Computer Graphics - Week 7

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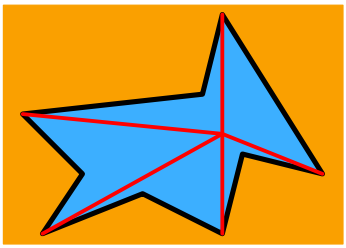
Questions about Last Week ?

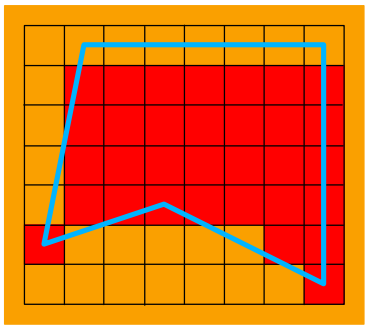
Comments about the Assignment

- **Specific comments**
  - The clip volume does not need to be closed
  - Rotate the polygon around the origin, not the center of the clip volume or the center of the polygon
  - Polygons are 2-sided, i.e. they are visible from both sides
  - Rasterization is done using integer arithmetic
  - If you encounter coincident edges, they should not appear
- **What are star-shaped polygons ?**
  - Star-shaped polygons have one interior star-point fromwhere all edges are visible
  - In the assignment all polygons are star-shaped with the first vertex a star point.
  - This is helpful for triangulation.



Comments about the Assignment (cont'd)

- **'s' command**
  - Displays rasterized clipped polygon on the screen rectangle
  - Rasterized polygon interpolate the colors based on the colors specified for the input polygon **after** clipping
  - Make sure shading results for interior pixels do not depend on clipping or rotation
- **'l' command**
  - Displays outline of the clipped polygon using OpenGL lines
  - Don't rasterize the lines onto the screen rectangle

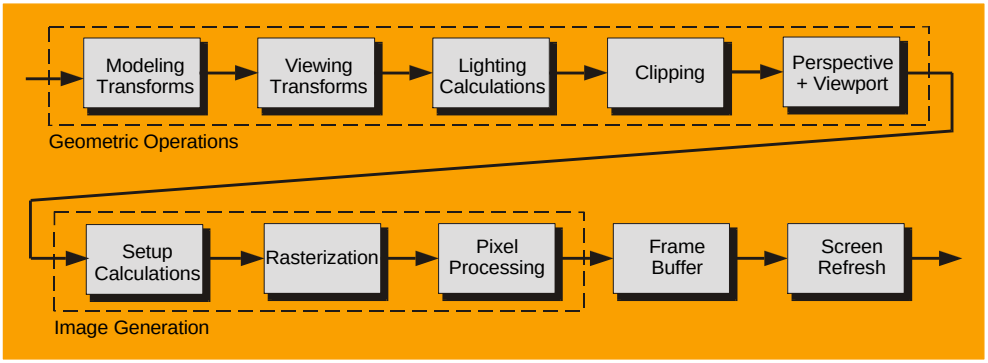


Overview of Week 7

- **Fragment Processing and Pixel Manipulation Methods**
  - Texture Mapping
  - Alpha Blending
  - Z-Buffering
- **Hidden-Surface Removal Algorithms**
  - Z-Buffering
  - Scanline algorithm
  - Depth-sorting algorithm

Fragment Processing (a.k.a. pixel processing) in the Rendering Pipeline

- **Fragment processing follows the scan conversion**
  - Processes the pixels generated by the scan conversion process
  - Forms the interface between scan conversion and the pixel buffers

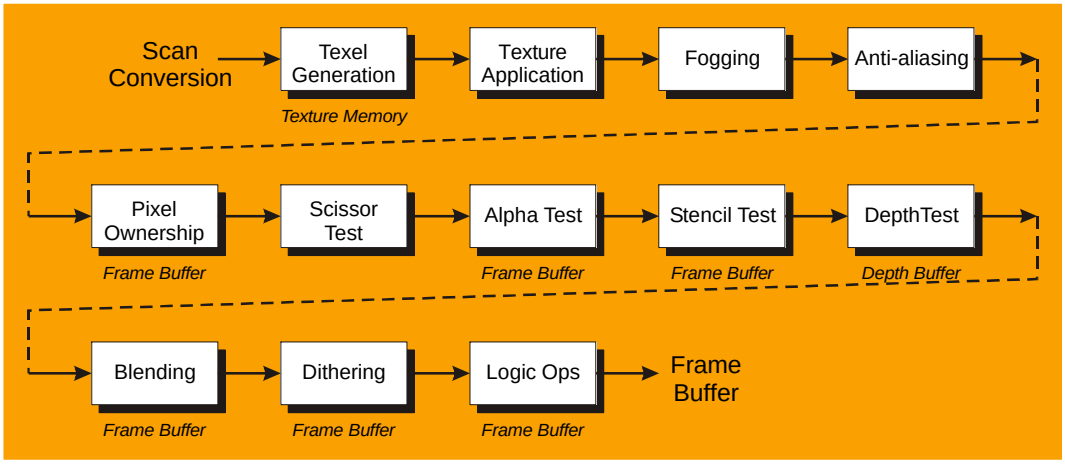


Fragment Processing Concepts

- **A *fragment* is are pixel data generated during scan conversion**
  - Pixel coordinates
  - Associated attributes, e.g. color, depth, texture, etc.
- ***Fragment Processing* manipulates the fragment data**
  - Look-up operations, e.g. texturing
  - Modification of pixel value based on global parameters, e.g. fogging
  - Test of fragment data against frame buffer data, depth test
  - Pixel arithmetic, e.g. alpha blending
  - Anti-aliasing and dithering
- **We will call *pixel* the data stored in the frame buffer**
  - To be distinguished from fragment data

Fragment Processing Pipeline (1)

- **OpenGL fragment processing pipeline**
  - Texturing, Fogging and Anti-aliasing
  - Pixel Tests
  - Frame Buffer Operations



Fragment Processing Pipeline (2)

- **Texturing** (... more in a few minutes)
  - Apply image information to a polygon
  - "Paste an image onto the polygon"
- **Fogging**
  - See lecture on lighting and shading models
- **Anti-aliasing**
  - Eliminate jaggies and broken-up polygons by accounting for partial pixel coverage by primitives

Fragment Processing Pipeline (3)

- **Pixel Tests**
  - Test various conditions about the fragment and the current frame buffer content
  - Determines whether the fragment is processed any further or discarded
- **Frame Buffer Operations**
  - Read - Modify - Write processing of frame buffer content
  - Combines fragment with current frame buffer contents

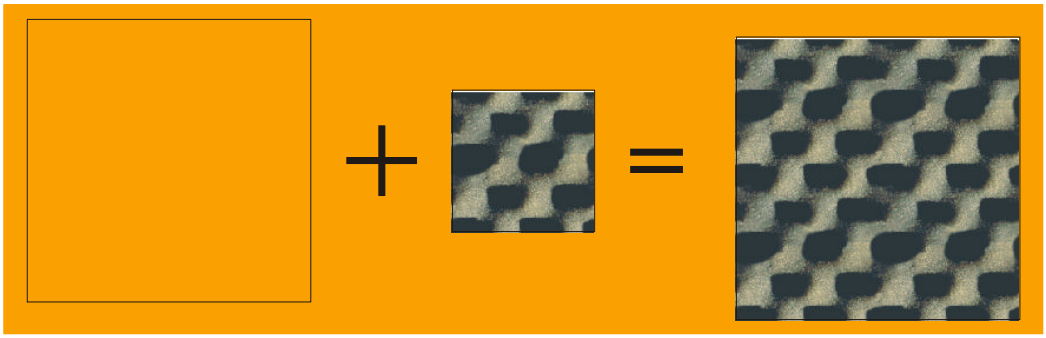
Fragment Processing Pipeline (4)

- **We will not go into all details of these operations**
  - See OpenGL programming guide for more details
- **We will discuss**
  - Texture Mapping
  - Blending
  - Z-Buffer

Texture Mapping

Texture Mapping: Example

- **Texture mapping:**
  - Pasting of an image to the interior of an object
  - If necessary, repeat the image to fill the entire interior
  - Texture coordinates defined across the object, define where the image pixels appear in the object.

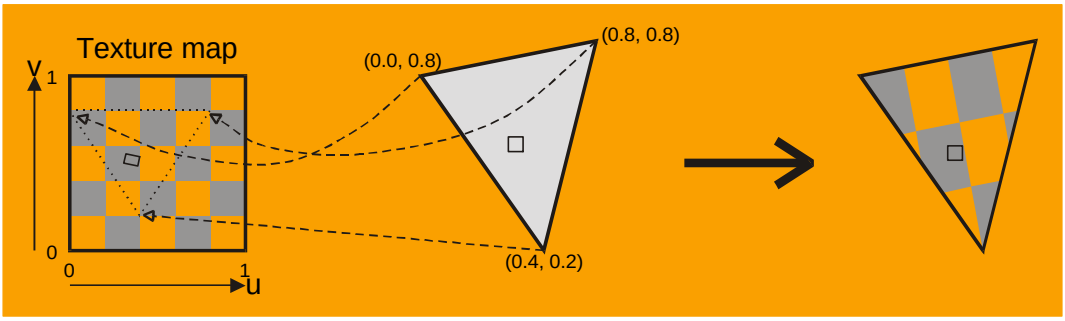


Texture Mapping Concepts

- ***Texture Map* is a 1/2/3-dimensional array of color values**
  - 2D texture maps are images
  - 3D texture maps are volume data
- ***Texels* are the individual pixels in the texture map**
  - Texels can be represented in a variety of formats, e.g. 1/4/8 bit color index, 16/24/32 bit true color
- ***Texture Coordinates* are indices (addresses) into the texture map**
  - Interpolated across primitives
  - Often denoted *(u,v)* coordinates

Texture Mapping Principle

- Texture coordinates are computed/assigned at vertices and interpolated across the triangle
- The texture coordinates are used to look up the texel
- Texel value is assigned to associated pixel



Texture Mapping: Sampling

- **Point Sampling**
  - If only the computed texture coordinates at the pixel are used
  - Will yield exactly one texel for every pixel (but generally not vice versa)
- **Area Sampling**
  - Determine all texels affecting the pixel
  - For instance map the 4 corners of the pixel and interpolate within the texture

Texture Mapping: Forward vs Inverse Mapping

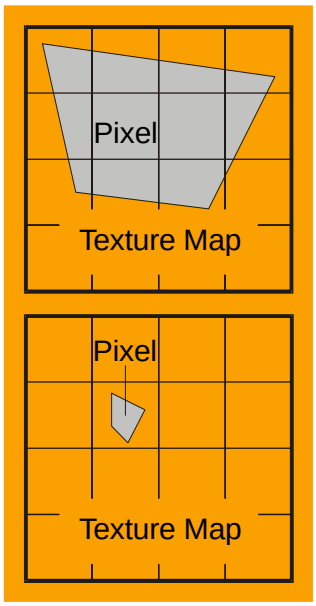
- **Texture mapping can be defined in 2 directions**

- ***Forward mapping* maps a texel into screen space**
  - Given a texture coordinate *(u,v)*, determine the corresponding pixel coordinate *(x,y)*
  - May leave holes in the pixel image, i.e. there may be pixels that no texel was mapped to
  - Often used in image processing

- **Inverse mapping maps pixels into texture space**
  - Given a pixel coordinate *(x,y)*, determine the corresponding texture coordinate *(u,v)*
  - May miss texels, i.e. there may be texels that no pixel maps to
  - Frequently used during texture mapping

Texture Filtering (1)

- **Both directions of mapping may create problems, if there is no 1:1 mapping between pixels and texels**
  - Will create artifacts
  - Texture breaks up if texels are missed (Minification)
  - Texture appears blocky if several pixels map into the same texel (Magnification)
  - Mixed cases are possible if magnified along one axis and minified along the other axis

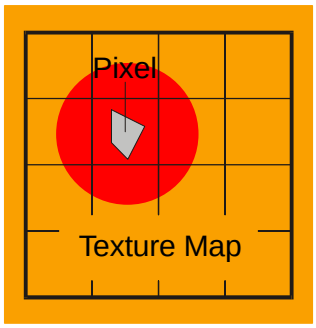


Texture Filtering (2)

- **The fundamental problem is a sampling problem**
  - For *minification* the texture is undersampled
  - The spatial sampling frequency is smaller than the spatial frequency of the texture map (less than one sample per texel)
  - For *magnification* the texture is oversampled
  - The spatial sampling frequency is higher than the spatial frequency of the texture map (more than one sample per texel)
- **Proper treatment of such problem requires filtering**
  - Without going into too many details ...

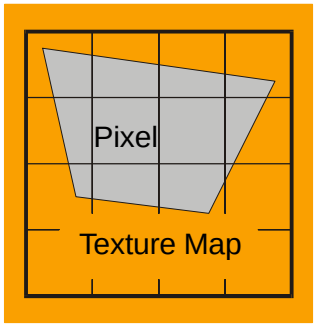
Texture Filtering (3)

- **Magnification**
  - Texture map can be considered sampling of a continuous function
  - Texture mapping resamples (reconstructs) that function
  - Neighboring texels must be taken into account
  - Consider a neighborhood around the sample point
  - Compute a weighted average



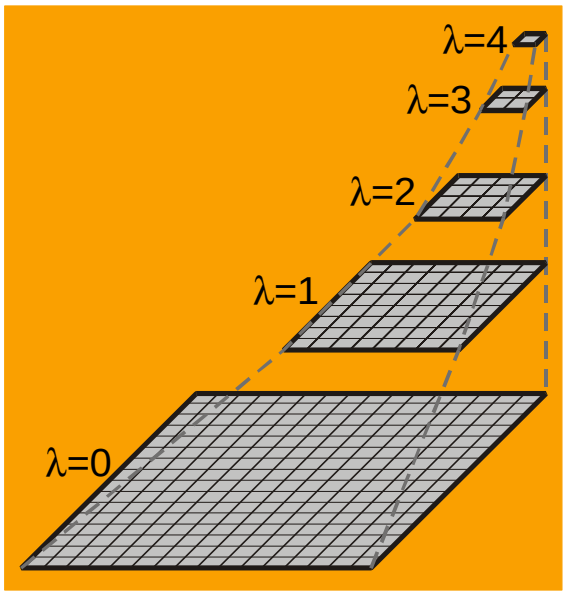
Texture Filtering (4)

- **Minification**
  - All texels contributing to the pixel must be taken into account
  - Integrate over the area a pixel covers in the texture map
  - This will take into account all texels contributing to the pixel
  - Fairly expensive to compute
  - There are several approximations to deal with this problem:
- **Mip-maps**
  - Down-sampled copies of the texture
- **Summed-area tables**
  - Precomputed integrals over axis-aligned rectangular areas in the texture



Texture Filtering (5): Mip-Mapping (i)

- **Hierarchy of texture images**
  - Original texture (base texture) is down-sampled repeatedly
  - Average 2x2 texel blocks into a texel of the next higher texture level
- **Select mip-map level based on minification**
  - Scale factor ρ (to be defined)
  - Level-of-Detail (LOD) $\lambda = \log_2(\rho)$



Texture Filtering (5): Mip-Mapping (ii)

- **Selection of mip-map level**
  - Ideally, unit step in pixel space result in a unit step in texture space
  - Look at derivatives of texture coordinates in pixel space
  - Use biggest step size to compute scale factor ρ

$$r = \max\left(\sqrt{\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial x}\right)^2}, \sqrt{\left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2}\right)$$

  - This expression is often simplified with slight loss of quality:

$$r = \max\left(\left|\frac{\partial u}{\partial x}\right|, \left|\frac{\partial u}{\partial y}\right|, \left|\frac{\partial v}{\partial x}\right|, \left|\frac{\partial v}{\partial y}\right|\right)$$

Texture Mapping (6)

- **Point Sampling**
  - Look up the nearest texel to the texture coordinate *(u,v)*
  - Only one texel affects the pixel at *(x,y)*
  - 1 Memory Access

$$t = T(\lfloor u \rfloor, \lfloor v \rfloor)$$

- **Bilinear Filtering**
  - Use a 2x2 texel neighborhood around (u,v) to compute the final texture value
  - 4 Memory Accesses
    8 Multiplications
    5 Additions

$$s = \lfloor u \rfloor \quad , \quad t = \lfloor v \rfloor$$
$$t = (1-a)(1-b)\cdot T(s,t) +$$
$$(1-a)b \cdot T(s,t+1) +$$
$$a(1-b)\cdot T(s+1,t) +$$
$$ab \cdot T(s+1,t+1)$$

Texture Mapping (7)

- **Linear Filtering**
  - Interpolated linearly between two mip-map levels
  - 2 Memory Accesses
    2 Multiplications
    1 Addition
- **Trilinear Filtering**
  - Bilinear interpolation within two adjacent mip-map levels
  - Linear interpolation between those two values
  - 8 Memory Accesses
    18 Multiplications
    16 Additions

$$t = a \cdot T_l(\lfloor u \rfloor, \lfloor v \rfloor) + (1-a) \cdot T_{l+1}(\lfloor u/2 \rfloor, \lfloor v/2 \rfloor)$$

$$s_l = \lfloor u \rfloor;\ t_l = \lfloor v \rfloor;$$
$$s_{l+1} = \lfloor u/2 \rfloor;\ t_{l+1} = \lfloor v/2 \rfloor$$
$$\begin{aligned} t = g \cdot [&(1-a)(1-b) \cdot T_l(s_l, t_l) + \\ &(1-a)b \cdot T_l(s_l, t_l + 1) + \\ &a(1-b) \cdot T_l(s_l + 1, t_l) + \\ &ab \cdot T_l(s_l + 1, t_l + 1)] + \\ (1-g) \cdot [&(1-a)(1-b) \cdot T_{l+1}(s_{l+1}, t_{l+1}) + \\ &(1-a)b \cdot T_{l+1}(s_{l+1}, t_{l+1} + 1) + \\ &a(1-b) \cdot T_{l+1}(s_{l+1} + 1, t_{l+1}) + \\ &ab \cdot T_{l+1}(s_{l+1} + 1, t_{l+1} + 1)] \end{aligned}$$

Texture Mapping (8)

- **Different filtering methods have different complexity**
  - Trilinear interpolation is most expensive, point sampling cheapest
  - Quality of filtering increases with required computation

Texture Filtering (4)

- **Minification**
  - All texels contributing to the pixel must be taken into account
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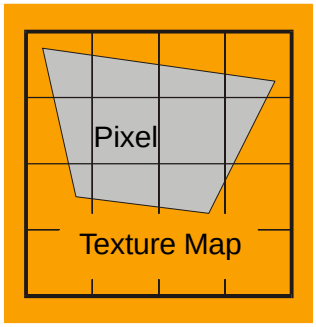
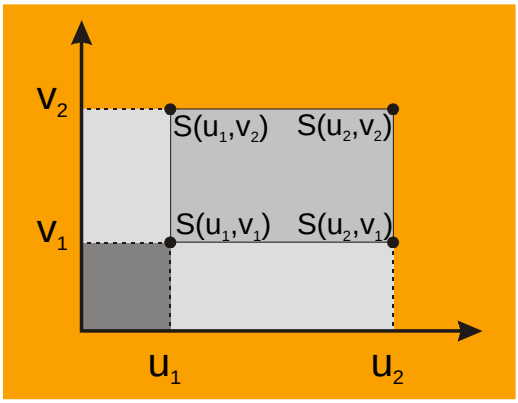


Texture Filtering (9): Summed Area Table

- **Precomputed table that stores the sum of all texels between the origin and a given texture coordinate**
  - Precomputation is costly
  - Supports rectangular regions instead of square regions in mip-mapping
- **For a given rectangular, axis-aligned area, the sum of all texels inside the rectangle is:**



$$S(u_1, v_1, u_2, v_2) = S_{22} - S_{12} - S_{21} + S_{11}$$

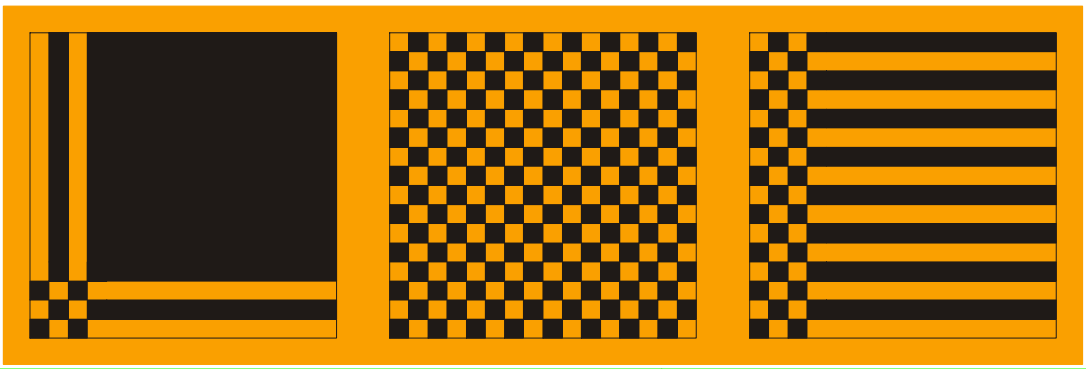
Assigning Texture Coordinates (1)

- **Basic problem**
  - Square texture images are applied to arbitrarily-shaped objects
  - Find a good way to map to (i.e. wrap around) texture to object

- **Application assigns texture coordinates at the vertices**
  - Complete freedom over how texture is applied to an object
  - Texture can be rotated, shifted and scaled
  - To avoid distortion of the texture, ensure that object's aspect ration matches the aspect ratio of the selected texture range

Assigning Texture Coordinates (2)

- **Typically, texture coordinates fall within the range [0,1].**
- **What happens if a texture coordinate falls outside of that range ?**
  - Clamp texture coordinate: $u' = \max(\min(u, 1.0), 0.0)$
  - Repeat the texture: $u' = u \bmod 1.0$



Assigning Texture Coordinates (3)

- **Textures can be applied "automatically"**
  - Compute texture coordinates based on the distance of object point from a plane *ax+by+cz+d*
  - This allows to project the texture onto the object similar to a slide projector
  - For instance: $u = x$ and $v = z$
  - For "cylindrical" objects, the texture can be wrapped around the object, by using the angle around an axis to address the texture
  - For instance, for an object centered around the z-axis (use sign-aware atan function !):

$$u = \frac{\text{atan}(x / y)}{2p} \quad \text{and} \quad v = z$$

OpenGL: Texture Mapping (1)

- **glTexImage[12]D()**
  - Specifies the texture image in various formats
  - Takes mipmap level, width, height, image data and various format parameters
  - Images must have width and height being powers of 2
- **glTexParameter*()**
  - Specifies filtering methods for magnification and minification
    - Can choose from point sampling + linear, bilinear and trilinear filters
  - Repeat vs. Clamping of texture coordinates
    - Can be set differently for u and v coordinates
- **glTexCoord*()**
  - Specifies a texture coordinate, similar to glVertex*() or glColor*()

OpenGL: Texture Mapping (2)

- **Texture Objects allow to define and use multiple textures efficiently**
  - A texture objects store the texture image and parameters defined for that texture, e.g. repeat, border and filtering modes
- **glGenTextures()**
  - Generates texture names (integer numbers)
- **glBindTexture()**
  - Creates texture object of specified type with given name (number)
  - Makes the bound texture the active texture, i.e. the one used for texture mapping, until a new texture is bound

OpenGL: Texture Mapping (3)

- **Automatic texture generation**
  - Uses a plane specified by four parameters
  - Plane equation is either evaluate for object coordinates (GL_OBJECT_LINEAR) or eye coordinates (GL_EYE_LINEAR)
  - Result of that evaluation determines texture coordinate
  - OpenGL also supports generation of texture coordinates for environment mapping, i.e. reflection on an ideal sphere.

Alpha-Blending

Alpha-Blending: Basics

- **Basic extension of RGB color model**
- **A fourth component is added**
  - Commonly referred to as Alpha or A: RGBA
  - So far, the pixel color was fully replaced by the fragment color
  - Alpha is used to blend a fragment's color with the stored pixel color
  - This allows to create a mix of the pixel and the fragment color
  - A=1 means fully opaque, A=0 means fully transparent
- **Alph-blending is used for various purposes**
  - Transparency
  - Anti-aliasing
  - Digital Compositing

Alpha-Blending: Transparency

- **Both fragment and frame buffer pixel may have an associated alpha value**
  - There are numerous possibilities to combine fragment and pixel color, taking into account the 2 alpha values (see e.g. OpenGL programming manual)
  - One of the most useful applications of alpha blending is to model transparent objects:

$$C_P = a \cdot C_F + (1 - a) \cdot C_P$$

  - When rendering scenes with transparent and opaque objects: Render all opaque objects first, then render transparent objects without writing the z-buffer

Double-Buffering

Double-Buffering

- **If all rendering occurs into the same buffer that is used for screen refresh, the image construction process is apparent**
  - No illusion of a standing image
  - Flickering as image is erased and updated
  - Memory contention between screen fresh and image generation
- **Double-buffering provides two buffers**
  - Front-buffer used for screen refresh, contains previous frame
  - Back-buffer used to construct the new image, i.e. the current frame
  - After the new image is finished, front and back buffers are swapped
  - To reduce flicker, buffer swap is synchronized with vertical retrace

Hidden Surface Removal

Hidden Surface Removal

- **Determine which objects are visible from a given viewpoint, i.e. which objects are hiding other objects**
- **This is a complex problem of at least $O(n^2)$ complexity (test every object against every other object)**
  - Complexity increases if there is no clear A-hides-B relationship between objects
- **We will look at different hidden-surface removal algorithms (a.k.a. visibility algorithms)**
  - Z-Buffer: Image space HSR algorithm
  - Scan-line Algorithms: Image space HSR algorithm
  - Depth-sorting Algorithm: Object space HSR algorithm

Z-Buffering: Basic Algorithm

- **Simple algorithm, that trades computational simplicity for memory requirements**
  - Allocate for every pixel a depth value
  - The depth value stores the z-value of the front-most (visible) object at that pixel
  - For new fragment, compare fragment's z-value with pixel's z-value
  - If fragment is closer to the viewer, replace pixel z and color

```
// Clear z-buffer
FOR (all pixels px)
  zb[px.x][px.y] = infinity;

// Scan conversion w/
z-buffer
FOR (each polygon p)
  FOR (each fragment f in p)
  { x = f.x ;  y = f.y ;
    IF (f.z < zbuffer[x][y])
    { zb[x][y] = f.z ;
      fb[x][y] = f.color ;
    }
  }
```


Z-Buffering: Properties

- **Requires significant amounts of memory**
  - W x H x nbytes, e.g. 1280 x 1024 x 32 bit = 5 MBytes
  - However, memory becomes cheaper rapidly
- **Image space algorithm**
  - No unnecessary computations
  - Subject to aliasing
- **Simple to implement**
  - Many hardware and software implementation
  - Fast execution
- **Universal**
  - Can be used with any primitive type
  - For instance, polygons, quadrics, splines, depthmaps

Z-Buffering: Artifacts

- **Z-Buffer errors**
  - Colinear edges and coplanar faces may generate slightly different depth values if not supported by the same vertices
  - Frequent changes in visibility creates typical z-buffer errors
- **Aliasing**
  - Only 1 object can be visible in each pixel
  - No blending amongst several objects sharing a pixel
- **Depth Compression**
  - Perspective projection distributes depth values non-uniformly
  - Depth values are spaced more closely near the eye, i.e. better resolution in the near field
  - Two different, distant points may map to the same z-value

Other Visibility Algorithms

- Scanline Algorithm
- Depth-sorting Algorithm

- We will look at some more HSR algorithms when we talk about spatial data structures
  - BSP trees
  - Octrees

Scanline Algorithm

- Last week we discussed a scanline algorithm to scan convert polygons

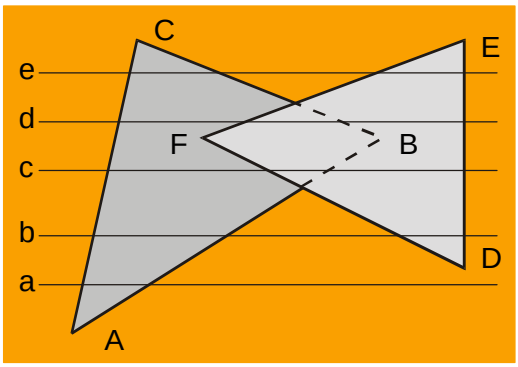
- We will extend this algorithm
  - Several polygons per scanline
  - Resolve visibility between polygons sharing a scanline

Scanline Algorithm for Scan Conversion of Polygons

- **Edge Table (ET)**
  - Bucket sorted list of all edges, with a bucket for each scanline
  - Edges are sorted by their minimum (maximum) Y-coordinate
- **Active Edge Table (AET)**
  - List of edges intersecting the current scanline
  - Sorted by increasing X-coordinate of the intersection
  - For each new scanline Y
    - Update X coordinate of intersection for active edges
    - Insert edges from the ET into the AET that become active, i.e. for which $Y_{MIN} = Y$
    - Remove edges from the AET that are no longer active, i.e. for which $Y_{MAX} = Y$
    - Resort AET
    - Compute starting and ending coordinates for spans defined by the active edges
    - Fill in pixel spans

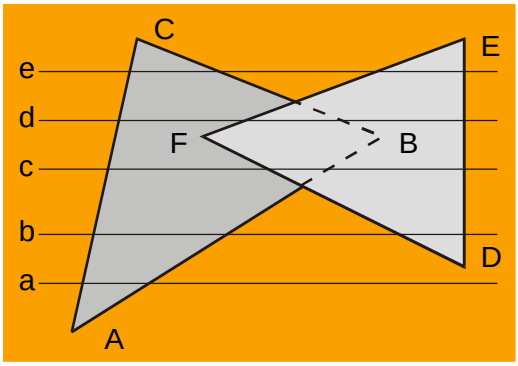
Scanline Algorithm Extension to Multiple Polygons (1)

- **In addition to the pixels covered by the individual polygons, the visible polgyons must be determined**
  - If polygons do not penetrate, visibility changes only at edges
  - For example, scanline (c)



Scanline Algorithm
Extension to Multiple Polygons (2)

- **Edge table ET is refined:**
  - Bucket sort edges by Y_{MIN}
  - Within each bucket, sort edges by slope
  - For each edge store $X(Y_{MIN})$, Y_{MAX}, dX/dY, polygon id
- **Active Edge Table AET remains:**
  - Edges are sorted by X of intersections with current scanline



Scanline Algorithm
Extension to Multiple Polygons (3)

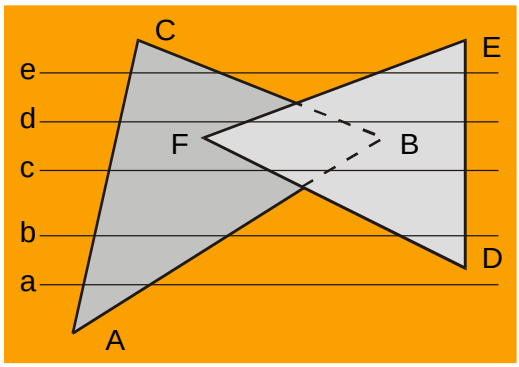
- **In addition to ET and AET, we also maintain a polygon table PT**
  - Geometric information, e.g. the plane equation
  - Attribute information
  - In/Out flag, initialized at leftmost pixel
  - Geometric and attribute data is read-only during scan conversion
  - Only the In/Out flag changes during scan conversion

Scanline Algorithm
Extension to Multiple Polygons (4)

- **Basic Algorithm**
  - Once the scanline enters a polygon, the respective In/Out flag is set
  - The algorithm keeps track of the number of set flags, e.g. by maintaining a list of active polygons (APT)
  - If at least one flag is set when the scanline enters a polygon, visibility of the new span is evaluated
  - Otherwise, the new span is visible
- **Visibility Determination**
  - Determine starting point of new span
    - x: edge-scanline intersection, y: current scanline
  - Evaluate plane equation for all active polygons (In/Out flag !)
  - The polygon with the closest z value is visible in the current span

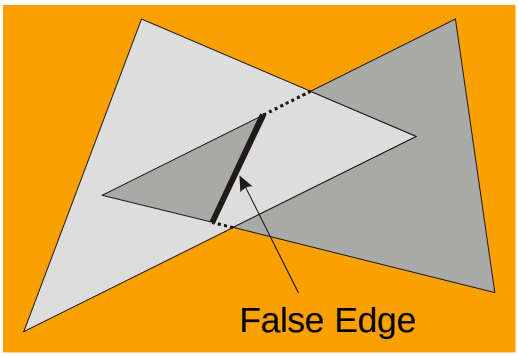
Scanline Algorithm
Extension to Multiple Polygons (5)

- **Example**
  - Scanline a:
    AET = {AC, AB}
  - Scanline b:
    AET = {AC, AB, DF, DE}
  - Scanline c:
    AET = {AC, DF, AB, DE}
    - Compute visibility when entering right triangle (both triangle active)
  - Scanline d:
    AET = {AC, FE, BC, DE}
    - Compute visibility when entering right triangle (both triangles active)
  - Scanline e:
    AET = {AC, BC, FE, DE}



Scanline Algorithm: Special Cases

- **Background color**
  - Pixels without any polgygons need to be set, too
  - Initialize the frame buffer before scan conversion
  - Or place a screen-sized rectangle behind all objects
- **Penetrating polygons**
  - If objects penetrate, visibility changes not only at edges
  - Either split objects to avoid piercing
  - Or calculate a "false edge" where visibility may change



Scanline Algorithm Combining with Z-Buffer

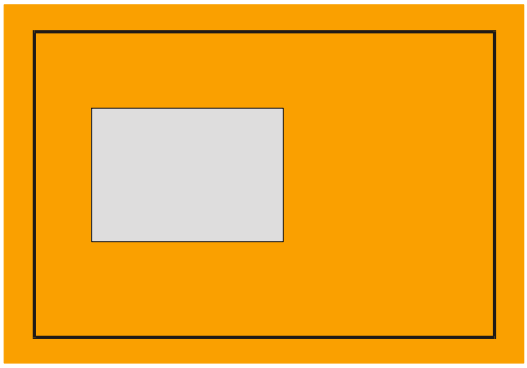
- **Keeping track of visibility changes by monitoring active edges and polygons can be avoided**
  - Allocated a z-buffer for one scanline
  - For all active polygons generate pixel color and pixel depth using the standard scanline scan-conversion algorithm
  - Resolve visibility using z-buffer algorithm
- **Advantage**
  - Only small z-buffer must be allocated
  - Allows implementation for very high screen resolution
- **Drawback**
  - Still requires sorting of polygons into edge tables

Depth-Sorting Algorithm: Painter's Algorithm (1)

- **Painter's Algorithm**
  - Construct the image back-to-front
  - Objects closer to the viewer overwrite more distant objects
  - No depth comparison required during the scan-conversion stage
  - Assumes that objects can be sorted (no overlaps or intersections)
  - Special case: 2 1/2 D Rendering
    - Objects are thought of as belonging to layers with constant z (or priority)
    - Back-to-Front rendering is no simple

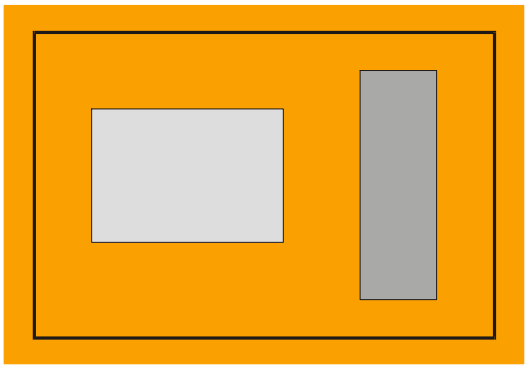
Depth-Sorting Algorithm: Painter's Algorithm (2a)

- **Painter's Algorithm: Example**



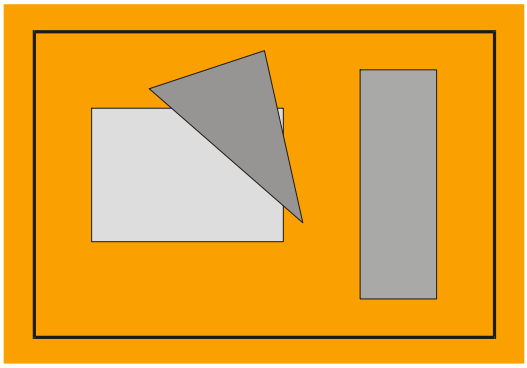
Depth-Sorting Algorithm: Painter's Algorithm (2b)

- Painter's Algorithm: Example



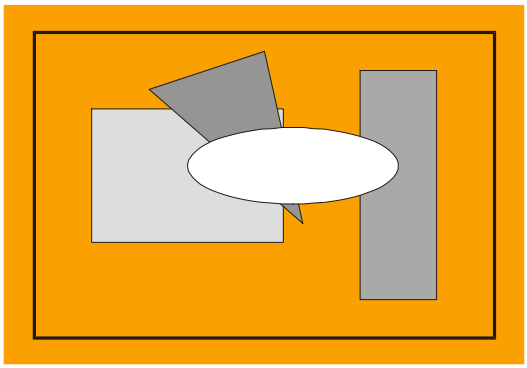
Depth-Sorting Algorithm: Painter's Algorithm (2c)

- Painter's Algorithm: Example



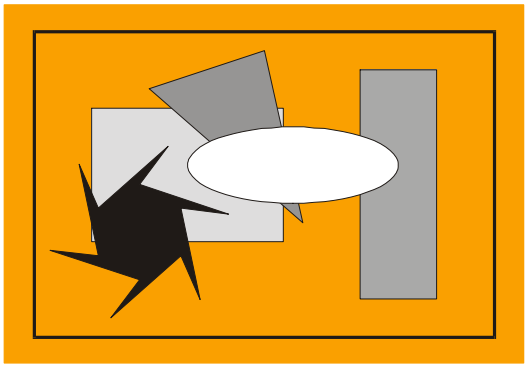
Depth-Sorting Algorithm: Painter's Algorithm (2d)

- Painter's Algorithm: Example



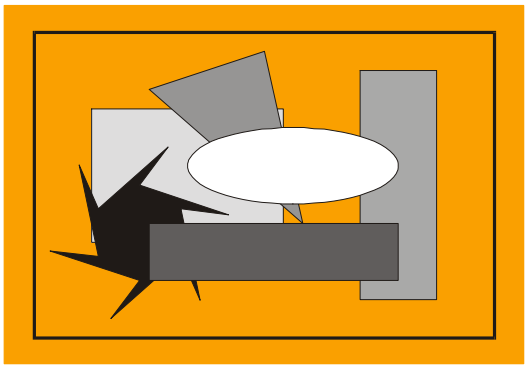
Depth-Sorting Algorithm: Painter's Algorithm (2e)

- Painter's Algorithm: Example



Depth-Sorting Algorithm: Painter's Algorithm (2f)

- **Painter's Algorithm: Example**



Depth Sorting Algorithm (1)

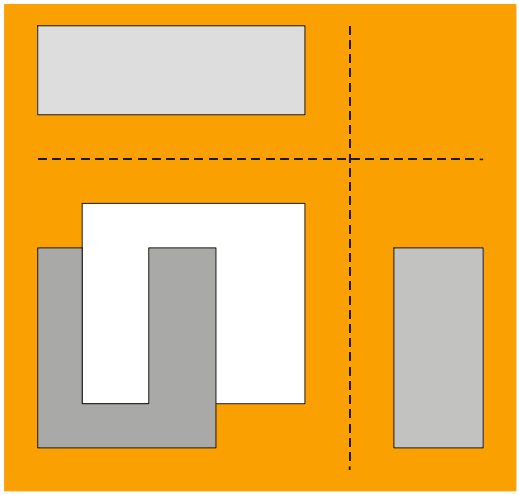
- **How can we ensure that objects are sorted in depth ?**
- **What happens if there is no z-ordering ?**

- **Algorithm by Newell, Newell and Sancha**
  - 1. Sort polygons by farthest z coordinate
    2. Resolve ambiguities in depth sorting
    3. Render polygons back to front

  - Without step 2, the algorithm defaults to the painter's algorithm
  - We will now look at various criteria to implement step 2
  - The ambiguity is resolved as soon as one of the criteria is met

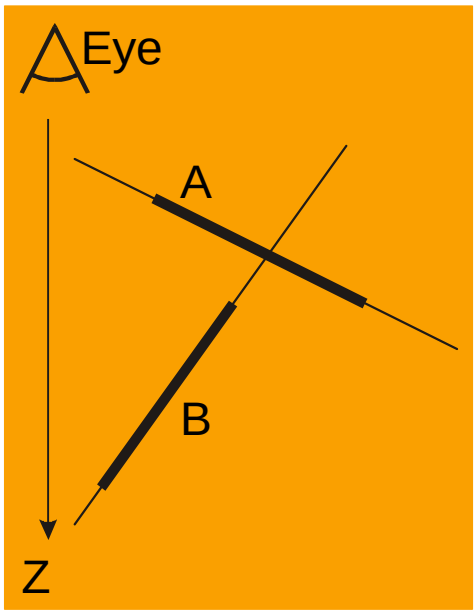
Depth Sorting Algorithm (2)

- **Criterion 1: Overlapping extents**
  - Do polygons overlap in X
  - Do polygons overlap in Y



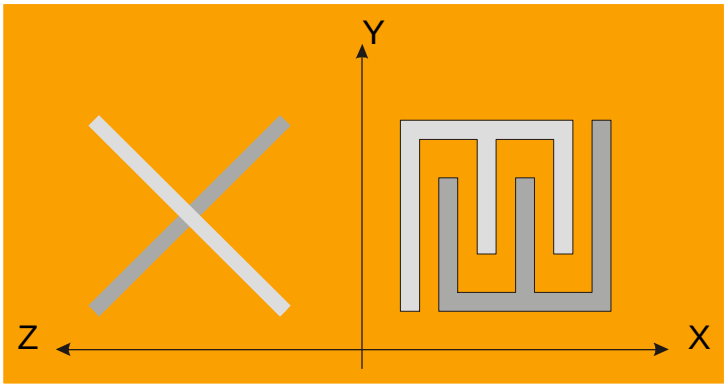
Depth Sorting Algorithm (3)

- **Criterion 2: Separating plane**
  - Is one polygon entirely on one side of the other polygon's plane (here: B)
  - Draw that polygon first if the eye is on the same side, otherwise draw the separating polygon first (here: A then B)



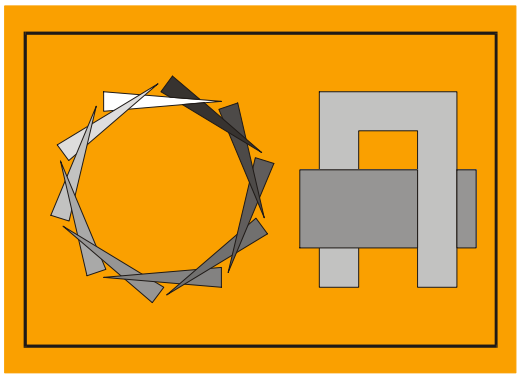
Depth-Sorting Algorithm (4)

- **Criterion 3: Overlapping projections**
  - Do the projections of the polygons overlap ?
  - If no overlap, the order of drawing is not important.



Depth-Sorting Algorithm (5)

- **What if these criteria do not resolve the visibility?**
  - Objects must be split to break the cyclical occlusion realtionship
  - Split occurs by the clipping one polygon against the plane of the other polygon
  - In order to avoid infinite loops (right example), polygons are marked as tested.
  - If a marked polygon is encountered, it is split.



Visibility Algorithms: Sorting

- **By now it should be clear that visibility determination is a sorting process**
  - One of the seminal papers in Computer Graphics classifies different hidden surface algorithms by when they sort objects
    - Sutherland, Sproull, Schumacker, "A Characterization of Ten Hidden-Surface Algorithms", ACM Computing Surveys, 6(1), March 1974, pp. 1-55.
- **Z-Buffer: Sorts in image space**
  - By Z in every pixel
- **Scanline algorithms: Sorts in image space**
  - First Y, then X, then Z
- **Depth-Sort algorithm: Sorts in object space**
  - First Z, then (if necessary) X and Y

Summary

- **Fragment Processing**
  - Texture Mapping
  - Alpha Blending
  - Z-Buffer
- **Visibility and Hidden-Surface Removal**
  - Z-Buffer
  - Scanline algorithm
  - Depth-sorting (painter's algorithm)

Homework

- **Read Foley et al. on Anti-aliasing**
  - Chapter 3.17
  - Chapter 14.10 for more detailed discussion
- **Familiarize yourself with VRML 2.0**
  - Specification at www.vrml.org/Specifications/VRML97
  - Read chapters 4+5, skim over 6

Next Week ...

- **Anti-aliasing**
  - Gentle introduction to sampling theory
  - Area sampling
  - Oversampling
  - Use of alpha-channel for anti-aliasing
- **VRML**
  - Introduction to scene graph concepts
  - Attributes
  - Most important node types