Lecture 9: Deferred Shading

Visual Computing Systems
CMU 15-869, Fall 2014
The course so far

The real-time graphics pipeline design and implementation

- Principle graphics abstractions
- Algorithms and modern high-performance implementations of those abstractions
- Rendering workload characteristics

SPMD programming abstractions

- Shading languages: extending the pipeline with application defined shading functions
- General purpose SPMD programming ("compute mode" abstractions)
- The GPU processor core implementation and how these abstractions map to these processors

Today... deferred shading

- An alternative pipeline structure (and one use of the compute-mode interface)
- We are about to cover several alternative rendering algorithms
  - Ray tracing
  - Image-based rendering
Deferred shading

- Popular algorithm for rendering in modern games
- Idea: restructure the rendering pipeline to perform shading after all occlusions have been resolved
- Not a new idea: implemented in several classic graphics systems, but not directly supported by most high-end GPUs
  - But modern graphics pipeline provides mechanisms to allow application to implement deferred shading efficiently
  - Natively implemented by PowerVR mobile GPUs
  - Classic hardware-supported implementations:
    - [Deering et al. 88]
    - UNC PixelFlow [Molnar et al. 92]
The graphics pipeline

"Feed-forward" rendering
Deferred shading pipeline

Two pass approach:

Do not use traditional pipeline to generate RGB image.

Fragment shader outputs surface properties (shader inputs) (e.g., position, normal, material diffuse color, specular color)

Rendering output is a screen-size 2D buffer representing information about the surface geometry visible at each pixel (called a “g-buffer”, for geometry buffer)
G-buffer = “geometry” buffer

Image Credit: J. Klint, “Deferred Rendering in Leadworks Engine”
Example G-buffer layout

Graphics pipeline configured to render to four RGBA output buffers (32-bits per pixel, per buffer)

<table>
<thead>
<tr>
<th>R8</th>
<th>G8</th>
<th>B8</th>
<th>A8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth 24bpp</td>
<td>Stencil</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lighting Accumulation RGB</td>
<td>Intensity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal X (FP16)</td>
<td>Normal Y (FP16)</td>
<td></td>
<td></td>
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<tr>
<td>Motion Vectors XY</td>
<td>Spec-Power</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diffuse Albedo RGB</td>
<td>Spec-Intensity</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Sun-Occlusion</td>
</tr>
</tbody>
</table>

Implementation on modern GPUs:
- Application binds “multiple render targets” (RT0, RT1, RT2, RT3 in figure) to pipeline
- Rendering geometry outputs to depth buffer + multiple color buffers

More intuitive to consider G-buffer as one big buffer with “fat” pixels
In the example above: $32 \times 5 = 160$ bits $= 20$ bytes per pixel

96-160 bits per pixel is common in games

Source: W. Engel, “Light-Prepass Renderer Mark III” SIGGRAPH 2009 Talks
Compressed G-buffer layout

G-buffer layout in Bungie’s Destiny (2014)

<table>
<thead>
<tr>
<th>8</th>
<th>8</th>
<th>8</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albedo Color RGB</td>
<td>Ambient Occlusion</td>
<td>RT0</td>
<td></td>
</tr>
<tr>
<td>Normal XYZ * (Biased Specular Smoothness)</td>
<td>Material ID</td>
<td>RT1</td>
<td></td>
</tr>
<tr>
<td>Depth</td>
<td>Stencil</td>
<td>DS</td>
<td></td>
</tr>
</tbody>
</table>

- Material information compressed using indirection
  - Store material ID in G-buffer
  - Material parameters other than albedo (specular shape/roughness/color) stored in table indexed by material ID
Deferred shading pipeline

Two pass approach:

Do not use traditional pipeline to generate RGB image.

Fragment shader outputs surface properties (shader inputs)
(e.g., position, normal, material diffuse color, specular color)

Rendering output is a screen-size 2D buffer representing information about the surface geometry visible at each pixel (called a “g-buffer”, for geometry buffer)

After all geometry has been rendered, execute shader for each sample in the G-buffer: shader reads geometry information for sample, computes RGB output

(Shading is deferred until all geometry processing -- including all occlusion computations -- is complete)
Two-pass deferred shading algorithm

- **Pass 1: geometry pass**
  - Render scene geometry using traditional pipeline
  - Write visible geometry information to G-buffer

- **Pass 2: shading pass**
  For each G-buffer sample, compute shading
  - Read G-buffer data for current sample
  - Accumulate contribution of all lights
  - Output final surface color for sample

Image Credit: J. Klint, “Deferred Rendering in Leadworks Engine”
Motivation: why deferred shading?

- **Shading is expensive: shade only visible fragments**
  - Deferred shading amounts to perfect early occlusion culling
  - But is triangle order invariant (will only shade visible fragments, regardless of application’s triangle submission order)
  - Also has nice property that the number of shaded fragments is independent of scene complexity (predictable shading performance)

- **Forward rendering shades small triangles inefficiently**
  - Recall shading granularity is quad fragments: multiple fragments generated for pixels along triangle edges
Recall: forward shading shades multiple fragments at pixels containing triangle boundaries.
Recall: forward shading shades multiple fragments at pixels containing triangle boundaries.
Motivation: why deferred shading?

- Shade only visible surface fragments
- Forward rendering shades small triangles inefficiently (quad-fragment granularity)
- Increasing complexity of lighting computations
  - Growing interest in scaling scenes to many light sources
1000 lights

[J. Andersson, SIGGRAPH 2009 Beyond Programmable shading course talk]
Lights

Graphics applications employ many kinds of lights

For efficiency, lights often specify finite volume of influence

Omnidirectional point light (with distance cutoff)

Directional spotlight

Environment light

Shadowed light
Forward rendering: naive many-light shader

```cpp
struct LightDefinition {
  int type;
  ...
}

sampler mySamp;
Texture2D<float3> myTex;
Texture2D<float> myEnvMaps[MAX_NUM_LIGHTS];
Texture2D<float> myShadowMaps[MAX_NUM_LIGHTS];
LightDefinition lightList[MAX_NUM_LIGHTS];
int numLights;

float4 shader(float3 norm, float2 uv)
{
  float3 kd = myTex.Sample(mySamp, uv);
  float4 result = float4(0, 0, 0, 0);
  for (int i=0; i<numLights; i++)
  {
    result += // eval contribution of light to surface reflectance here
  }
  return result;
}
```
Rendering as a triple for-loop

Naive forward rasterization-based renderer:

initialize \( z_{\text{closest}}[] \) to INFINITY // store closest-surface-so-far for all samples
initialize color[] // store scene color for all samples
bind all relevant shadow maps, etc.

for each triangle \( t \) in scene: // loop 1: triangles
  \( t_{\text{proj}} = \text{project_triangle}(t) \)

for each sample \( s \) in frame buffer: // loop 2: visibility samples
  if (\( t_{\text{proj}} \) covers \( s \))
    for each light \( l \) in scene: // loop 3: lights
      accumulate contribution of light \( l \) to surface appearance
      if (depth of \( t \) at \( s \) is closer than \( z_{\text{closest}}[s] \))
        update \( z_{\text{closest}}[s] \) and color\([s]\)

Triangles are outermost loop:

Triangle setup performed once, amortized across many samples

High coherence in shading computations (fragments are from the same triangle: same shader program, similar data access)

Efficient rasterization techniques ( tiled, hierarchical, bounding boxes) serve to reduce \( T \times S \) complexity of finding covered samples.
Rendering as a triple for-loop

Naive forward rasterization-based renderer:

initialize $z_{\text{closest}}[]$ to $\text{INFINITY}$  // store closest surface-so-far for all samples
initialize color[]  // store scene color for all samples
bind all relevant shadow maps, etc.
for each triangle $t$ in scene:  // loop 1: triangles
  $t_{\text{proj}} = \text{project}_\text{triangle}(t)$
  for each sample $s$ in frame buffer:  // loop 2: visibility samples
    if ($t_{\text{proj}}$ covers $s$)
      for each light $l$ in scene:  // loop 3: lights
        accumulate contribution of light $l$ to surface appearance
        if (depth of $t$ at $s$ is closer than $z_{\text{closest}}[s]$)
          update $z_{\text{closest}}[s]$ and color[$s$]

$F \times L$ loop: # fragments $\times$ # lights

In practice: not all lights illuminate all surfaces (contribution of light

Would like to be more efficient in computing these interactions (just light we
were efficient computing triangle/visibility sample interactions.)
Naive many-light shader with culling

```cpp
struct LightDefinition {
  int type;
  ...
};

sampler mySamp;
Texture2D<float3> myTex;
Texture2D<float> myEnvMaps[MAX_NUM_LIGHTS];
Texture2D<float> myShadowMaps[MAX_NUM_LIGHTS];
LightDefinition lightList[MAX_NUM_LIGHTS];
int numLights;

float4 shader(float3 norm, float2 uv) {
  float3 kd = myTex.Sample(mySamp, uv);
  float4 result = float4(0, 0, 0, 0);
  for (int i=0; i<numLights; i++) {
    if (this fragment is illuminated by current light) {
      if (lightList[i].type == SPOTLIGHT)
        result += // eval contribution of light here
      else if (lightList[i].type == POINTLIGHT)
        result += // eval contribution of light here
      else if ...
    }
  }
  return result;
}
```

Large footprint:
Assets for all lights (shadow maps, environment maps, etc.) must be allocated and bound to pipeline

Execution divergence:
1. Different outcomes for “is illuminated” predicate
2. Different logic to perform test (based on light type)
3. Different logic in loop body (based on light type, shadowed/unshadowed, etc.)

Work inefficient:
Predicate evaluated for each fragment/light pair:
\(O(F \times L)\) work
  \(F\) = number of fragments
  \(L\) = number of lights
  (spatial coherence in predicate should exist)
Forward rendering: techniques for scaling to many lights

- **Goal:** avoid performing $F \times L$ “is-illuminated” checks
- **Solution:** application maintains per-object light lists
  - Each object stores list of lights that illuminate it
  - CPU computes this list each frame by intersecting light volumes with scene geometry (light-geometry interactions computed per light-object pair, not light-fragment pair)
Light lists

Example: compute lists based on conservative bounding volumes for lights and scene objects

Resulting per-object lists:
- Obj 1: L1
- Obj 2: L2
- Obj 3: L2
- Obj 4: L2, L4
- Obj 5: L3, L4
Forward rendering: techniques for scaling to many lights

- Application maintains light lists
  - Computed conservatively per frame

- Option 1: draw scene in many small batches
  - First generate data structures for all lights: e.g., shadow maps
  - Before drawing each object, only bind data for relevant lights
  - Precompile shader variants for different sets of bound lights (4-light version, 8-light version...)
    - Low execution divergence during fragment shading
    - Many graphics state changes, small draw batch sizes (draw call = single object, or group of objects with the same number of lights)
Recall: rendering as a triple for-loop

Naive forward rasterization-based renderer:

initialize $z_{\text{closest}}[]$ to INFINITY  // store closest surface-so-far for all samples
initialize color[]  // store scene color for all samples
bind all relevant shadow maps, etc.

for each triangle $t$ in scene:  // loop 1: triangles
  $t_{\text{proj}} = \text{project_triangle}(t)$
  for each sample $s$ in frame buffer:  // loop 2: visibility samples
    if ($t_{\text{proj}}$ covers $s$)
      for each light $l$ in scene:  // loop 3: lights
        accumulate contribution of light $l$ to surface appearance
        if (depth of $t$ at $s$ is closer than $z_{\text{closest}}[s]$)
          update $z_{\text{closest}}[s]$ and color[$s$]
Reordering triangles for light coherence

Shader code is specialized to a specific number of lights:

initialize $z_{\text{closest}}[]$ to INFINITY // store closest surface-so-far for all samples
initialize color[] // store scene color for all samples
bind all relevant shadow maps, etc.

for each group of triangles with the same number of lights: // loop 0: groups of triangles
  bind specific shader for number of lights
  for each triangle $t$ in group: // loop 1: triangles
    $t_{\text{proj}} = \text{project\_triangle}(t)$
    for each sample $s$ in frame buffer: // loop 2: visibility samples
      if ($t_{\text{proj}}$ covers $s$)
        for lights 1 through 4: // loop 3: lights (specialized for 4 lights)
          accumulate contribution of light $l$ to surface appearance
          if (depth of $t$ at $s$ is closer than $z_{\text{closest}}[s]$)
            update $z_{\text{closest}}[s]$ and color[$s$]
Multi-pass rendering for light coherence

initialize $z_{\text{closest}}[]$ to INFINITY  // store closest surface-so-far for all samples
initialize color[]  // store scene color for all samples
assume $z$ buffer is initialized using a $z$ prepass.

for each light $l$ in scene:  // loop 1: lights
  bind single light shader specific to current light type
  bind relevant shadow map, etc.
  for each triangle $t$ lit by light:
    $t_{\text{proj}} = \text{project\_triangle}(t)$
    for each sample $s$ in frame buffer:  // loop 2: triangles
      if ($t_{\text{proj}}$ covers $s$)
        accumulate contribution of light $l$ to surface appearance  // specialized to 1 light
        if (depth of $t$ == $z_{\text{closest}}[s]$)
          update color[$s$]

Reorder loops: draw scene once per light

Each pass, only draw triangles illuminated by current light (per-light object lists)
Shader accumulates illumination of visible fragments from current light into frame buffer
Forward rendering: techniques for scaling to many lights

- **Application maintains light lists**
  - Computed conservatively per frame

- **Option 1: draw scene in many small batches**
  - First generate data structures for all lights: e.g., shadow maps
  - Compute per-object light lists, before drawing each object, only bind data for relevant lights
  - Precompile **specialized shaders** for different sets of bound lights (4-light version, etc...)
  - For each object:
    - Render object with specialized shader for relevant lights
  - **Good:** low execution divergence during fragment shading
  - **Bad:** many graphics state changes (draw call = single object, or group of objects with the same number of lights)

- **Option 2: multi-pass rendering**
  - Compute per-light lists (for each light, compute illuminated objects)
  - For each light:
    - Compute necessary data structures (e.g., shadow maps)
    - Render scene with additive blending (only render geometry illuminated by light)
  - **Good:** Minimal footprint for light data
  - **Good:** Low execution divergence during fragment shading
  - **Bad:** Significant overheads: redundant geometry processing, many G-buffer accesses, redundant execution of common shading sub-expressions in fragment shader

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Stream over scene geometry

Stream over lights
Basic many light deferred shading algorithm

initialize z_closest[] to INFINITY  // store closest-surface-so-far for all samples
initialize gbuffer[]  // store surface information for all samples

for each triangle t in scene:  // loop 1: triangles
  t_proj = project_triangle(t)
  for each sample s in frame buffer:  // loop 2: visibility samples
    if (t_proj covers s)
      emit geometry information
      if (depth of t at s is closer than z_closest[s])
        update z_closest[s] and gbuffer[s]

initialize color[]  // store color for all samples
for each light in scene:  // loop 1: lights
  bind single light shader specific to current light type
  bind relevant shadow map, etc.
  for each sample s in frame buffer:  // loop 2: visibility samples
    load gbuffer[s]
    accumulate contribution of current light to surface appearance into color[s]

- **Good**
  - Only process scene geometry once (only in phase 1)
  - Outer loop of phase 2 is over lights:
    - Avoids light data footprint issues (stream over lights)
    - Continues to avoid divergent execution in fragment shader
  - Recall other deferred benefits: only shade visibility samples (and no more)

- **Bad?**
Basic many light deferred shading algorithm

initialize \( z_{\text{closest}}[] \) to INFINITY  // store closest-surface-so-far for all samples
initialize gbuffer[]  // store surface information for all samples

for each triangle \( t \) in scene:  // loop 1: triangles
  \( t_{\text{proj}} = \text{project}\_triangle}(t) \)
  for each sample \( s \) in frame buffer:  // loop 2: visibility samples
    if \( (t_{\text{proj}} \text{ covers } s) \)
      emit geometry information
      if (depth of \( t \) at \( s \) is closer than \( z_{\text{closest}}[s] \))
        update \( z_{\text{closest}}[s] \) and gbuffer[s]

initialize color[]  // store color for all samples

for each light in scene:  // loop 1: lights
  bind single light shader specific to current light type
  bind relevant shadow map, etc.
  for each sample \( s \) in frame buffer:  // loop 2: visibility samples
    load gbuffer[s]
    accumulate contribution of current light to surface appearance into color[s]

- **Bad:**
  - High G-buffer footprint: G-buffer has large footprint (especially when G-buffer is supersampled!)
  - **High bandwidth costs** (read G-buffer each pass, output to frame buffer)
  - Exactly one shading computation per frame-buffer sample
    - Does not support transparency (need multiple fragments per pixel)
    - Challenging to implement MSAA efficiently (more on this to come)
Reducing deferred shading bandwidth costs

- **Process multiple lights in each phase 2 accumulation pass**
  - Amortizes G-buffer load and frame buffer write across lighting computations for multiple lights

- **Only perform shading computations for G-buffer samples illuminated by light**
  - Technique 1: rasterize geometry of light volume (only generate fragments for covered G-buffer samples)
    - Light-fragment interaction predicate is evaluated by rasterizer, not in shader
  - Technique 2: CPU computes screen-aligned quad covered by light volume, renders quad
  - Many other techniques for culling light/G-buffer sample interactions

**Light volume geometry**
If volume is convex, rendering only the front-facing triangles of the light volume will generate fragments in the yellow shaded region (these are the only g-buffer samples that can be effected by the light)
Visualization of light-sample interaction count
Per-light culling is performed using a screen-aligned quad per light
(depth of quad is nearest point in light volume: early Z will cull fragments behind scene geometry)

Number of lights evaluated per G-buffer sample
(scene contains 1024 point lights)

Image Credit: A. Lauritzen
Tile-based deferred shading

- Main idea: exploit coherence in light-sample interactions
  - Compute set of lights that influence a small tile of G-buffer samples, then compute contribution of lights to samples in the tile

- Efficient implementation enabled by compute shader
  - Amortize G-buffer load, frame-buffer write across all lights
  - Amortize light data load across tile samples
  - Amortize light-sample culling across samples in a tile
Tile-based deferred shading

Step 1: Perform G-buffer generation pass to create G-buffer and Z-buffer
Step 2: Shade G-buffer using compute shader.
Each compute shader thread group is responsible for shading a 16x16 sample tile of the G-buffer (256 threads per group)

LightDescription tileLightList[MAX_LIGHTS]; // stored in group shared memory

All threads cooperatively compute Z-min, Zmax for current tile
barrier;

for each light: // parallel across threads in thread group (parallel over lights)
  if (light volume intersects tile frustum)
    append light to tileLightList // stored in shared memory
barrier;

for each sample: // parallel across threads in group (parallel over samples)
  result = float4(0,0,0,0)
  load G-buffer data for sample
  for each light in tileLightList: // no divergence across samples
    result += evaluate contribution of light

store result to appropriate position in frame buffer
Tiled-based light culling

Yellow boxes: screen-aligned light volume bounding boxes
Blue boxes: screen tile boundaries

Image credit: HMREngine: http://www.hmrengine.com/blog/?p=399
Tile-based deferred shading: good light culling efficiency

(16x16 granularity of light culling is apparent in figure)

Number of lights evaluated per G-buffer sample

(scene contains 1024 point lights)

Image Credit: A. Lauritzen
Culling inefficiency near silhouettes

Light intersects tile frustum, but neither surface

Tile screen boundaries + tile (zmin, zmax) define a frustum
Depth bounds are not tight when tile contains an object silhouette
Tiled vs. conventional deferred shading

Deferred shading rendering performance: 1920x1080 resolution

[Diagram showing performance comparison between deferred shading and tiled methods for different numbers of point lights.]

[Lauritzen 2009]
“Forward plus” rendering

- Tile-based (hierarchical) light culling is not unique to deferred shading
- “Forward+” rendering involves three phases

Phase 1: Render Z-prepass to populate depth buffer (process all geometry)
Phase 2: In compute shader: compute zmin/zmax for all tiles, compute light lists for screen tiles
Phase 3: Render scene with shading enabled (process all geometry again)
  - Fragment shader determines which tile it resides in
  - Shader uses tile’s precomputed light list when computing surface illumination

- Achieves light culling benefits of tiled-deferred approach in a forward renderer (it’s just another reordering of the loops!)
  - Primary difference is how shading is scheduled:
    - Forward+ recomputes shading inputs using a second geometry pass (“rematerialization” of shading inputs via extra computation) but stores light lists in memory between phase 2 and phase 3.
    - Tiled-deferred stores shading inputs in the G-buffer. It never stores light lists in off-chip memory (only compute shader shared memory) because the light list is consumed immediately after its construction in the shader.
Challenge: anti-aliasing geometry in a deferred renderer
Main idea: decouple shading sampling rate from visibility sampling rate

- Depth buffer: stores depth per sample
- Color buffer: stores color per sample
- Resample color buffer to get final image pixel values
MSAA in a deferred shading system

- Deferred shading performs exactly one shading computation per G-buffer sample *

- MSAA: shades once per triangle contributing coverage to samples in a pixel
  - So the effective shading rate is adaptive
  - For pixels in interior of projected triangle: this is one shading computation per pixel
  - For pixels on boundary of triangles, extra shading occurs
    - This is desirable: extra shading necessary to anti-alias object silhouettes
    - Undesirable consequence of MSAA is extra shading when two adjacent triangles from the same surface surface meet.

* This is also why transparency is challenging in a deferred shading system
Two anti-aliasing solutions for deferred shading

Super-sample G-buffer
- Generate super-sampled G-buffer (e.g., 4 samples per pixel)
- Shade all G-buffer samples
- Resample shaded results to get final frame-buffer pixels
- Problems:
  - Increased G-buffer footprint and G-buffer read/write bandwidth (remember: “fat samples” are stored per G-buffer sample)
  - $1900 \times 1200 \times 4 \text{spp} \times 20 \text{bytes per sample} = 173 \text{ MB frame-buffer}$
  - Increases shading cost because system shades at visibility rate, not once per pixel!

Intelligently filter aliased shading results
- Does not increase G-buffer footprint or shading cost
- Current popular technique: morphological anti-aliasing (MLAA)
Morphological anti-aliasing (MLAA) [Reshetov 09]

Detect carefully designed patterns in rendered image
For detected patterns, blend neighboring pixels according to a few simple rules (“hallucinate” a smooth edge)

Z-shapes:
U-shapes:
L-shapes:

Z and U shape decomposition into L-shapes:
Morphological anti-aliasing (MLAA)

Aliased image (one shading sample per pixel)

Zoomed views (top: aliased, bottom: after MLAA)

After filtering using MLAA

[Reshetov 09]
Anti-aliasing solutions for deferred shading

- **Super-sample G-buffer, super-sample shading**
  - Increases G-buffer footprint and shading cost

- **Intelligently filter aliased shading results (MLAA popular choice)**
  - Does not increase G-buffer footprint or shading costs, but may produce artifacts (hallucinates edges/detail)

- **Application implements MSAA on its own (without HW support)**
  - Render super-sampled G-buffer
  - Launch one shader instance for each output image sample, not each G-buffer sample
  - New shader implementation:
    - Detect if pixel contains an edge // how might this be done without geometry information?
    - If pixel contains an edge:
      - Shade all G-buffer samples for pixel (sequentially in shader)
      - Resample results into single per pixel color output (e.g., using box filter)
    - else:
      - Shade only one G-buffer sample for this pixel, store result
  - Increases G-buffer footprint, but approximately same shading cost as MSAA
  - Some additional BW cost (to detect edges) + potential execution divergence in shader
Handling divergence when implementing MSAA in a shader

Red pixels = These pixels contain edges (require additional shading)

Adaptive shading rate increases divergence in shader execution
(recall eliminating shading divergence was one of the motivations of deferred shading)

Can apply standard gamut of data-parallel programming solutions:

e.g., multi-pass solution:
  - Phase 1: categorize pixels, set stencil buffer
  - Phase 2: shade pixels requiring one shading computation
  - Phase 3: flip stencil value, shade pixels requiring N shading computations

This solution is a common bandwidth vs. execution coherence trade-off!
(recall earlier in lecture: same principle applied when sorting geometry draw calls by active lights)
Deferred shading in mobile GPUs

- **Energy-efficient rendering**
  - Philosophy: aggressive cull unnecessary fragment work to conserve energy

- **Implementation of OpenGL ES graphics pipeline by imagination PowerVR GPUs** is sort-middle tiled (just like assignment 1) with deferred shading
  - Note: deferred shading is implemented as an optimization by the OpenGL system, not on top of the graphics pipeline by the application as discussed so far in this lecture

Phase 2 implementation of tiled renderer: (bin processing)

For each bin:
  - For each triangle in bin’s triangle list:
    - Rasterize triangle (store only triangle id per G-buffer sample)

  // Determine quad fragments that contribute to frame buffer
  For each sample in tile:
    - Given triangle id, compute fragment that corresponds to sample
    - Add fragment to list of fragments to shade (if not in list already)

  // Shade only fragments that contribute coverage
  For each fragment that must be shared:
    - Shade fragment and contribute results into frame buffer

G-buffer stored what triangle covers each sample, not the full set of surface properties (these can be computed as needed based on the triangle ID)
Deferred shading summary

- Main idea: perform shading calculations after all geometry processing operations (rasterization, occlusions) are complete

- Modern motivations
  - Scaling scenes to complex lighting conditions (many lights, diverse lights)
  - High geometric complexity (due to tessellation) increases overhead of Z-prepass, so it’s useful to store and reload results of geometry processing (rather than repeat it)
  - Yet another motivation: tiny triangles increase overhead of quad-fragment-based forward shading

- Computes (more-or-less) the same result as forward rendering; reorder key rendering loops to change schedule of computation
  - Key loops: for all lights, for all samples, for all drawing primitives
  - Different footprint characteristics
    - Trade footprint of scene light data structures for G-buffer footprint
  - Different bandwidth characteristics
  - Different execution coherence characteristics
    - Traditionally deferred shading has traded bandwidth for increased batch sizes and coherence
    - Tile-based methods improve bandwidth requirements considerably
    - MSAA changes bandwidth, execution coherence equation yet again

- Keep in mind: not a technique used for transparent surfaces
Final comments

- **Which is better, forward or deferred shading?**
  - Depends on context
  - Is geometric complexity high? (prepass might be costly)
  - Are triangles small? (forward shading has overhead)
  - Is multi-sample anti-aliasing desired? (G-buffer footprint might be too large)
  - Is there significant divergence impacting lighting computations?

- **Common tradeoff: bandwidth vs. execution coherence**
  - Another example of relying on high bandwidth to achieve high ALU utilization
  - In graphics: typically manifest as multi-pass algorithms

- **One lesson from today: when considering new techniques or a new system design, be cognizant of interoperability with existing features and optimizations**
  - Deferred shading is not compatible with hardware-accelerated MSAA implementations (application must role its own version of MSAA... and still takes a large G-buffer footprint hit)
  - Deferred shading does not support transparent surfaces
Reading

- *A Sort-Based Deferred Shading Architecture for Decoupled Sampling.* P. Clarberg et al.
  SIGGRAPH 2013