MESH SHADEERS IN TURING
AGENDA

- Motivation
- Research
- Mesh Shaders
- API Extensions
- Examples
MOTIVATION

Detail Geometry

• Vegetation, undergrowth, greebles
• Fine geometric detail at massive scale
• Pre-computed topologies for LODs
• Efficient submission of small objects
• Flexible instancing
MOTIVATION

Auxiliary Meshes

- Proxy hull objects
- Iso-surface extraction
- Particles
- Text glyphs
- Lines/Stippling etc.
- Instancing of very basic shapes
MOTIVATION

CAD Models

• High geometric complexity
• Large assemblies can easily reach multiple 100 million triangles
• VR demands high framerates
• Cannot always rely on static solutions (animations, clipping etc.)
GENERAL DIRECTIONS

IMPROVE RAW RENDERING
Instancing, Multi-Draw-Indirect etc. already in use
Look into fixed function performance

IMPROVE GEOMETRIC PROGRAMMING
Geometry Shader (maybe not)
Tessellation Shader (great for certain patterns)
Compute Shader (generate rendered data)
Fixed Function Blocks

**Primitive Distributor (PD):**
Creates vertex batches via serial indexbuffer processing

**Viewport Culling (VPC):**
Discards triangles (backface, frustum, samplegrid)

Let’s use SM to do more work!
Easier to justify adding more of those 😊
HARDWARE

Primitive Distributor

PD performs index de-duplication every frame

High bandwidth requirement

Wasteful for static topologies

Fill batch with up to 32 unique vertices and up to 32 primitives

Indices are local to batch, can use few bits
**MESHLETS**

Pre-generate primitive batches for static topology and replace classic indexbuffer

Each meshlet can have up to a predefined maximum number of vertices and primitives

- **Meshlet Desc Buffer**: Begin & count of unique vertices, Begin & count of primitive indices, Cluster culling information
- **Vertex Index Buffer**: Primitive indices are relative to vertex begin
- **Primitive Index Buffer**: Prim 1
MESHLETS

Allow more primitives than vertices

We can achieve higher vertex-reuse and save bandwidth

Twice as much triangles as vertices is ideal, we perceive average loads around 1.6x

Memory footprint of the three buffers is lower than classic indexbuffer!
(meshlet descriptor as single 128-bit value)
INDEX BUFFER BUILDING
Quadro Research

Use **compute shader** to build per object **culled index buffers** from meshlets.

Similar to work by G. Wihidal [4], S. Aaltonen [5] and W. Engel [6]. They, however, mostly worked from regular indexbuffers.

<table>
<thead>
<tr>
<th>Tech</th>
<th>Time [ms]</th>
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<tbody>
<tr>
<td>Standard</td>
<td>6.7</td>
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<tr>
<td>CS Meshlet cull / draw</td>
<td>2.6 / 0.4</td>
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</table>

Operate on triangle clusters per work group

- 256 vertices / 512 primitives as maximum (256 threads per WG)

23 M triangles

Model courtesy of PTC

Older HW generation
INDEX BUFFER BUILDING

Shader Phases

Compute provides flexible use of threads
Shared memory encodes the mesh’s indices and vertices

// e.g. #Vertices = 256, #Primitives = 512
// WorkGroup = 256 threads

Load meshlet description
Cull entire cluster (optional early out)
Load block of primitive indices per thread
Load & transform 1 vertex per thread
Stored in shared memory

Barrier

Cull 2 triangles per thread &
Output surviving indices (local prefix sum etc.)
INDEX BUFFER BUILDING

Issues

PRO

Works universally, can beat fixed function on high rejection

Can save some bandwidth as unused vertex attributes are not fetched

CON

Compute launch overhead (need large jobs)

Storing of indexbuffer, refetching vertices (slower on low culling rate)

On-chip allocation for work group with fully culled clusters (registers etc.)
MESH SHADERS
MESH SHADERS
New programming model for geometry processing

Evolution from singleton shaders to cooperative groups

- Pixel lighting ➔ Tile-based lighting via compute
- Vertex processing ➔ Meshlet processing

Essential components

- Compute-like execution model - data sharing and sync
- No fixed-function fetch for index processing or vertices
- Flexible work creation/tessellation with one level of expansion
- Standardized interface to screen-space pipeline
EXECUTION

SHADER INVOCATIONS

Input

uint WorkGroupID

Thread group

Output & temporary memory \(\leq 16\) KB

Generic Output or Vertices/Indices

Shared Memory

Fixed compile-time allocation size

Dispatched as 1D grid

Cooperative access to per-workgroup memory

Manual synchronization required (barrier(...)...
<table>
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<th>Thread Mapping</th>
<th>Topology</th>
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<td>Vertex Shader</td>
<td>No access to connectivity</td>
<td>1 Vertex</td>
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<tr>
<td>Geometry Shader</td>
<td>Variable output doesn’t fit HW well</td>
<td>1 Primitive / 1 Output strip</td>
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<tr>
<td>Tessellation Shader</td>
<td>Fixed-function topology</td>
<td>1 Patch / 1 Evaluated vertex</td>
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<td>Mesh Shader</td>
<td>Compute shader features</td>
<td>Flexible</td>
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PIPELINE

TRADITIONAL VTG PIPELINE

Pipelined memory, keeping interstage data on chip

TASK/MESH PIPELINE

Optional Expansion

Pipelined memory ...
PIPELINE

Optional Expansion

LAUNCH
# via API
WorkGroupID

TASK SHADER

WORK GENERATION

MESH SHADER
WorkGroupID

PRIMITIVE ASSEMBLY

PIXEL SHADER

# Children
Generic Output

Raw access for each child task

# Primitives
Vertex Attributes
Primitive Attributes
Primitive Indices (uint8)
True per-primitive output attributes

Builtins like layer, viewport mask etc.

But also custom values and not just flat vertex attributes (e.g. per-triangle normal, faceID, ...)
Task shader allows culling (subpixel, frustum, back-face, occlusion…)

Can also implement LOD picking to minimize mesh workgroups

Not just about triangle models represented as meshlets

Use your own encodings for geometry, all data fetched by shader (compression etc.)

Provides more efficient procedural geometry creation (points, lines, triangles)

Can implement basic compute trees with disabled rasterizer
TREE EXPANSION

- **LAUNCH**: e.g. 3 Tasks
  - **TASK SHADER**: WorkGroupID 0
  - **MESH SHADER**: WorkGroupID 0, Primitive 0, 1, 2, ...

- **Spawn up to 64K children per workgroup**

- **ID is relative to parent**

- **Workgroups are launched ordered within level (execution can be out of order)**

- **Primitive ordering is depth-first**
LIMITATIONS

Currently workgroup size = 1 warp = 32 threads

256 vertices maximum (recommended 64 vertices)

512 primitives maximum (allocation prefers 40, 84, 126, 254 or 510 triangles)

The smaller the outputs, the more warps can be in flight

Try to use small data types (barycentrics help with interpolation after unpack)

Avoid very inbalanced expansion trees
Pipelines with mesh shaders are created via NVAPI using a new mesh shader extension

```c
void NvAPI_D3D12_CreateGraphicsPipelineState(
    ID3D12Device *pDevice,
    const D3D12_GRAPHICS_PIPELINE_STATE_DESC *pPSODesc,
    NvU32 numExtensions,
    const NVAPI_D3D12_PSO_EXTENSION_DESC **ppExtensions,
    ID3D12PipelineState **ppPSO);
```
GLSL: \texttt{GL_NV_mesh_shader}, VK: \texttt{VK_NV_mesh_shader}

Introduces new graphics stages (\texttt{TASK}, \texttt{MESH}) that cannot be combined with VTG stages.

New draw calls operate only with appropriate pipeline (similar calls in GL)

\begin{verbatim}
void vkCmdDrawMeshTasks(VkCommandBuffer buffer, uint32_t count, uint32_t first);
void vkCmdDrawMeshTasksIndirect(...);
void vkCmdDrawMeshTasksIndirectCount(...);
\end{verbatim}
// Same as compute
layout(local_size_x = 32) in;
in uvec3 gl_WorkGroupID;
in uvec3 gl_LocalInvocationID;
...
shared MyStruct mySharedData;

// New for task shader
out uint gl_TaskCountNV;

// New for mesh shader
layout(max_veritces = 64) out;
layout(max_primitives = 126) out;
layout(triangles/lines/points) out;
out uint gl_PrimitivesCountNV;
out uint gl_PrimitiveIndicesNV[];

out gl_MeshPerVertex {
  vec4 gl_Position;
  float gl_PointSize;
  float gl_ClipDistance[];
  float gl_CullDistance[];
} gl_MeshVerticesNV[]; // [max_vertices]

perprimitiveNV out gl_MeshPerPrimitive {
  int gl_PrimitiveID;
  int gl_Layer;
  int gl_ViewportIndex
  int gl_ViewportMask;
} gl_MeshPrimitivesNV[]; // [max_primitives]

taskNV in/out MyCustomTaskData {
  ...
} myCustomData;
layout(local_size_x = 32) in;
layout(max_vertices = 32, max_primitives = 32, triangles) out;

out MyVertex { // Define custom per-vertex as usual (interfaces with fragment shader)
  vec3 normal;
} myOut[];

void main() {
  uint idx = gl_LocalInvocationID.x; uvec4 meshlet = meshInfos[gl_WorkGroupID.x];

  uint vertex = min(idx, meshlet.x - 1);
  myOut[idx].normal = texelFetch(texNormal, meshlet.y + vertex).xyz;
  gl_MeshVerticesNV[idx].gl_Position = texelFetch(texVbo, meshlet.y + vertex);

  uint primitive = min(idx, meshlet.z - 1);
  uint primitiveData = texelFetch(texTopology, meshlet.w + primitive);
  gl_PrimitiveIndicesNV[idx * 3 + 0] = (primitiveData << 0) & 0xFF;
  gl_PrimitiveIndicesNV[idx * 3 + 1] = (primitiveData << 8) & 0xFF;
  gl_PrimitiveIndicesNV[idx * 3 + 2] = (primitiveData << 16) & 0xFF;
  gl_PrimitiveCountNV = info.z; // Same for entire workgroup
}
CAD SAMPLE

Open source sample

Task shader handles cluster culling:

• Outside frustum
• User clipping plane
• Back-face cluster
• Below custom pixel size
HW is still quite fast on triangle culling, focus on cluster culling

Separate positions from other interleaved attributes

Per-triangle culling may be beneficial to skip loading fat vertices (high sub-pixel ratio)

taskNV out Task {
    uint baseID;
    uint8_t subIDs[GROUP_SIZE];
} OUT;

void main() {
    bool render = cull(gl_GlobalInvocationID.x);
    uvec4 renderBits = subgroupBallot(render);
    gl_TaskCountNV = subgroupBallotBitCount(renderBits);

    OUT.baseID = gl_WorkGroupID.x * GROUP_SIZE;
    uint idxOffset = subgroupBallotExclusiveBitCount(renderBits);
    OUT.subIDs[idxOffset] = uint8_t(gl_LocalInvocationID.x);
}
Maximize utilization of vertices and primitives

Use existing vertex cache optimizing algorithms to improve index buffers prior converting to meshlet

Various linear time algorithms exist, e.g. by T. Forsyth [7]
Caveat: may cause worse cluster culling (especially in CAD)

Meshlet compression (indices, vertices etc.)
TINY DRAW CALLS

Some scenes suffer from low-complexity drawcalls (< 512 triangles)

Task shaders can serve as faster alternative to Multi Draw Indirect (MDI)

• MDI or instanced drawing can still be bottlenecked by GPU
• Task shaders provide distributed draw call generation across chip
• Also more flexible than classic instancing (change LOD etc.)
LINE STIPPLING

Task shader computes tessellation factor per curve/arc etc.

Mesh shader generates triangle strips

Use per-curve spin-lock for ordered append to compute running distance across child meshlets (workgroup launch ordering guarantees forward progress)

Custom line styles, caps, widths etc. See GTC talk on shader-driven line rendering [8]

Geometry stipples

Texture space stipples
PROCEDURAL MESHES

Generate geometric shapes procedurally
Can use task shader to e.g. only create visible meshes

```c
void main() {
    const uint GRID = 5;
    uint vertIdx = gl_LocalInvocationID.x;
    vec4 gridPos = vec4(vertIdx % GRID, vertIdx / GRID, 0, 1);
    gl_MeshVerticesNV[vertIdx].gl_Position = mvp * gridPos;

    uint primIdx = gl_LocalInvocationID.x * 6;
    uint primOffset = primIdx / (GRID - 1);
    gl_PrimitiveIndicesNV[primIdx + 0] = primOffset;
    gl_PrimitiveIndicesNV[primIdx + 1] = primOffset + GRID;
    gl_PrimitiveIndicesNV[primIdx + 2] = primOffset + GRID + 1;
    gl_PrimitiveIndicesNV[primIdx + 3] = primOffset;
    gl_PrimitiveIndicesNV[primIdx + 4] = primOffset + GRID + 1;
    gl_PrimitiveIndicesNV[primIdx + 5] = primOffset + 1;

    gl_PrimitiveCountNV = (GRID - 1) * (GRID - 1) * 2;
}
```
Mesh & task shaders are a flexible new tool to create geometry on the chip. Built on top of proven technology of the hardware’s tessellation pipeline. Supplementary to existing pipeline strengths. Better scalability for low-complexity geometry or high-complexity fixed topologies.
THANK YOU

contributor[] = {
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    // programming model
    Yury Uralsky,
    Henry Moreton,
    // hardware design
    Ziyad Hakura,
    // hardware early tests
    Samba Wen,
    // VK/GL/GLSL/SPIR-V driver
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[2] https://www.flickr.com/photos/14136614@N03/6209344182
[3] k-DOPs as Tighter Bounding Volumes for Better Occlusion Performance - Bartz, Klosowski & Staneker
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