Computer Graphics

Camera & Projective Transformations

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Motivation

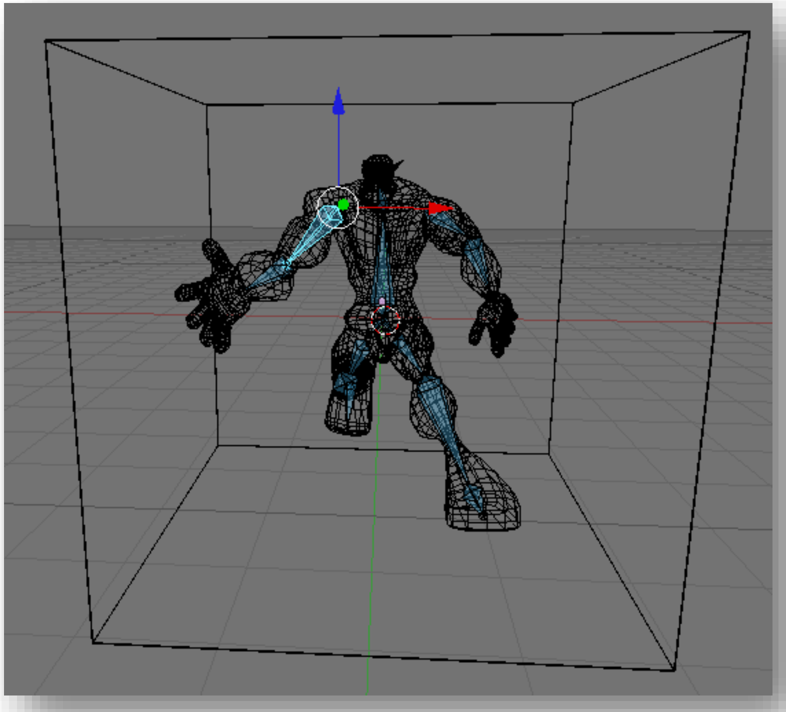
- **Rasterization works on 2D primitives (+ depth)**
- **Need to project 3D world onto 2D screen**
- **Based on**
  - Positioning of objects in 3D space
  - Positioning of the virtual camera

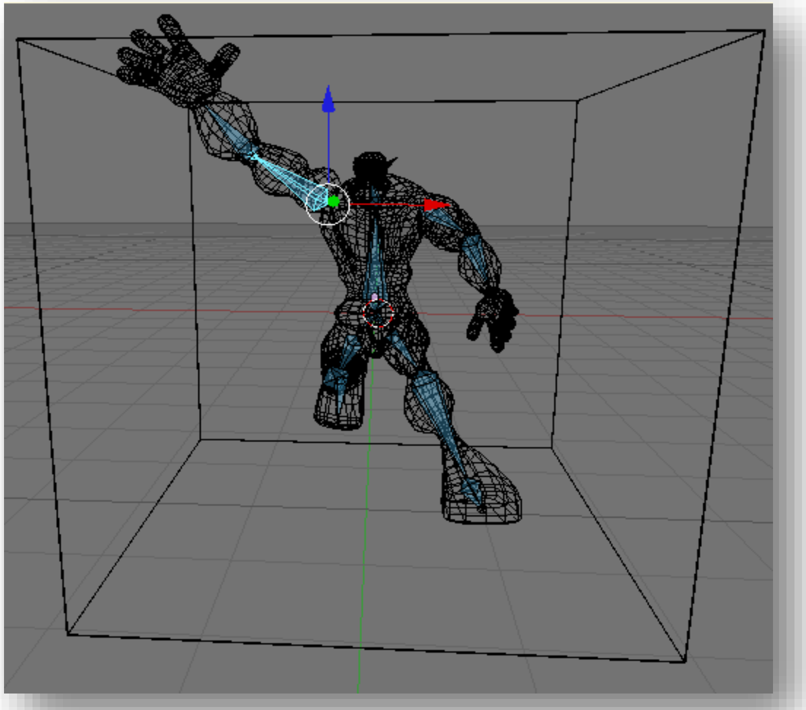
Coordinate Systems

- **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
    - Rigid objects: constant translation, rotation per object, (scaling)
    - Animated objects: time-varying transformation in world-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)
  - Shading executed here (interpolation of color 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

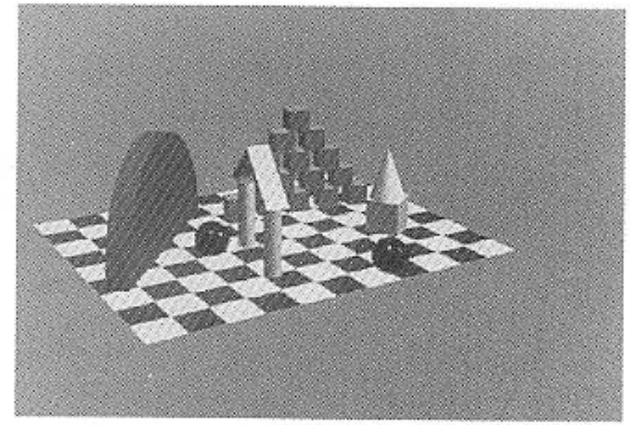
- **Hierarchy of transformations**

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

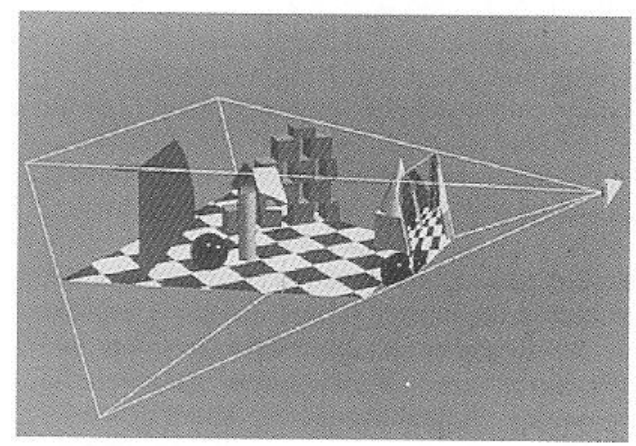
  - Each transformation is relative to its parent
    - Concatenated my multiplying and pushing onto a stack
    - Going back by poping from the stack
  - This transformation stack was so common, it *was* build into OpenGL

Coordinate Transformations

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



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

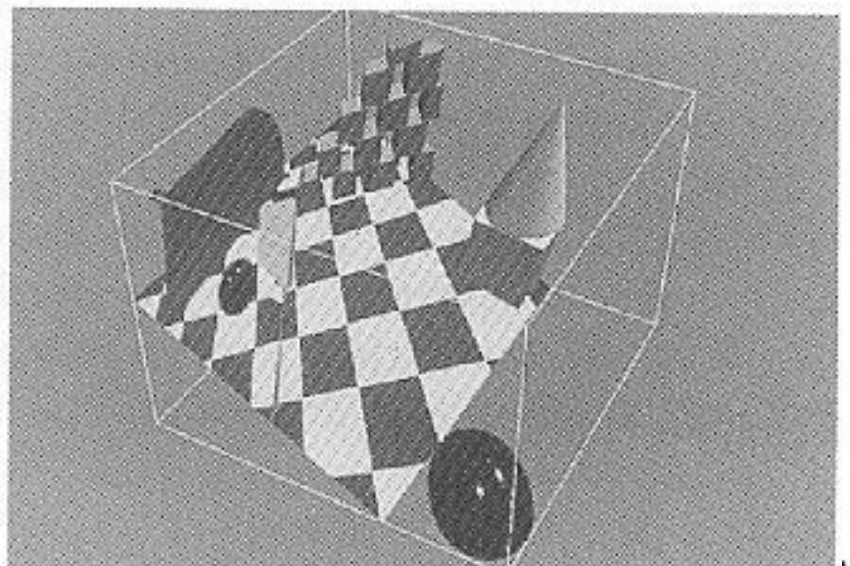


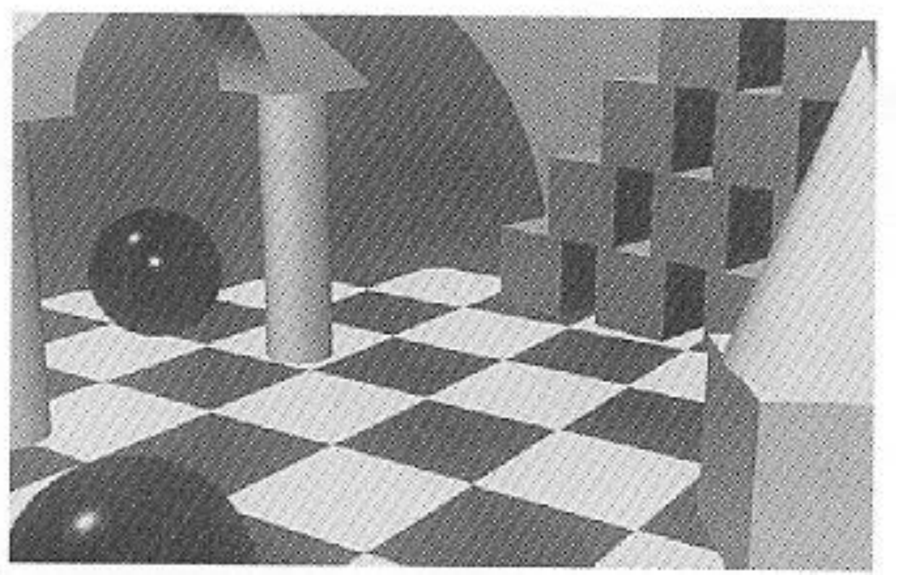
- **Combination: Modelview transformation**
  - Used by *traditional* OpenGL (although world space is conceptually intuitive, it isn't explicitly exposed)

Coordinate Transformations

- **Projective transformation**
  - Eye space to normalized device space (defined by view frustum)
  - Parallel or perspective projection
  - 3D to 2D: Preservation of depth in Z coordinate

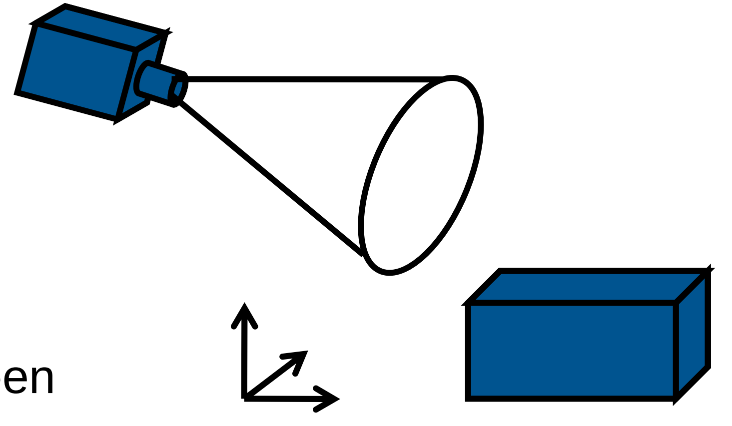
- **Viewport transformation**
  - Normalized device space to window (raster) coordinates





Camera & Perspective Transforms

- **Goal**
  - Compute the transformation between points in 3D and pixels on the screen
  - Required for rasterization algorithms (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



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

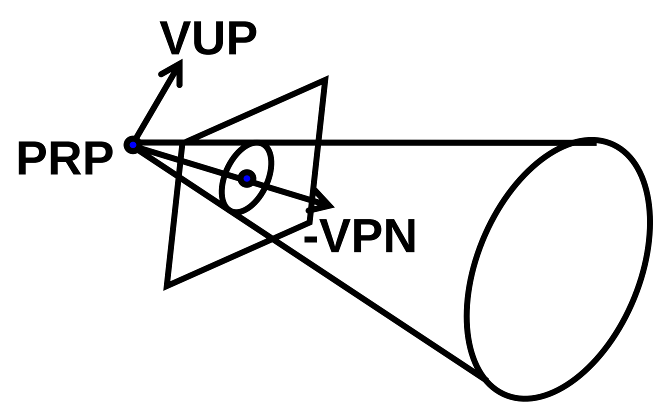
Viewing Transformation

- **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

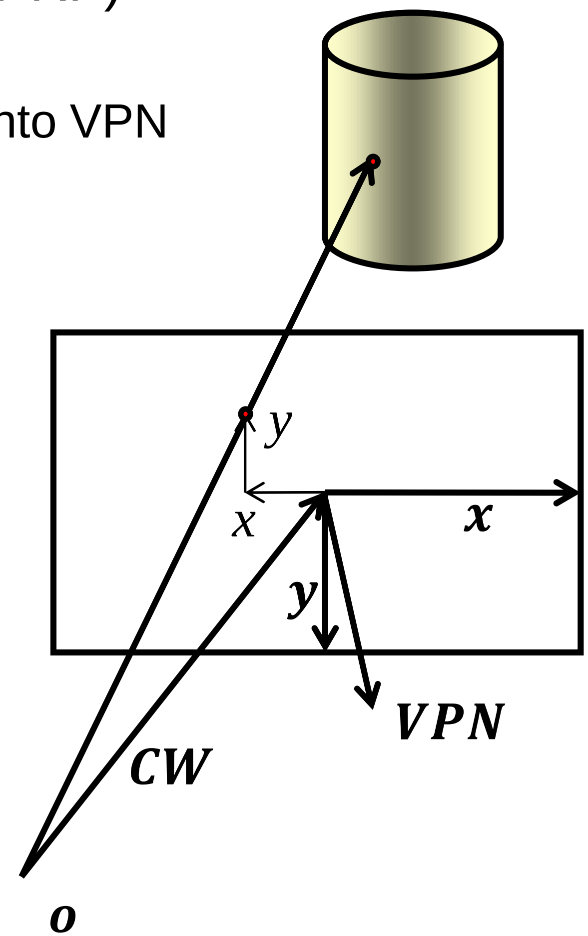


Perspective Transformation

- **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
  - 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

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: $\mathrm{camera}_{ratio} = |x|/|y|$



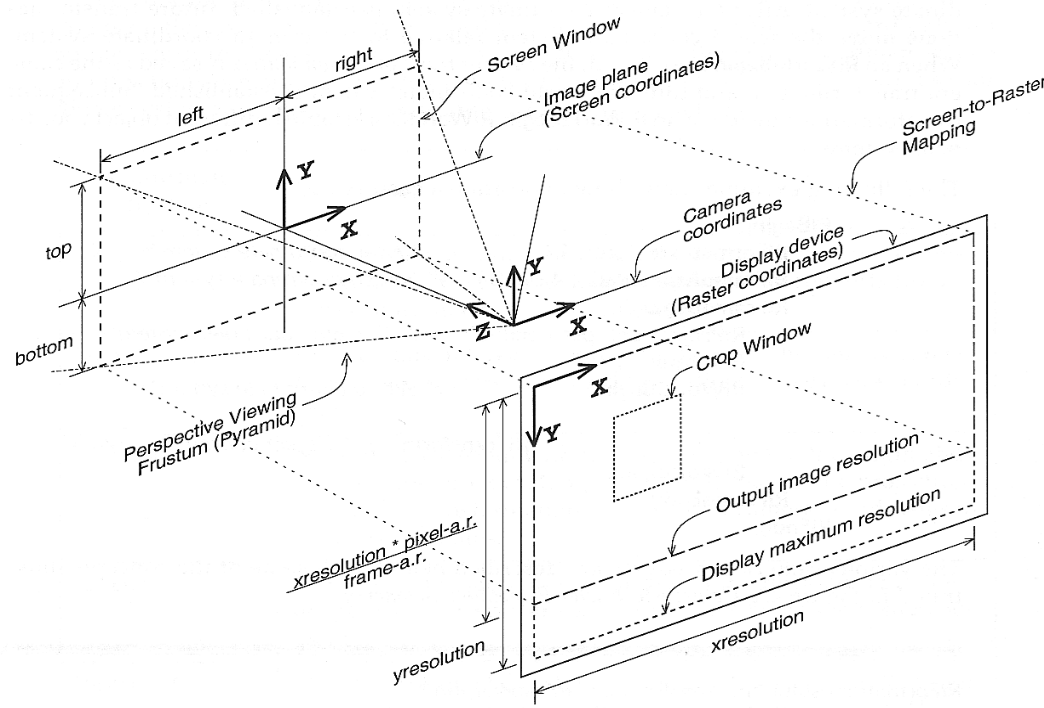
PRP: Projection reference point
VPN: View plane normal
VUP: View up vector
CW: Center of window

Viewport Transformation

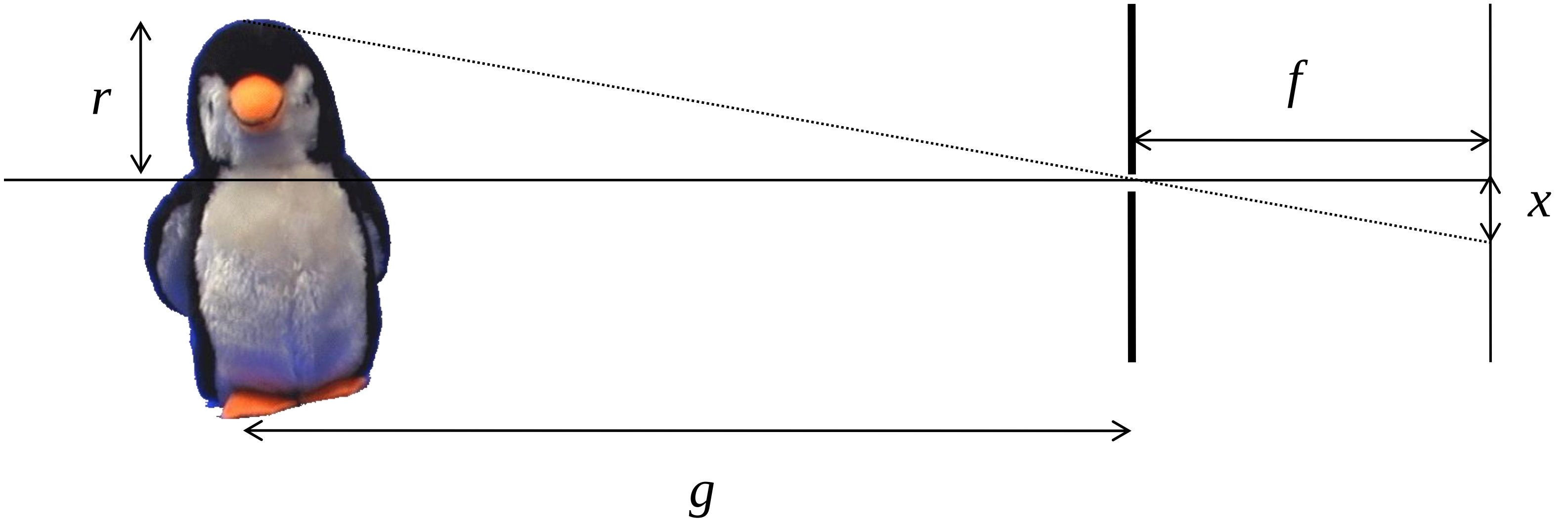
- **Normalized Device Coordinates (NDC)**
  - Intrinsic camera parameters transform to NDC
    - $[0,1]^2$ for x, y across the screen window
    - [0,1] for z (depth)
- **Mapping NDC to raster coordinates on the screen**
  - $xres, yres$: Size of window in pixels
    - Should have same aspect ratios to avoid distortion
      - $camera_{ratio} = \frac{xres}{yres}\frac{pixelspacing_x}{pixelspacing_y}$,
    - Horizontal and vertical pixel spacing (distance between 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

Camera Parameters: Rend.Man

- **RenderMan camera specification**
  - Almost identical to above description
    - 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



Pinhole Camera Model



$$\frac{r}{g} = \frac{x}{f} \Rightarrow x = \frac{fr}{g}$$

Infinitesimally small pinhole

⇒ Theoretical (non-physical) model

⇒ Sharp image everywhere

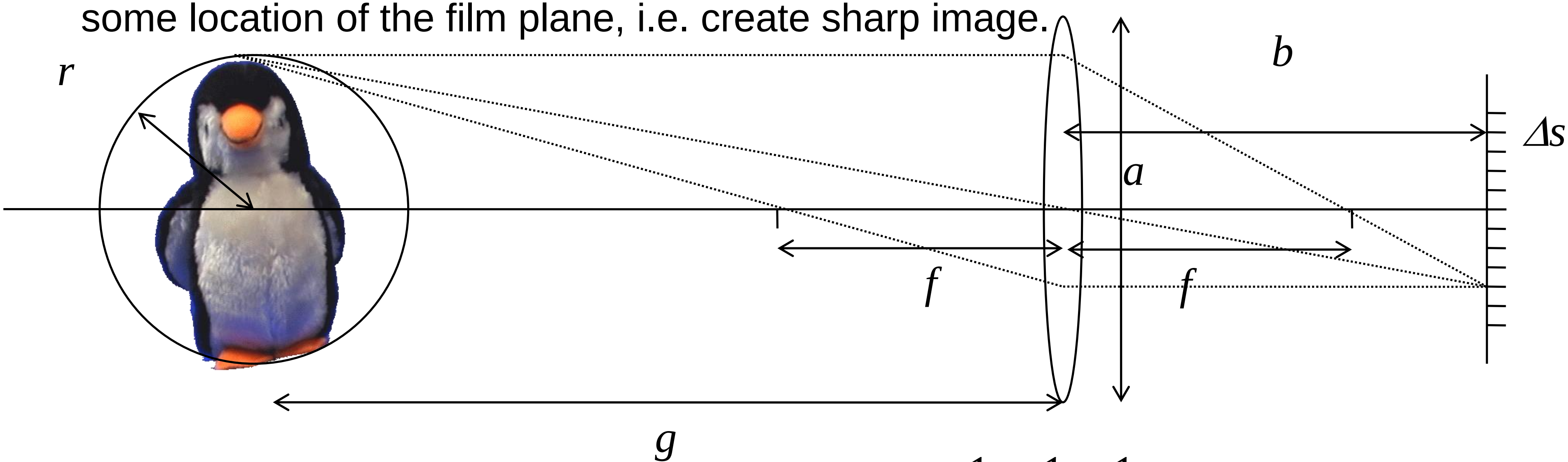
⇒ Infinite depth of field

⇒ Infinitely dark image in reality

⇒ Diffraction effects in reality

Thin Lens Model

Lens focuses light from given position on object through finite-size aperture onto some location of the film plane, i.e. create sharp image.

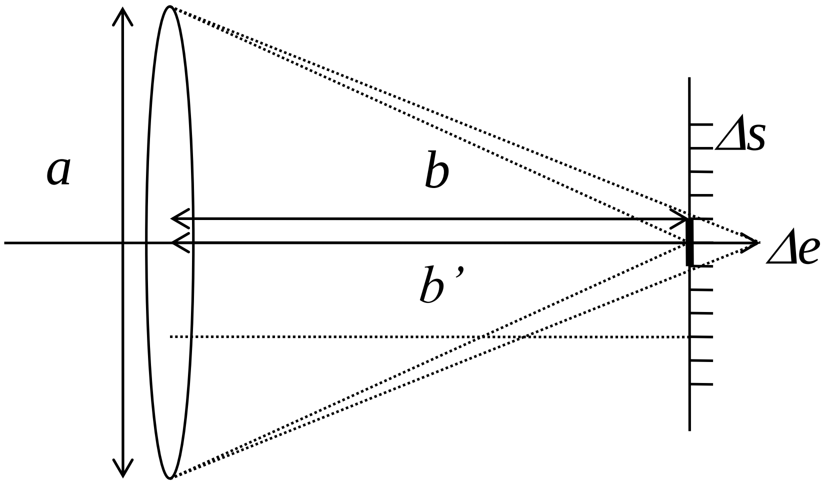


Lens formula defines reciprocal focal length (focus distance from lens of parallel light) $\frac{1}{f} = \frac{1}{b} + \frac{1}{g}$

Object center at distance *g* is in focus at $b = \frac{fg}{g-f}$

Object front at distance *g-r* is in focus at $b' = \frac{f(g-r)}{(g-r)-f}$

Thin Lens Model: Depth of Field



Circle of confusion (CoC) $\Delta e = \left| a\left(1 - \frac{b}{b'}\right) \right|$

Sharpness criterion based on pixel size and CoC $\Delta s > \Delta e$

DOF: Defined radius r, such that CoC smaller than Δ*s*

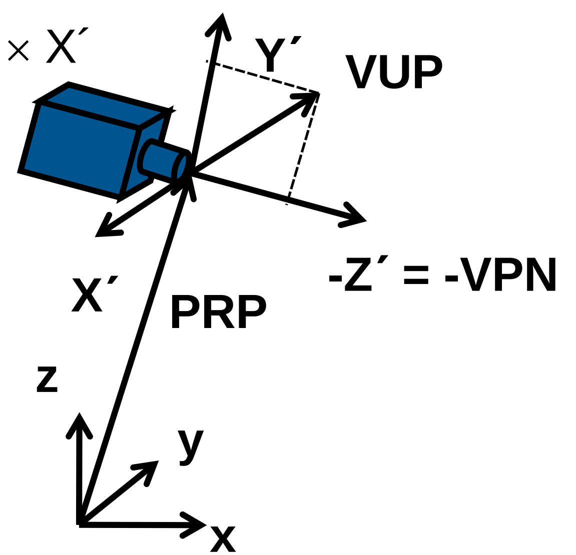
Depth of field (DOF) $r < \frac{g\Delta s(g-f)}{af + \Delta s(g-f)} \Rightarrow r \propto \frac{1}{a}$

The smaller the aperture, the larger the depth of field

Viewing Transformation

- **Let's put this all together**
- **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**
  - Translation followed by rotation

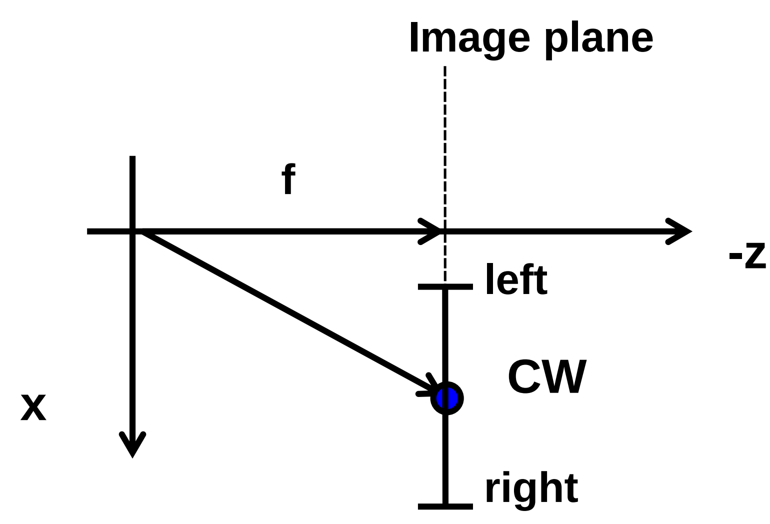
$$V = RT = \begin{pmatrix} X'_x & Y'_x & Z'_x & 0 \\ X'_y & Y'_y & Z'_y & 0 \\ X'_z & Y'_z & Z'_z & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}^T T(-PRP)$$



Sheared Perspective Transformation

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

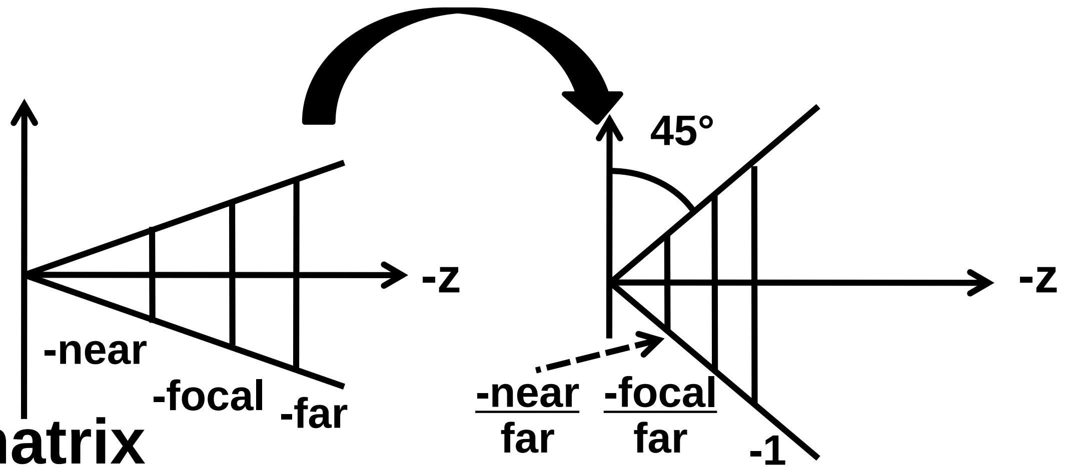
$$H = \begin{pmatrix} 1 & 0 & -\frac{CW_x}{CW_z} & 0 \\ 0 & 1 & -\frac{CW_y}{CW_z} & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$



View from top

Normalizing

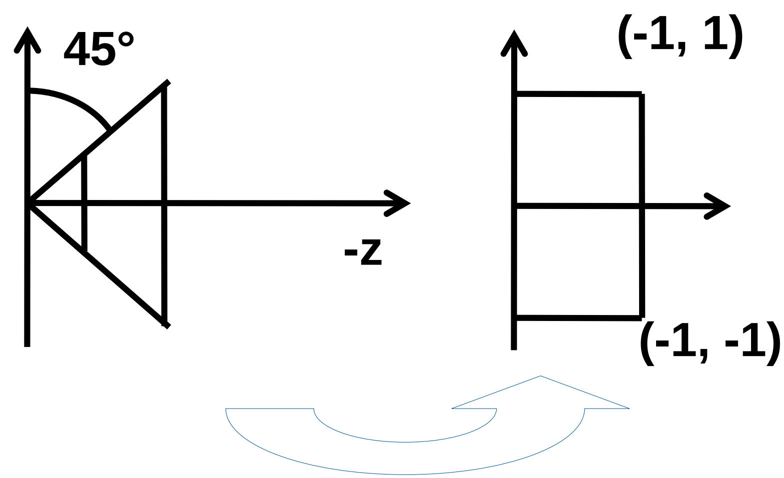
- **Step 2: Scaling to canonical viewing frustum**
  - Scale in X and Y such that screen window boundaries open at 45 degree angles (at focal plane)
  - Scale in Z such that far clipping plane is at Z= -1



- **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

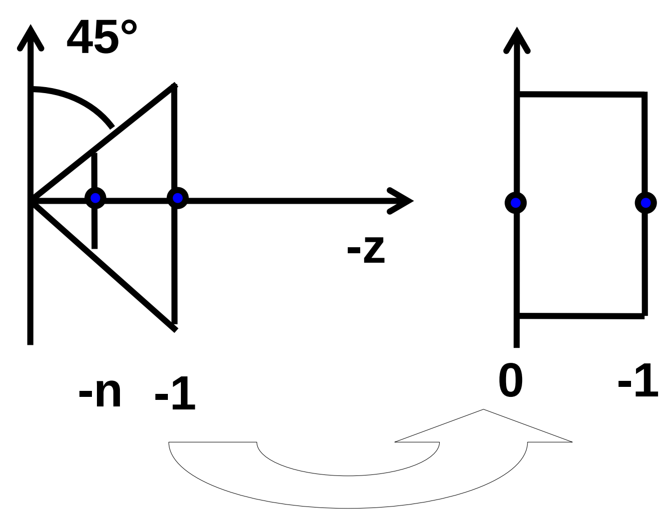
- **Step 3: Perspective transformation**
  - From canonical perspective viewing frustum (= cone at origin around -Z-axis) to regular box $[-1 .. 1]^2 \times [0 .. 1]$
- **Mapping of X and Y**
  - Lines through the origin are mapped to lines parallel to the Z-axis
    - x´= x/-z and y´= y/-z (coordinate 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 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 $(0,0,0,1)=P(0,0,-n,1)$
- **Resulting Projective transformation**
  - $P = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \frac{1}{1-n} & \frac{n}{1-n} \\ 0 & 0 & -1 & 0 \end{pmatrix}$
  - Transform Z non-linearly (in 3D)
    - $z' = -\frac{z+n}{z(1-n)}$



Parallel Projection to 2D

- **Parallel projection to $[-1 .. 1]^2$**
  - Formally scaling in Z with factor 0
  - Typically maintains Z in [0,1] for depth buffering
    - As a vertex attribute (see OpenGL later)
- **Transformation from $[-1 .. 1]^2$ to NDC ($[0 .. 1]^2$)**
  - Scaling (by 1/2 in X and Y) and translation (by (1/2,1/2))
- **Projection matrix for combined transformation**
  - Delivers normalized device coordinates
    - $P_{parallel} = \begin{pmatrix} \frac{1}{2} & 0 & 0 & \frac{1}{2} \\ 0 & \frac{1}{2} & 0 & \frac{1}{2} \\ 0 & 0 & 0 \text{ or } 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$

Viewport Transformation

- **Scaling and translation in 2D**
  - Scaling matrix to map to entire window on screen
    - $S_{raster}(xres, yres)$
    - No distortion if aspects ration have been handled correctly earlier
    - Sometime need to reverse direction of y
      - Some formats have origin at bottom left, some at top left
      - Needs additional translation
  - 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**

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

Camera Transformation

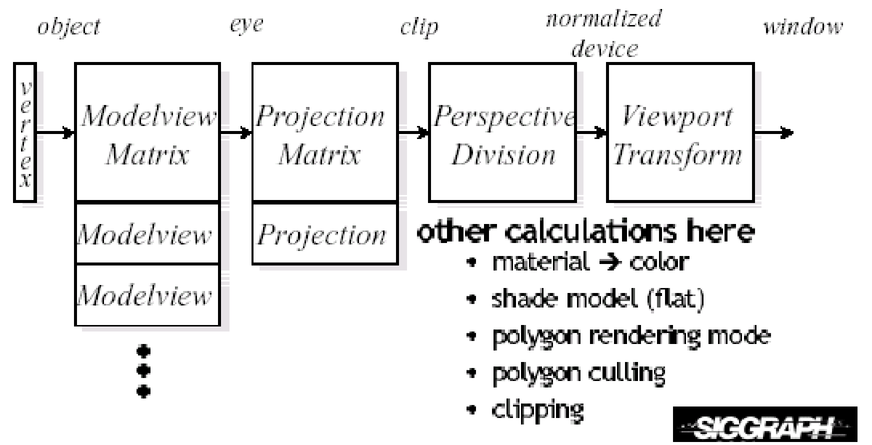
- **Complete transformation (combination of matrices)**
  - Perspective Projection
    - $T_{camera} = T_{raster}\, S_{raster}\, P_{parallel}\, P_{persp}\, S_{far}\, S_{xy}\, H\, R\, T$
  - Orthographic Projection
    - $T_{camera} = T_{raster}\, S_{raster}\, P_{parallel}\, S_{xyz}\, T_{near} H\, R\,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

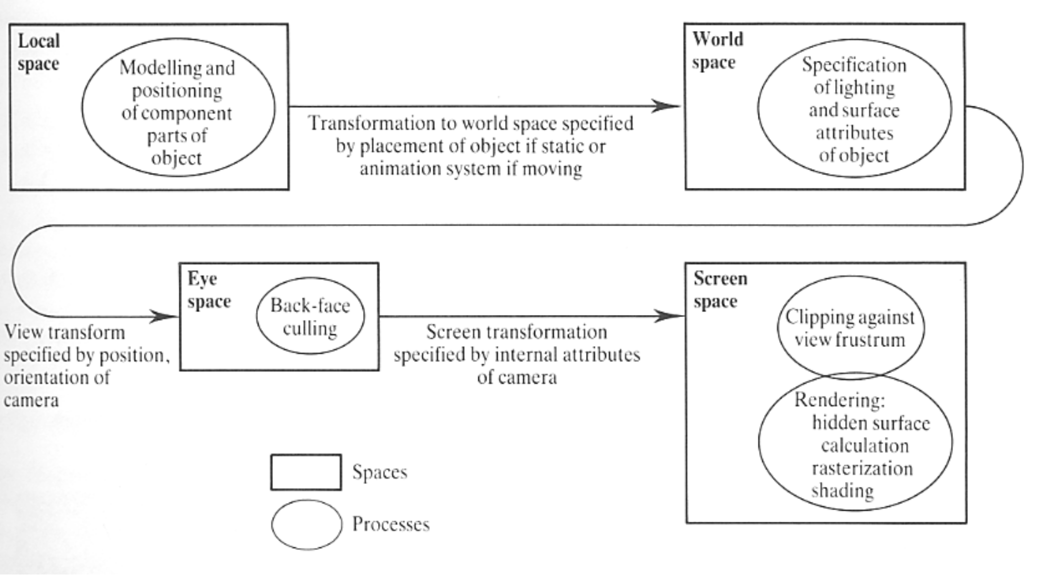
- **Other representations**
  - Other literature uses different conventions
    - Different camera parameters as input
    - Different canonical viewing frustum
    - Different normalized coordinates
      - $[-1 .. 1]^3$ versus $[0 .. 1]^3$ versus ...
  - ...

  → *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

- **Traditional ModelView matrix**
  - Modeling transformations AND viewing transformation
  - No explicit world coordinates
- **Traditional Perspective transformation**
  - Simple specification
    - glFrustum(left, right, bottom, top, near, far)
    - glOrtho(left, right, bottom, top, near, far)

- **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)