to prevent the inversion
- ✓No theoretically guaranteed to avoid foldovers



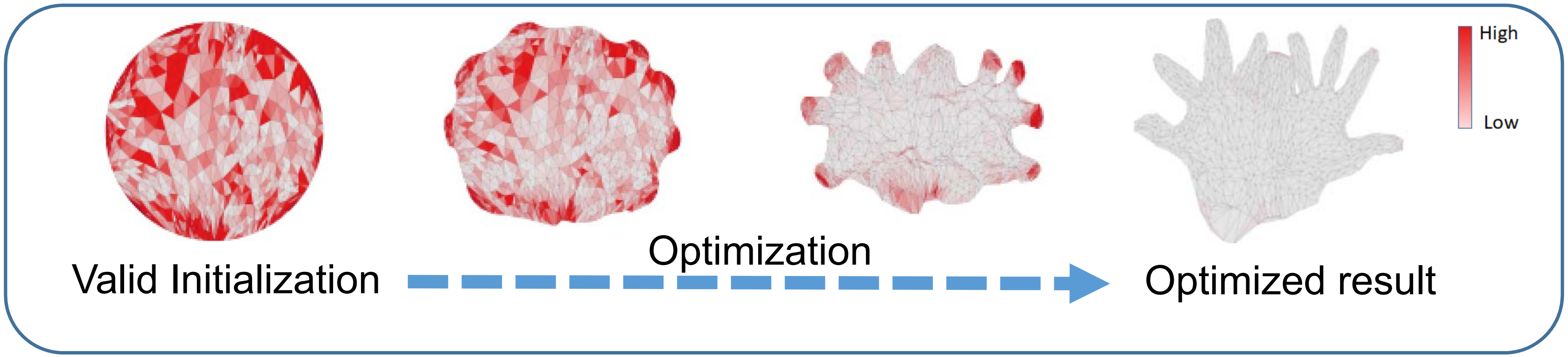
[Fu and Liu. Computing Inversion-Free Mappings by Simplex Assembly. Siggraph Asia 2016]

Methods of Mesh arameterization

- Tutte’s method and its variants
  - Tutte’s method [Tutte 1963; Floater 1997, 2003]
  - Variants [Weber and Zorin 2014; Aigerman and Lipman 2015, 2016; Aigerman et al. 2017; Bright et al. 2017;]
- Geometry-based optimization methods
  - Representation based methods [Sheffer and Sturler 2001; Sheffer et al. 2005; Chien et al. 2016b; Fu and Liu 2016]
  - ARAP [Sorkine and Alex 2007; Liu et al. 2008]
  - Bounded distortion methods [Lipman 2012; Aigerman et al. 2014; Kovalsky et al. 2015]
- Foldover free guaranteed optimization methods
  - [Smith and Schaefer 2015; Kovalsky et al. 2016; Jiang et al. 2017; Claici et al. 2017; Rabinovich et al. 2017; Shtengel et al. 2017; Zhu et al. 2018]

Flip-free parameterization methods

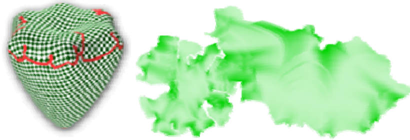
- Start with a flip-free (valid) initialization
- Reducing the distortion while guaranteeing the validity
  - Generally non-convex nonlinear optimization



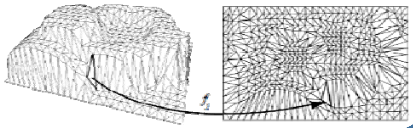
Low distortion cost functions

- Conformal
  [Degener et al. 2003]
  $\frac{\sigma_2}{\sigma_1}$

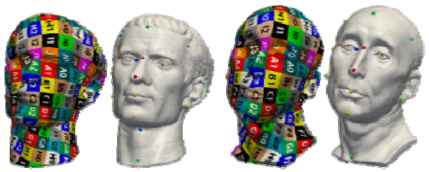
- Maximal Isometric Distortion
  [Sorkine et al. 2002]
  $\max(\sigma_2, \frac{1}{\sigma_1})$



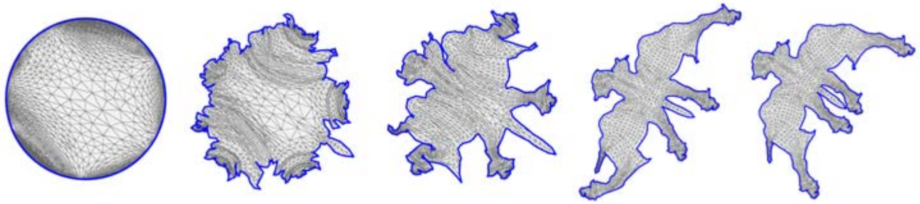
- MIPS
  [Hormann and Greiner 2000]
  $\frac{\sigma_1}{\sigma_2} + \frac{\sigma_2}{\sigma_1}$



- Isometric
  [Aigermann et al. 2014]
  $\sqrt{\sigma_2^2 + \frac{1}{\sigma_1^2}}$



- Symmetric Dirichlet energy
  [Smith and Schaefer 2015]
  $\sigma_1^2 + \frac{1}{\sigma_1^2} + \sigma_2^2 + \frac{1}{\sigma_2^2}$



Formulation of Optimization

$$\min_{V} E(V) = \sum_{t \in T} \left(\sigma_1^2 + \frac{1}{\sigma_1^2} + \sigma_2^2 + \frac{1}{\sigma_2^2}\right)$$

s.t. $\quad \sigma_1 \sigma_2 > 0, \quad \forall t$

- The cost function is highly nonlinear and nonconvex
- The constraints are nonlinear
- The Heissian matrix is highly non-definite

Computationally expensive for large scale meshes!

Solver for the optimization

Optimization formulation: $\min_x E(x) = \sum_t \ E_t(x)$

Input: a valid parameterization initialization x_0

Repeat

$\boxed{\boldsymbol{p} = -H^{-1}\nabla E(\boldsymbol{x})}$ How to find a good decent direction?

$\alpha_{max} \leftarrow$ injective maximal search step

$\alpha \leftarrow$line search by backtracking from α_{max}

$\boldsymbol{x} \leftarrow \boldsymbol{x} + \alpha \boldsymbol{p}$

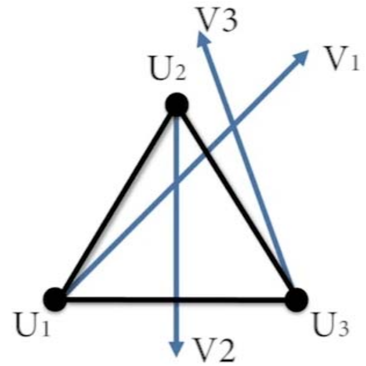
Until converged

Output: a locally injective parameterization

Maximal Search Step

- ✓ Explicitly limit the maximal line search step to prevent foldover

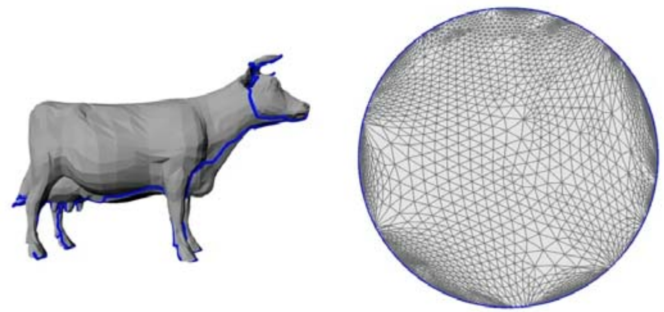
$$det\begin{pmatrix}(U_2+V_2t)-(U_1+V_1t)\\(U_3+V_3t)-(U_1+V_1t)\end{pmatrix}=0$$



- ✓ Use a locally supported barrier function to prevent the boundary collision

$$\max\left(0,\frac{\epsilon}{dist(U_i,\overline{U_1U_2})}-1\right)^2$$

- ✓ Solver: L-BFGS



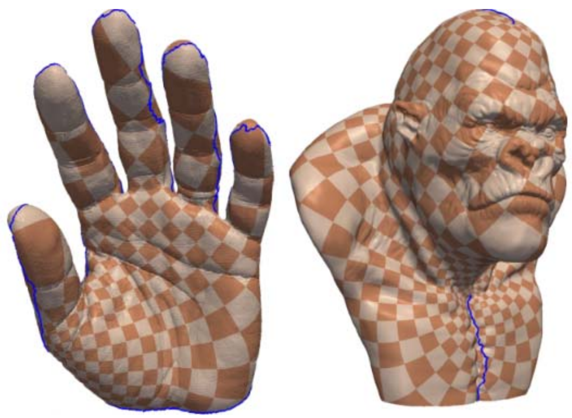
Smith and Schaefer. Bijective Parameterization with Free Boundaries. Siggraph 2015.

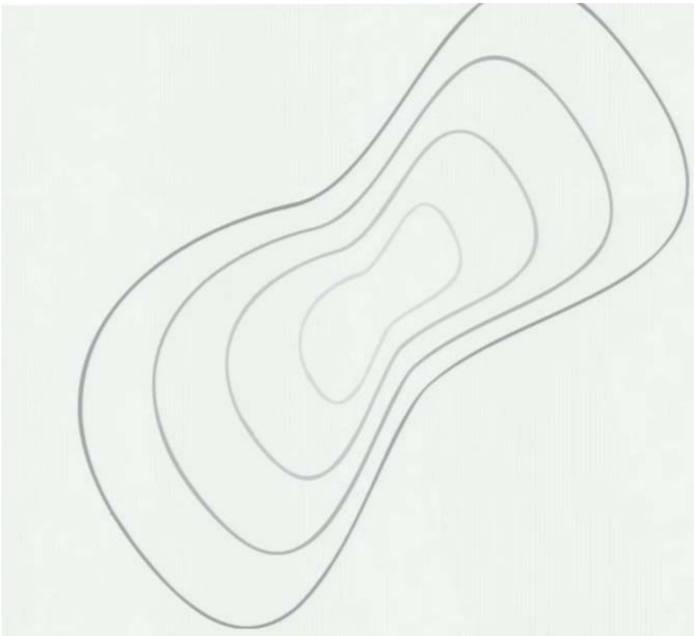
Accelerated Quadratic Proxy (AQP)

✓H = discrete Laplacian L

✓Acceleration

✓First-order method





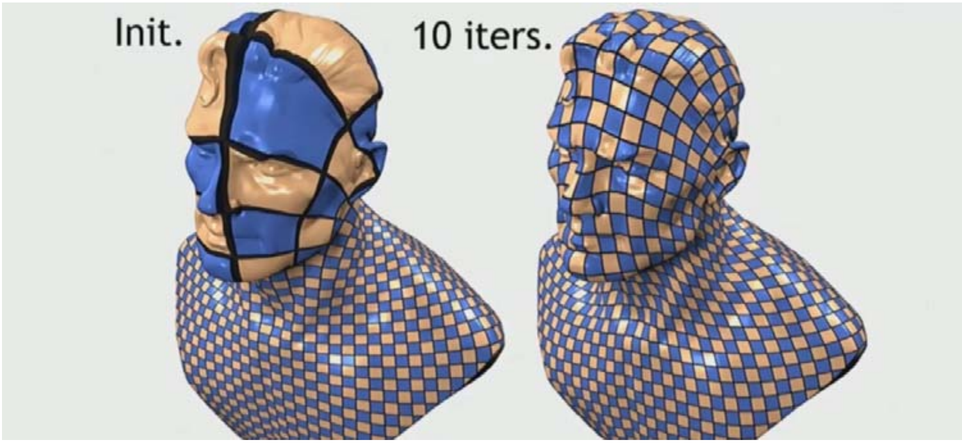
Kovalsky et al. Accelerated Quadratic Proxy for Geometric Optimization. Siggraph 2016.

Scalable Locally Injective Mappings (SLIM)

- ✓ H = reweighted Laplacian L
- ✓ Compute the weight matrix W_J by the matching gradients condition

$$\nabla_J E_W^R = \nabla_J E_{RI}$$

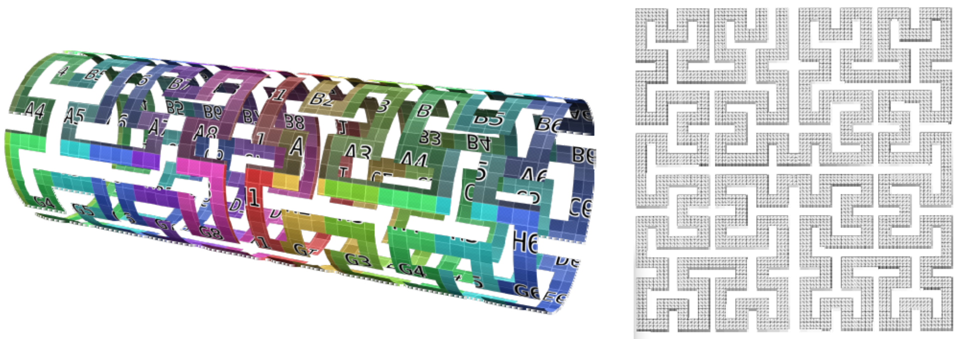
- ✓ Quickly recovers from a bad initialization, but slowly converge to a local minimum
- ✓ First-order method

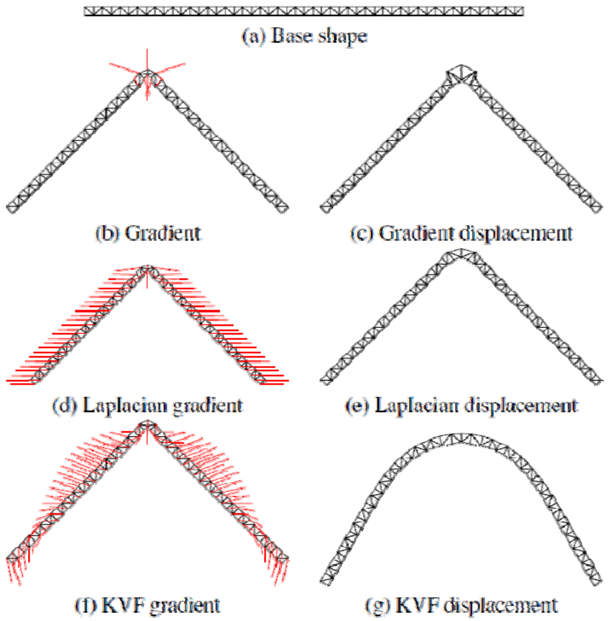


Rabinovich et al. Scalable Locally Injective Mappings. Siggraph 2017.

Isometry-Aware Preconditioning (AKVF)

- ✓ H = approximate killing vector field operator $K(x)$
- ✓ $K(x)$ converts the local distortion gradient into a global near-rigid decent direction
- ✓ First-order method



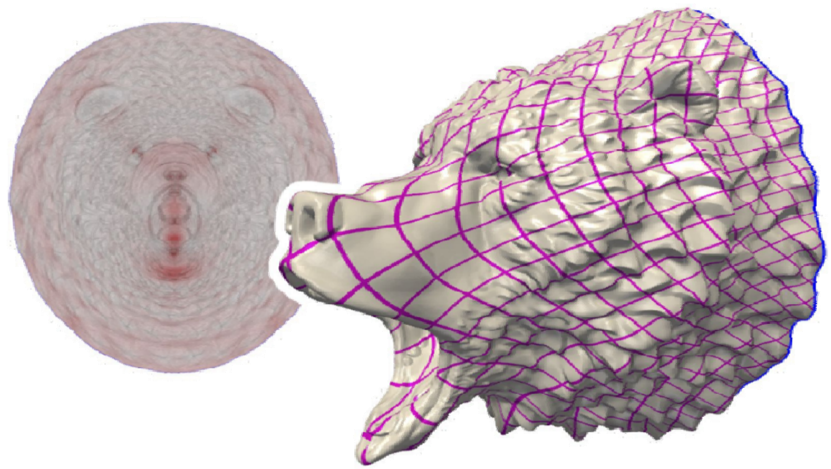


Claici et al. Isometry-Aware Preconditioning for Mesh Parameterization. SGP 2017.

Composite Majorization (CM)

✓Use a tight convex proxy to approximate the objective function by convex-concave decomposition

$$E = E^{+} + E^{-}$$



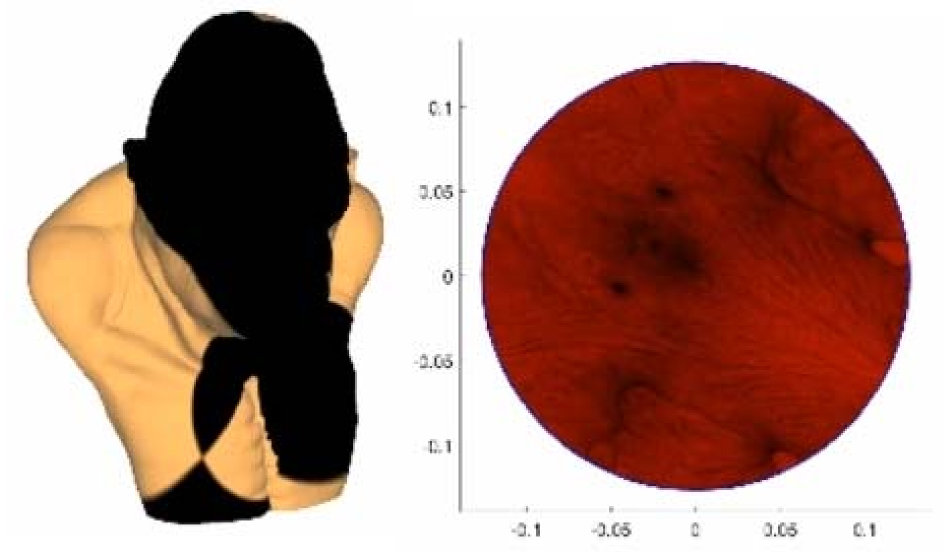
✓$H = \nabla^2 E^{+}$

✓Second-order method

Shtengel et al. Geometric Optimization via Composite Majorization. Siggraph 2017.

Blended Cured Quasi-Newton (BCQN)

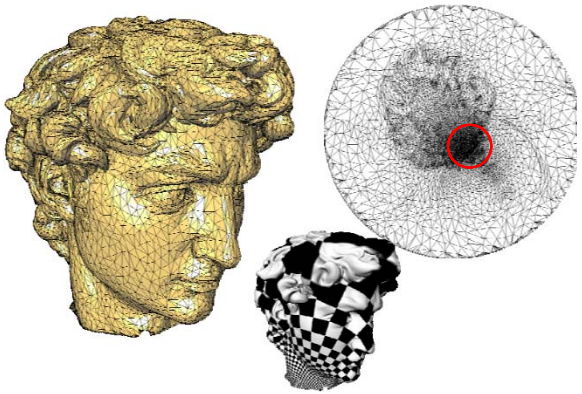
- ✓ Blended quasi-Newton method
- ✓ Barrier-aware line search filtering
- ✓ Second-order method



Zhu et al. Blended Cured quasi-Newton for Distortion Optimization. Siggraph 2018.

Progressive Parameterization

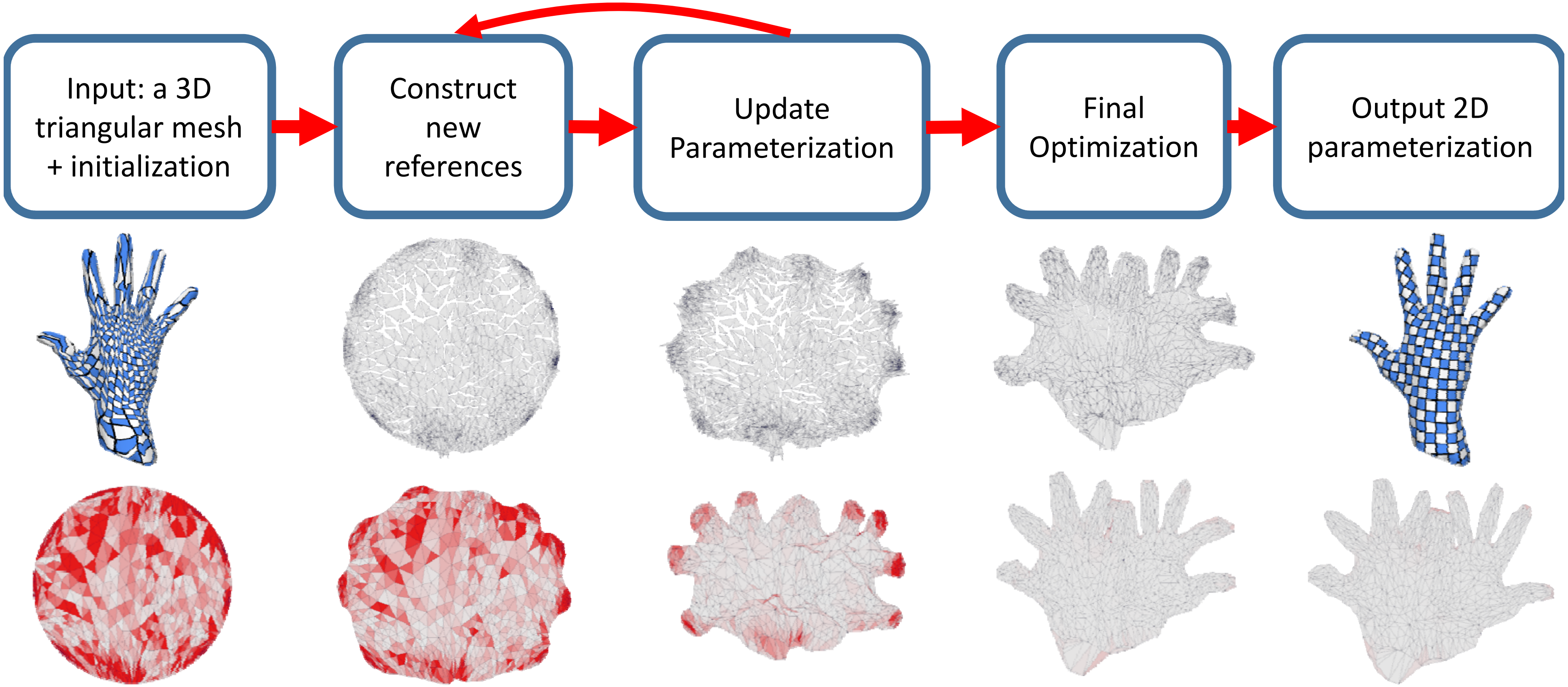
- Key observations
  - Near-degenerate triangles (i.e., large distortion) in the initializations by Tutte's method
  - Small iterative step and slow convergence in existing methods
  - Key: even one extremely large distortion term can restrict the line search step size!



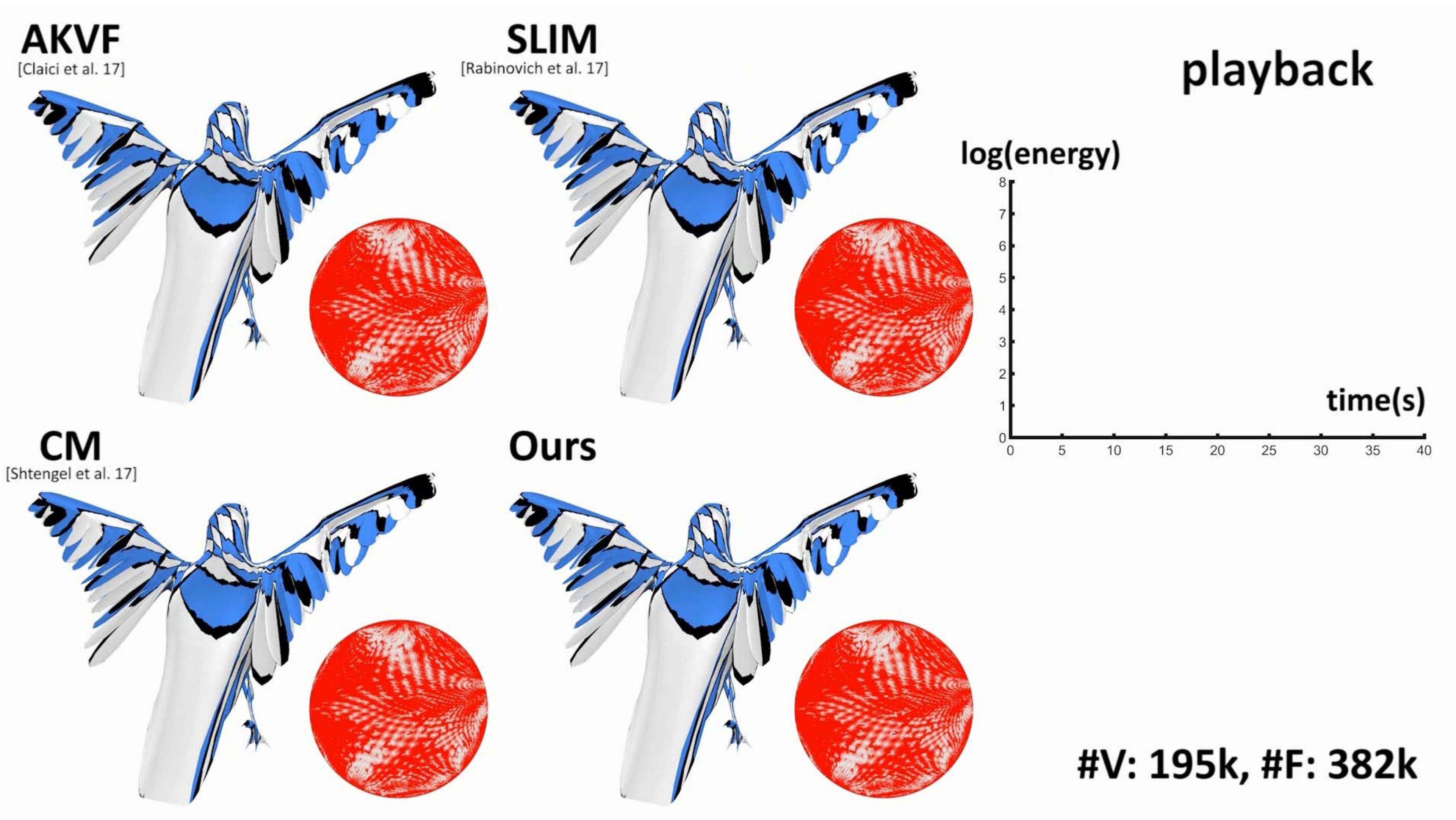
Idea: If we kill extremely large distortion terms, we may obtain larger line search step size and thus faster convergence!

[Ligang Liu et al. Progressive Parameterizations. Siggraph 2018]

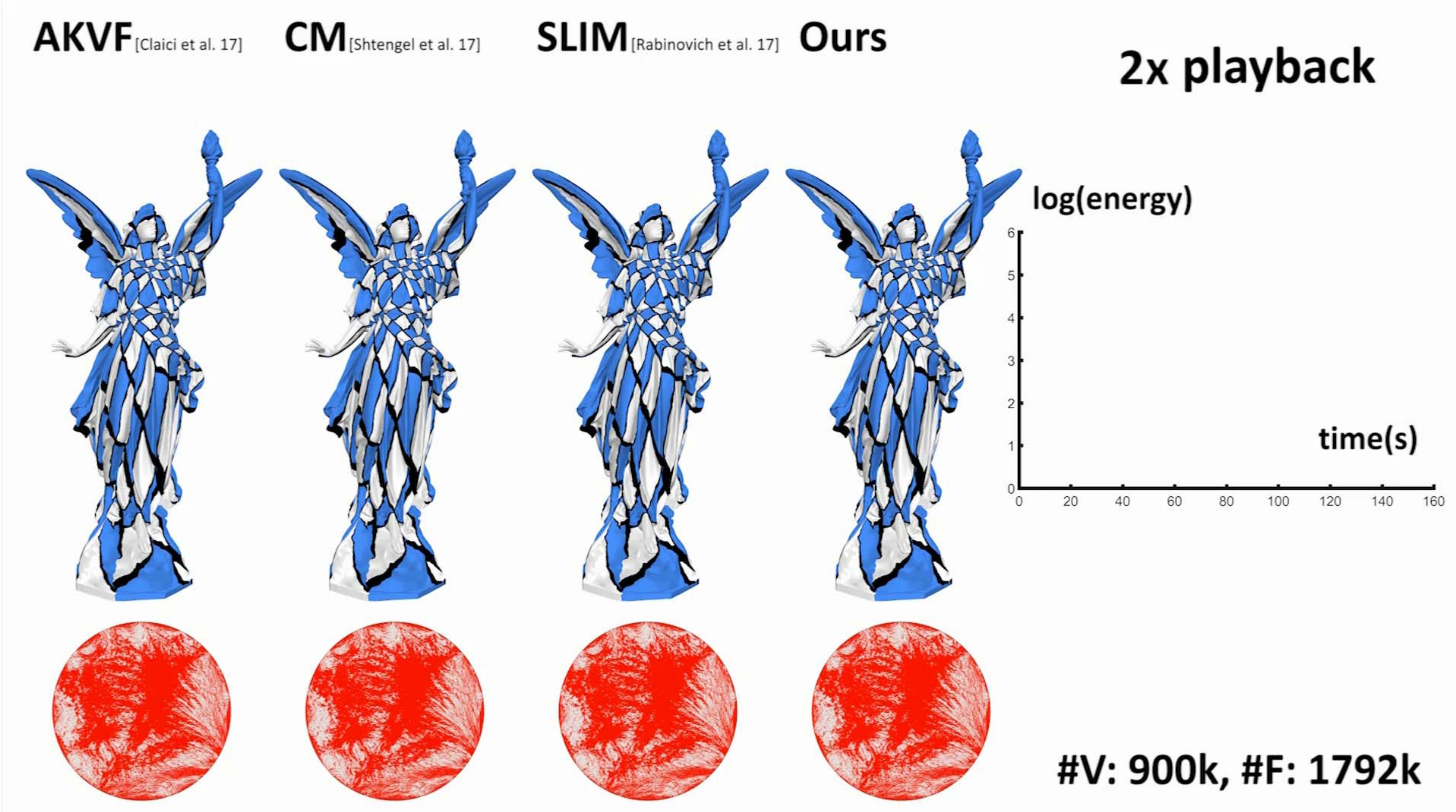
Progressive Paramerization



[Ligang Liu et al. Progressive Parameterizations. Siggraph 2018]



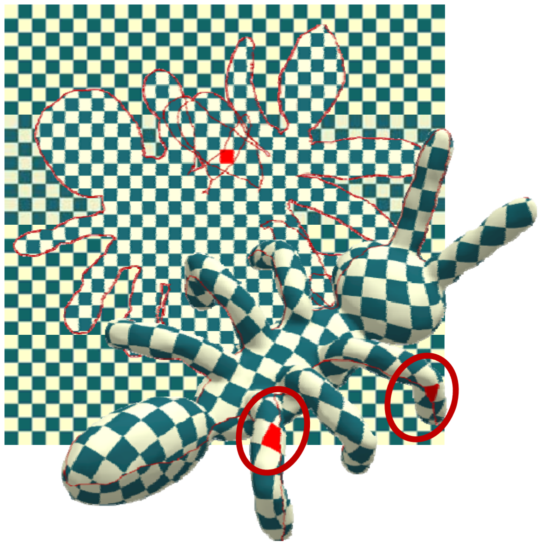
AKVF
[Claici et al. 17]
SLIM
[Rabinovich et al. 17]
playback
log(energy)
8
7
6
5
4
3
2
1
0
time(s)
0
5
10
15
20
25
30
35
40
CM
[Shtengel et al. 17]
Ours
#V: 195k, #F: 382k


AKVF [Claici et al. 17]
CM [Shtengel et al. 17]
SLIM [Rabinovich et al. 17]
Ours
2x playback
log(energy)
time(s)
0
1
2
3
4
5
6
0
20
40
60
80
100
120
140
160
#V: 900k, #F: 1792k

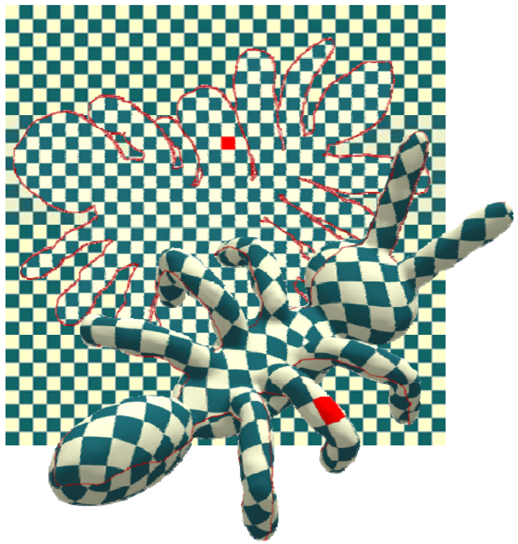
Bijective Parameterizations

Bijective Parameterization

- Globally intersection-free



Intersection



Intersection-free

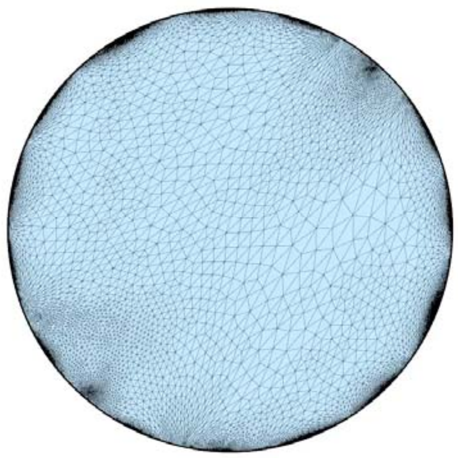
Quasi-Newton (QN) [Smith et al. 2015]

Quasi-Newton solver with slow convergence!

Energy: 1.027

Time: 8.57s

Iterations: 3553



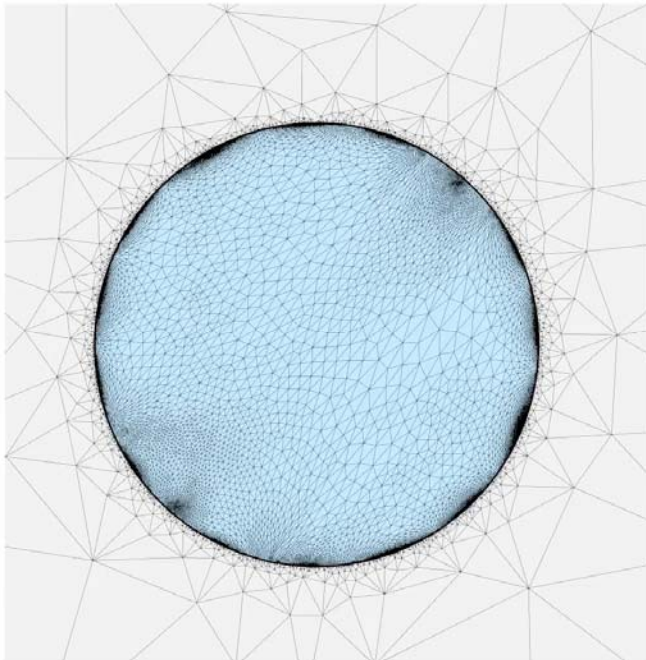
Scaffold [Jiang et al. 2017]

Linear systems with updated nonzero structure matrices!

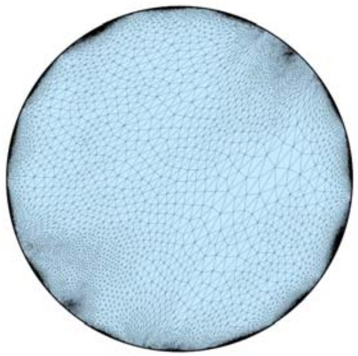
Energy: 1.027

Time: 3.22s

Iterations: 24

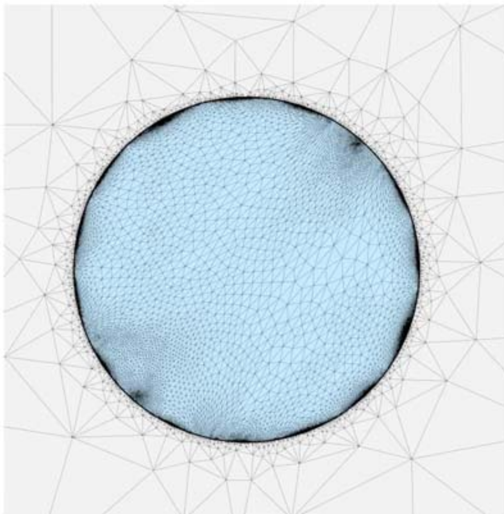


Efficient Bijective Parameterizations
[Su et al. Siggraph 2020]



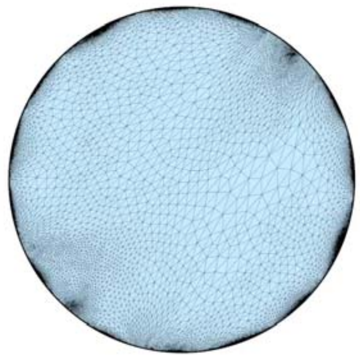
[Smith et al. 2015]

Slow convergence



[Jiang et al. 2017]

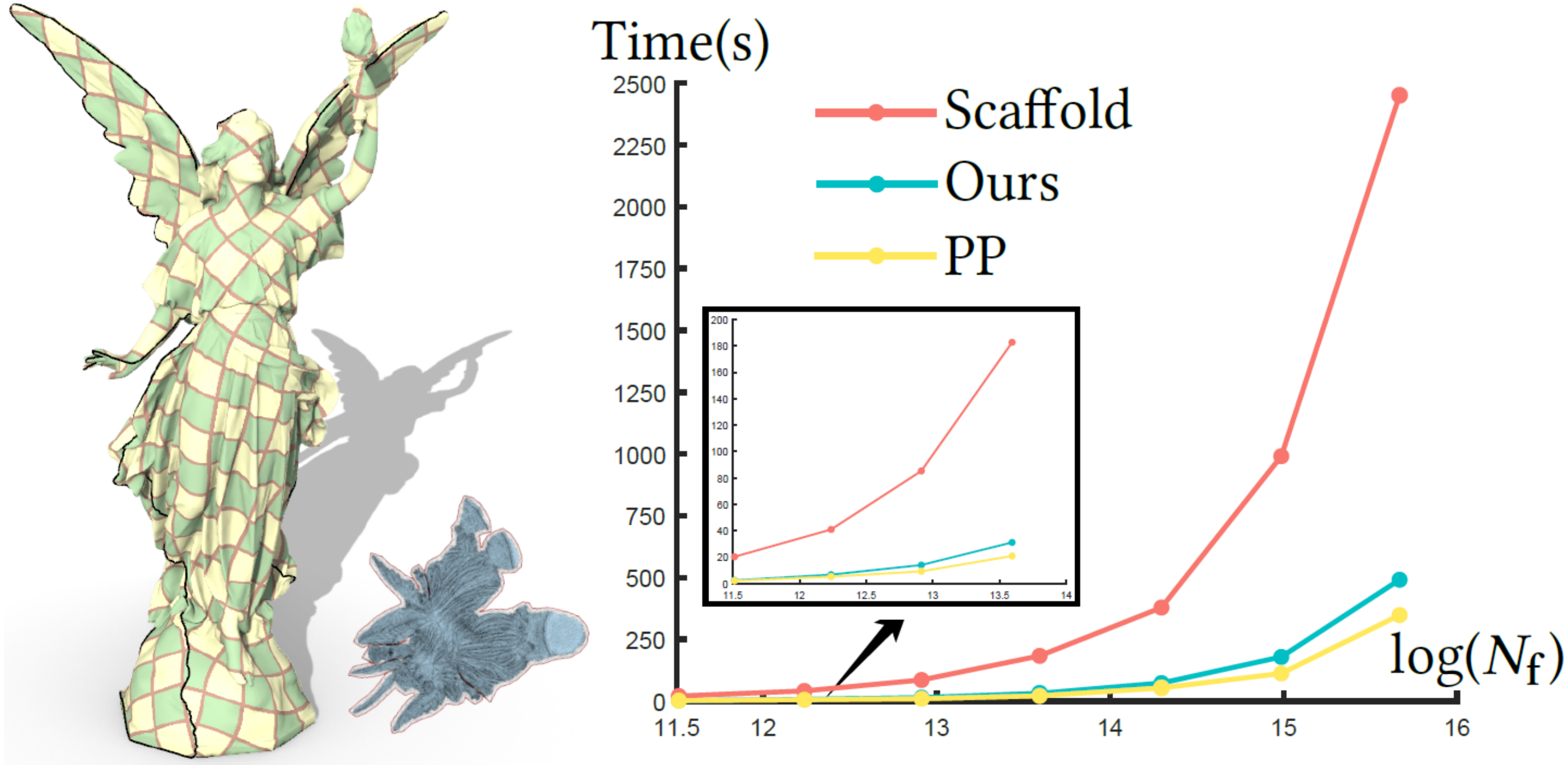
Updated scaffold mesh

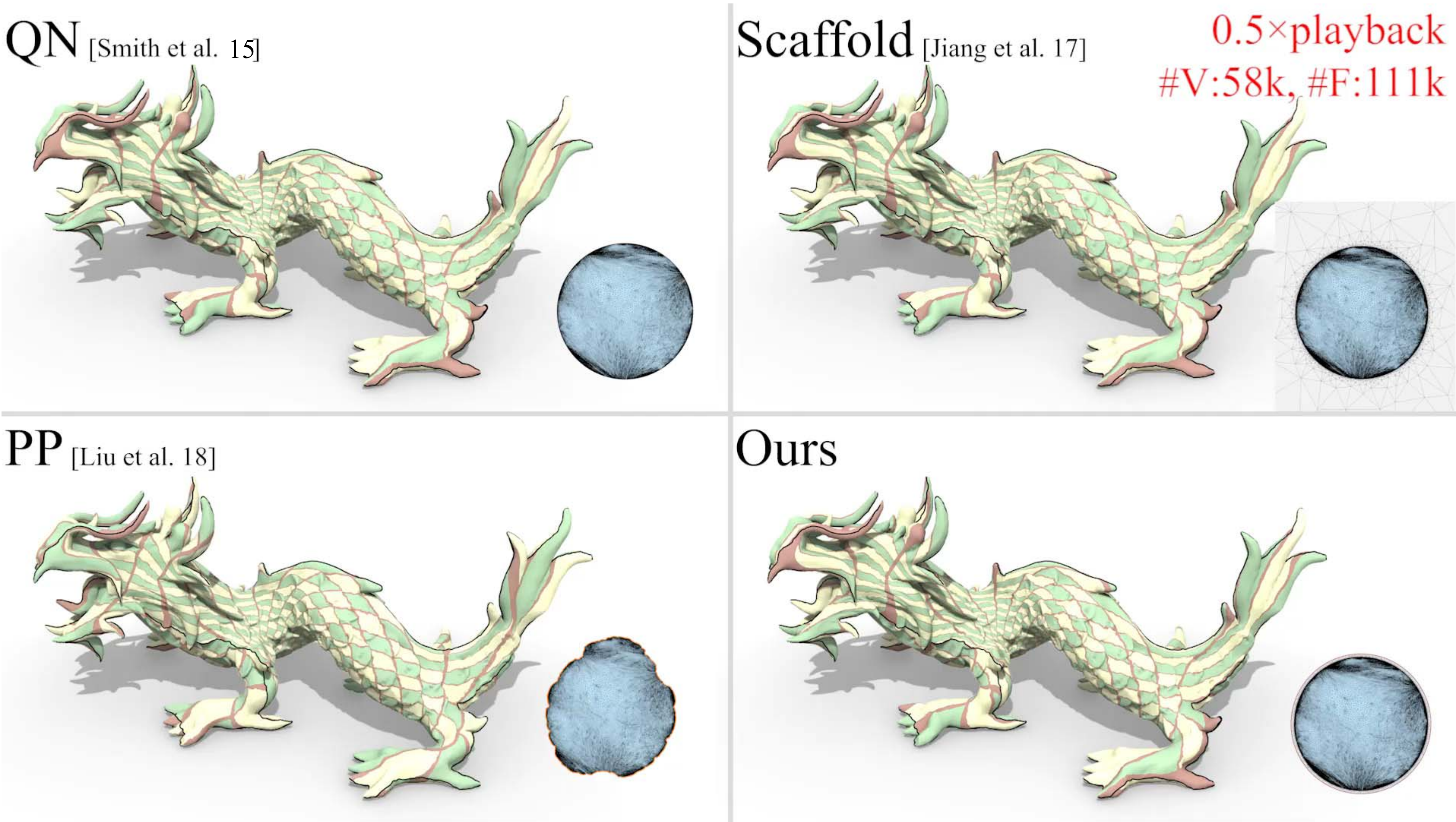


[Su et al. 2020]

Much more efficient

Comparisons

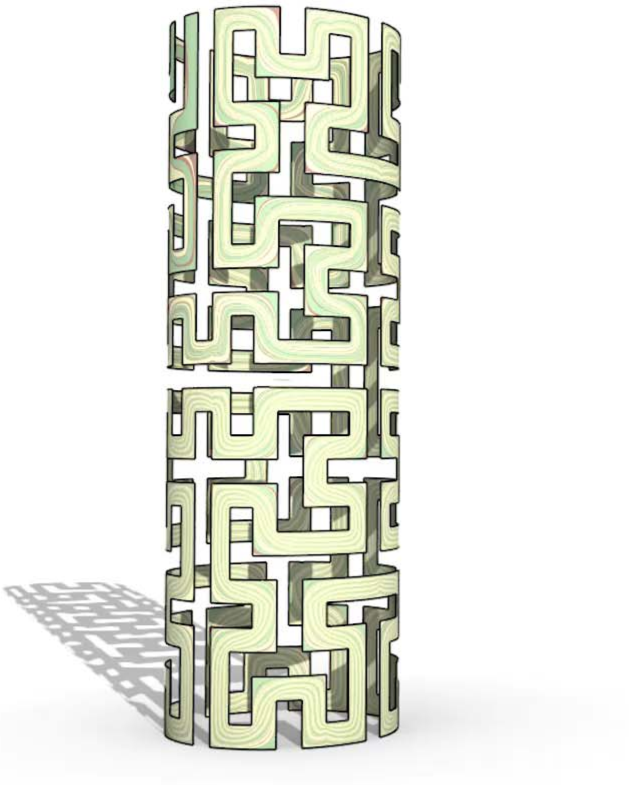


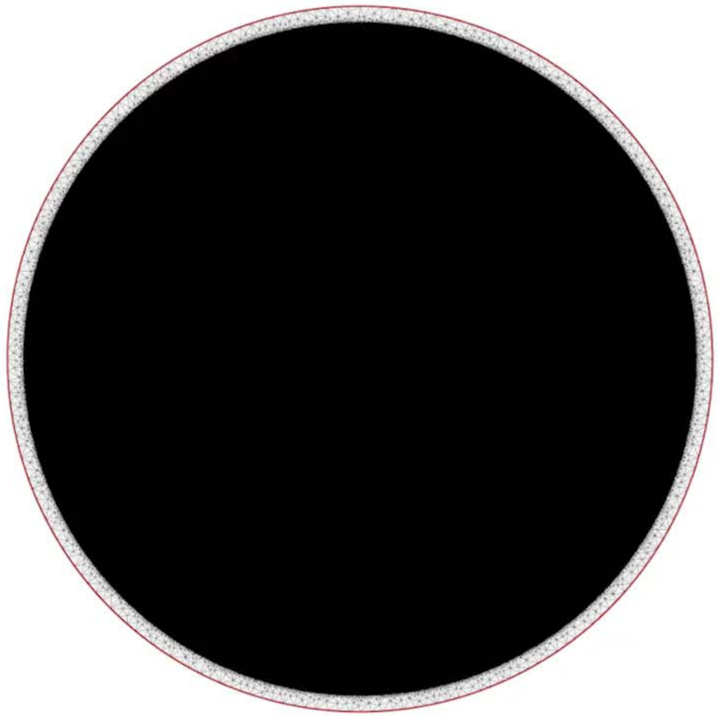


QN [Smith et al. 15]
Scaffold [Jiang et al. 17]
0.5×playback
#V:58k, #F:111k
PP [Liu et al. 18]
Ours

Hilbert-curve-shaped developable surface

5×playback
#V:80k, #F:147k





封闭曲面的割缝问题

割缝问题：封闭曲面的参数化

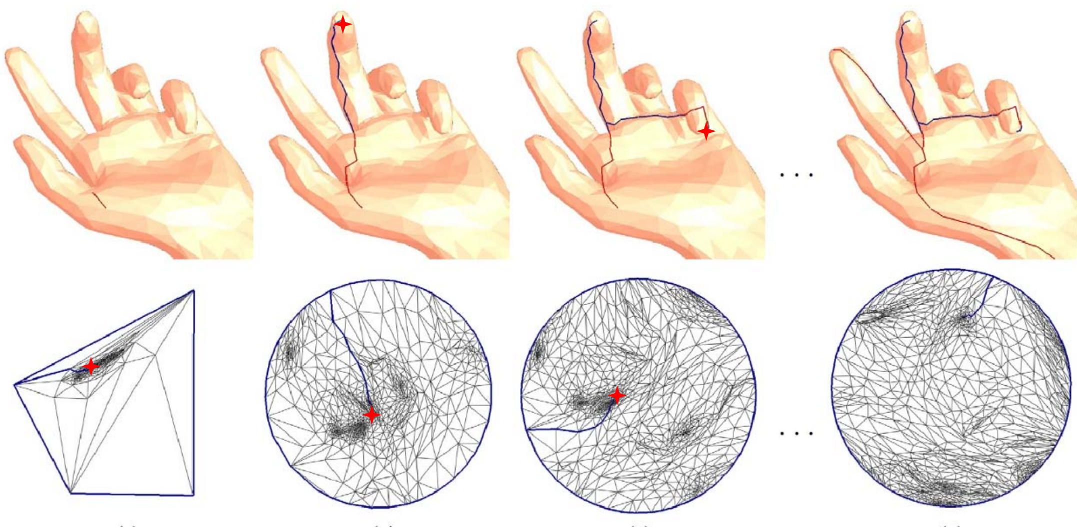
- A closed surface cannot be flattened
- A cut is needed to cut it open into a disk-like patch

Existing Works

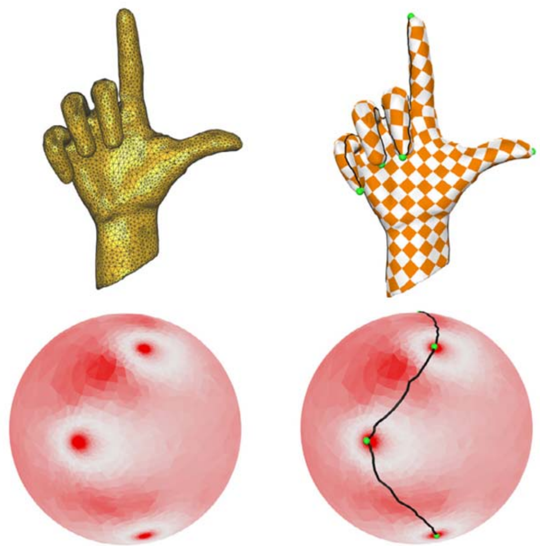
- Minimum spanning tree method
  - [Sheffer 2002; Sheffer and Hart 2002; Chai et al. 2018]
- Mesh segmentation approaches
  - [Julius et al. 2005; Lévy et al. 2002; Sander et al. 2002, 2003; Zhang et al. 2005; Zhou et al. 2004]
- Simultaneous optimization
  - [Poranne et al. 2017; Li et al. 2018]
- Variational method
  - [Sharp and Crane 2018]

Minimum spanning tree methods

- Nodes: extrema points with high curvature/distortion etc.

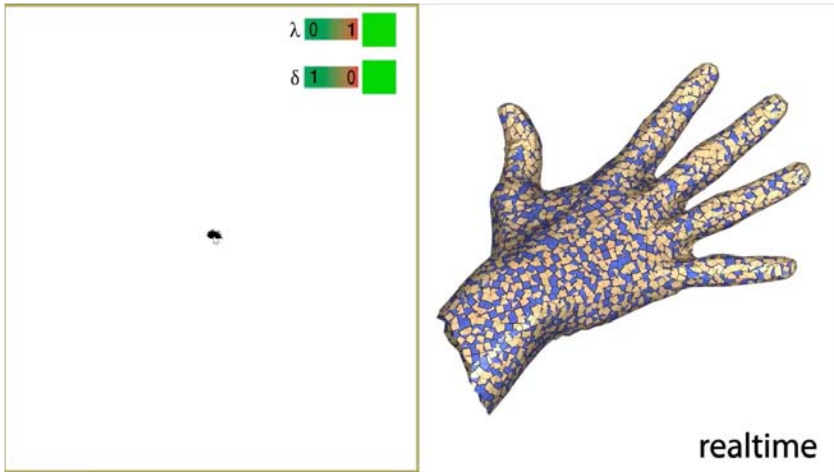


[Gu et al. 2002]

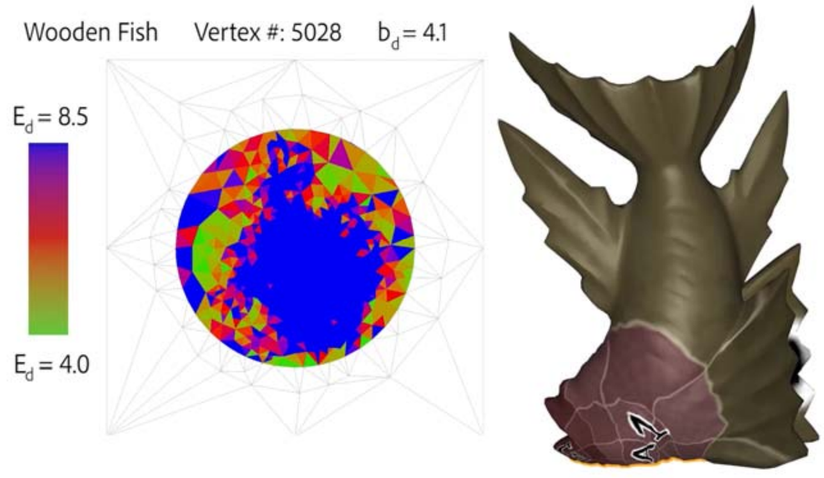


[Chai et al. 2018]

Simultaneous optimization



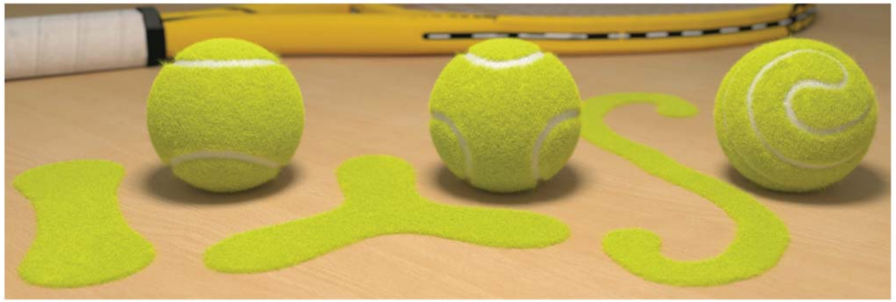
AutoCuts [Poranne et al. 2017]

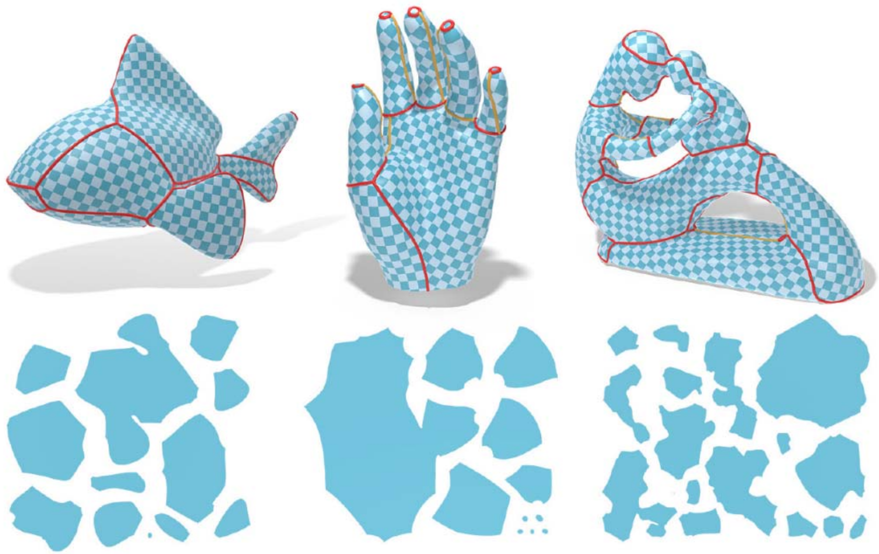


OptCuts [Li et al. 2018]

Variational Surface Cutting

[Sharp and Crane 2018]





Computational Peeling Art Design

Hao Liu, Xiao-Teng Zhang, Xiao-Ming Fu, Zhi-Chao Dong, **Ligang Liu**
USTC

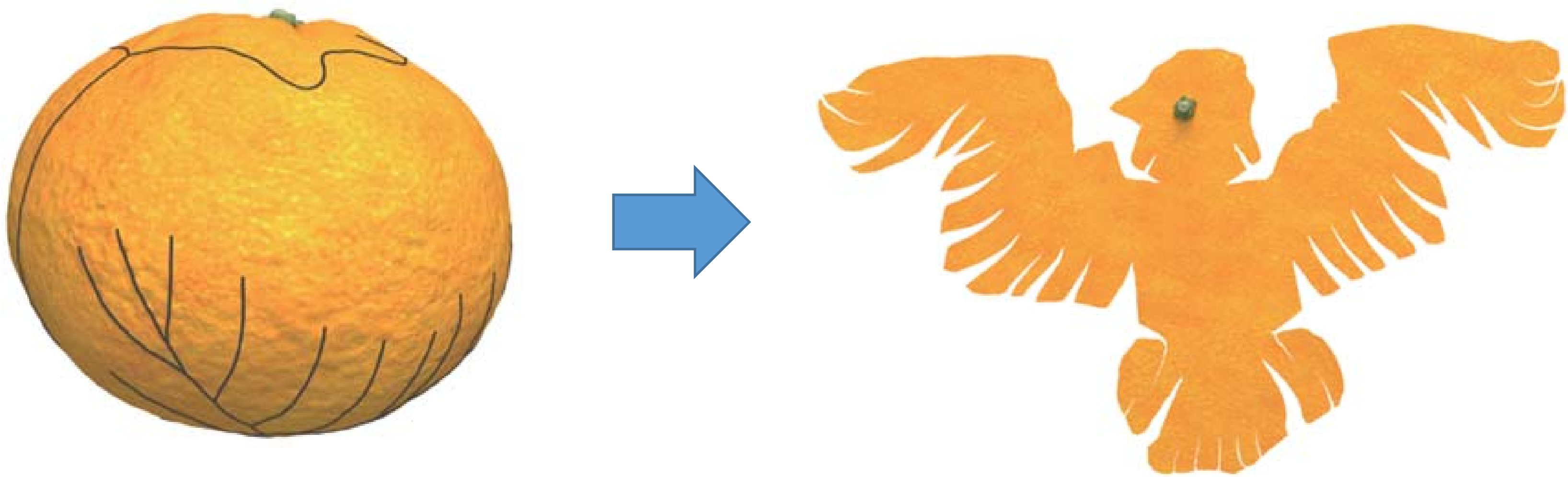
thrive
SIGGRAPH2019
LOS ANGELES • 28 JULY – 1 AUGUST


www.okadas.com
https://www.youtube.com/watch?v=JIOUHAkQdc4
Peeling art design
NOW I'VE SEEN EVERYTHING


Yoshihiro Okada’s method

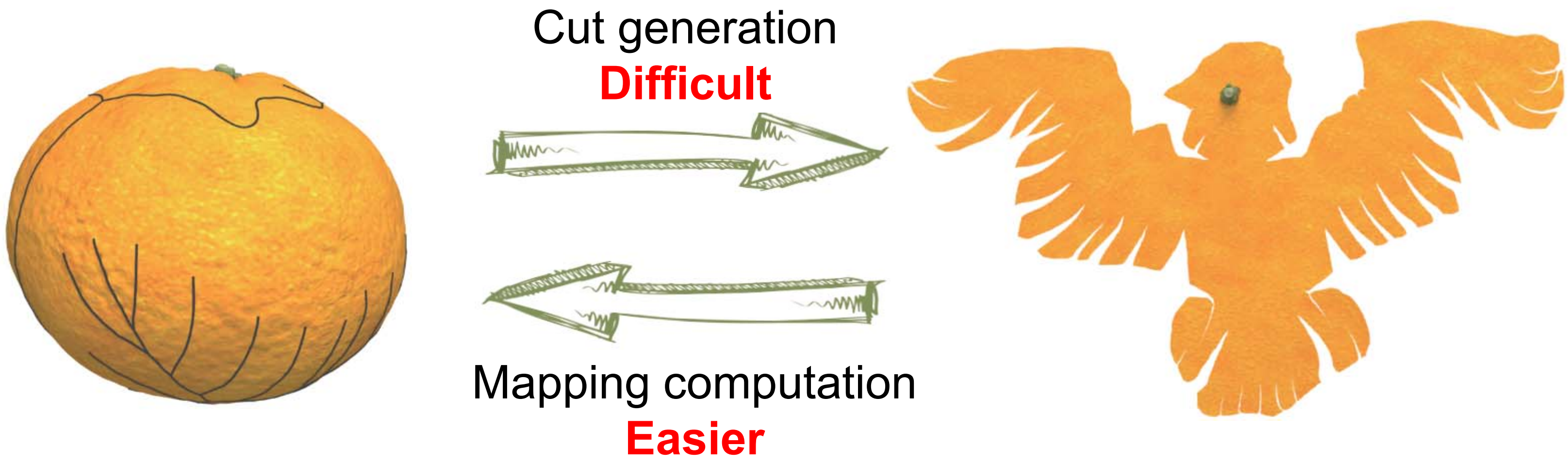
Cut Generation Problem

- Finding a cut such that its unfolding approximates a given input shape

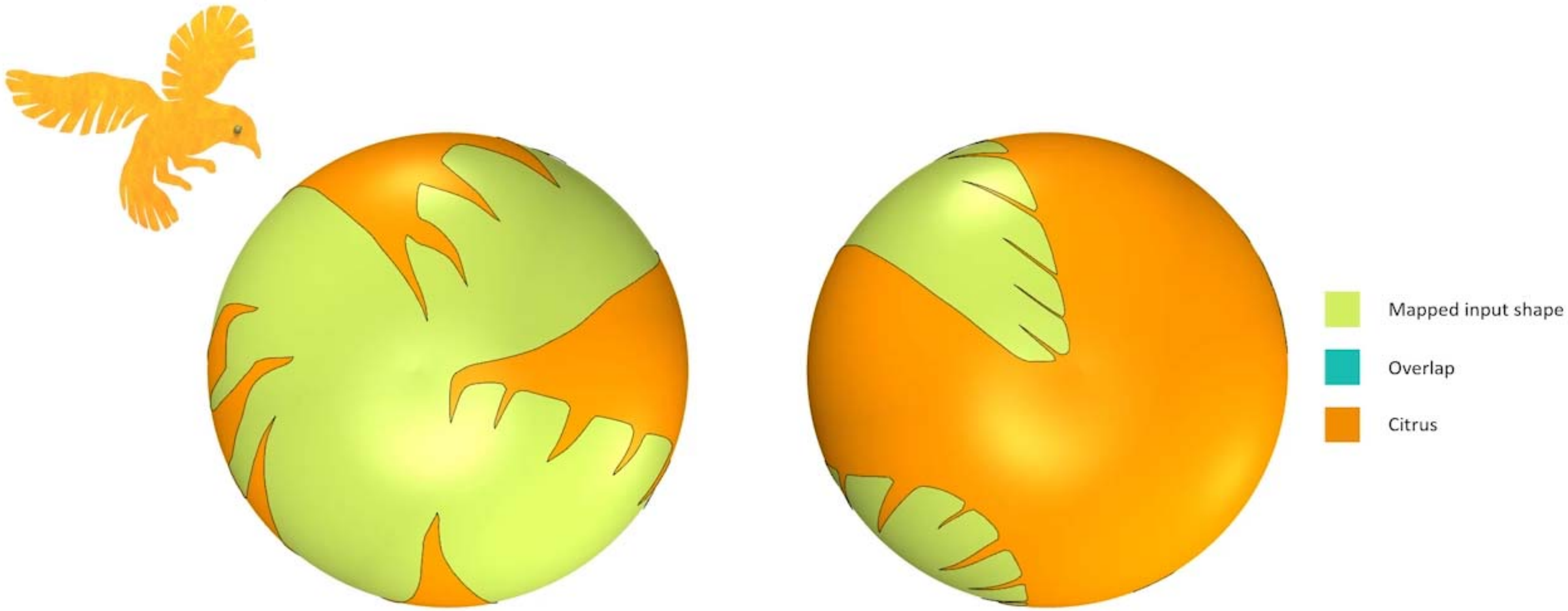


Input 2D shape

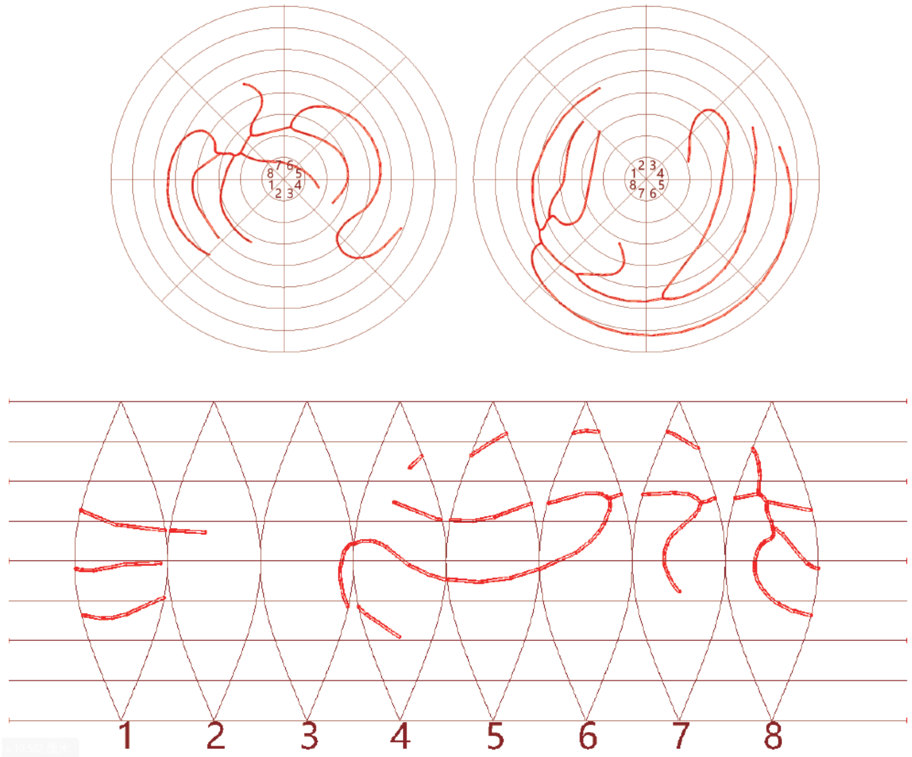
Key idea: map 2D shape onto the surface

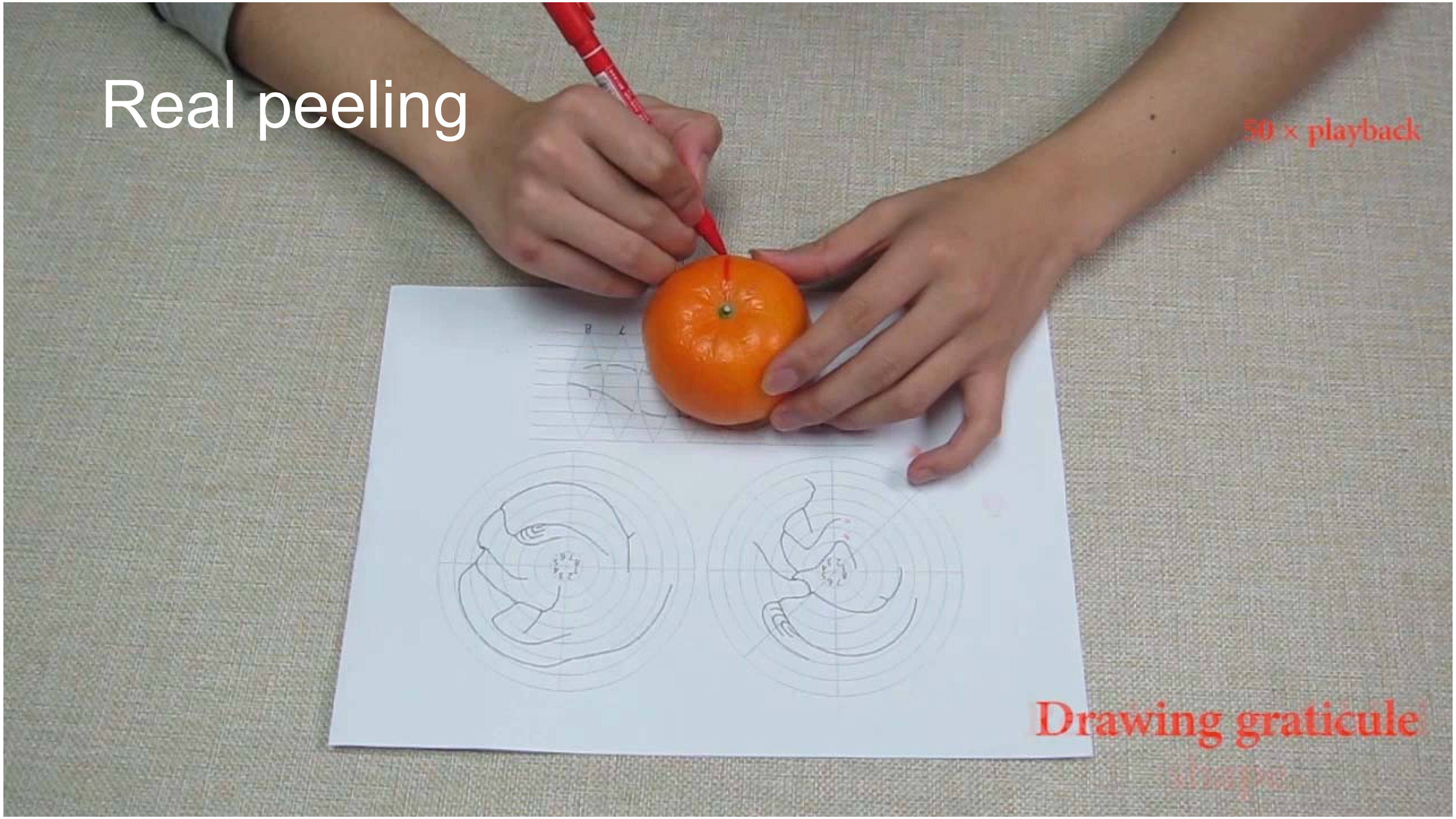


Mapping Result



Real peeling




Real peeling
50 × playback
Drawing graticule

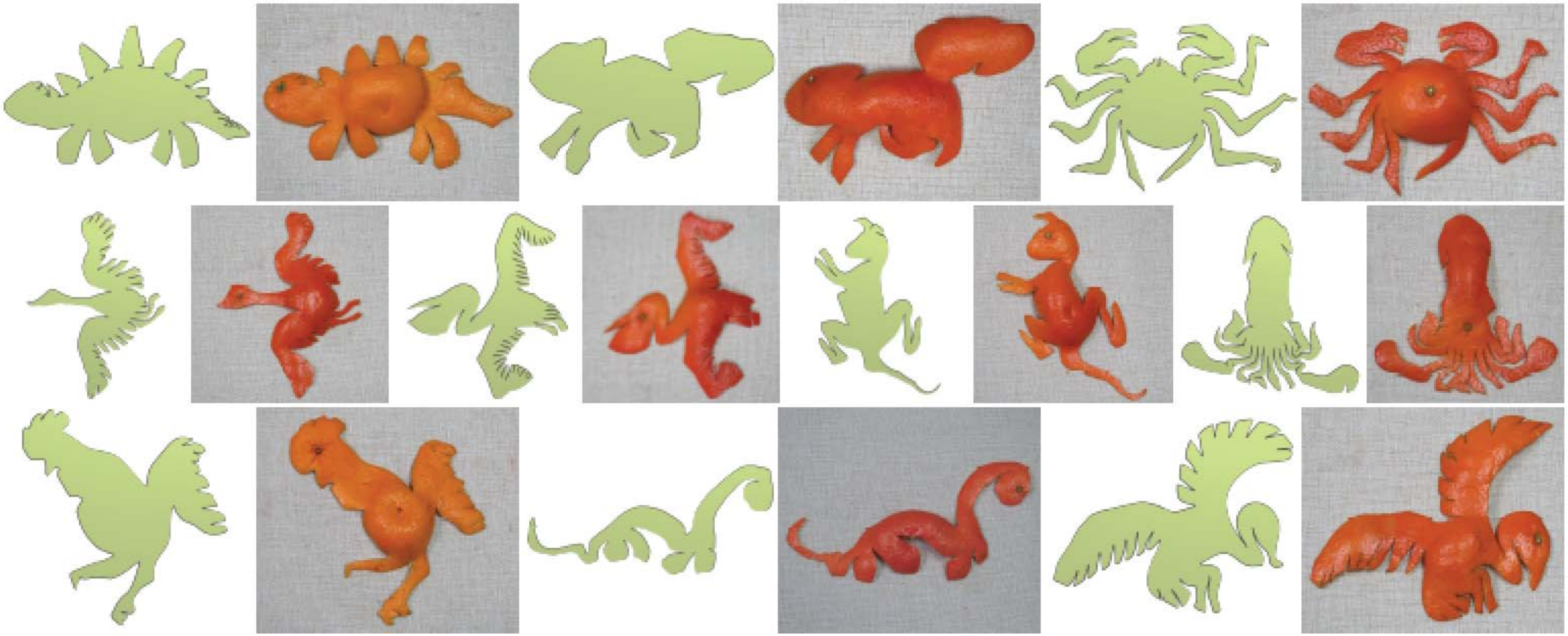
Comparison to Yoshihiro Okada

Okada

Ours

Dove Eagle Shrimp

More Results



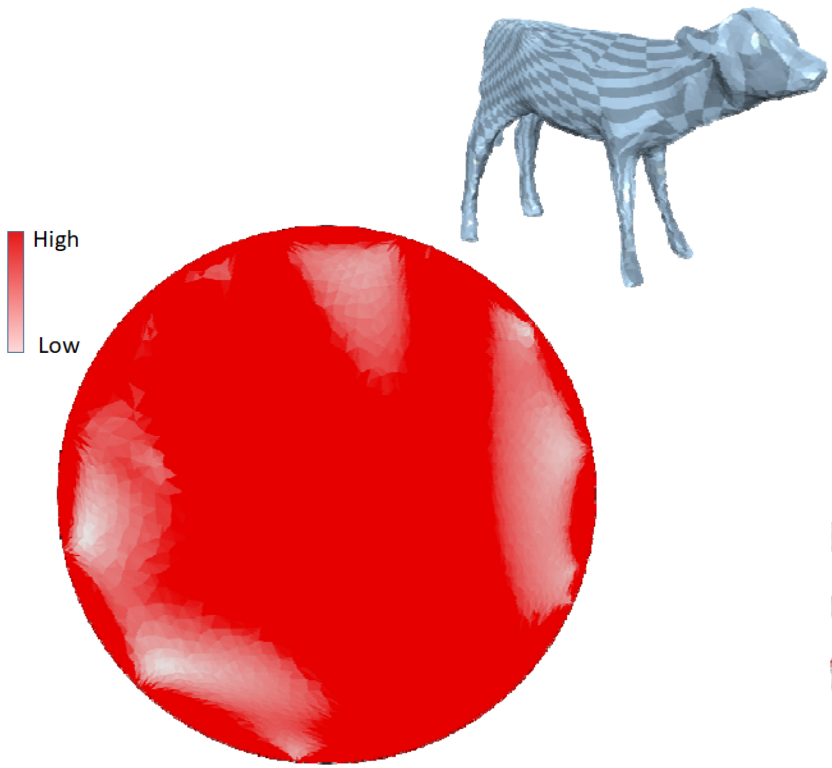
Real peeling of middle/elementary school students

Real Peeling Results

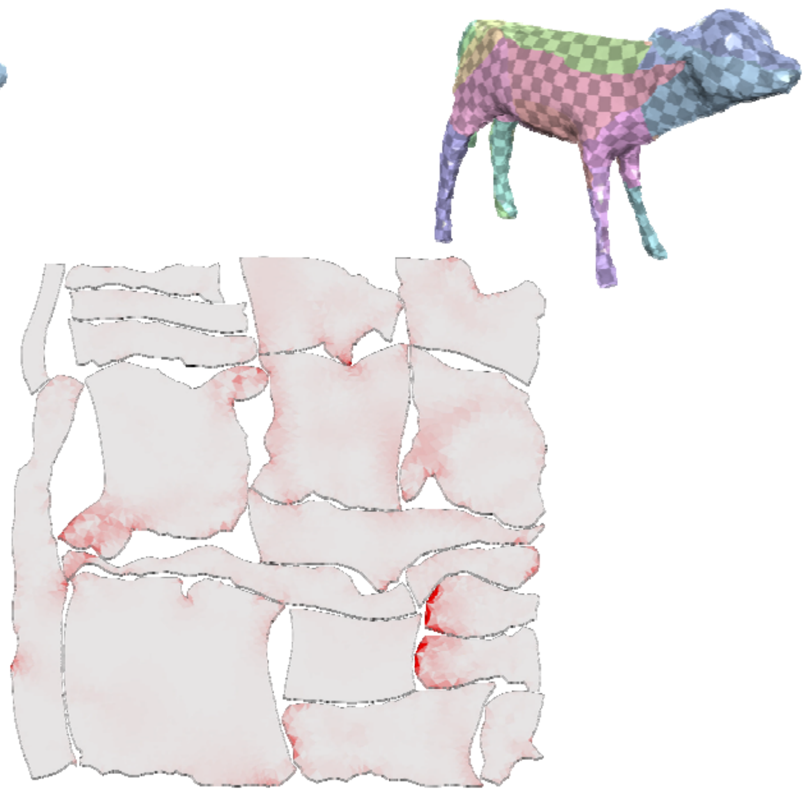
纹理地图：多片参数化

Texture Atlas

Multi-charts Parameterization



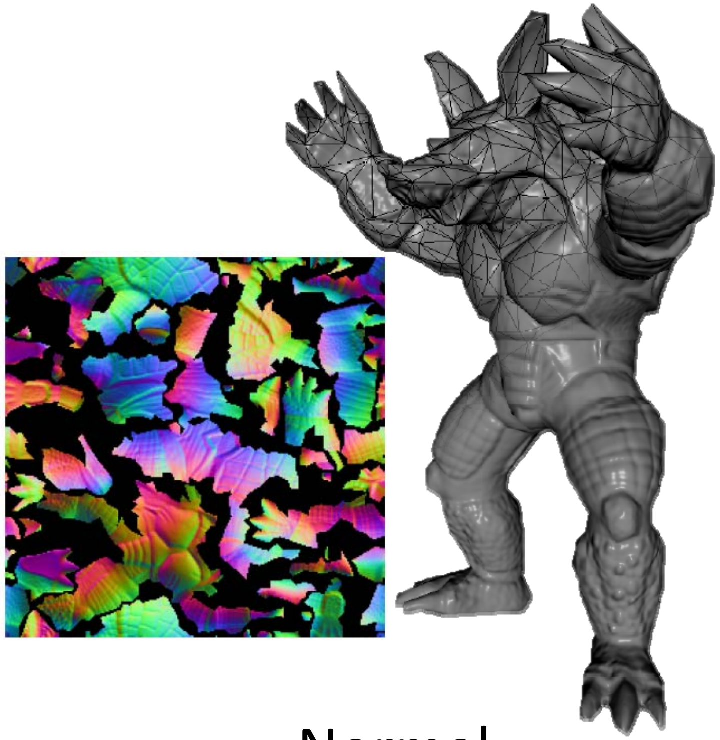
One chart



Multiple charts

Texture Atlas

Color

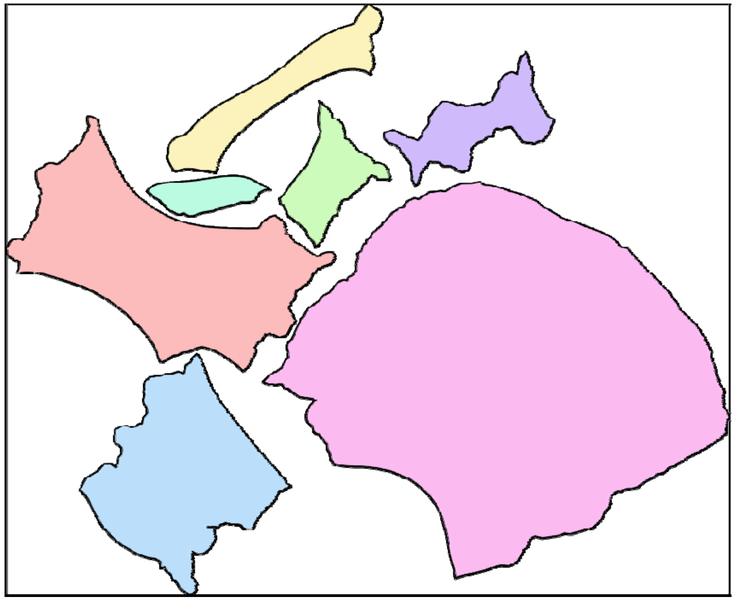


Normal

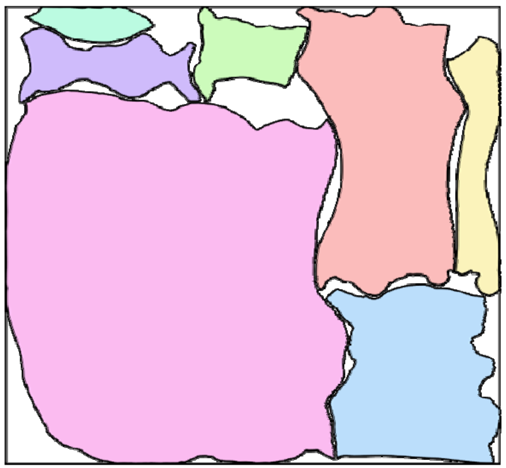
images courtesy of Hoppe

Atlas Generation: Minimizing Packing Efficiency (PE)

- A packing problem: NP hard!



PE=45.6%

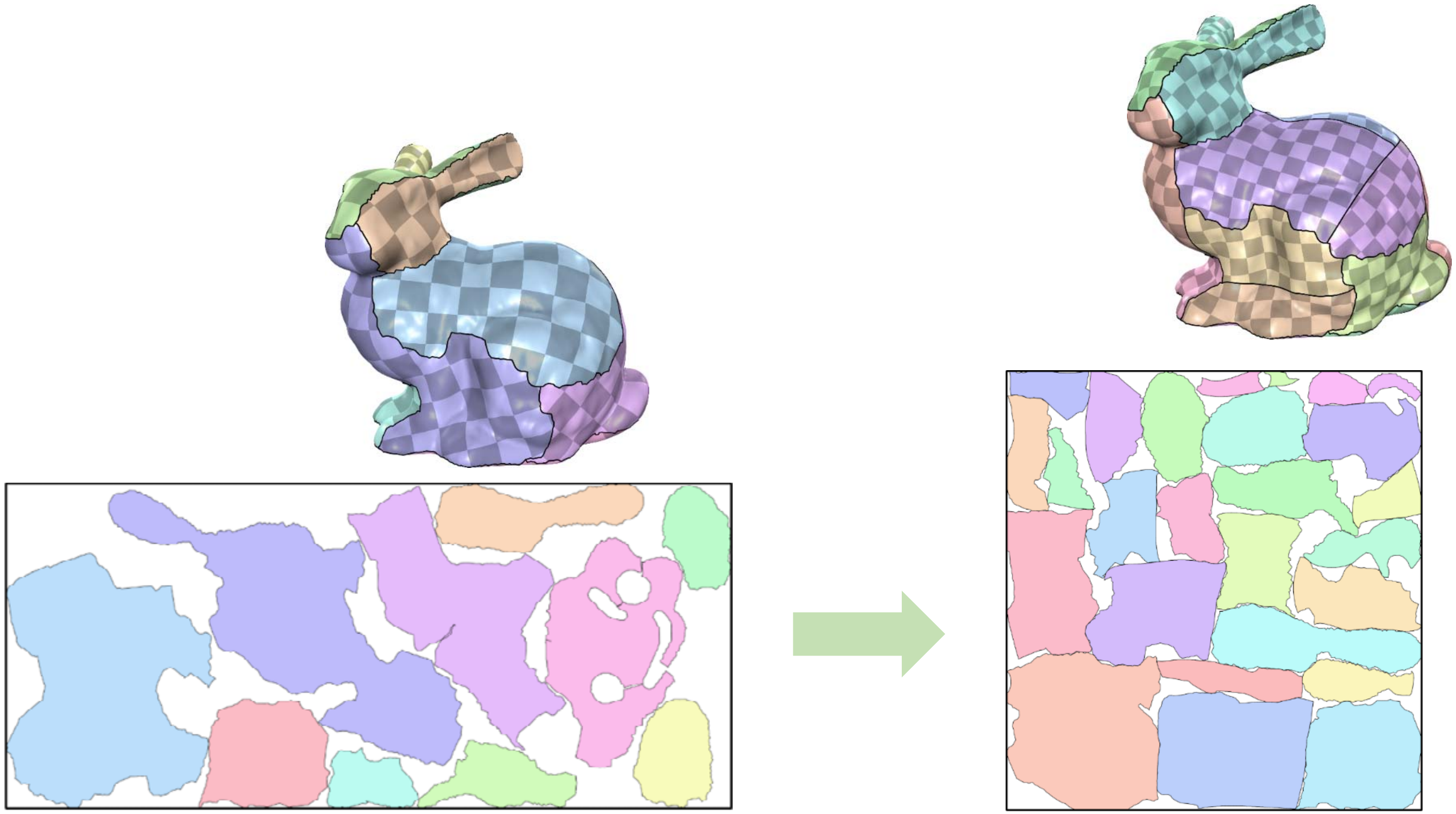


PE=86.1%

Atlas Generation

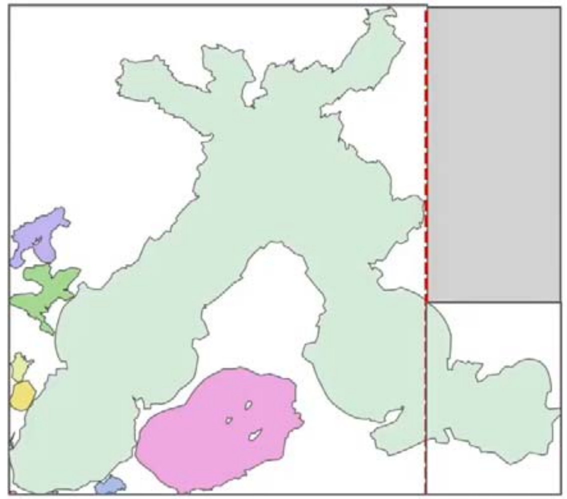
- Low Distortion
  - [Golla et al. 2018; Liu et al. 2018; Shtengel et al. 2017; Zhu et al. 2018]
- Consistent orientation
  - [Floater 2003; Tutte 1963; Claici et al. 2017; Hormann and Greiner 2000; Rabinovich et al. 2017; Schüller et al. 2013]
- Bijection
  - [Jiang et al. 2017; Smith and Schaefer 2015]
- Low boundary length
  - [Li et al. 2018; Poranne et al. 2017; Sorkine et al. 2002]
- Packing efficiency
  - Box cutter [Limper et al. 2018]
  - Bounded Packing Efficiency [Liu et al. 2019]

Atlas Refinement: Higher PE

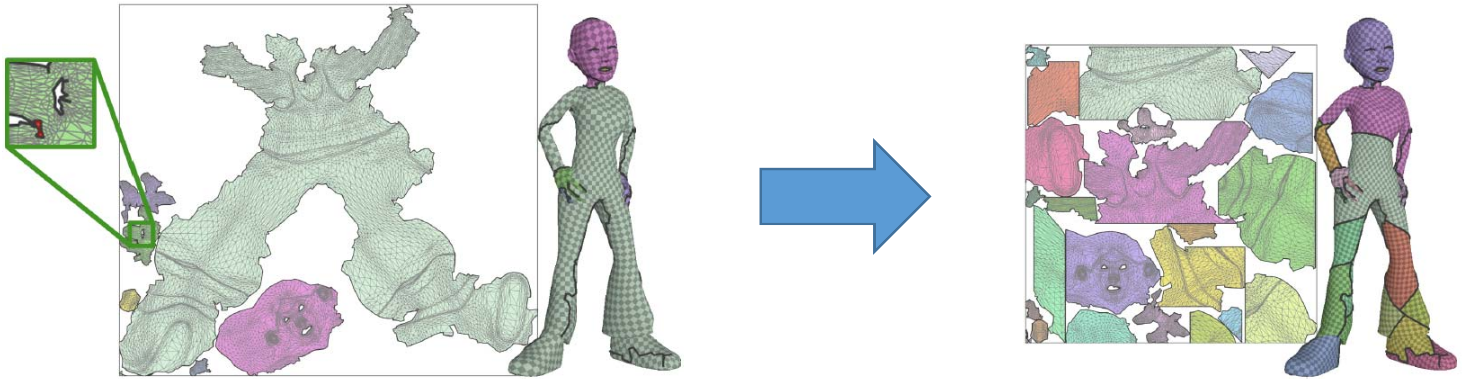


Higher PE

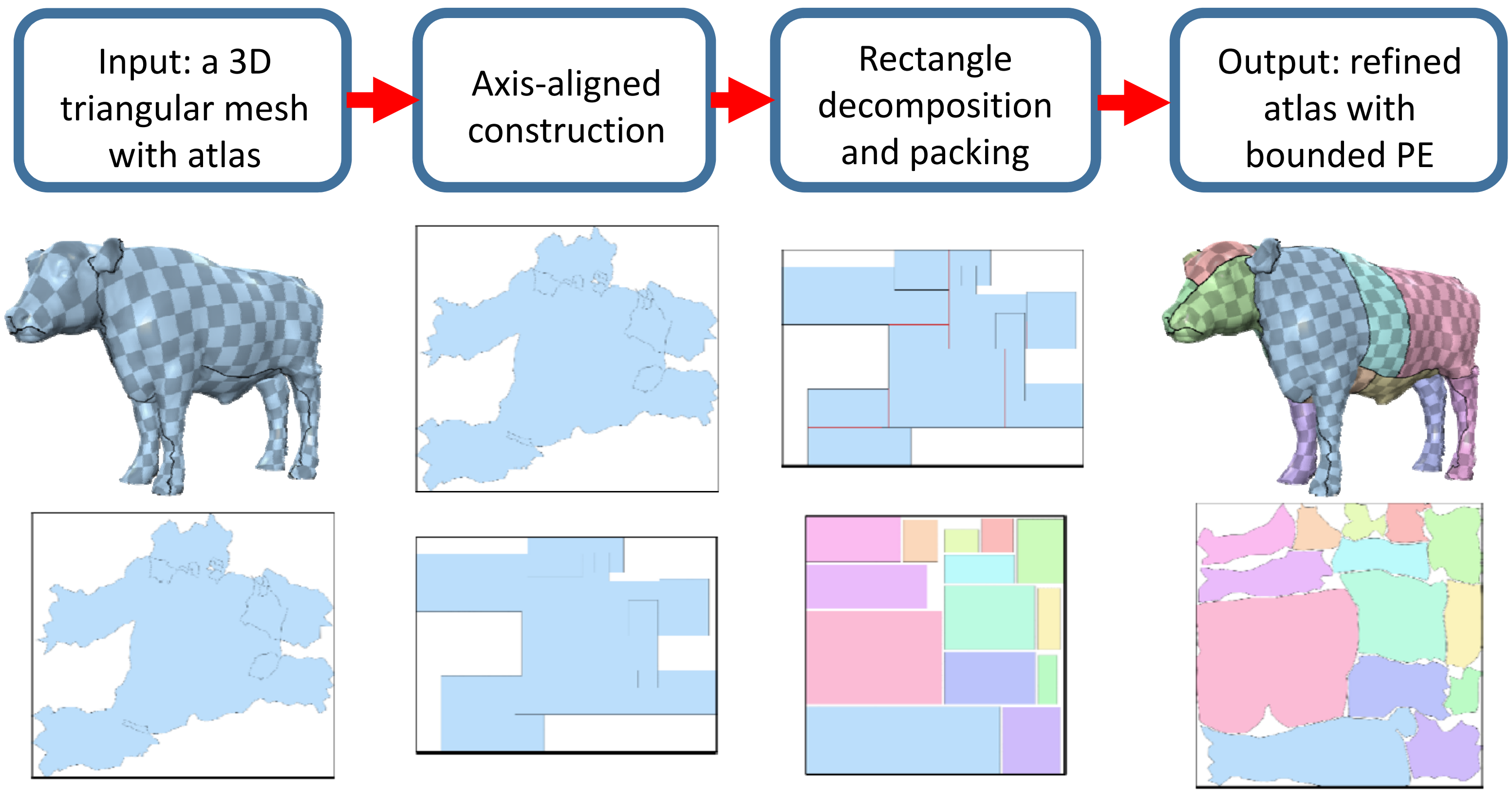
Box Cutter [Limper et al. 2018]



- Atlas refinement
  - Remove overlaps
  - Improve packing efficiency
- No additional distortion
- Bounded boundary length elongation



Bounded Packing Efficiency



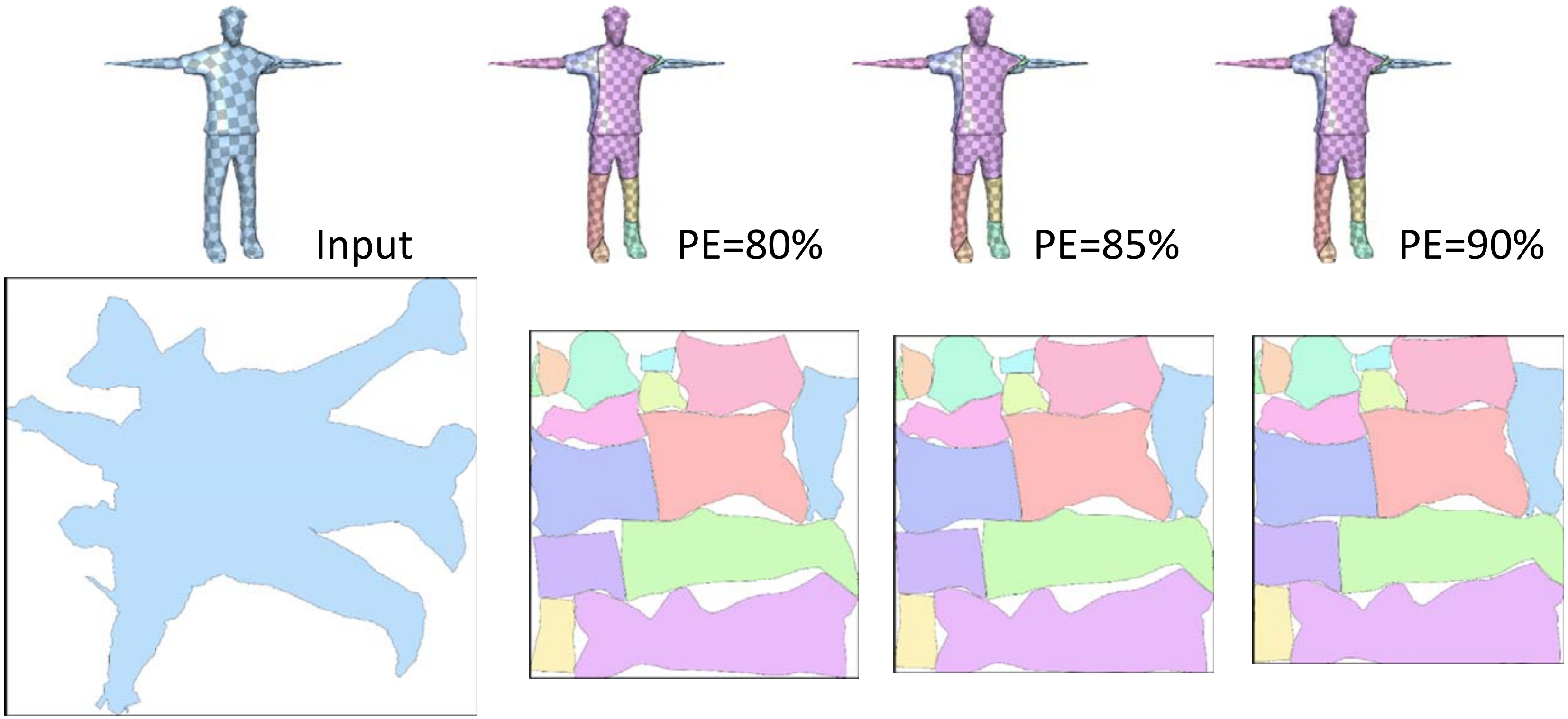
[Liu et al. Atlas Refinement with Bounded Packing Efficiency. Siggraph 2019.]

PE Bounds

PE=80.4%

PE=92.6%

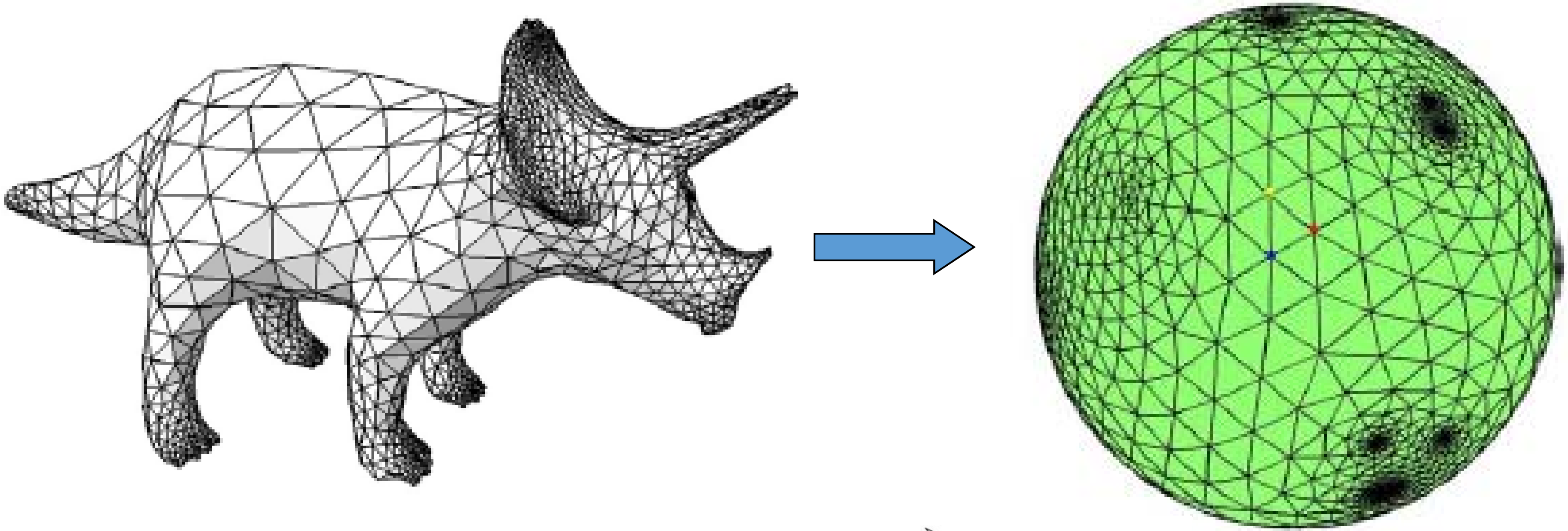
Different PE Bounds

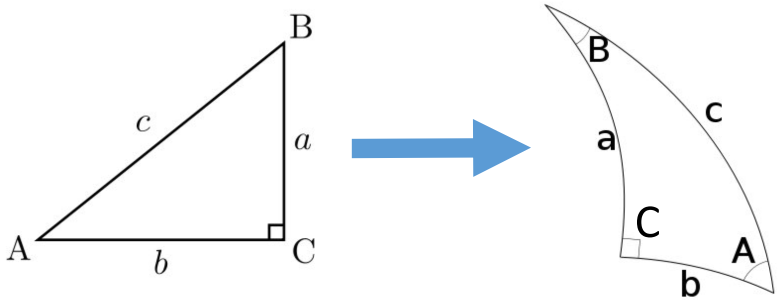


球面参数化

问题：球面参数化

- 输入：亏格为0的封闭曲面（拓扑同胚于球面）

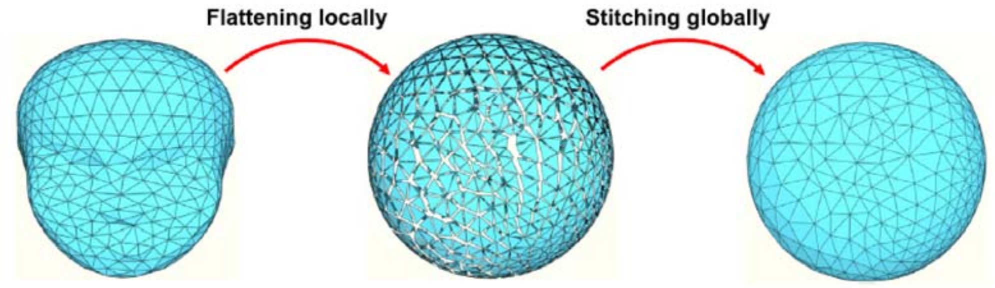




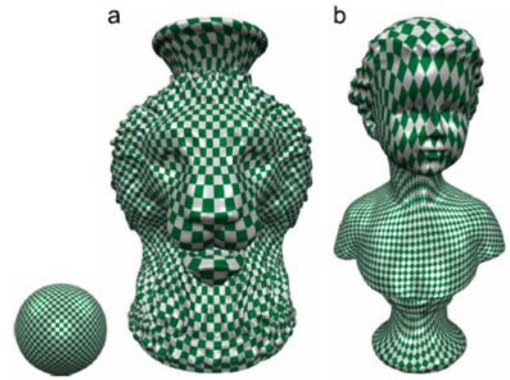
球面参数化的主要方法

- Direct methods
  - [Kent et al. 1992], [Kobbelt et al. 99], [Gu et al. 03]
- Optimization methods
  - [Sheffer et al. 04], [Li et al.06&07], [Zayer et al.06], [Friedel et al., 07], [Kazhdan et al. 2012], [Wan et al. 12&13], [Wang et al., 14&16]
- Coarse-to-fine methods
  - [Praun and Hoppe 04], [Tang et al. 16], [Hu et al. 17]

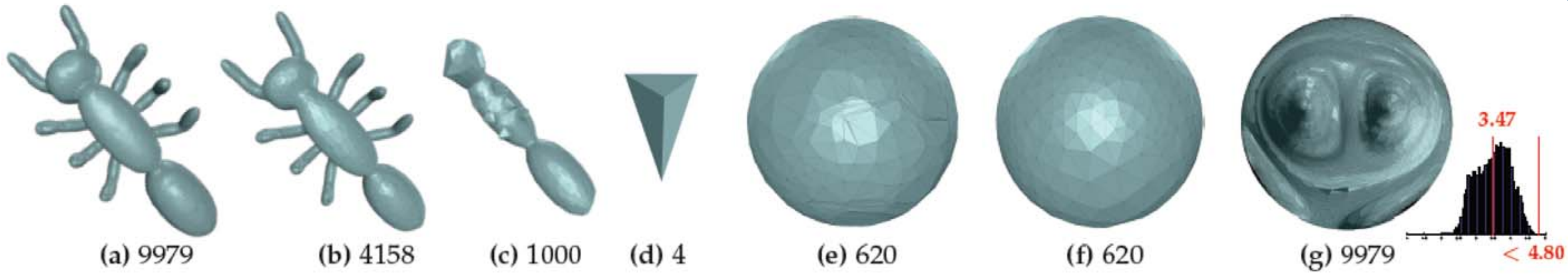
Our Works on Spherical Parameterization



ARAP method [Wang et al. 2014]



AMIPS method [Wang et al. 2016]



Hierarchical method [Hu et al. 2017]

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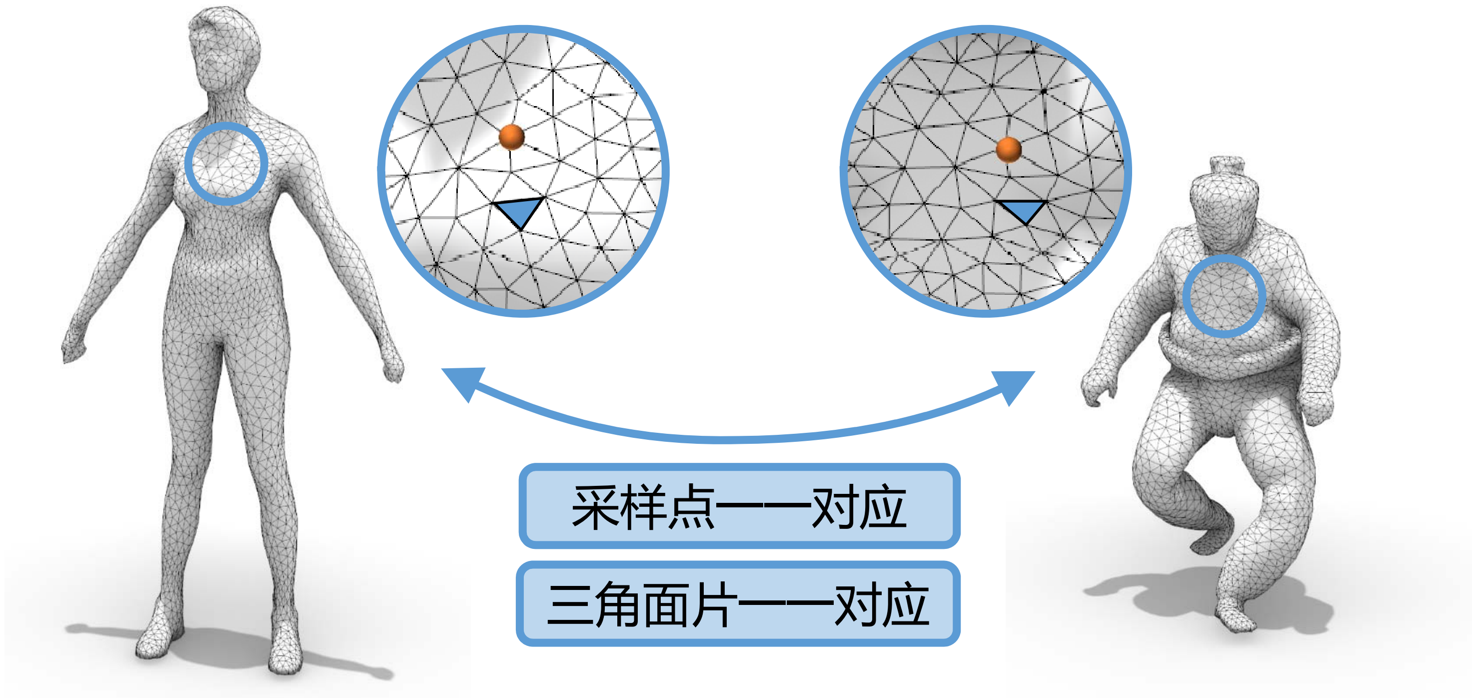
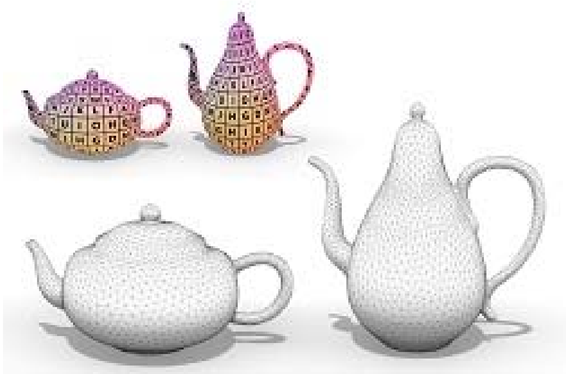
Mapping between Mesh Surfaces

- 相容性网格（Compatible mesh）：一组具有相同连接关系且与给定模型形状近似的网格



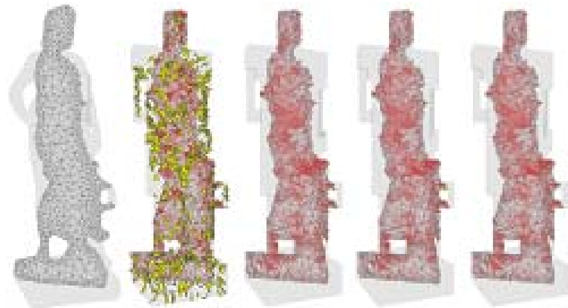
Our Works on Compatible Mappings



Yang et al. Siggraph 2020

Yang et al. IEEE TVCG 2019

Yang et al. Pacific Graphics 2019



Su et al. Pacific Graphics 2019

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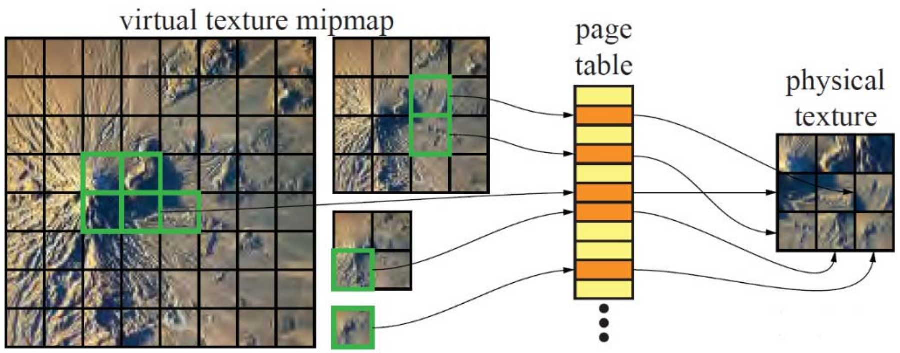
总结： 曲面参数化

- 几何处理的基本问题：大量的应用
- 是一个从3D到2D的降维问题：将几何数据表达为图像
- 特殊的几何结构（三角网格）：特殊的优化方法
- Next: 大型场景的压缩、传输、调度、渲染...

虚幻5：宣传片



Virtual geometry

Future Work and Challenges

- Fundamental problem for CG (geometry/simulation/rendering)
- Trade-of quality/efficiency/complexity
- Coupled solution
  - Parameterizaiton, cutting, atlas
- Other methods
  - Diffusion for optimization
  - Better initializations than Tutte's method
  - Learning based methods

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谢 谢 ！