252-0538-00L, Spring 2025

Shape Modeling and Geometry Processing

Introduction and Overview

INTERACTIVE GEOMETRY LAB

February 19, 2025

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Teaching team

Lectures

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Exercises

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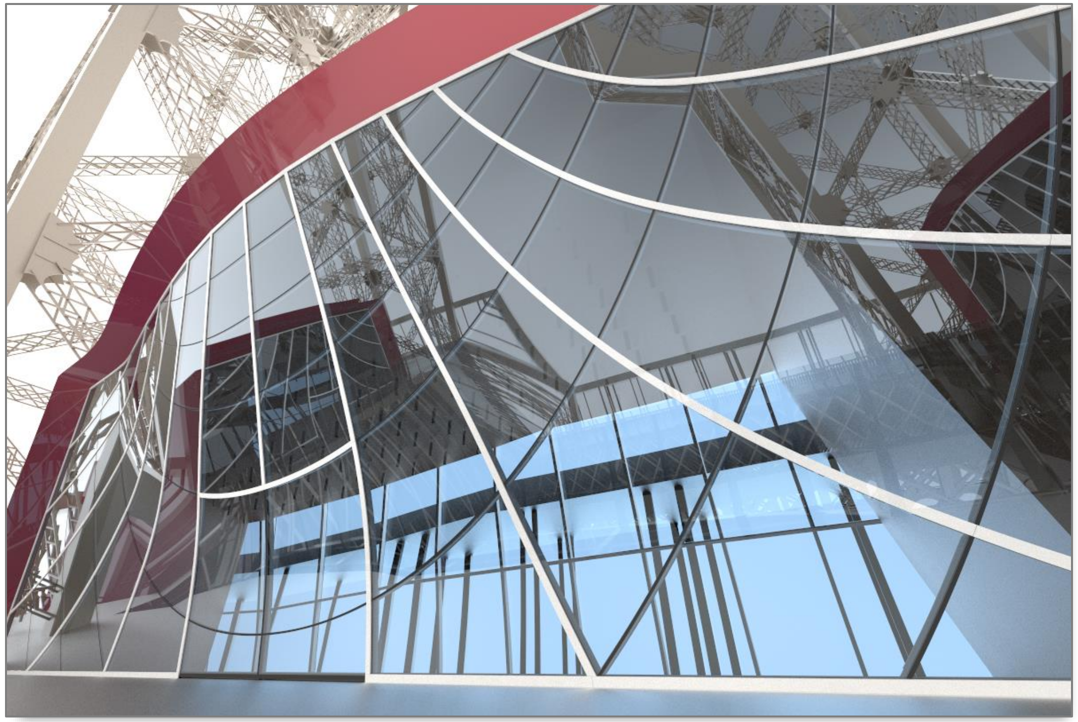
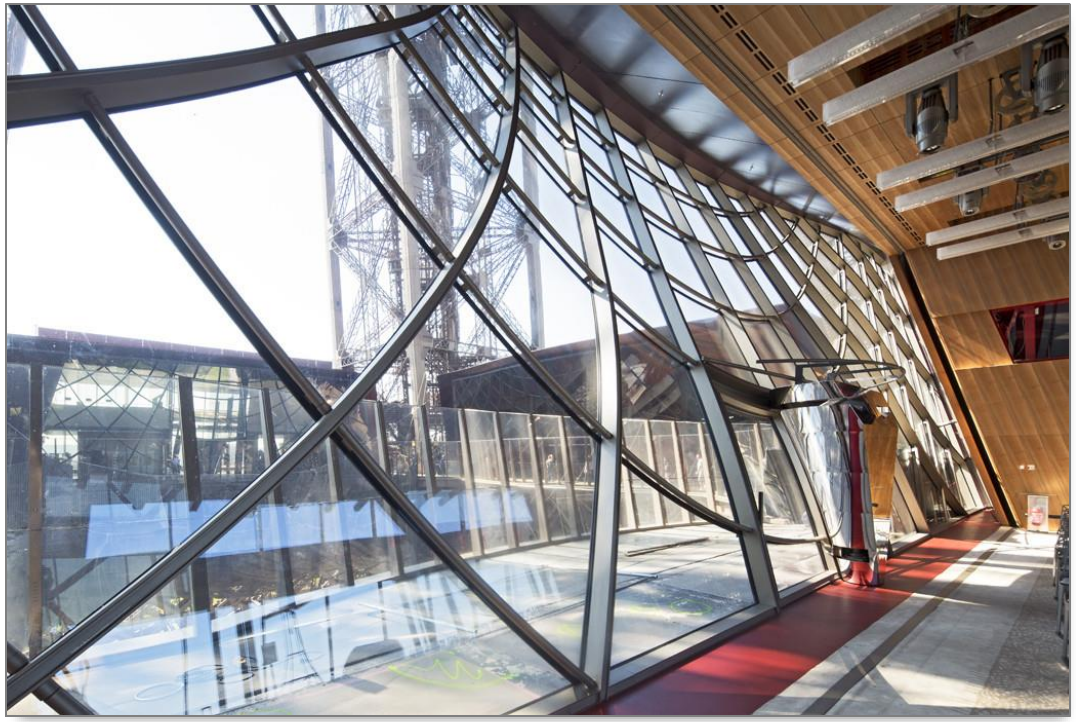
Motivation

- Most manufactured objects are designed on a computer
- Digital 3D content creation is in high demand: entertainment, marketing, virtual worlds, art…
- Digital manufacturing technologies: 3D printing, CNC milling, injection molding, machine knitting
- Machine perception, generative AI, VR/AR/XR, self-driving cars…

Where is it?

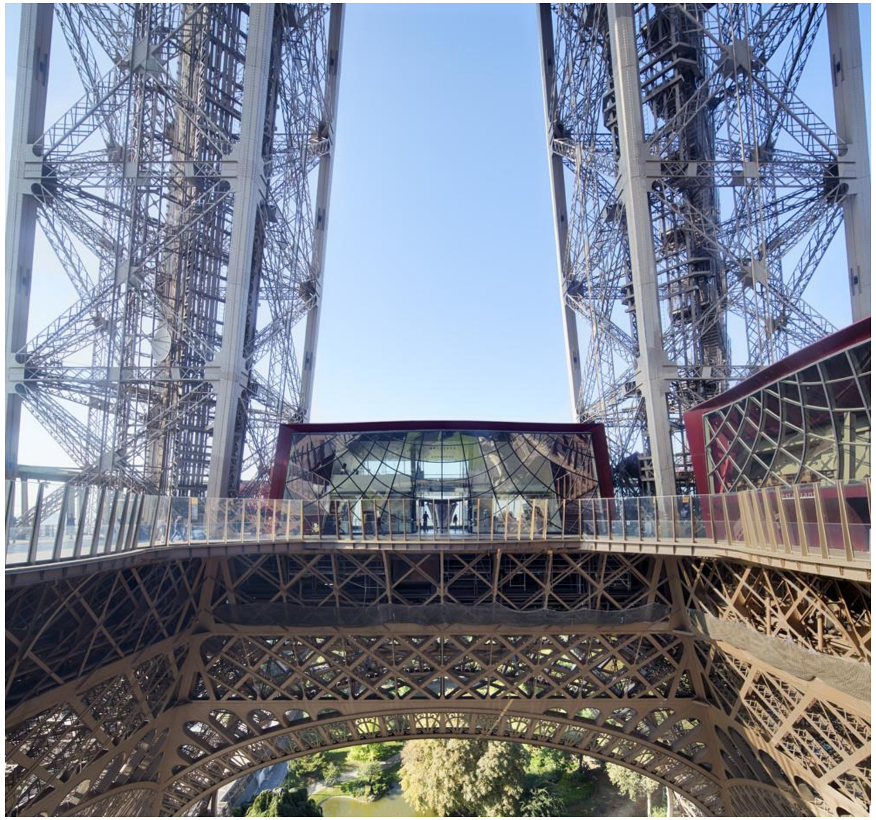




Hint ☺

Motivation

- Eifel Tower new pavilion on the 1st floor. Curved glass panels.



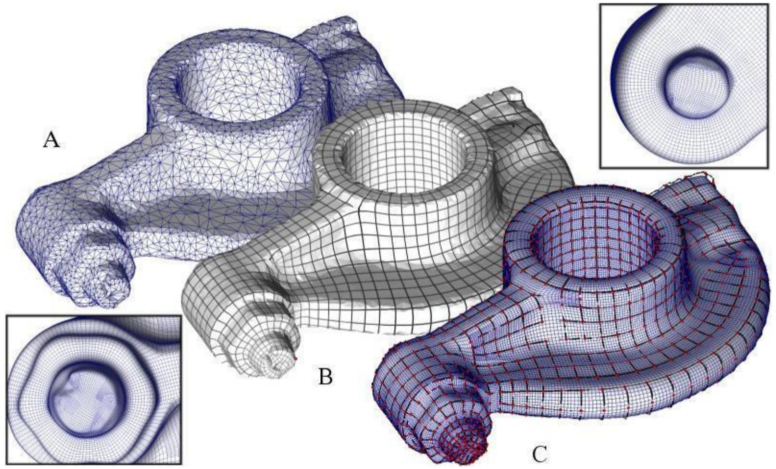
Images sources: [archdaily](), [moitti-rivière]()

Course Goals

- Learn how to design, program and analyze algorithms for **interactive 3D shape modeling** and **digital geometry processing**
  - **Theory** and **applications** of 3D shape processing
  - **Hands-on experience** with shape modeling and geometry processing **algorithms**

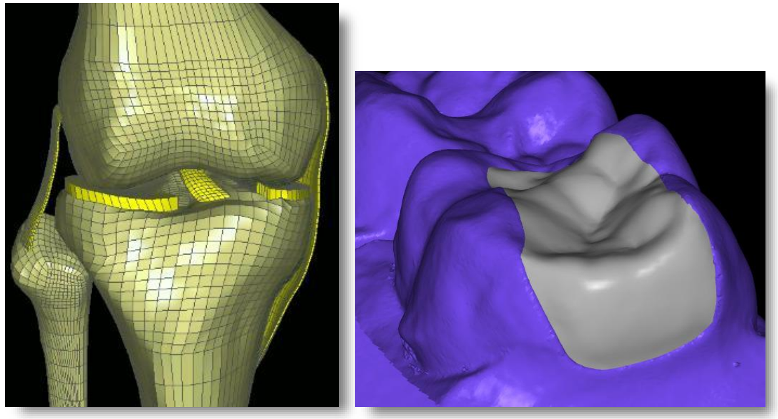
Geometric Modeling and Processing

- To describe any real-life or imagined object on the computer: start with shape (2D/3D)
- Geometry processing: digital modeling of 2D/3D geometry

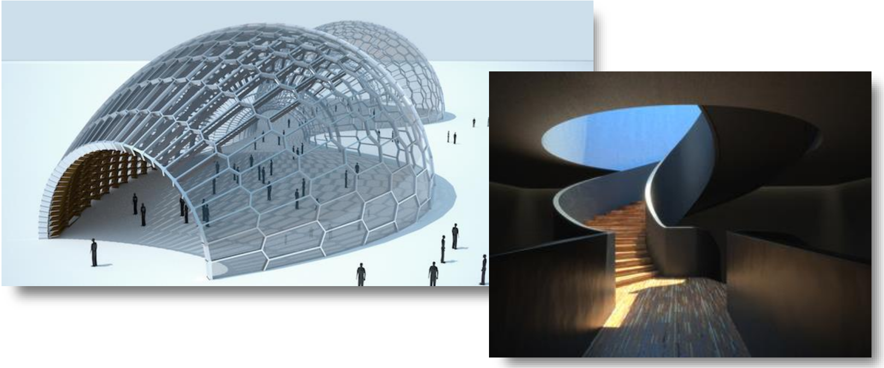


Applications

Product design and prototyping



Medicine, prosthetics



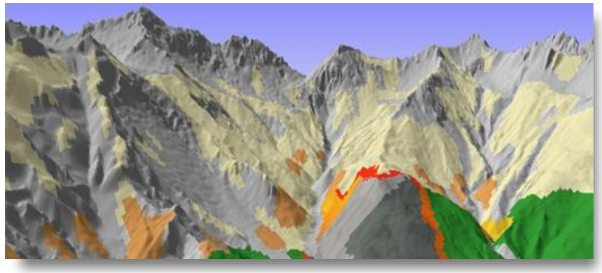
Architecture

Cultural heritage

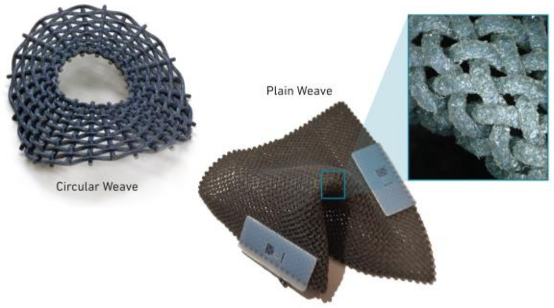
Digital humans & avatars

Applications

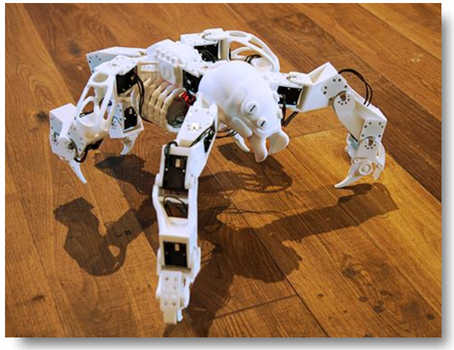
Source: Esri



Geographical systems, city and landscape planning



Source: Engineering Design and Computing Laboratory



Manufacturing, 3D printing, robotic fabrication

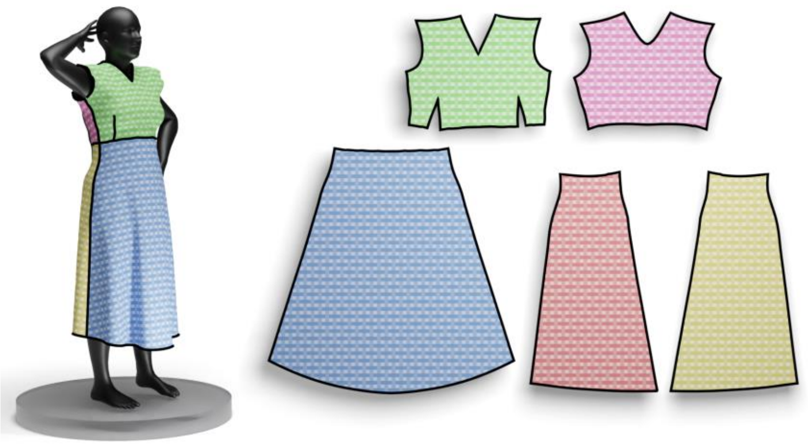
Manufacturing at scale

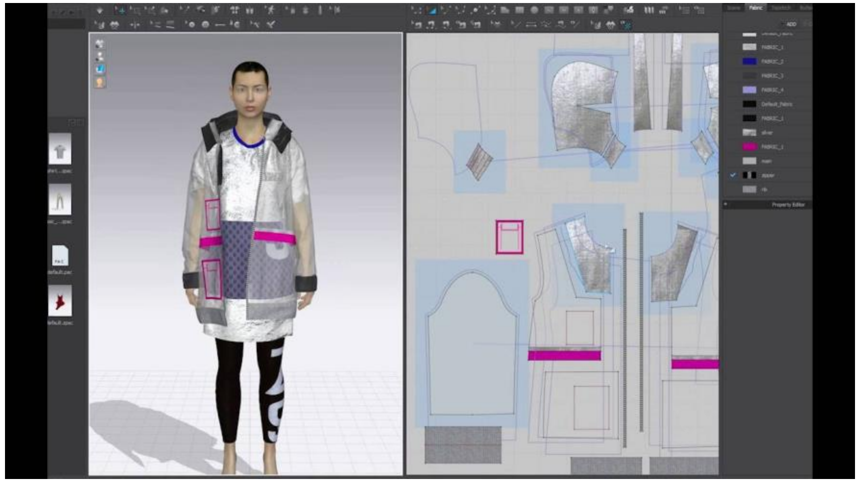
- Geometry determines aesthetics **and** physics/structural properties

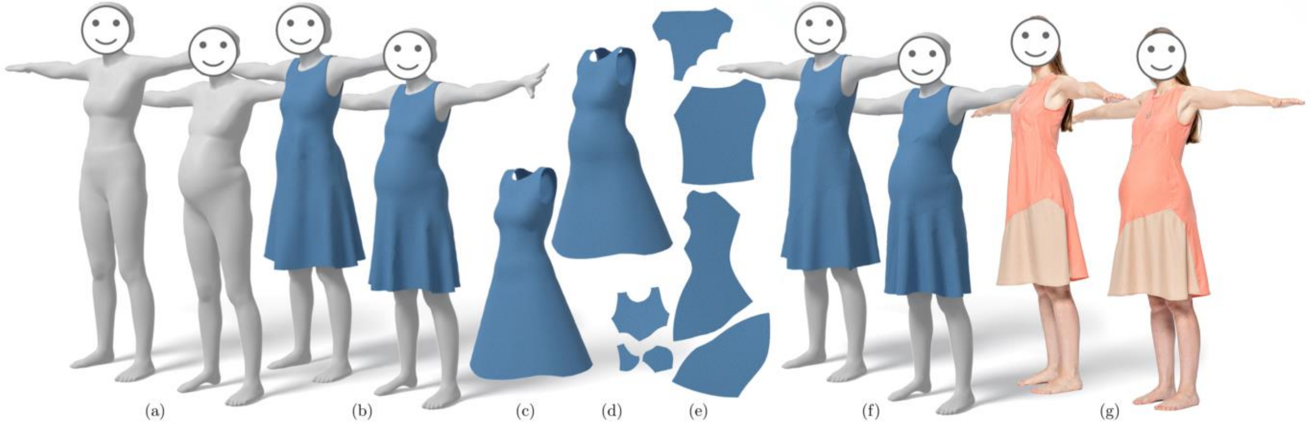


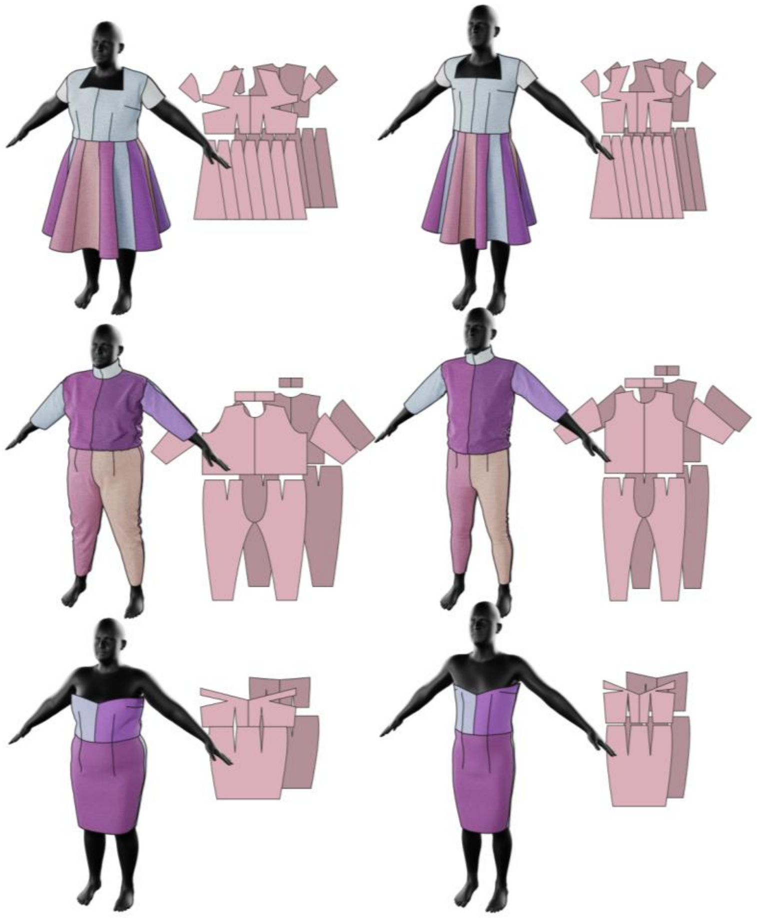
3D printed unreinforced masonry bridge, BLOCK research group (ETHZ)

Applications









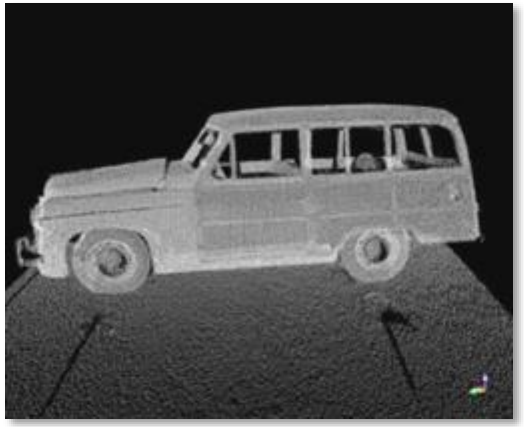
Apparel design, real and virtual fashion

Digital Geometry Processing (DGP)

- **Processing of discrete (polygonal mesh) models**

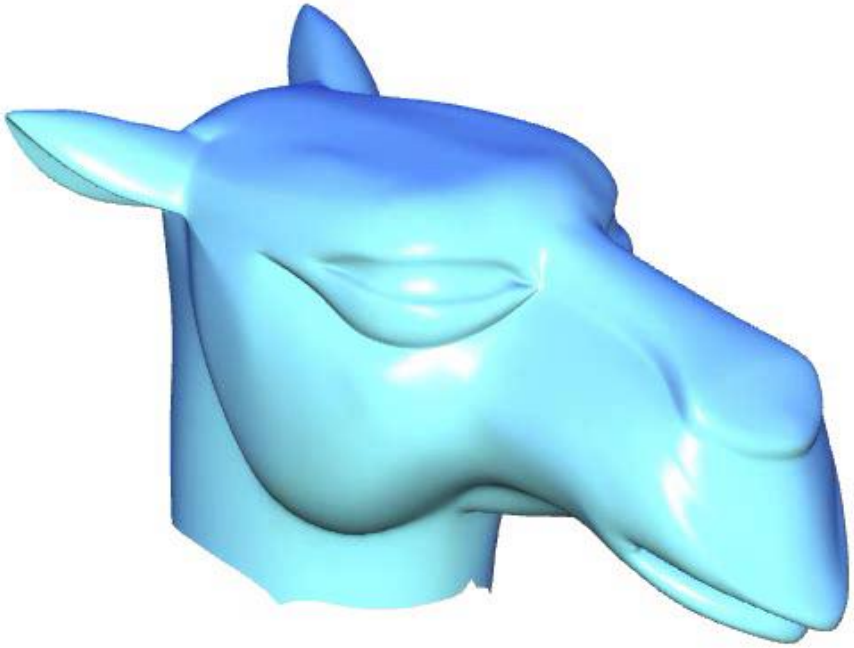
- **Why discrete?**
  - Simplicity – ease of description
  - Efficiently rendered by graphics hardware
  - Output of most acquisition tools (computer vision, CT/MRI, LIDAR…)
  - Input to most simulation/analysis tools (FE solvers)





Interactive Shape Modeling

- Tools for design, editing and animation of digital shapes
  - Interactive = fast
  - Intuitive = convenient interface and predictable outcome

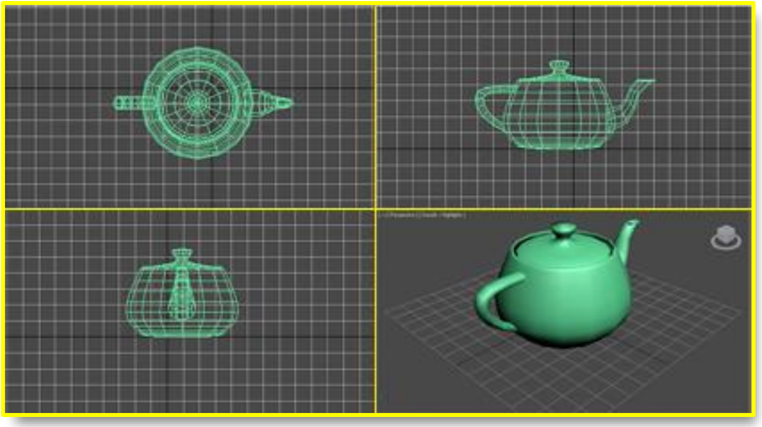


http://youtu.be/EMx6yNe23ug

Digital Shape Modeling

- How do shapes find their way into computers?
  - Geometric modeling is difficult

Humans have no direct "video out"



"Translation" from 2D to 3D is hard

Digital Shape Modeling

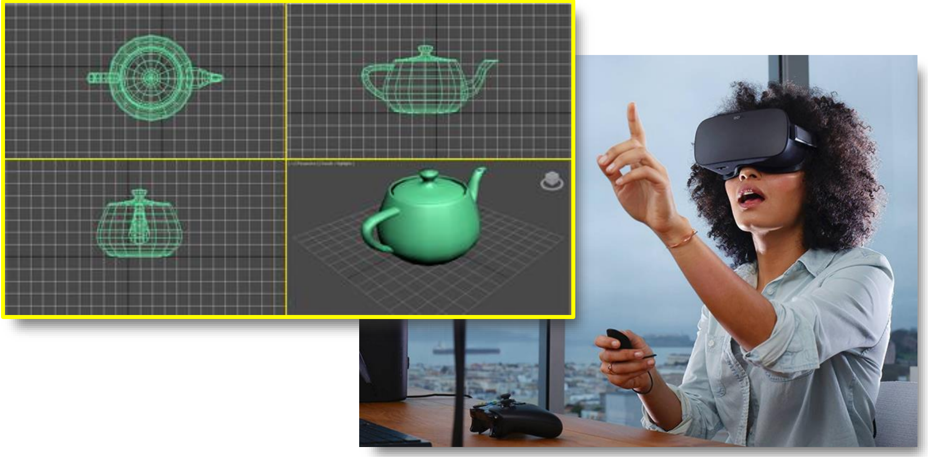
- How do shapes find their way into computers?
  - Geometric modeling is difficult

Humans have no direct “video out”

“Translation” from 3D to 3D is also not easy

Digital Shape Modeling

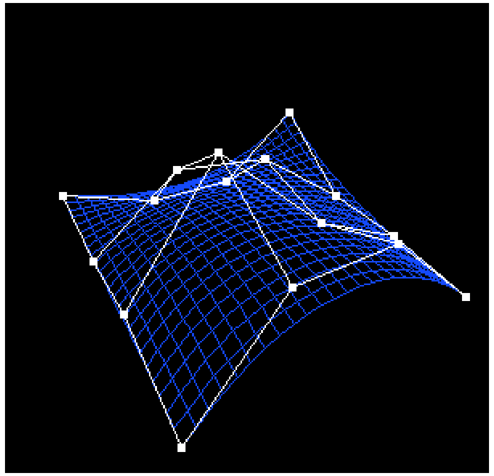
- How do shapes find their way into computers?
  - Geometric modeling is difficult



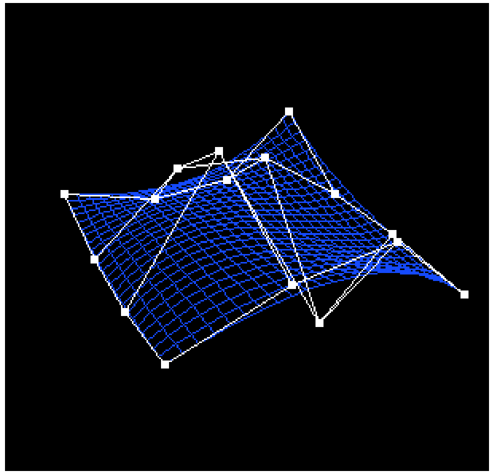
Hope: computation can compensate for lack of direct ability to convey visual information

Computer-Aided Geometric Design

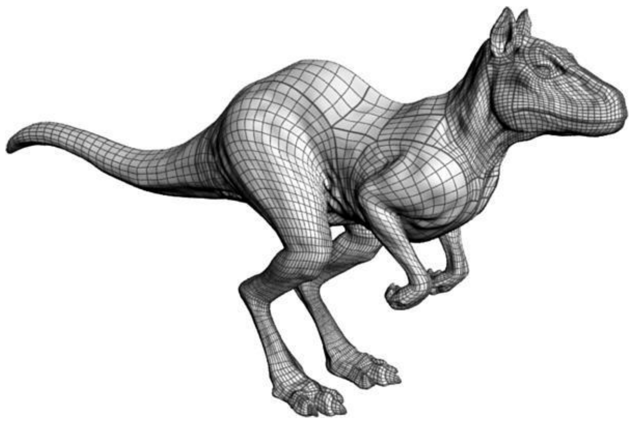
- Traditional pipeline for modeling shapes from scratch



User defines a layout of surface patches and control points

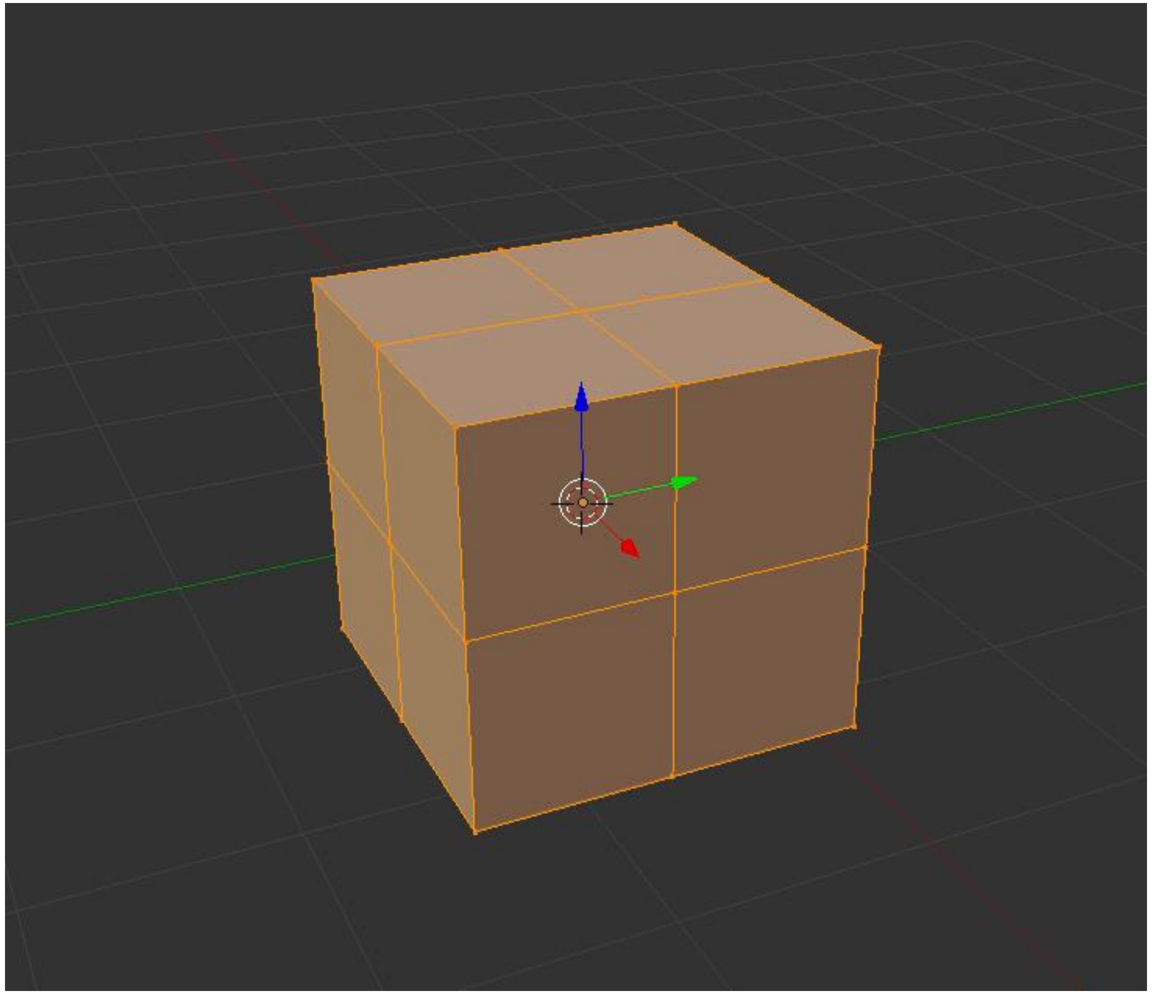


Editing is performed by moving control points and/or prescribing tangents



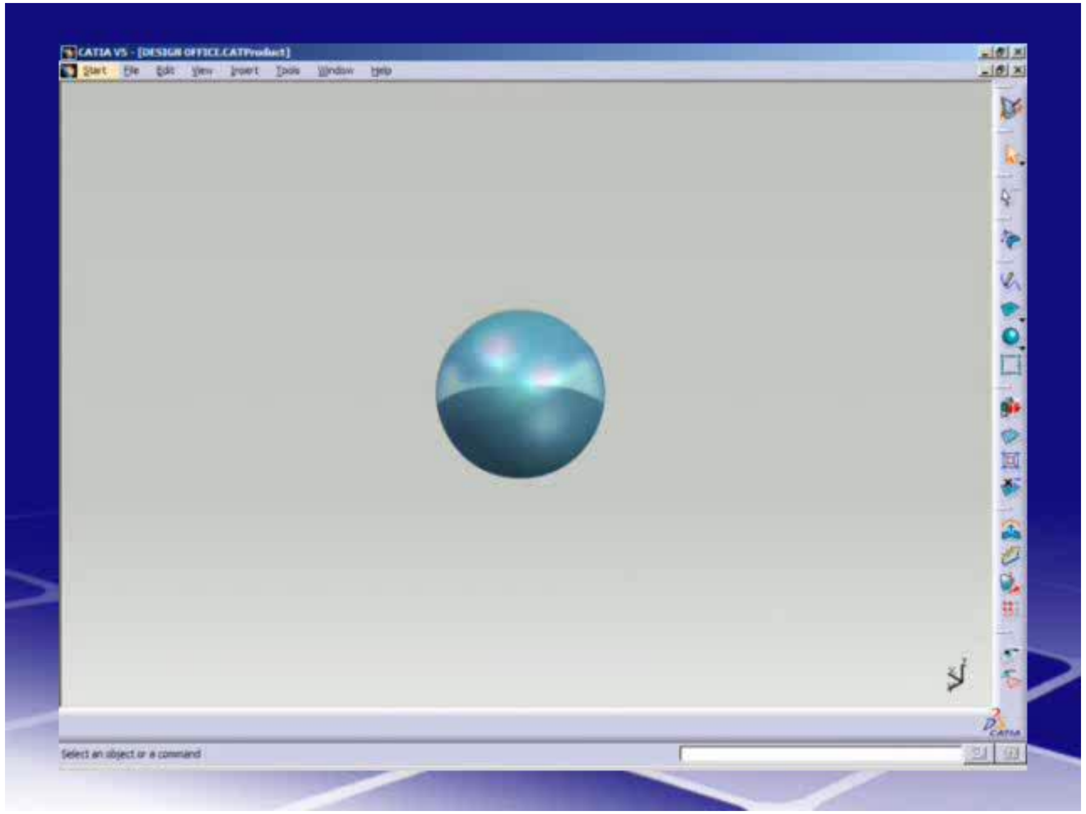
Patch-based construction of a surface

Blender Demo



Computer-Aided Geometric Design

- High-quality surfaces
- Constrained modeling
- Requires a specific idea of the object first
  - Not easy to experiment and explore alternatives
- Requires training, skill and tedious work

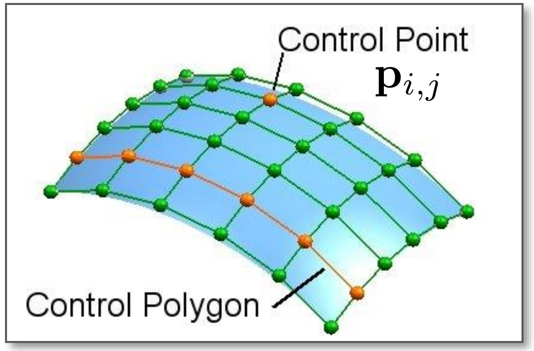


CATIA, Dassault Systemes

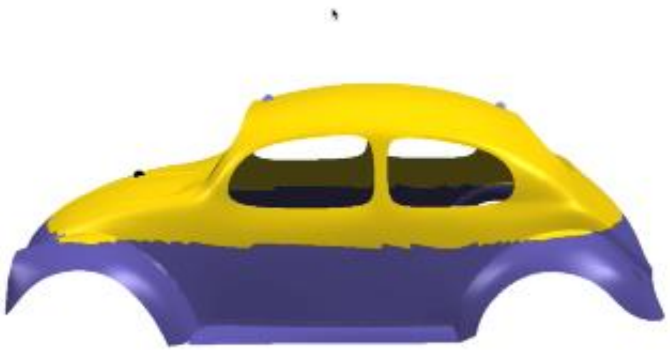
http://youtu.be/gTC5zMktMr0

Traditional CAD vs Meshes

$$\mathbf{x}(u,v) = \sum_{i,j} \mathbf{p}_{i,j} B_i(u) B_j(v)$$



$$\min_{\mathbf{x}} \; E(\mathbf{x}) \quad s.t. \; \mathbf{x}|_{\mathcal{C}} = \mathbf{x}_{\text{fixed}}$$



User has more freedom!
Select and manipulate arbitrary regions.

Traditional CAD vs Meshes

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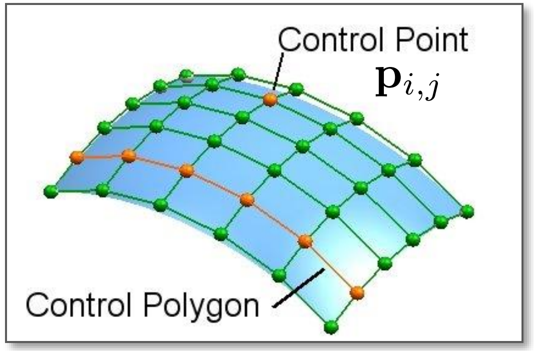
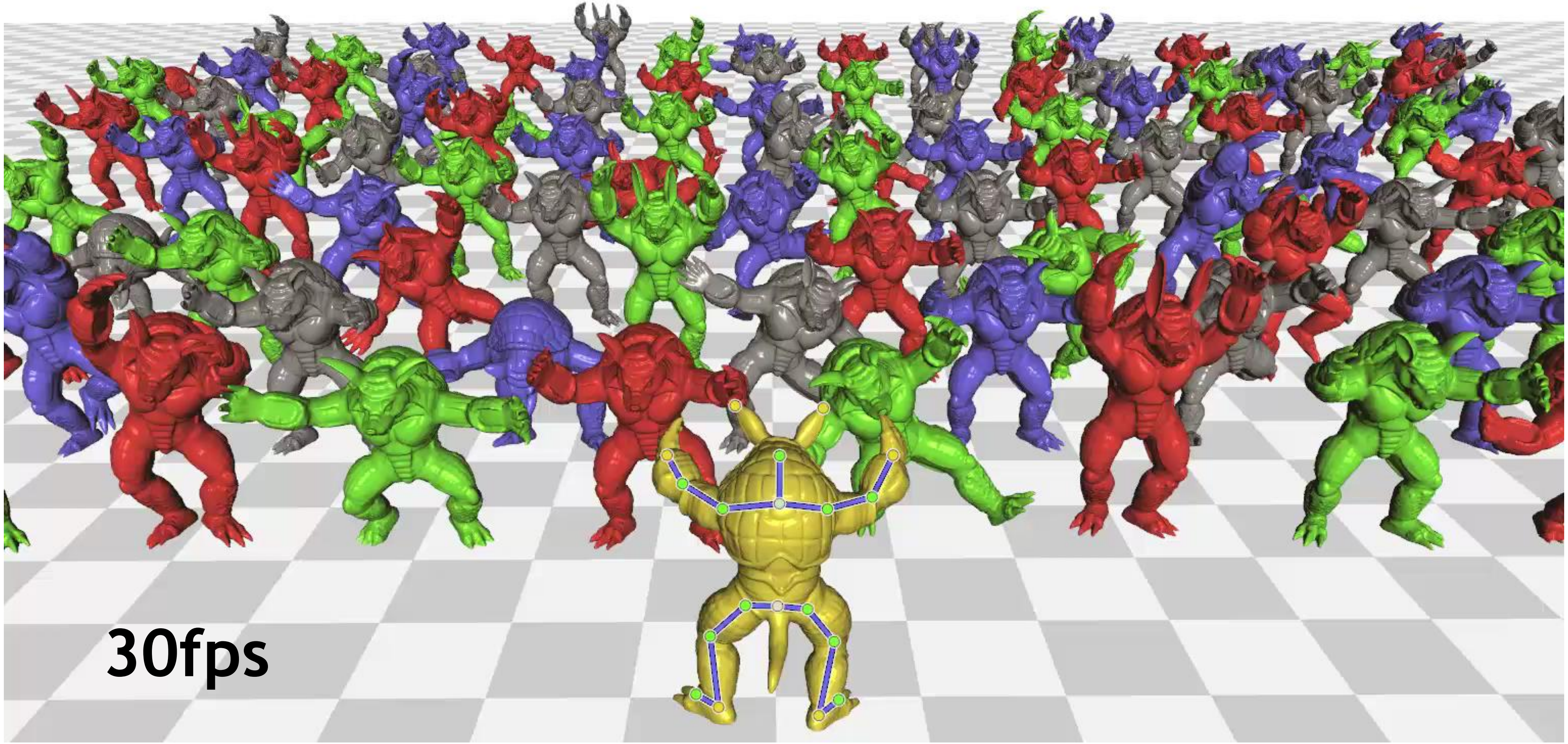


$$\min_{\mathbf{x}} \; E(\mathbf{x}) \quad s.t. \; \mathbf{x}|_{\mathcal{C}} = \mathbf{x}_{\text{fixed}}$$

User has more freedom!
Select and manipulate arbitrary regions.

100 Armadillos, 86K triangles each



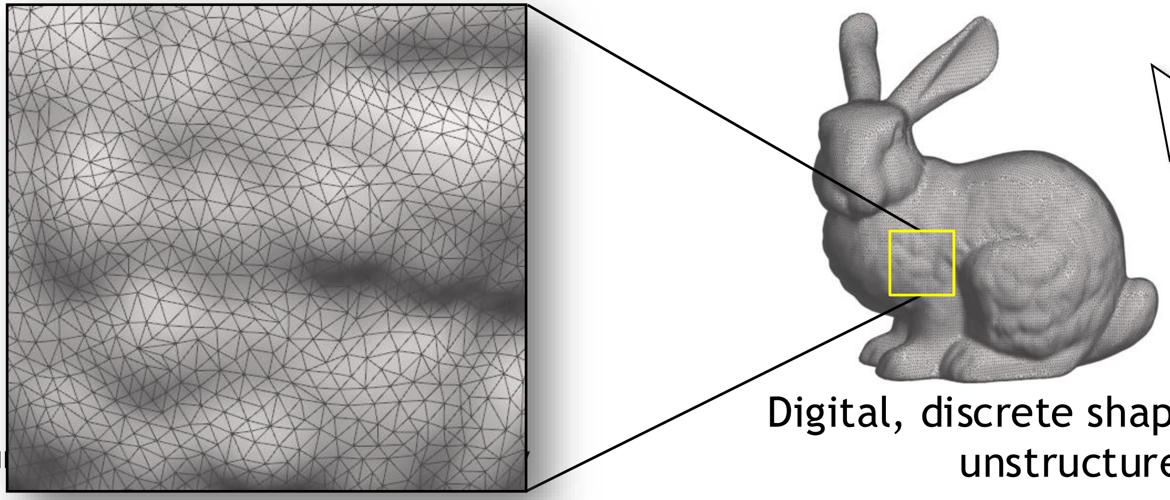
Modern Geometry Acquisition Pipeline

Physical object

scanning

3D point samples, range images

DGP

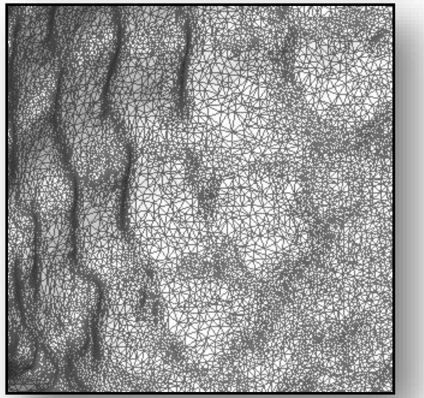


The Stanford Bu

Digital, discrete shape representation:
unstructured mesh

Unstructured Digital Shapes

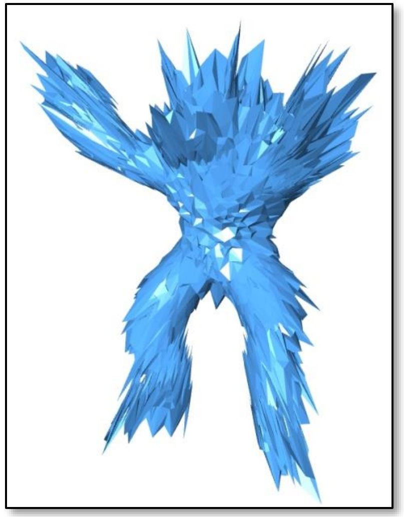
- How to **edit** and **animate**?
- How to convert to a **structured representation**?
- Computational challenge:
  very **large amounts of data**,
  yet modeling has to
  remain **interactive**



Thai statue, 10M triangles, Stanford 3D Scanning Repository

Tools?

- Use techniques from both CS & Math
  - Discrete differential geometry
  - Numerical methods
  - Numerical linear algebra
  - Graph theory
  - PDEs
  - ...
- ... combined with intuition and creativity ...
- work on real data, write/use sophisticated code



Organization

- Course website:
  https://igl.ethz.ch/teaching/shape-modeling/sm2025/
- Weekly* lectures and exercise sessions
- Prerequisites:
  - Computer Graphics or Visual Computing – somewhat soft condition
  - Knowledge of C++ programming – firm condition

* *see course website for the precise schedule*

Course Materials

- No book covers all topics
  - Many of the topics are recent research results
  - The following book might be helpful:
    Polygon Mesh Processing,
    Mario Botsch, Leif Kobbelt, Mark Pauly, Pierre Alliez, Bruno Levy, AK Peters, 2010.
    http://www.pmp-book.org/
    Several copies available in the CS library.

- We will **link** to relevant papers in the **course slides**
- Lecture slides available on the website shortly after the class

- Papers from: SIGGRAPH, Symposium on Geometry Processing (SGP), EUROGRAPHICS, etc.
  Useful website:
  https://kesen.realtimerendering.com/

Grading

- Homework assignments — 80%
  - Mesh / libigl “Hello, world!”
  - Surface reconstruction
  - DDG tutorial and smoothing – optional, ungraded
  - Mesh parameterization
  - Detail preserving shape deformation
  - Articulated character deformation/animation
- Multiple choice, timed assignment (60 min) (last lecture slot, 28.05.2025) — 20%
- All programming assignments are in C++, details on Friday in the TA session.

Policy

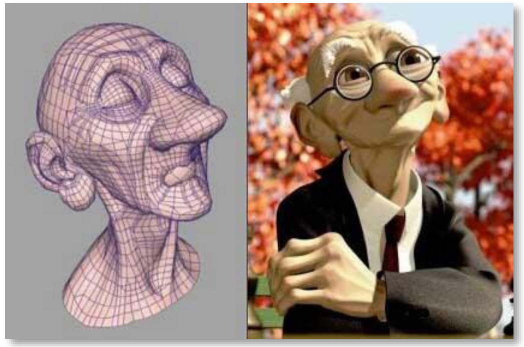
- Homework assignments to be done individually
  - May consult (also via forum) but may not collaborate
  - Plagiarism checks on all assignments, zero tolerance policy
  - More details in the exercise section

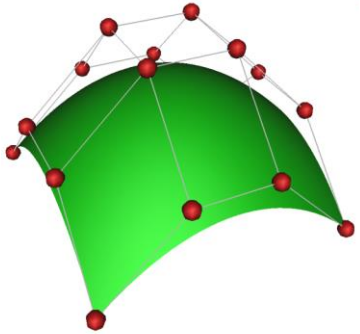
- Laptops in class – last occupied row only, please ☺

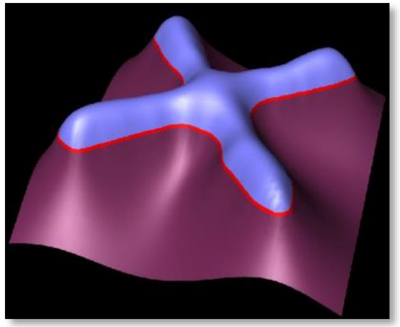
- Feel free to participate and ask questions!

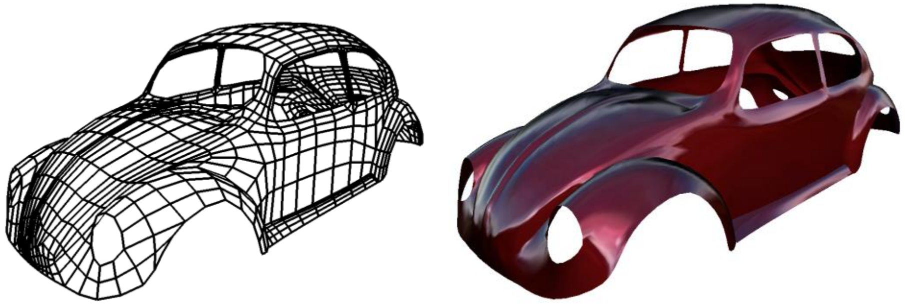
Course Topics

- Overview of **shape representations**
  - Parametric curves/surfaces
  - Implicit surfaces
  - Polygonal meshes



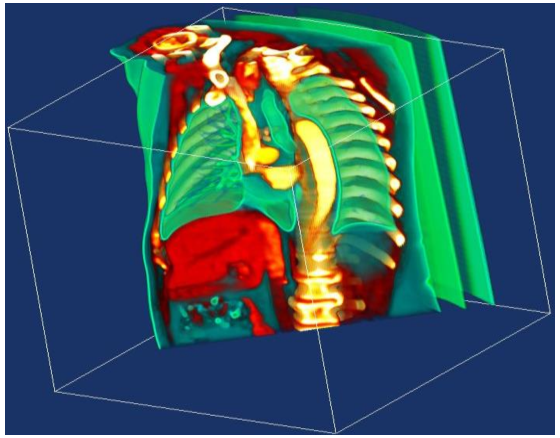
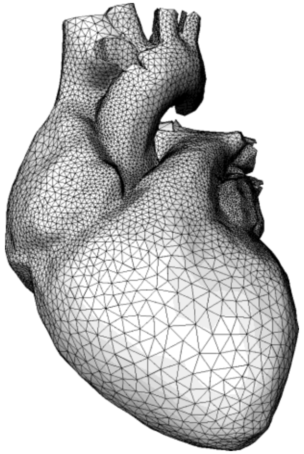
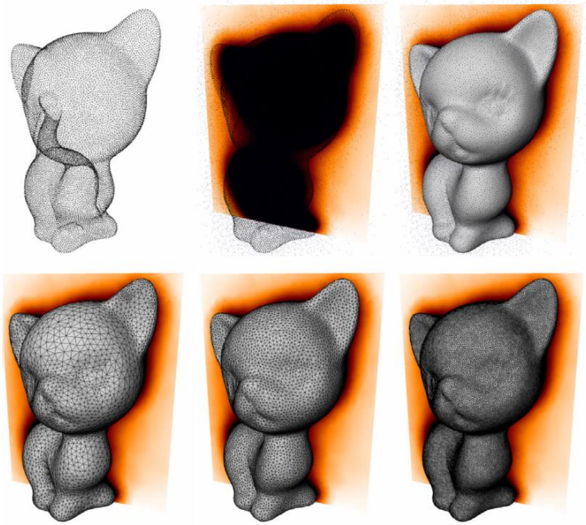
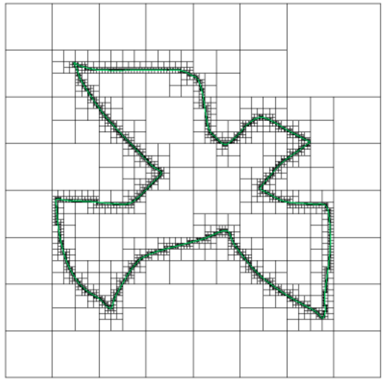






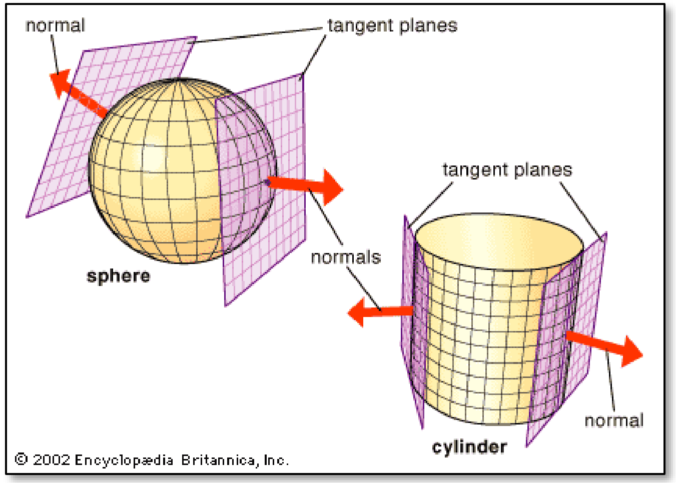
Course Topics

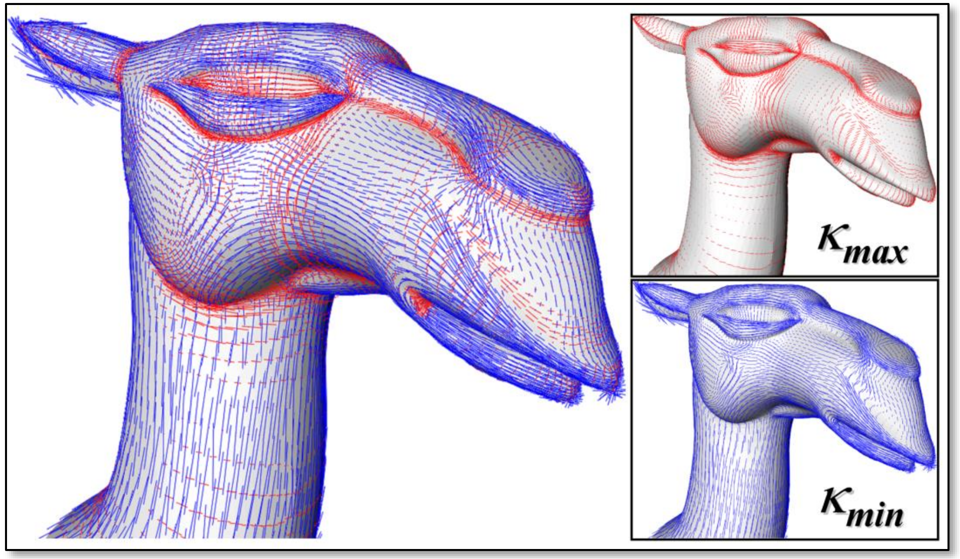
- **Shape acquisition**
  - Scanning/imaging
  - Reconstruction


Course Topics

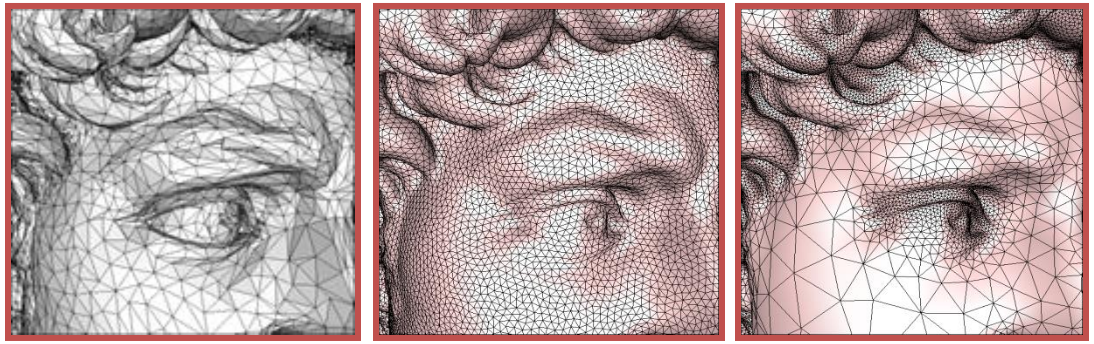
- **Differential geometry**
  - Continuous and discrete
  - Powerful tool to analyze and model shapes

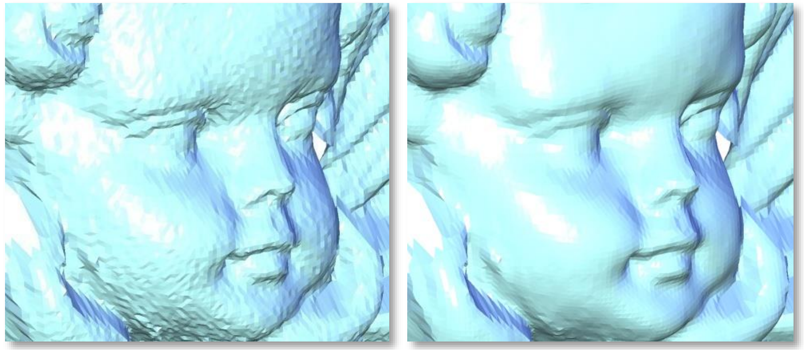




Course Topics

- **Digital geometry processing**
  - Denoising, smoothing, simplification, remeshing, parameterization, compression



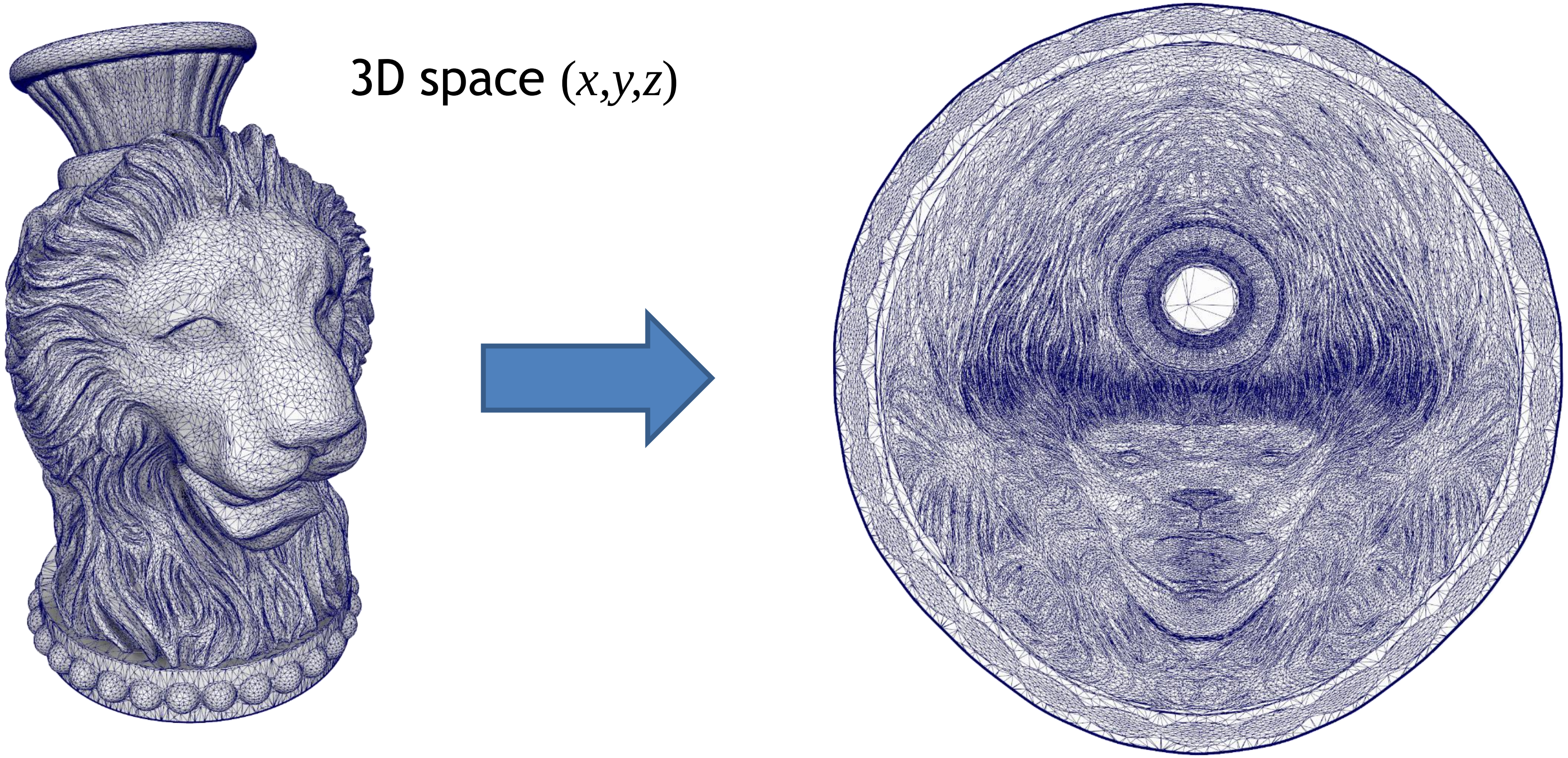


Course Topics

- Parameterization

2D parameter domain (u,v)

3D space (x,y,z)

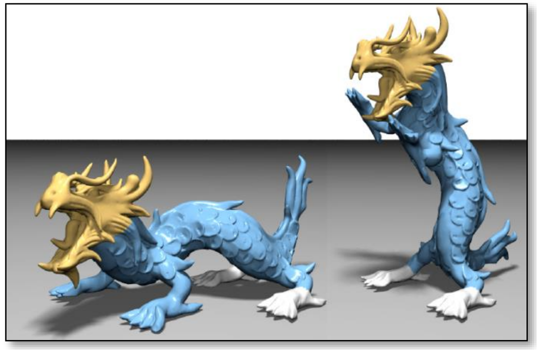


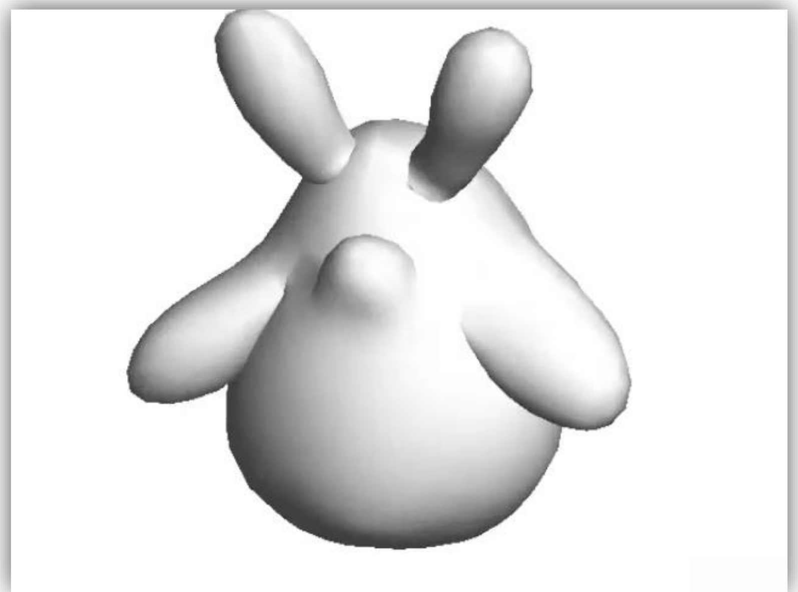
Course Topics

- Parameterization

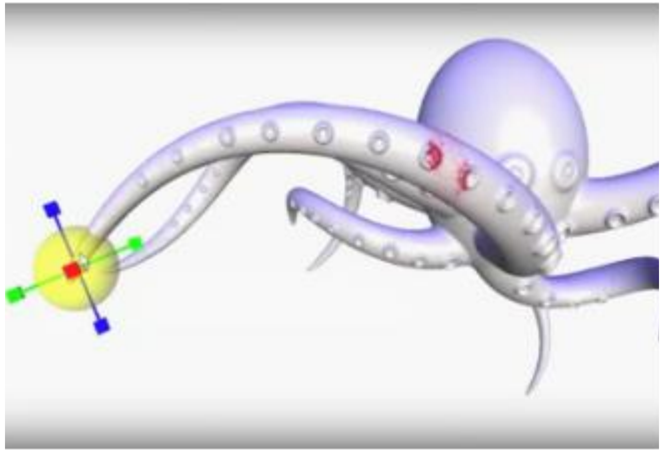
Course Topics

- Shape creation and editing





http://youtu.be/W0XGkS7zebo



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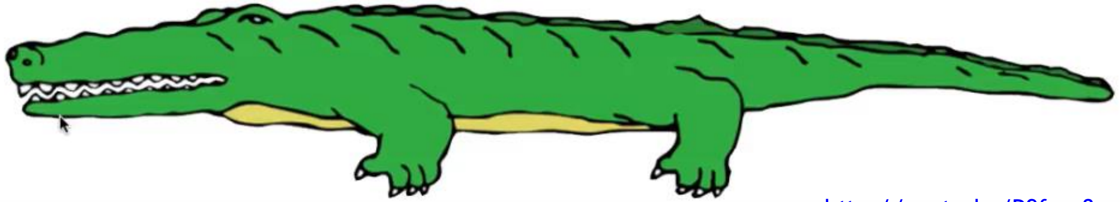
Course Topics

- Skinning, animation



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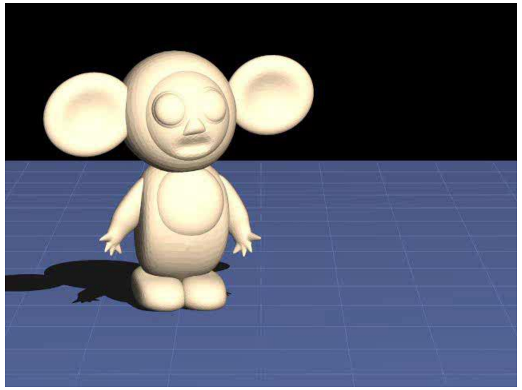
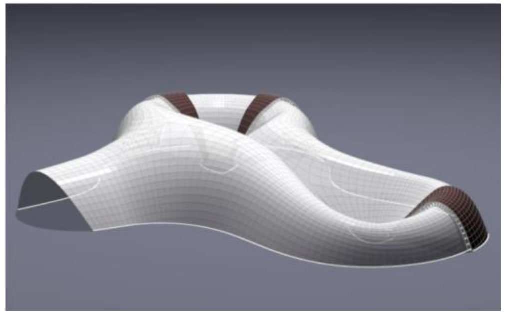
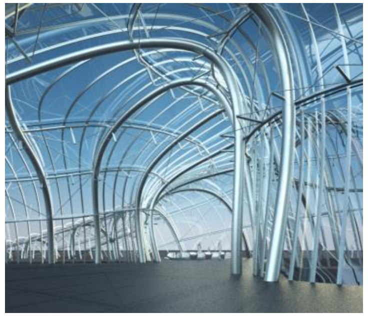
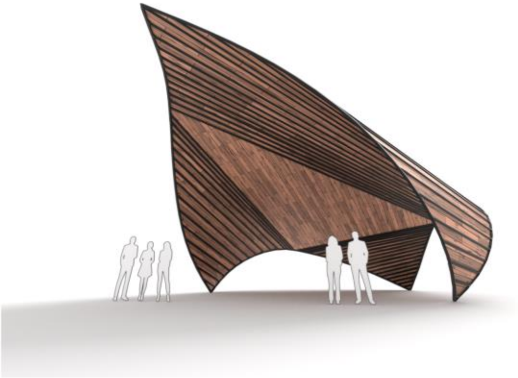
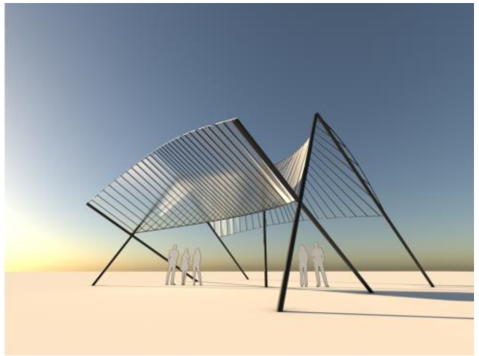
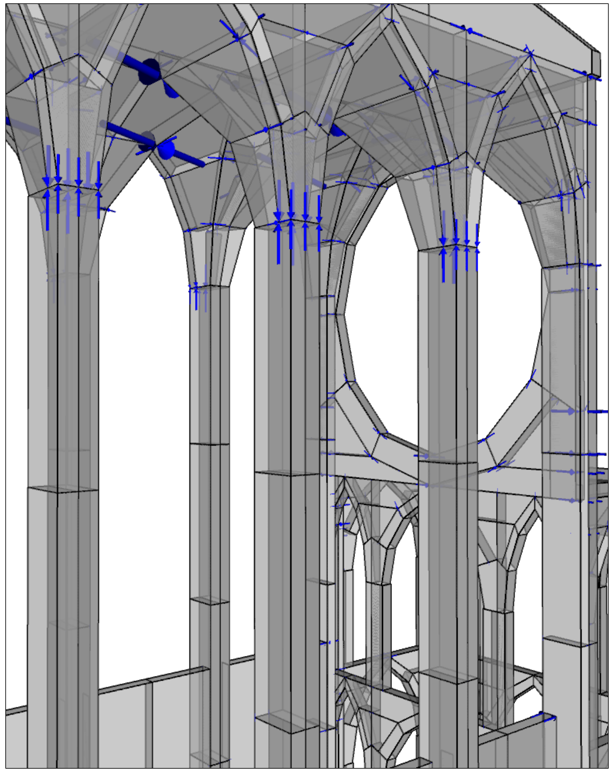


http://www.mit.edu/~ibaran/autorig/

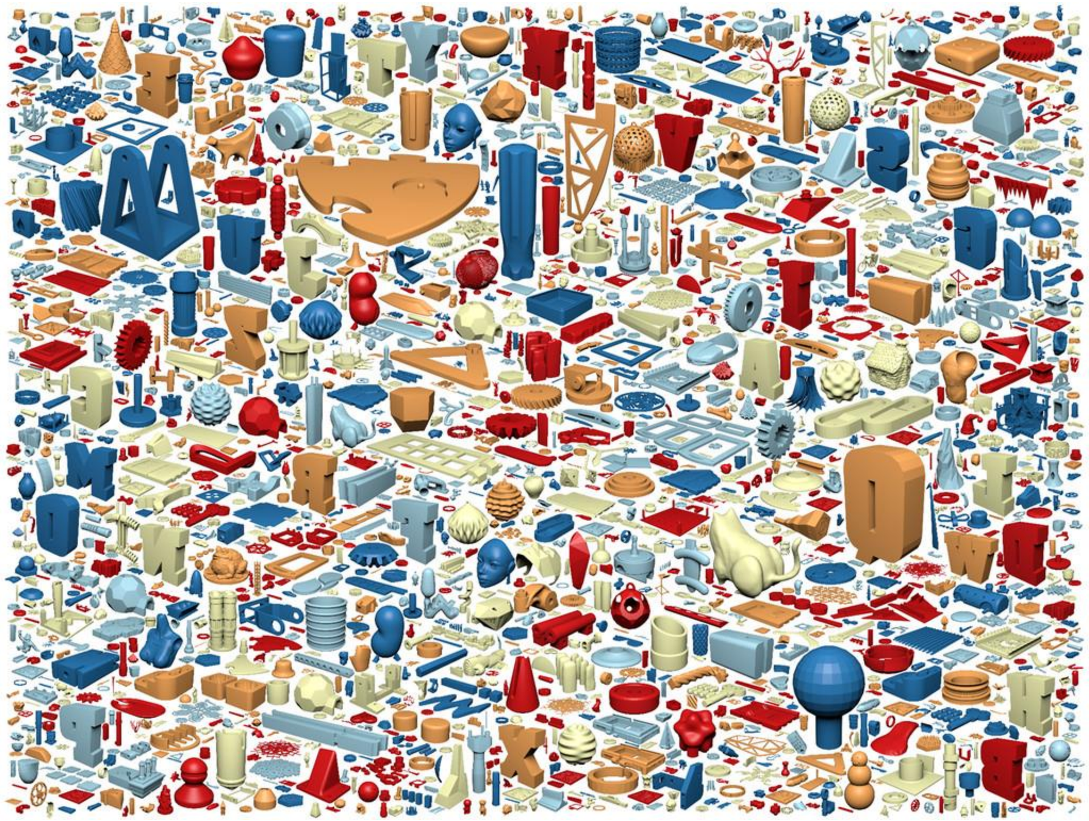
Advanced topics – TBD

- Architectural geometry, developable surfaces

Advanced topics – TBD

- Data driven geometry processing and learning



Hertz et al. 2022: the **SPAGHETTI** system (a deep neural network).
Shape parts and the rules for their relationships are automatically learned.

Thank you

INTERACTIVE GEOMETRY LAB

February 19, 2025

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich