Praktikum

Geometry Processing

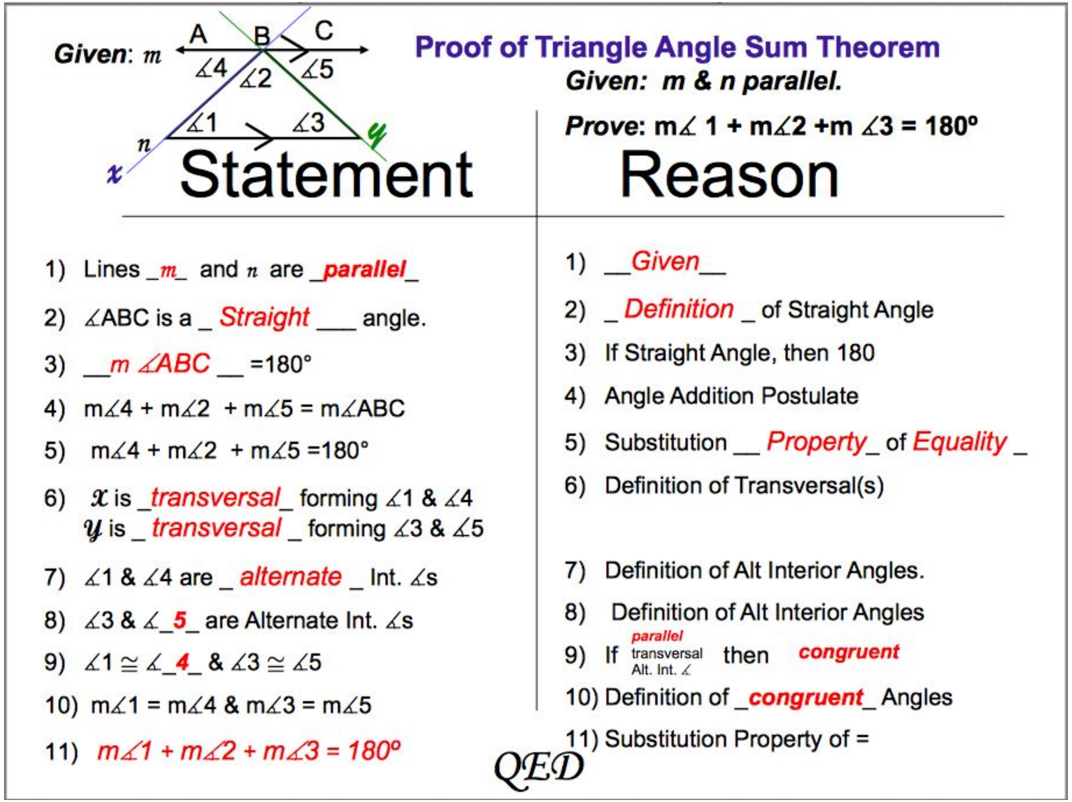
1 Introduction

Ludwig-Maximilians-Universität München

Session 1: Introduction

- Motivation
- Recap: Graphics Pipelines
- Geometry Representations
- Blender Basics
- Summary

This course is *not* about ...



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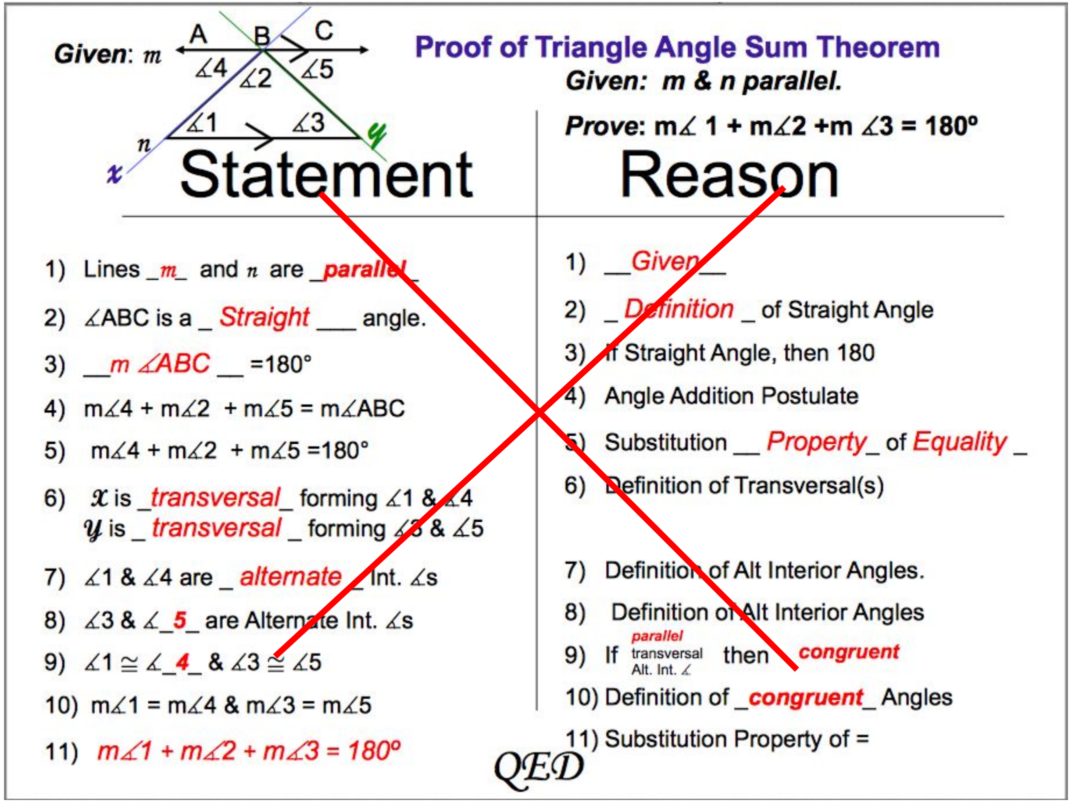
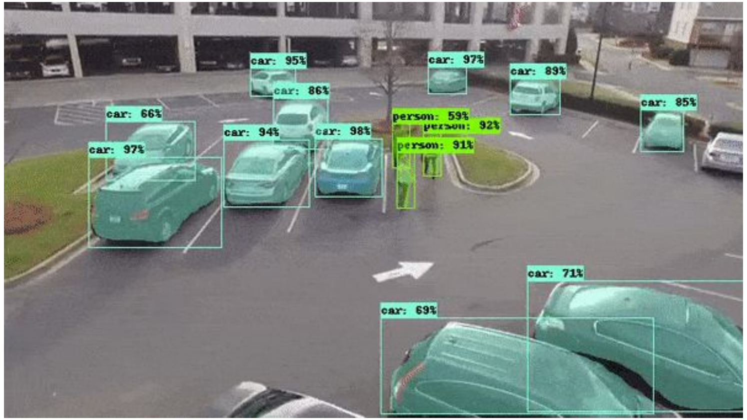
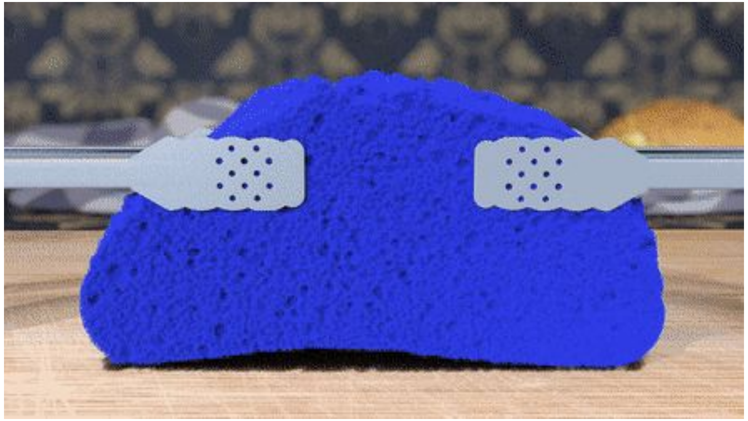


This course is *not* about ...

[Yan et al. 2015]



[He et al. 2018]



[Wolper et al. 2019]

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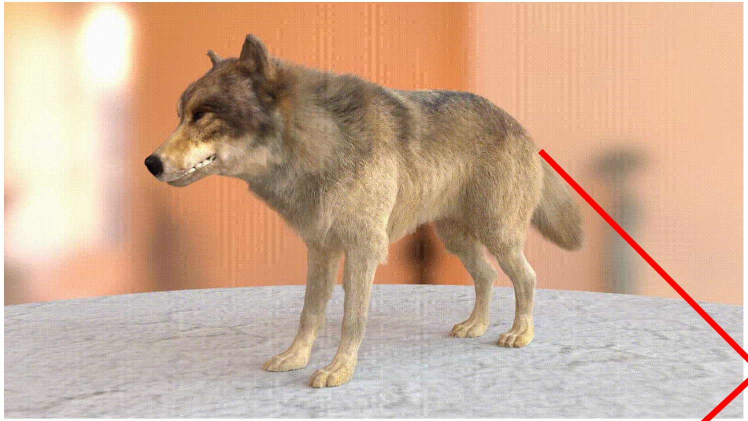

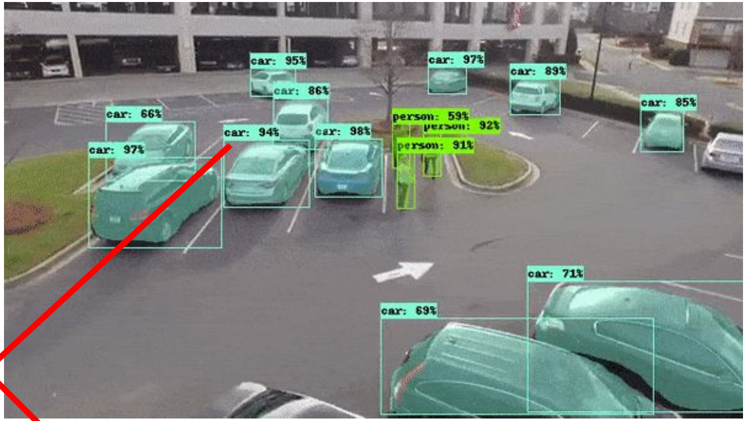

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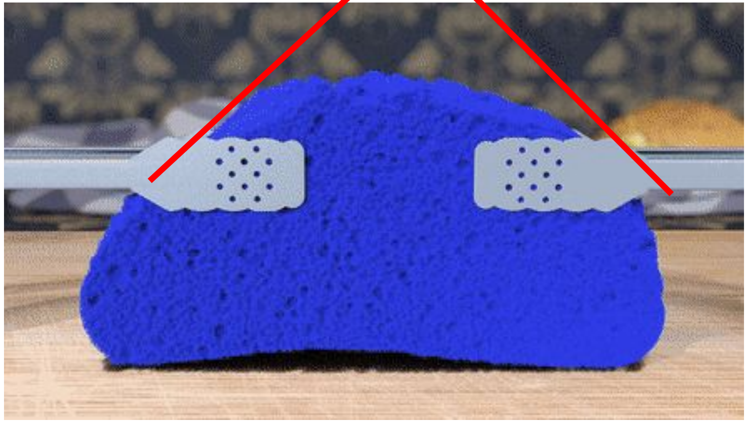

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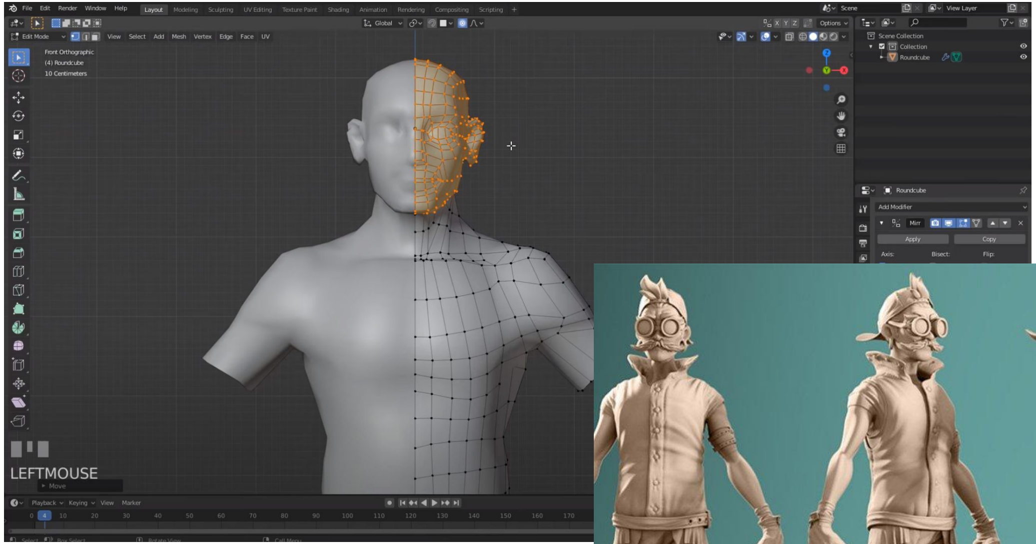
This course is also *not* about ...



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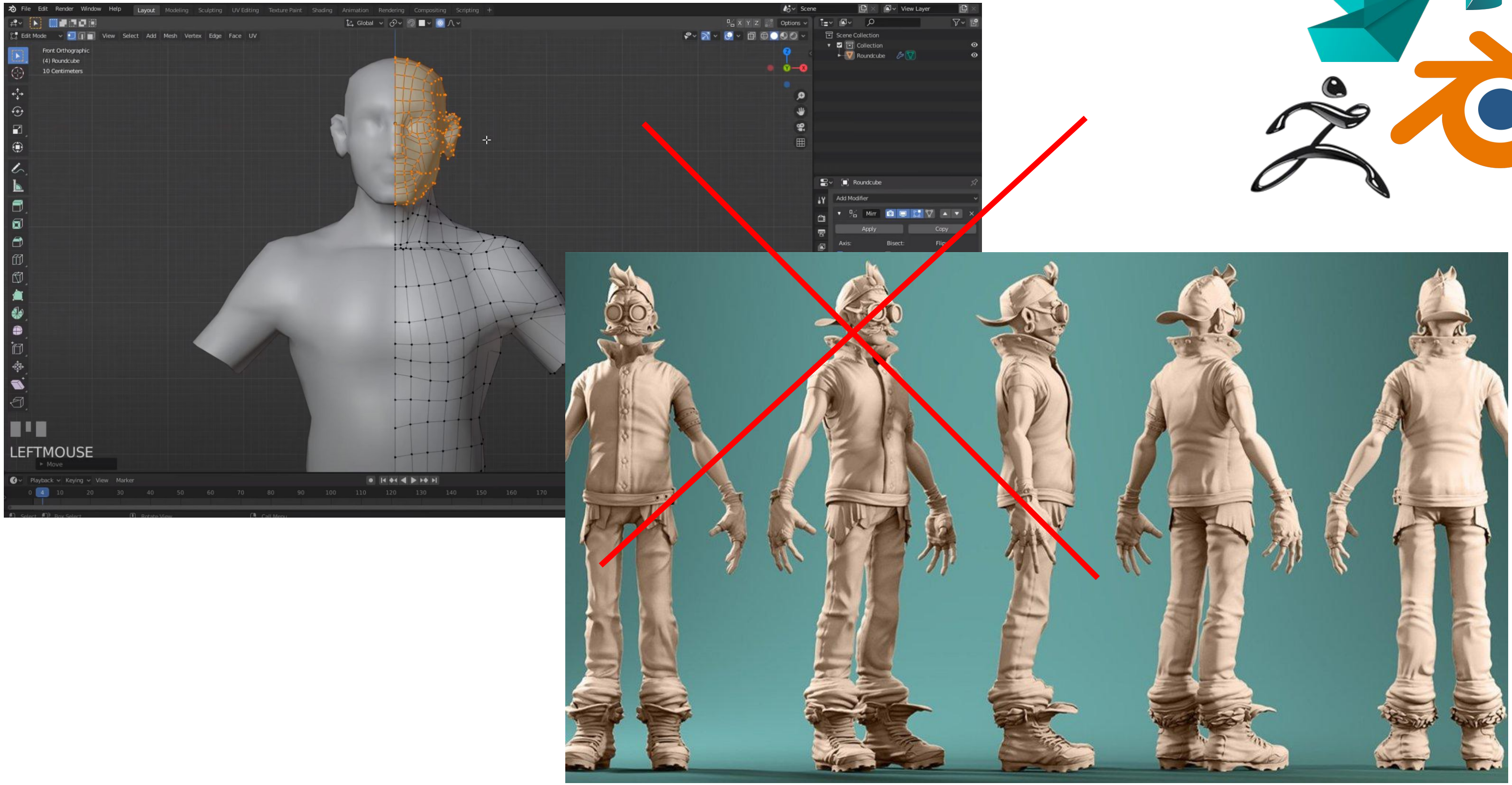
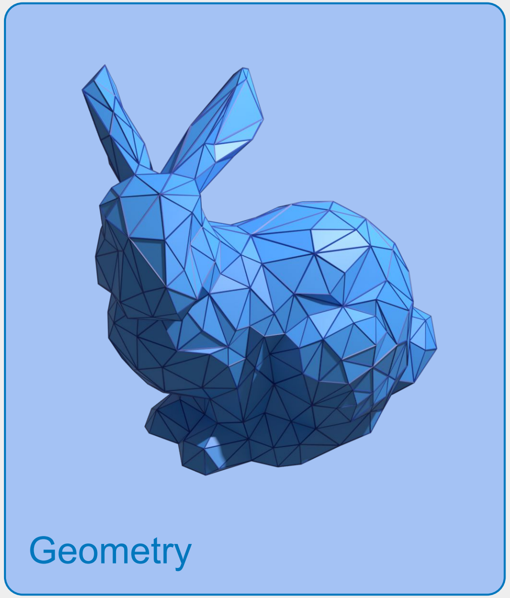
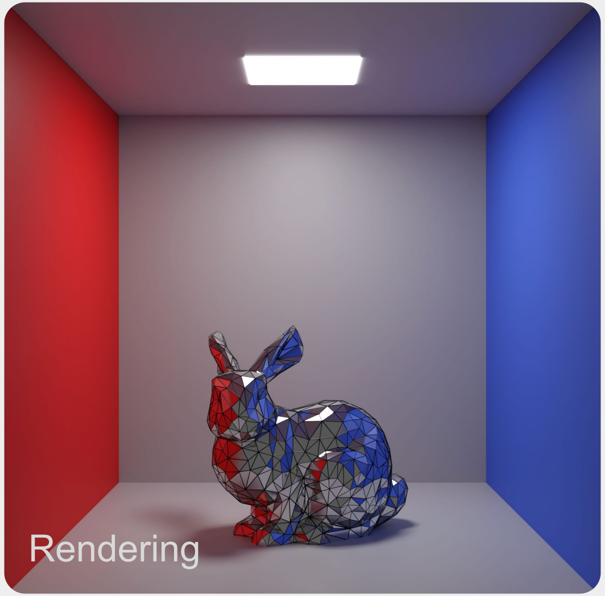


This course is a direct extend to the CG1 for geometry





Computer Graphics

This course is a direct extend to the CG1 for geometry

We will Focus on How to Deal with 3D Geometries *Algorithmically*

Curvature;

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 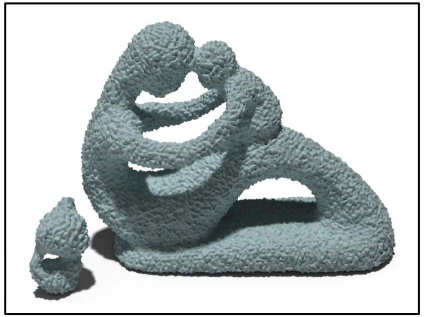

Curvature; Smoothing;

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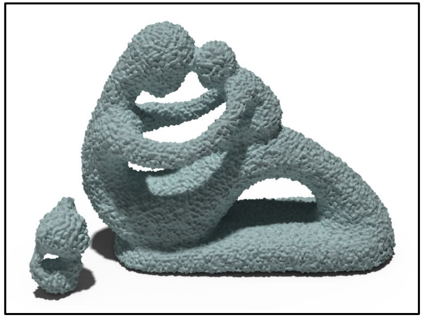
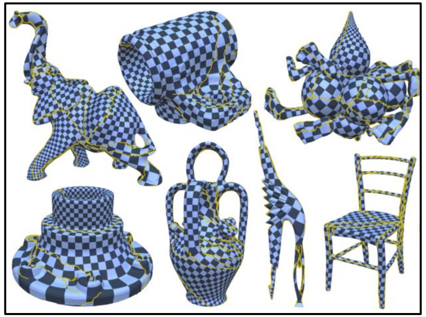
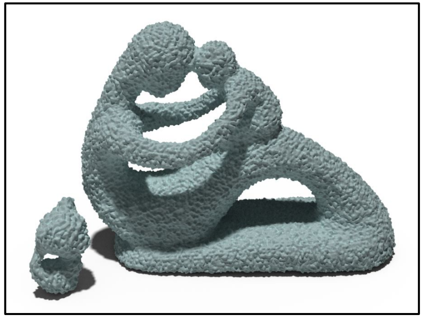
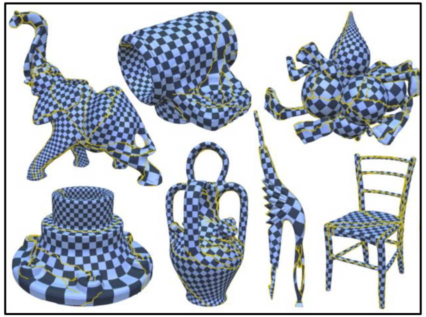
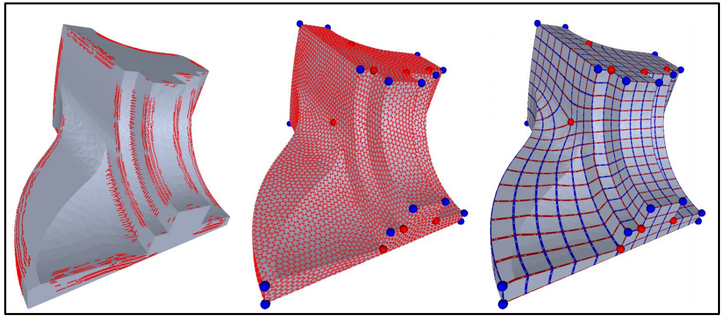




Curvature; Smoothing; Parameterization;

We will Focus on How to Deal with 3D Geometries *Algorithmically*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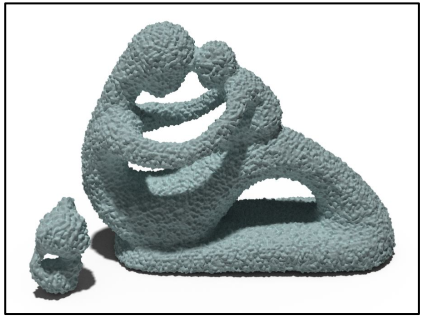
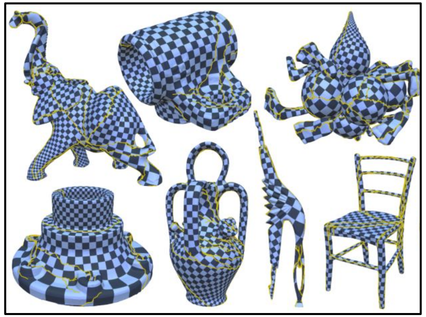
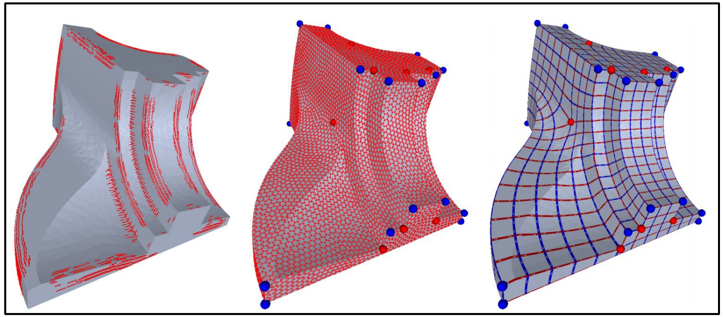

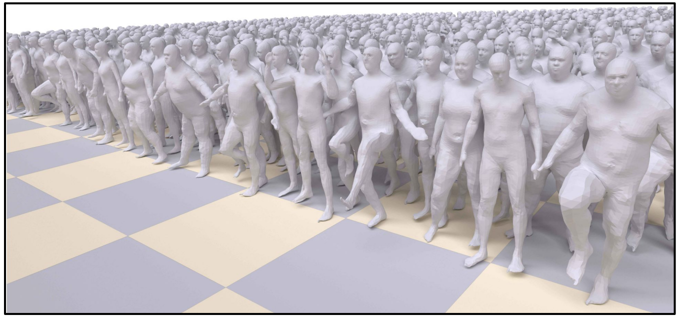

Curvature; Smoothing; Parameterization; Remeshing; Deformation;

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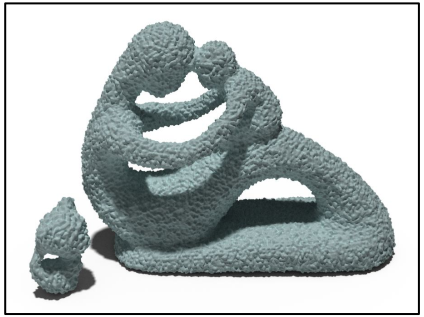
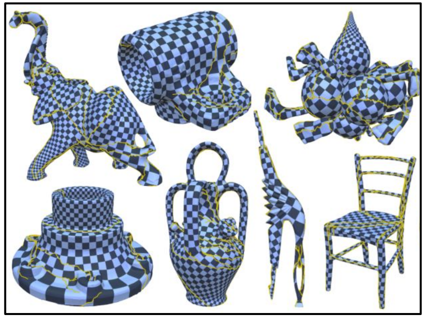
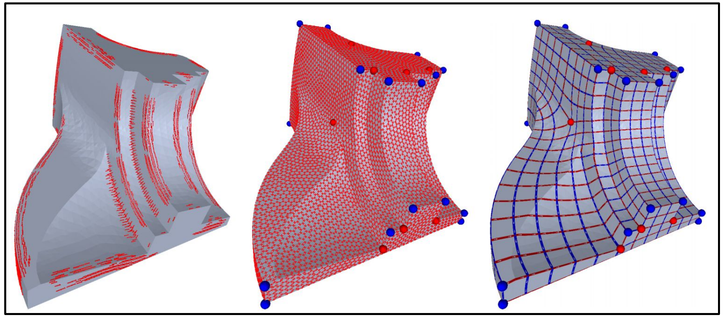

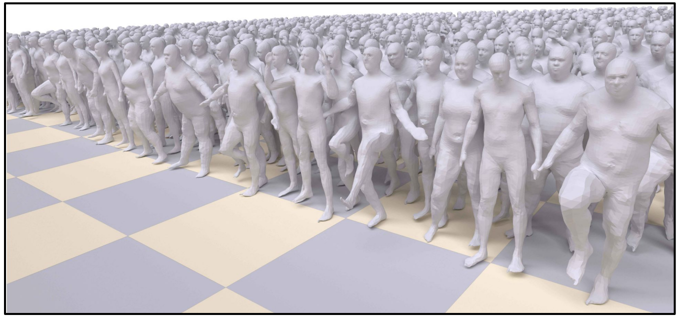
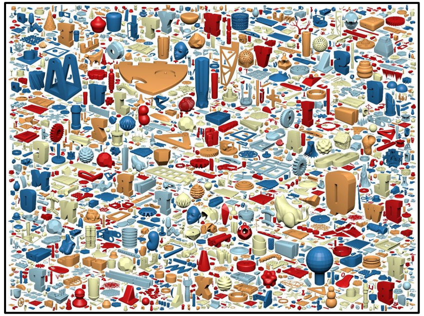

……

Curvature; Smoothing; Parameterization; Remeshing; Deformation; Shape Analysis; ...

This Course remains Interdisciplinary ...

$$\mathcal{H}(\mathcal{M}, \mathcal{M}') = \sqrt{\frac{1}{|\mathcal{S}|} \iint_{v \in \mathcal{S}} d(p, \mathcal{S}')^2 \mathrm{d}\mathcal{S}}$$

Mathematics

Formal foundation: **Differential geometry**, numeric analysis, …
(back to 19 century)

Geometry Processing

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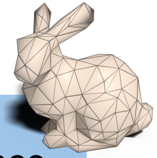
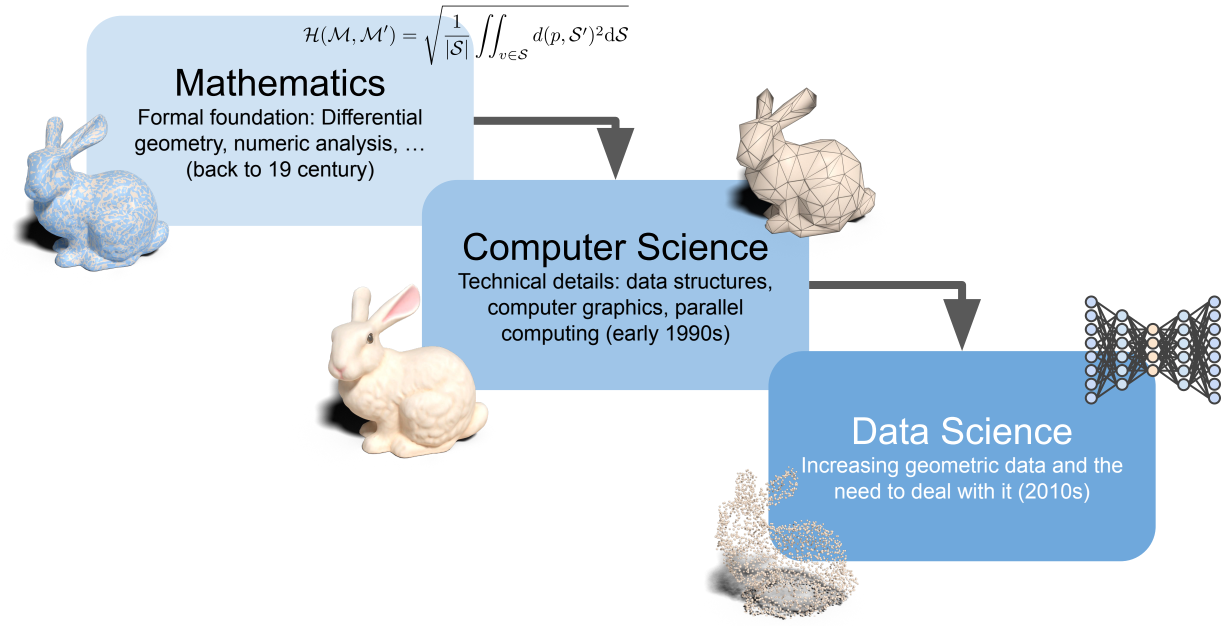


Computer Science

Technical details: data structures, computer graphics, parallel computing (early 1990s)

Geometry Processing

This Course remains Interdisciplinary ...



Geometry Processing

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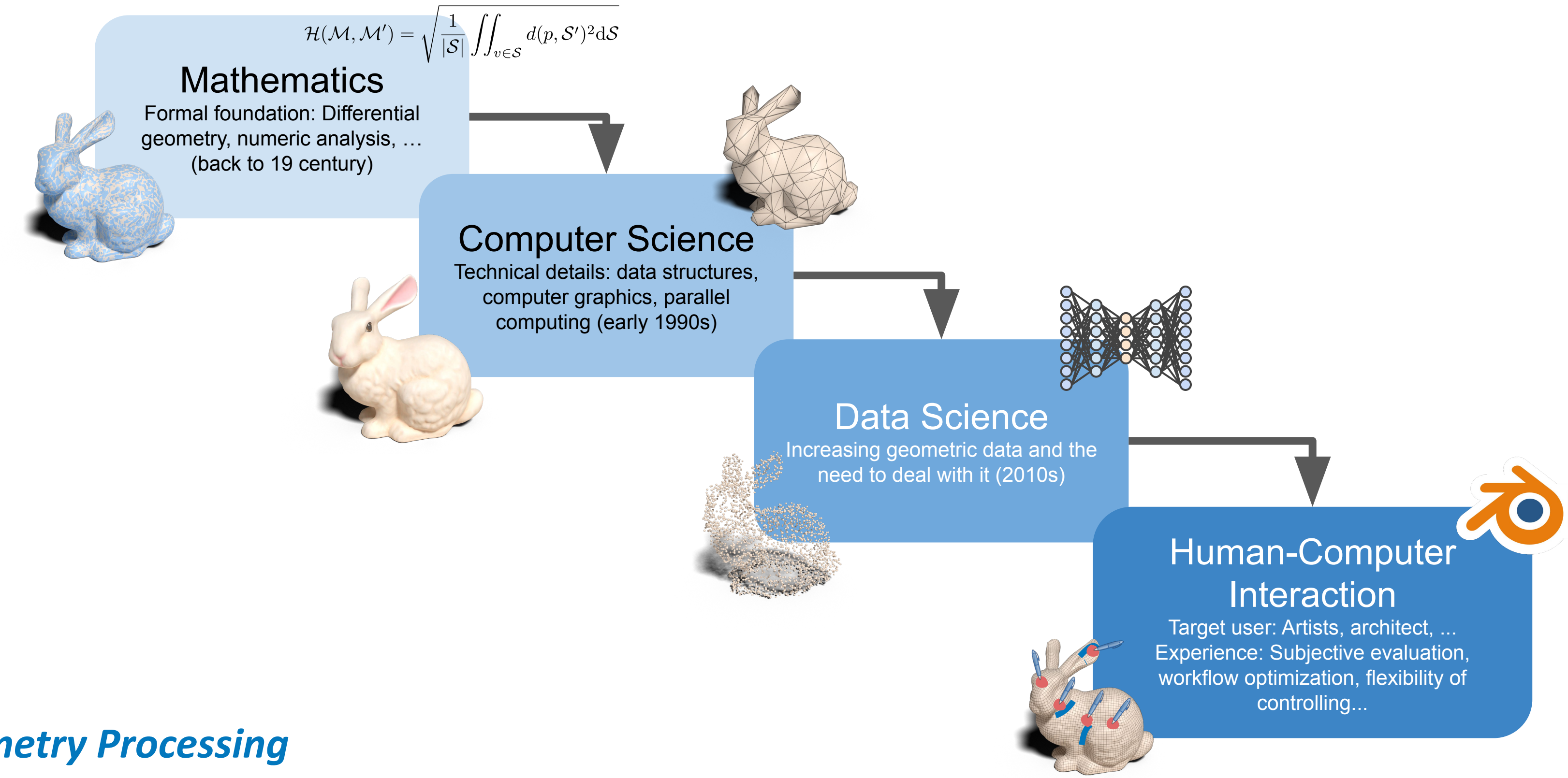

Geometry Processing

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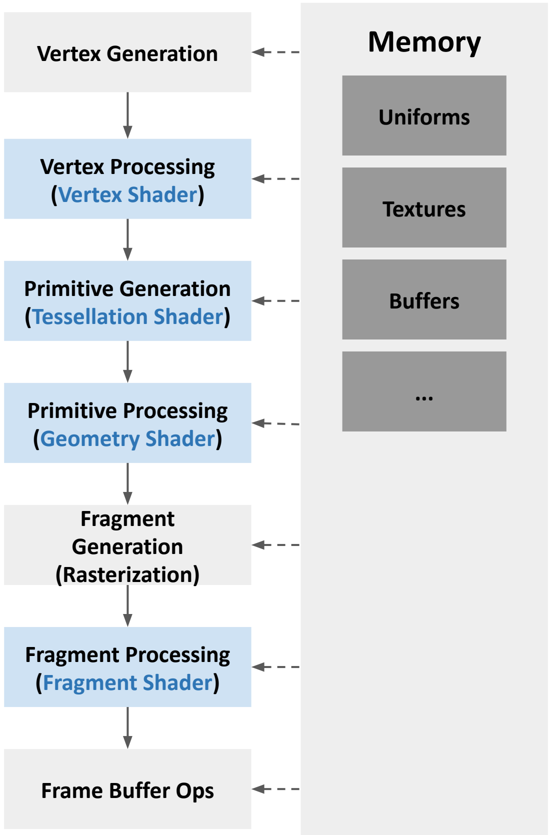
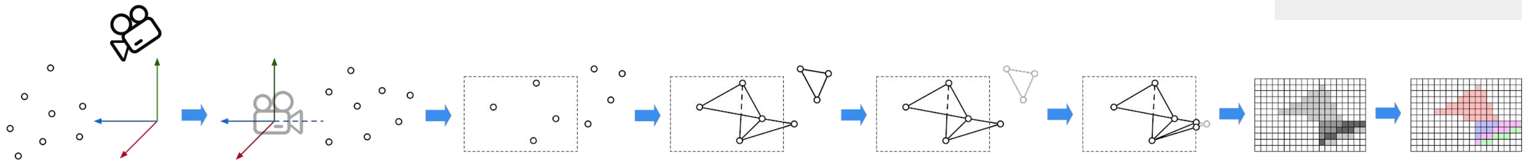
Rasterization Pipeline

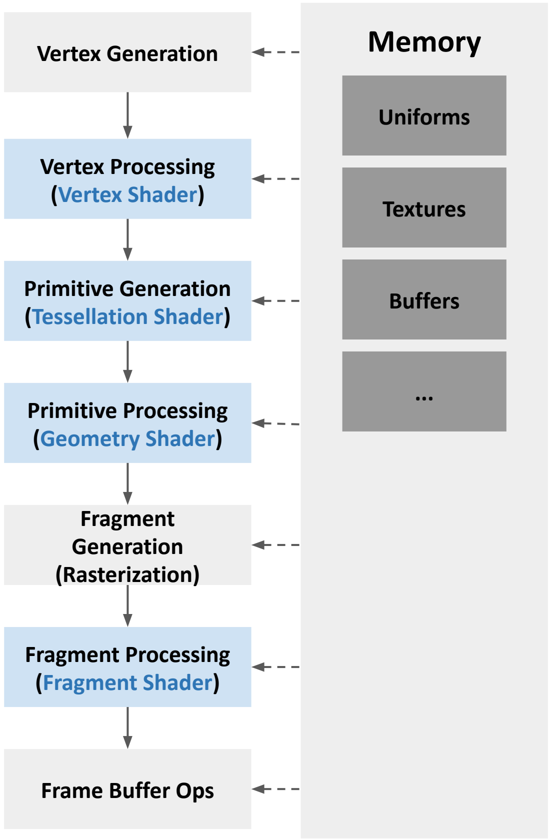
```
init frame buffer
init depth buffer
for each triangle t in scene {
   tp = project(t)
   for each pixel p in frame buffer {
       if tp covers p {
           if z passes depth test at p {
               update z buffer and frame buffer
           }
       }
   }
}
flush frame buffer to monitor
```

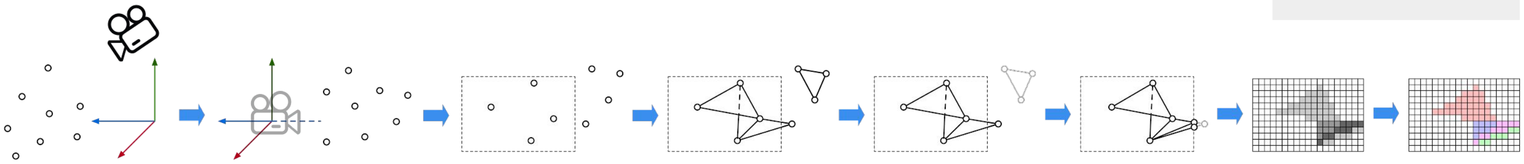




Rasterization Pipeline

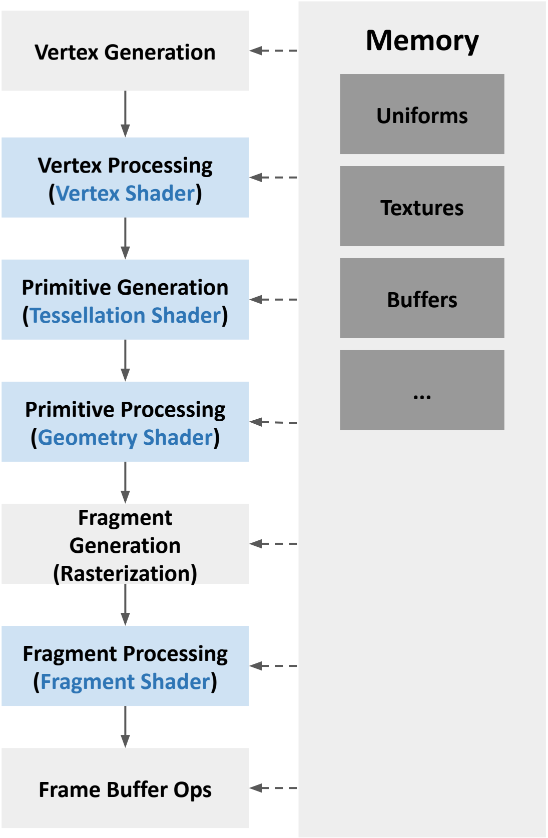
```
init frame buffer
init depth buffer
for each triangle t in scene {
   tp = project(t) // MVP
   for each pixel p in frame buffer {
       if tp covers p {
           if z passes depth test at p {
               update z buffer and frame buffer
           }
       }
   }
}
flush frame buffer to monitor
```

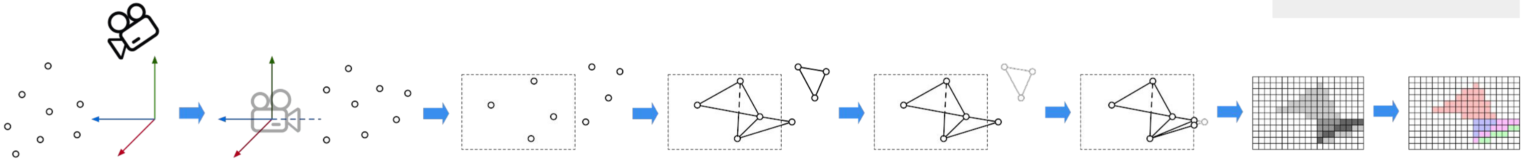




Rasterization Pipeline

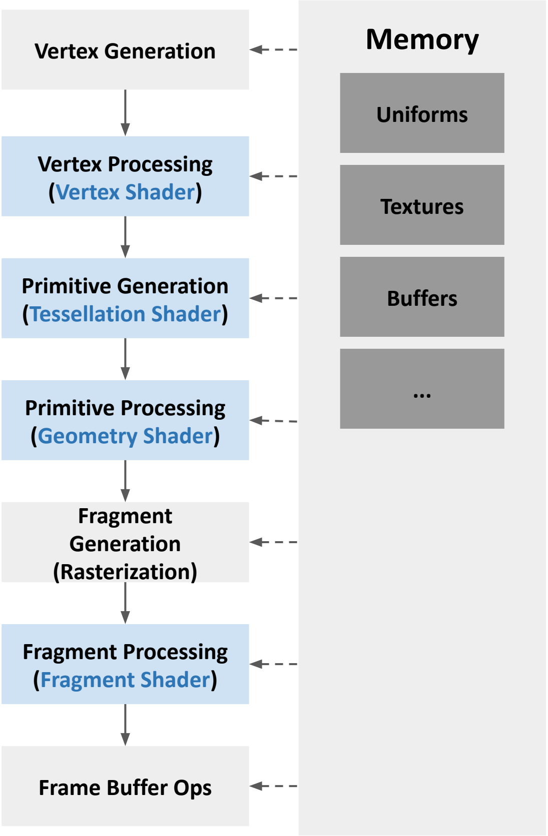
```
init frame buffer
init depth buffer
for each triangle t in scene {
   tp = project(t) // MVP
   for each pixel p in frame buffer {
       if tp covers p { // culling
           if z passes depth test at p {
               update z buffer and frame buffer
           }
       }
   }
}
flush frame buffer to monitor
```

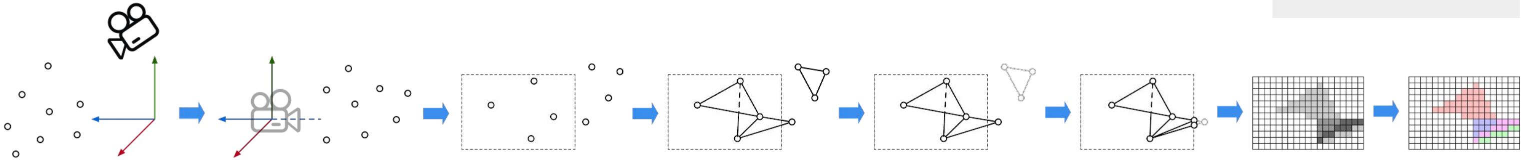




Rasterization Pipeline

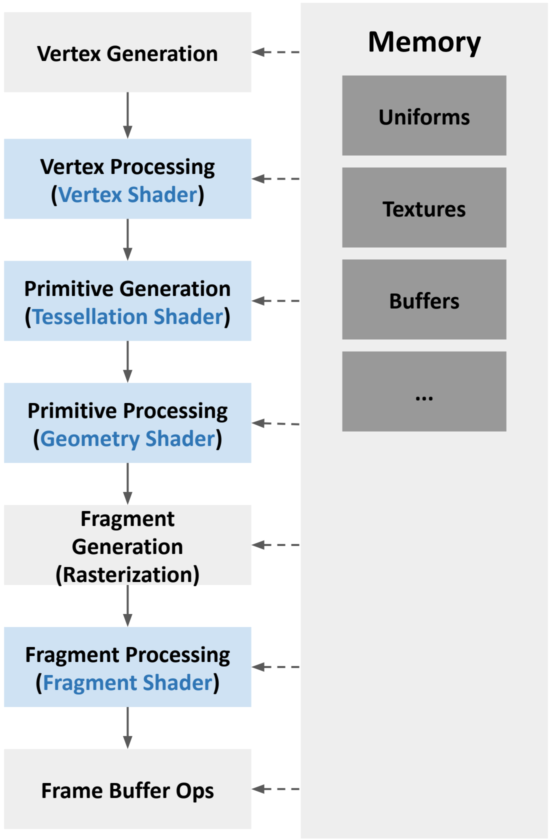
```
init frame buffer
init depth buffer
for each triangle t in scene {
   tp = project(t) // MVP
   for each pixel p in frame buffer {
       if tp covers p { // culling
           if z passes depth test at p { // depth-test
               update z buffer and frame buffer
           }
       }
   }
}
flush frame buffer to monitor
```

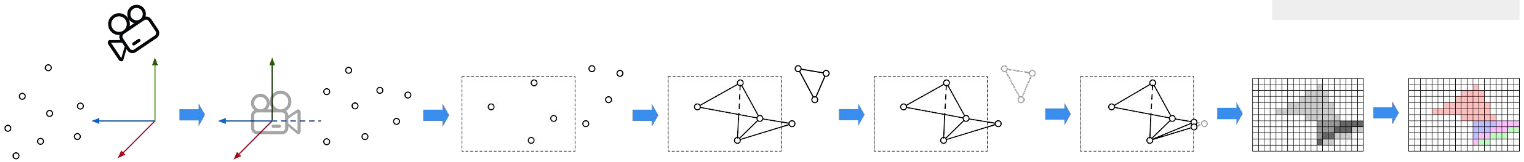




Rasterization Pipeline

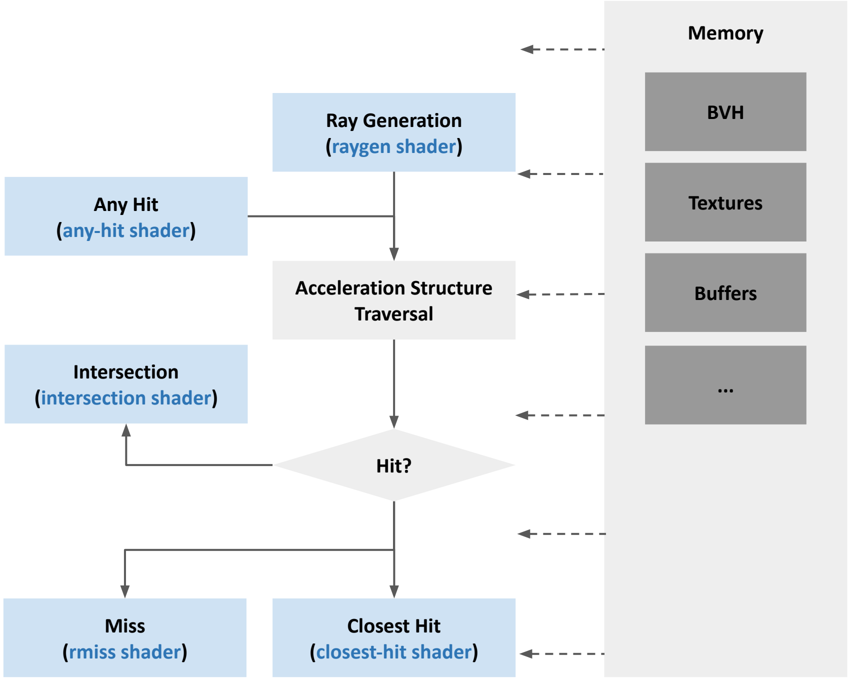
```
init frame buffer
init depth buffer
for each triangle t in scene {
   tp = project(t) // MVP
   for each pixel p in frame buffer {
       if tp covers p { // culling
           if z passes depth test at p { // depth-test
               update z buffer and frame buffer // interpolation & update
           }
       }
   }
}
flush frame buffer to monitor
```

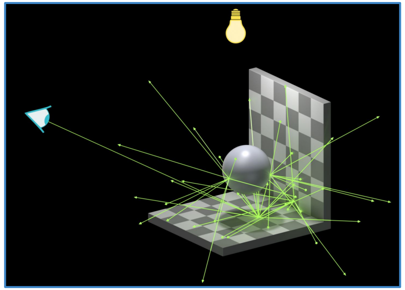


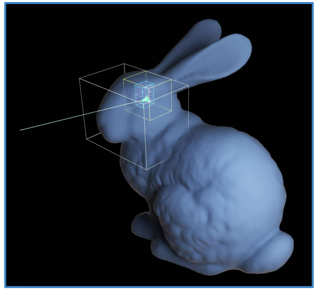


Ray Tracing Pipeline

```
init frame buffer
for each pixel p in frame buffer {
    construct a ray from p
    for ray bounces is not over {
        for each triangle t in the scene {
            if ray hit t at x {
                keep x if closest and update the ray
                break
            }
        }
    }
    update frame buffer
}
flush frame buffer to monitor
```







Ray Tracing Pipeline

```
init frame buffer
for each pixel p in frame buffer {
   construct a ray from p        // ray generation
   for ray bounces is not over {
      for each triangle t in the scene {
         if ray hit t at x {
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            break
         }
      }
   }
   update frame buffer
}
flush frame buffer to monitor
```
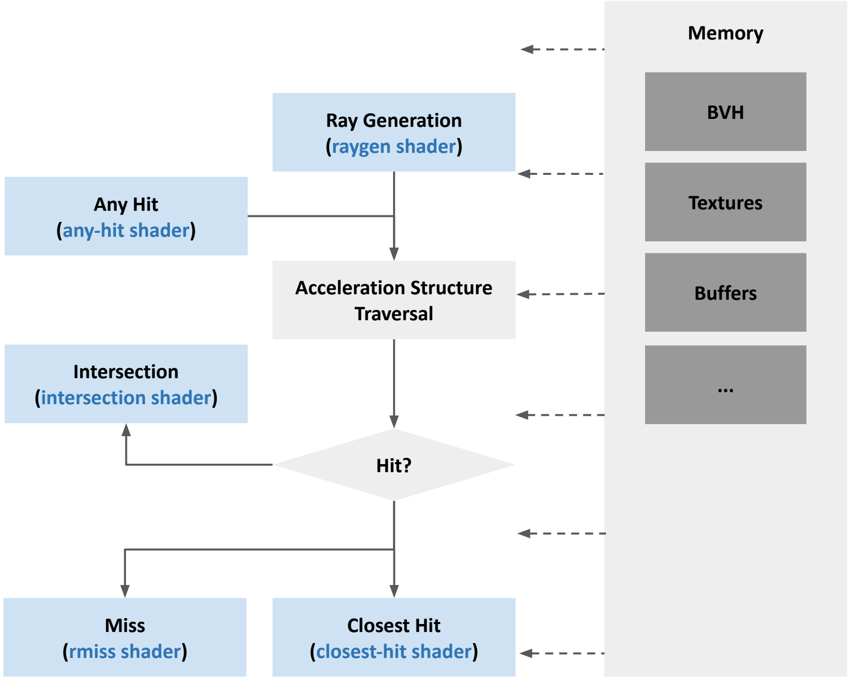
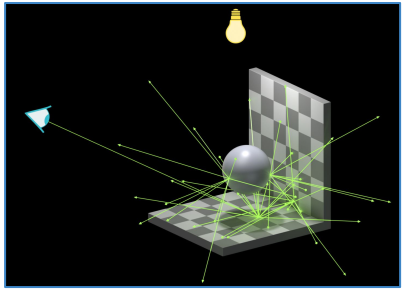
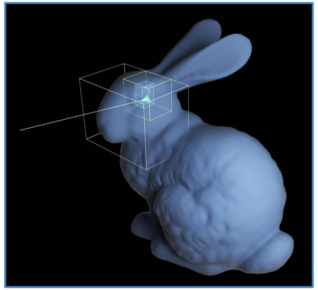
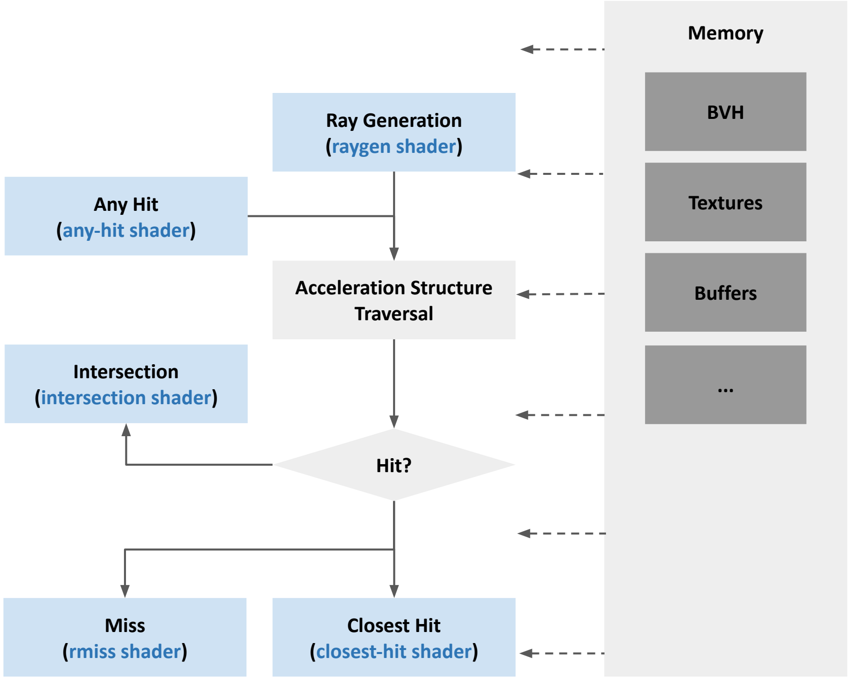



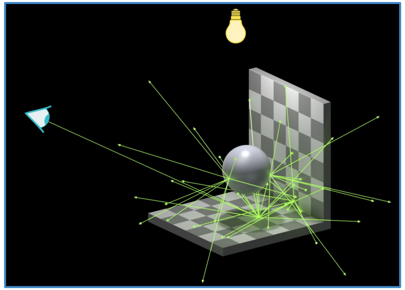


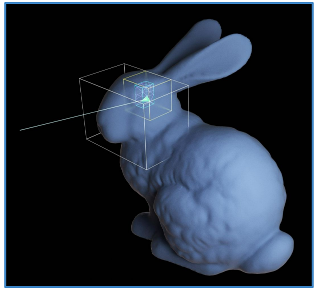


Ray Tracing Pipeline

```
init frame buffer
for each pixel p in frame buffer {
   construct a ray from p         // ray generation
   for ray bounces is not over { // russian roulette
       for each triangle t in the scene {
           if ray hit t at x {
               keep x if closest and update the ray
               break
           }
       }
   }
   update frame buffer
}
flush frame buffer to monitor
```

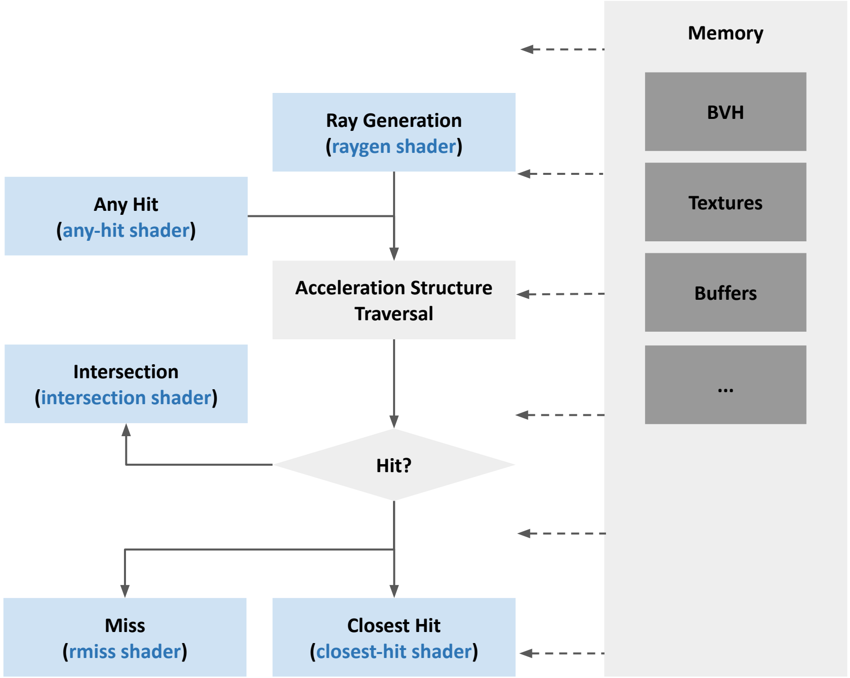


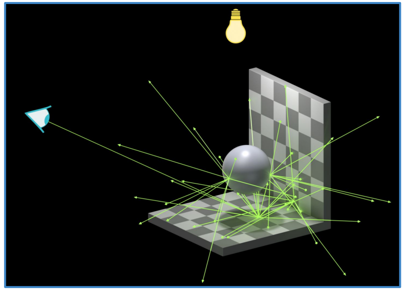


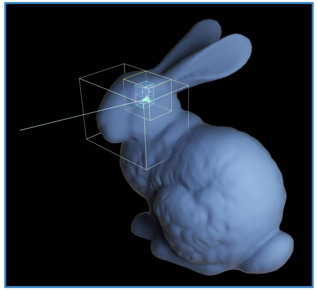


Ray Tracing Pipeline

```
init frame buffer
for each pixel p in frame buffer {
   construct a ray from p        // ray generation
   for ray bounces is not over { // russian roulette
       for each triangle t in the scene { // BVH
           if ray hit t at x {
               keep x if closest and update the ray
               break
           }
       }
   }
   update frame buffer
}
flush frame buffer to monitor
```







Ray Tracing Pipeline

```
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   for ray bounces is not over { // russian roulette
       for each triangle t in the scene { // BVH
           if ray hit t at x {    // ray casting
               keep x if closest and update the ray
               break
           }
       }
   }
   update frame buffer
}
flush frame buffer to monitor
```

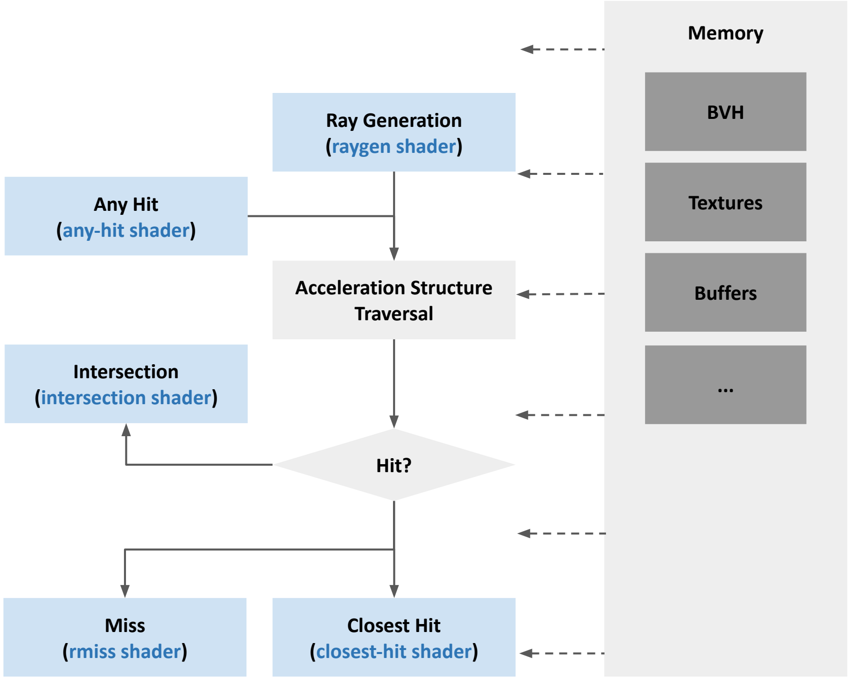

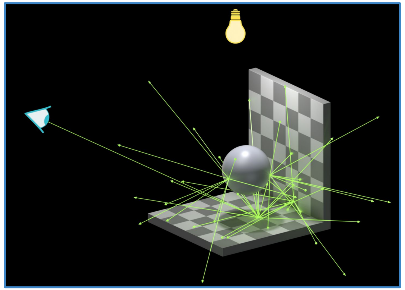

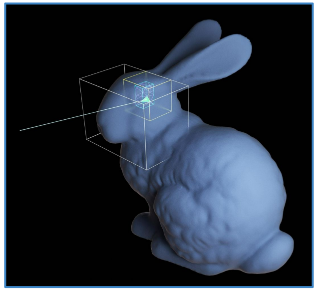

Unanswered Questions (in CG1)

- How geometric objects are created/loaded?

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- Why interpolation is done by barycentric coordinates instead of a different way?

Unanswered Questions (in CG1)

- How geometric objects are created/loaded?
- How geometries are stored in file/memory?
- How vertex normals/UVs are created/defined?
- Why interpolation is done by barycentric coordinates instead of a different way?
- How to deal with normals/uvs if a mesh is modified?
- …

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- How geometries are stored in file/memory?
- How vertex normals/UVs are created/defined?
- Why interpolation is done by barycentric coordinates instead of a different way?
- How to deal with normals/uvs if a mesh is modified?
- …

Let's restart from the very beginning…

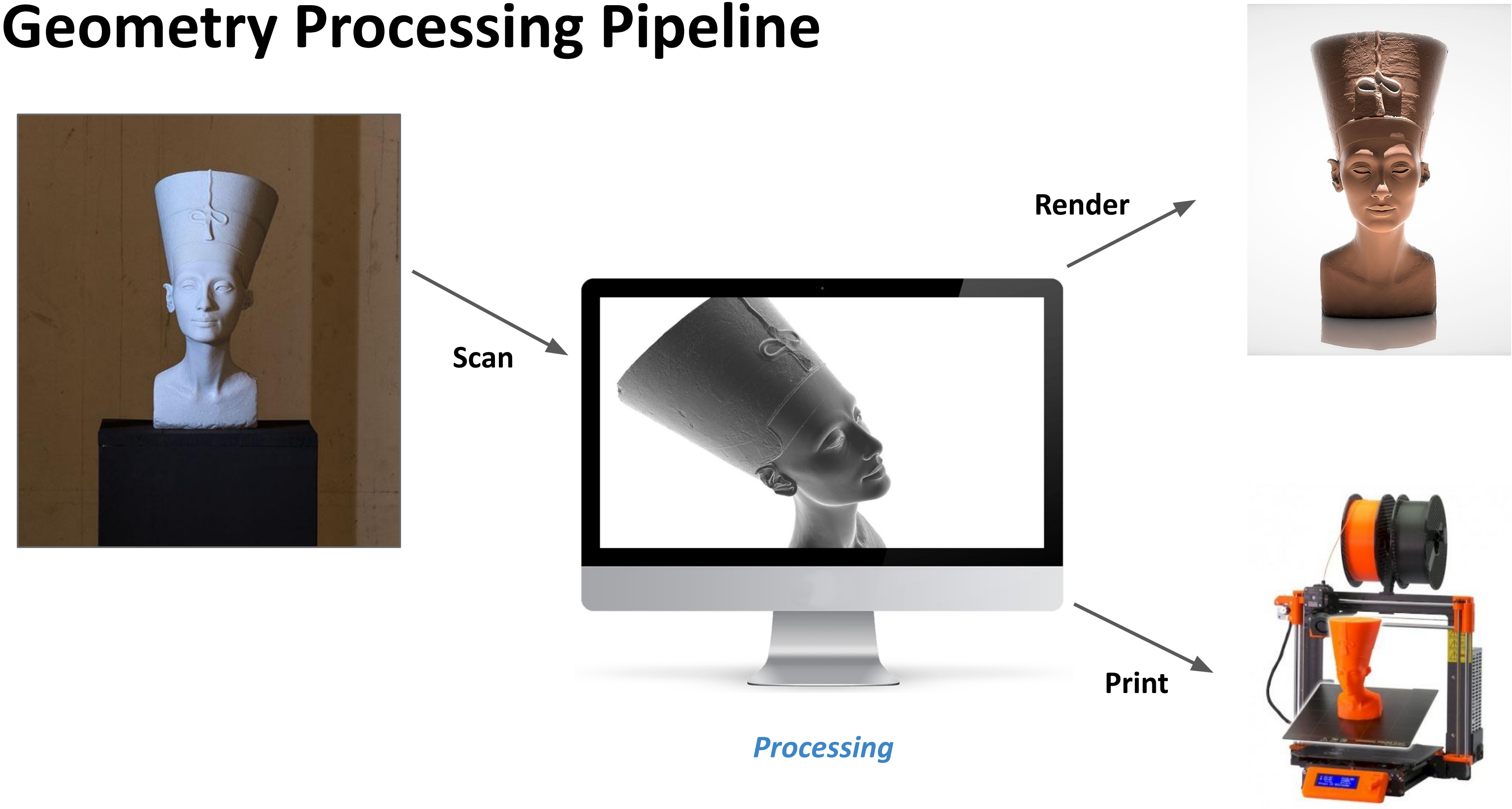
Geometry Processing Pipeline

Geometry Processing Pipeline

Scan

Processing

Geometry Processing Pipeline



Session 1: Introduction

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Representations of Geometry Objects

Point cloud

Voxels

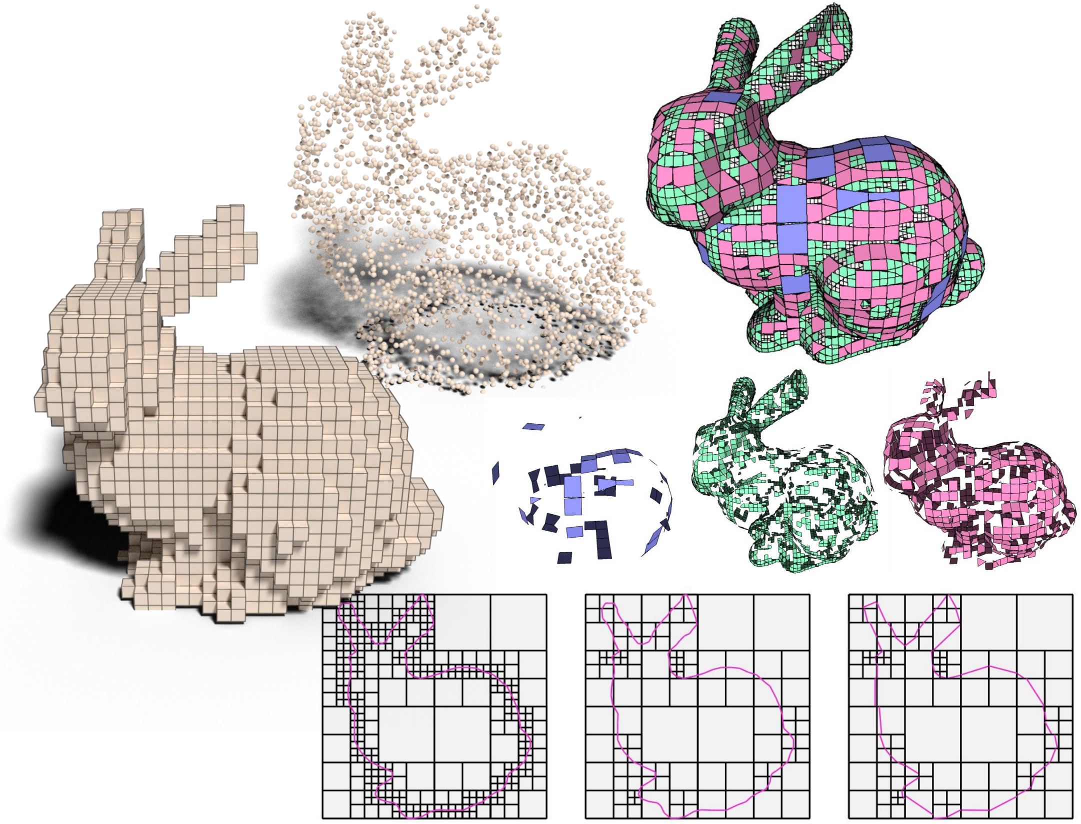
Patches

Implicit

Explicit

Parametric

...



Representations of Geometry Objects

Point cloud

Voxels

Patches

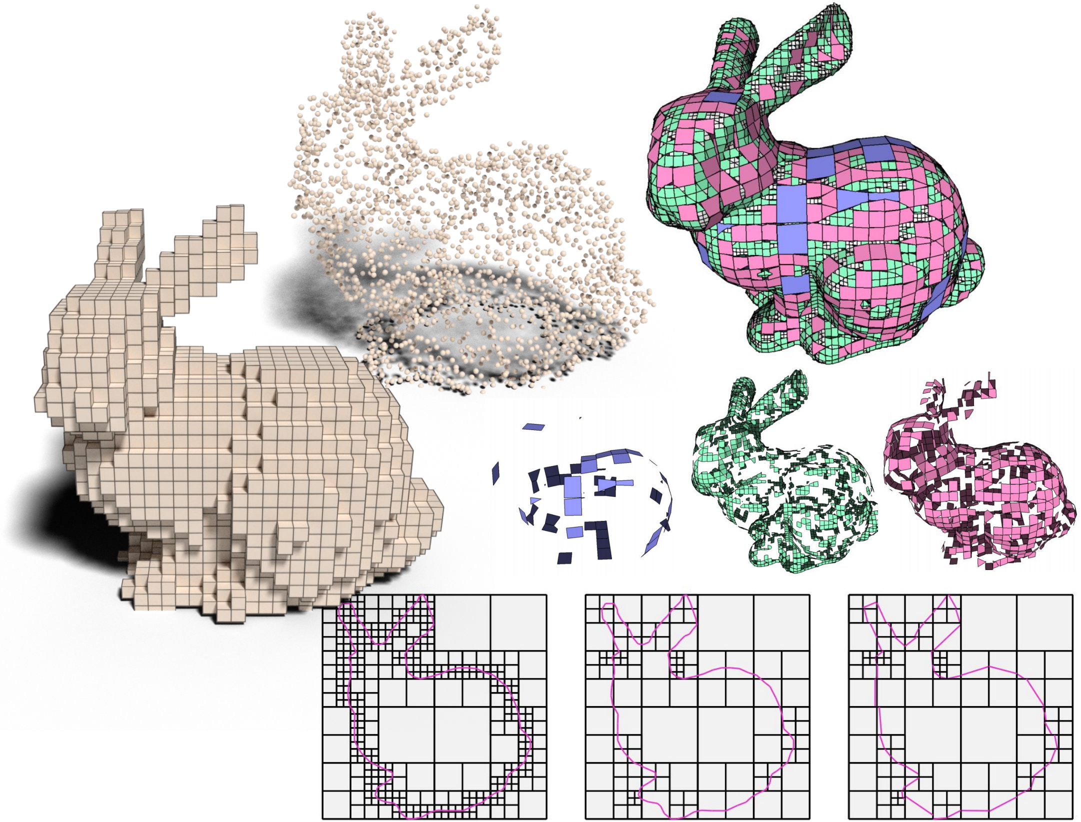
Implicit

Explicit

Parametric

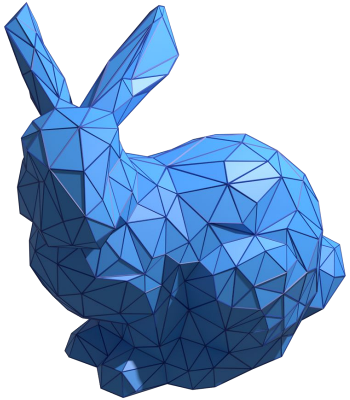
Mesh-based Surface

...



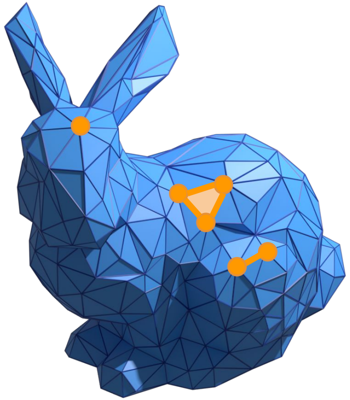
Polygonal Mesh

- A collection of polygons: a segment of a piecewise linear surface representation



Polygonal Mesh

- A collection of polygons: a segment of a piecewise linear surface representation
- *Geometrical* component
  - Vertices $\mathcal{V} = \{v_1, v_2, ..., v_V\}, v_i \in \mathbb{R}^3$
- *Topological* components
  - Faces $\mathcal{F} = \{f_1, f_2, ..., f_F\}$
  - Edges $\mathcal{E} = \{e_1, e_2, ..., e_E\}$
- A polygonal mesh can be formulated as $\mathcal{M} = (\mathcal{V}, \mathcal{F}, \mathcal{E})$



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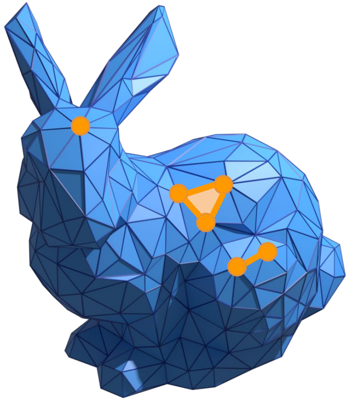
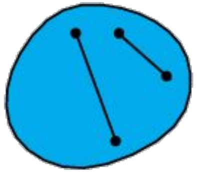
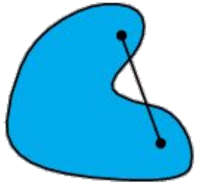


Q: Why are meshes different from graphs?

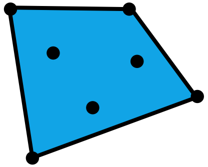
Terminologies



Convex



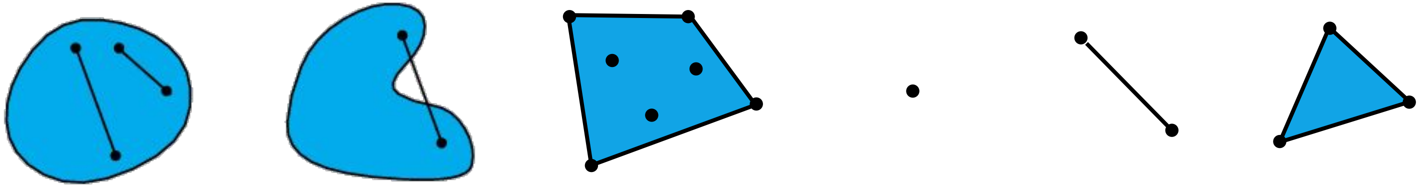
Non-convex



Convex Hull

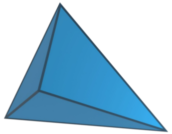
- *Convex* and *Convex Hull*

Terminologies



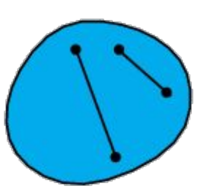
Convex Non-convex Convex Hull 0-simplex 1-simplex 2-simplex

- *Convex* and *Convex Hull*
- *k-Simplex*: the convex hull of k+1 affine-independent vertices
  - e.g. tetrahedra is a ***3-simplex***

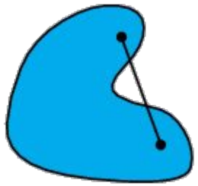


3-simplex

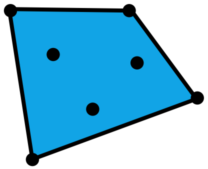
Terminologies



Convex

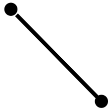


Non-convex

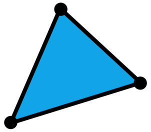


Convex Hull

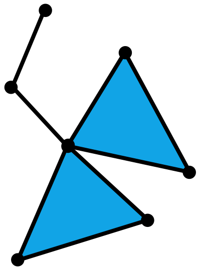
0-simplex



1-simplex

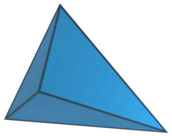


2-simplex



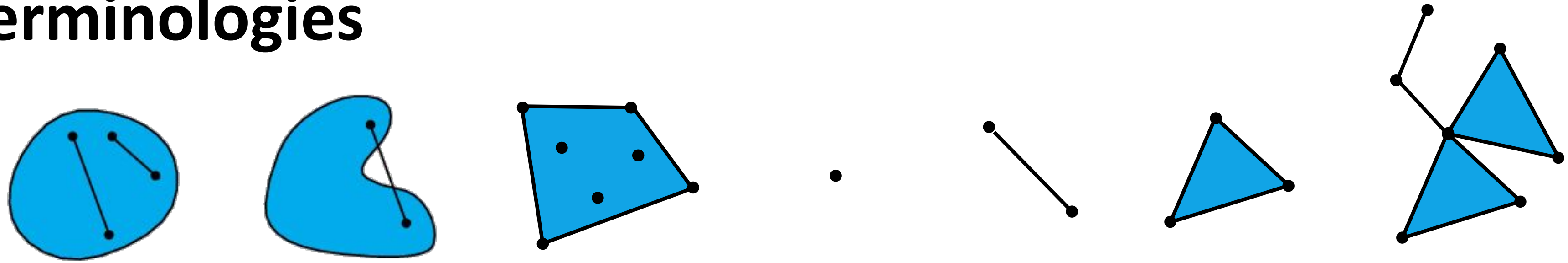
simplicial complex

- *Convex* and *Convex Hull*
- *k-Simplex*: the convex hull of k+1 affine-independent vertices
  - e.g. tetrahedra is a ***3-simplex***
- *Face*: any simplices of a subset of vertices



3-simplex

Terminologies



Convex | Non-convex | Convex Hull | 0-simplex | 1-simplex | 2-simplex | simplicial complex

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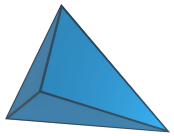
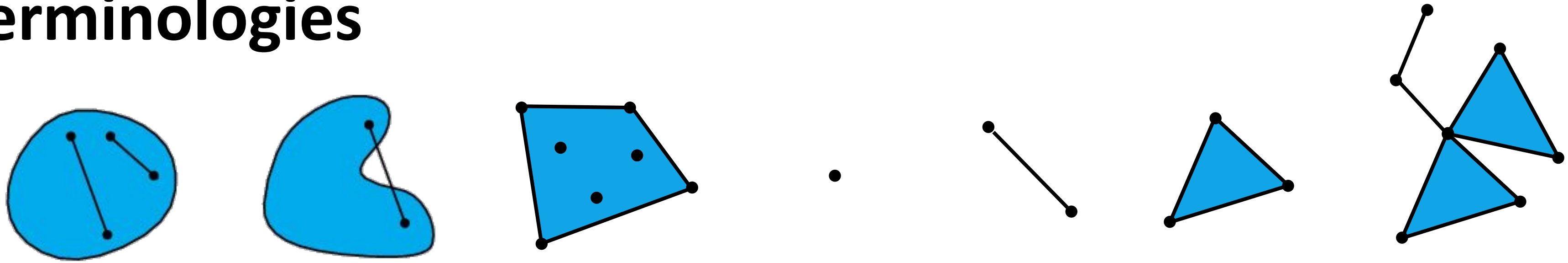
- *k-Simplex*: the convex hull of k+1 affine-independent vertices
  - e.g. tetrahedra is a ***3-simplex***
- *Face*: any simplices of a subset of vertices
- *Simplicial complex*: a collection of simplices
  - e.g. Graph is simplicial ***1-complexes***, triangle meshes are simplicial ***2-complexes***



3-simplex

Terminologies



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- *k-Simplex*: the convex hull of k+1 affine-independent vertices
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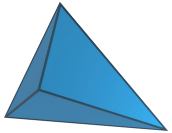
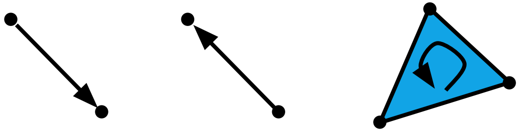
  - e.g. Graph is simplicial ***1-complexes***, triangle meshes are simplicial ***2-complexes***
- Simplex can have ***orientation***

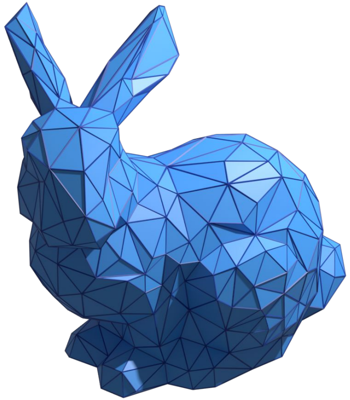


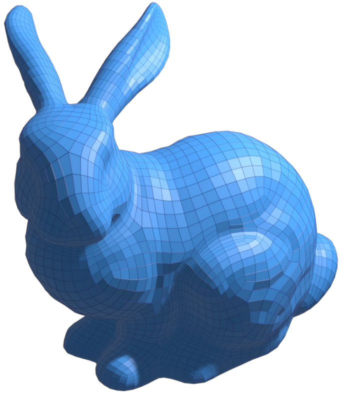


Types of Polygon Meshes

- Triangle Meshes
- Quadrilateral meshes
- ...

Q: What do they have in common?





Typological Invariant: *Euler-Poincaré Formula*

$$F - E + V = 2(1-g)$$

***g*enus: #holes**

Euler characteristic

Euler characteristic allows to check topological property at constant time

e.g. the euler characteristic of a convex polyhedron is 2

Corollary (why?):

- Triangle Mesh
  - F ≈ 2V, E ≈ 3V
  - avg. vertex degree = 6
- Quad Mesh
  - F ≈ V, E ≈ 2V
  - avg. vertex degree = 4

g=0 g=1 g=2 g=3

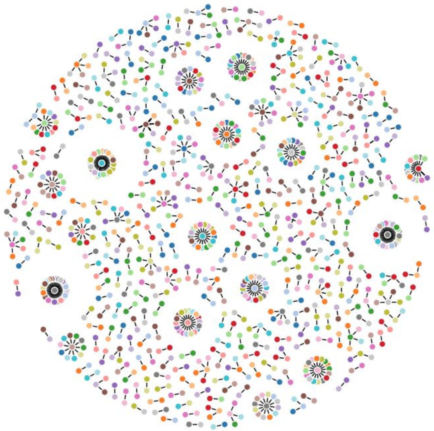
Why Polygons?

- Polygon mesh is a good surface compromise of "physical" solid
  - Think about approximation error (recall Taylor formula from calculus)
- Arbitrary topology
- Flexibility for piecewise smooth surfaces
- Flexibility for adaptive refinement (subdivision)
- Render efficiency
- ...

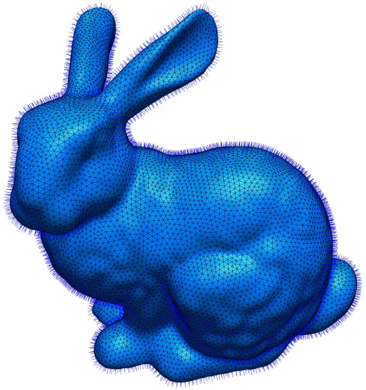
What's an appropriate data structure represent polygon-based surface geometry?

Mesh Data Structure: Critical Information

- Position (x, y, z)

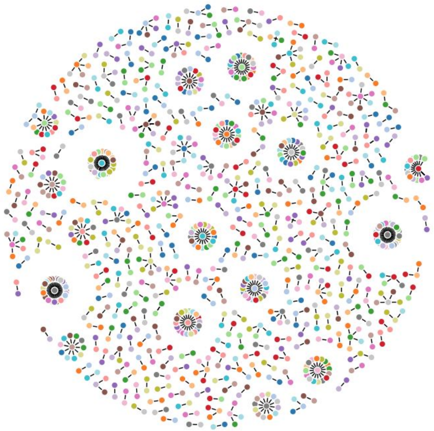


v.s.



Mesh Data Structure: Critical Information

- **Position (x, y, z)**
- *Attributes, e.g. per-vertex/face normals, UV coordinates, per-vertex/face colors*



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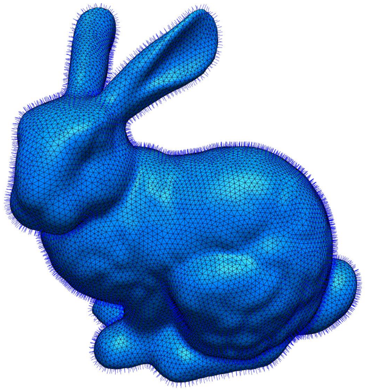
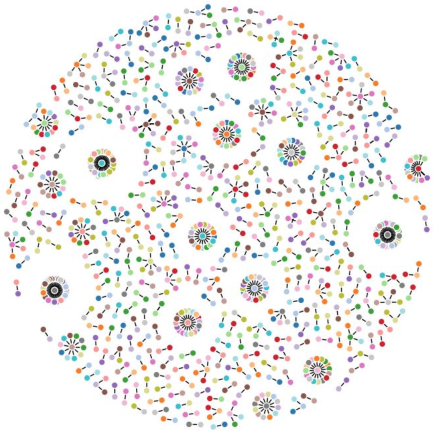


Mesh Data Structure: Geometric Information

- **Position (x, y, z)**
- *Attributes, e.g. per-vertex/face normals, UV coordinates, per-vertex/face colors*
- ***Connectivity***



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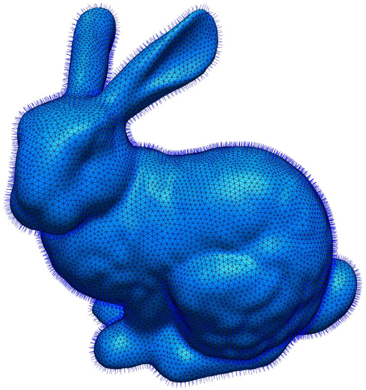
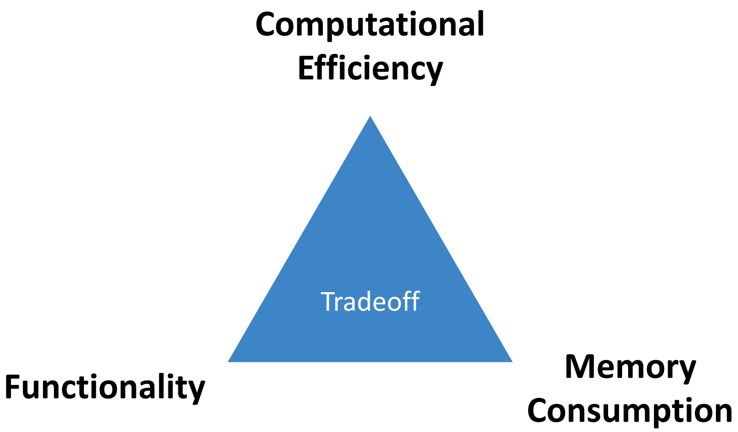


Mesh Data Structure: Optimized on-demand

- Optimize for storage, e.g. persistent on a cache/disk, compressed for consumption
- Optimize for runtime rendering tasks, e.g. Vertex buffer, BVH, fetch efficiency
- Optimize for queries, e.g. What are the vertices and faces of a given face?
- Optimize for manipulation, e.g. Add, remove, collapse, reconstruct a edge/face?
- ...

Mesh Data Structure: Evaluation Criteria

- Preprocessing time, e.g. Time complexity to build a structure from another format
- Query time, e.g. Time complexity of search adjacency faces of a given edge
- Operation time, e.g. Time complexity of removing an edge/face
- Space complexity, e.g. Storage consumption of a structure



Why connectivity is important and how to represent it?

- Connectivity conveys the understanding of ***local*** information of a vertex
- With connectivity, one can avoid expensive searches
- Different types of connectivity
  - No connectivity: Face set
  - Vertex-based connectivity: Shared vertex
  - Face-based connectivity: Shared face
  - Edge-based connectivity: Shared edge
  - Halfedge-based connectivity

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  - Edge-based connectivity: Shared edge
  - Halfedge-based connectivity
- We will revisit more about why local operations are so important later

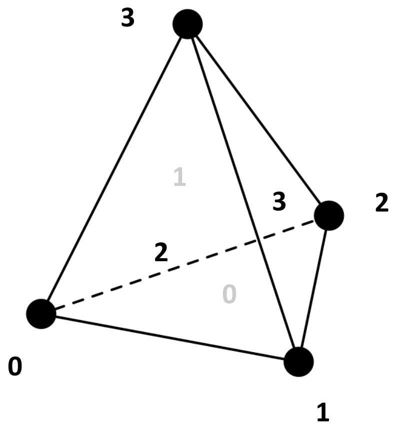
Shared Vertex (.obj, .off formats)

Basic Idea: isolate vertex positions, store an ***adjacency list*** for **vertices**

- Storage cost
  - 1 floating number = 4 bytes
  - 1 vertex = 4*3 = 12 bytes
  - 1 face = 4*2 = 12 bytes
  - total: #v * 12 + #f * 12 ≈ #v * 12 * 3 = 36 bytes/vertex
- Pros
  - Still simple, and with small redundancy
- Cons
  - No access to neighbors (why?)

Vertices
`x1,y1,z1`
`x2,y2,z3`
...
`xv,yv,zv`

Triangles
`i11,i12,i13`
`i21,i22,i23`
...
...
...
`in1,in2,in3`



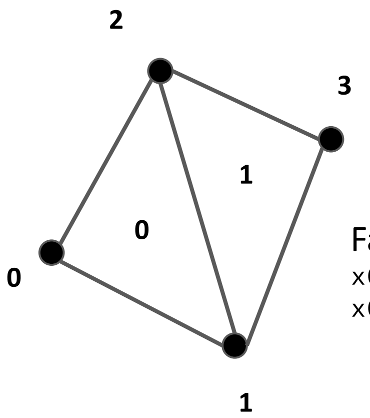
Adjacency list for vertices:
0: 0 2 1
1: 0 3 2
2: 3 0 1
3: 3 1 2

Face Set (.stl format)

Basic Idea: each row stores the vertices of the face (***array***)

- Storage cost
  - 1 floating number = 4 bytes
  - 1 face = 4*9 = 36 bytes
  - 1 vertex ≈ 2*36 = 72 bytes (why?)
  - total: 72 bytes/vertex
- Pros
  - Very simple
- Cons
  - No connectivity
  - Redundancy (why?)

Triangles		
x11,y11,z11	x12,y12,z12	x13,y13,z13
x21,y21,z21	x22,y22,z22	x23,y23,z23
...	...	...
xn1,yn1,zn1	xn2,yn2,zn2	xn3,yn3,zn3



Face array:
x00,y00,z00;x01,y01,z01;x02,y02,z02
x01,y01,z01;x13,y13,z13;x02,y02,z02

Face-based Connectivity

Basic Idea: store an ***adjacency list*** for **faces** and **neighboring faces**

- Vertex contains
  - Position
  - Associated face
- A face contains
  - Vertices
  - Face neighbors
- Pros
  - Constant time to access all neighboring faces
- Cons
  - No edge information

Vertices	
x1,y1,z1	f1
x2,y2,z3	f2
...	...
xv,yv,zv	fn

Triangles	
i11,i12,i13	f11,f12,f13
i21,i22,i23	f21,f22,f23
...	
...	
...	
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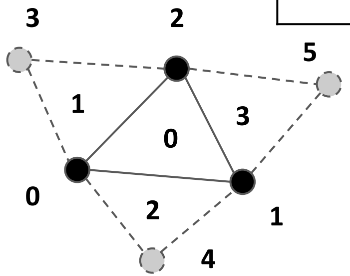
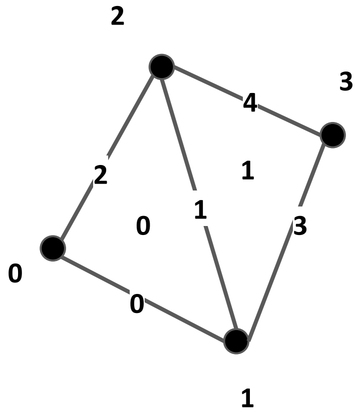


Adjacency List:
```
0: 0 1 2; 1 2 3
1: 0 2 3; 0
2: 0 4 1; 0
3: 1 5 2; 0
```

Edge-based Connectivity

Basic Idea: store an ***adjacency list*** for **edges**

- Vertex contains
  - Position
  - 1 adjacent edge index
- A edge contains
  - vertex indices
  - neighboring face indices
  - edges
- A face contains 1 edge index
- Pros: Constant time to access all neighboring faces and edges
- Cons: No edges orientation (why matters?)



Adjacency List:
0: 1 2
1: 0 3 2 4
2: 0 1
3: 4 1
4: 3 1

Incidence Matrix

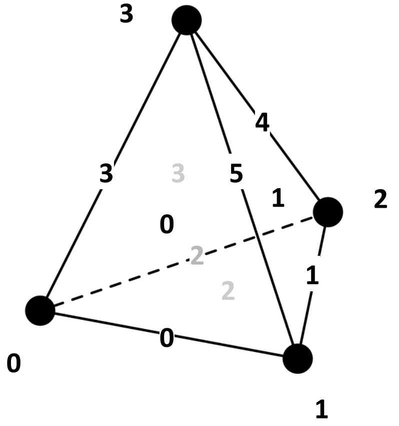
Basic idea: Store ***all*** neighbor informations via incidence matrices

Vertex-Edge Matrix

```
   0 1 2 3
0: 1 1 0 0
1: 0 1 1 0
2: 1 0 1 0
3: 1 0 0 1
4: 0 0 1 1
5: 0 1 0 1
```

Edge-Face Matrix

```
   0 1 2 3 4 5
0: 1 0 0 1 0 1
1: 0 1 0 0 1 1
2: 1 1 1 0 0 0
3: 0 0 1 1 1 0
```



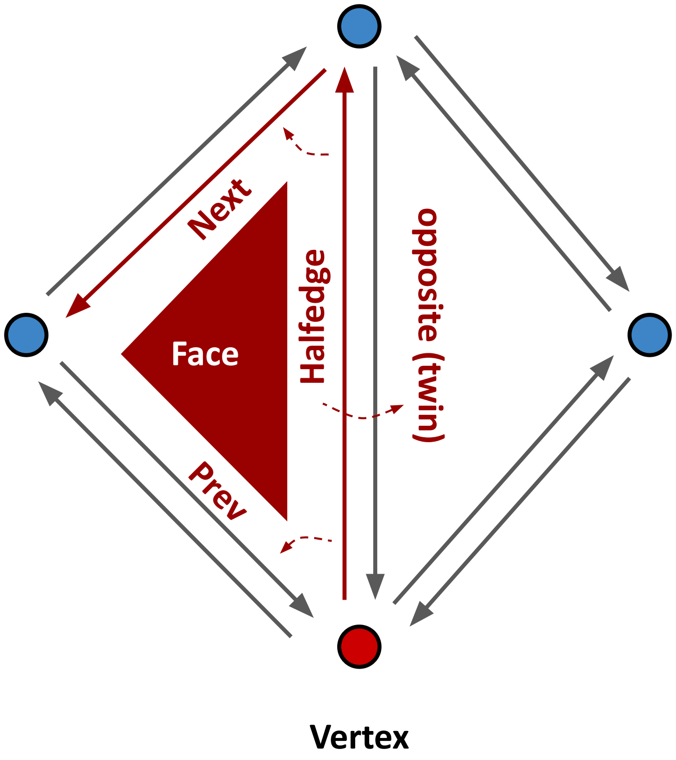
For large meshes, most of the elements will be zero

⇒ Use sparse matrix for tasks at scale

Data Structure: *Halfedge*

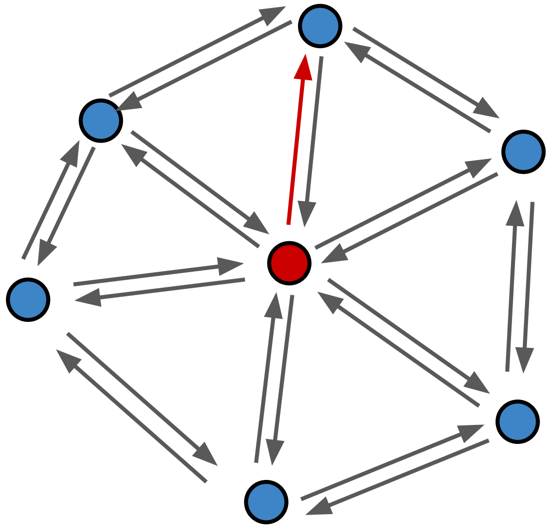
Basic idea: each edge gets split into two half edges

- Vertex
  - Position
  - 1 Halfedge
- Halfedge
  - 1 Vertex
  - 1 Face
  - Prev; Next; Opposite (Twin)
- Face
  - 1 Halfedge



Example 1: Access All Adjacency Edges with Halfedge

```
/**
 * numAdjacentEdges returns the number of adjacency edges of the given vertex
 * @param v is an vertex from a haledge-based mesh
 */
function numAdjacentEdges(v: Vertex) {
   const e0 = v.halfedge
   let edge_indices = [e0.index]
   for (let e = e0.opposite.next; e != e0; e = e.opposite.next) {
       edge_indices.push(e.index)
   }
   return edge_indices.length
}
```



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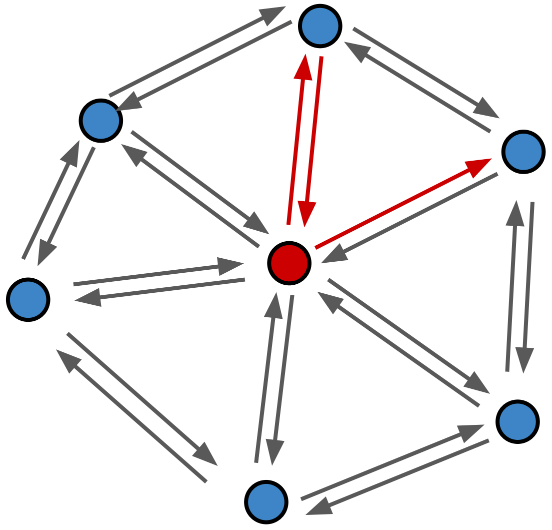

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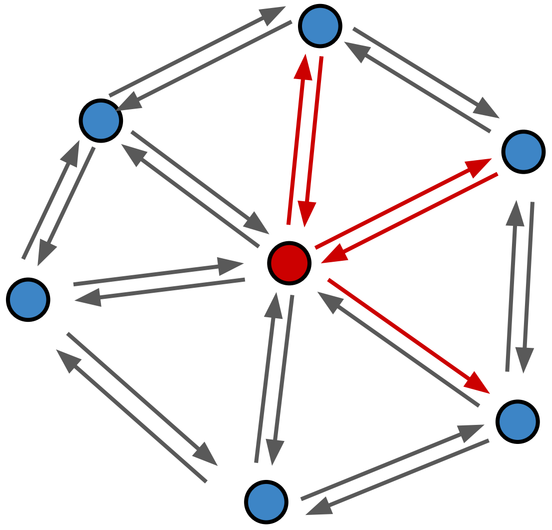
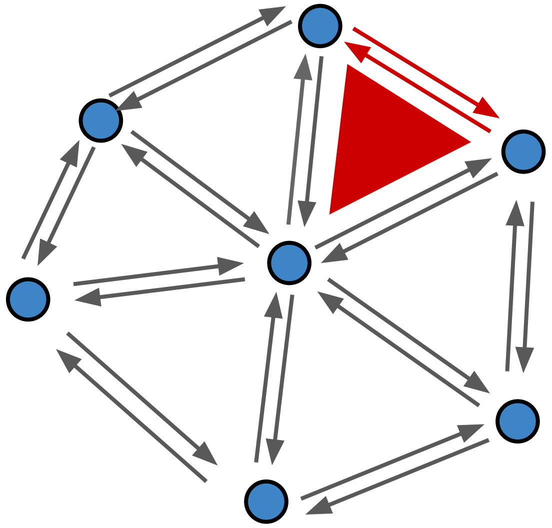


Example 2: Check if an edge is on the boundary of a mesh

```
class Halfedge {
    ...

    onBoundary() {
        let connectedFaces = 0
        if (this.face != null) {
            connectedFaces++
        }
        if (this.opposite.face != null) {
            connectedFaces++
        }
        if (connectedFaces != 1) {
            return false
        }
        return true
    }
}
```



See the benefits of halfedge?

- Key benefits: makes traversal easy
  - Easy for editing a mesh: constant time access of local neighbors
- Cons?

Manifold v.s. Non-Manifold

Manifold:

1. Each *edge is incident to one or two faces*, and

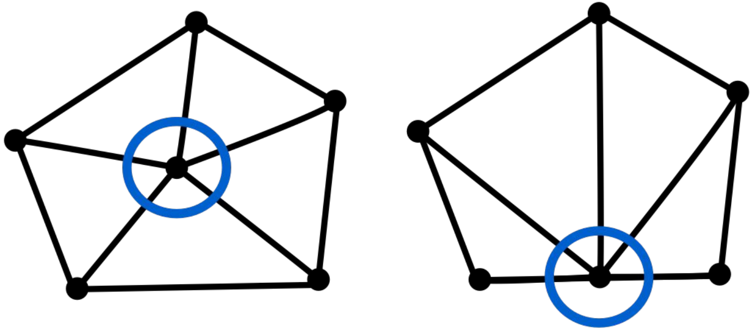
2. *faces incident to a vertex from a closed or open fan*.

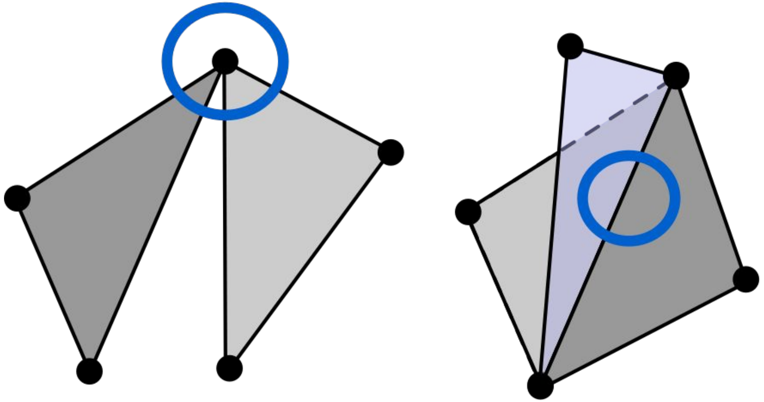
Non-manifold:

1. every edges is constrained in only two polygons (no "fins")

2. the polygons containing each vertex makes a single "fan"

Q: Can halfedge structure deal with non-manifolds?





Alternatives to Halfedge

Winged edge

Corner table

Quadedge

…

Similar to halfedge and each stores local neighborhood information

Tradeoffs in general:

+ Convenient and better access time for individual elements, easy for traversal of locals

- Additional storage; cache incoherent; ...

More Sophisticated Mesh Data Structures

BMesh from Blender

FbxMesh from Autodesk

FDynamicMesh from Unreal Engine

…

These data structures are not only for geometry processing purpose but also impacts the subsequent workflows, such as animation, rendering, etc.

Why Mesh Representation Is Still an Issue Today?

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- We will have time to revisit theses questions in later sessions.
- Be careful & patient 😀
- Let's now go for some thing maybe more funny...

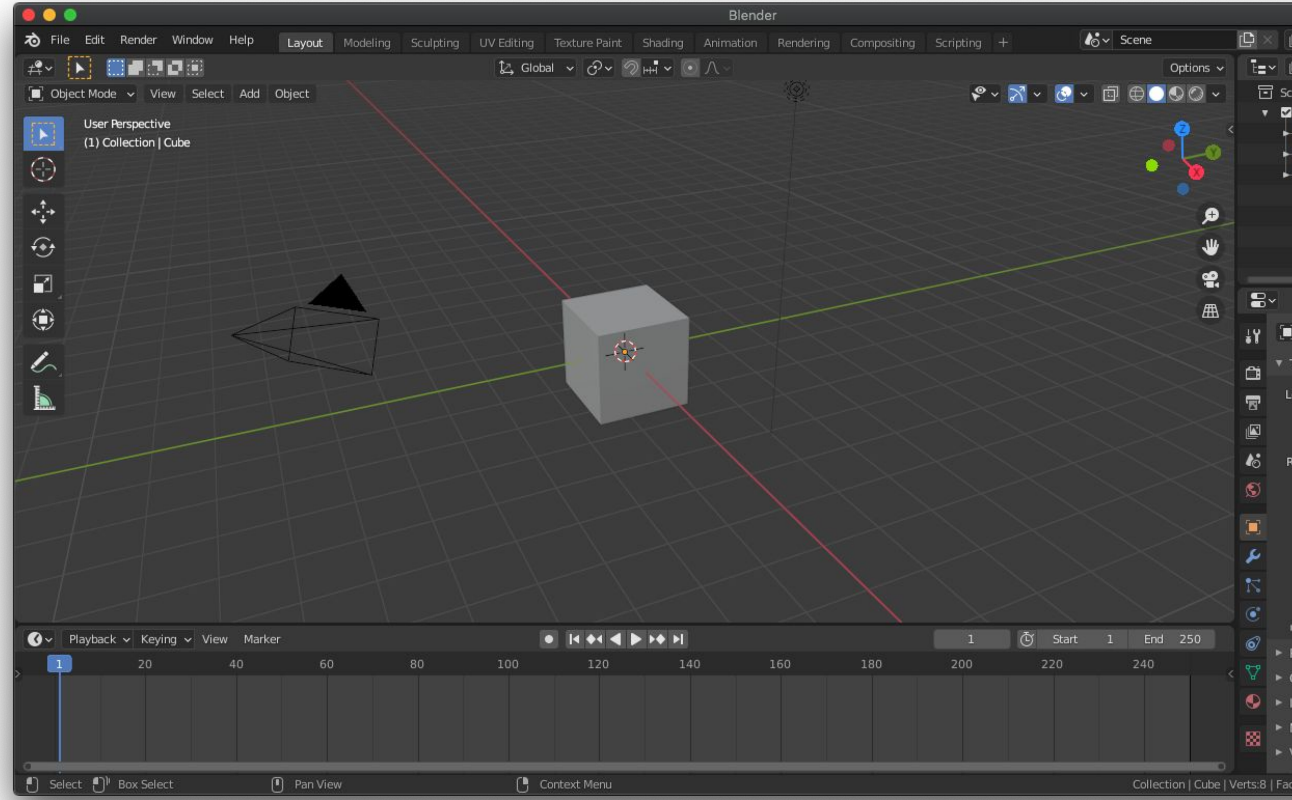
Session 1: Introduction

- Motivation
- Recap: Graphics Pipelines
- Geometry Representations
- Blender Basics
- Summary

Blender

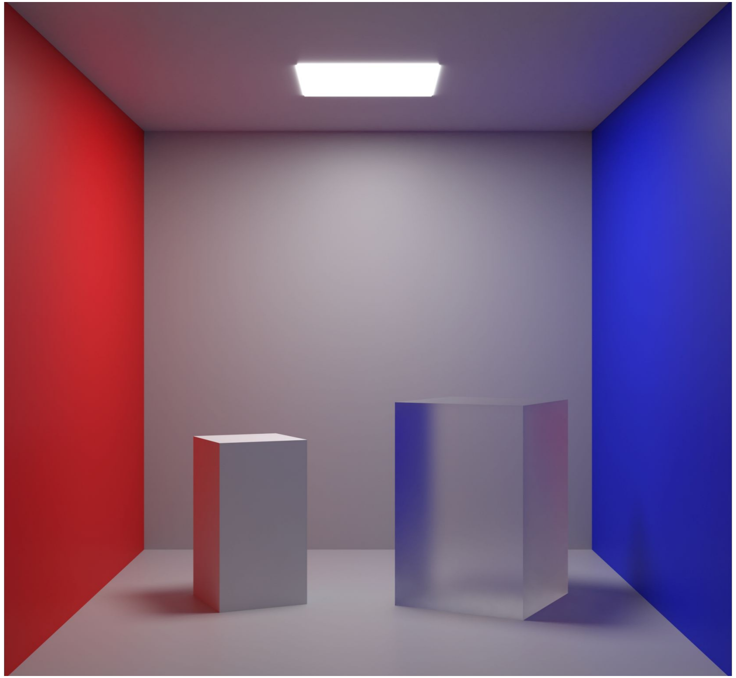
Why not XYZ?

Because of *open source*



Practice: Reproduce The Cornell Box in Blender

- What are the geometry objects do we need for the Cornell box?
- What are their material properties?



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Summary

- Geometry representation has a long term impact on the geometry processing pipeline
- Mesh is a good compromise and the connectivity is critical for local operations
- No-free Lunch! ⇒ Think about the task, then choose (or design) the right structure
- Understanding the modeling process helps understand more processing workflows

	Adjacency List Based Structure	Incident Matrices Based Structure	Halfedge Based Structure
Constant-time neighborhood access?	No	Yes	Yes
Easy to remove elements?	No	No	Yes
Deal with non-manifold geometry?	Yes	Yes	No