Computer Graphics

Camera & Projective Transformations

Philipp Slusallek

Motivation

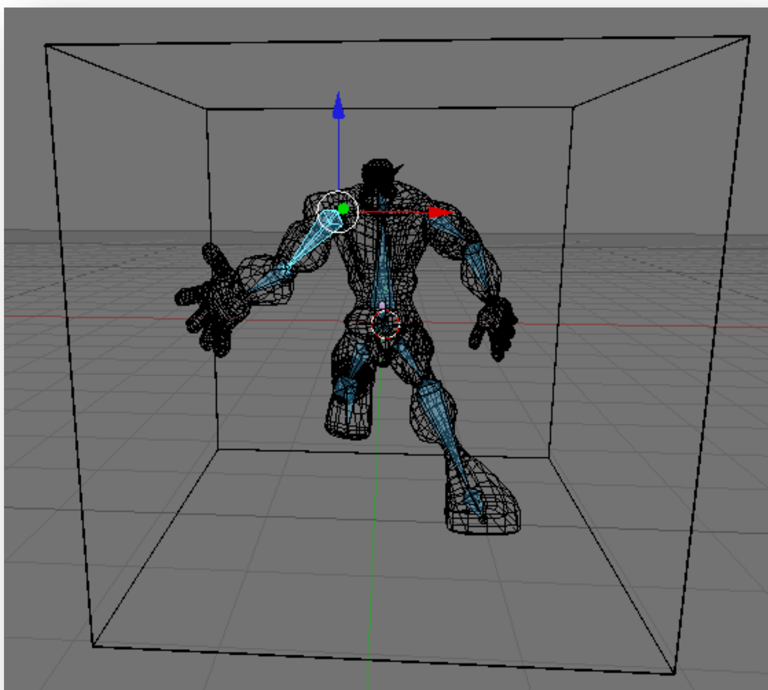
- **Rasterization works on 2D primitives (+ depth)**
- **Need to project 3D world onto 2D screen**
- **Based on**
  - Positioning of objects in 3D space
  - Positioning and parameters of the virtual camera

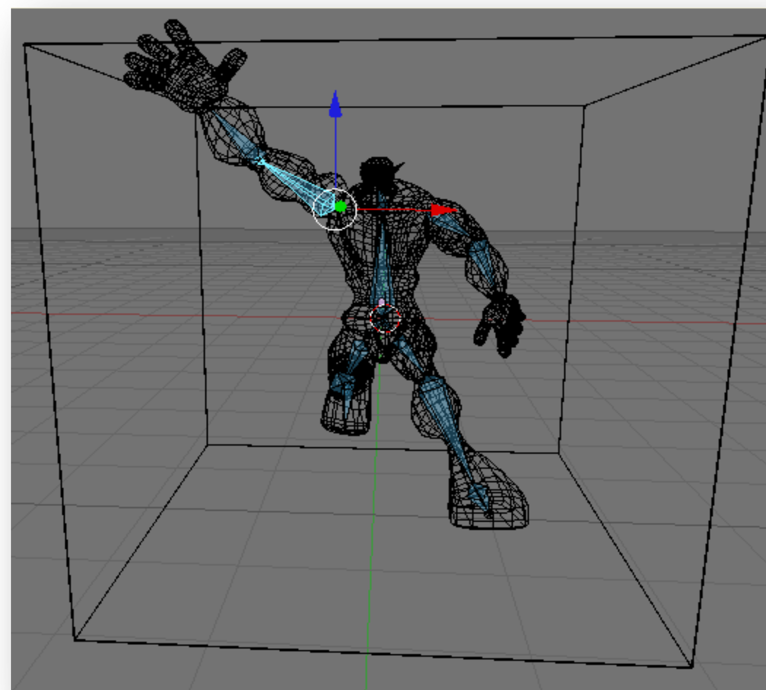
Coordinate Systems

- **Local (object) coordinate system (3D)**
  - Object vertex positions
  - Can be hierarchically nested in each other (scene graph, transf. stack)
- **World (global) coordinate system (3D)**
  - Scene composition and object placement
    - Mostly rigid objects: translation, rotation per object, (scaling)
    - Animated objects: time-varying transformation in world or local space
  - Illumination can be computed in this space
- **Camera/view/eye coordinate system (3D)**
  - Coordinates relative to camera pose (position & orientation)
    - Camera itself specified relative to world space
  - Illumination can also be done in this space
- **Normalized device coordinate system (2.5D)**
  - After *perspective transformation*, rectilinear, in $[0, 1]^3$
  - Normalization to view frustum (for rasterization and depth buffer)
  - Rasterization & shading done here (e.g., interpolation across triangle)
- **Window/screen (raster) coordinate system (2D)**
  - 2D transformation to place image in window on the screen

Hierarchical Coordinate Systems

- **Used in Scene Graphs**
  – Group objects hierarchically
  – Local coordinate system is relative to parent coordinate system
  – Apply transformation to the parent to change the whole sub-tree (or sub-graph)





Hierarchical Coordinate Systems

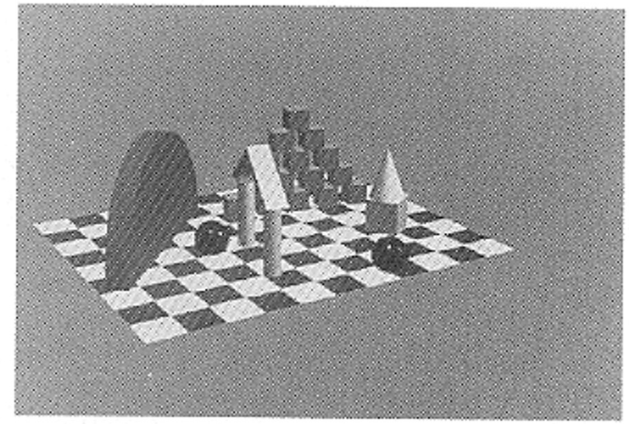
- **Hierarchy of transformations**

T_root	Positions the character in the world	
T_ShoulderR	Moves to the right shoulder	
T_ShoulderRJoint	Rotates in the shoulder (3 DOF)	← User
T_UpperArmR	Moves to the Elbow	
T_ElbowRJoint	Rotates in the Elbow (1 DOF)	← User
T_LowerArmR	Moves to the wrist	
T_WristRJoint	Rotates in the wrist (1 DOF)	← User
…..	Further for the right hand and the fingers	
T_ShoulderL	Moves to the left shoulder	
T_ShoulderLJoint	Rotates in the shoulder (3 DOF)	← User
T_UpperArmL	Moves to the Elbow	
T_ElbowLJoint	Rotates in the Elbow (1 DOF)	← User
T_LowerArmL	Moves to the wrist	
…..	Further for the left hand and the fingers	

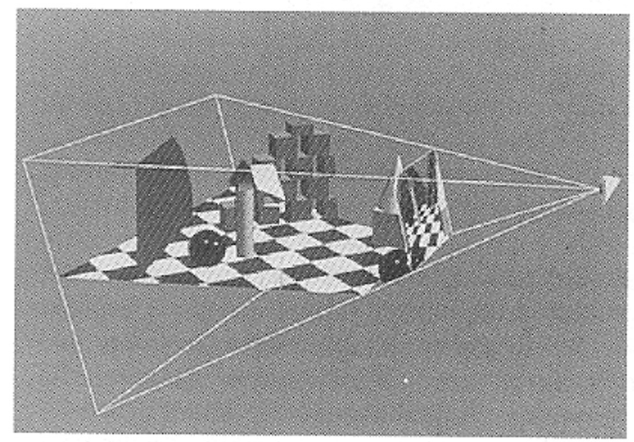
- Each transformation is relative to its parent
  - Concatenated by multiplying (from right) and pushing onto a stack
  - Going back by poping from the stack
- This transformation stack was so common, it *was* built into OpenGL

Coordinate Transformations

- **Model transformation**
  - Object space to world space
  - Can be hierarchically nested
  - Typically an affine transformation
  - As just discussed



- **View transformation**
  - World space to eye space
  - Typically an affine transformation

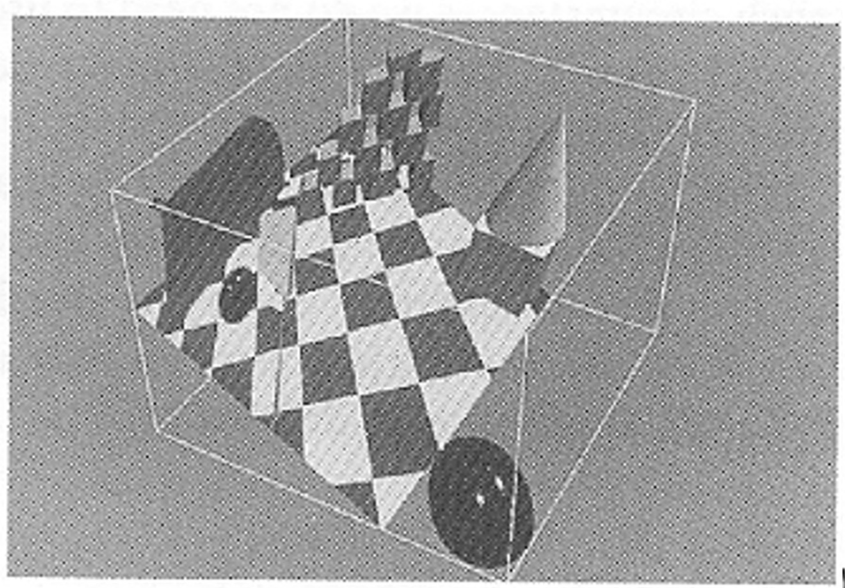
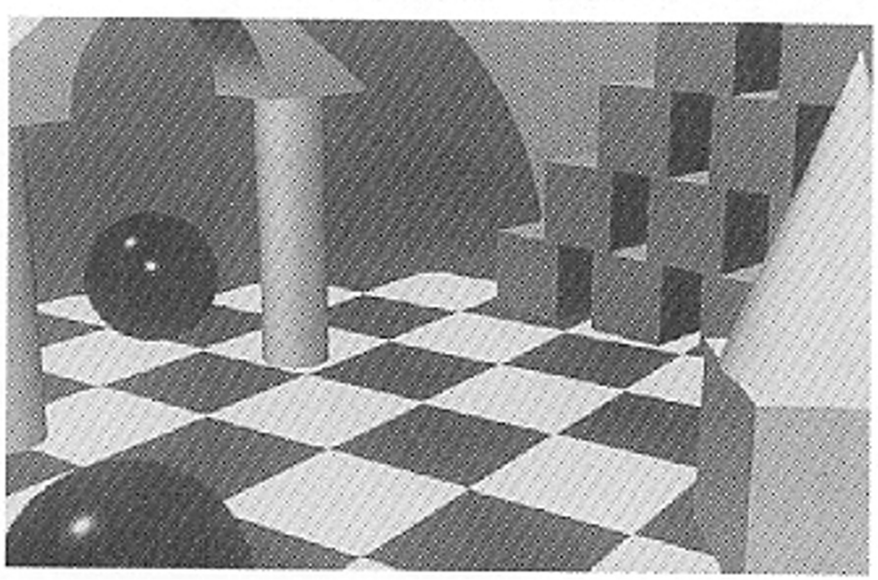


- **Combination of both: *Modelview* transformation**
  - Used by *traditional* OpenGL (although world space is conceptually intuitive, it was not explicitly exposed in OpenGL)

Coordinate Transformations

- **Projective transformation**
  - Eye space to normalized device space
  - Parallel or perspective projection (defined by view frustum)
  - 3D to 2D: With preservation of depth (2.5 D)

- **Viewport transformation**
  - Normalized device space to window (raster) coordinates

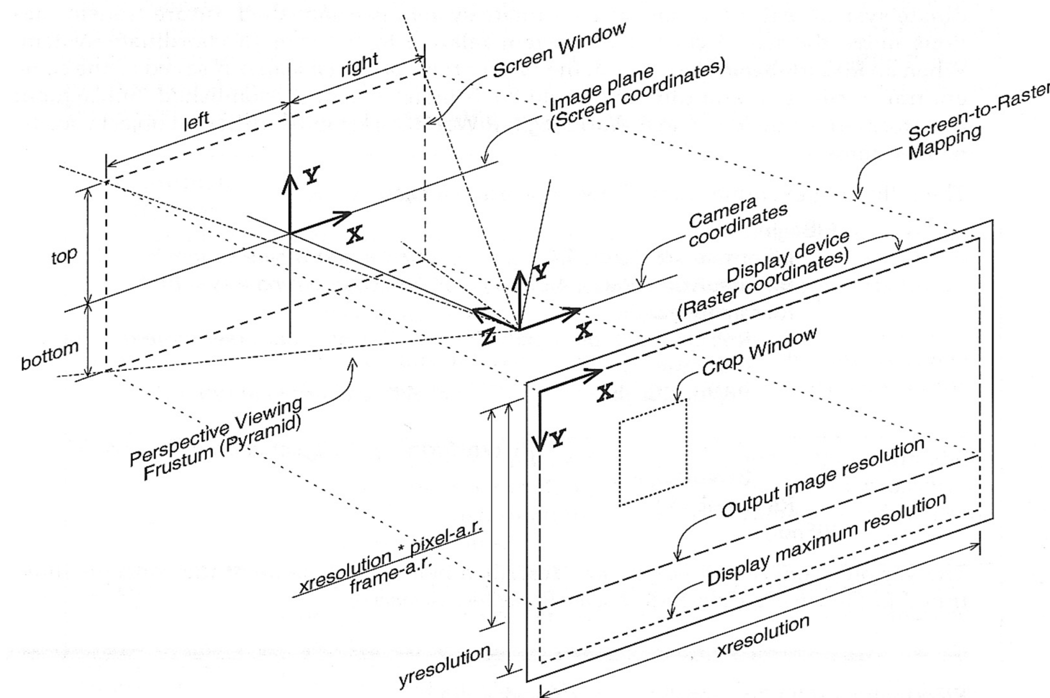



Camera Parameters: Rend.Man

- **RenderMan camera specification**
  - Distance of Screen Window from origin given by “field of view” (fov)
    - fov: Full angle of segment (-1,0) to (1,0), when seen from origin
  - CW given implicitly
  - No offset on screen

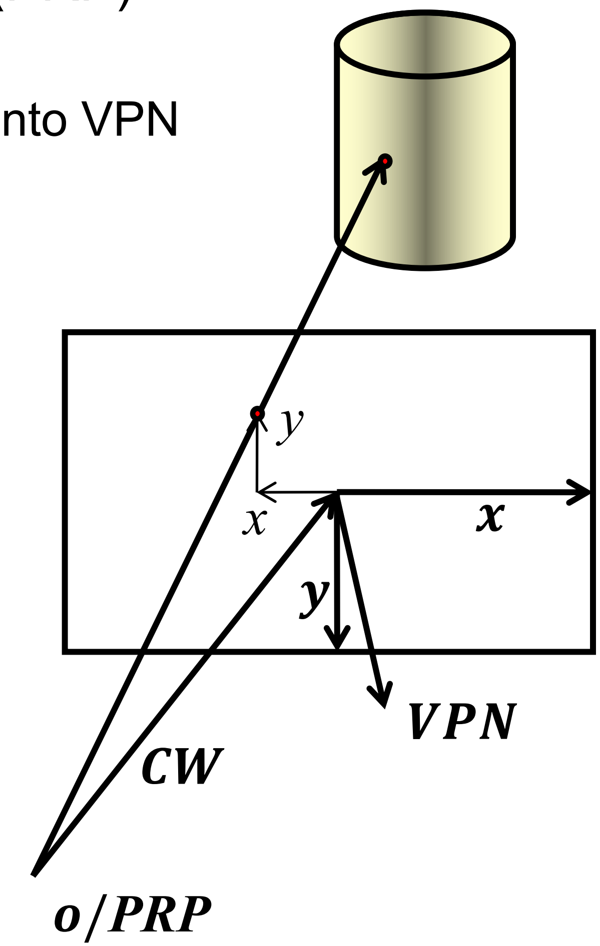
  - Note: Left-handed coordinate system!

  - All geometry is assumed to be in camera coordinates!
    - Or needs to be transformed into it



Simple Camera Parameters

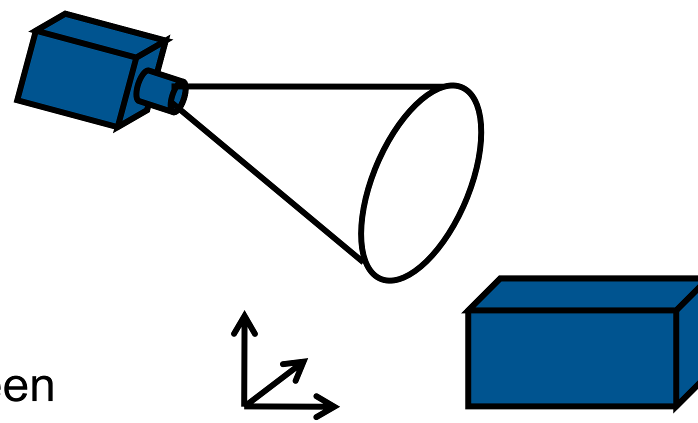
- **Camera definition (typically used in ray tracers)**
  - $\boldsymbol{o} \in \mathbb{R}^3$: center of projection, point of view (PRP)
  - $\boldsymbol{CW} \in \mathbb{R}^3$: vector to center of window
    - "Focal length": projection of vector to CW onto VPN
      - $focal = |(CW - o) \cdot VPN|$
  - $\boldsymbol{x}, \boldsymbol{y} \in \mathbb{R}^3$: span of half viewing window
    - $\mathrm{VPN} = (\boldsymbol{y} \times \boldsymbol{x}) / |(\boldsymbol{y} \times \boldsymbol{x})|$
    - $\mathrm{VUP} = -\boldsymbol{y}$
    - $width = 2|\boldsymbol{x}|$
    - $height = 2|\boldsymbol{y}|$
    - Aspect ratio: $\mathrm{camera}_{ratio} = |x|/|y|$



PRP: Projection reference point
VPN: View plane normal
VUP: View up vector
CW: Center of window

Fulll Camera Transformation

- **Goal**
  - Compute the transformation between points in 3D and pixels on the screen
  - Required for rasterization algorithms (e.g., OpenGL)
    - They project all primitives from 3D to 2D
    - Rasterization happens in 2D (actually 2.5D, XY plus Z attribute)
- **Given**
  - Camera *pose* (pos. & orient.)
    - *Extrinsic* parameters
  - Camera *configuration*
    - *Intrinsic* parameters
  - Pixel raster description
    - Resolution and placement on screen

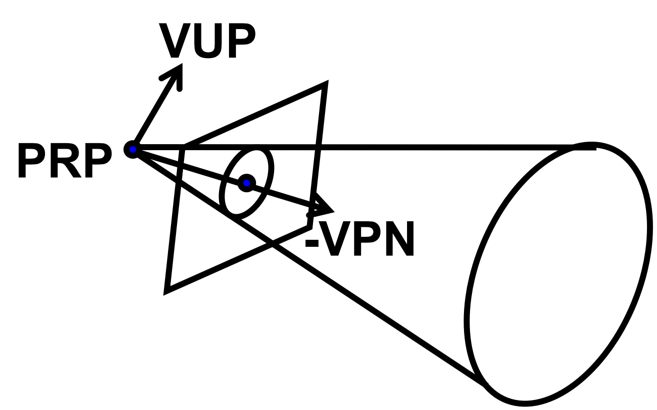


- **In the following: Stepwise Approach**
  - Express each transformation step in homogeneous coordinates
  - Multiply all 4x4 matrices to combine transformations

Camera Transformation

- **Need camera position and orientation in world space**
  - External (extrinsic) camera parameters
    - Center of projection: projection reference point (PRP)
    - Optical axis: view-plane normal (VPN)
    - View up vector (VUP)
      - Not necessarily orthogonal to VPN, but not co-linear
- **Needed Transformations**

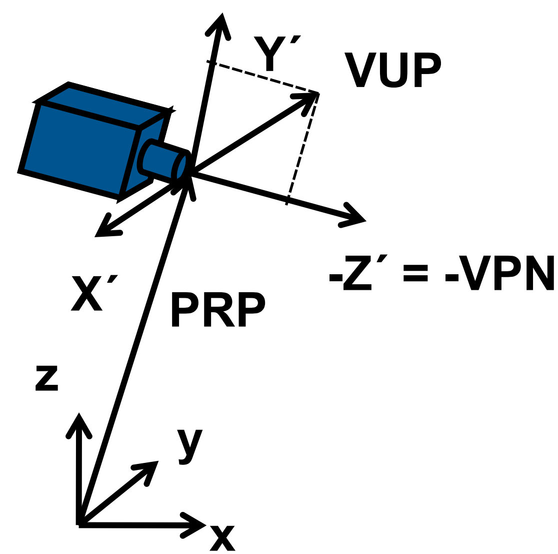
  1) Translation of PRP to the origin (-PRP)
  2) Rotation such that viewing direction is along negative Z axis
  2a) Rotate such that VUP is pointing up on screen



Camera Transformation

- **Goal:Camera: at origin, view along –Z, Y upwards**
  - Assume right-handed coordinate system!
  - Translation of PRP to the origin
  - Rotation of VPN to Z-axis
  - Rotation of projection of VUP to Y-axis
- **Rotations**
  - Build orthonormal basis for the camera and form inverse
    - Z´= VPN, X´= normalize(VUP x VPN), Y´= Z´ × X´
- **Viewing transformation** V
  - Translation T followed by rotation R

$$V = RT = \begin{pmatrix} X'_x & Y'_x & Z'_x & 0 \\ X'_y & Y'_y & Z'_y & 0 \\ X'_z & Y'_z & Z'_z & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}^T T(-PRP)$$



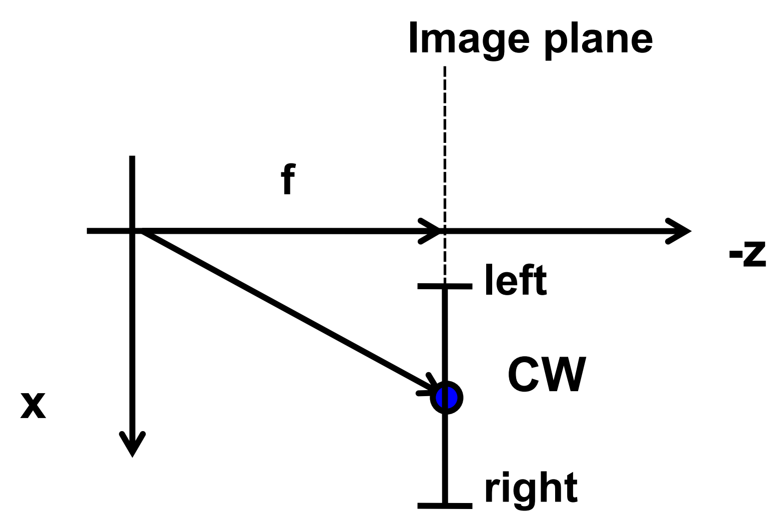
Viewing Transformation

- **Define projection (perspective or orthographic)**
  - Needs internal (intrinsic) camera parameters
  - Screen window (Center Window (CW), width, height)
    - Window size/position on image plane (relative to VPN intersection)
    - Window center relative to PRP determines viewing direction ($\neq$ VPN)
  - Focal length (f)
    - Distance of projection plane from camera along VPN
    - Smaller focal length means larger field of view
  - Alternative: Field of view (fov) (defines width of view frustum)
    - Often used instead of screen window and focal length
      - Only valid when screen window is centered around VPN (often the case)
    - Vertical (or horizontal) angle plus aspect ratio (width/height)
      - Or two angles (both angles may be half or full angles, beware!)
  - Near and far clipping planes
    - Given as distances from the PRP along VPN
    - Near clipping plane avoids singularity at origin (division by zero)
    - Far clipping plane restricts the depth for fixed-point representation in HW

Shearing Transformation

- **Step 1: VPN may not go through center of window**
  - Possible oblique viewing configuration
- **Shear**
  - Shear space such that window center is along Z-axis
  - Window center CW (in 3D view coordinates)
    - RenderMan: CW = ((right+left)/2, (top+bottom)/2, -focal)^T
- **Shear matrix**

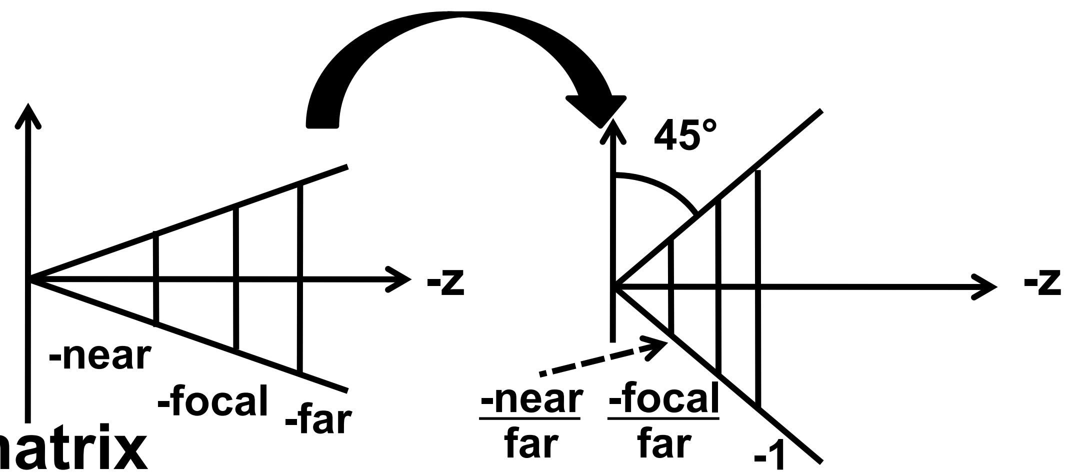
$$H = \begin{pmatrix} 1 & 0 & -\frac{CW_x}{CW_z} & 0 \\ 0 & 1 & -\frac{CW_y}{CW_z} & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$



View from top

Normalizing

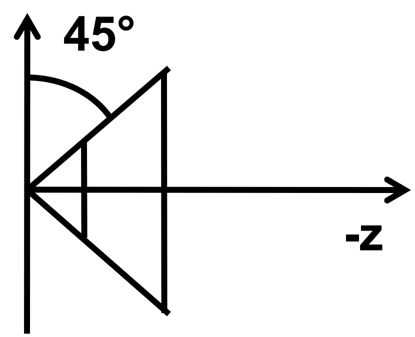
- **Step 2: Scaling to canonical viewing frustum**
  - Goal: Scale in X and Y such that screen window boundaries open at 45-degree angles (at focal plane)
  - Scale in Z such that far clipping plane is at Z= -1

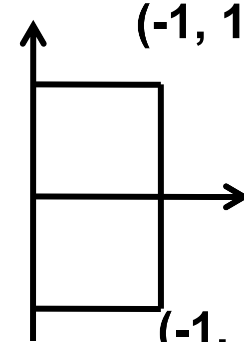


- **Scaling matrix**
  - $S = S_{far} S_{xy} = \begin{pmatrix} \frac{1}{far} & 0 & 0 & 0 \\ 0 & \frac{1}{far} & 0 & 0 \\ 0 & 0 & \frac{1}{far} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \frac{2focal}{width} & 0 & 0 & 0 \\ 0 & \frac{2focal}{height} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$

Perspective Transformation

- **Step 3: Perspective transformation**
  - From canonical perspective viewing frustum (= cone at origin around -Z-axis, 45° opening) to regular box $[-1 .. 1]^2 \times [0 .. 1]$
- **Mapping of X and Y**
  - Lines through the origin are mapped to lines parallel to the Z-axis
    - $x' = x/-z$ and $y' = y/-z$ (coordinate given by slope with respect to -z!)
  - Do not change X and Y additively (first two rows stay the same)
  - Set W to –z so we divide by it when converting back to 3D
    - Determines last row

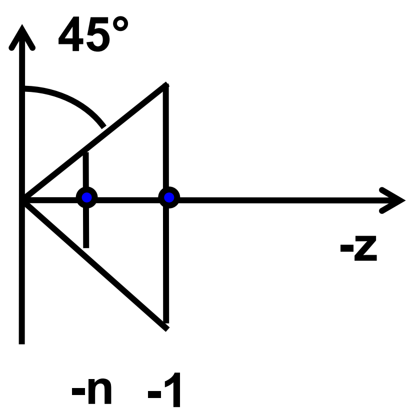


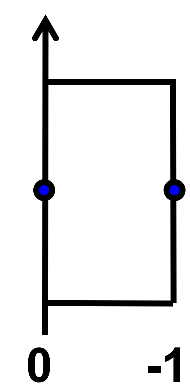


- **Perspective transformation**
  - $P = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ \boxed{A} & \boxed{B} & \boxed{C} & \boxed{D} \\ 0 & 0 & -1 & 0 \end{pmatrix}$ Still unknown
  - **Note: Perspective projection = perspective transformation + parallel projection**

Perspective Transformation

- **Computation of the coefficients A, B, C, D**
  - No shear of Z with respect to X and Y
    - A = B = 0
  - Mapping of two known points
    - Computation of the two remaining parameters C and D
      - n = near / far (due to previous scaling by 1/far)
    - Following mapping must hold
      - $(0{,}0,-1,1)^T = P(0{,}0,-1{,}1)^T$ and $(0{,}0{,}0,1)^T = P(0{,}0,-n,1)^T$
- **Resulting Projective transformation**
  - $P = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \frac{1}{1-n} & \frac{n}{1-n} \\ 0 & 0 & -1 & 0 \end{pmatrix}$
  - Transforms Z non-linearly (in 3D)
    - $z' = -\frac{z+n}{z(1-n)}$





Parallel Projection to 2D

- **Parallel projection $P_{parallel}$ to [-1 .. 1]²**
  - Formally scaling in Z with factor 0
  - Typically still maintains Z in [0,1] for depth buffering
    - As a vertex attribute (see OpenGL later)

- **Normalizing Transform N**
  - From $[-1 .. 1]^2$ to NDC ($[0 .. 1]^2$)
  - Scaling (by 1/2 in X and Y) and translation (by (1/2,1/2))

$$P_{parallel} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 \text{ or } 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad N = \begin{pmatrix} 1/2 & 0 & 0 & 1/2 \\ 0 & 1/2 & 0 & 1/2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Viewport Transformation

- **Normalized Device Coordinates (NDC)**
  - Intrinsic camera parameters transform to NDC
    - $[0,1]^2$ for x, y across the screen window
    - [0,1] for z (depth)
- **Mapping NDC to raster coordinates on the screen**
  - $xres, yres$: Size of window in pixels
    - Should have same aspect ratios to avoid distortion
      - $camera_{ratio} = \frac{xres}{yres} \frac{pixelspacing_x}{pixelspacing_y},$
    - Horizontal and vertical pixel spacing (distance between pixel centers)
      - Today, typically the same but can be different e.g. for some video formats
  - Position of window on the screen
    - Offset of window from origin of screen
      - $posx$ and $posy$ given in pixels
    - Depends on where the origin is on the screen (top left, bottom left)
  - “Scissor box” or “crop window” (region of interest)
    - No change in mapping but limits which pixels are rendered

Viewport Transformation

- **Scaling and translation in 2D**
  - Scaling matrix to map to entire window on screen
    - $S_{raster}(xres, yres)$
    - No distortion if aspect ratios have been handled correctly earlier
      - I.e. aspect ratio of window in world space == aspect ratio of raster window
    - In some cases, one needs to reverse direction of y
      - Some formats have screen origin at bottom left, some at top left
      - Needs additional translation/scaling
  - Positioning on the screen
    - Translation $T_{raster}(xpos, ypos)$
    - May be different depending on raster coordinate system
      - Origin at upper left or lower left

Orthographic Projection

- **Step 2a: Translation (orthographic)**
  - Bring near clipping plane into the origin
- **Step 2b: Scaling to regular box [-1 .. 1]^2 x [0 .. -1]**
- **Mapping of X and Y**

– $P_o = S_{xyz} T_{near} = \begin{pmatrix} \frac{2}{width} & 0 & 0 & 0 \\ 0 & \frac{2}{height} & 0 & 0 \\ 0 & 0 & \frac{1}{far-near} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & near \\ 0 & 0 & 0 & 1 \end{pmatrix}$

Full Camera Transformation

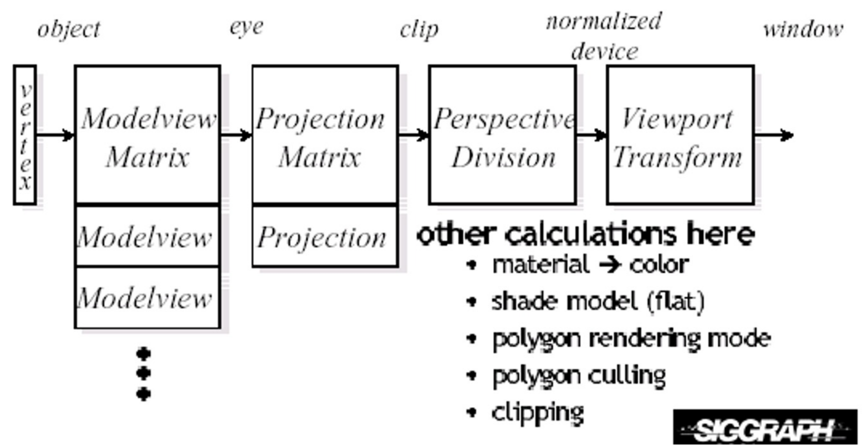
- **Complete transformation (combination of matrices)**
  - Perspective Projection
    - $T_{camera} = T_{raster}\, S_{raster}\, N\, P_{parallel}\, P_{persp}\, S_{far}\, S_{xy}\, H\, R\, T$
  - Orthographic Projection
    - $T_{camera} = T_{raster}\, S_{raster}\, N\, P_{parallel}\, S_{xyz}\, T_{near} \cdot H\, R\, T$

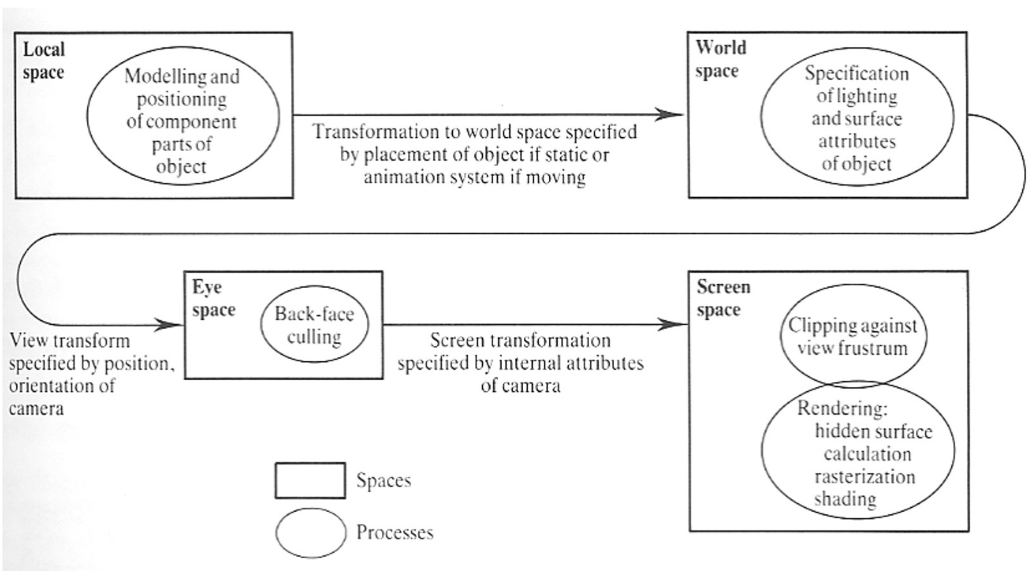
- **Other representations**
  - Other literature uses different conventions
    - Different camera parameters as input
    - Different canonical viewing frustum
    - Different normalized coordinates
      - $[-1\ ..\ 1]^3$ versus $[0\ ..1]^3$ versus ...
  - ...

→ Results in different transformation matrices – so be careful !!!

Per-Vertex Transformations

- ***Traditional*** **OpenGL pipeline**
  - Hierarchical modeling
    - Modelview matrix stack
    - Projection matrix stack
  - Each stack can be independently pushed/popped
  - Matrices can be applied/multiplied to top stack element
- **Today**
  - Arbitrary matrices as attributes to vertex shaders that apply them as they wish (later)
  - All matrix stack handling must now be done by application





OpenGL

- **Modern OpenGL**
  - Transformation provided by app, applied by vertex shader
  - Vertex or Geometry shader must output clip space vertices
    - Clip space: Just before perspective divide (by w)
- **Viewport transformation**
  - glViewport(x, y, width, height)
  - Now can even have multiple viewports
    - glViewportIndexed(idx, x, y, width, height)
  - Controlling the depth range (after Perspective transformation)
    - glDepthRangeIndexed(idx, near, far)

Discussion

- **Pinhole camera model**
  - Linear in homogeneous coordinates
- **A lot of things that we ignored**
  - Complex lenses distortion, aberrations
  - Flare
  - Depth-of-field
  - Vignetting