Stereoscopy, From XY to Z

http://developer.nvidia.com/siggraph-2011-stereoscopy-course

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SIGGRAPH | 2011 | Vancouver

NVIDIA

Agenda

9:00	Welcome	
9:05	Stereoscopy fundamentals and depth perception	Samuel Gateau
9:40	Stereopsis and 3D hints	Marc Salvati
10:10	Depth as storytelling tool	Robert Neuman
10:30	Real-time & gaming techniques	Samuel Gateau
11:00	Cartoon Authoring for 3D	Marc Salvati
11:30	Creative choices for 3D	Robert Salvati
11:50	Managing a depth budget	Robert Salvati
12:10	Questions	

Course available at
http://developer.nvidia.com/siggraph-2011-stereoscopy-course

Special Thanks...

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STEREOSCOPIC

by Lightspeed Design, Inc.

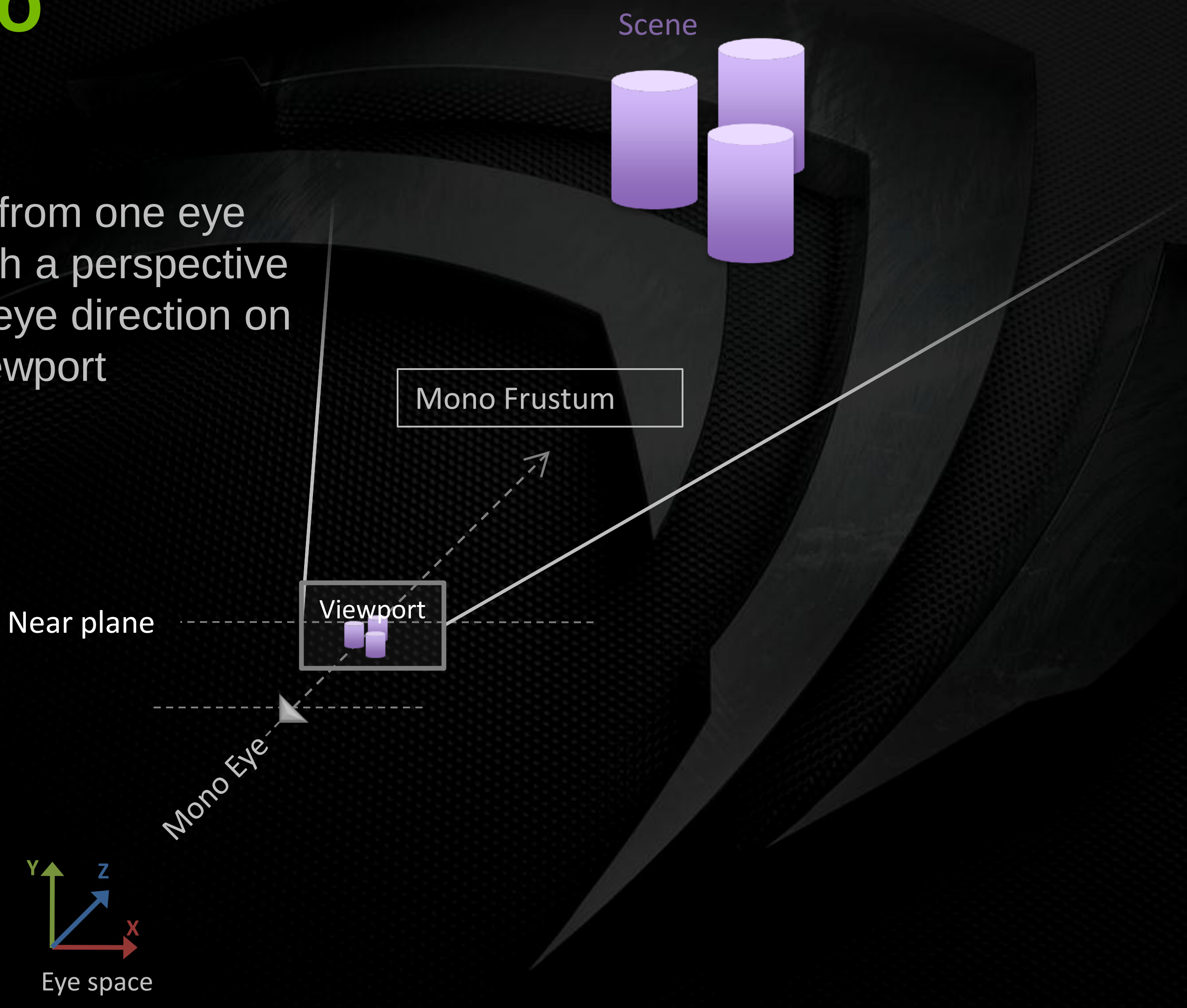
How does it work ?

Changes to the rendering pipe

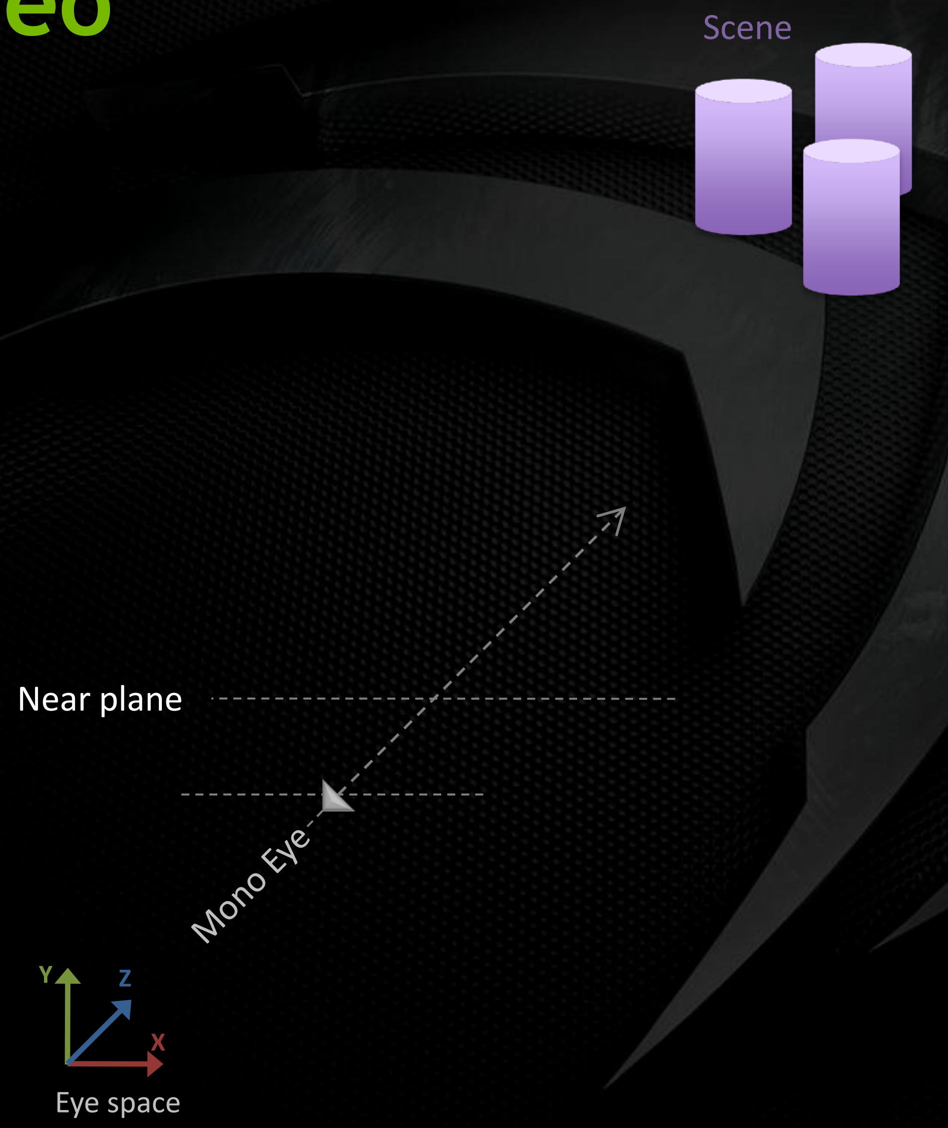
TWO EYES, ONE SCREEN, TWO IMAGES

In Mono

Scene is viewed from one eye and projected with a perspective projection along eye direction on Near plane in Viewport

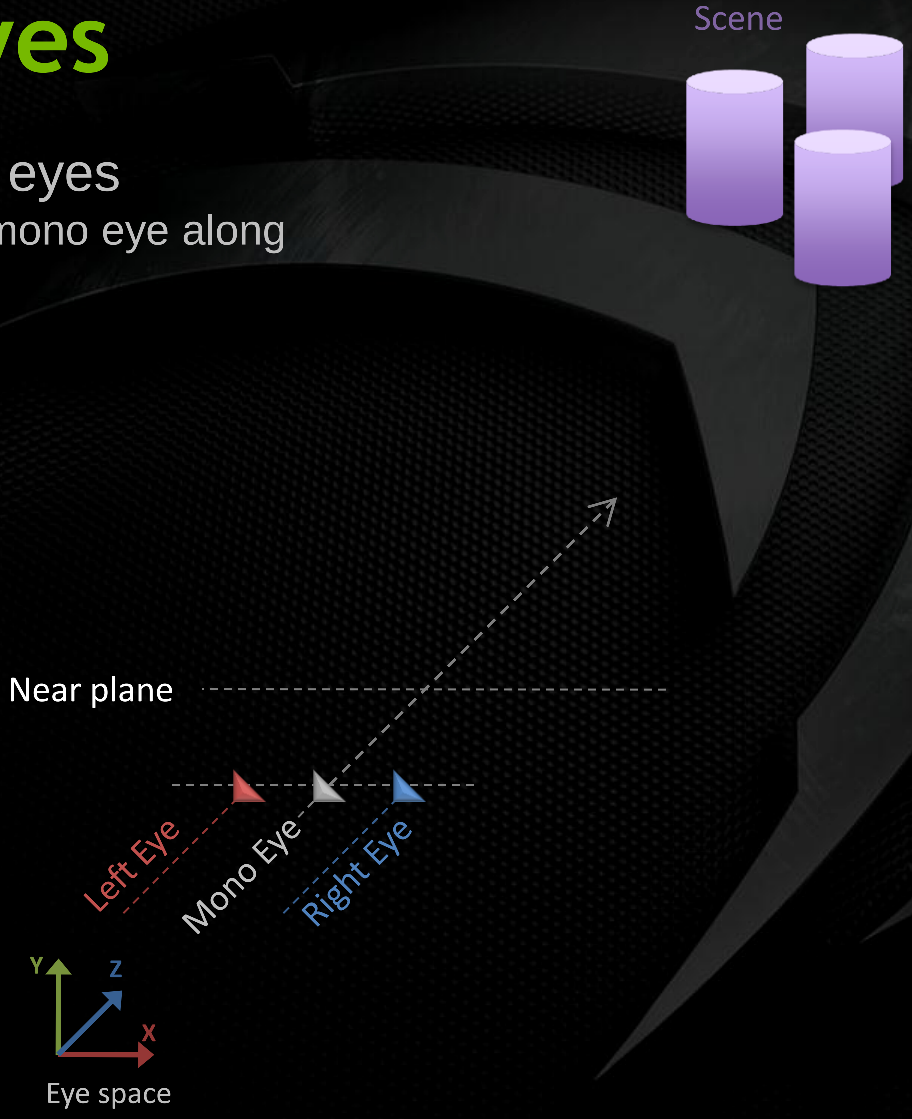


In Stereo



In Stereo:
Two eyes

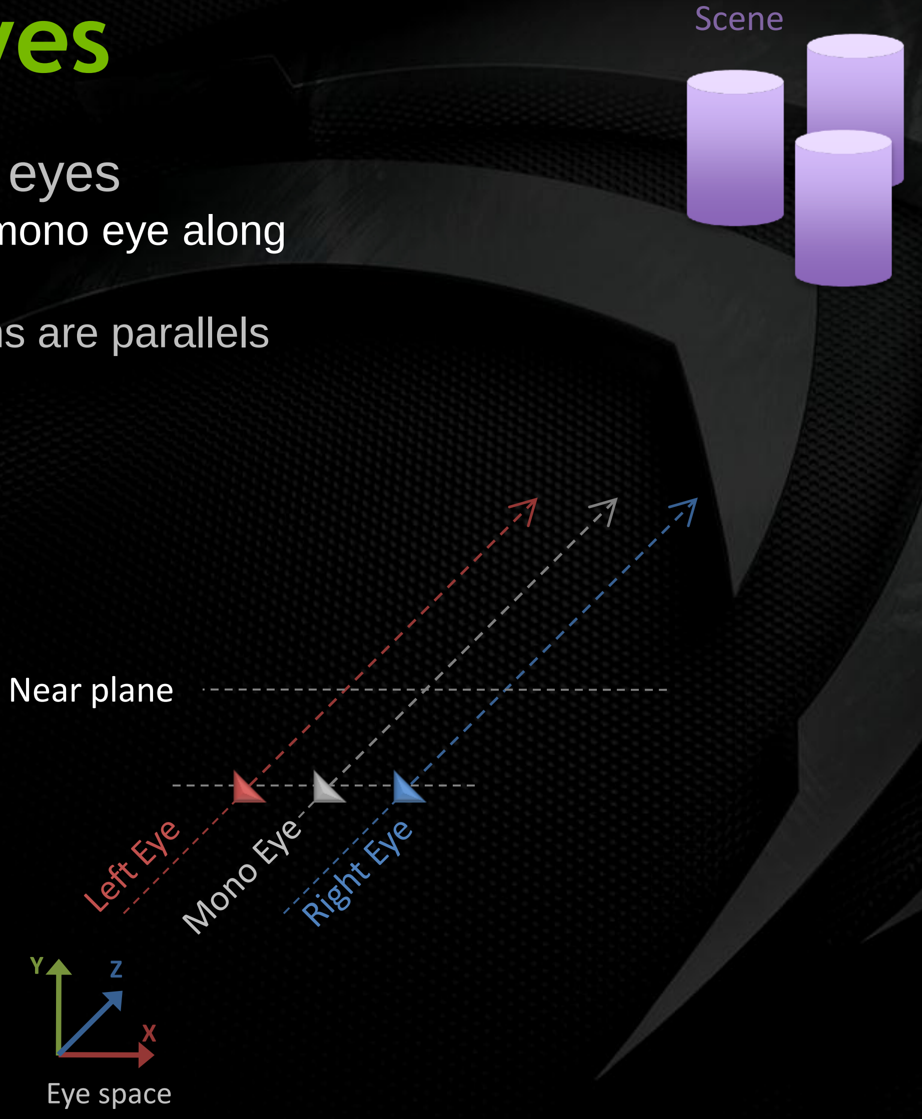
Left and Right eyes
- Shifting the mono eye along the X axis



In Stereo:
Two eyes

Left and Right eyes

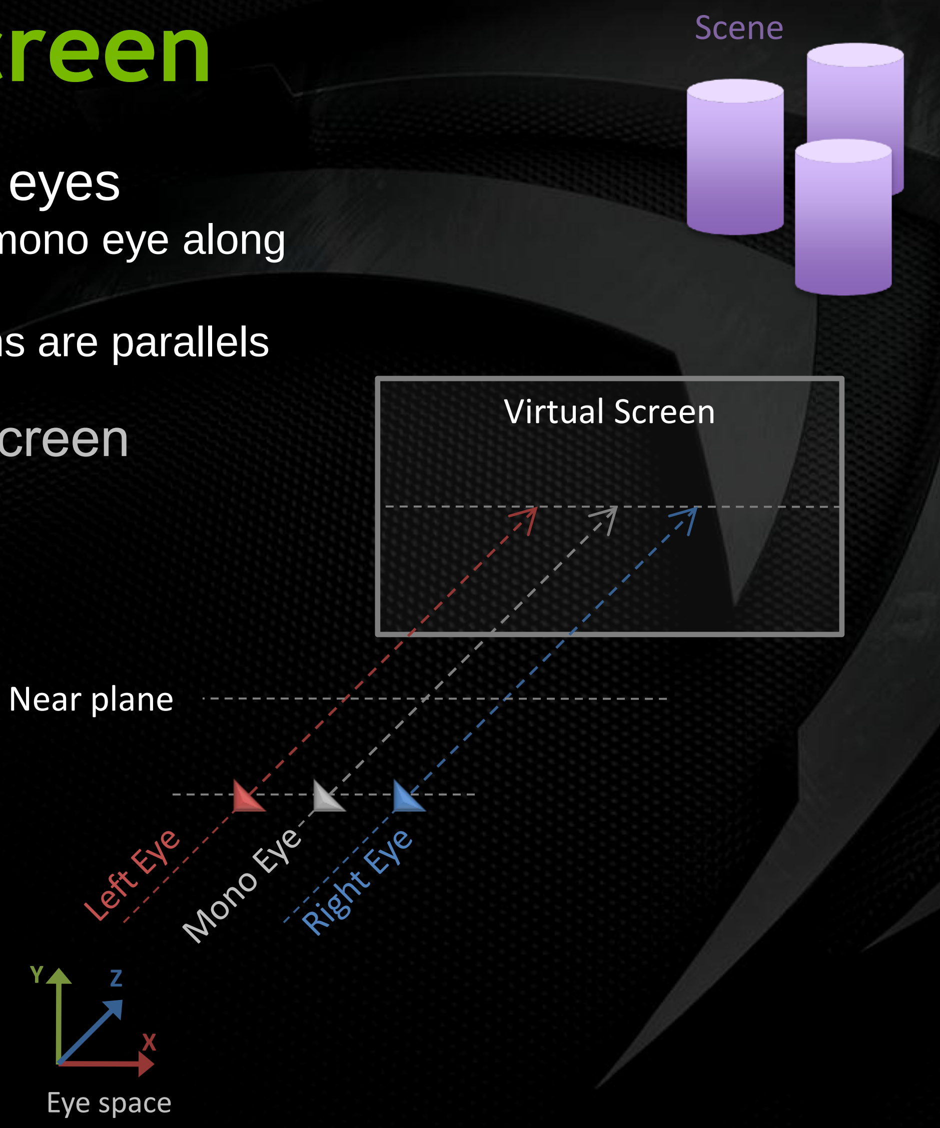
- Shifting the mono eye along the X axis
- Eye directions are parallels



In Stereo: Two Eyes,
One Screen

Left and Right eyes
- Shifting the mono eye along the X axis
- Eye directions are parallels

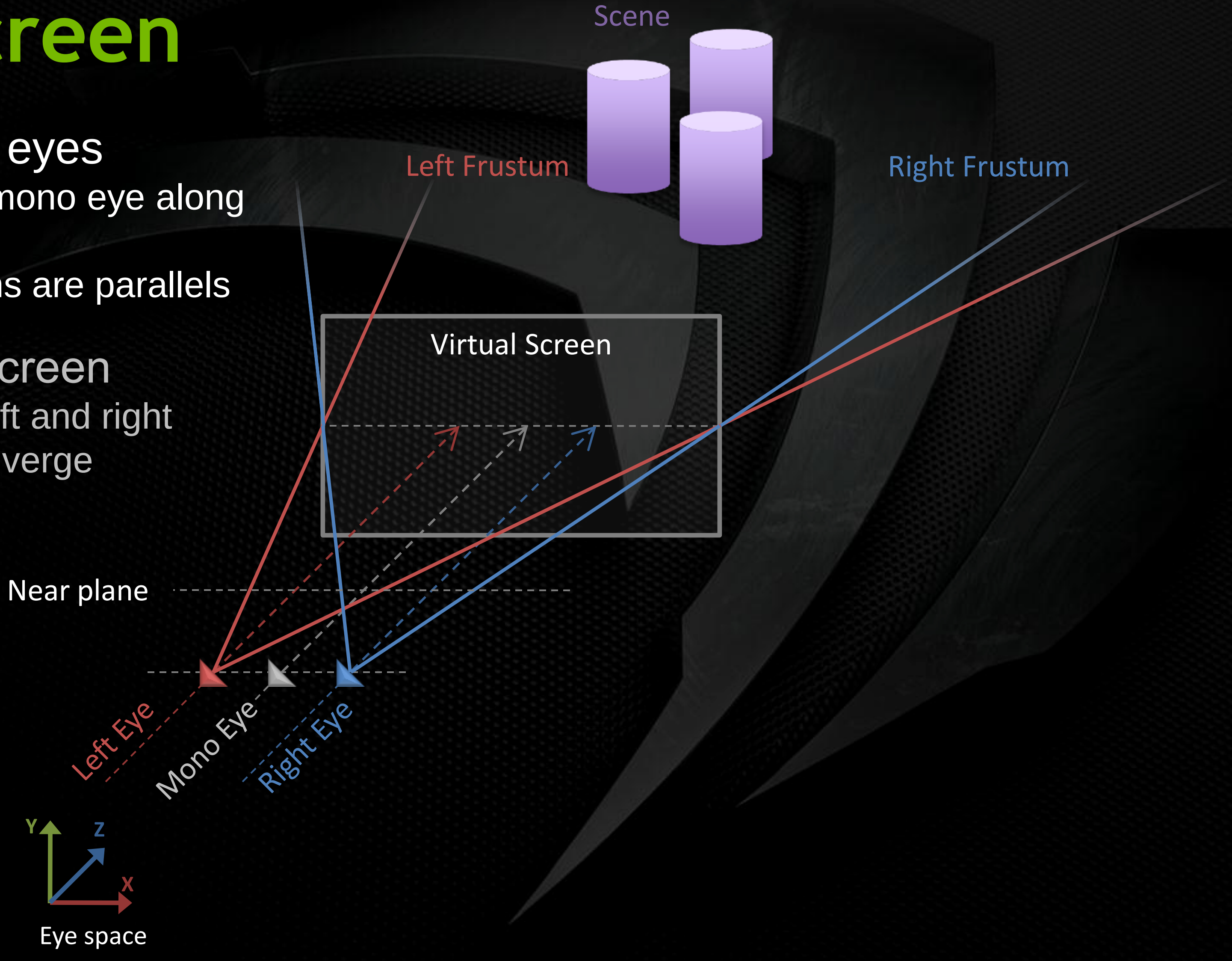
One "virtual" screen



In Stereo: Two Eyes,
One Screen

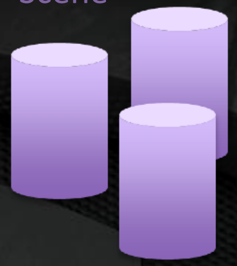
Left and Right eyes
- Shifting the mono eye along the X axis
- Eye directions are parallels

One “virtual” screen
- Where the left and right frustums converge



In Stereo: Two Eyes, One Screen,

Two Images



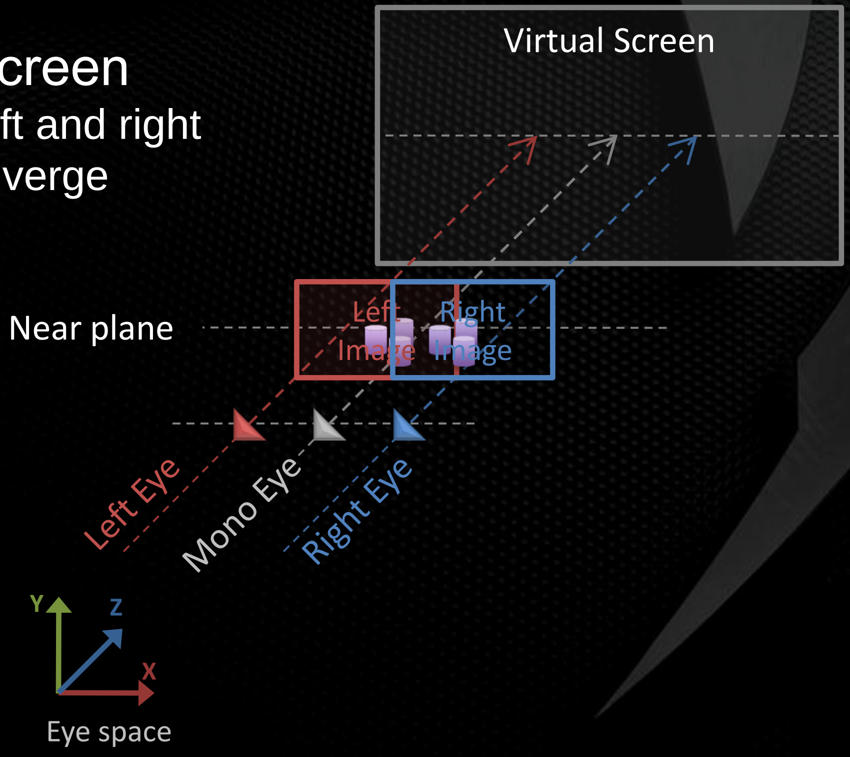
Left and Right eyes

Shifting the mono eye along the X axis

Eye directions are parallels

One "virtual" screen

Where the left and right frustums converge

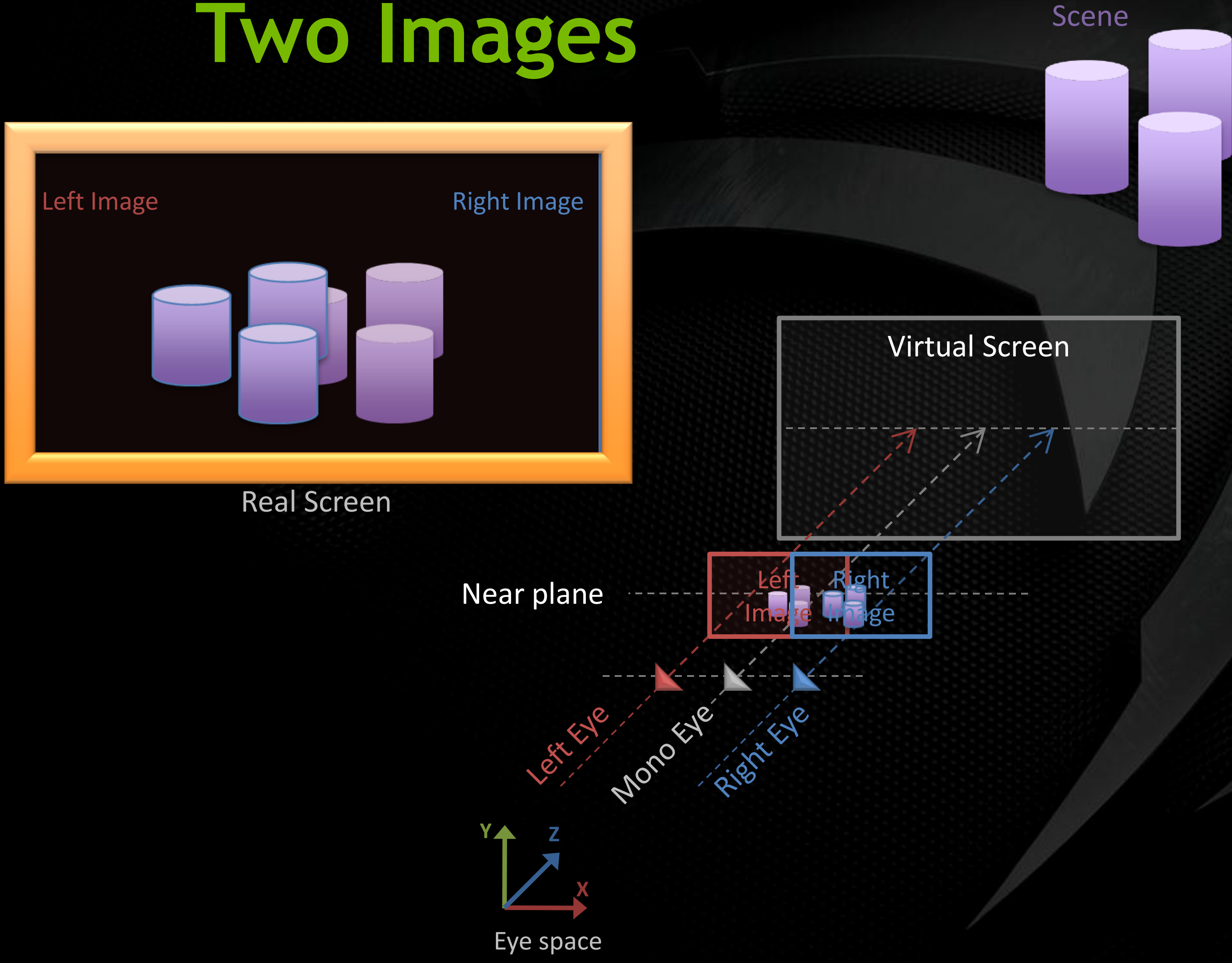


Two images

2 images are generated at the near plane in each views

In Stereo: Two Eyes, One Screen,

Two Images



Two images

2 images are generated at the near plane in each views

Presented independently to each eyes of the user on the real screen

Stereoscopic Rendering

Render geometry twice

From left and right eyes

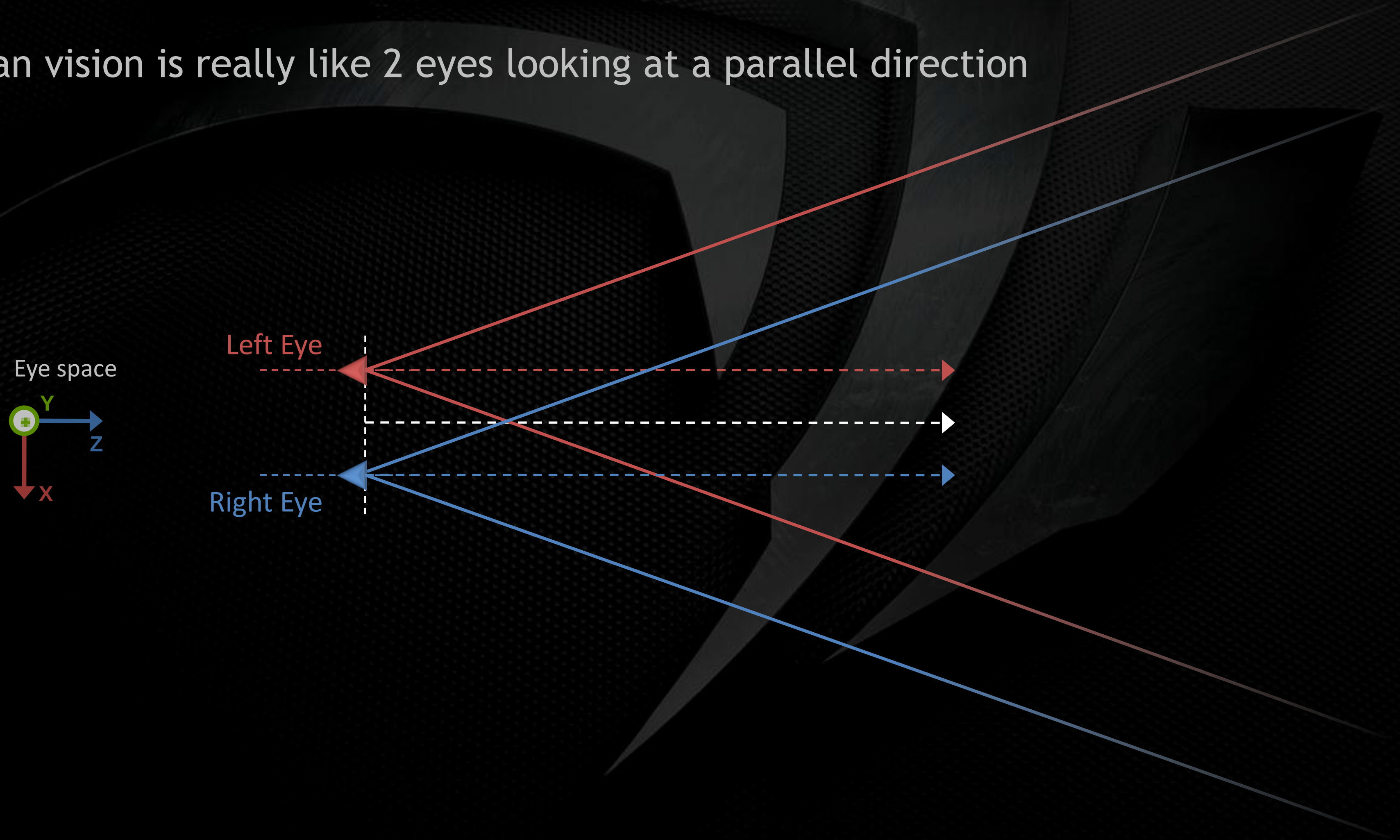
Into left and right images

Basic definitions so we all speak English

DEFINING STEREO PROJECTION

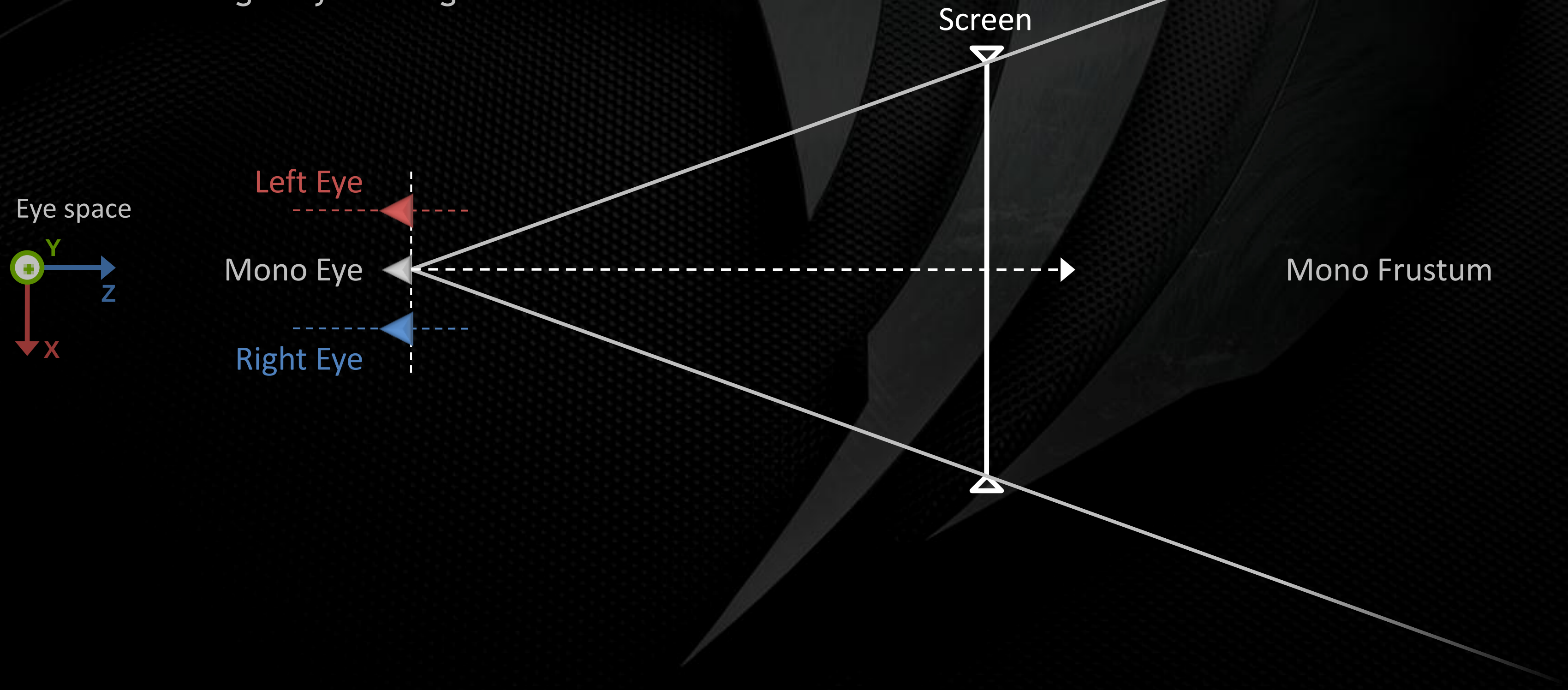
Stereo Projection

- Human vision is really like 2 eyes looking at a parallel direction



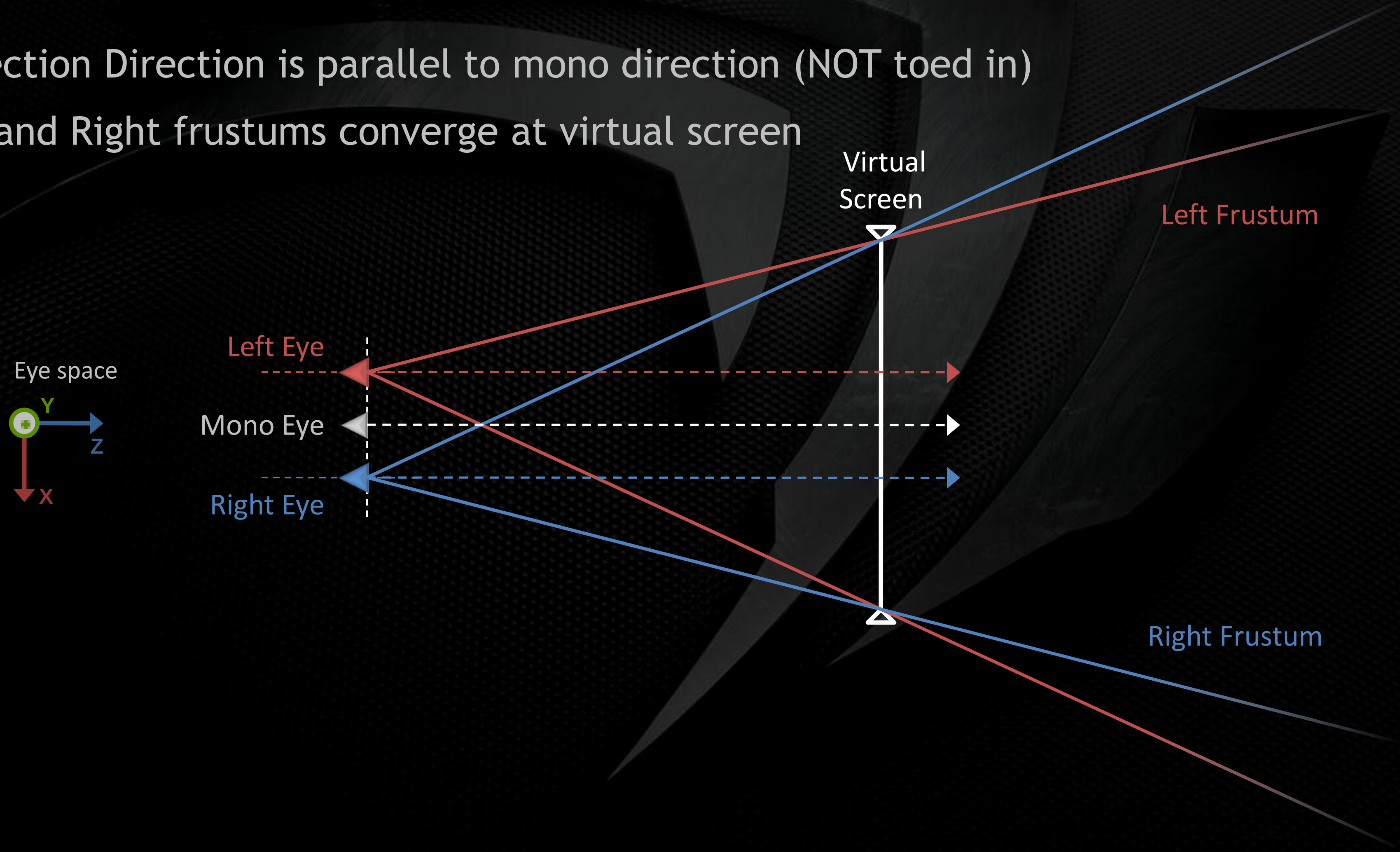
Stereo Projection

- Stereo projection matrix is a horizontally offset version of regular mono projection matrix
  - Offset Left / Right eyes along X axis



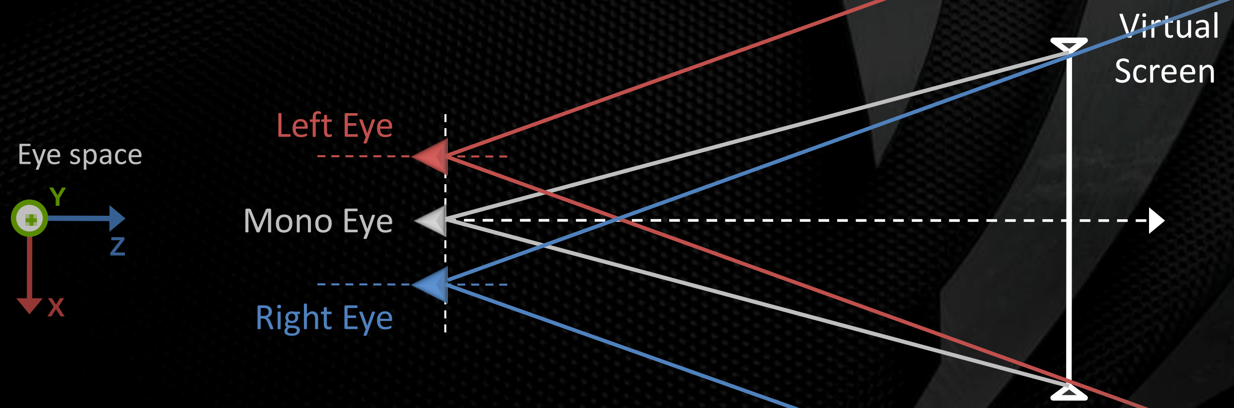
Stereo Projection

- Projection Direction is parallel to mono direction (NOT toed in)
- Left and Right frustums converge at virtual screen



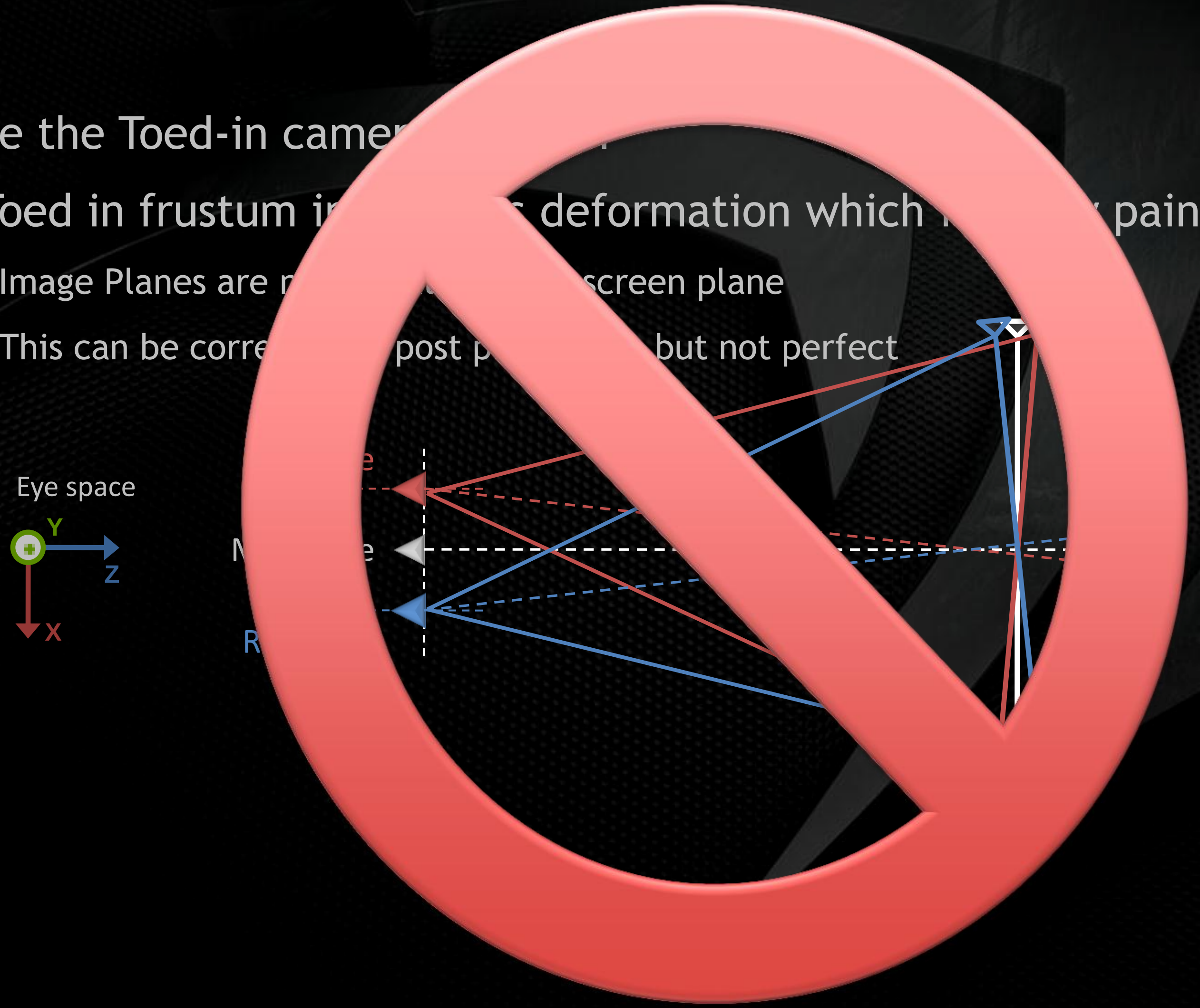
Parallel, NOT Toed in!

- Historically, live camera mounted in parallel stereo would waste a lot of the view field
  - Waste view field is wasted film area



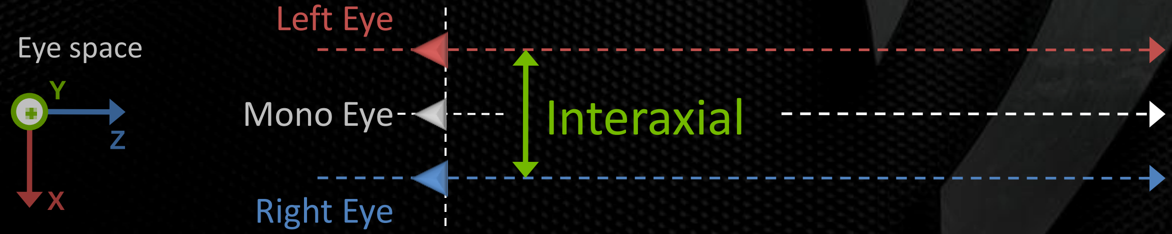
Parallel, NOT Toed in!

- Hence the Toed-in camer
- But Toed in frustum i deformation which painful
  - Image Planes are screen plane
  - This can be corre post p but not perfect



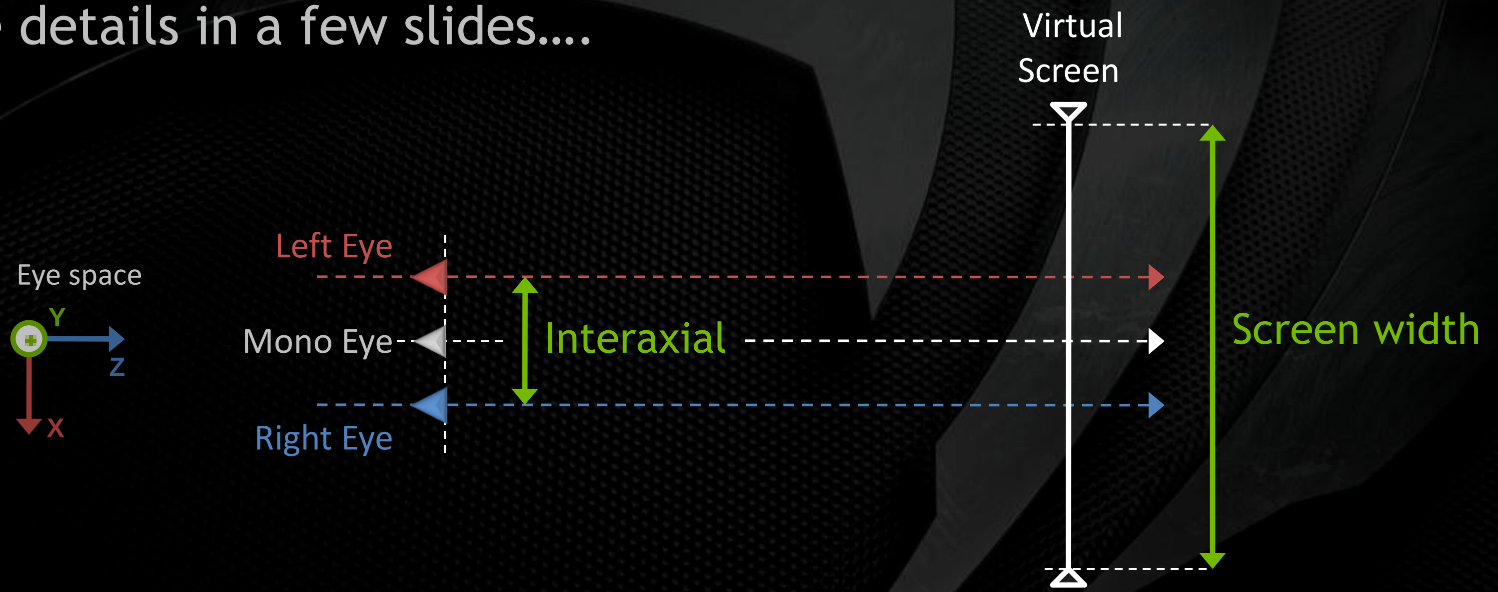
Interaxial

- Distance between the 2 virtual eyes in eye space
- The mono, left & right eyes directions are all parallels



Separation

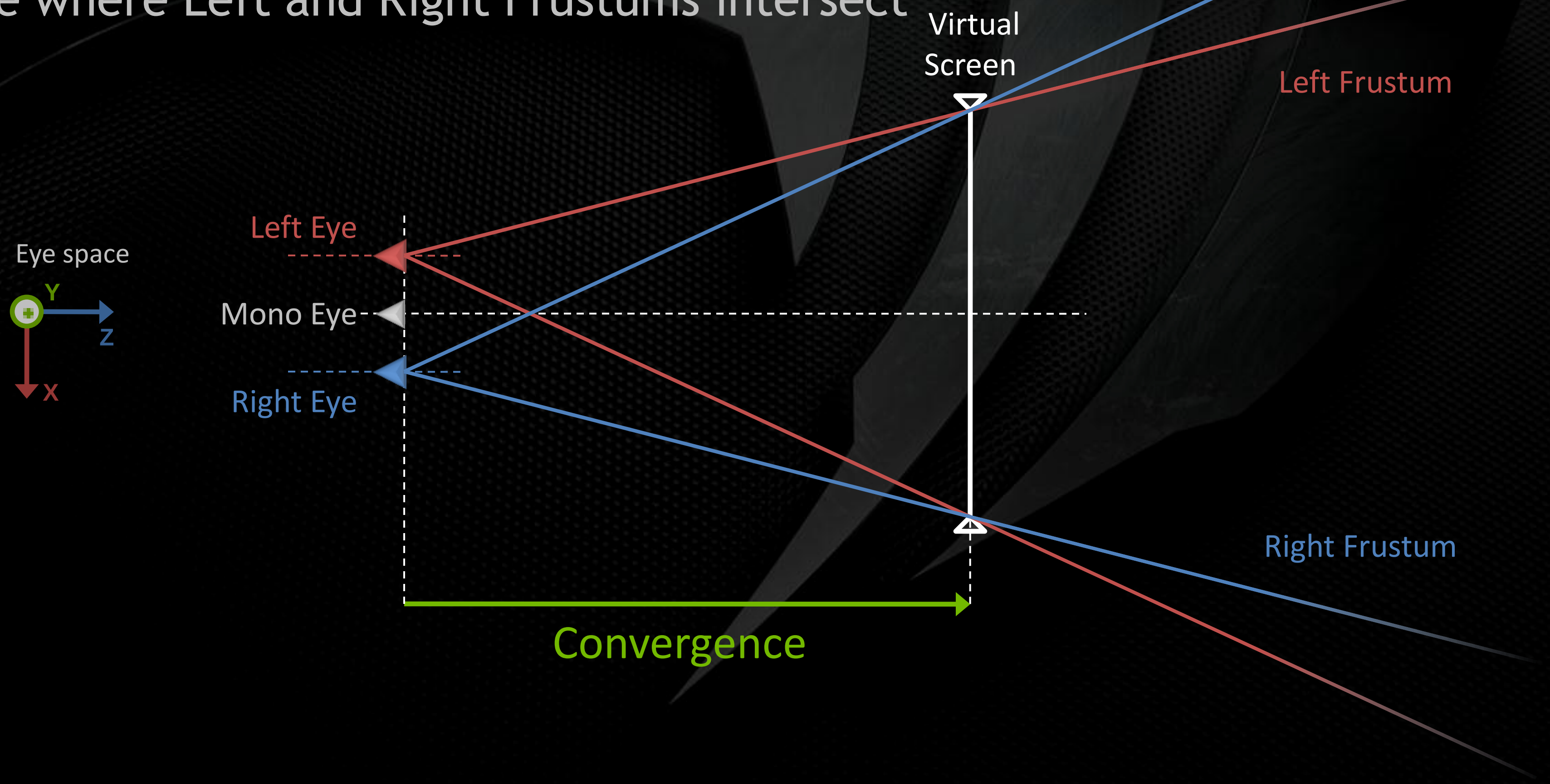
- The normalized version of interaxial by the virtual screen width
- More details in a few slides….



$$\boxed{Separation = \frac{Interaxial}{Screen\ width}}$$

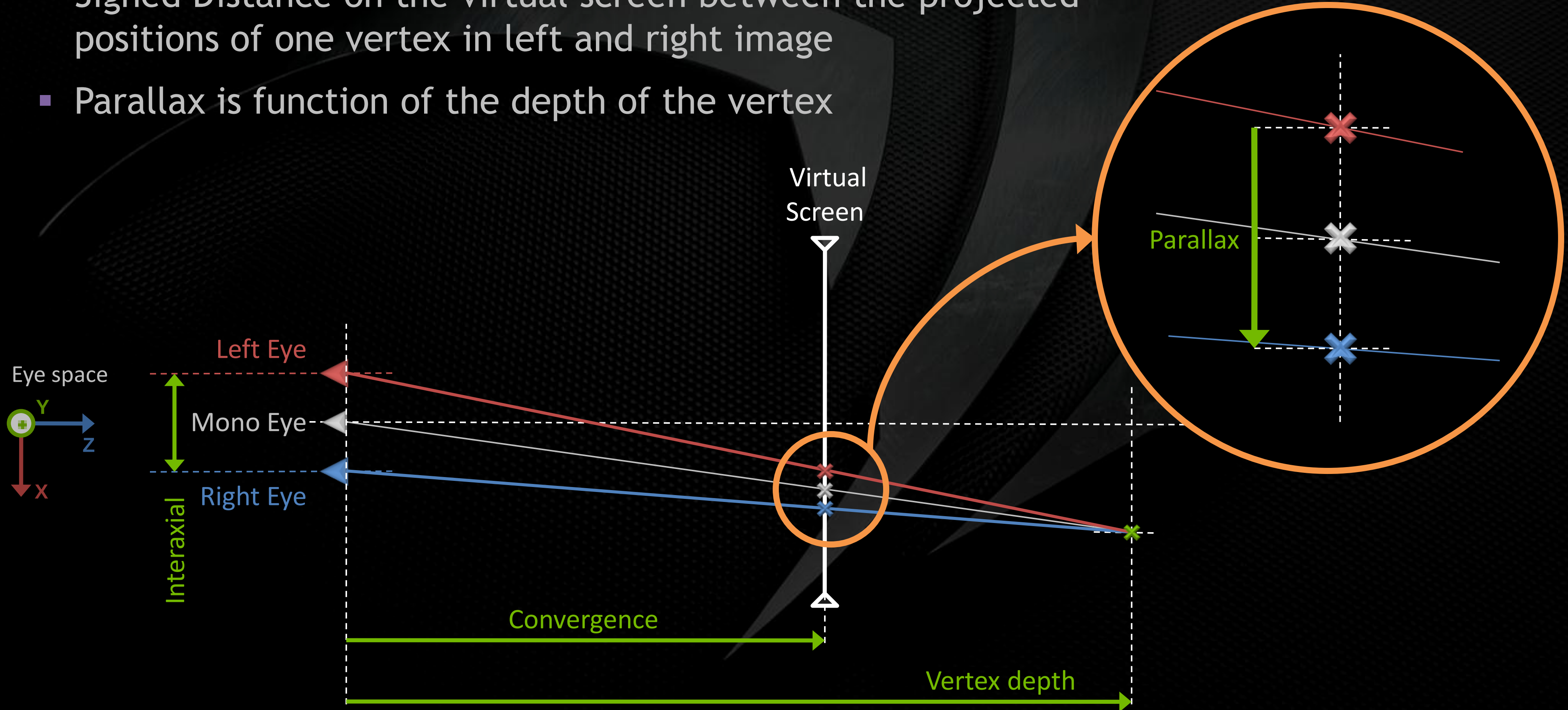
Convergence

- Virtual Screen's depth in eye space ("Screen Depth")
- Plane where Left and Right Frustums intersect



Parallax

- Signed Distance on the virtual screen between the projected positions of one vertex in left and right image
- Parallax is function of the depth of the vertex



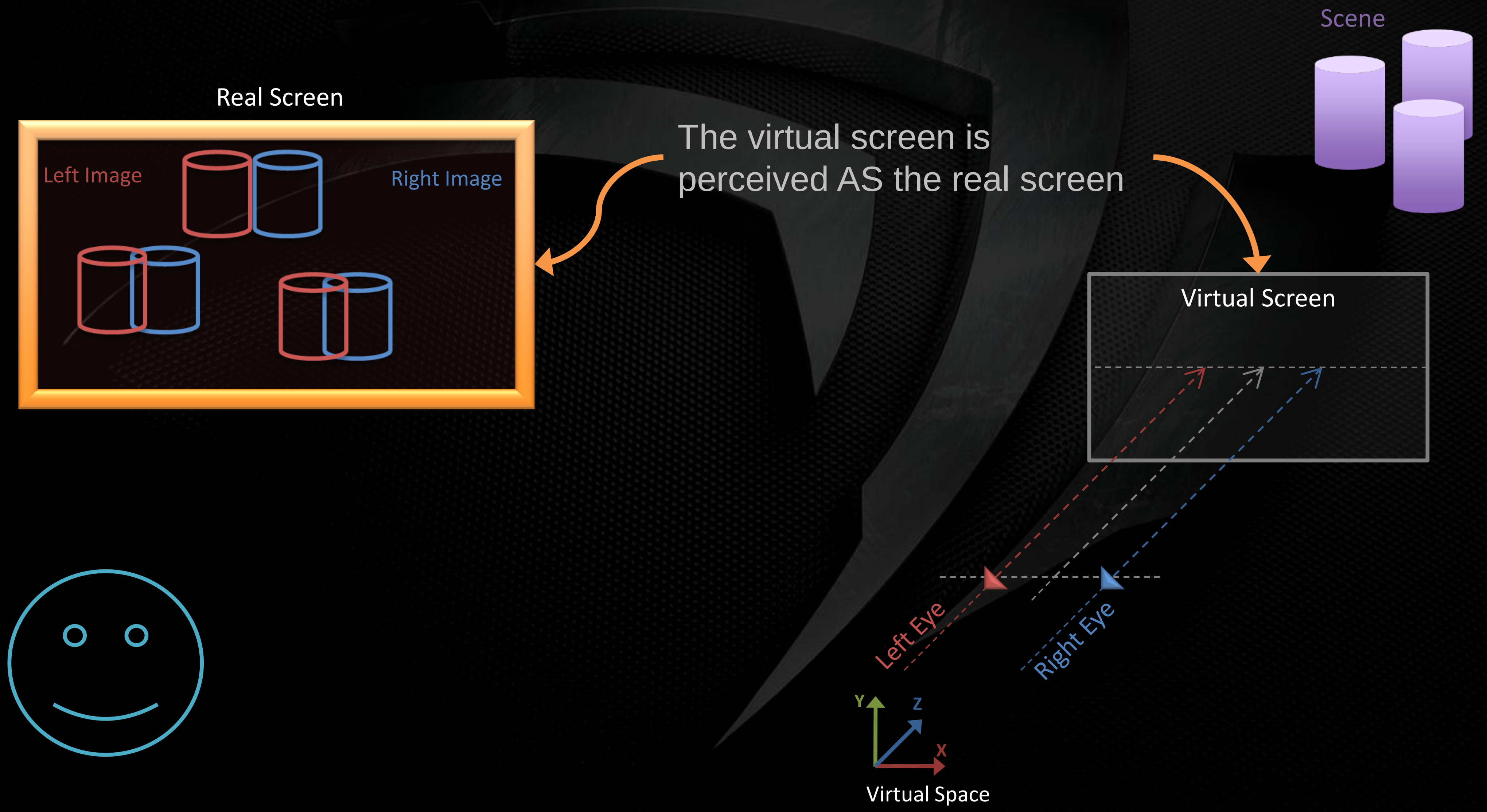
Depth Perception

Where the magic happens

DEPTH PERCEPTION

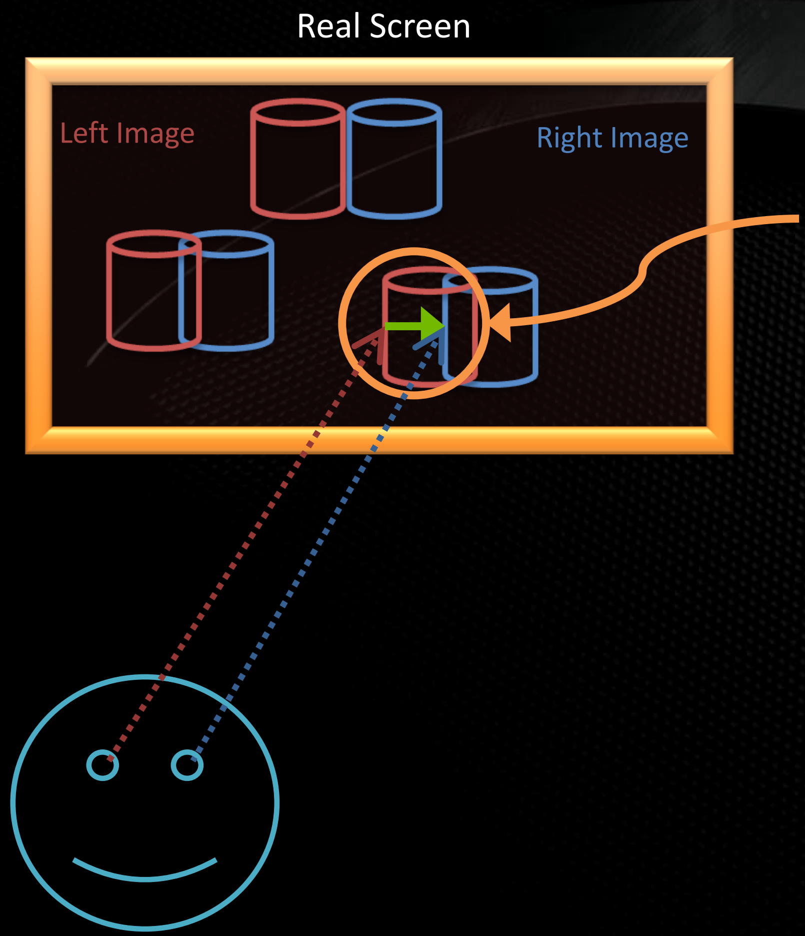
Virtual vs. Real Screen

The virtual screen is perceived AS the real screen

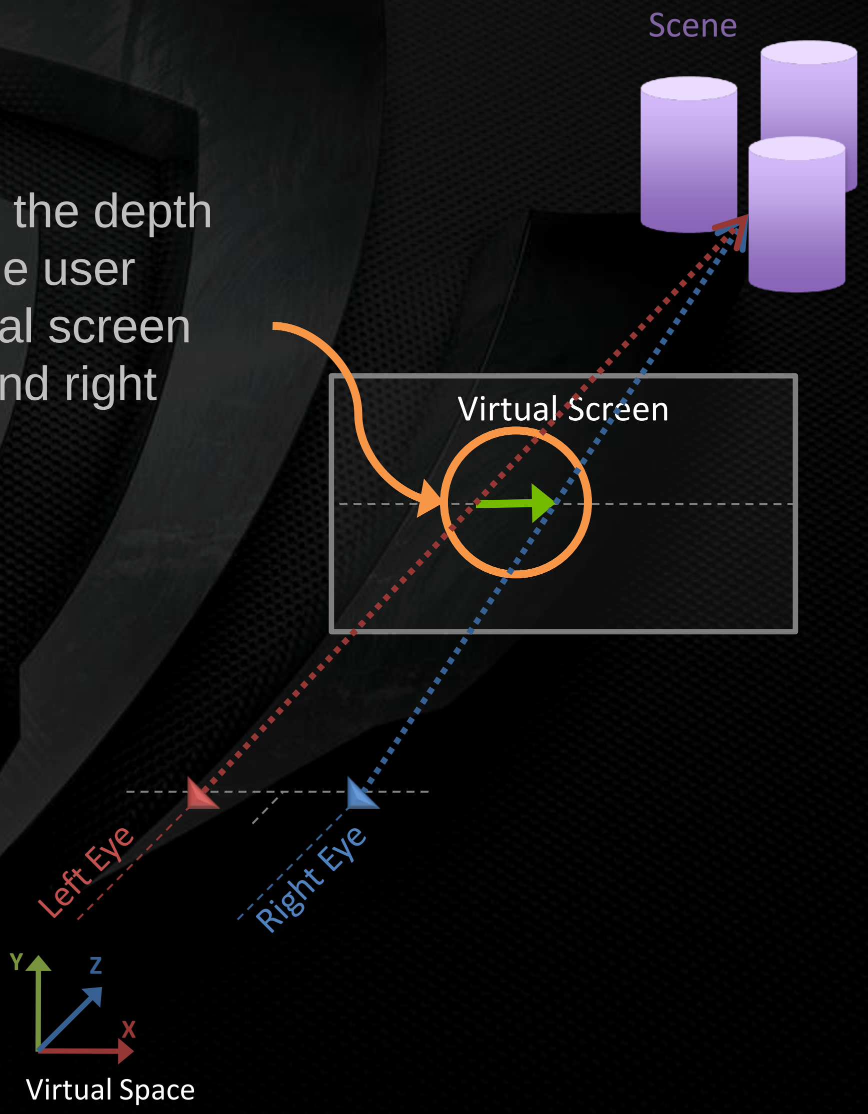


Parallax is Depth

Parallax is Depth

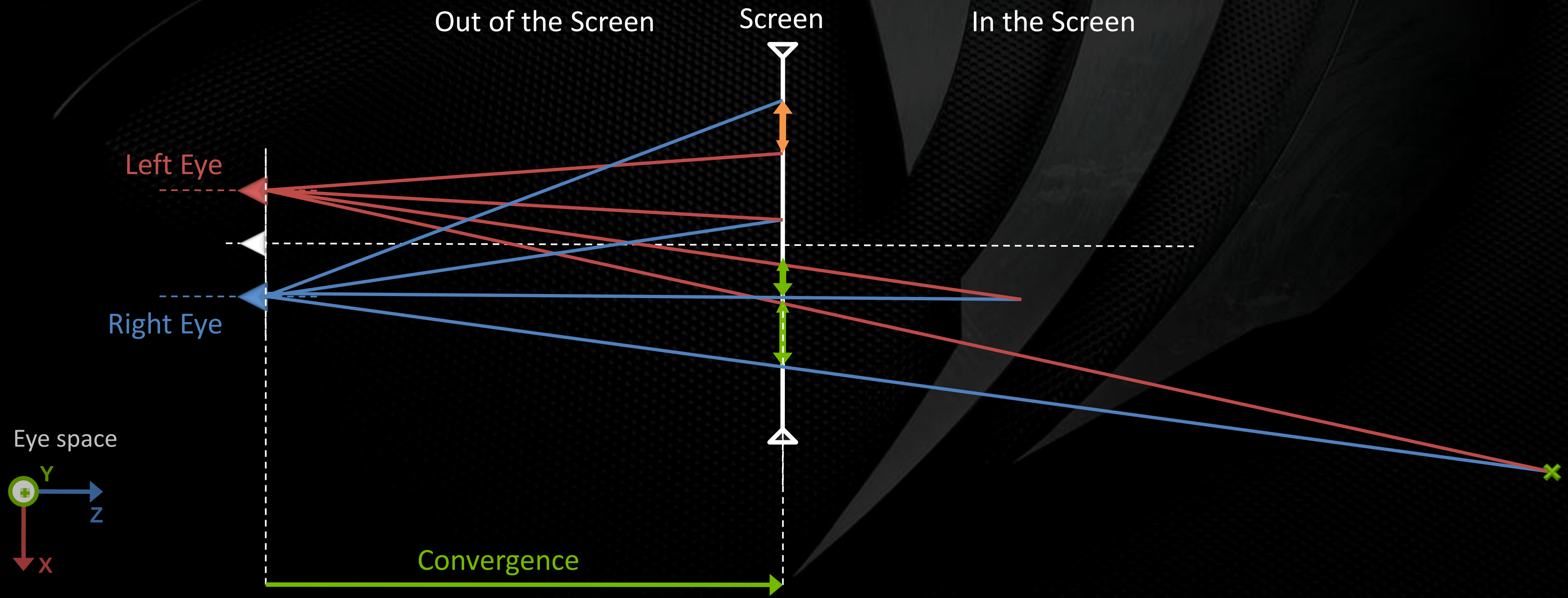


Parallax creates the depth perception for the user looking at the real screen presenting left and right images



In / Out of the Screen

Vertex Depth	Parallax	Vertex Appears
Further than Convergence	Positive	In the Screen
Equal Convergence	Zero	At the Screen
Closer than Convergence	Negative	Out of the Screen



Equations !!!

COMPUTING PARALLAX & PROJECTION MATRIX

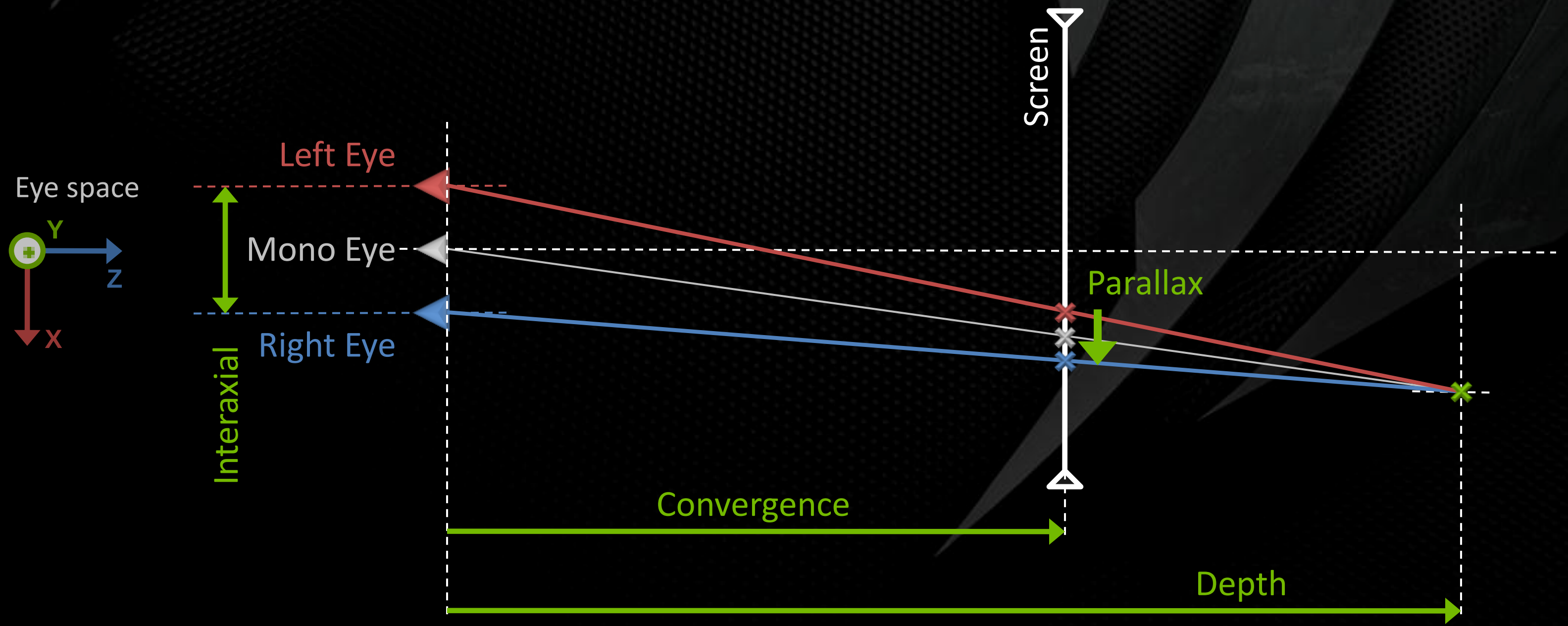
Computing Parallax

Thank you Thales

In eye space:

$$\frac{Parallax_{eye}}{Interaxial} = \frac{Depth - Convergence}{Depth}$$

$$Parallax_{eye} = Interaxial \times \left(1 - \frac{Convergence}{Depth}\right)$$

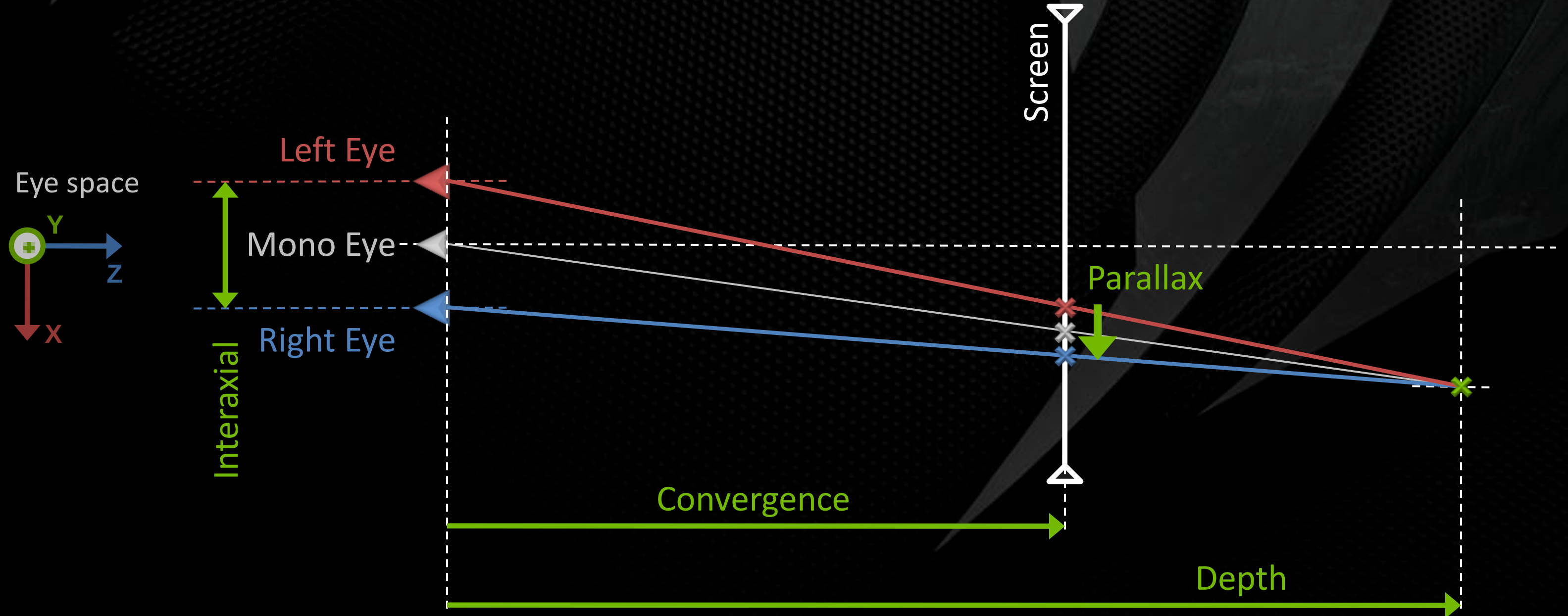


Computing Parallax

In image space (not pixels but in range [0,1])

In image space: $$Parallax_{image} = \frac{Parallax_{eye}}{Screen\ width} = \frac{Interaxial}{Screen\ width} \times \left(1 - \frac{Convergence}{Depth}\right)$$

$$Parallax_{image} = Separation \times \left(1 - \frac{Convergence}{Depth}\right)$$



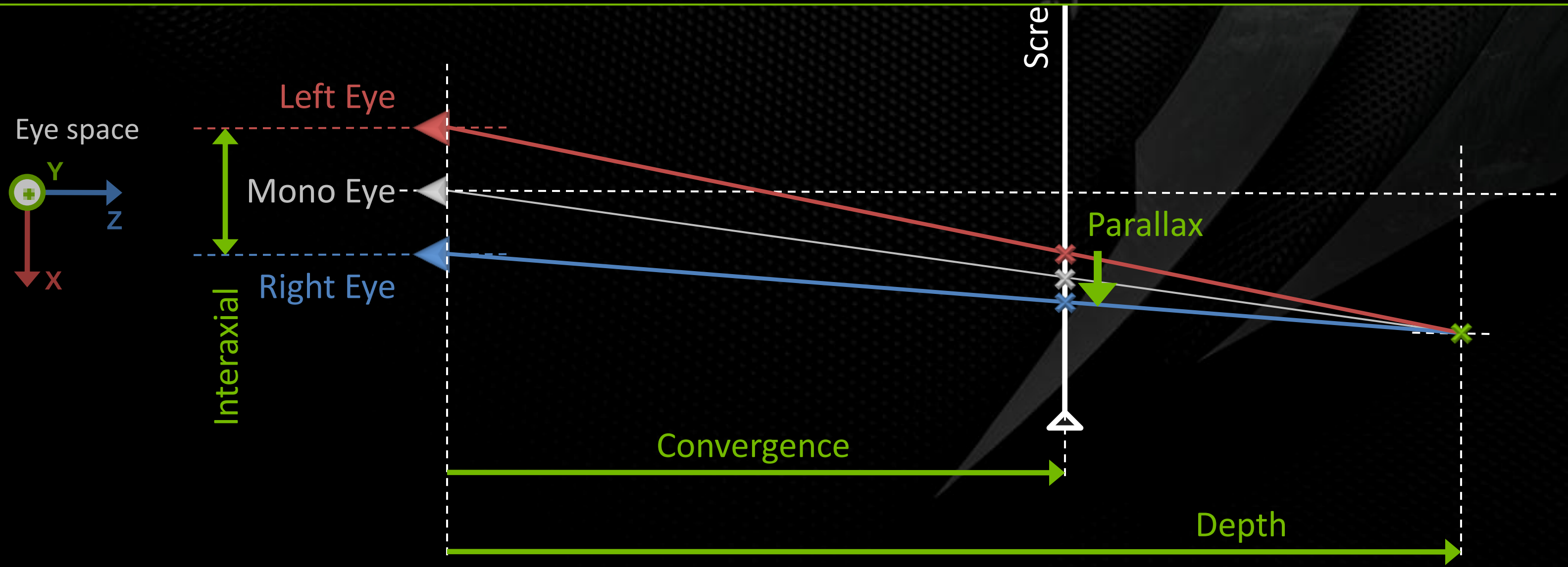
Computing Parallax

And clip space for free

In eye space: $$Parallax_{eye} = Interaxial \times \left(1 - \frac{Convergence}{Depth}\right)$$

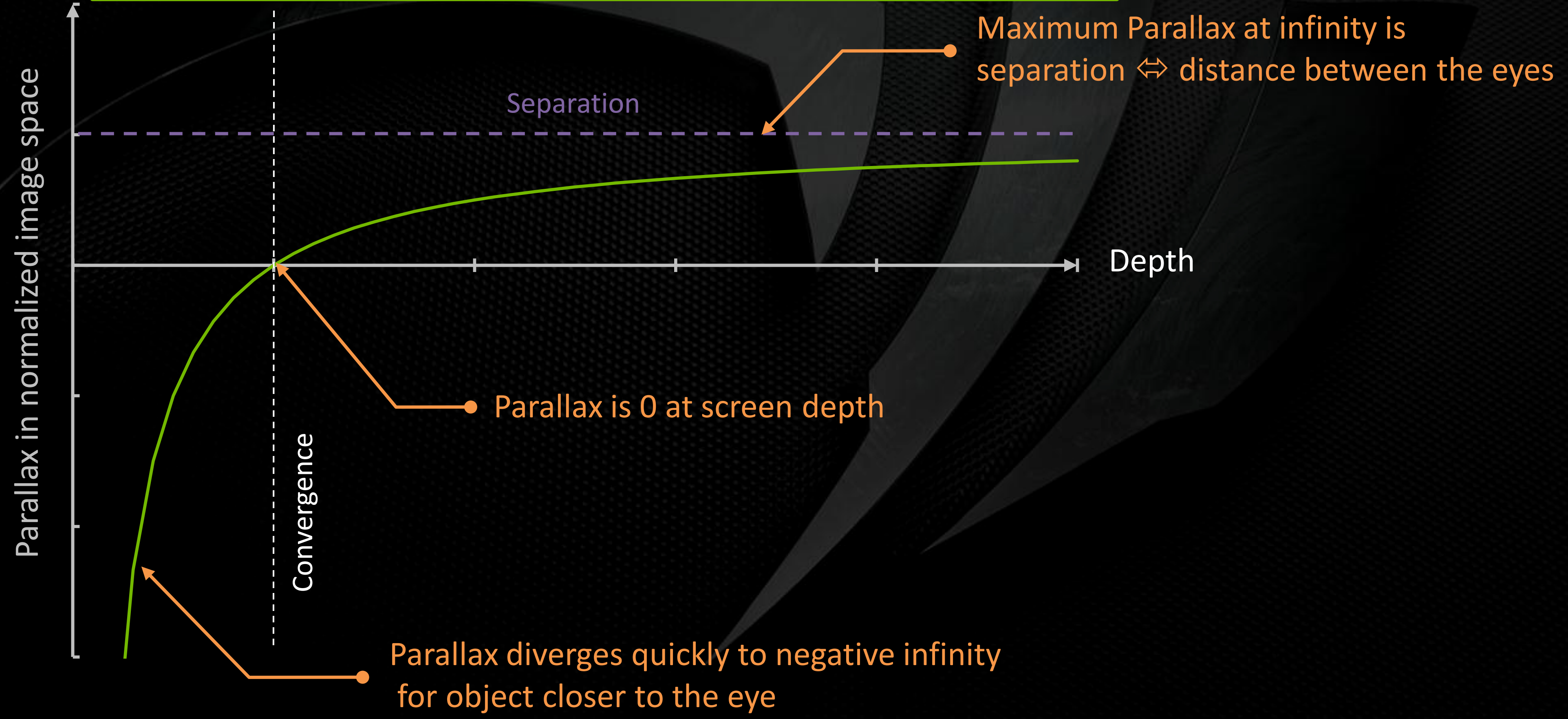
In image space: $$Parallax_{image} = Separation \times \left(1 - \frac{Convergence}{Depth}\right)$$

In clip space: $$Parallax_{clip} = 2 \times Separation \times (Depth - Convergence)$$



Parallax in normalized image space

$$Parallax = Separation \times \left(1 - \frac{Convergence}{Depth}\right)$$



Take care of your audience

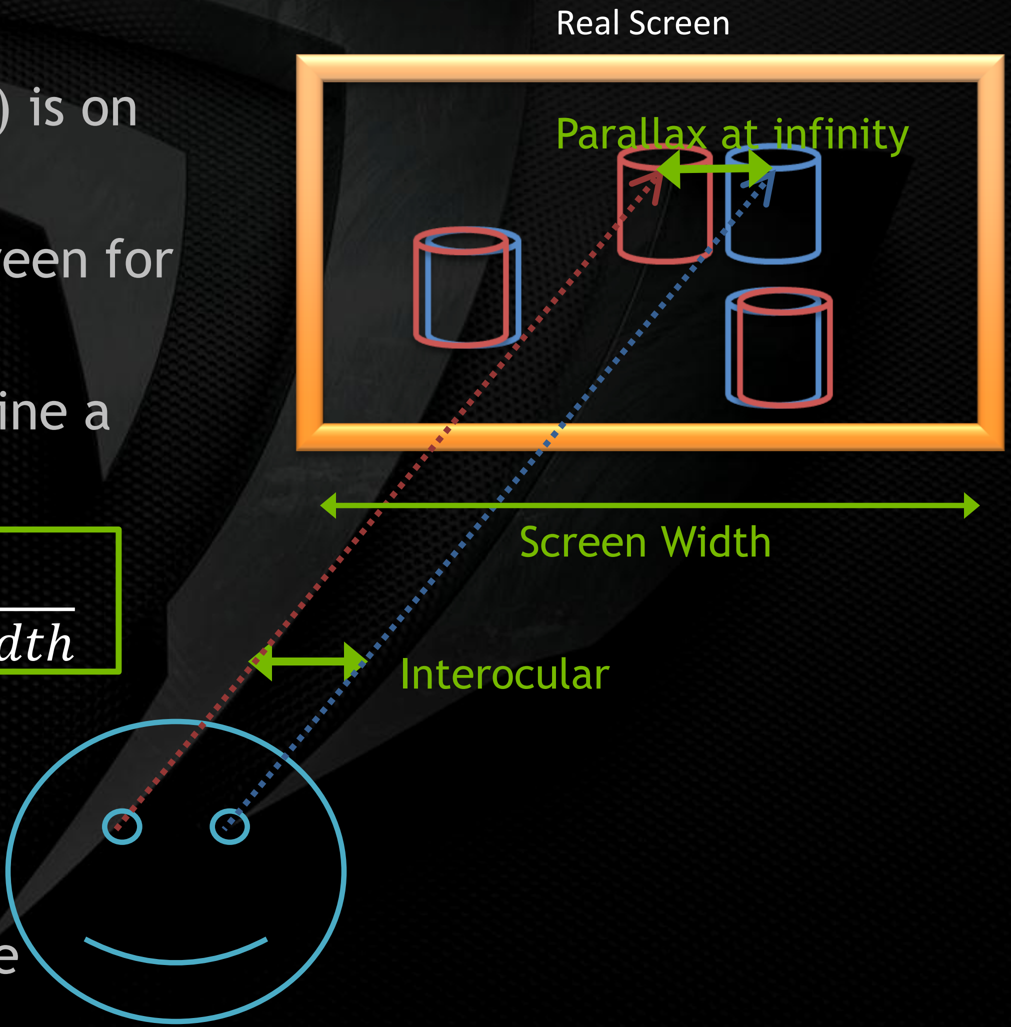
REAL EYE SEPARATION

Real Eye Separation

- Interocular (distance between the eyes) is on average 2.5” ⇔ 6.5 cm
- Equivalent to the visible parallax on screen for objects at infinity
- Depending on the screen width, we define a normalized “Real Eye Separation”

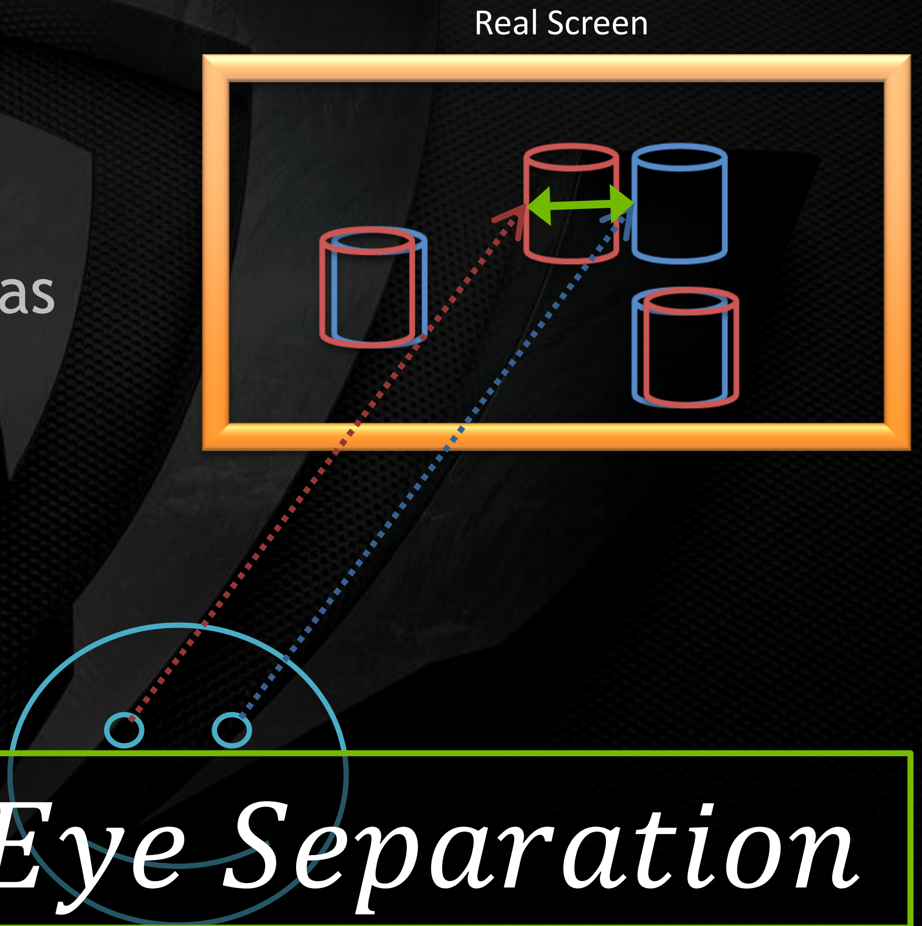
$$\boxed{Real\ Eye\ Separation = \frac{Interocular}{Real\ Screen\ Width}}$$

- Different for each screen model
- A reference maximum value for the Separation used in the stereo projection for a comfortable experience



Real Eye Separation is infinity

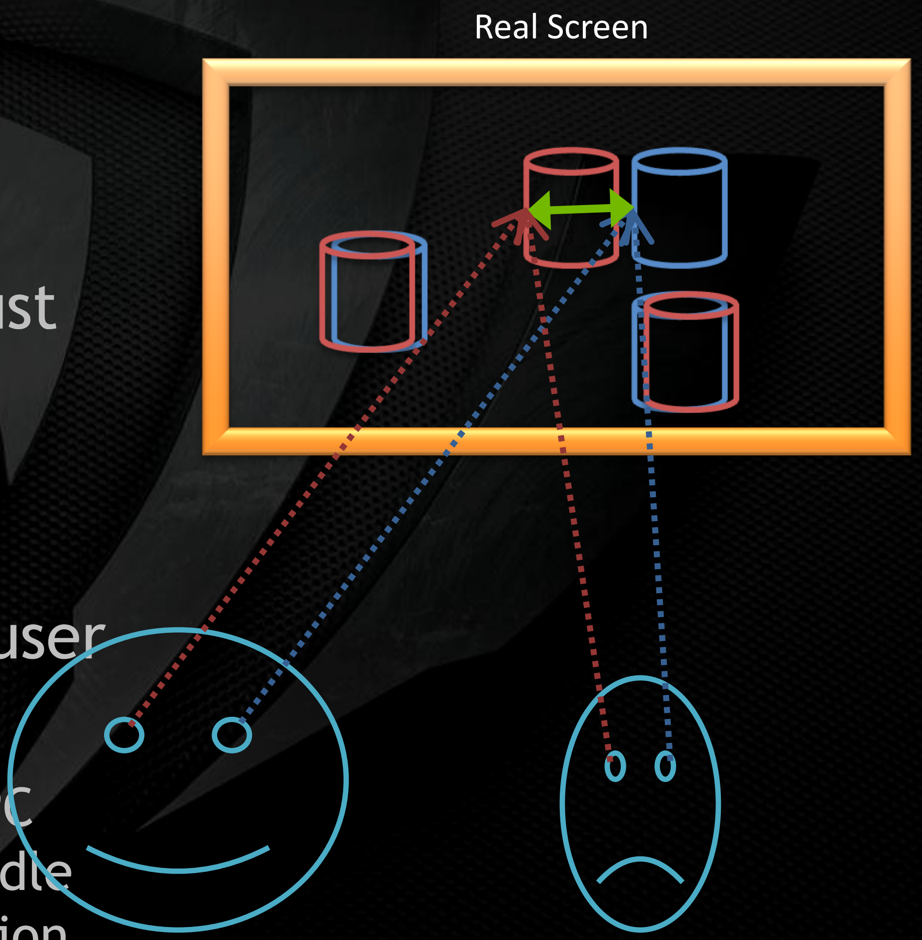
- The maximum Parallax at infinity is Separation
- Real Eye Separation should be used as the very maximum Separation value



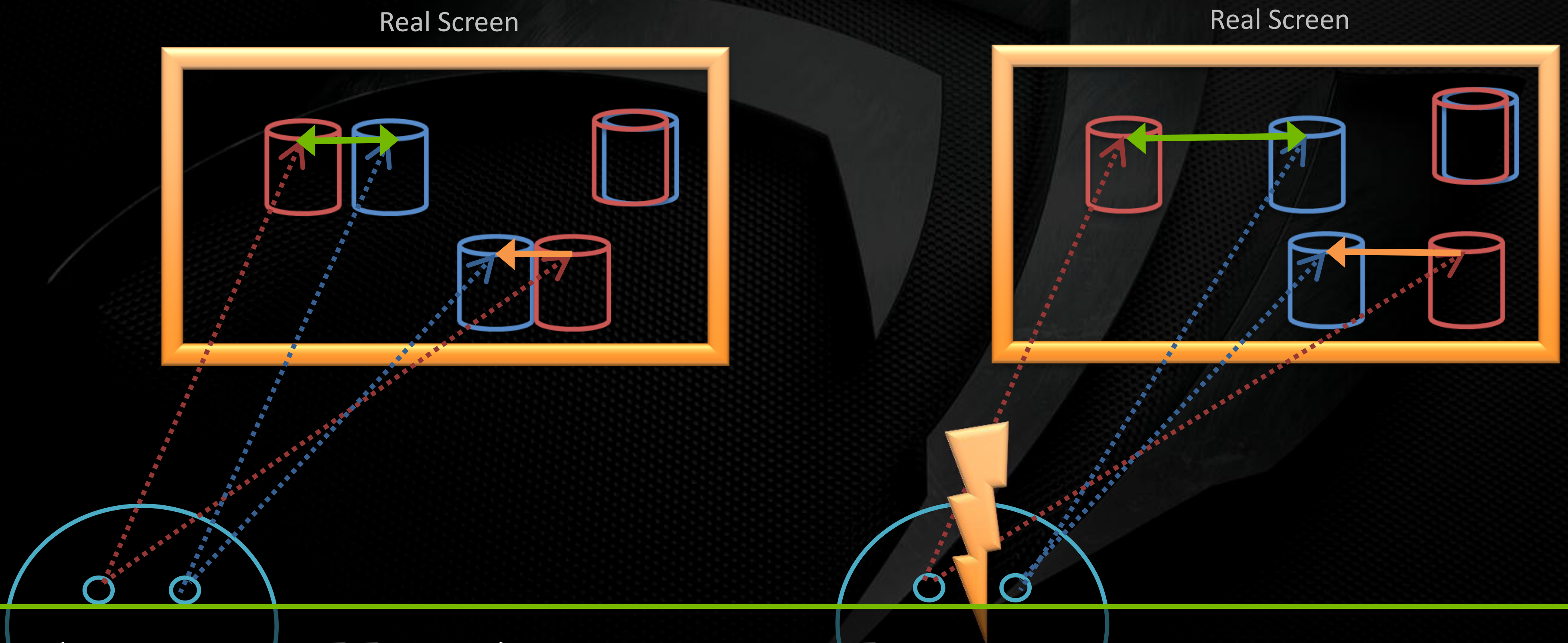
$$Separation < Real\ Eye\ Separation$$

Separation must be Comfortable

- Never make the viewer look diverge
  - People don’t have the same eyes
- For Animation movie, separation must be very conservative because of the variety of the screen formats
  - IMAX vs Home theatre
- For Interactive application, let the user adjust Separation
  - When the screen is close to the user (PC scenario) most of the users cannot handle more than 50% of the Real Eye Separation

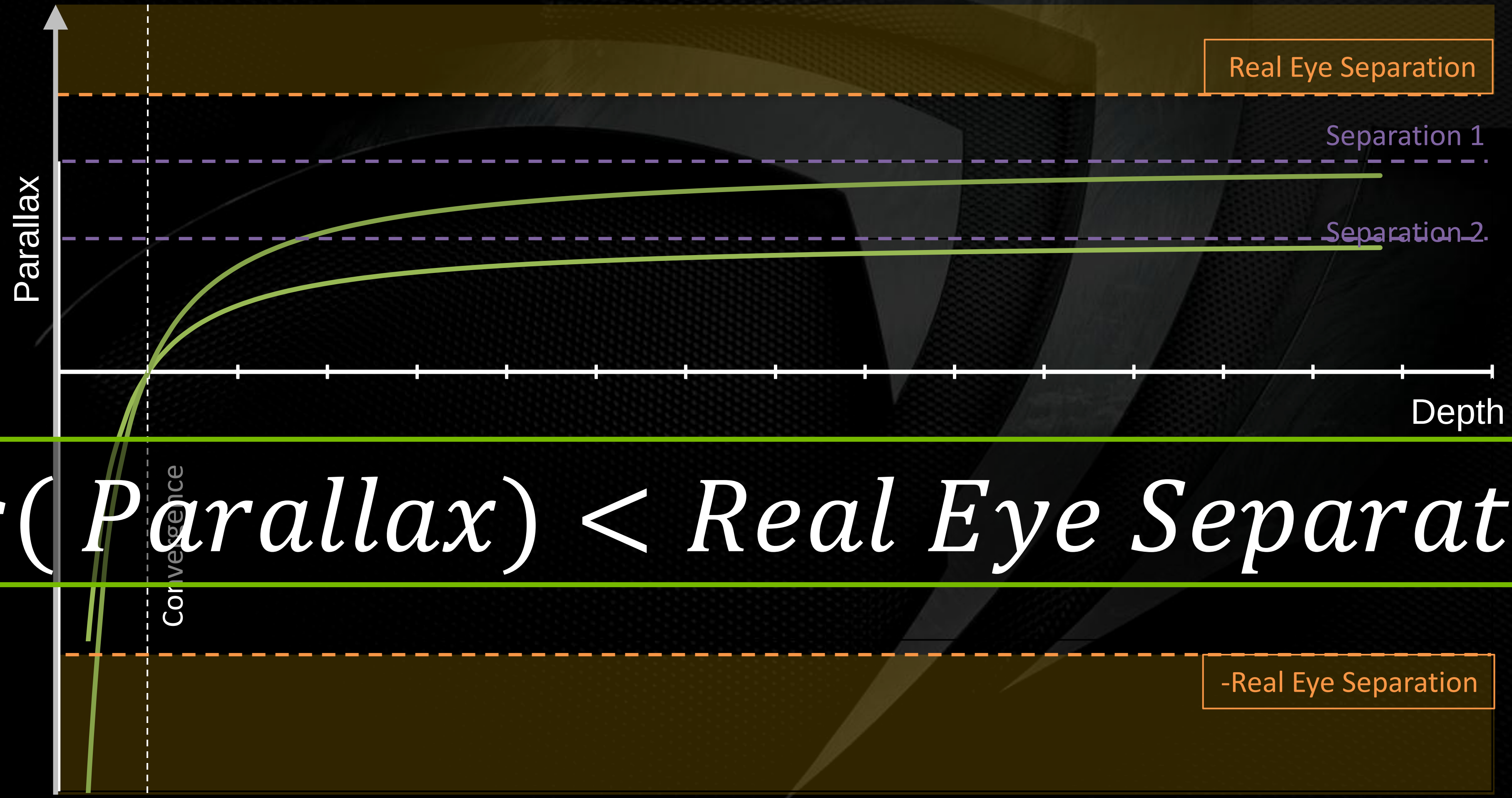


Real Eye Separation is the Maximum Parallax



$$abs(Parallax) < Real\ Eye\ Separation$$

Safe Parallax Range



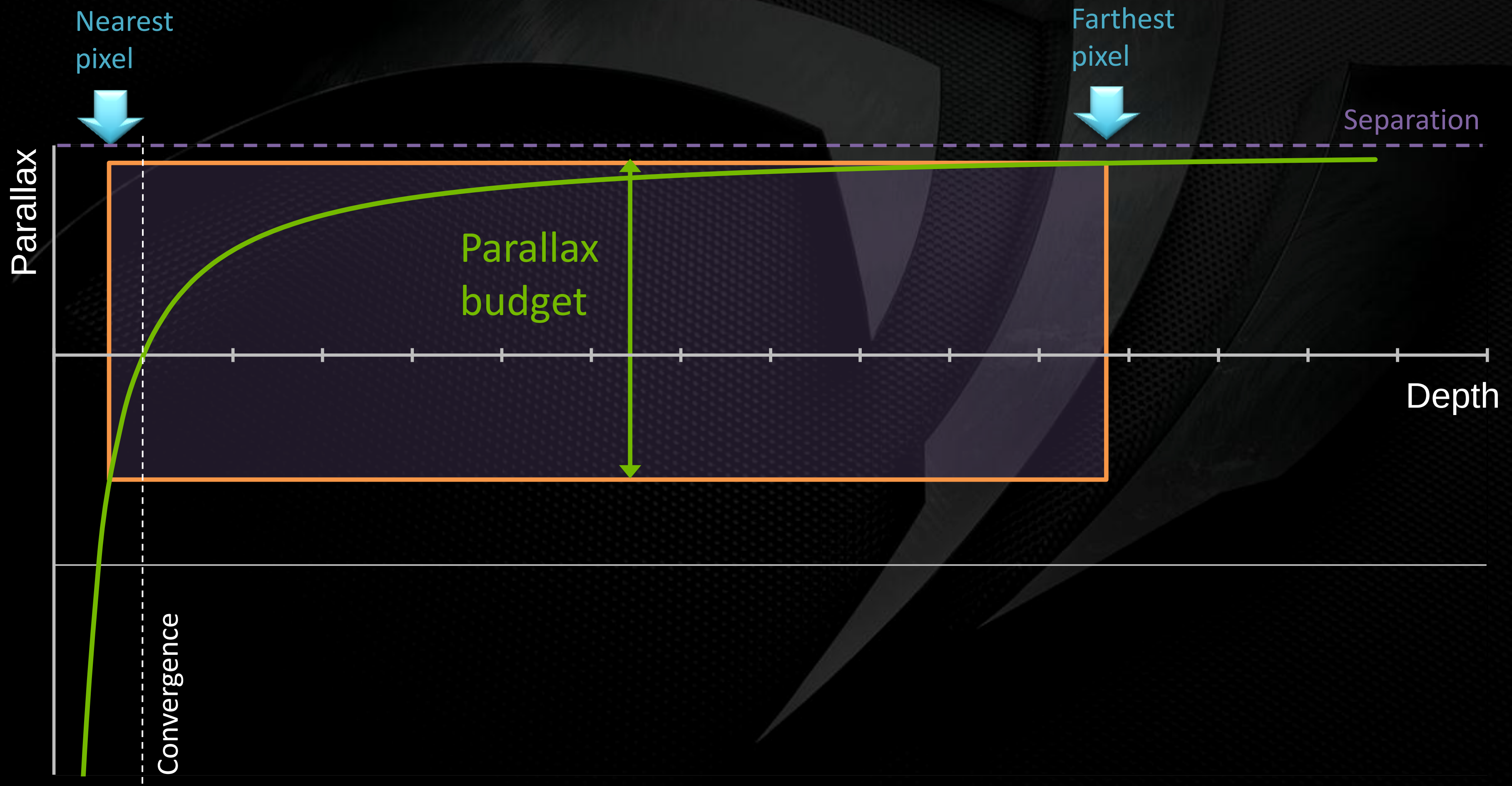
$$abs(Parallax) < Real\ Eye\ Separation$$

Convergence and Separation working together

PARALLAX BUDGET

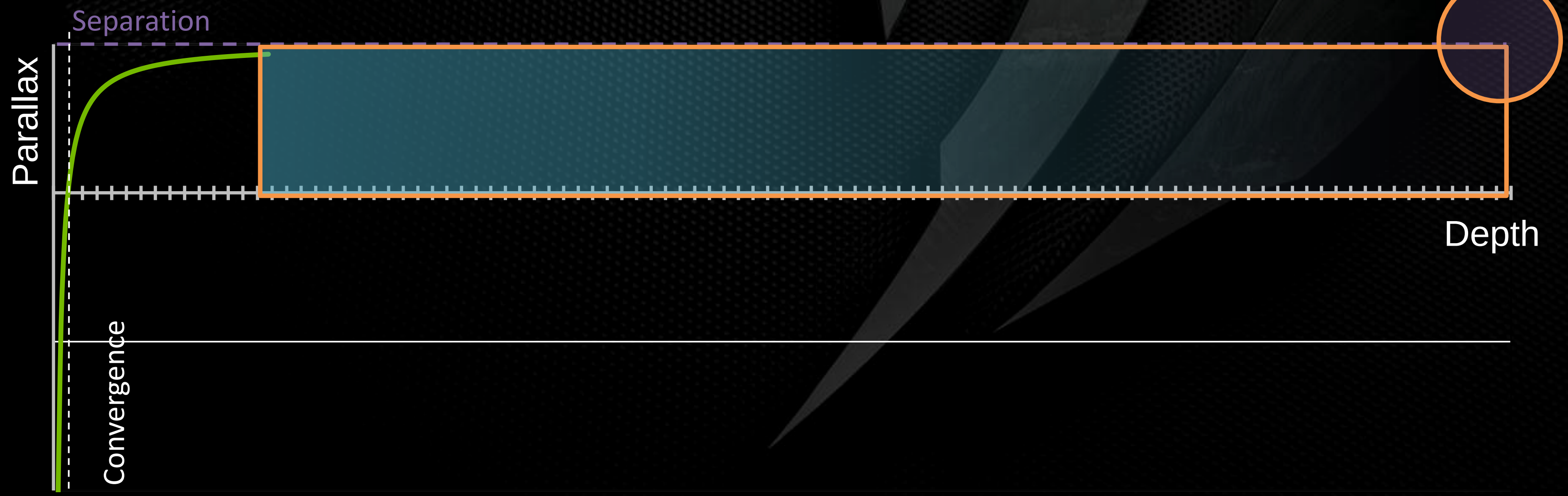
Parallax Budget

How much parallax variation is used in the frame



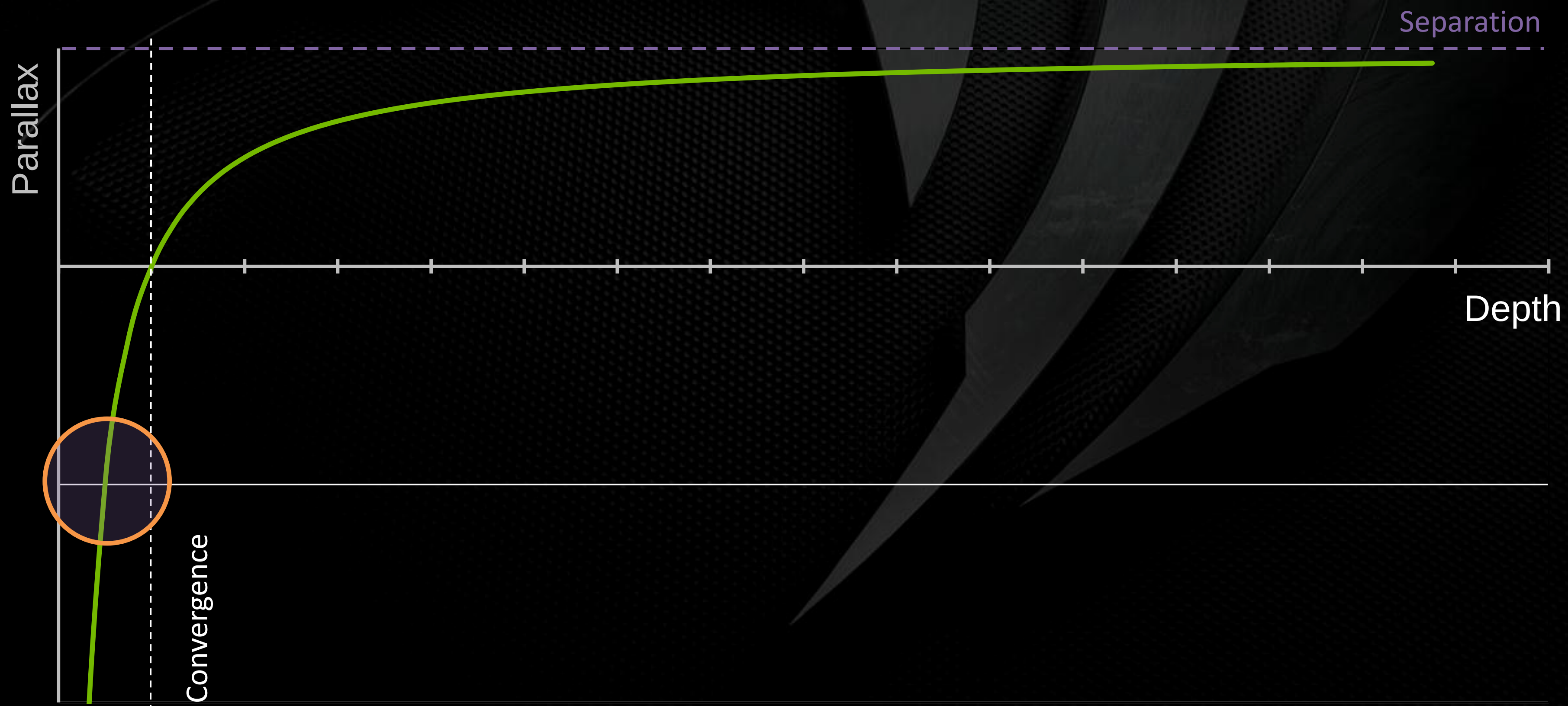
In Screen : Farthest Pixel

- At 100 * Convergence, Parallax is 99% of the Separation
  - For pixels further than 100 * Convergence,
    Elements looks flat on the far distance with no depth differentiation
- Between 10 to 100 * Convergence, Parallax vary of only 9%
  - Objects in that range have a subtle depth differentiation



Out of the Screen : Nearest pixel

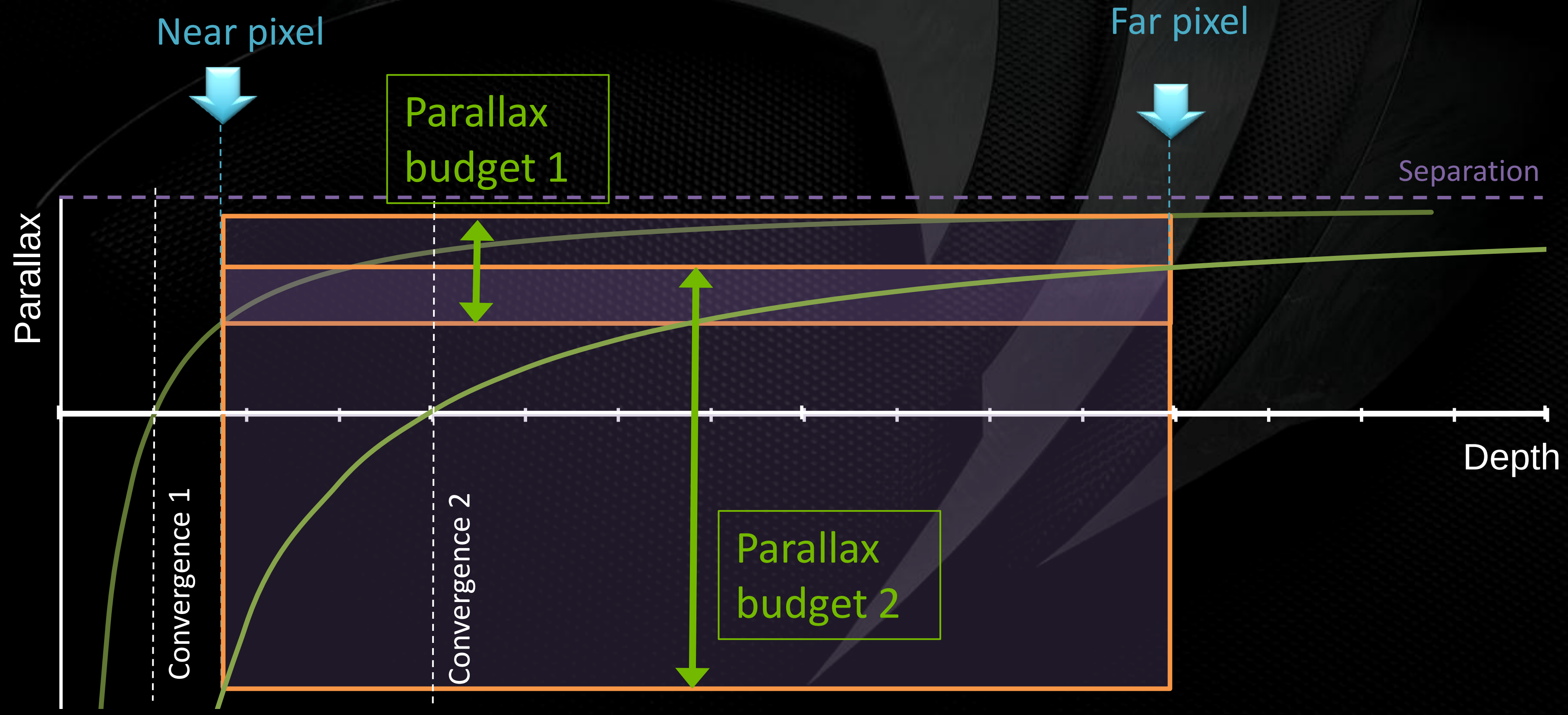
- At Convergence / 2, Parallax is equal to -Separation, out of the screen
  - Parallax is very large (> Separation) and can cause eye strains



Convergence sets the scene in the screen

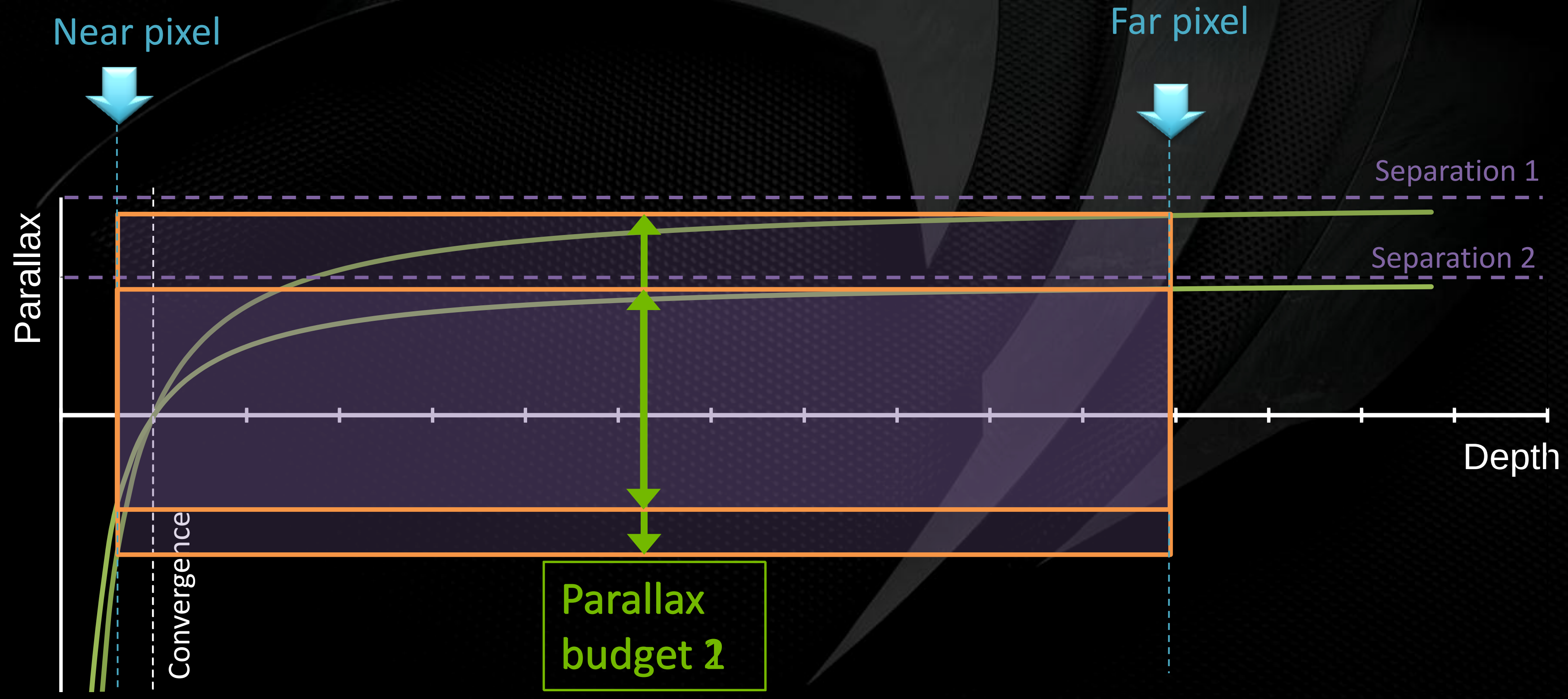
Defines the window into the virtual space

Defines the style of stereo effect achieved (in / out of the screen)



Separation scales the parallax budget

Scales the depth perception of the frame



Adjust Convergence

- Convergence is a Camera parameter driven by the look of the frame
  - Artistic / Gameplay decision
  - Should adjust for each camera shot / mode
    - Make sure the scene elements are in the range [Convergence / 2, 100 * Convergence]
  - Adjust it to use the Parallax Budget properly
  - Dynamic Convergence is a bad idea
    - Except for specific transition cases

Stereopsis and 3D Hints

Depth as storytelling tool

Agenda

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Real-time & Gaming Techniques

Let’s do it

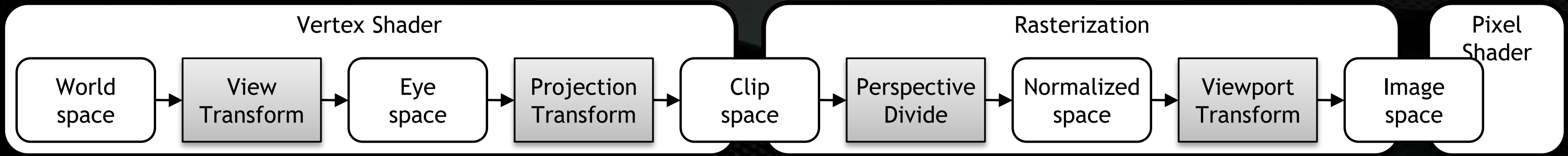
RENDERING IN STEREO

Stereoscopic Rendering

Render geometry twice	Do stereo drawcalls	Duplicate drawcalls
From left and right eyes	Apply stereo projection	Modify projection matrix
Into left and right images	Use stereo surfaces	Duplicate render surfaces

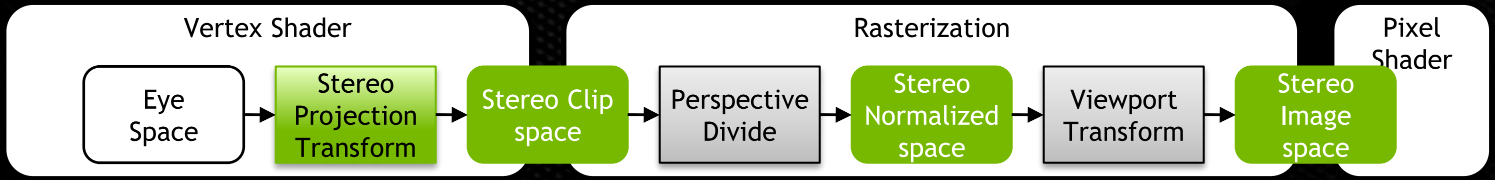
How to implement stereo projection ?

- Start from the mono transformation stack

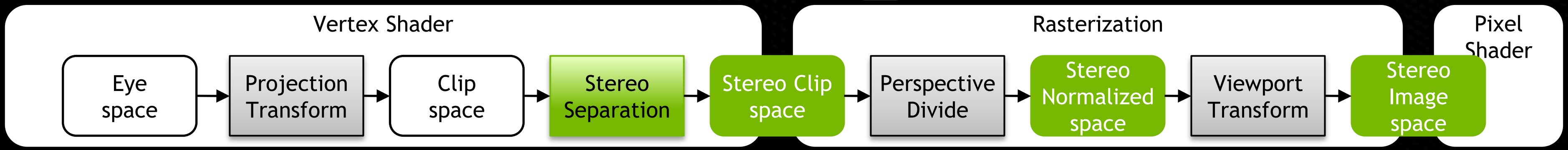


- Inject the side, separation and convergence to get a stereo transformation stack

Stereo Projection Matrix



Stereo shift on clip position



Stereo Projection Matrix

Right handed column major matrix (OpenGL style)

- Modified version of the Projection matrix for stereo to transform geometry position from eye space to stereo clip space
  - $Pos_{clip\ stereo} = \boldsymbol{Projection}_{stereo} \times Pos_{eye}$

Right handed column major matrix (OpenGL style)

$$\boldsymbol{Projection}_{stereo} = \begin{bmatrix} p11 & 0 & p13 - side * separation & -side * separation * convergence \\ 0 & p22 & p23 & 0 \\ 0 & 0 & p33 & p34 \\ 0 & 0 & -1 & 0 \end{bmatrix}$$

Side is -1 for left, +1 for right

pij are the coefficients of the standard mono perspective projection

Stereo Projection Matrix

Left handed row major matrix (D3D9 style)

- $Pos_{clip\ stereo} = Pos_{eye} \times \boldsymbol{Projection}_{stereo}$

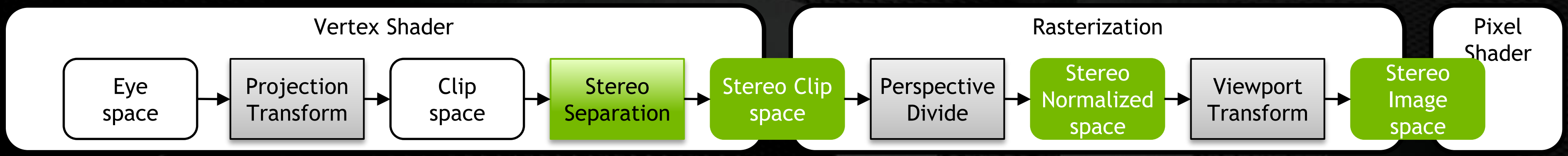
Left handed row major matrix (D3D9 style)

$$\boldsymbol{Projection}_{stereo} = \begin{bmatrix} p11 & 0 & 0 & 0 \\ 0 & p22 & p32 & 0 \\ p13 + side * separation & 0 & p33 & 1 \\ -side * separation * convergence & 0 & p34 & 0 \end{bmatrix}$$

Side is -1 for left, +1 for right

pij are the coefficients of the standard mono perspective projection

Stereo shift on clip position



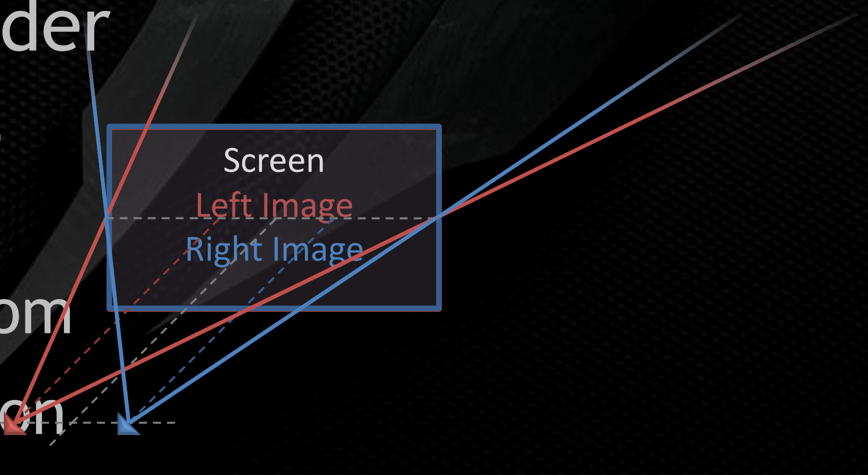
- Just before rasterization in the vertex shader, offset the clip position by the parallax amount

$$clipPos.x \mathrel{+}= Side * Separation * (clipPos.w - Convergence)$$

Side is -1 for left, +1 for right

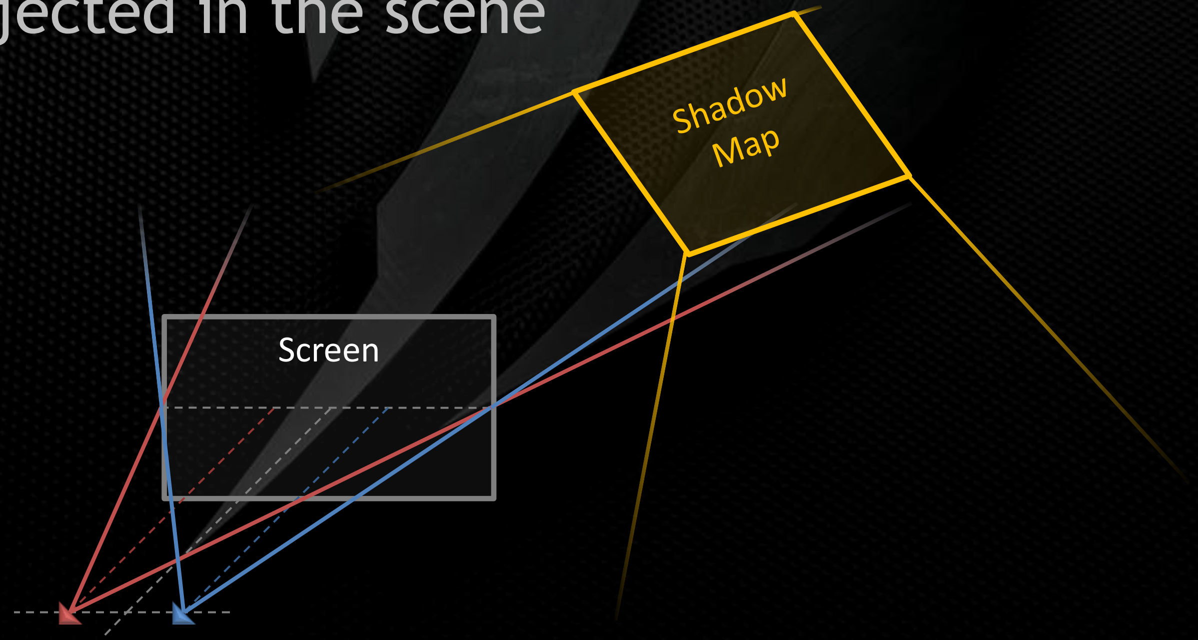
Stereo rendering surfaces

- View dependent render targets must be duplicated
  - Back buffer
  - Depth Stencil buffer
- Intermediate full screen render targets used to process final image
  - High dynamic range, Blur, Bloom
  - Screen Space Ambient Occlusion



Mono rendering surfaces

- View independent render targets DON'T need to be duplicated
  - Shadow map
  - Spot light maps projected in the scene



How to do the stereo drawcalls ?

- Simply draw the geometries twice, in left and right versions of stereo surfaces
- Can be executed per scene pass
  - Draw left frame completely
  - Then Draw right frame completely
  - Need to modify the rendering loop
- Or for each individual objects
  - Bind Left Render target, Setup state for left projection, Draw geometry
  - Bind Right render target, Setup state for right projection, Draw Geometry
  - Might be less intrusive in an engine
- Not everything in the scene needs to be drawn
  - Just depends on the render target type

When to do what?

Use Case	Render Target Type	Stereo Projection	Stereo Drawcalls
Shadow maps	Mono	No Use Shadow projection	Draw Once
Main frame Any Forward rendering pass	Stereo	Yes	Draw Twice
Reflection maps	Stereo	Yes Generate a stereo reflection projection	Draw Twice
Post processing effect (Drawing a full screen quad)	Stereo	No No Projection needed at all	Draw Twice
Deferred shading lighting pass (Drawing a full screen quad)	Stereo G-buffers	Yes Be careful of the Unprojection Should be stereo	Draw twice

Real-time technique

What could go possibly wrong ?

EVERYTHING IS UNDER CONTROL

3D Objects

- All the 3D objects in the scene should be rendered using a unique Perspective Projection in a given frame
- All the 3D objects must have a coherent depth relative to the scene
- Lighting effects are visible in 3D so should be computed correctly
  - Highlight and specular are probably best looking evaluated with mono eye origin
  - Reflection and Refraction should be evaluated with stereo eyes

Pseudo 3D objects : Sky box, Billboards…

- Sky box should be drawn with a valid depth further than the regular scene
  - Must be Stereo Projected
  - Best is at a very Far distance so Parallax is maximum
  - And cover the full screen
- Billboard elements (Particles, leaves) should be rendered in a plane parallel to the viewing plane
  - Doesn’t look perfect
- Relief mapping cannot be abused

Several 3D scenes

- Different 3D scenes rendered in the same frame using different scales
  - Portrait viewport of selected character
  - Split screen
- Since scale of the scene is different, Must use a different Convergence to render each scene

Out of the screen objects

- The user's brain is fighting against the perception of hovering objects out of the screen
  - Extra care must be taken to achieve a convincing effect
- Objects should not be clipped by the edges of the window
  - Be aware of the extra horizontal guard bands
- Move object slowly from inside the screen to the outside area to give eyes time to adapt
  - Make smooth visibility transitions
  - No blinking
- Realistic rendering helps

2D Objects

Starcraft2 screenshot , Courtesy of Blizzard

2D object in depth attached to 3D anchor point

Billboards in depth Particles with 3D positions

2D objects presenting User interface at screen

2D Objects must be drawn at a valid Depth

- With no stereo projection
  - Head Up Display interface
  - UI elements
  - Either draw with no stereo projection or with stereo projection at Convergence
- At the correct depth when interacting with the 3D scene
  - Labels or billboards in the scene
  - Must be drawn with stereo projection
  - Use the depth of the 3D anchor point used to define the position in 2D window space
- Needs to modify the 2D ortho projection to take into account Stereo

2D to 3D conversion

shader function

```
float4 2Dto3DclipPosition(
    in float2 posClip : POSITION, // Input position in clip space
    uniform float depth           // Depth where to draw the 2D object
    ) : POSITION                  // Output the position in clip space
{
    return float4(
        posClip.xy * depth,   // Simply scale the posClip by the depth
                              // to compensate for the division by W
                              // performed before rasterization

        0,          // Z is not used if the depth buffer is not used
                    // If needed Z = ( depth * f - nf )/(f - n);
                    // ( For DirectX )

        depth ); // W is the Z in eye space
}
```

Selection, Pointing in S3D

- Selection or pointing UI interacting with the 3D scene don't work if drawn mono
  - Mouse Cursor at the pointed object's depth
    Can not use the HW cursor
  - Crosshair
- Needs to modify the projection to take into account depth of pointed elements
  - Draw the UI as a 2D element in depth at the depth of the scene where pointed
  - Compute the depth from the Graphics Engine or eval on the fly from the depth buffer (Contact me for more info)
- Selection Rectangle is not perfect, could be improved
  - Cf nvidia talk at GDC 2008

Performance considerations

- At worse the frame rate is divided by 2
- But applications are rarely GPU bound so less expensive in practice
  - Since using Vsynch when running in stereo, you see the standard Vsync frequence jumps
- Not all the rendering is executed twice (Shadow maps)

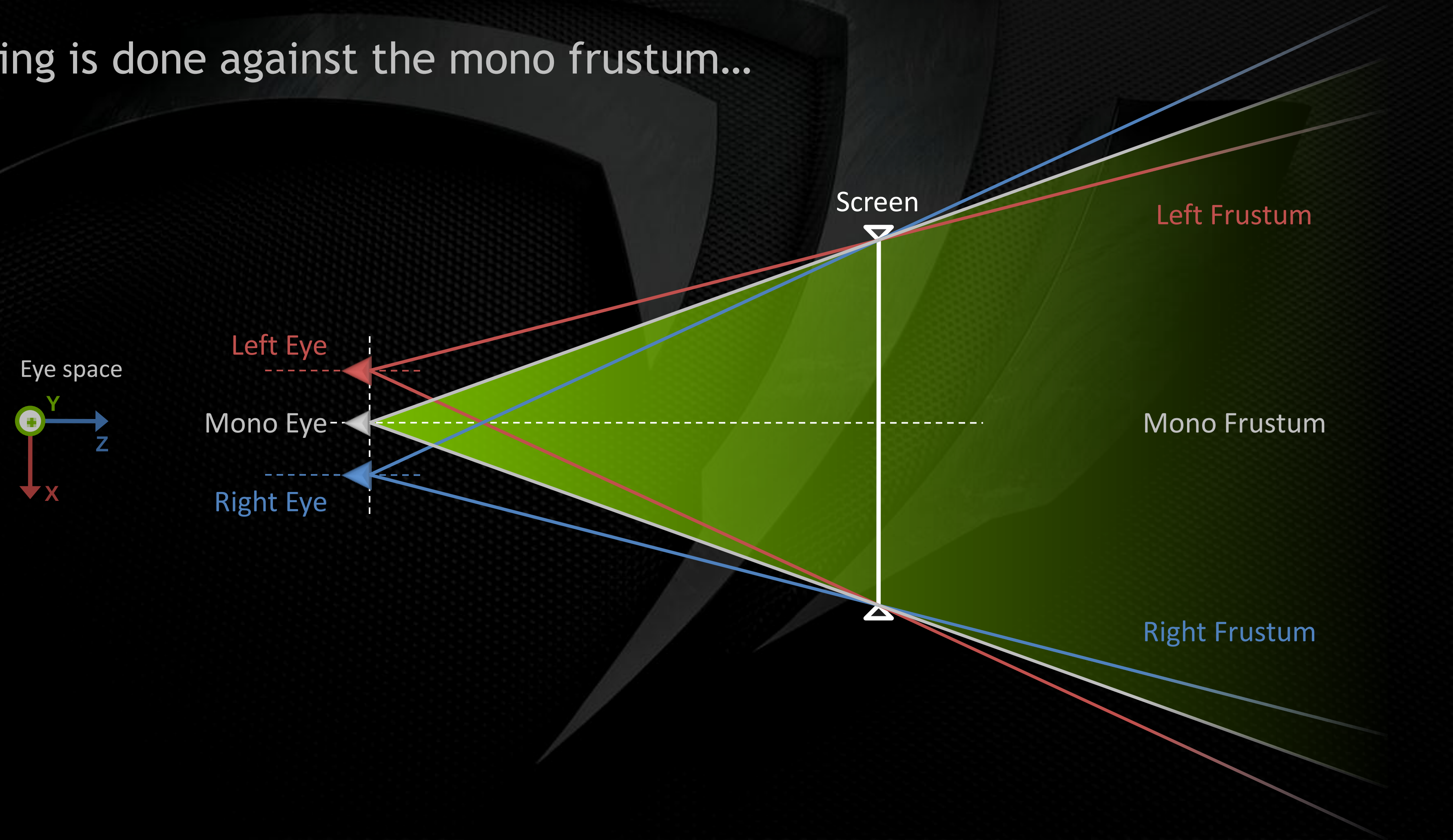
- Memory is allocated twice for all the stereo surfaces
  - Try to reuse render targets when possible to save memory

- Get another GPU ☺

STEREO CULLING

3D Objects Culling

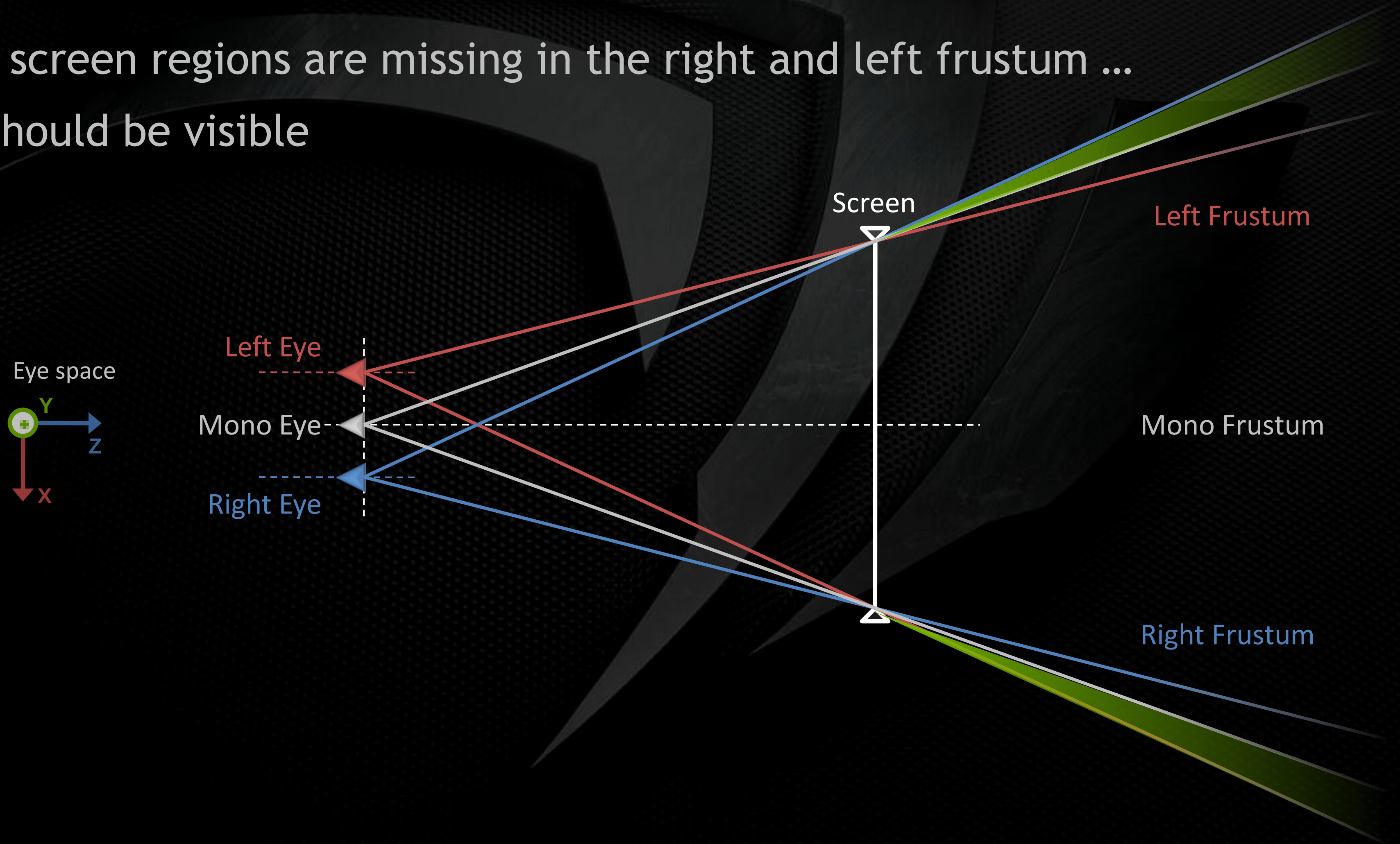
When culling is done against the mono frustum…



3D Objects Culling

… Some in screen regions are missing in the right and left frustum …

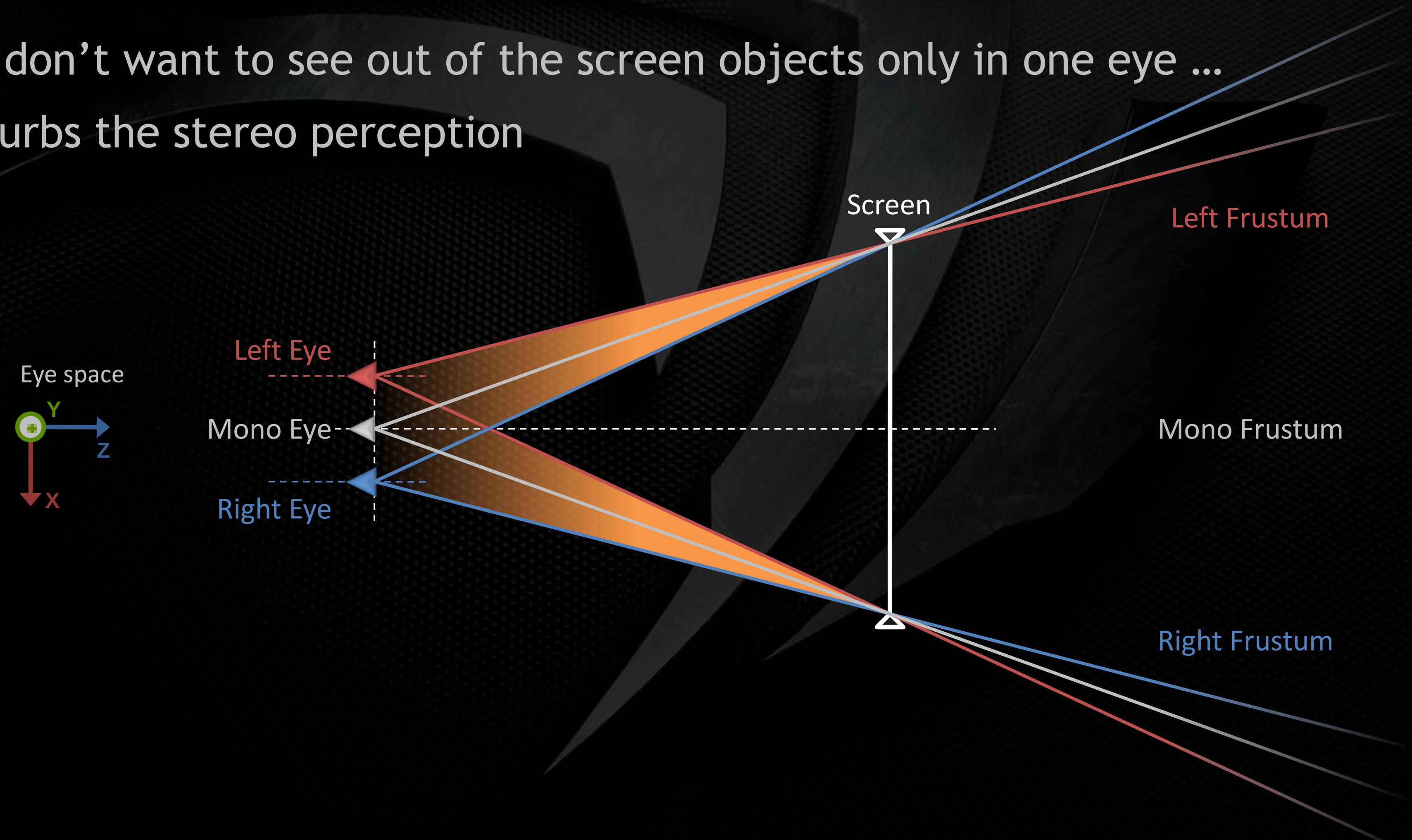
They should be visible



3D Objects Culling

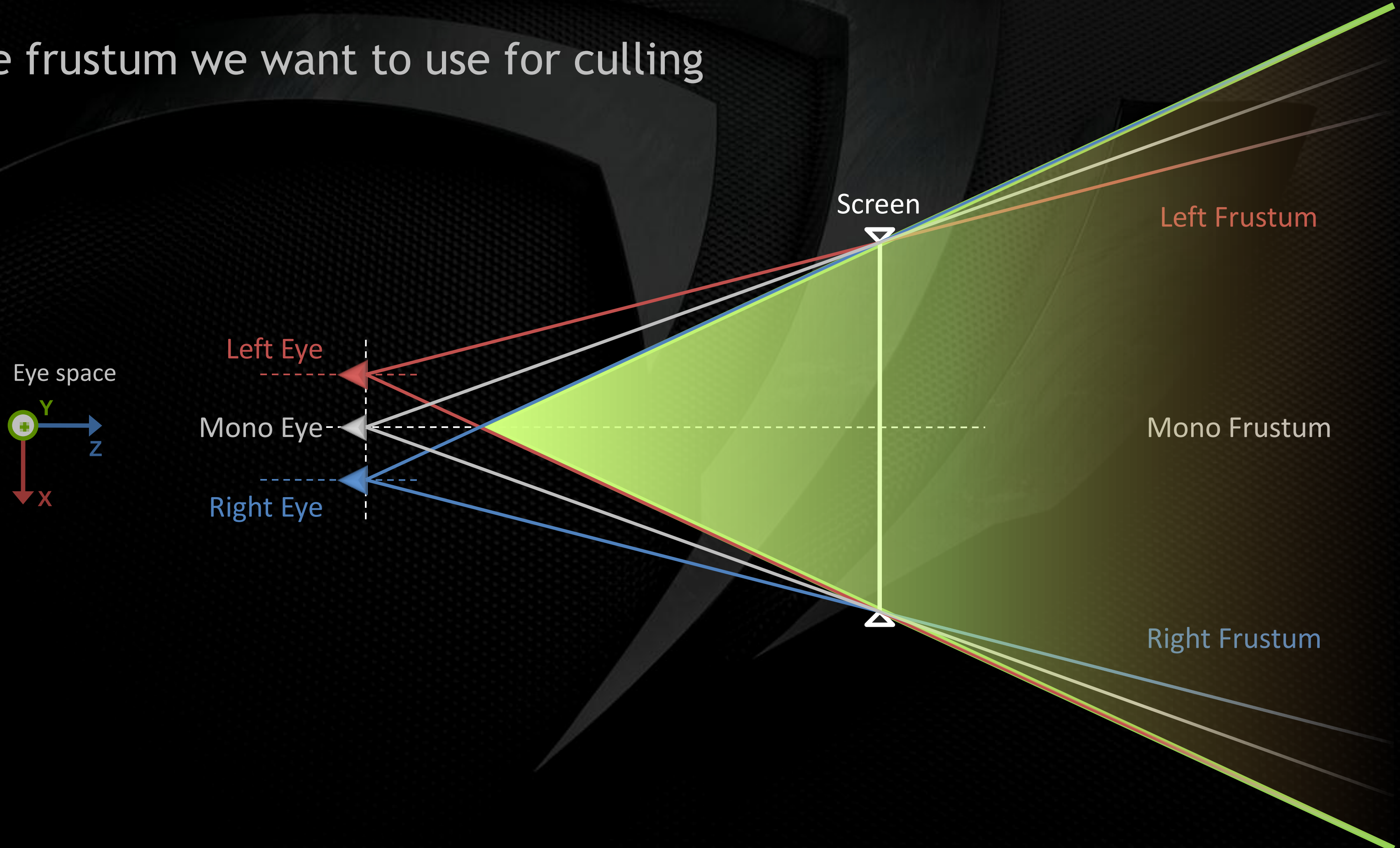
… And we don't want to see out of the screen objects only in one eye …

It disturbs the stereo perception



3D Objects Culling

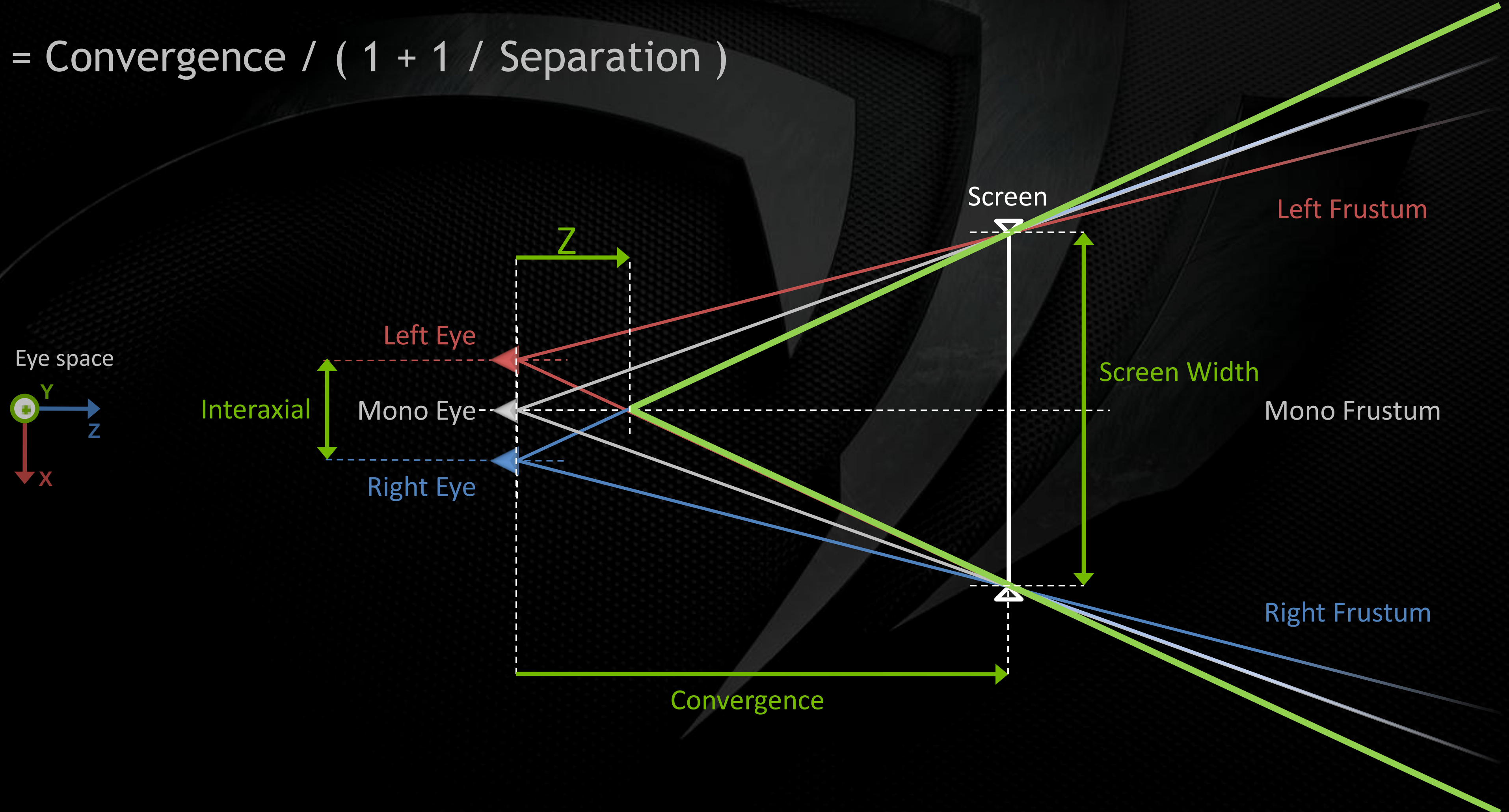
Here is the frustum we want to use for culling



3D Objects Culling

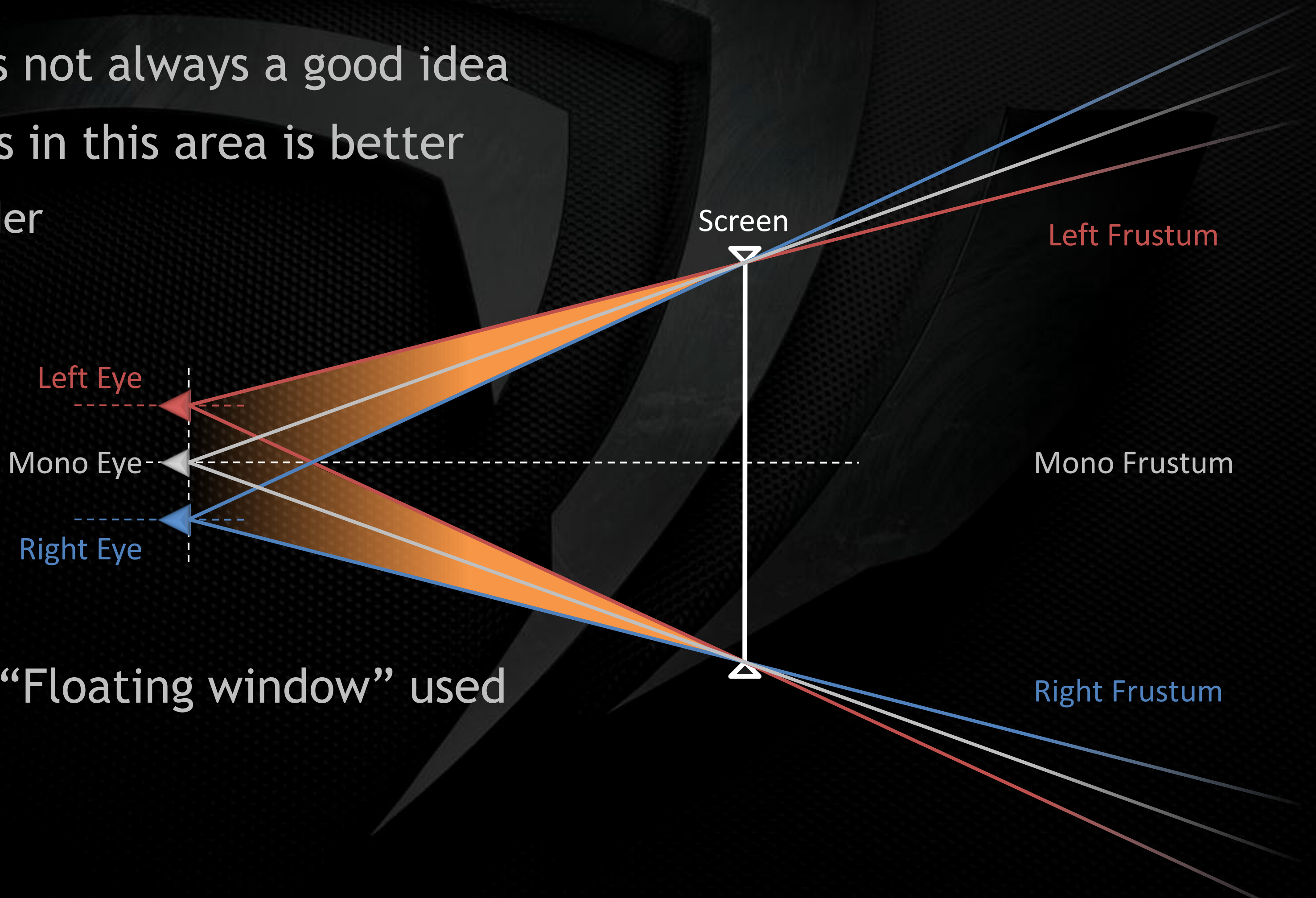
Computing Stereo Frustum origin offset

Z = Convergence / (1 + 1 / Separation)



3D Objects Culling

- Culling this area is not always a good idea
- Blacking out pixels in this area is better
  - Through a shader

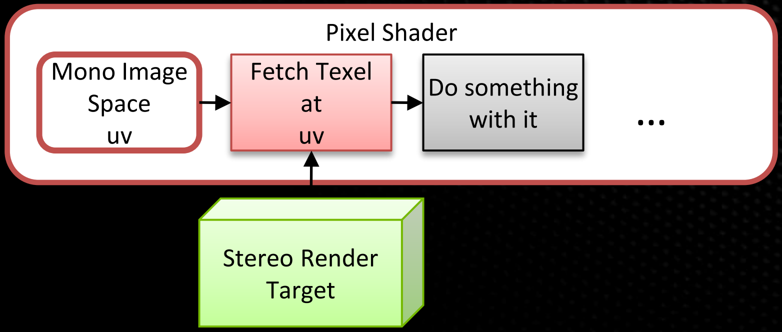


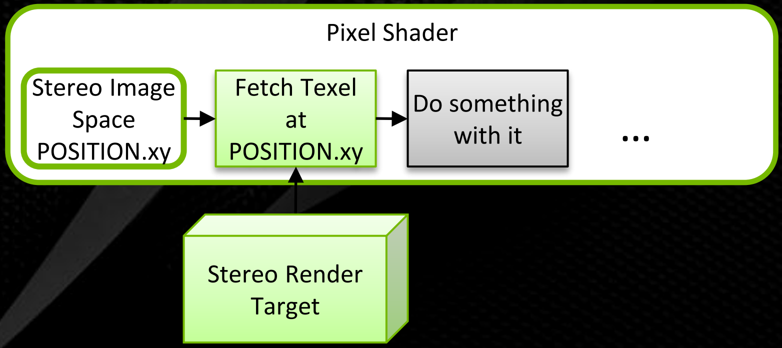
- Equivalent to the “Floating window” used in movies

STEREO TRANSFORM STACK TRICKS

Fetching Stereo Render Target

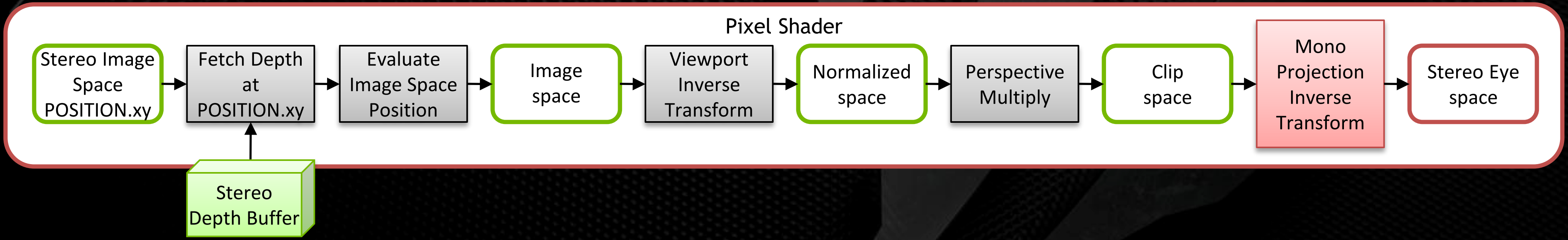
- When fetching from a stereo render target use the good texture coordinate
  - Render target is addressed in STEREO IMAGE SPACE
  - Use the pixel position provided in the pixel shader
  - Or use a texture coordinate computed in the vertex shader correctly

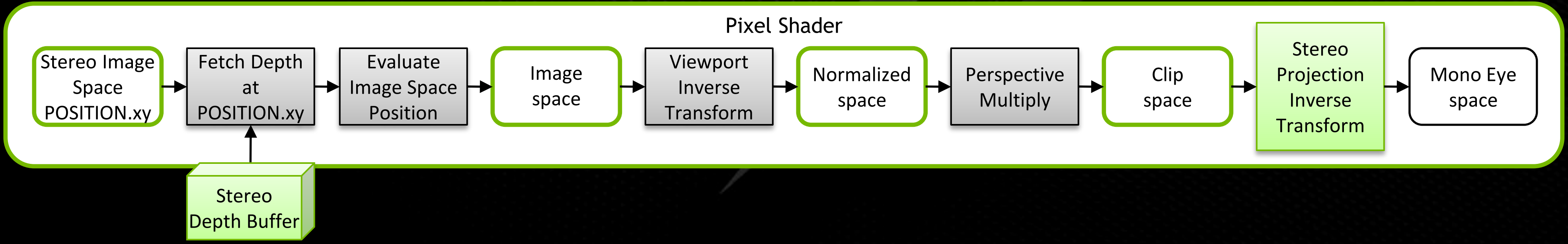




Unprojection in pixel shader

- When doing deferred shading technique, Pixel shader fetch the depth buffer (beware of the texcoord used, cf previous slide)
  - And evaluate a 3D clip position from the Depth fetched and XY viewport position
  - Make sure to use a Stereo Unprojection Inverse transformation to go to Mono Eye space
  - Otherwise you will be in a Stereo Eye Space !





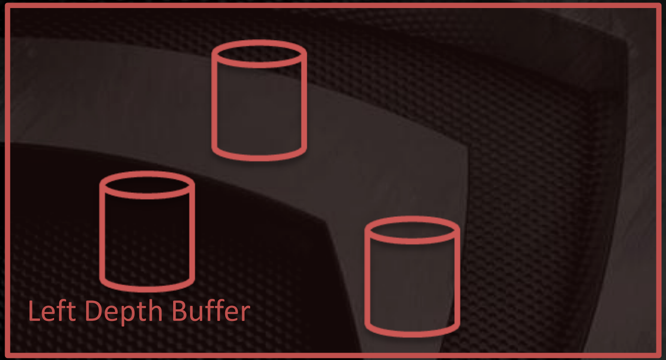
What's under this screen pixel ?

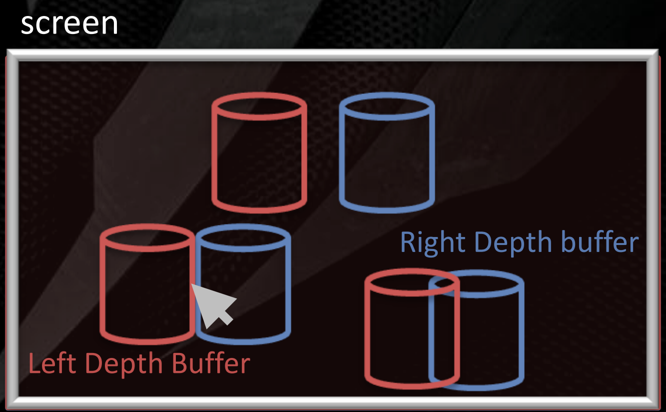
SELECTION IN S3D

From stereo depth buffers to parallax

Aka, What's under that cursor ?

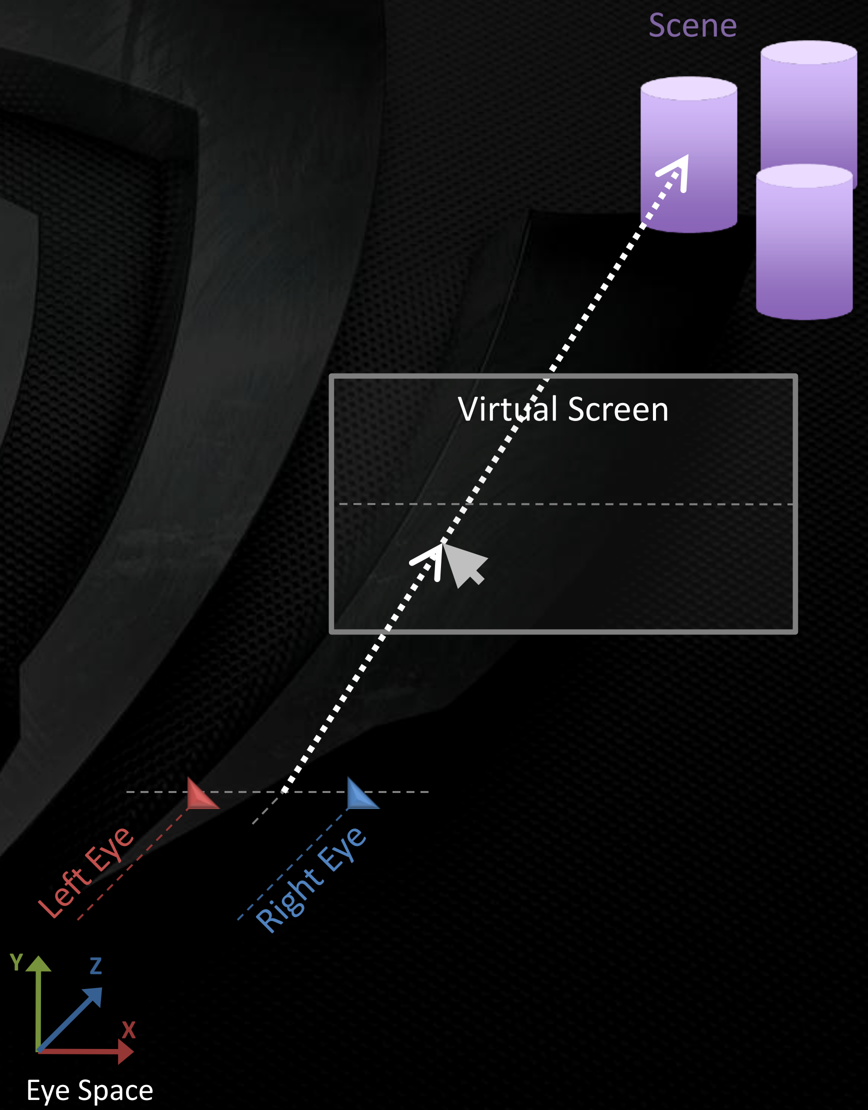
- Given the left and right depth buffers
- A pixel position in the screen (Cursor)
- How to find the unique fragment of the scene under that pixel like we would do in the mono case ?



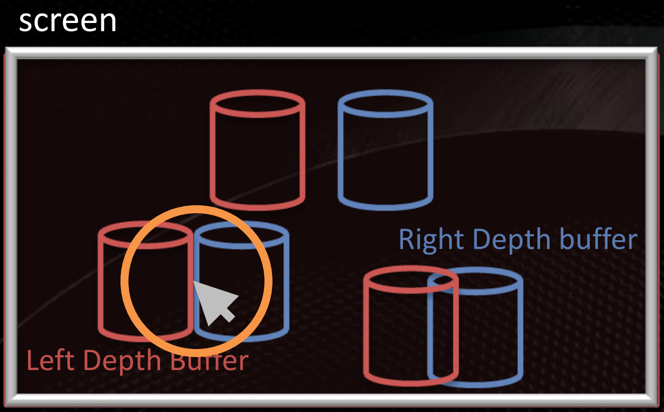


From stereo depth buffers to parallax

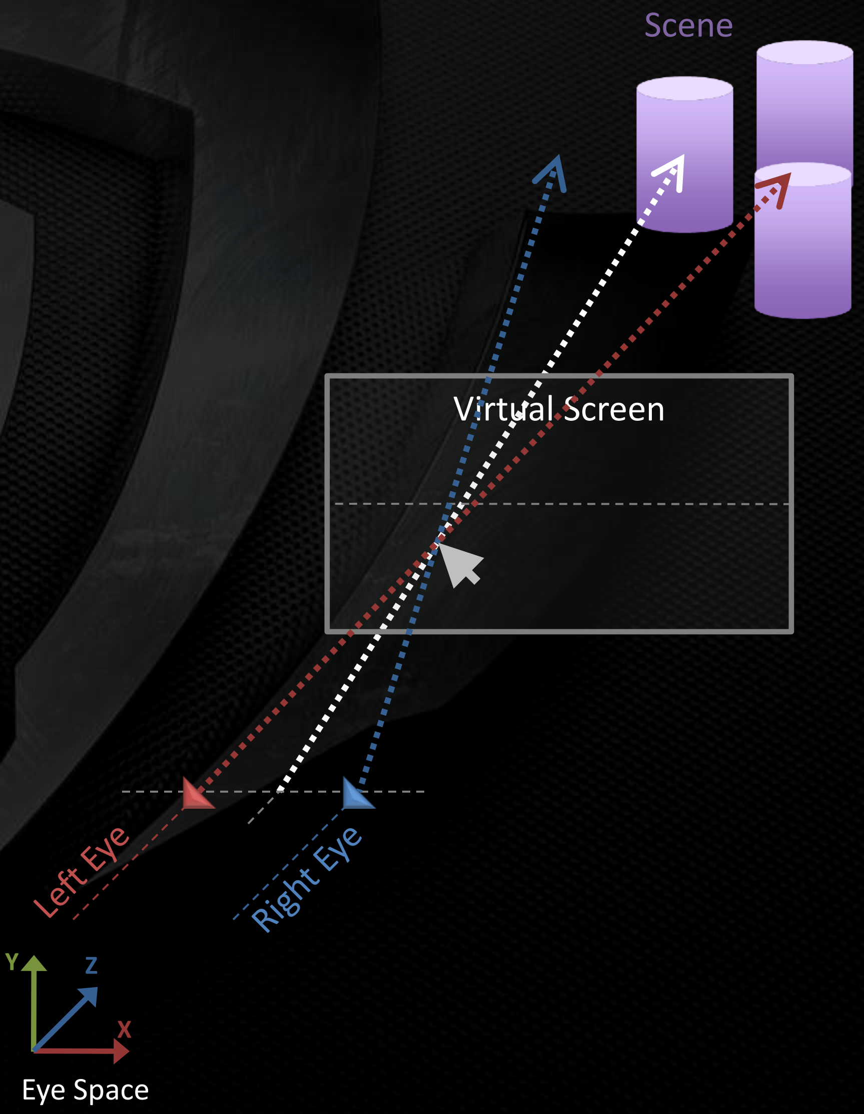
- There is a unique solution in mono
  - which is not trivial in stereo…



From stereo depth buffers to parallax

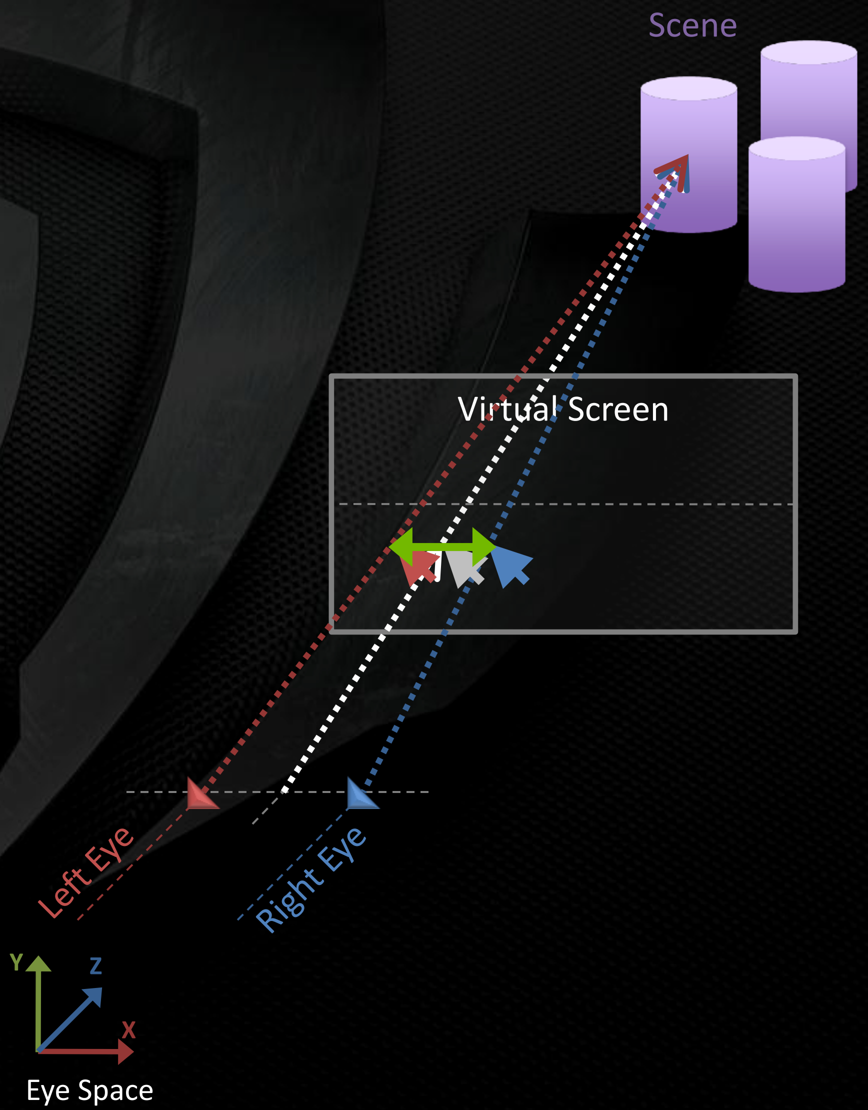


- The fragments are different at the Cursor position in left and right buffer



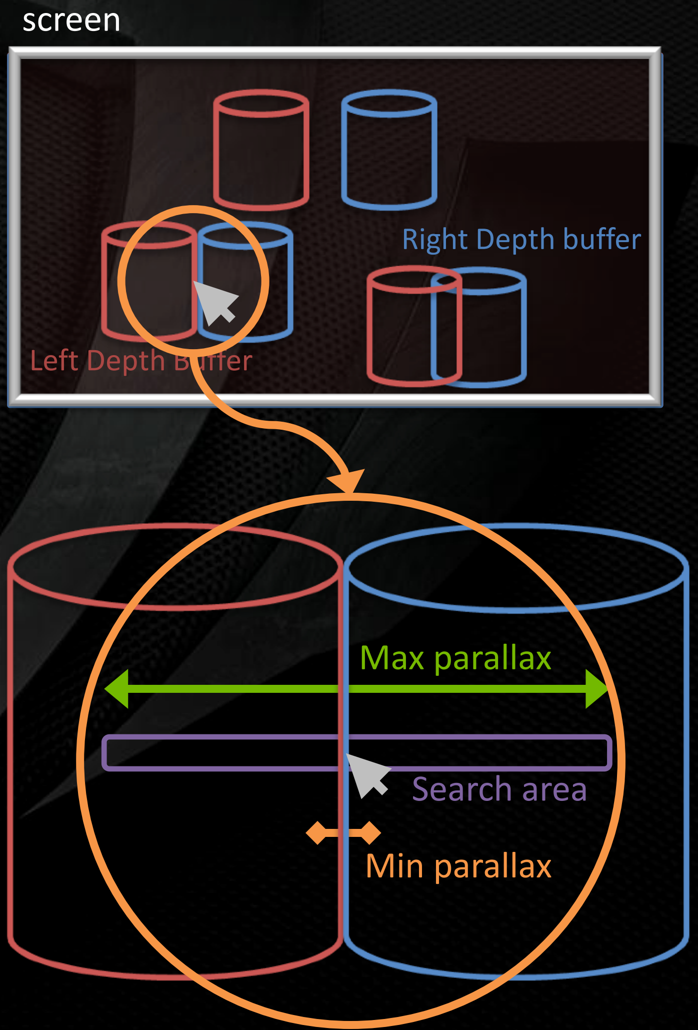
From stereo depth buffers to parallax

- Correct left and right cursor locations
  - Are pointing at the same scene fragment
  - Are shifted away from the mono position from Parallax



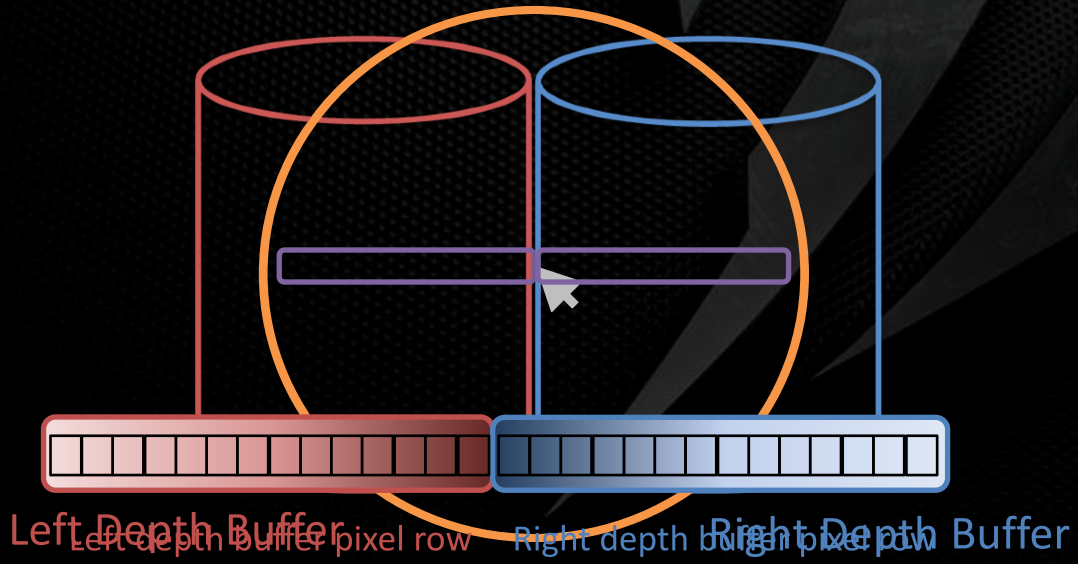
From stereo depth buffers to parallax

- Parallax is bounded in a given range of pixels [*MinParallax*, *MaxParallax*]
  - Deduced From the range [near, far]
- So we know where to look in the depth buffers
  - Correct location for the left & right pixels is in the neighborhood of the mono pixel
  - Now we need a technique to find the correct solution in left and right depth buffers in this area



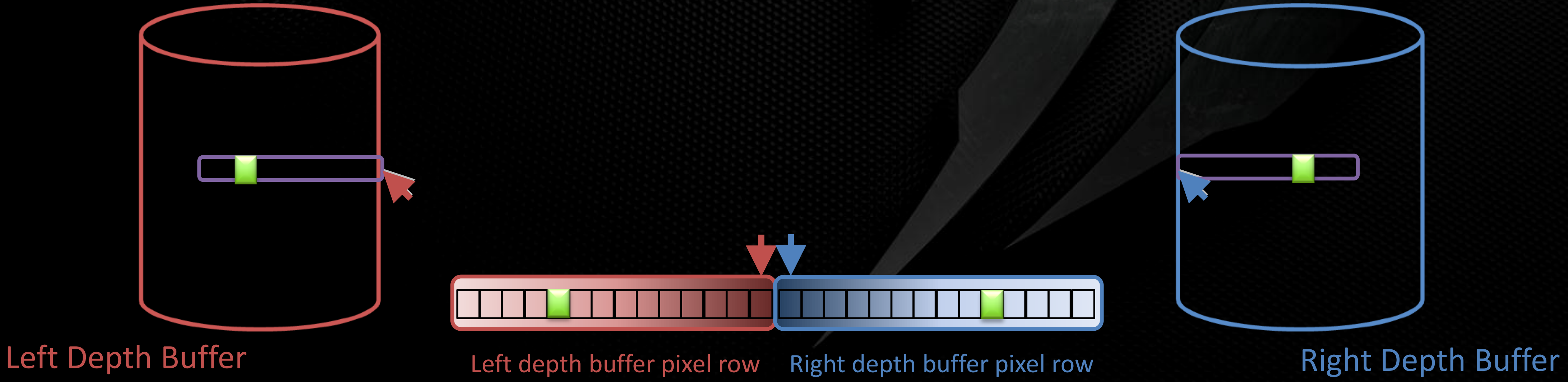
From stereo depth buffers to parallax

- Search area in each buffer is only half of the total parallax range and symmetrical around the mono pixel
- Look into pixel segment from the depth buffers



From stereo depth buffers to parallax

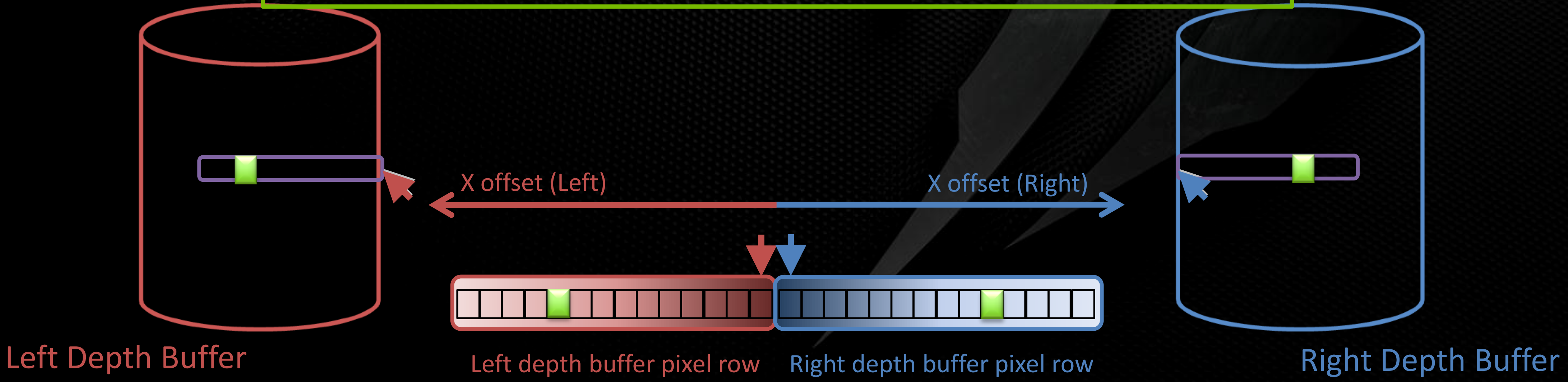
- The left and right pixels over the same scene fragment
  - Are horizontally at the same distance away from the mono pixel because they should be shifted by the same half parallax
  - And the 2 depths found should be equal and evaluate to the correct half parallax



From stereo depth buffers to parallax

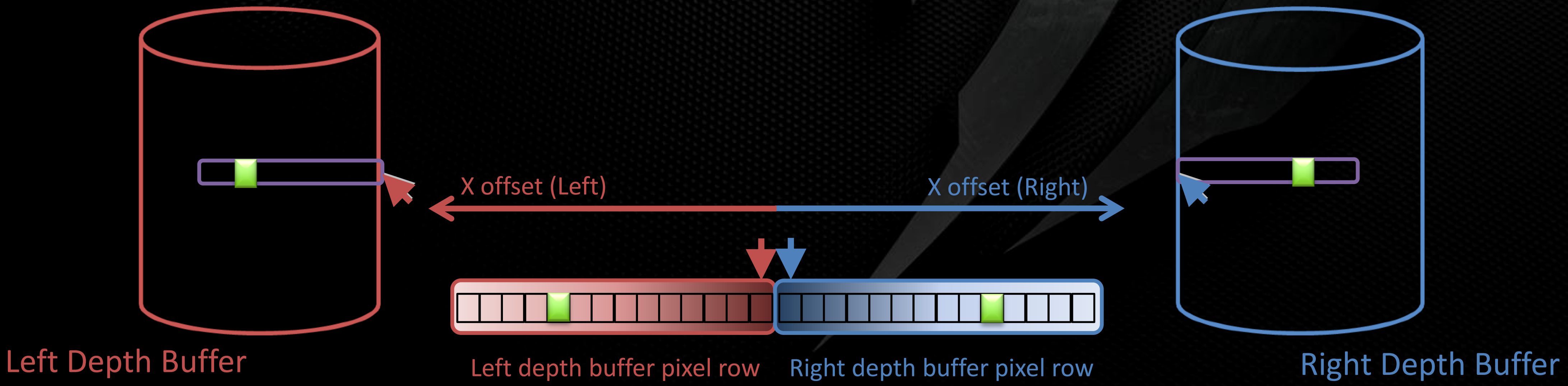
- Start search from the mono pixel
- Progress on both sides pixel by pixel to find the one where

$$Parallax(\,depth\,) = Xoffset$$
$$Xoffset_{left} = Xoffset_{right}$$



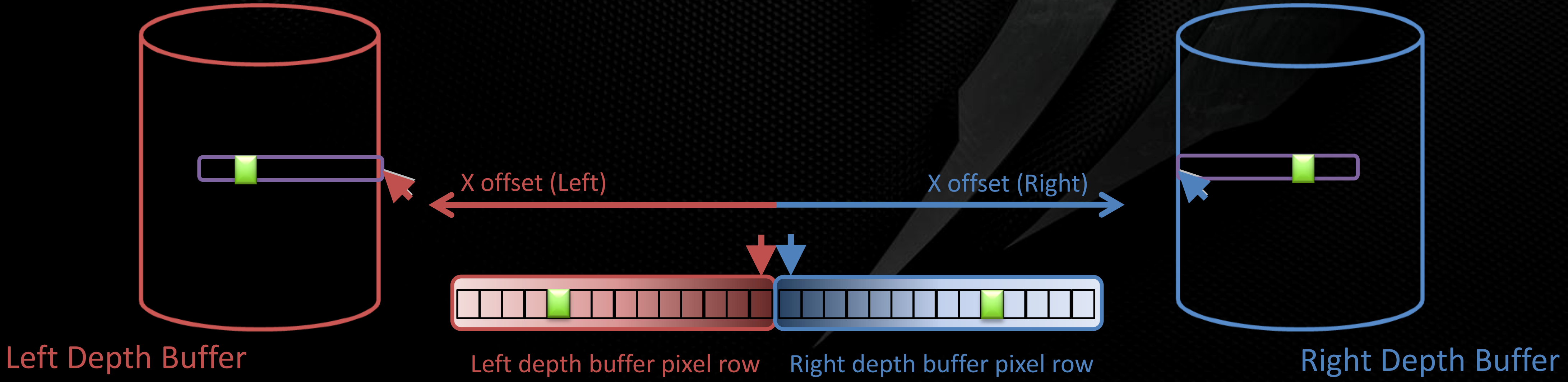
From stereo depth buffers to parallax

- Min parallax could be negative
  - Scene out of the screen
- Look into both directions around the mono pixel



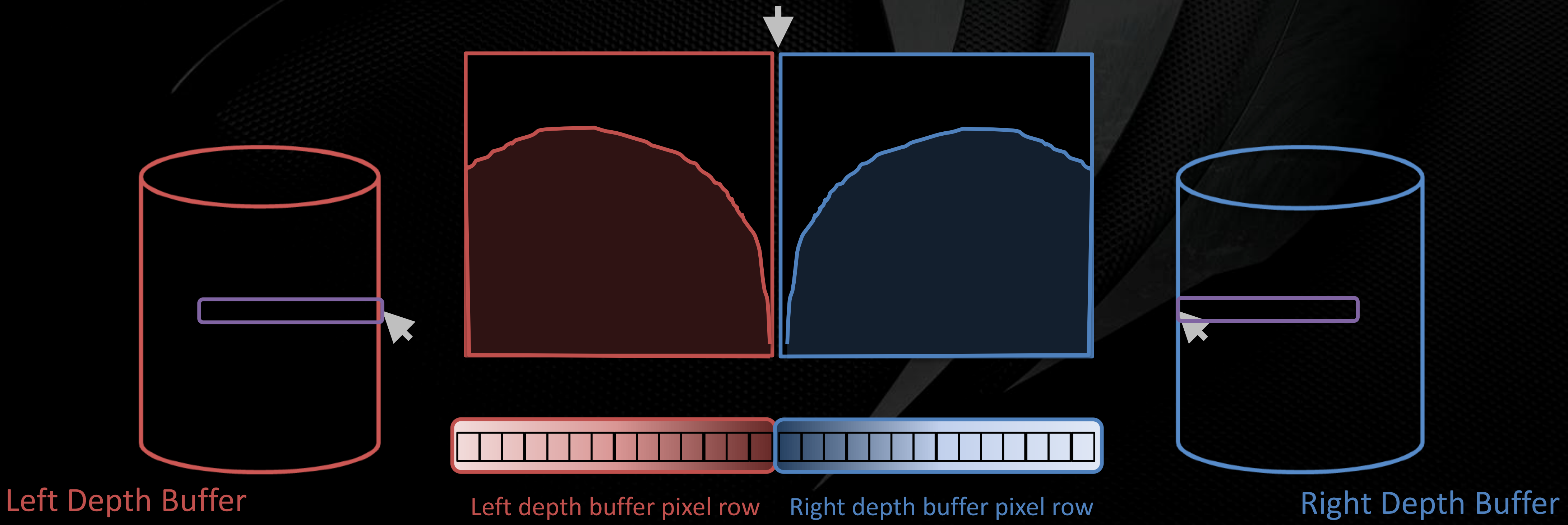
From stereo depth buffers to parallax

- Start search from the mono pixel
- Progress on both side pixel by pixel to find the one where
  - Parallax(Depth) / 2 = Xoffset
  - Xoffset Right



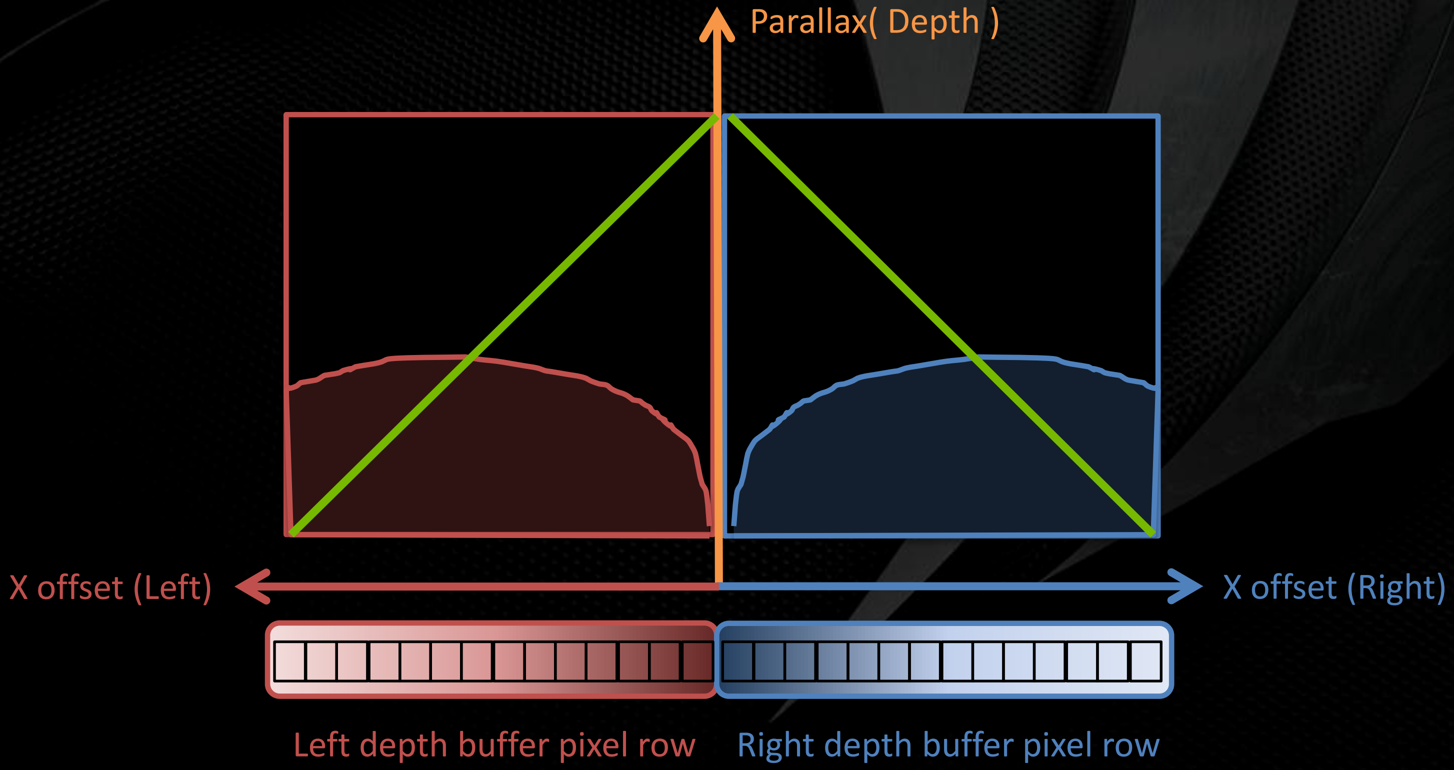
From stereo depth buffers to parallax

- Start search from the mono pixel



From stereo depth buffers to parallax

- **Progress pixel by pixel to find the one where**
- Parallax(depth) / 2 = X offset
-



Cartoon authoring for 3D

Creative choices for 3D

Managing a depth budget

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