Computational Conformal Geometry Applied in Computer Science

Computational and Conformal Geometry

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Thanks

- Thank Chris for giving me the great chance to present my recent works.

Thanks

- Thank my first advisor, professor David Mumford, for his guidance and advices.

Thanks

- Thank Professor Sullivan, his seminal works kindled my interested in conformal geometry.
- Thank Professor Ken Stephenson for his valuable advices and consistent help during the last several years.

Collaborators

- Mathematicians
  - Prof. Shing-Tung Yau
  - Prof. Feng Luo
  - Prof. Zeng-Xue He
- Computer Scientists
  - Prof. Hong Qin
  - Prof. Arie Kaufman
  - Prof. Dimitris Samaras
  - Prof. Klaus Muller
  - Prof. Joe, Esther
  - Prof. Jie Gao

Contributors

- Researchers in center of visual computing
  - Junho Kim, Ying He, Wei Hong
- Phd Students
  - Miao Jin, Tim Yin, Xin Li, Huayi Zeng, Wei Zeng, Feng Qiu
- Researchers from other departments
  - Peisen Huang , Song Zhang
  - Jerome Liang
  - Lance Cong

Outline

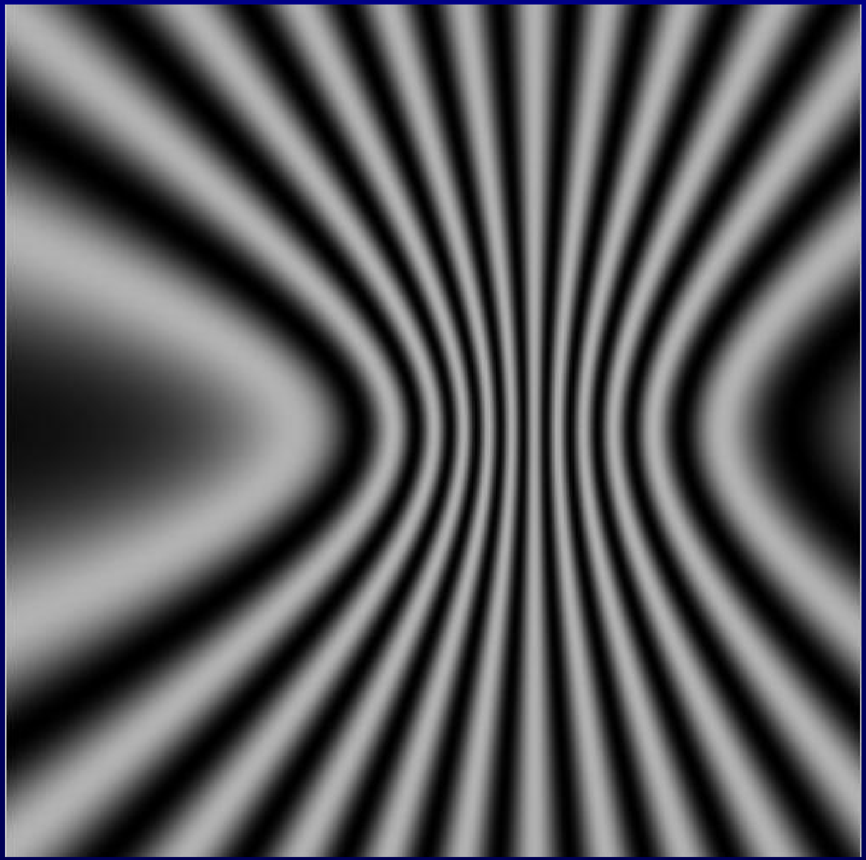
- Applications of conformal geometry
  - Computer graphics
  - Computer vision
  - Medical imaging
  - Scientific Computing
  - Geometric Modeling
- Computational Methods
  - Harmonic Map
  - Holomorphic forms
  - Discrete surface Ricci flow

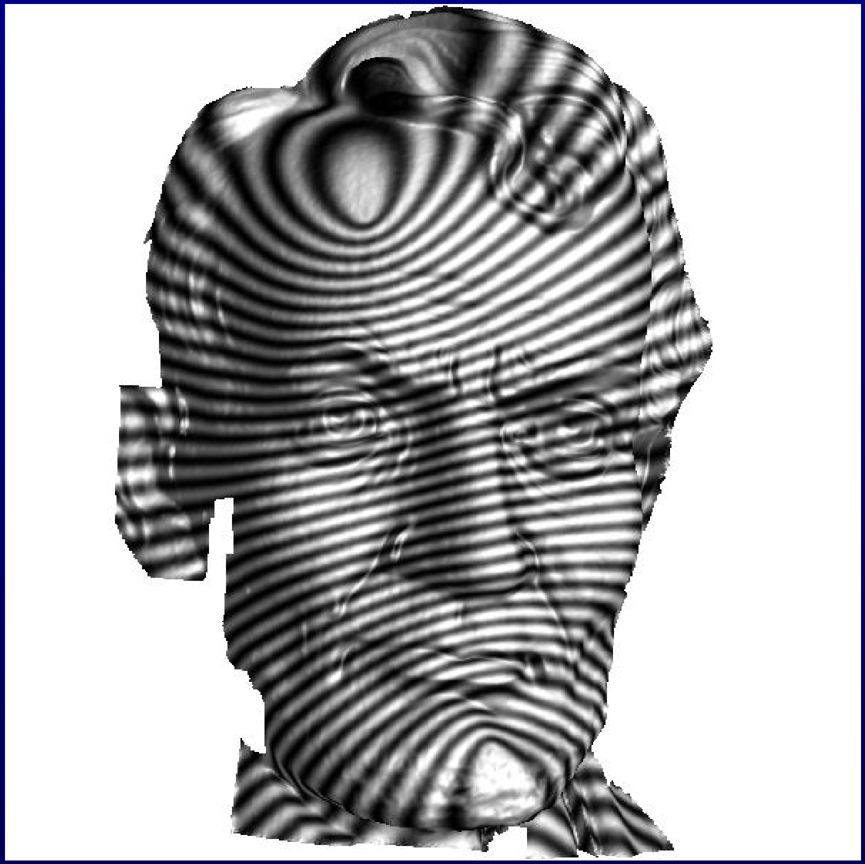
Conformal Geometry in Computer Science

- Conformal geometry is getting more and more popular in computer science since 2000, the major reasons are:
  - The rapid development of 3D scanning technology, shape acquisition is becoming much easier
  - The fast development of computer hardware, especially the graphics hardware – GPU.

Applications in Computer Vision

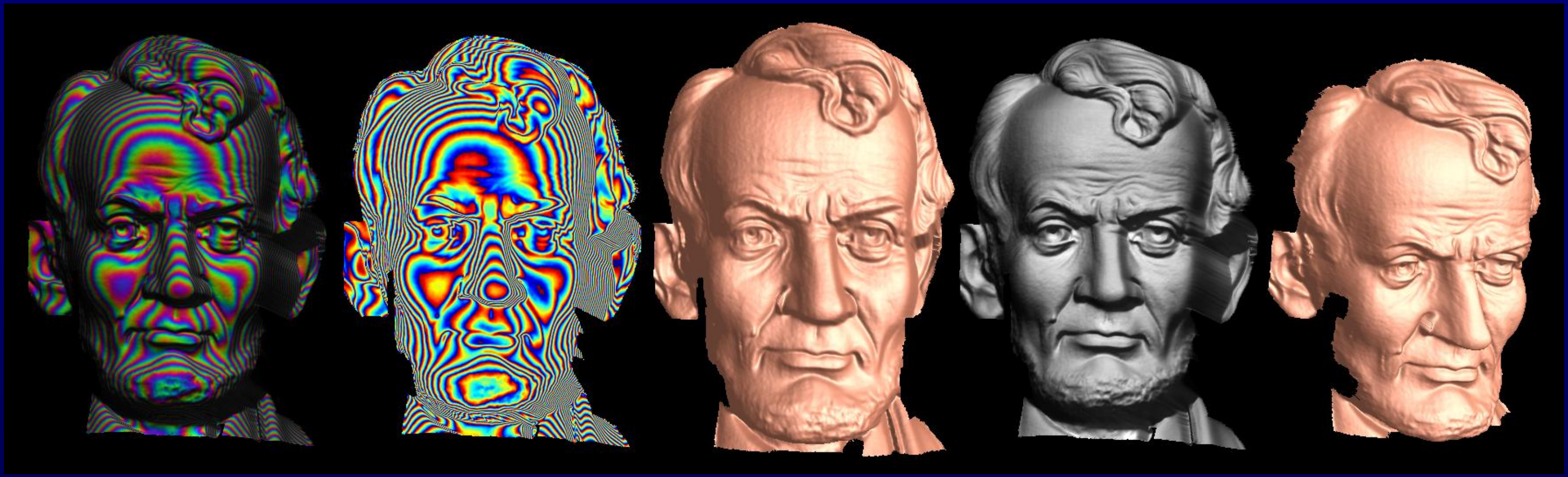
Wave Optics - Light Interference





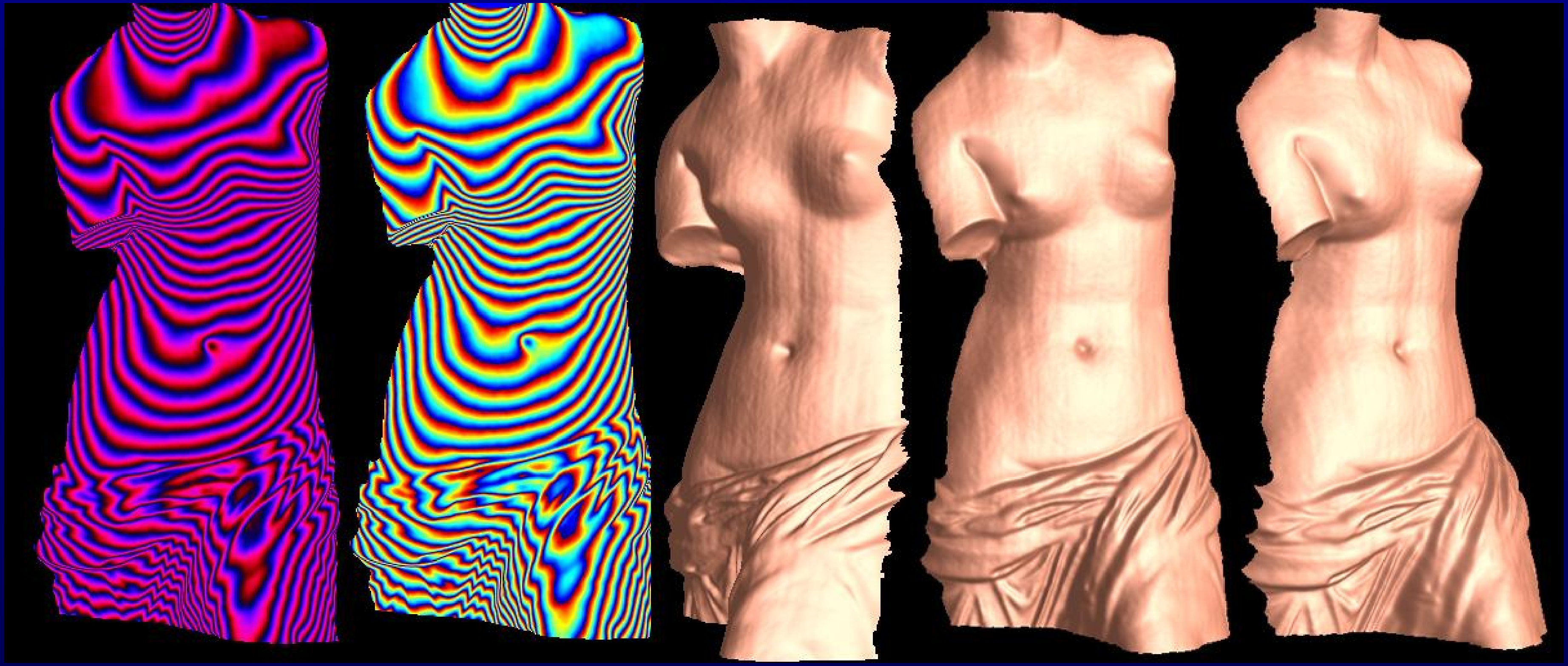
Three Channel Geometry Video

- Geometry is reconstructed by 3 fringe images

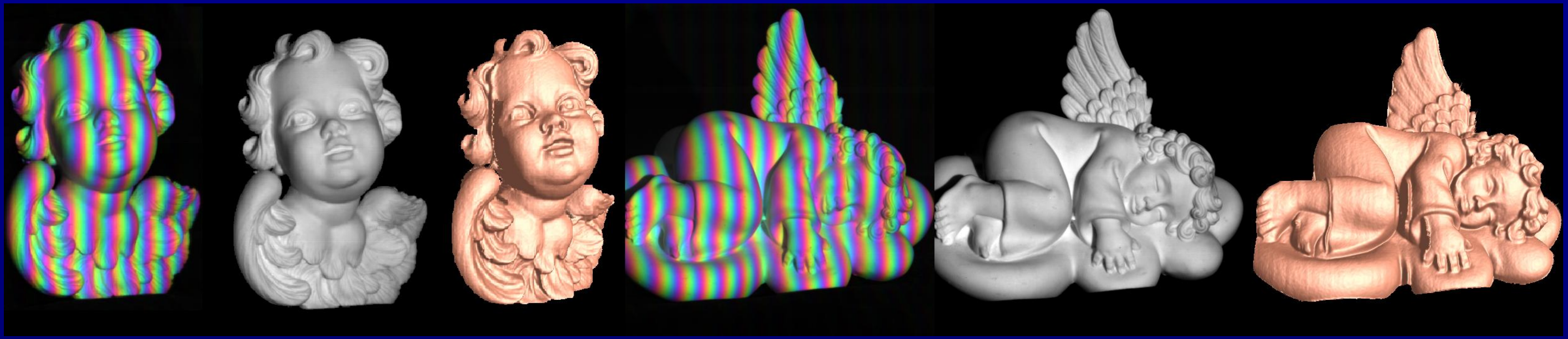


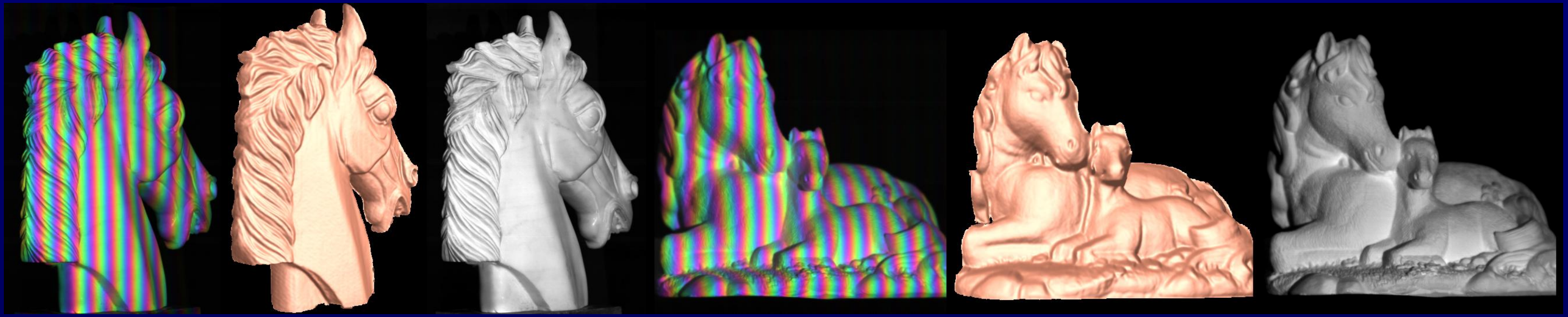
3D Acquisition

3D Acquisition

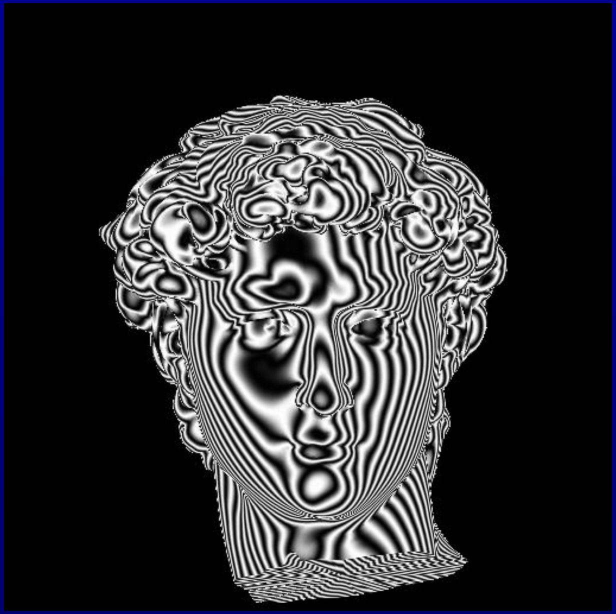


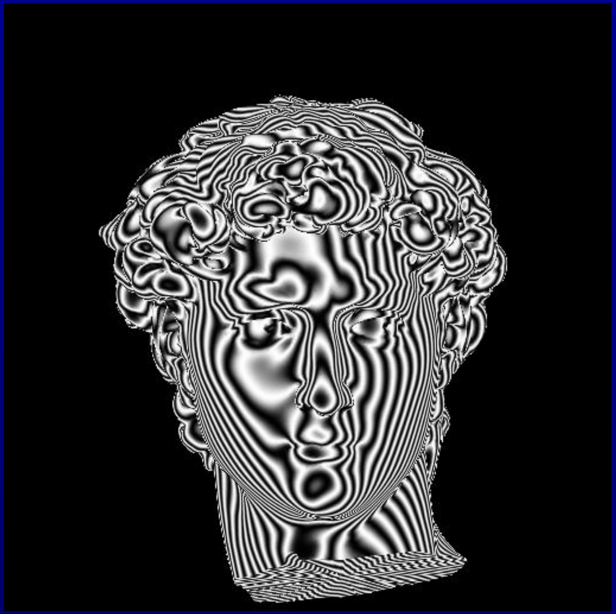
3D Acquisition





Digital fringe projection and phase shifting



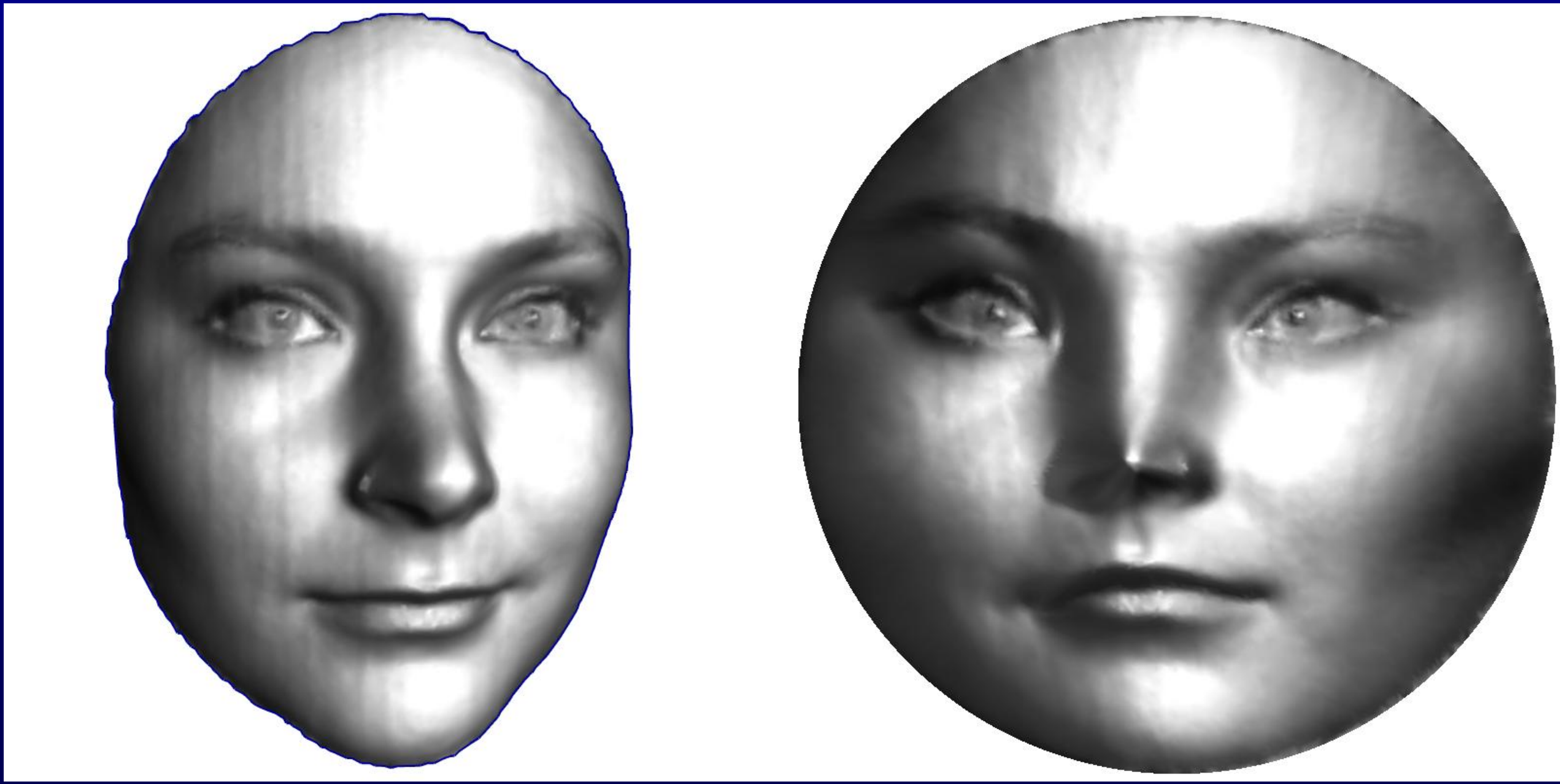


3D Data Acquisition

- High resolution
- High speed

Summary: 3D Video Camera

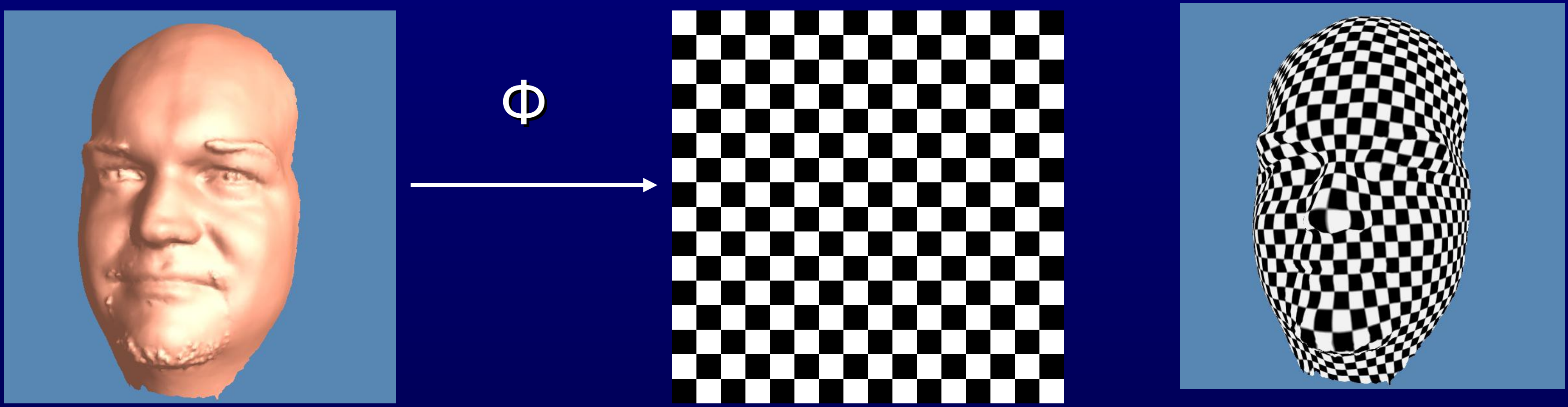
Riemann Mapping



Conformal Mapping

- Scaling first fundamental from
- Angle preserving
- Similarities in the small

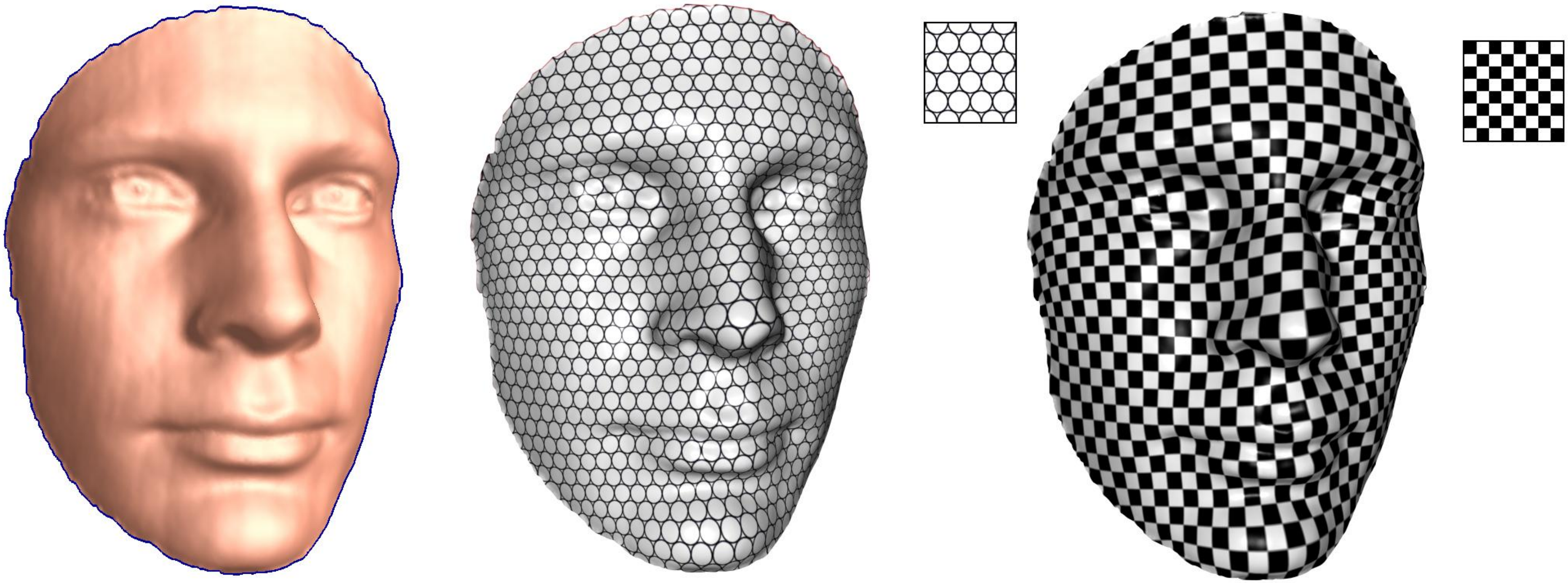
$$\varphi : M_1 \rightarrow M_2 , g_{ij} = \lambda \varphi^{\text{¿}} \tilde{g}_{ij}$$



M_1 M_2

Riemann Mapping

Riemann Mapping

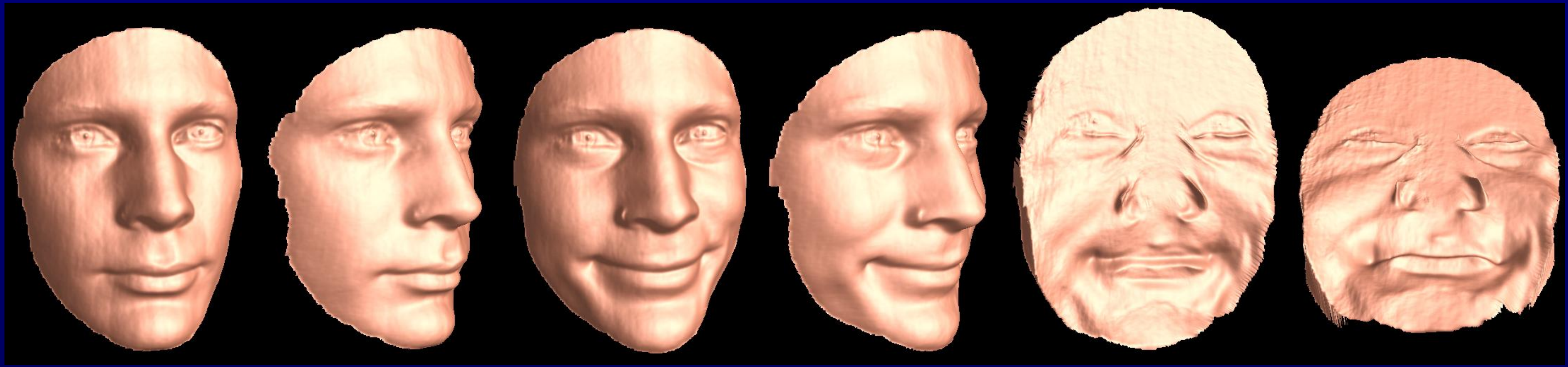


Geometric matching

- Parameterize surfaces to a canonical domain
- Match features by parameter
- Depends on geometry continuously

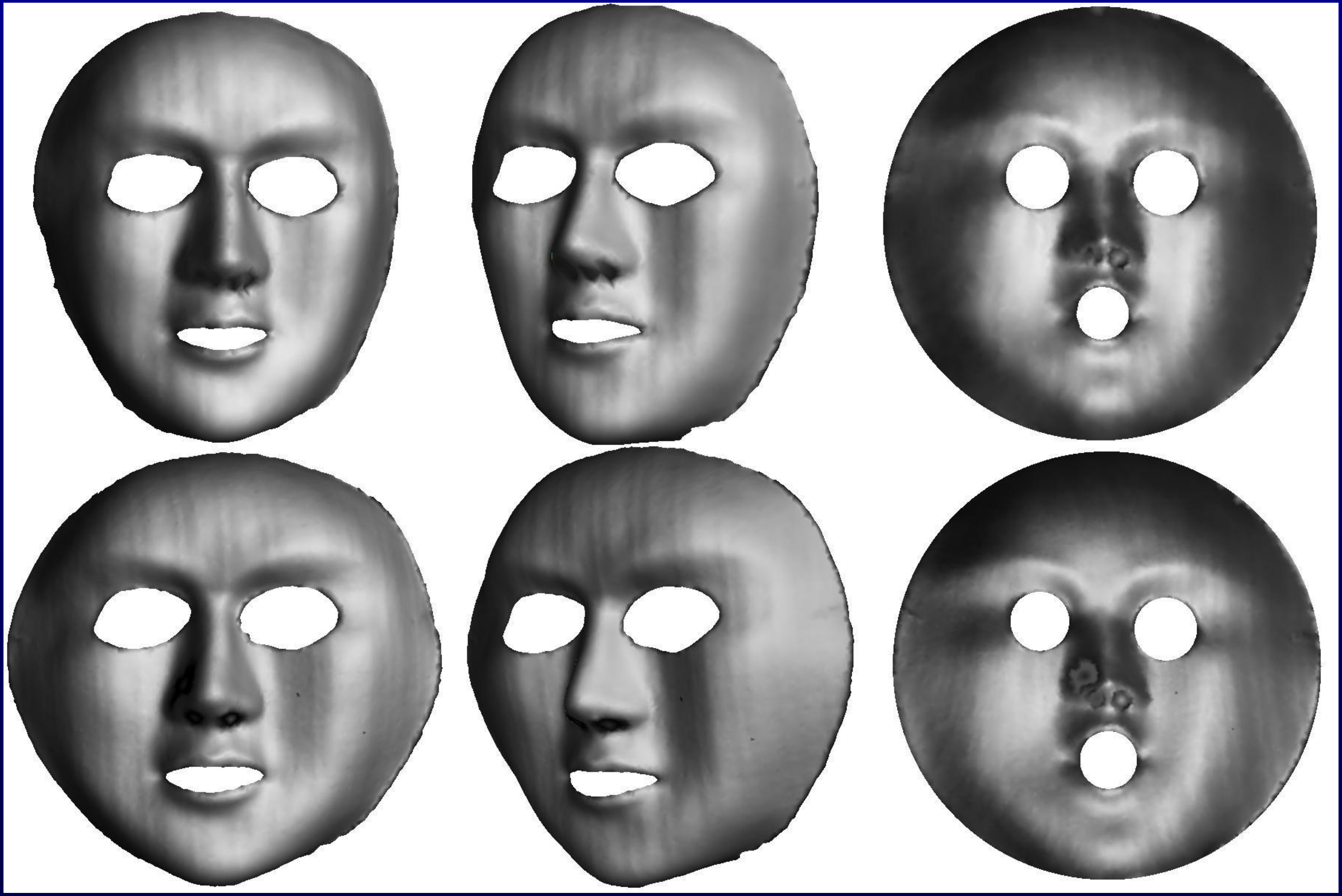
demo

Animators: automatic facial expression generation

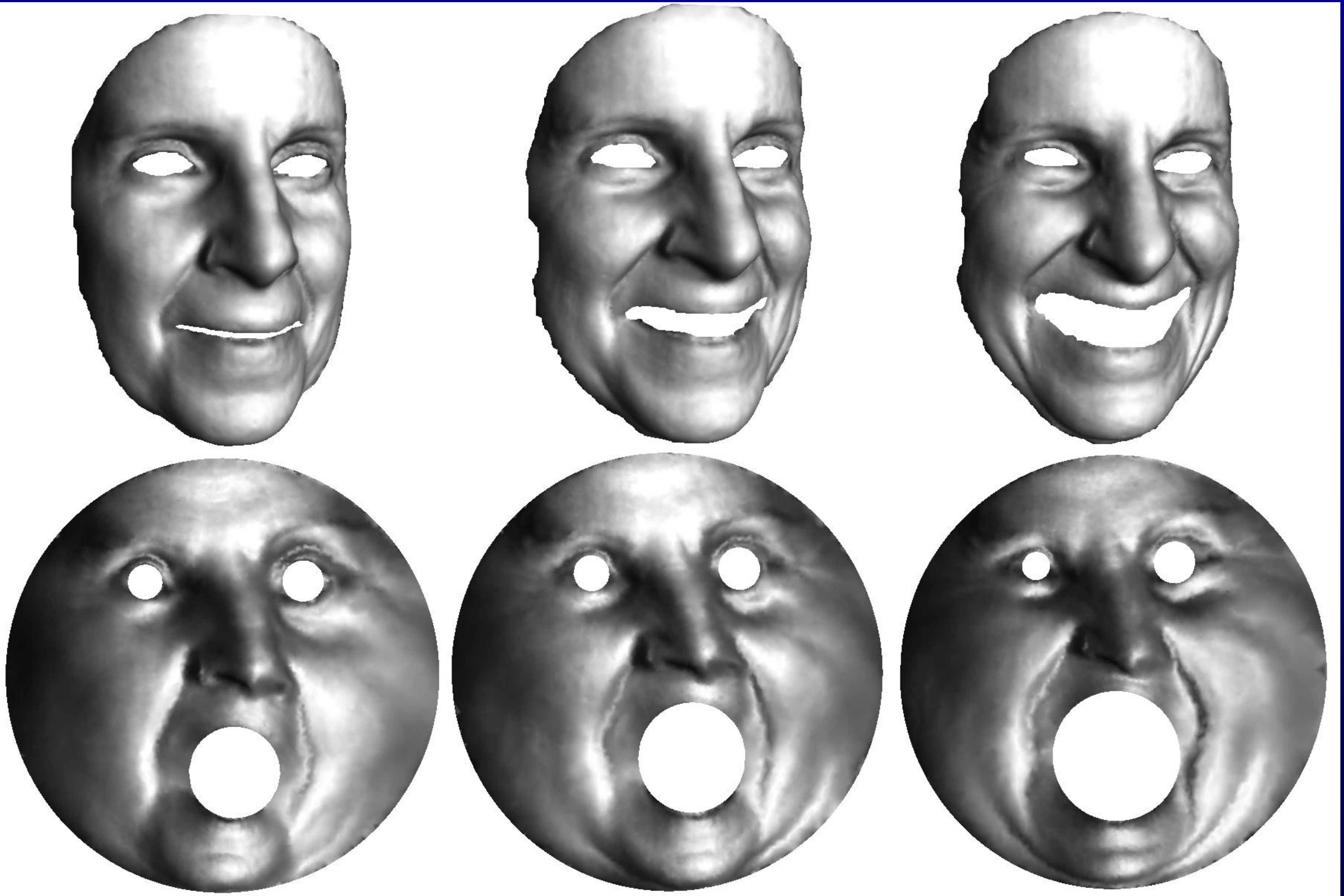


demo demo demo

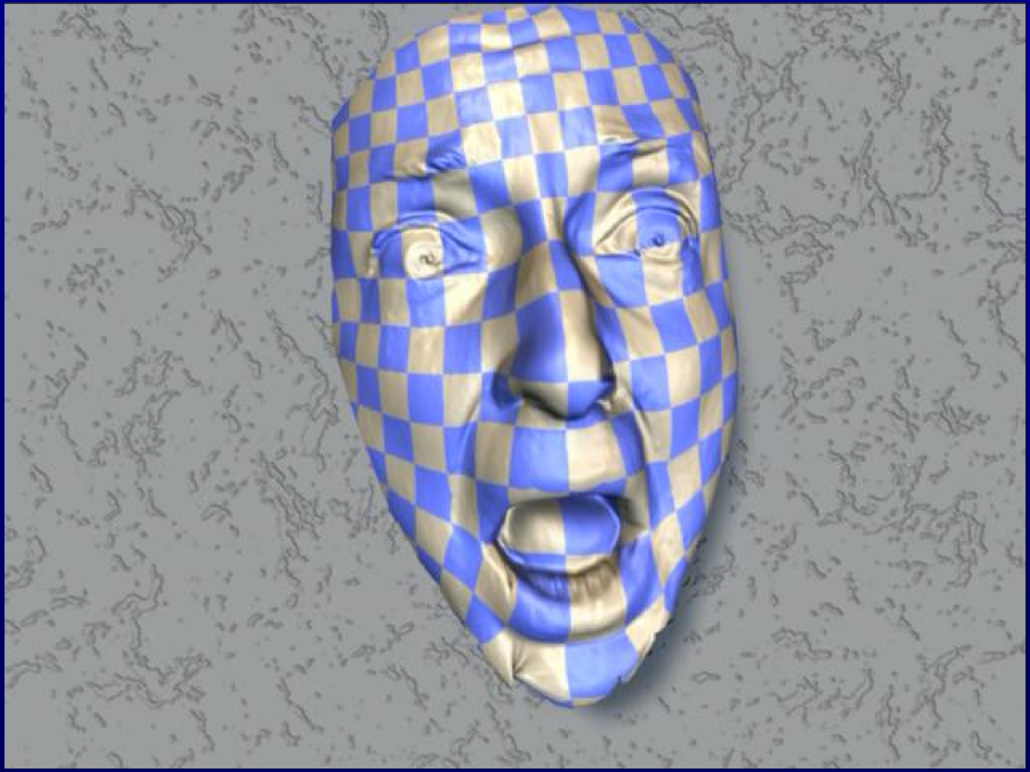
Conformal Invariants



Conformal Invariants

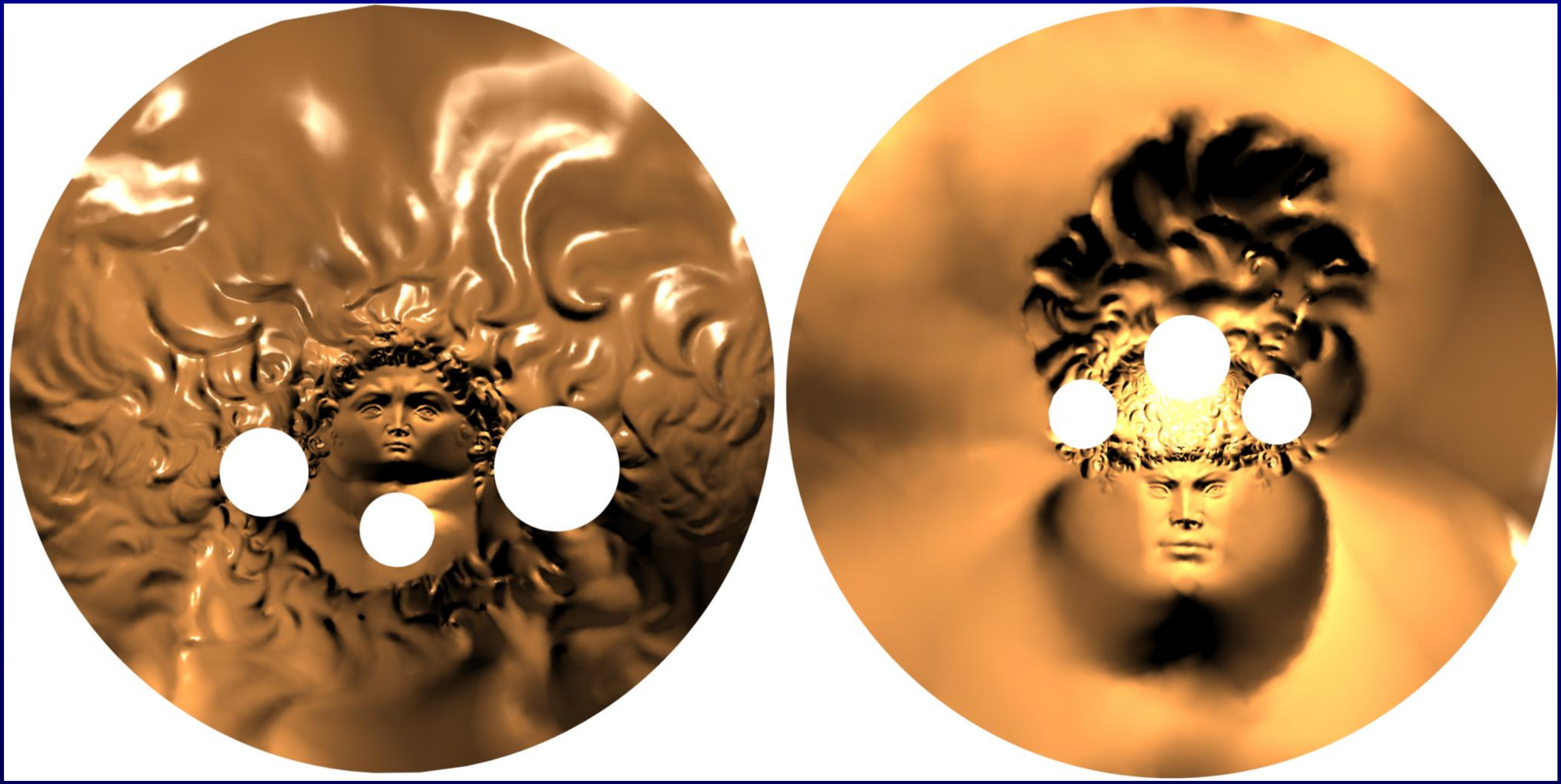


Face Registration



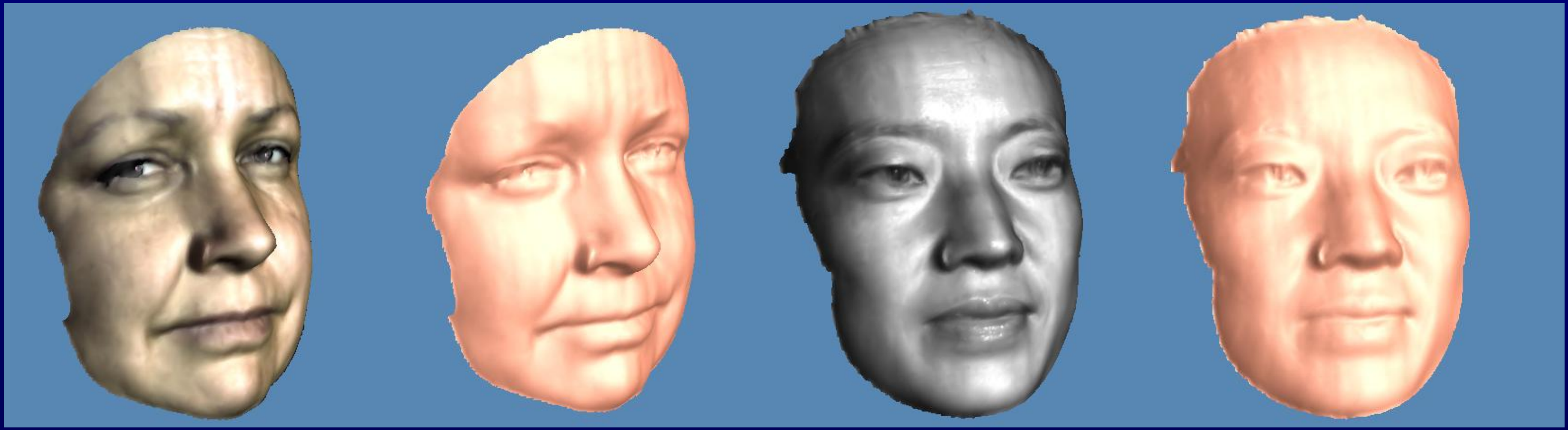
Virtual Actor

GeoUV



Summary: 3D Video Camera

- **Faster Speed**
- **Higher resolution**
- **Cheaper cost**



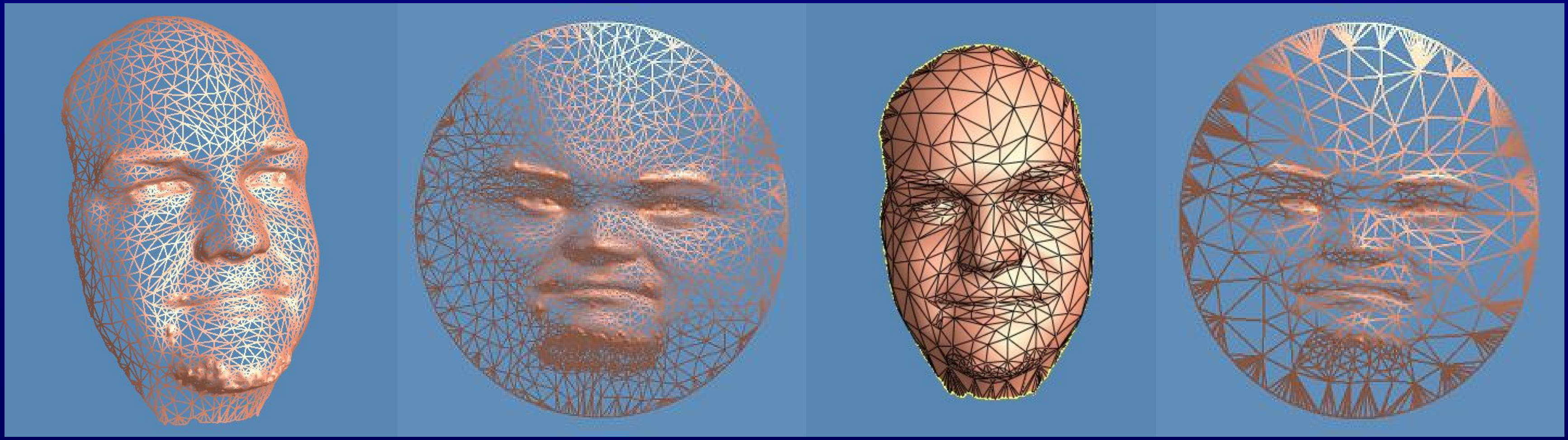
Surfaces with boundaries

- Copy the surface, invert the orientation
- Glue two copies together along the boundaries
- Treat the doubling as a closed surface
- Keep symmetry



Conformal mapping properties

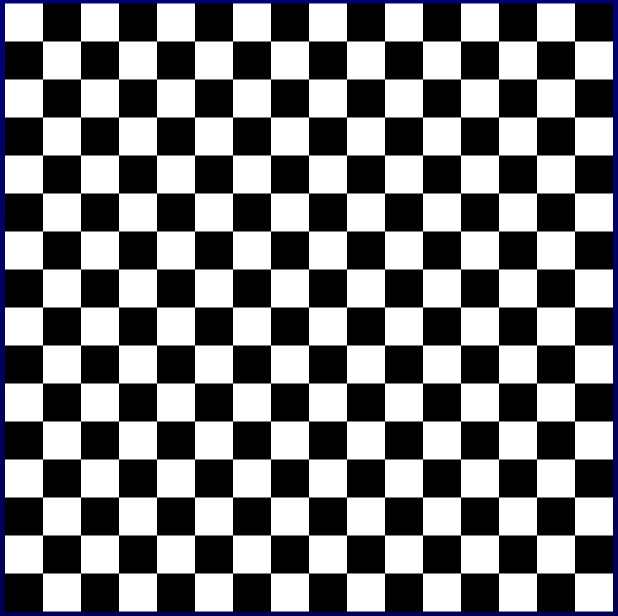
- Intrinsic to geometry
- Insensitive to triangulations and noise

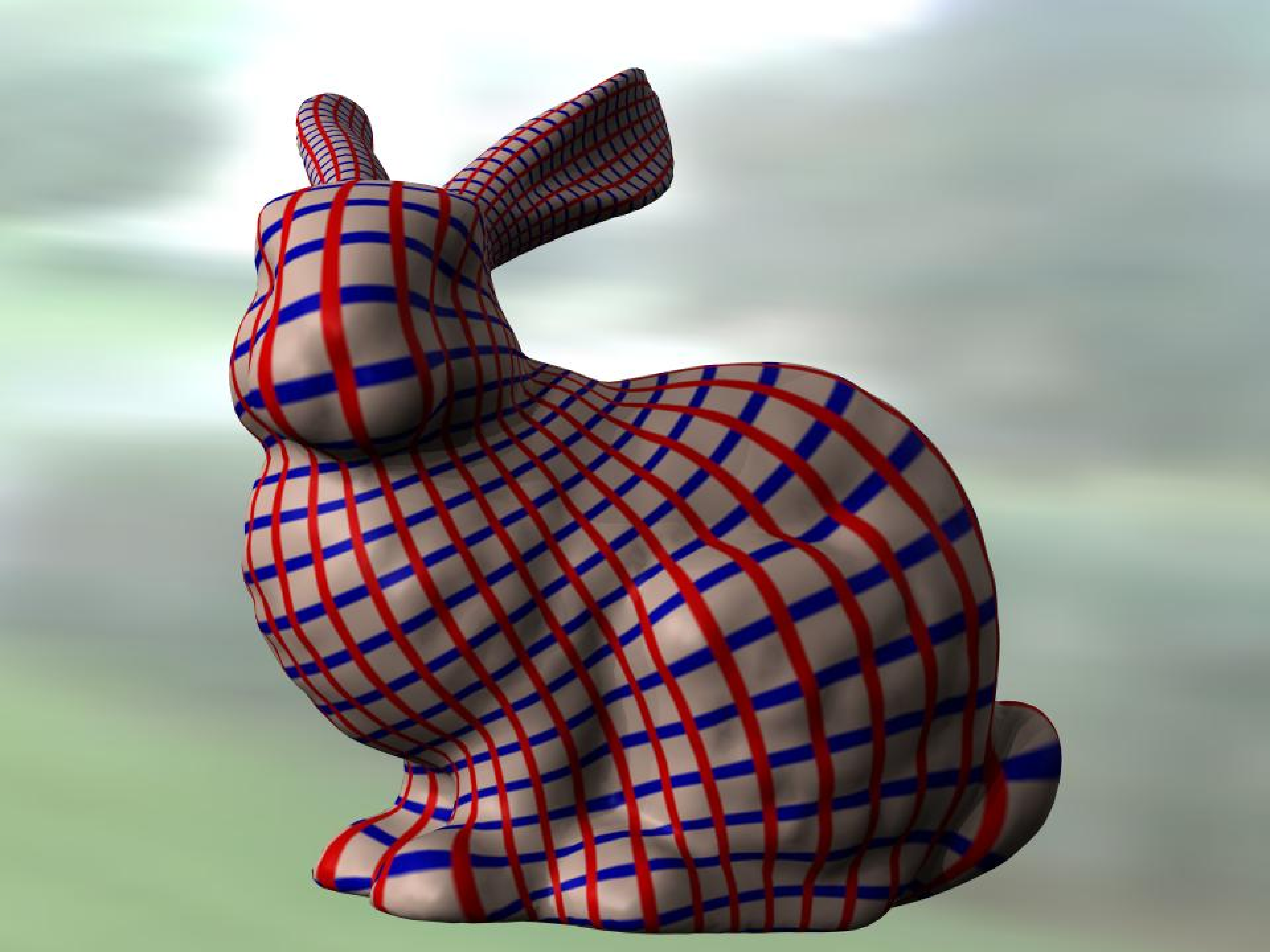


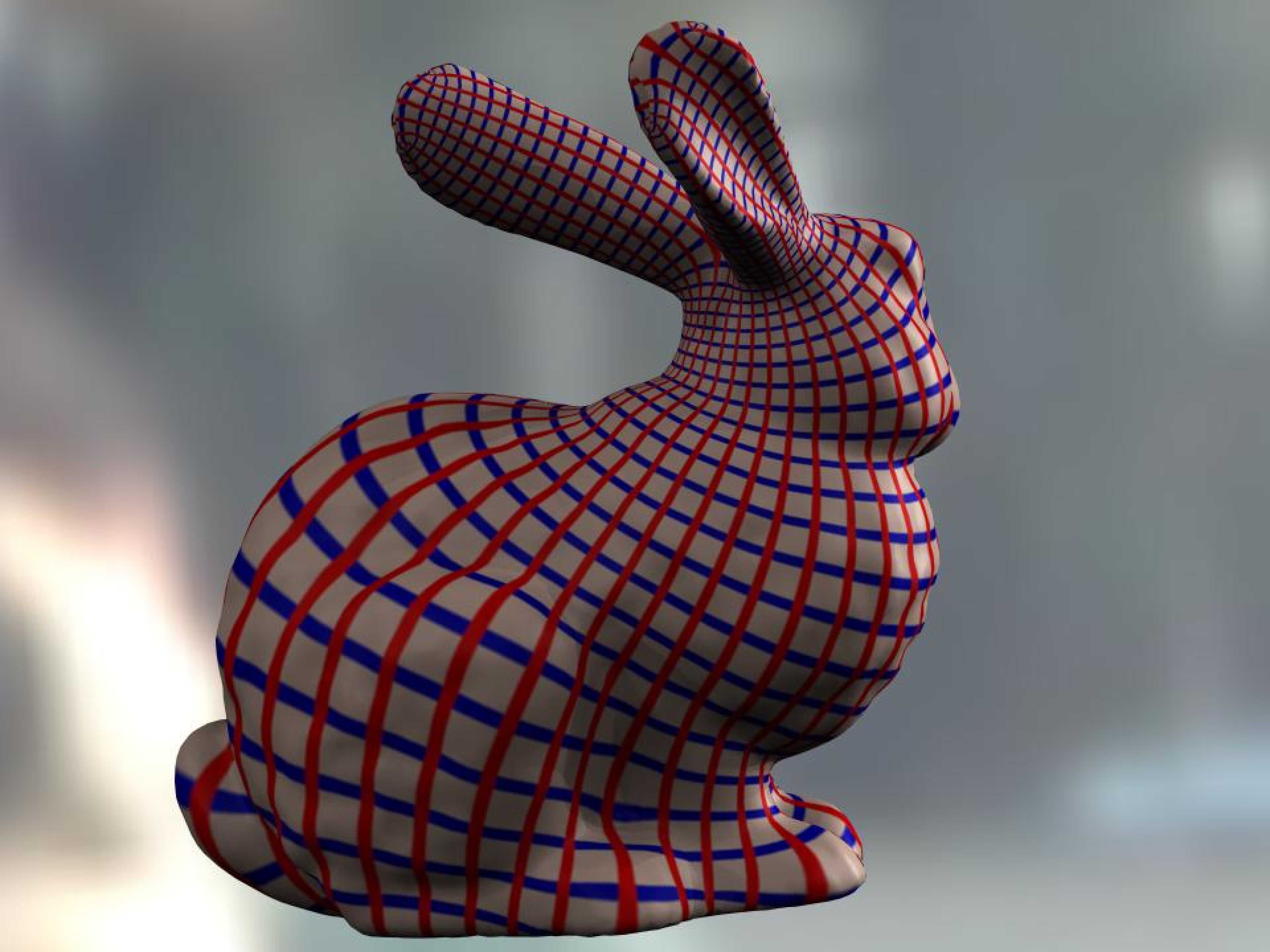
Computer Graphics - Rendering

Global Conformal Parameterization

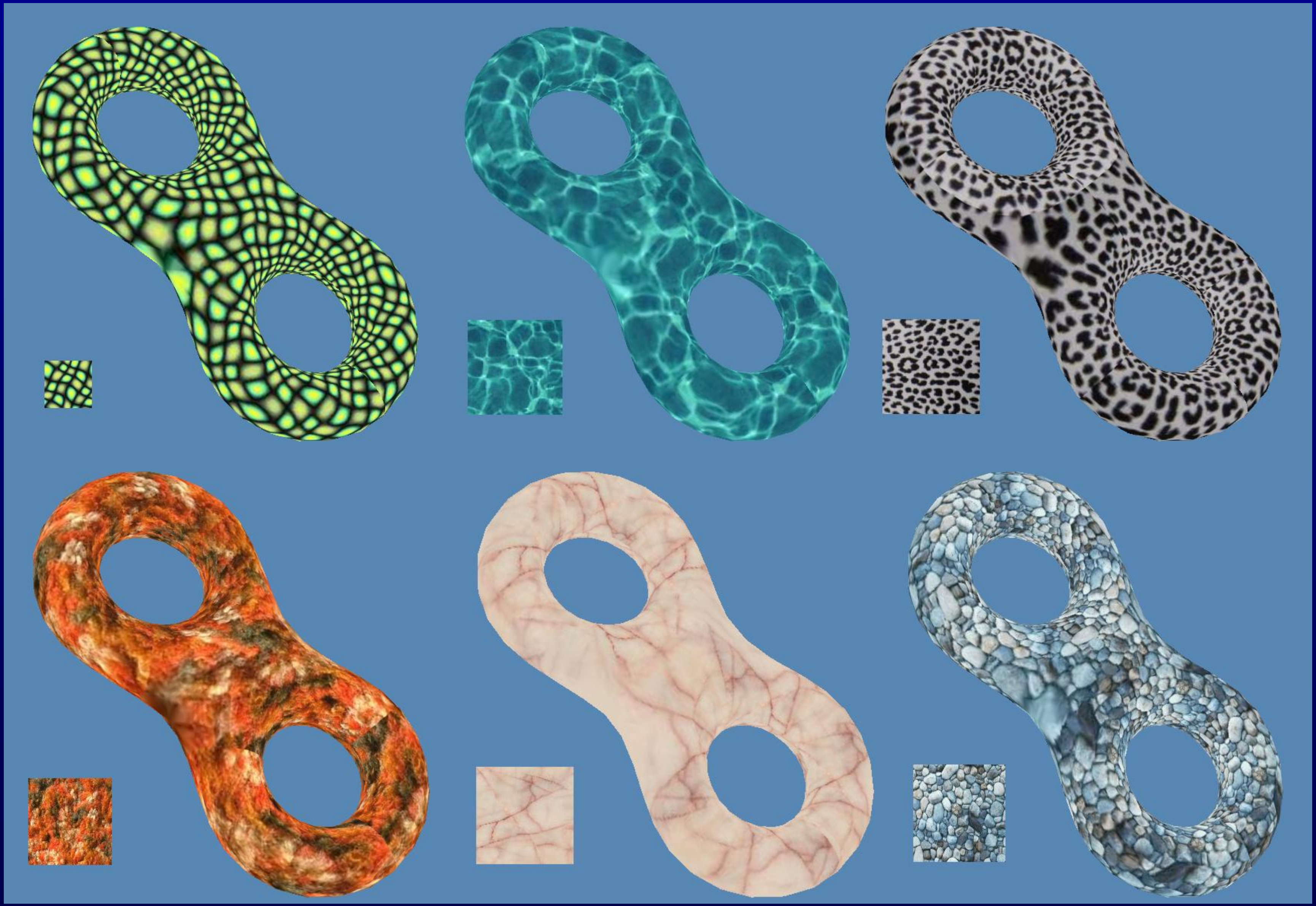
- Conformality is held everywhere.
- All oriented metric surfaces are Riemann surfaces.



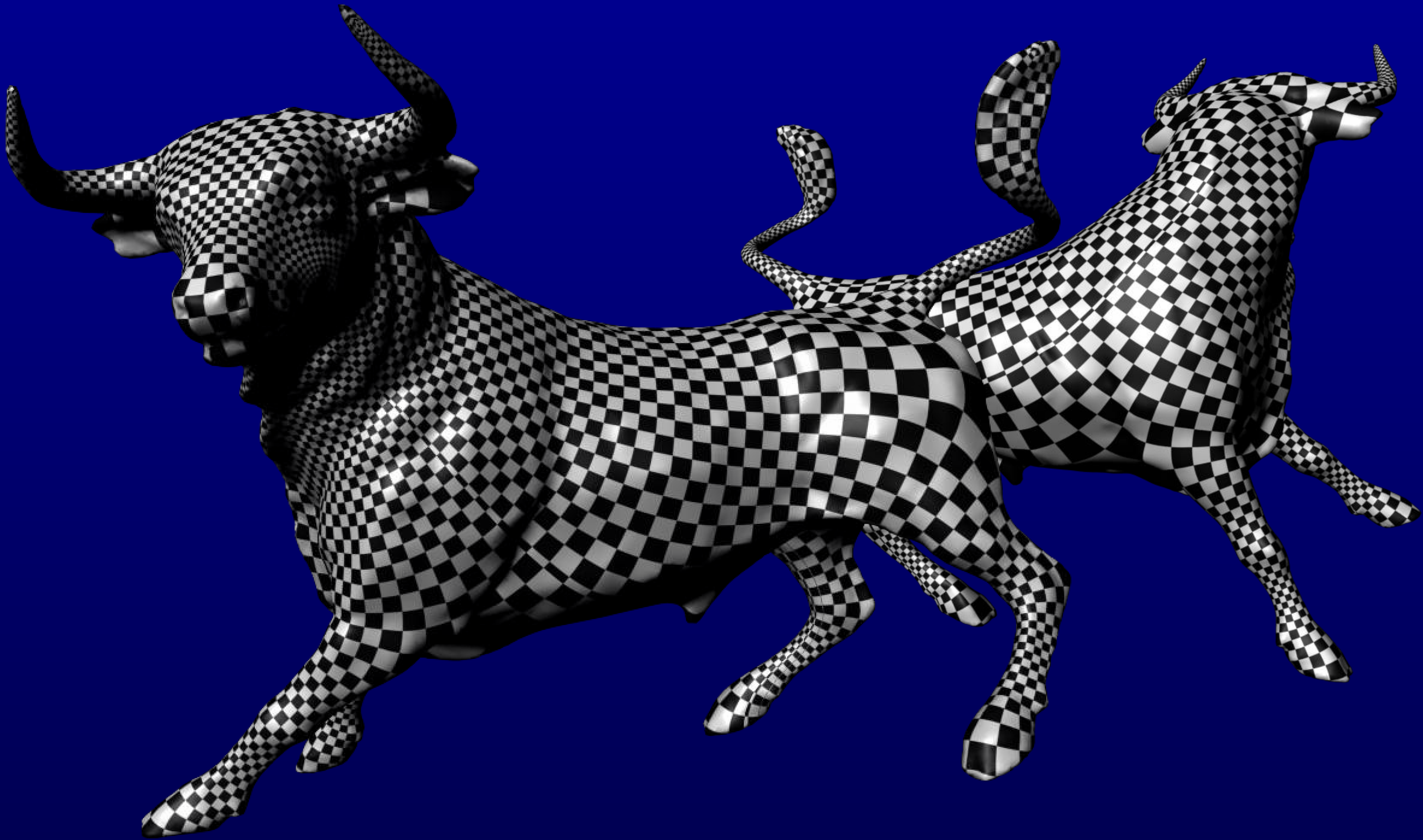




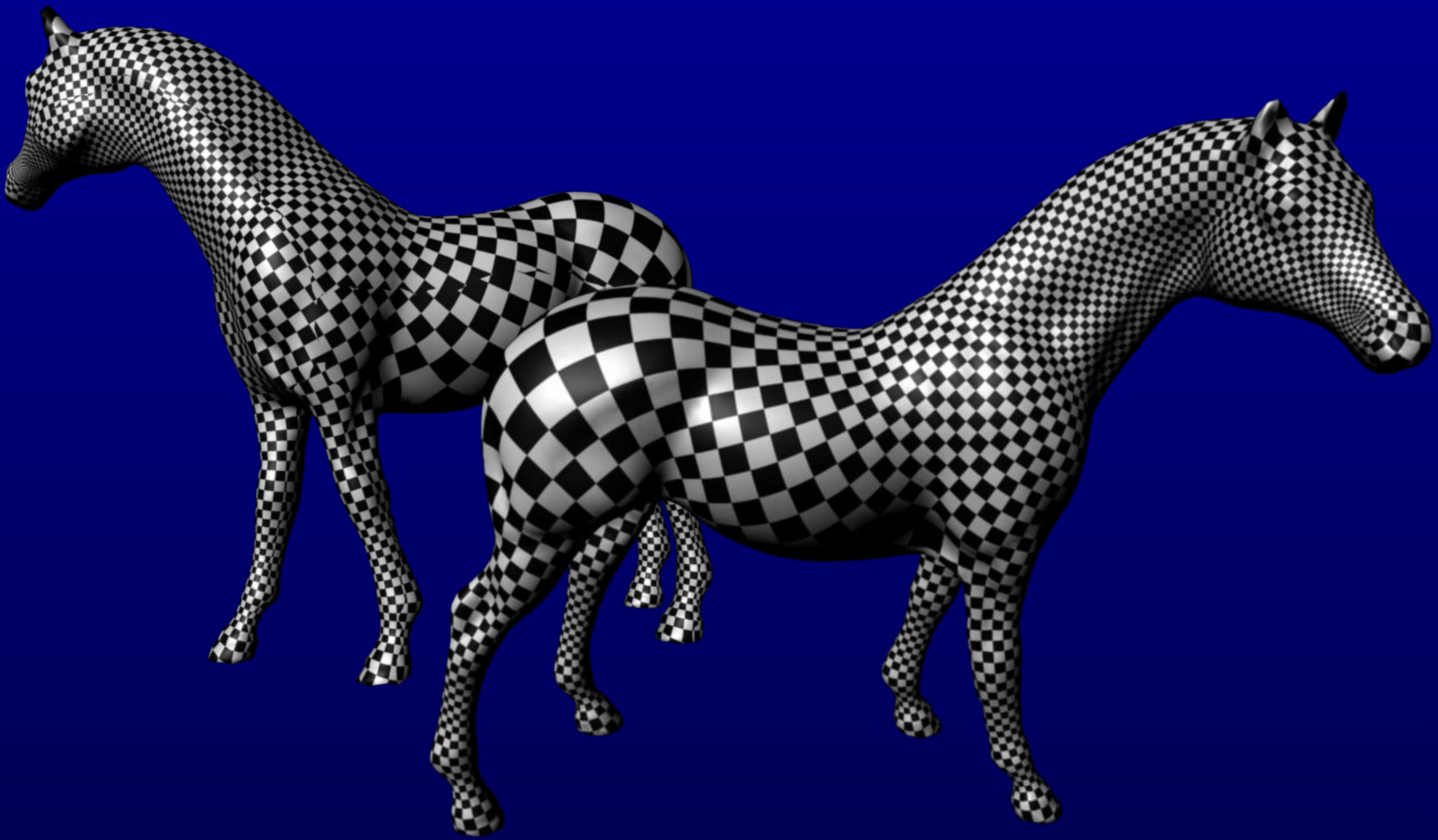
Texture Mapping – Nondistortion



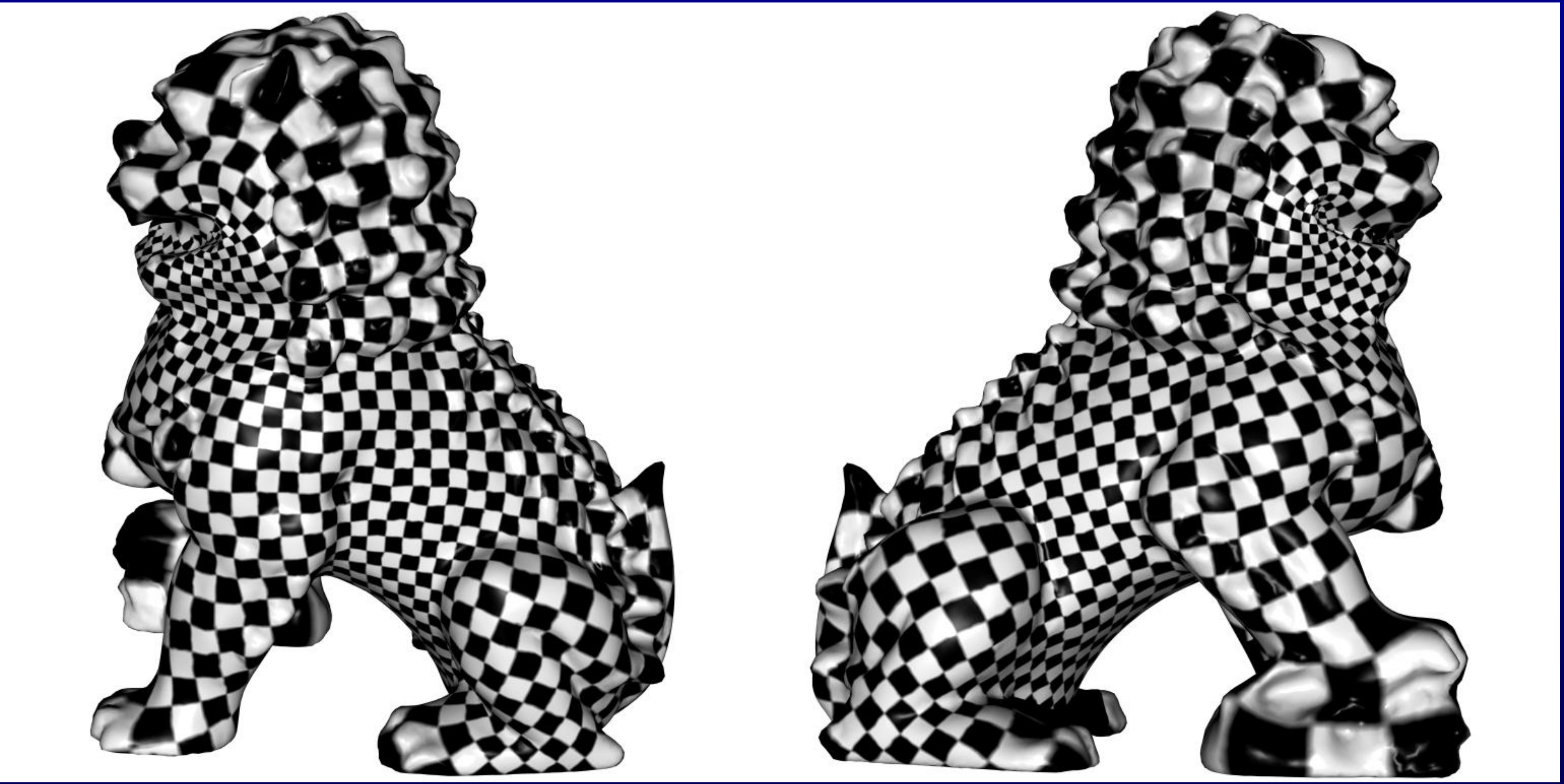
GeoUV



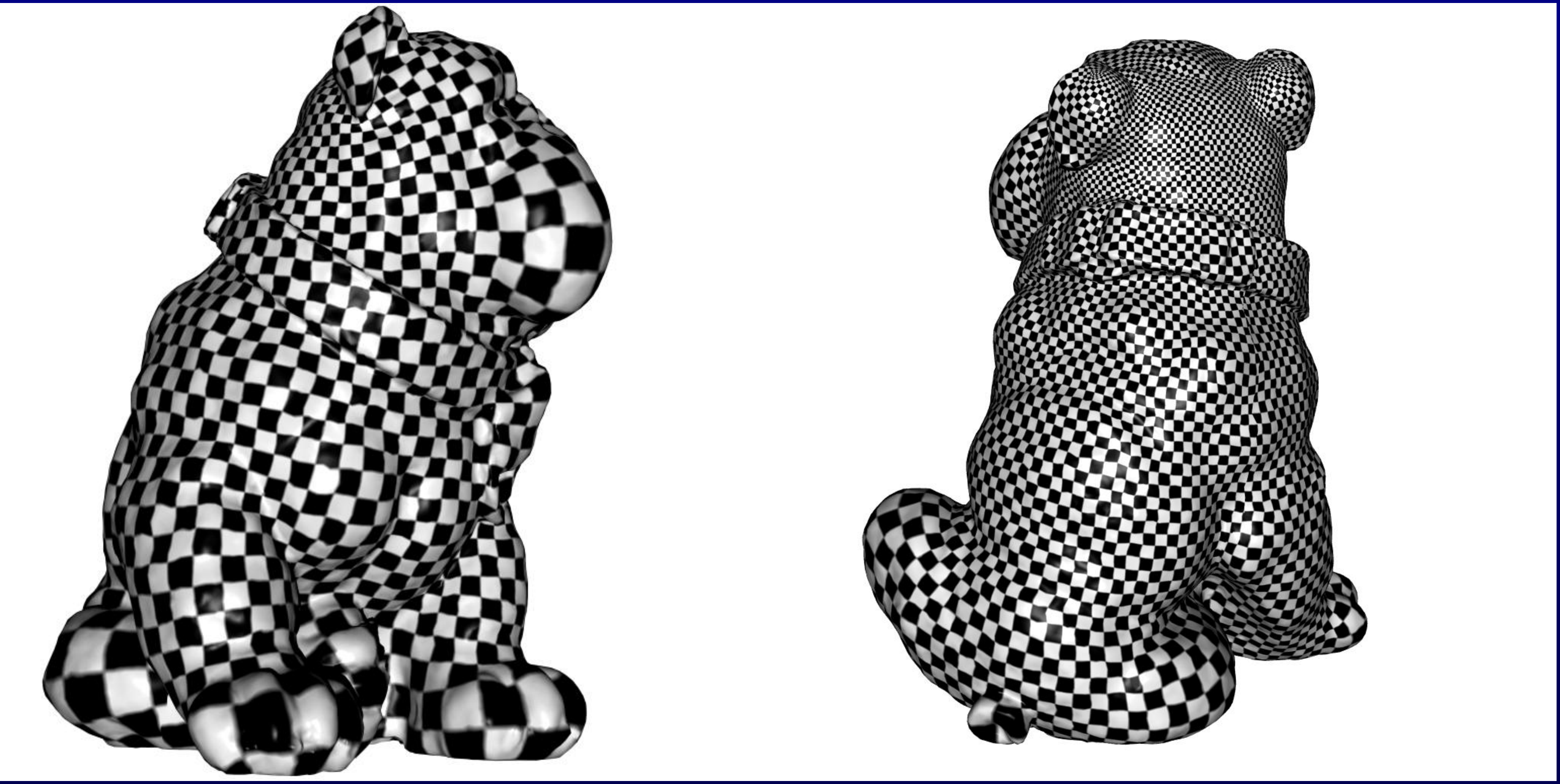
GeoUV



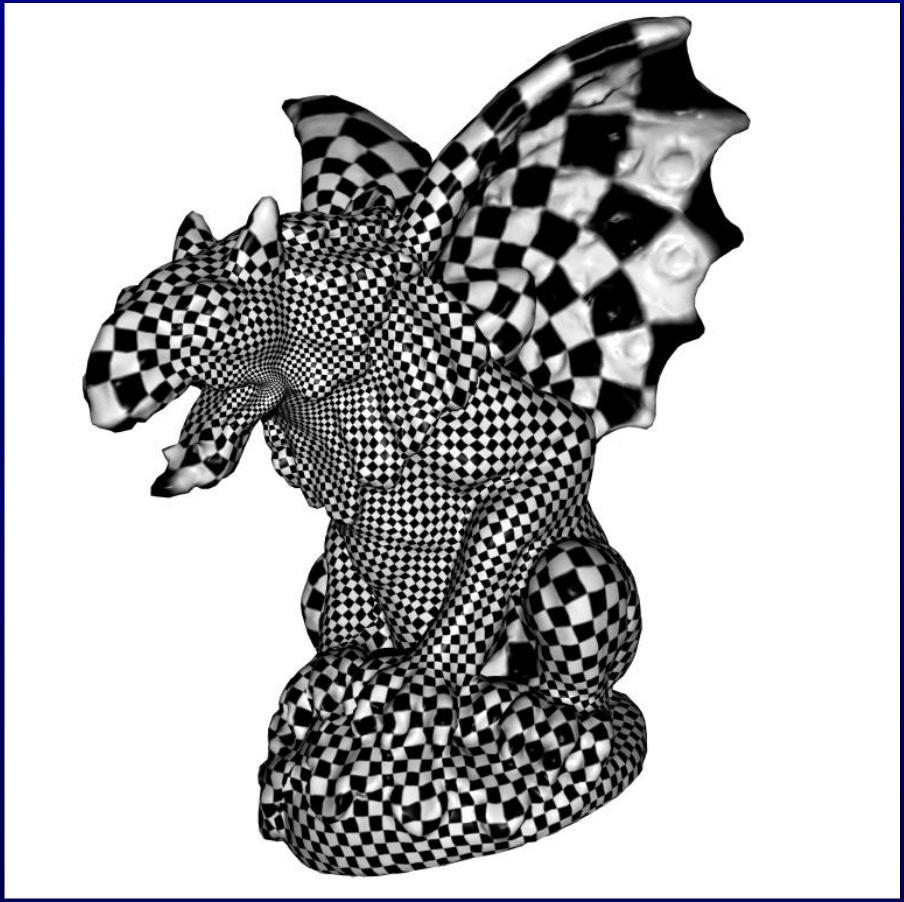
GeoUV

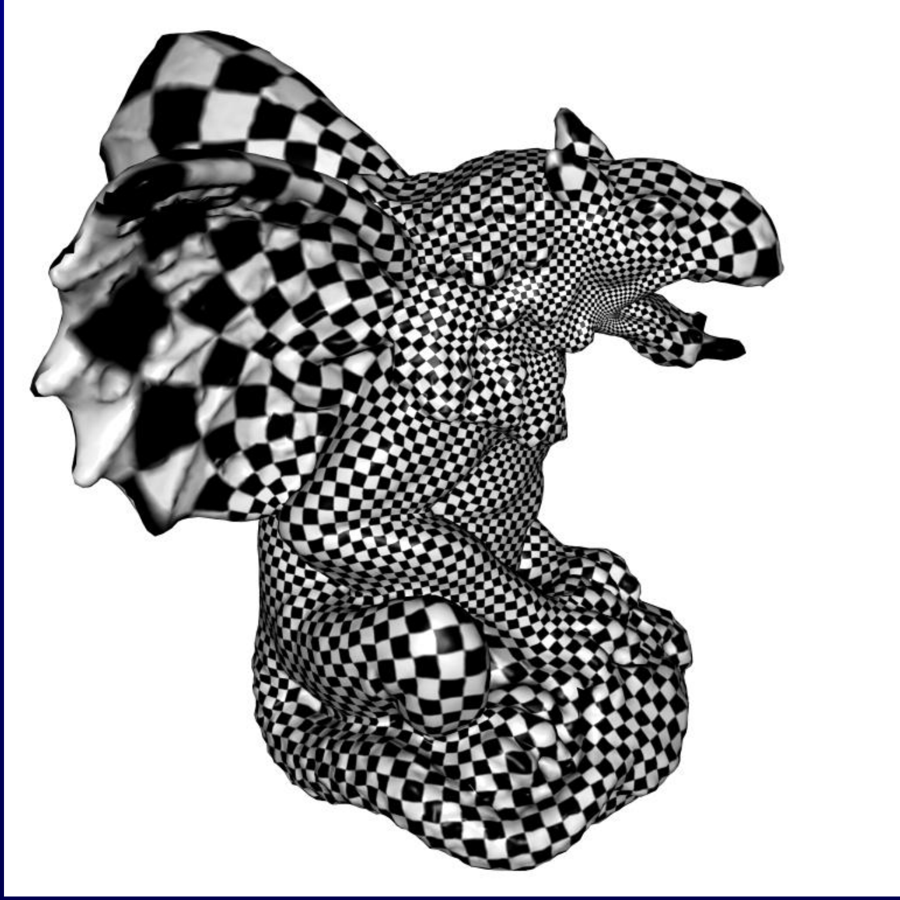


GeoUV

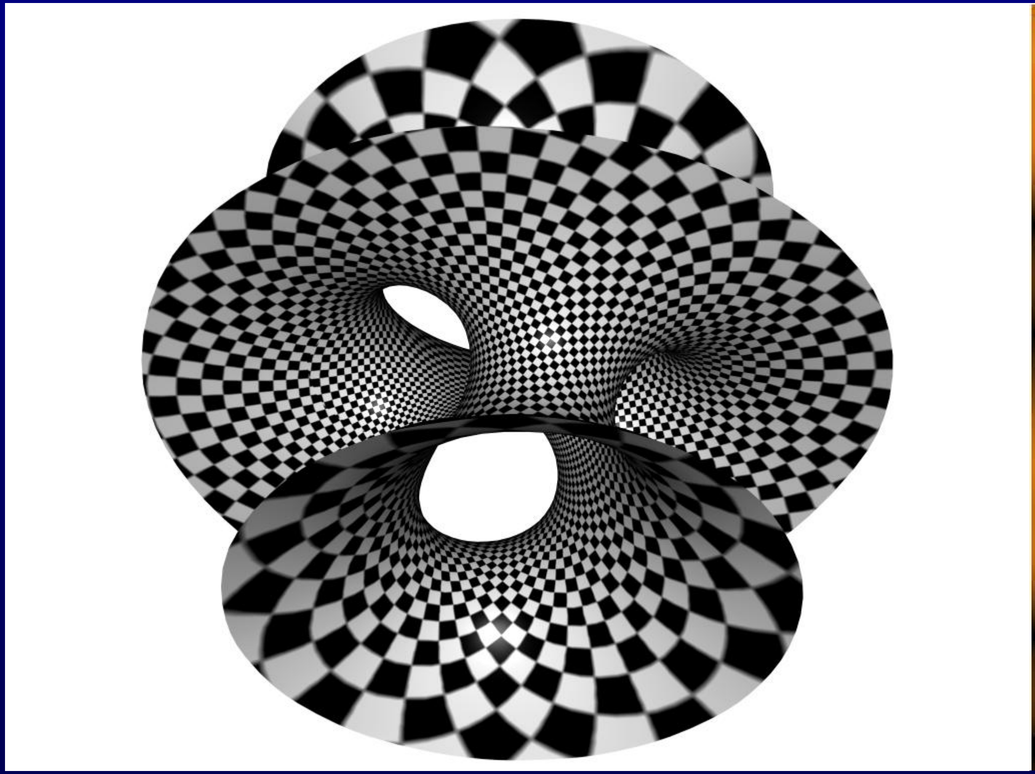


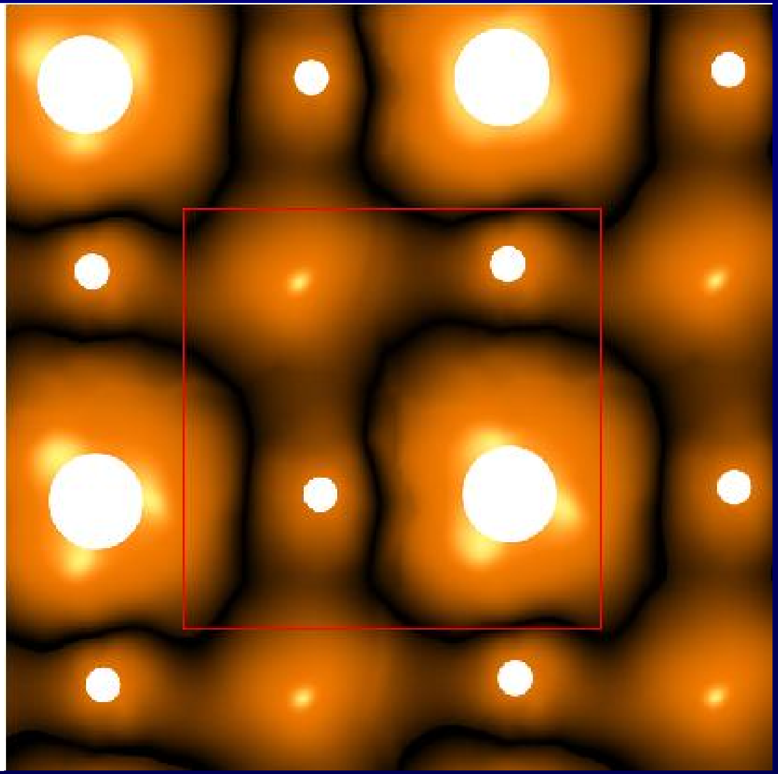
GeoUV



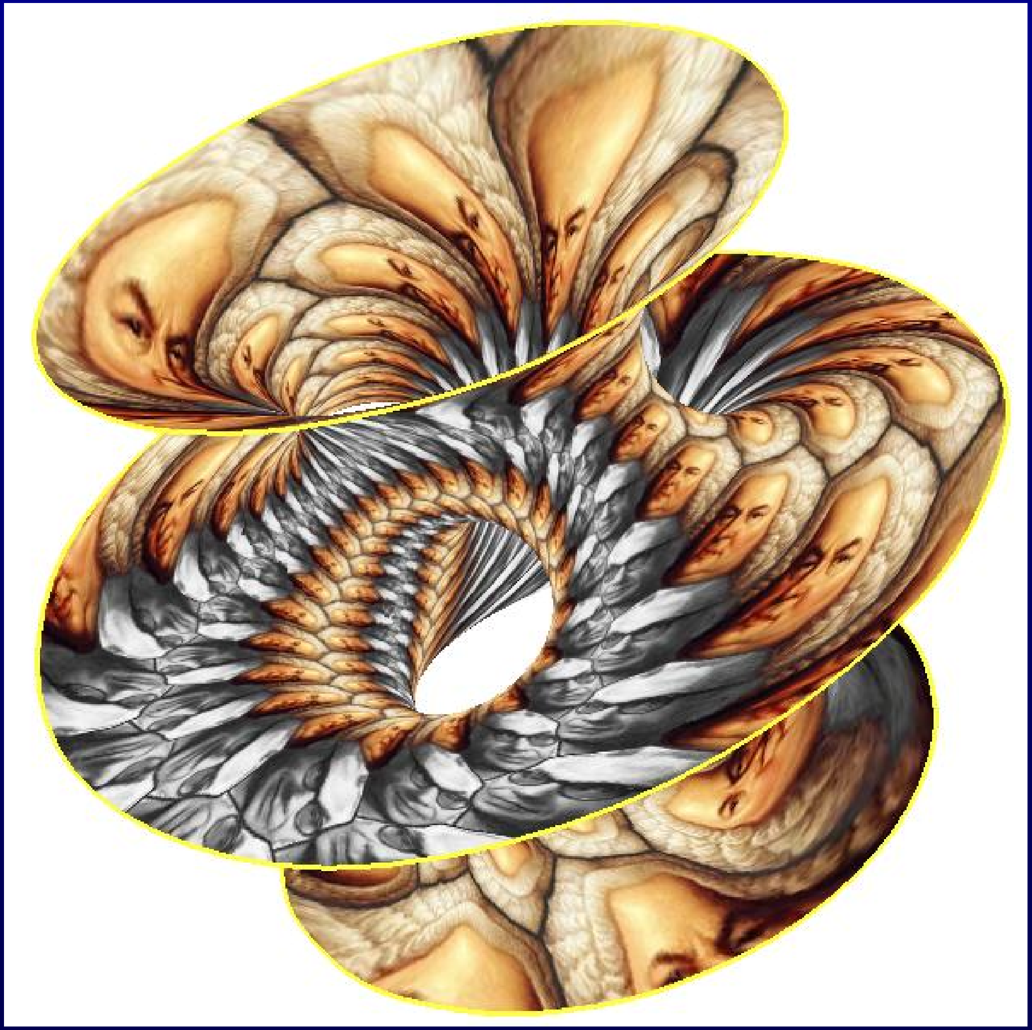


GeoUV





Manifold TSpline



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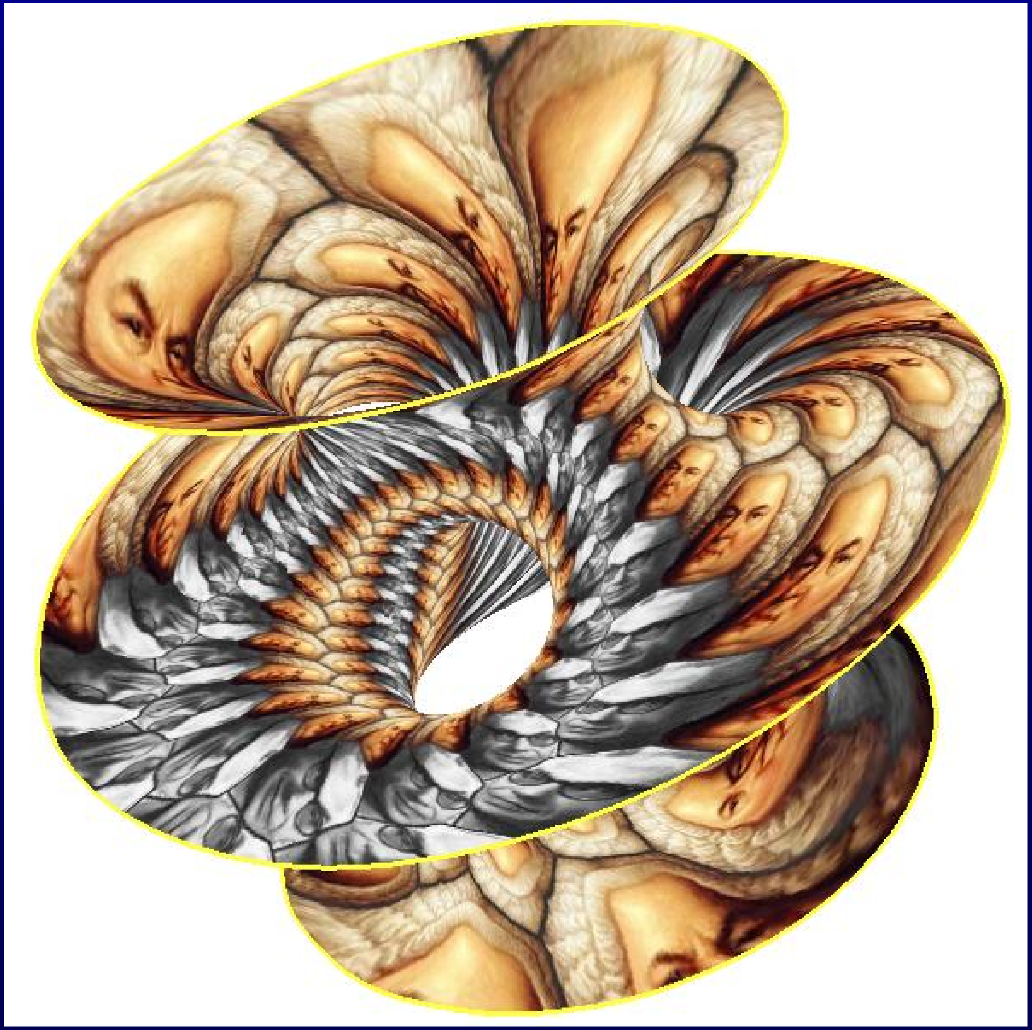

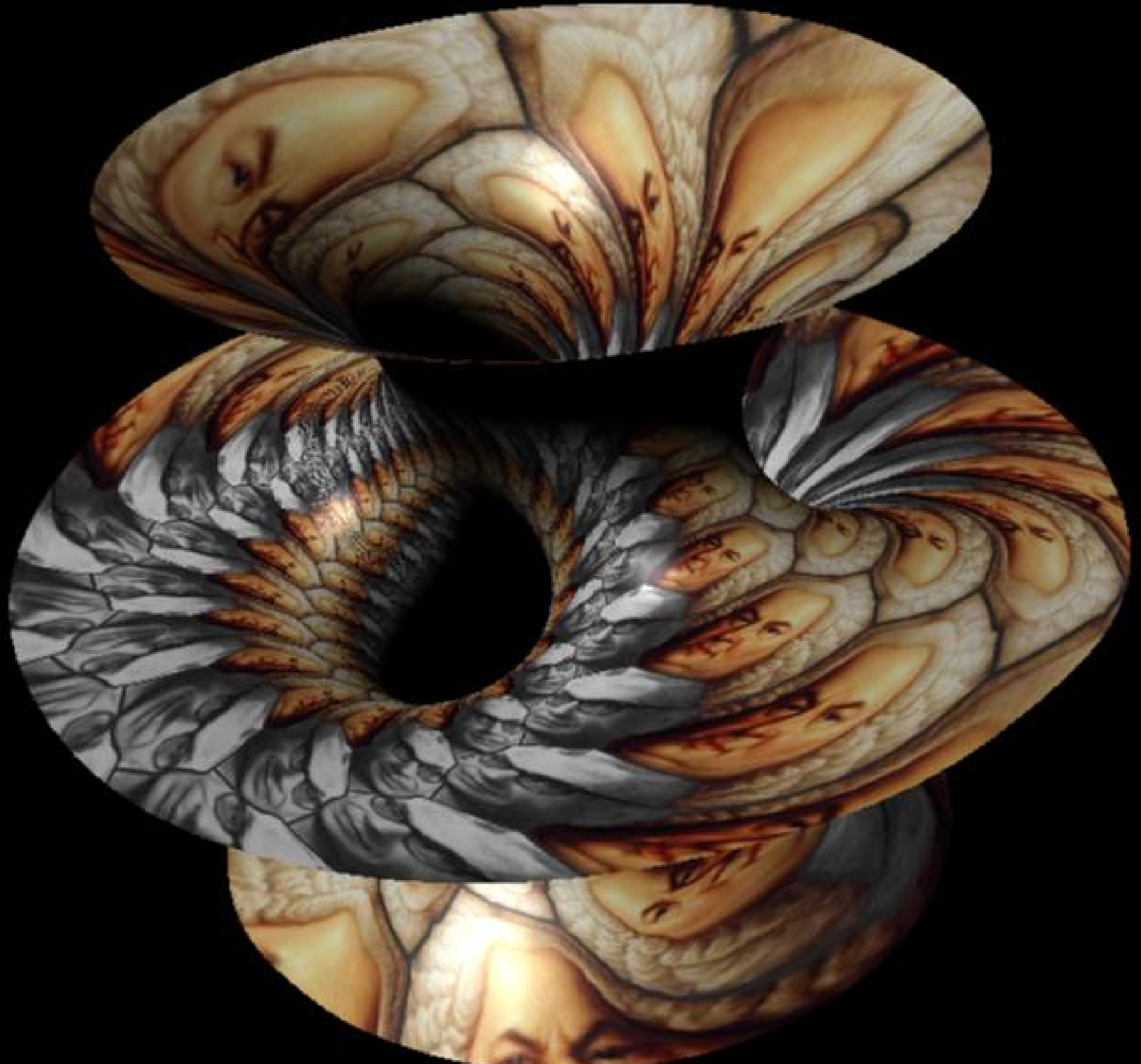

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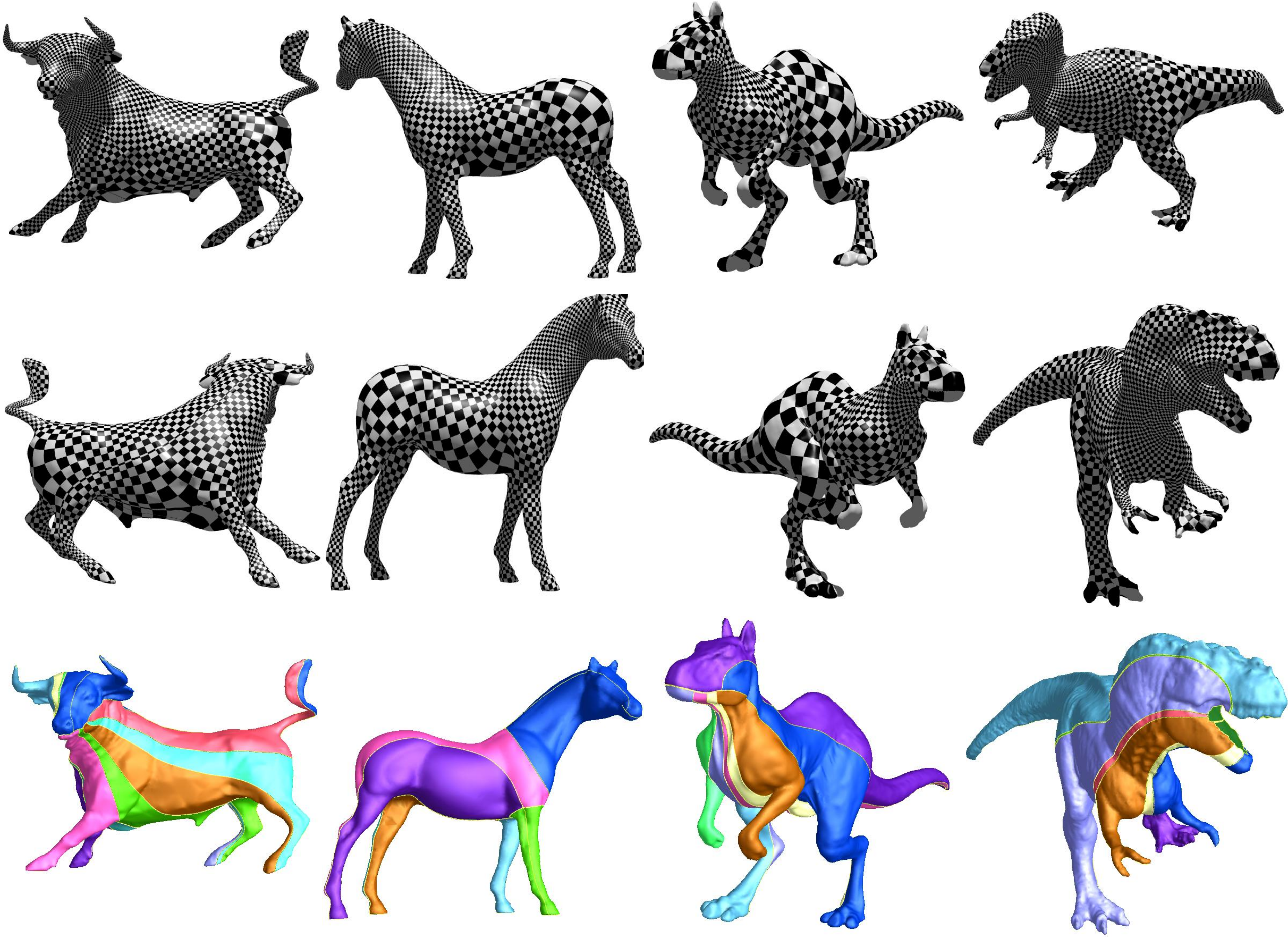
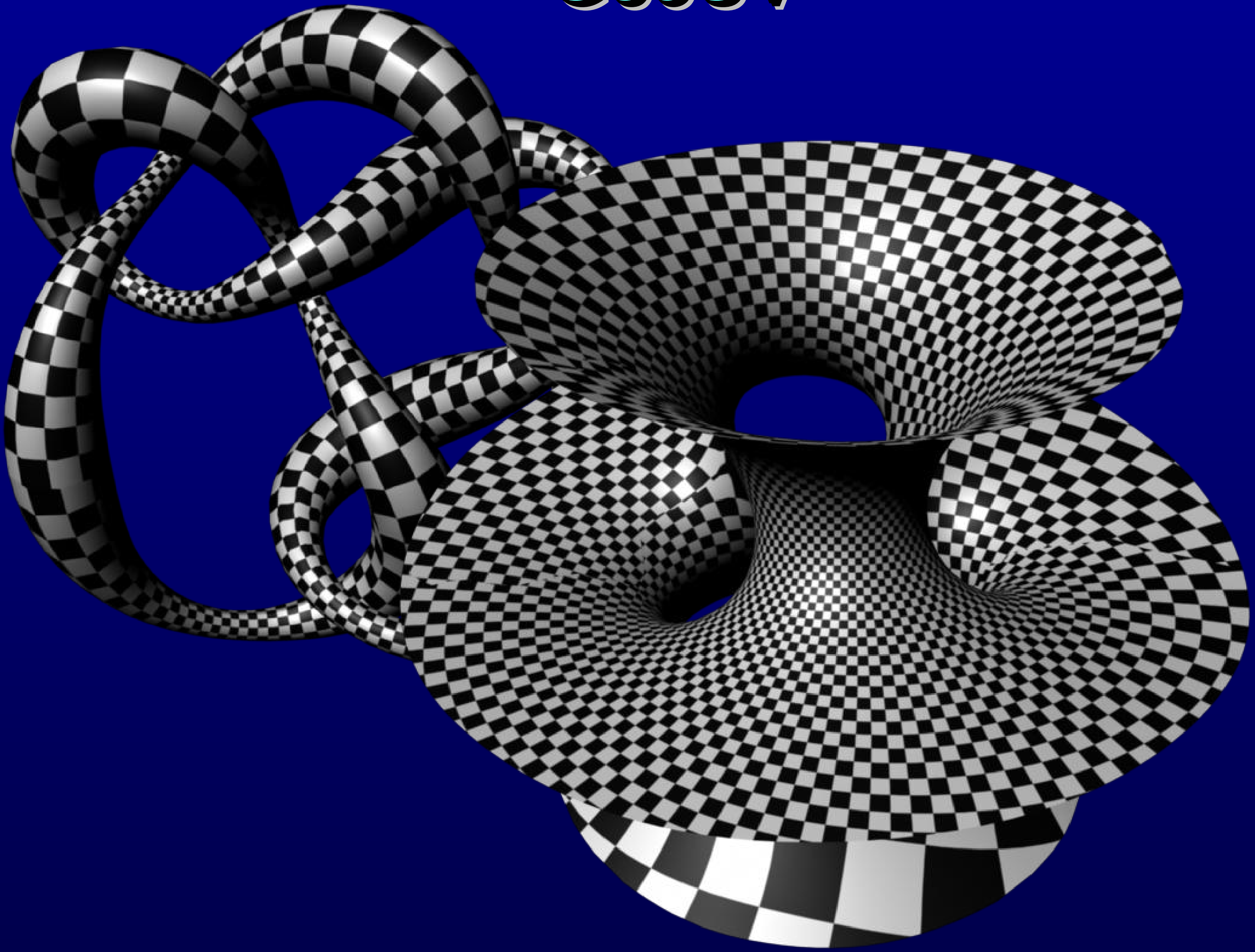


GeoUV



Holomorphic One Form Basis

- Dual to each handle

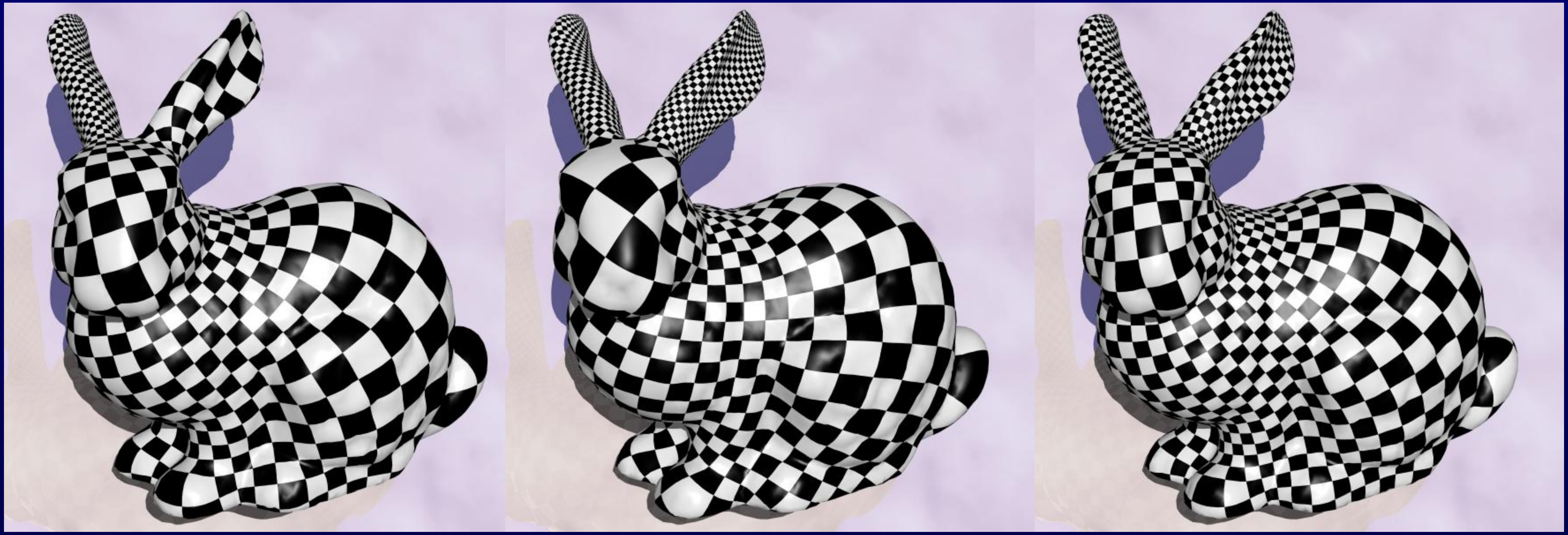
demo

Holomorphic one-form space

- 2g real dimension
- Dual to homology

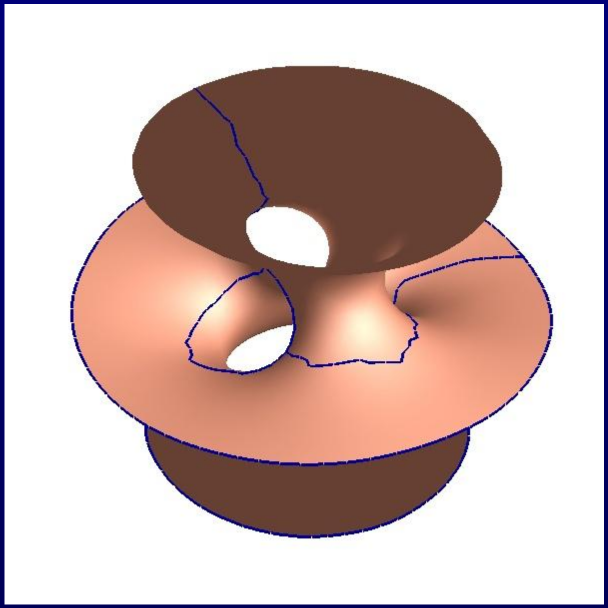
Linear combination

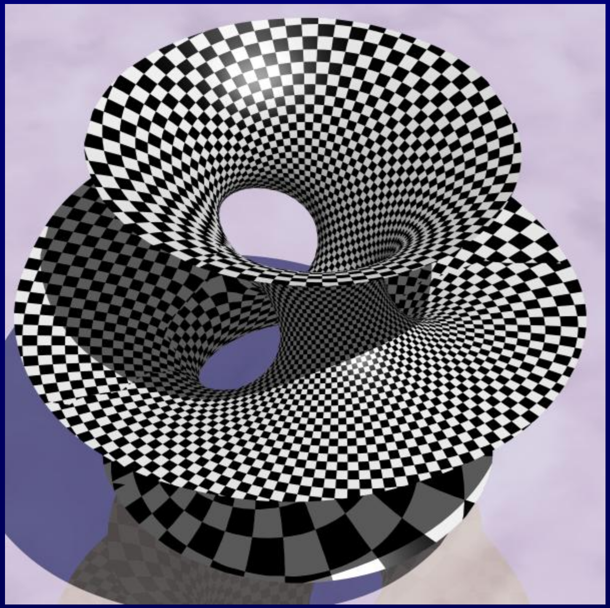
- Linearly combine holomorphic 1-form bases
- Different holomorphic one-form,different properties (conformal factor, zero points)



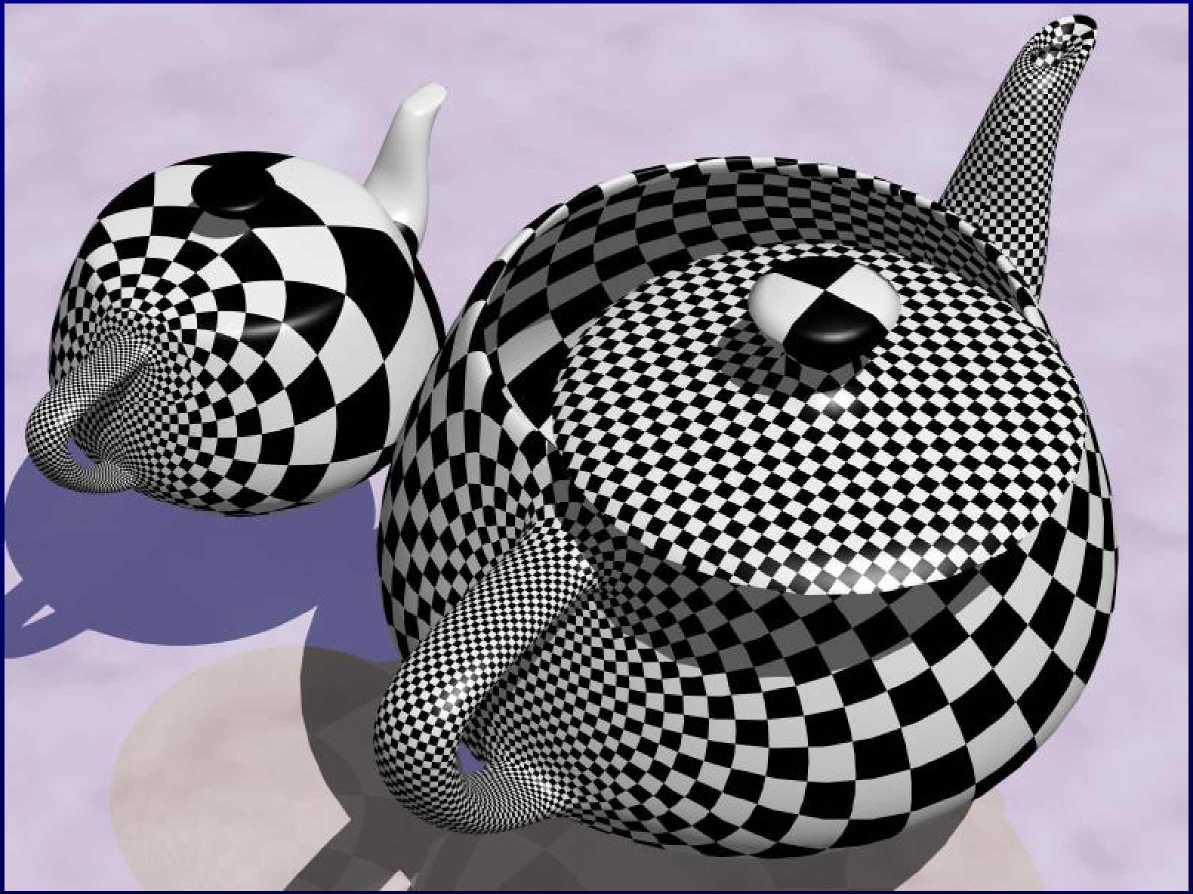
Example:Minimal Surface

- Genus one, 3 boundaries
- Genus four



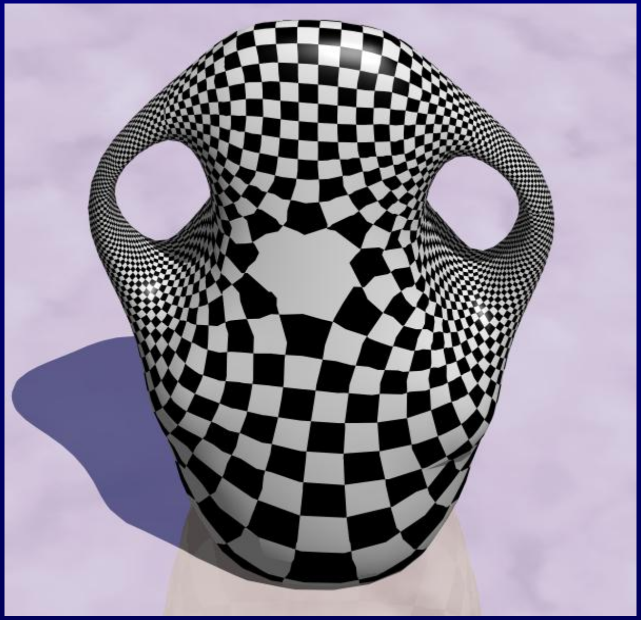


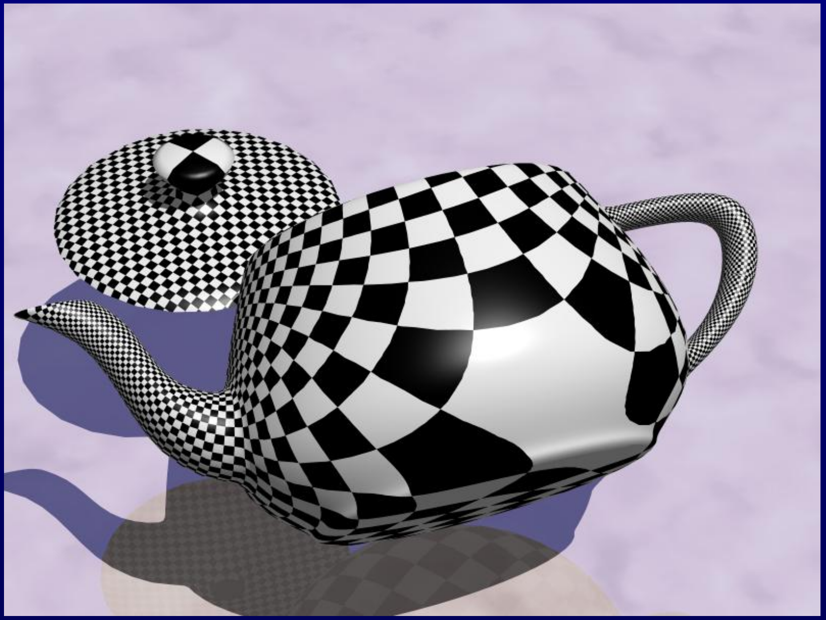
Teapot Model



Zero points

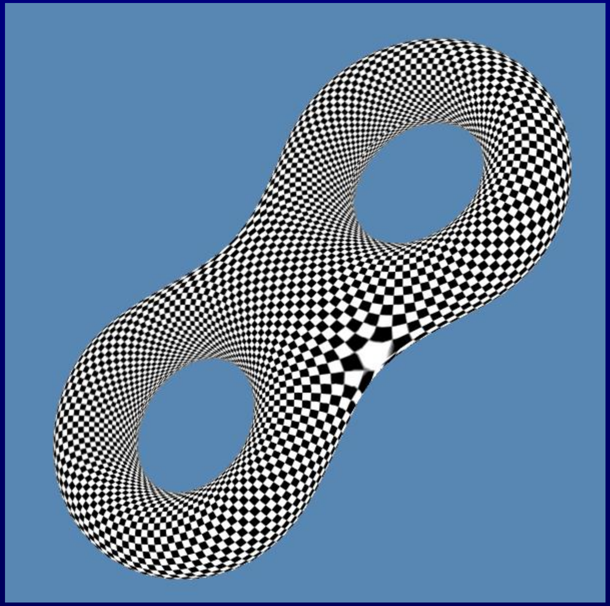
- Zero points of the tangential vector fields

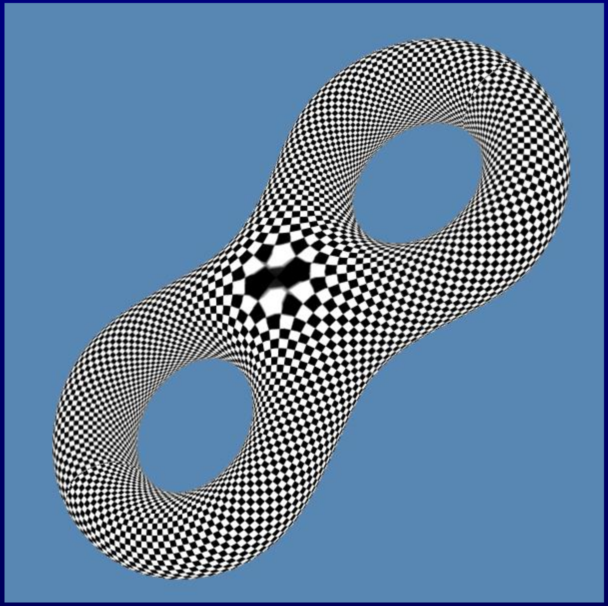




Zero points

- Different holomorphic one-form, different zero points



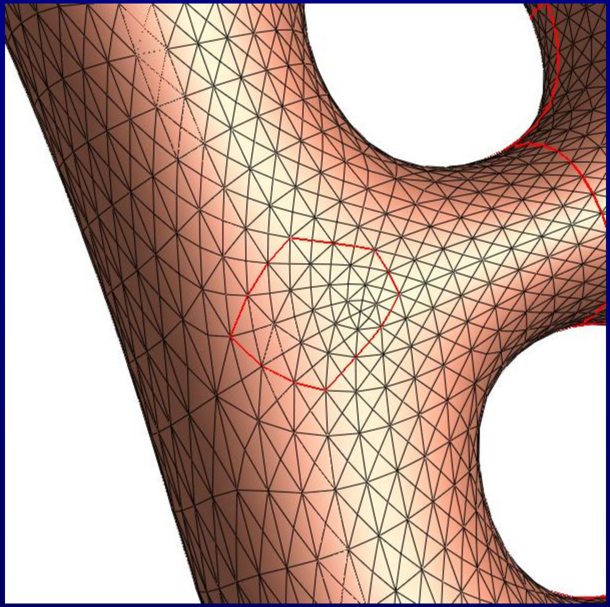


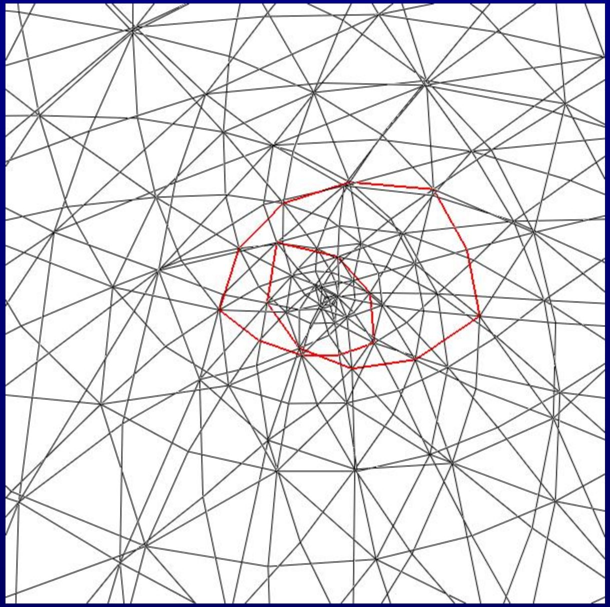
demo

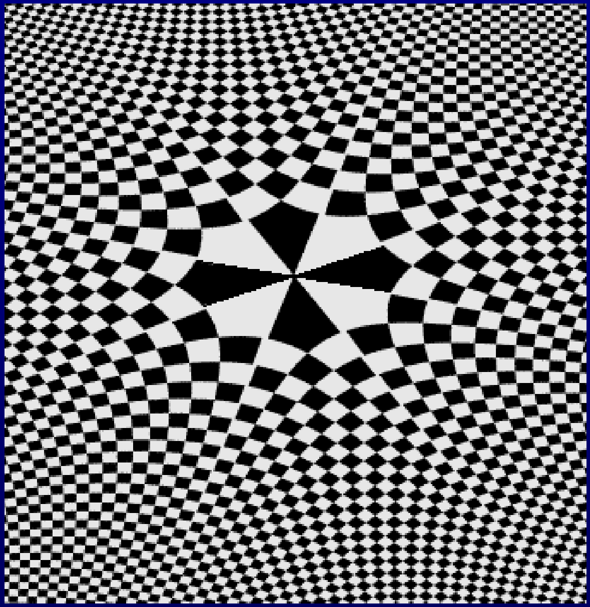
demo

Zero Points

Locally it behaves like $\omega = z^2$

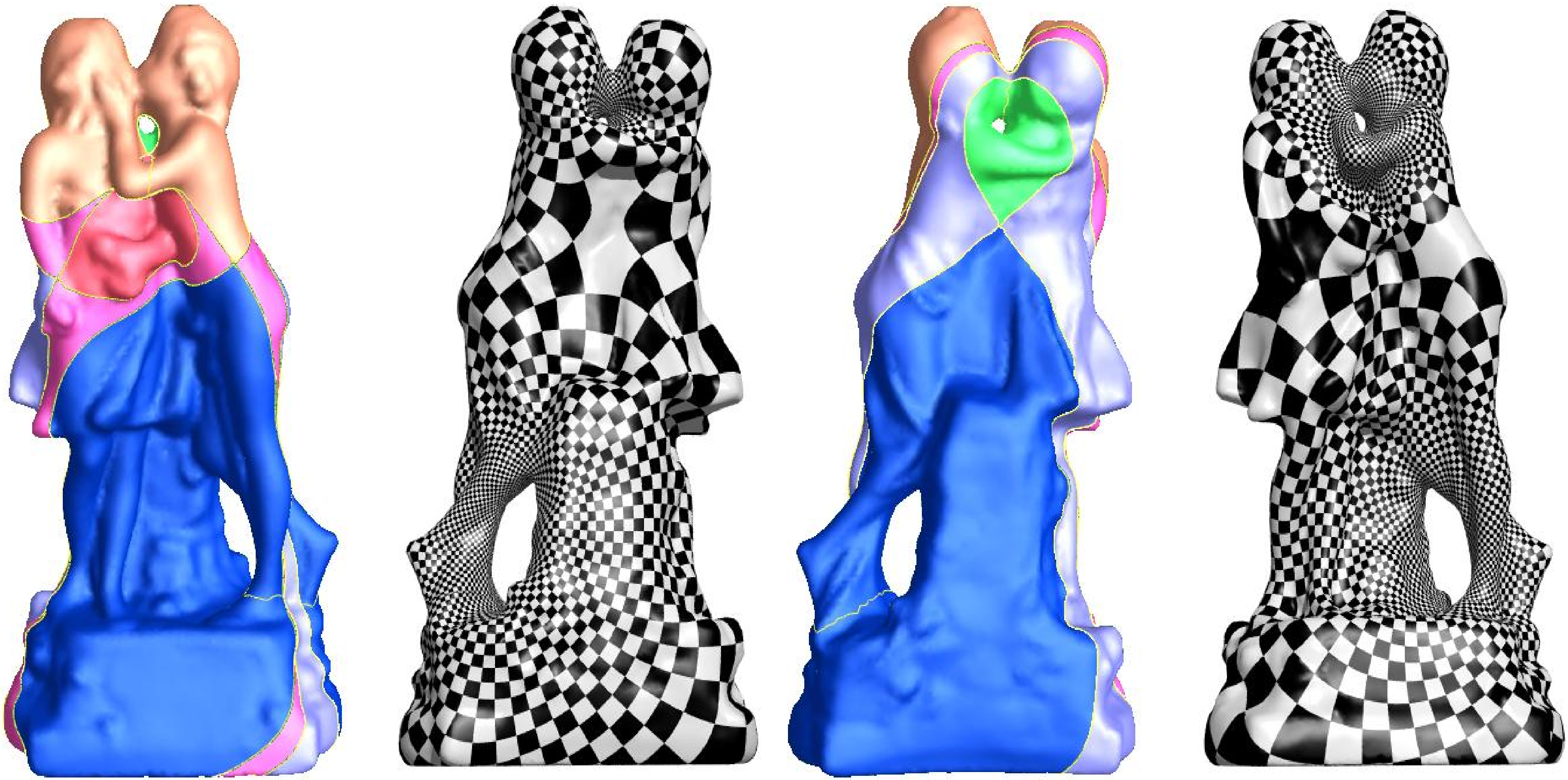






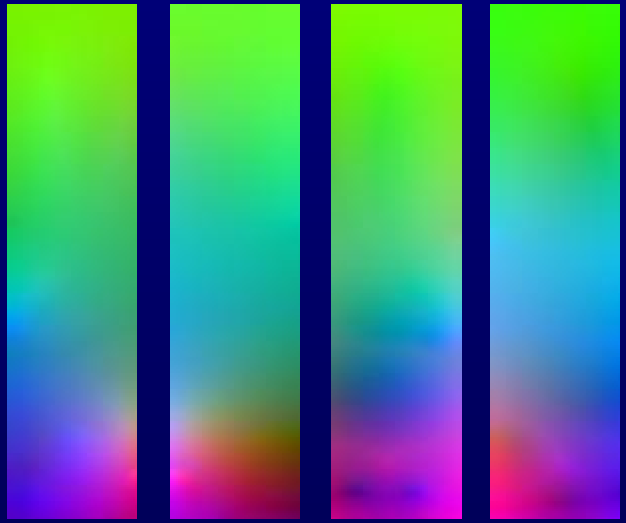
demo demo demo

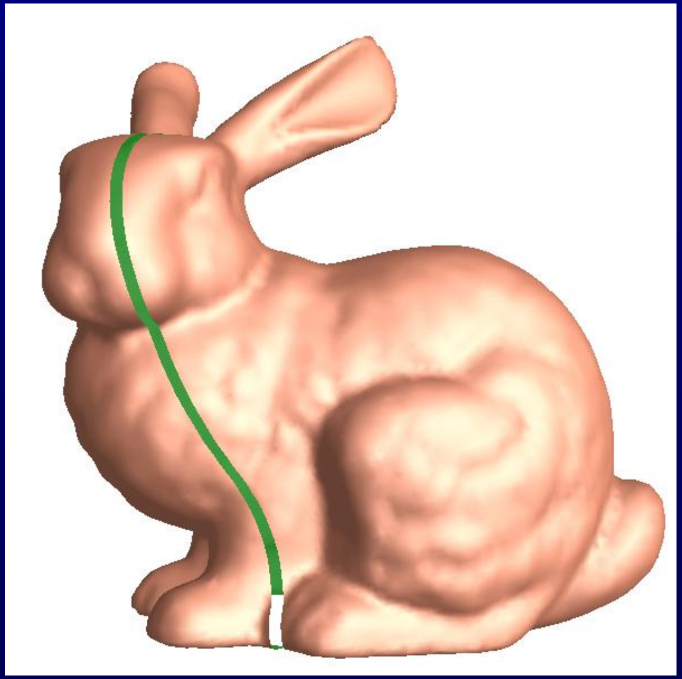
Riemann Surface Structure



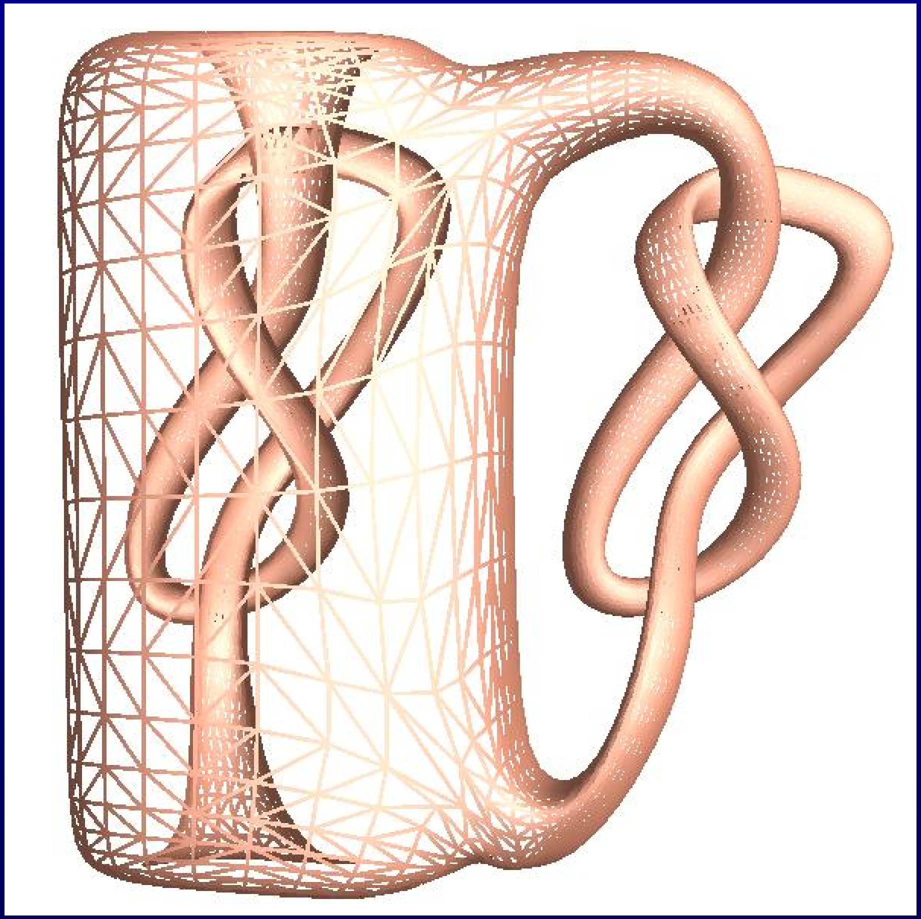
Media for geometry

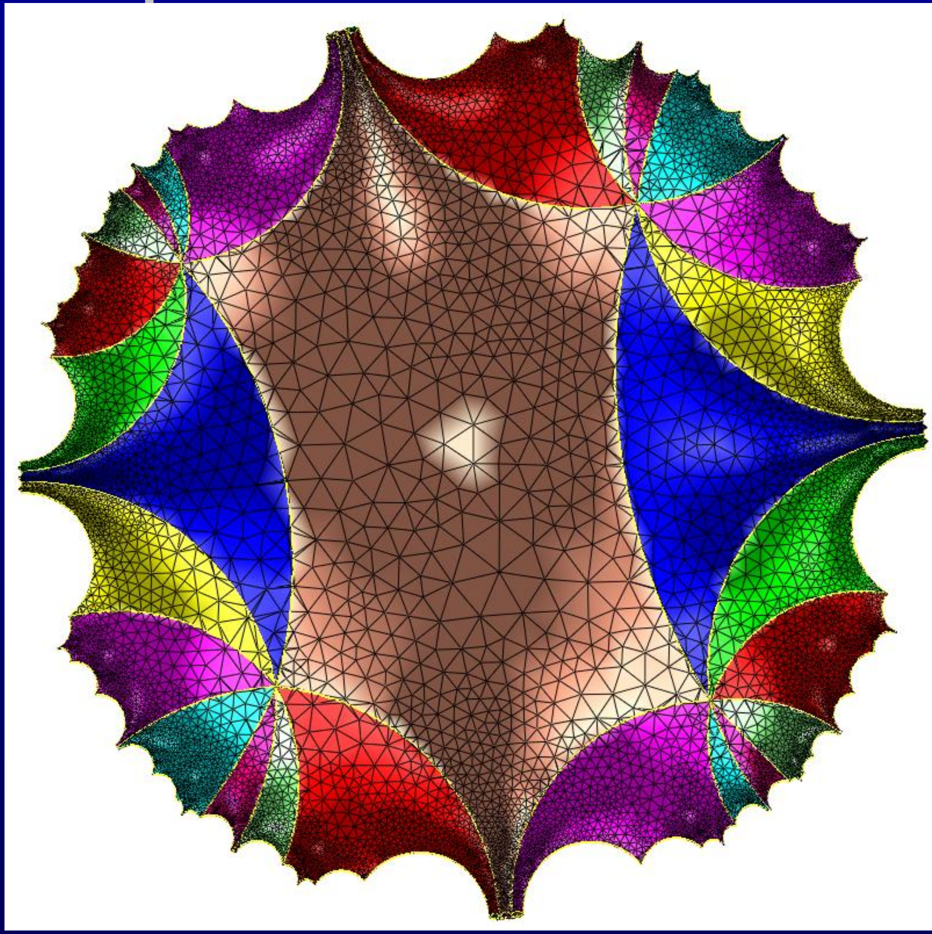
- Use regular grids to sample each chart
- Optimal Decomposition to triangle strips (J. Mitchell)



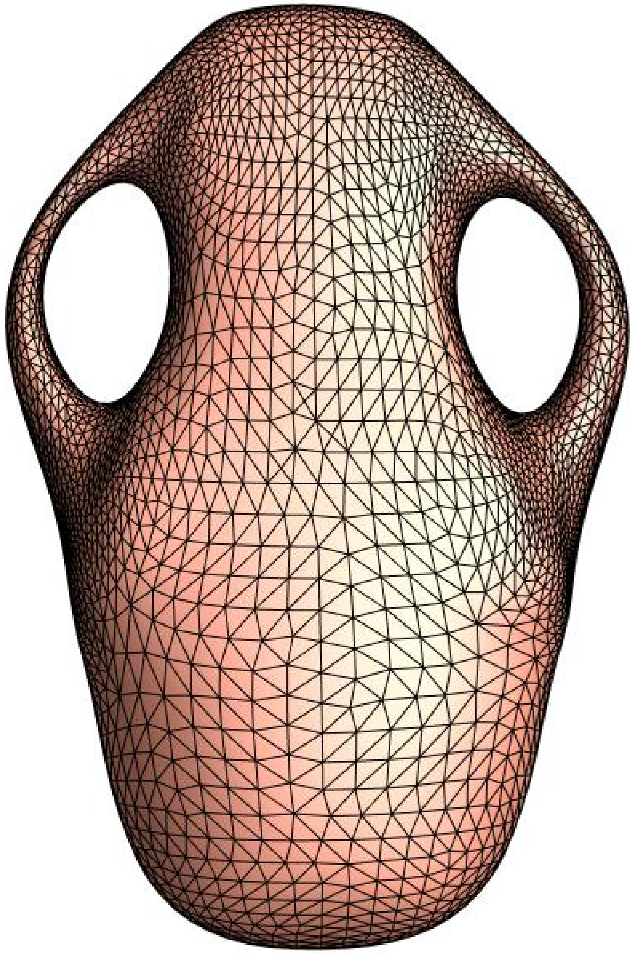


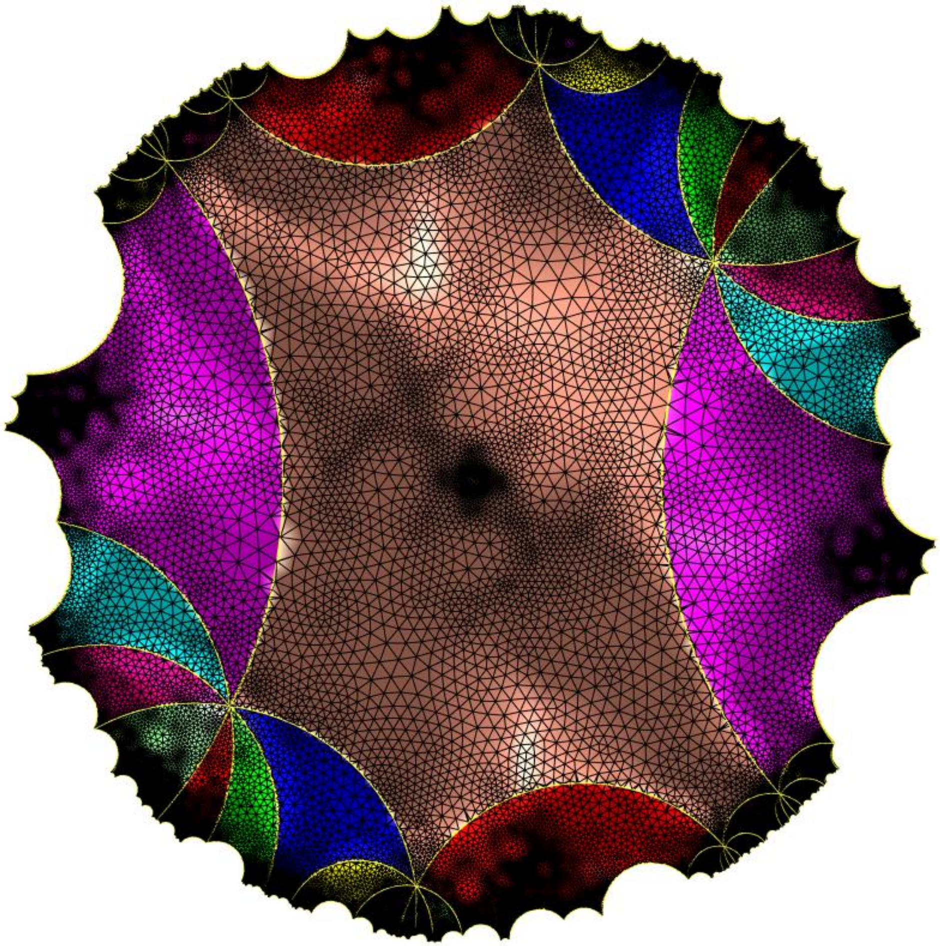
Manifold TSpline



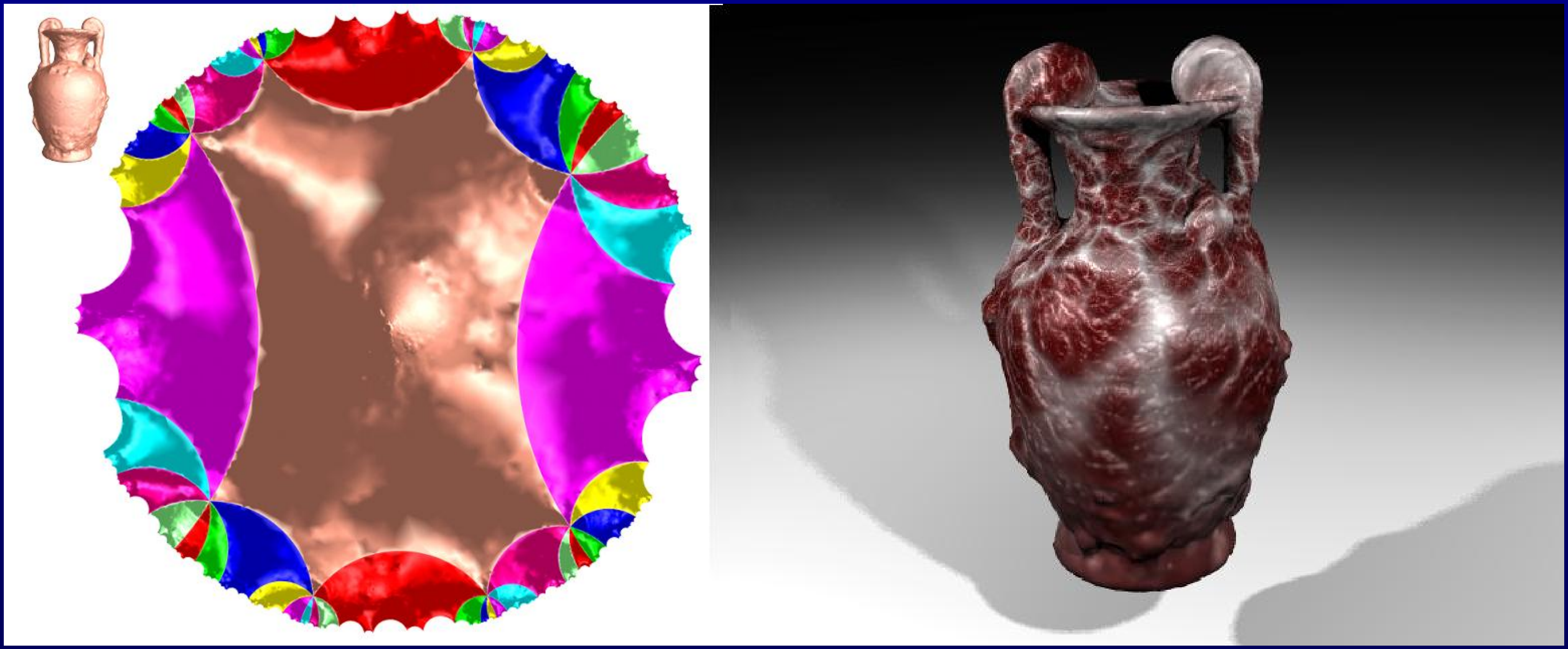


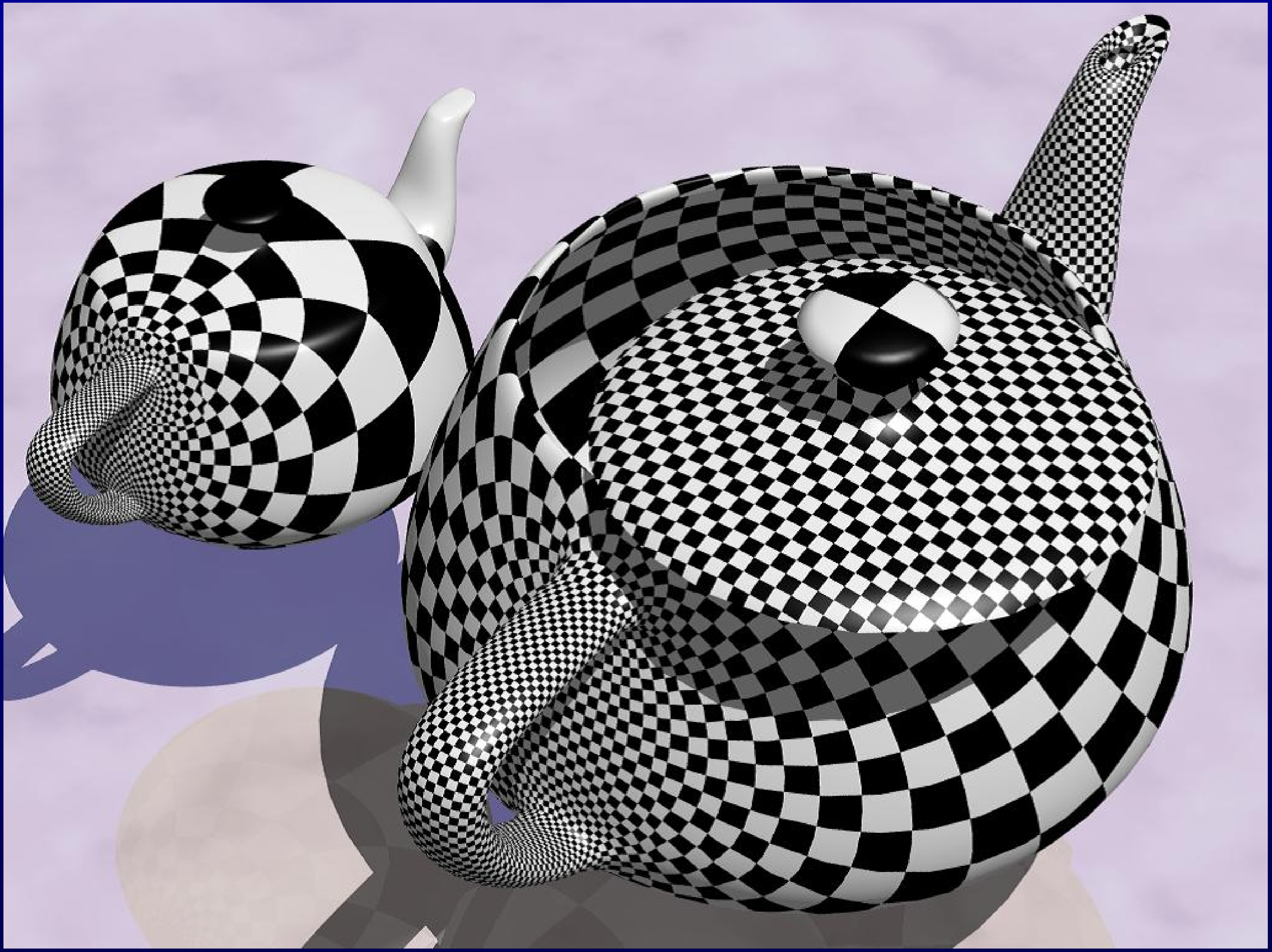
Manifold TSpline





Manifold TSpline

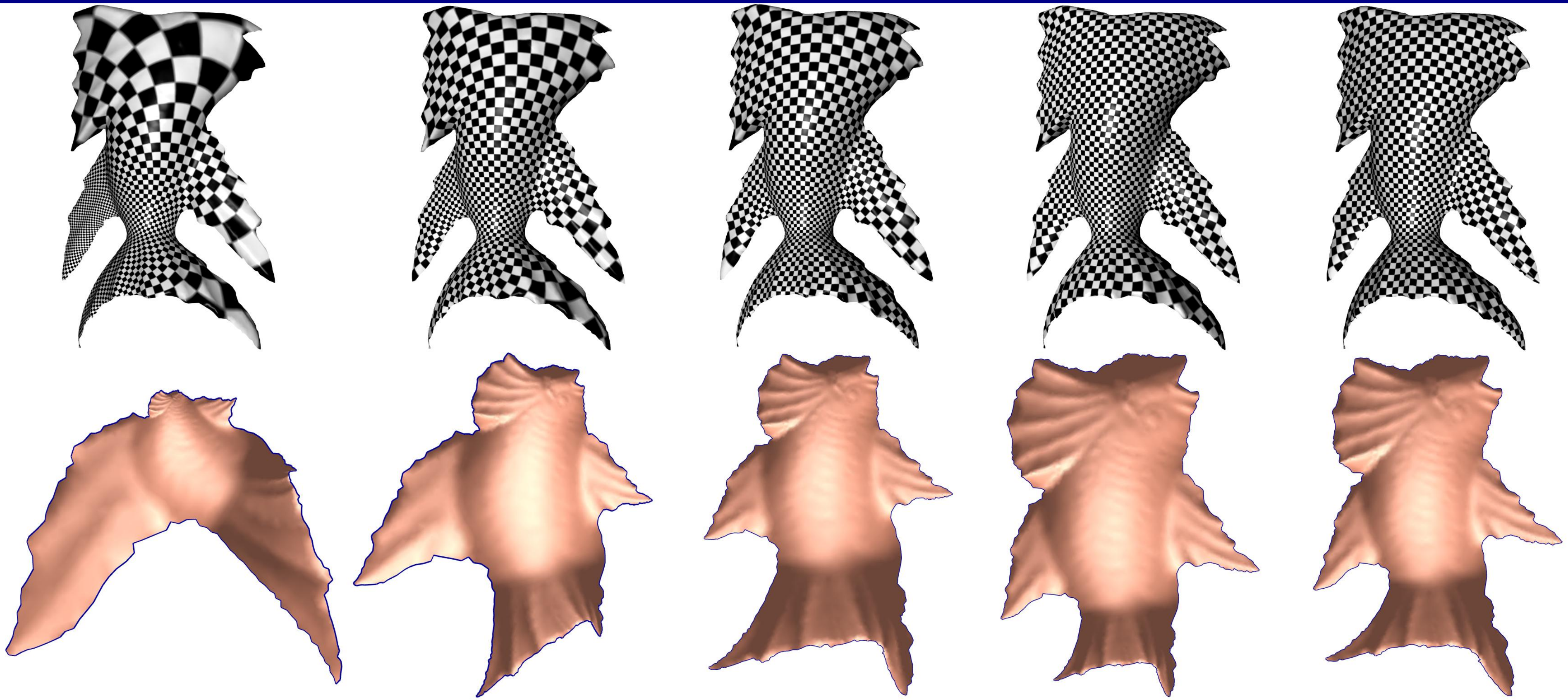




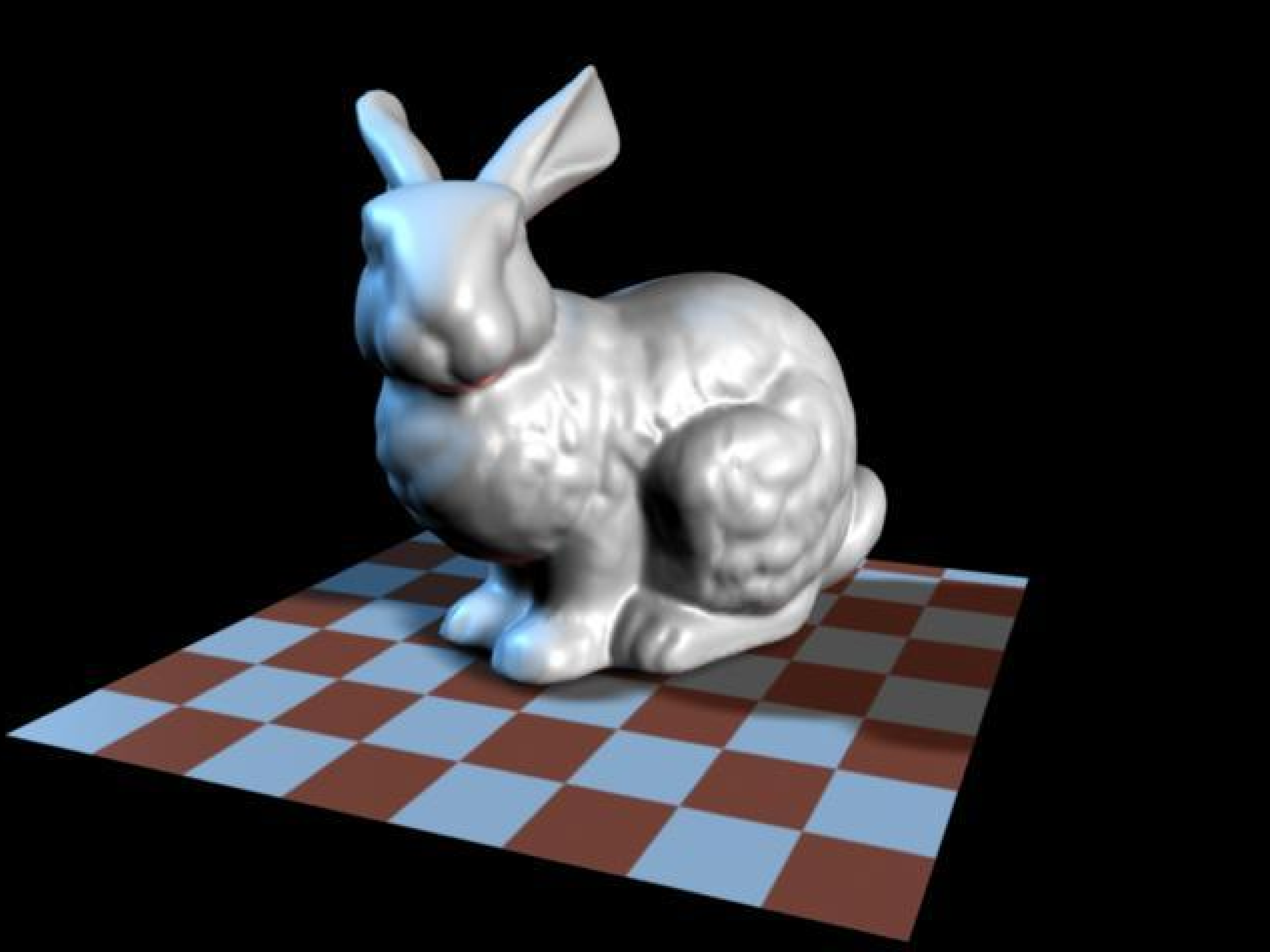
Manifold TSpline

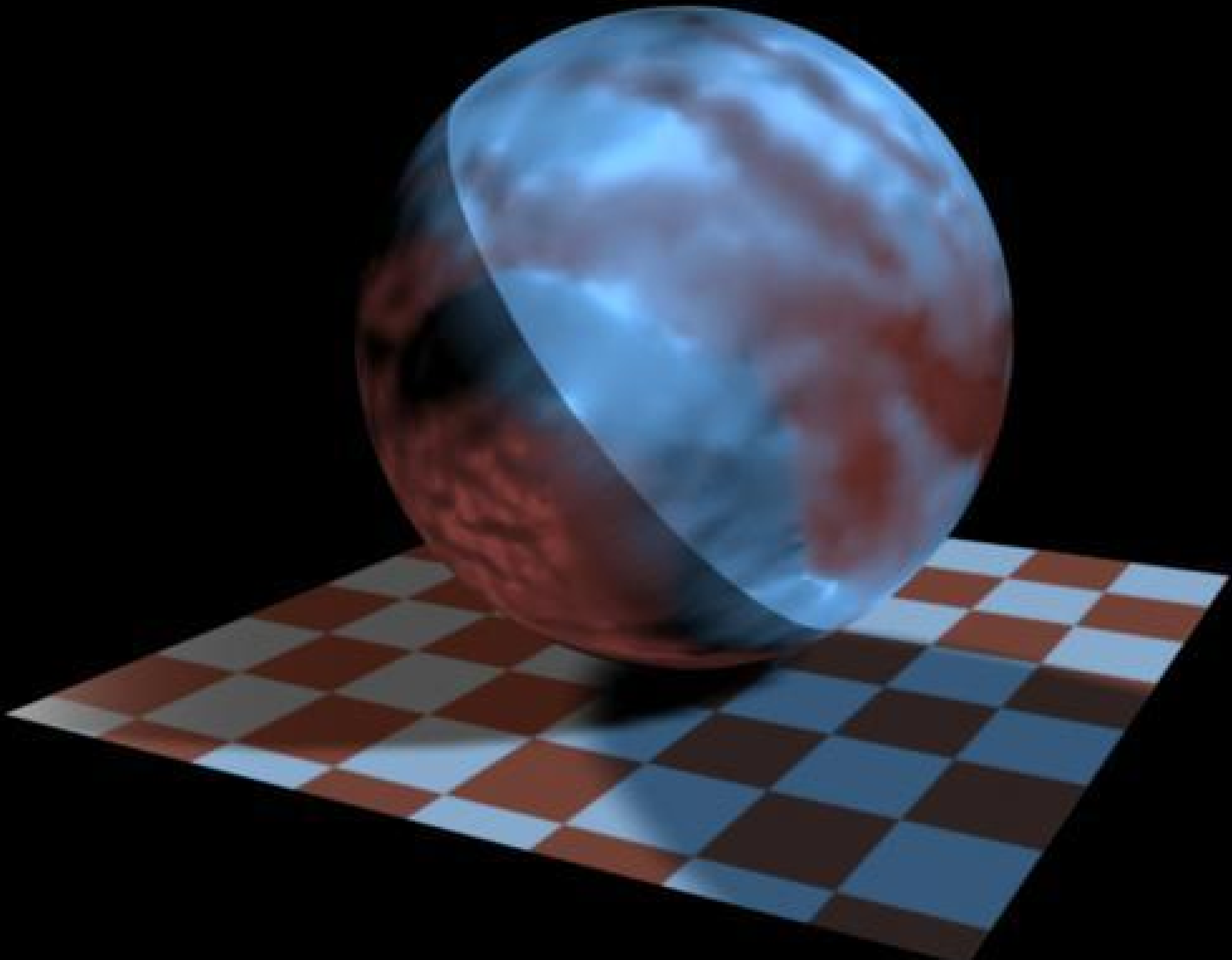
Efficient Rendering

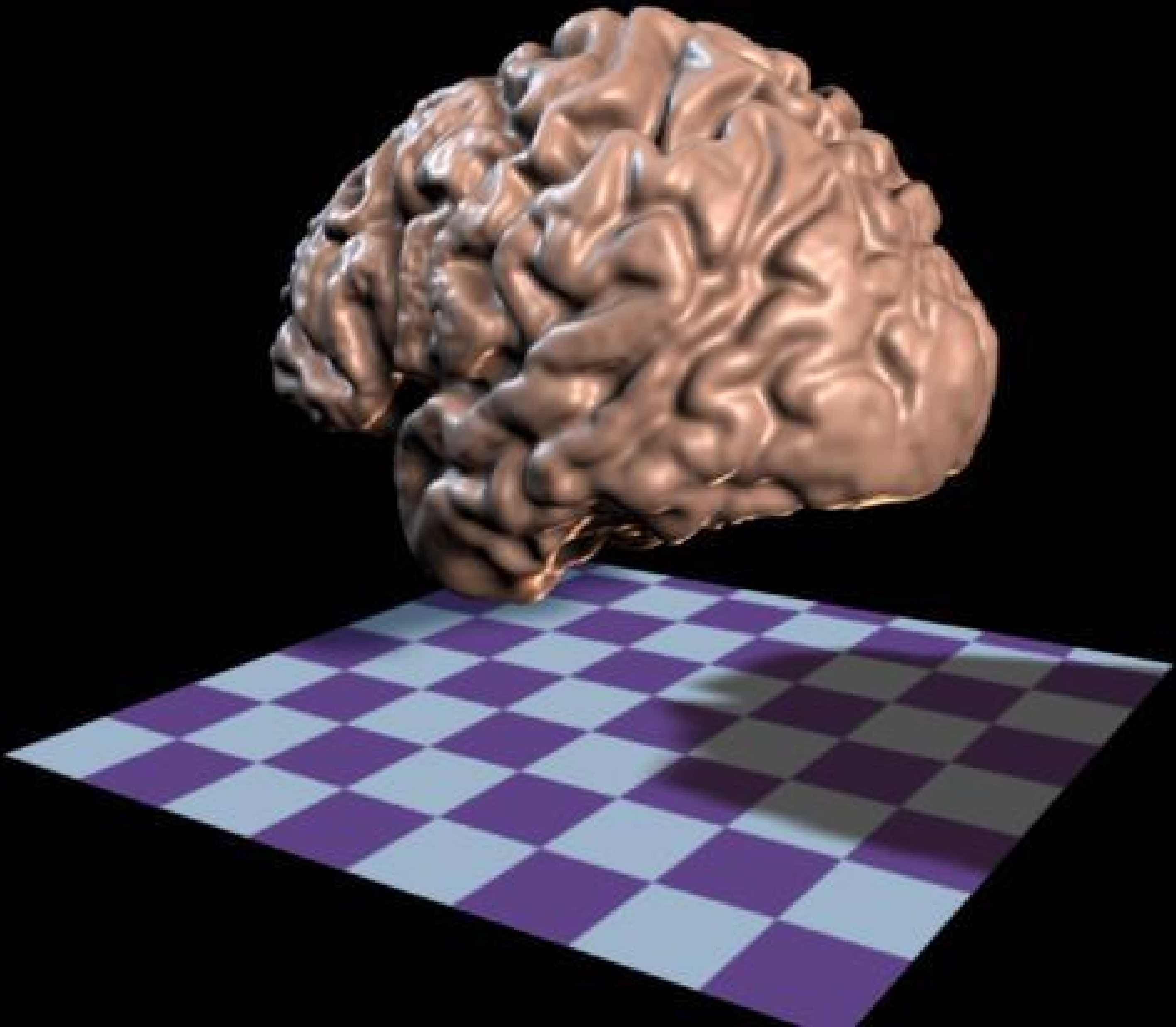
Optimal Parameterizations

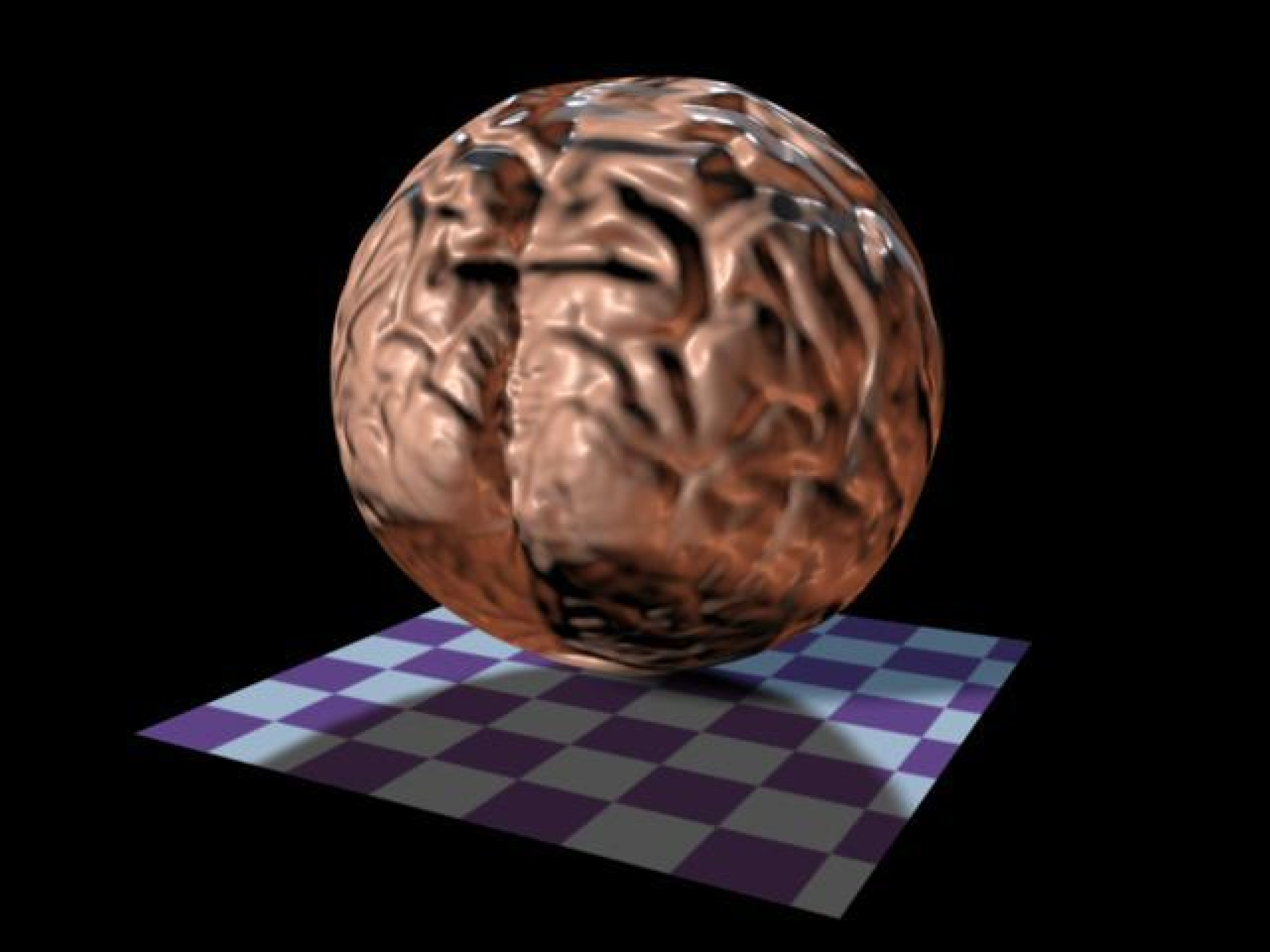


Medical Imaging



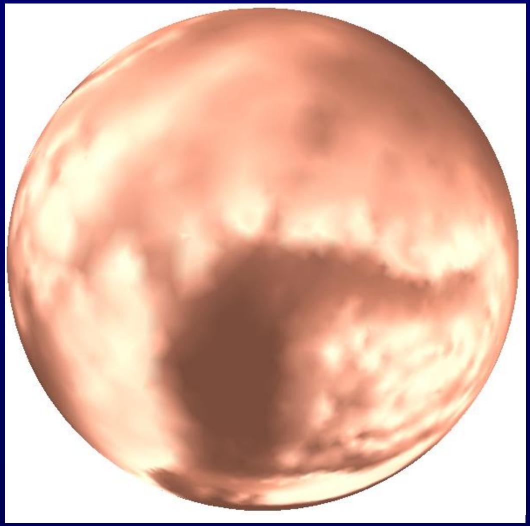






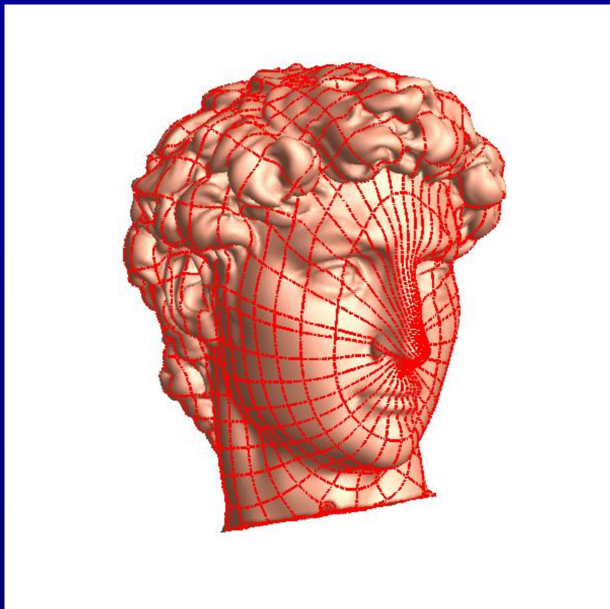
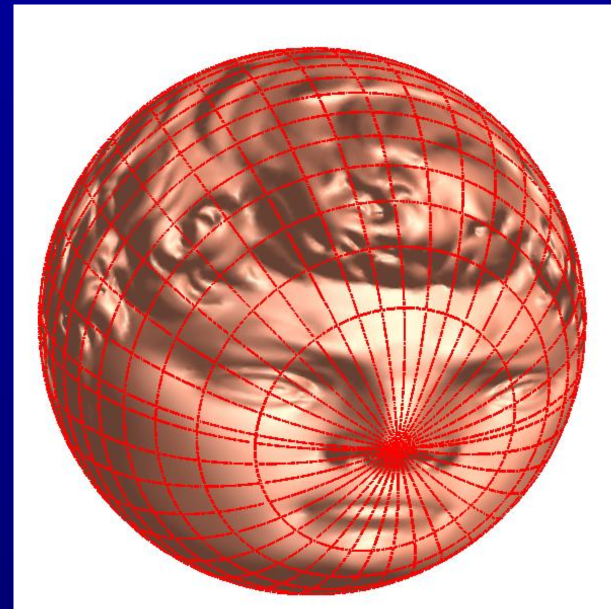
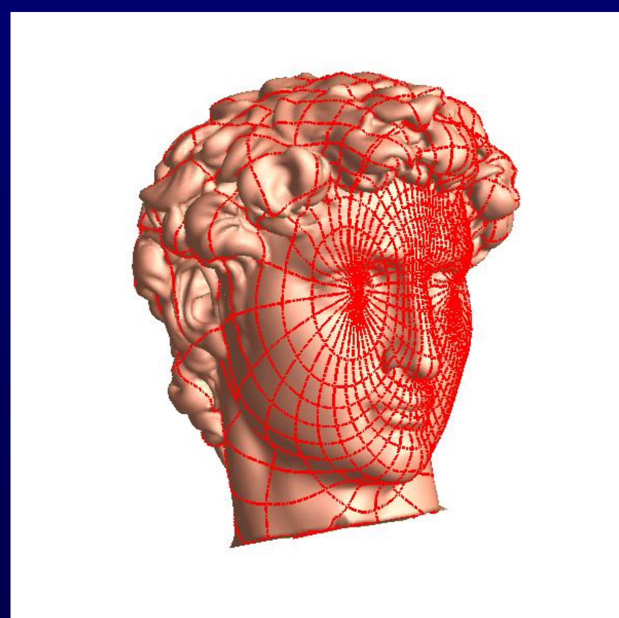
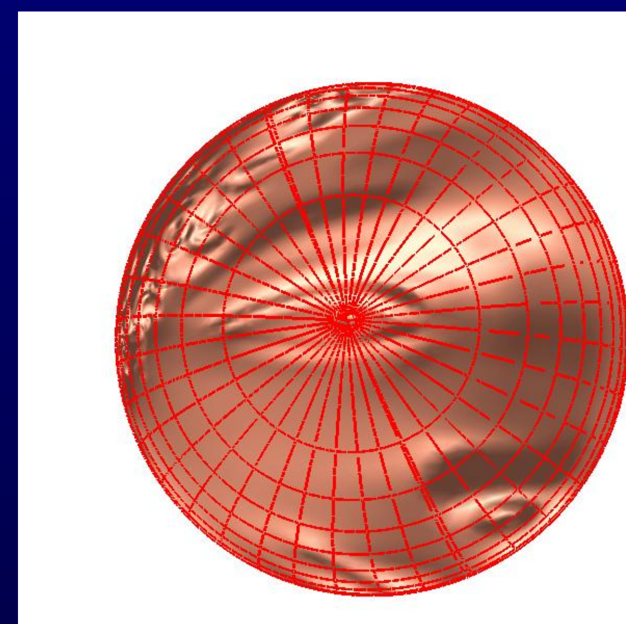
Genus 0 surfaces

- All conformally equivalent
- Harmonic is equivalent to conformal
- Mobius group



demo

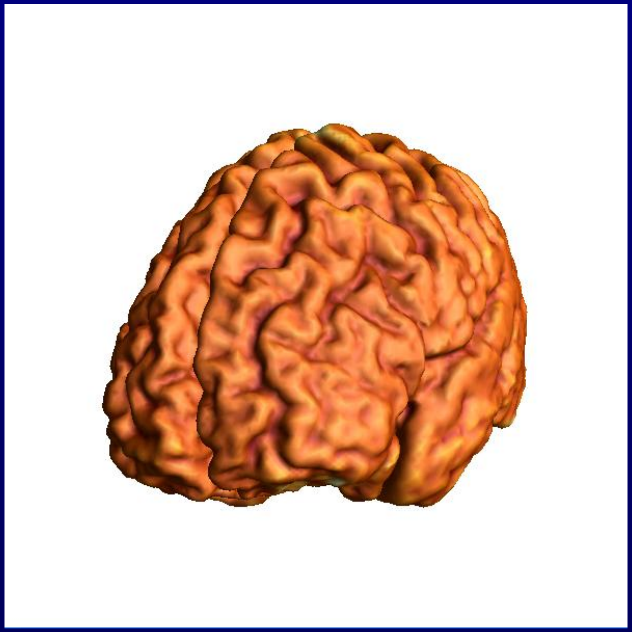
Conformal Mapping

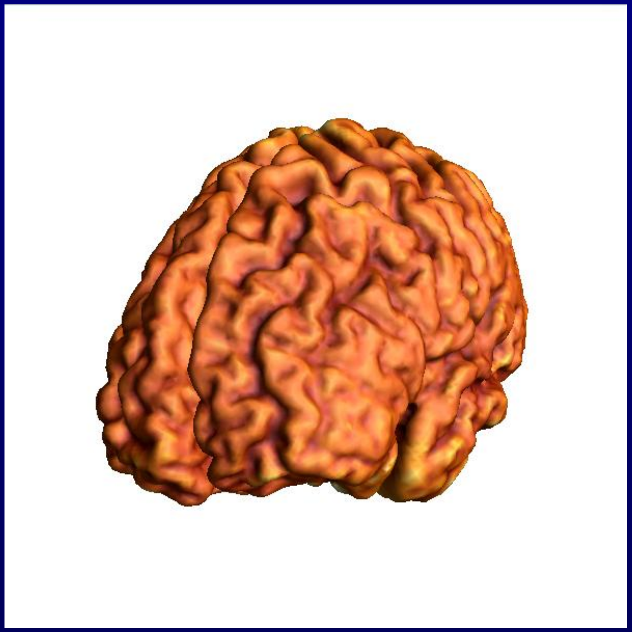





Surfaces with boundaries

- Copy the surface, invert the orientation
- Glue two copies together along the boundaries
- Treat the doubling as a closed surface
- Keep symmetry

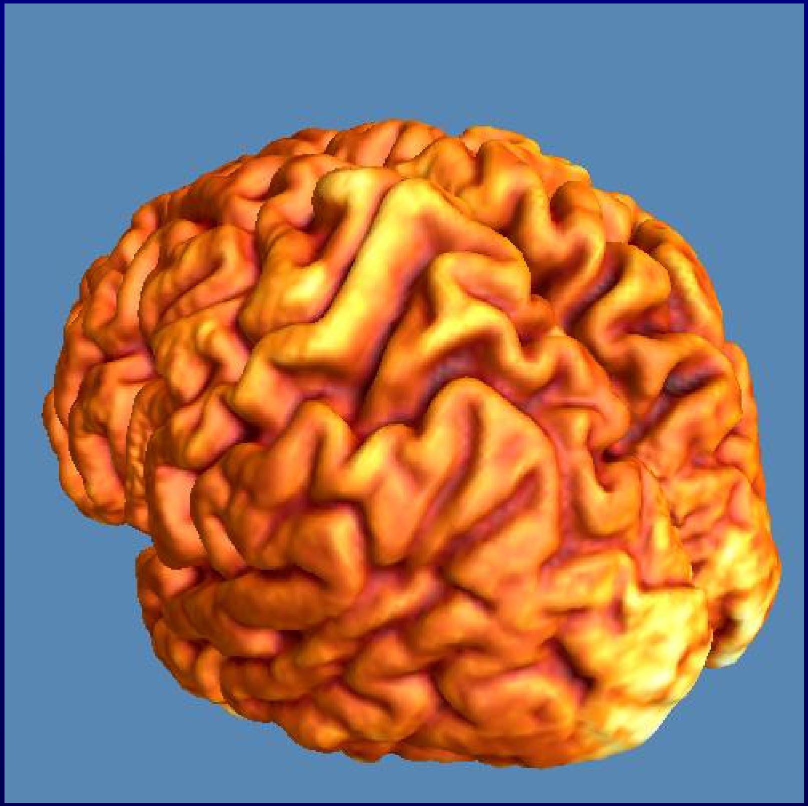
Geometry Matching-brain mapping

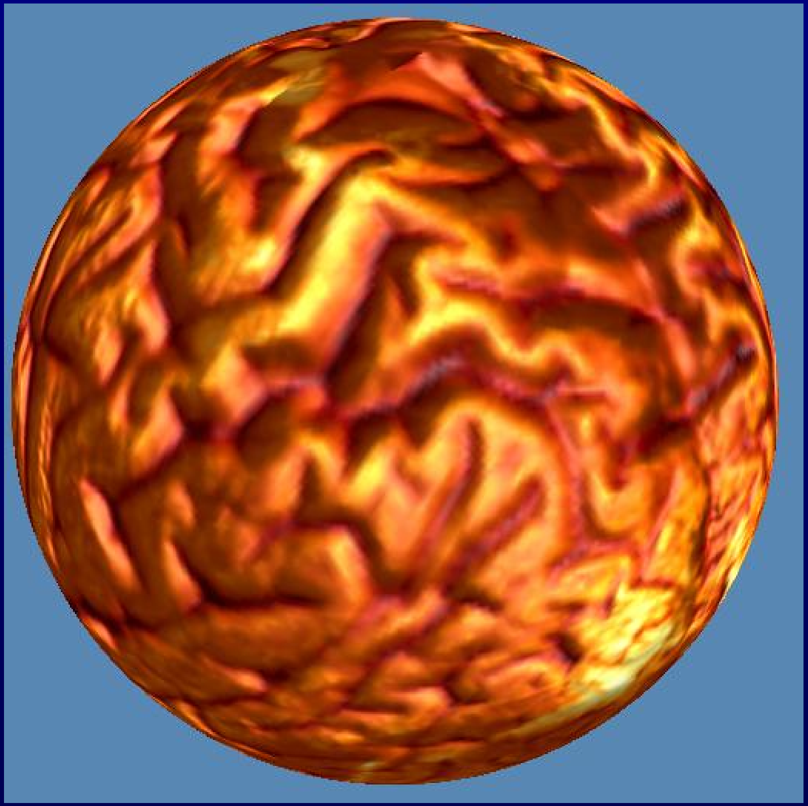




Conformal Brain Mapping

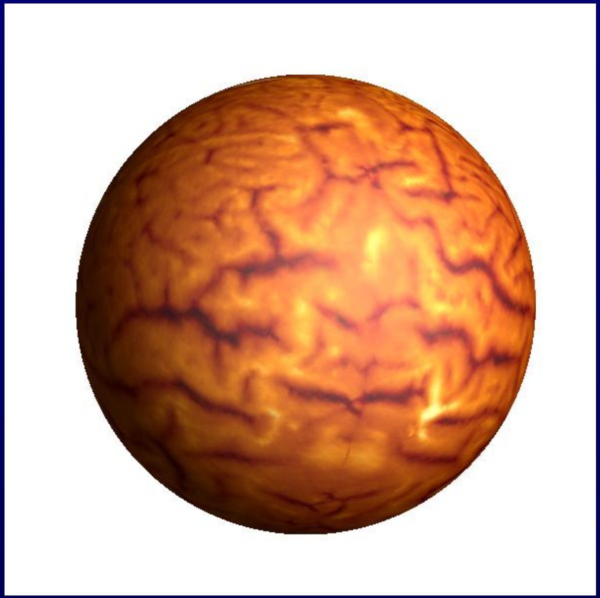
- Brain to Sphere



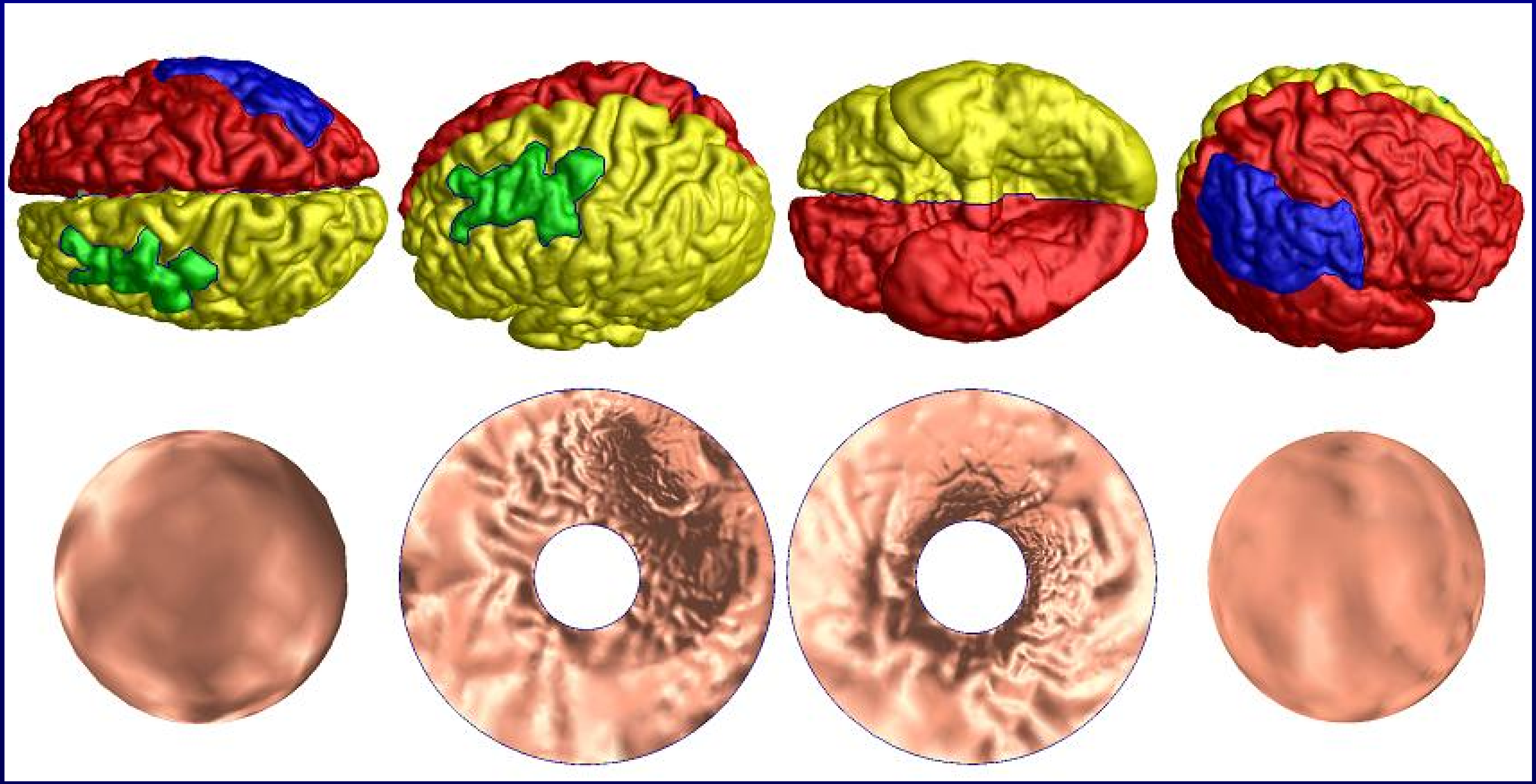


Geometric Matching-brain mapping

- Minimize L2 norm under Mobius transformation
- Least square problem

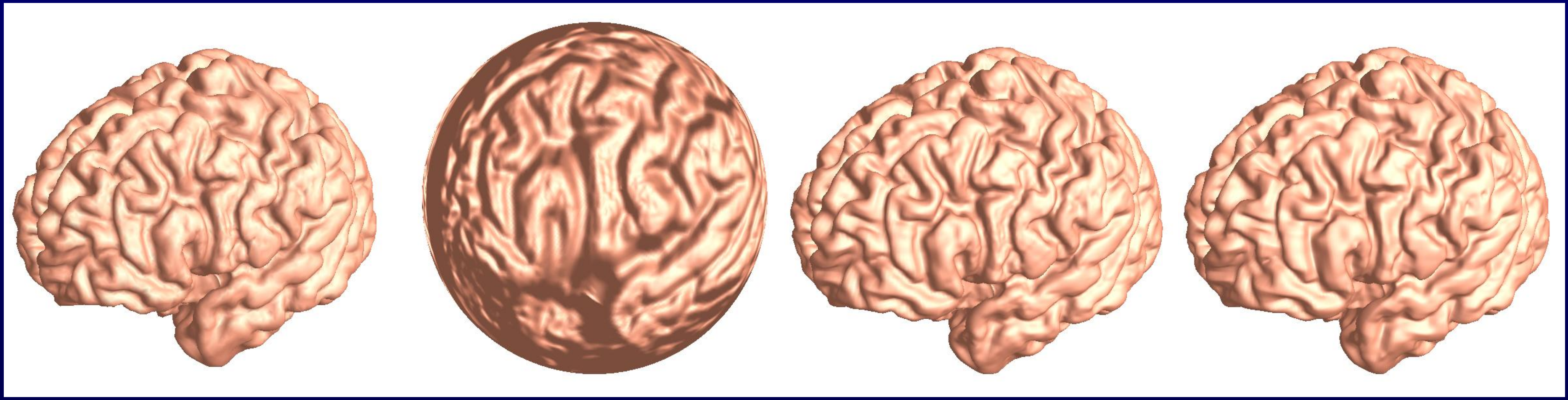


Conformal Brain Mapping

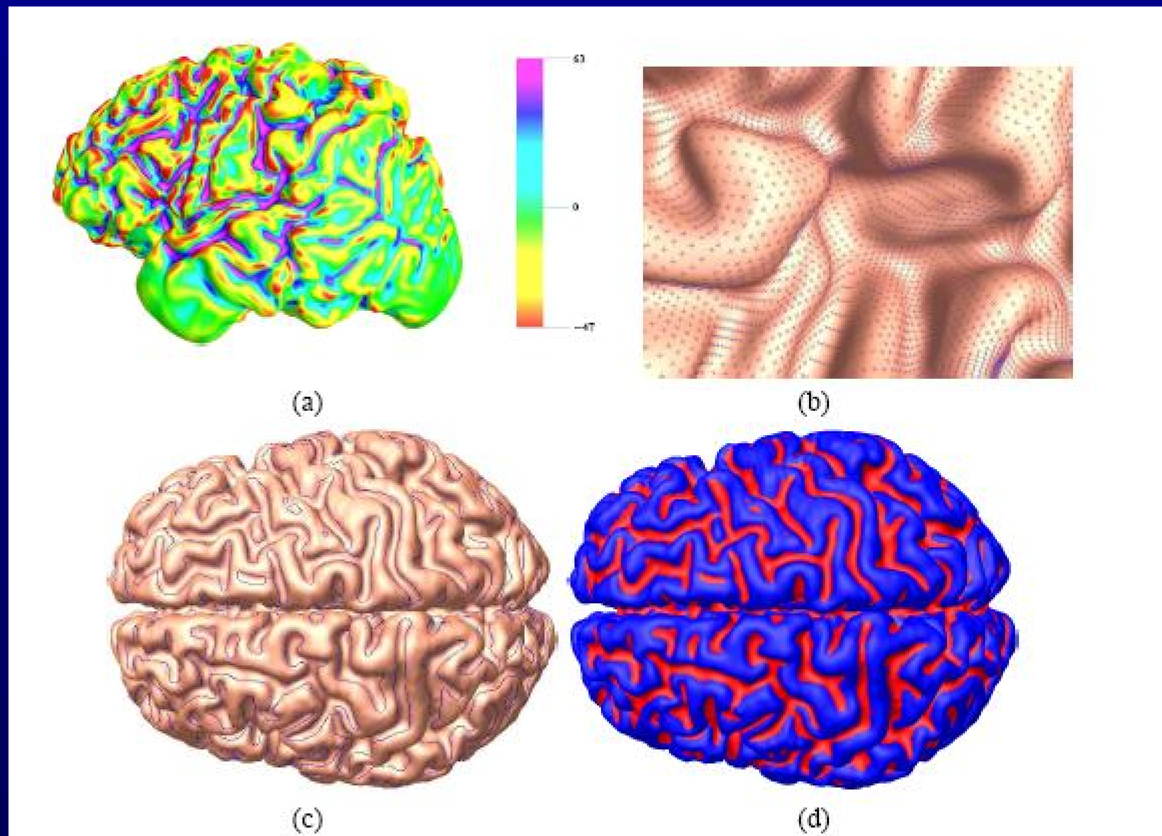


Geometry Compression

- Spherical harmonic functions
- Spectrum compression



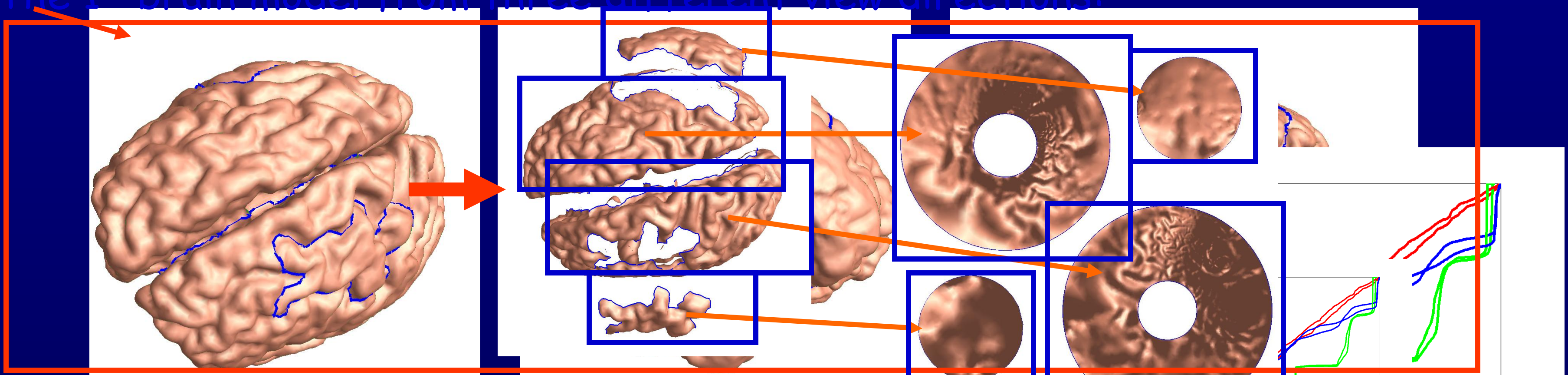
Manifold Spline



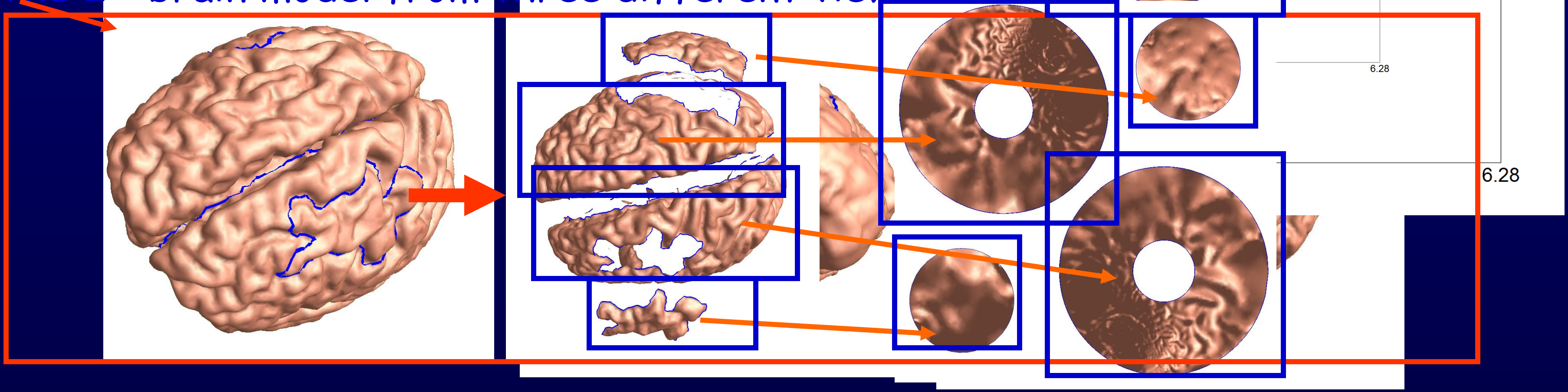
Surface Segmentation/Matching

Boundary curve matching →Segmentation → Sub-patch matching

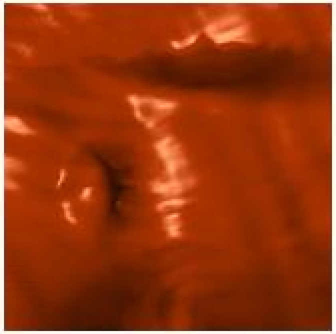
The 1st brain model from three different view directions:

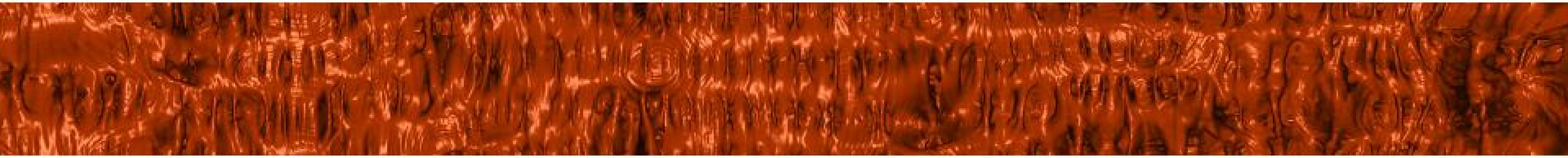


The 2nd brain model from three different view directions:

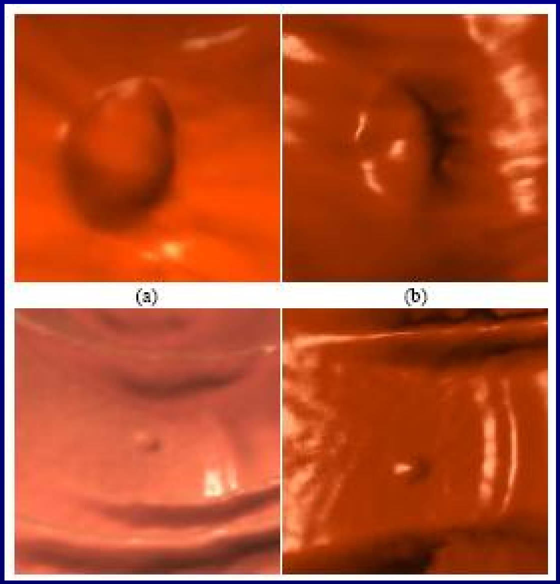


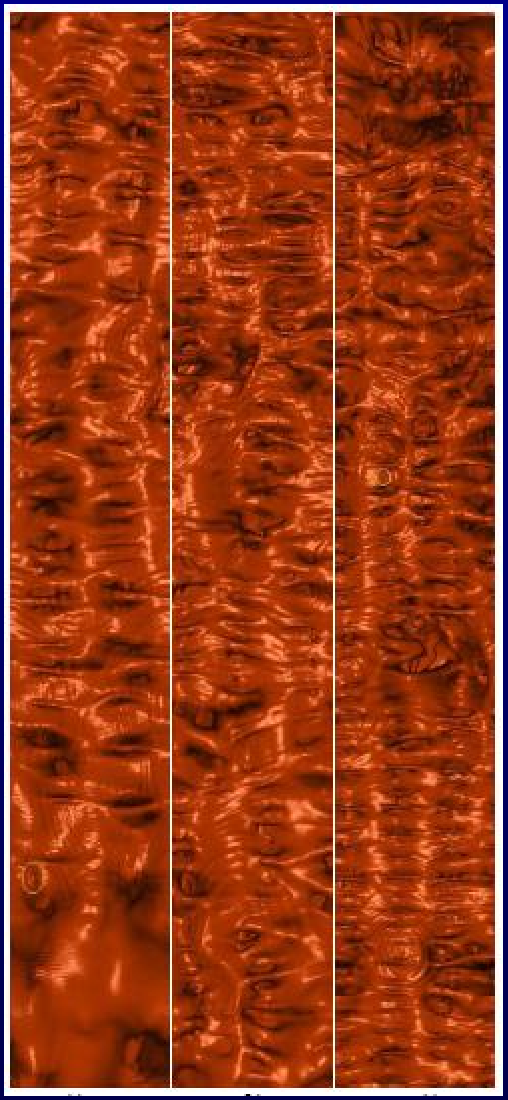
Conformal Colon Flattening





Conformal Colon Flattening

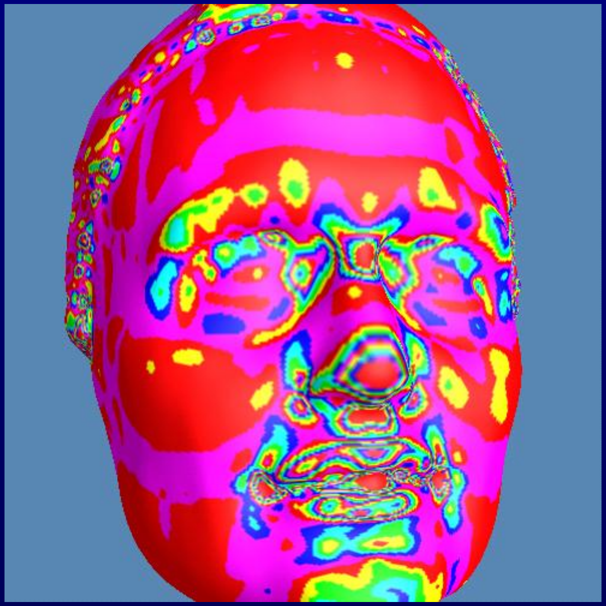


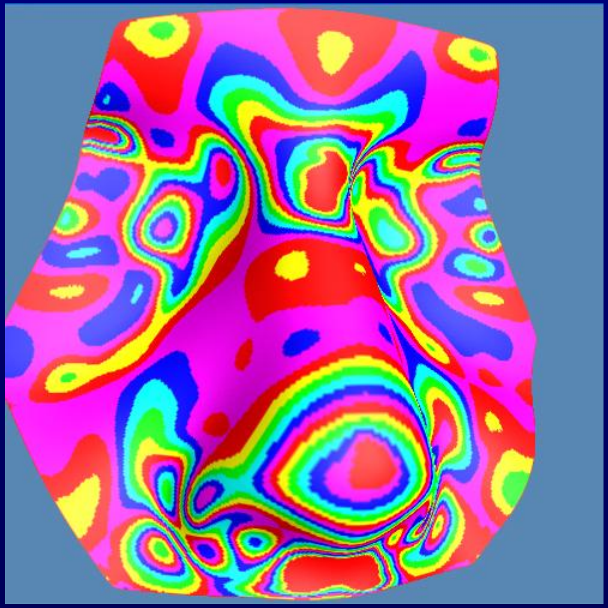


Scientific Computation

Geometric Matching

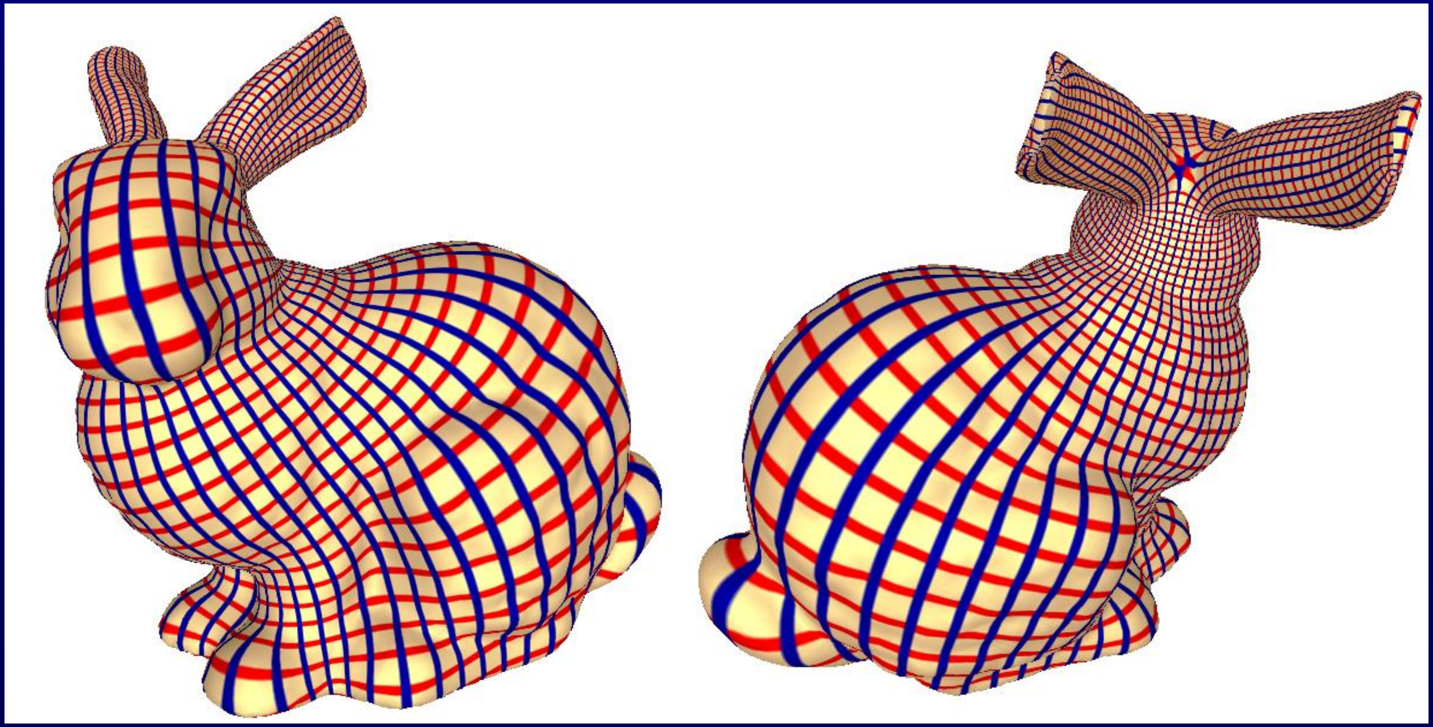
- Level set of Gaussian curvature
- Gradient of gaussian curvature





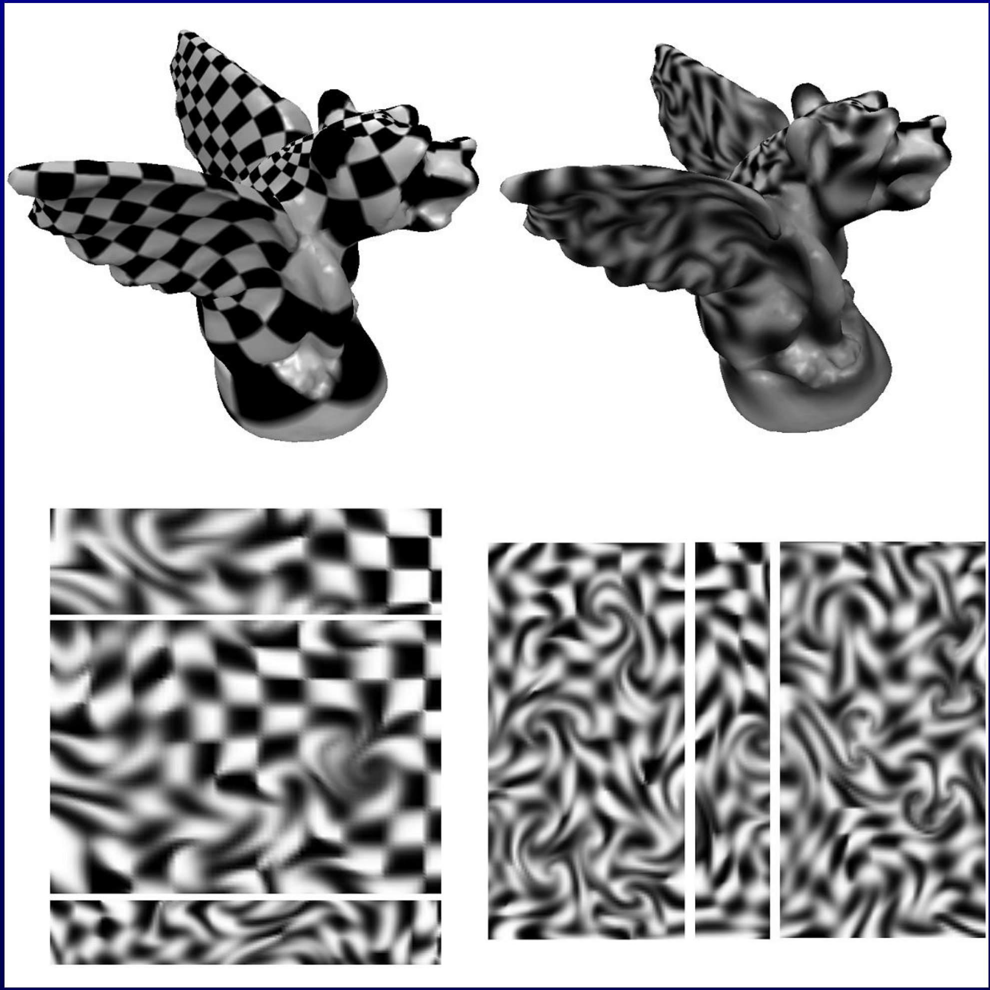
Flows on Mesh

- Curvilinear Grids
- Holomorphic Flow Segmenation
- Transition functions are holomorphic

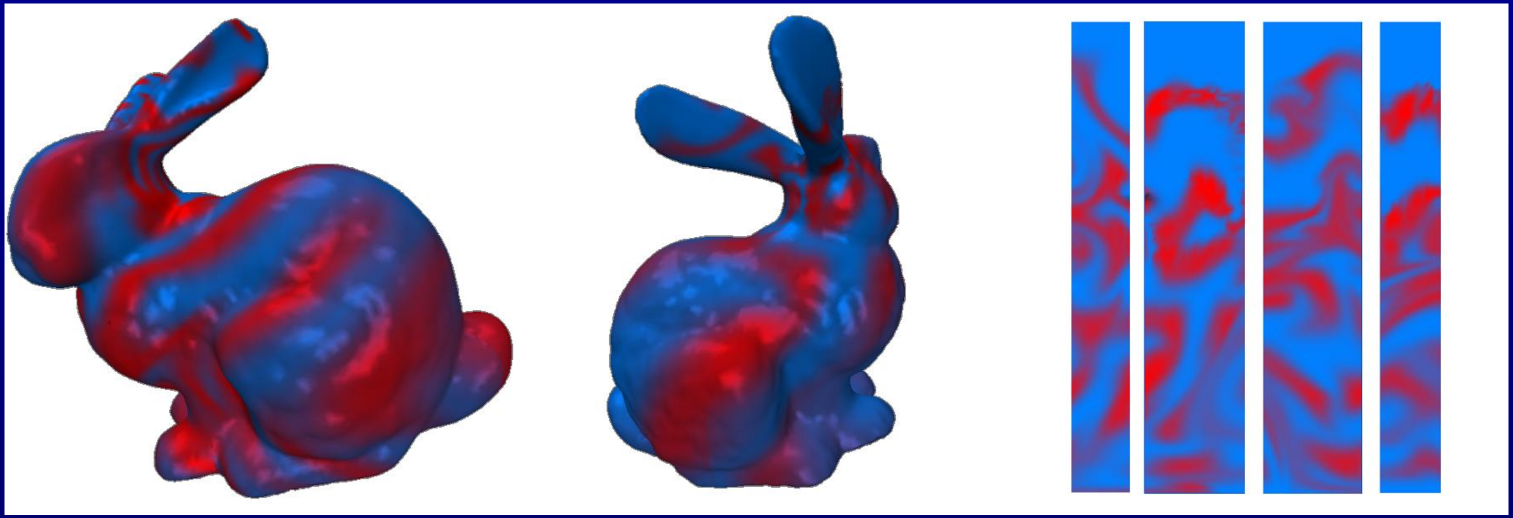


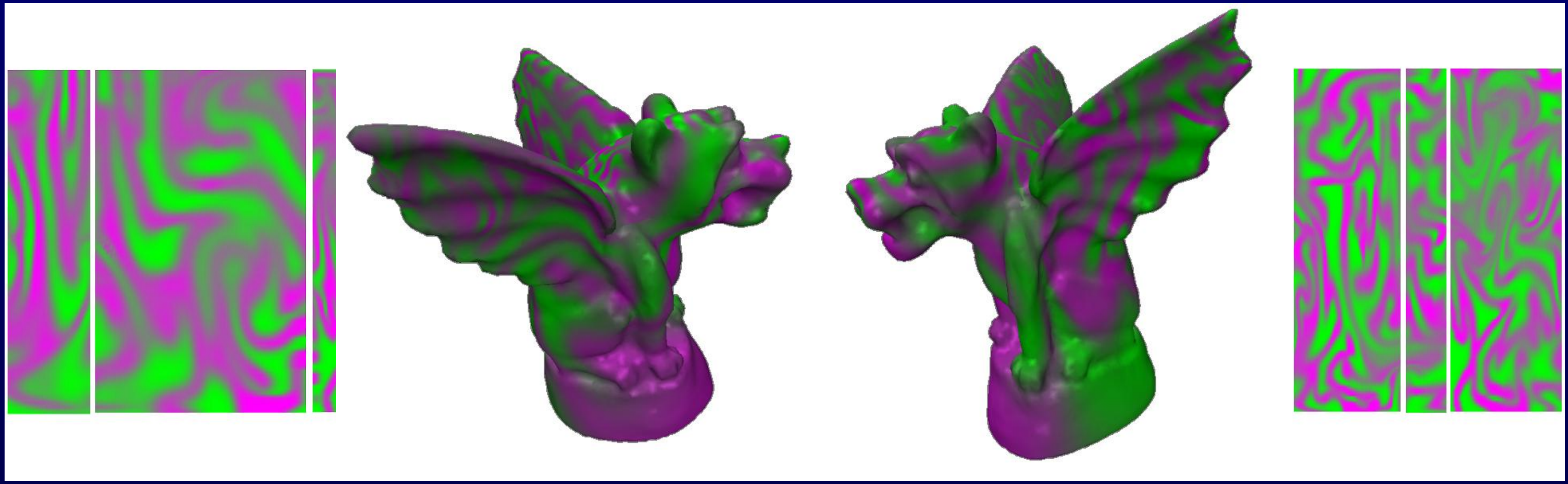
Flows on Mesh

- Navier-Stokes Equations
- Co-variant differentiation
- Simpler differential operators
- No singularities
- Arbitrary meshes

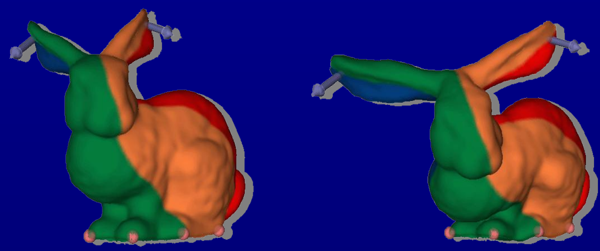


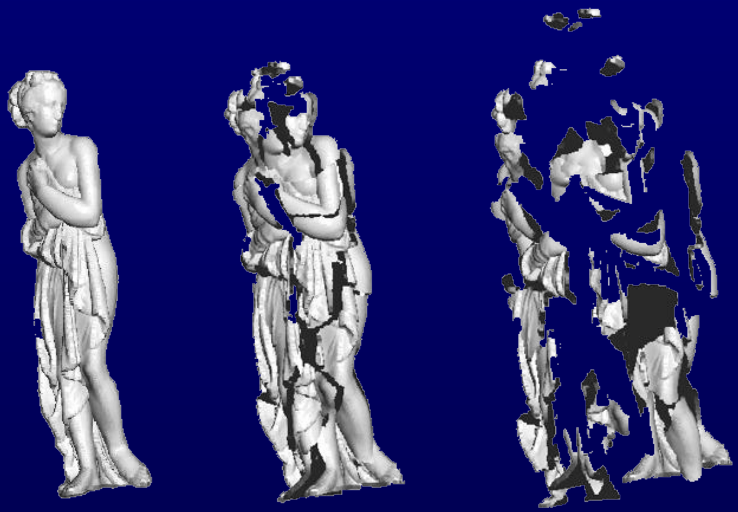
Flows on Mesh

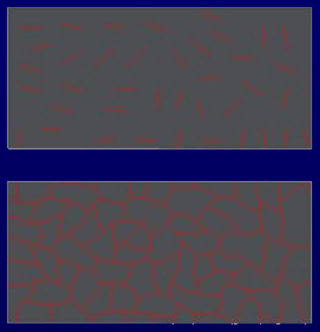




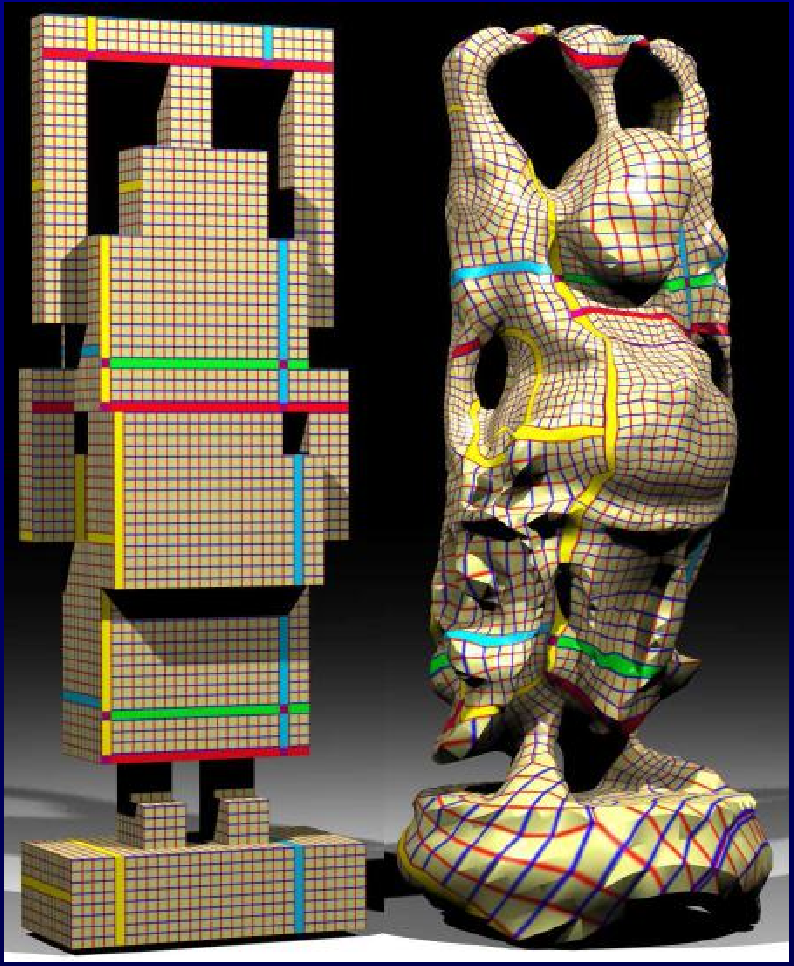
Physical Simulation





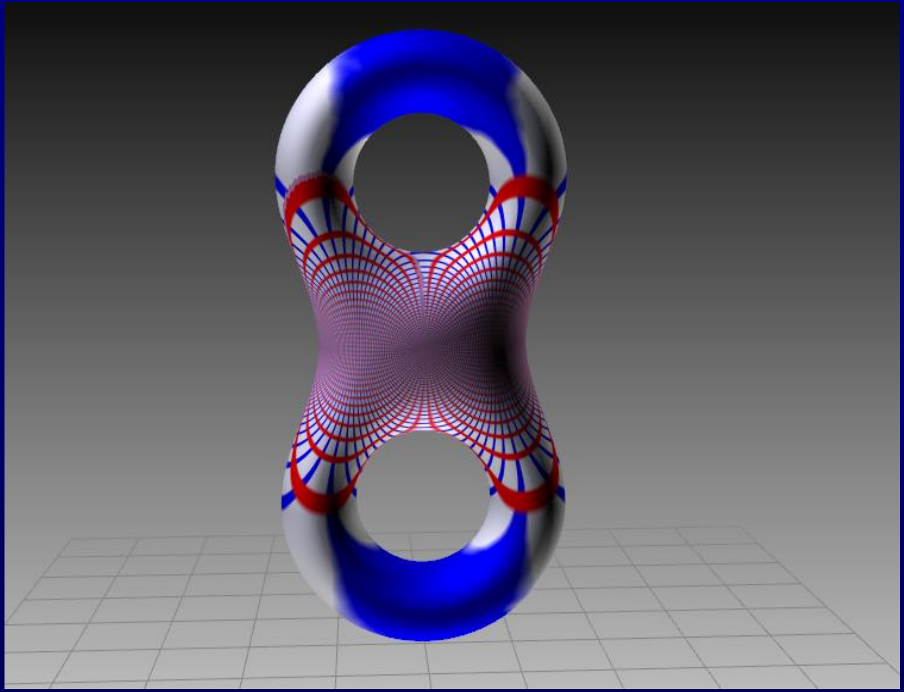


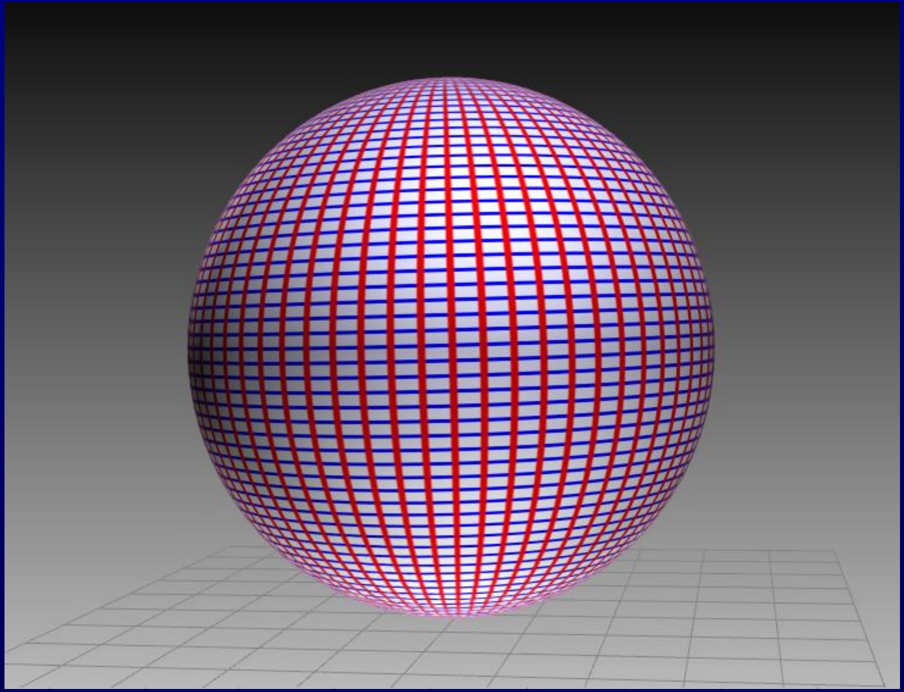
Surface Matching



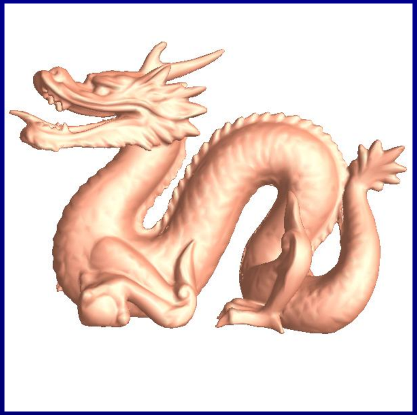
Quasi-Conformal Maps

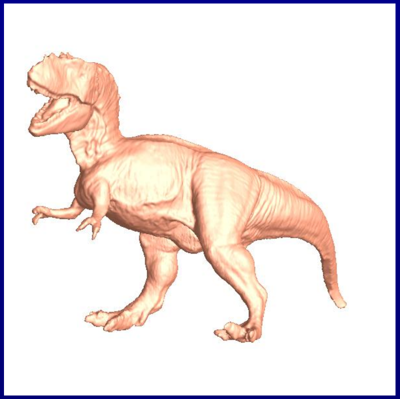
Meromorphic Function

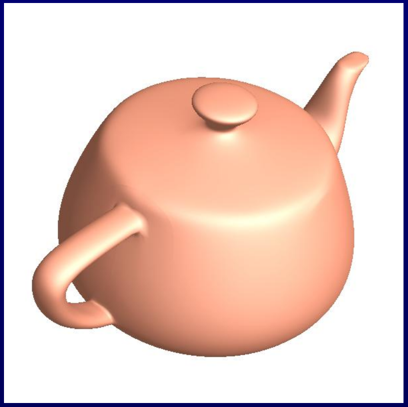




Geometry classification
Geometric Database application



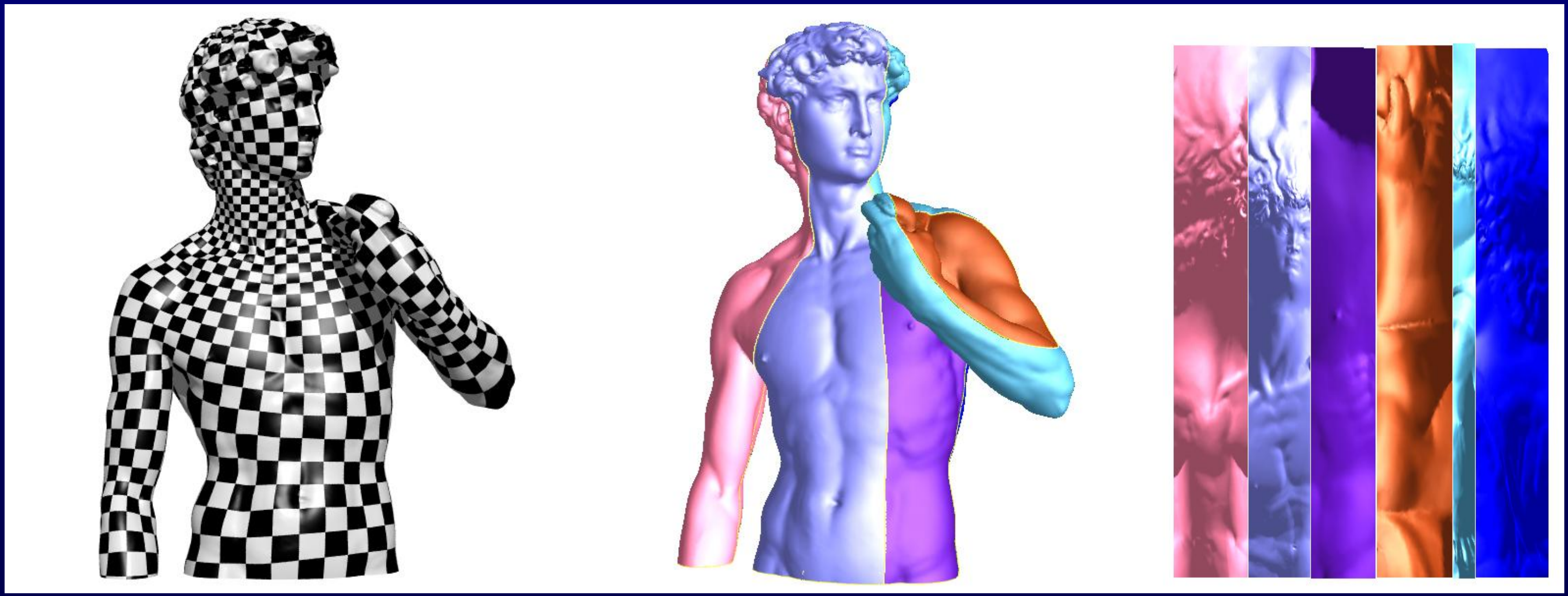


Space of Riemann Surfaces
Teichmuller Space

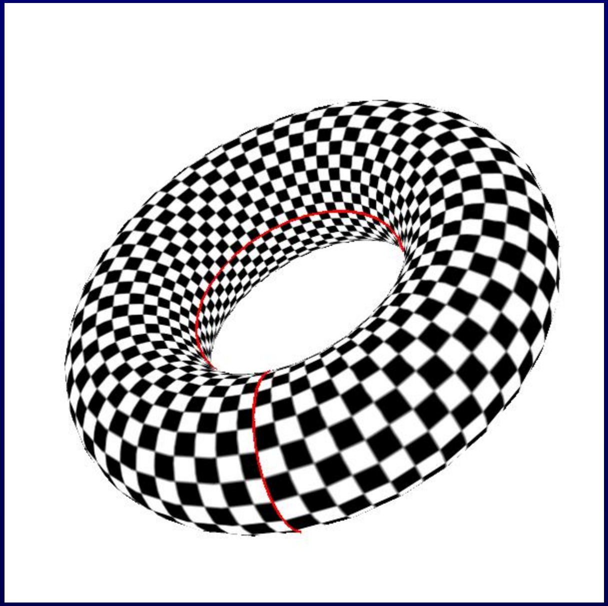
Theorem:

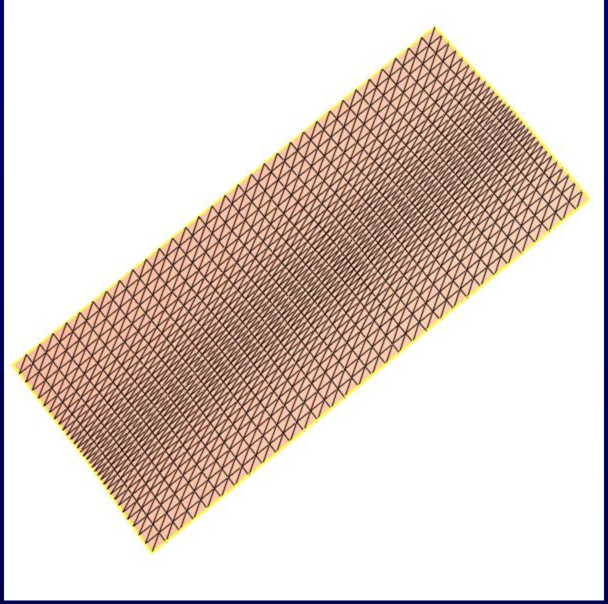
Teichmuller Space for Genus 0 surface is only one point, for Genus 1 surfaces is 2 dimensional, for genus g surface is 6g-6 dimension.



Conformal invariants - Periods

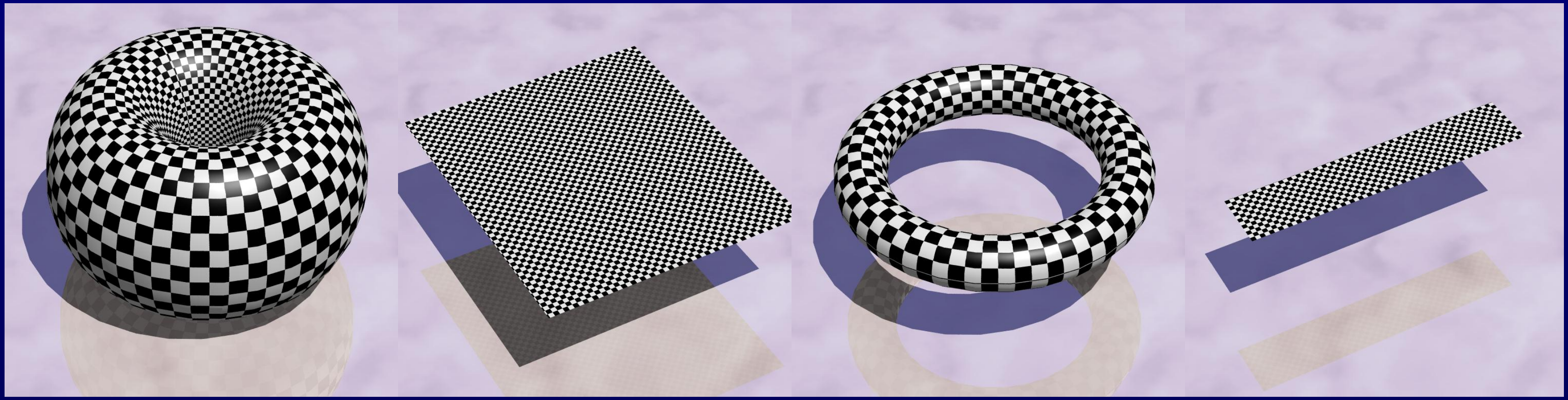
- Torus is conformally mapped to a parallelogram
- The shape factors of the parallelogram are conformal invariants



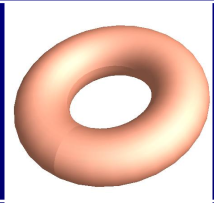
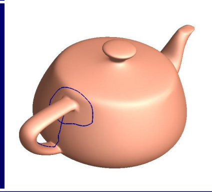
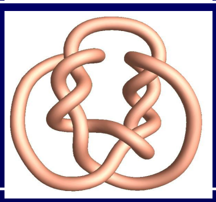
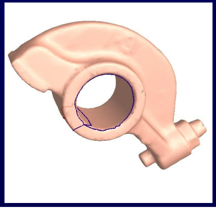


Conformal invariants - periods

- Topologically equivalent
- Not Conformally equivalent

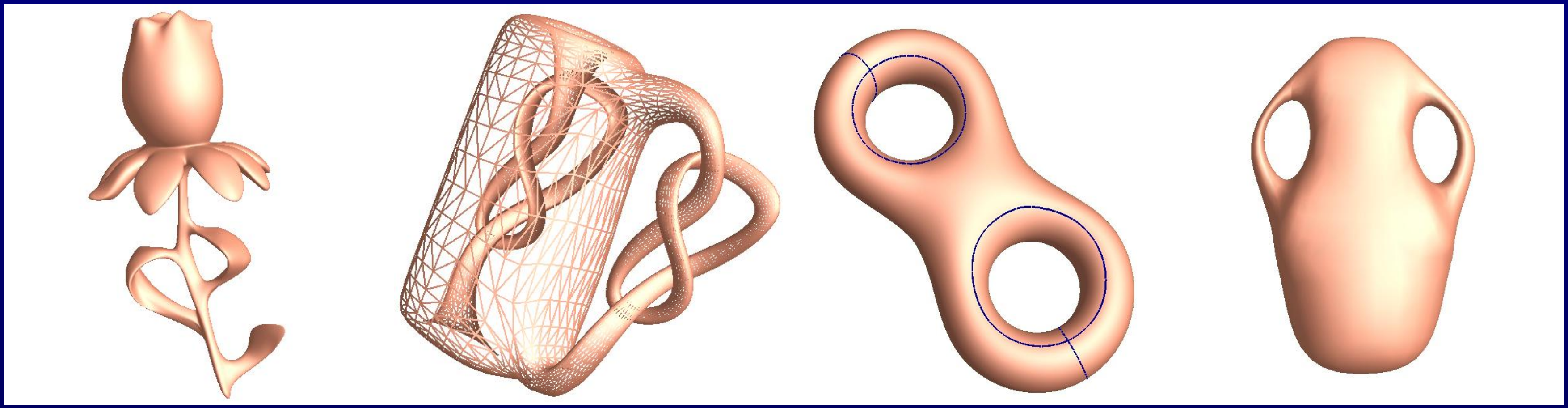


Conformal Invariants - periods

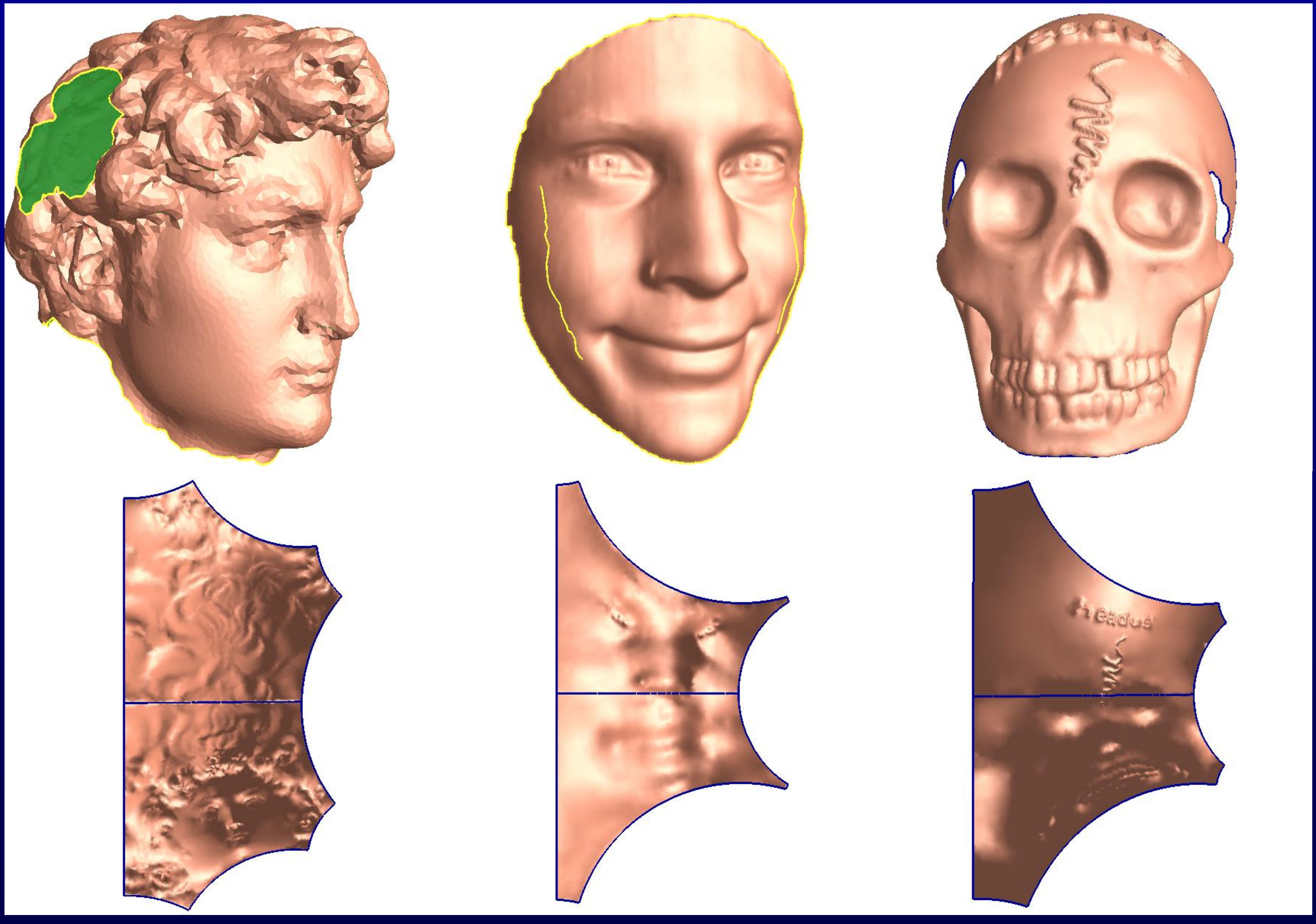
Snap shot	mesh	Angle	length ratio	Vertices	faces
	Torus	89.987	2.2916	1089	2048
	Teapot	89.95	3.026	17024	34048
	knot	85.1	31.150	5808	11616
	rocker	85.432	4.993	3750	7500

Conformal invariants – period matrix

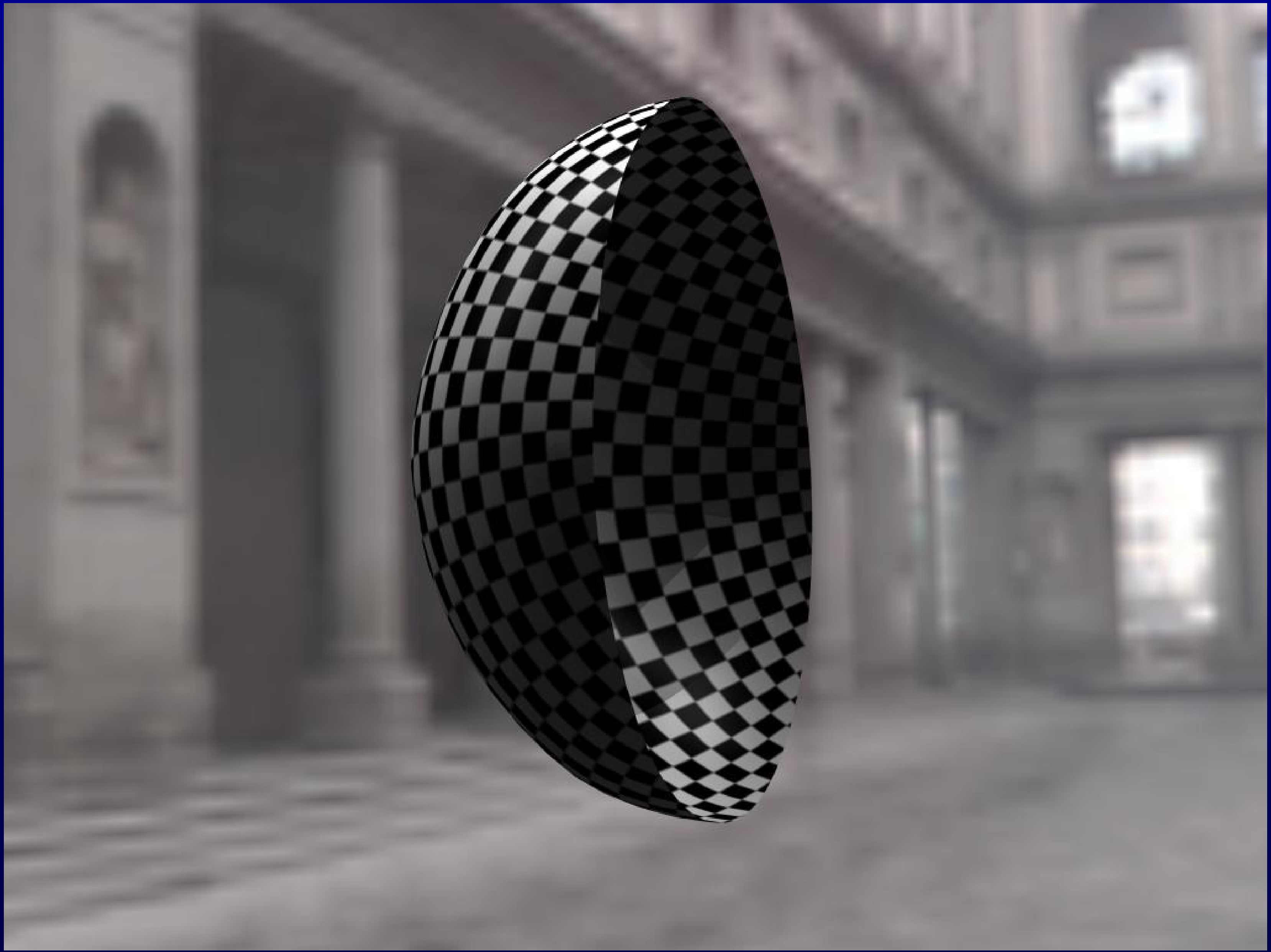
- High genus case – period matrix



Tecimuller Coordinates



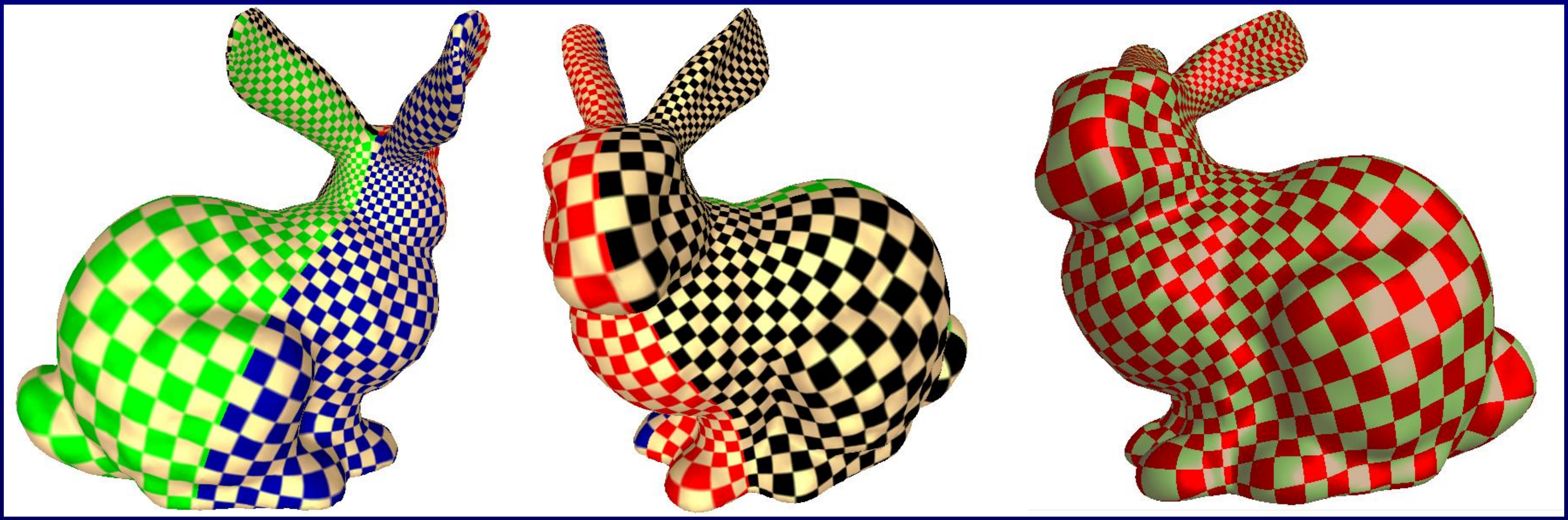
Visualize Curvature Flow



Geometric Modeling - Manifold Spline

Mesh Spline Conversion

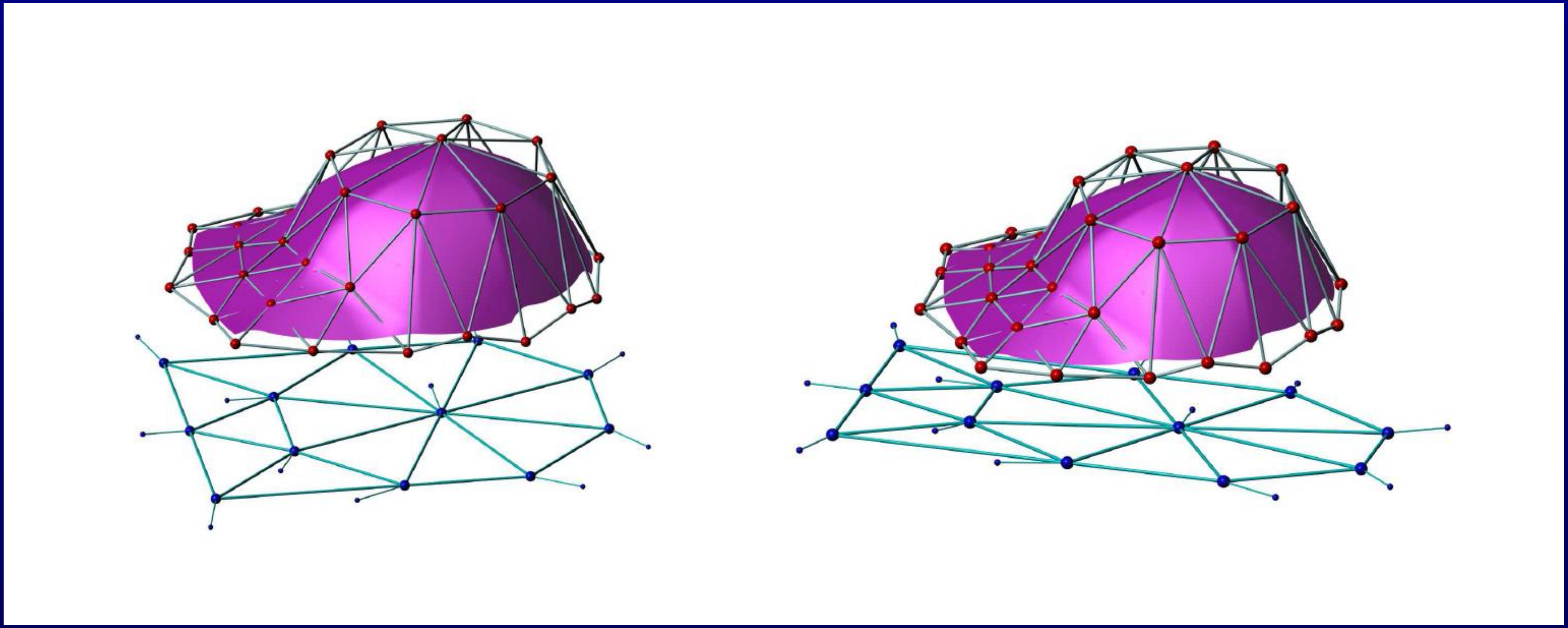
- Convert mesh to T-Spline



Goal: Generalize Planar Spline to Surfaces

- Long Lasting Open Problem in CAGD:
  - Can splines are defined on general manifolds?
  - If it is impossible, what is the intrinsic obstacle?
  - If it is possible, how to construct the manifold spline?

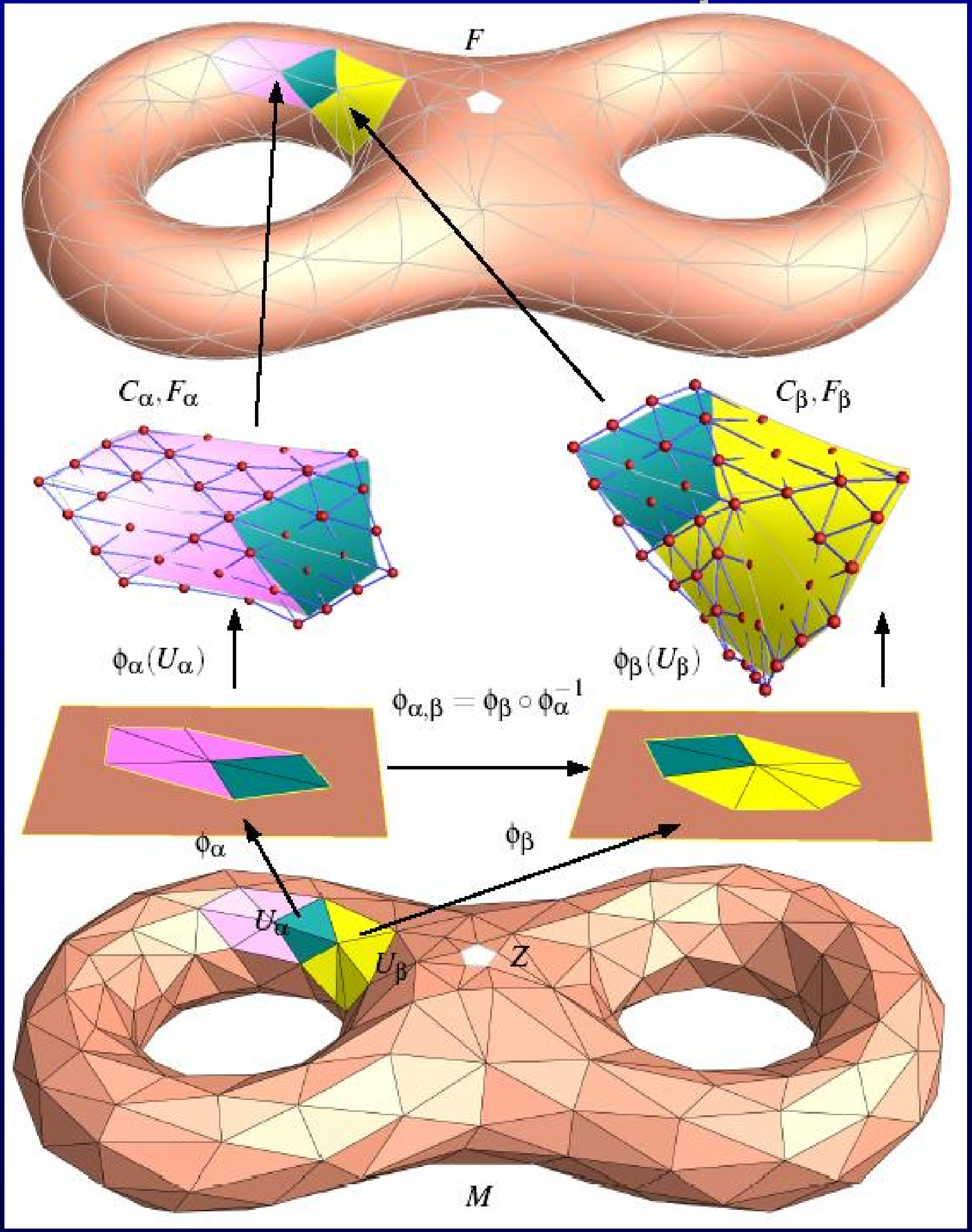
Triangular B-spline : Parametric Affine Invariance



Main theorem

- A domain manifold M with an atlas A, a spline scheme S, such that
  - S is parametric affine invariant
  - S has local support
  - S is complete (polynomial reproduction)
- M admits manifold spline with scheme S, if and only if A is affine (all coordinate transition functions are affine.)

Manifold Spline



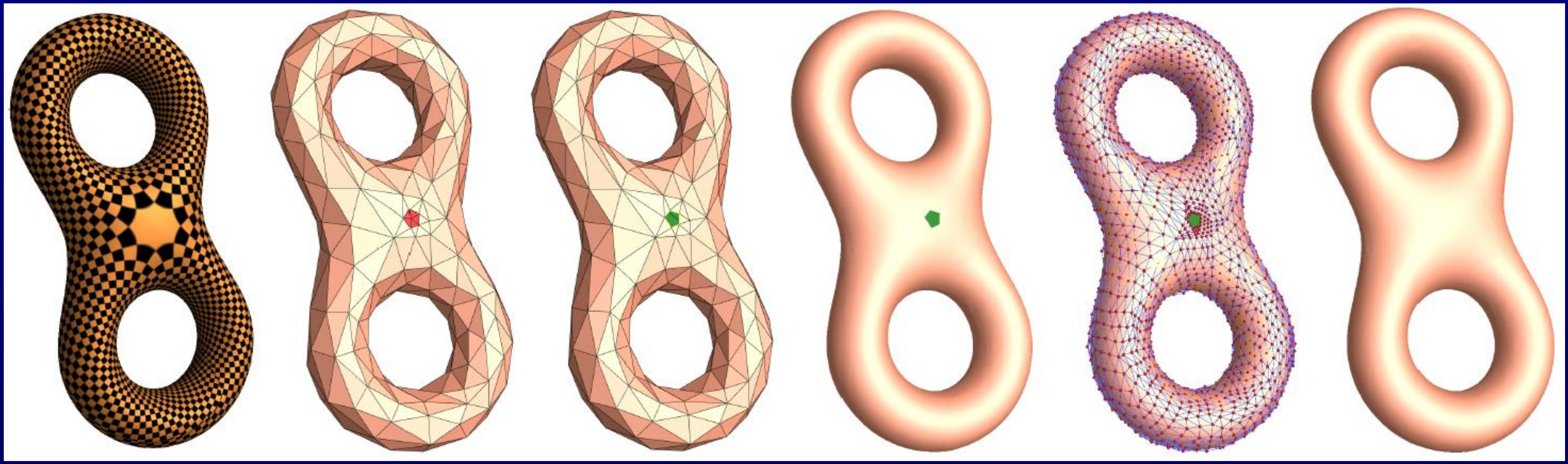
Existence of Affine Structure theorem

- A closed 2-manifold M admits an affine atlas, if and only if M is a torus.
- Any open 2-manifolds admits an affine atlas.

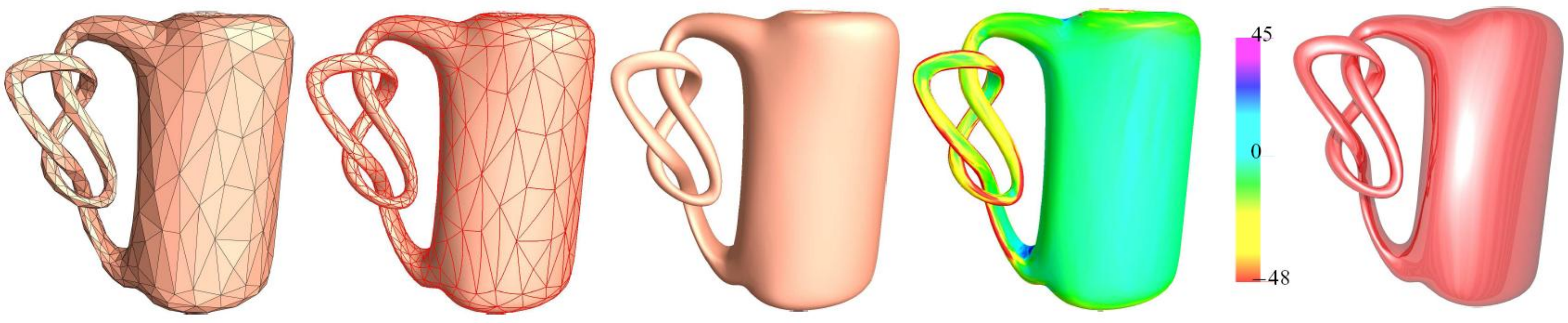
Construction theorem

- A holomorphic differential one-form induced an affine atlas on the Riemann surface with 2g-2 extraordinary points.
- A flat metric induces an affine atlas.

Manifold Spline

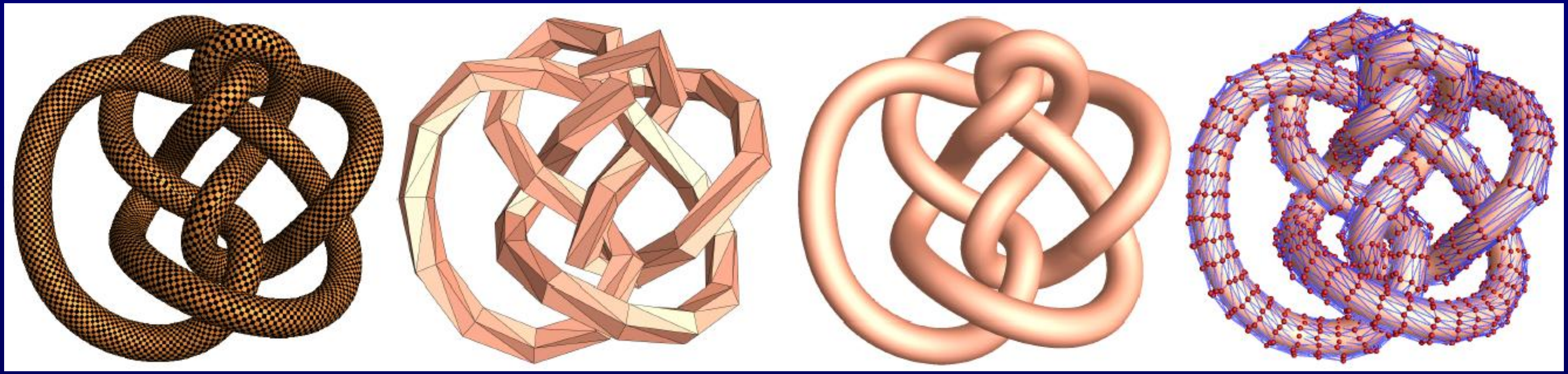


Manifold Spline

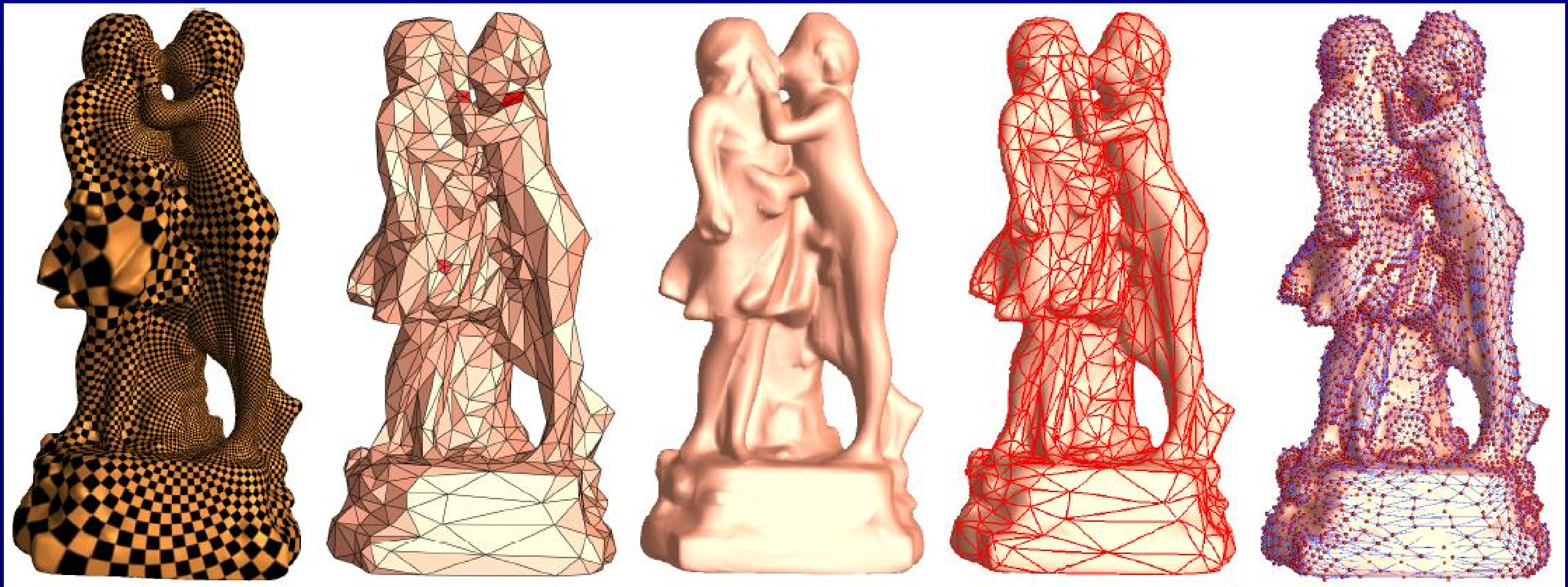


(a) parametric domain (b) spline (c) spline (d) mean curvature (f) isophotes

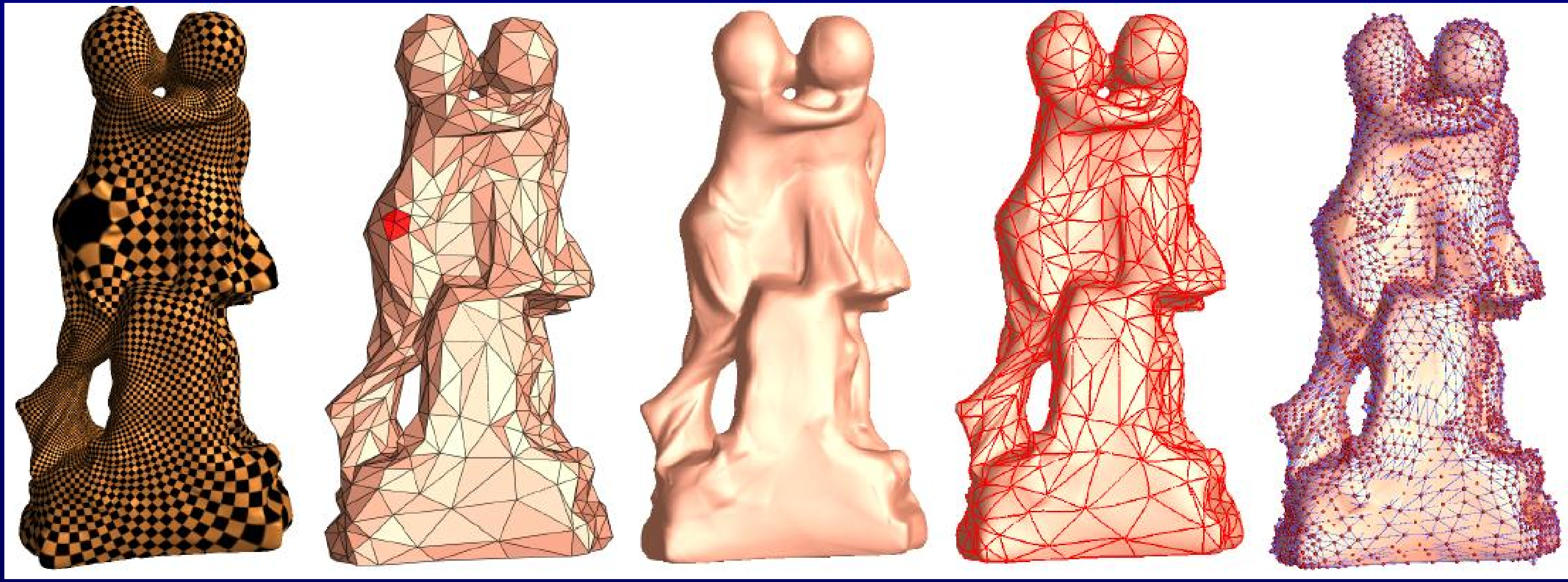
Manifold Spline



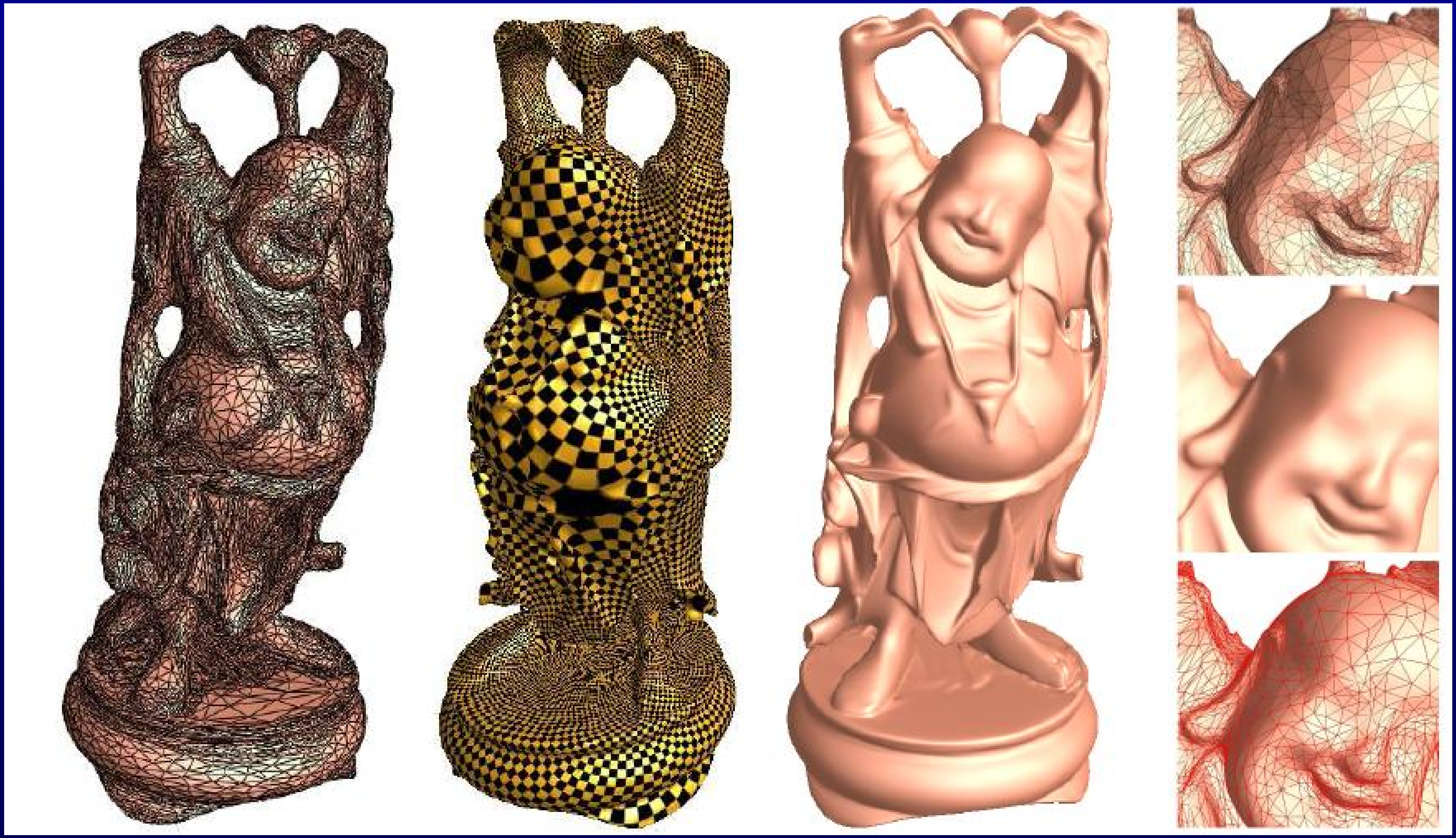
Manifold Spline



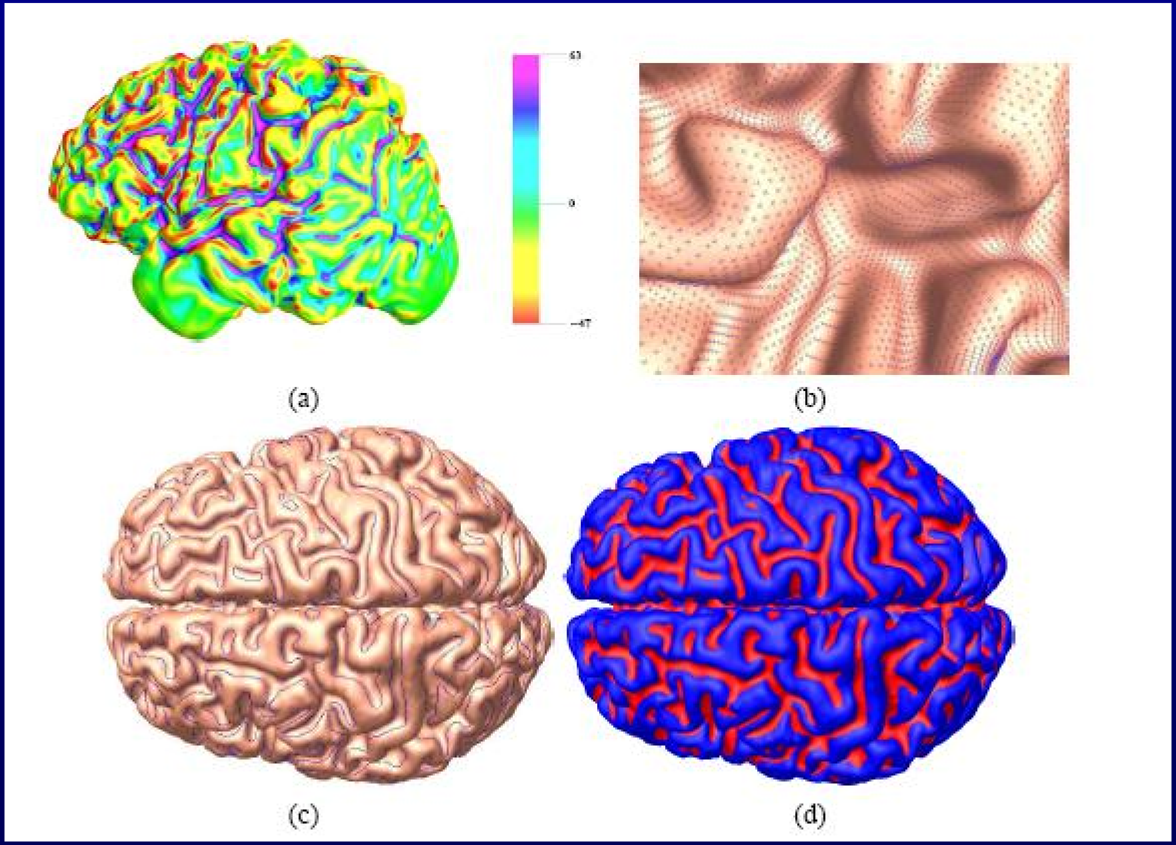
Manifold Spline



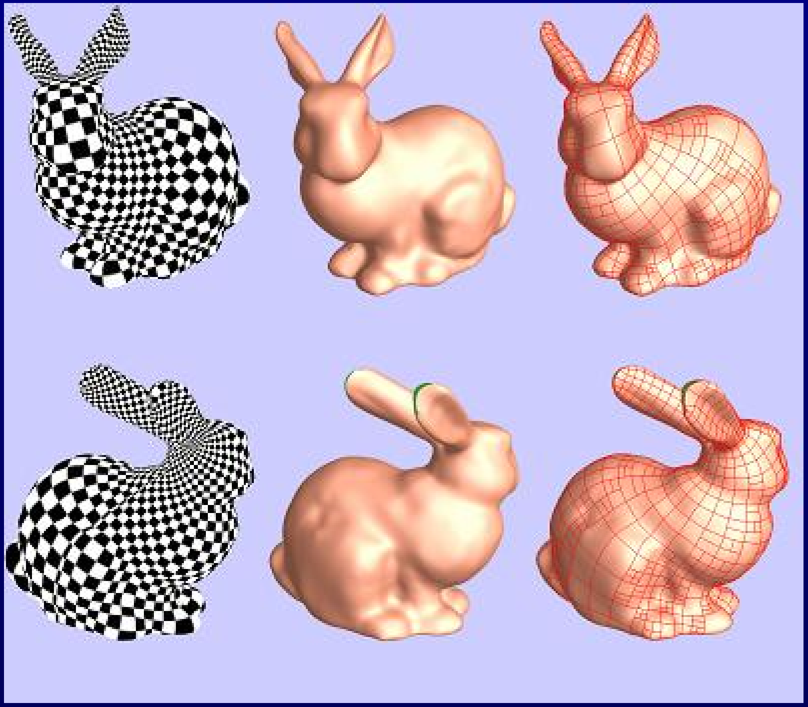
Manifold Spline



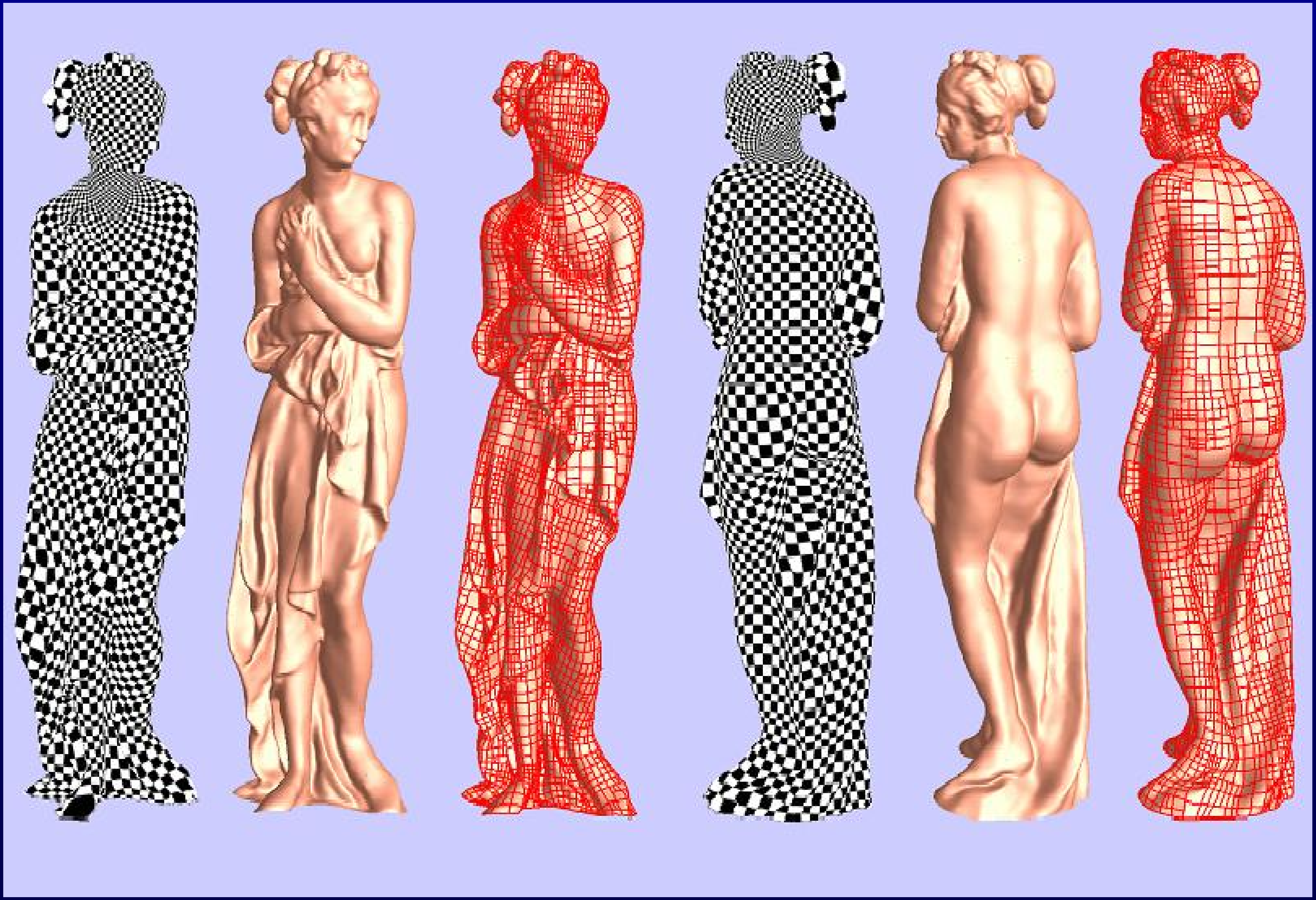
Manifold Spline



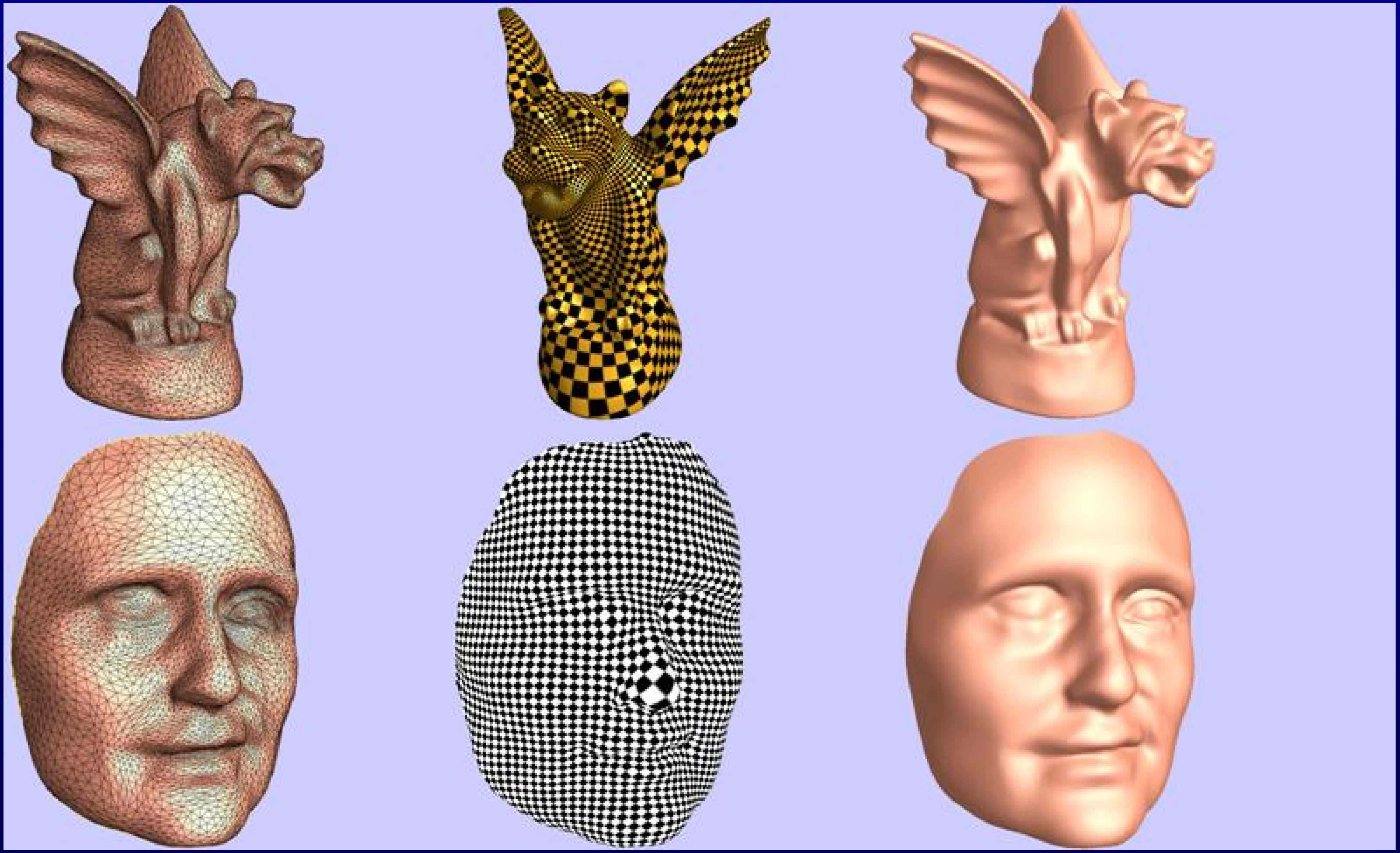
Manifold TSpline



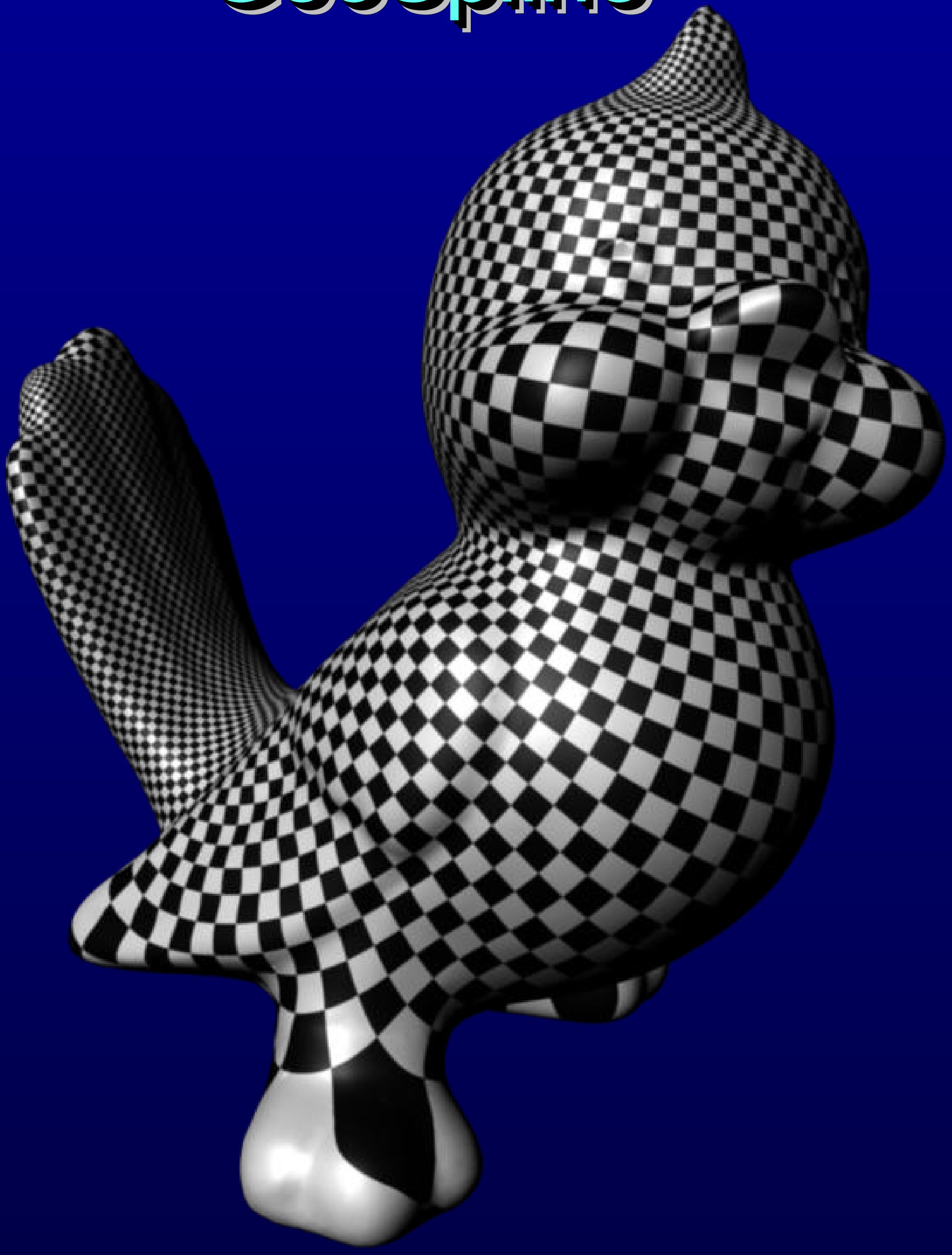
Manifold TSpline



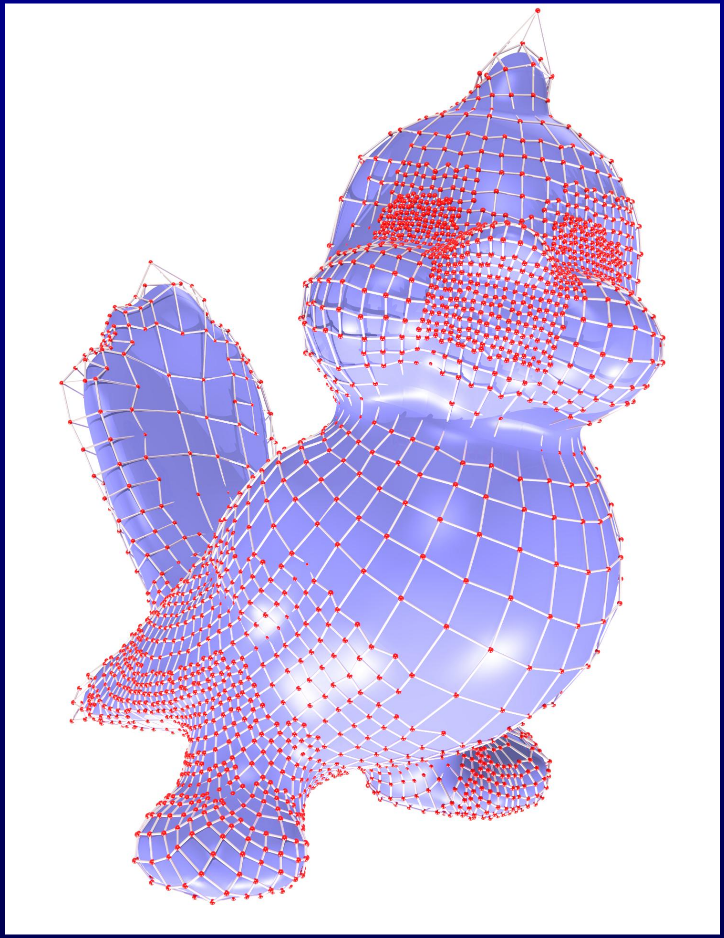
Manifold TSpline

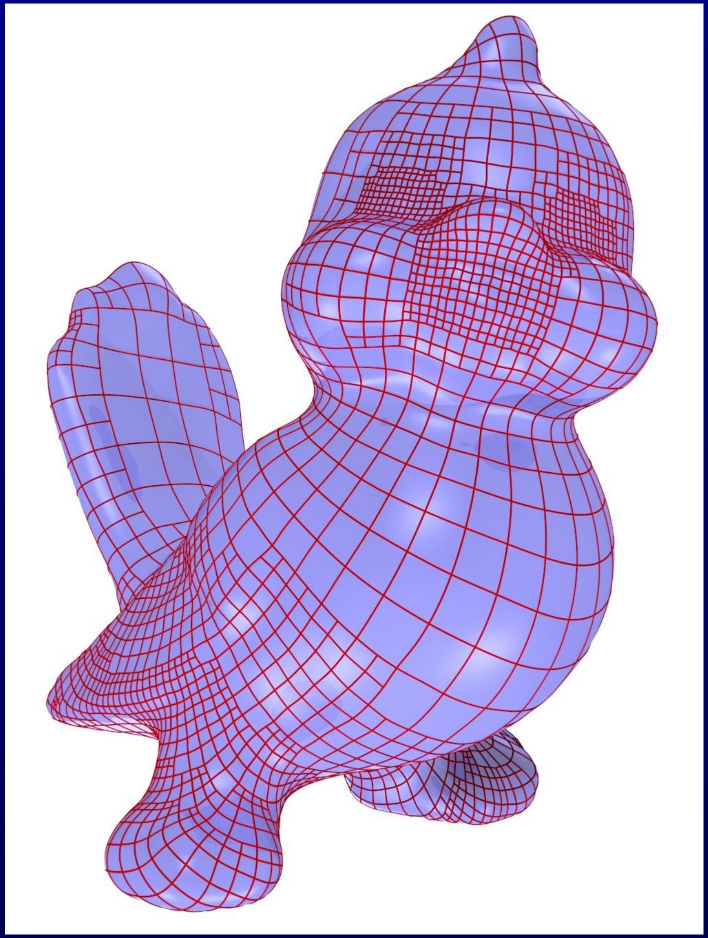


GeoSpline

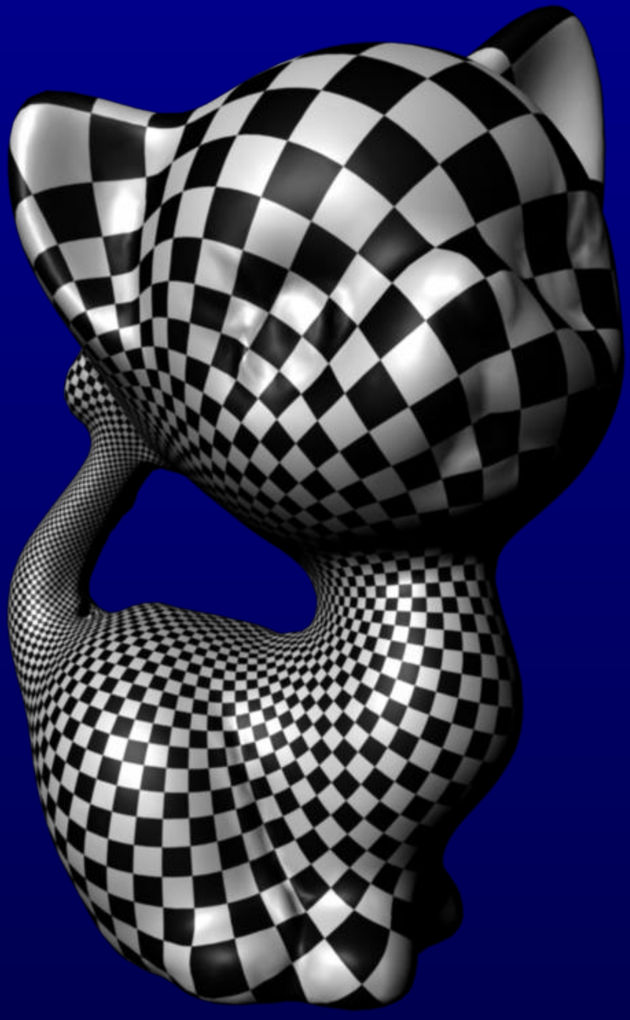


GeoSpline





GeoSpline



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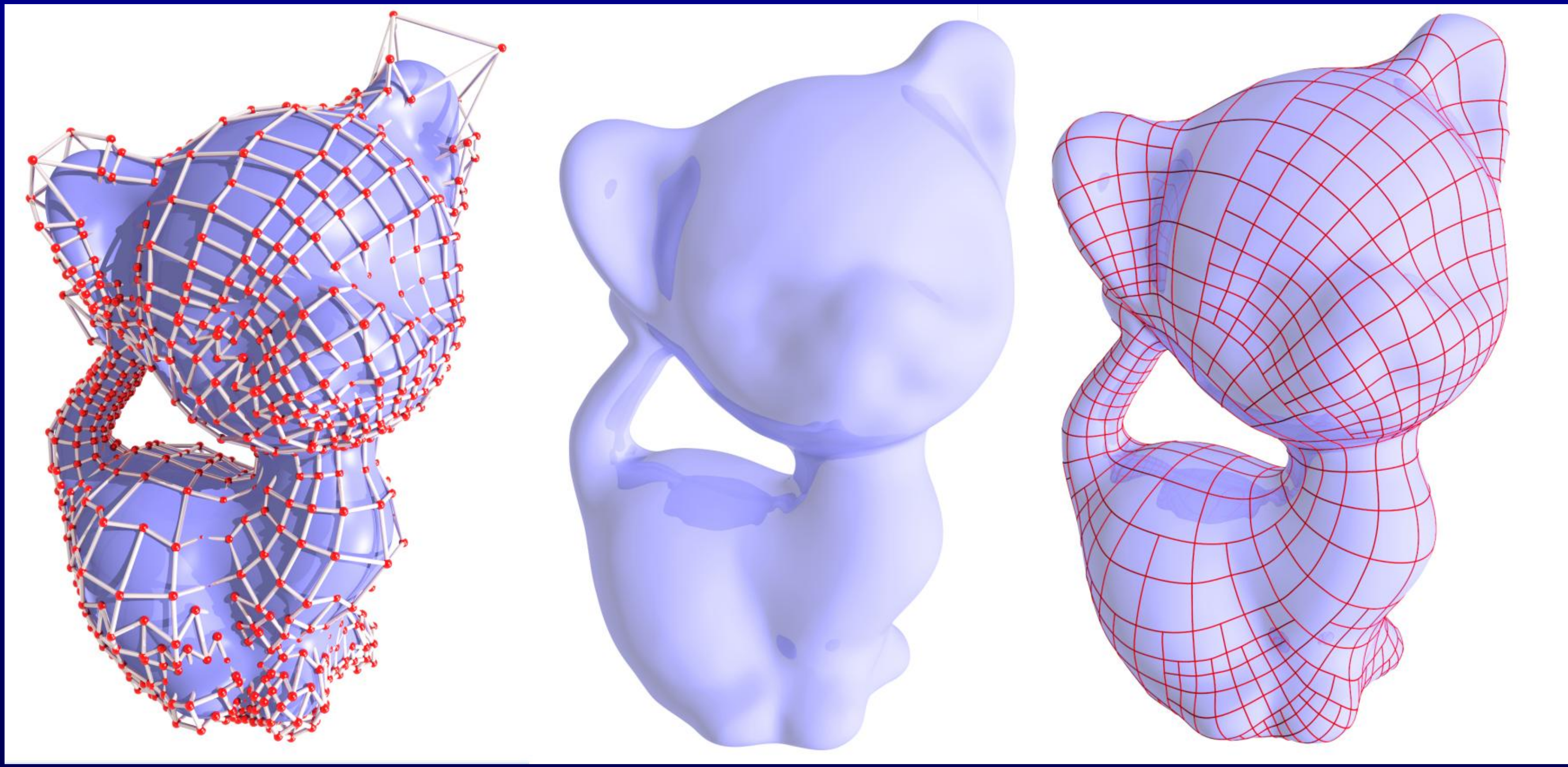
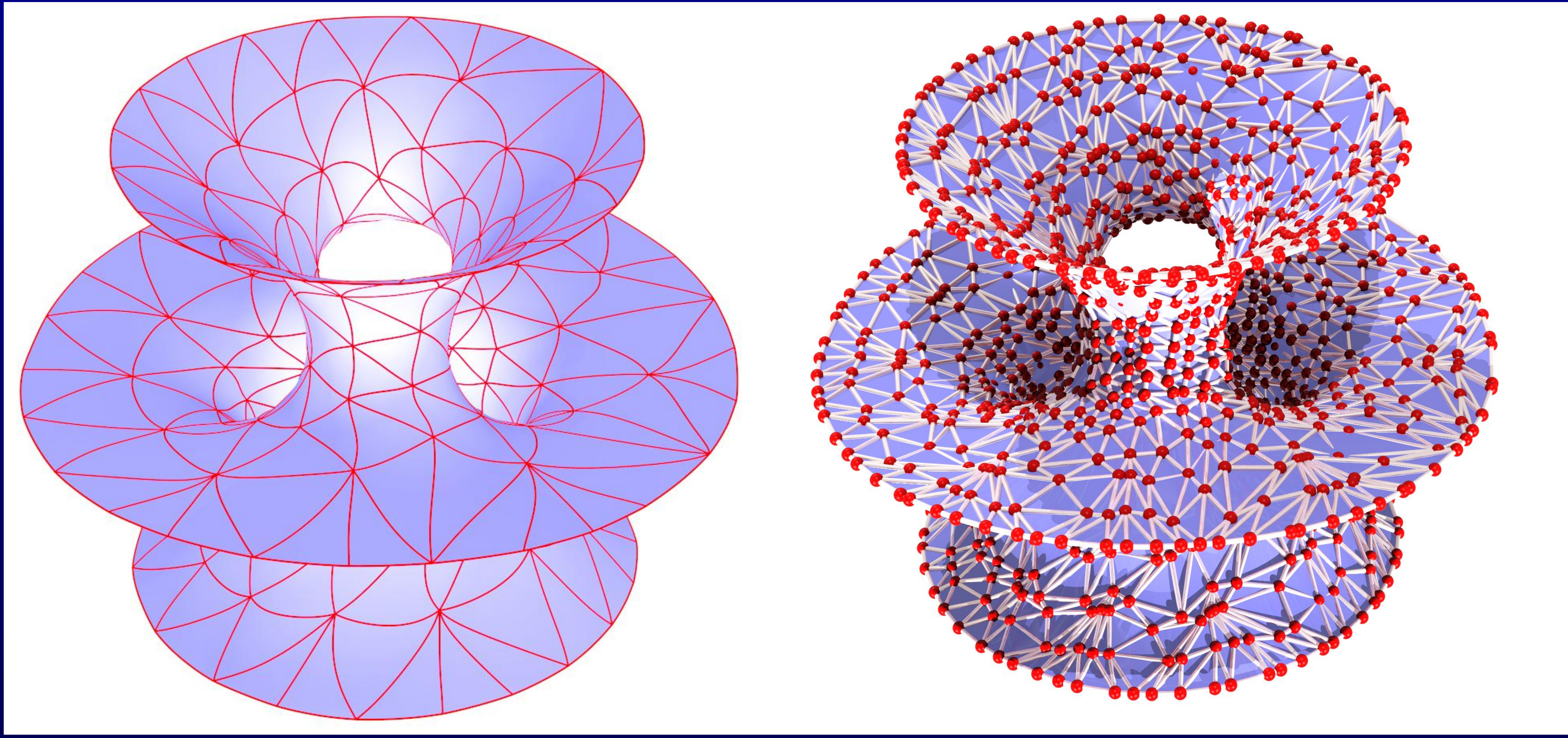
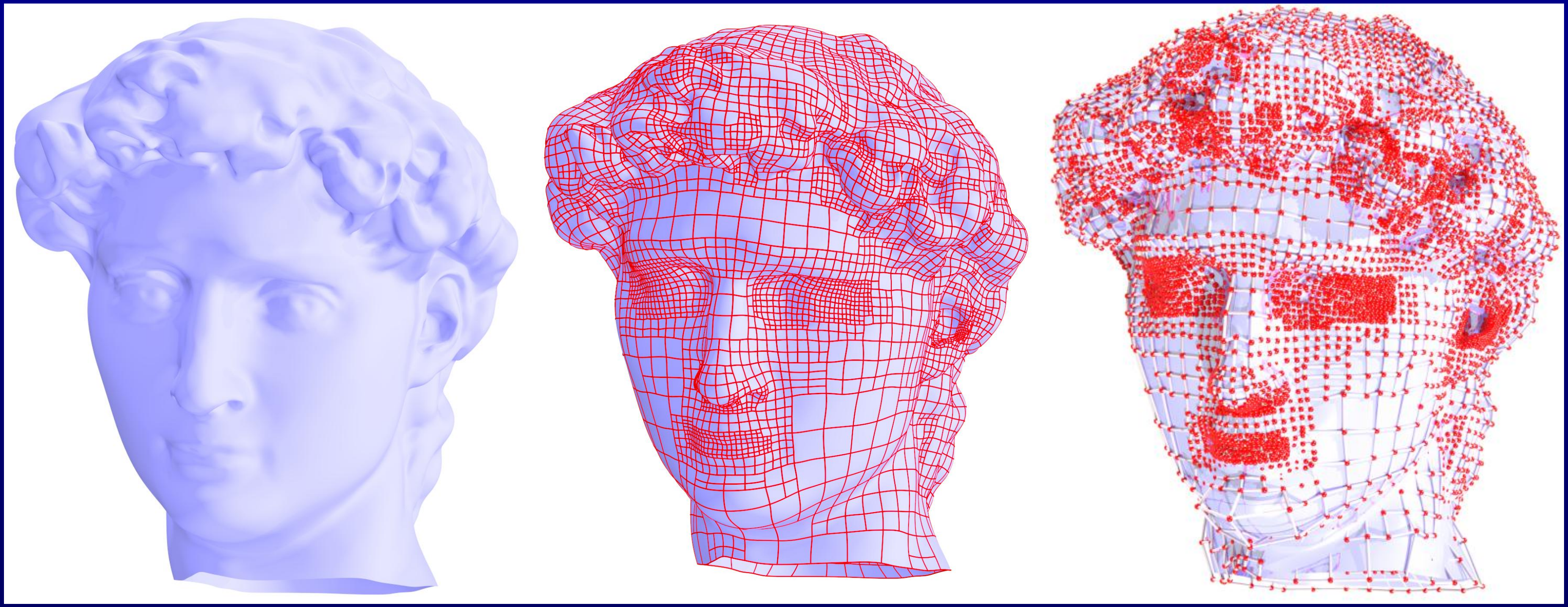


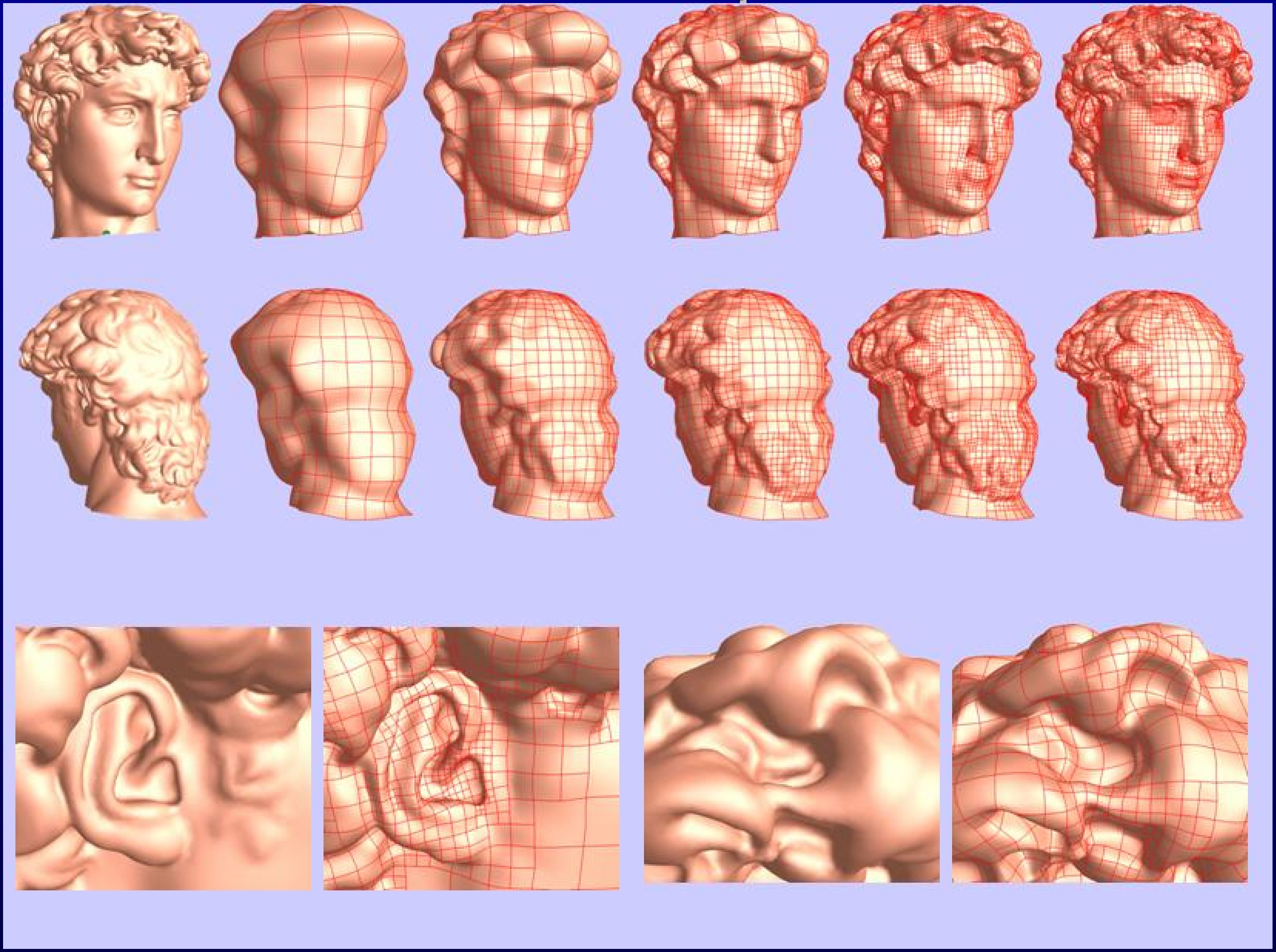
GeoSpline

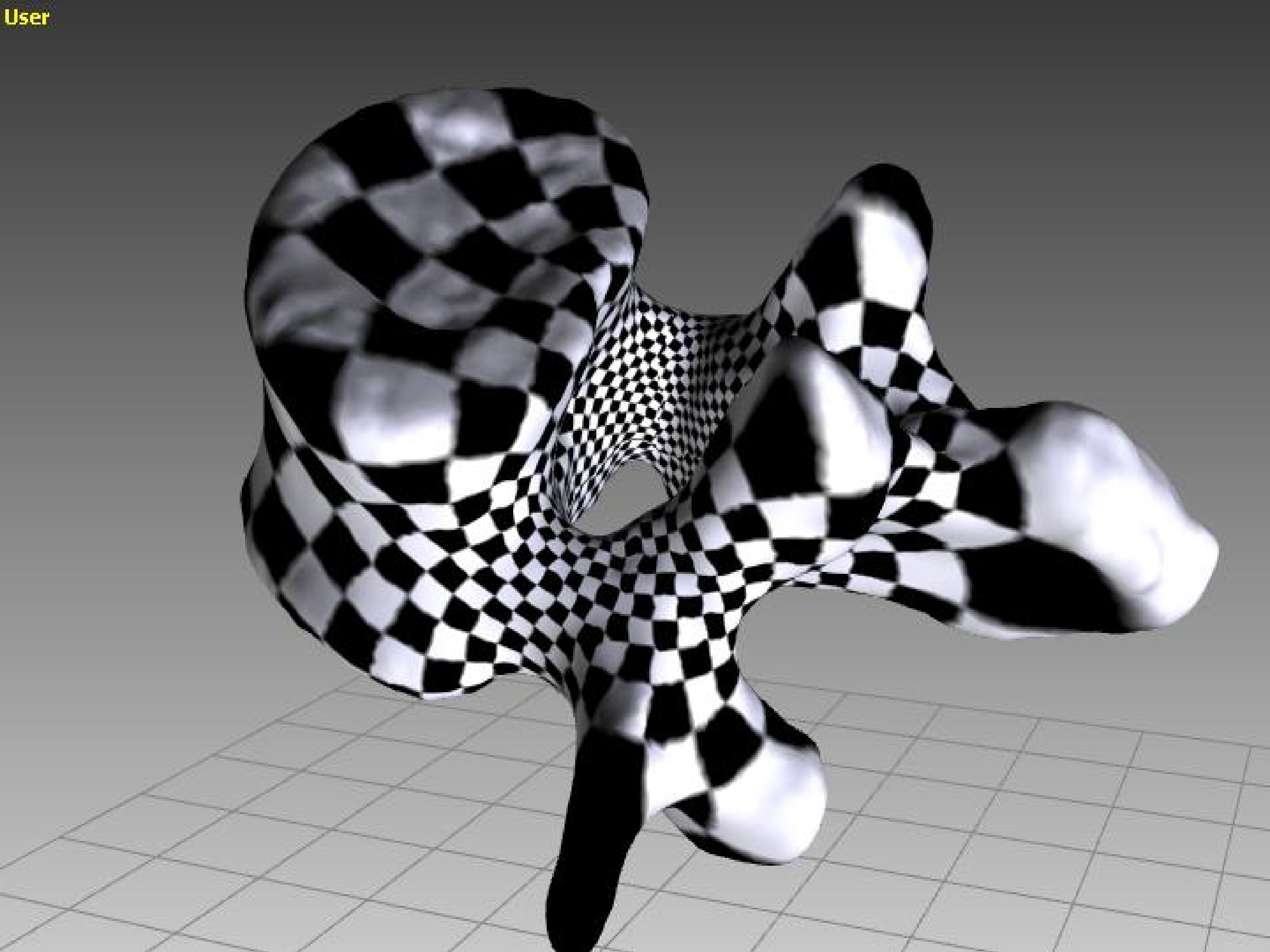


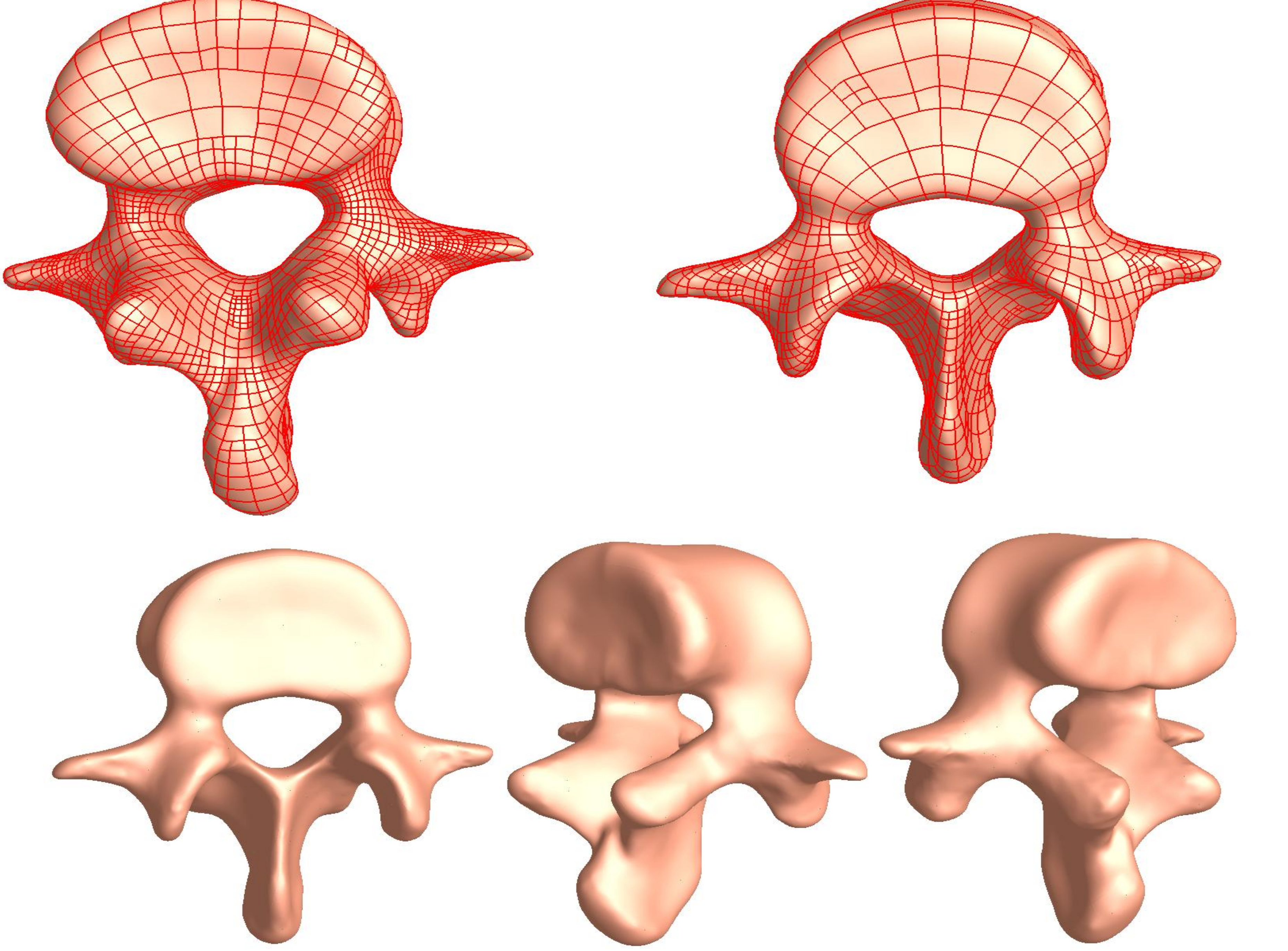
GeoSpline



Manifold TSpline




User



Conformal Geometry Applied in Computer Science

David Gu[1]

[1]Department of Computer Science
State University of New York at Stony Brook

Computational and Conformal Geometry

Collaborators

The work is collaborated with the

Mathematicians

Shing-Tung Yau, Feng Luo, Zeng-Xue He

Computer Scientists

Arie Kaufman, Hong Qin, Dimitris Samaras, Klaus Mueller, Joe Mitchell, Esther Arkin, Jie Gao

Artist

Lance Cong

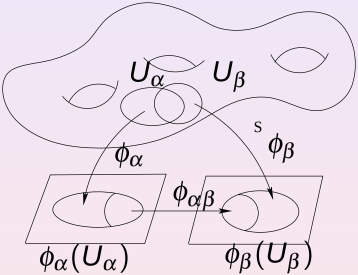
and many faculty members in computer science department in Stony Brook University.

Collaborators

The work is implemented by many students in the *Center of Visual Computing*. Especially, Miao Jin, Junho Kim, Xiaotian Yin, Wei Zeng and Xin Li.

Definition (Conformal Structure)

An atlas is conformal, if all its transition maps are conformal (biholomorphic). A conformal structure is the maximal conformal atlas. A topological surface with an conformal structure is called a Riemann Surface.

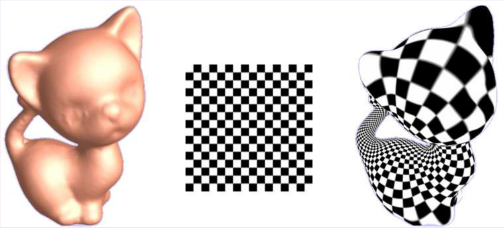


Relation between conformal structure and Riemannian metric

Isothermal Coordinates

A surface Σ with a Riemannian metric $\mathbf{g}$, a local coordinate system (u,v) is an isothermal coordinate system, if

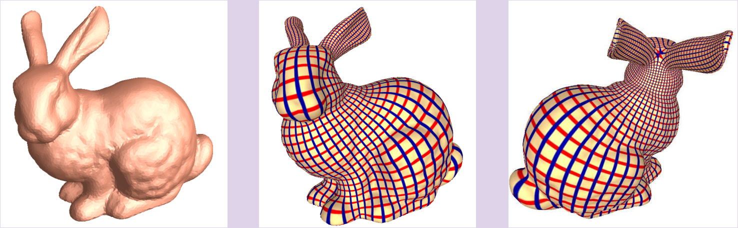
$$\mathbf{g} = e^{2u}(du^2 + dv^2).$$



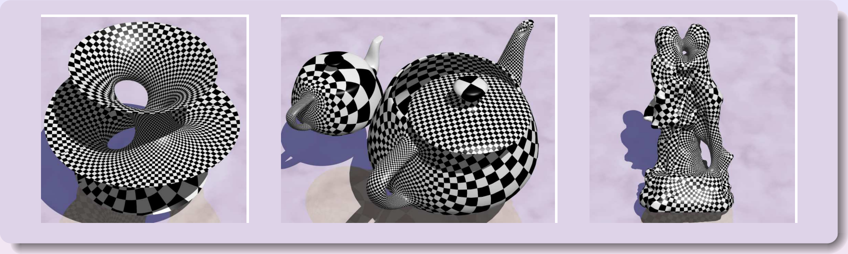
The atlas formed by isothermal coordinate systems is an conformal atlas.

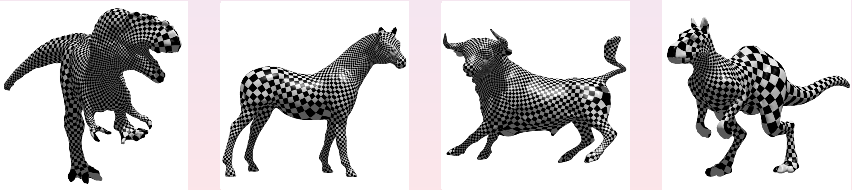
All metric surfaces are Riemann surfaces.

Conformal Structure



Conformal Structure





Heat Flow

Suppose the temperature field on the surface is $T(u,v,t)$, the surface is with a Riemannian metric $\mathbf{g}$, then the temperature will evolve according to the heat flow:

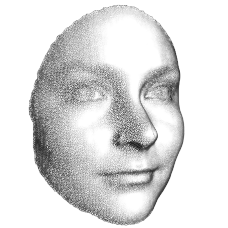
$$\frac{dT(u,v,t)}{dt} = \Delta_{\mathbf{g}} T(u,v,t),$$

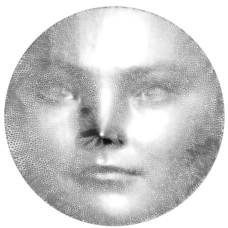
at the steady state

$$\Delta_{\mathbf{g}} T(u,v,\infty) \equiv 0,$$

which is called a harmonic function.

Heat Flow Acting on Linear Maps

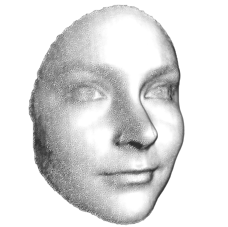


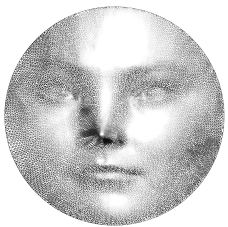


Linear Harmonic Maps

Heat flow acting on the maps

$$\frac{d\phi(u,v,t)}{dt} = \Delta\phi(u,v,t).$$





Linear Harmonic Maps

Heat flow acting on the maps

$$\frac{d\phi(u,v,t)}{dt} = \Delta\phi(u,v,t).$$

Heat Flow Acting on nonlinear Maps

Non-linear Harmonic Maps

Heat flow acting on the maps

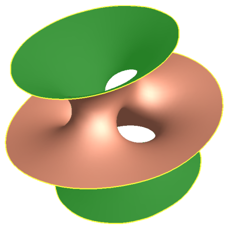
$$\frac{d\phi(u,v,t)}{dt} = \Delta\phi(u,v,t) - (\Delta\phi(u,v,t))^{\perp}$$

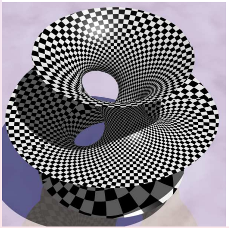
Heat Flow Acting on nonlinear Maps

Non-linear Harmonic Maps

Heat flow acting on the maps

$$\frac{d\phi(u,v,t)}{dt} = \Delta\phi(u,v,t) - (\Delta\phi(u,v,t))^{\perp}$$

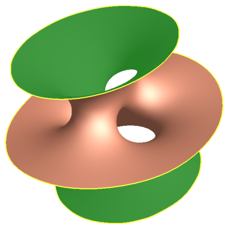


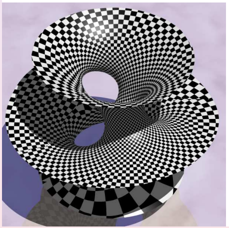


Holomorphic 1-forms

Heat flow acting on 1-forms, the heat flow is

$$\frac{d\omega(u,v,t)}{dt} = \Delta\omega(u,v,t).$$





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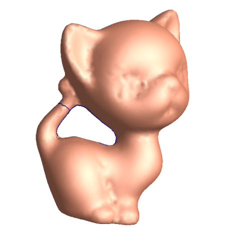
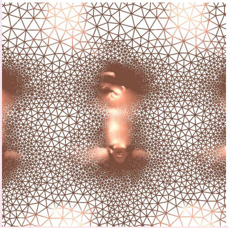
Heat Flow Acting on Metrics

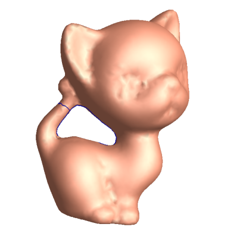


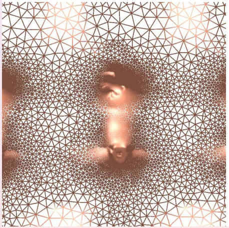


Euclidean Ricci Flow

Heat flow acting on metrics, the curvature satisfies the heat flow

$$\frac{dK(u,v,t)}{dt} = \Delta_{g(t)} K(u,v,t).$$





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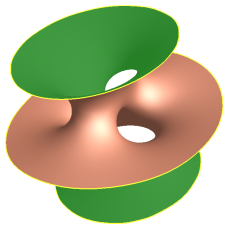

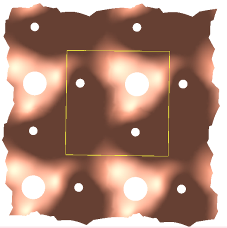

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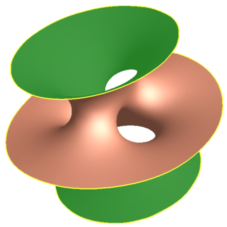

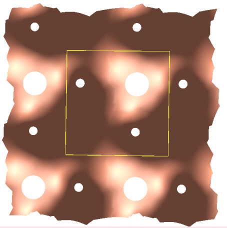

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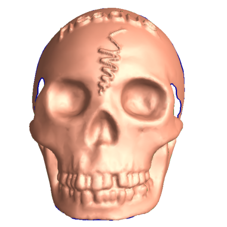

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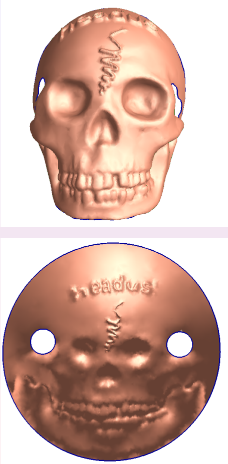

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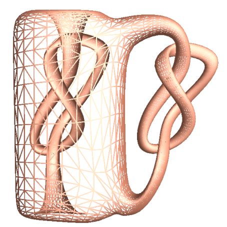

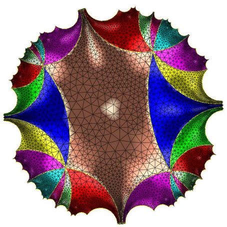

Hyperbolic Ricci Flow

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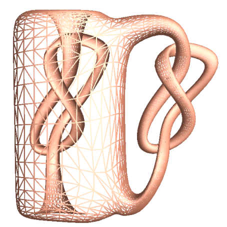

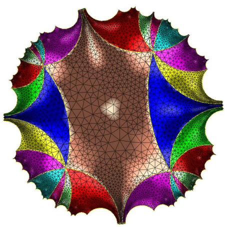

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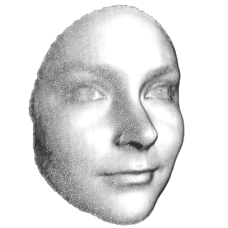
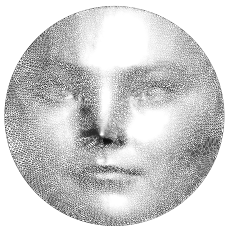
Heat Flow Acting on Linear Maps





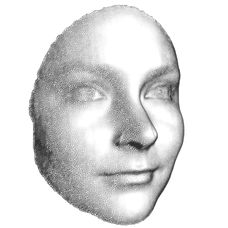
Linear Harmonic Maps

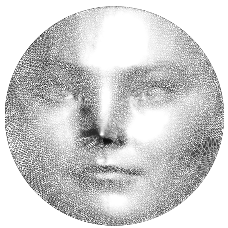
Heat flow acting on the maps

$$\frac{d\phi(u,v,t)}{dt} = \Delta\phi(u,v,t).$$

Theorem (Rado's theorem)

Assume $\Omega \subset \mathbb{R}^2$ is a convex domain with smooth boundary $\partial\Omega$. Given any homeomorphism $\phi : S^1 \to \partial\Omega$, there exists a unique harmonic map $u : D \to \Omega$, such that $u = \phi$ on $\partial D = S^1$ and u is a diffeomorphism.





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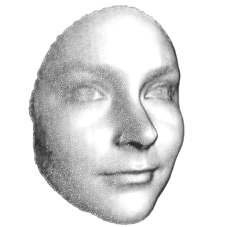
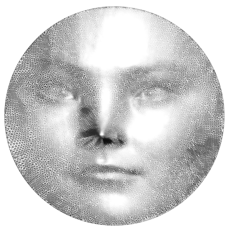




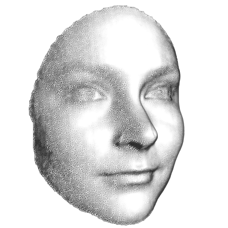
Finite Element Method

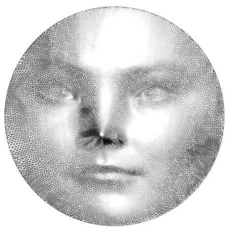
Given a mesh Σ, for an edge e_{ij} connecting vertices v_i and v_j, suppose two angles against e are α, β, the define *edge weight* as

$$w_{ij} = \frac{1}{2}(\cot\alpha + \cot\beta)$$

suppose a map $\phi : \Sigma \to \mathbb{R}^2$, then the discrete energy is

$$E(\phi) = \sum_{e_{ij}} w_{ij} |\phi(v_i) - \phi(v_j)|^2.$$





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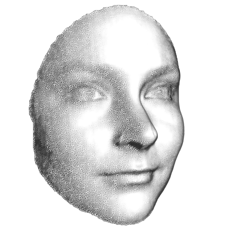
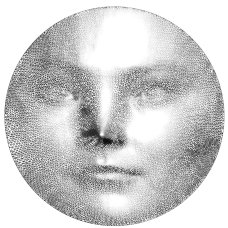




Finite Element Method

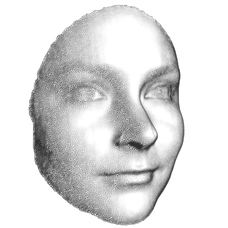
Discrete Laplace-Beltrami operator

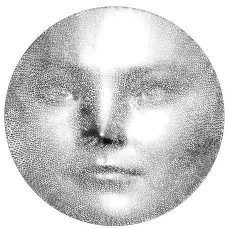
$$\Delta\phi(v_i) = \sum_{e_{ij}} w_{ij}(\phi(v_i) - \phi(v_j)),$$

Heat flow

$$\phi(v_i) -= \Delta\phi(v_i)\varepsilon,$$

where ε is a small constant.





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Non-linear Harmonic Maps

Heat flow acting on the maps

$$\frac{d\phi(u,v,t)}{dt} = \Delta\phi(u,v,t) - (\Delta\phi(u,v,t))^{\perp}$$

Theorem (Heat Flow for Topological Sphere)

The heat flow of a map from a closed genus zero surface to the unit sphere converges to a conformal map under normalization constraints. The conformal map is a diffeomorphism.

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Discrete Approximation

Heat flow acting on the maps

$$\phi(v_i) - = (\Delta\phi(v_i) - \Delta\phi(v_i)^{\perp})\varepsilon$$

where $\Delta\phi(v_i))^{\perp}$ is defined as

$$< \Delta\phi(v_i), \phi(v_i) > \phi(v_i).$$

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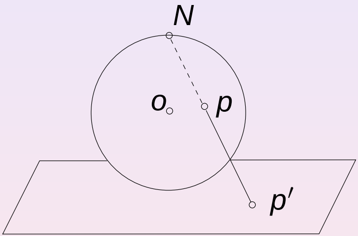
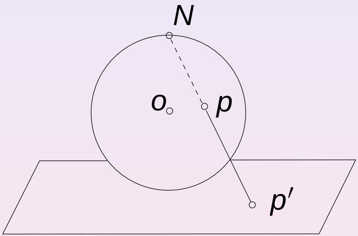
Spherical Conformal Maps



Stereo graphic projection

A conformal map from the unit sphere $p(x,y,z)$ to the complex plane

$$p' = \frac{2}{2-z}p,$$



Stereo graphic projection

A conformal map from the unit sphere $p(x,y,z)$ to the complex plane

$$p' = \frac{2}{2-z}p,$$

Möbius Transform

A Möbius transform on the complex plane $\phi:\mathbb{C}\to\mathbb{C}$ is

$$\phi(z)=\frac{az+b}{cz+d}, ad-bc=1,$$

where $a,b,c,d\in\mathbb{C}$

Theorem (Conformal Automorphism Group)

The conformal maps from a unit sphere to itself (or the complex plane) differ by a Möbius map.

Normalization

In order to remove the Möbius ambiguity, spherical harmonic map in normalized

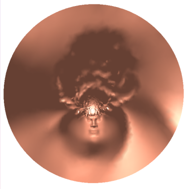
1. Compute the mass center of the image,

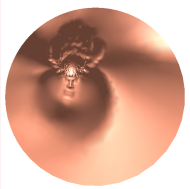
$$\mathbf{c} = \sum_{v_i} \phi(v_i),$$

2. Normalize

$$\phi(v_i) = \frac{\phi(v_i) - \mathbf{c}}{|\phi(v_i) - \mathbf{c}|}$$

Riemann Mapping Theorem

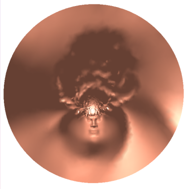


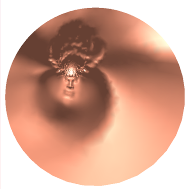


Topological Disk Conformal Mapping

1. Double cover
2. Conformally map the doubled surface to the unit sphere
3. Use the sphere Möbius transformation to make the mapping symmetric.
4. Use stereographic projection to map each hemisphere to the unit disk.

Riemann Mapping Theorem





Möbius Transformation

A Möbius transformation from the unit disk to itself is a conformal map

$$\phi(z) = e^{i\theta}\frac{z - z_0}{1 - \bar{z}_0 z}.$$

Theorem (Riemann Mapping)

Any metric topological disk can be conformally mapped to the unit disk, the mapping is unique up to a Möbius transformation.

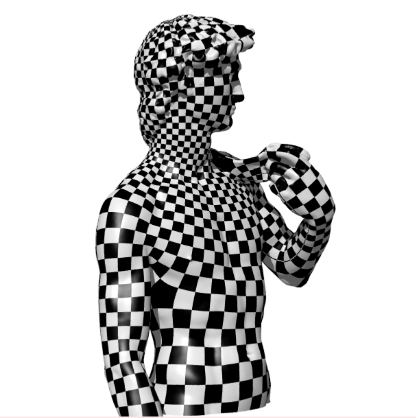
Definition (Holomorphic 1-form)

Suppose Σ is a Riemann surface, $\{z_\alpha\}$ is a local complex parameter, a holomorphic 1-form ω has a local representation as

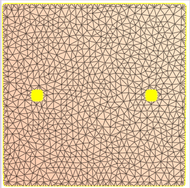
$$\omega = f(z_\alpha)dz_\alpha,$$

where $f(z_\alpha)$ is a holomorphic function.

Locally, ω is the derivative of a holomorphic function. Globally, it is not.

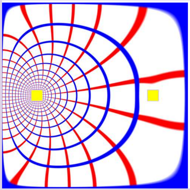


Original Surface

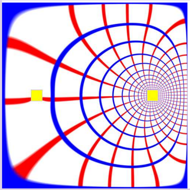


Holomorphic 1-forms

One basis holomorphic 1-form

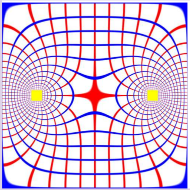


Another one basis holomorphic 1-form

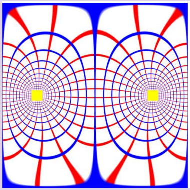


Holomorphic 1-forms

Summation of ω_1 and ω_2

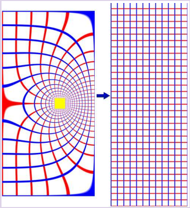


Difference between ω_1 and ω_2



Holomorphic 1-forms

Holomorphic 1-form induces a conformal parameterization.



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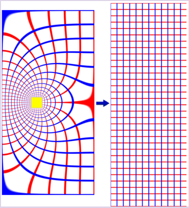
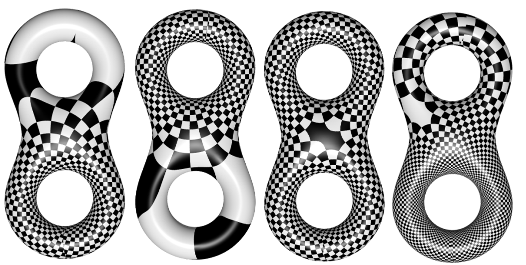


Theorem (Holomorphic 1-forms)

All holomorphic 1-forms form a linear space $\Omega(\Sigma)$ which is isomorphic to the first cohomology group $H^1(\Sigma, \mathbb{R})$.

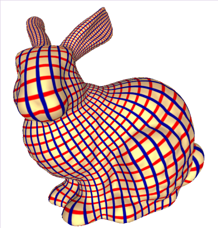


Holomorphic 1-forms

Holomorphic 1-form ω can be treated as two real 1-forms $\omega = (\omega_0, \omega_1)$.

Furthermore, we can treat each 1-form as a vector field, such that

1. $curl\, \omega_0 \equiv 0$
2. $div\, \omega_0 \equiv 0$
3. $\omega_1 = \mathbf{n} \times \omega_0$, where **n** is the normal field.



Holomorphic 1-forms

Intuition Hodge star operator rotates a vector field about the normal a right angle.

Definition (Hodge Star)

Hodge star operator is defined in the following:

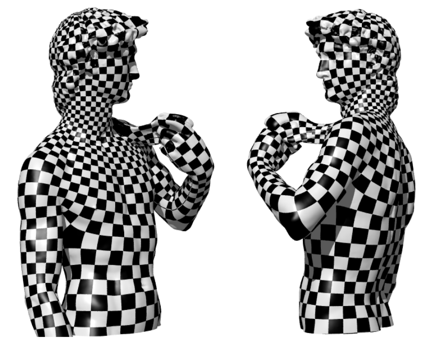
$$*dx = dy, *dy = -dx,$$

Definition (harmonic 1-form)

Suppose Σ is a Riemann surface, ω is differential 1-form, locally ω is the derivative of a harmonic function. Symbolically,

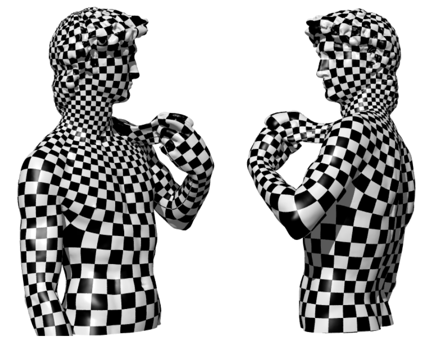
$$d\omega = 0, *d*\omega = 0.$$

Globally , such harmonic function doesn't exist



Theorem (Hodge)

Each cohomologous class has a unique harmonic 1-form.



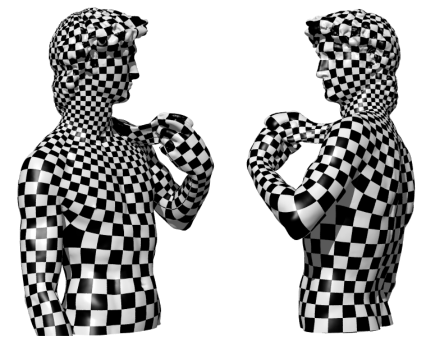
Holomorphic 1-forms

Algorithm for Holomorphic 1-forms

Input : A triangle mesh Σ.
Output : Basis for holomorphic 1-forms

1. Compute cohomology basis $\{\omega_1, \omega_2, \cdots, \omega_n\}$.
2. Heat flow to deform ω_i to harmonic 1-forms.
3. Compute hodge star of ω_i's.
4. return holomorphic 1-form basis

$$\{\omega_1 + \sqrt{-1} * \omega_1, \omega_2 + \sqrt{-1} * \omega_2, \cdots, \omega_n + \sqrt{-1} * \omega_n\}$$



Holomorphic 1-forms

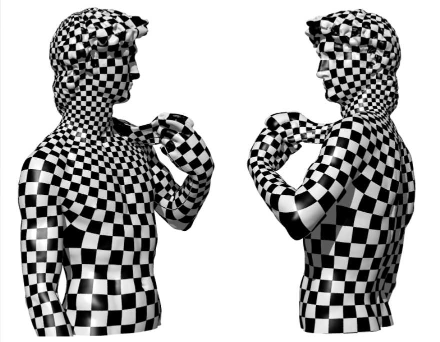
Heat Flow for 1-forms

Suppose $\omega : \{Edges\} \to \mathbb{R}$ is a closed 1-form. Let $f : \{Vertices\} \to \mathbb{R}$ is a function, then

$$f - = \Delta(\omega + df) \times \varepsilon,$$

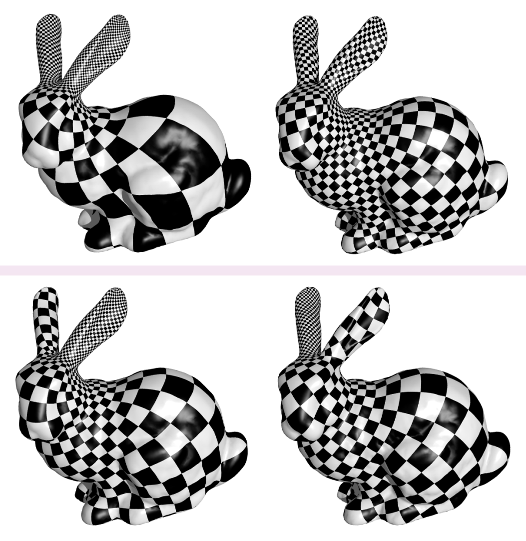
where $\Delta(\omega + df)(v_i)$

$$\sum_{e_{ij}} w_{ij}(\omega(e_{ij}) + f(v_j) - f(v_i)).$$



Holomorphic 1-forms

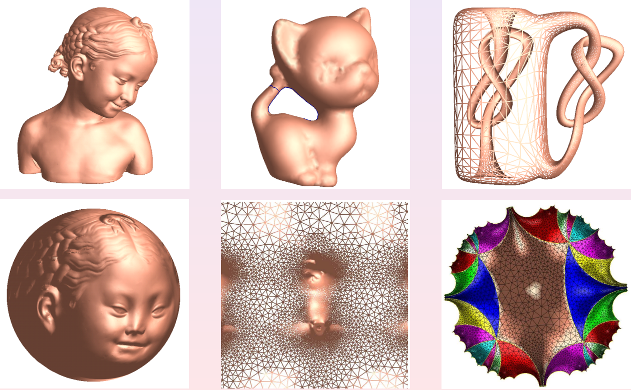
Choose the best cohomology class to optimize the distortion,



Uniformization

Theorem (Poincaré Uniformization Theorem)

Let $(\Sigma, \mathbf{g})$ be a compact 2-dimensional Riemannian manifold. Then there is a metric $\tilde{\mathbf{g}} = e^{2\lambda}\mathbf{g}$ conformal to $\mathbf{g}$ which has constant Gauss curvature.



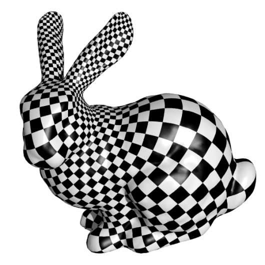
Spherical   Euclidean   Hyperbolic

Definition

Suppose Σ is a surface with a Riemannian metric,

$$\mathbf{g} = \begin{pmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{pmatrix}$$

Suppose $\lambda : \Sigma \to \mathbb{R}$ is a function defined on the surface, then $e^{2\lambda}\mathbf{g}$ is also a Riemannian metric on Σ and called a conformal metric. $e^{2\lambda}$ is called the conformal factor.



Angles are invariant measured by conformal metrics.

Suppose $\bar{\mathbf{g}} = e^{2\lambda}\mathbf{g}$ is a conformal metric on the surface, then the Gaussian curvature on interior points are

$$\bar{K} = e^{-2\lambda}(-\Delta\lambda + K),$$

geodesic curvature on the boundary

$$\bar{k_g} = e^{-\lambda}(\partial_n\lambda + k_g).$$

Definition (Surface Ricci Flow)

A closed surface with a Riemannian metric $\mathbf{g}$, the Ricci flow on it is defined as

$$\frac{dg_{ij}}{dt} = -Kg_{ij}.$$

If the total area of the surface is preserved during the flow, the Ricci flow will converge to a metric such that the Gaussian curvature is constant every where.

Theorem (Hamilton 1982)

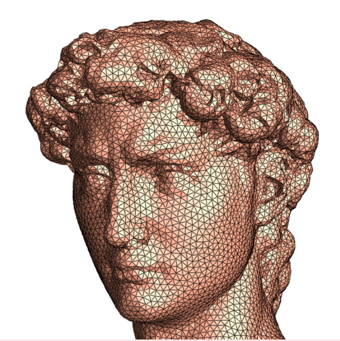
For a closed surface of non-positive Euler characteristic, if the total area of the surface is preserved during the flow, the Ricci flow will converge to a metric such that the Gaussian curvature is constant (equals to $\bar{K}$) every where.

Theorem (Chow)

For a closed surface of positive Euler characteristic, if the total area of the surface is preserved during the flow, the Ricci flow will converge to a metric such that the Gaussian curvature is constant (equals to $\bar{K}$) every where.

Generic Surface Model - Triangular Mesh

- Surfaces are represented as polyhedron triangular meshes.
- Isometric gluing of triangles in $\mathbb{E}^2$.
- Isometric gluing of triangles in $\mathbb{H}^2, \mathbb{S}^2$.



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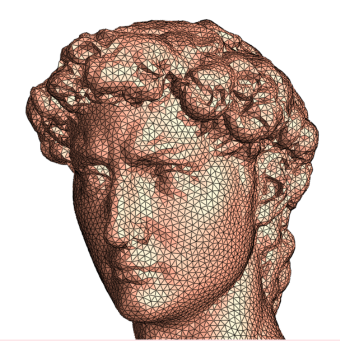

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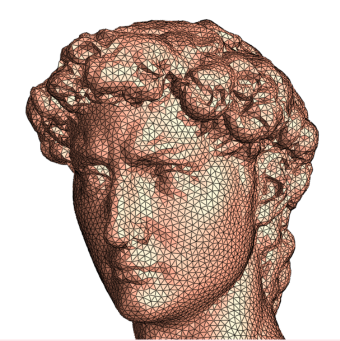
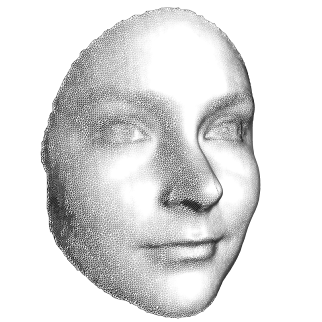


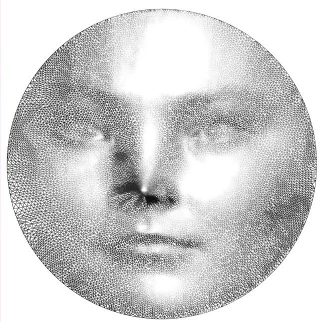
Discrete Metrics

Definition (Discrete Metric)

A Discrete Metric on a triangular mesh is a function defined on the vertices, $l : E = \{all\ edges\} \rightarrow \mathbb{R}^+$, satisfies triangular inequality.

A mesh has infinite metrics.

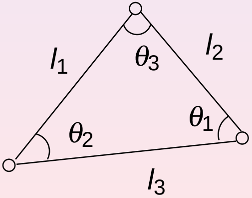




Metric

- Discrete Metric: $l : E = \{all\ edges\} \rightarrow \mathbb{R}^1$, satisfies triangular inequality.
- Metrics determine curvatures by cosine law.

$$\cos\theta_i = \frac{l_j^2 + l_k^2 - l_i^2}{2l_j l_k}, l \neq j \neq k \neq i$$



Derivative Cosine Law

Theorem (Derivative Cosine Law)

Consider an Euclidean triangle $\theta_i = \theta_i(l_1, l_2, l_3)$, $i \neq j \neq k \neq i$, then

$$\frac{1}{\sin\theta_i}\frac{\partial\theta_i}{\partial l_j} = \frac{1}{\sin\theta_j}\frac{\partial\theta_j}{\partial l_i}$$

Discrete Curvature

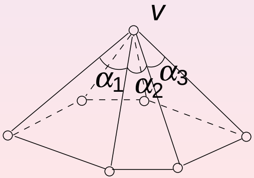
Definition (Discrete Curvature)

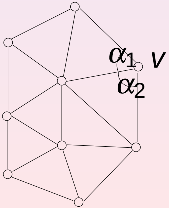
Discrete curvature: $K : V = \{vertices\} \to \mathbb{R}^1$.

$$K(v) = 2\pi - \sum_i \alpha_i, v \notin \partial M; K(v) = \pi - \sum_i \alpha_i, v \in \partial M$$

Theorem (Discrete Gauss-Bonnet theorem)

$$\sum_{v \notin \partial M} K(v) + \sum_{v \in \partial M} K(v) = 2\pi\chi(M).$$

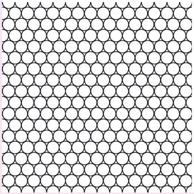
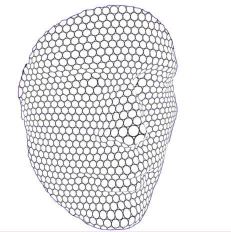




Conformal metric deformation

Conformal maps Properties

- transform infinitesimal circles to infinitesimal circles.
- preserve the intersection angles among circles.

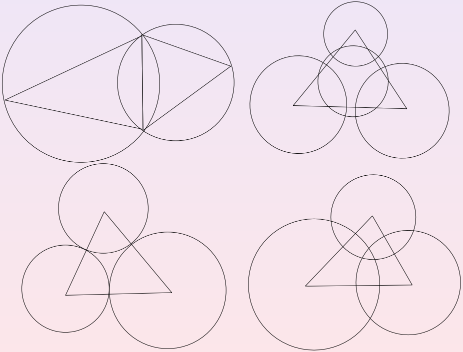
Idea - Approximate conformal metric deformation

Replace infinitesimal circles by circles with finite radii.

Different Circle Patterns

Circle Patterns

There are many local settings for circle patterns. The radius is variable, the intersection angles do not change.



Circle Packing Metric

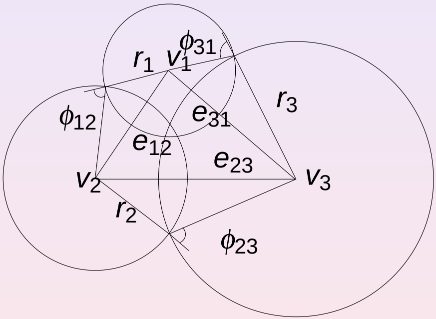
CP Metric

We associate each vertex v_i with a circle with radius γ_i. On edge e_{ij}, the two circles intersect at the angle of Φ_{ij}. The edge lengths are

$$l_{ij}^2 = \gamma_i^2 + \gamma_j^2 + 2\gamma_i\gamma_j \cos\Phi_{ij}$$

CP Metric (Σ, Γ, Φ), Σ triangulation,

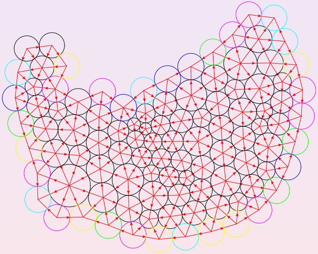
$$\Gamma = \{\gamma_i | \forall v_i\}, \Phi = \{\phi_{ij} | \forall e_{ij}\}$$

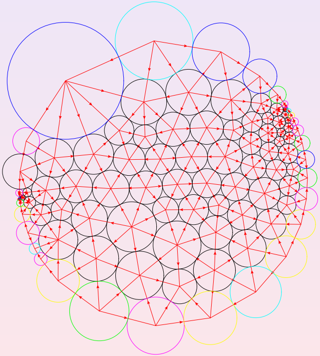


Conformal Equivalent Circle Packing Metrics

Definition (Conformal Equivalent Circle Packing Metrics)

Two circle packing metrics of the same mesh M, $\{M, \Gamma_1, \Phi_1\}$ and $\{M, \Gamma_2, \Phi_2\}$, are *conformal equivalent*, if Φ_1 equals to Φ_2.





Conformal Metric Space

Suppose the vertex set of the mesh is $\{v_1, v_2, \cdots, v_n\}$, we represent a conformal circle packing metric by $\mathbf{u} = (u_1, u_2, \cdots, u_n)$, where $u_i = \log \gamma_i$.

Definition (Normalized Conformal Circle Packing Metric Space)

Each conformal equivalence class of circle packing metrics form a space, we call it *conformal circle packing metric space*. Because scaling doesn't affect curvature, we require $\sum_i u_i = 0$. All such $\mathbf{u}$ form a hyper-plane in the $\mathbb{R}^n$, denoted as Π_u. We call Π_u the *normalized conformal circle packing metric space*.

Curvature Space

Definition (Discrete Curvature Space)

We use $\mathbf{k} = (k_1, k_2, \cdots, k_n)$ to represent the curvature on the vertices of the mesh. Then all such $\mathbf{k}$ form the *discrete curvature space*, which is on a hyper-plane in $\mathbb{R}^n$, $\sum_i k_i = 2\pi\chi(M)$, $\chi(M)$ is the Euler number of the mesh.

Curvature Map

Definition (Discrete Curvature Map)

The discrete curvature Equation defines a discrete curvature map

$$K: \mathbf{u} \to \mathbf{k}. \tag{1}$$

Image of Curvature Map

Given any subset $I \subset V$, let F_I be the set of all faces in M whose vertices are in I and let the link of I, denoted by $Lk(I)$, be the set of pairs (e,v) of an edge e and a vertex v so that (1) the end points of e are not in I and (2) the vertex v is in I and (3) e and v form a triangle.

Theorem (Image of Curvature Space)

All possible curvatures functions **k** *induced by a conformal equivalence class of circle packing metrics* $\{M,\Gamma,\Phi\}$*, where* Γ *varies but* Φ *is fixed, form a* $n-1$ *dimensional convex polytope, such that the total curvature satisfies the Gauss-Bonnet theorem and for any proper subset* $I \subset V$*,*

$$\frac{2\pi|I|\chi(M)}{|V|} > -\sum_{(e,v)\in Lk(I)} (\pi - \Phi(e)) + 2\pi\chi(F_I). \quad (2)$$

The convex polytope is denoted as Ω_k*.*

Theorem (Inverse Curvature Map)

The curvature map K from normalized conformal circle packing metrics space Π_u to the image of curvature map Ω_k is a C^∞ diffeomorphism, furthermore, it is real analytic.
The derivative map $dK : T\Pi_u(\mathbf{u}) \to T\Omega_k(\mathbf{k})$, satisfies the discrete Poisson equation,

$$d\mathbf{k} = \Delta(\mathbf{u})d\mathbf{u}, \tag{3}$$

where $T\Pi_u(\mathbf{u})$ is the tangent space of Π_u at the point $\mathbf{u}$, $T\Omega_k(\mathbf{k})$ is the tangent space of Ω_k at the point $\mathbf{k}$, $\Delta(\mathbf{u})$ is a positive definite matrix when constrained on $T\Pi_u(\mathbf{u})$.

Discrete Euclidean Ricci flow

Definition (Discrete Ricci flow)

A mesh Σ with a circle packing metric $\{\Sigma, \Gamma, \Phi\}$, where $\Gamma = \{\gamma_i, v_i \in V\}$ are the vertex radii, $\Phi = \{\Phi_{ij}, e_{ij} \in E\}$ are the angles associated with each edge, the discrete Ricci flow on Σ is defined as

$$\frac{d\gamma_i}{dt} = (\bar{K}_i - K_i)\gamma_i,$$

where $\bar{K}_i$ are the target curvatures on vertices. If $\bar{K}_i \equiv 0$, the flow with normalized total area leads to a metric with constant Gaussian curvature.

Idea

Metric deformation is driven by curvature.

Discrete Euclidean Ricci flow

Theorem (Chow and Luo 2002)

A discrete Euclidean Ricci flow $\{\Sigma,\Gamma,\Phi\} \to \{M,\bar{\Gamma},\Phi\}$ *converges.*

$$|K_i(t)-\bar{K}_i| < c_1 e^{-c_2 t},$$

and

$$|\gamma_i(t)-\bar{\gamma}_i| < c_1 e^{-c_2 t},$$

where c_1, c_2 *are positive numbers.*

Definition

Let $u_i = ln\gamma_i$, the Ricci energy is defined as

$$f(\mathbf{u}) = \int_{\mathbf{u}_0}^{\mathbf{u}} \sum_{i=1}^{n} (K_i - \bar{K}_i) du_i,$$

where $\mathbf{u} = (u_1, u_2, \cdots, u_n)$, $\mathbf{u}_0 = (0, 0, \cdots, 0)$.

Derivative Euclidean Cosine Law

Theorem (Ricci Energy)

Euclidean Ricci energy is Well defined and convex, namely, there exists a unique global minimum.

Proof.

In an Euclidean triangle, with angles $(\theta_1, \theta_2, \theta_3)$ and radius $(\gamma_1, \gamma_2, \gamma_3)$, let $u_i = ln\gamma_i$, according to Euclidean cosine law,

$$\frac{\partial \theta_i}{\partial u_j} = \frac{\partial \theta_j}{\partial u_i}.$$

Therefore $\omega = \sum \theta_i du_i$ is a closed 1-form. The Euclidean Ricci energy is well defined. Direct computation verifies that Hessian matrix is positive definite. $\square$

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Newton's method for Euclidean Ricci energy

Gradient descent Method

Ricci flow is the gradient descent method for minimizing Ricci energy,

$$\nabla f = (K_1 - \bar{K}_1, K_2 - \bar{K}_2, \cdots, K_n - \bar{K}_n).$$

Newton's method

The Hessian matrix of Ricci energy is

$$\frac{\partial^2 f}{\partial u_i \partial u_j} = \frac{\partial K_i}{\partial u_j}.$$

Newton's method can be applied directly.

Ricci Flow for Uniform Flat Metric

Suppose Σ is a closed genus one mesh,

1. Compute the circle packing metric (Γ, Φ).
2. Set the target curvature to be zero for each vertex

$$\bar{K}_i \equiv 0, \forall v_i \in V$$

3. Minimize the Euclidean Ricci energy using Newton's method to get the target radii $\bar{\Gamma}$.
4. Compute the target flat metric.

Algorithm : uniform flat metric for open surfaces

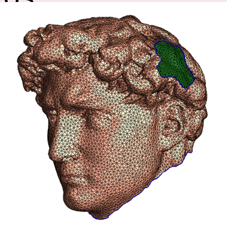
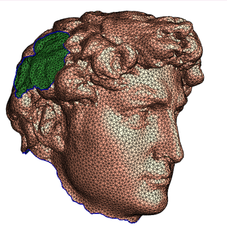
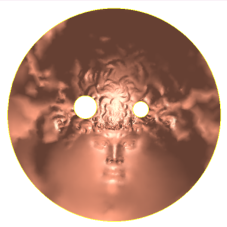
Given a surface Σ with genus g and b boundaries, then it Euler number is

$$\chi(\Sigma) = 2 - 2g - b.$$

Suppose the boundary of Σ is a set of closed curves

$$\partial\Sigma = C_1 \cup C_2 \cup C_3 \cdots C_b.$$

The total curvature for each C_i is denoted as $2m_i\pi, m_i \in \mathbb{Z}$, and $\sum_{i=1}^{b} m_i = \chi(\Sigma)$. The target curvature for interior vertices are zeros.

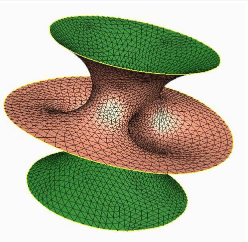




Euclidean Ricci flow for open surfaces

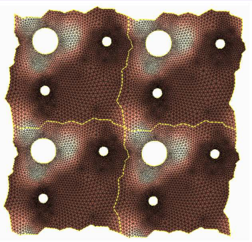
- Use Newton's method to minimize the Ricci energy to update the metric.
- Adjust the boundary vertex curvature to be proportional to the ratio between the current lengths of the adjacent edges and the current total length of the boundary component.
- Repeat until the process converges.

Embedding

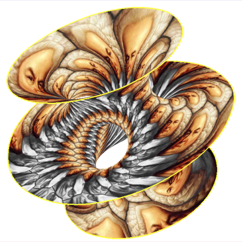
1. Determine the planar shape of each triangle using 3 edge lengths.
2. Glue all triangles on the plane along their common edges by rigid motions. Because the metric is flat, the gluing process is coherent and results in a planar embedding.



original surface
genus 1, 3 boundaries

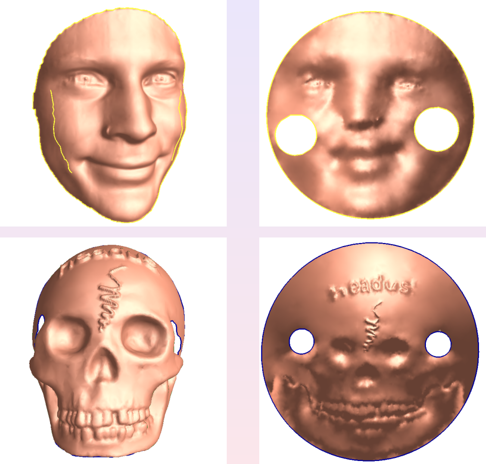


universal cover
embedded in $\mathbb{R}^2$

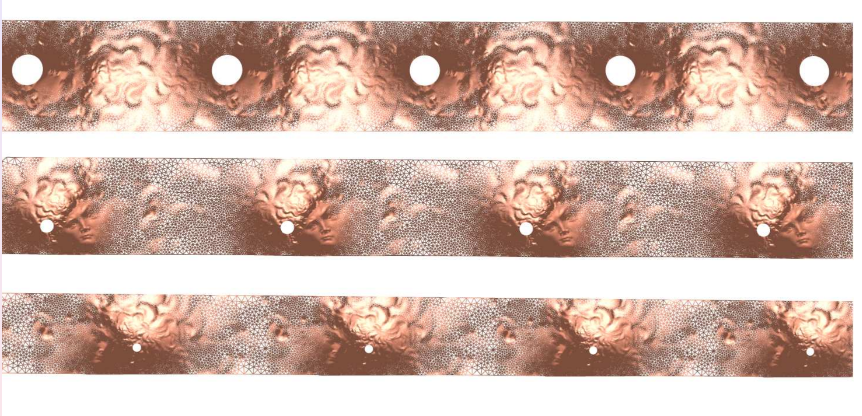


texture mapping

Euclidean Uniform Flat Metric

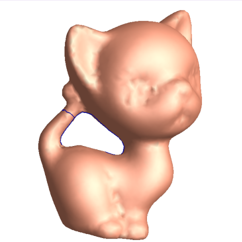


Euclidean Uniform Flat Metric

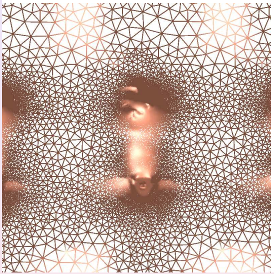


Different boundaries are mapped to straight lines.

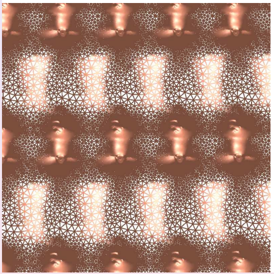
Euclidean Uniform Flat Metric



original surface



fundamental domain



universal cover

Optimal Parameterizations Problem

Optimal Conformal Parameterizations

A surface has infinite conformal mappings, different mappings have different area distortions.

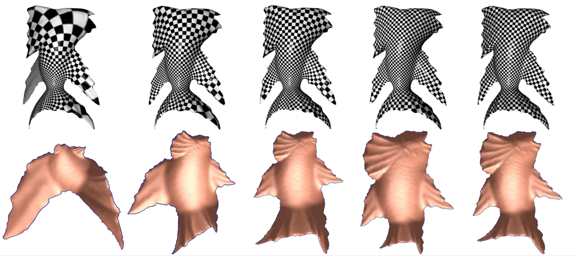
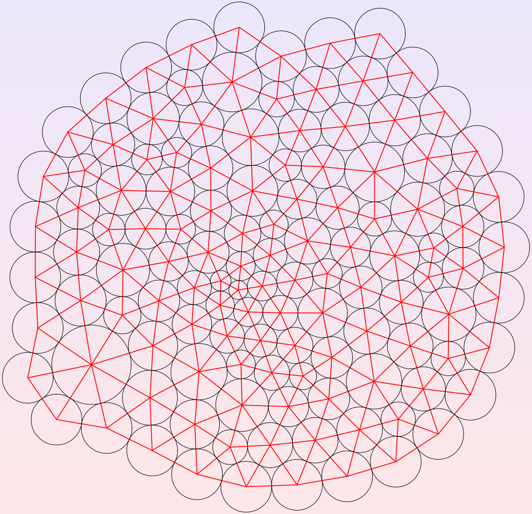
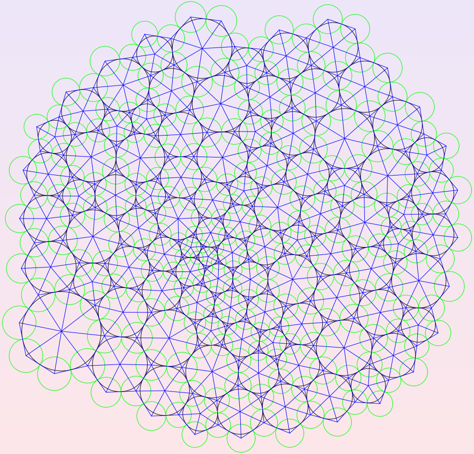


Figure: There are an infinity number of conformal parameterizations of a given surface. We minimize the area distortion within the conformal mappings.

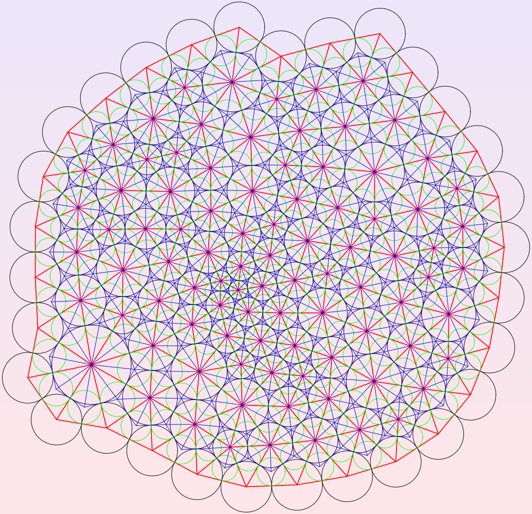
Dual Ricci Flow Method



Dual Ricci Flow Method



Dual Ricci Flow Method

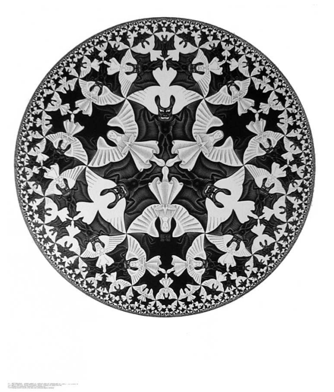


Conformal Model : Poincaré Disk

Poincaré disk

A unit disk $|z| < 1$ with the Riemannian metric

$$ds^2 = \frac{4dzd\bar{z}}{(1-\bar{z}z)^2}.$$

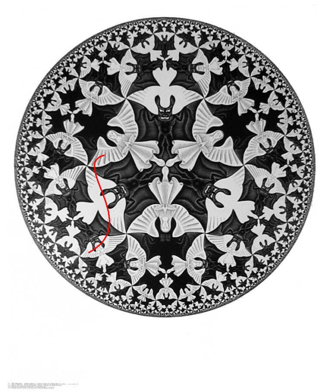


Conformal Model : Poincaré Disk

Poincaré disk

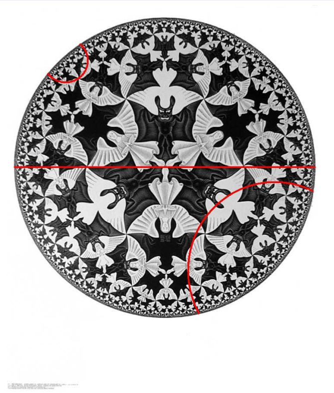
The rigid motion is the Möbius transformation

$$e^{i\theta}\frac{z-z_0}{1-\bar{z}_0 z}.$$



Poincaré disk

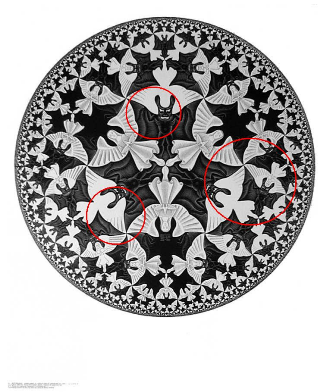
The hyperbolic line through two point z_0, z_1 is the circular arc through z_0, z_1 and perpendicular to the boundary circle $|z| = 1$.



Conformal Model : Poincaré Disk

Poincaré disk

A hyperbolic circle (c,γ) on Poincare disk is also an Euclidean circle (C,R) on the plane, such that $\mathbf{C} = \frac{2-2\mu^2}{1-\mu^2|\mathbf{c}|^2}$, $R^2 = |\mathbf{C}|^2 - \frac{|\mathbf{c}|^2-\mu^2}{1-\mu^2|\mathbf{c}|^2}$, $\mu = \frac{e^r-1}{e^r+1}$.



Discrete Hyperbolic Ricci Flow

Definition (Discrete Hyperbolic Ricci Flow)

Let

$$u_i = ln \tanh \frac{\gamma_i}{2},$$

Discrete hyperbolic Ricci flow for a mesh Σ is

$$\frac{du_i}{dt} = \bar{K}_i - K_i, \bar{K}_i \equiv 0,$$

the Euler number of Σ is negative, $\chi(\Sigma) < 0$.

Theorem (Discrete Hyperbolic Ricci flow, Chow and Luo 2002)

A hyperbolic discrete Ricci flow $(M,\Gamma,\Phi) \rightarrow (M,\bar{\Gamma},\Phi)$ *converges,*

$$|K_i(t) - \bar{K}_i| < c_1 e^{-c_2 t},$$

and

$$|\gamma_i(t) - \bar{\gamma}_i| < c_1 e^{-c_2 t},$$

where c_1, c_2 *are positive numbers.*

Discrete Hyperbolic Ricci Energy

Definition (Discrete Hyperbolic Ricci Energy)

The discrete Hyperbolic Ricci energy is defined as

$$f(\mathbf{u}) = \int_{\mathbf{u}_0}^{\mathbf{u}} \sum_{i=1}^{n} (\bar{K}_i - K_i) du_i.$$

Discrete hyperbolic Ricci flow is the gradient descendent method to minimize the discrete hyperbolic ricci energy.

Derivative hyperbolic Cosine Law

Theorem (Hyperbolic Discrete Ricci Energy)

Discrete hyperbolic Ricci energy is well defined and convex, namely, there exists a unique global minimum.

Proof.

In a hyperbolic triangle, with angles $(\theta_1, \theta_2, \theta_3)$ and radius $(\gamma_1, \gamma_2, \gamma_3)$, $u_i = ln \tanh \frac{\gamma_i}{2}$, according to hyperbolic cosine law,

$$\frac{\partial \theta_i}{\partial u_j} = \frac{\partial \theta_j}{\partial u_i}.$$

Therefore $\omega = \sum \theta_i du_i$ is a closed 1-form. The hyperbolic Ricci energy is convex. Direct computation verifies the Hessian matrix is positive definite. □

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Algorithm: Computing Hyperbolic uniformization metric

Hyperbolic Ricci Energy Optimization

1. Set target curvature $K(v_i) \equiv 0$.
2. Optimize the hyperbolic Ricci energy using Newton's method, with the constraint the total area is preserved.

Flattening Mesh in Hyperbolic Space

1. Determine the shape of each triangle.
2. Glue the hyperbolic triangles coherently by Möbius transformation.

Key: all computations use hyperbolic geometry.

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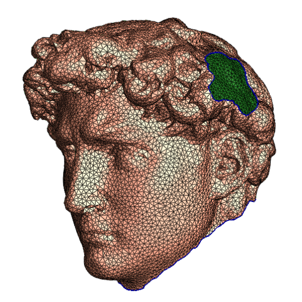
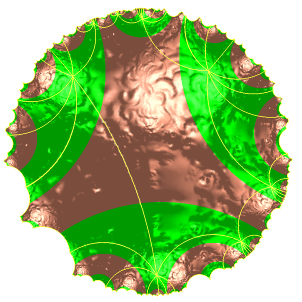
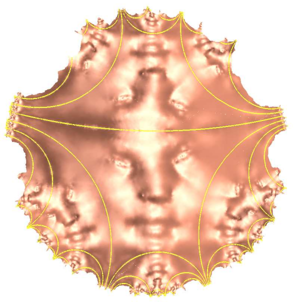




Genus 0 surface with 3 boundaries. The double covered surface is of genus 2. The boundaries are mapped to hyperbolic lines.

Hyperbolic Uniformization Metric



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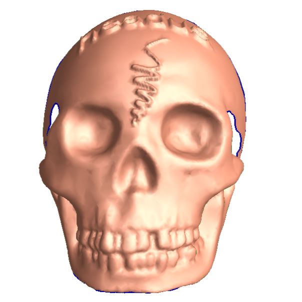

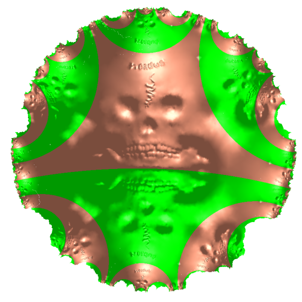

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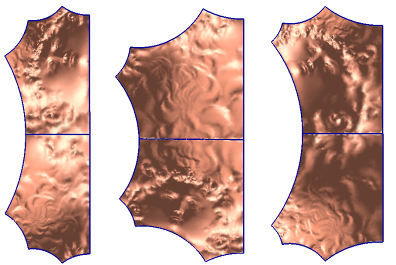
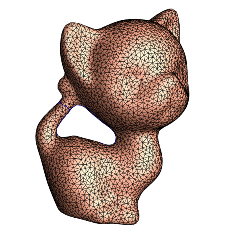
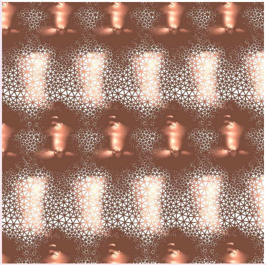


Embedding in the upper half plane hyperbolic space model. Different period embedded in the hyperbolic space. The boundaries are mapped to hyperbolic lines.





Universal Cover

A pair $(\bar{\Sigma}, \pi)$ is a universal cover of a surface Σ, if

- Surface $\bar{\Sigma}$ is simply connected.
- Projection $\pi : \bar{\Sigma} \to \Sigma$ is a local homeomorphism.

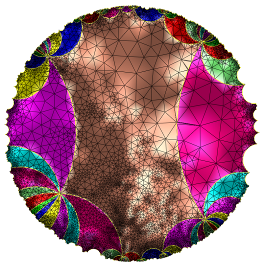
Deck Transformation

A transformation $\phi : \bar{\Sigma} \to \bar{\Sigma}$ is a deck transformation, if

$$\pi = \pi \circ \phi.$$

A deck transformation maps one period to another.

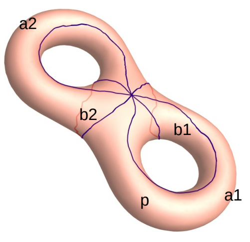
Fuchsian Group

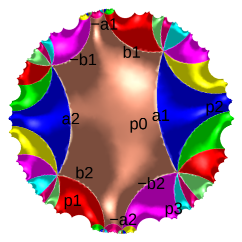


Definition (Funchsian Group)

Suppose Σ is a surface, **g** is its uniformization metric, $(\bar{\Sigma}, \pi)$ is the universal cover of Σ. **g** is also the uniformization metric of $\bar{\Sigma}$. A deck transformation of $(\bar{\Sigma}, \mathbf{g})$ is a Möbius transformation. All deck transformations form the Fuchsian group of Σ.

Fuchsian group indicates the intrinsic symmetry of the surface.





The Fuchsian group is isomorphic to the fundamental group

	$e^{i\theta}$	z_0
a_1	$-0.631374 + i0.775478$	$+0.730593 + i0.574094$
b_1	$+0.035487 - i0.999370$	$+0.185274 - i0.945890$
a_2	$-0.473156 + i0.880978$	$-0.798610 - i0.411091$
b_2	$-0.044416 - i0.999013$	$+0.035502 + i0.964858$

Klein Model

Klein Model

Another Hyperbolic space model is Klein Model, suppose $\mathbf{s}, \mathbf{t}$ are two points on the unit disk, the distance is

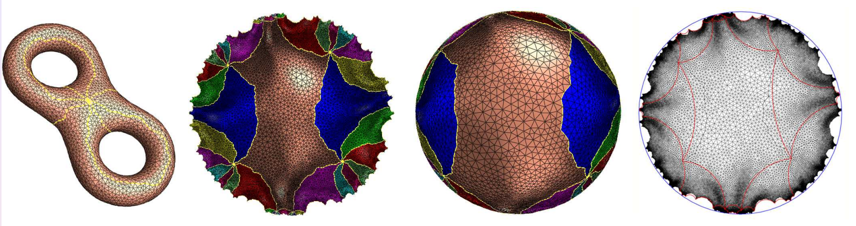
$$d(s,t) = arccosh \frac{1 - \mathbf{s}\cdot\mathbf{t}}{\sqrt{(1-\mathbf{s}\cdot\mathbf{s})(1-\mathbf{t}\cdot\mathbf{t})}}$$

Poincaré vs. Klein Model

From Poincaré model to Klien model is straight froward

$$\beta(z) = \frac{2z}{1+\bar{z}z}, \beta^{-1}(z) = \frac{1-\sqrt{1-\bar{z}z}}{\bar{z}z},$$

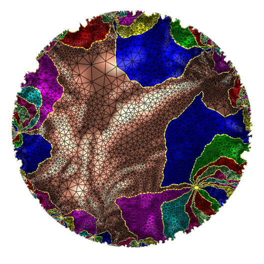
Assume ϕ is a Möbius transformation, then transition maps $\beta\circ\phi\circ\beta^{-1}$ are real projective.



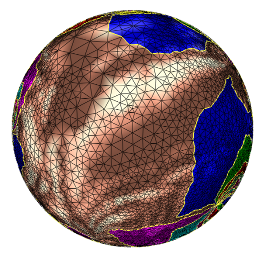
Real projective structure

The embedding of the universal cover in the Poincaré disk is converted to the embedding in the Klein model, which induces a real projective atlas of the surface.

Surface

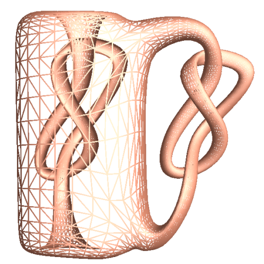


Hyperbolic Structure

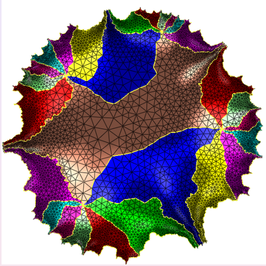


Projective Structure

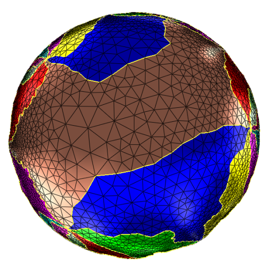
Hyperbolic and Real Projective Structure



Surface, courtesy of Cindy Grimm



Hyperbolic Structure



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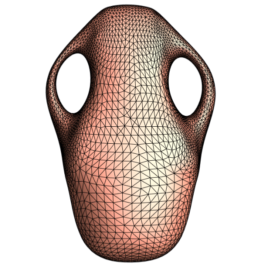
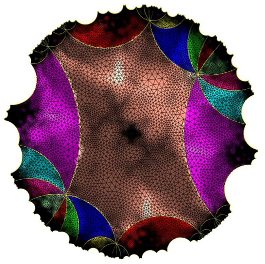
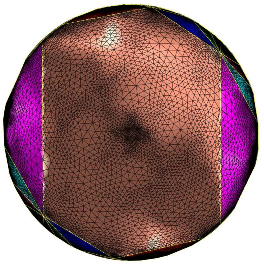

Surface


Hyperbolic Structure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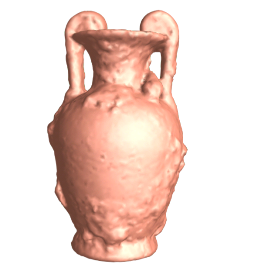

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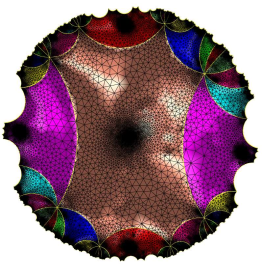

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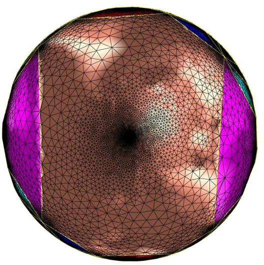
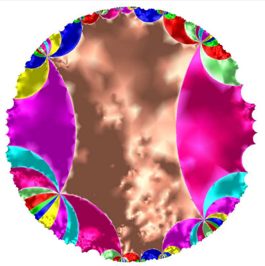
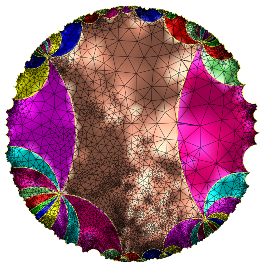


Projective Structure

Hyperbolic Uniformization Metric

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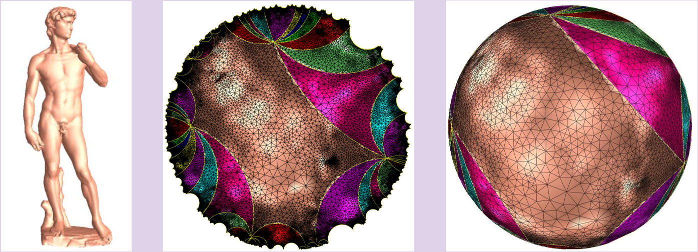

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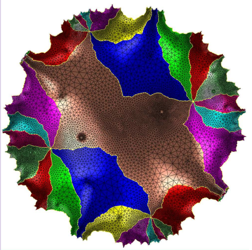
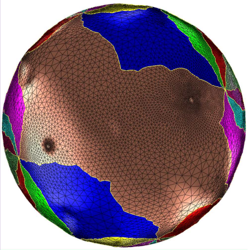
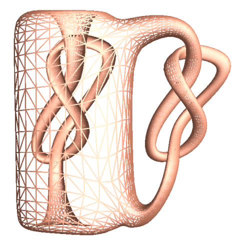
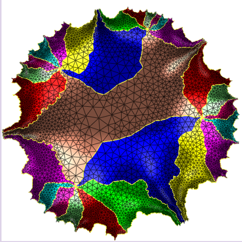
  

Thanks

For more information, please email to gu@cs.sunysb.edu.





Thank you!