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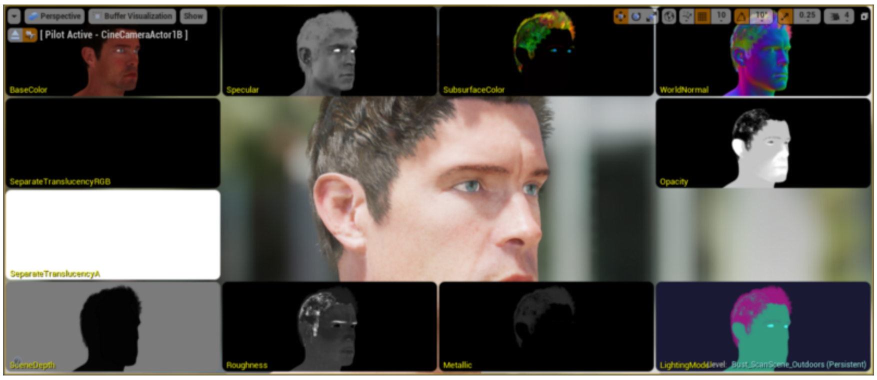
Unreal Engine 4 Rendering Part 4: The Deferred Shading Pipeline

(If you haven't read Part 3 in this series, it is available here)

The Deferred Shading Base Pass

In part 3 we finished examining the C++ side of things and are finally ready to look at how everything works on the GPU. We'll take a deeper look at how a Vertex Factory controls the input to the common base pass vertex shader code, and how tessellation is handled (with its additional Hull and Domain stages), as well as touching on how a Material Graph ends up inside of your HLSL code.

After we understand how the parts are put together we're going to step through the deferred pass and look at some of the various steps it goes through. This will let us know at what part a surface shader is run, and what modifying things in the material graph actually end up doing.



A Second Look at Vertex Factories

Back in Part 2 we briefly discussed how the Vertex Factory can change the data that is fed into the Vertex shader. Unreal makes the ultimately smart decision to trade learning complexity for a reduced amount of code duplication. We'll be using *LocalVertexFactory.ush* and

BasePassVertexCommon.ush in our example and referring to *GpuSkinVertexFactory.ush* as the thing to compare against, as they both use the same vertex shader.

Changing Input Data

Different types of meshes will ultimately need different data to accomplish what they do, ie: GPU skinned verts need more data than simple static meshes. Unreal handles these differences on the CPU side with `FVertexFactory` , but on the GPU side it's a little trickier.

Because all Vertex Factories share the same vertex shader (for the base pass at least) they use a generically named input structure `FVertexFactoryInput` .

Because Unreal is using the same vertex shader, but are including different code for each vertex factory, Unreal redefines the `FVertexFactoryInput` structure in each vertex factory. This struct is uniquely defined in *GpuSkinVertexFactory.ush*, *LandscapeVertexFactory.ush*, *LocalVertexFactory.ush* and several others. Obviously including all of these files isn't going to work—instead *BasePassVertexCommon.ush* includes */Engine/Generated/VertexFactory.ush*. This is set to the correct Vertex Factory when the shader is compiled which allows the engine to know which implementation of `FVertexFactoryInput` to use. We talked briefly about using a macro to declare a vertex factory in part 2 and you had to provide a shader file—this is why.

So now the data input for our base pass vertex shader matches the type of vertex data we're uploading. The next issue is that different vertex factories will need different data interpolated between the VS and PS. Again, the *BasePassVertexShader.usf* calls generic functions— `GetVertexFactoryIntermediates` , `VertexFactoryGetWorldPosition` , `GetMaterialVertexParameters` . If we do another Find in Files we'll discover that each **VertexFactory.ush* has defined these functions to be unique to their own needs.

```
Search "GetVertexFactoryIntermediates(FVertexFactoryInput Input)" (9 hits in 9 files)
  H:\UE4_Github\Engine\Shaders\Private\GpuSkinVertexFactory.ush (1 hit)
    Line 496: FVertexFactoryIntermediates GetVertexFactoryIntermediates(FVertexFactoryInput Input)
  H:\UE4_Github\Engine\Shaders\Private\LandscapeVertexFactory.ush (1 hit)
    Line 561: FVertexFactoryIntermediates GetVertexFactoryIntermediates(FVertexFactoryInput Input)
  H:\UE4_Github\Engine\Shaders\Private\LocalVertexFactory.ush (1 hit)
    Line 614: FVertexFactoryIntermediates GetVertexFactoryIntermediates(FVertexFactoryInput Input)
  H:\UE4_Github\Engine\Shaders\Private\MeshParticleVertexFactory.ush (1 hit)
    Line 369: FVertexFactoryIntermediates GetVertexFactoryIntermediates(FVertexFactoryInput Input)
  H:\UE4_Github\Engine\Shaders\Private\NiagaraMeshVertexFactory.ush (1 hit)
    Line 395: FVertexFactoryIntermediates GetVertexFactoryIntermediates(FVertexFactoryInput Input)
  H:\UE4_Github\Engine\Shaders\Private\NiagaraRibbonVertexFactory.ush (1 hit)
    Line 283: FVertexFactoryIntermediates GetVertexFactoryIntermediates(FVertexFactoryInput Input)
  H:\UE4_Github\Engine\Shaders\Private\NiagaraSpriteVertexFactory.ush (1 hit)
    Line 620: FVertexFactoryIntermediates GetVertexFactoryIntermediates(FVertexFactoryInput Input)
  H:\UE4_Github\Engine\Shaders\Private\ParticleBeamTrailVertexFactory.ush (1 hit)
    Line 179: FVertexFactoryIntermediates GetVertexFactoryIntermediates(FVertexFactoryInput Input)
  H:\UE4_Github\Engine\Shaders\Private\ParticleSpriteVertexFactory.ush (1 hit)
    Line 479: FVertexFactoryIntermediates GetVertexFactoryIntermediates(FVertexFactoryInput Input)
```

Each Vertex Factory re-implements this function

Changing Output Data

Now we need to look at how we get data from the Vertex Shader to the Pixel Shader. Unsurprisingly, the output from *BasePassVertexShader.usf* is another generically named struct (`FBasePassVSOutput`) who's implementation depends on the vertex factory. There's a little snag here though—If you have Tessellation enabled there's two stages between the Vertex shader and Pixel shader (the Hull and Domain stages), and these stages need different data than if it was just the VS to PS.

Enter Unreal's next trick. They use `#define` to change the meaning of `FBasePassVSOutput` and it can either be defined as the simple `FBasePassVSToPS` struct, or for tessellation, `FBasePassVSToDS` (this code can be found in *BasePassVertexCommon.ush*). The two structures have nearly the same contents, except the Domain Shader version adds a few extra variables. Now, what about those unique per-vertex factory interpolations we needed? Unreal solves this by creating `FVertexFactoryInterpolantsVSToPS` and `FBasePassInterpolantsVSToPS` as members of the `FBasePassVSOutput` . Surprise! `FVertexFactoryInterpolantsVSToPS` is defined in each of the **VertexFactory.ush* files, meaning that we're still passing the correct data between stages, even if we stop to add a Hull/Domain stage in the middle. `FBasePassInterpolantsVSToPS` isn't redefined as the stuff stored in this struct doesn't depend on anything unique to a specific vertex factory, holding things like VertexFog values, AmbientLightingVector, etc.

Unreal's redefinition technique abstracts away most of the differences in the base pass vertex shader, allowing common code to be used regardless of tessellation or specific vertex factory.

Base Pass Vertex Shader

Now that we know how Unreal handles differences in shader stages and tessellation support, we're going to look at what each shader in the Deferred Shading pipeline actually do.

The *BasePassVertexShader.usf* ends up being pretty simple overall. For the most part the Vertex Shader is simply calculating and assigning the BasePassInterpolants and the VertexFactoryInterpolants, though how these values are calculated gets a bit more complicated—there's lots of special cases where they've chosen to only declare certain interpolators under certain preprocessor defines and then only assign those under matching defines.

For example, near the bottom of the Vertex Shader we can see a define `#if WRITES_VELOCITY_TO_GBUFFER` which calculates the velocity on a per-vertex basis by calculating the difference between its position last frame and this frame. Once calculated it stores it in the BasePassInterpolants variable, but if you look over there they've wrapped the declaration of that variable in a matching `#if WRITES_VELOCITY_TO_GBUFFER`.

This means that only shader variants that write velocity to the GBuffer will calculate it—This helps cut down on the amount of data passed between stages, which means less bandwidth which in turn results in faster shaders.

```
#if PRECOMPUTED_IRRADIANCE_VOLUME_LIGHTING && TRANSLUCENCY_ANY_PERVERTEX_LIGHTING
    float3 BrickTextureUVs = ComputeVolumetricLightmapBrickTextureUVs(WorldPositionForVertexLighting);

    #if TRANSLUCENCY_LIGHTING_VOLUMETRIC_PERVERTEX_NONDIRECTIONAL
        FOneBandSHVectorRGB IrradianceSH = GetVolumetricLightmapSH1(BrickTextureUVs);
        Output.BasePassInterpolants.VertexIndirectAmbient = float3(IrradianceSH.R.V, IrradianceSH.G.V, IrradianceSH.B.V);
    #elif TRANSLUCENCY_LIGHTING_VOLUMETRIC_PERVERTEX_DIRECTIONAL
        // Need to interpolate directional lighting so we can incorporate a normal in the pixel shader
        FTwoBandSHVectorRGB IrradianceSH = GetVolumetricLightmapSH2(BrickTextureUVs);
        Output.BasePassInterpolants.VertexIndirectSH[0] = IrradianceSH.R.V;
        Output.BasePassInterpolants.VertexIndirectSH[1] = IrradianceSH.G.V;
        Output.BasePassInterpolants.VertexIndirectSH[2] = IrradianceSH.B.V;
    #endif
#endif
```

Boilerplate Code that you don't have to touch!

Base Pass Pixel Shader

This is where things start to get quite a bit complicated, and is probably where everyone gets scared off normally. Take a deep breath, assume most things inside of preprocessor checks don't exist and we'll get through this together!

Material Graph to HLSL

When we create a material graph inside of Unreal, Unreal translates your node network into HLSL code. This code is inserted into the HLSL shaders by the compiler. If we look at *MaterialTemplate.ush* it contains a number of structures (like `FPixelMaterialInputs`) that have no body—instead they just have a `%s` . Unreal uses this as a string format and replaces it with the code specific to your material graph.

This text replacement isn't limited to just structures, *MaterialTemplate.ush* also includes several functions which have no implementation. For example, `half GetMaterialCustomData0` , `half3 GetMaterialBaseColor` , `half3 GetMaterialNormal` are all different functions that have their content filled out based on your material graph. This allows you to call these functions from the pixel shader and know that it will execute the calculations you have created in your Material graph and will return you the resulting value for that pixel.

```
half GetMaterialCustomData1(FMaterialPixelParameters Parameters)
{
%s;
}

half3 GetShadowColor(FPixelMaterialInputs Parameters)
{
    return Parameters.ShadowColor;
}
```

Some functions have their contents filled in by C++, others have actual definitions

The "Primitive" Variable

Throughout the code you will find references to a variable named "Primitive"—searching for it in the shader files yields no declaration though! This is because it's actually declared on the C++ side through some macro magic. This macro declares a struct that is set by the renderer before each primitive is drawn on the GPU.

The full list of variables that it supports can be found in *PrimitiveUniformShaderParameters.h* from the macro at the top. By default it includes things like `LocalToWorld` , `WorldToLocal` , `ObjectWorldPositionAndRadius` , `LightingChannelMask` , etc.

Creating the GBuffer

Deferred shading uses the concept of a "GBuffer" (Geometry Buffer) which is a series of render targets that store different bits of information about the geometry such as the world normal, base color, roughness, etc. Unreal samples these buffers when lighting is calculated to determine the final shading. Before it gets there though, Unreal goes through a few steps to create and fill it.

The exact contents of the GBuffer can differ, the number of channels and their uses can be shuffled around depending on your project settings. A common case example is a 5 texture GBuffer, A through E. `GBufferA.rgb = World Normal` , with `PerObjectGBufferData` filling the alpha channel. `GBufferB.rgba = Metallic, Specular, Roughness, ShadingModelID` . `GBufferC.rgb` is the `BaseColor` with `GBufferAO` filling the alpha channel. `GBufferD` is dedicated to custom data and `GBufferE` is for precomputed shadow factors.

Inside *BasePassPixelShader.usf* the `FPixelShaderInOut_MainPS` function acts as the entry point for the pixel shader. This function looks quite complicated due to the numerous preprocessor defines but is mostly filled with boilerplate code. Unreal uses several different methods to calculate the required data for the GBuffer depending on what lighting model and features you have enabled. Unless you need to change some of this boilerplate code, the first significant function is partway down where the shader gets the values for `BaseColor` , `Metallic` , `Specular` , `MaterialAO` , and `Roughness` . It does this by calling the functions declared in *MaterialTemplate.ush* and their implementations are defined by your material graph.

```
// Store the results in local variables and reuse instead of calling the functions multiple times.
half3 BaseColor = GetMaterialBaseColor(PixelMaterialInputs);
half  Metallic = GetMaterialMetallic(PixelMaterialInputs);
half  Specular = GetMaterialSpecular(PixelMaterialInputs);

float MaterialAO = GetMaterialAmbientOcclusion(PixelMaterialInputs);
float Roughness = GetMaterialRoughness(PixelMaterialInputs);

// 0..1, SubsurfaceProfileId = int(x * 255)
float SubsurfaceProfile = 0;
```

The shader caches the result of the material graph calls to avoid executing their functions multiple times.

Now that we have sampled some of the data channels, Unreal is going to modify some of them for certain shading models. For example, if you're using a shading model which uses Subsurface Scattering (Subsurface, Subsurface Profile, Preintegrated Skin, two sided foliage or cloth) then Unreal will calculate a Subsurface color based on the call to `GetMaterialSubsurfaceData`. If the lighting model is *not* one of these it uses the default value of zero. The Subsurface Color values are now part of further calculations, but unless you're using a shading model that writes to the value it will simply be zero!

After calculating Subsurface Color Unreal allows DBuffer Decals to modify the results of the GBuffer if you have it enabled in your project. After doing some math Unreal applies the DBufferData to the BaseColor, Metallic, Specular, Roughness, Normal and Subsurface Color channels.

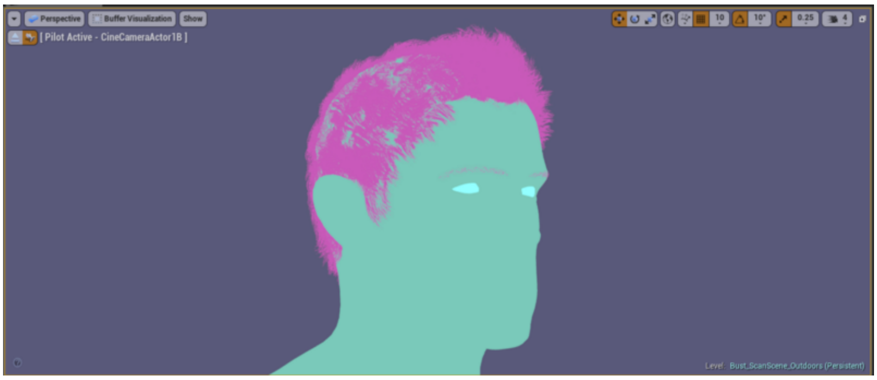
After allowing DBuffer Decals to modify the data Unreal calculates the Opacity (using the result from your material graph) and does some volumetric lightmap calculations. Finally it creates the `FGBufferData` struct and it packs all of this data into it with each FGBufferData instance representing a single pixel.

Setting the GBuffer Shading Model

The next thing on Unreal's list is to let each shading model modify the GBuffer as it sees fit. To accomplish this, Unreal has a function called `SetGBufferForShadingModel` inside of *ShadingModelMaterials.ush*. This function takes our Opacity, BaseColor, Metallic, Specular, Roughness and Subsurface data and allows each shading model to assign the data to the GBuffer struct however it would like.

Most shading models simply assign the incoming data without modification but certain shading models (such as Subsurface related ones) will encode additional data into the GBuffer using the custom data channels. The other important thing this function does is it writes the `ShadingModelID` to the GBuffer. This is an integer value stored per-pixel that lets the deferred pass look up what shading model each pixel should use later.

It's important to note here that if you want to use the CustomData channels of the GBuffer you'll need to modify *BasePassCommon.ush* which has a preprocessor define for `WRITES_CUSTOMDATA_TO_GBUFFER` . If you try to use the CustomData part of the GBuffer without making sure your shading model is added here it will be discarded and you won't get any values later!



A single model that uses three different shading models—hair, eyes and skin.

Using the Data

Now that we've let each lighting model choose how they're going to write their data into the `FGBufferData` struct, the *BasePassPixelShader* is going to do a fair bit more boilerplate code and house keeping—calculating per pixel velocity, doing subsurface color changes, overriding the roughness for ForceFullyRough, etc.

After this boilerplate code though Unreal will get precomputed indirect lighting and skylight data (`GetPrecomputedIndirectLightingAndSkyLight`) and adds that to the DiffuseColor for the GBuffer. There's a fair bit of code related to translucent forward shading, vertex fogging, and debugging, and we eventually come down to the end of the `FGBufferData` struct. Unreal calls `EncodeGBuffer` (*DeferredShadingCommon.ush*) which takes in the `FGBufferData` struct and writes it out to the various GBuffer textures, A-E.

That wraps up the end of the Base Pass Pixel Shader for the most part. You'll notice that there's no mention of lighting or shadows in this function. This is because in a deferred renderer these calculations are deferred until later! We'll look at that next.

Review

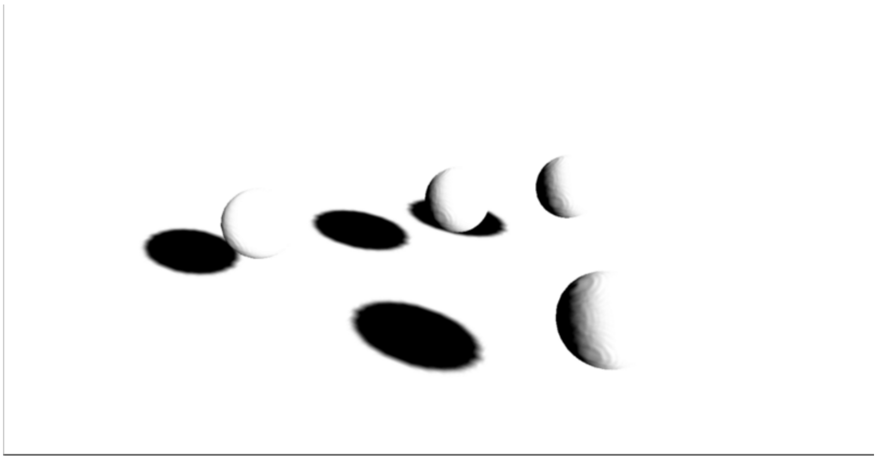
The BasePassPixelShader is responsible for sampling the various PBR data channels by calling into functions generated by your Material graph. This data is packed into a `FGBufferData` which is passed around to various functions that modify the data based on various shading models. The shading model determines the `ShadingModelID` that is written to the texture for choosing which shading model to use later. Finally the data in the `FGBufferData` is encoded into multiple render targets for use later.

Deferred Light Pixel Shader

We're going to look at *DeferredLightPixelShaders.usf* next as this is where each light's influence on a pixel is calculated. To do this, Unreal uses a simple vertex shader to draw appropriate geometry that matches the possible influence of each light ie: a sphere for point lights and a cone for spot lights. This creates a mask on which pixels the pixel shader needs to be run on which makes lights that fill less pixels cheaper.

Shadowed and Unshadowed Lights

Unreal draws lighting in multiple stages. Non shadow-casting lights are drawn first, and then indirect lighting (via light propegation volumes) is drawn. Finally Unreal draws all shadow casting lights. Unreal uses similar pixel shaders for shadow casting and non-shadow casting lights—the difference between them comes from additional pre-processing steps for shadow casting lights. For each light, Unreal computes a *ScreenShadowMaskTexture* which is a screenspace representation of the shadowed pixels in your scene.



A ScreenShadowMaskTexture for a simple scene with some spheres in it

To do this, Unreal renders geometry that appears to be matched to the bounding box of each object in your scene, and geometric representations of objects in your scene. It *does not re-render the objects in your scene* and instead samples the GBuffer combining the depth of a given pixel to see if it would be in the way of a cast light shadow. Sound complicated? Don't worry, it is. The good news is that the only takeaway we need here is that each shadowed light computes a screenspace representation of what surfaces are in shadow and this data is used later!

Base Pass Pixel Shader

Now that we know shadowed lights create a screenspace shadow texture we can go back to looking at how the base pass pixel shader works. As a reminder, this is run for each light in the scene so for any object that has multiple lights affecting it it will be run multiple times per pixel. The pixel shader can be quite simple, we'll be interested more in the functions this pixel shader calls.

```
void RadialPixelMain( float4 InScreenPosition, float4
SVPos, out float4 OutColor)
{
// Intermediate variables have been removed for
brevity
FScreenSpaceData ScreenSpaceData =
GetScreenSpaceData(ScreenUV);
FDeferredLightData LightData =
SetupLightDataForStandardDeferred();
```

```
OutColor = GetDynamicLighting(WorldPosition,
CameraVector, ScreenSpaceData.GBuffer,
ScreenSpaceData.AmbientOcclusion,
ScreenSpaceData.GBuffer.ShadingModelID, LightData,
GetPerPixelLightAttenuation(ScreenUV), Dither,
Random);

OutColor *=
ComputeLightProfileMultiplier(WorldPosition,
DeferredLightUniforms_LightPosition,
DeferredLightUniforms_NormalizedLightDirection);
}
```

There's only a couple of functions so we'll hop through what each one does. `GetScreenSpaceData` retrieves the information from the GBuffer for a given pixel. `SetupLightDataForStandardDeferred` calculates information such as the light direction, light color, falloff, etc. Finally, it calls `GetDynamicLighting` and passes in all of the data we've calculated so far—where the pixel is, what the GBuffer data is, what Shading Model ID to use, and our light's information.

GetDynamicLighting

The `GetDynamicLighting` (located in *DeferredLightingCommon.ush*) function is quite long and looks complicated but a lot of the complications are due various settings on each light. This function calculates a `SurfaceShadow` and `SubsurfaceShadow` variables which are initialized to 1.0—if there *are shadows* then the value becomes lower than one. This is important as we multiply values against it later, so for now just accept that a higher value is less shadowed.

If shadowing is enabled then `GetShadowTerms` is called. This uses the light attenuation buffer from earlier (called *ScreenShadowMaskTexture*) to determine shadow terms for a given pixel. There are a ton of different places shadow data can come from, (Unreal stores light function + per object shadows in the `z` channel, per-object sub surface scattering in `w`, whole-scene directional light shadows in `x` and whole scene directional light sub surface scattering in `y`, and static shadowing comes from the appropriate GBuffer channel) and GetShadowTerms writes this information out to our `SurfaceShadow` and `SubsurfaceShadow` variables from earlier.

Now that we've determined the shadow factor for both surface and subsurface data we calculate light attenuation. Attenuation is effectively the falloff in energy based on the distance from the light and can be modified to create different effects, ie: Toon shading often removes Attenuation from the calculation so that your distance to a light source doesn't matter. Unreal calculates `SurfaceAttenuation` and `SubsurfaceAttenuation` separately based on distance, light radius and falloff, and our shadow term. **Shadowing is combined with attenuation**, which means our future calculations only take *attenuation strength* into account.

Finally we calculate our Surface Shading for this pixel. **Surface Shading takes the GBuffer, Surface Roughness, Area Light Specular, Light Direction, View Direction, and Normal** into account. Roughness is determined by our GBuffer data. Area Light Specular uses physically based rendering (based on our light data and roughness) to calculate a new energy value and can modify the roughness and light vector.

```
float3 StandardShading( float3 DiffuseColor, float3 SpecularColor, float3 LobeRoughness, float3 LobeEnergy, float3 L, float3 V, half3 N )
{
    float NoL = dot(N, L);
    float NoV = dot(N, V);
    float LoV = dot(L, V);
    float InvLenH = rsqrt( 2 + 2 * LoV );
    float NoH = saturate( ( NoL + NoV ) * InvLenH );
    float VoH = saturate( InvLenH + InvLenH * LoV );
    NoL = saturate(NoL);
    NoV = saturate(abs(NoV) + 1e-5);

```

The standard shading model uses various data in its calculations

Surface Shading finally gives us a chance to modify how each surface responds to this data. This function is located in *ShadingModels.ush* and is just a big switch statement that looks at our ShadingModel ID that was written into the GBuffer way earlier! Many of the lighting models share a standard shading function, but some of the more unusual shading models use their own custom implementations. **Surface Shading does not take attenuation into account,** so it only deals with calculating the color of the surface without shadows.

Attenuation (which is distance + shadow) isn't taken into account until the Light Accumulator is run. The Light Accumulator takes the surface lighting and attenuation into account and adds together surface and sub-surface lighting correctly after multiplying them by the light attenuation value.

Finally the Dynamic Lighting function returns the total light accumulated by the Light Accumulator. In practice this is just surface + subsurface lighting but the code is complicated by subsurface properties and debug options.

ComputeLightProfileMultiplier

Finally the last thing the *DeferredLightPixelShader* does is multiply the color calculated by `GetDynamicLighting` by the value from `ComputeLightProfileMultiplier`. This function allows for the use of 1D IES light profile textures. If an IES light profile is not being used for that light then the resulting value is not changed.

Accumulated Light

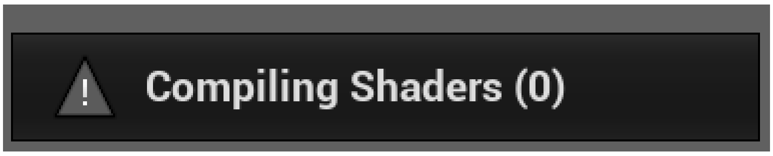
Because the *BasePassPixelShaders* are run for every light that affects an object, Unreal accumulates this lighting and stores it in a buffer. This buffer isn't even drawn to the screen until several steps later in the `ResolveSceneColor` step. Several additional things are calculated before that such as translucent objects (which are drawn using traditional forward rendering techniques), screen space temporal anti aliasing and screen space reflections.

Review

For each light shadow data is calculated in screen space and combines static shadow, subsurface shadow and directional shadows. Then approximate geometry is drawn for each light and the influence of that light on each pixel is drawn. The surface shading is calculated based on GBuffer data and shading model and then is multiplied by light attenuation. Light attenuation is a combination of light settings (distance, falloff, etc.) and shadow sampling. The output of each surface shading is accumulated together to produce the final light value

Next Post

We've covered a good deal of background information on the rendering system and how the different sections all fit together. In the next post we're going to start talking about shader permutations and trying to find find ways to reduce the amount of times you need to recompile shaders so you spend less time waiting and more time coding! The next post is available here!


Compiling Shaders (0)