



Projection Matrix Tricks

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**Terathon
Software**

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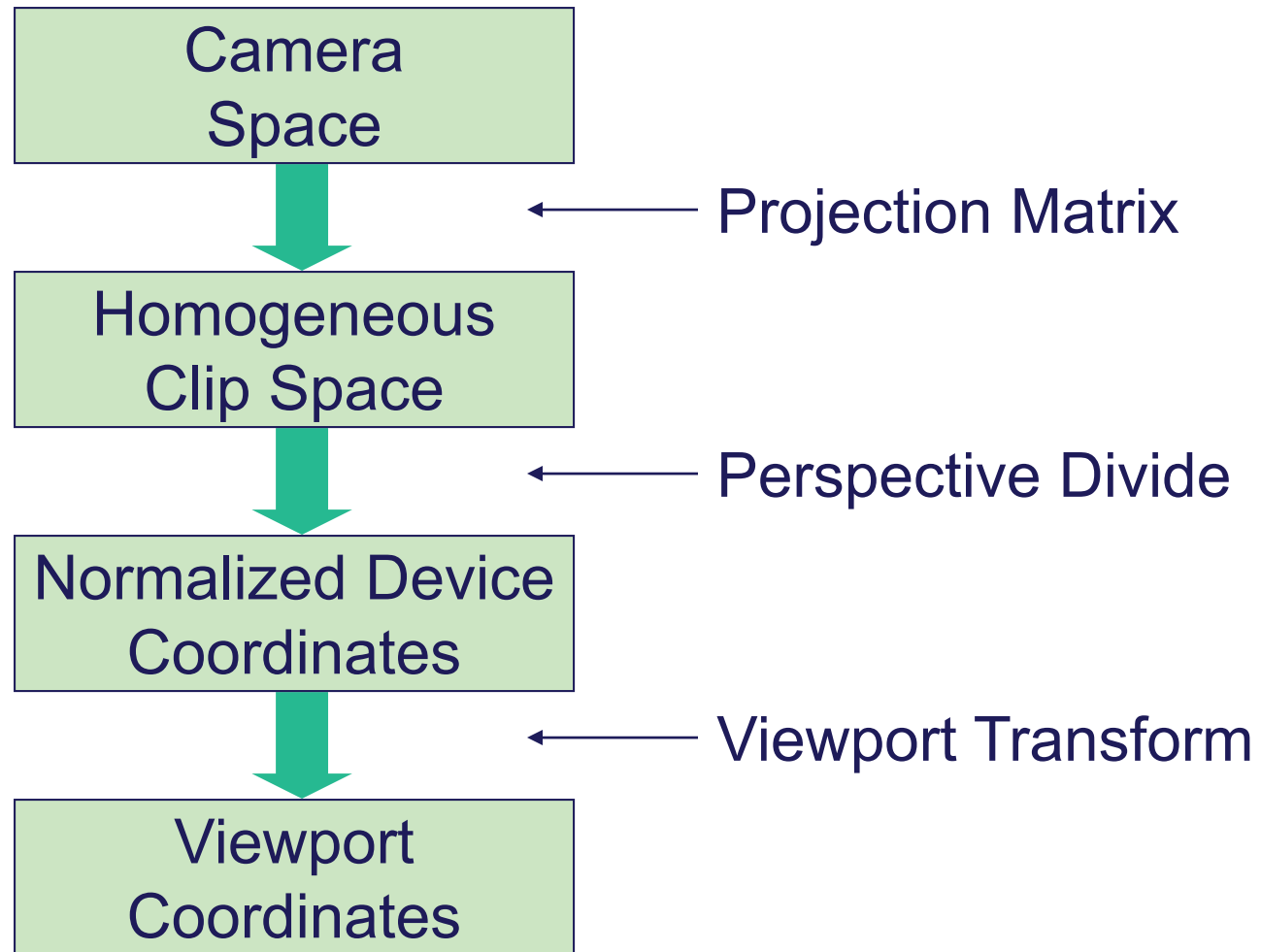


Outline

- Projection Matrix Internals
 - Infinite Projection Matrix
 - Depth Modification
 - Oblique Near Clipping Plane
-
- Slides available at <http://www.terathon.com/>



From Camera to Screen





Projection Matrix

- The 4×4 projection matrix is really just a linear transformation in homogeneous space
- It doesn't actually perform the projection, but just sets things up right for the next step
- The projection occurs when you divide by w to get from homogenous coordinates to 3-space



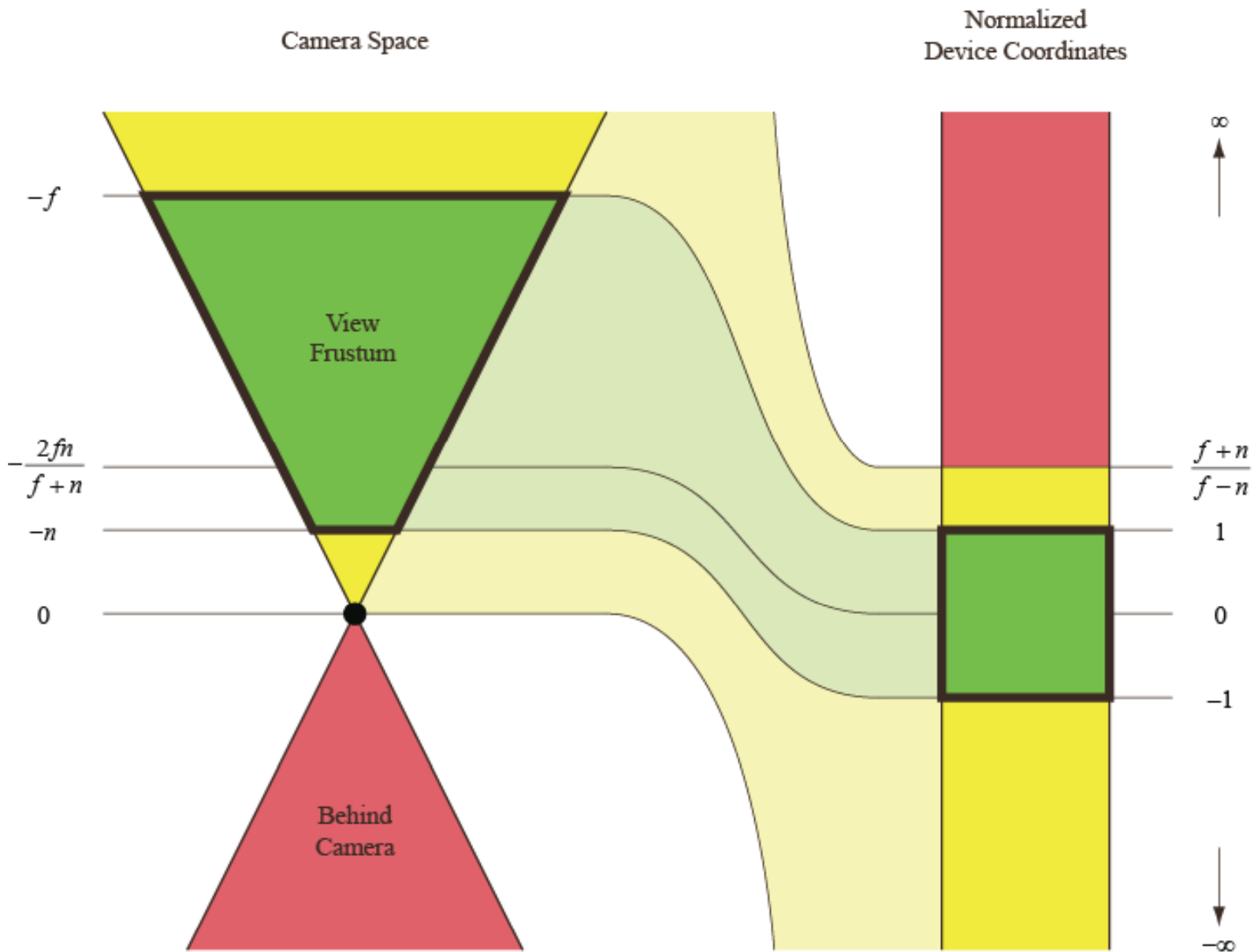
OpenGL projection matrix

- n, f = distances to near, far planes
- e = focal length = $1 / \tan(\text{FOV} / 2)$
- a = viewport height / width

$$\begin{bmatrix} e & 0 & 0 & 0 \\ 0 & e/a & 0 & 0 \\ 0 & 0 & -\frac{f+n}{f-n} & -\frac{2fn}{f-n} \\ 0 & 0 & -1 & 0 \end{bmatrix}$$

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Infinite Projection Matrix

- Take limit as f goes to infinity

$$\lim_{f \rightarrow \infty} \begin{bmatrix} e & 0 & 0 & 0 \\ 0 & e/a & 0 & 0 \\ 0 & 0 & -\frac{f+n}{f-n} & -\frac{2fn}{f-n} \\ 0 & 0 & -1 & 0 \end{bmatrix} = \begin{bmatrix} e & 0 & 0 & 0 \\ 0 & e/a & 0 & 0 \\ 0 & 0 & -1 & -2n \\ 0 & 0 & -1 & 0 \end{bmatrix}$$



Infinite Projection Matrix

- Directions are mapped to points on the infinitely distant far plane
- A direction is a 4D vector with $w = 0$ (and at least one nonzero x, y, z)
- Good for rendering sky objects
 - Skybox, sun, moon, stars
- Also good for rendering stencil shadow volume caps



Infinite Projection Matrix

- The important fact is that z and w are equal after transformation to clip space:

$$\begin{bmatrix} e & 0 & 0 & 0 \\ 0 & e/a & 0 & 0 \\ 0 & 0 & -1 & -2n \\ 0 & 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 0 \end{bmatrix} = \begin{bmatrix} ex \\ (e/a)y \\ -z \\ -z \end{bmatrix}$$



Infinite Projection Matrix

- After perspective divide, the z coordinate should be exactly 1.0, meaning that the projected point is precisely on the far plane:

$$\begin{bmatrix} ex \\ (e/a)y \\ -z \\ -z \end{bmatrix} \rightarrow \begin{bmatrix} -ex/z \\ -ey/az \\ 1 \end{bmatrix}$$



Infinite Projection Matrix

- But there's a problem...
- The hardware doesn't actually perform the perspective divide immediately after applying the projection matrix
- Instead, the viewport transformation is applied to the (x, y, z) coordinates first



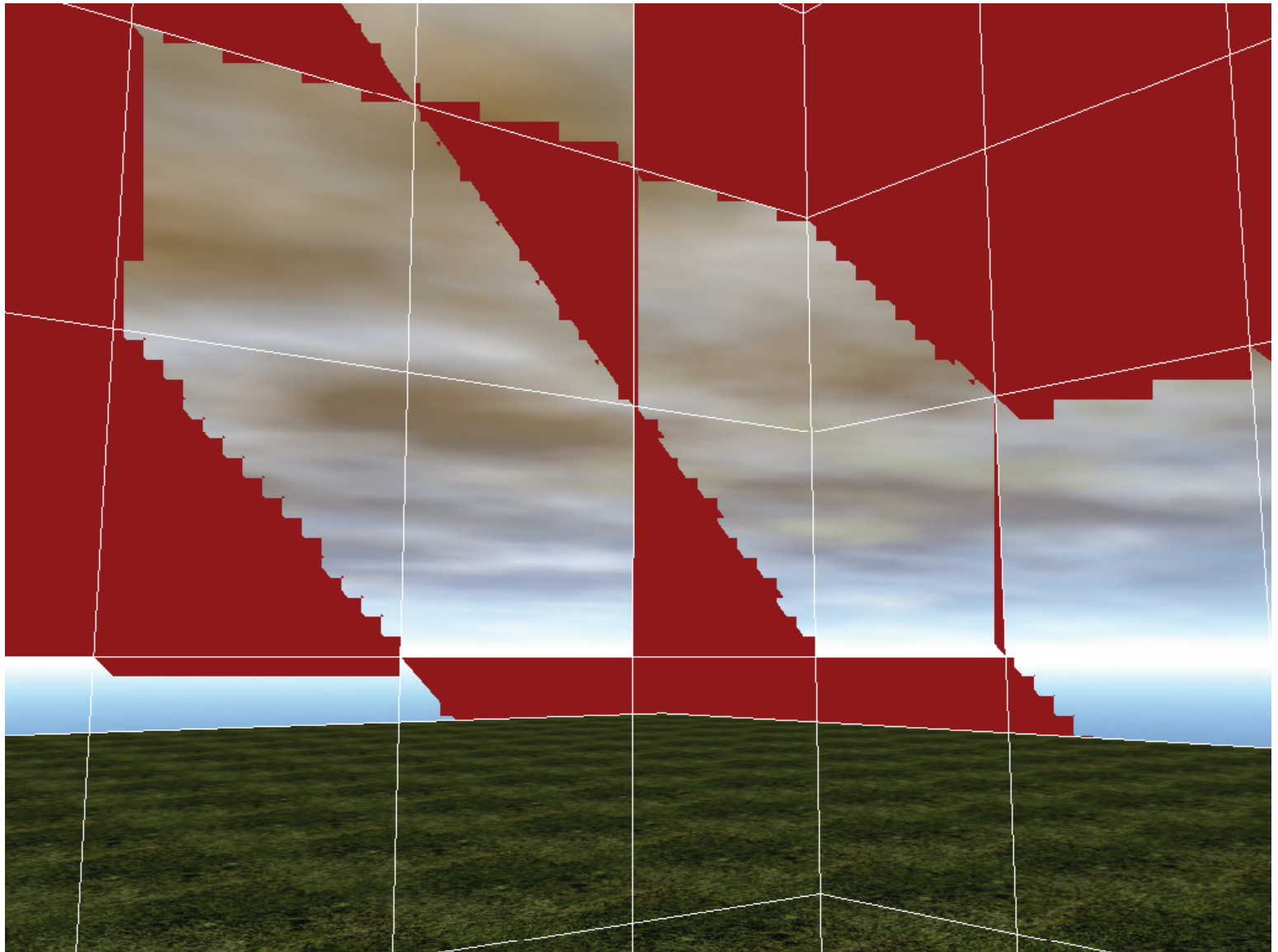
Infinite Projection Matrix

- Ordinarily, z is mapped from the range $[-1, 1]$ in NDC to $[0, 1]$ in viewport space by multiplying by 0.5 and adding 0.5
- This operation can result in a loss of precision in the lowest bits
- Result is a depth slightly smaller than 1.0 or slightly bigger than 1.0



Infinite Projection Matrix

- If the viewport-space z coordinate is slightly bigger than 1.0, then fragment culling occurs
- The hardware thinks the fragments are beyond the far plane
- Can be corrected by enabling `GL_DEPTH_CLAMP_NV`, but this is a vendor-specific solution



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Infinite Projection Matrix

- Universal solution is to modify projection matrix so that viewport-space z is always slightly less than 1.0 for points on the far plane:

$$\begin{bmatrix} e & 0 & 0 & 0 \\ 0 & e/a & 0 & 0 \\ 0 & 0 & \varepsilon - 1 & (\varepsilon - 2)n \\ 0 & 0 & -1 & 0 \end{bmatrix}$$



Infinite Projection Matrix

- This matrix still maps the near plane to -1 , but the infinite far plane is now mapped to $1 - \varepsilon$

$$\begin{bmatrix} \varepsilon - 1 & (\varepsilon - 2)n \\ -1 & 0 \end{bmatrix} \begin{bmatrix} -n \\ 1 \end{bmatrix} = \begin{bmatrix} -n \\ n \end{bmatrix}$$

$$\begin{bmatrix} \varepsilon - 1 & (\varepsilon - 2)n \\ -1 & 0 \end{bmatrix} \begin{bmatrix} z \\ 0 \end{bmatrix} = \begin{bmatrix} z(\varepsilon - 1) \\ -z \end{bmatrix}$$



Infinite Projection Matrix

- Because we're calculating $\varepsilon - 1$ and $\varepsilon - 2$, we need to choose

$$\varepsilon \geq 2^{-22} \approx 2.4 \times 10^{-7}$$

so that 32-bit floating-point precision limits aren't exceeded



Depth Modification

- Several methods exist for performing polygon offset
 - Hardware support through `glPolygonOffset`
 - Fiddle with `glDepthRange`
 - Tweak the projection matrix



Depth Modification

- `glPolygonOffset` works well, but
 - Can adversely affect hierarchical z culling performance
 - Not guaranteed to be consistent across different GPUs
- Adjusting depth range
 - Reduces overall depth precision
- Both require extra state changes



Depth Modification

- NDC depth is given by a function of the lower-right 2×2 portion of the projection matrix:

$$\begin{bmatrix} -\frac{f+n}{f-n} & -\frac{2fn}{f-n} \\ -1 & 0 \end{bmatrix} \begin{bmatrix} z \\ 1 \end{bmatrix} = \begin{bmatrix} -\frac{f+n}{f-n}z - \frac{2fn}{f-n} \\ -z \end{bmatrix}$$

$$z_{NDC} = \frac{f+n}{f-n} + \frac{2fn}{z(f-n)}$$



Depth Modification

- We can add a constant offset ε to the NDC depth as follows:

$$\begin{bmatrix} -\frac{f+n}{f-n} - \varepsilon & -\frac{2fn}{f-n} \\ -1 & 0 \end{bmatrix} \begin{bmatrix} z \\ 1 \end{bmatrix} = \begin{bmatrix} \left(-\frac{f+n}{f-n} - \varepsilon \right) z - \frac{2fn}{f-n} \\ -z \end{bmatrix}$$

$$z_{NDC} = \frac{f+n}{f-n} + \frac{2fn}{z(f-n)} + \varepsilon$$



Depth Modification

- w-coordinate unaffected
- Thus, x and y coordinates unaffected
- z offset is constant in NDC
- But this is not constant in camera space
- For a given offset in camera space, the corresponding offset in NDC depends on the depth



Depth Modification

- What happens to a camera-space offset δ ?

$$\begin{bmatrix} -\frac{f+n}{f-n} & -\frac{2fn}{f-n} \\ -1 & 0 \end{bmatrix} \begin{bmatrix} z+\delta \\ 1 \end{bmatrix} = \begin{bmatrix} -\frac{f+n}{f-n}(z+\delta) - \frac{2fn}{f-n} \\ -(z+\delta) \end{bmatrix}$$

$$z_{NDC} = \frac{f+n}{f-n} + \frac{2fn}{z(f-n)} - \frac{2fn}{f-n} \left(\frac{\delta}{z(z+\delta)} \right)$$



Depth Modification

- NDC offset as a function of camera-space offset δ and camera-space z :

$$\varepsilon(\delta, z) = -\frac{2fn}{f-n} \left(\frac{\delta}{z(z+\delta)} \right)$$

- Remember, δ is positive for an offset toward camera



Depth Modification

- Need to make sure that ε is big enough to make a difference in a typical 24-bit integer z buffer
- NDC range of $[-1, 1]$ is divided into 2^{24} possible depth values
- So $|\varepsilon|$ should be at least $2/2^{24} = 2^{-23}$



Depth Modification

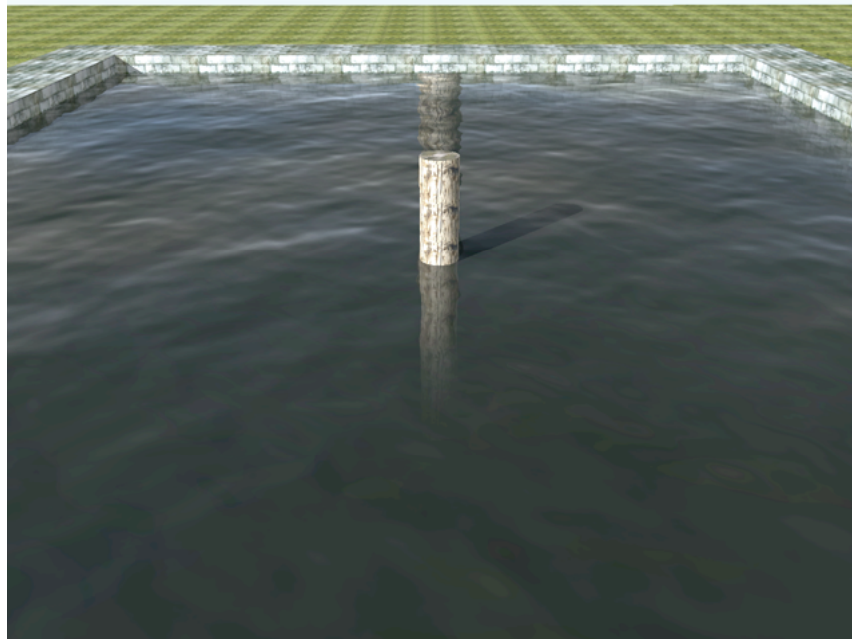
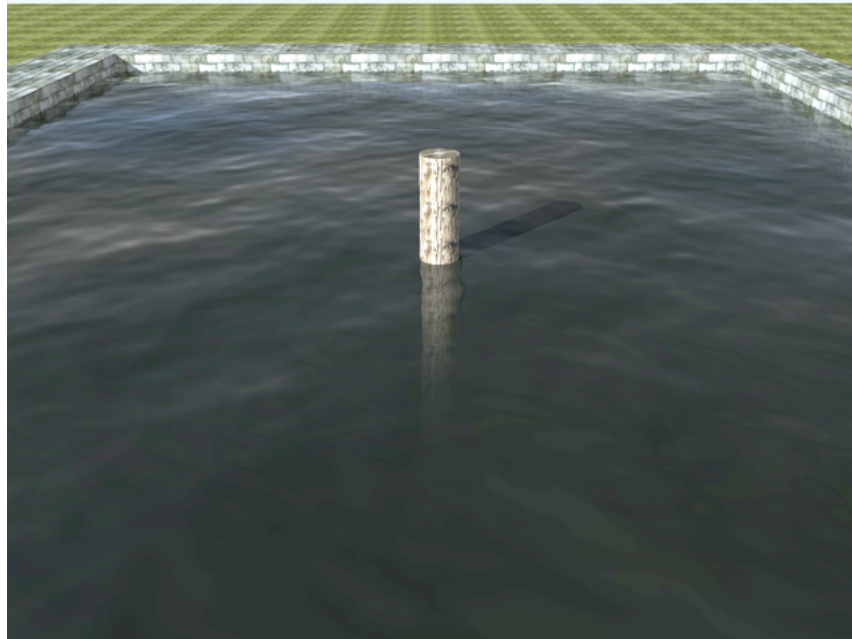
- But we're adding ε to $(f + n)/(f - n)$, which is close to 1.0
- Not enough bits of precision in 32-bit float for this
- So in practice, it's necessary to use

$$|\varepsilon| \geq 2^{-21} \approx 4.8 \times 10^{-7}$$



Oblique Near Clipping Plane

- It's sometimes necessary to restrict rendering to one side of some arbitrary plane in a scene
- For example, mirrors and water surfaces



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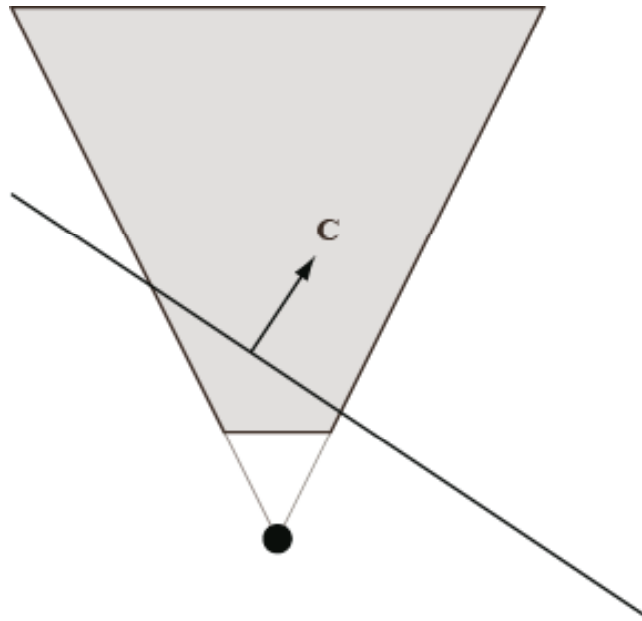
Oblique Near Clipping Plane

- Using an extra hardware clipping plane seems like the ideal solution
 - But some older hardware doesn't support user clipping planes
 - Enabling a user clipping plane could require modifying your vertex programs
 - There's a slight chance that a user clipping plane will slow down your fragment programs



Oblique Near Clipping Plane

- Extra clipping plane almost always redundant with near plane
- No need to clip against both planes





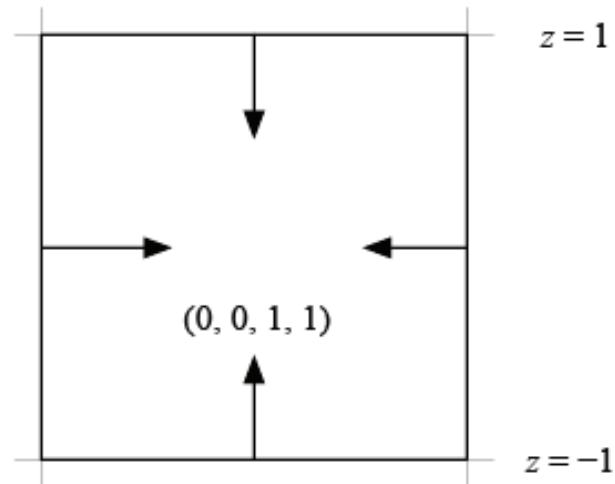
Oblique Near Clipping Plane

- We can modify the projection matrix so that the near plane is moved to an arbitrary location
- No user clipping plane required
- No redundancy



Oblique Near Clipping Plane

- In NDC, the near plane has coordinates $(0, 0, 1, 1)$





Oblique Near Clipping Plane

- Planes are transformed from NDC to camera space by the transpose of the projection matrix
- So the plane $(0, 0, 1, 1)$ becomes $M_3 + M_4$, where M_i is the i -th row of the projection matrix
- M_4 must remain $(0, 0, -1, 0)$ so that perspective correction still works right



Oblique Near Clipping Plane

- Let $C = (C_x, C_y, C_z, C_w)$ be the camera-space plane that we want to clip against instead of the conventional near plane
- We assume the camera is on the negative side of the plane, so $C_w < 0$
- We must have $C = M_3 + M_4$, where $M_4 = (0, 0, -1, 0)$



Oblique Near Clipping Plane

- $M_3 = C - M_4 = (C_x, C_y, C_z + 1, C_w)$

$$M = \begin{bmatrix} e & 0 & 0 & 0 \\ 0 & e/a & 0 & 0 \\ C_x & C_y & C_z + 1 & C_w \\ 0 & 0 & -1 & 0 \end{bmatrix}$$

- This matrix maps points on the plane C to the $z = -1$ plane in NDC



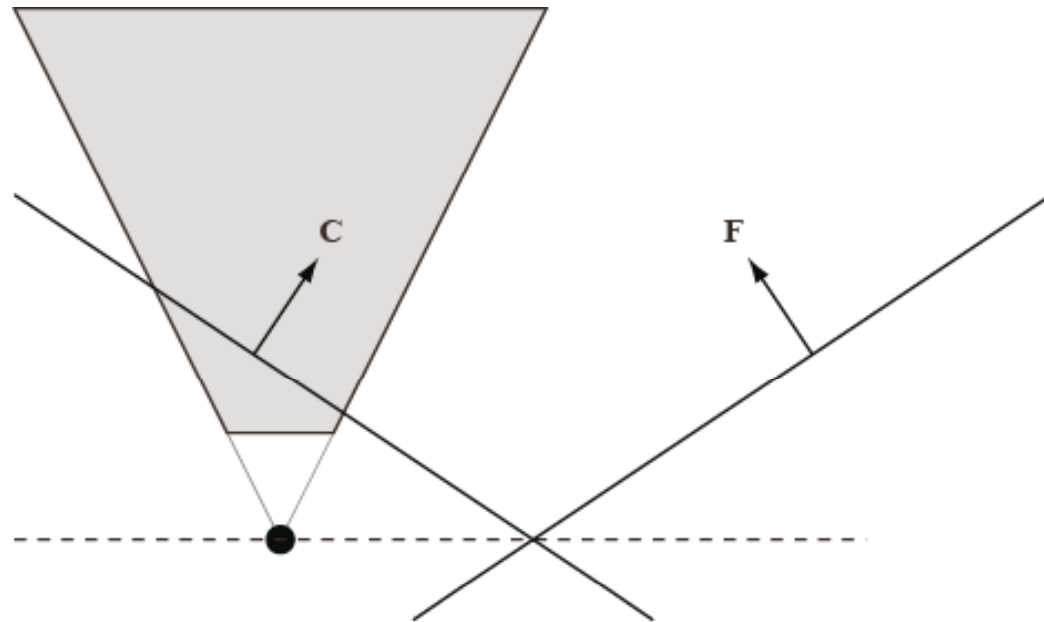
Oblique Near Clipping Plane

- But what happens to the far plane?
- $F = M_4 - M_3 = 2M_4 - C$
- Near plane and far plane differ only in the z coordinate
- Thus, they must coincide where they intersect the $z = 0$ plane



Oblique Near Clipping Plane

- Far plane is completely hosed!





Oblique Near Clipping Plane

- Depths in NDC no longer represent distance from camera plane, but correspond to the position between the oblique near and far planes
- We can minimize the effect, and in practice it's not so bad



Oblique Near Clipping Plane

- We still have a free parameter: the clipping plane C can be scaled
- Scaling C has the effect of changing the orientation of the far plane F
- We want to make the new view frustum as small as possible while still including the conventional view frustum



Oblique Near Clipping Plane

- Let $F = 2M_4 - aC$
- Choose the point Q which lies furthest opposite the near plane in NDC:

$$Q = M^{-1} \cdot (\text{sgn}(C_x), \text{sgn}(C_y), 1, 1)$$

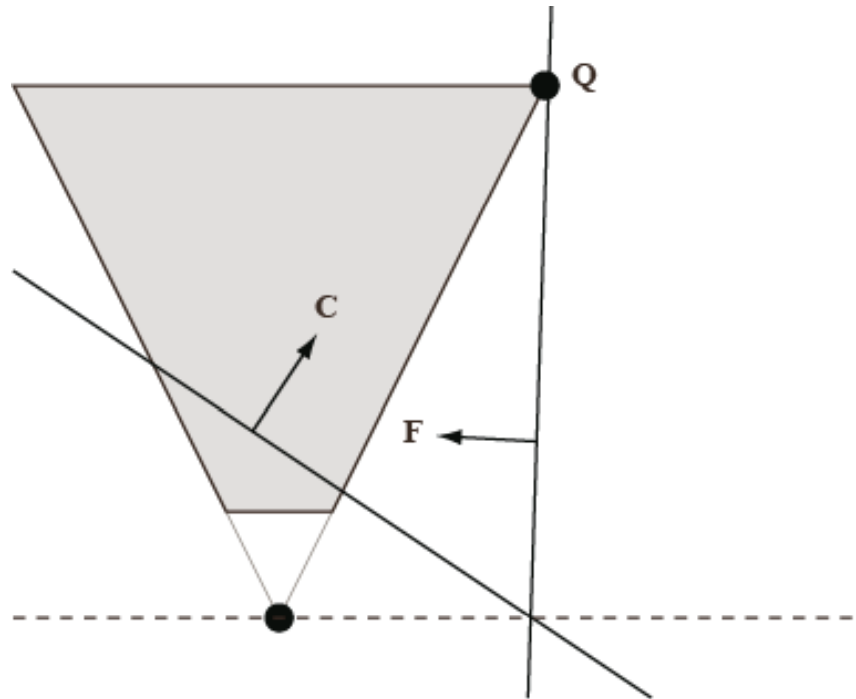
- Solve for a such that Q lies in plane F (i.e., $F \cdot Q = 0$):

$$a = \frac{2M_4 \cdot Q}{C \cdot Q}$$



Oblique Near Clipping Plane

- Near plane doesn't move, but far plane becomes optimal





Oblique Near Clipping Plane

- This also works for infinite view frustum
- Far plane ends up being parallel to one of the edges between two side planes

- For more analysis, see *Journal of Game Development*, Vol 1, No 2



Questions?

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