Basic Mesh Data Structures

CS 418: Interactive Computer Graphics

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Polygonal Meshes

Rasterization engines typically rely on polygonal meshes (specifically triangle meshes) to represent surfaces

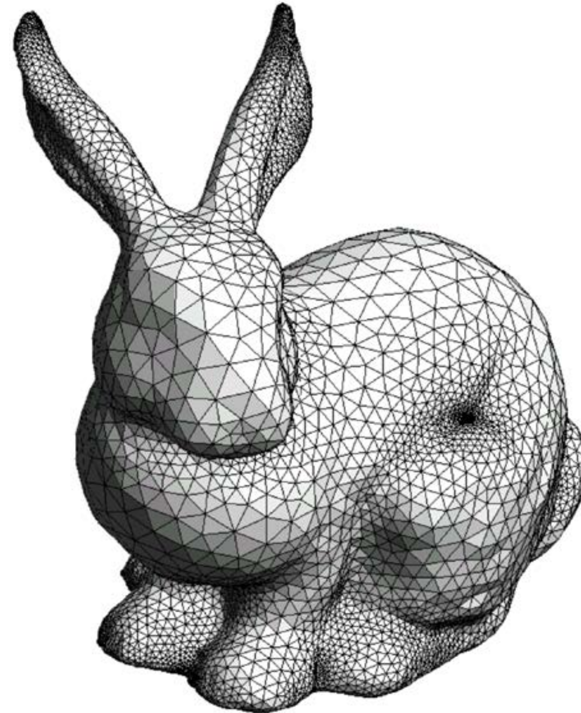
Modern GPUs are designed specifically to rasterize triangles

Many advantages to using triangles:

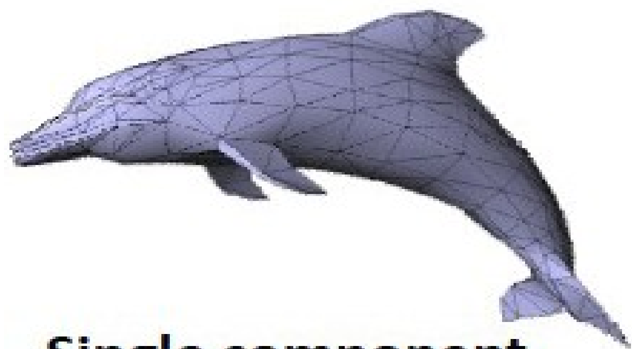
- Simplest 2D primitive…in fact it is a ***2-simplex***
- Any 2D polygon can be triangulated
- Can easily represent sharp surface features

Any disadvantages you can think of?

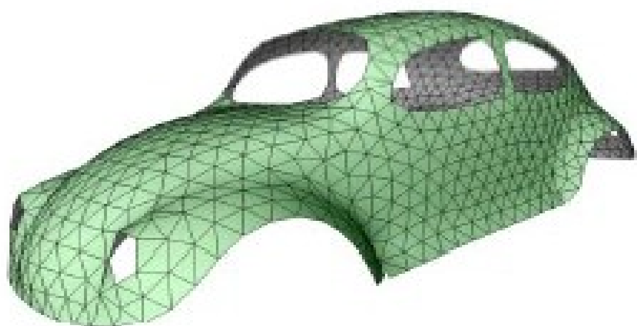
Why do we say 2D when we are rendering in 3D?



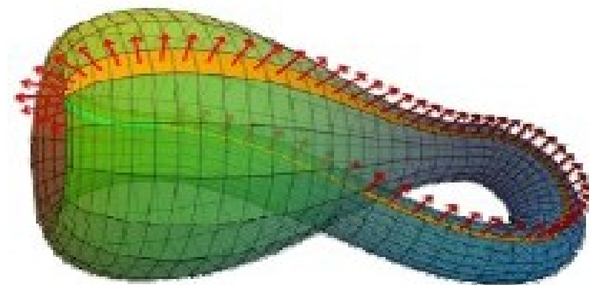
Surface Mesh Properties



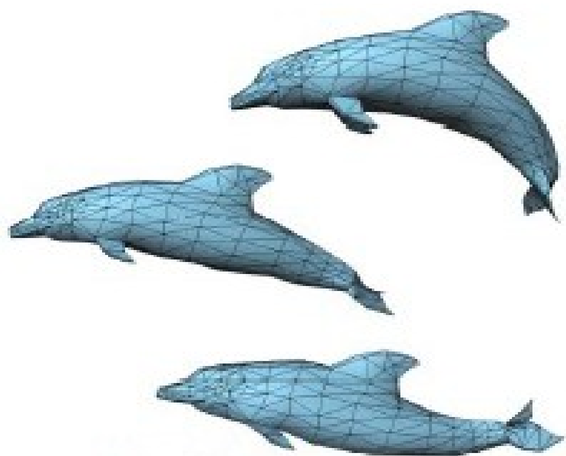
Single component, closed, triangular, orientable manifold



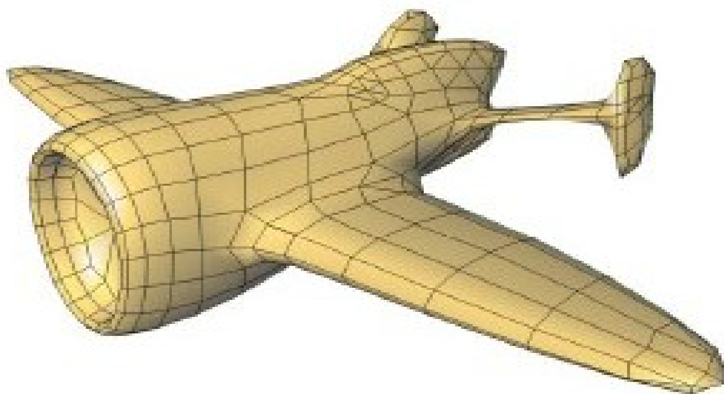
With boundaries



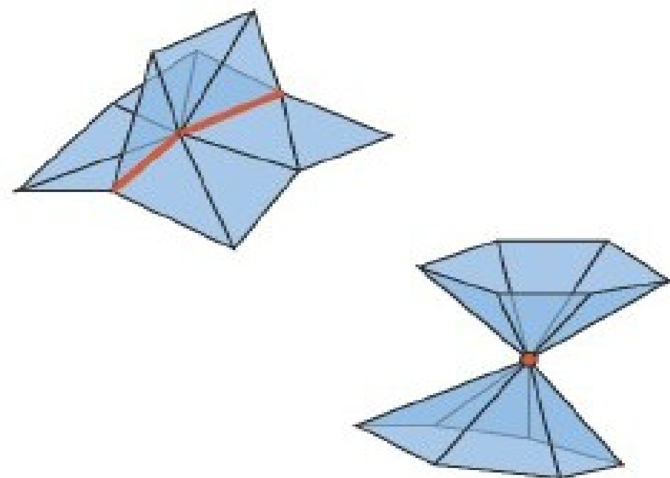
Not orientable



Multiple components

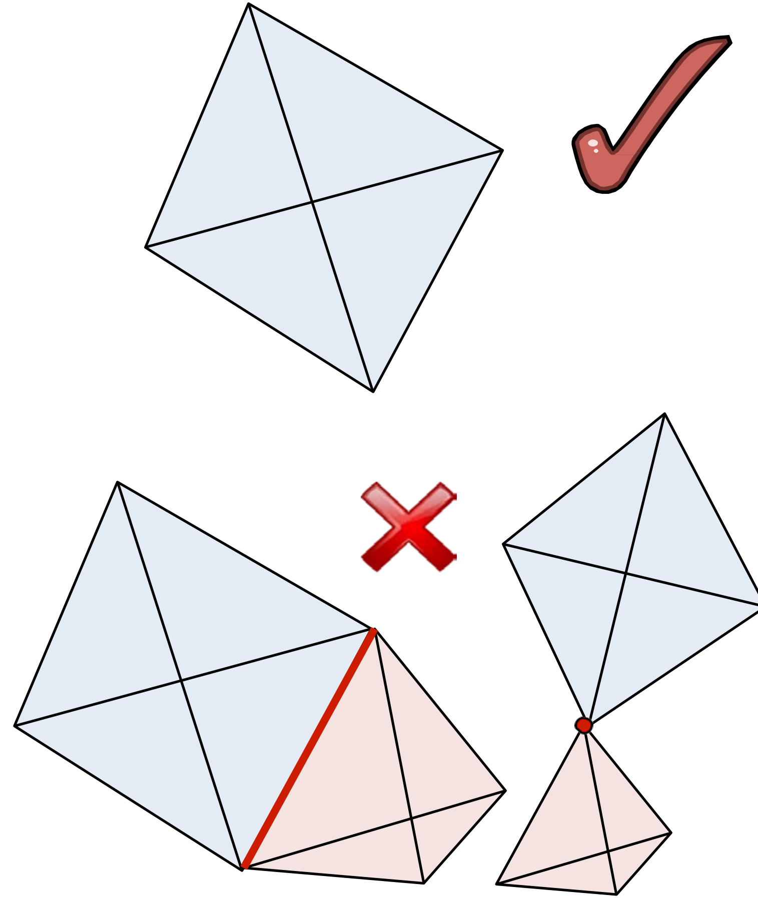


Not only triangles



Non manifold

Surface Mesh Properties

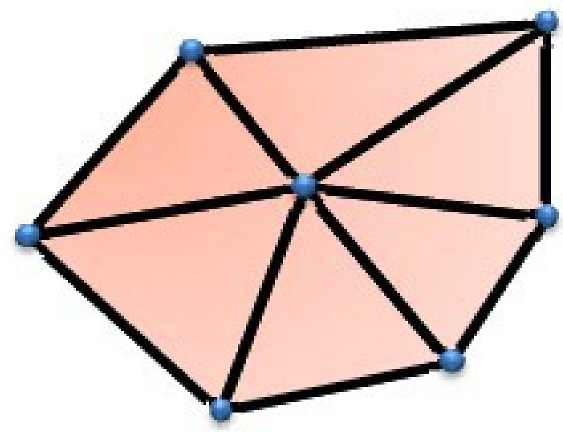


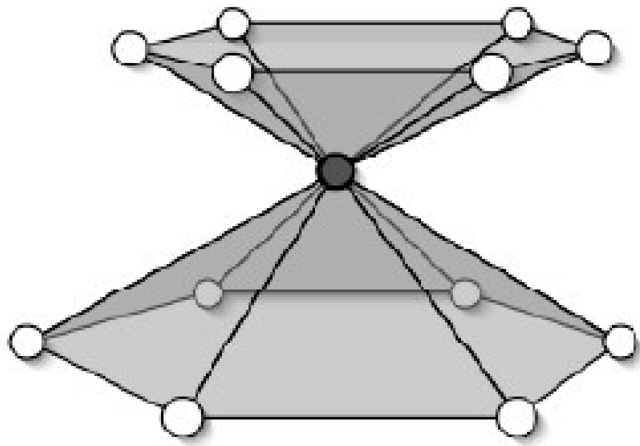
Manifold:
1.Every edge connects exactly two faces
2. Vertex neighborhood is "disk-like"

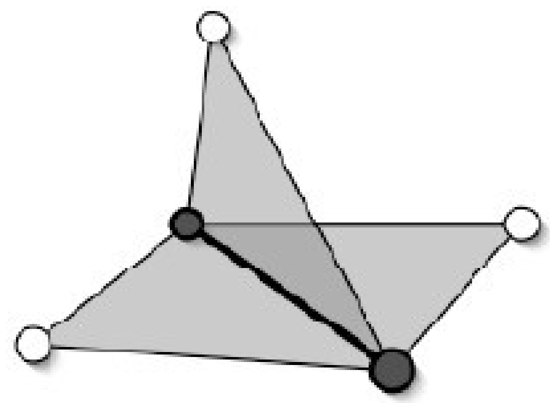
Orientable: Consistent normals
Watertight: Orientable + Manifold
Boundary: Some edges boundonly one face
Ordered: Vertices in CCW order when viewed from normal

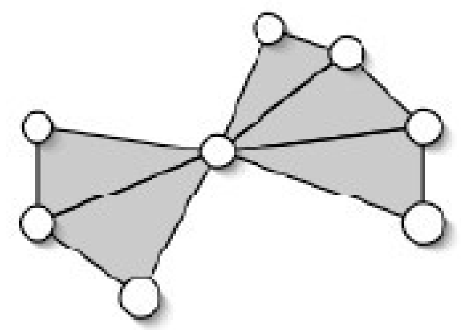
2-Manifold Mesh Examples

Disk-shaped neighborhoods



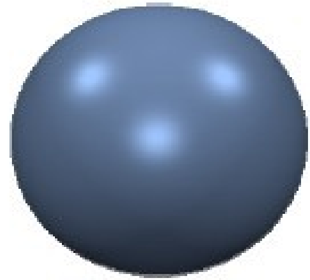






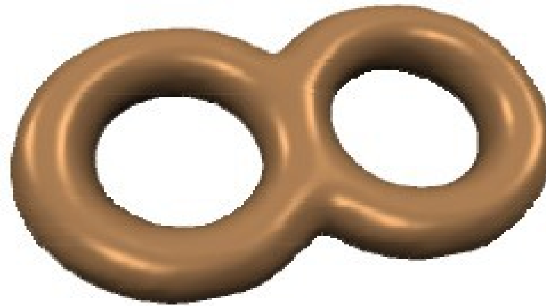
non-manifolds

Genus



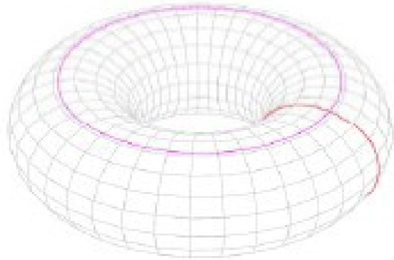
Genus 0

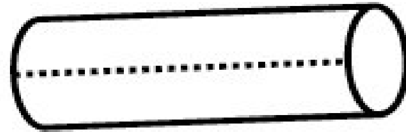
Genus 1



Genus 2

Genus ?





Euler Characteristic

For a closed (no boundary), manifold, connected surface mesh:

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

V = number of vertices
E = number of edges
F = number of faces
G = genus (number of holes in the surface)

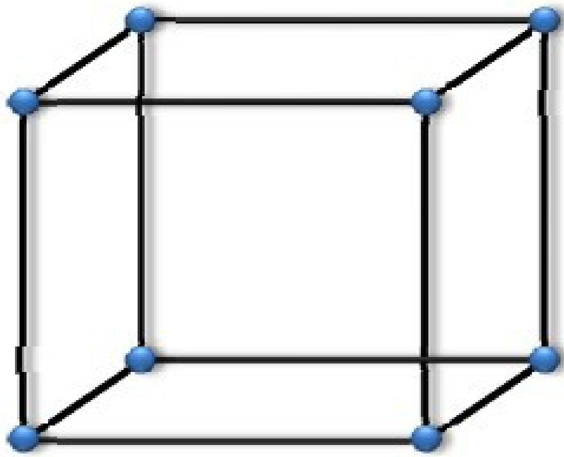
A **2-manifold** is a surface (locally like a plane)

Leonhard Euler
1707 – 1783

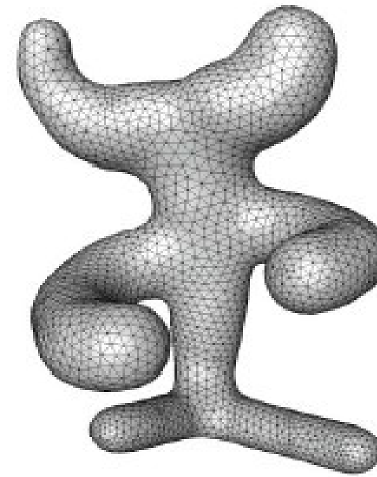
Can you think of anything else named for him?

Euler Characteristic for Closed 2-Manifold Polygonal Meshes

$$V + F - E = \chi$$ Euler characteristic



$V = 8$
$E = 12$
$F = 6$
$\chi = 8 + 6 - 12 = 2$



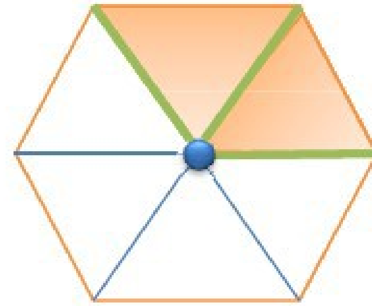
$V = 3890$
$E = 11664$
$F = 7776$
$\chi = 2$

…and if they are triangle meshes

- *Triangle* mesh statistics

  $E \approx 3V$

  $F \approx 2V$

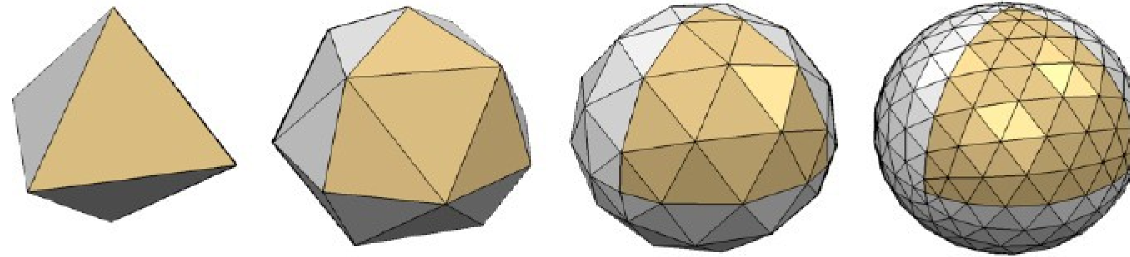


- Avg. valence ≈ 6

  Show using Euler Formula

Aside from being totally interesting on their own, these formulas are useful for computing memory usage

Mesh Data Structures



Need to store

- Geometry
- Connectivity

Can be used as file formats or internal formats

Considerations

- Space
- Efficient operations

Mesh processing has different requirements than rendering

- Example: Deforming a mesh when simulating physics…

Mesh Data Structure: Face Set (STL)

- face:
  - 3 positions

Triangles		
x_{11} y_{11} z_{11}	x_{12} y_{12} z_{12}	x_{13} y_{13} z_{13}
x_{21} y_{21} z_{21}	x_{22} y_{22} z_{22}	x_{23} y_{23} z_{23}
...	...	...
x_{F1} y_{F1} z_{F1}	x_{F2} y_{F2} z_{F2}	x_{F3} y_{F3} z_{F3}

36 B/f = 72 B/v

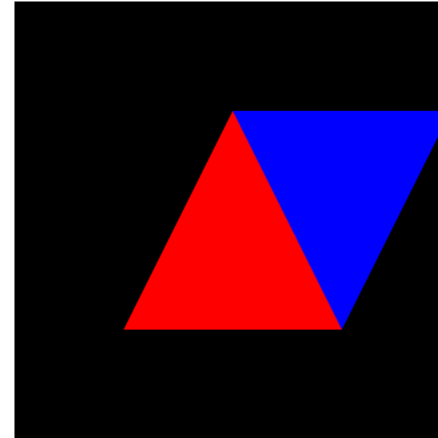
no connectivity!

Corresponds to structure used for WebGL call

```
gl.drawArrays(gl.TRIANGLES, 0, vertexPositionBuffer.numberOfItems);
```

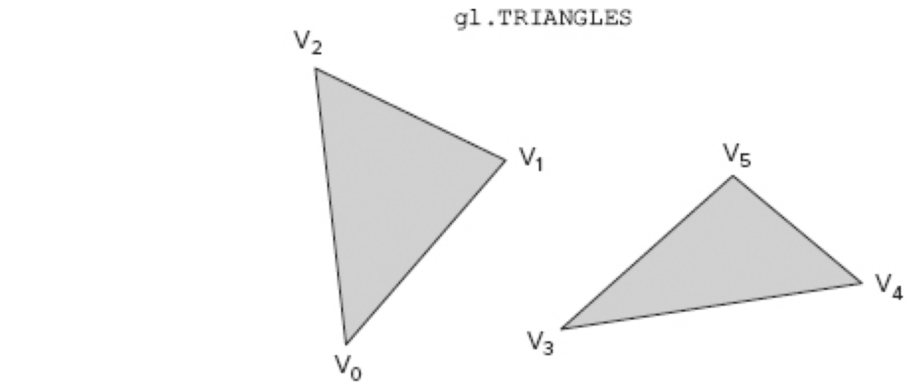
gl.TRIANGLES

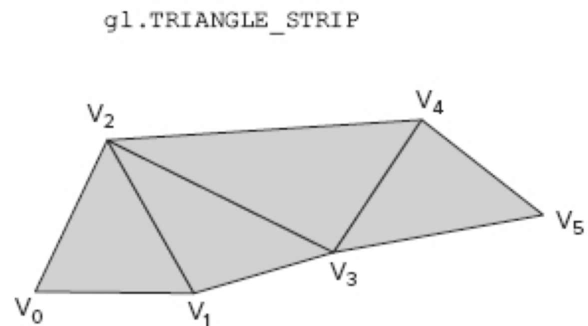
```
vertexPositionBuffer = gl.createBuffer();

gl.bindBuffer(gl.ARRAY_BUFFER, vertexPositionBuffer);

var triangleVertices = [

        0.0,  0.5,  0.0,

       -0.5, -0.5,  0.0,

        0.5, -0.5,  0.0,

        0.0,  0.5,  0.0,

        1.0, 0.5,  0.0,

        0.5, -0.5,  0.0

  ];

gl.bufferData(gl.ARRAY_BUFFER, new
        Float32Array(triangleVertices), gl.STATIC_DRAW);

vertexPositionBuffer.itemSize = 3;

vertexPositionBuffer.numberOfItems = 6;

…
gl.drawArrays(gl.TRIANGLES, 0,
vertexPositionBuffer.numberOfItems);
```

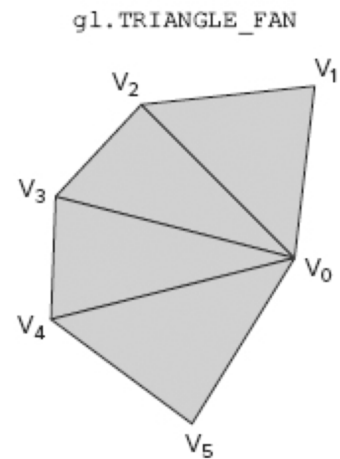


- Assuming you are using gl.drawArrays():
  - Each triangle requires you specify three new vertices
  - Number of triangles = number vertices/3

Geometric Primitives in WebGL







WebGL supports 3 basic geometric primitives:

1. Triangles
2. Lines
3. Point Sprites

We've already seen one way to send triangles into the pipeline.

There are three different triangle drawing modes depending on how you specify the connectivity:

gl.TRIANGLES
gl.TRIANGLE_STRIP
gl.TRIANGLE_FAN

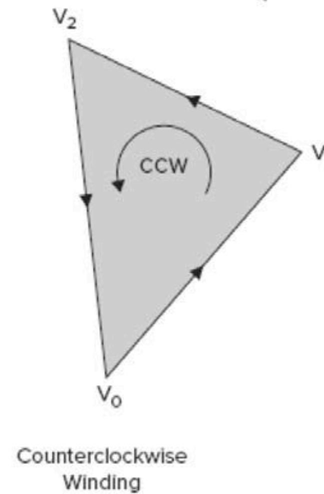
gl.TRIANGLE_STRIP

```
vertexPositionBuffer = gl.createBuffer();
gl.bindBuffer(gl.ARRAY_BUFFER, vertexPositionBuffer);
var triangleVertices = [
        -0.5, -0.5,  0.0,
         0.5, -0.5,  0.0,
         0.0,  0.5,  0.0,
         1.0, 0.5,  0.0,
];
gl.bufferData(gl.ARRAY_BUFFER, new
        Float32Array(triangleVertices), gl.STATIC_DRAW);
vertexPositionBuffer.itemSize = 3;
vertexPositionBuffer.numberOfItems = 4;
....
gl.drawArrays(gl.TRIANGLE_STRIP, 0,
vertexPositionBuffer.numberOfItems);
```

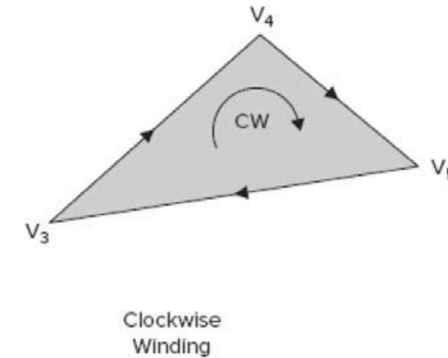
- Allows you to reuse vertices when drawing triangles that share vertices.
- Number of triangles = what?
- Notice that per-triangle color is not easy to achieve
- Order of the vertices is important

Winding Order

- Winding order is determined by the order of the vertices making up a triangle when seen from the viewing direction.
- Equivalently, winding order tells you the direction of the triangle surface normal.
- CCW is traditional and is WebGL default: gl.frontFace(gl.CCW)
- For triangle strips, winding order determines the order in which vertices in the buffer are used to form triangles



Counterclockwise Winding



Clockwise Winding

TRIANGLE NUMBER	CORNER 1	CORNER 2	CORNER 3
1	V_0	V_1	V_2
2	V_2	V_1	V_3
3	V_2	V_3	V_4
4	V_4	V_3	V_5

gl.TRIANGLE_FAN

```
vertexPositionBuffer = gl.createBuffer();
gl.bindBuffer(gl.ARRAY_BUFFER, vertexPositionBuffer);
var triangleVertices = [
         0.5, -0.5,  0.0,
        1.0, 0.5,  0.0,
         0.0,  0.5,  0.0,
        -0.5, -0.5,  0.0,
];
gl.bufferData(gl.ARRAY_BUFFER, new
        Float32Array(triangleVertices), gl.STATIC_DRAW);
vertexPositionBuffer.itemSize = 3;
vertexPositionBuffer.numberOfItems = 4;
....
gl.drawArrays(gl.TRIANGLE_FAN, 0,
vertexPositionBuffer.numberOfItems);
```

- First vertex is the fan center
- Next two vertices specify the first triangle
- Each succeeding vertex forms a triangle with the center and previous vertex
- How many triangles for a given number of vertices?
- Are fans and strips equivalent?

Mesh Data Structure: Indexed Face Set (OBJ)

- vertex:
  - position
- face:
  - vertex indices

Vertices
x_1 y_1 z_1
...
x_v y_v z_v

Triangles
v_{11} v_{12} v_{13}
...
...
...
...
v_{F1} v_{F2} v_{F3}

12 B/v + 12 B/f = 36 B/v

no neighborhood info

The OBJ file format is a popular storage format for meshes

Developed by Wavefront Technologies…now part of AutoDesk

Text files with .obj extension

```
# List of geometric vertices
v 0.123 0.234 0.345 1.0
v ...
v ...
# List of triangles
f 1 3 4
f 2 4 5
...
```

Indexed Face Set

Can be used for offline storage…a file format

Or can be used as an internal data structure

One block of data are the vertices

- Each vertex is a set of 3 coordinates
- Often referred to as the geometry of the mesh

Another block of data is the set of triangles

- Each triangle is set of 3 integers vertex IDs
- The vertex IDs are indices into the vertex block

What are some advantages of this representation?

Vertices
x_1 y_1 z_1
…
x_V y_V z_V

Triangles
v_{11} v_{12} v_{13}
…
…
…
…
v_{F1} v_{F2} v_{F3}

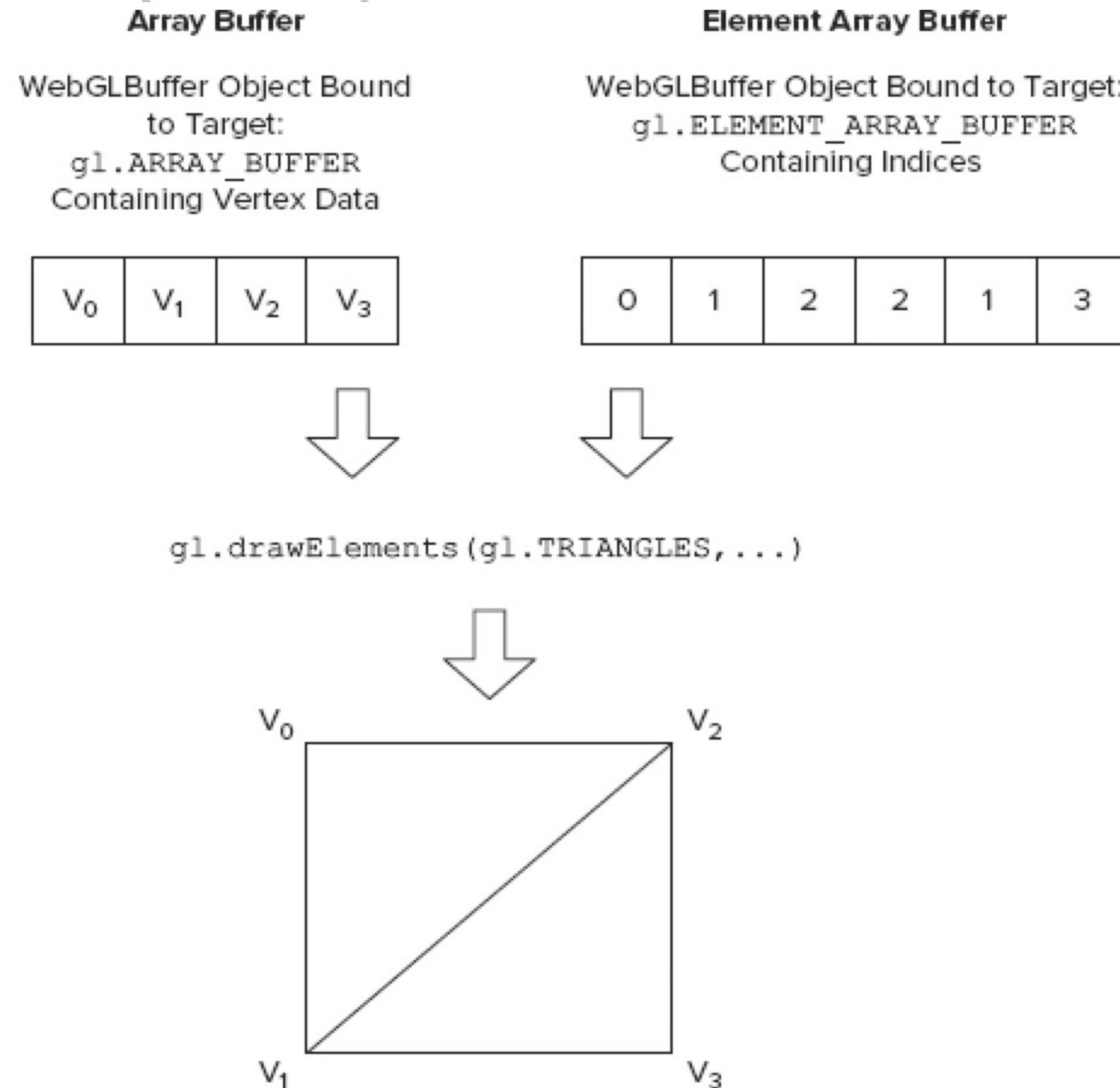
Indexed Meshes in WebGL

WebGL supports drawing indexed face meshes

Simply need another buffer for the indexed faces

```
function draw() {
...
gl.bindBuffer(gl.ARRAY_BUFFER,meshVertexPositionBuffer);
gl.vertexAttribPointer(
  shaderProgram.vertexPositionAttribute,
  meshVertexPositionBuffer.itemSize,gl.FLOAT, false, 0,
  0);

gl.bindBuffer(gl.ELEMENT_ARRAY_BUFFER, meshIndexBuffer);
gl.drawElements(gl.TRIANGLES,
   meshIndexBuffer.numberOfItems, gl.UNSIGNED_SHORT, 0);
}
```

WebGL: gl.drawElements() method



We'll see how to do this in the next MP

Setting up Indexed Drawing

```
function setupBuffers() {
meshVertexPositionBuffer = gl.createBuffer();

gl.bindBuffer(gl.ARRAY_BUFFER, meshVertexPositionBuffer);
var meshVertexPositions  = [1.0,  5.0, 0.0,…];

gl.bufferData(gl.ARRAY_BUFFER, new
           Float32Array(meshVertexPositions),
           gl.STATIC_DRAW);
meshVertexPositionBuffer.itemSize  = 3;
meshVertexPositionBuffer.numberOfItems  = 36;
gl.enableVertexAttribArray(
           shaderProgram.vertexPositionAttribute);
```

Setting up Indexed Drawing

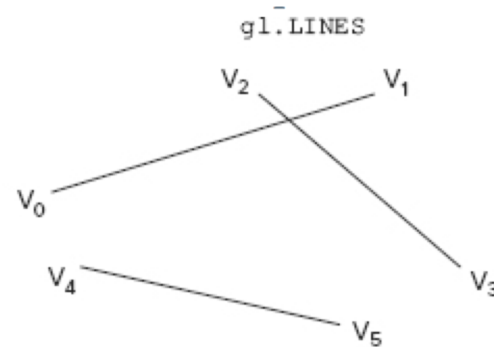
```
meshIndexBuffer = gl.createBuffer();
gl.bindBuffer(gl.ELEMENT_ARRAY_BUFFER,meshIndexBuffer);
var meshIndex = [ 0, 1, 2, 2, 1, 3, 2, 3, 4, …];
gl.bufferData(gl.ELEMENT_ARRAY_BUFFER, new
              Uint16Array(meshIndex), gl.STATIC_DRAW);
meshIndexBuffer.itemSize = 1;
meshIndexBuffer.numberOfItems = 150;
}
```

Other WebGL Primitives: Lines

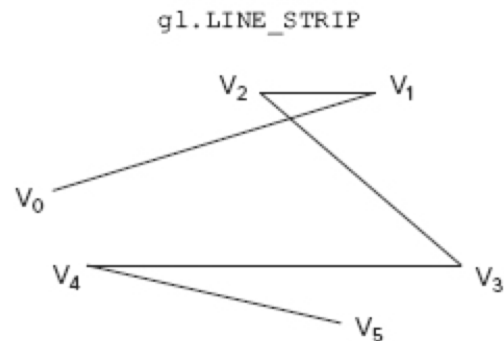
gl.LINES draws independent lines (v0,v1), (v2,v3), (v4,v5)

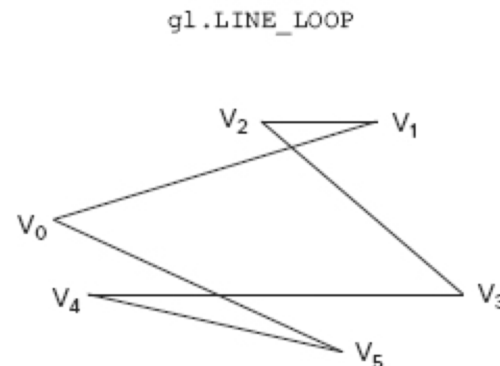
gl.LINE_STRIP draws a polyline (v0,v1),(v1,v2),(v2,v3),(v3,v4),(v4,v5)

gl.LINE_LOOP draws a line strip with a line connecting the first and final vertex



Generally have poor visual quality in most browser implemenations….people often use triangle strips instead.





Other WebGL Primitives: Point Sprites

The star field below uses some extra shader code to achieve it's look

Specified with gl.POINTS mode

Renders one point per vertex in the buffer

Uses N pixels in the point is specified using **`gl.pointSize(N)`**

Using Multiple Buffers

```
gl.bindBuffer(gl.ARRAY_BUFFER, vertexBuffer1);
gl.vertexAttribPointer(shaderProgram.vertexPositionAttribute,
        vertexBuffer1.itemSize, gl.FLOAT, false, 0, 0);
gl.bindBuffer(gl.ARRAY_BUFFER, vertexColorBuffer1);
gl.vertexAttribPointer(shaderProgram.vertexColorAttribute,
        vertexColorBuffer1.itemSize, gl.FLOAT, false, 0, 0);
gl.drawArrays(gl.TRIANGLES, 0, vertexBuffer1);
gl.bindBuffer(gl.ARRAY_BUFFER, vertexBuffer2);
gl.vertexAttribPointer(shaderProgram.vertexPositionAttribute,
vertexBuffer2.itemSize, gl.FLOAT, false, 0, 0);
gl.bindBuffer(gl.ARRAY_BUFFER, vertexColorBuffer2);
gl.vertexAttribPointer(shaderProgram.vertexColorAttribute,
vertexColorBuffer2.itemSize, gl.FLOAT, false, 0, 0);
gl.drawArrays(gl.TRIANGLES, 0, vertexBuffer2.numItems);
```

Complex scenes and geometry may require more than one buffer

You can use more than one vertex buffer

Set them up like you did the the first buffer

Call gl.drawArrays multiple time in your draw function

Is there a way to draw multiple objects from a single buffer?

Minimizing `draw` calls

- You generally want as few calls to gl.drawArrays as possible
  - Same is true for gl.drawElements…we'll discuss that later
- For triangle strips, you can insert degenerate triangles into the stream
  - These triangles will have two identical vertices and 0 area
- Can connect strips using a sequence of degenerate triangles
- Better to do this with gl.drawElements
  - Bigger performance hit for gl.drawArrays due to cache effects

Back Face Culling

- Backface culling is an optimization technique
- It drops backfacing polygons from the pipeline.
- Why would backface culling be useful?

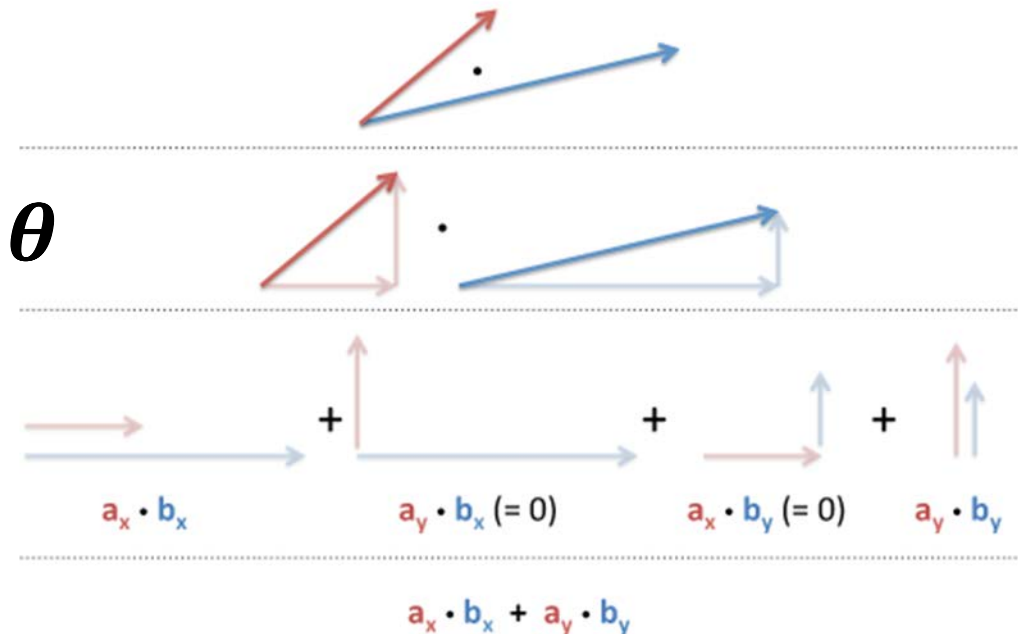
- What artifact do you see here?

- Backface culling is not hidden surface removal

Vector Dot Product

The *dot product* or *inner product* of two vectors is

$$\boldsymbol{u} \cdot \boldsymbol{v} = \boldsymbol{u}_x \boldsymbol{v}_x + \boldsymbol{u}_y \boldsymbol{v}_y + \cdots = \|\boldsymbol{u}\| \|\boldsymbol{v}\| \cos \boldsymbol{\theta}$$

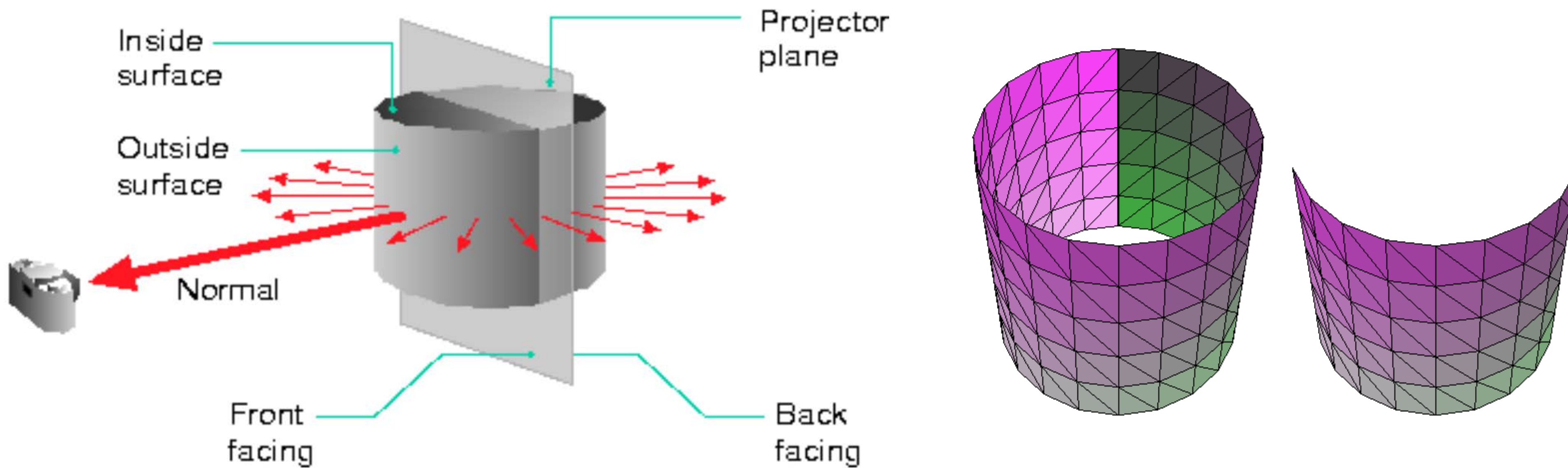


Can think of it as a measure of how aligned the vectors are

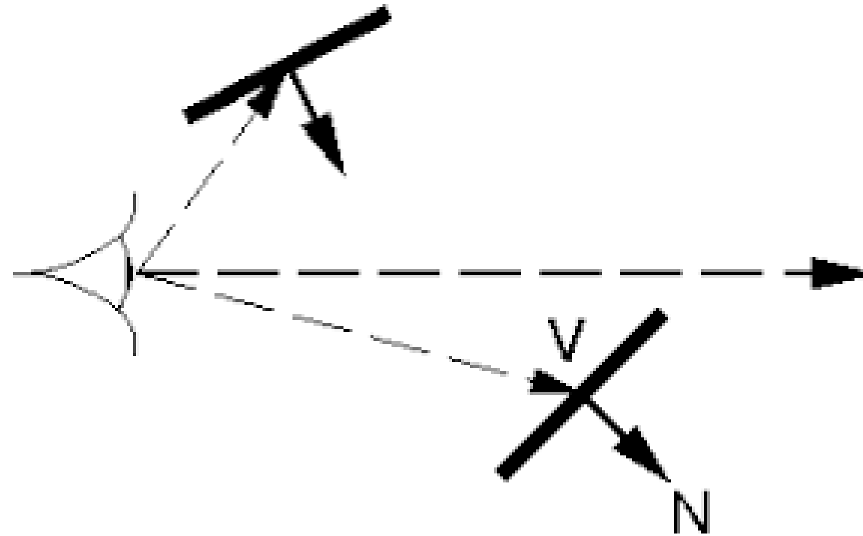
Vector Dot Product

Is a polygon facing away from the viewer?

We can decide by using a dot product test



Back Face Culling



- Decide whether the view vector V
  runs from the surface to the eyepoint or **from the eyepoint to the surface**
    - For this test, we'll **use eyepoint to surface**.
- So, if 90 ≤ θ ≤ 270
  where θ > 0
  then dot product is negative and polygon faces viewer
- IF the dot product is positive ***then polygon does not face viewer***

WebGL Back Face Culling

Polygon culling is disabled by default. To enable or disable culling, use the `enable()` and `disable()` methods with the argument `gl.CULL_FACE`.

```
gl.enable(gl.CULL_FACE);
gl.cullFace(gl.FRONT_AND_BACK);
```

To check the current cull face mode, query the `CULL_FACE_MODE` constant.

```
gl.getParameter(gl.CULL_FACE_MODE) === gl.FRONT_AND_BACK;
// true
```