Rendering Engine Part A

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Rendering a 3D Scene

- Involves these basic steps
  - Describe Virtual Scene
  - Placing Virtual Camera (virtual light sensors)
  - Define Light Sources
  - Define Visual Properties of Surfaces
  - Solving the Rendering /Shading Equation

Goal of Rendering

- Photorealism vs. real-time performance

UnrealEngine

- A real-time engine has at mose 33.3 ms to generate each image (for 30 FPS)

Describing a Scene

- Scenes are composed of Objects
  - Opaque
  - Transparent
  - Translucent

- Opaque objects can be rendered considering only the surface
- Real-time engines deal with opaque surfaces and approximate transparcy with alpha

Representing Surfaces

- Parametric Surface Equations
- Patches (Bézier, NURBS)
- Subdivision Surfaces
- Triangle Meshes

Triangle Meshes

- Triangles as a piece-wise linear approximation to a surface.
- Triangles the polygon of choicec for real-time rendering because:
  - Simplest polygon
  - Always planar
  - Remain triangles under most transformations
  - Hardware for triangle rasterization

Tessellation

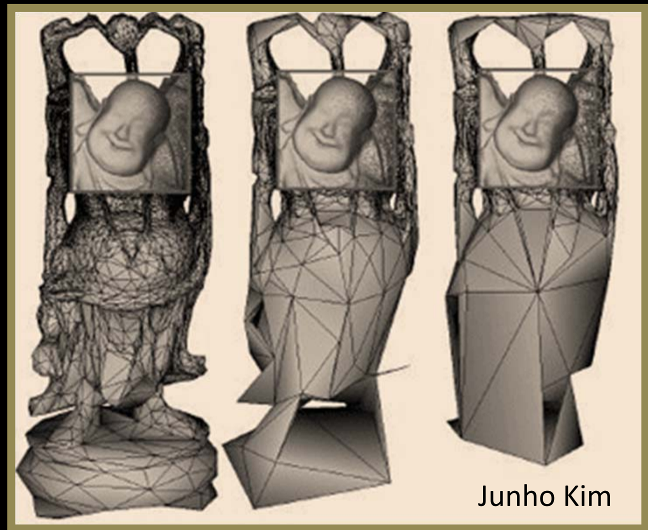
- The process of dividing a surface up into a collection of discrete polygons (triangles or quads)
- Triangulation is tessellation of a surface into triangles
- Ideally tessellate as much as needed for camera

Tessellation and LOD

- Approximate right density of tessellation with Level of Detail (LOD) versions of objects

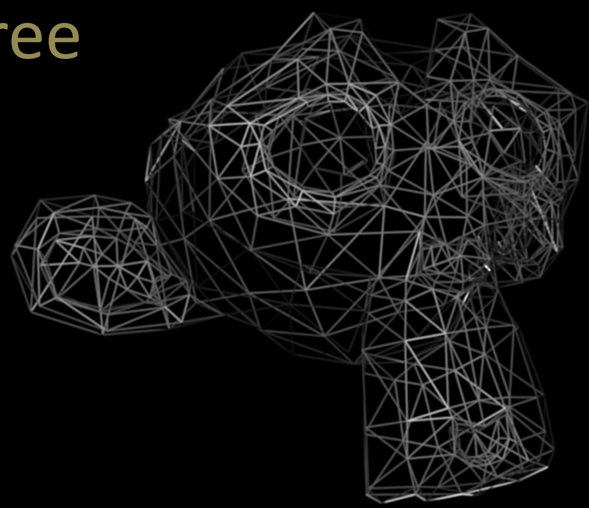
Tessellation and Detail

- Dynamic Tessellation
  - Grid patterns e.g. for terrain
  - Fewer and fewer grid points used for tessellation further away from camera
- Progressive Meshes
  - Single high-resolution mesh
  - Automatically detessellated furthe away (collapsing edges)



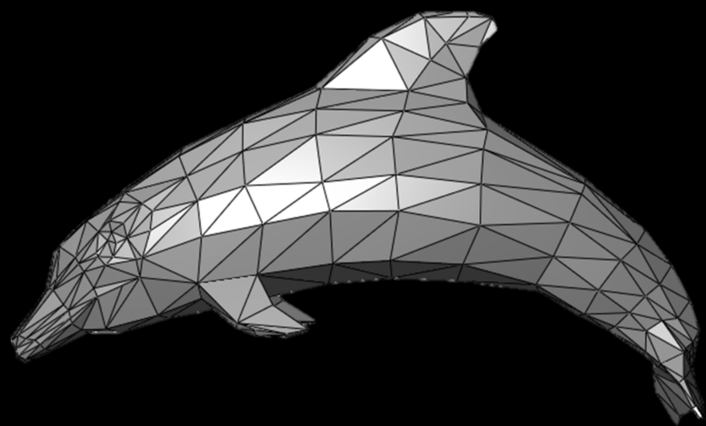
Constructing Triangle Meshes

- Pick a Winding Order
  - Counterclockwise typical (but arbitrarily picked)
  - Determines which side is front and which is back
- Triangle Lists
  - List vertices in groups of three



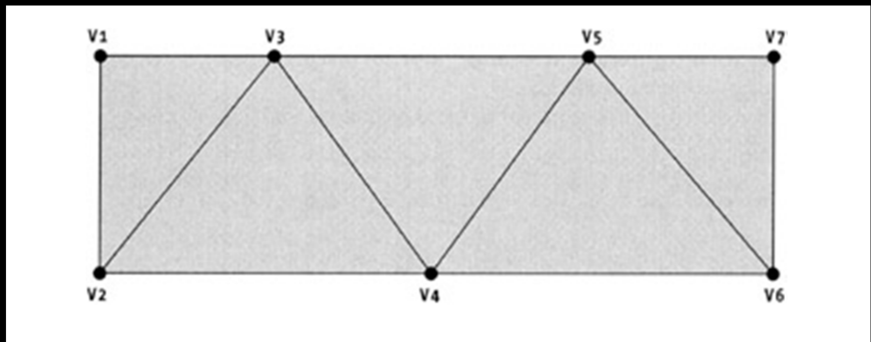
Constructing Triangle Meshes

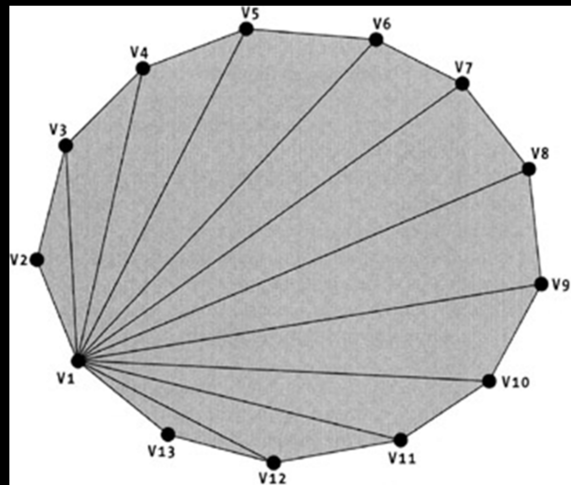
- Indexed Triangle Lists
  - – Duplicated vertices waste memory and GPU cycles
  - – Store vertices once in Vertex Buffer and use light-weight indecies in an Index Buffer to define the triples of triangle vertices



Constructing Triangle Meshes

- Triangle Strips and Fans eliminate need for an index buffer while still reducing vertex duplication





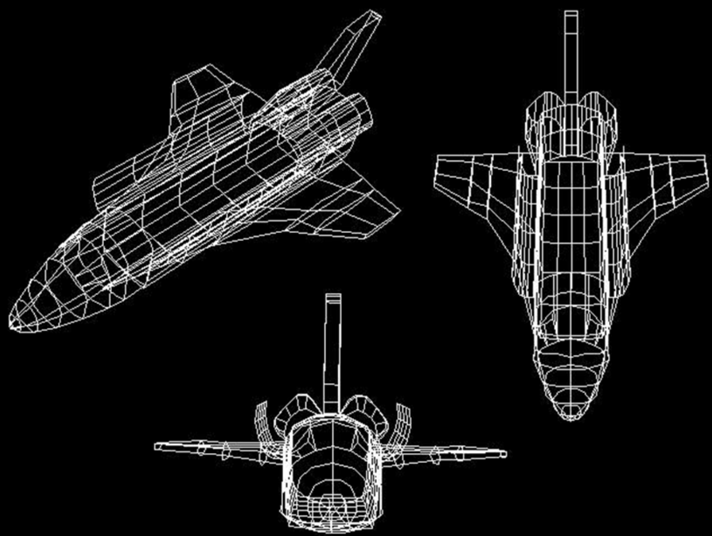
- Predefined order of vertices
- Combined in a certain way to form triangles

Vertex Cache Optimization

- As vertices are processed by vertex shaders they are cached for reuse
- Strips and fans improve cache coherency
- A vertex cache optimizer can manipulate other triangle meshes offline to optimize vertex reuse

Model Space

- Positions of triangle vertices given relative to coordinate system called model space (also local or object space)
- The orientation of this coordinate system is arbitrary but typically aligned with a front, left (right), up direction



Instancing in World Space

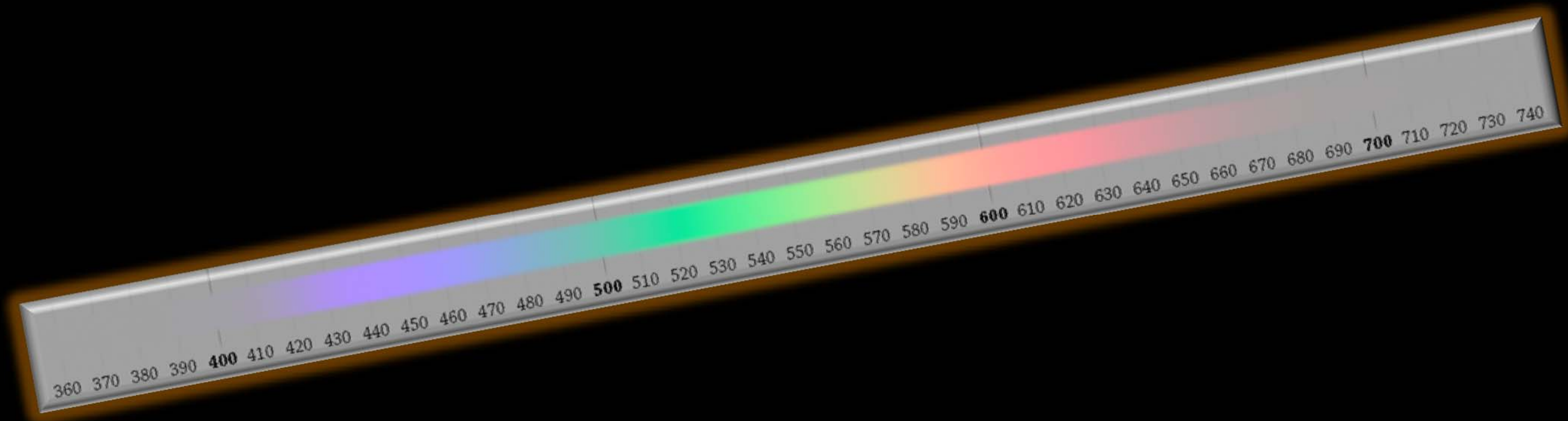
- Mesh instances are positioned and oriented in a scene with respect to a world space coordinate system
- The mesh's vertices are converted from model space to world space using a model-to-world matrix
- Special care has to be taken when converting normals from model to world space. Need to use inverse transpose matrix if scale and shear

Visual Properties of Surfaces

- How does light interact with the surface?
  - Surface Normal
  - Diffuse Color
  - Shininess / Reflectivity
  - Roughness or Texture
  - Degree of Opacity or Transparency
  - Index of Refraction

Light and Color

- Light is electromagnetic radiation
- Color determined by intensity and wavelength
- Visible light in 740nm to 380nm range
- Beams can contain one or more wavelengths



Light-Object Interactions

- Many complex interactions with matter
- Goverened by
  - Medium
  - Interface between media
- Surface is an interface between media

Light-Object Interaction

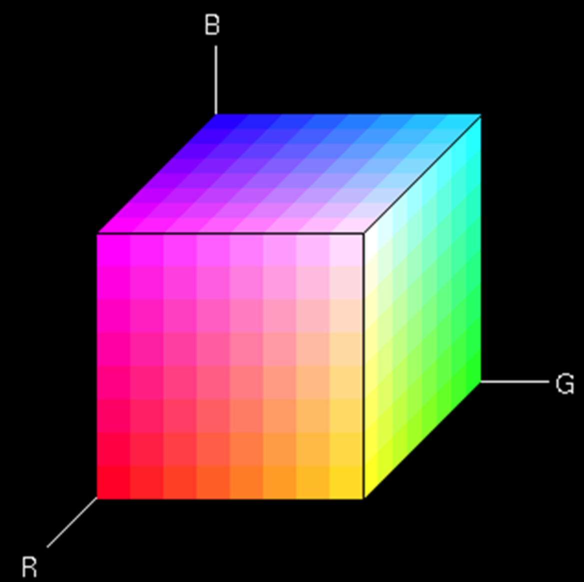
- What can light do?
  - Be absorbed
  - Be reflected
  - Be transmitted through an object and be refracted in the process
  - Be diffracted when passing through narrow openings (not usually modeled)

Light-Object Interaction

- Certain wavelengths absorbed by surface, others reflected
- Those not absorbed give off the perceived color
- Reflected can be diffuse (scattered equally in all directions) or specular (reflect directly or spread in narrow cone)
- Transmitted through volume, light can be scattered, partially absorbed or refracted

Color Spaces and Color Models

- Color model three dimensional because of three types of color sensors (cones) in our eyes, which are sensitive to different wavelengths of light
- Most commonly RGB
  - RGB888 uses 8 bits per channel
  - RGBA adds alpha channel



Vertex Attributes

- The simplest way to describe the visual properties of a surface is to specify them at discrete points on the surface
- Vertices are such points
- Visual properties in vertices are called vertex attributes

Vertex Attributes

- Position vector
- Vertex normal
- Vertex tangent and bitangent (tangent space)
- Diffuse color
- Specular color
- Texture coordinates
- Skinning weights

Stored in different combinations in differrent vertex formats

Vertex Formats

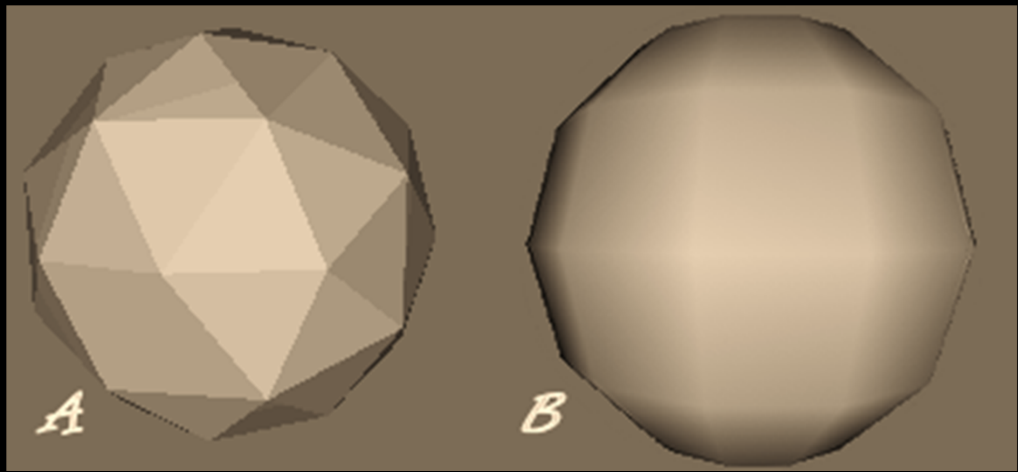
- Vertex attributes are stored within data structures called vertex format
- Not all combinations of vertex attributes can be handled by all hardware, therefore these have to be compatible
- However, modern GPUs are capable of extracting the subset of attributes that they actually need

Attribute Interpolation

- Attributes at a triangle‘s vertices are discretized approximations to the visual properties of the surface as a whole.
- When rendering the triangle, the interior as „seen“ through each pixel on the screen matters
- Simple linear interpolation of per-vertex attributes to determine per-pixel attributes is possible

Attribute Interpolation

- Gouraud Shading is an example of per-vertex color attributes interpolated to determine per-pixel color



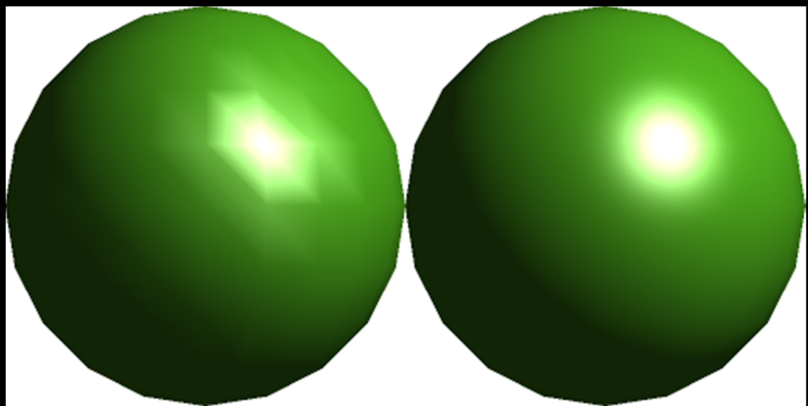
Vertex Normals and Smoothing

- Simplest way to light a mesh is to calculate color per-vertex, using the vertex normal and direction to light source
- Normals can be made to point in such a way that the interpolation across the entire surface is smooth, resulting in rounded corners

Per-vertex Lighting Error

- Linear-interpolation of per-vertex data can cause visual errors
- For example when rendering specular highlights (the highlight calculated at a vertex gets spread out towards the other vertices)

Per-vertex lighting



Per-pixel lighting

Textures

- One way to provide per-pixel information is through texture maps
- Textures can contain color information, applied to the interiors of triangles of a mesh
- Textures can also contain other information for per-pixel calculation, e.g. normals
- Individual picture elements of textures are called texels (different from on-screen pixels)

Textures

- Typically texture sizes have to be powers of two and possibly even square
  - 512x512 or 1024x1024 are common
- Types of textures include
  - Diffuse maps (diffuse color)
  - Normal maps
  - Gloss maps
  - Environment maps
  - ...and just about anything we need for calculation

Texture Coordinates

- 2D textures need to be projected onto a 3D mesh so that values can be looked up for each interior triangle pixel
- Each texture exists in texture space (uv space), where coordinates range from (0,0) to (1,1)
- The projection is made possible by storing texture (u,v) coordinates with each vertex in the mesh, mapping each triangle onto a 2D triangle in the texture

Texture Addressing Modes

- Texture coordinates are permitted to be outside the [0, 1] range
- What happens outside of the range is determiend by the texture addressing mode
  - Wrap
  - Mirror
  - Clamp
  - Border color

Texture Formats

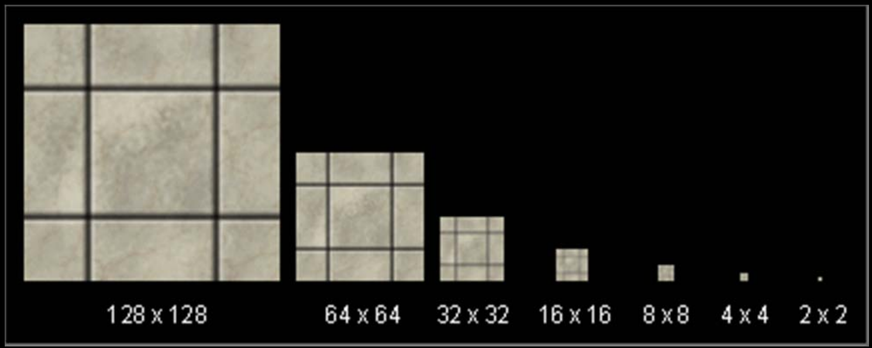
- Texture bitmaps typically stored as
  - Targa (.tga)
  - Portable Network Graphics (.png)
  - Windows Bitmap (.bmp)
  - Tagged Image Format (.tif)
- Compressed textures also supportd, e.g. DirectX supports DXT texture compression

Texel Density

- Texel Density is the ratio of texels to pixels
  - Imagine viewing the texels through a single pixel on the screen
- When low, we see the edges of the texel
- When high, image may band or swim, and memory is wasted
- Texel density of 1 would be ideal

Mipmapping

- We can approximate texel density of 1 with Mipmapping
- Mipmaps of a texture are lower-resolution versions, each half the height of previous one
- Graphics hardware picks the mip level that produces the best texel density



World Space Texel Density

- We can also measure the ratio of texels per world unit of measurement
- E.g. texels per meter or cm
- A low ratio may result in washed out environments
- Studios provide guidelines for this per game title

Texture Filtering

- When rending a pixel of a textured triangle, the hardware samples the texture map by seeing where pixel falls in texture space
- Not usually a one-to-one mapping between texels and pixels
- May need to sample more than one texel and blend together → texture filtering

Texture Filtering

- Most graphics cards support
  - Nearest neighbor: Just pick the closest texel and mipmap
  - Bilinear: Four surrounding texels blended in the nearest mipmap
  - Trilinear: Do bilinear filtering on two nearest mipmaps, then interpolate (less abrupt mip levels)
  - Anisotropic: Samples texels within trapezoidal regions based on view angle

Materials

- A material is a complete description of the visual properties of a mesh
  - Textures mapped onto surface
  - Shader programs used
  - Shader inputs
  - Etc.
- Vertex attributes typically not part of this, but mesh-material pairs often called render packets

Light Transport Models

- Mathematical models of light-surface and light-volume interactions
- Divided up into Local illumination models and Global illumination models
- Direct lighting is a simple local illumination model (phong lighting)
- Indirect lighting is an example of a global illumination model (ray tracing, radiosity)

The Phong Lighting Model

- Models light reflected from a surface as a sum of
  - Ambient term
  - Diffuse term
  - Specular term

Light Sources

- Approximations of real-world light sources
  - Static lighting
  - Ambient lights
  - Directional lights
  - Point lights
  - Spot lights
  - Area lights
  - Emissive lights