
THE ORDER
1886
Readyatdawn
STUDIOS

Crafting a Next-Gen Material Pipeline for The Order: 1886

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Readyatdawn STUDIOS

About Our Project

- Brand-new IP
- Alternate history 19th-century London
- PS4 Exclusive
- ~100 developers

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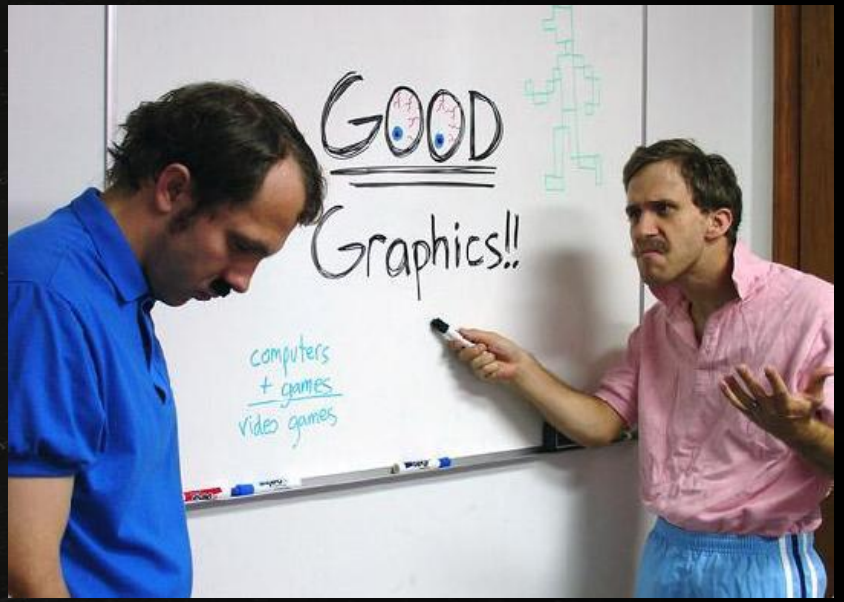
About Our Project

- Work began in early 2011
- Originally just 2 graphics programmers
  - Now we have 5!



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Engine Overview

- Latest version of our in-house engine
- Windows(DX11) and PS4, but heavily geared towards PS4
  - Fine-grained task scheduling
  - Low-overhead, multithreaded cmd buffer generation
  - PS4 Secret Sauce™
- Physically based rendering from the start

Engine Overview

- Core tools framework uses C++ and Qt
  - Built on common UI core
  - Can be embedded in Maya
- Custom build pipeline built in C++
  - Major engineering effort
  - Heavily multithreaded
  - Processed assets cached on local servers

Engine Overview

- Renderer embedded in Maya
  - Uses DX11 Viewport 2.0 override (Maya 2014)
  - Render using their device instead of our own
  - Tell Maya which UI to draw
- Materials/particles/lens flares/etc. can be live edited inside of Maya
- Serves as primary level editor

Memory

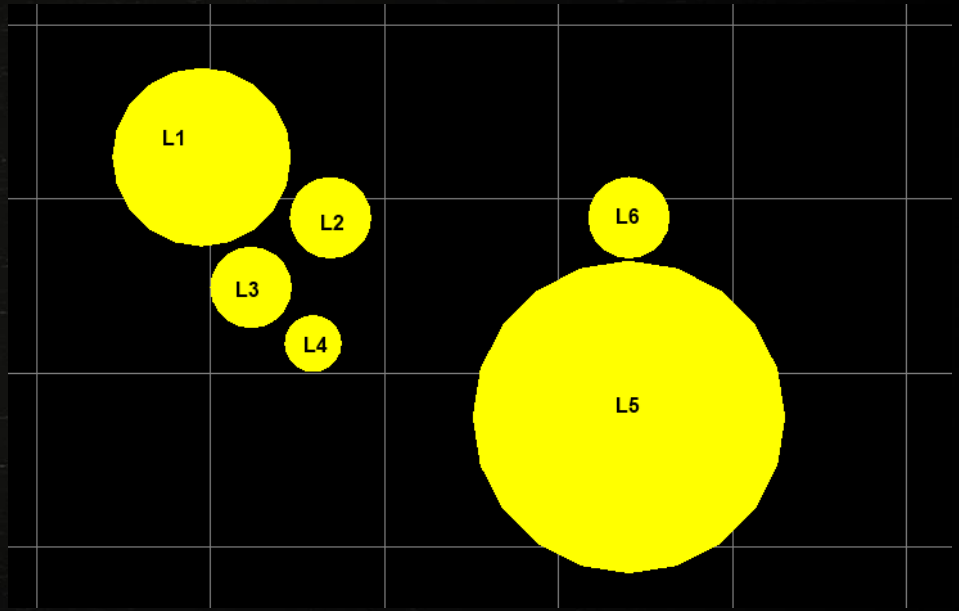
- 2 GB texture budget
- 128 MiB sound budget
- 700 MiB level geometry
- 600 MiB character textures
- 250 MiB global textures (FX, UI, light maps, etc..)
  - Even characters have lightmap data
- 700 MiB animation

Memory

- Environmental art is mapped at 512 pixels per unit
- Standard environment tilling texture is 1024x1024

Lighting Pipeline

- Tiled forward lighting (AKA Forward+)
  - Depth prepass
  - CS bins lights per tile
  - Two depth partitions
  - Punctual light sources (no area lights…yet!)



Lighting Pipeline

- Transparents fully lit with diffuse + specular
  - Separate depth prepass + depth buffer for transparents
  - Transparent light list generated per-tile
    - TileMinDepth = TileMin(transparentDepth)
    - TileMaxDepth = TileMax(opaqueDepth)
  - Also support per-vertex lighting for particles

Lighting Pipeline

- Lightmaps for static geo
  - Baked on GPU farm using Optix
  - H-basis for directional variation
- SH probes for dynamics
  - 3rd-order (9 coefficients)
- Pre-convolved specular probes
  - Cubemaps rendered in-engine, convolved in a compute shader

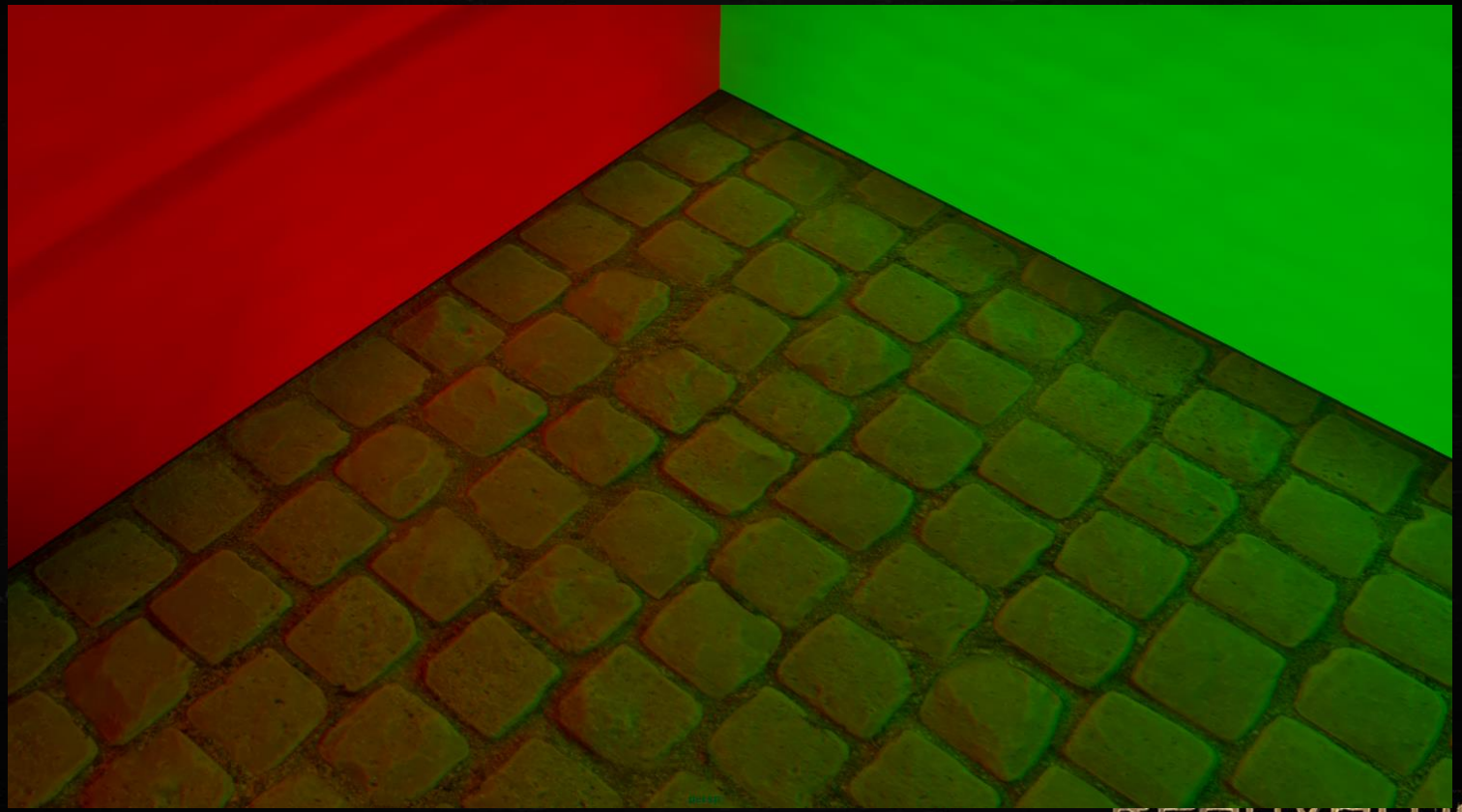
Lighting Pipeline

Lighting Pipeline

Lighting Pipeline

Lighting Pipeline

Lighting Pipeline



Ambient Occlusion

- Directional AO maps (H-basis) baked for characters and static geo
- Static geo only uses it to occlude specular from probes
- Dynamic geo applies AO to diffuse from SH probes

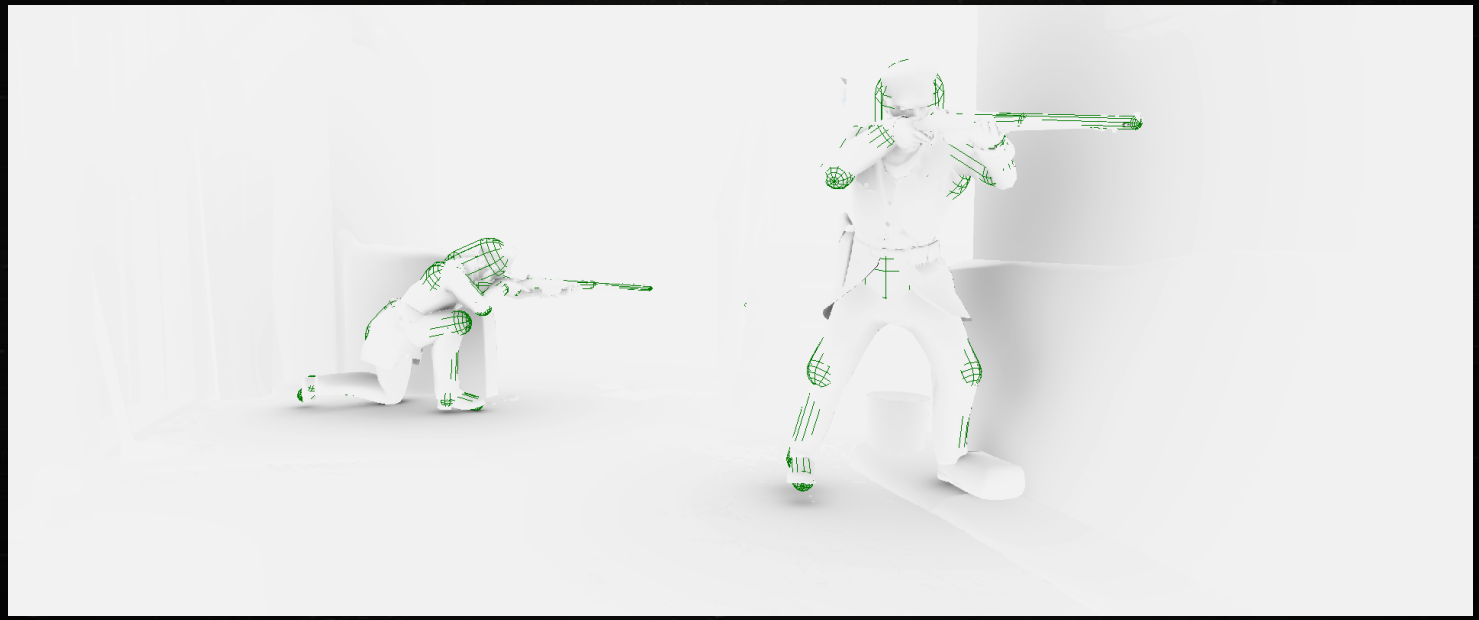
Without Reflection Occlusion

With Reflection Occlusion

Reflection Occlusion Visualization

Ambient Occlusion

- Dynamic AO from capsules skinned to characters



AO Capsules Off

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AO Capsules On

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Core Shading Model

- Default specular BRDF is Cook-Torrance
  - D term is GGX distribution from Walter et al.
  - Matching Smith G term derived in same paper
  - Schlick's approximation for Fresnel
  - Lambertian diffuse, balanced with specular intensity

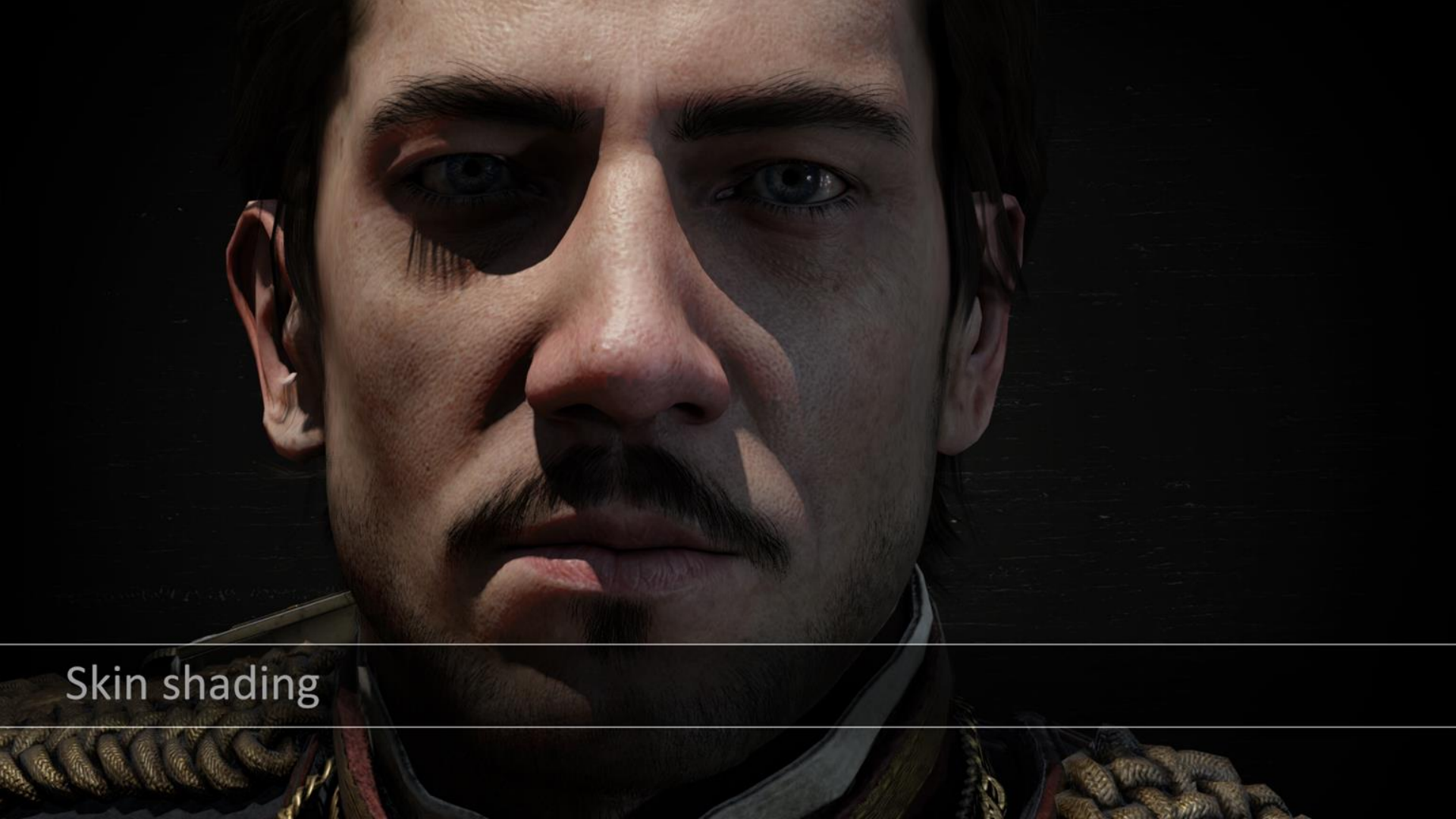
Core Shading Model

- GGX + Cook Torrance == Lots of math
  - But we have lots of ALU!
- Can be optimized
  - Don’t use trig
  - Fold Smith G term into denominator
  - See our course notes from SIGGRAPH
- Have artists work with sqrt(roughness)
  - More intuitive, better for blending

```
// Helper for computing the GGX visibility term
float GGX_V1(in float m2, in float nDotX) {
    return 1.0f / (nDotX + sqrt(m2 + (1 - m2) * nDotX * nDotX));
}

// Computes the specular term using a GGX microfacet distribution. m is roughness, n is the surface normal, h is the
// half vector, and l is the direction to the light source
float GGX_Specular(in float m, in float3 n, in float3 h, in float3 v, in float3 l) {
    float nDotH = saturate(dot(n, h));
    float nDotL = saturate(dot(n, l));
    float nDotV = saturate(dot(n, v));

    float nDotH2 = nDotH * nDotH;
    float m2 = m * m;

    // Calculate the distribution term
    float d = m2 / (Pi * pow(nDotH * nDotH * (m2 - 1) + 1, 2.0f));

    // Calculate the matching visibility term
    float v1i = GGX_V1(m2, nDotL);
    float v1o = GGX_V1(m2, nDotV);
    float vis = v1i * v1o;

    // Multiply this result with the Fresnel term
    return d * vis;
}
```

Core Shading Model

- Other BRDFs available
  - Beckmann (also taken from Walter et al.)
  - Anisotropic GGX
  - Hair (Kajiya-Kay)
  - Skin (pre-integrated diffuse)
  - Cloth



Skin shading

Skin

- Our most expensive shader!
  - Texture lookup per light based on N dot L
  - Multiple specular lobes
- Didn’t use shader gradient-based curvature
  - Too many artifacts
  - Used curvature maps instead

Pre-integrated skin diffuse with SH

$$D(\theta, r) = \frac{\int_{-\pi}^{\pi} \cos(\theta + x) R(2r \sin(x/2)) dx}{\int_{-\pi}^{\pi} R(2r \sin(x/2)) dx}$$

$$D_n(r) = 2\pi \int_0^{\pi/2} Y_{n,0}(\theta) D(\theta, r) sin(\theta) d\theta$$

$$f_{skinSH}(\mathbf{n}, r) = \sum_{l=0}^{2} \sum_{m=-1}^{l} \sqrt{\frac{4\pi}{2l+1}} D_l(r) L_{l,m} Y_{l,m}(n)$$

Ambient Skin (Diffuse only)

Left is using normal SH lighting convolved with cosine kernel

Right is using SH lighting convolved with the scattering kernel

Hair Shading

- Not physically-based ☹
- Kajiya-Kay
  - Haven't had time to investigate real-time Marschner
- Tweaked Fresnel curve
- SH diffuse using tangent direction
  - Analytic Tangent Irradiance Environment Maps for Anisotropic Surfaces[Mehta 2012]

Hair Shading

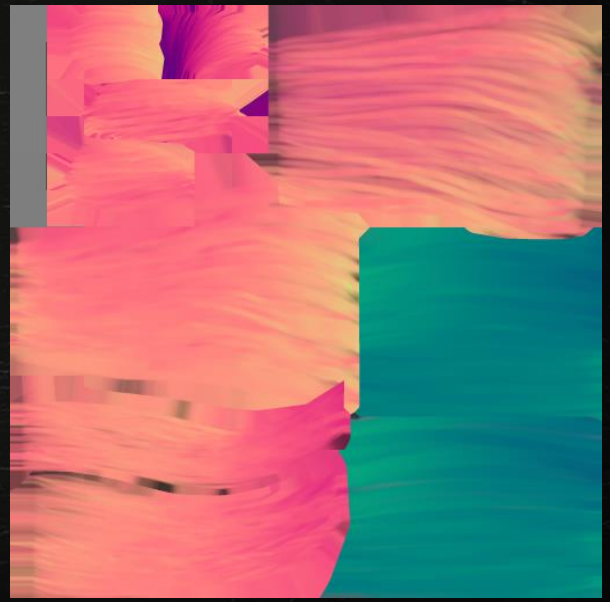
- Secondary specular lobe
  - Shifted along tangent towards tips
  - Takes albedo color

Hair Shading

- Shift maps to break up highlights
  - Additional shift along tangent direction

Hair Shading

- Flow maps to define tangent direction
  - Authored in Mari

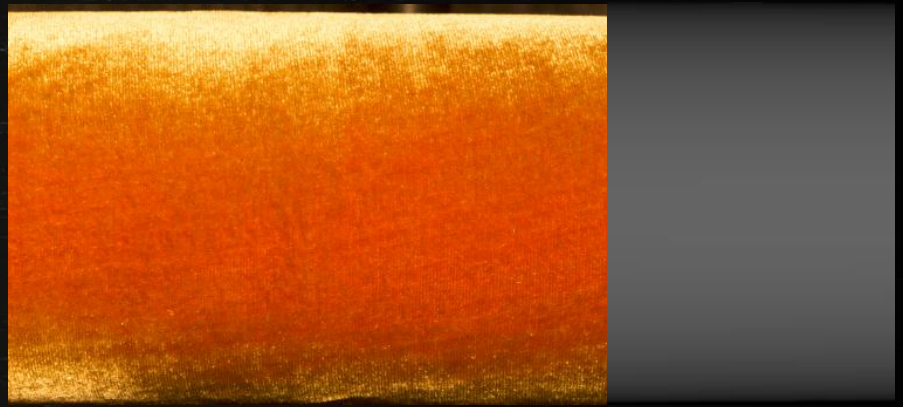


Cloth Shading

Cloth Shading

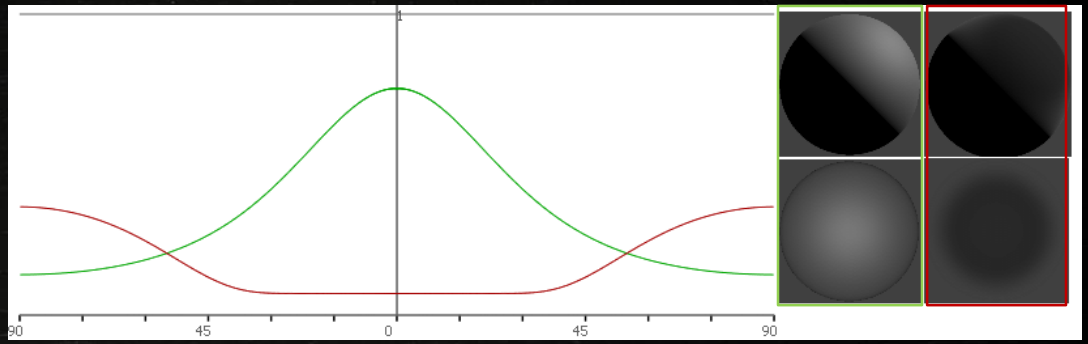
Observations from photo reference:

- Soft specular lobe with large smooth falloffs
- Fuzz on the rim from asperity scattering
- Low specular contribution at front facing angles
- Some fabrics have two toned specular colors

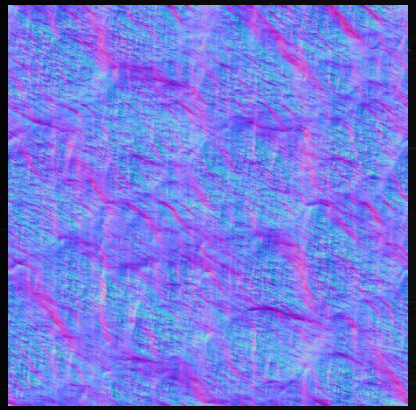


Cloth Shading

- Inverted Gaussian for asperity scattering
- Translation from origin to give more specular at front facing angles
- No geometry term



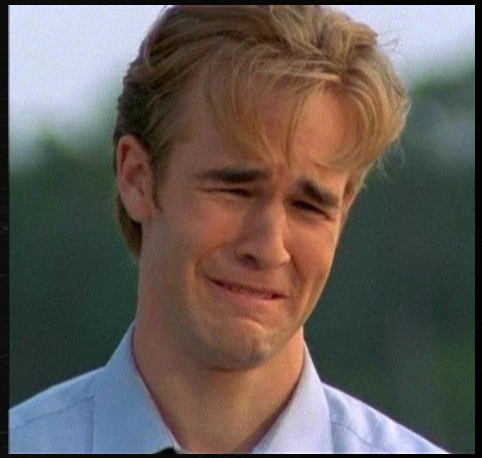
Specular Aliasing



+

$$f(\mathbf{l},\mathbf{v}) = \frac{F(\mathbf{v},\mathbf{h})\,G(\mathbf{l},\mathbf{v},\mathbf{h})\,D(\mathbf{h})}{4\,(\mathbf{n}\cdot\mathbf{l})\,(\mathbf{n}\cdot\mathbf{v})}$$

=



Specular Aliasing

- Modify roughness maps to reduce aliasing
- Using technique based on “Frequency Domain Normal Map Filtering” by Han et al.

$$f^{\text{eff}}(\mathbf{l},\mathbf{v};\gamma) = \int_{\Omega} f(\mathbf{l},\mathbf{v})\gamma(\mathbf{n})d\mathbf{n}$$

$$f_{lm}^{\text{eff}} = \sqrt{\frac{4\pi}{2l+1}} f_l \gamma_{lm}$$

Specular Aliasing

- Represent NDF as spherical Gaussian (vMF distribution)
- Approximate BRDF in SH as a Gaussian
- Convolution of two Gaussians is a new Gaussian
- Use relationship to compute new roughness

BRDF NDF

$$\Lambda_l f_l^{\text{eff}} = e^{(\alpha l)^2} e^{-\frac{l^2}{2\kappa}} = e^{(\alpha' l)^2}$$

New Roughness

$$\alpha' = \sqrt{\alpha^2 + (2\kappa)^{-1}}$$

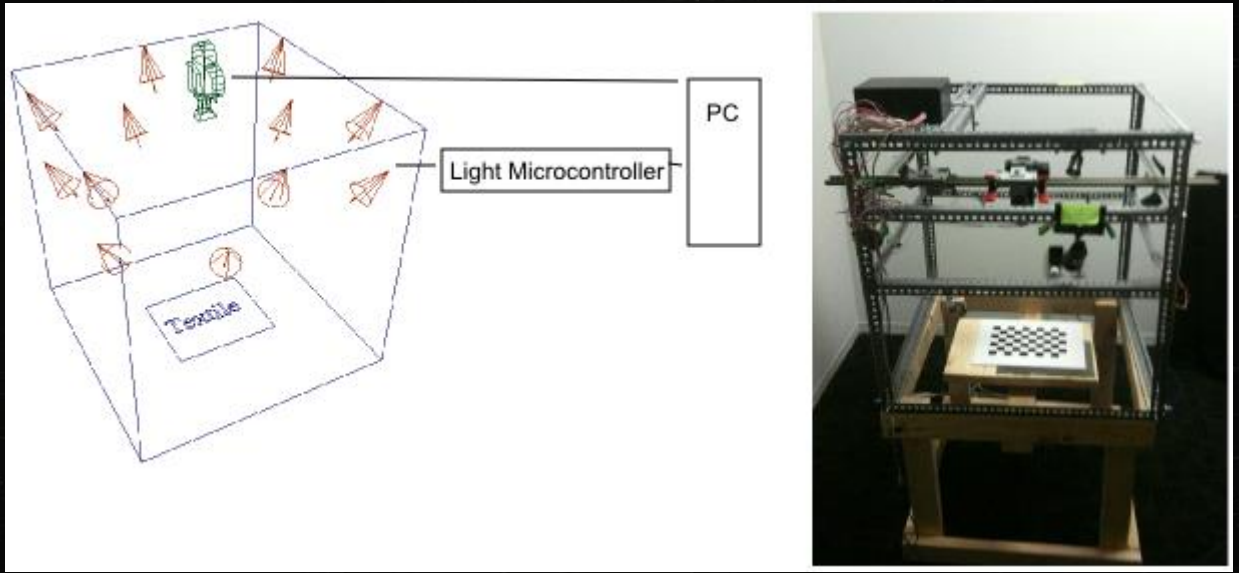
No AA

Ours

Ground Truth

3D Material Scanning

Scanning



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Scanning

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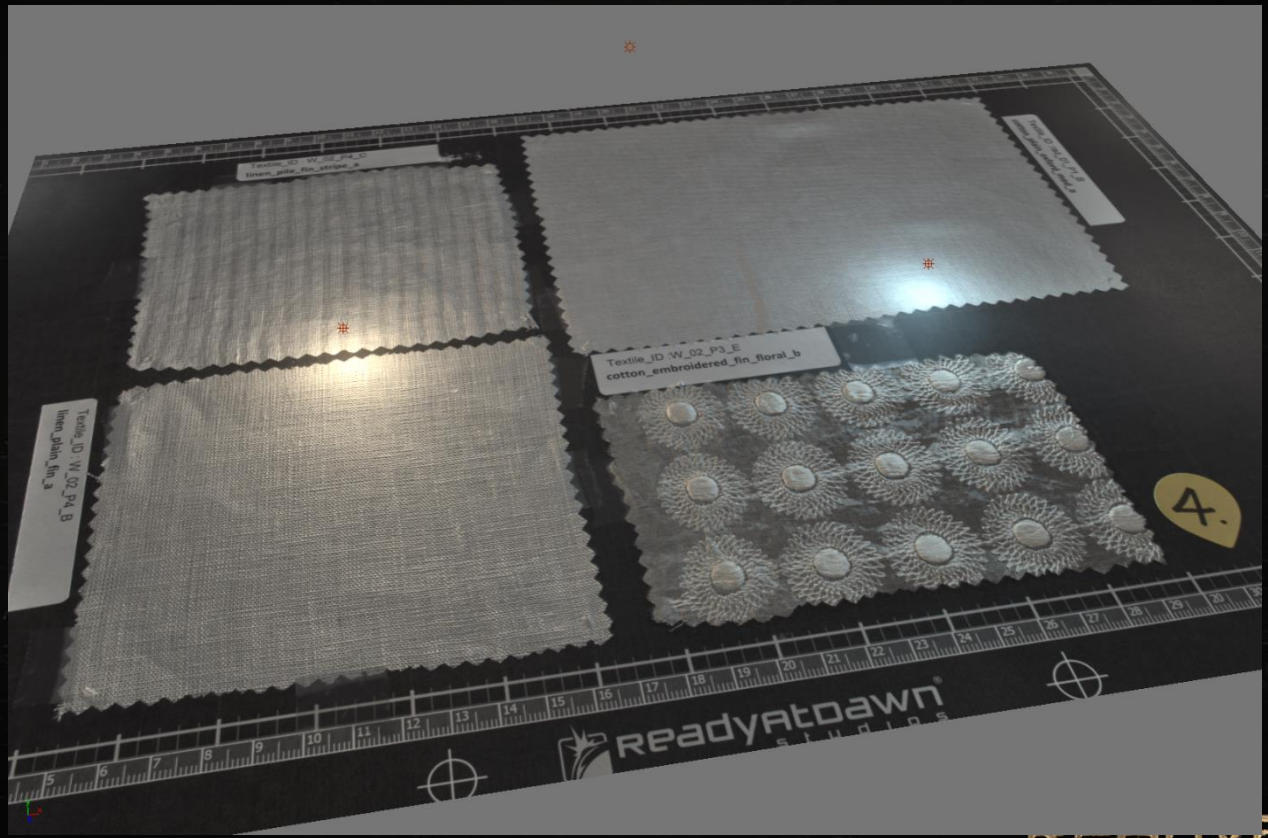
Scanning



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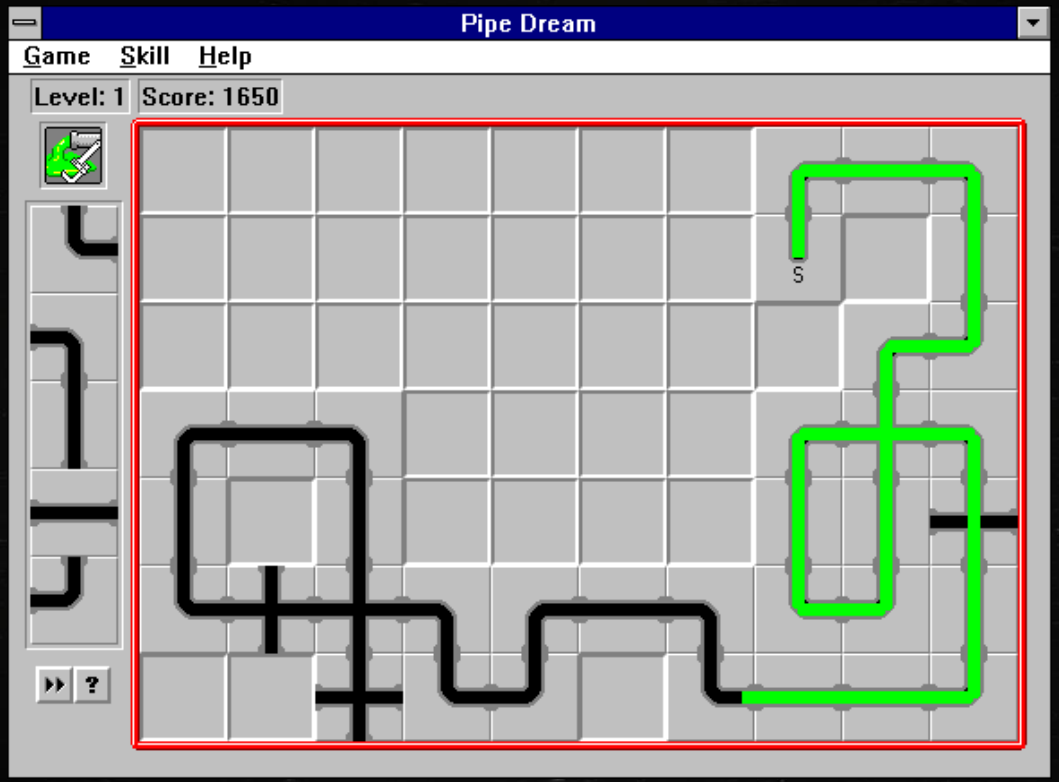
Material Pipeline



Material Pipeline

- Materials = text assets
- Uses our custom data language (radattr)
- Language supports:
  - Types
  - Inheritance
  - UI layouts
  - Metadata

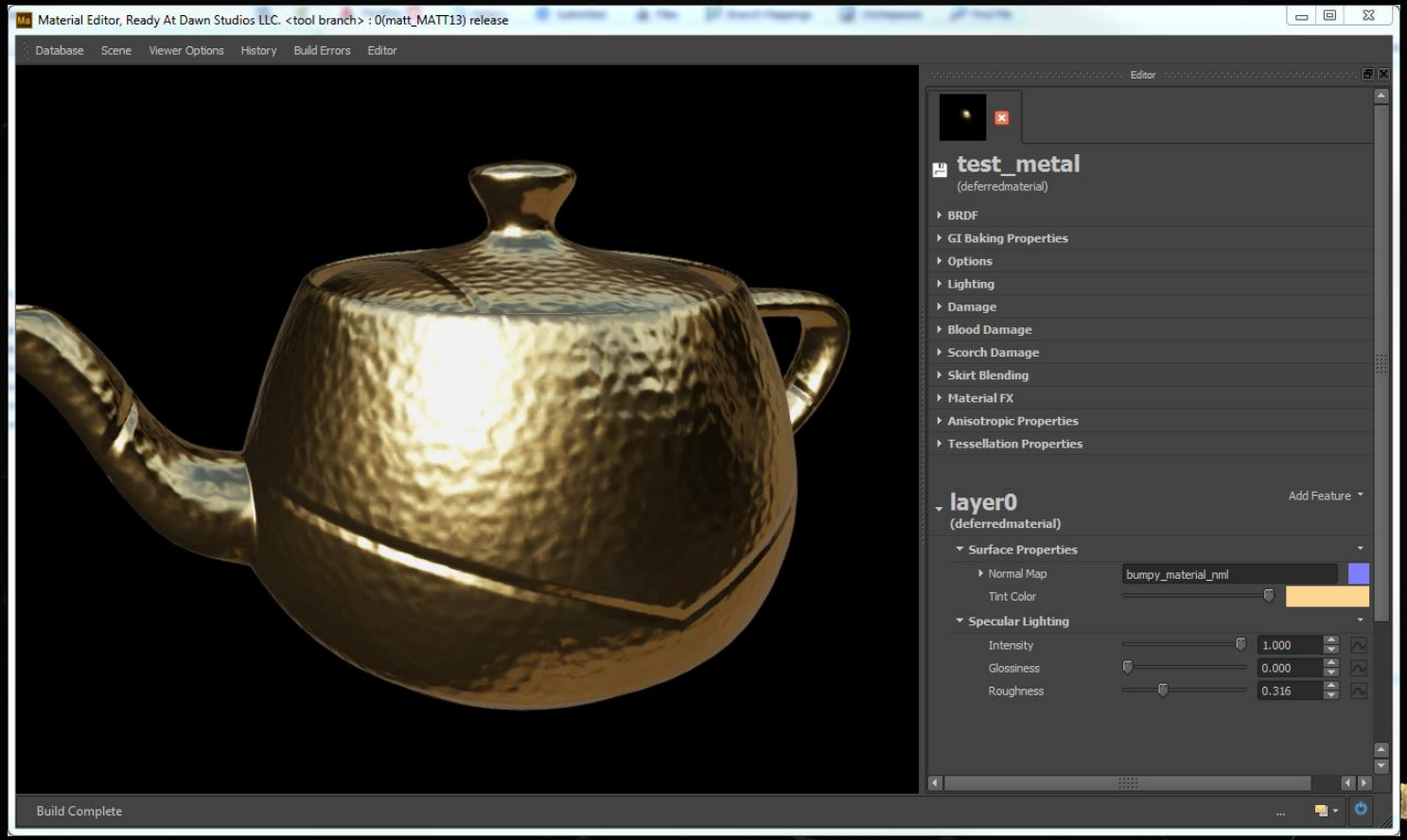
```
:bumpy_material := ( opaquematerial
    :enable_diffuse_ = true
    :enable_specular_ = true
    :specular_map = ( :name = "bumpy_material_spc" )
    :normal_map = ( :name = "bumpy_material_nml" )
    :specular_intensity = 0.05
    :specular_roughness = 0.1
)

:bumpy_material_red := ( bumpymaterial
    :albedo_tint_color = ( Color
        :r = 1.0
        :g = 0.0
        :b = 0.0
    )
)
```

Material Pipeline

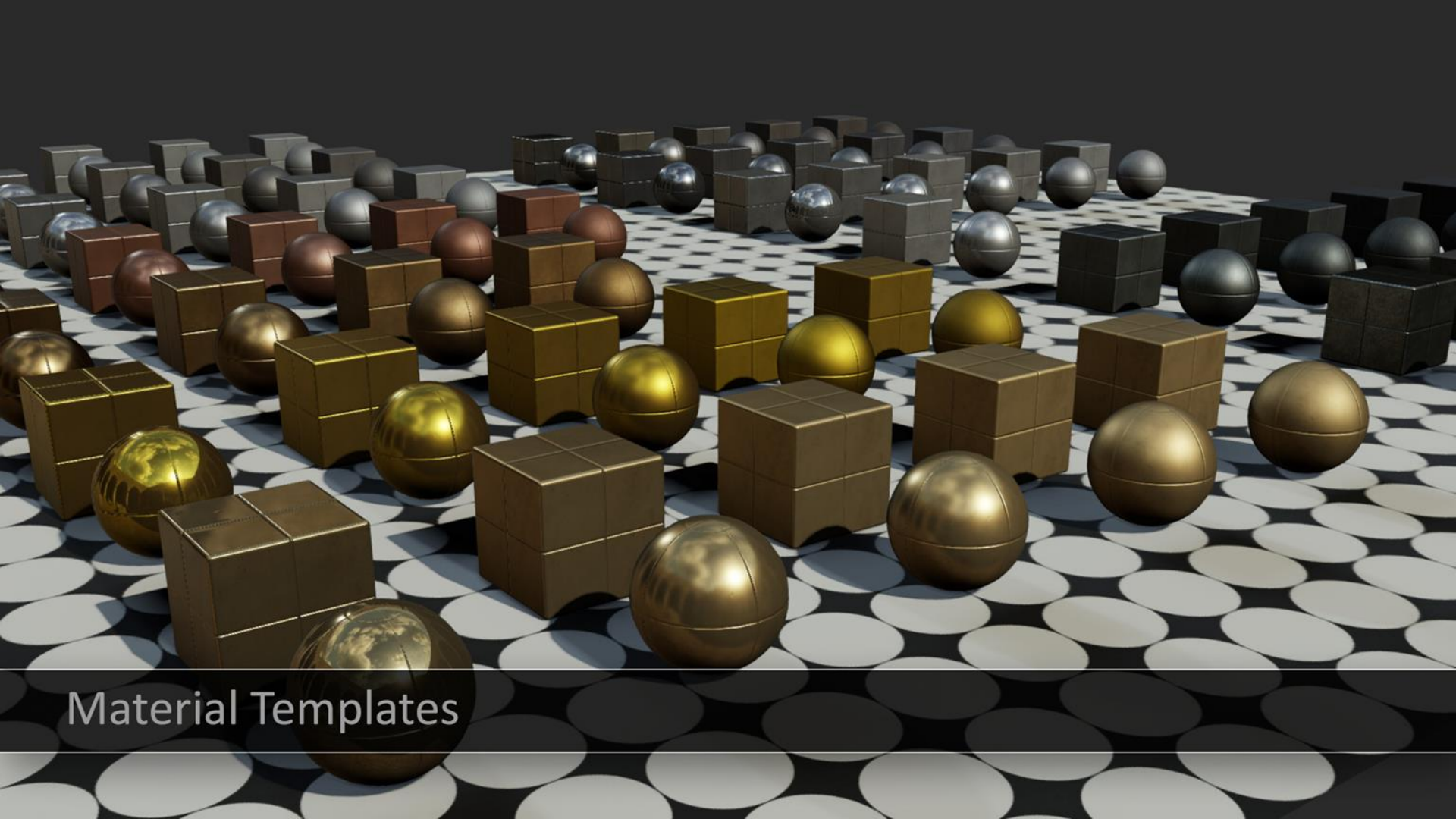
- Material authoring is feature-based
  - No shader trees
- Material editor tool for real-time editing
  - Can also be hosted inside of Maya

Material Pipeline

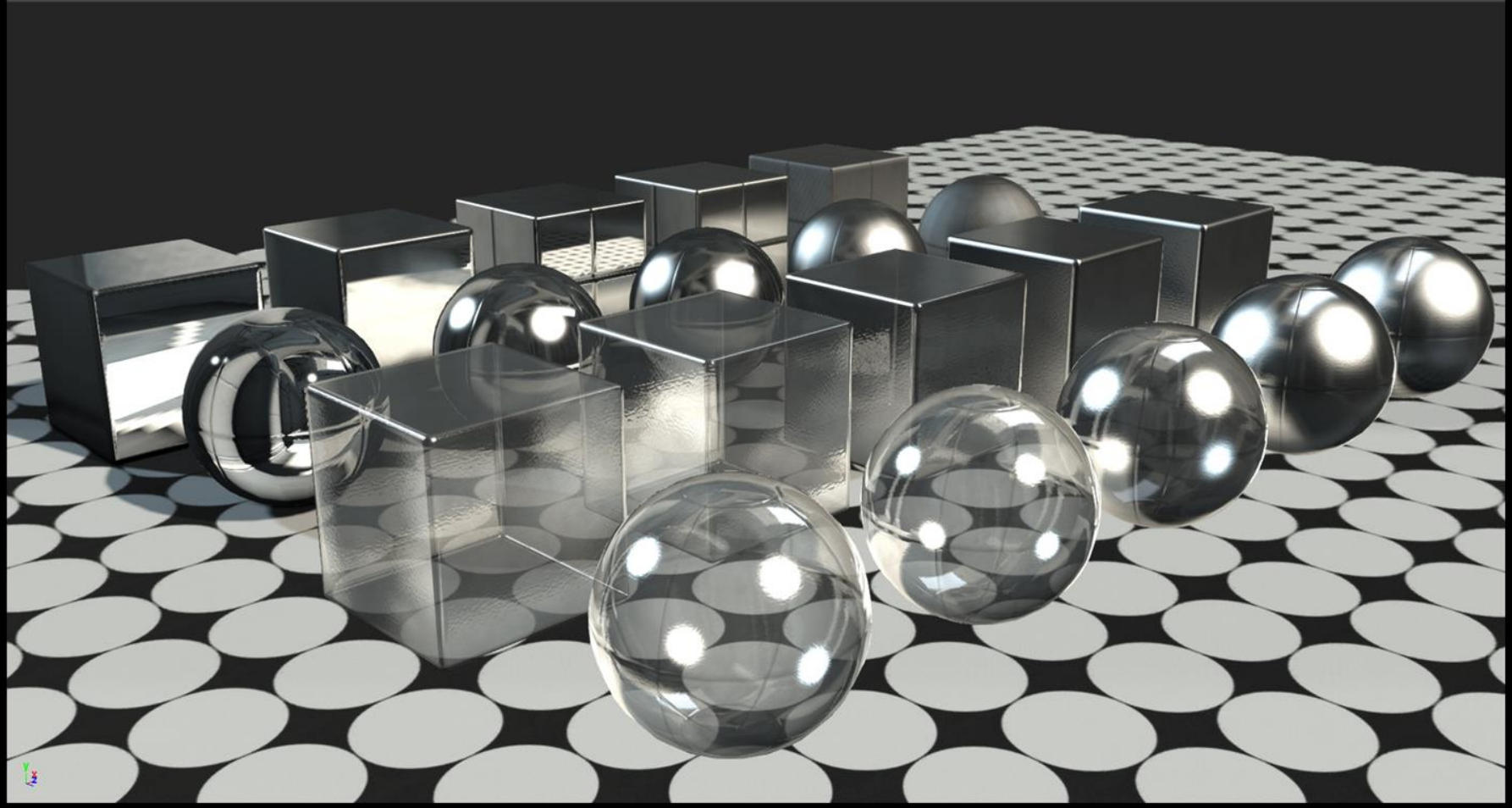


Material Pipeline

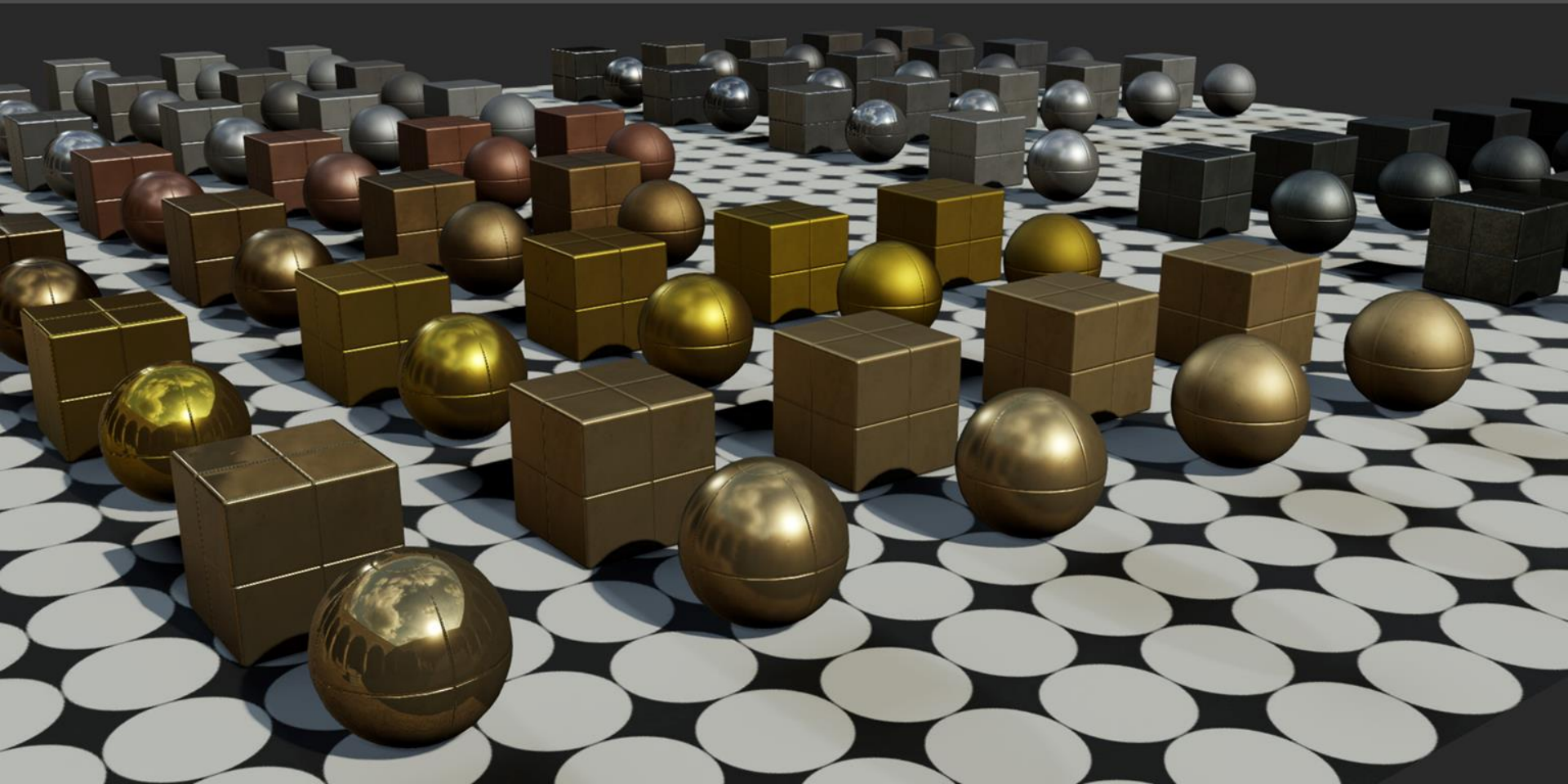
- radattr inheritance used to make *templates*
- Common parameters shared in base material
- Derived material only stores changes from base
- Quicker asset creation
- Global changes can be made in a single asset


Material Templates

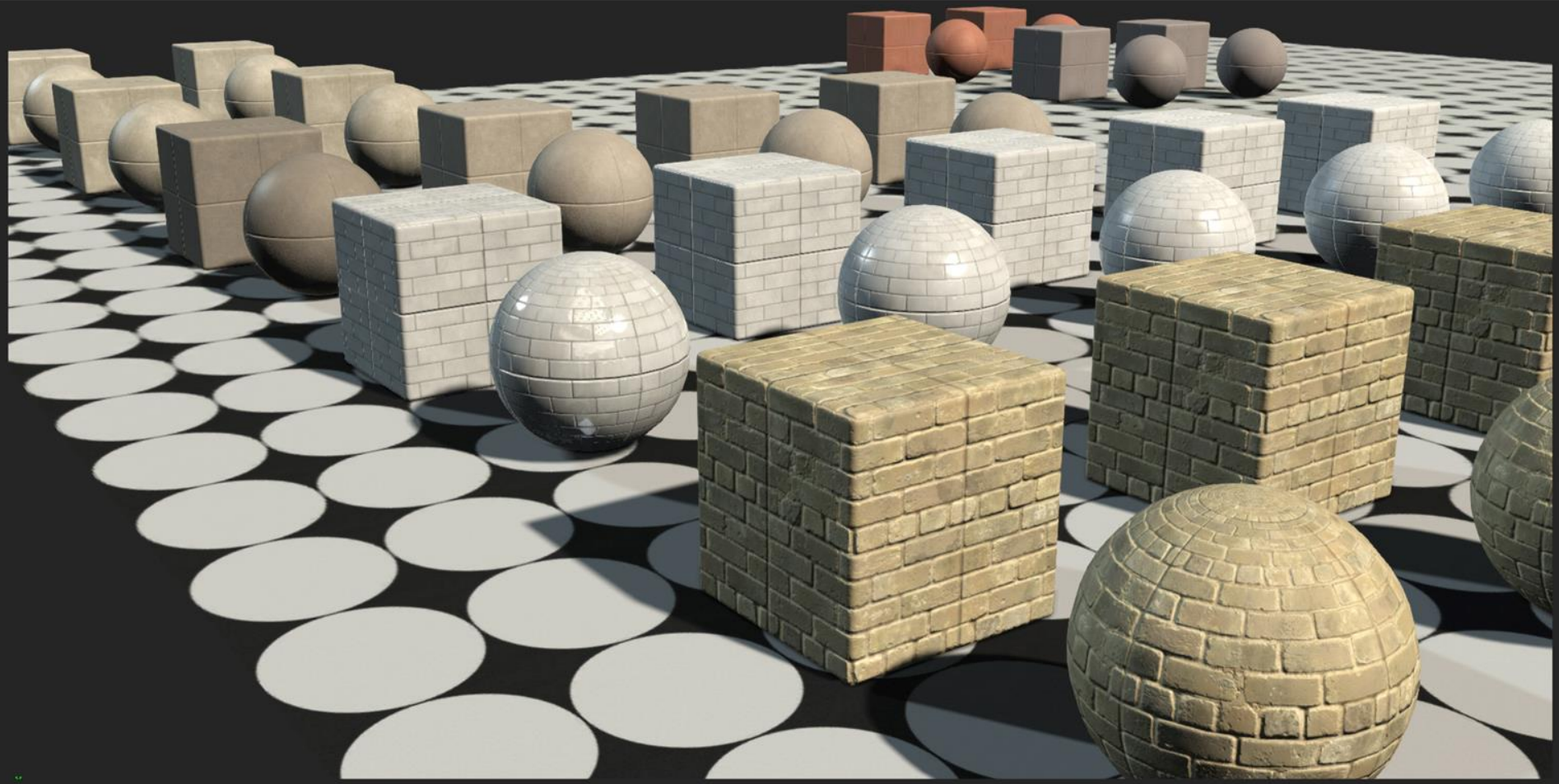
Global Material Templates: Sample Glass Subset



Global Material Templates: Sample Metal Subset

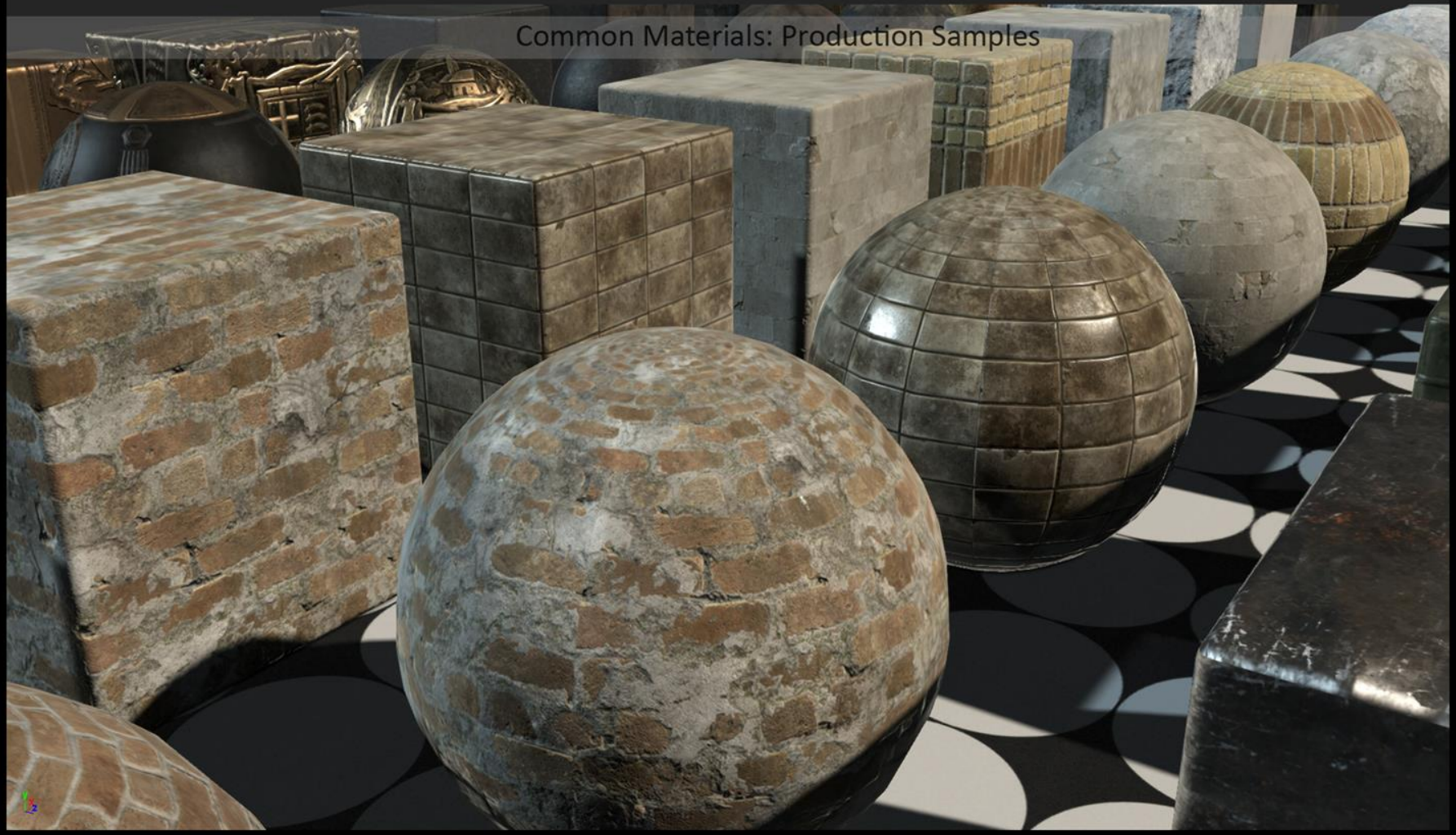


Global Material Templates: Sample Masonry Subset

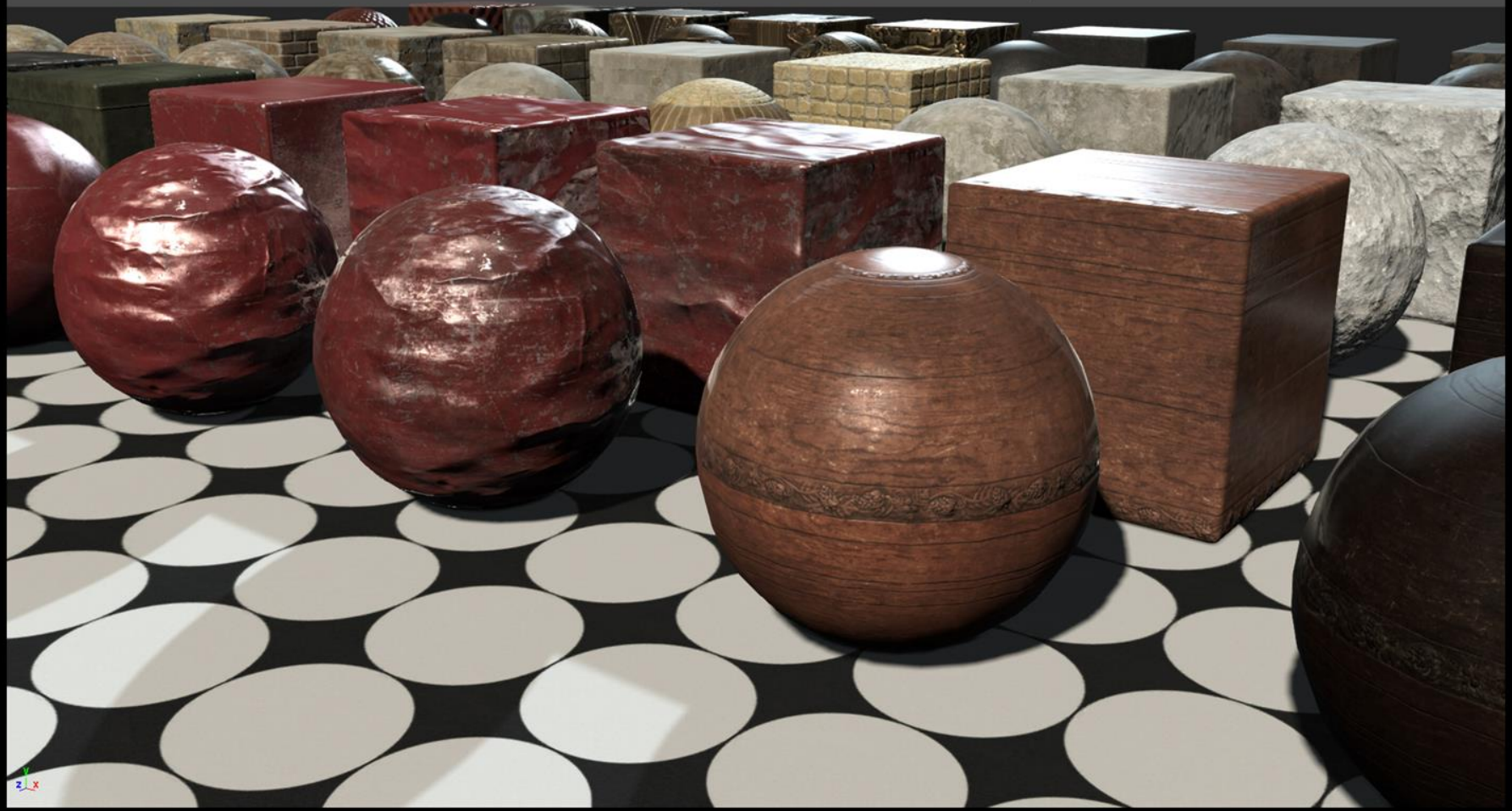


Common Materials: Production Samples

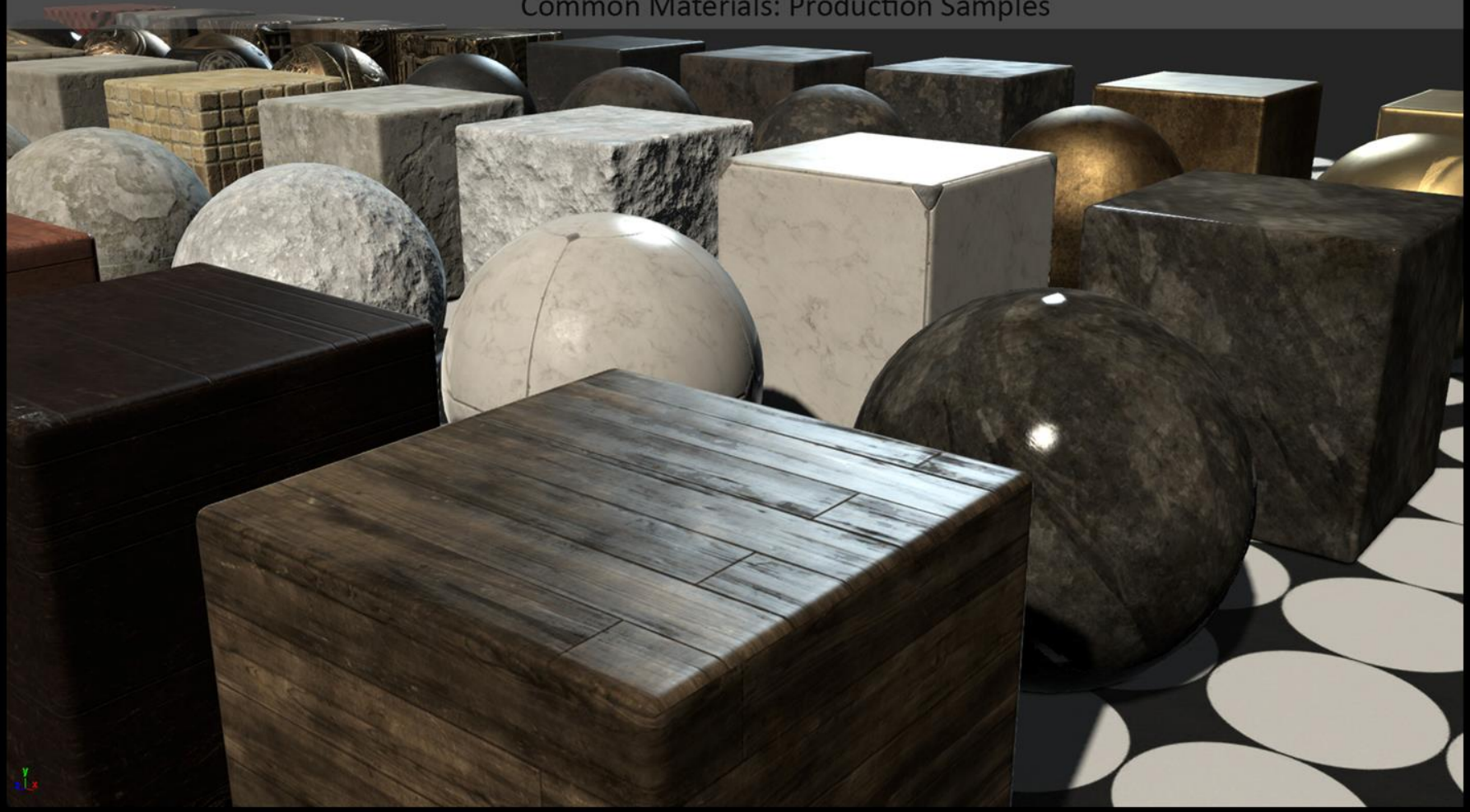
Common Materials: Production Samples



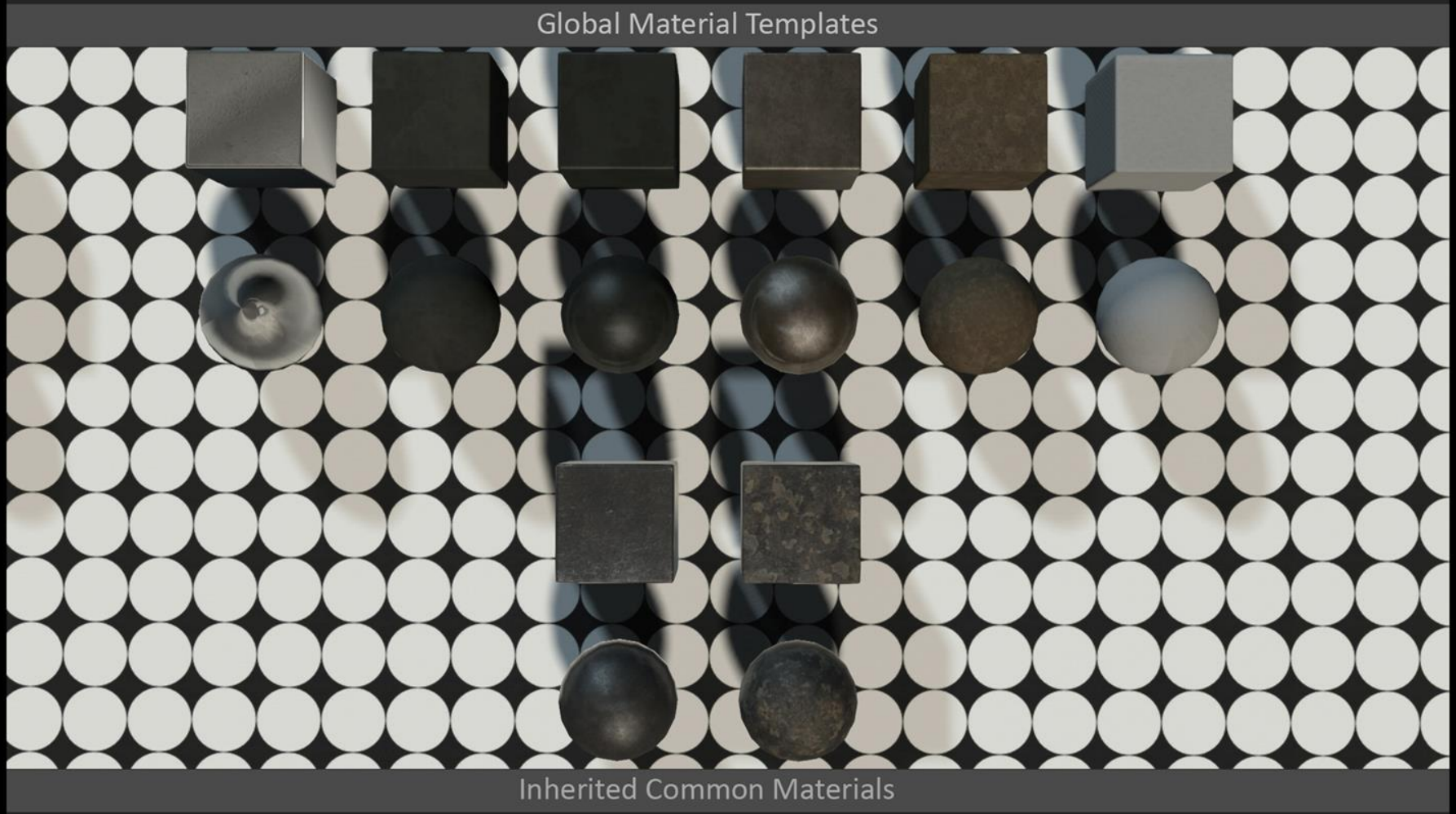
Common Materials: Production Samples

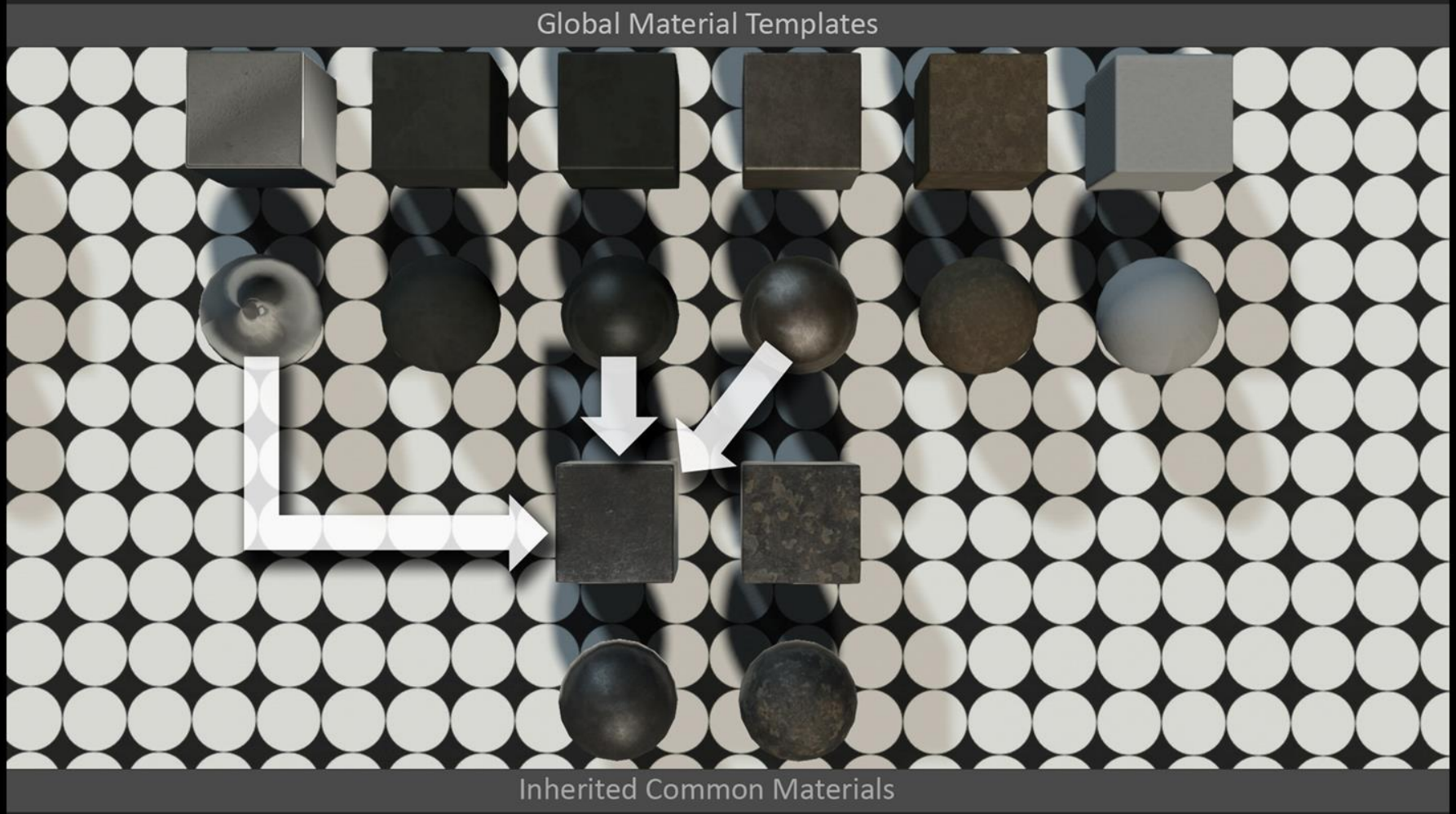


Common Materials: Production Samples



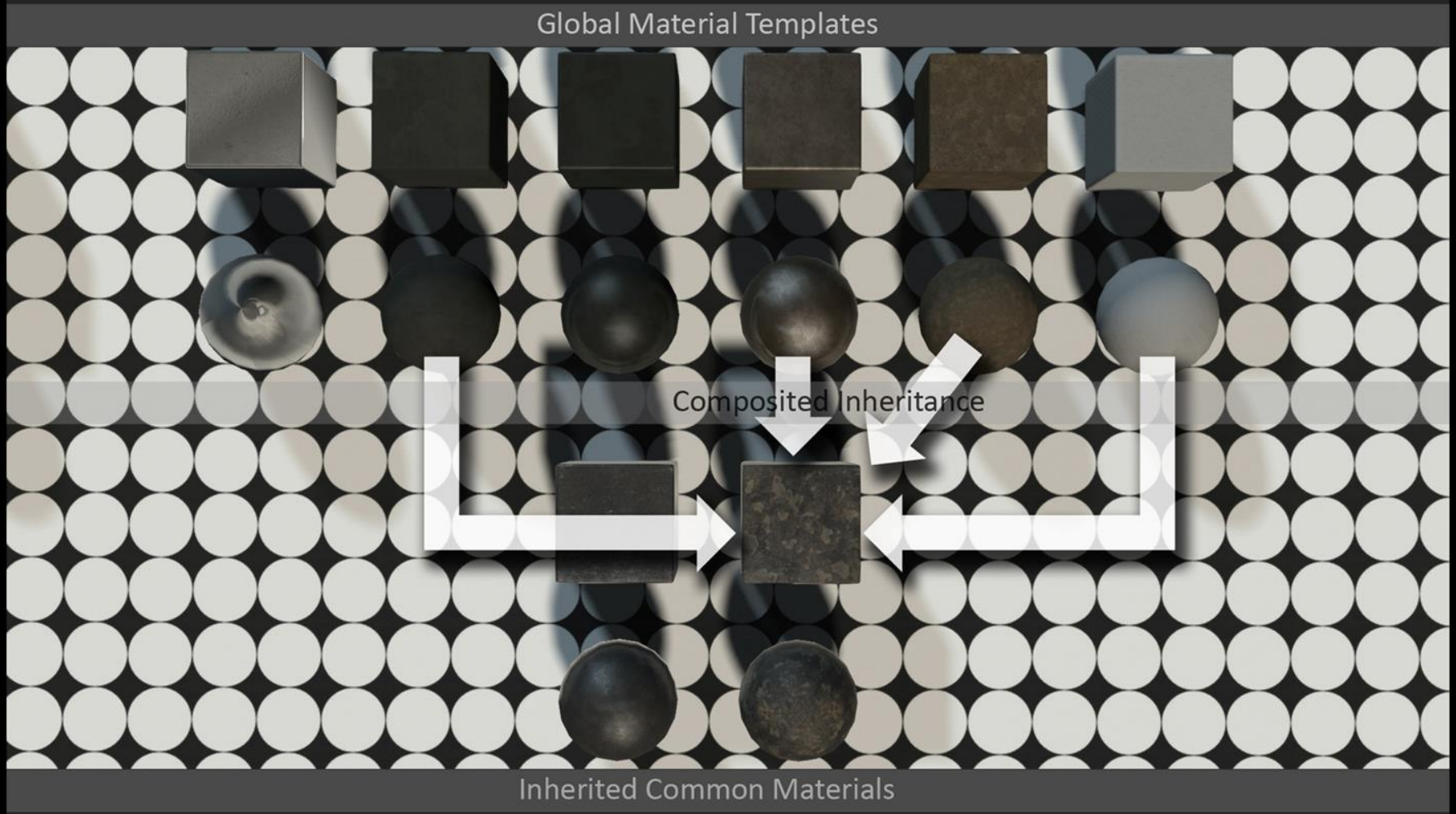
Common Materials: Production Samples


Global Material Templates
Inherited Common Materials


Global Material Templates
Inherited Common Materials

Global Material Templates

Inherited Common Materials


Global Material Templates
Composited Inheritance
Inherited Common Materials

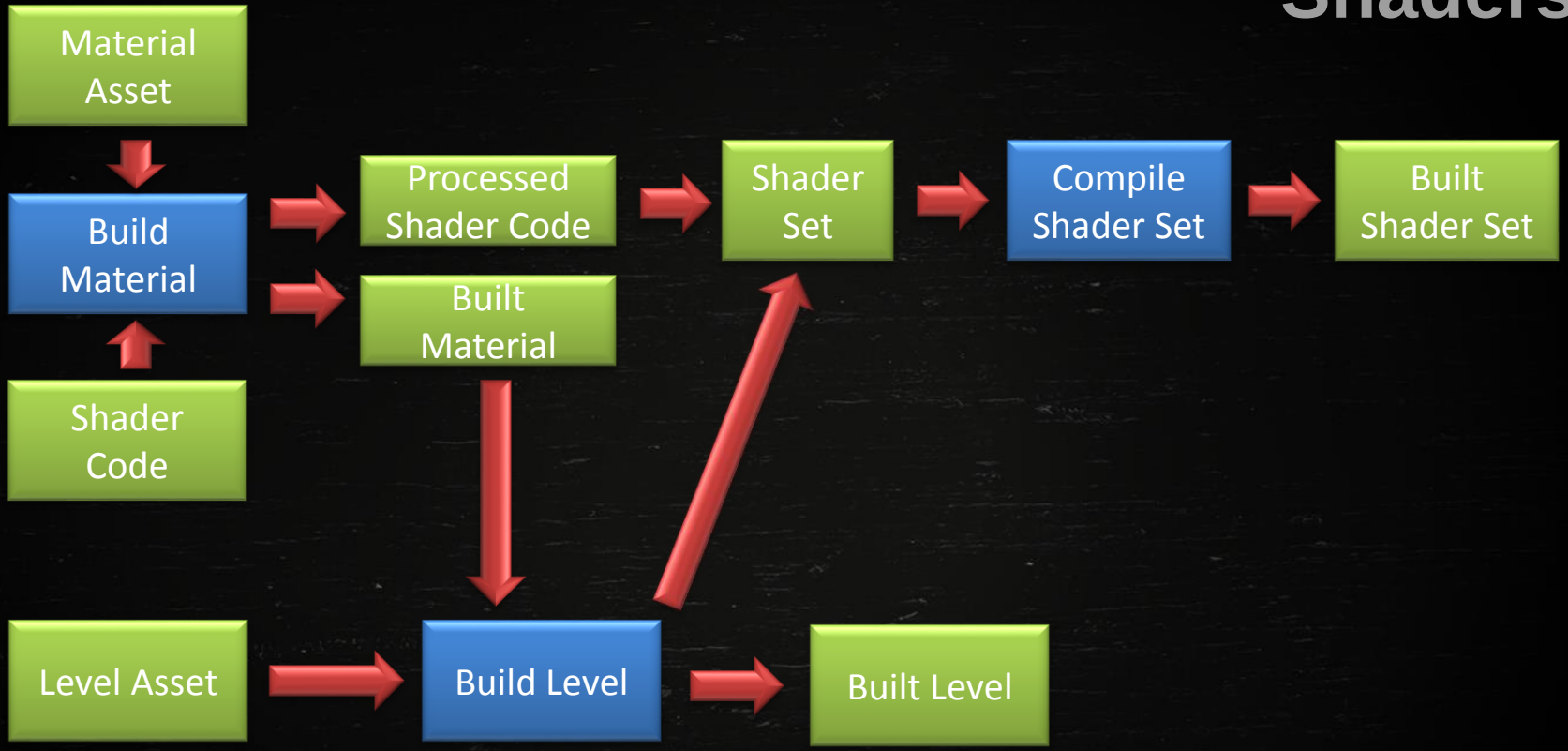
Shaders

- Hand-written ubershaders
  - Lots of #if's
- Major material features = macro definitions
- Parameters (spec intensity, roughness, etc.) hard-coded into the shader, except when animated or composited
- Some code is auto-generated to handle textures and animated parameters

Shaders

- Pre-defined “permutations”
  - Permutation = macro definition + entry point
- Permutations for skinning, blend shapes, instancing, light maps, etc.
- Debug permutation for visualization/debugging
- Shaders compiled in build pipeline based on permutation + material

Shaders



Shaders

- Pros:
  - Shaders are optimized for a material
    - Optimizer has full access
  - No runtime compiling for the game itself (used by tools)
- Cons:
  - *Lots* of shaders to compile!
    - We cache everything, but iteration can be slow
  - Monolithic shaders are hard to debug
  - Lean heavily on the compiler

Material Compositing

Material Compositing

- Mostly offline process
- Material asset specifies composite “stack”
- Each layer in the stack has:
  - Referenced material
  - Blend mask
  - Blending parameters
- Recursively build + composite referenced materials
- Combine each layer 1 by 1 using pixel shader

Material Compositing

- Generates parameter maps from materials and blending maps
- Support compositing subset of BRDFs
  - Cloth, GGX, and Anisotropic
  - Compositing cloth requires applying 2 BRDFs

Material Compositing

Map	R Channel	G Channel	B Channel	A Channel	Format
1	Normals X	Normals Y	N/A	N/A	BC5
2	Diffuse R	Diffuse G	Diffuse B	Alpha (Optional)	BC1 or BC3
3	Specular R	Specular G	Specular B	Specular Intensity	BC3
4	Roughness	AO	BRDF Blend	Anisotropy	BC3

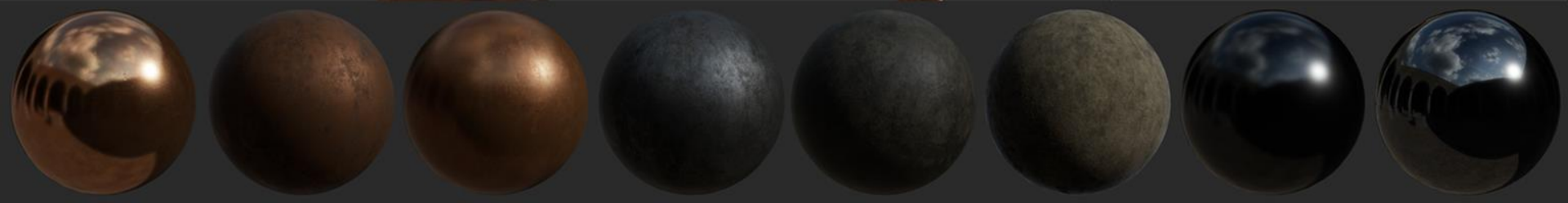
Material Compositing

```
// Compositing pixel shader run on a quad covering the entire output texture
CompositeOutput CompositePS(in float2 UV : UV) {
    CompositeOutput output;

    float blendAmt = BlendScale * BlendMap.Sample(Sampler, UV);
    float4 diffuseA = DiffuseTintA * DiffuseMapA.Sample(Sampler, UV);
    float4 diffuseB = DiffuseTintB * DiffuseMapB.Sample(Sampler, UV);
    float diffuseBlendAmt = blendAmt * DiffuseContribution;
    output.Diffuse = Blend(diffuseA, diffuseB, diffuseBlendAmt,
                           DiffuseBlendMode);

    // Do the same for specular, normals, AO, etc.

    return output;
}
```

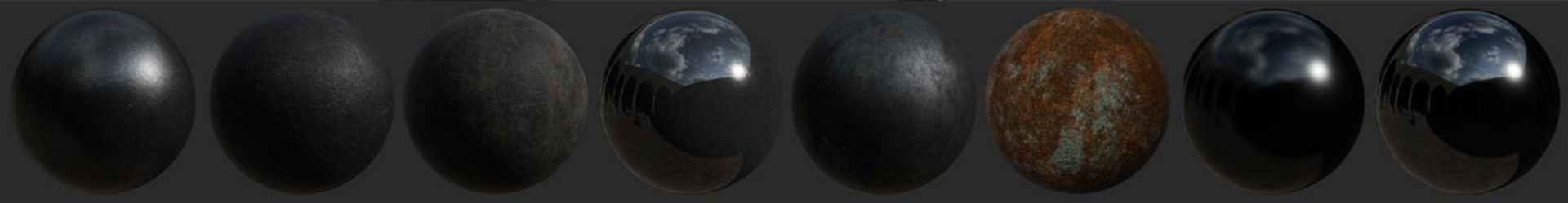


prp_well_pump_c_tarnished_copper_source
(mtt_copper_polished_075)

- BRDF
- GI Baking Properties
- Options
- Lighting
- Damage
- Skirt Blending
- Material FX
- Anisotropic Properties
- Tessellation Properties

layer0 (mtt_copper_polished_075) — Add Feature

- Surface Properties
- Diffuse Lighting
- Specular Lighting
- Composite Materials
  - Material - BASE, cmn_copper_a_tile_dark
  - Material - BASE VARIATION WORN, cmn_copper_a_tile_worn_light
  - Material - BASE VARIATION TARNISHED, cmn_tarnished_a_tile_light
  - Material - TARNISHED, cmn_steel_a_tile_worn_dark
  - Material - PRISTINE, cmn_copper_a_tile_pristine_light
  - Material - DIRT, cmn_dirt_fine_a_tile_tan_dark
  - Material - WET 50, cmn_water_dampness_050
  - Material - WET, cmn_water_dampness_100



prp_well_pump_c_worn_enamel_black_source
(cmn_enamel_fine_a_tile_pristine_black)

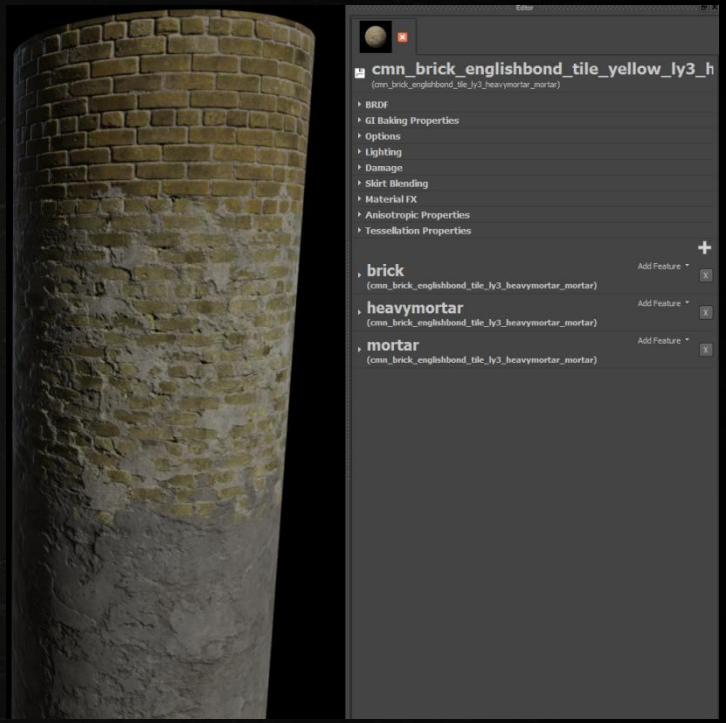
- BRDF
- GI Baking Properties
- Options
- Lighting
- Damage
- Skirt Blending
- Material FX
- Anisotropic Properties
- Tessellation Properties

layer0 (cmn_enamel_fine_a_tile_pristine_black) — Add Feature

- Surface Properties
- Diffuse Lighting
- Specular Lighting
- Composite Materials
  - Material - BASE, cmn_enamel_fine_a_tile_pristine_black
  - Material - BASE VARIATION WORN, cmn_enamel_fine_a_tile_black
  - Material - BASE VARIATION TARNISHED, cmn_enamel_fine_a_tile_wo
  - Material - TARNISHED, cmn_steel_a_tile_worn_dark
  - Material - PRISTINE, cmn_steel_a_tile_pristine_dark
  - Material - RUST, cmn_rust_coarse_a_tile_brown_mix
  - Material - WET, cmn_water_dampness_075
  - Material - WET 50, cmn_water_dampness_050

Material Layers

- Up to 4 layers
  - Derived from base materials
  - Separate compositing chain per layer
  - Driven by vertex colors



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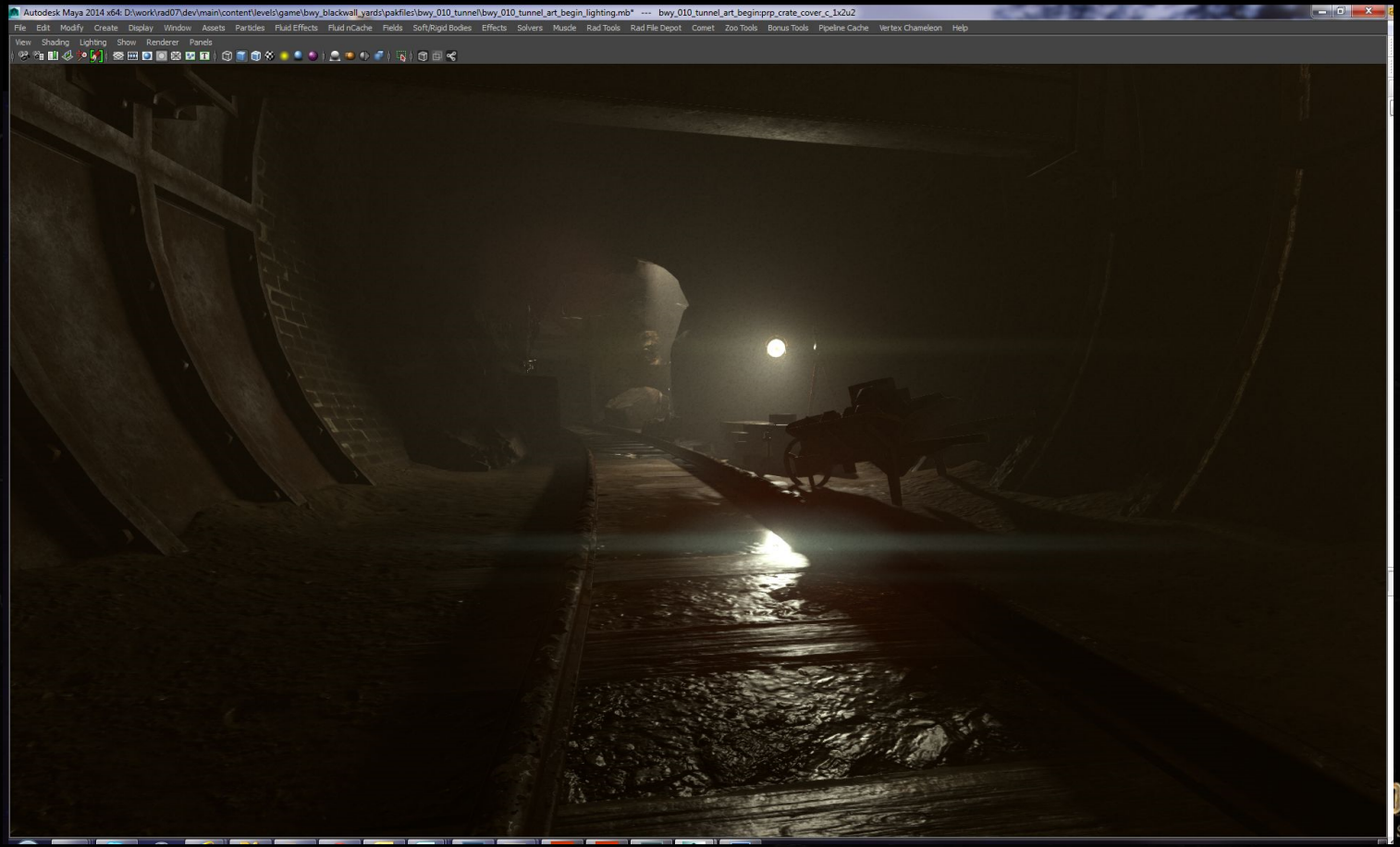
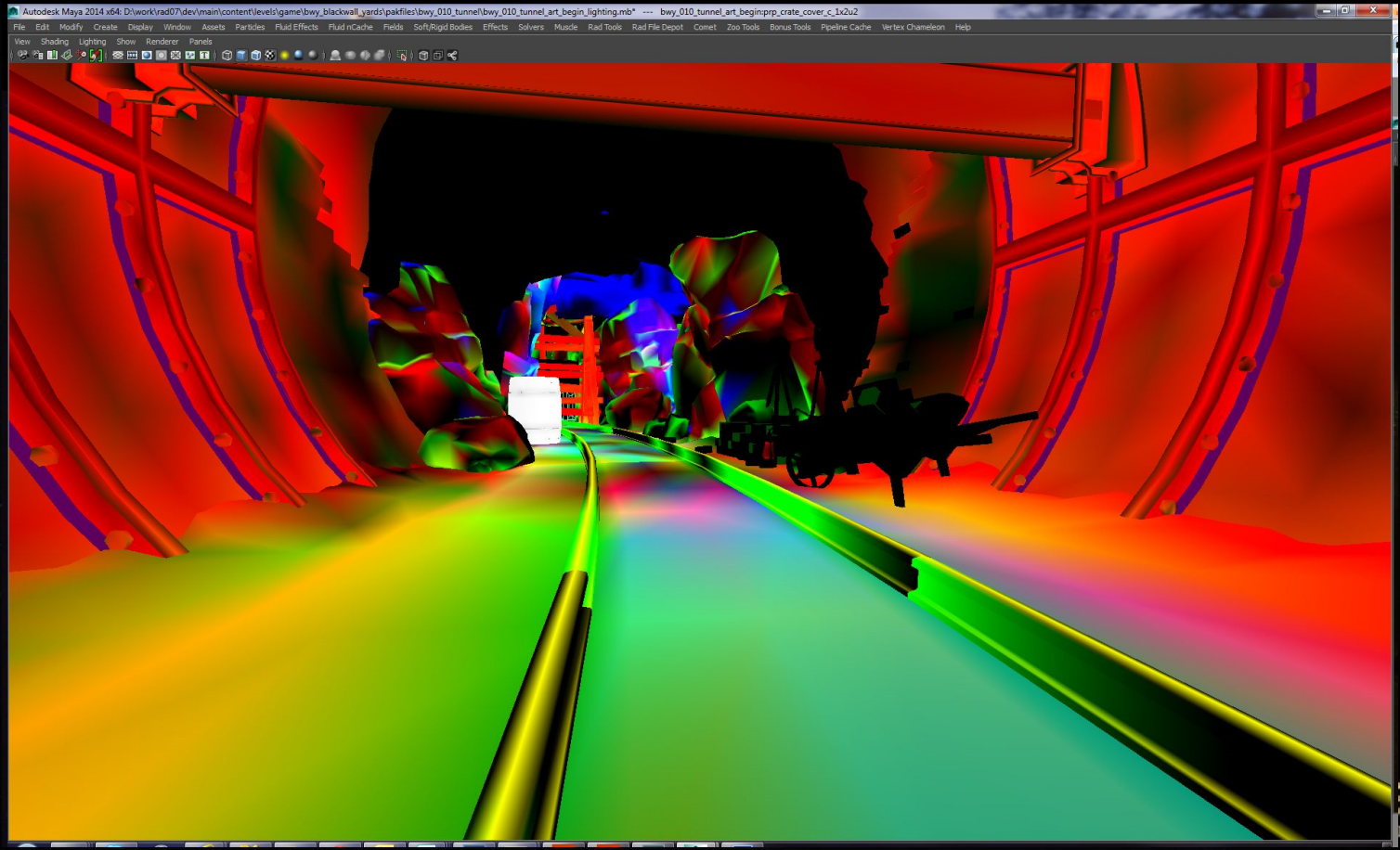
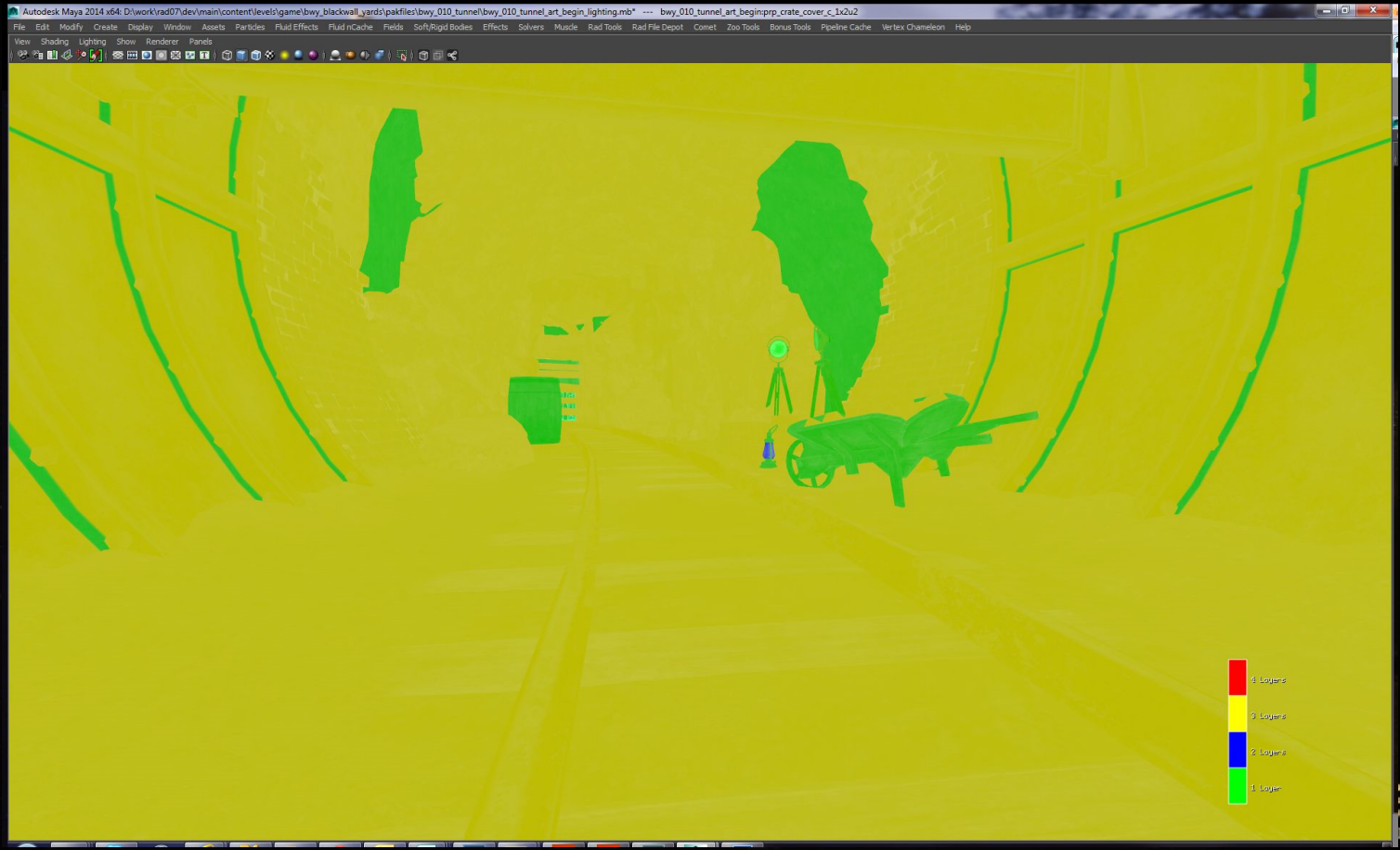
Material Layers



Material Layers



Material Layers



Material Layers

```
LayerParams combinedParams;

[unroll]
for(uint i = 0; i < NumLayers; ++i) {
    // Build all layer params from textures and hard-coded
    // material parameters
    LayerParams layerParams = GetLayerParams(i, MatParams, Textures);

    // Blend with the previous layer using vertex data and blend masks
    combinedParams = BlendLayer(combinedParams, layerParams, vtxData,
                                BlendMode, Textures);
}

// Calculate all lighting using the blended params
return ComputeLighting(combinedParams);
```

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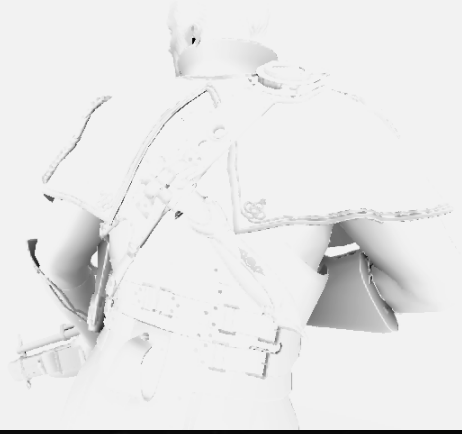

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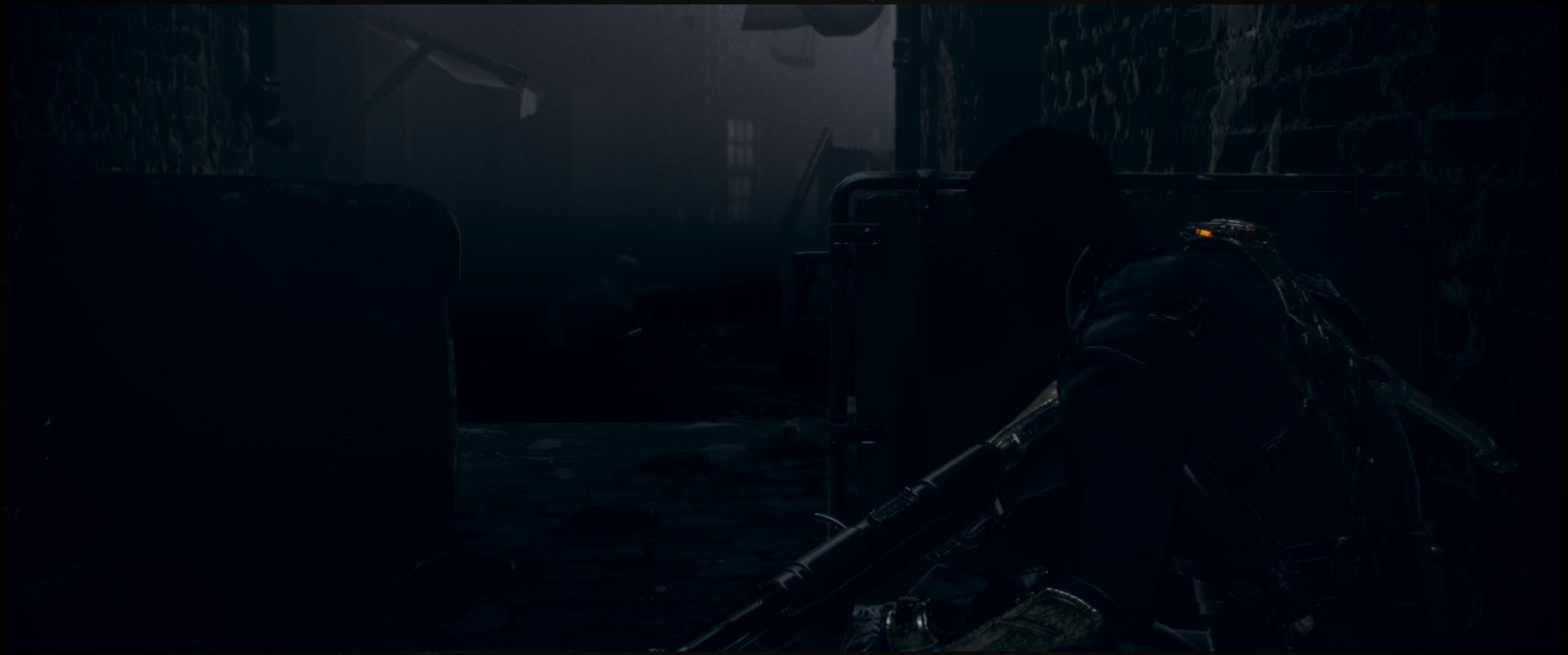
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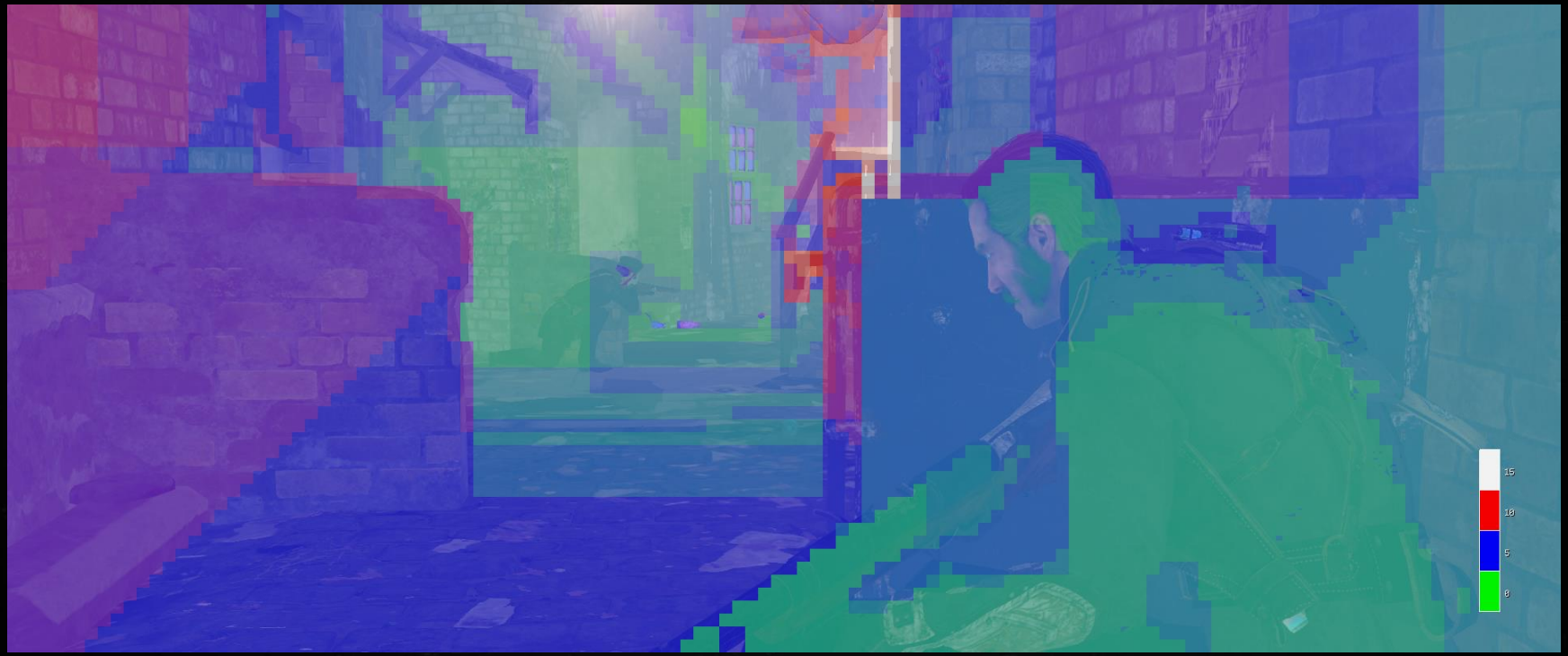

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Questions?