Implementing Stereoscopic 3D in Your Applications

Room C | 09/20/2010 – 16:00 – 17:20

Samuel Gateau, NVIDIA, Steve Nash, NVIDIA

GPU TECHNOLOGY CONFERENCE

PRESENTED BY NVIDIA.

Agenda

- How It Works
- NVIDIA 3D Vision
- Implementation Example
- Stereoscopic Basics
- Depth Perception
- Parallax Budget
- Rendering in Stereo
- What's Next?

3D vs Stereo

- "In 3D" is the new "Stereo"
  - They are used interchangeably, stereoscopic rendering is the technical means to make an image "In 3D"
- Each eye gets its own view rendered with a slightly different camera location: usually about as far apart as your eyes
- Stereo displays and APIs are used to manage these two views

Stereo

Not Stereo

Stereoscopic Basics

How It Works

Applications render a Left Eye view and Right Eye view with slight offset between

Left Eye view

Right Eye view

A Stereoscopic display then shows the left eye view for even frames (0, 2, 4, etc) and the right eye view for odd frames (1, 3, 5, etc).

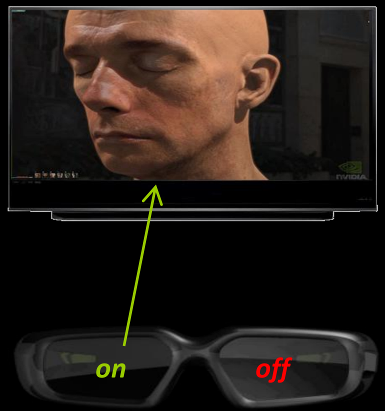
Stereoscopic Basics

How It Works

In this example active shutter glasses black-out the right lens when the left eye view is shown on the display and black-out the left lens when the right eye view is shown on the display.

This means that the refresh rate of the display is effectively cut in half for each eye. (e.g. a display running at 120 Hz is 60 Hz per eye)

Left eye view on, right lens blocked



Right eye view on, left lens blocked

The resulting image for the end user is a combined image that appears to have depth in front of and behind the stereoscopic 3D Display.

GPU TECHNOLOGY CONFERENCE

NVIDIA 3D Vision

Software
3D Vision SW automatically converts mono games to Stereo
Direct X only

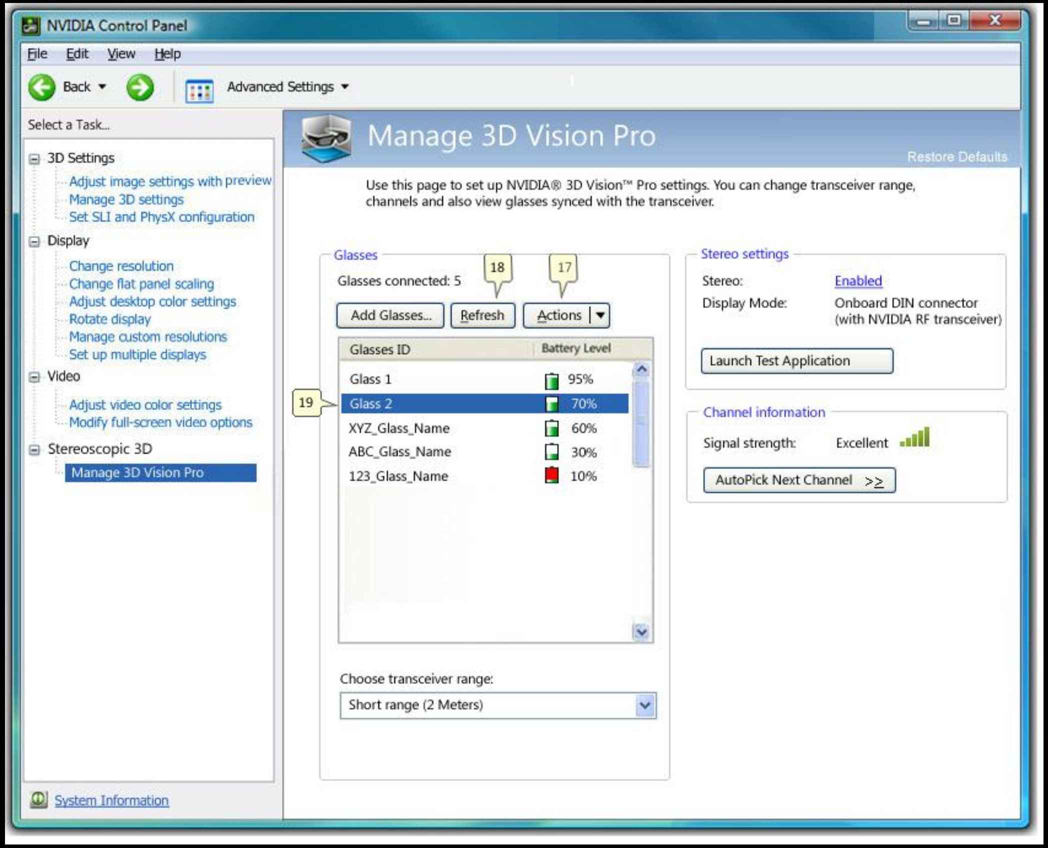
Hardware
IR communication
3D Vision certified displays
Support for single screen or 1x3 configurations

NVIDIA 3D Vision Pro

Software
Supports Consumer 3D Vision SW or Quad Buffered Stereo
QBS: OpenGL or DirectX For DX QBS, e-mail 3DVisionPro_apps@nvidia.com for help

Hardware
RF communication
3D Vision certified displays, Passive Displays, CRTs and projectors
Up to 8 displays
Mix Stereo and Regular Displays
G-Sync support for multiple displays and systems
Direct connection to GPU mini-DIN

NVIDIA 3D Vision Pro

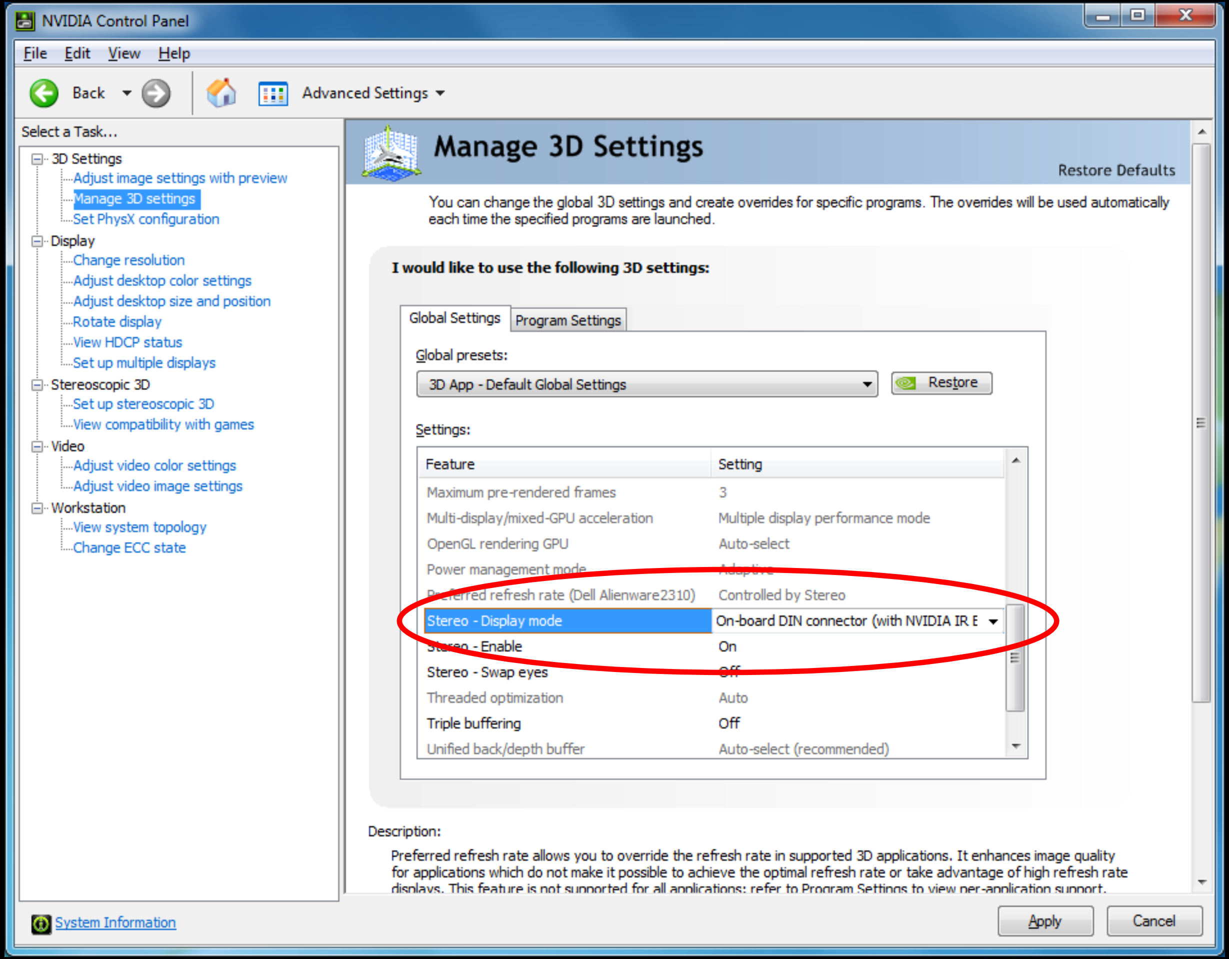


Hardware – cont'd
Designed for multi-user professional installations
No line of sight requirement, no dead spots, no cross talk
RF bi-directional communication with UI
50m range
Easily deploy in office no matter what the floor plan

Implementation Example

Implementation Example: OpenGL

Step 1: Configure for Stereo



Implementation Example: OpenGL

Step 2: Query and request PFD_STEREO

```
iPixelFormat = DescribePixelFormat(hdc, 1,
sizeof(PIXELFORMATDESCRIPTOR), &pfd);
while (iPixelFormat) {

   DescribePixelFormat(hdc, iPixelFormat,
      sizeof(PIXELFORMATDESCRIPTOR), &pfd);

      if (pfd.dwFlags & PFD_STEREO){
         iStereoPixelFormats++;
      }
      iPixelFormat--;
   }
if (iStereoPixelFormats== 0)
   // no stereo pixel formats available
   StereoIsAvailable = FALSE;
else
   StereoIsAvailable = TRUE;
```

Implementation Example: OpenGL

Step 2 cont'd

```
if (StereoIsAvailable){
    ZeroMemory(&pfd, sizeof(PIXELFORMATDESCRIPTOR));
    pfd.nSize = sizeof(PIXELFORMATDESCRIPTOR);
    pfd.nVersion          = 1;
    pfd.dwFlags           = PFD_DRAW_TO_WINDOW |
                            PFD_SUPPORT_OPENGL |
                            PFD_DOUBLEBUFFER |
                            PFD_STEREO;
    pfd.iPixelType        = PFD_TYPE_RGBA;
    pfd.cColorBits        = 24;

    iPixelFormat = ChoosePixelFormat(hdc, &pfd);

    if (iPixelFormat != 0){
        if (SetPixelFormat(hdc, iPixelFormat, &pfd)){
            hglrc = wglCreateContext(hdc);
            if (hglrc != NULL){
                if (wglMakeCurrent(hdc, hglrc)){
                …
```

GPU TECHNOLOGY CONFERENCE

PRESENTED BY NVIDIA.

Implementation Example: OpenGL

Step 3: Render to Left/Right buffer with offset between

```
// Select back left buffer
glDrawBuffer(GL_BACK_LEFT);
glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
// Setup the frustum for the left eye
glMatrixMode(GL_PROJECTION);
glLoadIdentity();
glFrustum(Xmin - FrustumAssymmetry,
          Xmax - FrustumAssymmetry,
          -0.75, 0.75, 0.65, 4.0);

glTranslatef(eyeOffset, 0.0f, 0.0f);

glMatrixMode(GL_MODELVIEW);
glLoadIdentity();

<Rendering calls>
```

Implementation Example: OpenGL

Step 3 cont'd

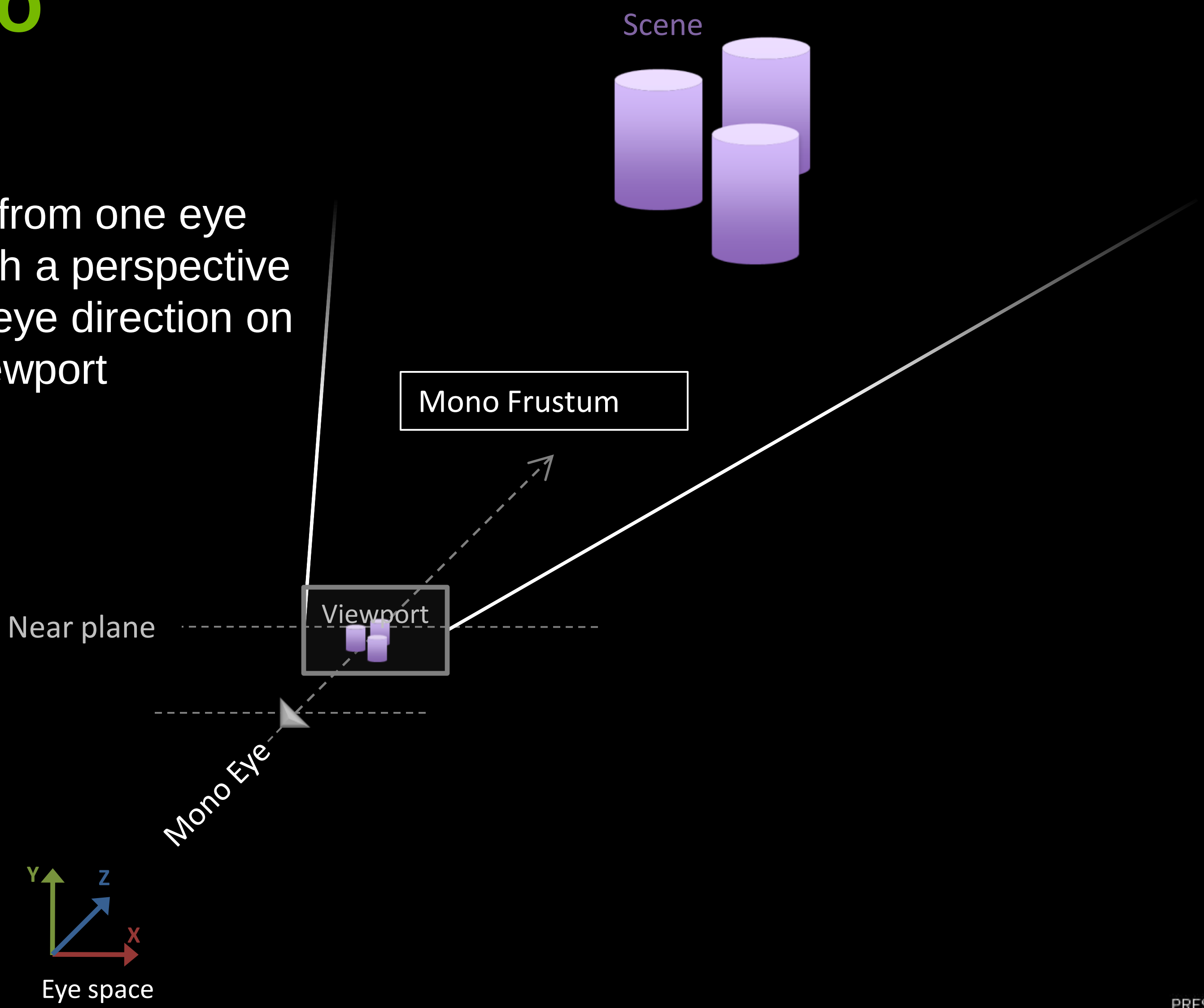
```
// Select back right buffer
glDrawBuffer(GL_BACK_RIGHT);
glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);

// Setup the frustum for the right eye.
glMatrixMode(GL_PROJECTION);
glLoadIdentity();
glFrustum(Xmin + FrustumAssymmetry,
          Xmax + FrustumAssymmetry,
          -0.75, 0.75, 0.65, 4.0);
glTranslatef(-eyeOffset, 0.0f, 0.0f);
glTranslatef(0.0f, 0.0f, -PULL_BACK);

glMatrixMode(GL_MODELVIEW);
glLoadIdentity();

<Rendering calls>
// Swaps both left and right buffers
SwapBuffers(hdc);
```

Changes to the rendering pipe

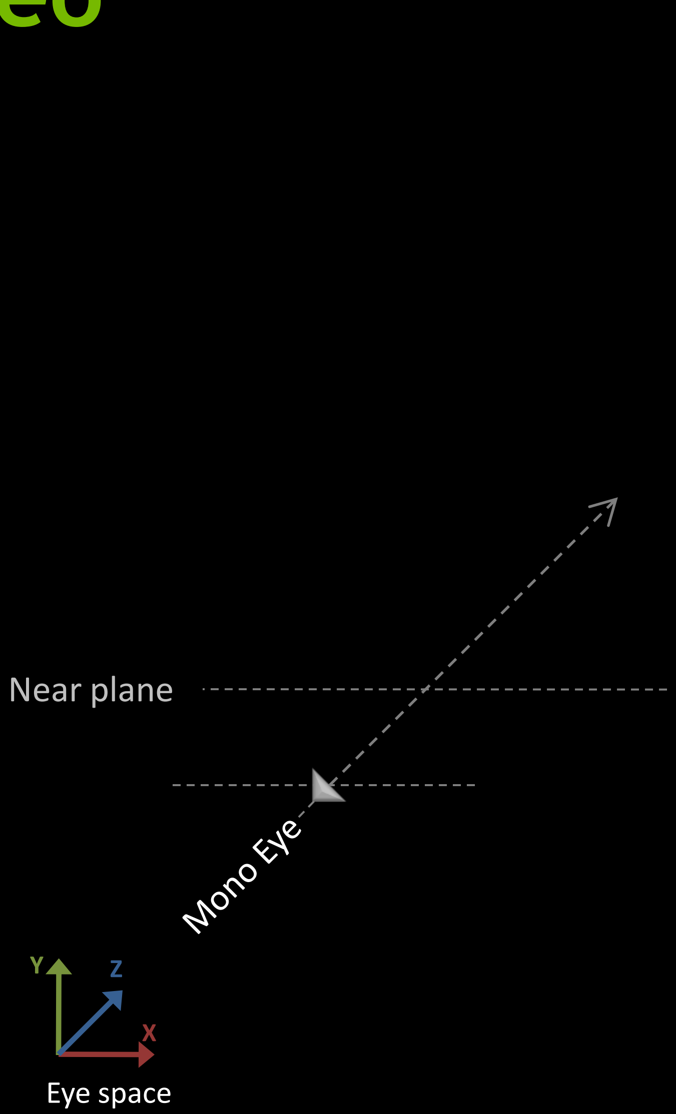
FROM MONO TO STEREO

In Mono

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

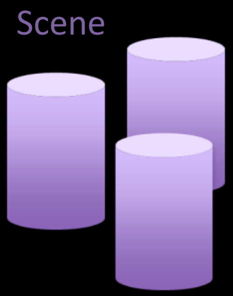


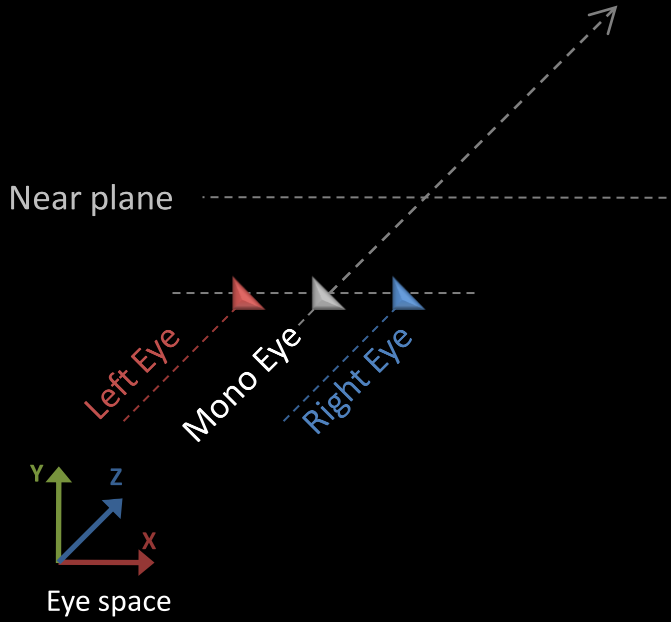
In Stereo



In Stereo:
Two eyes

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



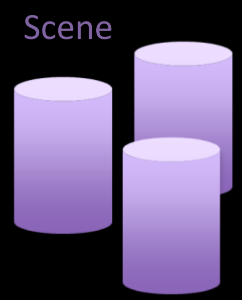


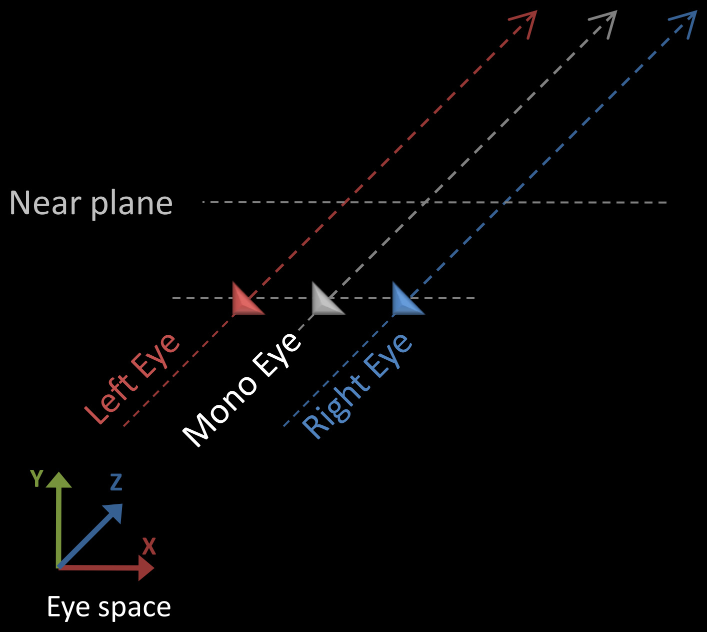
In Stereo:

Two eyes

Left and Right eyes

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





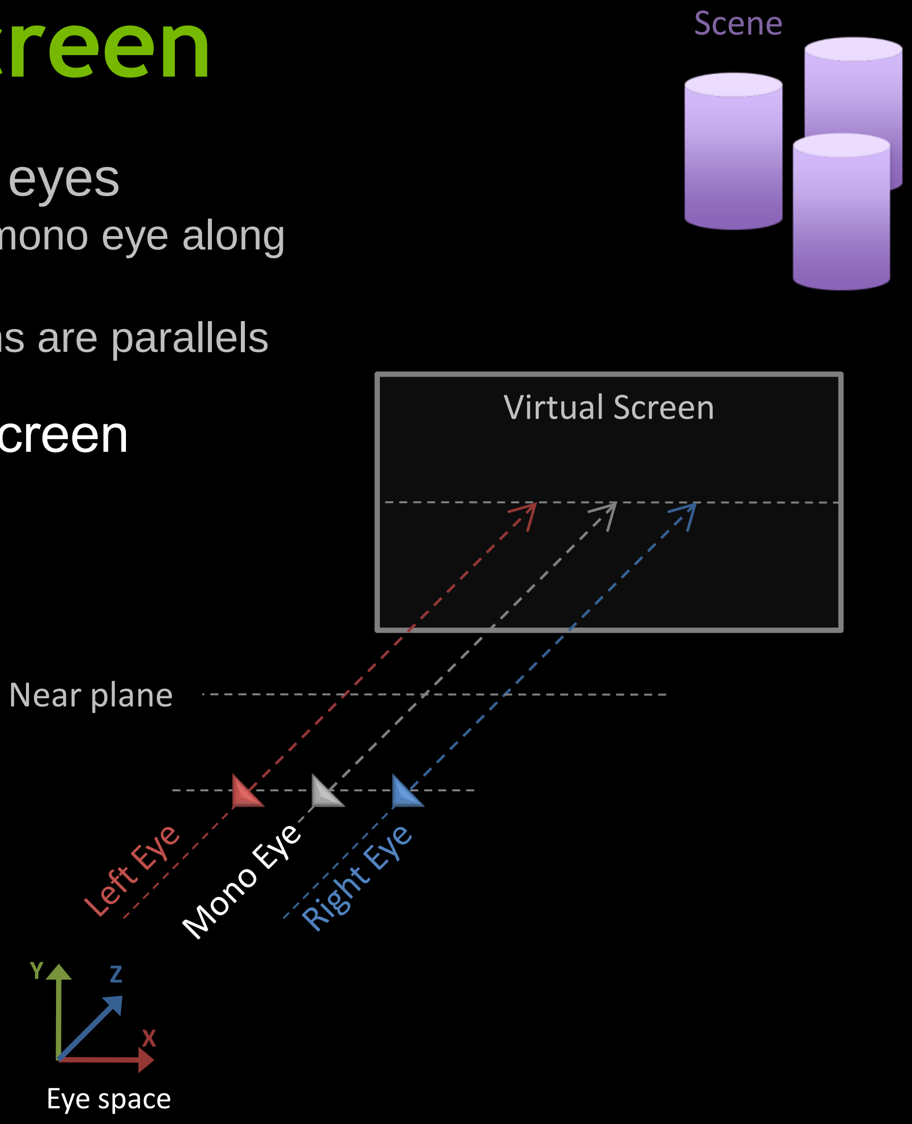
In Stereo: Two Eyes,

One Screen

Left and Right eyes

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

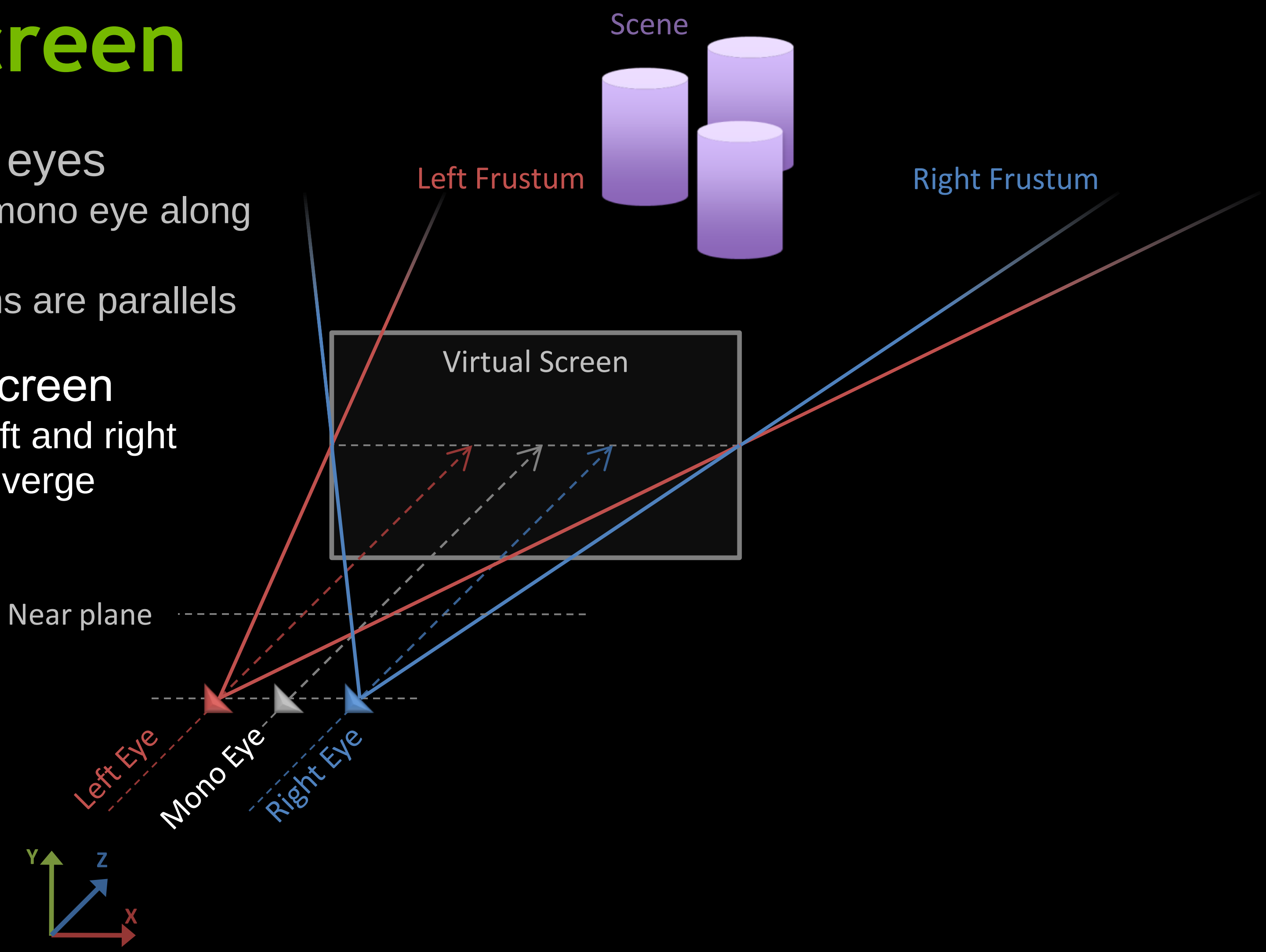
One “virtual” screen



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,

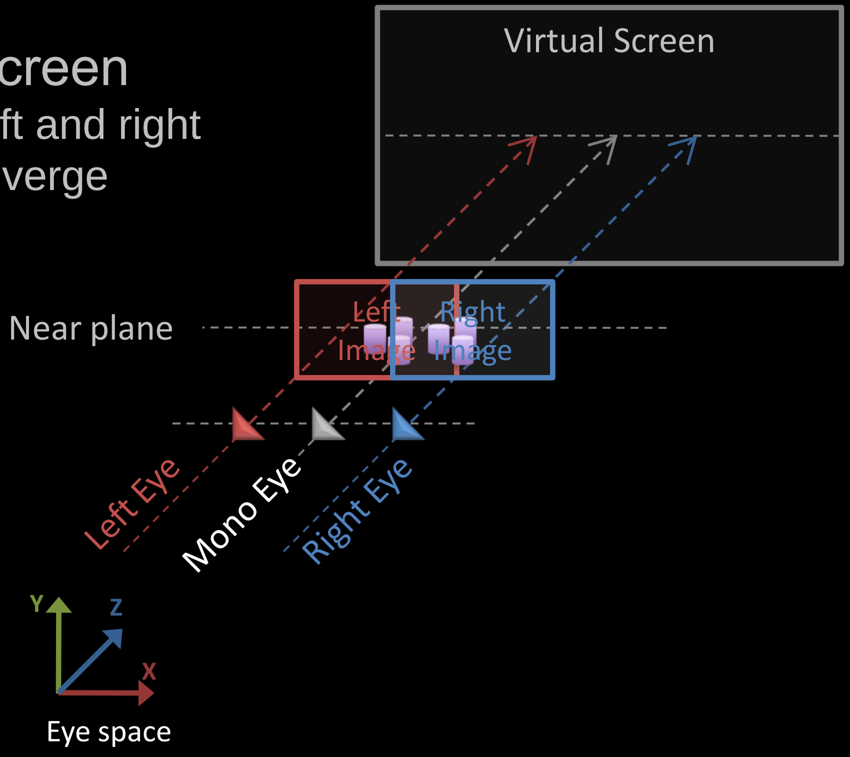
Two Images

Left and Right eyes

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

One “virtual” screen

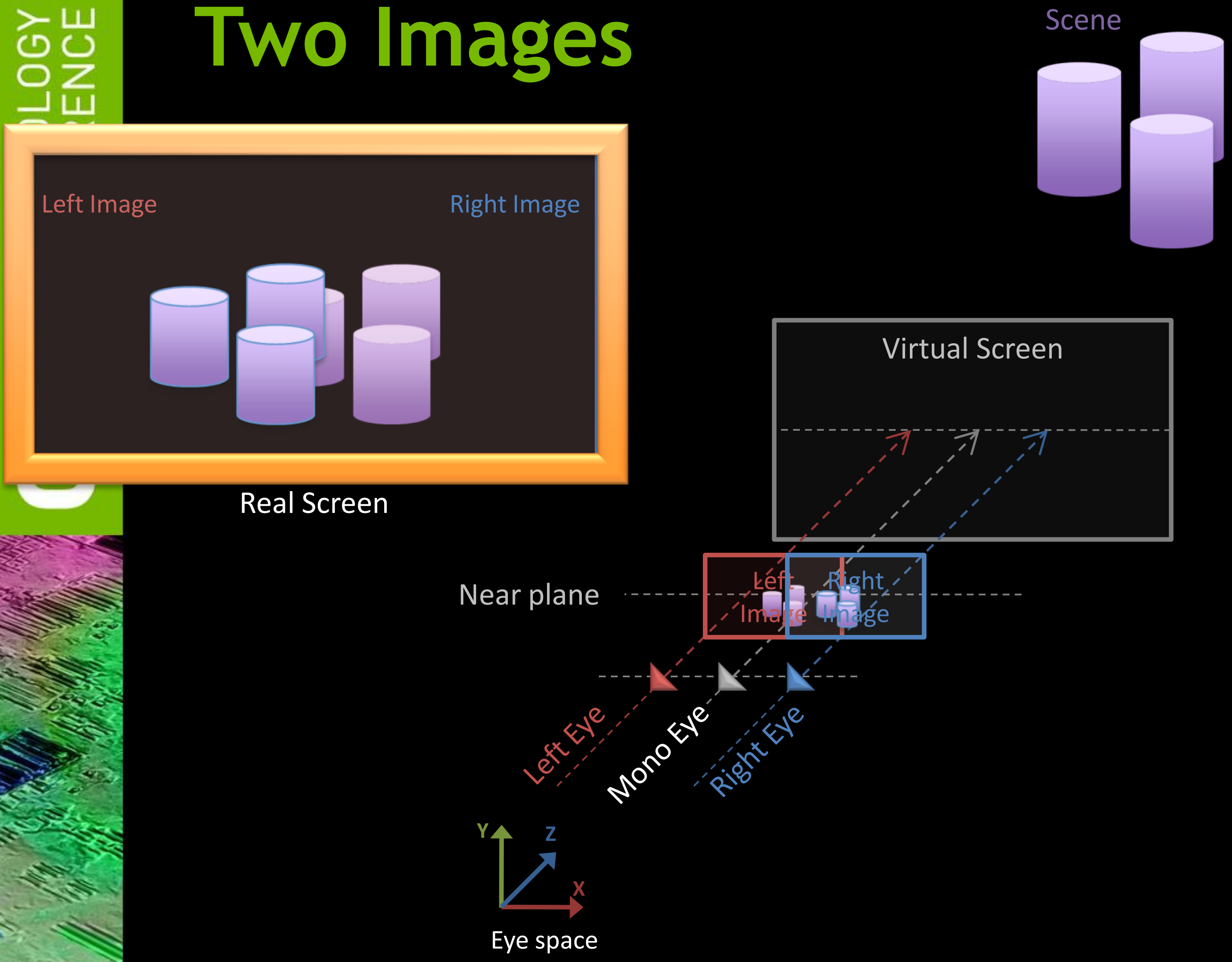
- Where the left and right frustums converge



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

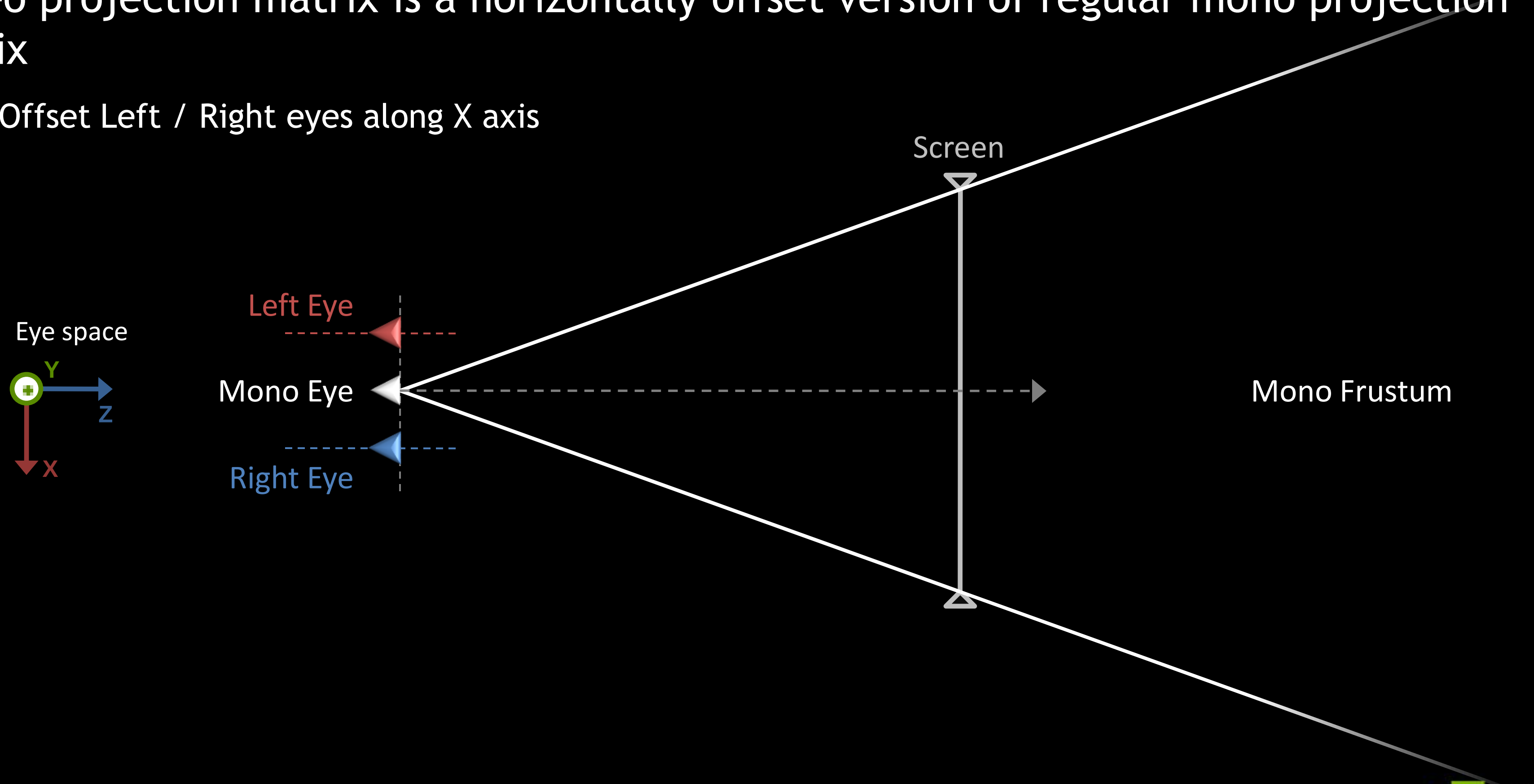
Into left and right images

Basic definitions so we all speak English

DEFINING STEREO PROJECTION

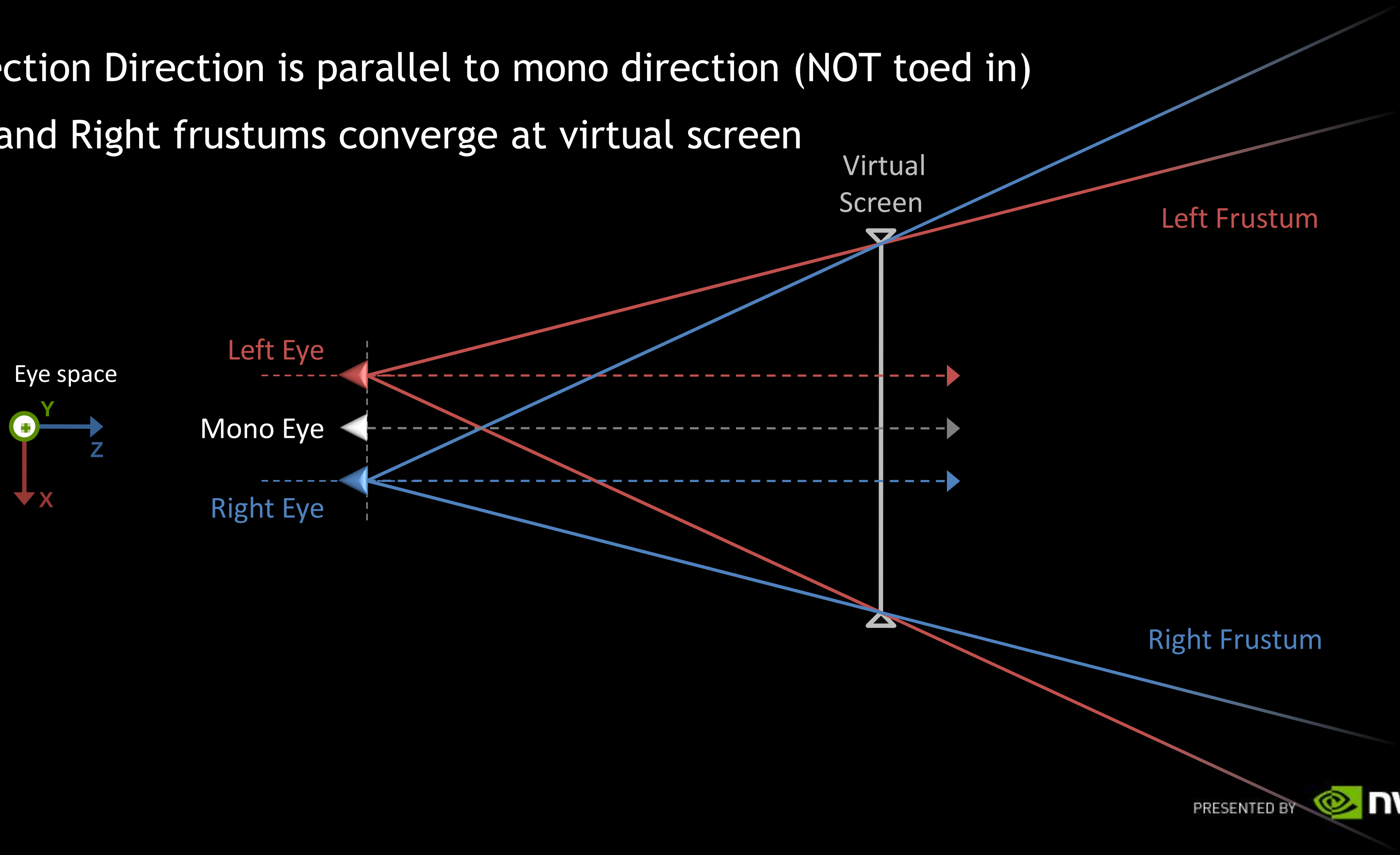
Stereo Projection

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



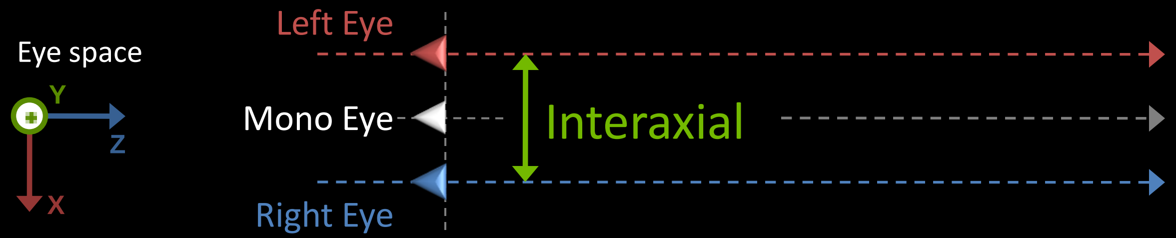
Stereo Projection

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



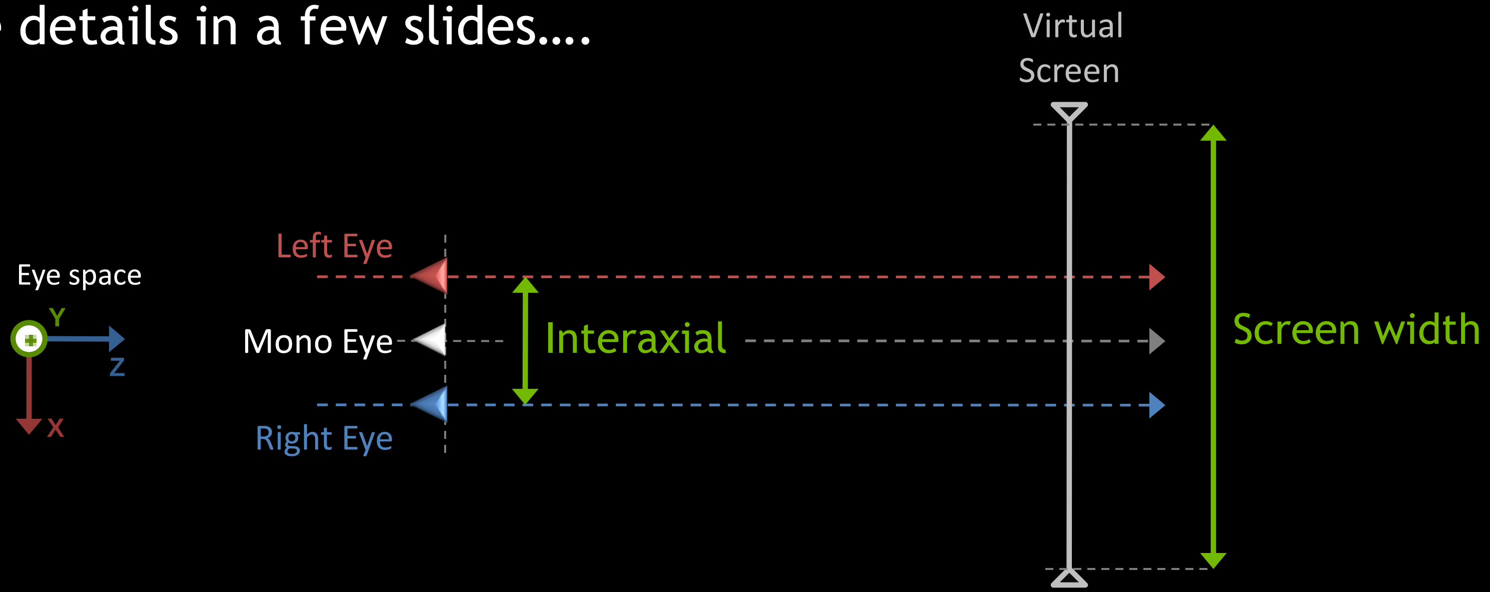
Interaxial

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



Separation

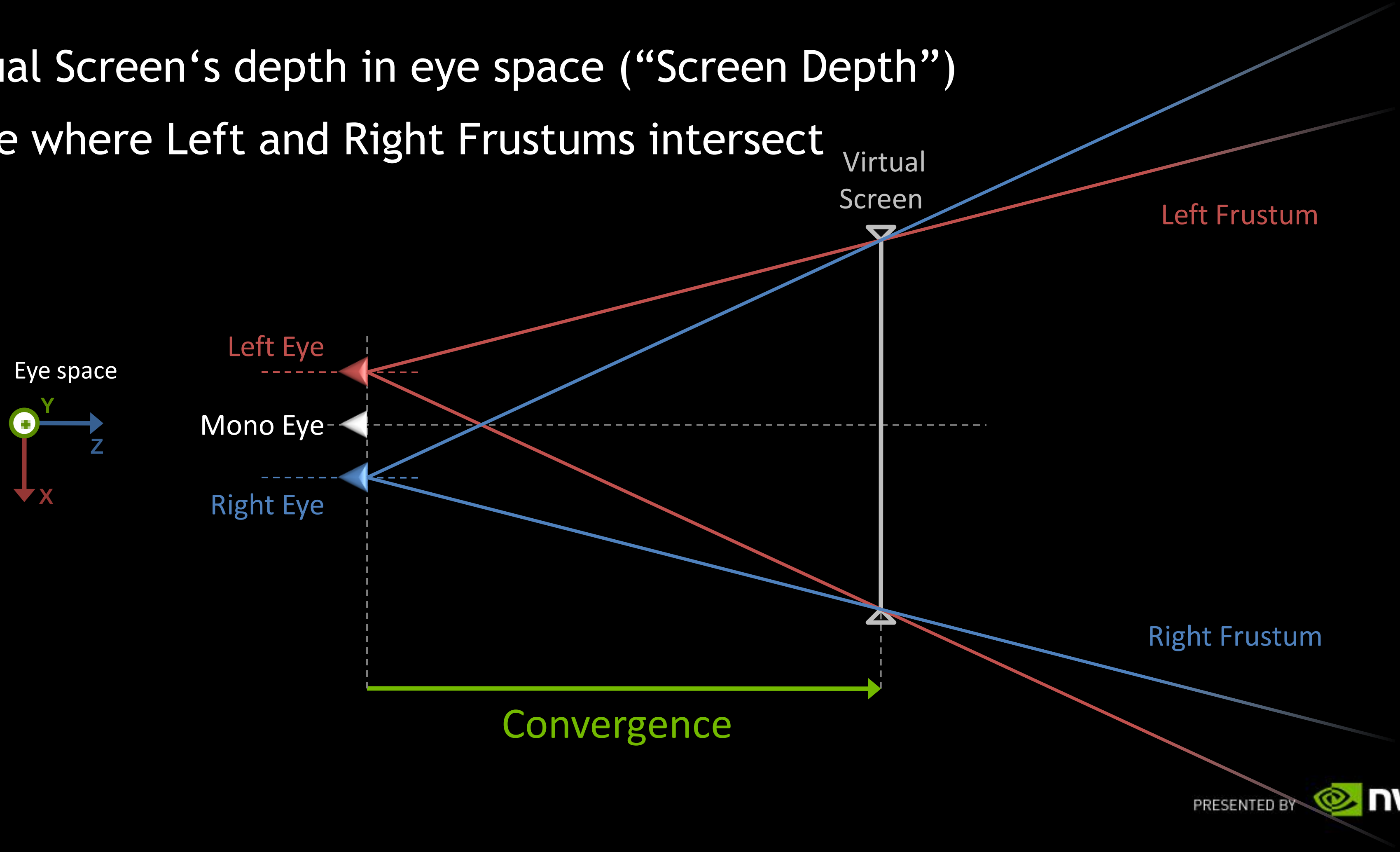
- The normalized version of interaxial by the virtual screen width
- More details in a few slides....



Separation = Interaxial / Screen Width

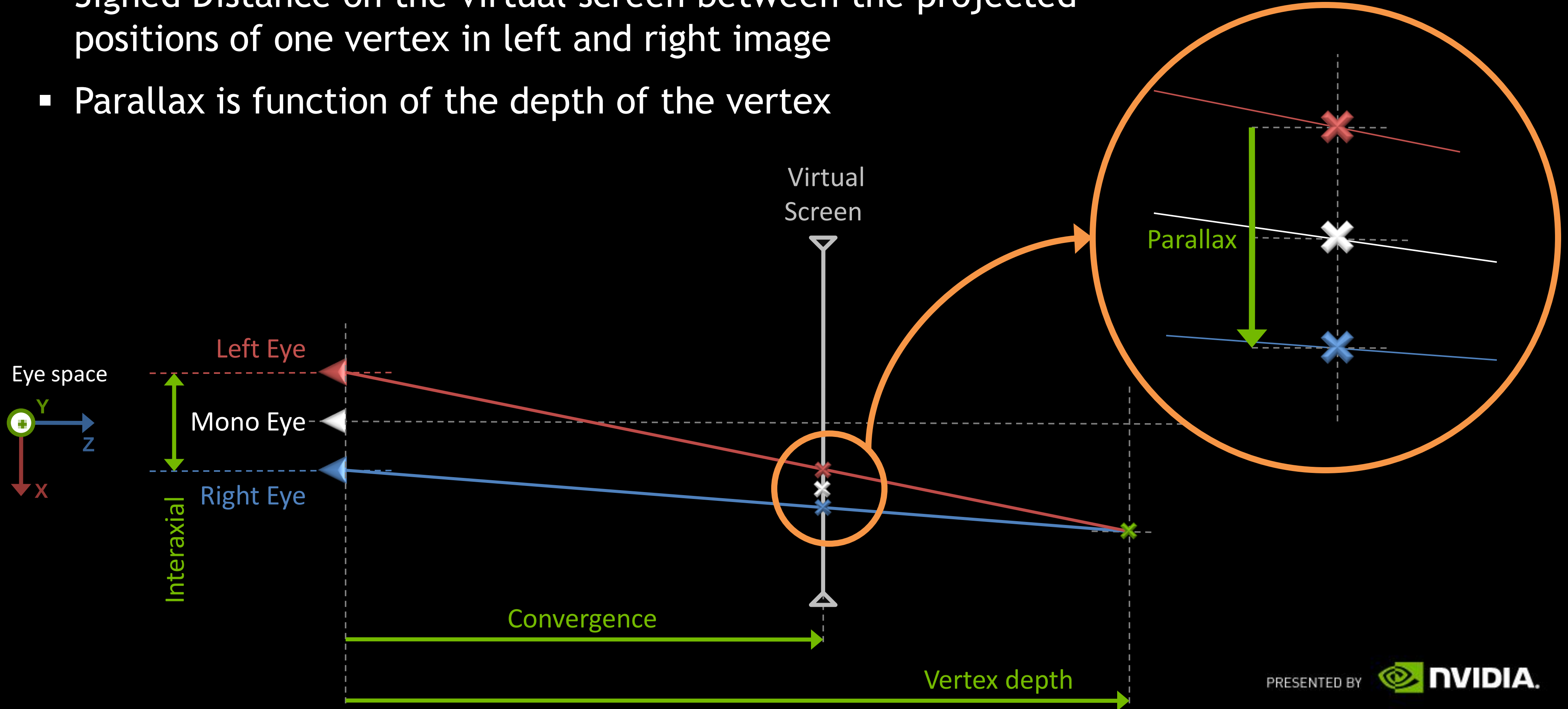
Convergence

- 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



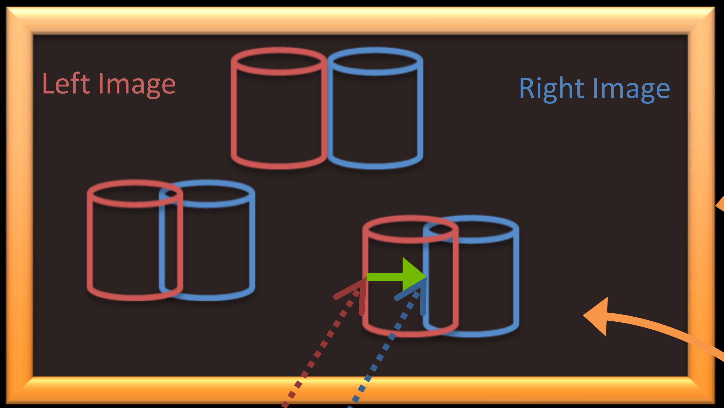
GPU TECHNOLOGY CONFERENCE

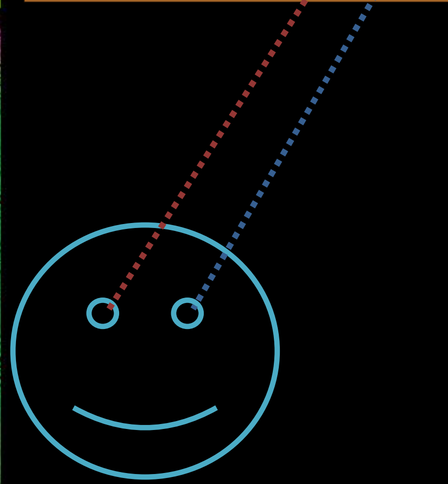
Where the magic happens and more equations

DEPTH PERCEPTION

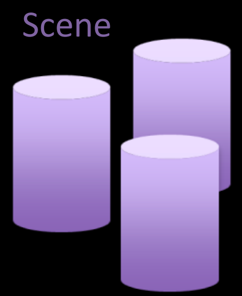
PRESENTED BY NVIDIA.

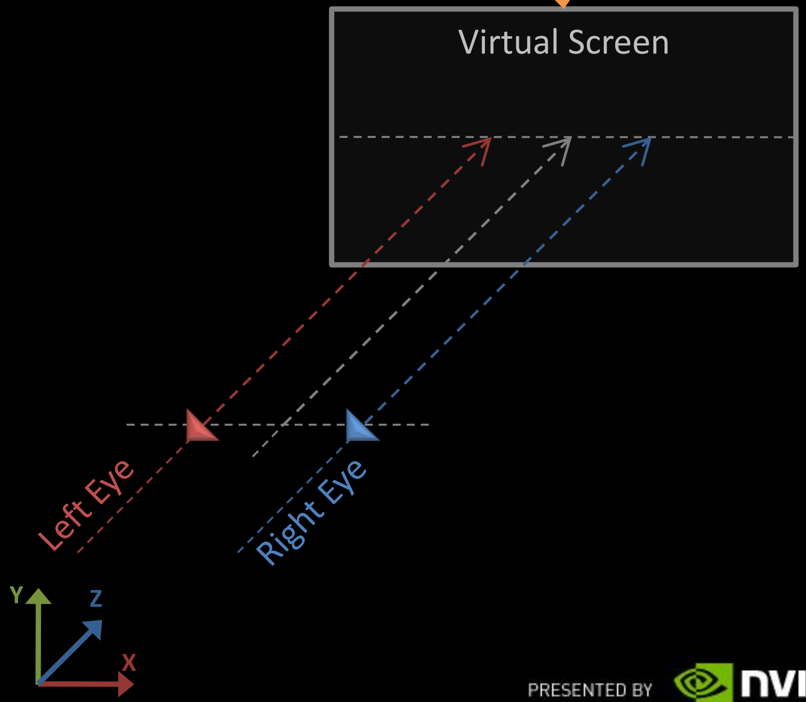
Virtual vs. Real Screen





The virtual screen is perceived AS the real screen

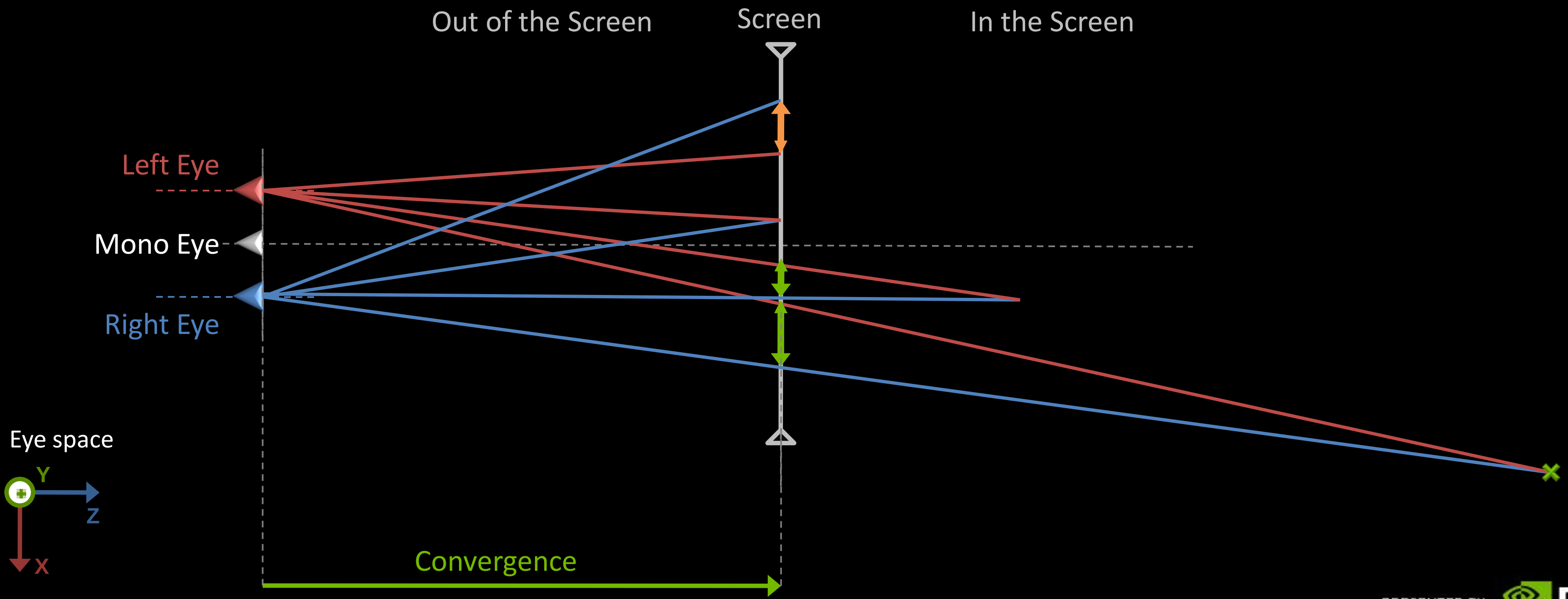




Parallax creates the depth perception for the user looking at the real screen presenting left and right images

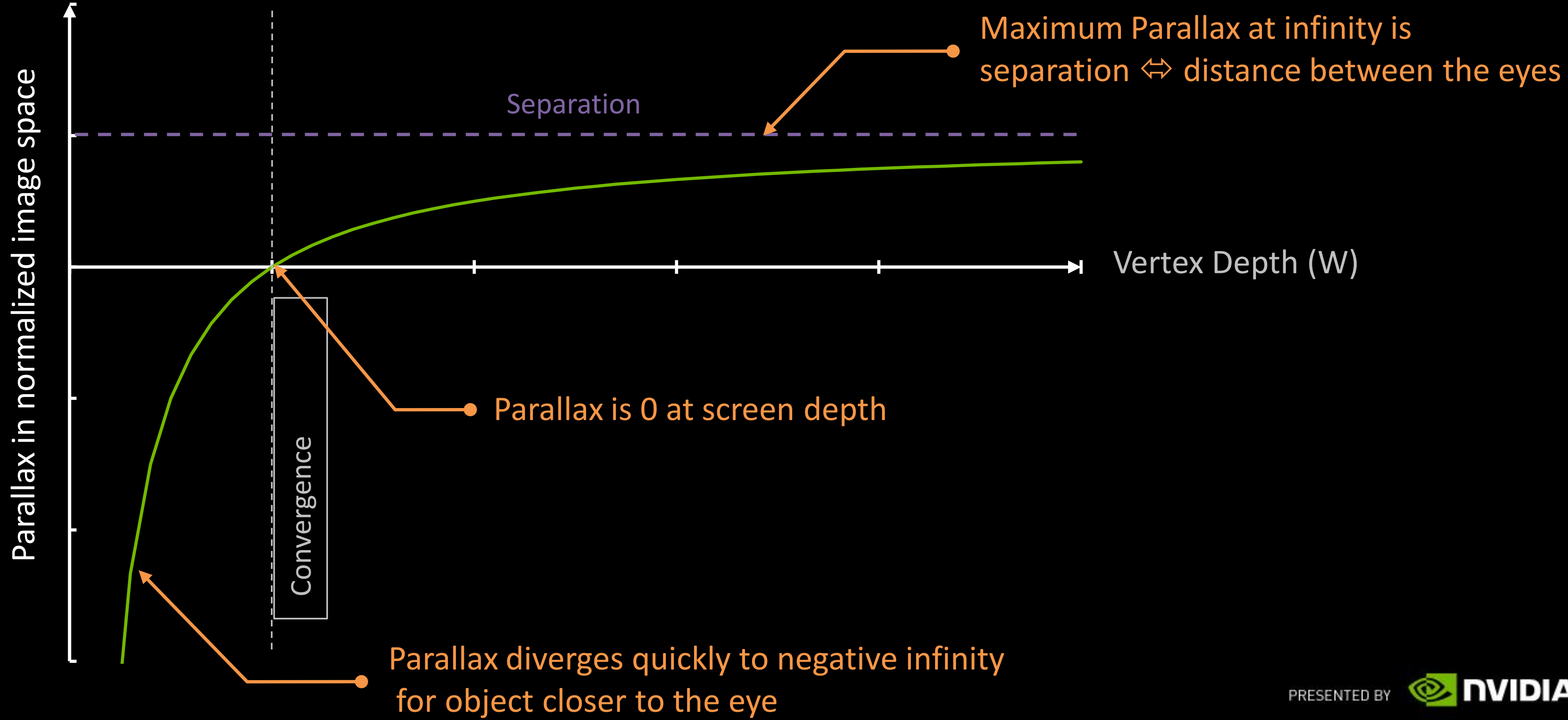
In / Out of the Screen

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



Parallax in normalized image space

Parallax = Separation * (1 – Convergence / W)

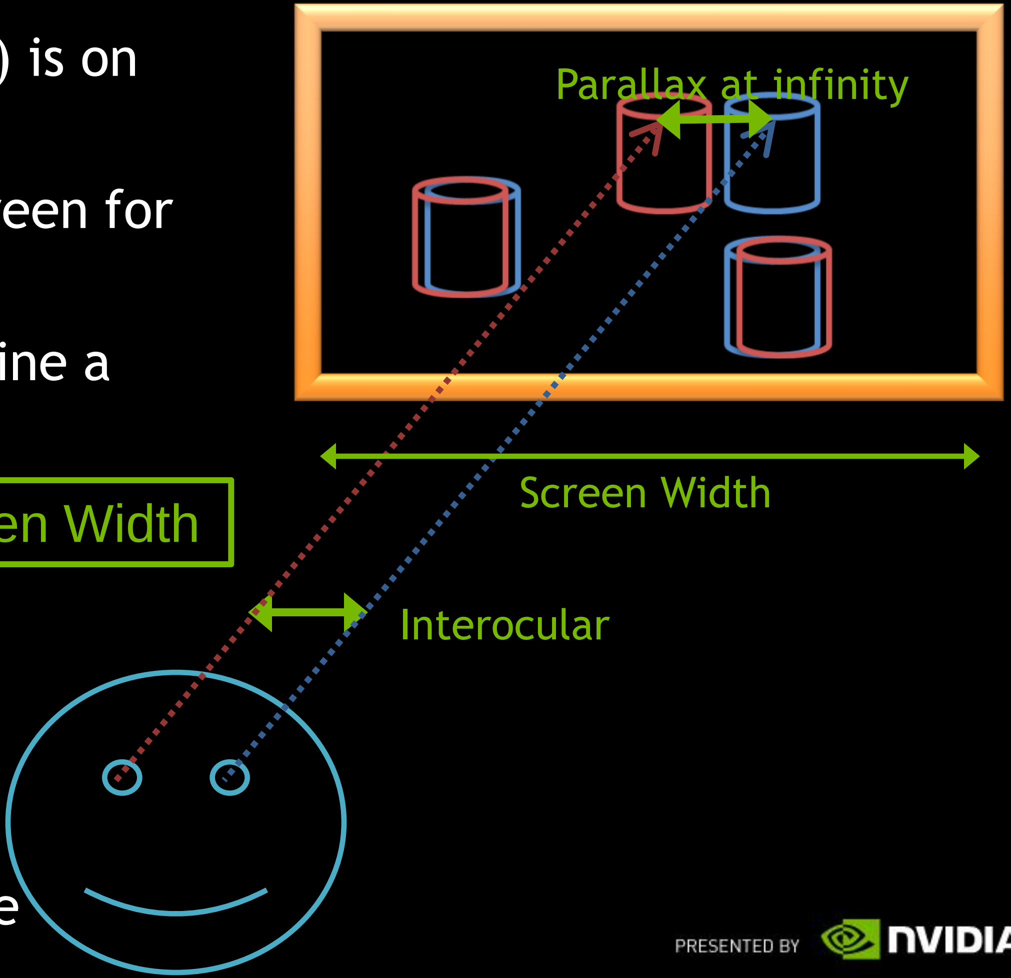


Eye Separation

- 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 “Eye Separation”

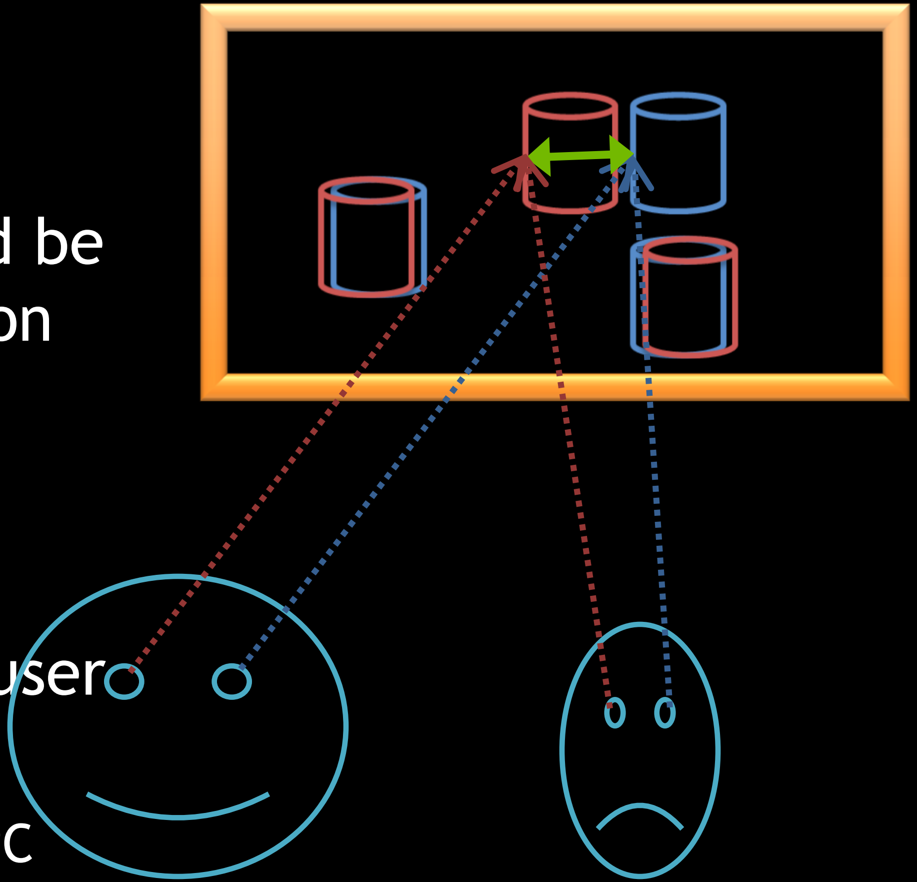
Eye Separation = Interocular / Real Screen Width

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

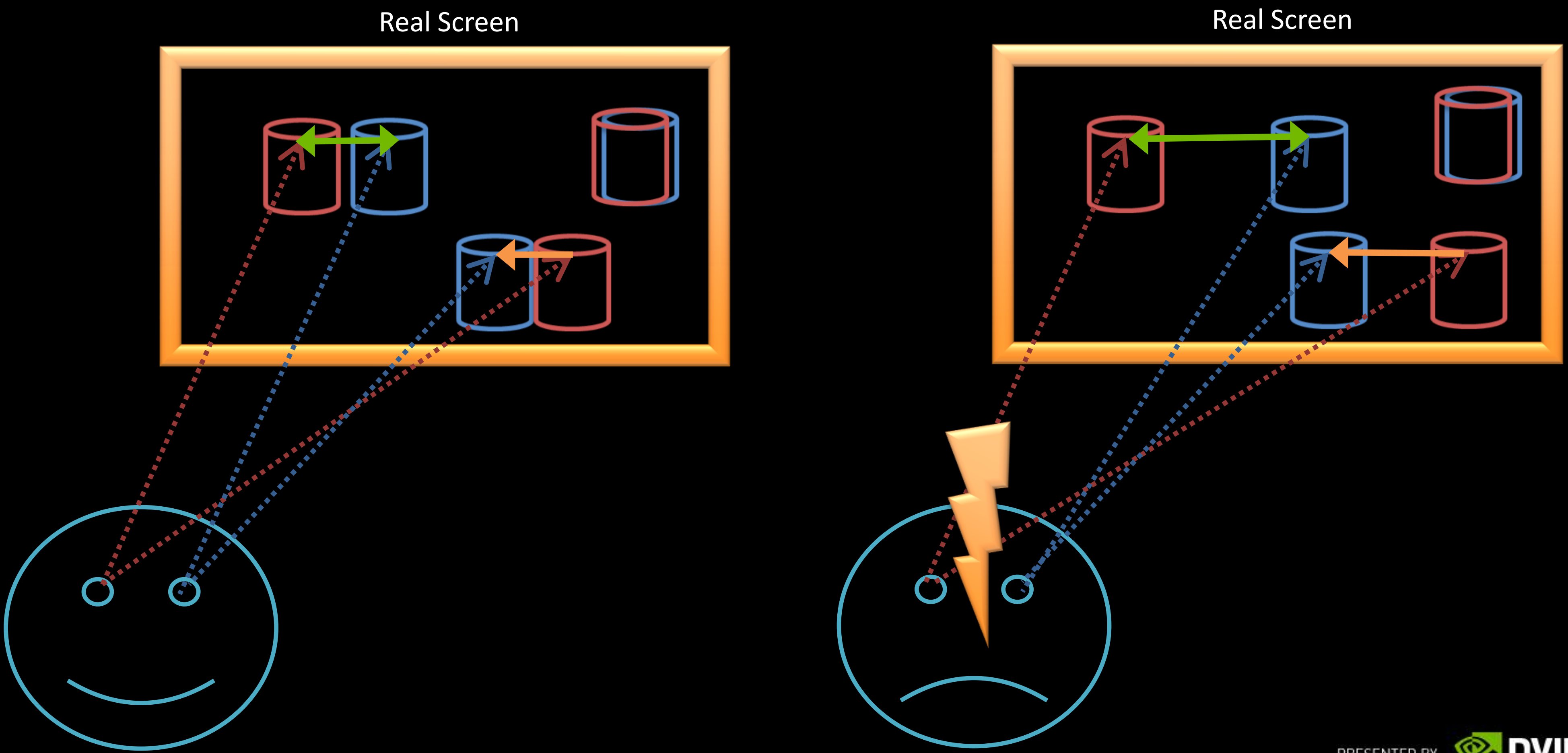


Separation should be Comfortable

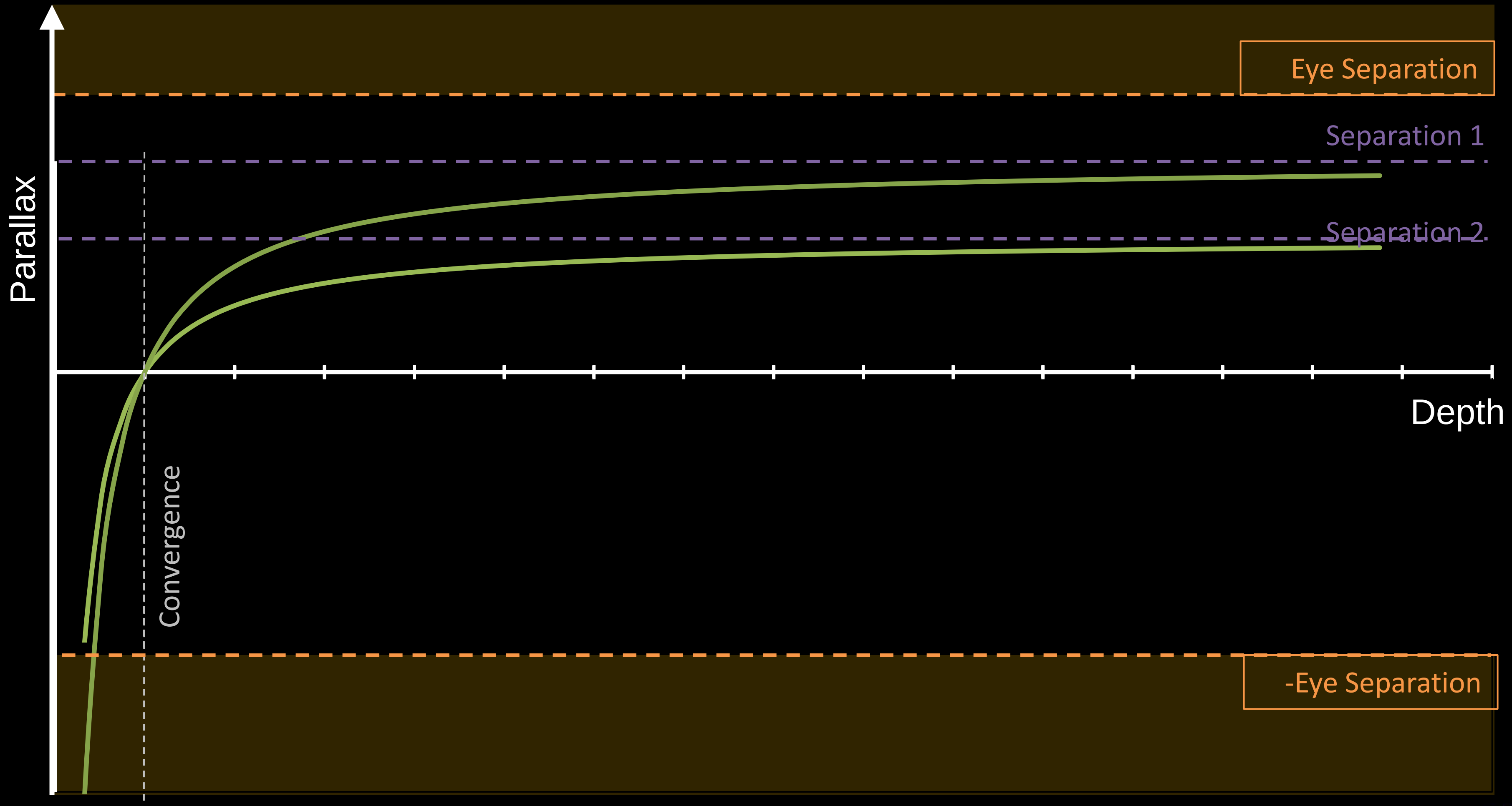
- The maximum parallax at infinity is Separation
- Eye Separation is an average, should be used as the very maximum Separation value
  - Never make the viewer look diverge
  - People don't have the same eyes
- For Interactive application, let the user adjust Separation
  - When the screen is close to the user (PC scenario) most of the users cannot handle more than 50% of the Eye Separation



Eye Separation is the Maximum Comfort Separation



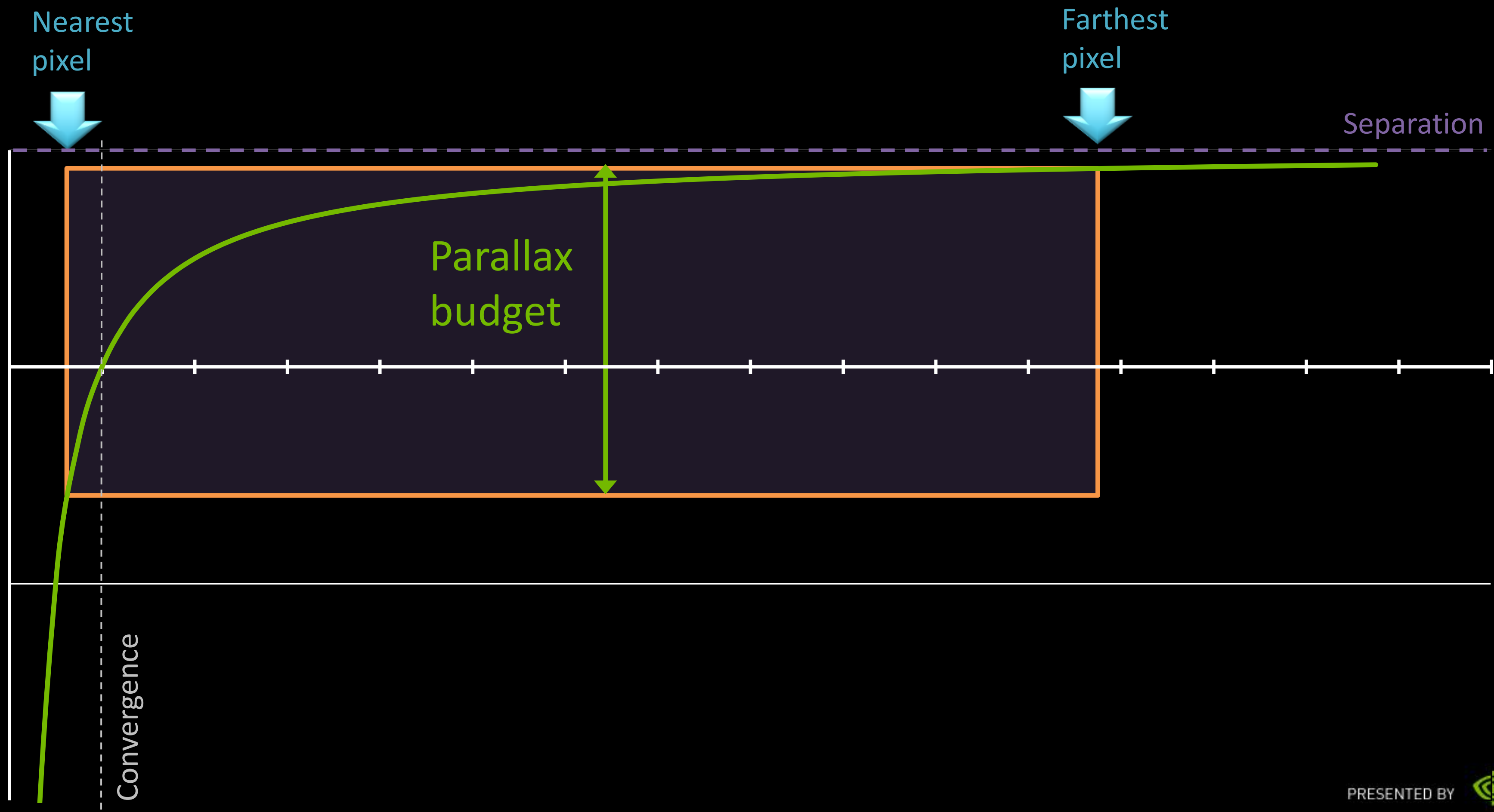
Safe Parallax Range



GPU TECHNOLOGY CONFERENCE

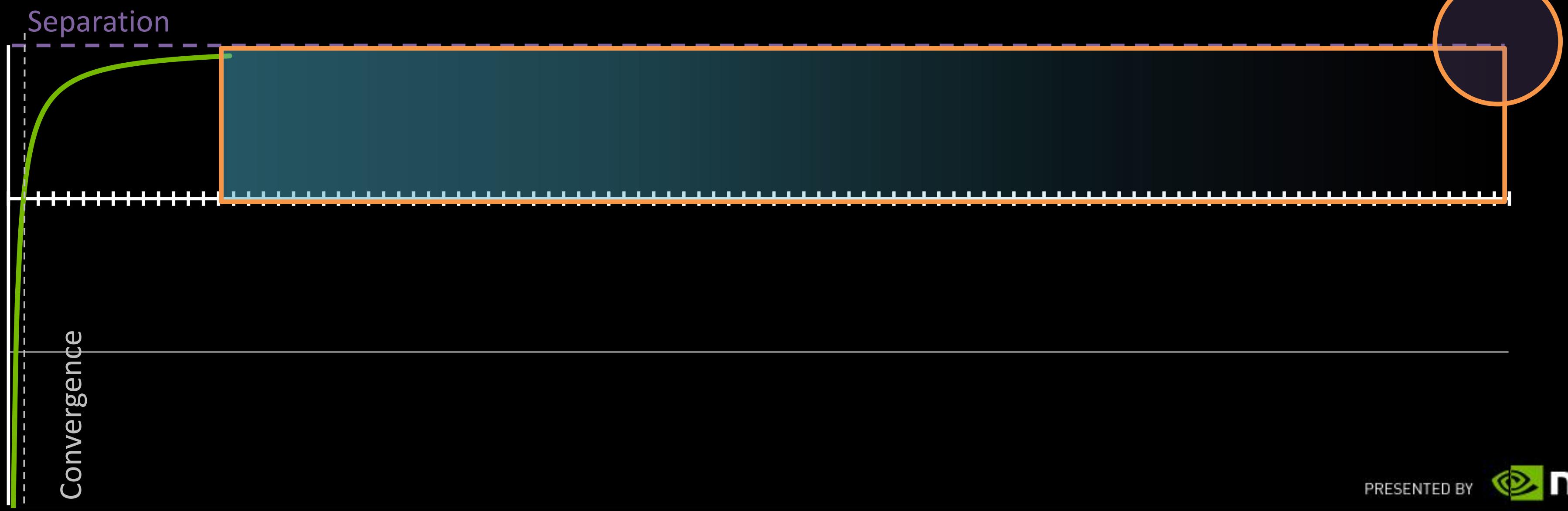
PARALLAX BUDGET

Parallax Budget
How much parallax variation is used in the frame



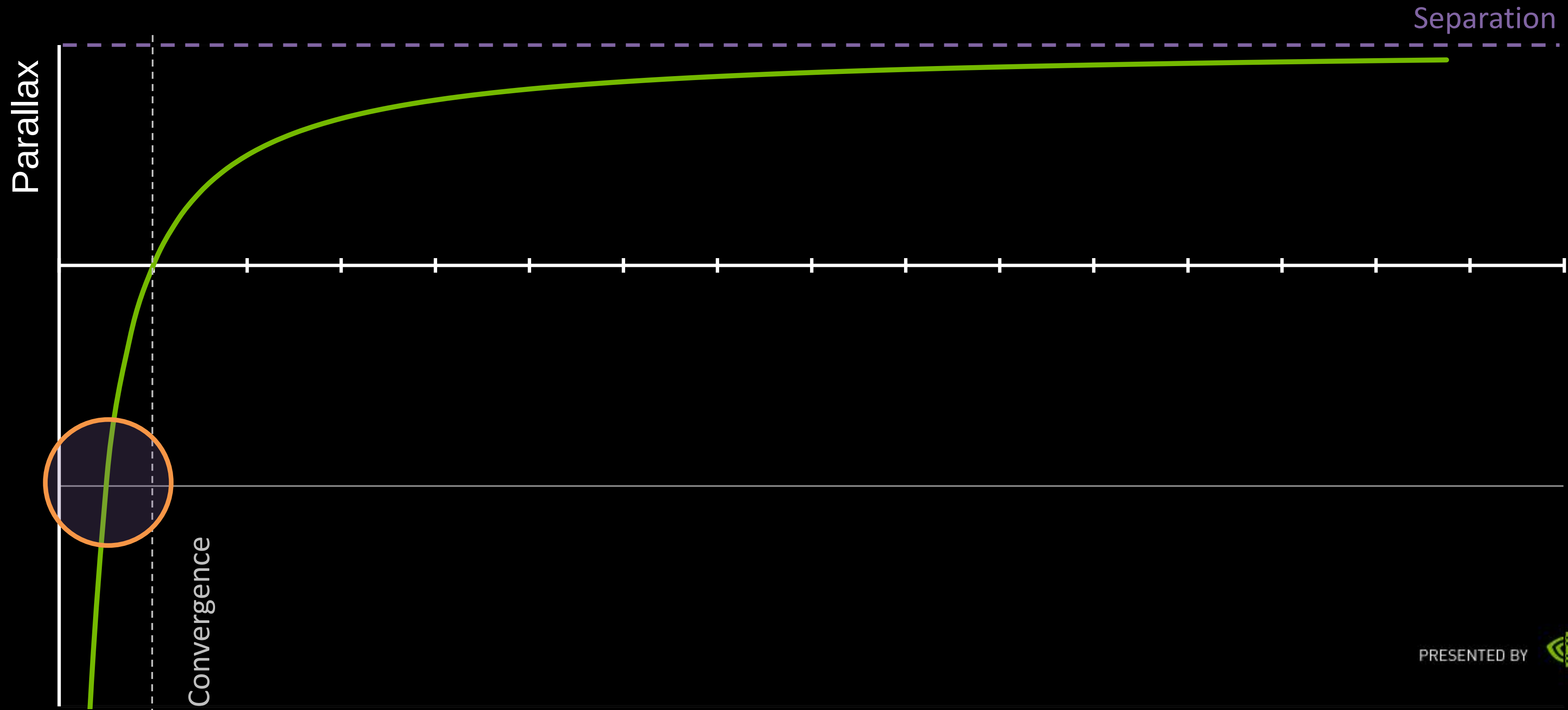
In Screen : Farthest Pixel

- 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

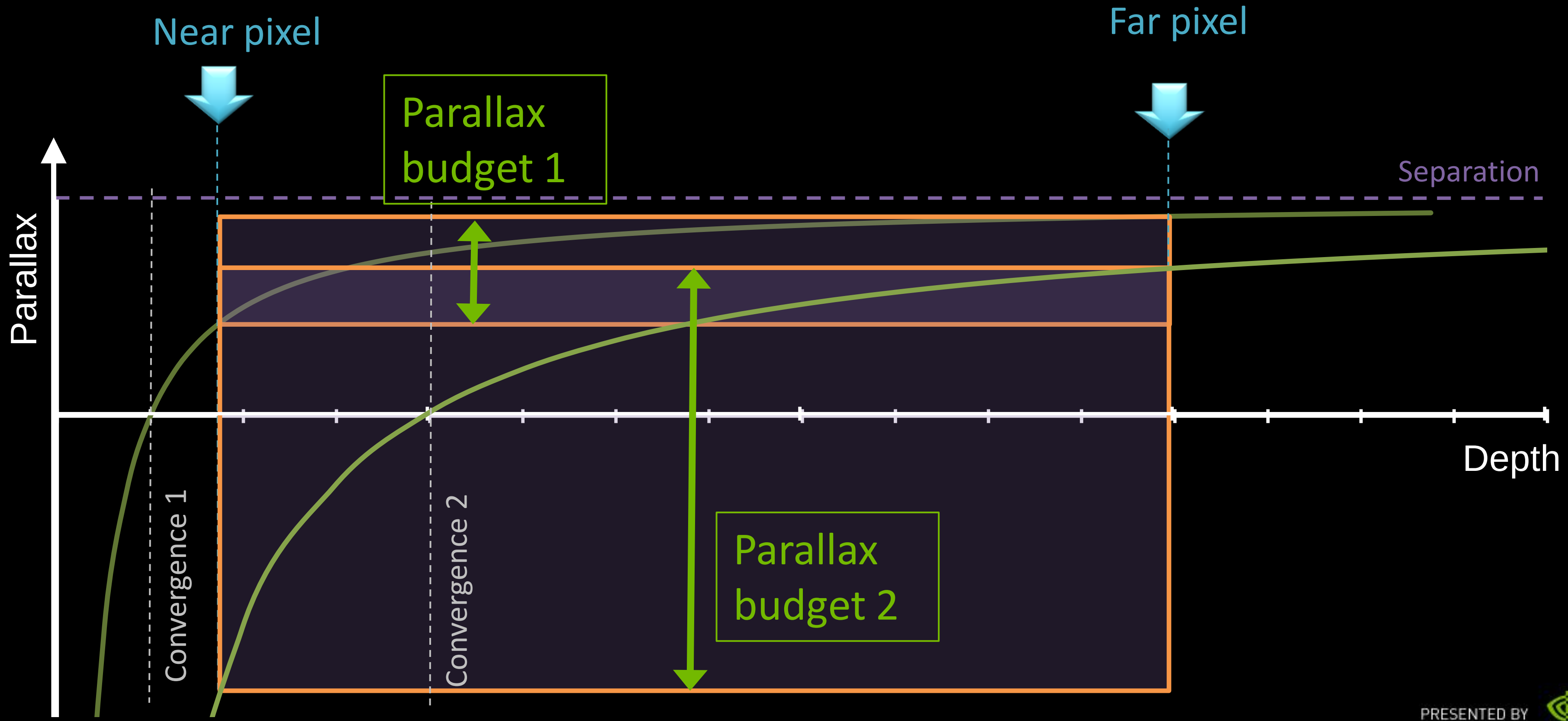
- At Convergence / 2, Parallax is equal to -Separation, out of the screen
  - Parallax is very large (> Separation) and can cause eye strains



Convergence sets the scene in the screen

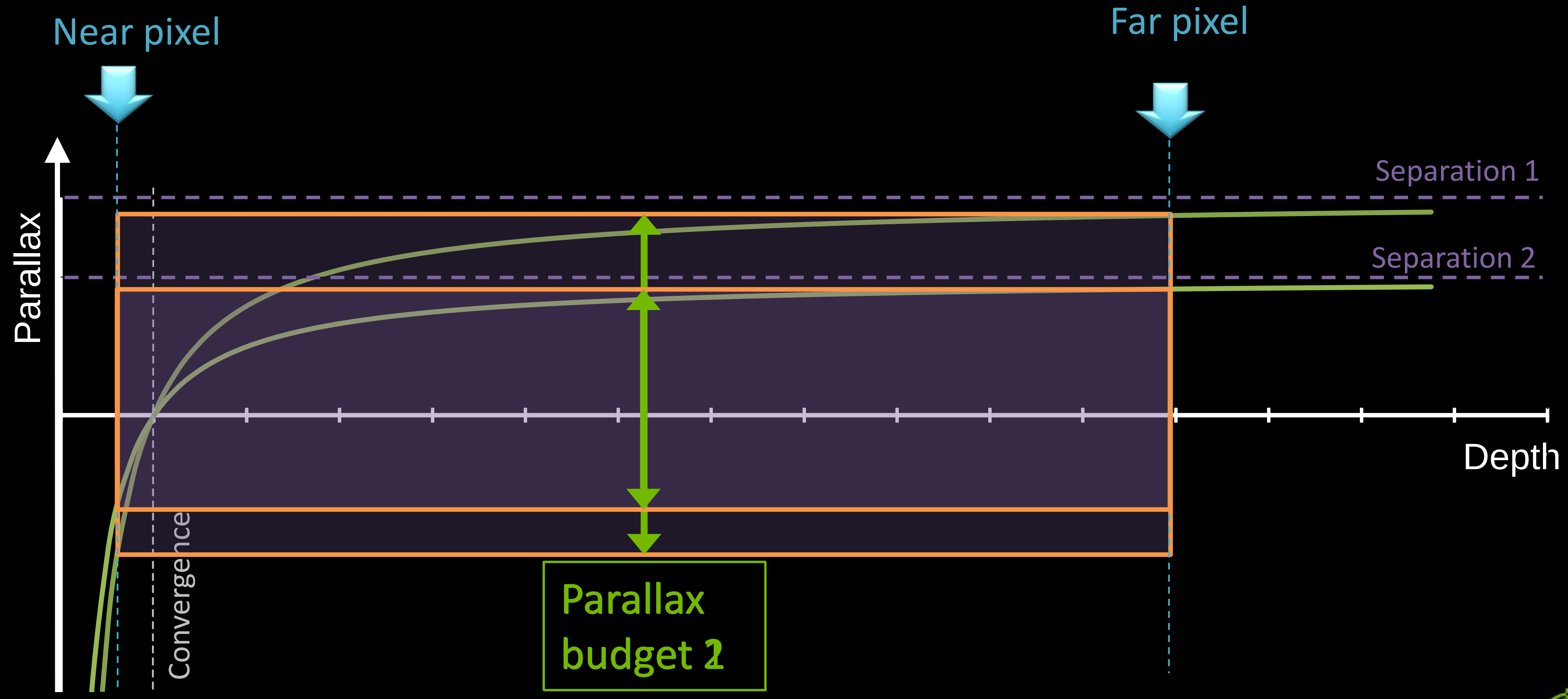
Defines the window into the virtual space

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 must be controlled by the application
- 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
    - Cf Bob Whitehill Talk (Pixar Stereographer) at Siggraph 2010
  - Dynamic Convergence is a bad idea
    - Except for specific transition cases
    - Analyze frame depth through an Histogram and focus points ?
      - Ongoing projects at NV

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

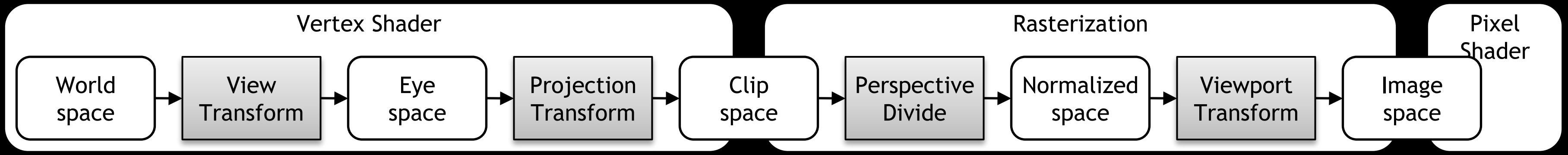
How to implement stereo projection ?

- Fully defined by mono projection and Separation & Convergence
- Replace the perspective projection matrix by an offset perspective projection
    - horizontal offset of Interaxial
    - Negative for Right eye
    - Positive for Left eye
- Or just before rasterization in the vertex shader, offset the clip position by the parallax amount (Nvidia 3D vision driver solution)

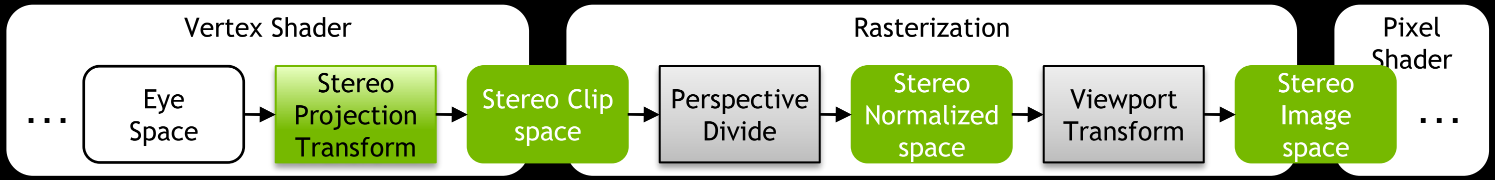
```
clipPos.x += EyeSign * Separation * ( clipPos.w – Convergence )
EyeSign = +1 for right, -1 for left
```

Stereo Transformation Pipeline

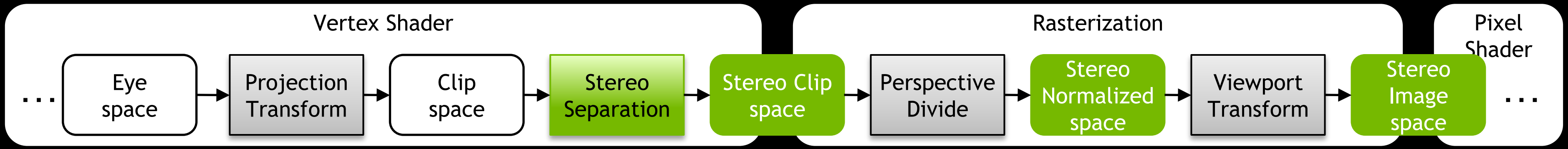
Standard Mono



Stereo Projection Matrix

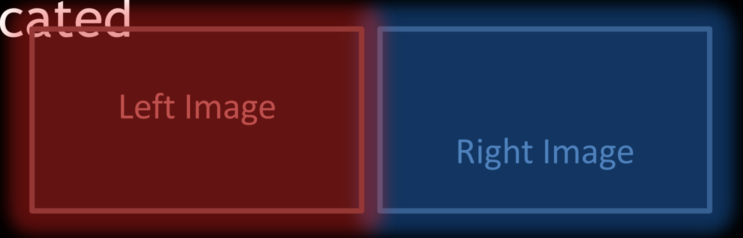


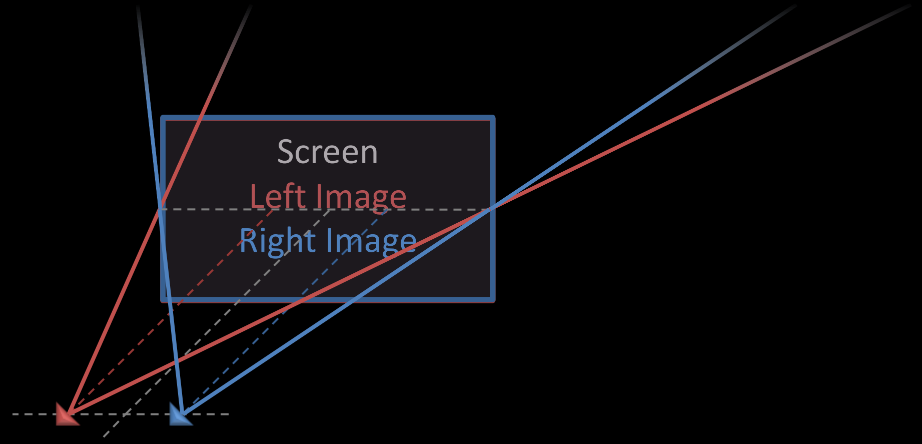
Stereo Separation on clip position



Stereo rendering surfaces

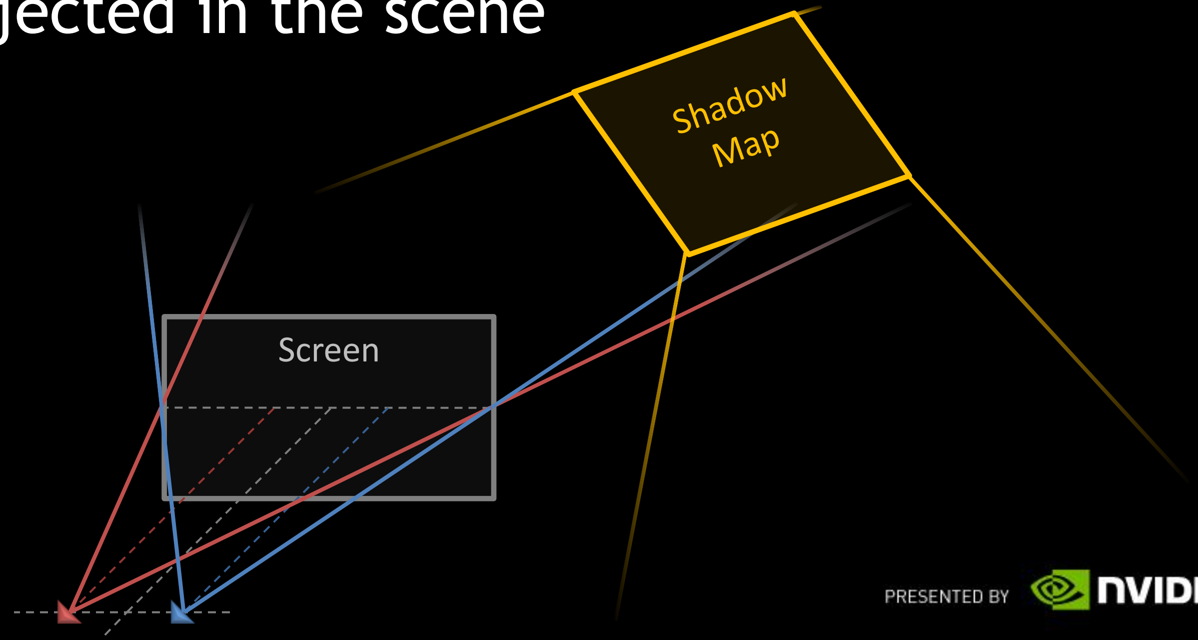
- View dependent render targets must be duplicated
  - Back buffer
  - Depth Stencil buffer
- Intermediate full screen render targets used to process final image
  - High dynamic range, Blur, Bloom
  - Screen Space Ambient Occlusion





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

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 looks bad

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

2D object in depth
attached to 3D anchor point

Starcraft2 screenshot , Courtesy of Blizzard

Billboards in depth
Particles with 3D positions

2D object in depth
attached to 3D anchor
point

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

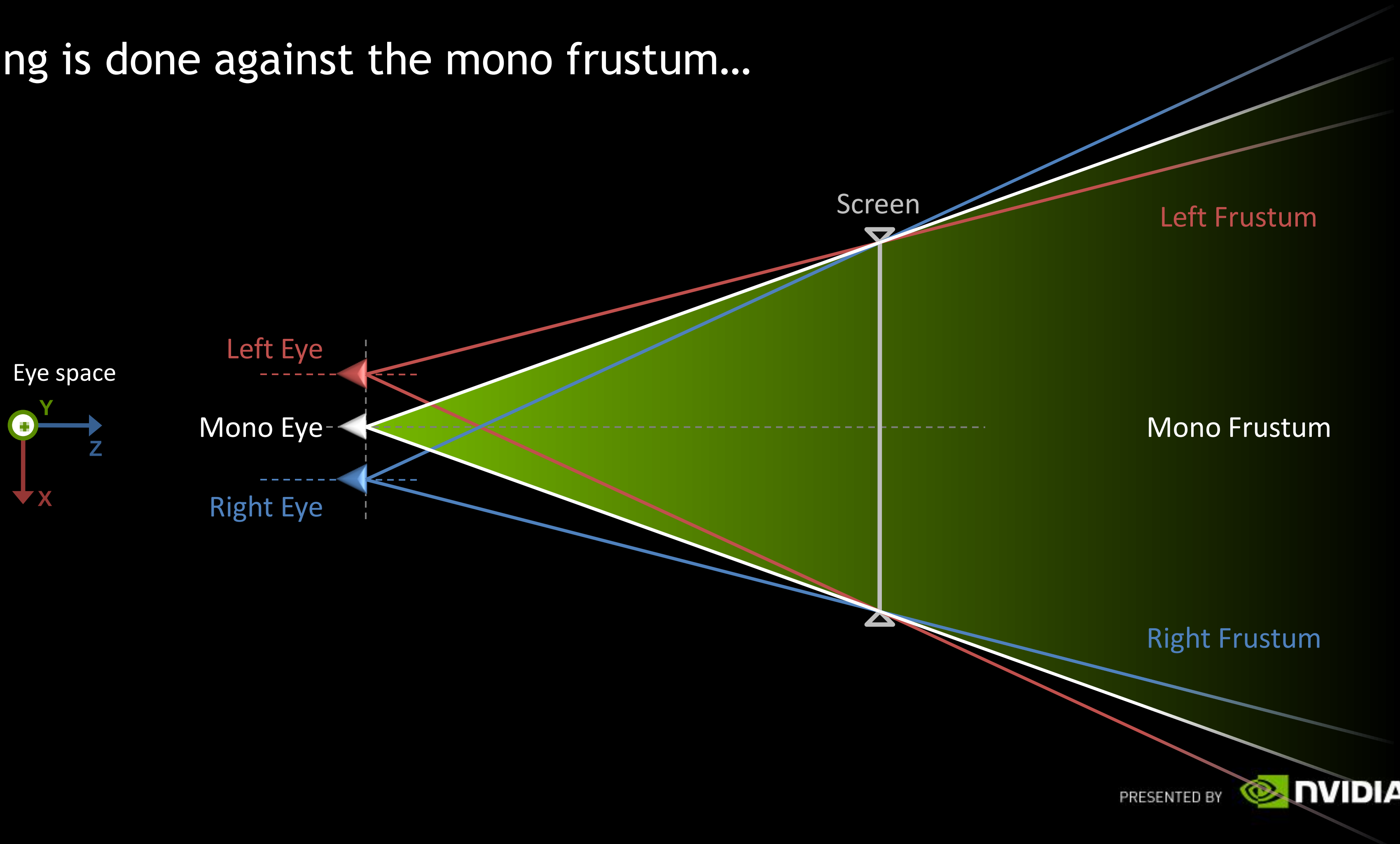
```
float4 2Dto3DclipPosition(
     in float2 posClip : POSITION, // Input position in clip space
     uniform float depth            // Depth where to draw the 2D object
     ) : POSITION                   // Output the position in clip space
{
     return float4(
          posClip.xy * depth,    // 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

3D Objects Culling

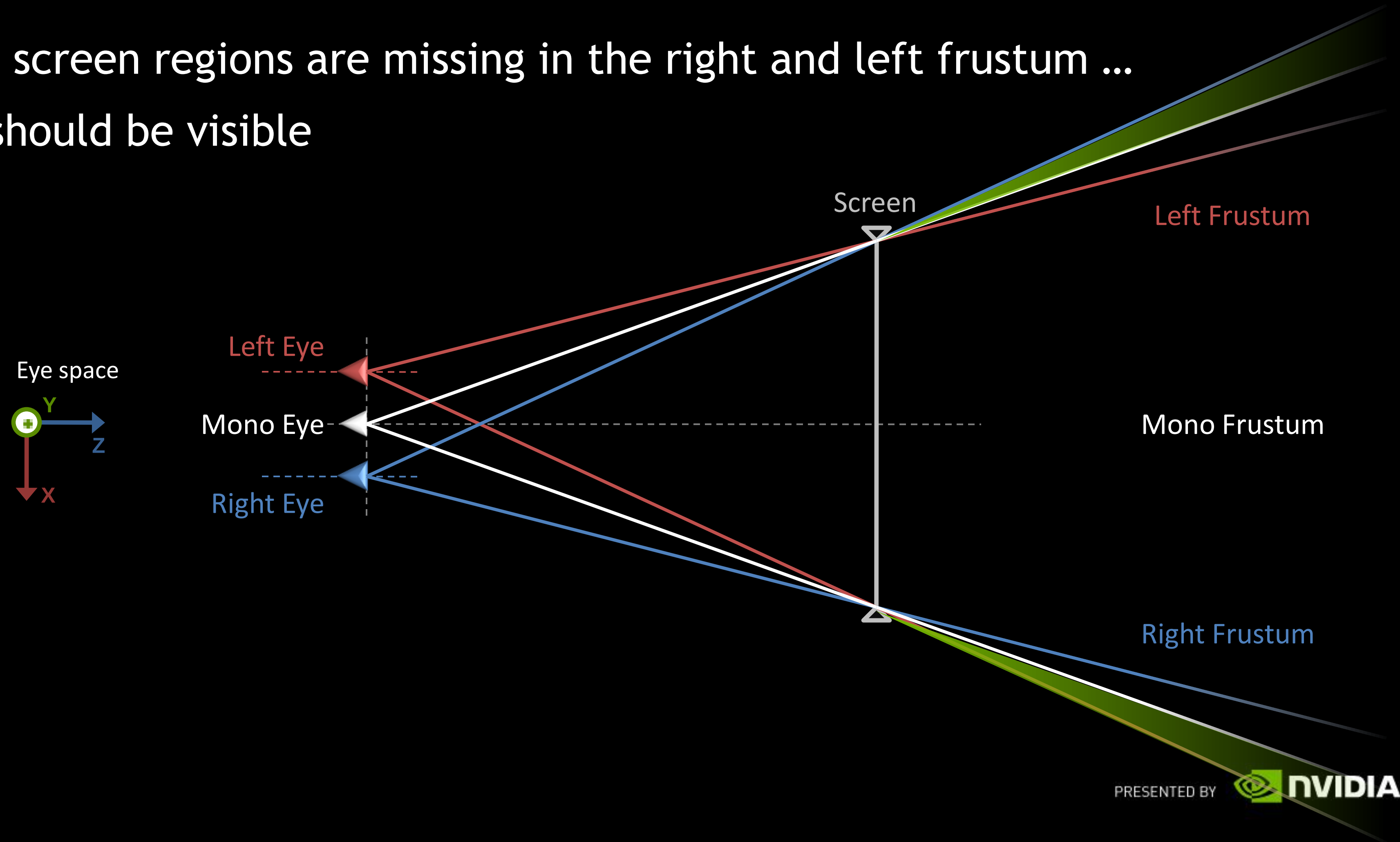
When culling is done against the mono frustum…



3D Objects Culling

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

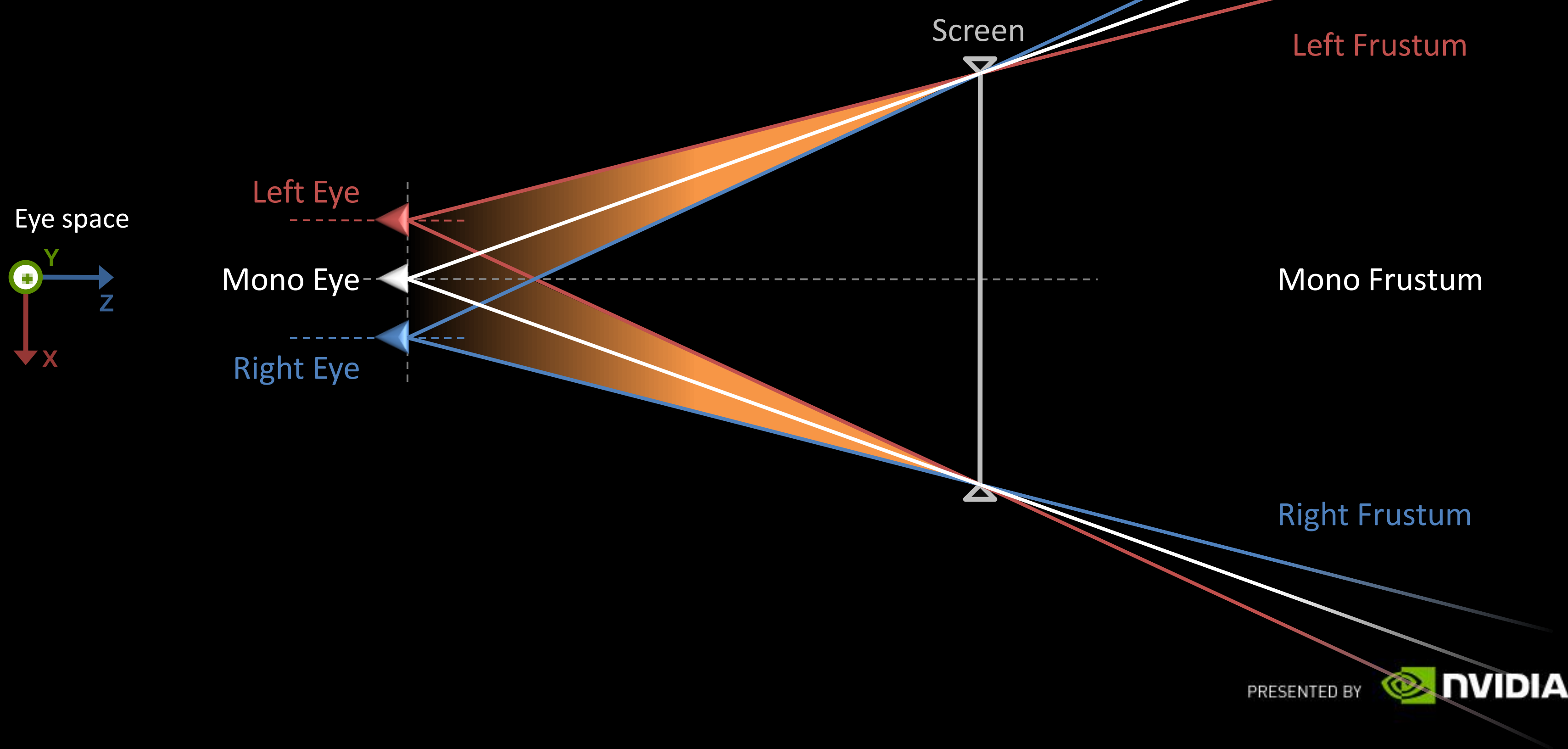
They should be visible



3D Objects Culling

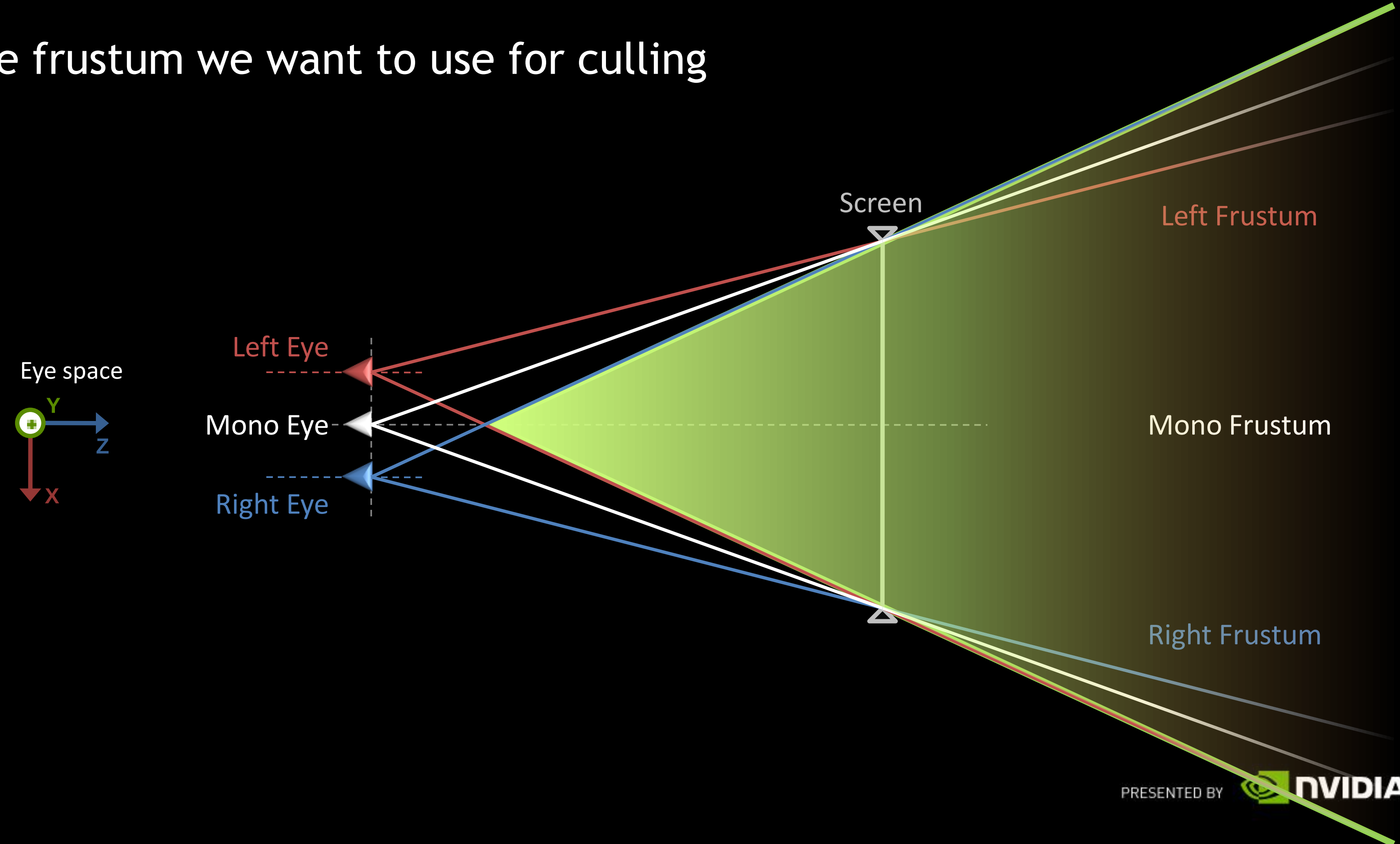
… And we don't want to see out of the screen objects only in one eye …

It disturbs the stereo perception



3D Objects Culling

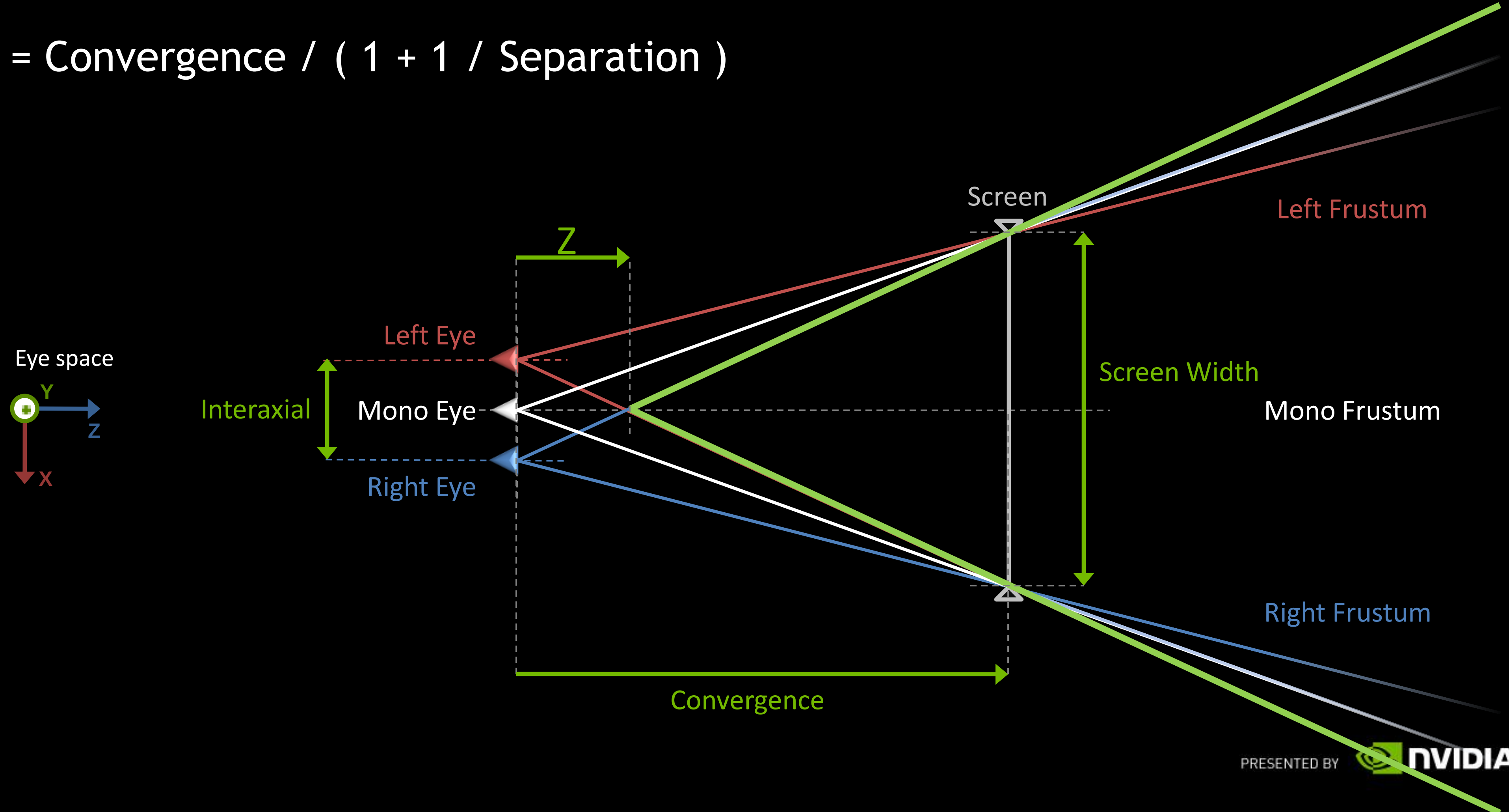
Here is the frustum we want to use for culling



3D Objects Culling

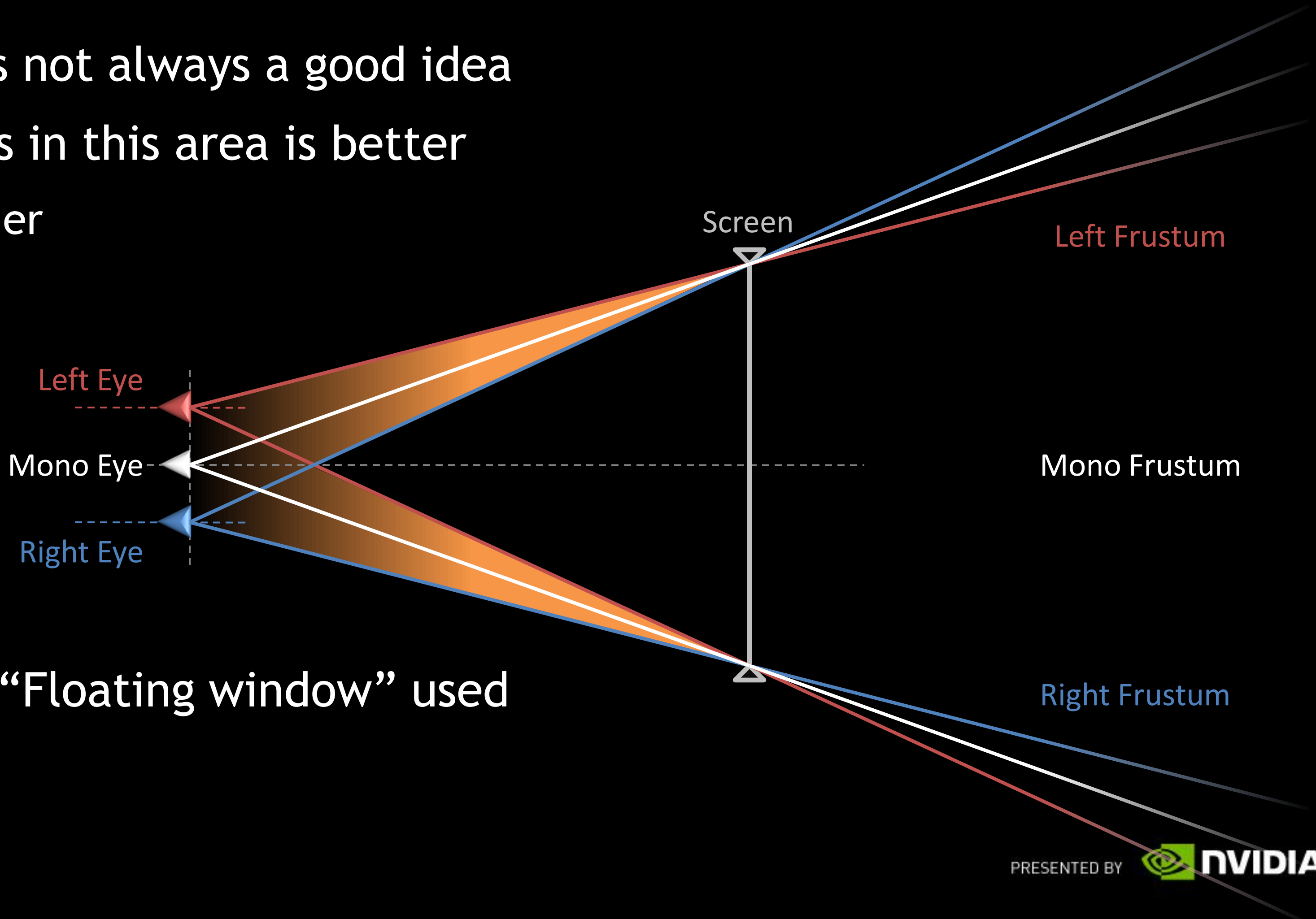
Computing Stereo Frustum origin offset

Z = Convergence / (1 + 1 / Separation)



3D Objects Culling

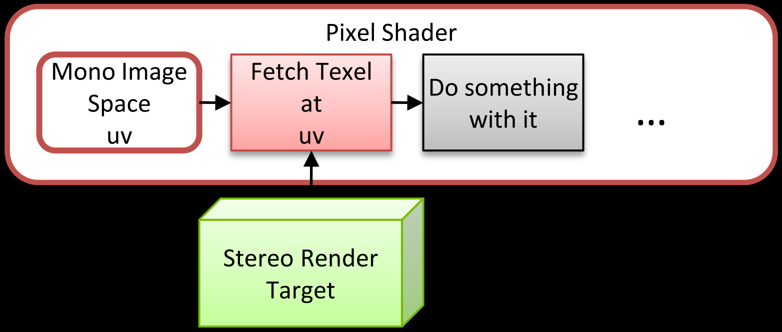
- Culling this area is not always a good idea
- Blacking out pixels in this area is better
  - Through a shader

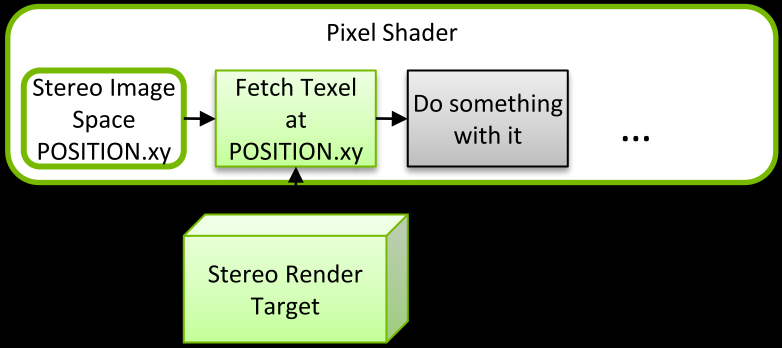


- Equivalent to the “Floating window” used in movies

Fetching Stereo Render Target

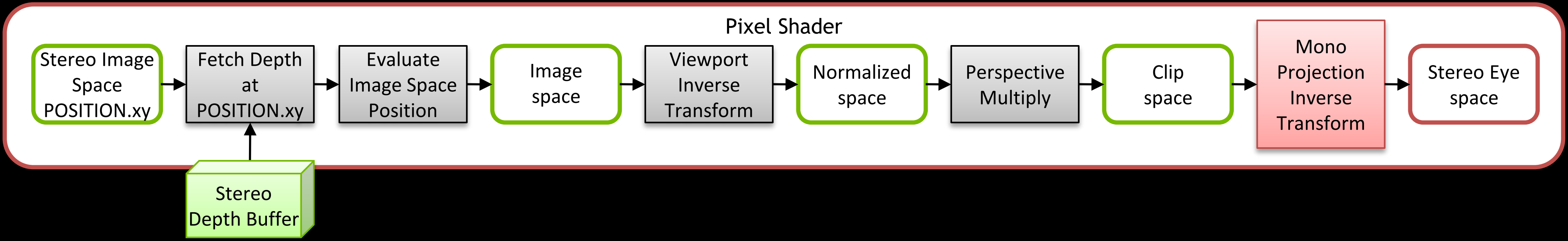
- When fetching from a stereo render target use the good texture coordinate
  - Render target is addressed in STEREO IMAGE SPACE
  - Use the pixel position provided in the pixel shader
  - Or use a texture coordinate computed in the vertex shader correctly

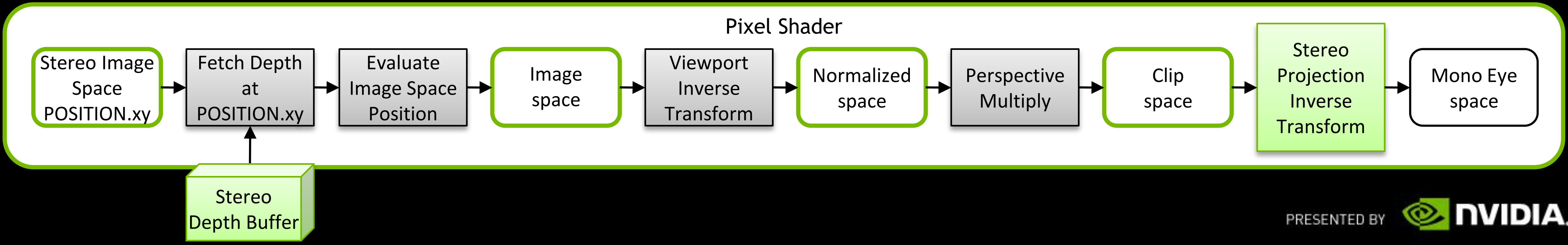




Unprojection in pixel shader

- 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 !





GPU TECHNOLOGY CONFERENCE

One or two things to look at

WHAT'S NEXT ?

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 ☺

Tessellation

- Works great with stereoscopy
- Unigine Demo

Letterbox

- Emphasize the out of the screen effect
- Simply Draw 2 extra horizontal bands at Convergence
  - Out of the screen objects can overdraw the bands

G-Force movie
from Walt DIsney

GPU TECHNOLOGY CONFERENCE

Nvidia Demo Sled

SHOW TIME