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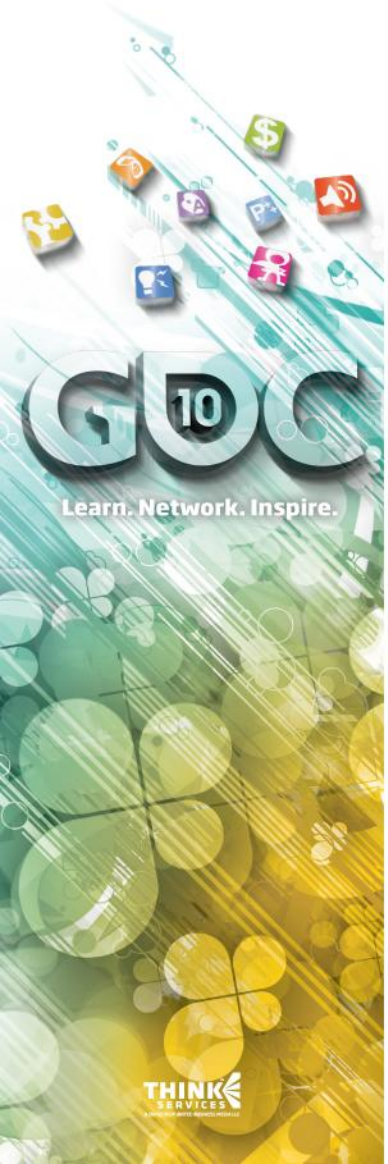
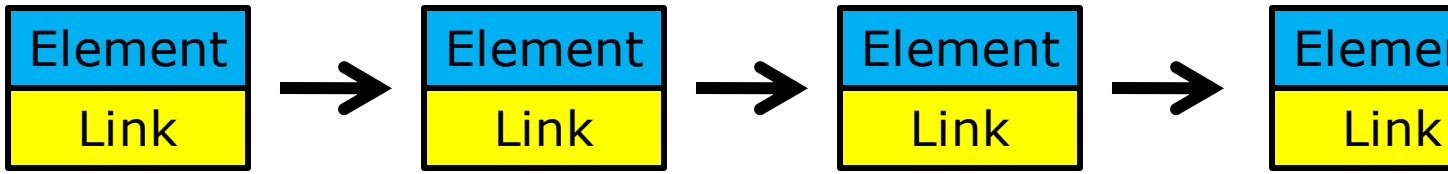


Per-Pixel Linked Lists with Direct3D 11



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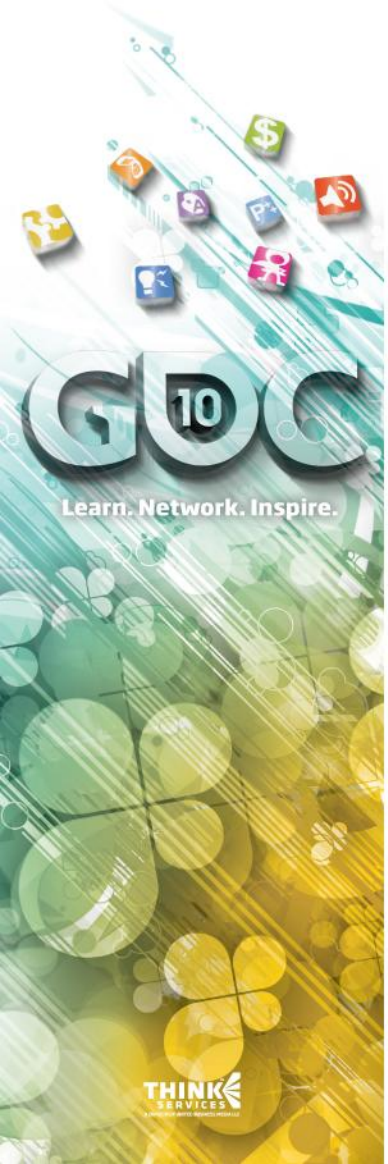
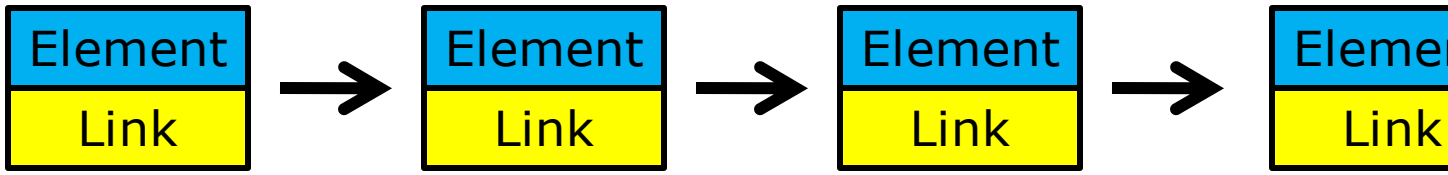


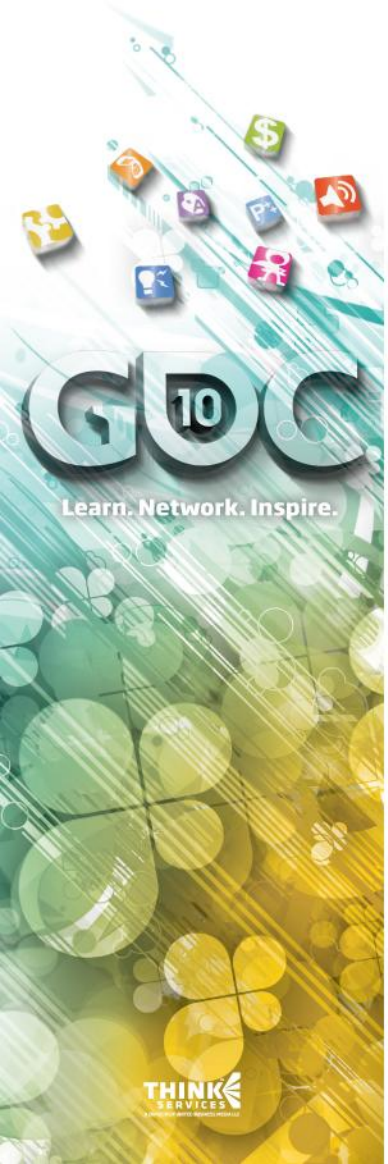
Why Linked Lists?

- Data structure useful for programming



- Very hard to implement efficiently with previous real-time graphics APIs
- DX11 allows efficient creation and parsing of linked lists
- Per-pixel linked lists
  - A collection of linked lists enumerating all pixels belonging to the same screen position

Two-step process



- 1) Linked List Creation
  - Store incoming fragments into linked lists
- 2) Rendering from Linked List
  - Linked List traversal and processing of stored fragments

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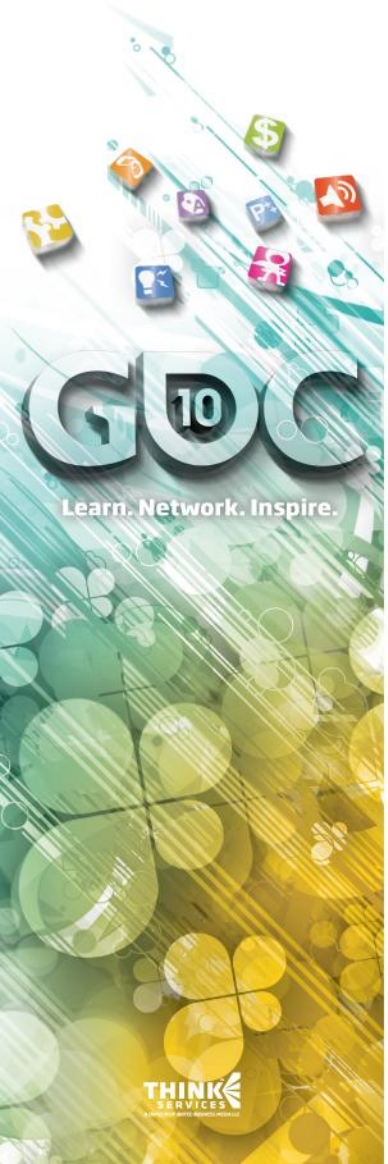

Creating Per-Pixel Linked Lists

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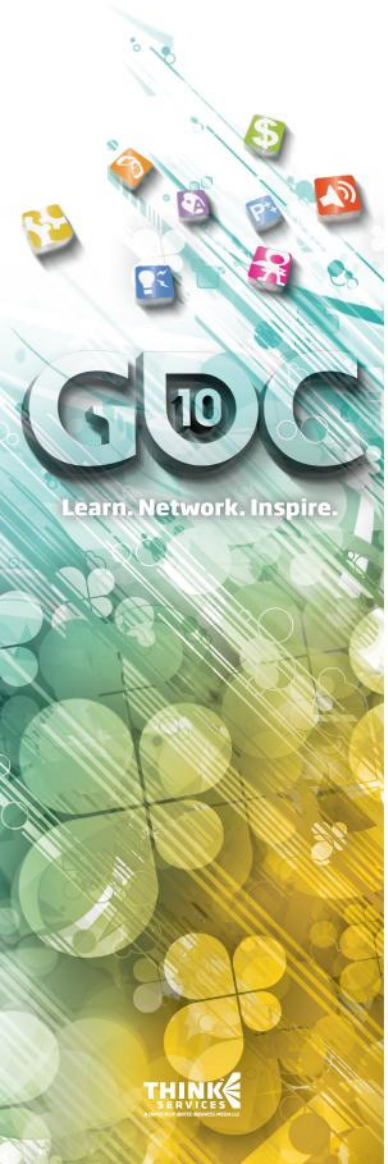
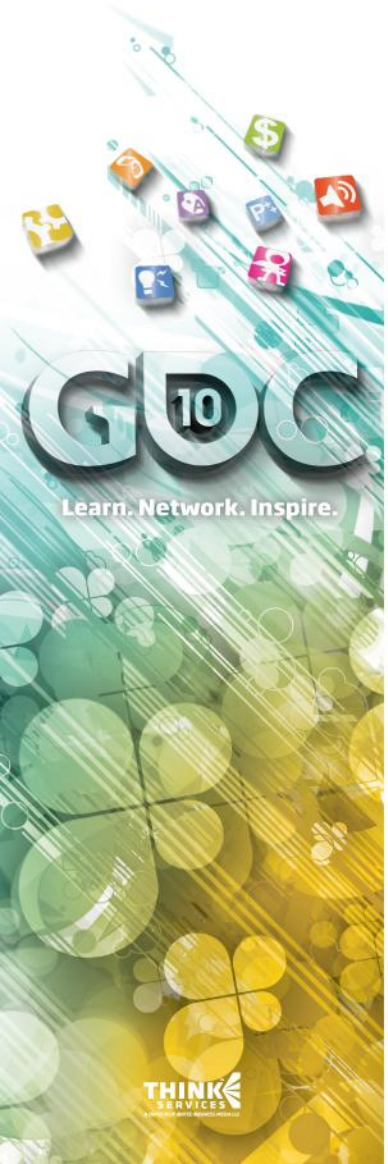


PS5.0 and UAVs

- Uses a Pixel Shader 5.0 to store fragments into linked lists
  - Not a Compute Shader 5.0!
- Uses atomic operations
- Two UAV buffers required
  - “Fragment & Link” buffer
  - “Start Offset” buffer

UAV = Unordered Access View

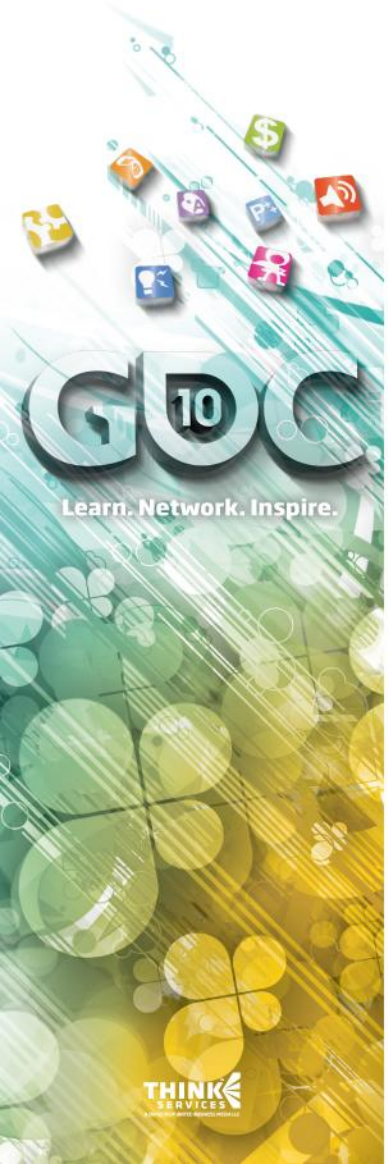


Fragment & Link Buffer

- The “Fragment & Link” buffer contains data and link for all fragments to store
- Must be large enough to store all fragments
- Created with Counter support

  D3D11_BUFFER_UAV_FLAG_COUNTER flag in UAV view
- Declaration:

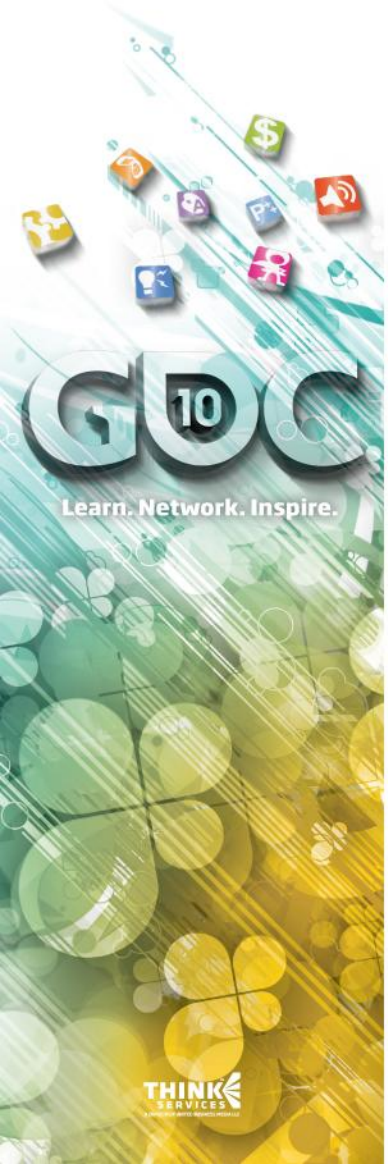
```
struct FragmentAndLinkBuffer_STRUCT
{
  FragmentData_STRUCT FragmentData;    // Fragment data
  uint uNext;                          // Link to next fragment
};
RWStructuredBuffer <FragmentAndLinkBuffer_STRUCT> FLBuffer;
```



Start Offset Buffer

- The “Start Offset” buffer contains the offset of the *last* fragment written at every pixel location
- Screen-sized:
  (width * height * sizeof(UINT32))
- Initialized to magic value (e.g. -1)
  - Magic value indicates no more fragments are stored (i.e. end of the list)
- Declaration:

```
RWByteAddressBuffer StartOffsetBuffer;
```



Linked List Creation (1)

- No color Render Target bound!
  - No rendering yet, just storing in L.L.
- Depth buffer bound if needed
  - OIT will need it in a few slides
- UAVs bounds as input/output:
  - StartOffsetBuffer (R/W)
  - FragmentAndLinkBuffer (W)

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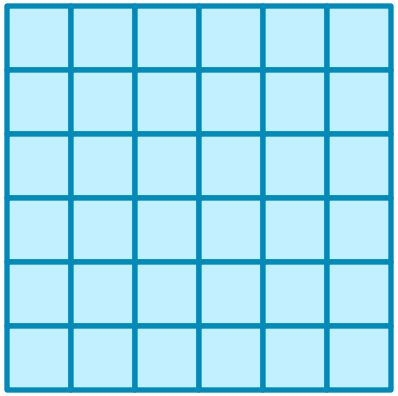
Linked List Creation (2a)

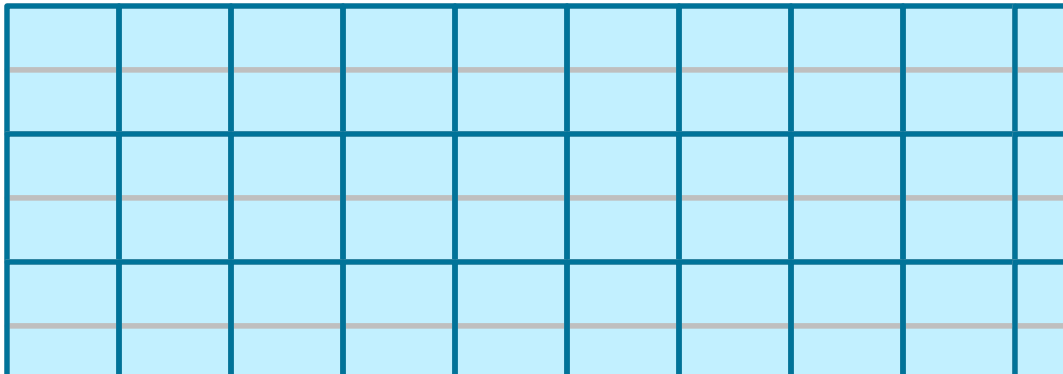
Start Offset Buffer

-1	-1	-1	-1	-1	-1
-1	-1	-1	-1	-1	-1
-1	-1	-1	-1	-1	-1
-1	-1	-1	-1	-1	-1
-1	-1	-1	-1	-1	-1
-1	-1	-1	-1	-1	-1

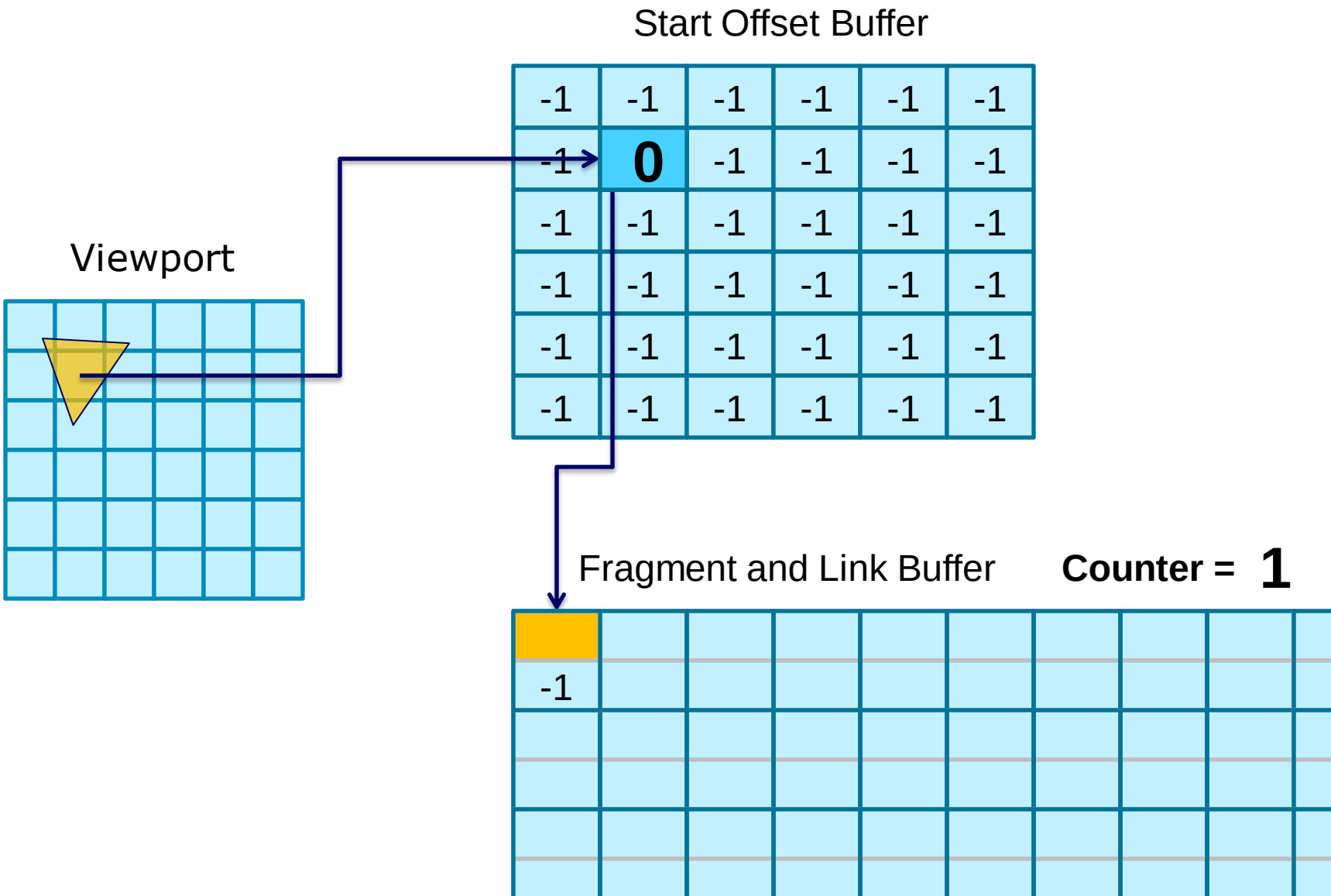
Viewport



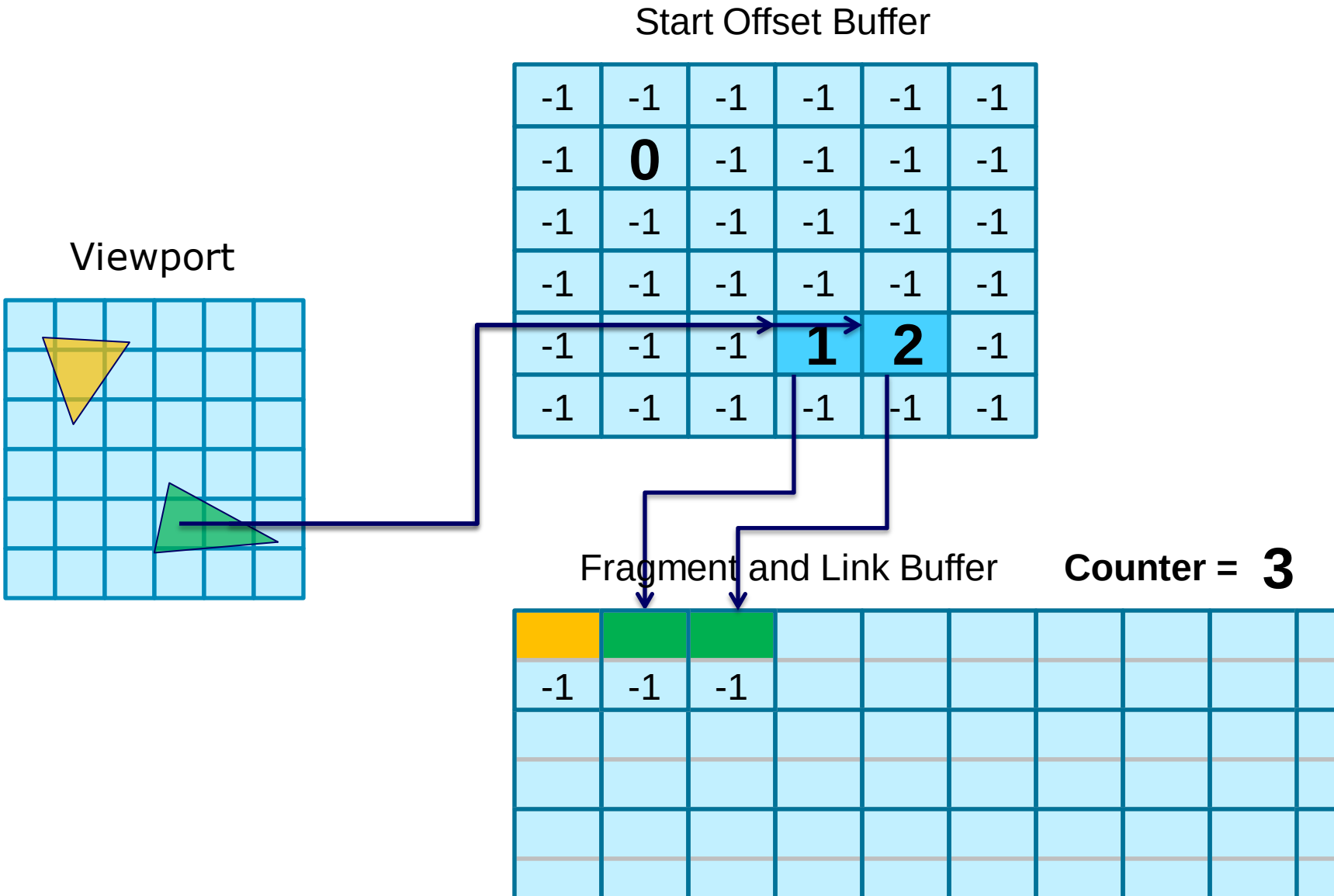
Fragment and Link Buffer **Counter = 0**



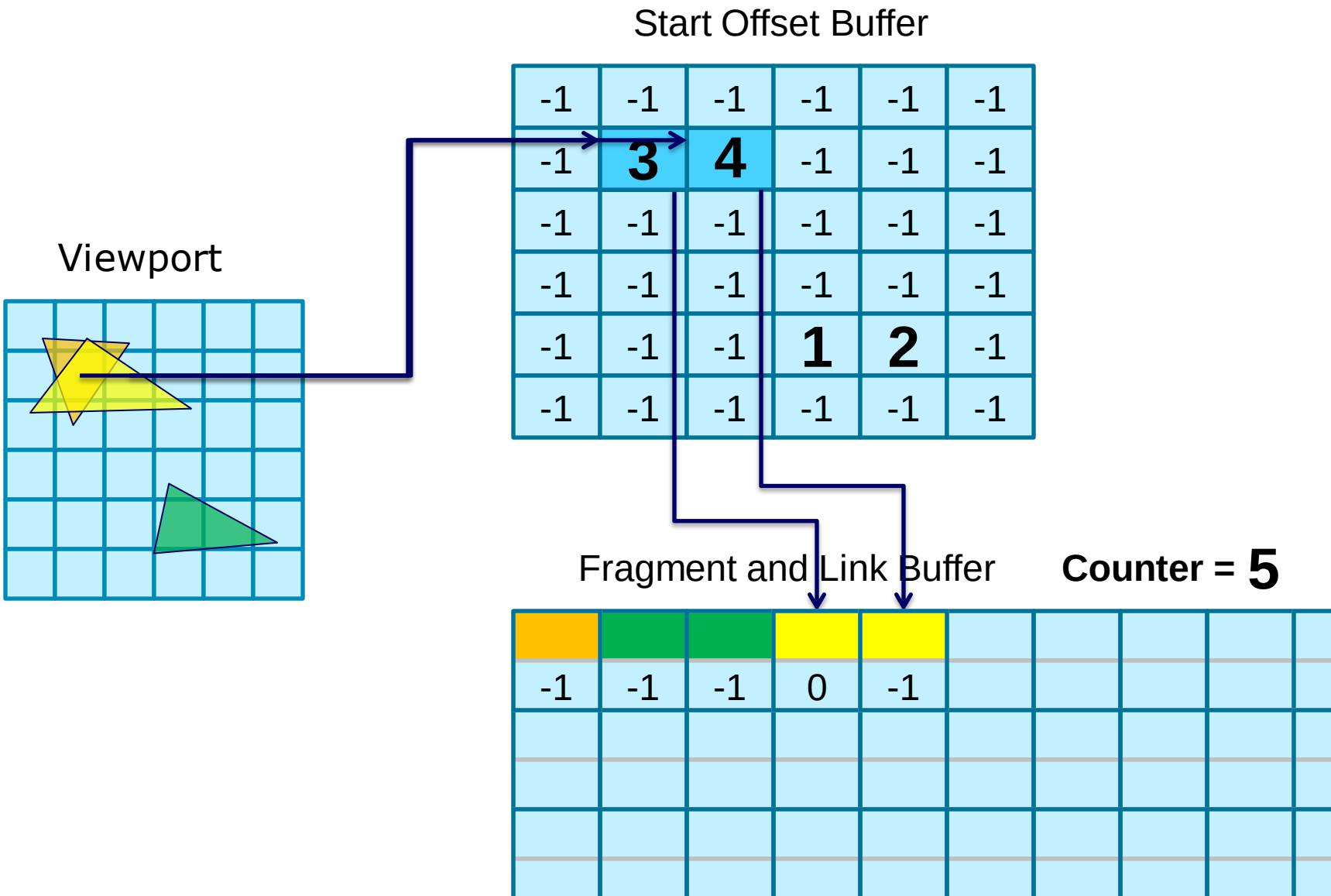
Linked List Creation (2b)



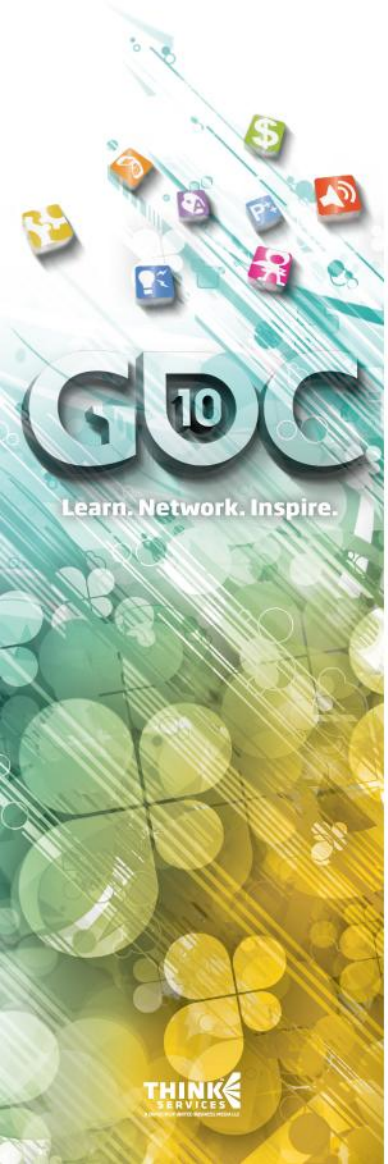
Linked List Creation (2c)



Linked List Creation (2d)



Linked List Creation - Code




```
float PS_StoreFragments(PS_INPUT input) : SV_Target
{
 // Calculate fragment data (color, depth, etc.)
 FragmentData_STRUCT FragmentData = ComputeFragment();

 // Retrieve current pixel count and increase counter
 uint uPixelCount = FLBuffer.IncrementCounter();

 // Exchange offsets in StartOffsetBuffer
 uint vPos = uint(input.vPos);
 uint uStartOffsetAddress= 4 * ( (SCREEN_WIDTH*vPos.y) + vPos.x );
 uint uOldStartOffset;
 StartOffsetBuffer.InterlockedExchange(
   uStartOffsetAddress, uPixelCount, uOldStartOffset);

 // Add new fragment entry in Fragment & Link Buffer
 FragmentAndLinkBuffer_STRUCT Element;
 Element.FragmentData  = FragmentData;
 Element.uNext         = uOldStartOffset;
 FLBuffer[uPixelCount] = Element;
}
```

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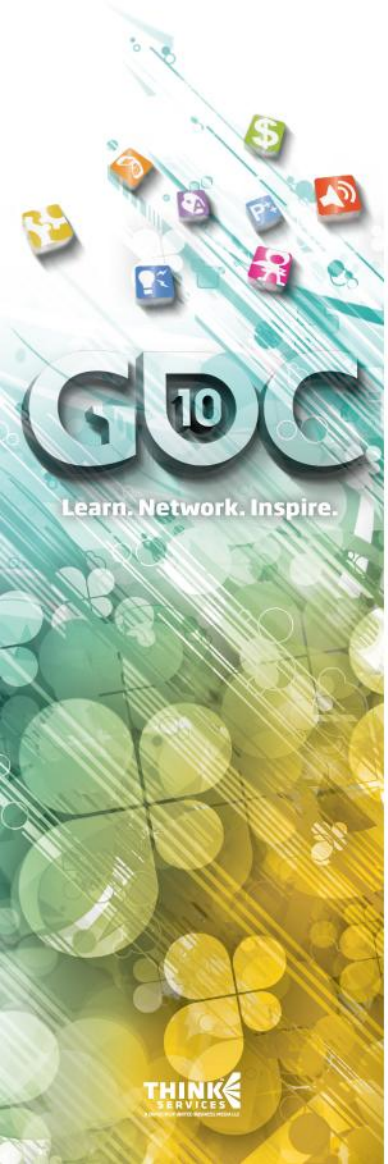
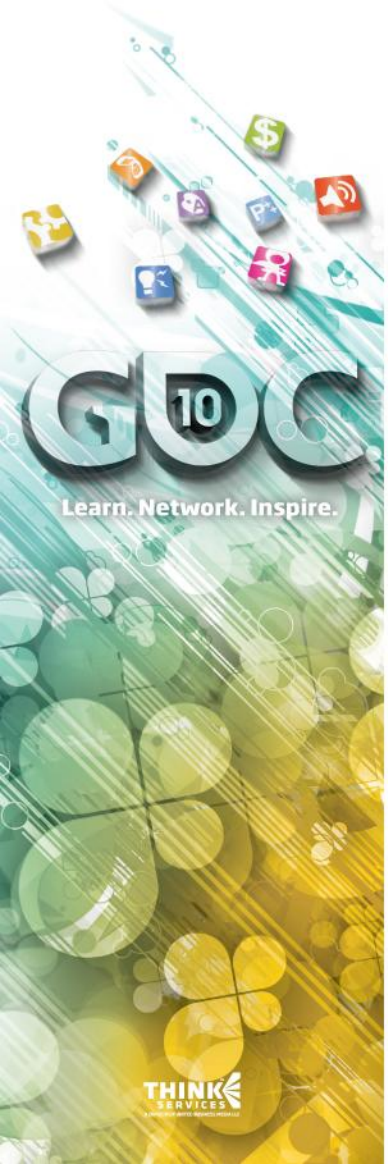


Traversing Per-Pixel Linked Lists



Rendering Pixels (1)

- "Start Offset" Buffer and "Fragment & Link" Buffer now bound as SRV

```
Buffer<uint> StartOffsetBufferSRV;
StructuredBuffer<FragmentAndLinkBuffer_STRUCT>
  FLBufferSRV;
```

- Render a fullscreen quad
- For each pixel, parse the linked list and retrieve fragments for this screen position
- Process list of fragments as required
  - Depends on algorithm
  - e.g. sorting, finding maximum, etc.

SRV = Shader Resource View

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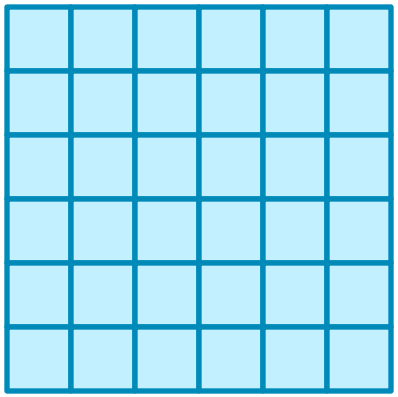
Rendering from Linked List

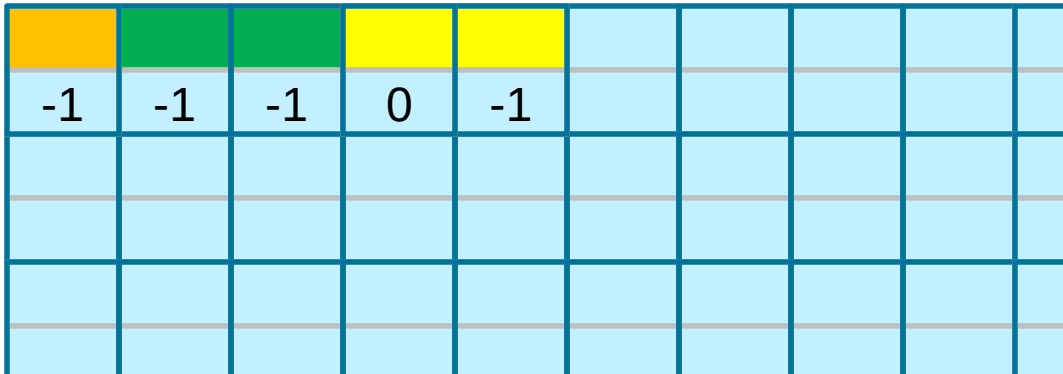
Start Offset Buffer

-1	-1	-1	-1	-1	-1
-1	**3**	**4**	-1	-1	-1
-1	-1	-1	-1	-1	-1
-1	-1	-1	-1	-1	-1
-1	-1	-1	**1**	**2**	-1
-1	-1	-1	-1	-1	-1

Render Target



Fragment and Link Buffer



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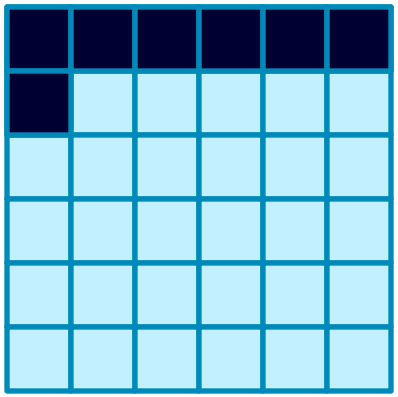
Rendering from Linked List

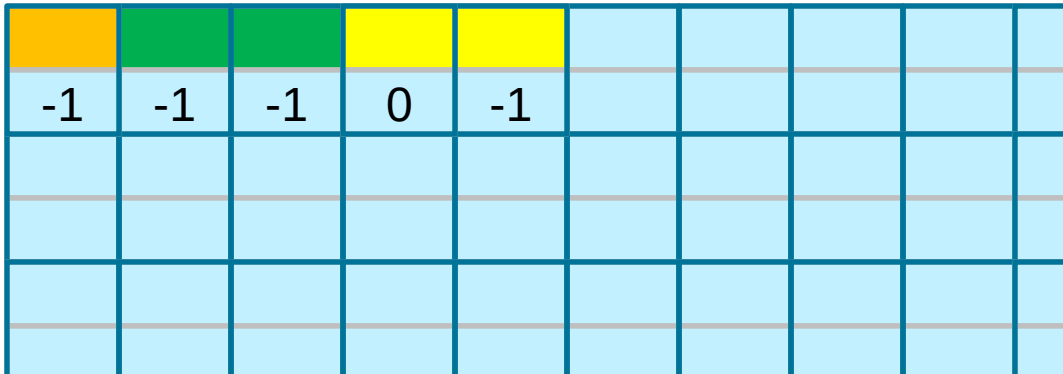
Start Offset Buffer

-1	-1	-1	-1	-1	-1
-1	**3**	**4**	-1	-1	-1
-1	-1	-1	-1	-1	-1
-1	-1	-1	-1	-1	-1
-1	-1	-1	**1**	**2**	-1
-1	-1	-1	-1	-1	-1

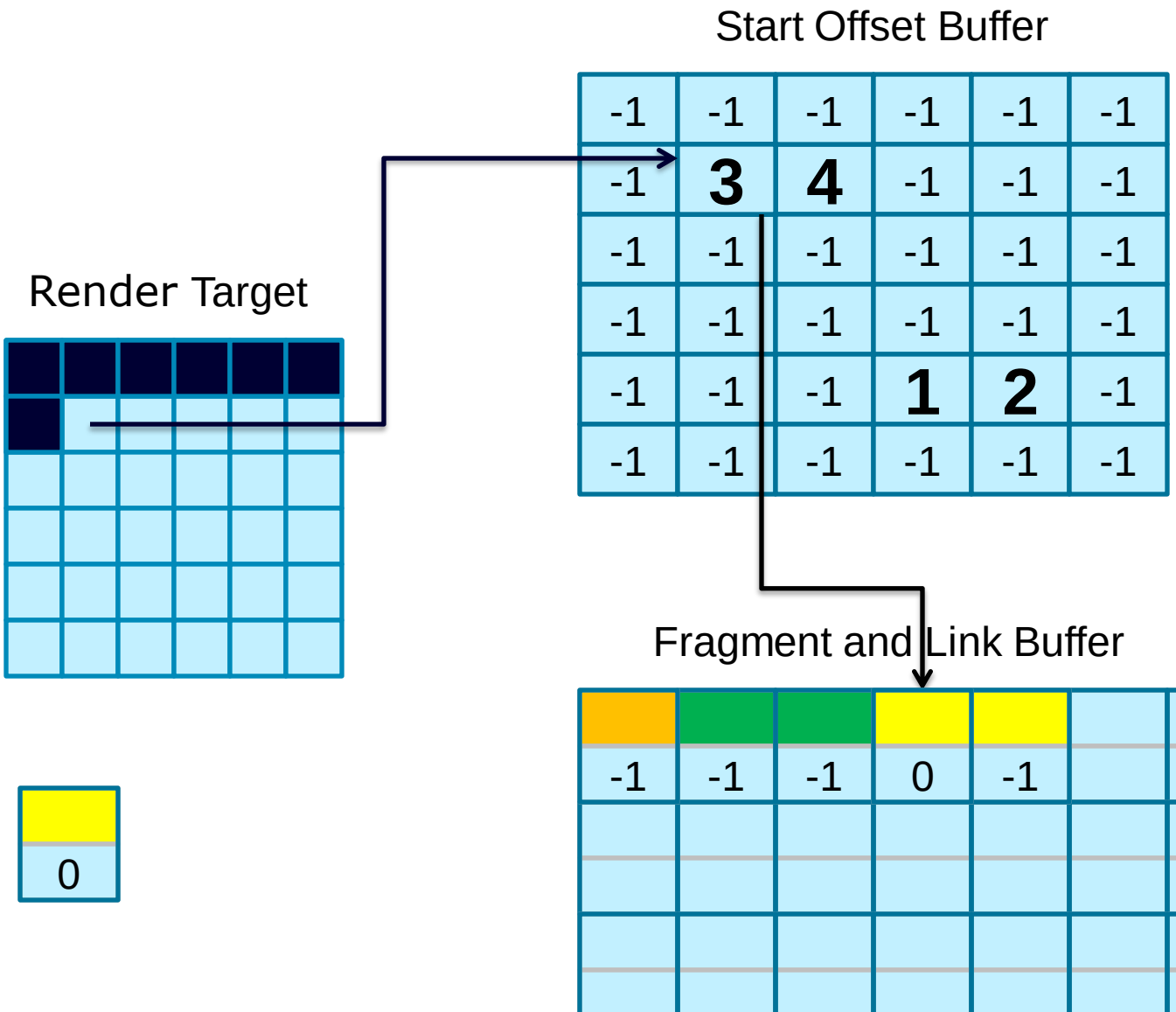
Render Target



Fragment and Link Buffer



Rendering from Linked List



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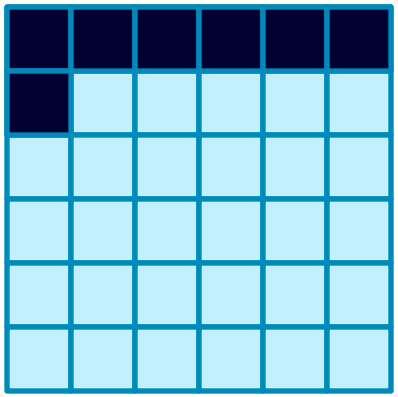
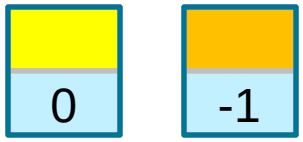
Rendering from Linked List

Start Offset Buffer

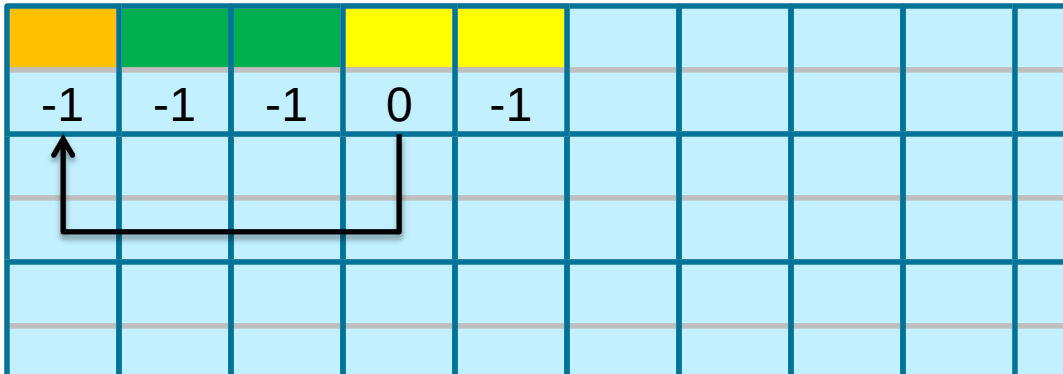
-1	-1	-1	-1	-1	-1
-1	**3**	**4**	-1	-1	-1
-1	-1	-1	-1	-1	-1
-1	-1	-1	-1	-1	-1
-1	-1	-1	**1**	**2**	-1
-1	-1	-1	-1	-1	-1

Render Target





Fragment and Link Buffer



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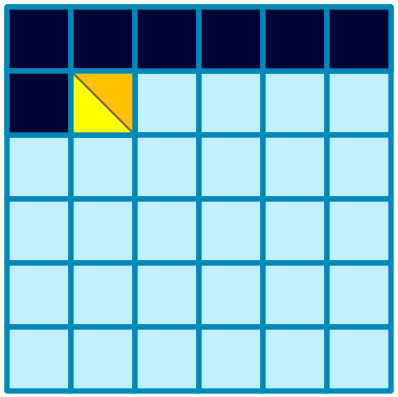
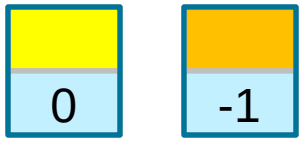
Rendering from Linked List

Start Offset Buffer

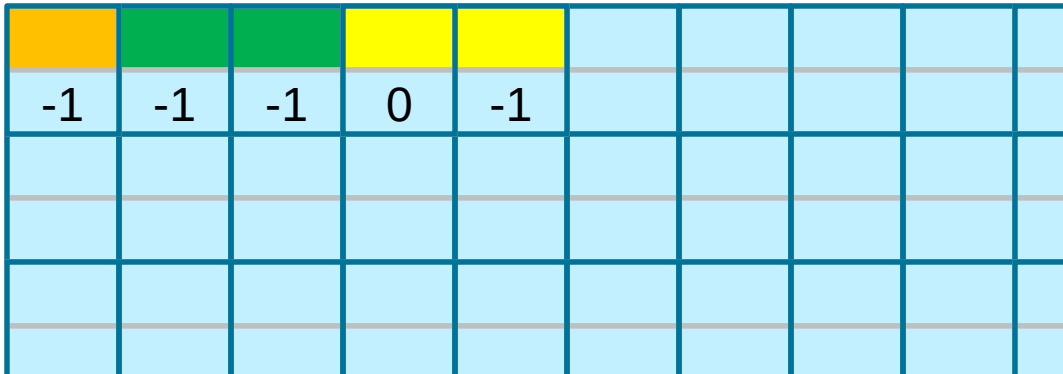
-1	-1	-1	-1	-1	-1
-1	**3**	**4**	-1	-1	-1
-1	-1	-1	-1	-1	-1
-1	-1	-1	-1	-1	-1
-1	-1	-1	**1**	**2**	-1
-1	-1	-1	-1	-1	-1

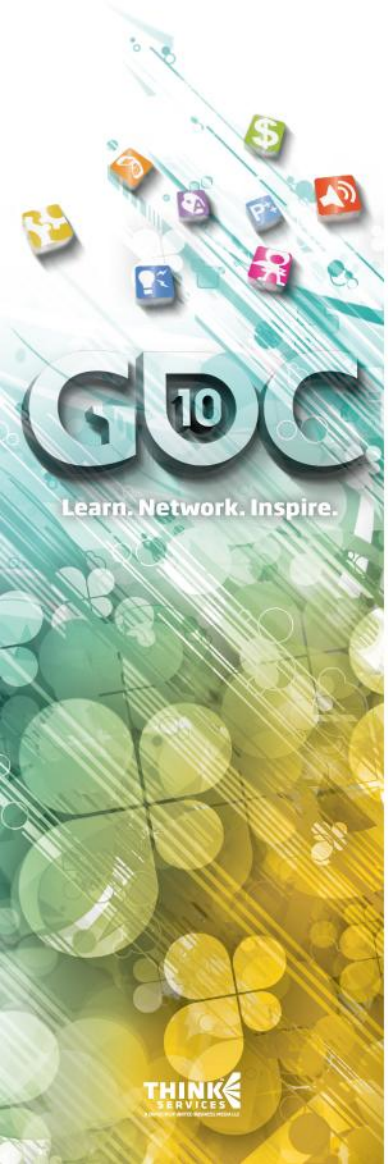
Render Target





Fragment and Link Buffer





Rendering Pixels (2)

```
float4 PS_RenderFragments(PS_INPUT input) : SV_Target
{
  // Calculate UINT-aligned start offset buffer address
  uint vPos = uint(input.vPos);
  uint uStartOffsetAddress =  SCREEN_WIDTH*vPos.y + vPos.x;
  // Fetch offset of first fragment for current pixel
  uint uOffset = StartOffsetBufferSRV.Load(uStartOffsetAddress);

  // Parse linked list for all fragments at this position
  float4 FinalColor=float4(0,0,0,0);
  while (uOffset!=0xFFFFFFFF)      // 0xFFFFFFFF is magic value
  {
    // Retrieve pixel at current offset
    Element=FLBufferSRV[uOffset];
    // Process pixel as required
    ProcessPixel(Element, FinalColor);
    // Retrieve next offset
    uOffset = Element.uNext;
  }
  return (FinalColor);
}
```

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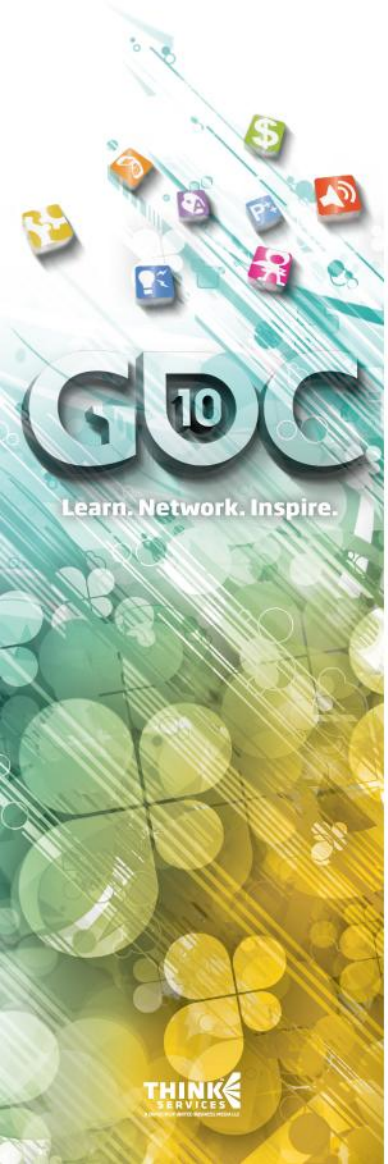

Order-Independent Transparency via Per-Pixel Linked Lists

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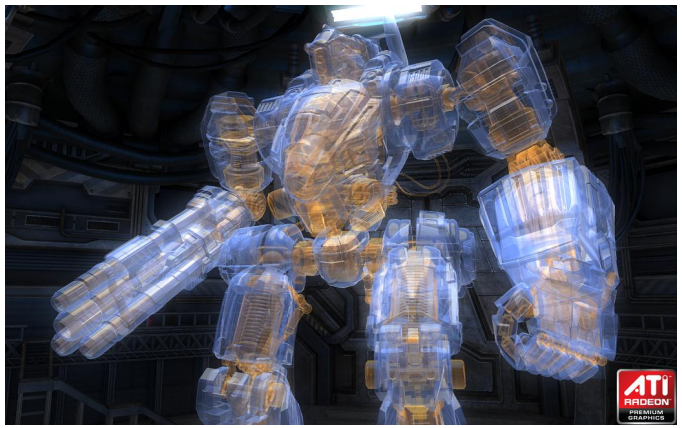

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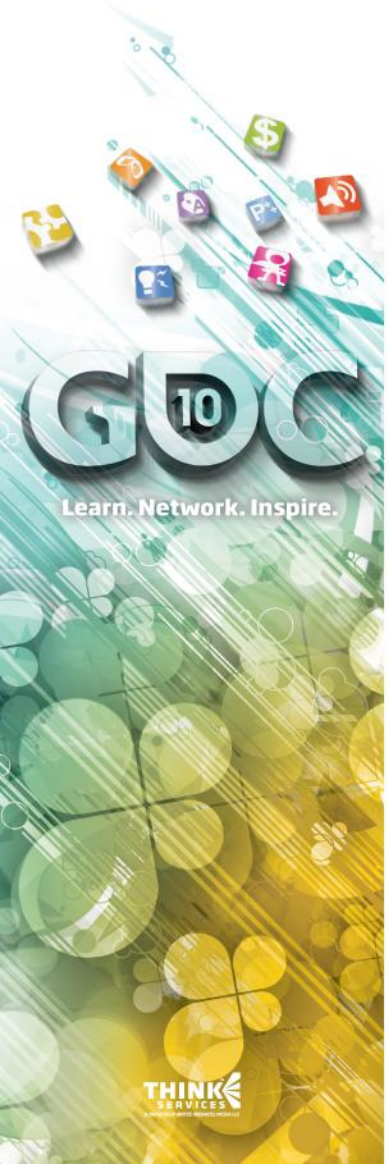

Description

- Straight application of the linked list algorithm
- Stores transparent fragments into PPLL
- Rendering phase sorts pixels in a back-to-front order and blends them manually in a pixel shader
  - Blend mode can be unique per-pixel!
- Special case for MSAA support

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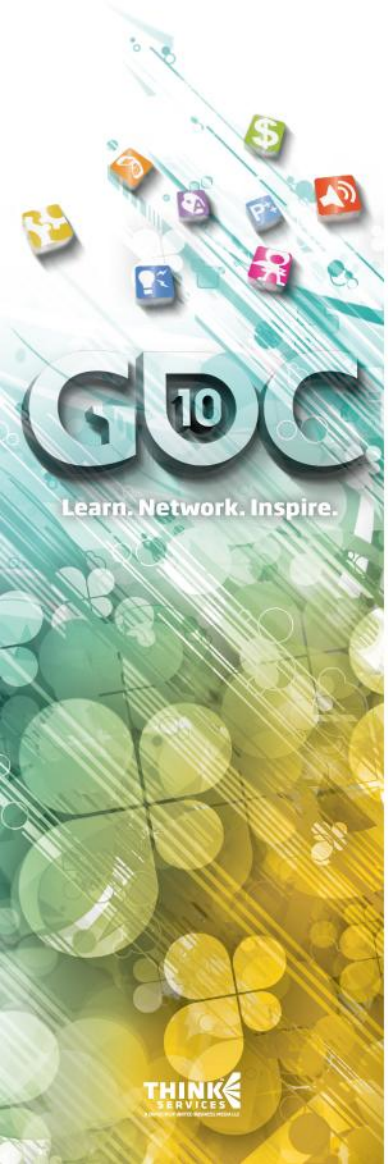
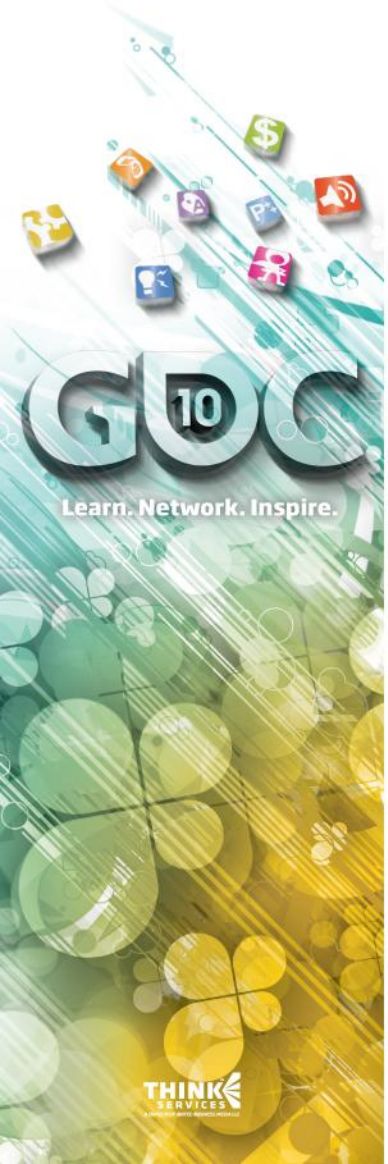


Linked List Structure

- Optimize performance by reducing amount of data to write to/read from UAV
- E.g. uint instead of float4 for color
- Example data structure for OIT:

```
struct FragmentAndLinkBuffer_STRUCT
{
  uint  uPixelColor;   // Packed pixel color
  uint  uDepth;        // Pixel depth
  uint  uNext;         // Address of next link
};
```

- May also get away with packed color and depth into the same uint! (if same alpha)
  - 16 bits color (565) + 16 bits depth
  - Performance/memory/quality trade-off



Visible Fragments Only!

- Use **`[earlydepthstencil]`** in front of Linked List creation pixel shader
- This ensures *only* transparent fragments that pass the depth test are stored
  - i.e. Visible fragments!
- Allows performance savings *and* rendering correctness!

```
[earlydepthstencil]
float PS_StoreFragments(PS_INPUT input) : SV_Target
{
   ...
}
```

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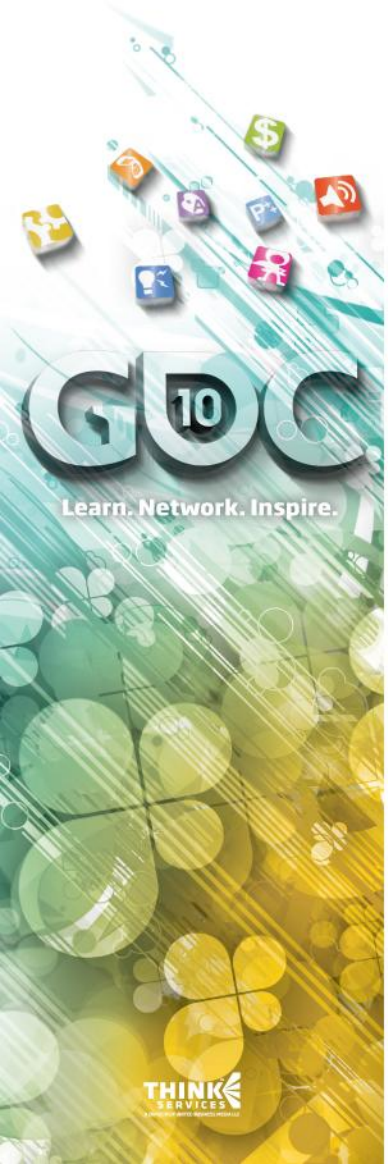
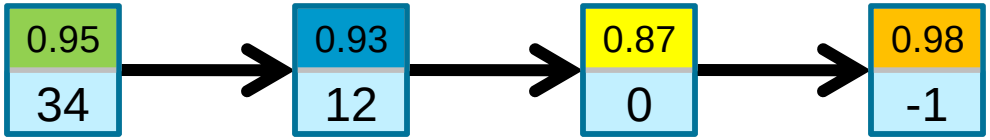


Sorting Pixels

- Sorting in place requires R/W access to Linked List
- Sparse memory accesses = slow!
- Better way is to copy all pixels into array of temp registers
  - Then do the sorting
- Temp array declaration means a hard limit on number of pixel per screen coordinates
  - Required trade-off for performance

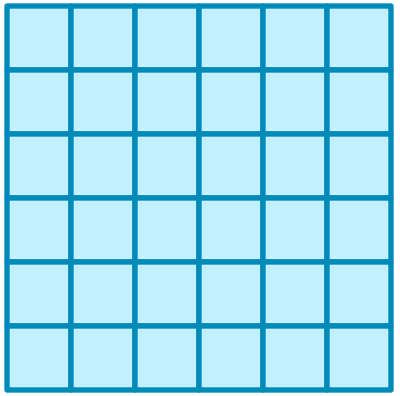
Sorting and Blending



Temp Array

PS color

Render Target



- Blend fragments back to front in PS
  - Blending algorithm up to app
  - Example: SRCALPHA-INVSRCALPHA
  - Or unique per pixel! (stored in fragment data)
- Background passed as input texture
  - Actual HW blending mode *disabled*

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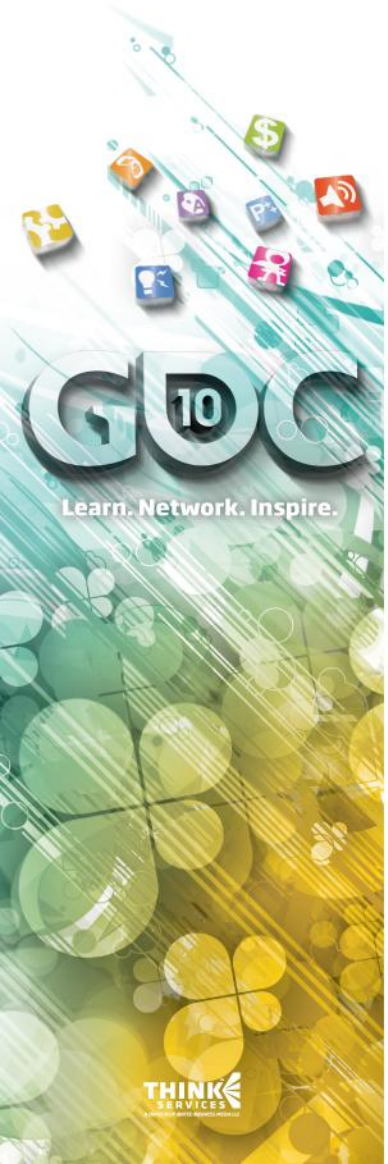
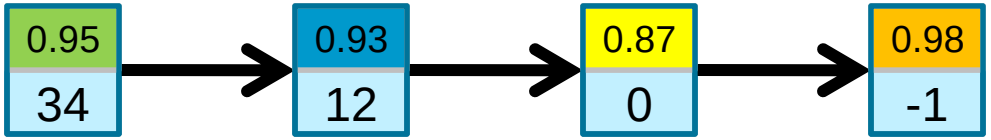
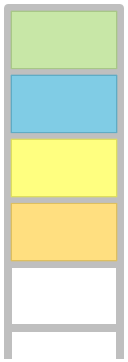


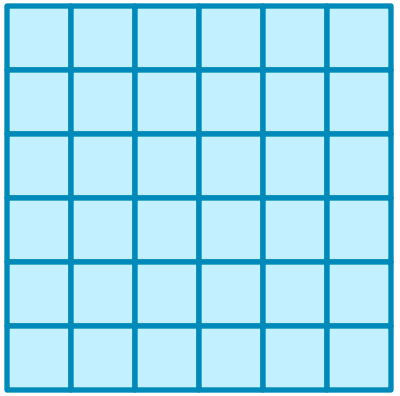
Sorting and Blending



Temp Array



Render Target



- Blend fragments back to front in PS
  - Blending algorithm up to app
  - Example: SRCALPHA-INVSRCALPHA
  - Or unique per pixel! (stored in fragment data)
- Background passed as input texture
  - Actual HW blending mode *disabled*

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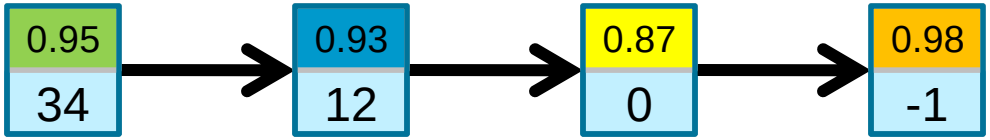

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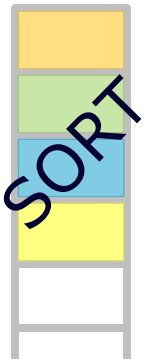

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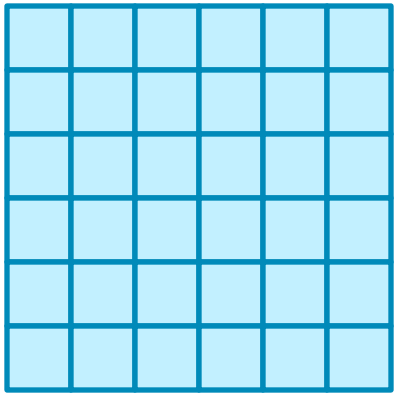

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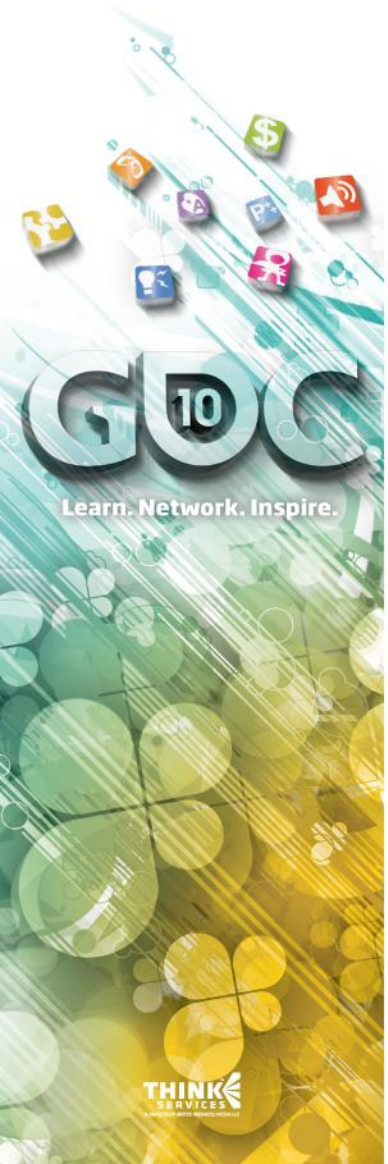

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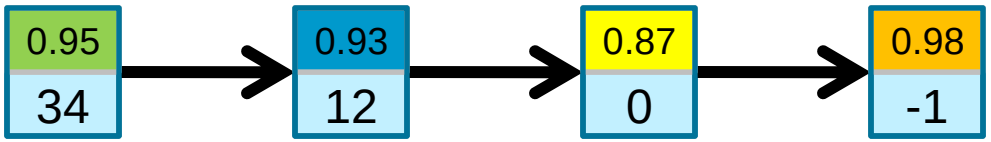

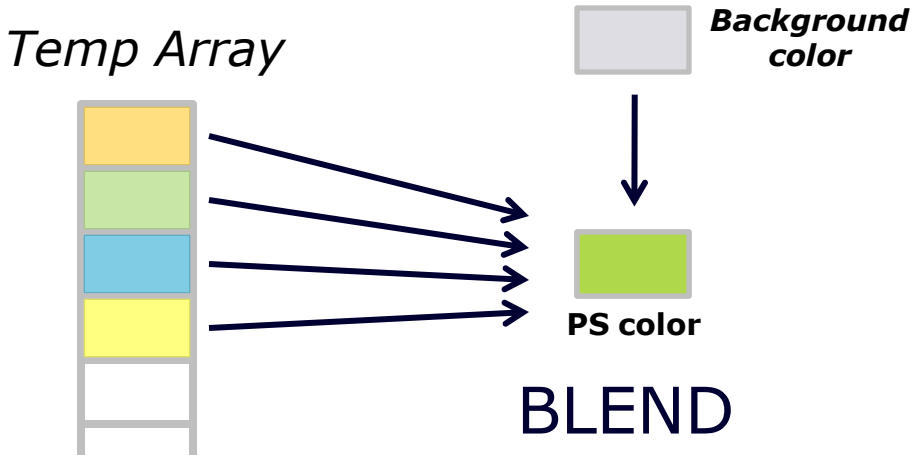

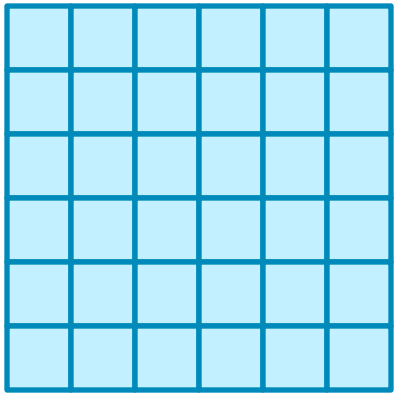

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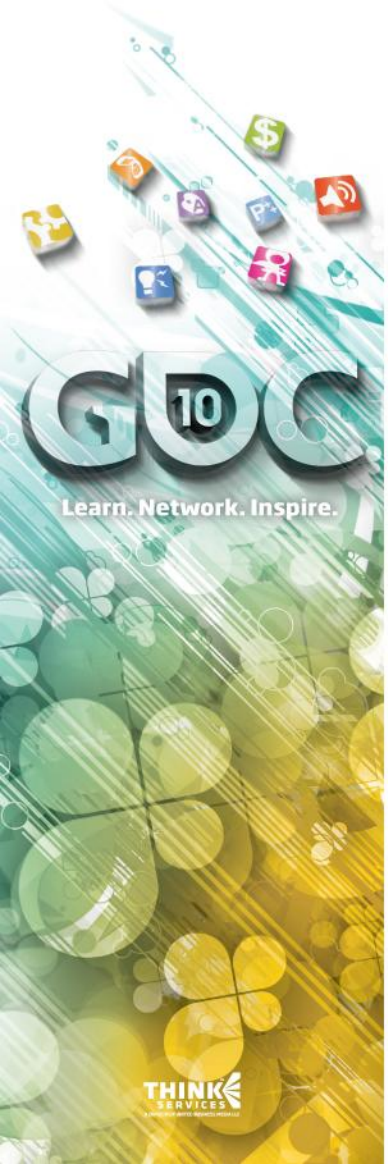
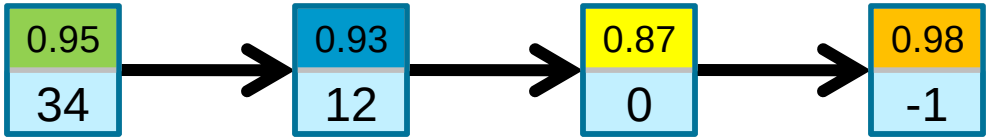
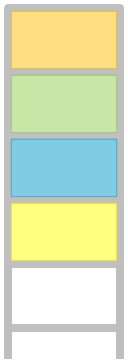


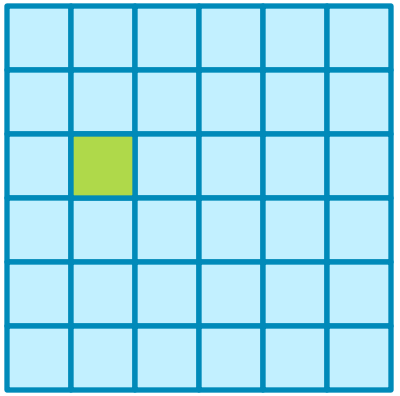
Sorting and Blending



Temp Array



Render Target



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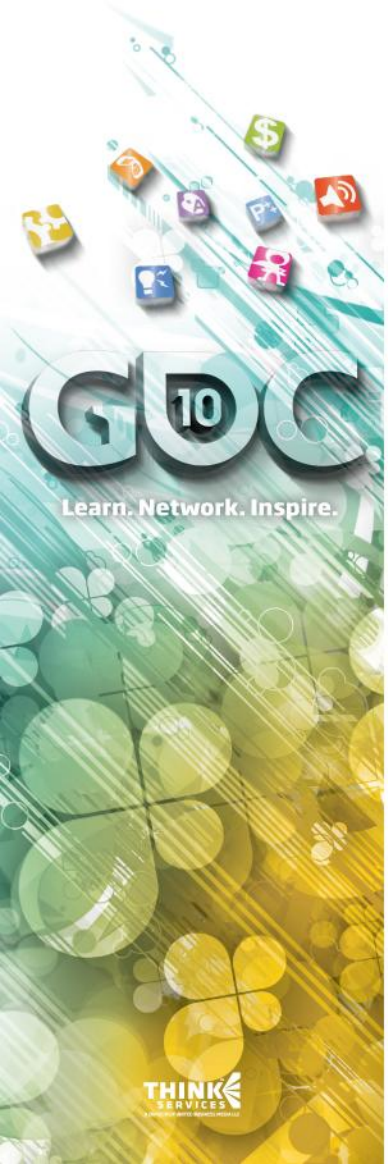


Storing Pixels for Sorting

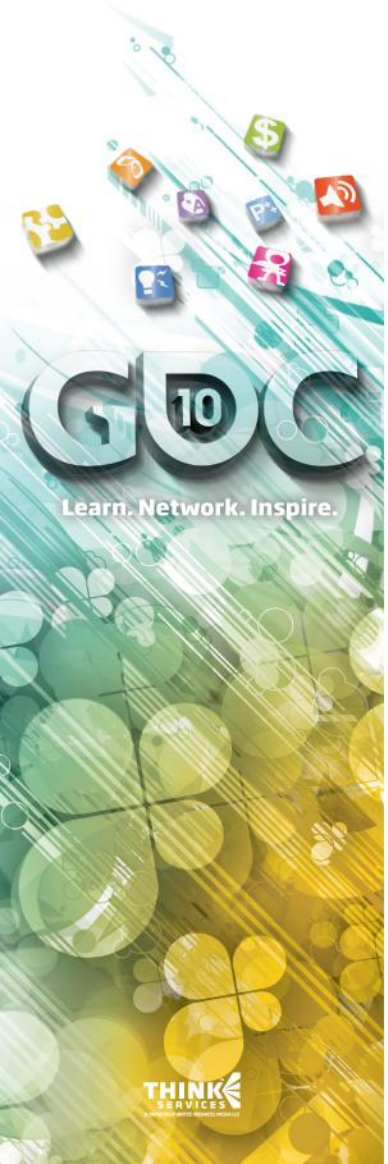
```
(...)

static uint2 SortedPixels[MAX_SORTED_PIXELS];
// Parse linked list for all pixels at this position
// and store them into temp array for later sorting
int nNumPixels=0;
while (uOffset!=0xFFFFFFFF)
{
   // Retrieve pixel at current offset
   Element=FLBufferSRV[uOffset];
   // Copy pixel data into temp array
   SortedPixels[nNumPixels++]=
        uint2(Element.uPixelColor, Element.uDepth);
   // Retrieve next offset
   [flatten]uOffset = (nNumPixels>=MAX_SORTED_PIXELS) ?
                      0xFFFFFFFF : Element.uNext;
}

// Sort pixels in-place
SortPixelsInPlace(SortedPixels, nNumPixels);

(...)
```

Pixel Blending in PS




```
(...)

// Retrieve current color from background texture
float4 vCurrentColor=BackgroundTexture.Load(int3(vPos.xy, 0));

// Rendering pixels using SRCALPHA-INVSRCALPHA blending
for (int k=0; k<nNumPixels; k++)
{
   // Retrieve next unblended furthermost pixel
   float4 vPixColor= UnpackFromUint(SortedPixels[k].x);

   // Manual blending between current fragment and previous one
   vCurrentColor.xyz= lerp(vCurrentColor.xyz, vPixColor.xyz,
                           vPixColor.w);
 }

 // Return manually-blended color
 return vCurrentColor;
}
```

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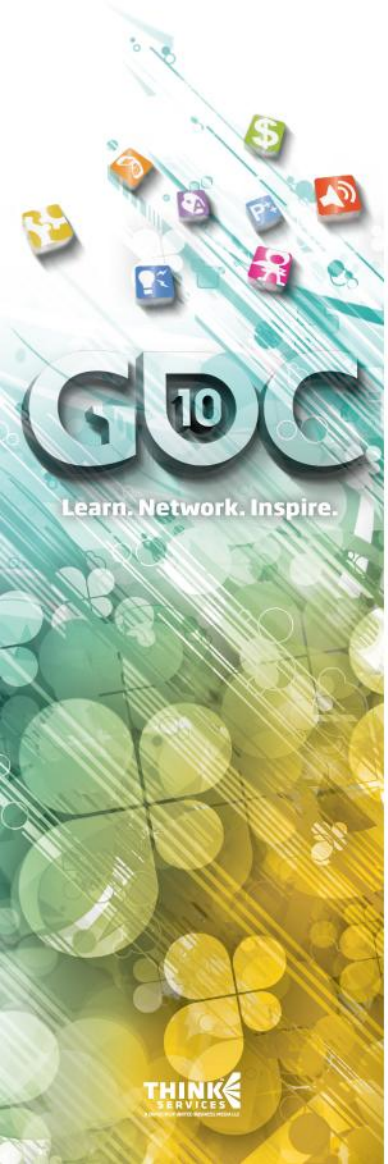
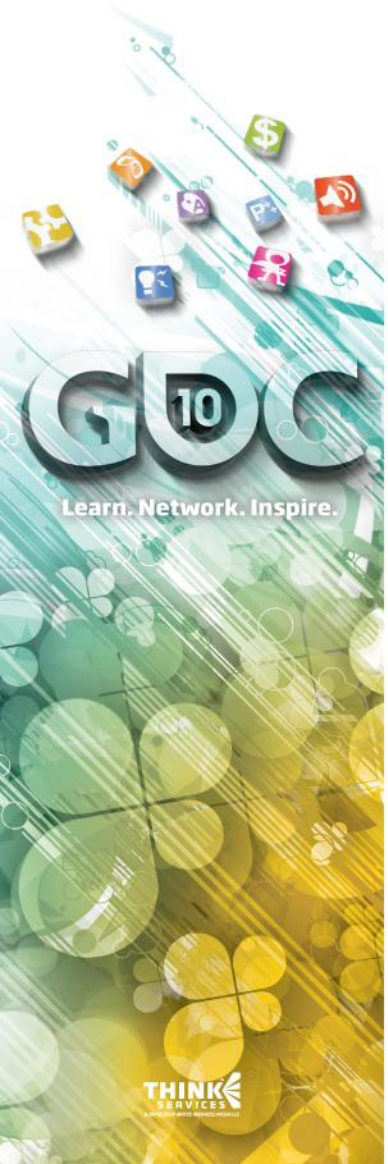


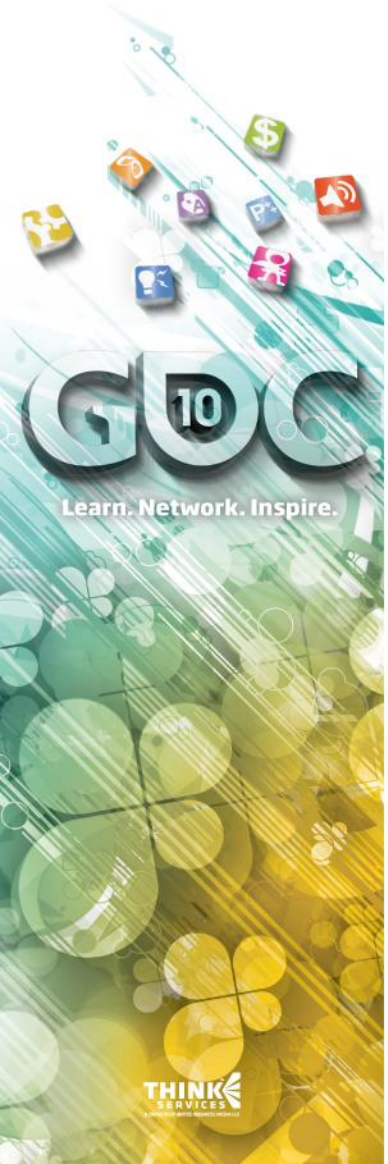
OIT via Per-Pixel Linked Lists with MSAA Support



Sample Coverage

- Storing individual samples into Linked Lists requires *a huge* amount of memory
  - ... and performance will suffer!
- Solution is to store transparent pixels into PPLL as before
- But including sample coverage too!
  - Requires as many bits as MSAA mode
- Declare SV_COVERAGE in PS structure

```
struct PS_INPUT
{
  float3 vNormal : NORMAL;
  float2 vTex    : TEXCOORD;
  float4 vPos    : SV_POSITION;
  uint uCoverage : SV_COVERAGE;
}
```

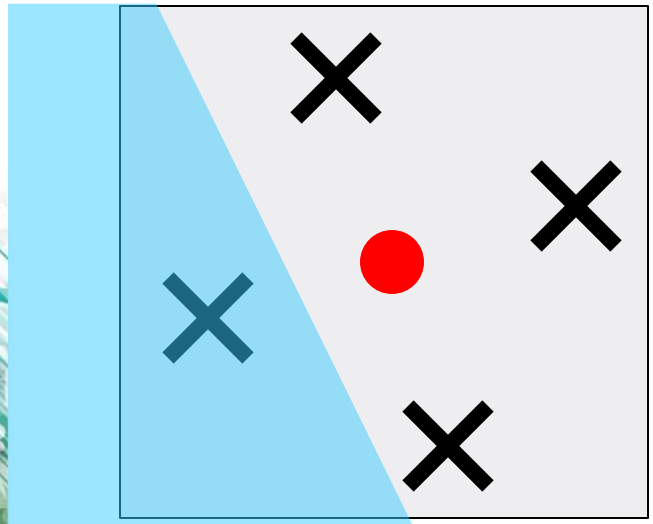


Linked List Structure

- Almost unchanged from previously
- Depth is now packed into 24 bits
- 8 Bits are used to store coverage

```
struct FragmentAndLinkBuffer_STRUCT
{
  uint  uPixelColor;        // Packed pixel color
  uint  uDepthAndCoverage; // Depth + coverage
  uint  uNext;              // Address of next link
};
```

Sample Coverage Example



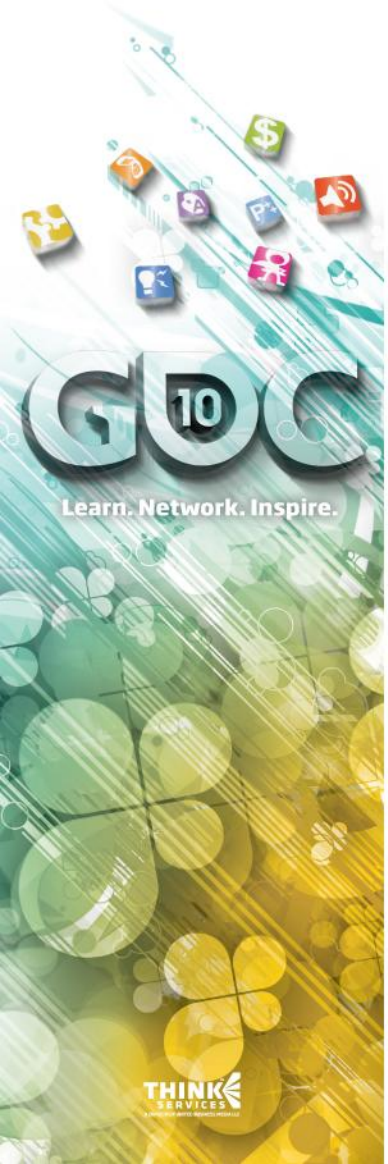

Pixel Center


Sample

- Third sample is covered

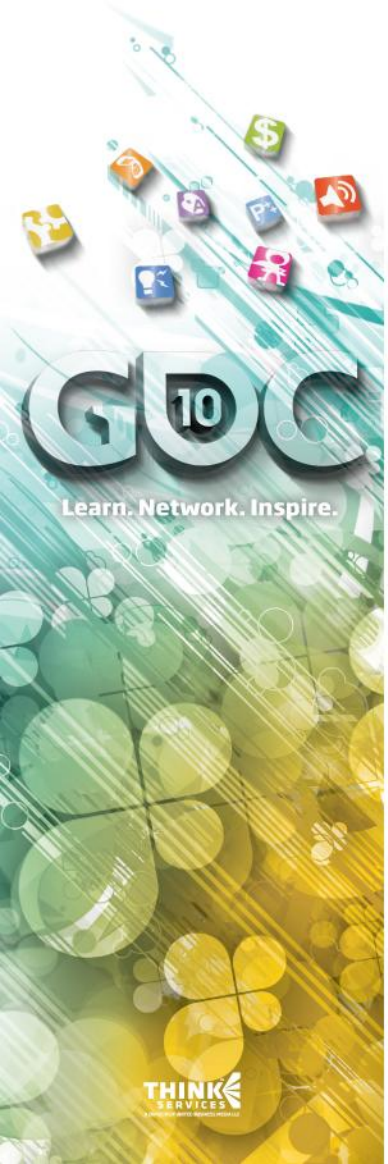
  uCoverage = 0x04 (0100 in binary)

```
Element.uDepthAndCoverage =
( In.vPos.z*(2^24-1) << 8 ) | In.uCoverage;
```



Rendering Samples (1)

- Rendering phase needs to be able to write individual samples
- Thus PS is run at sample frequency
  - Can be done by declaring SV_SAMPLEINDEX in input structure
- Parse linked list and store pixels into temp array for later sorting
  - Similar to non-MSAA case
  - Difference is to only store sample if coverage matches sample index being rasterized



Rendering Samples (2)

```
static uint2 SortedPixels[MAX_SORTED_PIXELS];

// Parse linked list for all pixels at this position
// and store them into temp array for later sorting
int nNumPixels=0;
while (uOffset!=0xFFFFFFFF)
{
   // Retrieve pixel at current offset
   Element=FLBufferSRV[uOffset];

   // Retrieve pixel coverage from linked list element
   uint uCoverage=UnpackCoverage(Element.uDepthAndCoverage);
   if ( uCoverage & (1<<In.uSampleIndex) )
   {
     // Coverage matches current sample so copy pixel
     SortedPixels[nNumPixels++]=Element;
   }
   // Retrieve next offset
   [flatten]uOffset = (nNumPixels>=MAX_SORTED_PIXELS) ?
                      0xFFFFFFFF : Element.uNext;
}
```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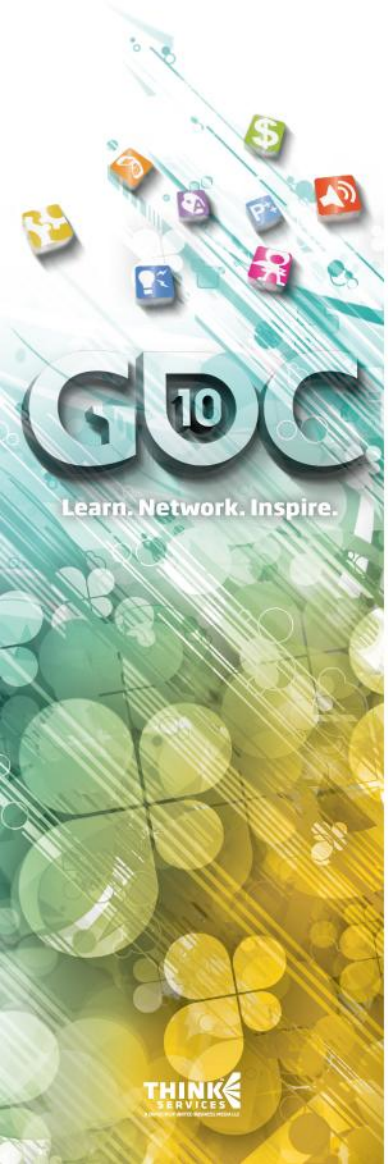

Q&A

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Credits for the basic idea of how to implement PPLL under Direct3D 11 go to Jakub Klarowicz (Techland), Holger Gruen and Nicolas Thibieroz (AMD)