
Game Developers Conference®
February 28 - March 4, 2011
Moscone Center, San Francisco
www.GDConf.com
GDC
UBM

High Performance Post-Processing

Nathan Hoobler, NVIDIA
(nhoobler@nvidia.com)

Image-Based Effects are Great!

Beautiful, But Costly

- Workload differs greatly from 3D rendering
- Bandwidth-hungry shaders
- Algorithms shoe-horned into Graphics API

Direct3D 11 provides great ways around this

New Resource Types

- Buffers / Structured Buffers
- Unordered Access Views (UAV)
  - RWTexture/RWBuffer
  - Allows arbitrary reads and writes from PS and CS
    - Ability to “scatter” provides new opportunities
    - Have to be aware of hazards and access patterns

New Intrinsic Operations

- Interlocked/Append operations
  - Allow parallel workloads to combine results easily
  - Useful for collapsing information across the image
  - Not free! Cost increases if a value is hit often
    - NV: This may be more efficient from Compute shaders
    - NV: Append is more efficient than IncrementCounter for dynamically growing UAVs
    - AMD: No special cases for performance

DirectCompute

- New shader mode that operates on arbitrary threads
- Frees processing from restrictions of gfx pipeline
- Full access to conventional Direct3D resources

DIRECTCOMPUTE REVIEW

Why use Compute?

- Allows much finer-level control of workload
- Inter-thread communication
- Hardware has more freedom for optimizations
- Just plain easier to write!

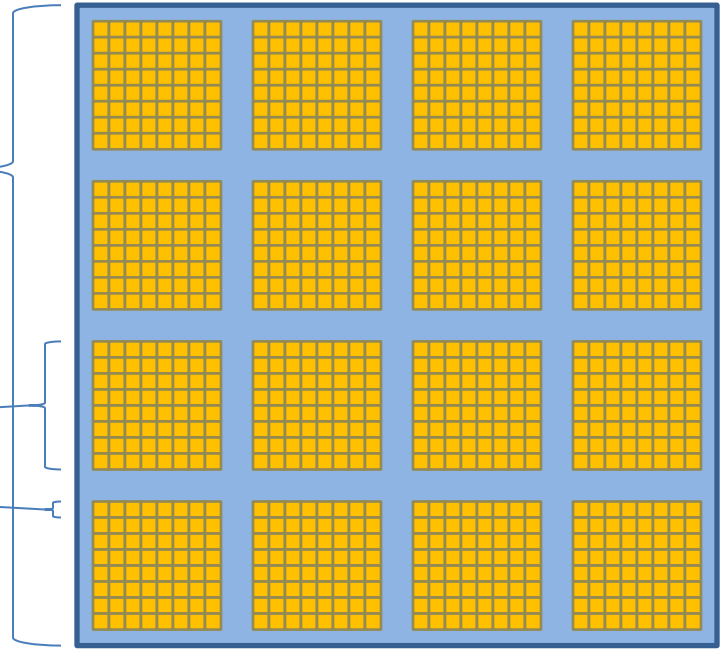
Threads, Groups, and Dispatches

- Shaders run as a set of several thread blocks that execute in parallel
  - "Threads" runs the code given in the shader
  - "Groups" are sets of threads that can communicate using on-chip memory
  - "Dispatches" are sets of groups

Dispatch Example

```
// CPU Code
pContext->CSSetUnorderedAccessViews(
          0, 1, &pOutputUAV, NULL);
pContext->CSSetShader(pSimpleCS);
pContext->Dispatch(4,4,1);
```

```
// HLSL Code
RWTexture<float3> uavOut : register(u0);
[numthreads(8,8,1)]
void SimpleCS(uint3 tID :
                    SV_DispatchThreadID)
{
    uavOut[tID] = float3(0,1,0);
}
```



DispatchIndirect

- Fetch Dispatch parameters from device buffer instead of from the CPU
- Let Compute work drive Compute!
  - Still bound by CPU to issue DispatchIndirect call
- Great when combined with Append buffers for dynamic workload generation

Memory Hierarchy

Memory Space	Speed	Visibility
Global Memory (Buffers, Textures, Constants)	Longest Latency	All Threads
Shared Memory (groupshared)	Fast	Single Group
Local Memory (Registers)	Very Fast	Single Thread

Inter-Thread Communication

- Threads in a group can communicate via shared mem
- Thread execution cannot depend on other groups!
  - Not all groups execute simultaneously
  - Groups can execute in any order within a Dispatch
  - **Inter-group dependency could lead to deadlocks**
- If a group relies on results from another group, split shader into multiple dispatches

Data Hazards and Stalls

- Re-binding a resource used as UAV may stall HW to avoid data hazards
  - Have to make sure all writes complete so they are visible to next dispatch
  - Driver may re-order unrelated Dispatch calls to hide this latency

Context Switch Overhead

- Have to be aware of context switch cost
  - Penalty switching between Graphics and Compute
  - Usually minimal unless repeatedly hit
  - Back-to-Back Dispatches avoid this, so group calls

OPTIMIZATION CONCEPTS

Common Pitfalls

Memory Limited

- Inefficient access pattern
- Inefficient formats
- Just too much data!

Computation Limited

- Divergent threads
- Bad Instruction Mix
- Poor Hardware Utilization

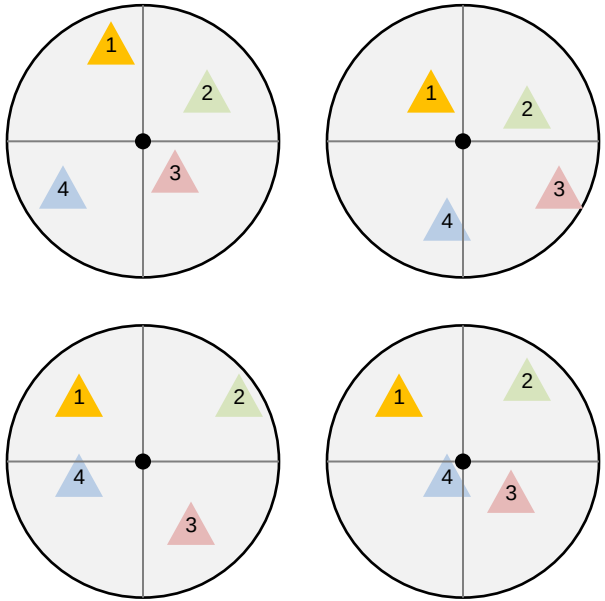
Memory Architecture

- D3D11 introduces complex memory systems
- Caching behavior depends on access mode
  - Buffers may hit cache better for linear accesses
  - Textures work better for less predictable/more 2D access within a group

Stratified Sampling

Bad – Poor Sample Locality

Good – Better for Cache



"Going with the Grain"

- Unlike textures, buffers are linear memory

- Be sure to read along the pitch of a 2D array mapped to a buffer where possible!

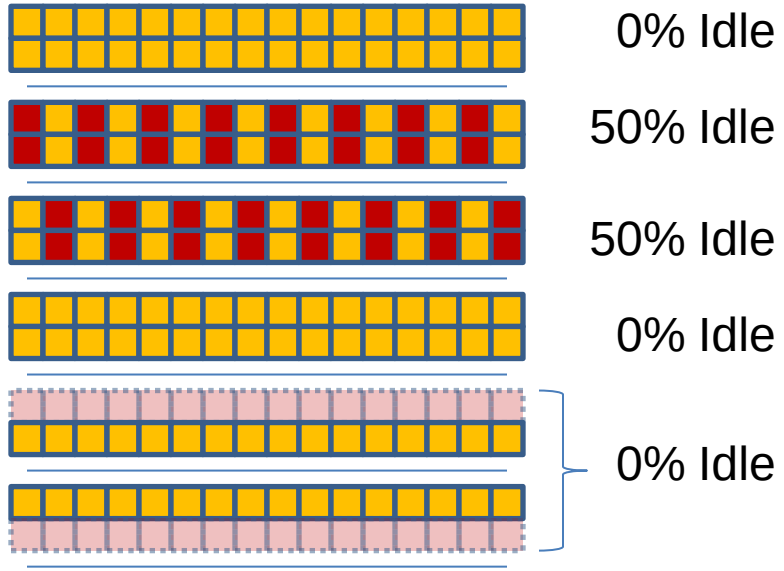
```
Buffer<float> srvInput;
[numthreads(128,1,1)]
void ReadCS(
  uint3 gID : SV_GroupID
  uint3 tID : SV_DispatchThreadID)
{
  float val;

  // Good: Reading along pitch
  val = srvRead[128*gID.x+tID.x];
  // ... Use data ...

  // Bad: Reading against pitch
  val = srvRead[128*tID.x+gID.x];
  // ... Use data ...
}
```

Divergence

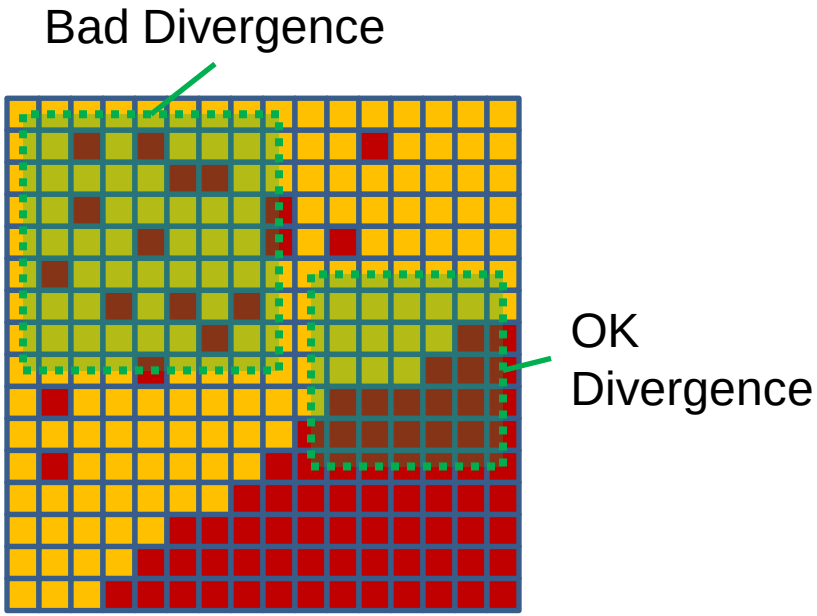
- Theoretically, threads execute independantly
- Practically, they execute in parallel wavefronts
  - Threads are “masked” for instructions in untaken branches while wavefront executes
  - Different wavefronts can diverge without cost
  - Wavefronts size is hardware specific
    - NV:32 AMD:64

Wavefront Divergence

```
// Assume WAVE_SIZE = wavefront size for
// the hardware (NV:32,AMD:64)
[numthreads(WAVE_SIZE,2,1)]
void DivergeCS(uint3 tID :
          SV_DispatchThreadID) {
  float val;
  // Divergent
  if (tID.x%2)
    val = ComplexFuncA(tID);
  else
    val = ComplexFuncB(tID);
  // Not divergent
  if (tID.y%2)
    val =+ ComplexFuncC(tID);
  else
    val =+ ComplexFuncD(tID);
  Output(tID, val);
}
```



Divergent Pixels



- In PS, threads are grouped into 2D clusters of samples
- Branches are OK if they're coherent across the image
  - Especially if it saves work!

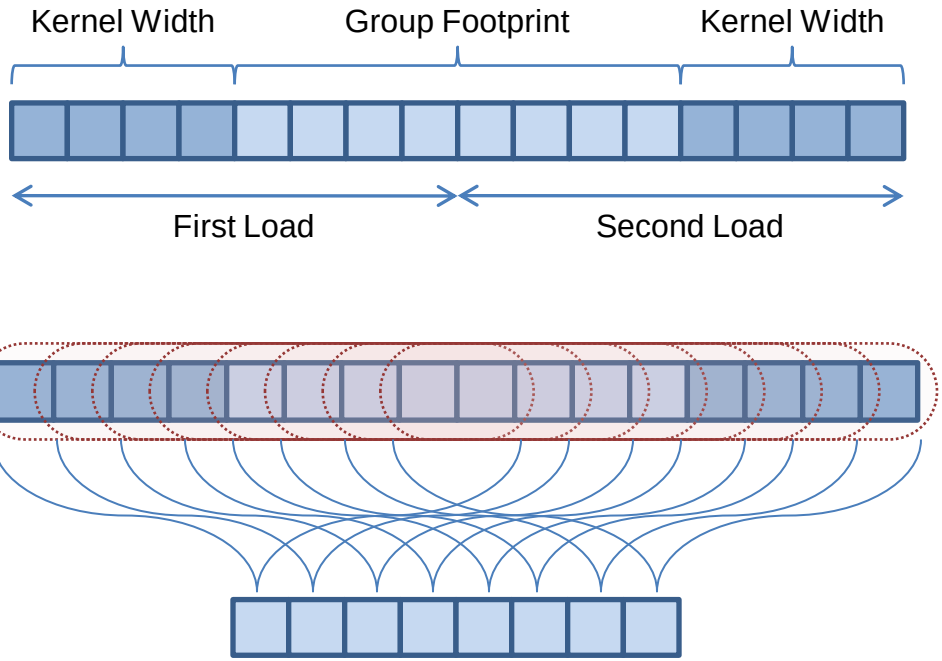
Utilization

- Create enough work to saturate hardware
  - Dozens of groups is about the sweet spot
- Maximize number of threads per group
  - Need enough to hide latency in the hardware
  - 256-512 is a good target
- Experiment with Shared memory usage
  - More shared memory = fewer groups/processor
  - Try making groups smaller when shared memory/thread increases

Group-Level Coordination

- Compute threads can communicate and share data via "`groupshared`" memory
  - Pre-load data used by every thread in a group
    - Unpacked values, Dynamic programming
    - Save bandwidth and computation
  - Share workload for common tasks
    - Compute the sum/max/etc of a set
    - More efficient than shared atomics

Pre-Loading into Shared Memory

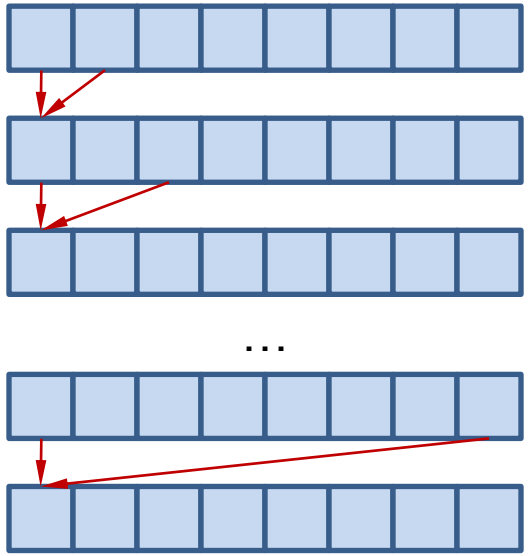


Separable Convolution:

- Read entire footprint of kernel into shared memory
- Fetch values from shared buffer and multiply by kernel for each pixel
- Read less often, and more efficiently!

Naïve Sum

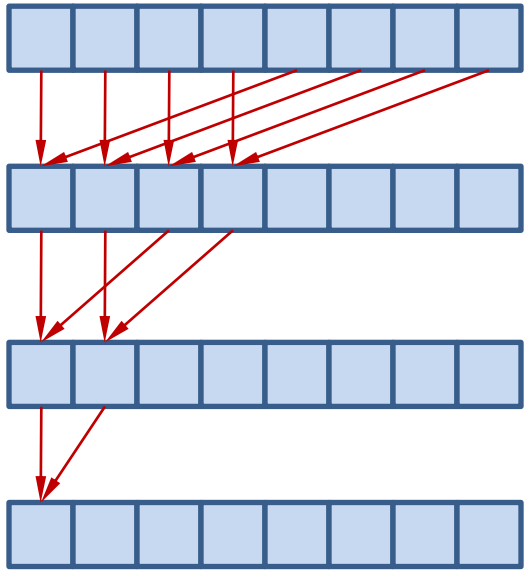
```
Buffer<float> srvIn;
groupshared float sSum;
[numthreads(GROUP_SIZE,1,1)]
void SimpleSumCS(…)
{
  if (gtID.x == 0)
  {
    sSum = 0;
    for(int t=1; t<8; ++t)
    {
      sSums += srvIn[tID+t];
    }
  }
  GroupMemoryBarrierWithGroupSync();
  // Use total
}
```



Most threads idle!
Atomics are no better

Parallel Sum

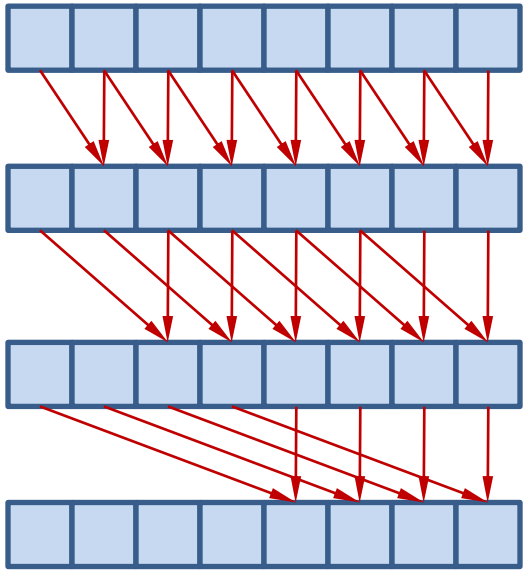
```
Buffer<float> srvIn;
groupshared float sSums[GROUP_SIZE];
[numthreads(GROUP_SIZE,1,1)]
void ParallelSumCS(…)
{
  sSums[gtID.x] = srvIn[tID];
  GroupMemoryBarrierWithGroupSync();
  for(int t=GROUP_SIZE/2; t>0; t=t>>1)
  {
    if (gtID.x < t)
      sSums[gtID.x] += sSums[gtId.x+t];
    GroupMemoryBarrier();
  }
  // Use result; total is in sSums[0]
}
```



O(N) ops, but in parallel!

Parallel Prefix Sum

```
Buffer<float> srvIn;
groupshared float sSums[GROUP_SIZE];
[numthreads(GROUP_SIZE,1,1)]
void ParallelSumCS(…)
{
  sSums[gtID.x] = srvIn[tID];
  GroupMemoryBarrierWithGroupSync();
  for(int t=1; t>GROUP_SIZE; t=t<<1)
  {
    if (gtID.x >= t)
      sSums[gtID.x] += sSums[gtId.x-t];
    GroupMemoryBarrier();
  }
  // Use results
  // sSums[N] = total of samples [0…N]
}
```



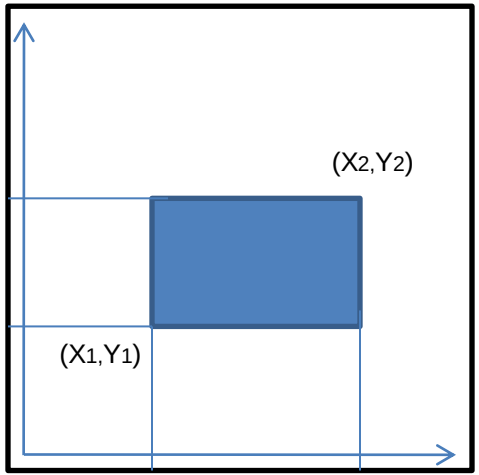
CASE STUDIES

Case Study: Summed Area Table

SAT Approach

- Create texture where each value is the sum of all pixels before it in the image

- Sample corners of region and use difference to compute average value

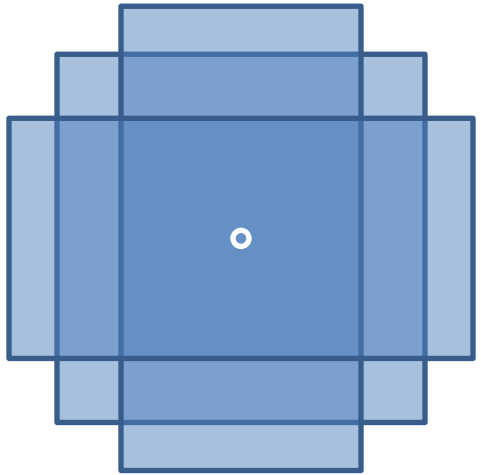


$$Avg = \frac{S(X2,Y2)-S(X2,Y1)-S(X1,Y2)+S(X1,Y1)}{((X2-X1)*(Y2-Y1))}$$

SAT Sampling

- Overlap multiple regions to better approximate filters

```
float3 BetterFilter(float2 center, float fSize)
{
  float3 value = float3(0,0,0);
  value += BoxFilter(center, 0.5*fSize, fSize);
  value += BoxFilter(center, fSize, 0.5*fSize);
  value += BoxFilter(center, 0.75*fSize, 0.75*fSize);
  value /= 3; // to account for overlap
  return value;
}
```



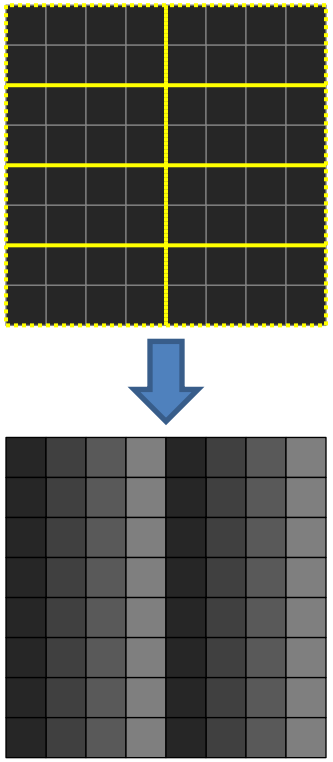
SAT Advantages

- Great technique blurring with varying kernels
  - Constant work per sample, regardless of kernel
  - Applications: DOF, sampling environment maps
- A textbook case for parallel prefix sum!

SAT Computation

Step 1: Sum Subsections

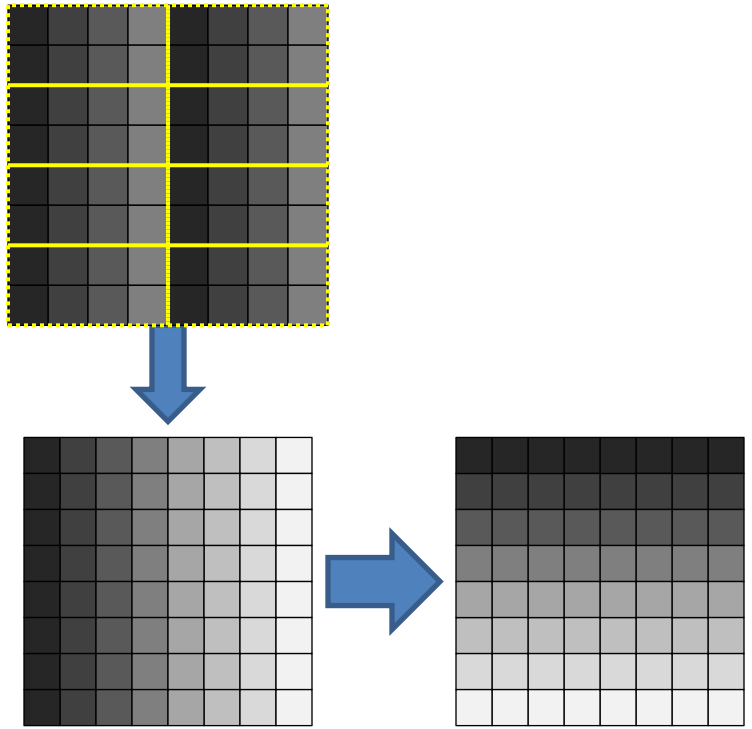
- Dispatch groups that sum segments of each row



SAT Computation

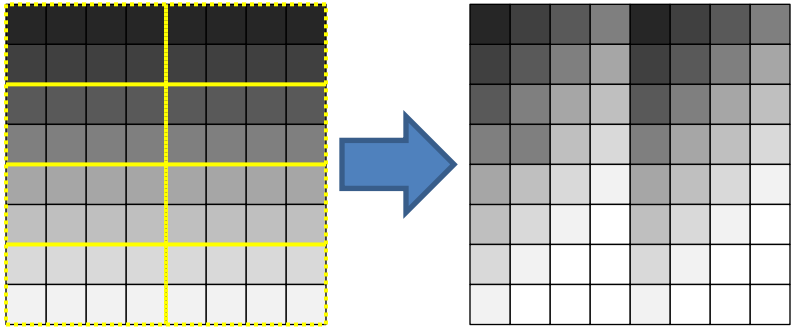
Step 2: Offset Segments

- Sum the last element of every group prior to this in parallel
- Add the total to each px in the row segment
- Output to new buffer, transposing coords

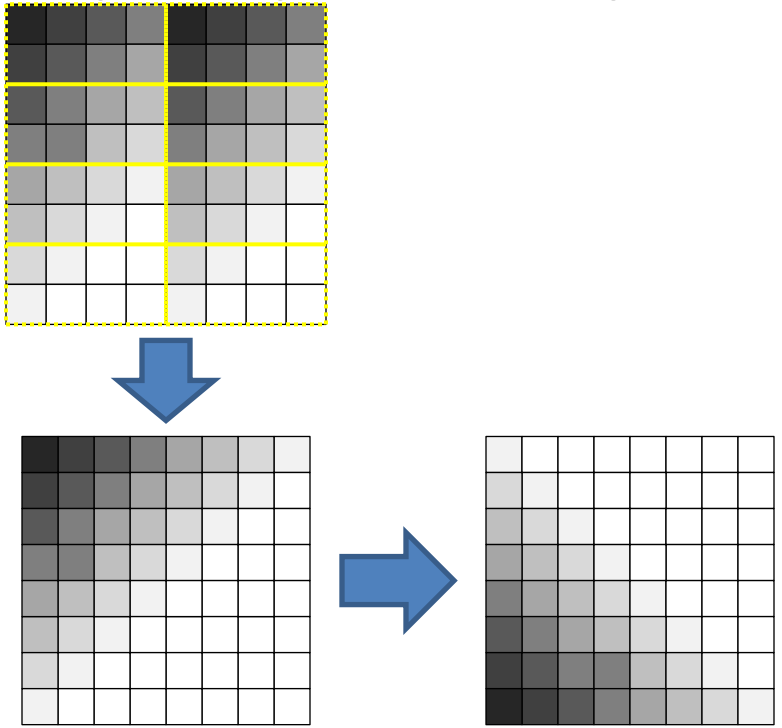


SAT Computation

Step 3: Repeat 1 (for columns)



Step 4: Repeat 2, transpose



Segment Sum Shader

1. Fetch values for the pixels covered by the group to shared memory
2. Perform a parallel prefix sum
3. Output results

```
#define GROUP_SIZE 16
#define WARP_SIZE 32
Texture2D<float3>   texInput  : register(t0);
RWTexture2D<float3> texOutput : register(u0);
groupshared float3 sSums[WARP_SIZE*GROUP_SIZE];

[numthreads( WARP_SIZE, GROUP_SIZE, 1 )]
void SumSegments_CS(uint3 groupID : SV_GroupID, uint3 threadID :
      SV_GroupThreadID, uint3 dispatchID : SV_DispatchThreadID)
{
  uint2 pixelID = uint2(dispatchID.x, dispatchID.y);

  // 1. Fetch Values
  sSums[threadID.x + threadID.y*WARP_SIZE] = texInput[pixelID];
  GroupMemoryBarrierWithGroupSync();

  // 2. Parallel Prefix-Sum
  for (int t=1; t<WARP_SIZE; t=t*2) {
    if (threadID.x >= t) {
      sSums[threadID.x+threadID.y*WARP_SIZE] += sSums[(threadID.x-
      t)+threadID.y*WARP_SIZE];
    }
    GroupMemoryBarrierWithGroupSync();
  }

  // 3. Output Results
  texOutput[pixelID] = sSums[threadID.x + threadID.y*WARP_SIZE];
}
```

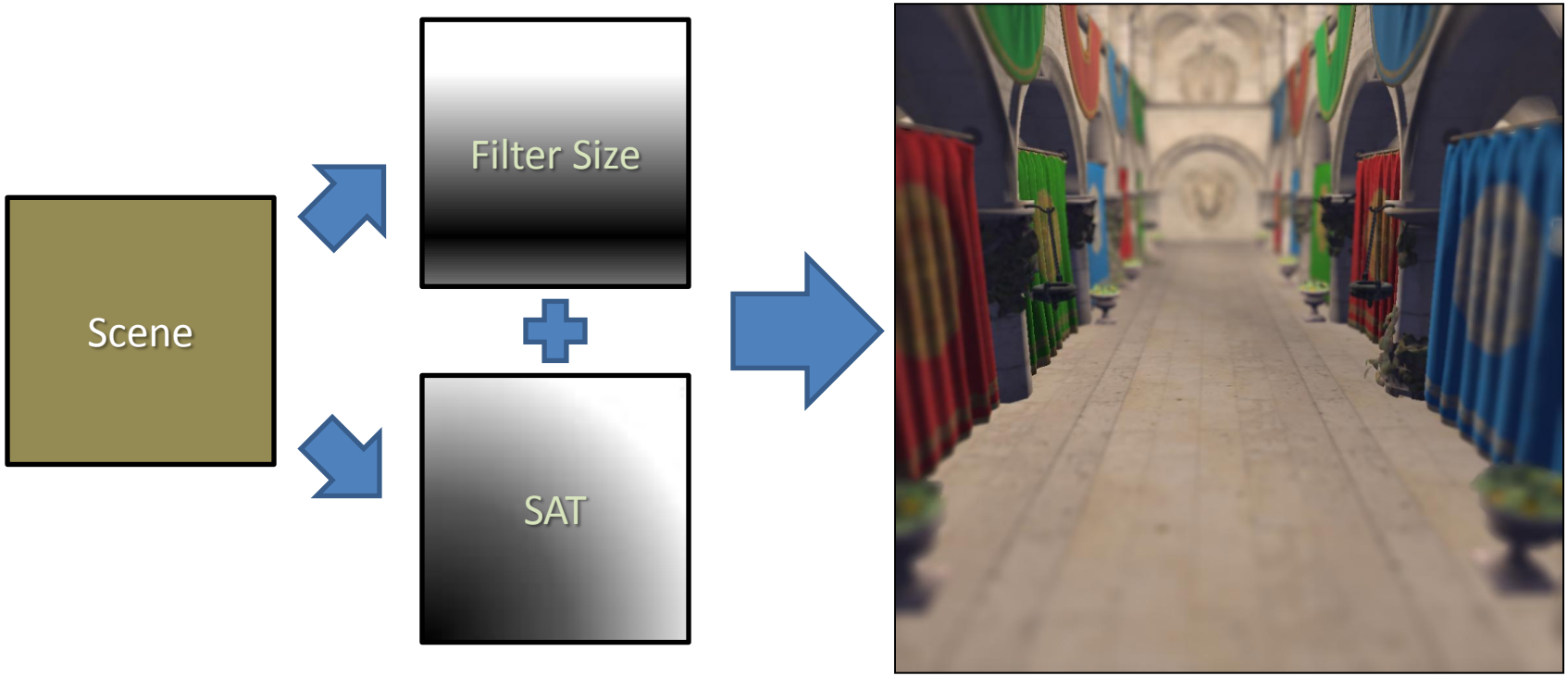
Segment Offset Shader

1. Fetch the totals of all previous segments
2. Perform a parallel sum of the segment totals
3. Add the final total to the value of each pixel in the segment to offset it, and transpose the coordinates for the next pass

In practice, do 1-2 multiple times based on image width (not shown for brevity)

```
#define GROUP_SIZE 16
#define WARP_SIZE 32
Texture2D<float3>   texInput  : register(t0);
RWTexture2D<float3> texOutput : register(u0);
groupshared float3 sOffsets[WARP_SIZE*GROUP_SIZE];
[numthreads( WARP_SIZE, GROUP_SIZE, 1 )]
void OffsetSegments_CS(uint3 groupID : SV_GroupID, uint3 threadID :
     SV_GroupThreadID, uint3 dispatchID : SV_DispatchThreadID)
{
  uint2 pixelID = uint2(dispatchID.x, dispatchID.y);
  // 1. Fetch the totals of previous segments
  if (threadID.x < groupID.x)
    sOffsets[threadID.y*WARP_SIZE + threadID.x] =
          texInput[uint2((threadID.x+1)*WARP_SIZE-1, pixelID.y)];
  else
    sOffsets[threadID.y*WARP_SIZE + threadID.x] = float3(0,0,0);
  GroupMemoryBarrierWithGroupSync();

  // 2. Parallel Sum
  for (int t=WARP_SIZE/2; t>0; t=t/2) {
    if (threadID.x < t)
      sOffsets[threadID.y*WARP_SIZE + threadID.x] +=
            sOffsets[threadID.y*WARP_SIZE + threadID.x+t];
    GroupMemoryBarrierWithGroupSync();
  }

  // 3. Output
  texOutput[uint2(pixelID.y, pixelID.x)] =
          sOffsets[threadID.y*WARP_SIZE] + texInput[pixelID];
}
```

SAT Depth of Field



Case Study: Scattered Bokeh

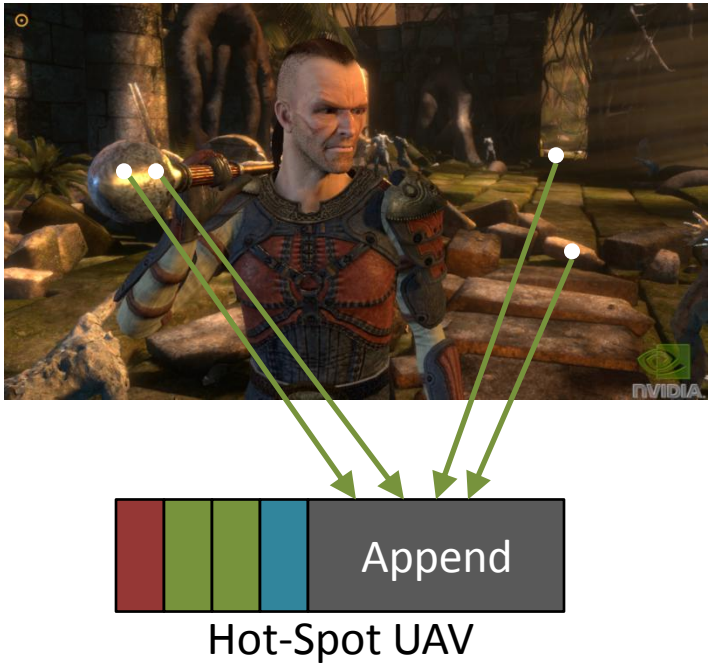
Scattered Bokeh

- “Hot-Spots” make up most of the visual impact
- Sparse samples can be computed more efficiently with a scattered approach

Scattered Bokeh

1: Gather Hot-Spots

- Identify pixels over threshold
- Append positions to UAV

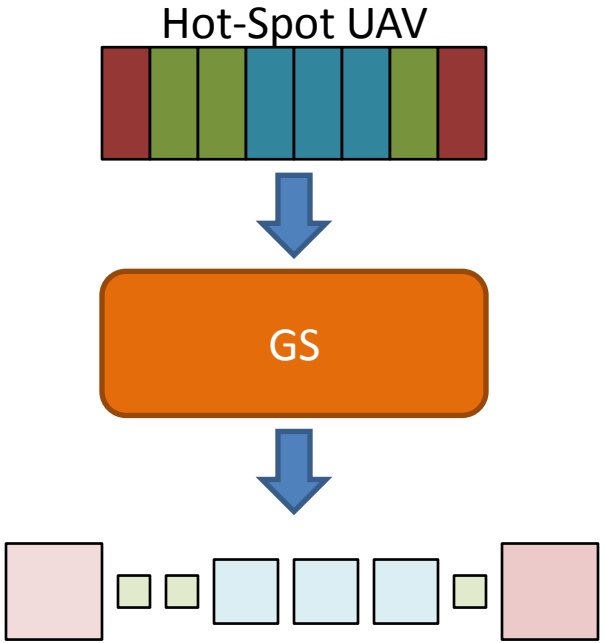


Scattered Bokeh

1: Gather Hot-Spots

2: Expand Samples

- Render buffer as point data
- Use GS to expand based on CoC



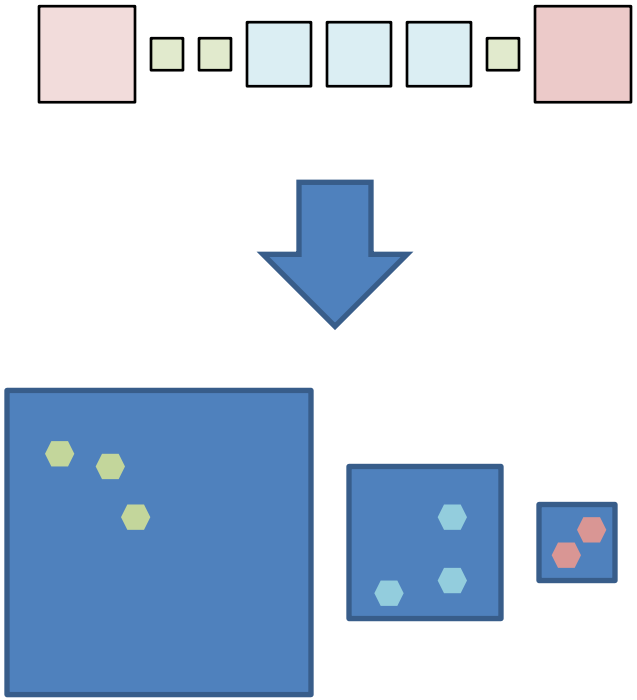
Scattered Bokeh

1: Gather Hot-Spots

2: Expand Samples

3: Accumulate Splats

- Mask quads with Bokeh pattern
- Accumulate masked splats
- Opt: To save fill rate, use a pyramid of textures and assign splats based on size



Scattered Bokeh

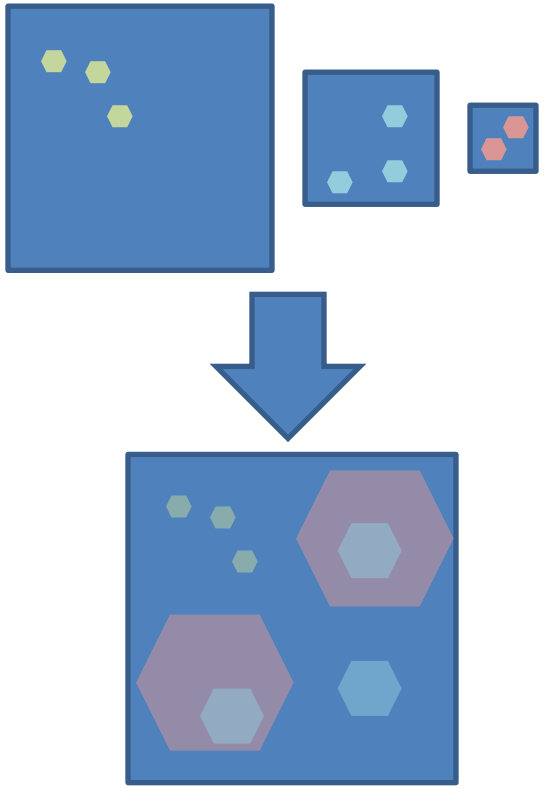
1: Gather Hot-Spots

2: Expand Samples

3: Accumulate Splats

4: Combine Results

- Splat straight to DOF'd image
- OR blend DOF with splat pyramid




Conventional DOF


DOF with Bokeh

QUESTIONS?