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CPT205 Computer Graphics

Hidden-Surface Removal

Lecture 12
2022-23

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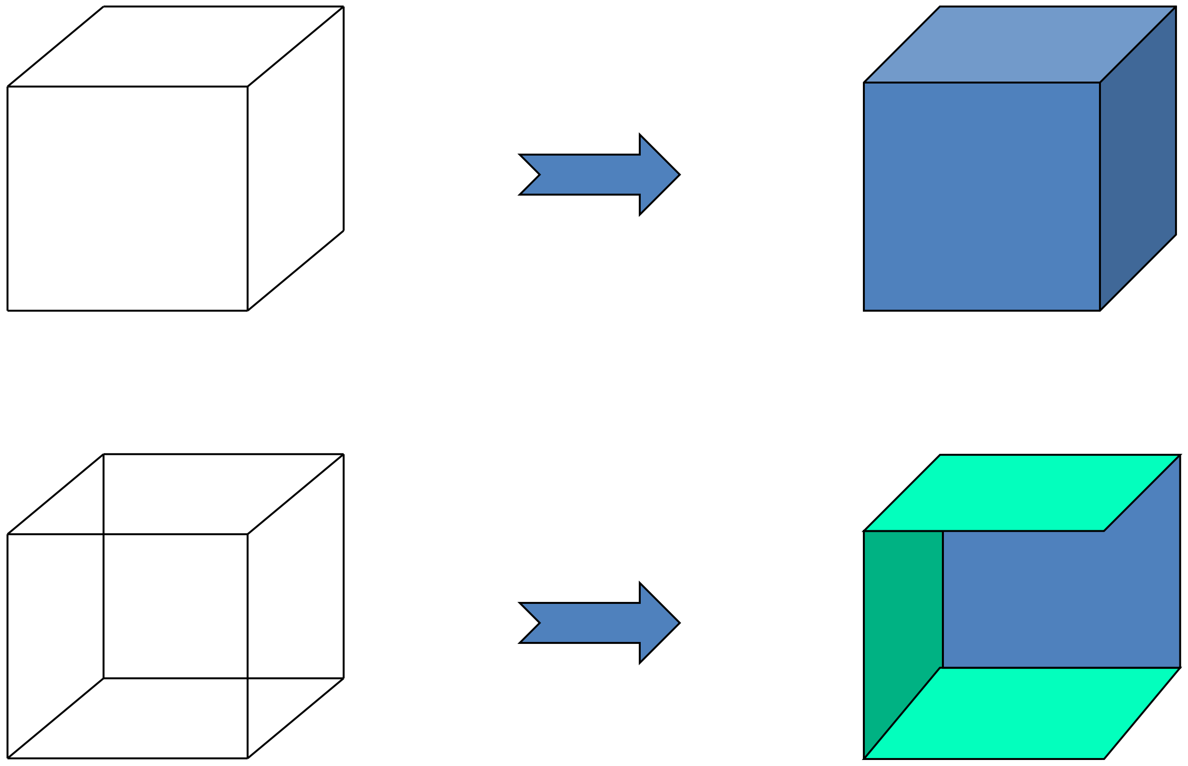
Topics for today

- **Concepts**
  - What is hidden-surface removal?
  - Why is hidden-surface removal important?
- **Hidden-surface removal algorithms**
  - Object space vs image space
  - Painter’s algorithm
  - Back-face culling
  - Z-buffer
  - BSP tree
- **Hidden-surface removal in OpenGL**

Clipping and hidden-surface removal

- Clipping has much in common with hidden-surface removal.
- In both cases, we try to remove objects that are not visible to the camera.
- Often we can use visibility or occlusion testing early in the process to eliminate as many polygons as possible before going through the entire pipeline.

Concepts (1)



Concepts (2)

- Display all visible surfaces, and do not display any occluded surfaces.

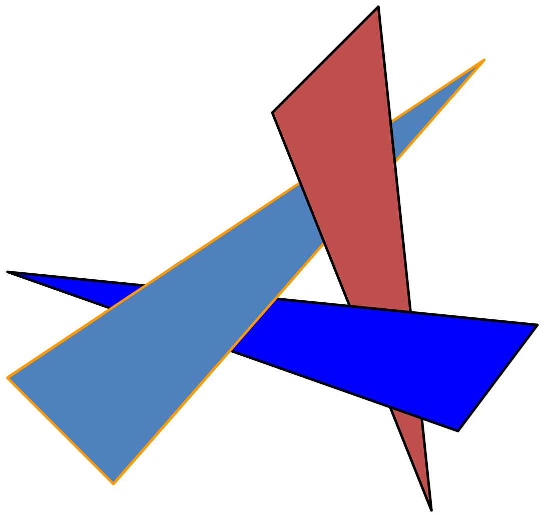
- Other names
  - Visible-surface detection
  - Hidden-surface elimination

- Determine which surfaces are visible and which are not.
  - Z-buffer is just one of hidden-surface removal algorithms.

- We can categorise into
  - Object-space methods
  - Image-space methods

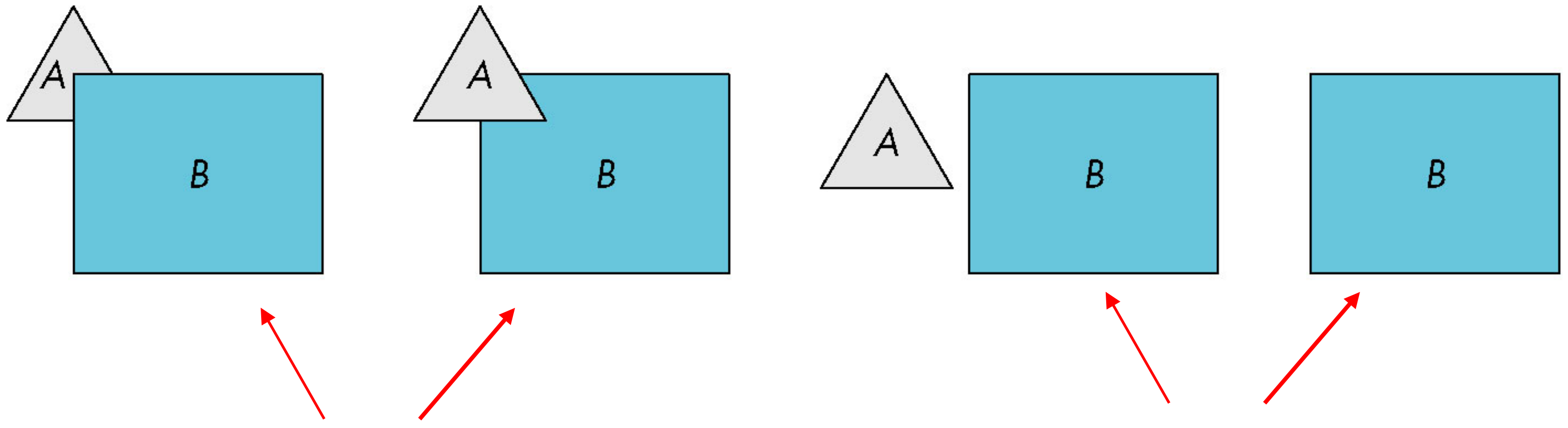
Concepts (3)

- Object space algorithms: determine which objects are in front of others
  - Resize does not require recalculation;
  - Works for static scenes;
  - May be difficult / impossible to determine.
- Image space algorithms: determine which object is visible at each pixel
  - Resize requires recalculation;
  - Works for dynamic scenes.



Object-space approach

- It uses pairwise testing between polygons (objects).



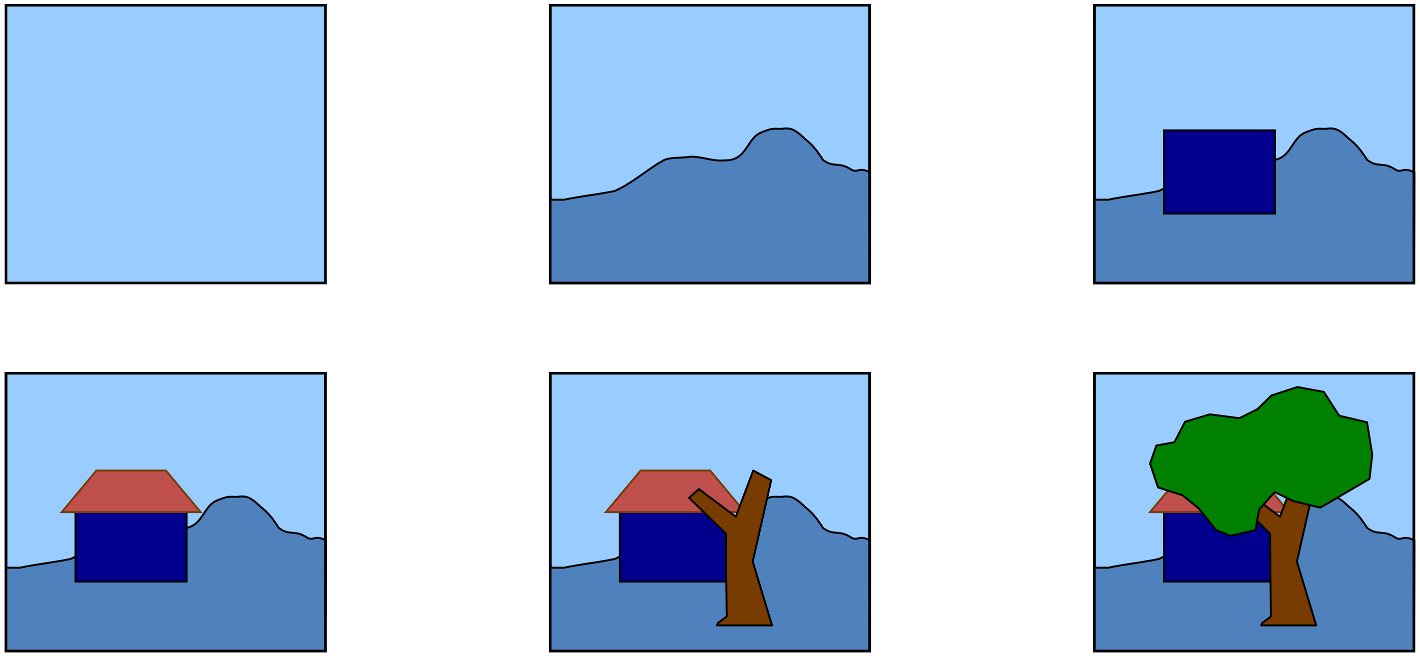
Partially obscuring

Can draw independently

- Worst case complexity $O(n^2)$ for n polygons.

Painter’s algorithm

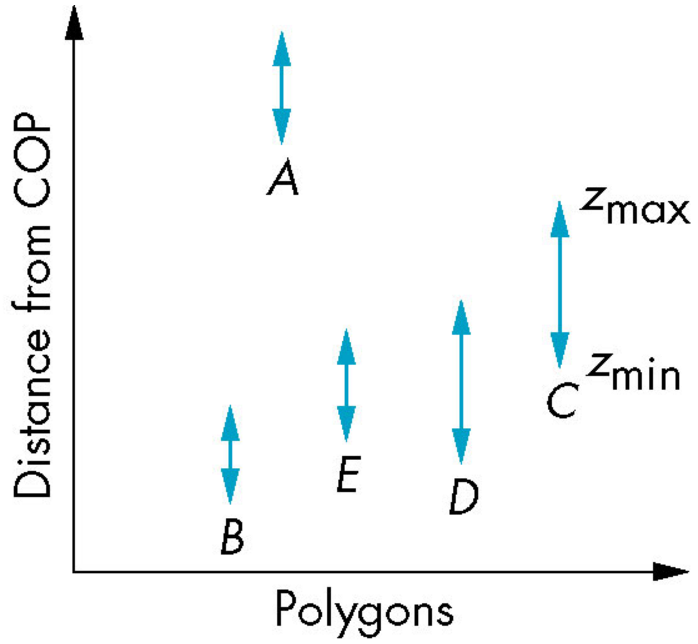
- It is an object-space algorithm.
- Render polygons in the back to front order so that polygons behind others are simply painted over.
- Sort surfaces/polygons by their depth (*z* value).



Painter's algorithm: Depth sort

- Requires ordering of polygons first
  - O(n log n) calculations for ordering
  - Not every polygon is either in front or behind all other polygons

- Orders polygons and deals with easy cases first and harder later.

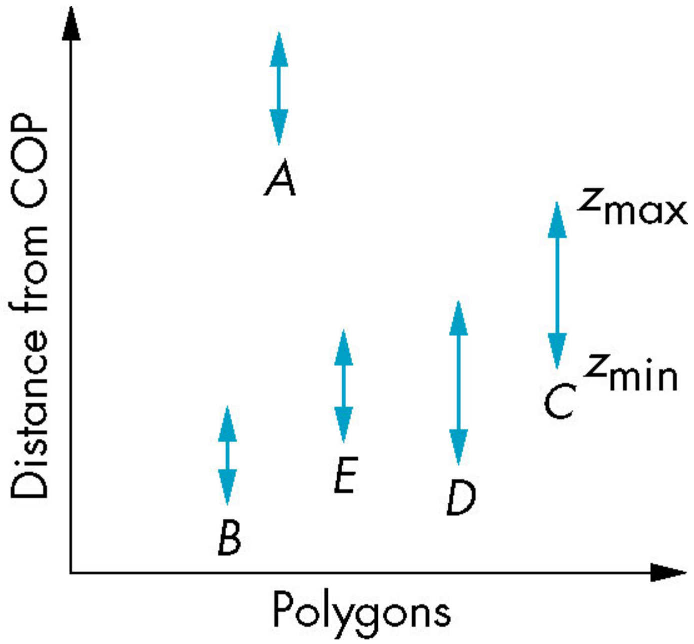


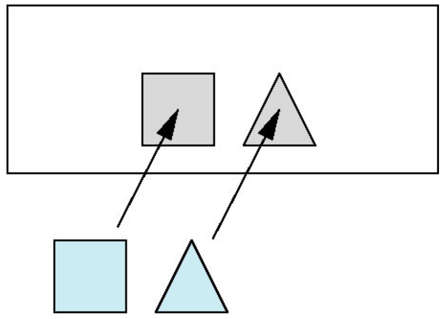
Polygons sorted by distance from Centre Of Projection (COP)

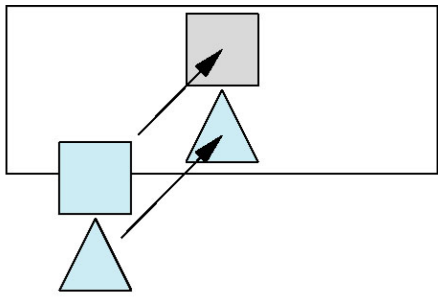
Painter's algorithm: Easy cases

- Polygon A lies entirely behind all other polygons, and can be painted first.

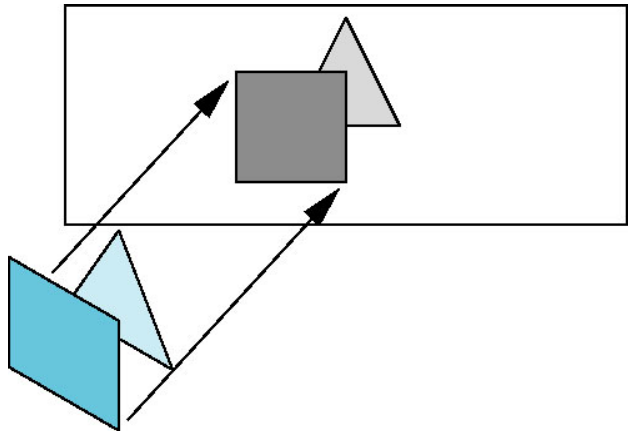
- Polygons which overlap in *z* but not in either *x* or *y*, can be painted independently.



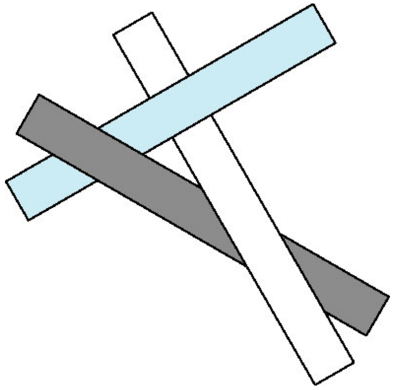

Test of overlap in *x*


Test of overlap in *y*

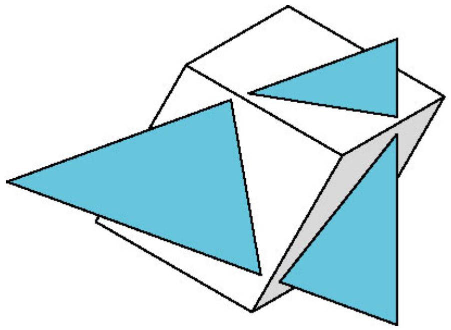
Painter’s algorithm: Hard cases



Overlap in all directions
(polygons with
overlapping projections)



Cyclic overlap



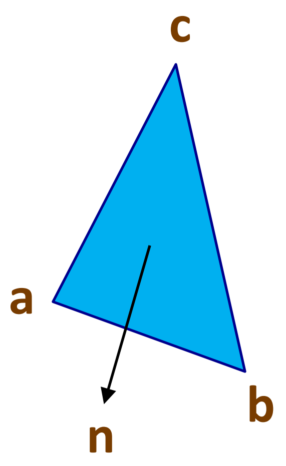
Penetration

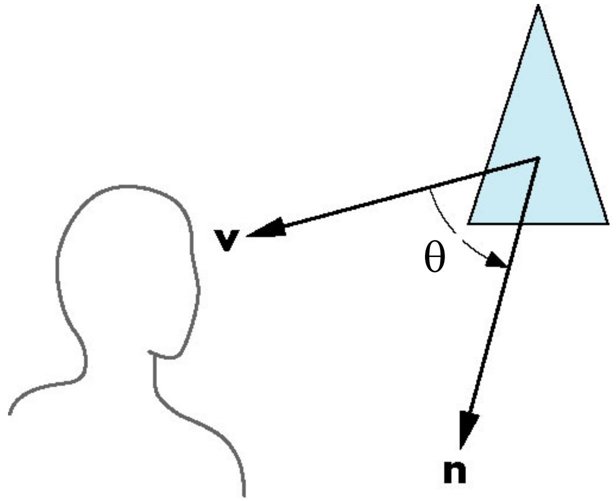
Back-face culling (1)

- Back-face culling is the process of comparing the position and orientation of polygons against the viewing direction **v**, with polygons facing away from the camera eliminated.
- This elimination minimises the amount of computational overhead involved in hidden-surface removal.
- Back-face culling is basically a test for determining the visibility of a polygon, and based on this test the polygon can be removed if not visible – also called back-surface removal.

Back-face culling (2)

- Assumes the object is a solid polyhedron.
- Compute polygon normal **n**:
  - Assume a counter-clockwise vertex order
  - For a triangle (**abc**): **n** = (**ab**) × (**bc**)
- If 90°≥ θ ≥ -90°, i.e. **v•n** ≥ 0, the polygon is a visible face.
- Furthermore, if the object descriptions are converted to projection co-ordinates and the viewing direction is parallel to the viewing z_v axis, i.e. **n** = $(0,0,1,1)^T$, only the sign of the *z* component of **n** is tested.

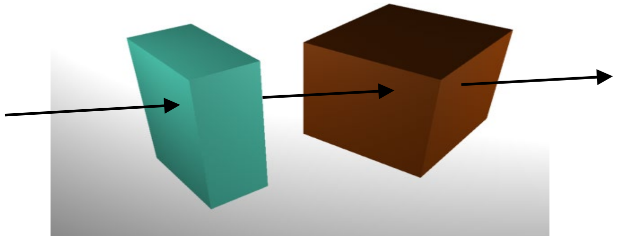


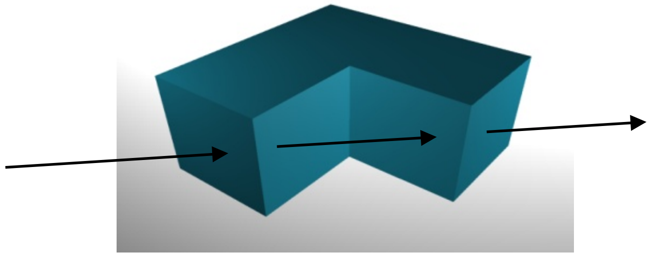


Back-face culling (3)

For each polygon P_i

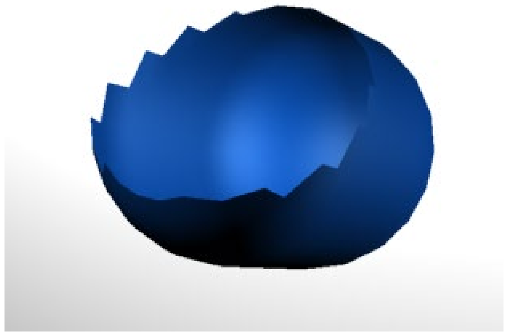
- ➢ Find polygon normal **n**
- ➢ Find viewer direction **v**
- ➢ IF **v•n** < 0
  Then CULL P_i



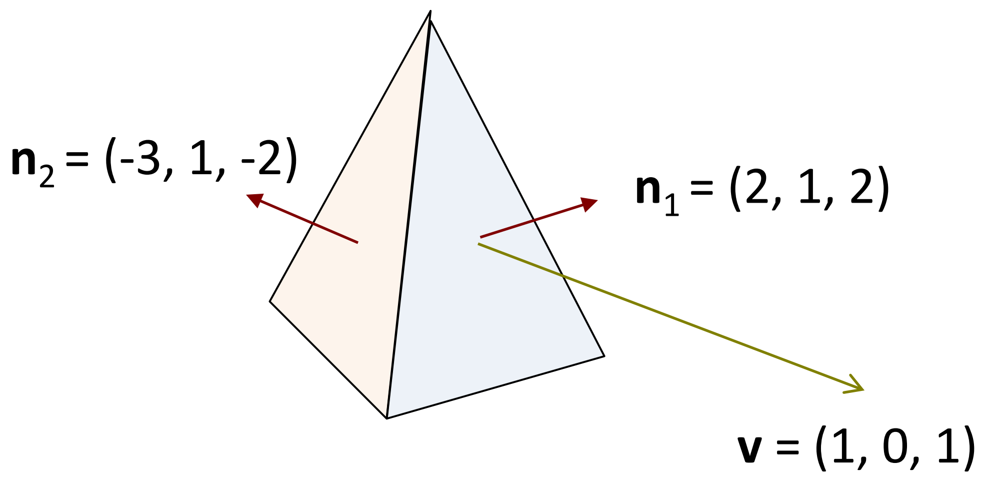


Back-face culling does not work for:

- ➢ Overlapping front faces due to
  - Multiple objects
  - Concave objects
- ➢ Non-polygonal models
- ➢ Non-closed Objects



Back-face culling: Example

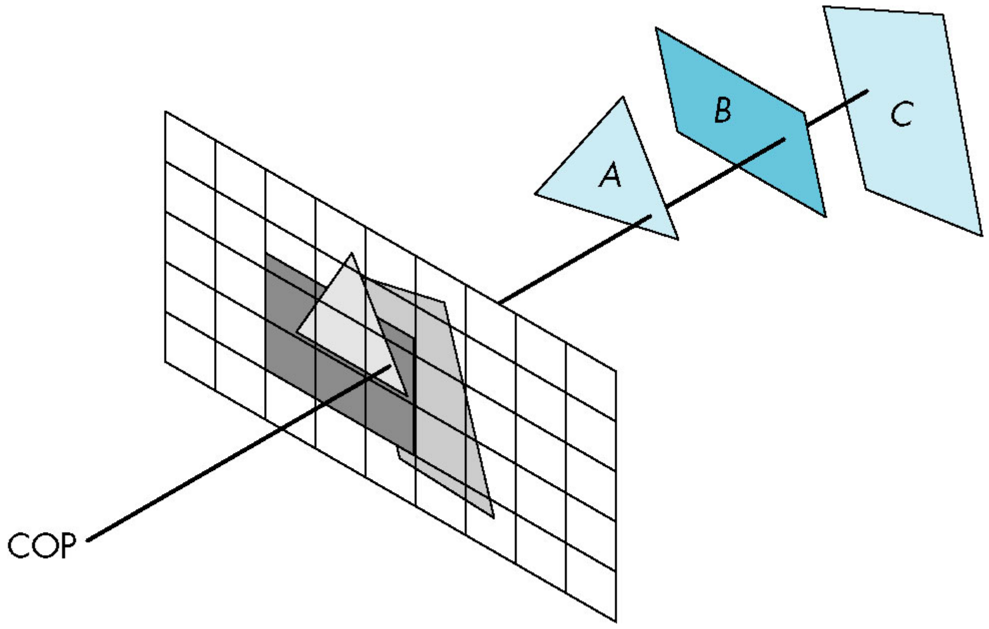


$\mathbf{n}_1 \cdot \mathbf{v} = (2, 1, 2) \cdot (1, 0, 1)$
$= 2 + 0 + 2 = 4,$
i.e. $\mathbf{n}_1 \cdot \mathbf{v} > 0$
so face$_1$ is a front facing polygon.

$\mathbf{n}_2 \cdot \mathbf{v} = (-3, 1, -2) \cdot (1, 0, 1)$
$= -3 + 0 - 2 = -5$
i.e. $\mathbf{n}_2 \cdot \mathbf{v} < 0$
so face$_2$ is a back facing polygon.

Image space approach

- Look at each projector (n*m projectors for an n*m framebuffer) and find the closest among k polygons
- Complexity O(nmk)
- Ray tracing
- Z-buffer



Z-buffer (1)

- We now know which pixels contain which objects; however since some pixels may contain two or more objects, we must calculate which of these objects are visible and which are hidden.
- In graphics hardware, hidden-surface removal is generally accomplished using the Z-buffer algorithm.

Z-buffer (2)

- In this algorithm, we set aside a two-dimensional array of memory (the Z-buffer) of the same size as the screen (number of rows * number of columns).
- This is in addition to the colour buffer (frame buffer) which we will use to store the colour values of pixels to be displayed.
- The Z-buffer will hold values which are depths (quite often z-values).
- The Z-buffer is initialised so that each element has the value of the far clipping plane (the largest possible z-value after clipping is performed).
- The colour buffer is initialised so that each element contains a value which is the background colour.

Z-buffer (3)

- Now for each polygon, we have a set of pixel values which the polygon covers.
- For each of the pixels, we compare its depth (z-value) with the value of the corresponding element already stored in the Z-buffer:
  - If this value is less than the previously stored value, the pixel is nearer the viewer than the previously encountered pixel;
  - Replace the value of the Z- buffer with the z value of the current pixel, and replace the value of the colour buffer with the value of the current pixel.
- Repeat for all polygons in the image.
- The implementation is typically done in normalised co-ordinates so that depth values range from 0 at the near clipping plane to 1.0 at the far clipping plane.

Z-buffer (4)

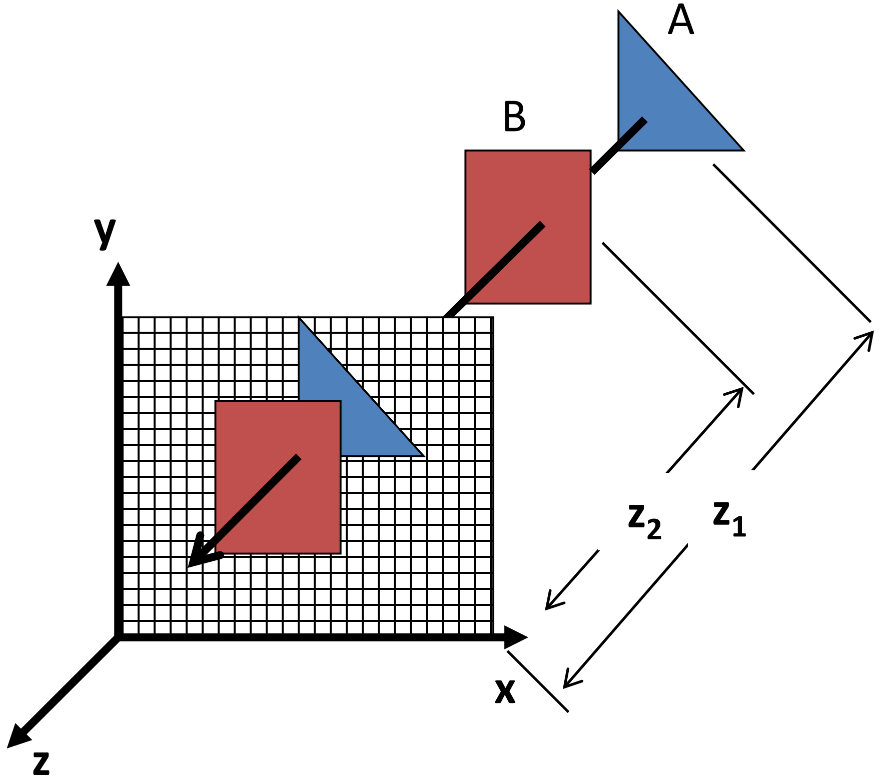
1. Initialise all *depth(x,y)* to 1.0 and *refresh(x,y)* to background colour

2. For each pixel

```
Get current value for depth(x,y)
Evaluate depth value z

If(z > depth(x,y))
{
    depth(x,y) = z
    refresh(x,y) = $I_s(x,y)$
}
```

Calculate this using relevant algorithms /illumination/fill colour/texture



Z-buffer (5)

Advantages

- The most widely used hidden-surface removal algorithm;
- Relatively easy to implement in hardware or software;
- An image-space algorithm which traverses scene and operates per polygon rather than per pixel;
- We rasterize polygon by polygon and determine which (part of) polygons get drawn on the screen.

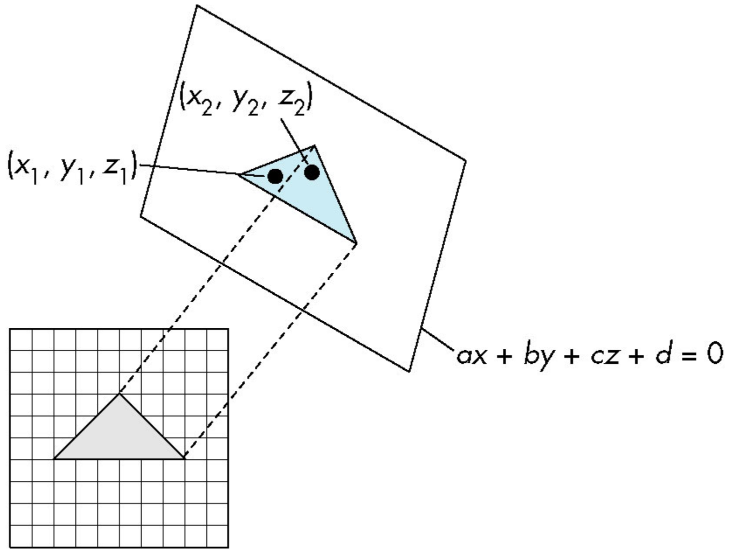
Memory requirements

- Relies on a secondary buffer called the Z-buffer or depth buffer;
- Z-buffer has the same width and height as the framebuffer;
- Each cell contains the z-value (distance from viewer) of the object at that pixel position.

Scan-line

If we work scan line by scan line as we move across a scan line, the depth changes satisfy $a\Delta x + b\Delta y + c\Delta z = 0$, noticing that the plane which contains the polygon is represented by
$ax + by + cz + d = 0$

Along scan line
$\Delta y = 0$
$\Delta z = -(a/c)*\Delta x$
In screen space $\Delta x = 1$
Only computed once per polygon.



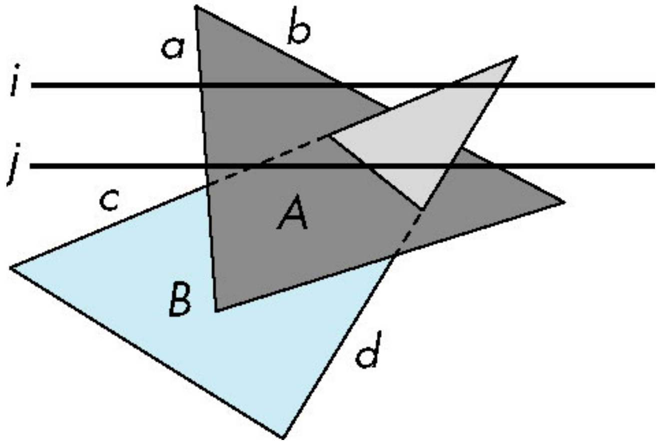
- ➢ Worst-case performance of an image-space algorithm is proportional to the number of primitives;
- ➢ Performance of z-buffer is proportional to the number of fragments generated by rasterization, which depends on the area of the rasterized polygons.

Scan-line algorithm

We can combine shading and hidden-surface removal through scan line algorithm.

Scan line i: no need for depth information, can only be in no or one polygon.

Scan line j: need depth information only when in more than one polygon.



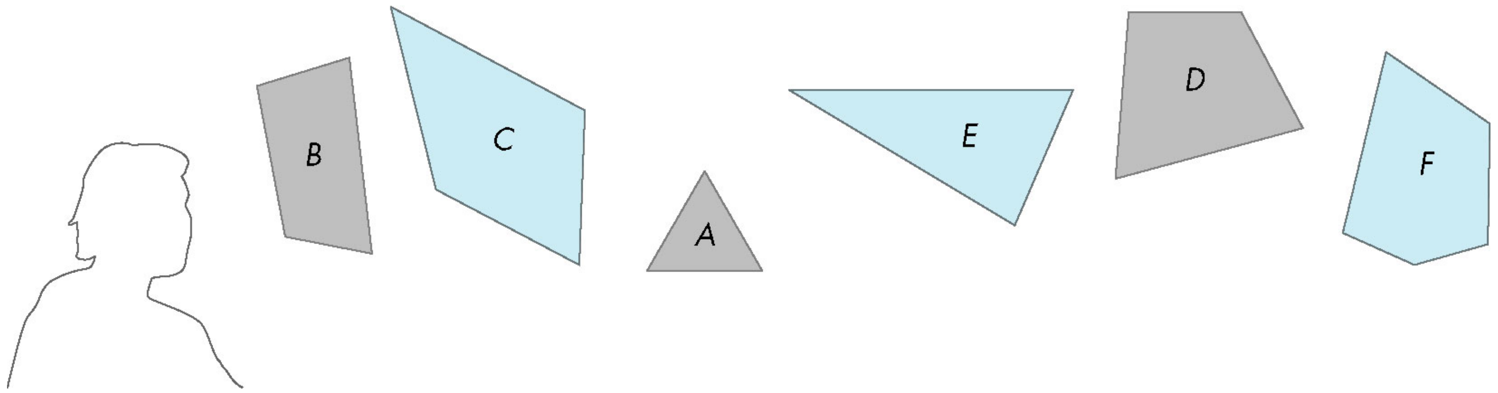
Scan-line algorithm: implementation

Need a data structure to store

- Flag for each polygon (inside/outside)
- Incremental structure for scan lines that stores which edges are encountered
- Parameters for planes

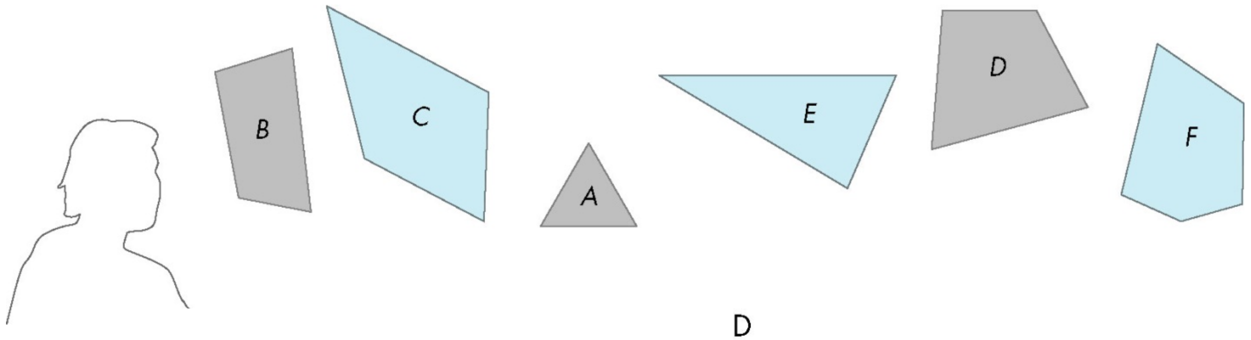
BSP tree (1)

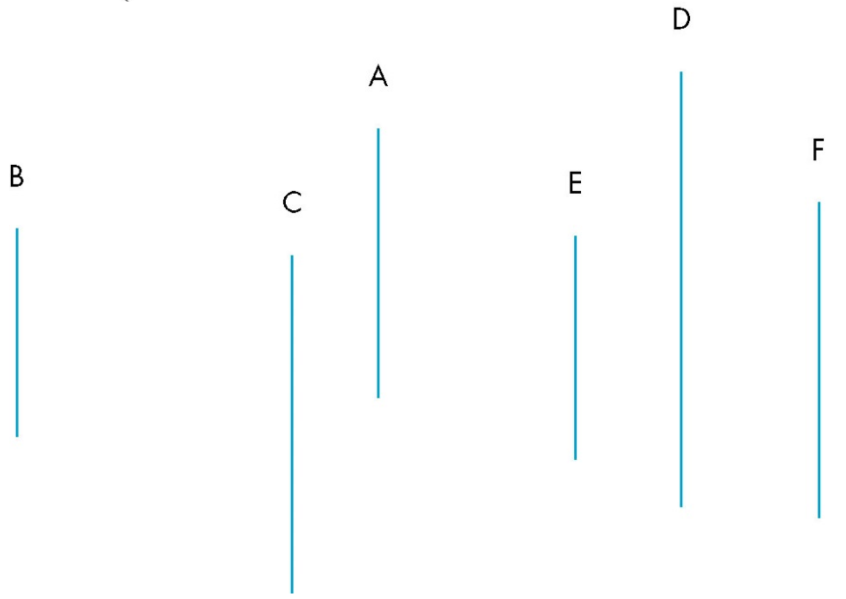
- In many real-time applications, such as games, we want to eliminate as many objects as possible within the application so that we can
  - reduce burden on pipeline
  - reduce traffic on bus
- Partition space with Binary Spatial Partition (BSP) Tree



BSP tree (2)

Consider 6 parallel planes. Plane A separates planes B and C from planes D, E and F.

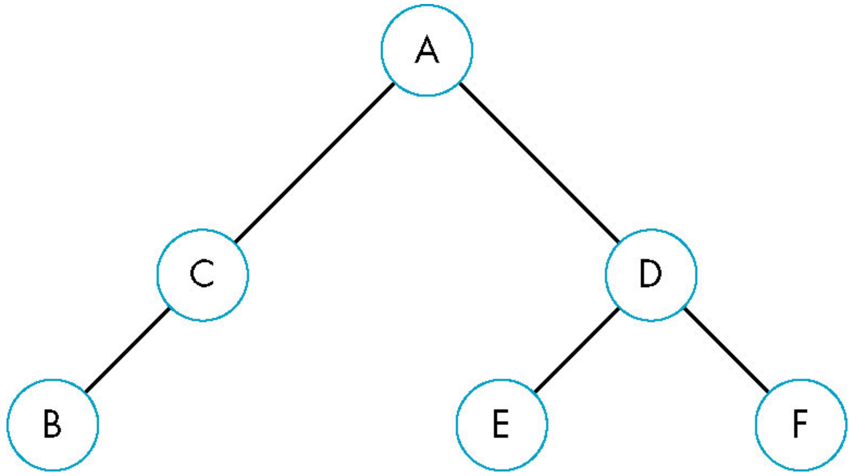




Top view

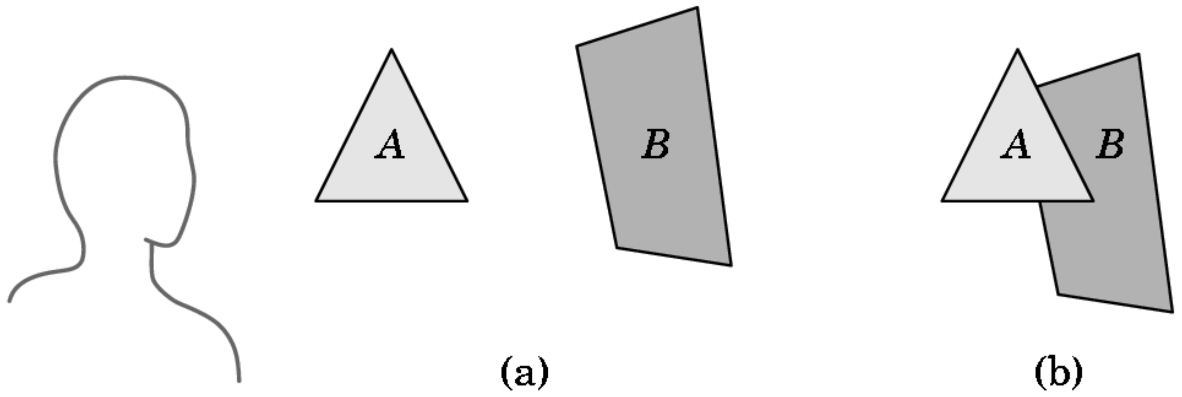
BSP tree (3)

- We can continue recursively
  - plane C separates B from A
  - plane D separates E and F
- We can put this information in a BSP tree
  - use the BSP tree for visibility and occlusion testing



BSP tree

- The *painter's algorithm* for hidden-surface removal works by drawing all faces, from back to front.
- How can we get a listing of the faces in the back-to-front order?
- Put them into a binary tree and traverse the tree, but in what order?



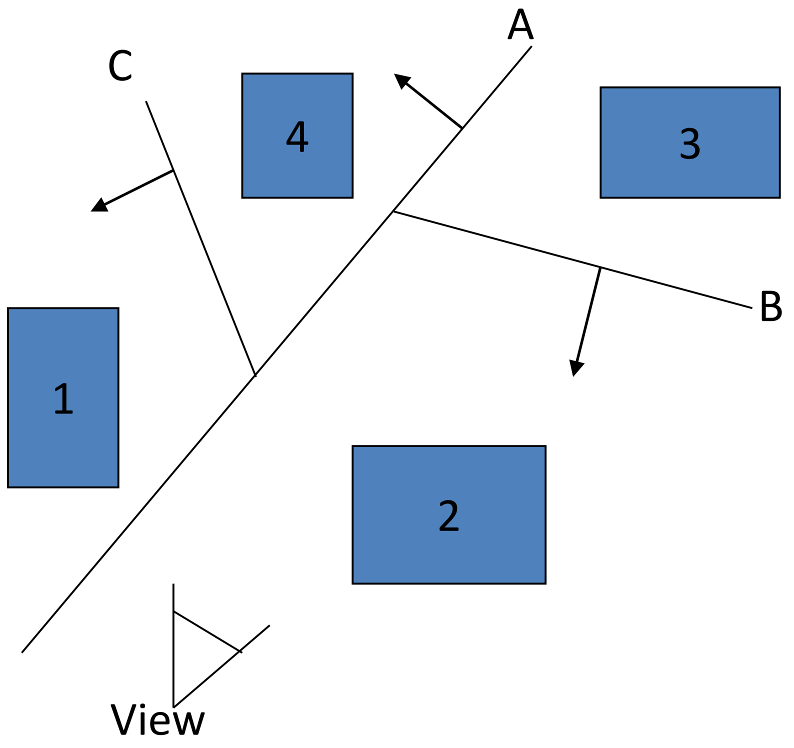
BSP tree

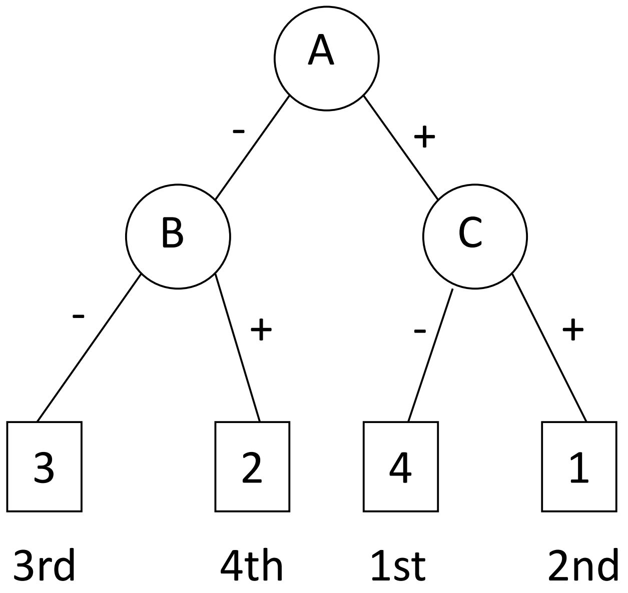
- Choose polygon (arbitrary)
- Split the cell using the plane on which the polygon lies
  - May have to chop polygons in two (clipping!)
- Continue until each cell contains only one polygon fragment
- Splitting planes could be chosen in other ways, but there is no efficient optimal algorithm for building BSP trees
  - BSP trees are not unique – there can be a number of alternatives for the same set of polygons
  - Optimal means minimum number of polygon fragments in a balanced tree

BSP tree: Rendering

- Observation: things on the opposite side of a splitting plane from the viewpoint cannot obscure things on the same side as the viewpoint.
- The rendering is recursive descent of the BSP tree.
- At each node (for back to front rendering):
  - Recurse down the side of the sub-tree that does not contain the viewpoint
    - Test viewpoint against the split plane to decide the polygon
  - Draw the polygon in the splitting plane
    - Paint over whatever has already been drawn
  - Recurse down the side of the tree containing the viewpoint

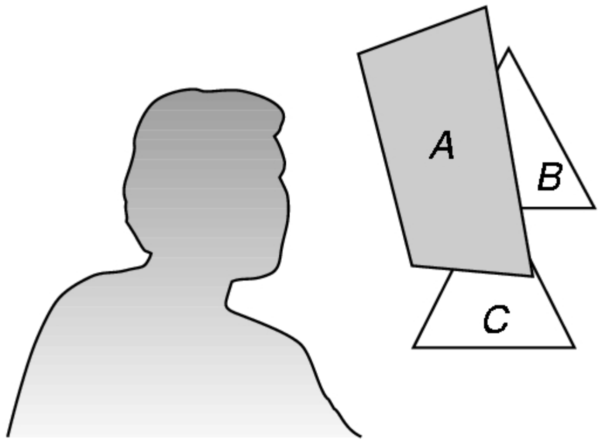
BSP tree: Rendering example





OpenGL functions for hidden-surface removal

- How is hidden-surface removal done in OpenGL?
- OpenGL uses the *z*-buffer algorithm that saves depth information as objects/triangles are rendered so that only the front objects appear in the image.



OpenGL Z-buffer functions

- The algorithm uses an extra buffer, the z-buffer, to store depth information as geometry travels down the pipeline.
- It must be
  - requested in `main.c`

    ```
    glutInitDisplayMode(GLUT_SINGLE |
                 GLUT_RGB | GLUT_DEPTH)
    ```
  - enabled in `init.c`

    ```
    glEnable(GL_DEPTH_TEST)
    ```
  - cleared in the display callback

    ```
    glClear(GL_COLOR_BUFFER_BIT |
                 GL_DEPTH_BUFFER_BIT)
    ```

OpenGL functions (1)

- OpenGL basic library provides functions for back-face removal and depth-buffer visibility testing.
- In addition, there are hidden-line removal functions for wireframe display, and scenes can be displayed with depth cueing.

OpenGL functions (2)

Face-culling functions - Back-face removal (or back-face culling) is accomplished with the functions

```
glEnable(GL_CULL_FACE);
glCullFace(GLenum);
```

- The parameter mode includes GL_BACK, GL_FRONT and GL_FRONT_AND_BACK. So front faces can be removed instead of back faces, or both front and back faces can be removed.
- The default value for `glCullFace()` is GL_BACK. Therefore, if `glEnable(GL_CULL_FACE)` is called to enable face culling without explicitly calling `glCullFace()`, back faces in the scene will be removed.

OpenGL functions (3)

Depth-buffer functions

- The first function is about the GLUT initialisation

```
glutInitDisplayMode(GLUT_SINGLE | GLUT_RGB |
                    GLUT_DEPTH);
```

- Depth buffer can then be initialised

```
glClear(GL_DEPTH_BUFFER_BIT);
```

- The depth-buffer visibility detection routines are activated / deactivated with

```
glEnable(GL_DEPTH_TEST);
glDisable(GL_DEPTH_TEST);
```

OpenGL functions (4)

- The depth values are normalised in the range [0.0, 1.0]. But to speed up the surface processing, a maximum depth value, maxDepth, can be specified between 0.0 and 1.0

```
glClearDepth(maxDepth);
```

- Projection co-ordinates are normalised in the range [-1.0, 1.0], and the depth values between the near and far clipping planes are further normalised in the range [0.0, 1.0] where 0.0 and 1.0 correspond to the near and far clipping planes respectively.

OpenGL functions (5)

- The function below allows adjustment of the clipping planes

```
glDepthRange(nearNormDepth, farNormDepth);
```

  where the default values for the two parameters are 0.0 and 1.0 respectively, and they can have a value in the range of [0.0, 1.0].

- Another function for extra options is

```
glDepthFunc(testCondition);
```

  `testCondistion` can have the following values: GL_LESS (default), GL_GREATER, GL_EQUAL, GL_NOTEQUAL, GL_LEQUAL, GL_GEQUAL, GL_NEVER (no points are processed), and GL_ALWAYS (all points are processed), to reduce calculations based on the application.

OpenGL functions (6)

- The status of the depth buffer can be set to read-only or read-write

```
glDepthMask(writeStatus);
```

- When `writeStatus` = GL_FALSE, the write mode in the depth buffer is disabled and only retrieval of values for comparison is possible.
- It is useful when a complex background is used with display of different foreground objects. After storing the background in the depth buffer, the write mode is disabled for processing the foreground, allowing the generation of a series of frames with different foreground objects or with one object in different positions for an animated sequence. It is also useful in displaying transparent objects.

OpenGL functions (7)

Wireframe surface-visibility functions - A wireframe display of an object can be generated with

```
glPolygonMode(GL_FRONT_AND_BACK, GL_LINE);
```

// In this case, both visible and hidden edges
// are displayed.

Depth-cueing functions - The brightness of an object is varied as a function of its distance to the viewing position

```
glEnable(GL_FOG);
glFog*(GL_FOG_MODE, GL_LINEAR);
```

// linear depth function for colour in [0.0, 1.0])

```
glFog*(GL_FOG_START, minDepth);
```

// specifies a different value for d_{min})

```
glFog*(GL_FOG_END, maxDepth);
```

// specifies a different value for d_{max})

Summary

- Concepts of hidden-surface removal
- Relationships between clipping and hidden-surface removal
- Important techniques for hidden-surface removal
  - Object-space and image-space approaches
  - Painter's algorithms
  - Back-face culling
  - Z-buffering
  - BSP tree
- OpenGL functions

  `glutInitDisplayMode(), glClear(), glClearDepth(maxDepth), glDepthRange(nearNormDepth,farNormDepth); glDepthFunc(testCondition), glDepthMask(writeStatus), glPolygonMode(), glEnable(GL_DEPTH_TEST), glEnable(GL_FOG), glCullFace()`