3D Polygon Rendering Pipeline

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Princeton University
COS 426, Spring 2008

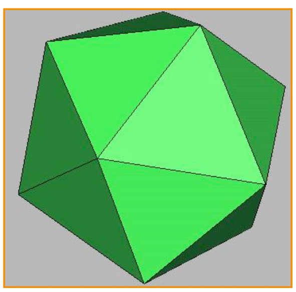
3D Rendering Scenarios

- Batch
  - One image generated with as much quality as possible for a particular set of rendering parameters
    - Take as much time as is needed (minutes)
    - Useful for photorealistism, movies, etc.
- Interactive
  - Images generated in fraction of a second (<1/10) as user controls rendering parameters (e.g., camera)
    - Achieve highest quality possible in given time
    - Useful for visualization, games, etc.


rayview

3D Polygon Rendering

- Many applications use rendering of 3D polygons with direct illumination

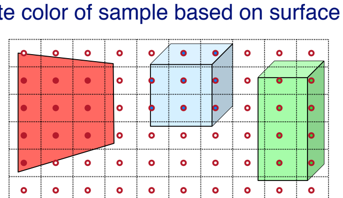


3D Polygon Rendering

- Many applications use rendering of 3D polygons with direct illumination

Ray Casting Revisited

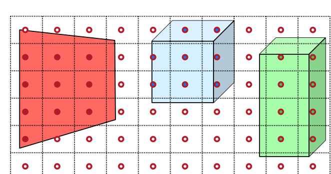
- For each sample …
  - Construct ray from eye position through view plane
  - Find first surface intersected by ray through pixel
  - Compute color of sample based on surface radiance



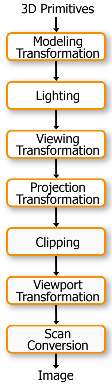
More efficient algorithms utilize spatial coherence!

3D Polygon Rendering

- We can render polygons faster if we take advantage of spatial coherence

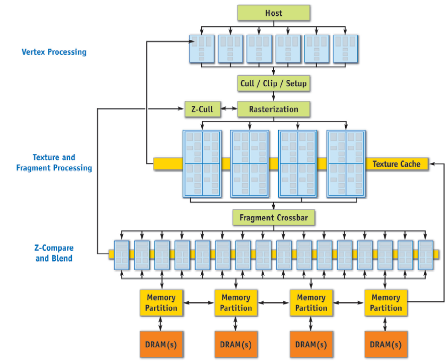


3D Rendering Pipeline (for direct illumination)



This is a pipelined sequence of operations to draw a 3D primitive into a 2D image

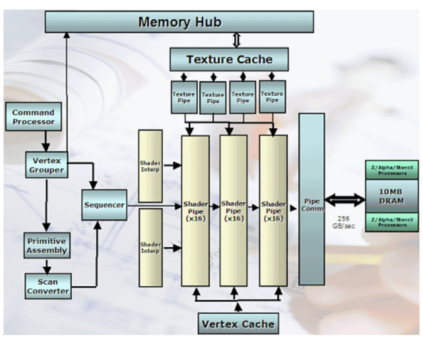
GPU Architecture



GeForce 6 Series Architecture

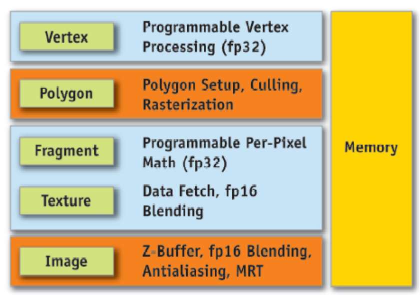
GPU Gems 2, NVIDIA

GPU Architecture



Xbox360, ATI

GPU Architecture



GeForce 6 Series Architecture

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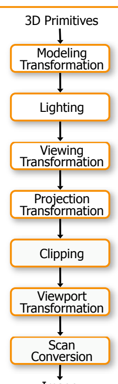
3D Rendering Pipeline (for direct illumination)



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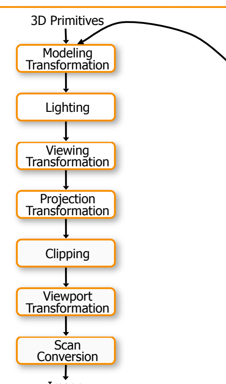
3D Rendering Pipeline (for direct illumination)




```
glBegin(GL_POLYGON);
glVertex3f(0.0, 0.0, 0.0);
glVertex3f(1.0, 0.0, 0.0);
glVertex3f(1.0, 1.0, 1.0);
glVertex3f(0.0, 1.0, 1.0);
glEnd();
```

OpenGL executes steps of 3D rendering pipeline for each polygon

3D Rendering Pipeline (for direct illumination)

3D Primitives	
Modeling Transformation	Transform into 3D world coordinate system
Lighting	
Viewing Transformation	
Projection Transformation	
Clipping	
Viewport Transformation	
Scan Conversion	
Image	

3D Rendering Pipeline (for direct illumination)

3D Primitives	
Modeling Transformation	Transform into 3D world coordinate system
Lighting	Illuminate according to lighting and reflectance
Viewing Transformation	
Projection Transformation	
Clipping	
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Image	

3D Rendering Pipeline (for direct illumination)

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Clipping	Clip primitives outside camera's view
Viewport Transformation	
Scan Conversion	
Image	

3D Rendering Pipeline (for direct illumination)

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3D Rendering Pipeline (for direct illumination)

3D Primitives

- Modeling Transformation — Transform into 3D world coordinate system
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- Scan Conversion — Draw pixels (includes texturing, hidden surface, ...)

Image

3D Rendering Pipeline (for direct illumination)

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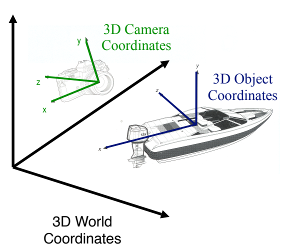
Image

Transformations

p(x,y,z)
- 3D Object Coordinates
- Modeling Transformation
- 3D World Coordinates
- Viewing Transformation
- 3D Camera Coordinates
- Projection Transformation
- 2D Screen Coordinates
- Viewport Transformation
- 2D Image Coordinates

p'(x',y')

Transformations map points from one coordinate system to another



Viewing Transformations

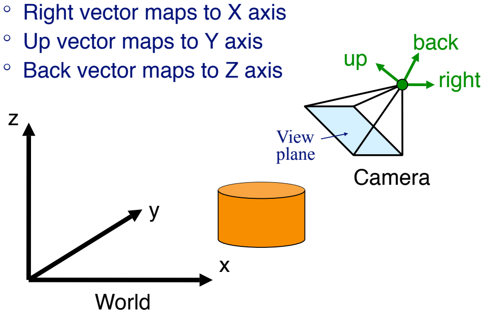
p(x,y,z)
- 3D Object Coordinates
- Modeling Transformation
- 3D World Coordinates
- Viewing Transformation
- 3D Camera Coordinates
- Projection Transformation
- 2D Screen Coordinates
- Viewport Transformation
- 2D Image Coordinates

p'(x',y')

} Viewing Transformations

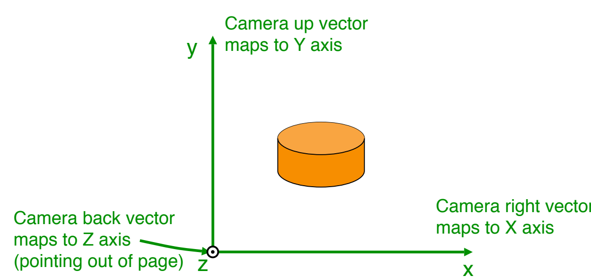
Viewing Transformation

- Mapping from world to camera coordinates
  - Eye position maps to origin
  - Right vector maps to X axis
  - Up vector maps to Y axis
  - Back vector maps to Z axis



Camera Coordinates

- Canonical coordinate system
  - Convention is right-handed (looking down -z axis)
  - Convenient for projection, clipping, etc.



Finding the viewing transformation

- We have the camera (in world coordinates)
- We want T taking objects from world to camera

$$p^C = T\, p^W$$

- Trick: find T^{-1} taking objects in camera to world

$$p^W = T^{-1} p^C$$

$$\begin{bmatrix} x' \\ y' \\ z' \\ w' \end{bmatrix} = \begin{bmatrix} a & b & c & d \\ e & f & g & h \\ i & j & k & l \\ m & n & o & p \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ w \end{bmatrix}$$

?

Finding the Viewing Transformation

- Trick: map from camera coordinates to world
  - Origin maps to eye position
  - Z axis maps to Back vector
  - Y axis maps to Up vector
  - X axis maps to Right vector

$$\begin{bmatrix} x' \\ y' \\ z' \\ w' \end{bmatrix} = \begin{bmatrix} R_x & U_x & B_x & E_x \\ R_y & U_y & B_y & E_y \\ R_z & U_z & B_z & E_z \\ R_w & U_w & B_w & E_w \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ w \end{bmatrix}$$

- This matrix is T^{-1} so we invert it to get T … easy!

Viewing Transformations

p(x,y,z)

3D Object Coordinates

Modeling Transformation

3D World Coordinates

Viewing Transformation

3D Camera Coordinates

Projection Transformation

2D Screen Coordinates

Viewport Transformation

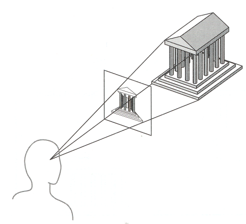
2D Image Coordinates

p'(x',y')

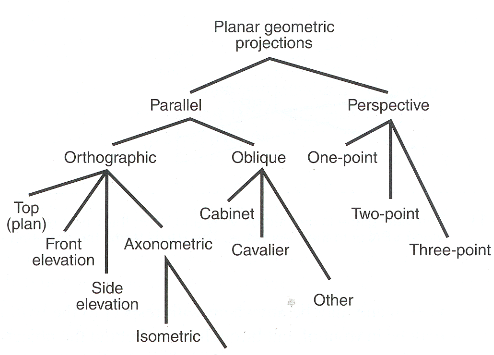
Viewing Transformations

Projection

- General definition:
  - Transform points in *n*-space to *m*-space (*m*<*n*)
- In computer graphics:
  - Map 3D camera coordinates to 2D screen coordinates

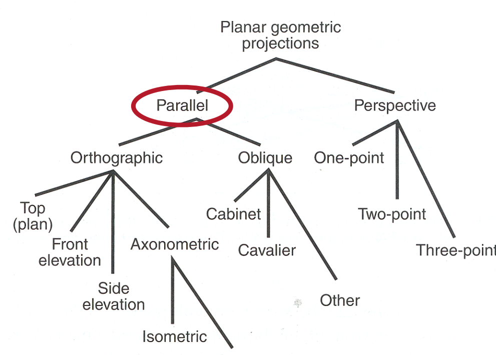


Taxonomy of Projections



FVFHP Figure 6.10

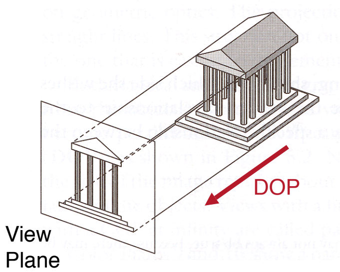
Taxonomy of Projections



FVFHP Figure 6.10

Parallel Projection

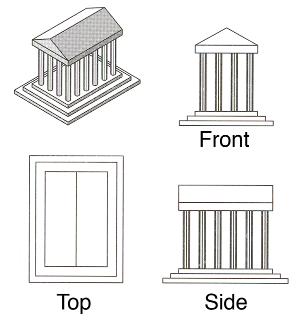
- Center of projection is at infinity
  - Direction of projection (DOP) same for all points



Angel Figure 5.4

Orthographic Projections

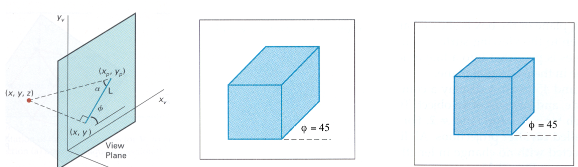
- DOP perpendicular to view plane



Angel Figure 5.5

Oblique Projections

- DOP not perpendicular to view plane

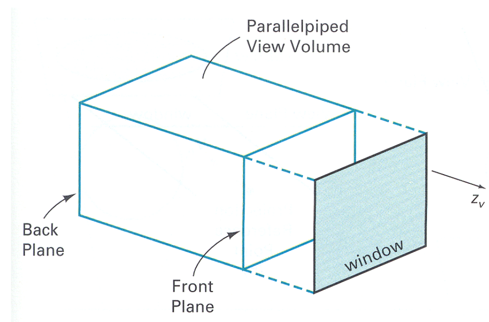


Cavalier
(DOP $\alpha = 45^{o}$)

Cabinet
(DOP $\alpha = 63.4^{o}$)

H&B Figure 12.24

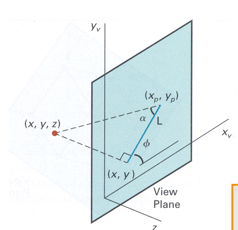
Parallel Projection View Volume



H&B Figure 12.30

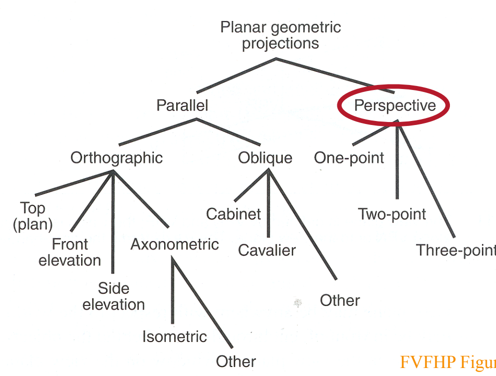
Parallel Projection Matrix

- General parallel projection transformation:



$$\begin{bmatrix} x_s \\ y_s \\ z_s \\ w_s \end{bmatrix} = \begin{bmatrix} 1 & 0 & L\cos\phi & 0 \\ 0 & 1 & L\sin\phi & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_c \\ y_c \\ z_c \\ 1 \end{bmatrix}$$

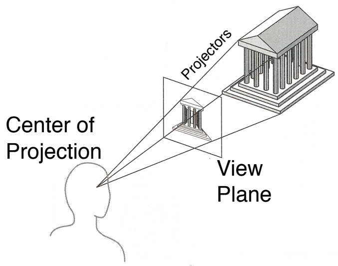
Taxonomy of Projections



FVFHP Figure 6.10

Perspective Projection

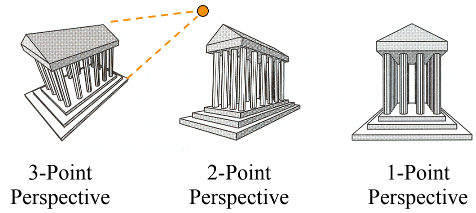
- Map points onto "view plane" along "projectors" emanating from "center of projection" (COP)



Angel Figure 5.9

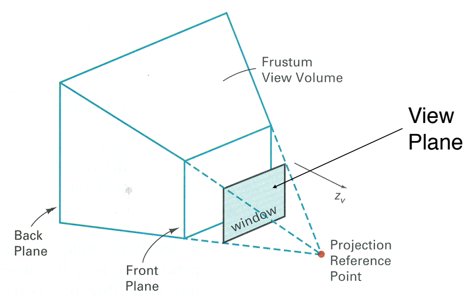
Perspective Projection

- How many vanishing points?



Angel Figure 5.10

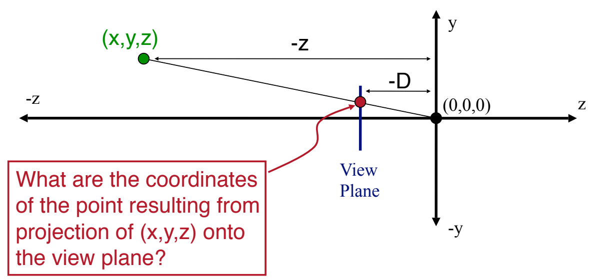
Perspective Projection View Volume



H&B Figure 12.30

Perspective Projection

- Compute 2D coordinates from 3D coordinates with similar triangles



Perspective Projection

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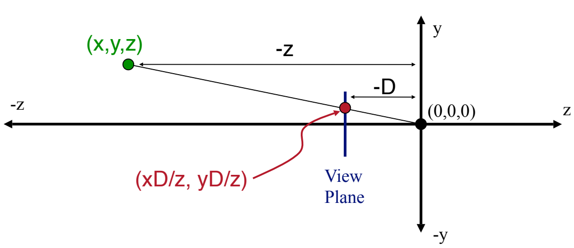


Perspective Projection Matrix

- 4x4 matrix representation?

$$x_s = x_c D / z_c$$
$$y_s = y_c D / z_c$$
$$z_s = D$$
$$w_s = 1$$

$$\begin{bmatrix} x_s \\ y_s \\ z_s \\ w_s \end{bmatrix} = \begin{bmatrix} ? & ? & ? & ? \\ ? & ? & ? & ? \\ ? & ? & ? & ? \\ ? & ? & ? & ? \end{bmatrix} \begin{bmatrix} x_c \\ y_c \\ z_c \\ 1 \end{bmatrix}$$

Perspective Projection Matrix

- 4x4 matrix representation?

$$
\begin{array}{lll}
x_s = x_c D / z_c & x_s = x' / w' & x' = x_c \\
y_s = y_c D / z_c & y_s = y' / w' & y' = y_c \\
z_s = D & z_s = z' / w' & z' = z_c \\
w_s = 1 & & w' = z_c / D
\end{array}
$$

$$
\begin{bmatrix} x_s \\ y_s \\ z_s \\ w_s \end{bmatrix} = \begin{bmatrix} ? & ? & ? & ? \\ ? & ? & ? & ? \\ ? & ? & ? & ? \\ ? & ? & ? & ? \end{bmatrix} \begin{bmatrix} x_c \\ y_c \\ z_c \\ 1 \end{bmatrix}
$$

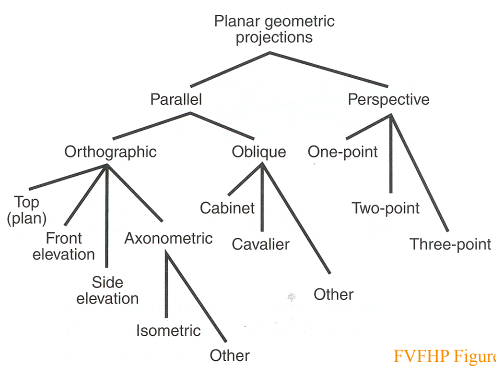
Perspective Projection Matrix

- 4x4 matrix representation?

$$
\begin{array}{lll}
x_s = x_c D / z_c & x_s = x' / w' & x' = x_c \\
y_s = y_c D / z_c & y_s = y' / w' & y' = y_c \\
z_s = D & z_s = z' / w' & z' = z_c \\
w_s = 1 & & w' = z_c / D
\end{array}
$$

$$
\begin{bmatrix} x_s \\ y_s \\ z_s \\ w_s \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 1/D & 0 \end{bmatrix} \begin{bmatrix} x_c \\ y_c \\ z_c \\ 1 \end{bmatrix}
$$

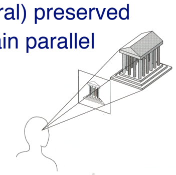
Taxonomy of Projections



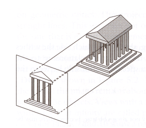
FVFHP Figure 6.10

Perspective vs. Parallel

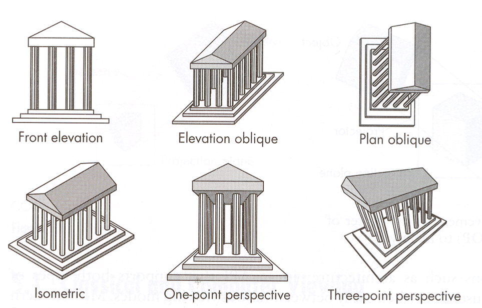
- Perspective projection
  - \+ Size varies inversely with distance - looks realistic
  - – Distance and angles are not (in general) preserved
  - – Parallel lines do not (in general) remain parallel



- Parallel projection
  - \+ Good for exact measurements
  - \+ Parallel lines remain parallel
  - – Angles are not (in general) preserved
  - – Less realistically looking



Classical Projections



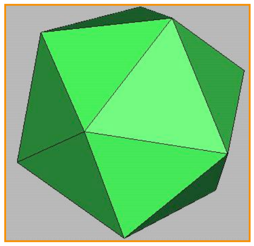
Angel Figure 5.3

Viewing Transformations Summary

- Camera transformation
  - Map 3D world coordinates to 3D camera coordinates
  - Matrix has camera vectors as rows
- Projection transformation
  - Map 3D camera coordinates to 2D screen coordinates
  - Two types of projections:
    - Parallel
    - Perspective

3D Rendering Pipeline (for direct illumination)

3D Primitives
↓ 3D Modeling Coordinates
Modeling Transformation
↓ 3D World Coordinates
Lighting
↓ 3D World Coordinates
Viewing Transformation
↓ 3D Camera Coordinates
Projection Transformation
↓ 2D Screen Coordinates
Clipping
↓ 2D Screen Coordinates
Viewport Transformation
↓ 2D Image Coordinates
Scan Conversion
↓ 2D Image Coordinates
Image



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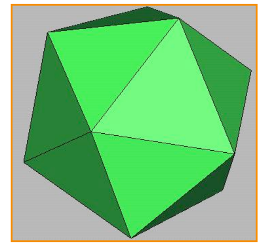


2D Rendering Pipeline

3D Primitives
↓
2D Primitives
↓
Clipping — Clip portions of geometric primitives residing outside the window
↓
Viewport Transformation — Transform the clipped primitives from screen to image coordinates
↓
Scan Conversion — Fill pixels representing primitives in screen coordinates
↓
Image

2D Rendering Pipeline

3D Primitives
↓
2D Primitives
↓
Clipping — Clip portions of geometric primitives residing outside the window
↓
Viewport Transformation — Transform the clipped primitives from screen to image coordinates
↓
Scan Conversion — Fill pixels representing primitives in screen coordinates
↓
Image

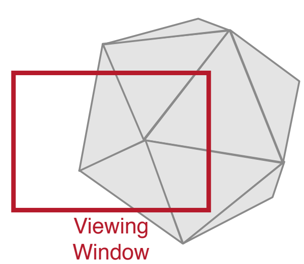
Clipping

- Avoid drawing parts of primitives outside window
  - Window defines part of scene being viewed
  - Must draw geometric primitives only inside window

Screen Coordinates

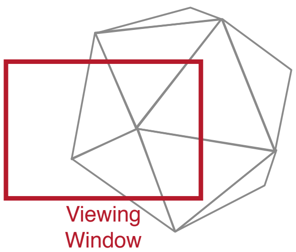
Clipping

- Avoid drawing parts of primitives outside window
  - Window defines part of scene being viewed
  - Must draw geometric primitives only inside window



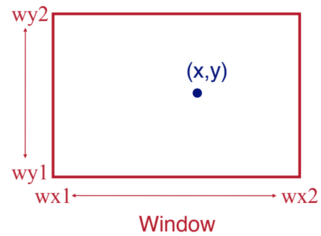
Clipping

- Avoid drawing parts of primitives outside window
  - Points
  - Lines
  - Polygons
  - Circles
  - etc.



Point Clipping

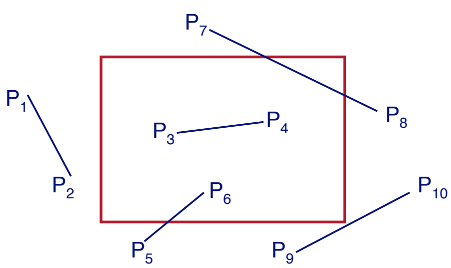
- Is point (x,y) inside the clip window?




```
inside =
  (x >= wx1) &&
  (x <= wx2) &&
  (y >= wy1) &&
  (y <= wy2);
```


Line Clipping

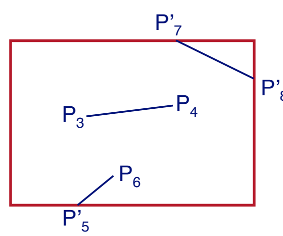
- Find the part of a line inside the clip window



Before Clipping

Line Clipping

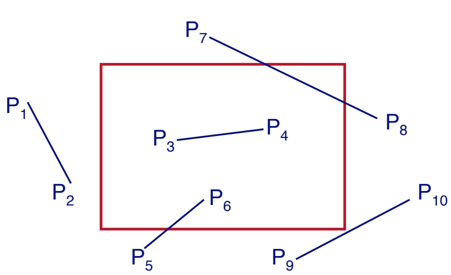
- Find the part of a line inside the clip window



After Clipping

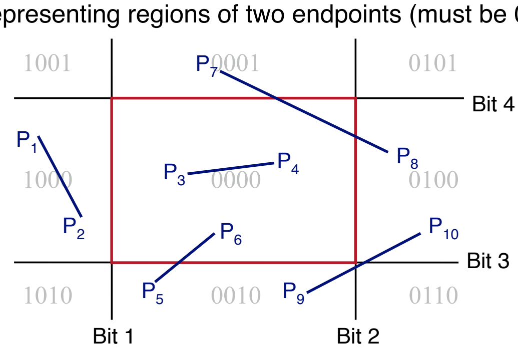
Cohen Sutherland Line Clipping

- Use simple tests to classify easy cases first



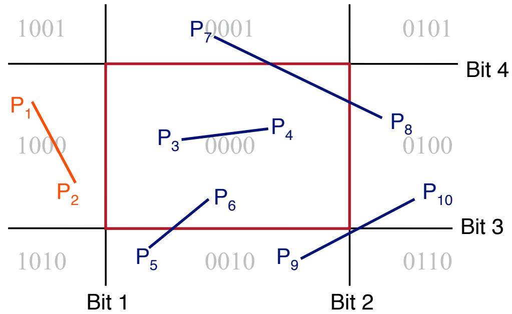
Cohen Sutherland Line Clipping

- Classify some lines quickly by AND of bit codes representing regions of two endpoints (must be 0)



Cohen Sutherland Line Clipping

- Classify some lines quickly by AND of bit codes representing regions of two endpoints (must be 0)



Cohen Sutherland Line Clipping

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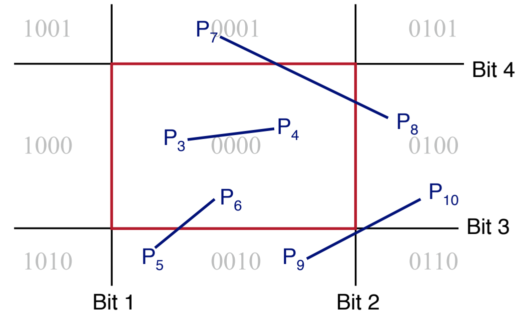
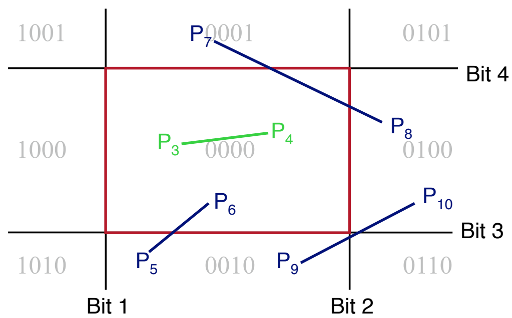


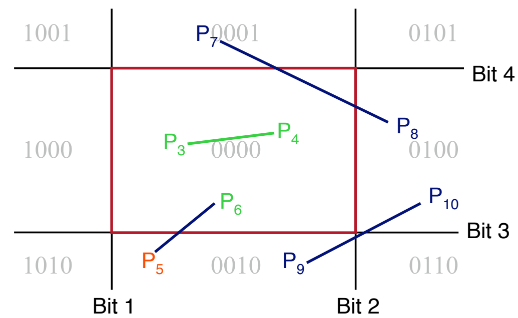
Cohen Sutherland Line Clipping

- Classify some lines quickly by AND of bit codes representing regions of two endpoints (must be 0)



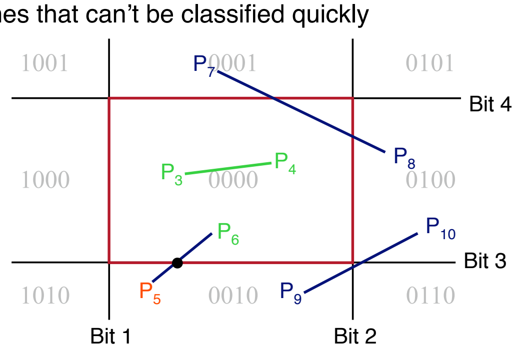
Cohen-Sutherland Line Clipping

- Compute interesections with window boundary for lines that can't be classified quickly



Cohen-Sutherland Line Clipping

- Compute interesections with window boundary for lines that can't be classified quickly



Cohen-Sutherland Line Clipping

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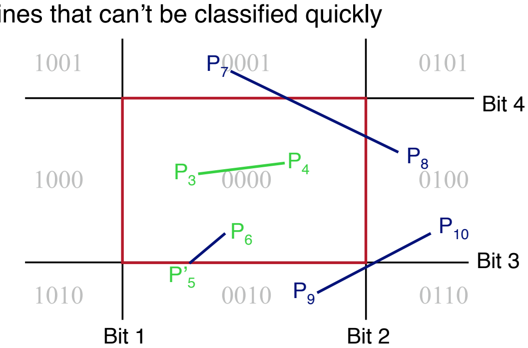
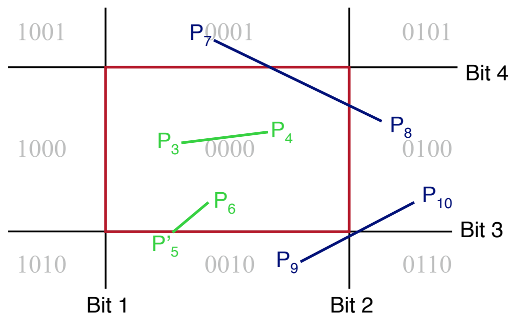


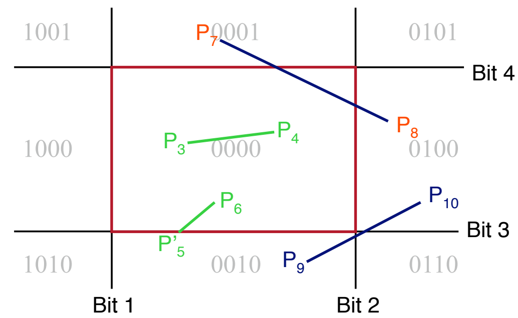
Cohen-Sutherland Line Clipping

- Compute interesections with window boundary for lines that can't be classified quickly



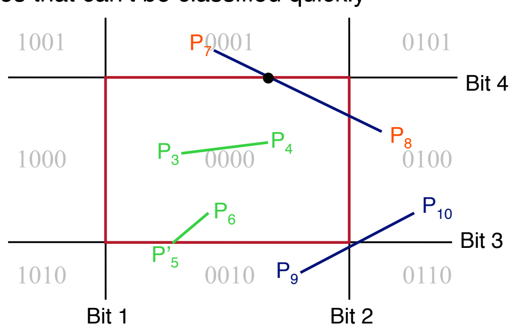
Cohen-Sutherland Line Clipping

- Compute interesections with window boundary for lines that can't be classified quickly



Cohen-Sutherland Line Clipping

- Compute interesections with window boundary for lines that can't be classified quickly



Cohen-Sutherland Line Clipping

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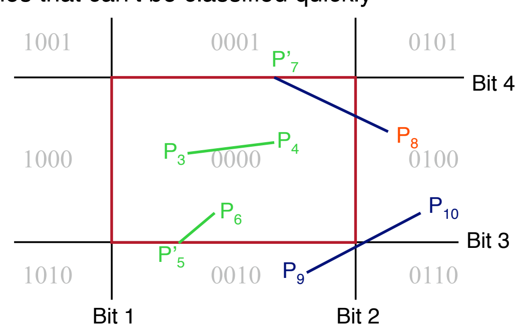

Cohen-Sutherland Line Clipping

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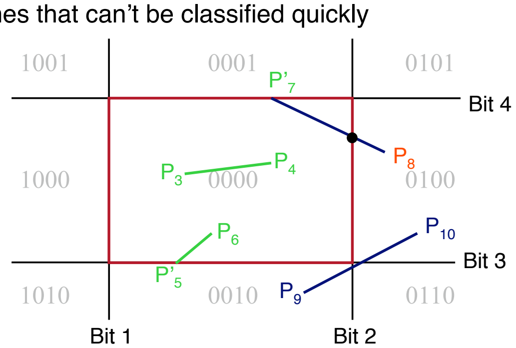

Cohen-Sutherland Line Clipping

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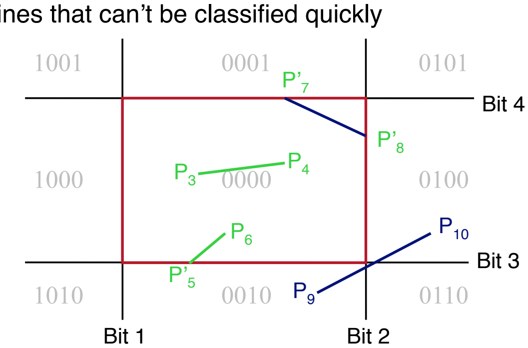

Cohen-Sutherland Line Clipping

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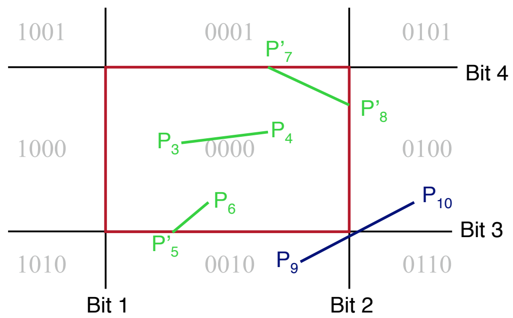
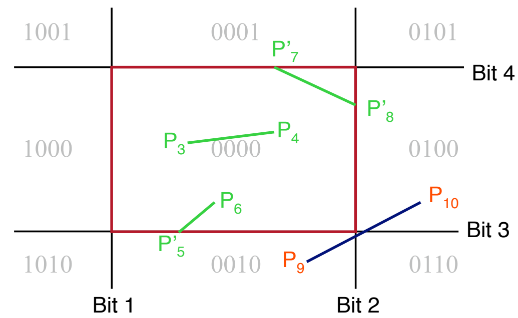


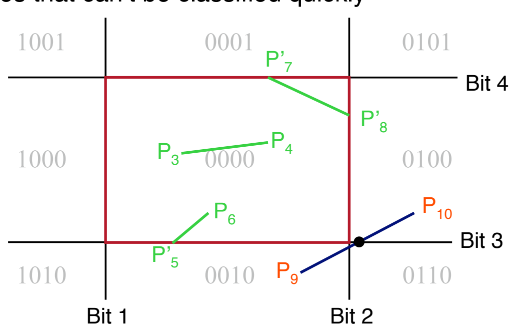
Cohen-Sutherland Line Clipping

- Compute interesections with window boundary for lines that can’t be classified quickly



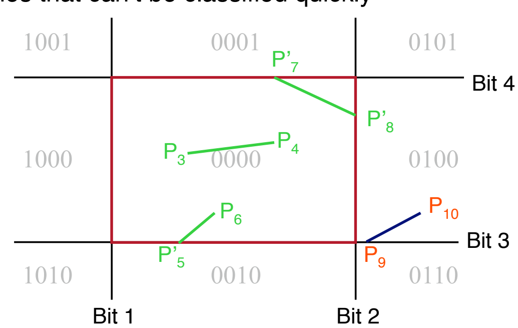
Cohen-Sutherland Line Clipping

- Compute interesections with window boundary for lines that can’t be classified quickly



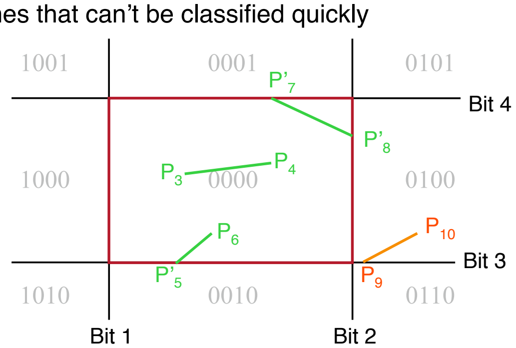
Cohen-Sutherland Line Clipping

- Compute interesections with window boundary for lines that can’t be classified quickly



Cohen-Sutherland Line Clipping

- Compute interesections with window boundary for lines that can’t be classified quickly



Cohen-Sutherland Line Clipping

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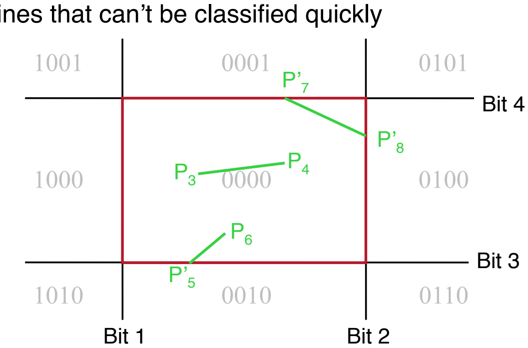
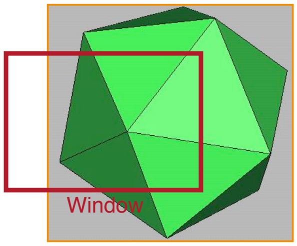


Clipping

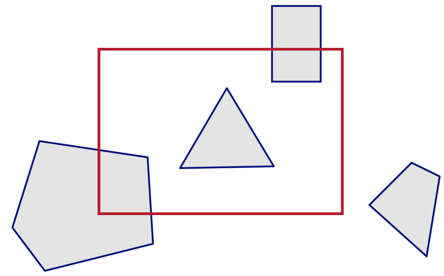
- Avoid drawing parts of primitives outside window
  - Points
  - Lines
  - Polygons
  - Circles
  - etc.



2D Screen Coordinates

Polygon Clipping

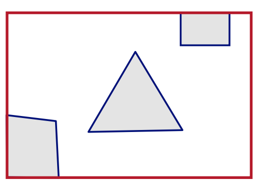
- Find the part of a polygon inside the clip window?



Before Clipping

Polygon Clipping

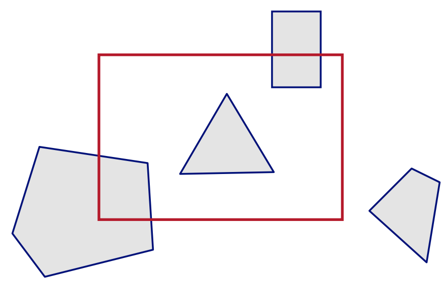
- Find the part of a polygon inside the clip window?



After Clipping

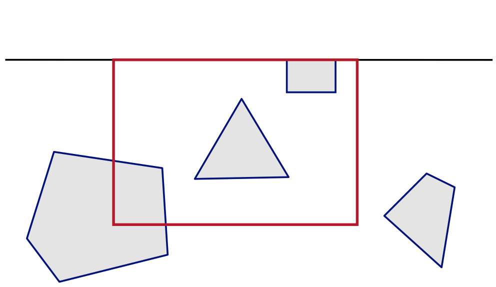
Sutherland Hodgeman Clipping

- Clip to each window boundary one at a time



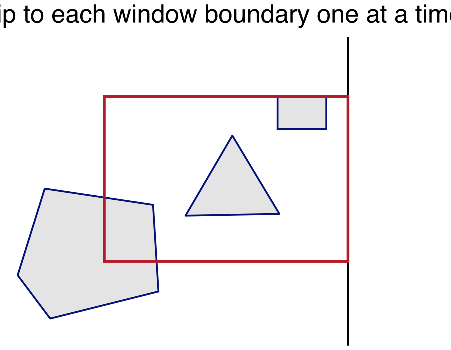
Sutherland Hodgeman Clipping

- Clip to each window boundary one at a time



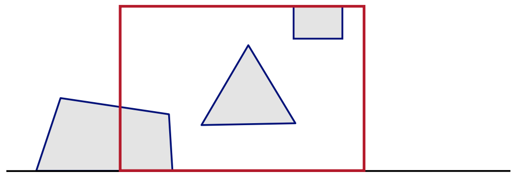
Sutherland Hodgeman Clipping

- Clip to each window boundary one at a time



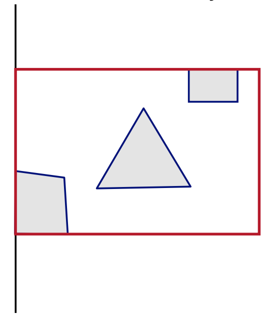
Sutherland Hodgeman Clipping

- Clip to each window boundary one at a time



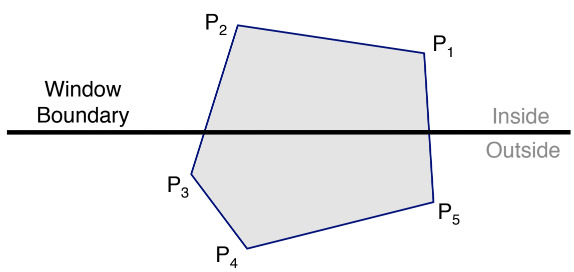
Sutherland Hodgeman Clipping

- Clip to each window boundary one at a time



Clipping to a Boundary

- Do inside test for each point in sequence, Insert new points when cross window boundary, Remove points outside window boundary



Clipping to a Boundary

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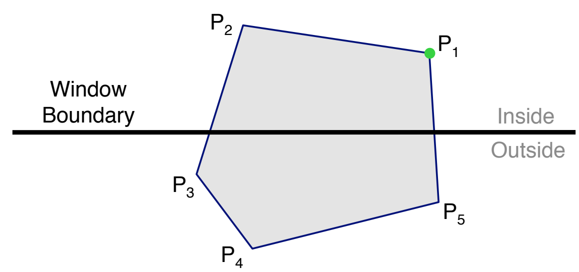
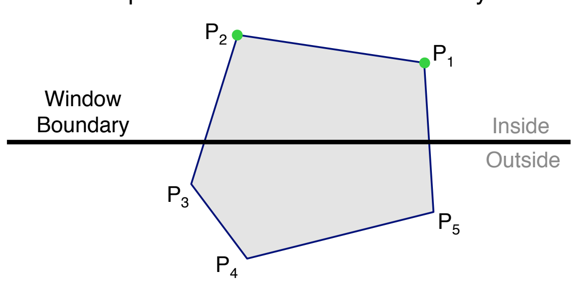


Clipping to a Boundary

- Do inside test for each point in sequence, Insert new points when cross window boundary, Remove points outside window boundary



Clipping to a Boundary

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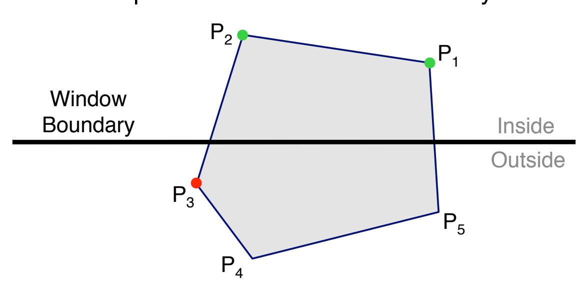

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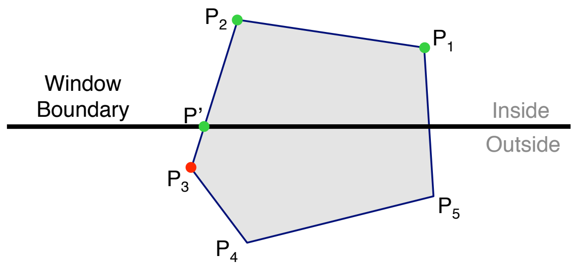

Clipping to a Boundary

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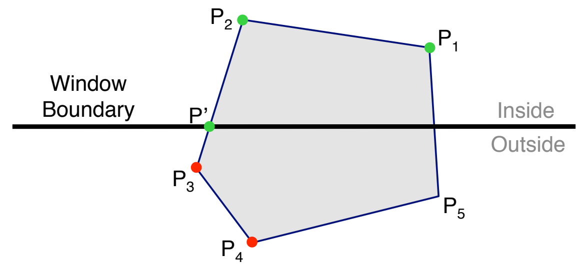

Clipping to a Boundary

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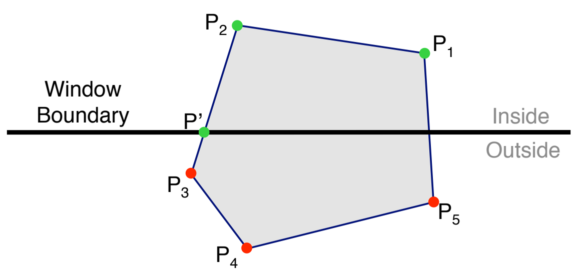

Clipping to a Boundary

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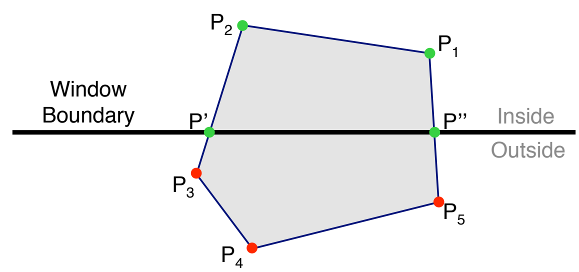

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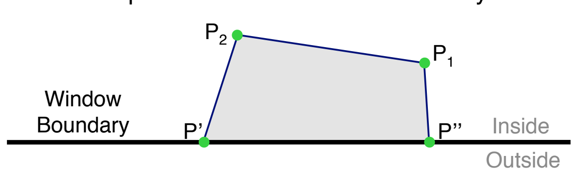


2D Rendering Pipeline

3D Primitives

↓

2D Primitives

↓

Clipping — Clip portions of geometric primitives residing outside the window

↓

Viewport Transformation — Transform the clipped primitives from screen to image coordinates

↓

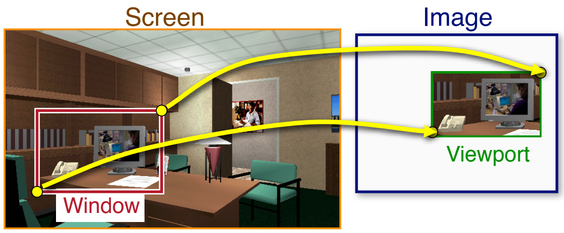
Scan Conversion — Fill pixels representing primitives in screen coordinates

↓

Image

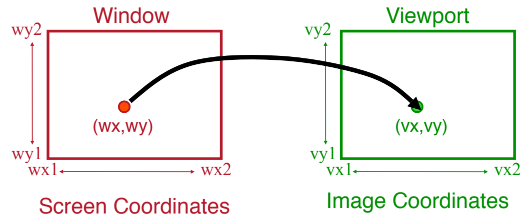
Viewport Transformation

- Transform 2D geometric primitives from screen coordinate system (normalized device coordinates) to image coordinate system (pixels)



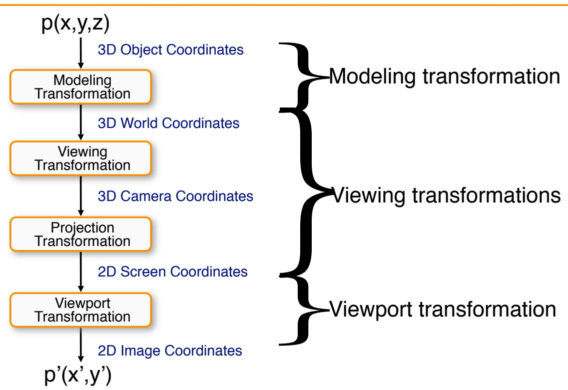
Viewport Transformation

- Window-to-viewport mapping

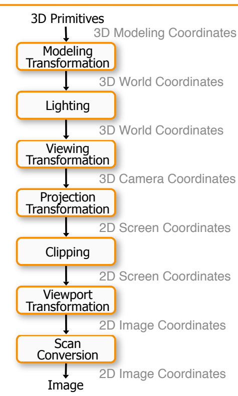


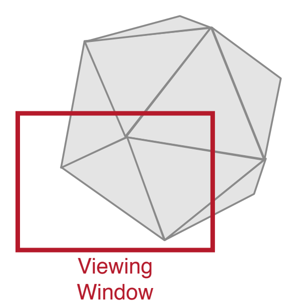

```
vx = vx1 + (wx - wx1) * (vx2 - vx1) / (wx2 - wx1);
vy = vy1 + (wy - wy1) * (vy2 - vy1) / (wy2 - wy1);
```


Summary of Transformations

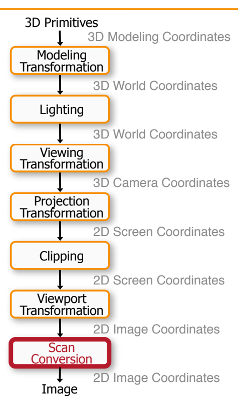


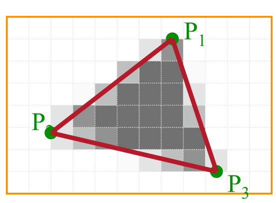
Summary





Next Time





Scan Conversion!