A Glimpse into Advances of Mesh Representation Learning

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IDC' 19 Spring, Bernried, Germany
~~April 5~~ April 3, 2019

Outline

1. Motivation
2. Common Industrial Approaches
   - Edge Collapse
   - Remeshing
3. Recent Advances
   - Discrete Riemannian Geometry
   - Mesh Representation Learning
4. Conclusion

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3D Object Representations

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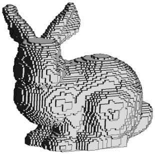
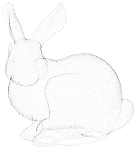
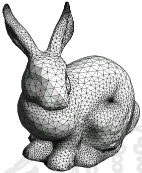
- 3D Objects has many representations:

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Memory Efficiency	Poor	Not good	Good
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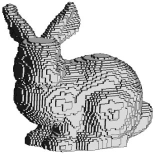
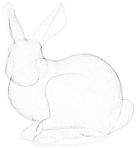
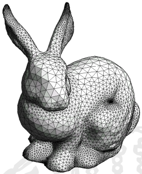

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- Most of the objects are represented via **triangulated meshes**.

Mesh Simplification 101

Mesh Simplification is one of the key phase in 3D surface reconstruction (modeling).

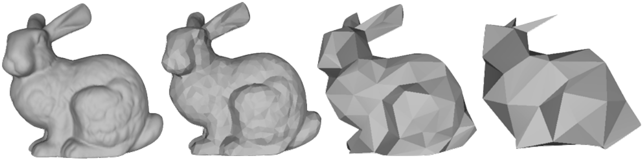

Figure: High Polygonal and Low Polygonal Representation

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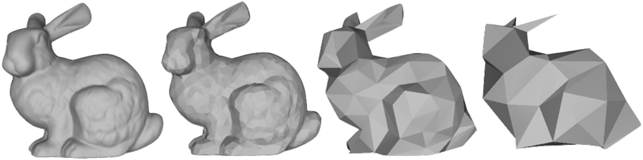
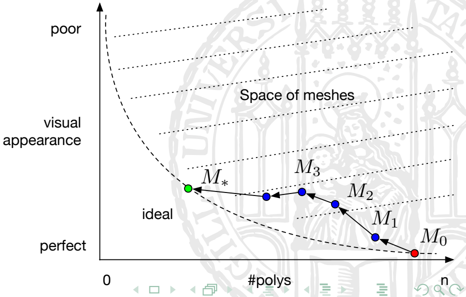


Figure: High Polygonal and Low Polygonal Representation

- Two common techniques:
  - Reduction: polygon reduction
  - Remeshing: topological reconstruction
- Process: M_0 (Initial Mesh) $\rightarrow M_1 \rightarrow M_2 \rightarrow \ldots \rightarrow M_*$ (Ideal Mesh)
- Factors: #polygons, viewport, ...



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- **3D Print**: reduce the complexity of a object to speed up the print
- **Biometric Authentication**: efficient model and recognize 3D faces
- and more...

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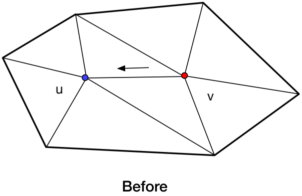
Mesh Energy $E(\mathcal{M})$ [Hoppe et al., 1993]:

$$E(\mathcal{M}) = E_{\mathtt{dist}}(K, V) + E_{\mathtt{rep}}(K) + E_{\mathtt{spring}}(K, V)$$

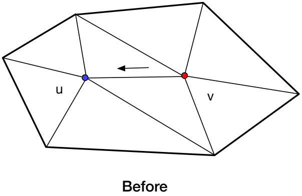
- $E_{\mathtt{dist}}$: distance energy sum of squared distances from X to the mesh
- $E_{\mathtt{rep}}$: representation energy penalizes meshes with a large number of vertices
- $E_{\mathtt{spring}}$: spring energy penalizes sharp dihedral angles in the mesh

Edge Collapse



Minimize the (curvature) cost of collapse:

Edge Collapse



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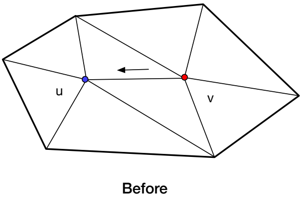

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$$\texttt{cost}(u,v) = \underbrace{||u-v||}_{\text{distance}} \times \max_{f \in T_u} \left\{ \min_{n \in T_{uv}} \left\{ \underbrace{1 - f.\texttt{normal} \cdot n.\texttt{normal}}_{\text{curvature}} \right\} \right\}$$

Adaptive Dual Contouring Remeshing [Ju et al., 2002]

Find a approximation of existing mesh. Key ideas:

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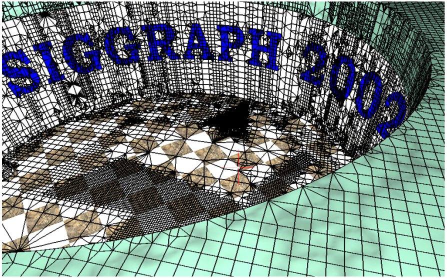
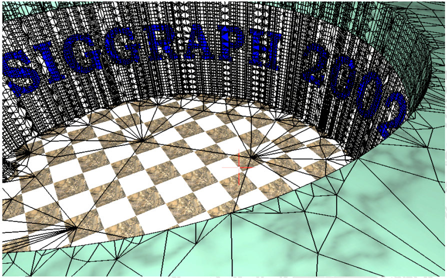
Find a approximation of existing mesh. Key ideas:

1. reduce or increase polygons
2. construct octree using quadradic errors and simplify the tree
3. recursively above steps





Industrial Solutions

- Open source 😃:
  - **Blender**: Decimate Modifier[1], Remesh Modifier[2]
  - **Meshlab**: Quadric Edge Collapse Decimation[1]

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A proficient designer takes almost 1 week:

```
input : Mesh M_0, Criterial (e.g. #polys, ...)
output: Simplified mesh M_*
begin
    repeat
        if has good visual appearance then
            polygon reduction
        else
            remeshing
        end
    until converge to target criterial;
end
```

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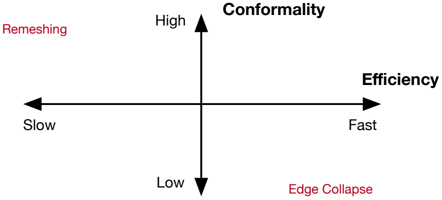
Comparison of Edge Collapse and Remeshing

Practical experience:



More: Topology-preserving, direction-preserving, area-preserving, distance-preserving, ...

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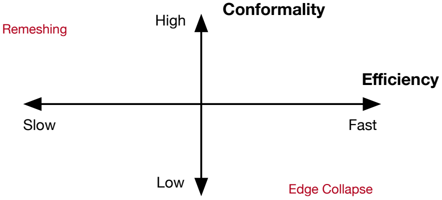

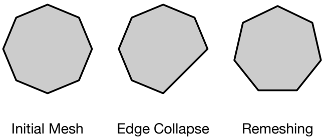

Figure: An octagon mesh simplification: comparing remeshing and edge collapse

More: Topology-preserving, direction-preserving, area-preserving, distance-preserving, ...

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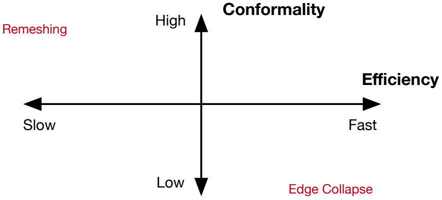

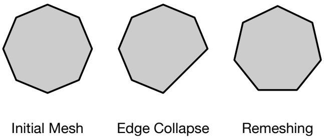

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Is there a way to facilitate them both?

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Bernhard Riemann

Euclidean Parallel postulate (simplified): In a plane, given a line and a point not on it, at most one line parallel to the given line can be drawn through the point.

Figure: **Bernhard Riemann (1826 – 1866)**

On the Hypotheses which lie at the Bases of Geometry.

Bernhard Riemann
Translated by William Kingdon Clifford

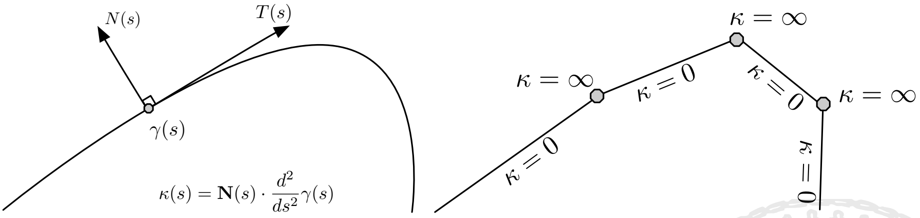
[*Nature*, Vol. VIII. Nos. 183, 184, pp. 14–17, 36, 37.]

Plan of the Investigation.

It is known that geometry assumes, as things given, both the notion of space and the first principles of constructions in space. She gives definitions of them which are merely nominal, while the true determinations appear in the form of axioms. The relation of these assumptions remains consequently in darkness; we neither perceive whether and how far their connection is necessary, nor *a priori*, whether it is possible.

From Euclid to Legendre (to name the most famous of modern reforming geometers) this darkness was cleared up neither by mathematicians nor by such philosophers as concerned themselves with it. The reason of this is doubtless that the general notion of multiply extended magnitudes (in which space-magnitudes are included) remained entirely unworked. I have in the first place, therefore, set myself the task of constructing the notion of a multiply extended magnitude out of general notions of magnitude. It will follow from this that a multiply extended magnitude is capable of different measure-relations, and consequently that space is only a particular case of a triply extended magnitude. But hence flows as a necessary consequence that the propositions of geometry cannot be derived from general notions of magnitude, but that the properties which distinguish space from other conceivable triply extended magnitudes are only to be deduced from experience. Thus arises the problem, to discover the simplest matters of fact from which the measure-relations of space may be determined; a problem which from the nature of the case is not completely determinate, since there may be several systems of matters of fact which suffice to determine the measure-relations of space—the most important system for our present purpose being that which Euclid has laid down as a foundation. These matters of fact are—like all

Revisited: Curvature From Continus to Discrete



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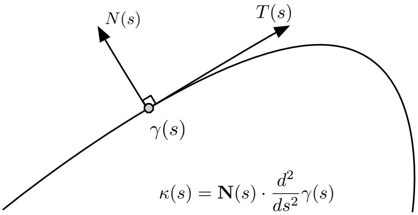
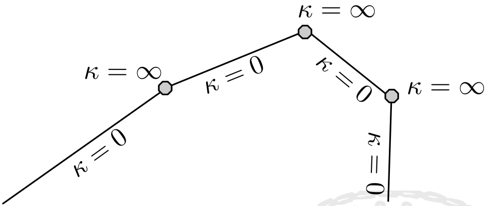
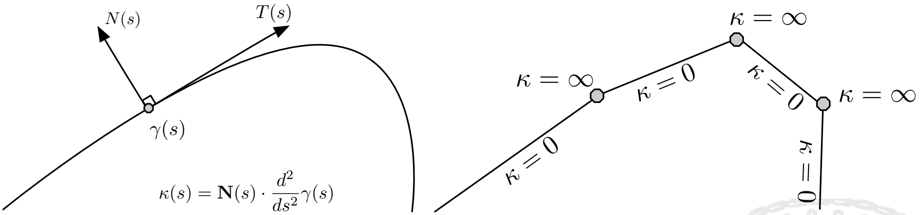




Theorem (Whitney-Graustein 1937, human readable version)

Not all properties of a smooth object can be preserved exactly at the discrete level.



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$\rightarrow$ **Discrete differential geometry** defines different discrete version of definitions to preserve various critical geometric properties.

Developable Surface [Stein et al., 2018]

Developable surface captures two key properties of smooth developable surfaces:

- Flattenability
- Presence of straight ruling lines

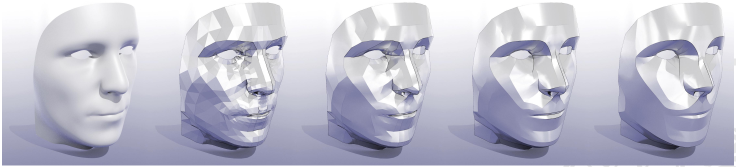


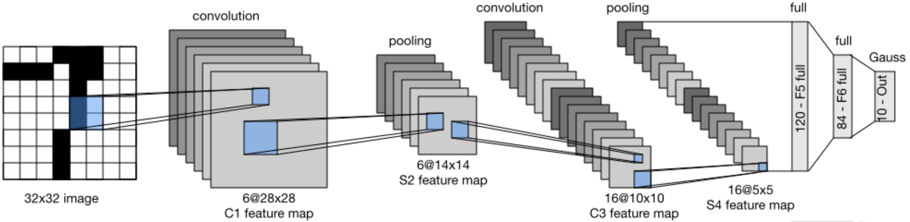
Figure: A given mesh evolves toward a shape comprised of flattenable pieces separated by highly regular seam curves.

Key Properties of Riemannian Manifolds

- Flattenability
- Presence of straight ruling lines
- **Locality!**
- ...

Convolutional Neural Network (CNN)

LetNet-5 [LeCun et al, 1998]:



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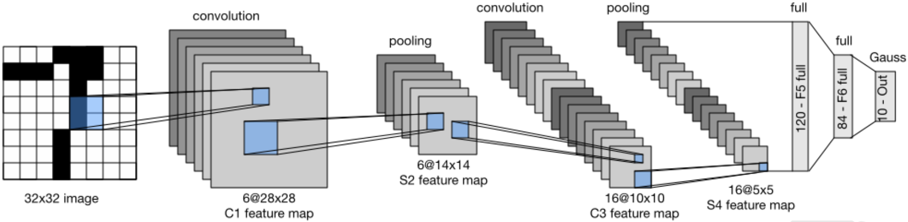

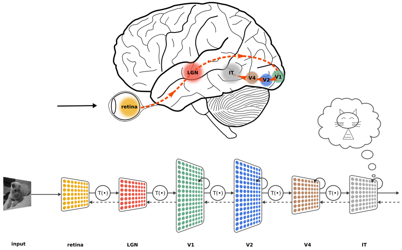

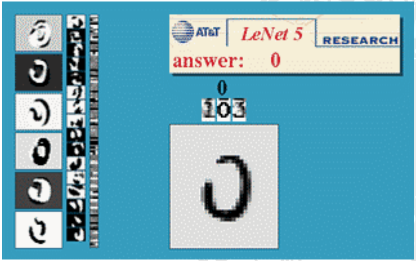

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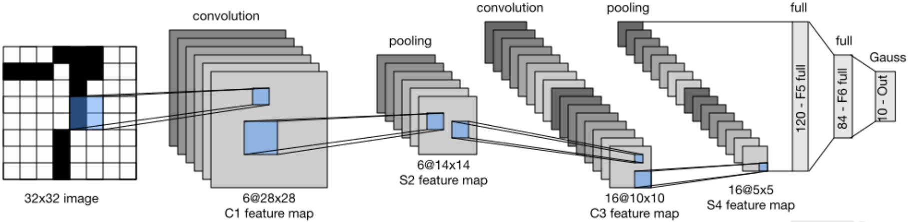
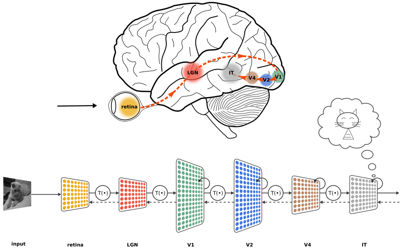
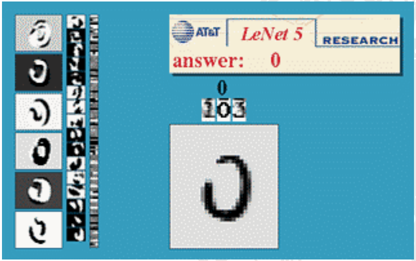
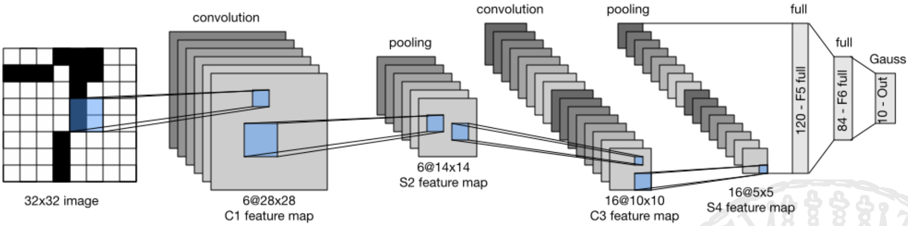






Key properties of CNNs



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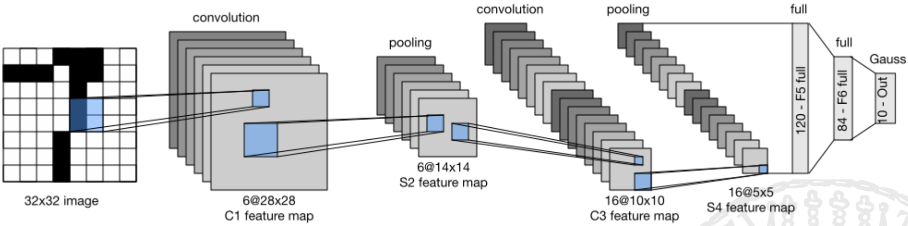

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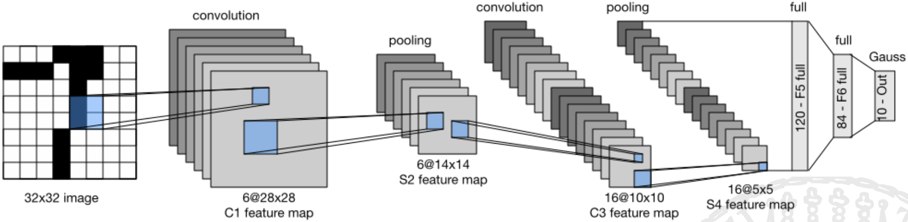
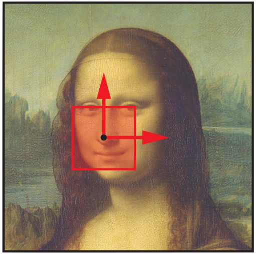
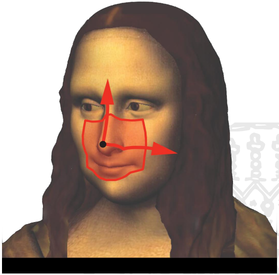


- 😃 Convolutional (Translation invariance)
- 😃 Filters localized in space (Deformation Stability)
- ...

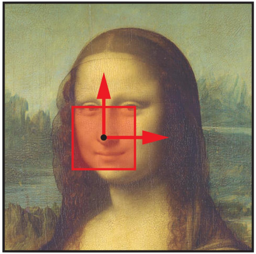
CNNs in Non-Euclidean Spaces

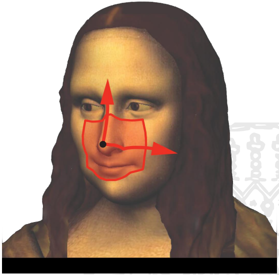
What convolutional operator fits non-Euclidean data?





What convolutional operator fits non-Euclidean data?
Patch filter [Bronstein et al., 2017]:





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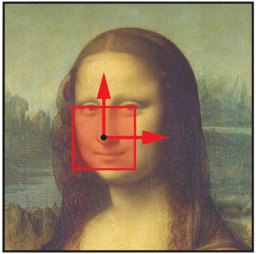

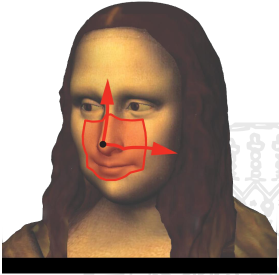

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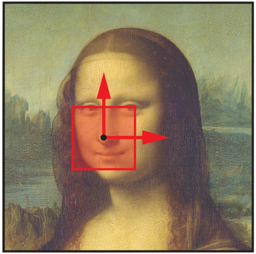
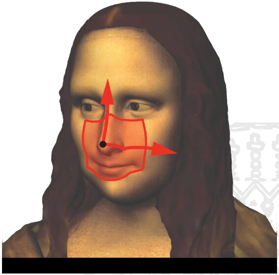
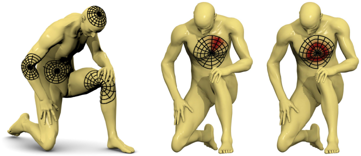




Geodesic CNN [Masci et al., 2015]



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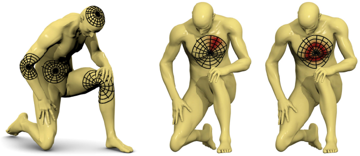

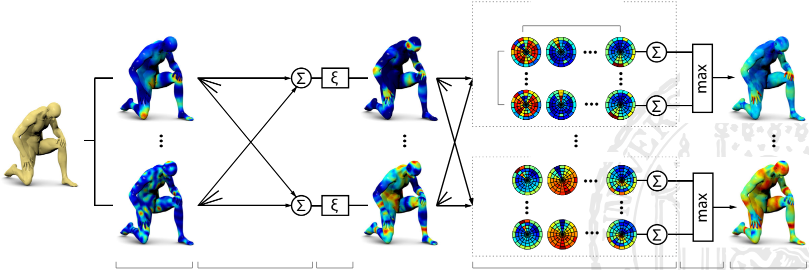

Figure: A Toy Geodesic CNN Architecture

Conv. Mesh Autoencoders [Ranjan et al., 2018]

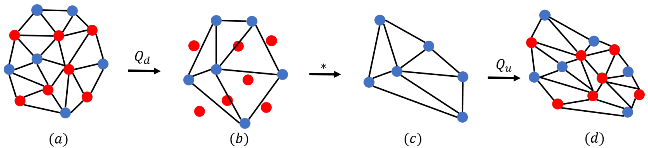

Figure: Mesh Sampling Op: (a) down-sampled (b) store the barycentric coordinates (c) transformed using convolutional operations (d) add contracted vertices at the barycentric locations.

Conv. Mesh Autoencoders [Ranjan et al., 2018]

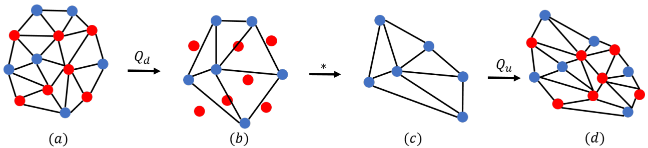

Figure: Mesh Sampling Op: (a) down-sampled (b) store the barycentric coordinates (c) transformed using convolutional operations (d) add contracted vertices at the barycentric locations.

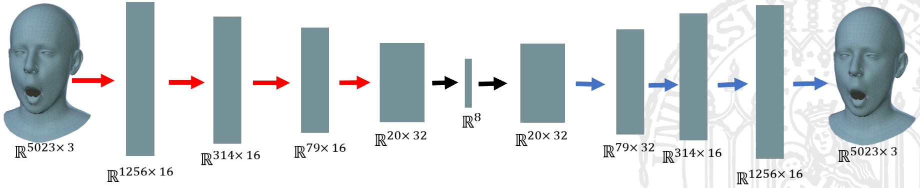

Figure: Convolutional Mesh Autoencoder: The red and blue arrows indicate down-sampling and up-sampling layers respectively.

Conv. Mesh Autoencoder (cont.) [Ranjan et al., 2018]

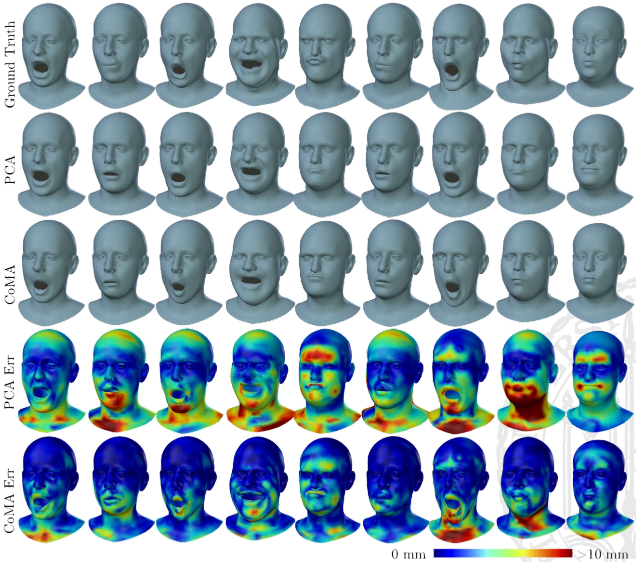

Figure: Comparison with PCA: Qualitative results for interpolation experiment

More Variants

- SurfaceNet [Kostrikov et al., 2017]
- MeshVAE [Tan et al., 2018]
- MeshCNN [Hanocka et al., 2019]
- MeshGAN [Cheng et al., 2019]
- Volumetric Representation Approaches
- Multi-view Representation Approaches
- ...

Outline

1. Motivation
2. Common Industrial Approaches
   - Edge Collapse
   - Remeshing
3. Recent Advances
   - Discrete Riemannian Geometry
   - Mesh Representation Learning
4. Conclusion

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Further Readings I

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Thank you!