30 JULY – 3 AUGUST Los Angeles
SIGGRAPH2017

Practical Multilayered Materials

CALL OF DUTY
INFINITE WARFARE

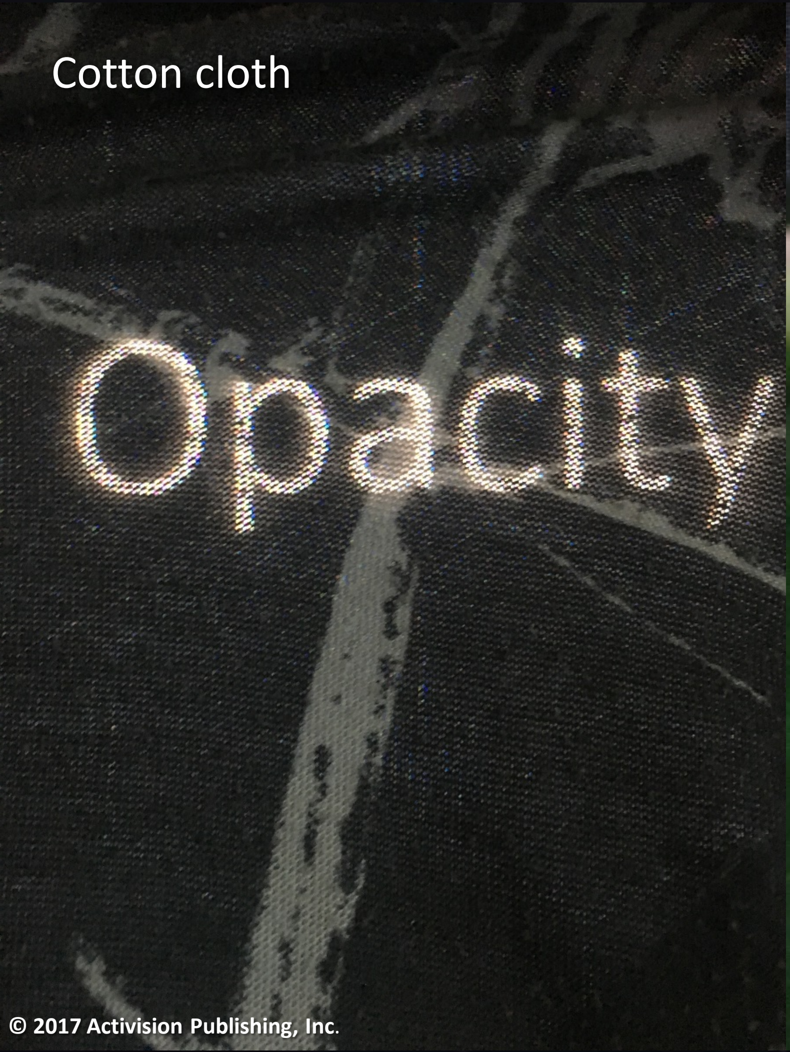
Michal Drobot
Principal Rendering Engineer

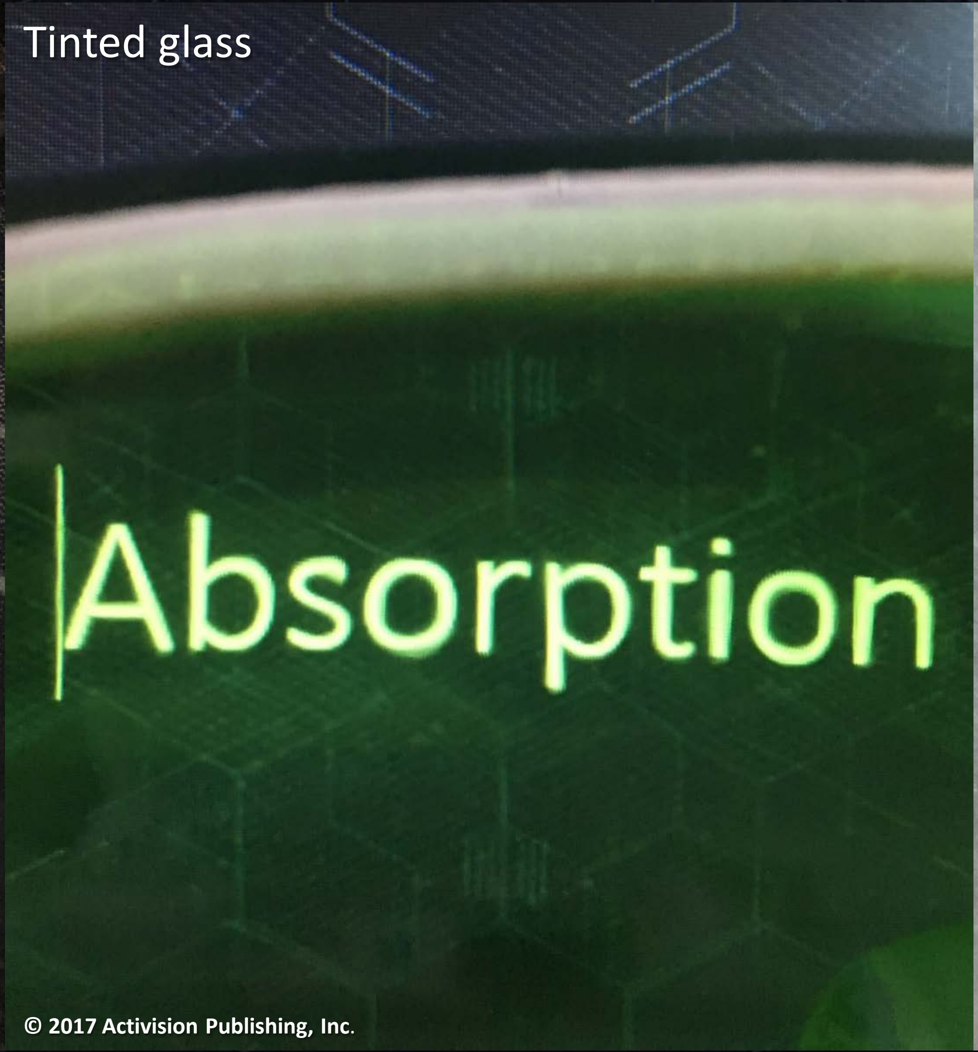
Adam Micciulla
Senior Rendering Engineer

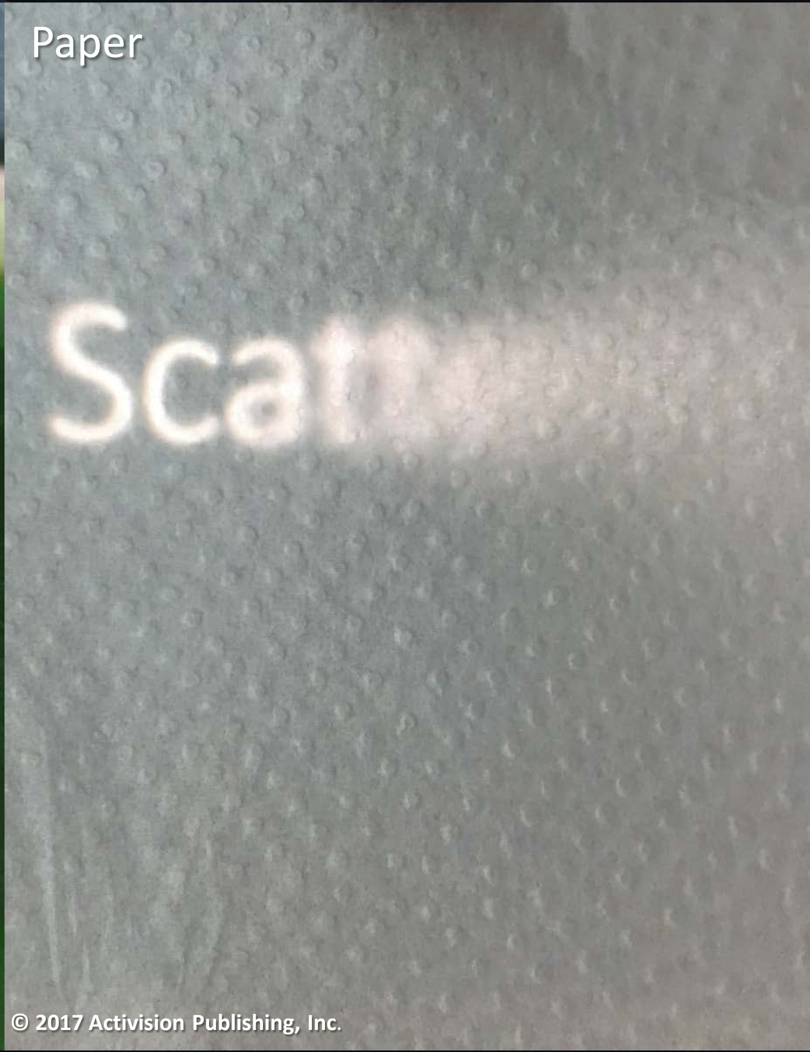
infinity ward ACTIVISION

Motivation

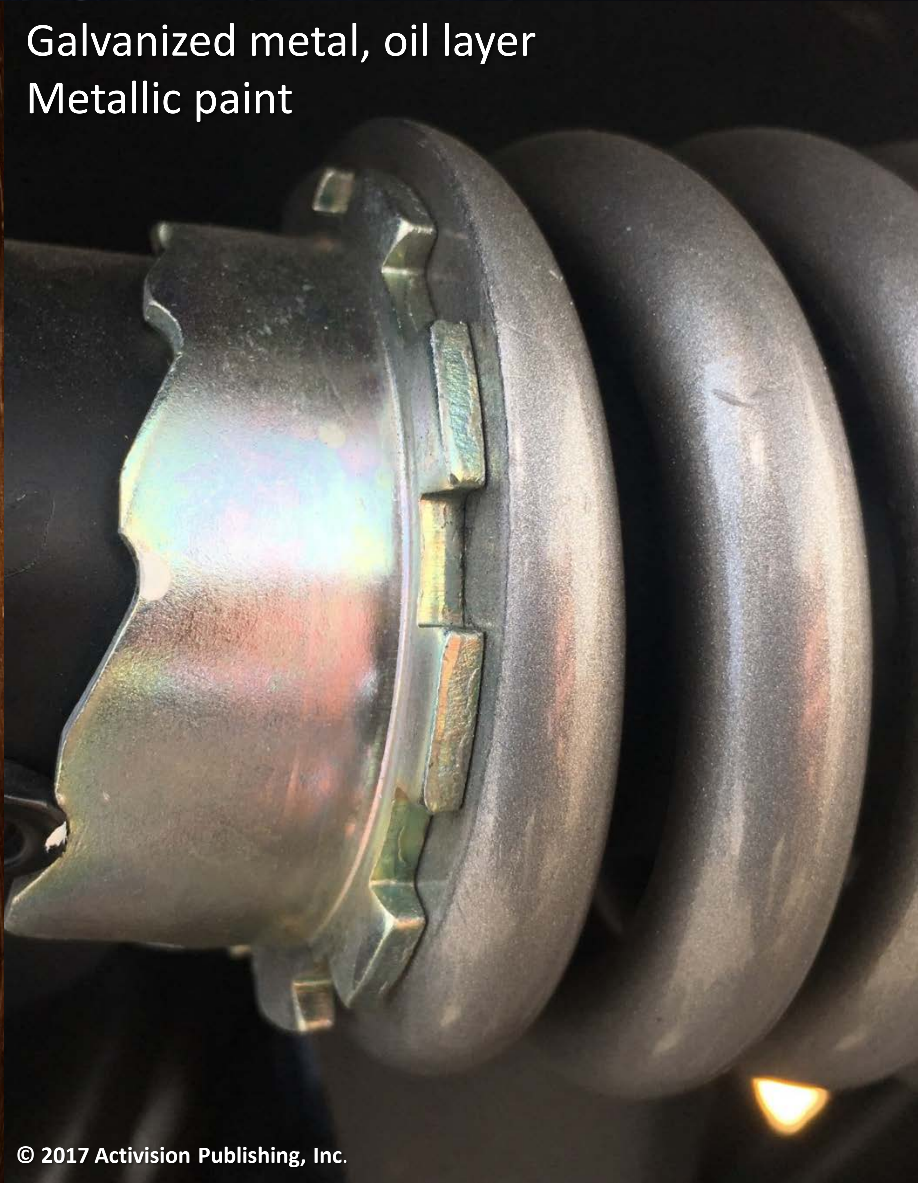
Opacity, Absorption, Scattering



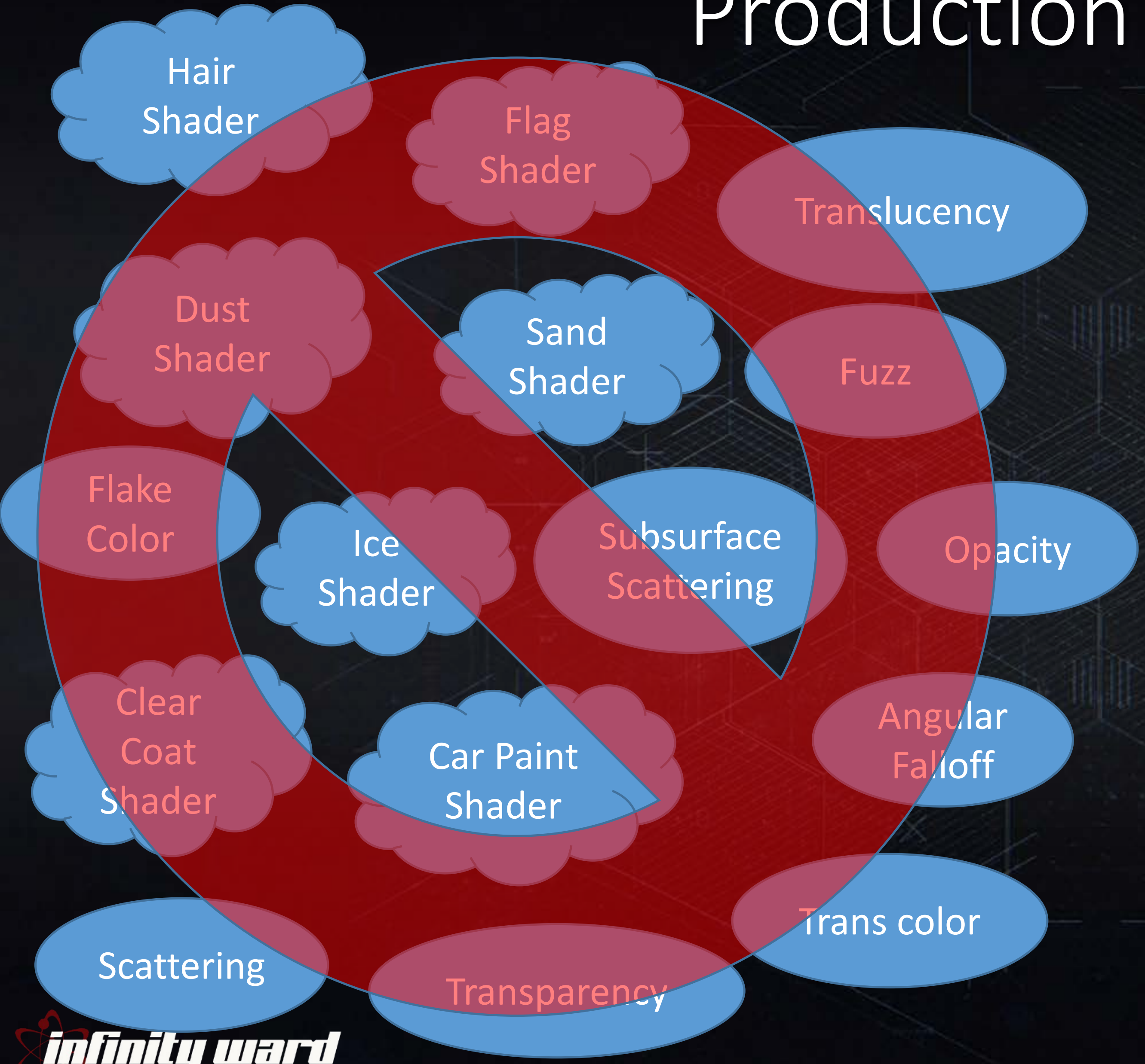




Complex Materials



Production Oriented



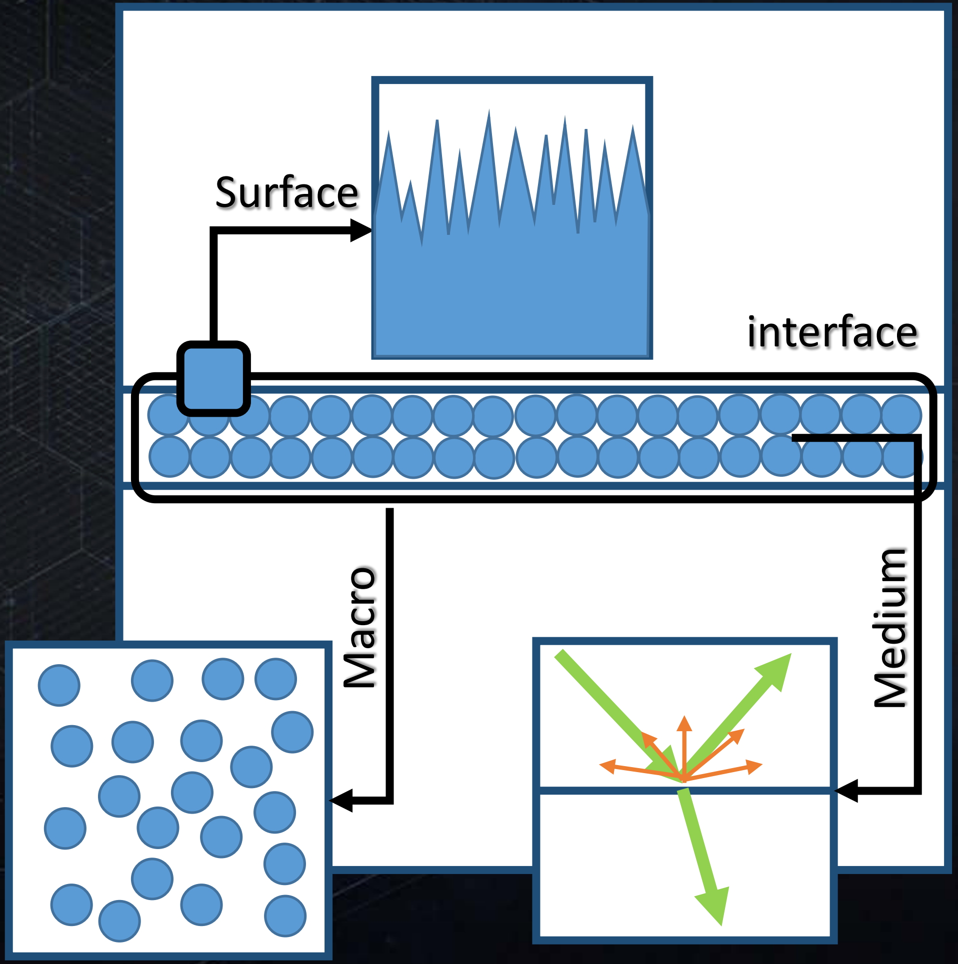
Unified Shading Model

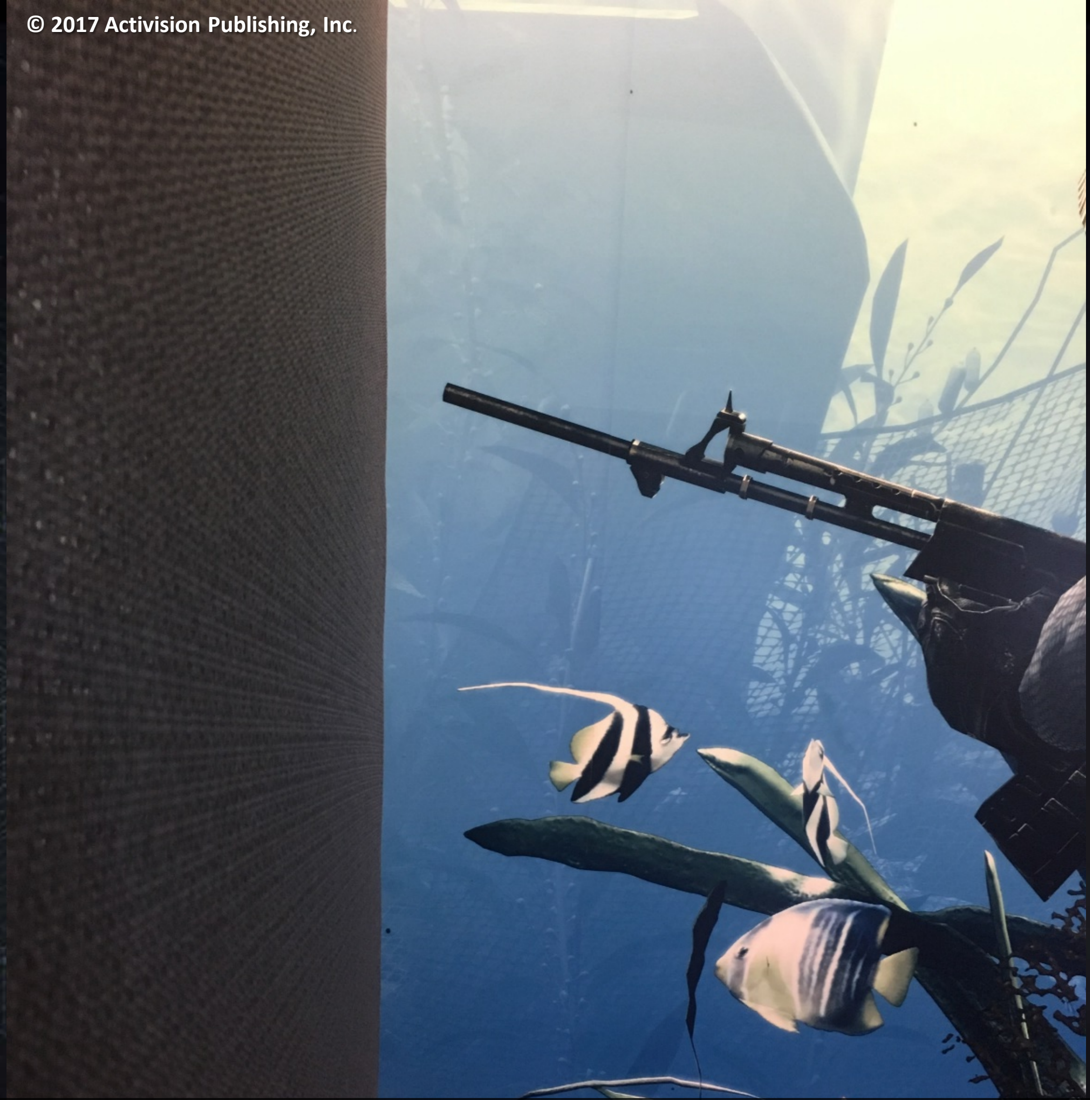
Unified Material Parametrization Model

Generalized Material Model

Generalized Material Model

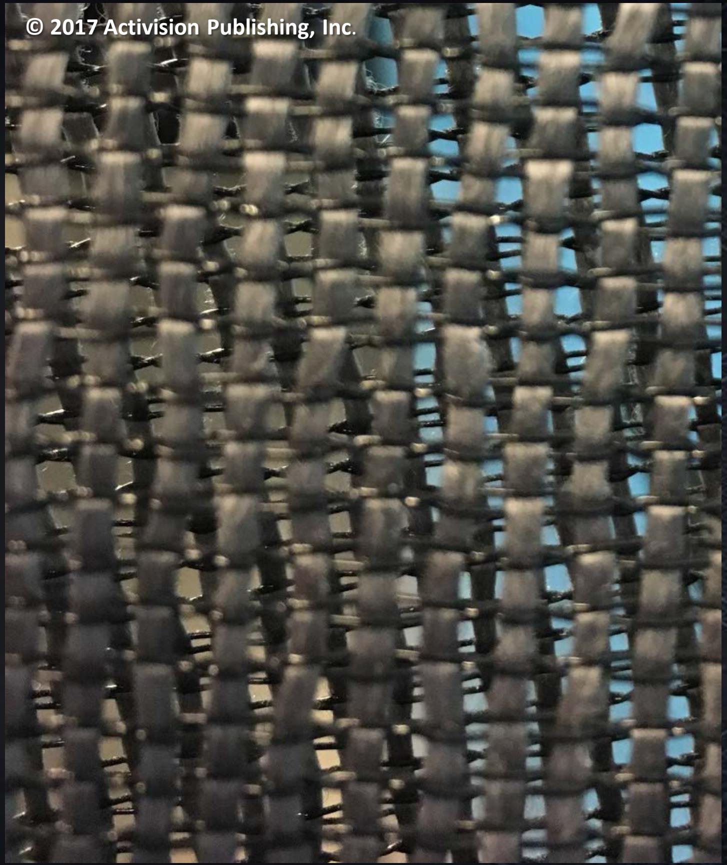
- Surface
  - Geometric structure at interface
- Macro
  - Geometric structure inside material
- Micro
  - Medium lighting model

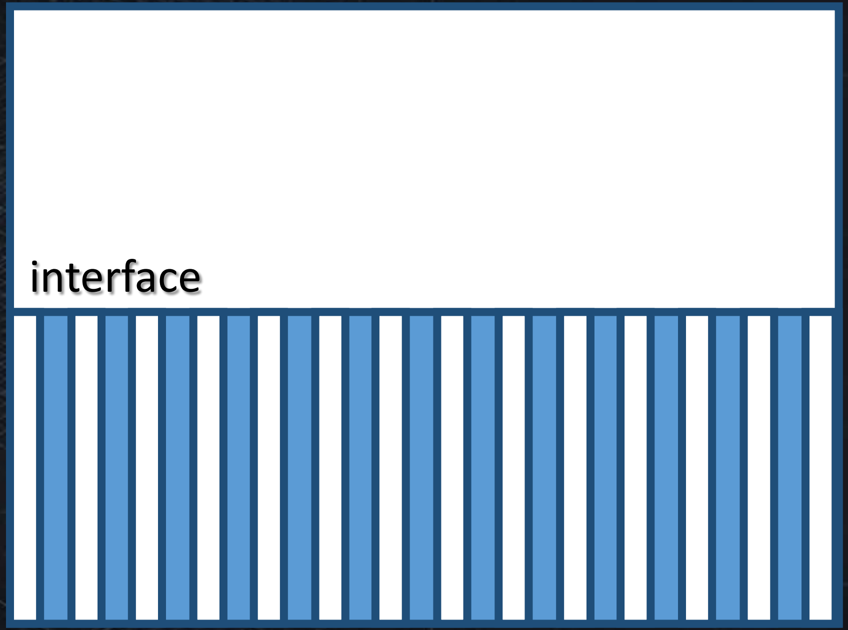




- Material with complex macro properties
  - Semi-opaque cloth
    - View dependent
    - Specular reflection remains

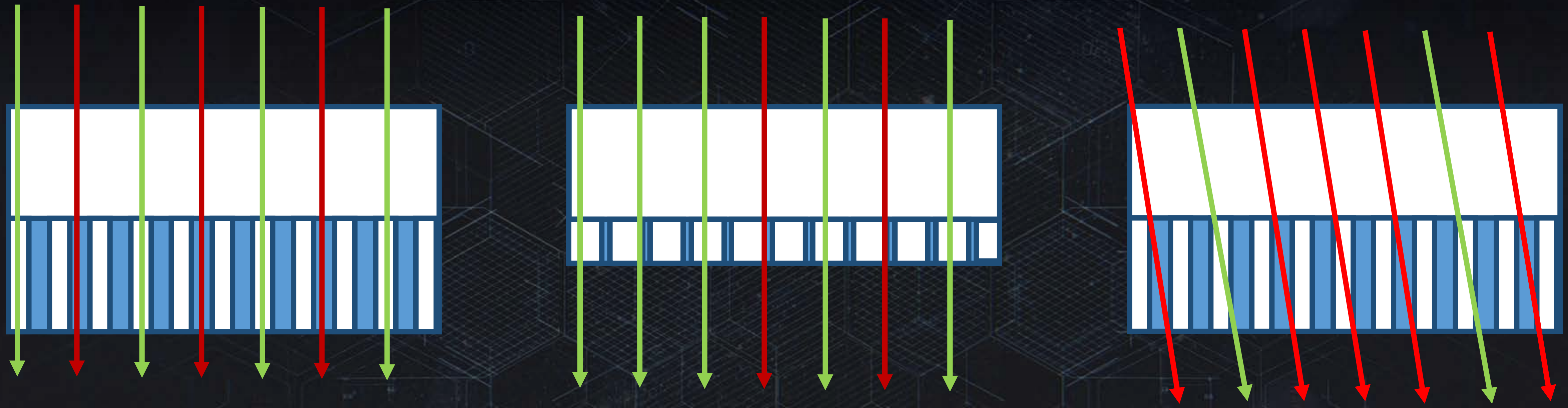
Macrostructure





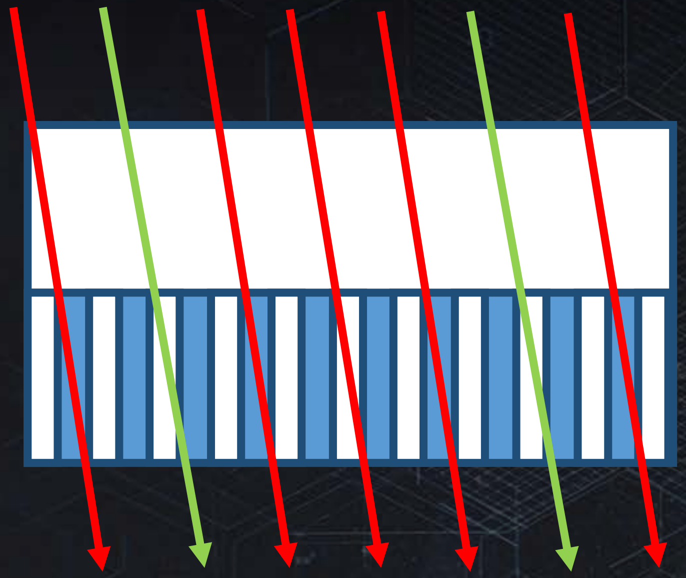
- Slice of cloth on macro level = tubes
- Density and length of tubes defines perceptual ‘opacity’

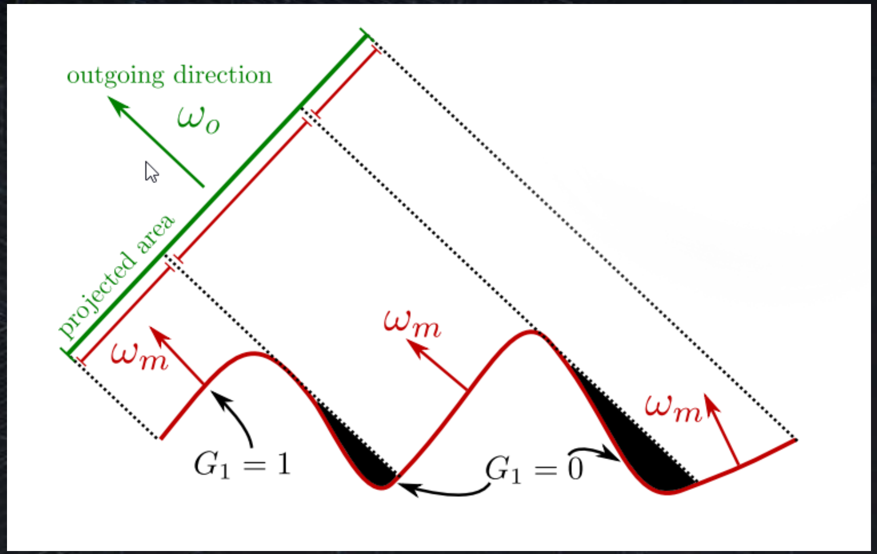
Physical Macrostructure



- Opacity is a function of view angle, density and thickness of tubes

Ad-hoc Physically Based Opacity





- Groove shadowing defines angular change in opacity
    - Inverse of Smith-Schlick Geometric Shadowing [HEI14]
- Macro groove layout implicitly given by ***density***
- Macro groove amplitude given by material ***thickness***

Simple opacity alpha

Simple opacity alpha

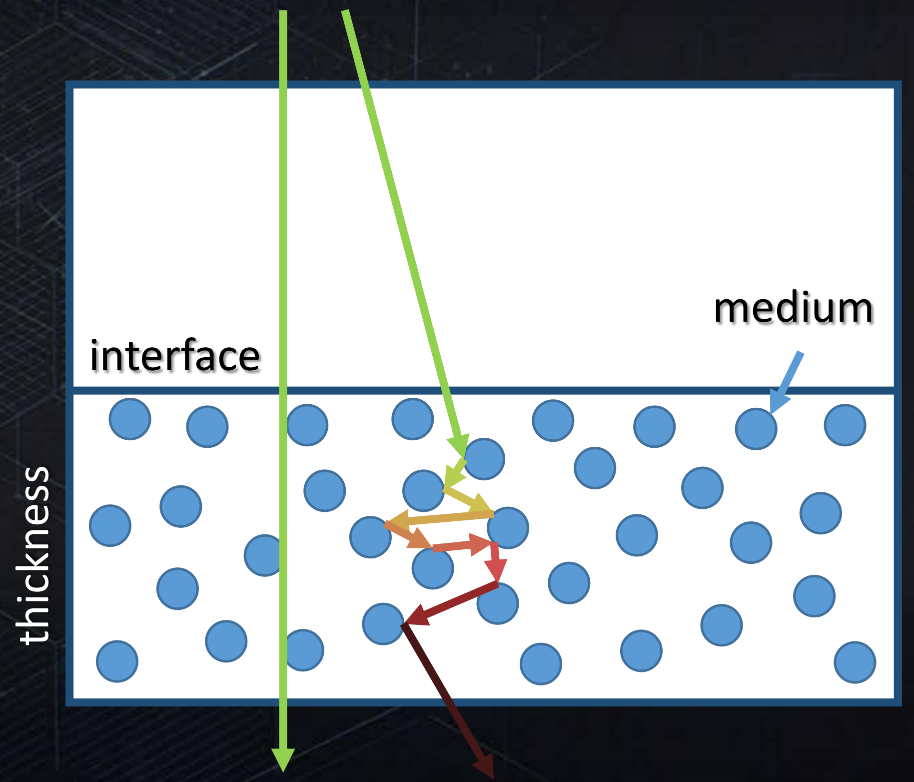
Geometric opacity: thin surface

Geometric opacity: thick surface

```
float PhysicallyBased_GeometricOpacity( float NdotV, float alpha, float t ) // t - thickness
{
  float x = NdotV;
  float g = 1.0f - ( x / ( x * ( 1.0 - t ) + t ) ); // Smith-Schlick G
  return lerp( alpha, 1.0f, g ); // base opacity lerp to ‘shadowed’. Counteracts opacity change due to mips
}
```

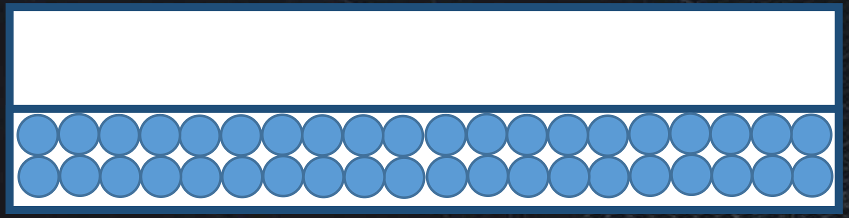
Generalized Macrostructure

- Material macro physical properties
  - *Density*
  - *Thickness*
- Opacity – derived from macro properties
  - Probability of ray passing through material on macro level
  - ***Affects whole BRDF (Diffuse & Specular)***
- Macro level scattering & absorption
  - Assumption - macro level does not influence micro level
  - Future research [HEI16]

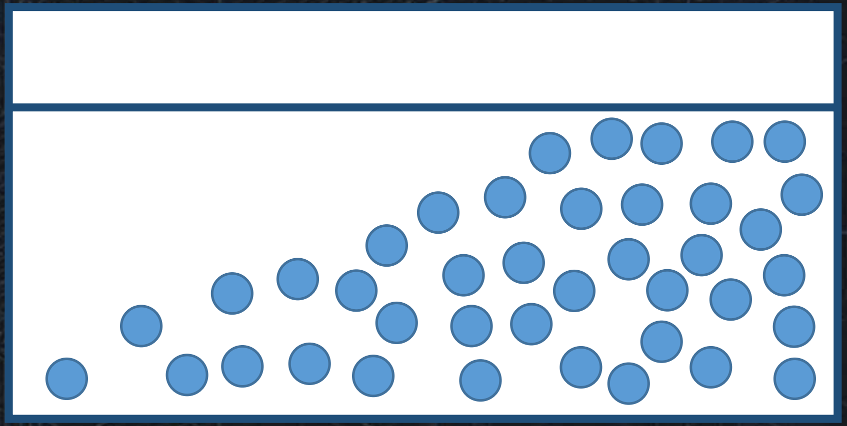


Generalized Macrostructure

- PCV
  - *Density* = 1
  - *Thickness* irrelevant

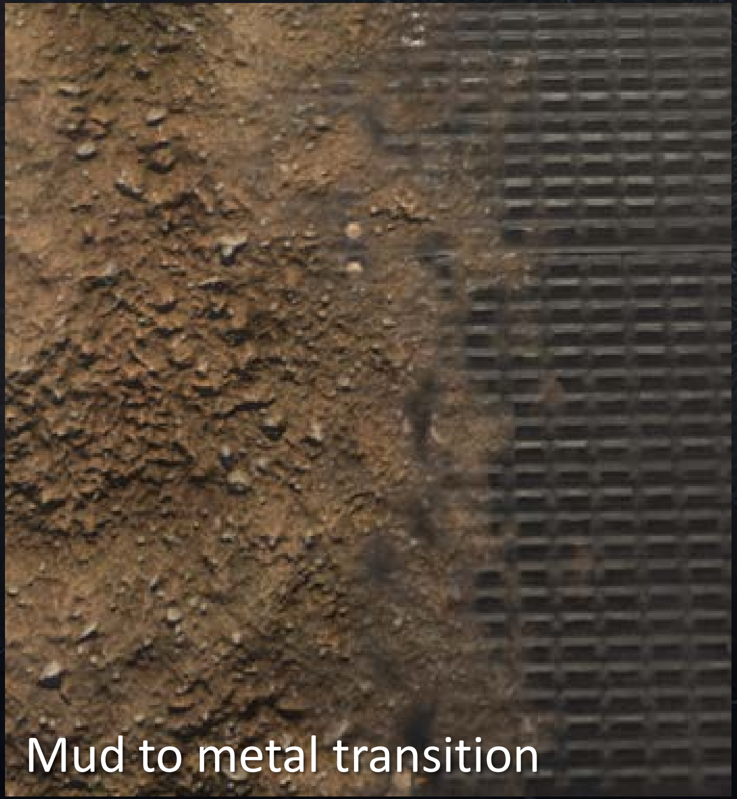


- Salt transition
  - *Density* < 1
  - *Thickness* relevant

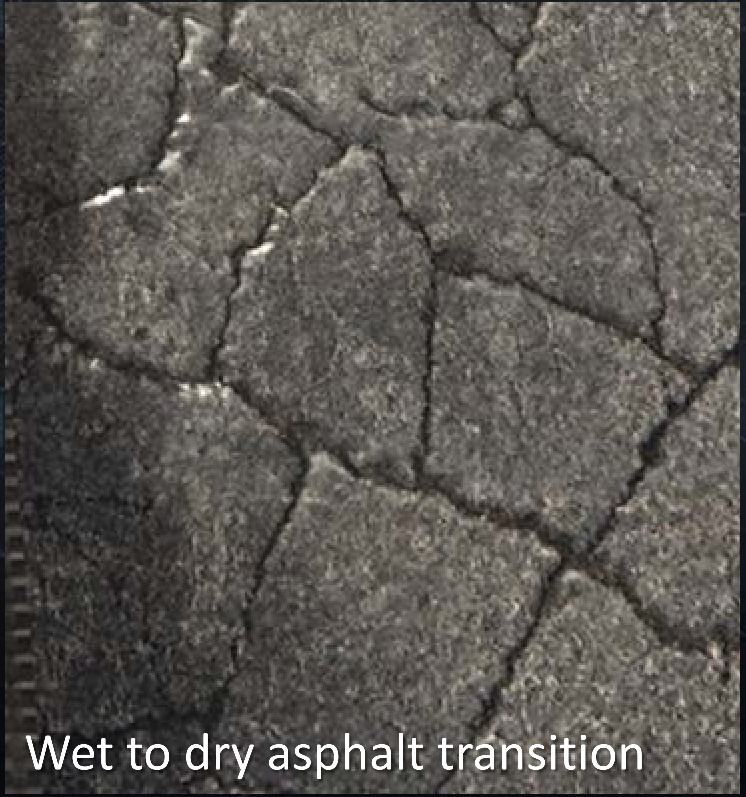


Generalized Macrostructure for Material Blending

- Density used for partial ‘material blend’ or ‘semi-opaque’ materials
- Heightfield as ‘thickness’ for height field blending [DRO10]



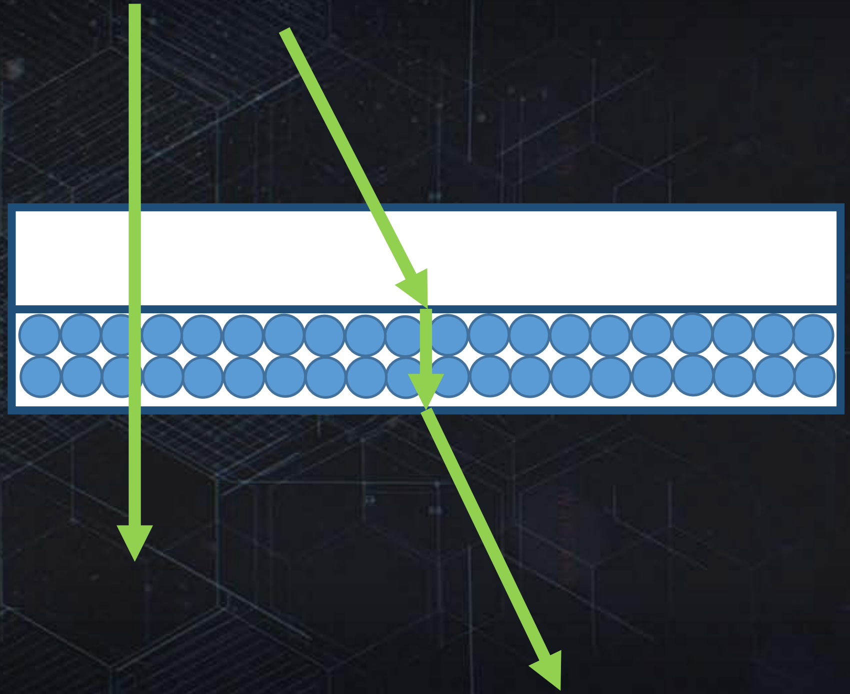
Mud to metal transition



Wet to dry asphalt transition

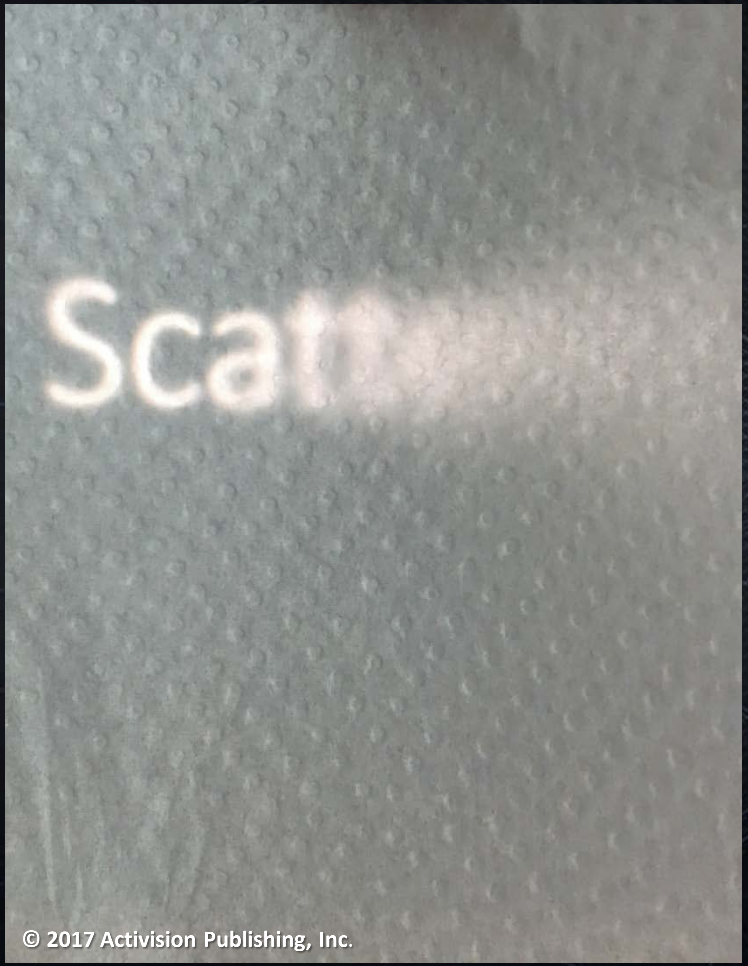
Microstructure

- Colored Glass
  - *Density* = 1
  - *Thickness* - relevant
  - *Medium IOR* - refraction



Microstructure

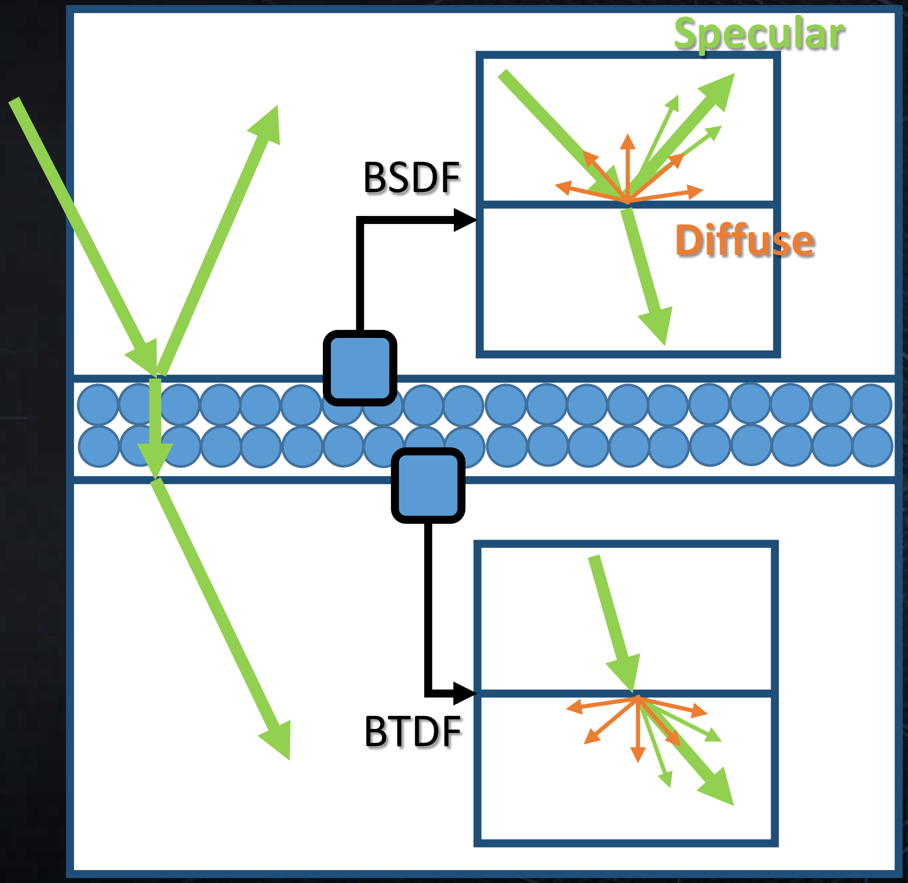
Thin Paper



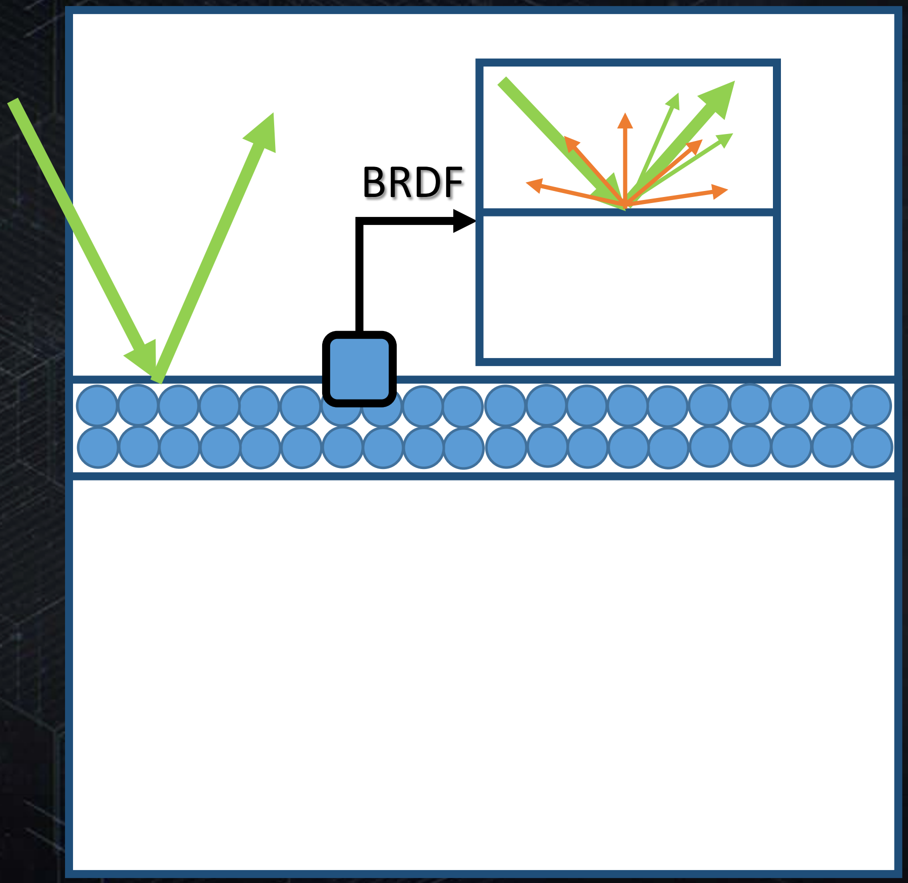
Solid Wood

Microstructure

Thin Paper

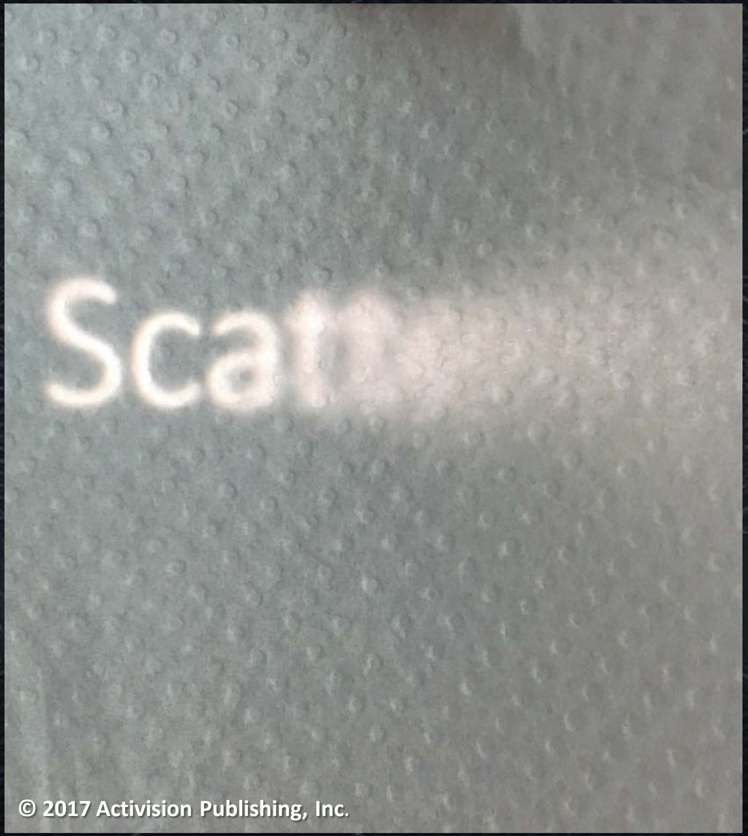


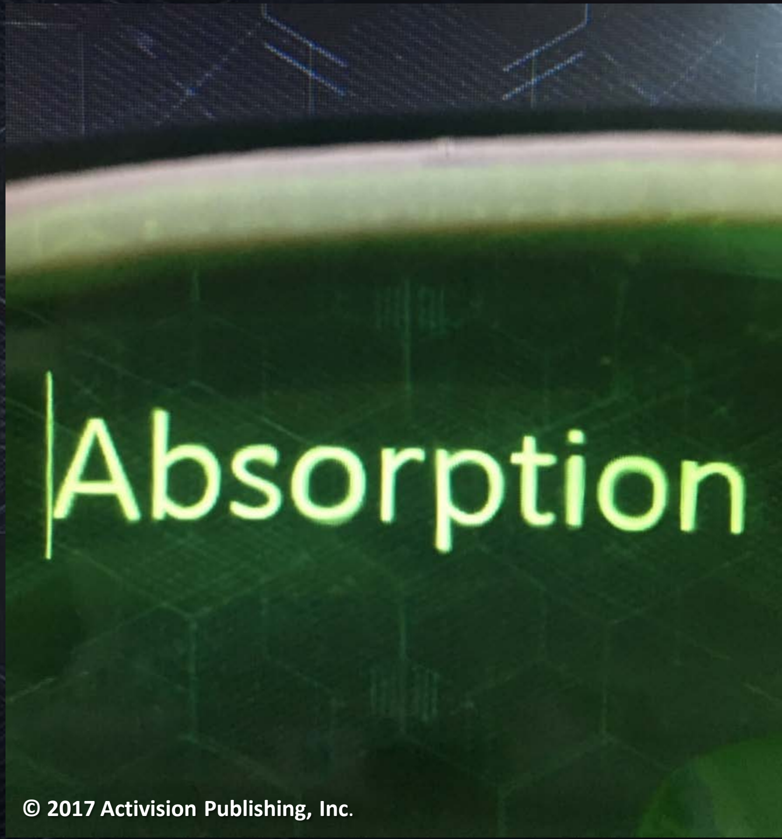
Solid Wood

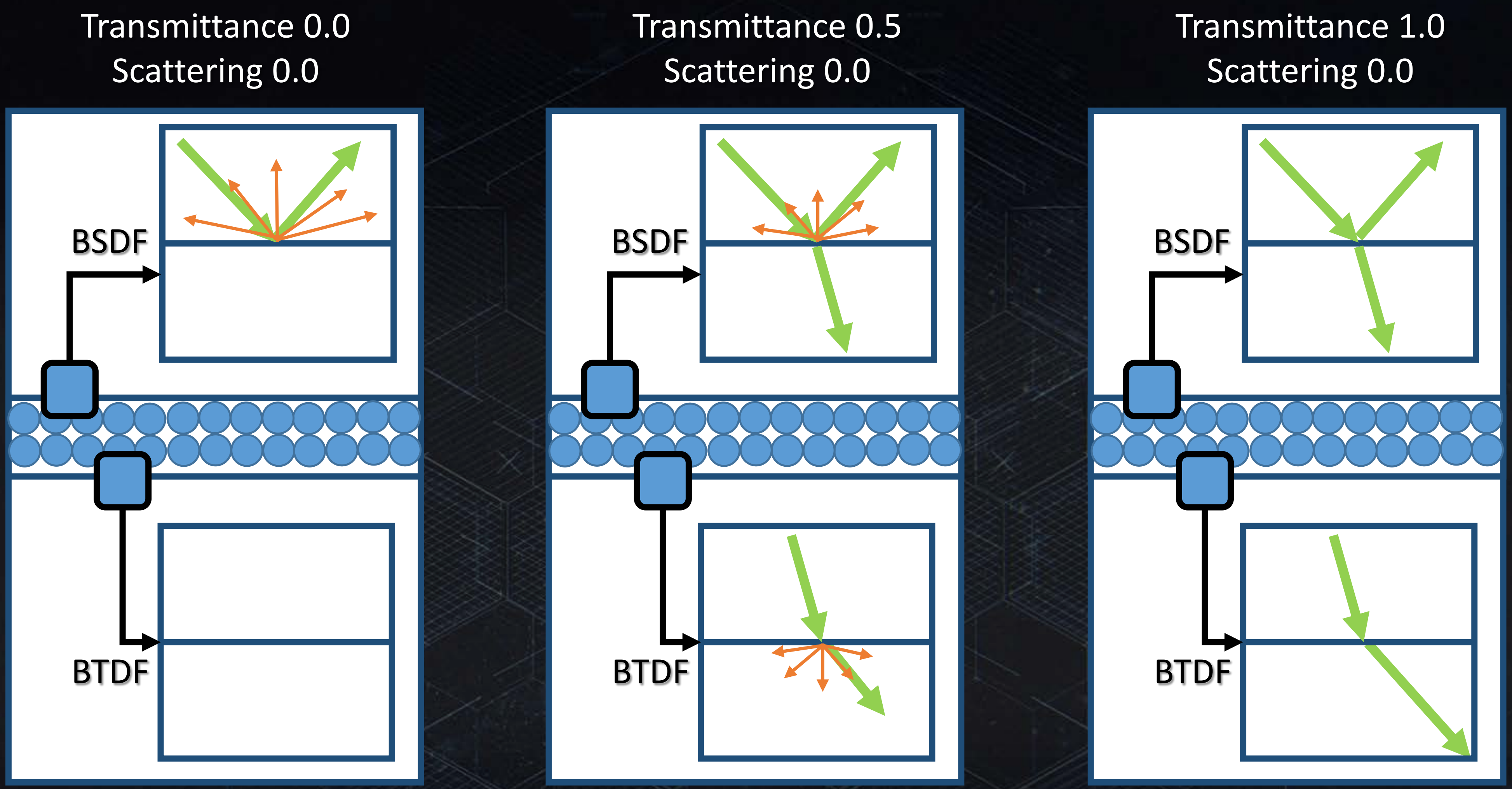


Microstructure

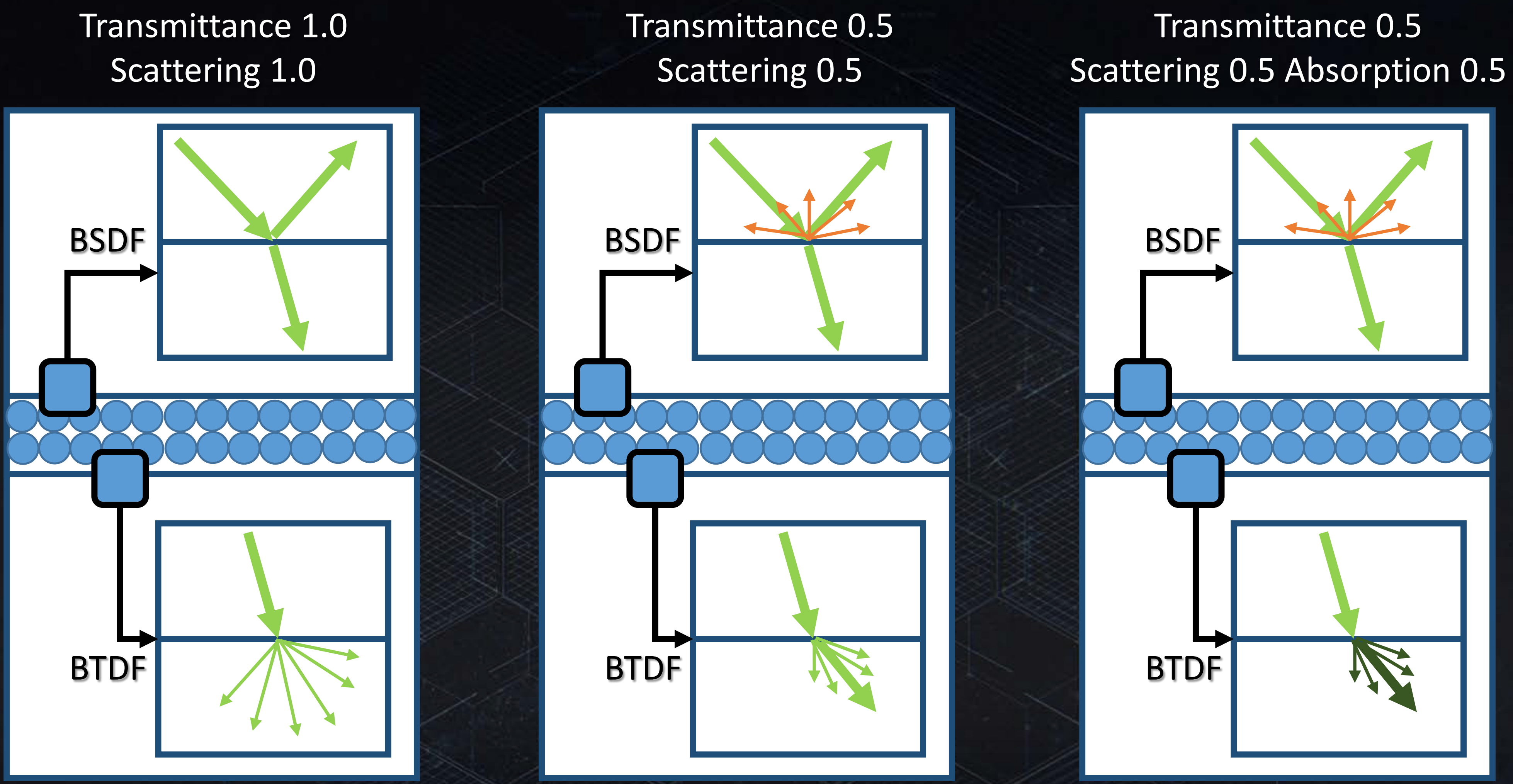
- Material micro physical properties (medium)
  - *Absorption*
  - *Scattering*
  - *IOR*
  - *Transmittance*
  - *Other BRDF properties*
- Conceptually similar to mix of volume and surface rendering [DUP16]







- Simple BSDF
  - *Transmittance* defines amount of diffuse energy that will be transmitted past medium interface

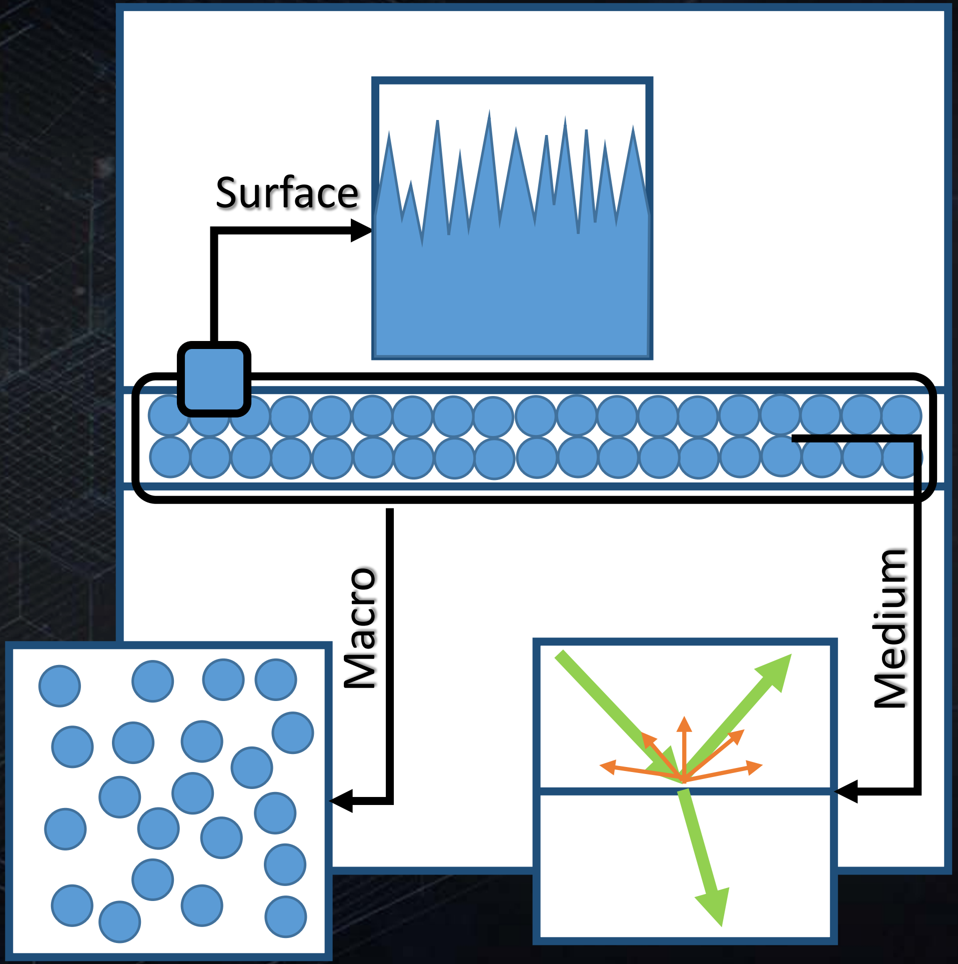


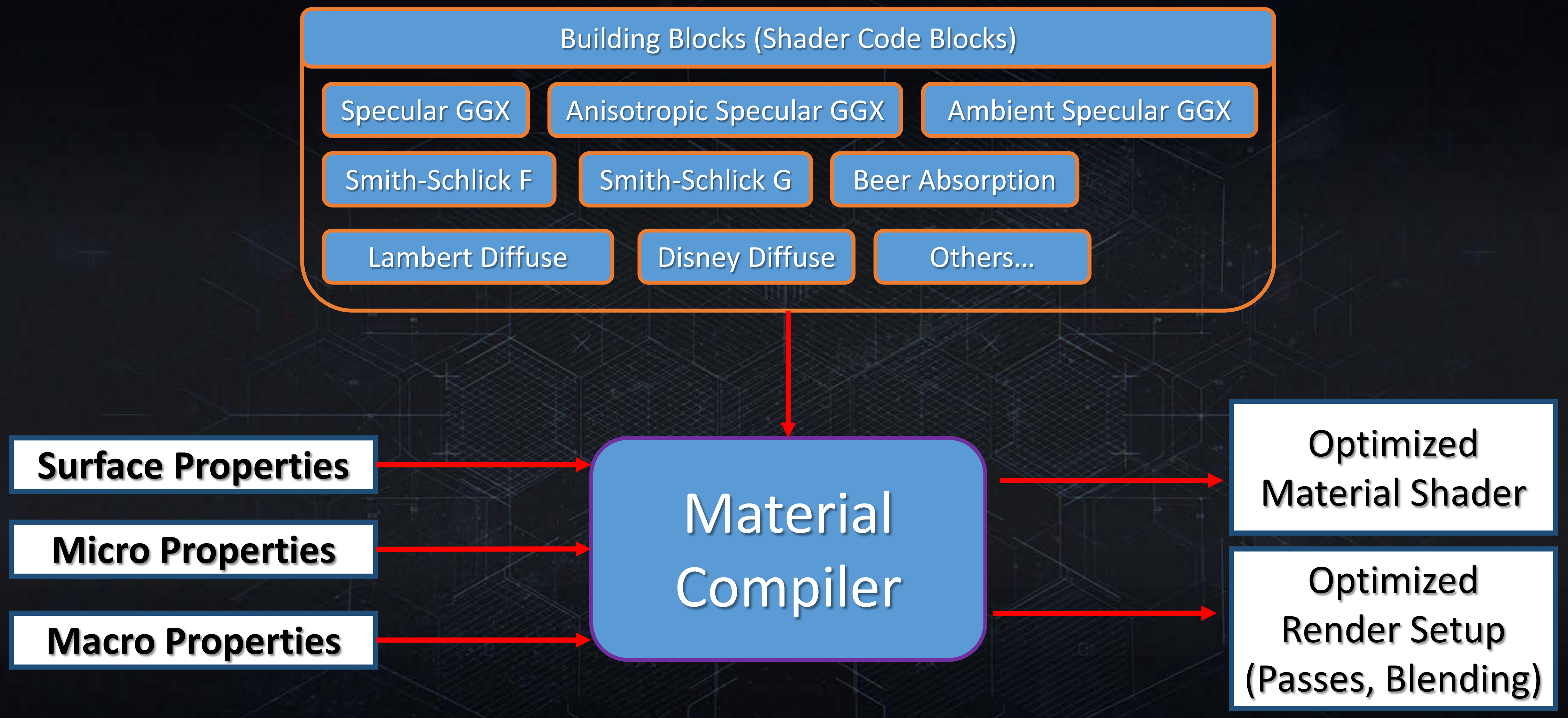
- Simple BTDF
  - Surface *roughness* and medium *scattering* define ray scattering on material exit
  - Medium *absorption* and ray length (macro *thickness* and ray angle) define ray absorption
    - Beer-Lambert Law

Material Compiler

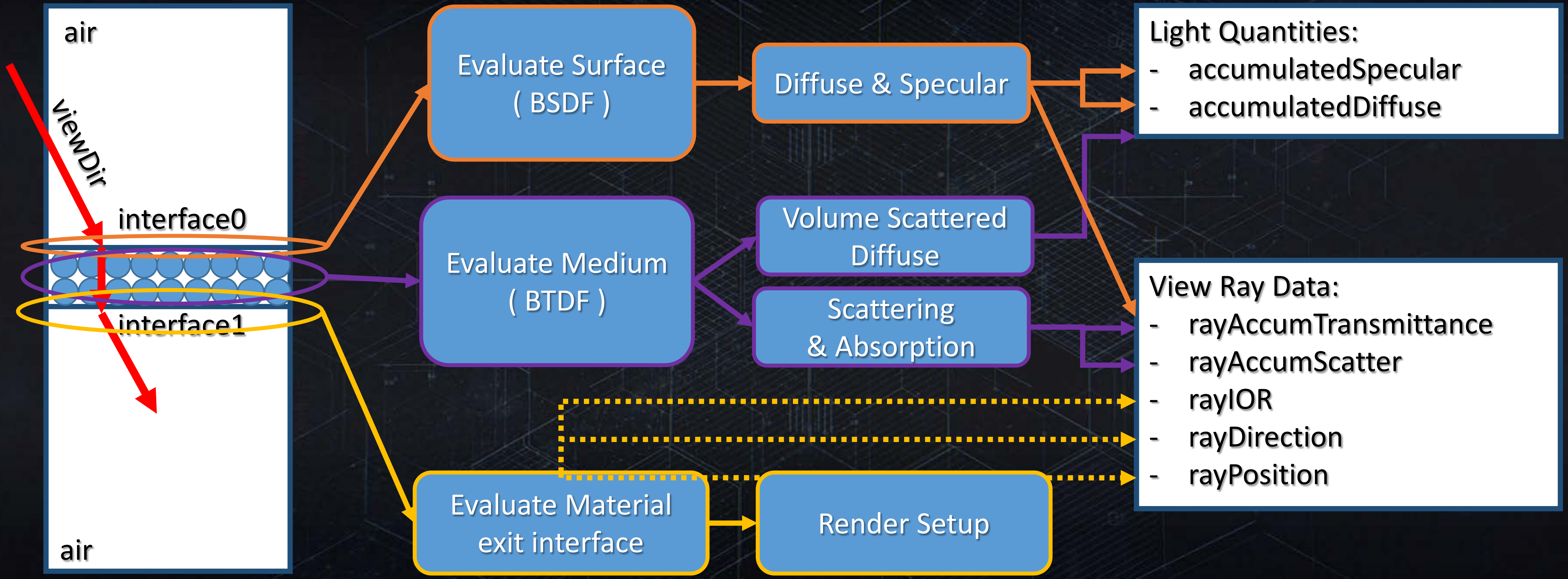
Art-Oriented Material Definition [BUR12]

- Surface (structural)
  - Normal
  - Roughness
- Macro (structural)
  - Density
  - Thickness
- Micro (medium)
  - Albedo
  - Sheen
  - Specular Color (IOR derived [BUR15])
  - Anisotropy
  - Transmittance
  - Absorption color (at distance [BUR15])
  - Scattering (at distance 'roughness' units)



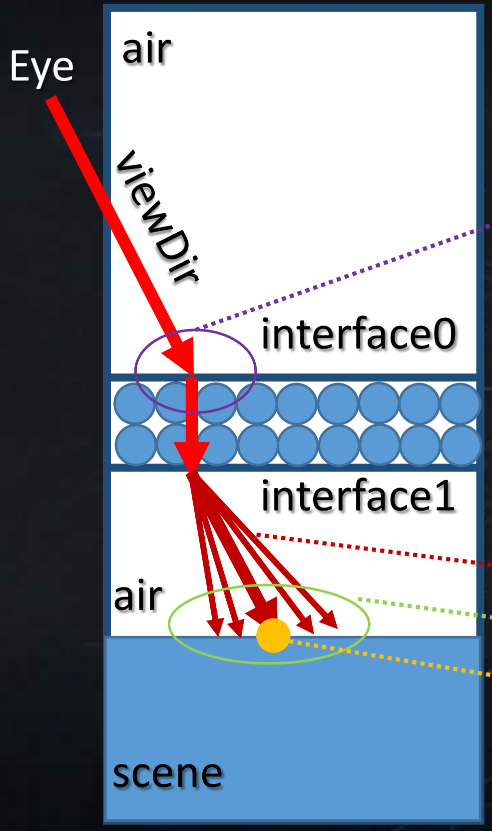

Building Blocks (Shader Code Blocks)
Specular GGX
Anisotropic Specular GGX
Ambient Specular GGX
Smith-Schlick F
Smith-Schlick G
Beer Absorption
Lambert Diffuse
Disney Diffuse
Others…
Surface Properties
Micro Properties
Macro Properties
Material Compiler
Optimized Material Shader
Optimized Render Setup (Passes, Blending)

Path-Based Material Evaluation



Blending

View Ray Entering the Medium

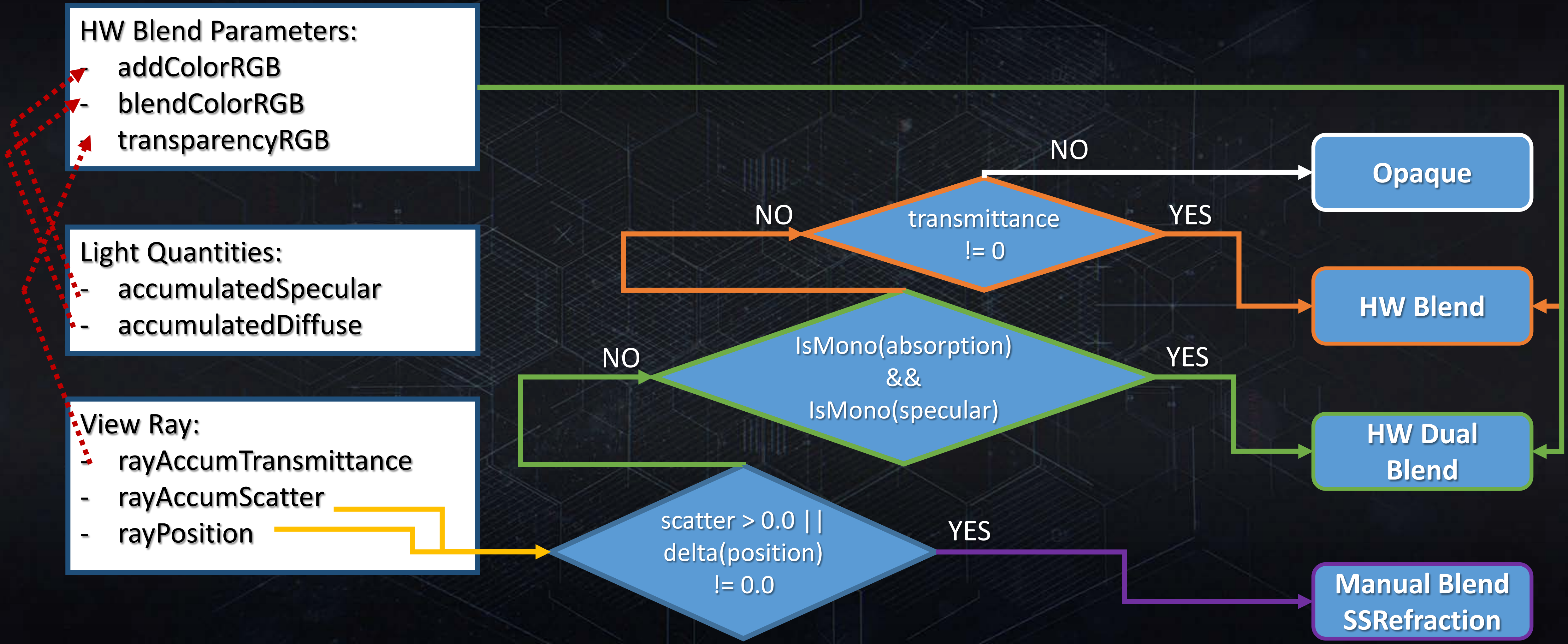


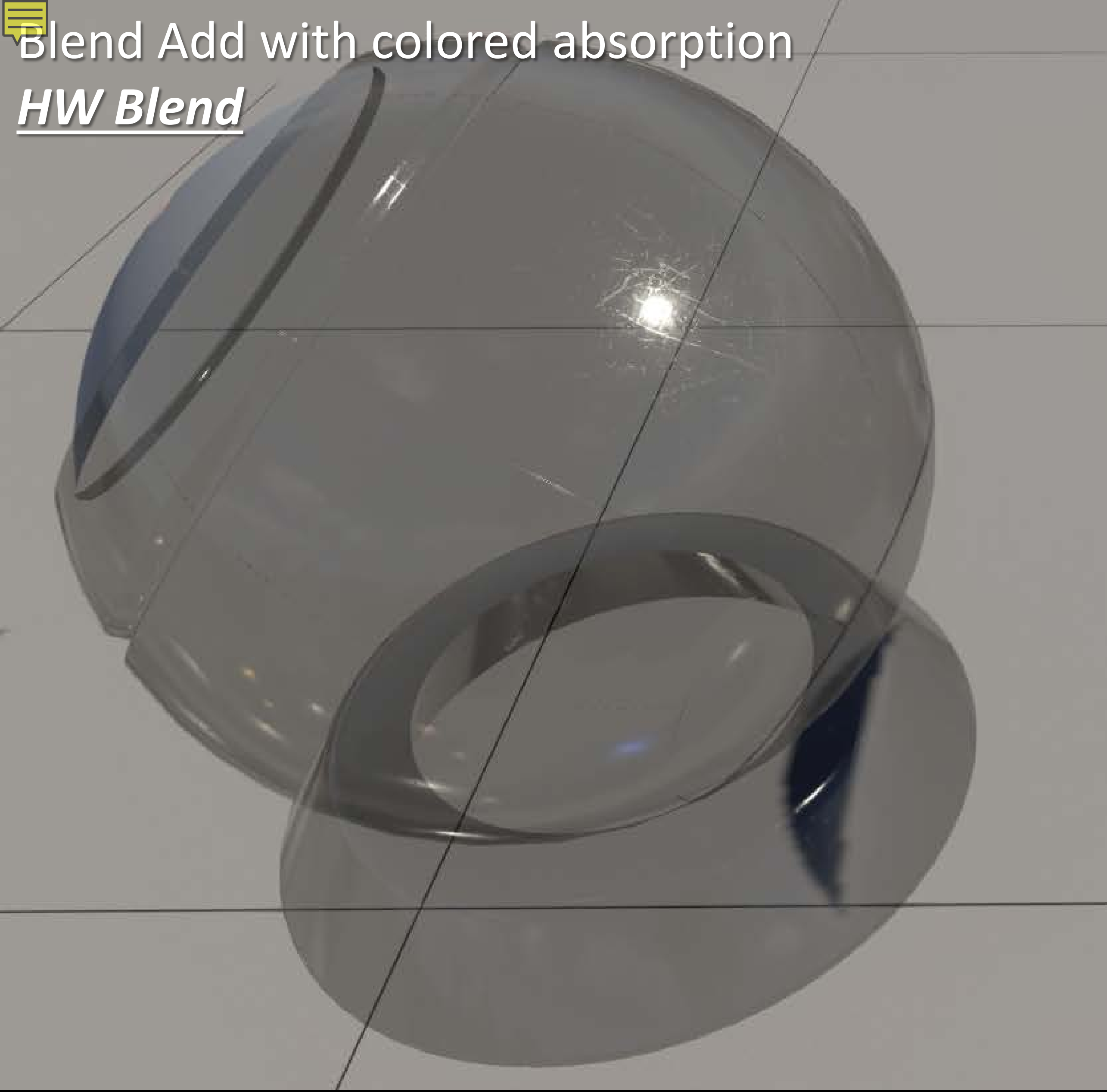
Light quantities (in eye dir):
- accumulatedSpecular
- accumulatedDiffuse

View Ray (at medium exit):
- rayAccumTransmittance
- rayAccumScatter
- rayPosition

```
Light  = specular +
         diffuse * (1.0f – transmittance)+
         Integral(scene(position), scattering)*
         transmittance
```

Material Compiler Blend Setup





Correct specular
Incorrect transmission

Correct specular
Correct transmission

```
// Pre-Multiplied Alpha
#if USE_BLENDFUNC_BLEND_ADD_RGB
    #define TRANS_TYPE float3
    struct PixelOutput{ float3 color :SV_TARGET0;
                        float3 color1 :SV_TARGET1; };
#elif USE_BLENDFUNC_BLEND_ADD
    #define TRANS_TYPE float
    struct PixelOutput{ float4 color :SV_TARGET0; };
#endif

PixelOutput GetBlendingOutput( float3 blendColor, float3 addColor,
                               TRANS_TYPE trans ) {
    PixelOutput fragment = ( PixelOutput) 0;
    float3 blend            = blendColor;
    float3 add              = addColor;
#if USE_BLENDFUNC_BLEND_ADD_RGB
    fragment.color1.rgb  = trans;
#elif USE_BLENDFUNC_BLEND_ADD
    fragment.color.a     = trans;
#endif
     fragment.color.rgb  = blend * trans + add;
     return fragment; }
```

HW Dual Blend
BLEND_ADD_RGB

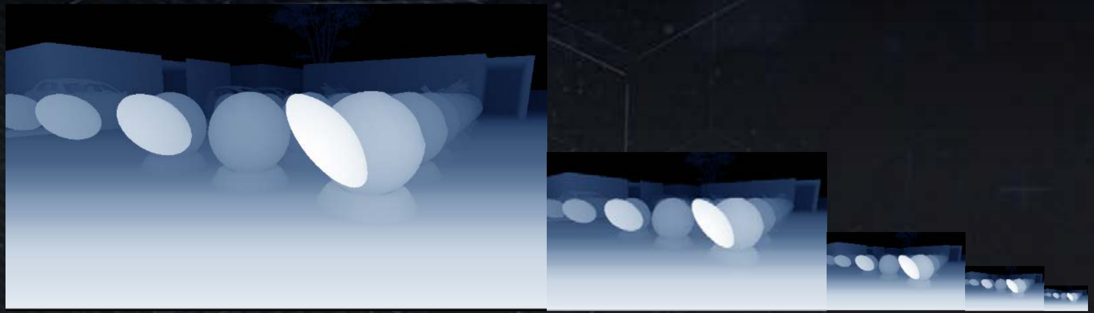
rgbOp	rgbSrc	rgbDst	aOp	aSrc	aDst
ADD	ONE	INV_SRC_ COLOR1	DISABLED	ONE	ZERO

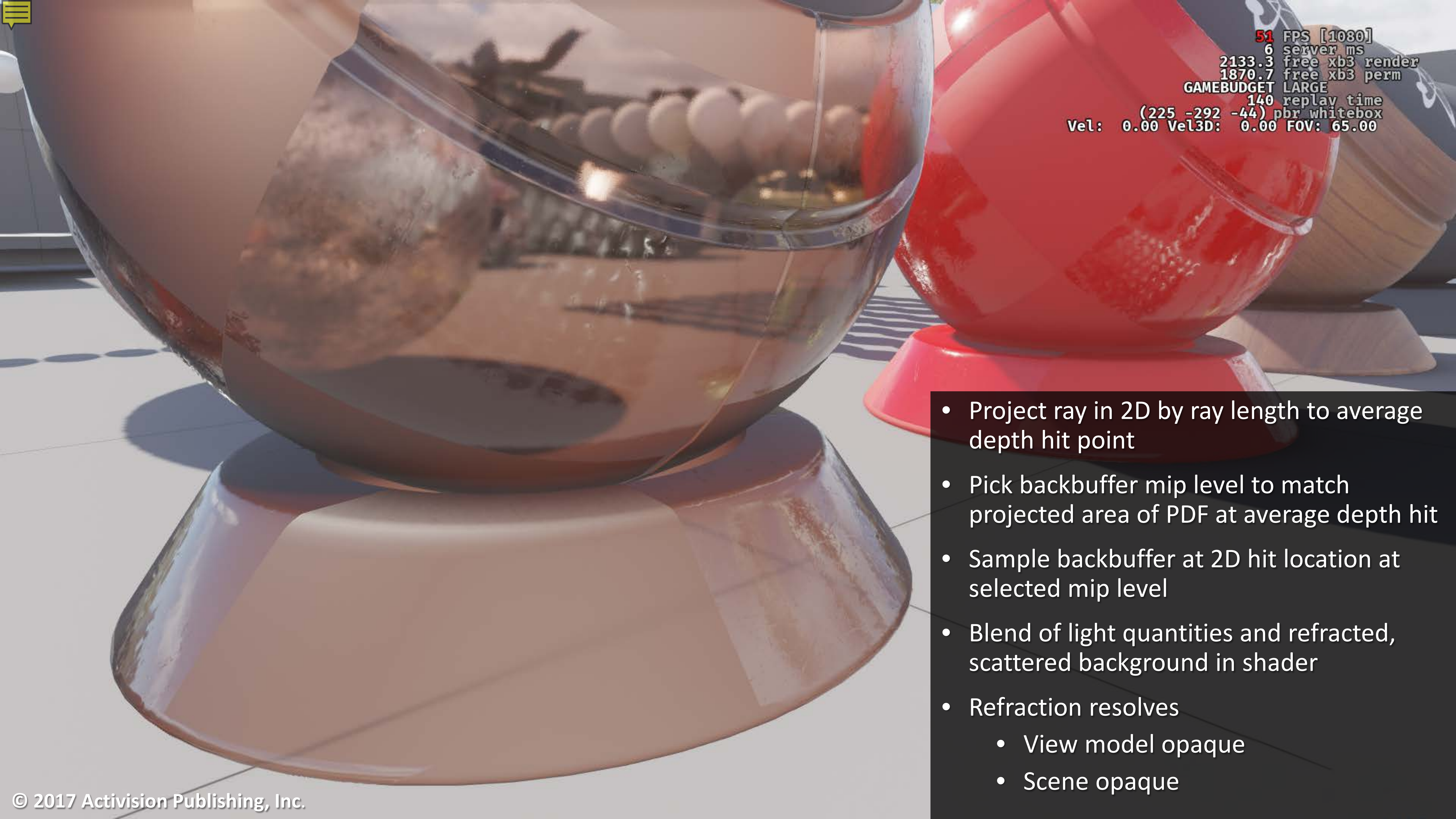
HW Blend
BLEND_ADD

rgbOp	rgbSrc	rgbDst	aOp	aSrc	aDst
ADD	ONE	INV_SRC_ ALPHA	DISABLED	ONE	ZERO

Manual Blend Screen Space Refraction

- rayScattering -> PDF [STA15]
- Calculate projected area of PDF
  - Re-use IBL filtering math
  - Re-use Glossy Screen Space Reflection math
- Pick depth pyramid mip
  - Projected area at short distance (~1m)
- Importance sample depth (using PDF)
  - Jittered/dithered
  - Averaged depth
- Pre-filter backbuffer into pyramid
  - PDF based importance sampling for each mip
  - Re-use pre-filtered IBL processing [MAN16]

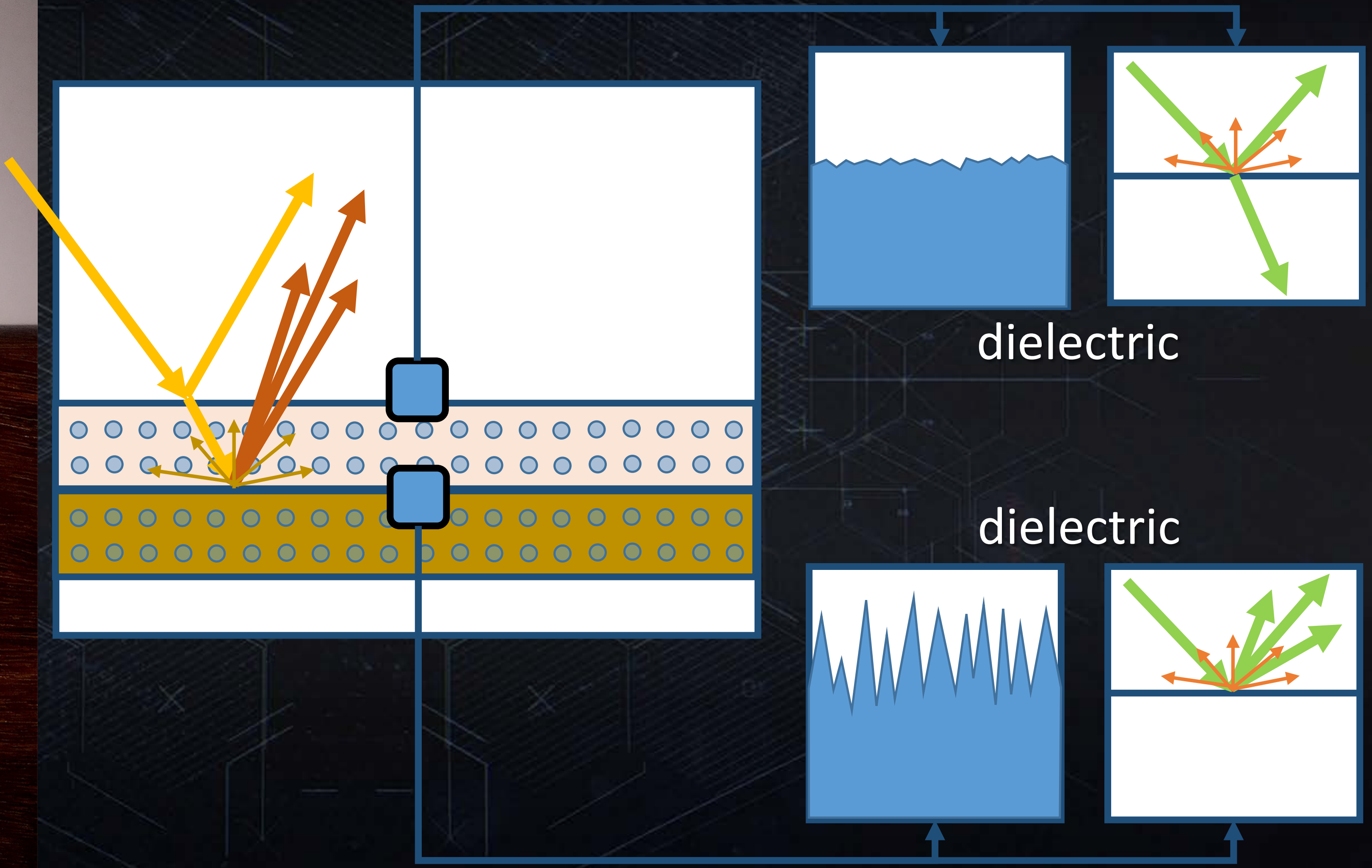




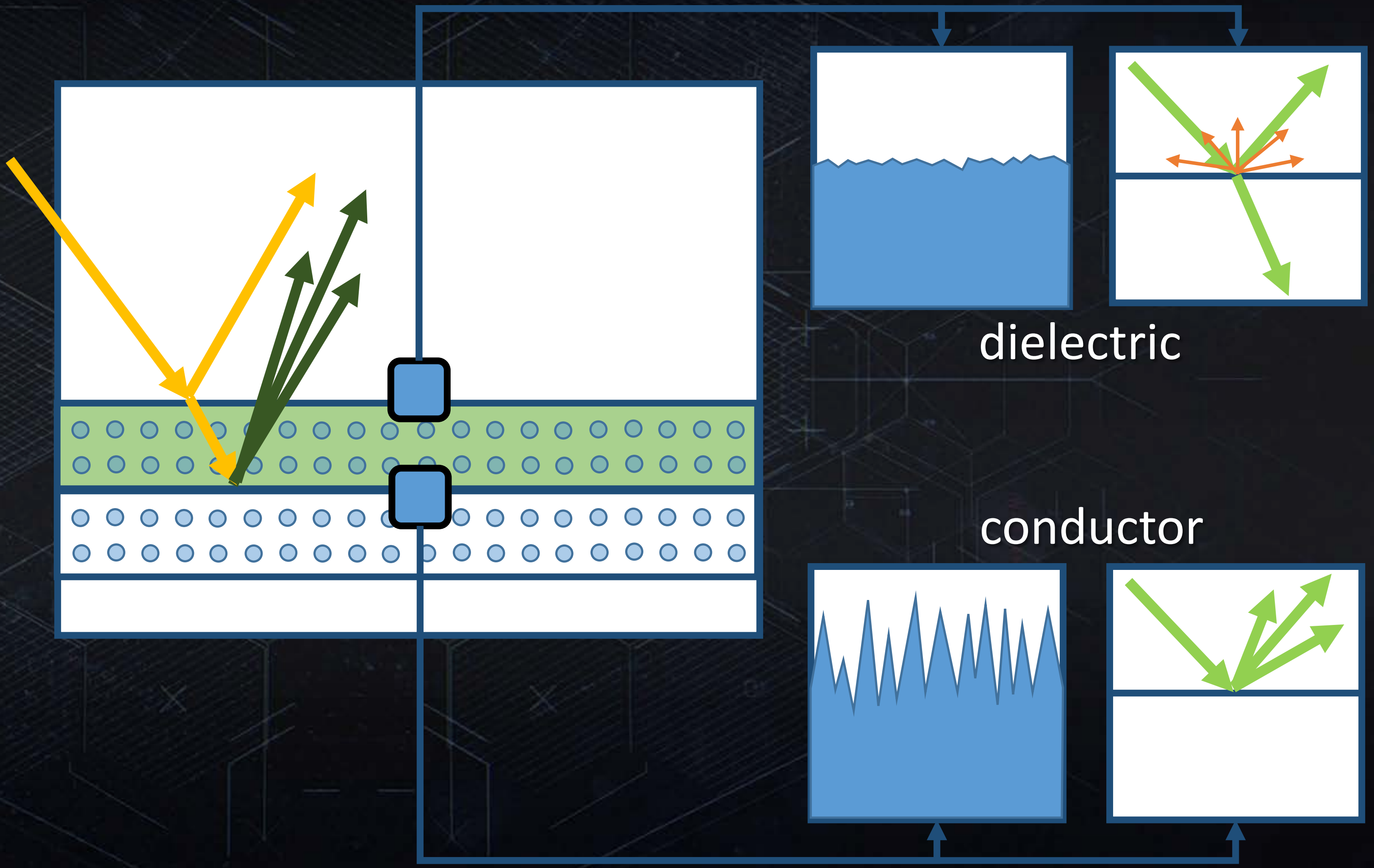
- Project ray in 2D by ray length to average depth hit point
- Pick backbuffer mip level to match projected area of PDF at average depth hit
- Sample backbuffer at 2D hit location at selected mip level
- Blend of light quantities and refracted, scattered background in shader
- Refraction resolves
  - View model opaque
  - Scene opaque

Multilayered Materials

Surface Decomposition

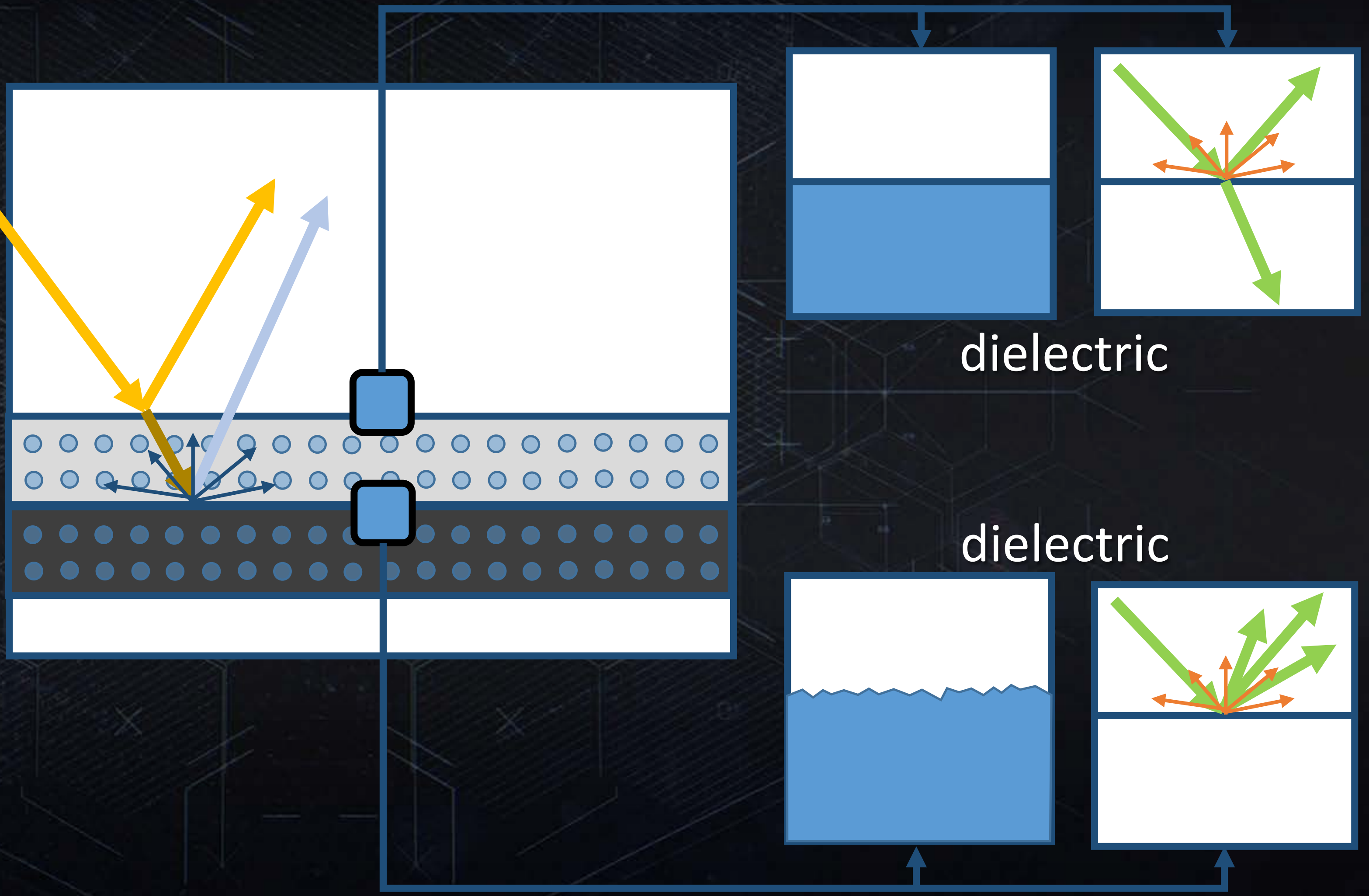


Surface Decomposition



Surface Decomposition

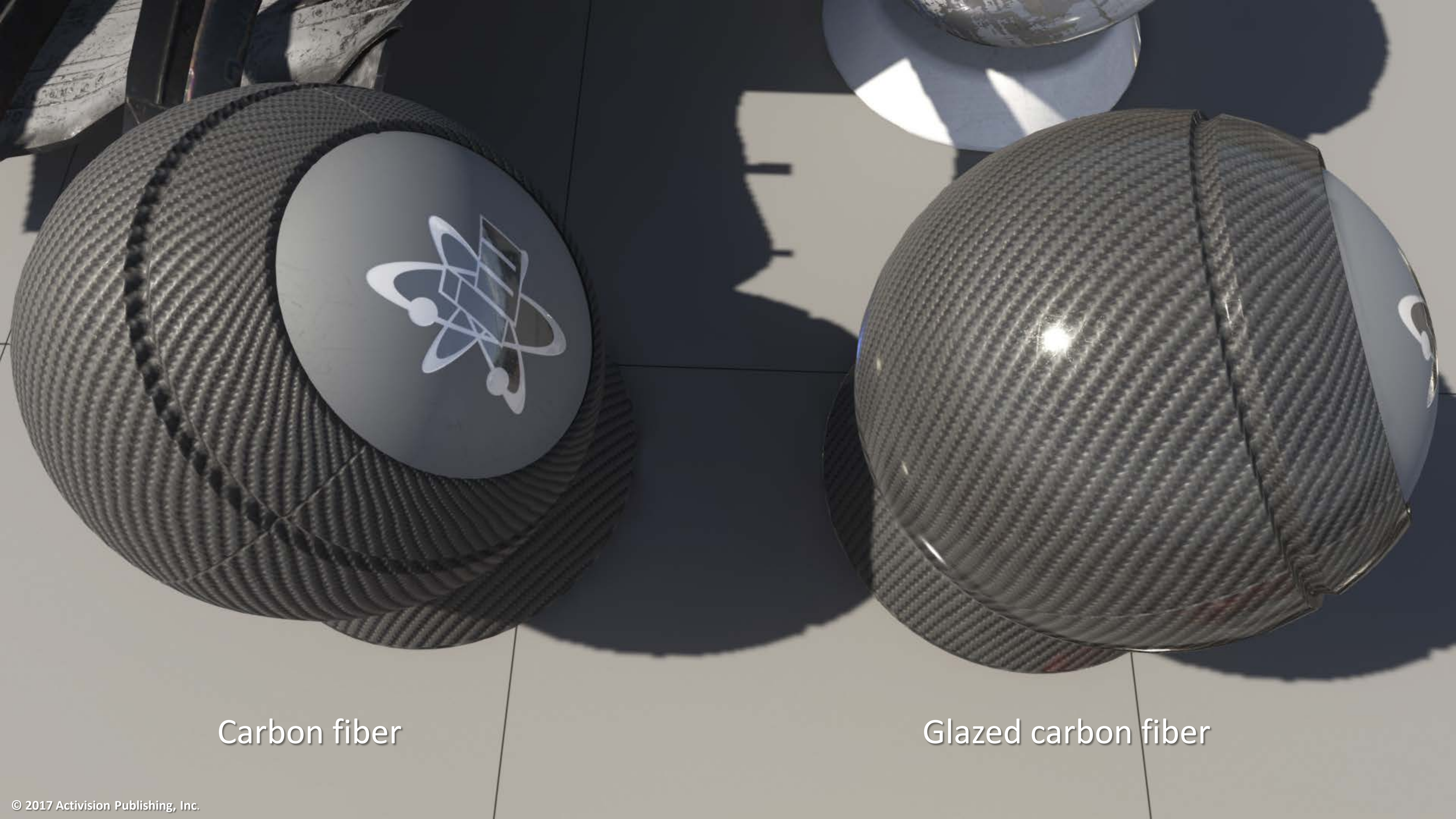
Glazed carbon fiber

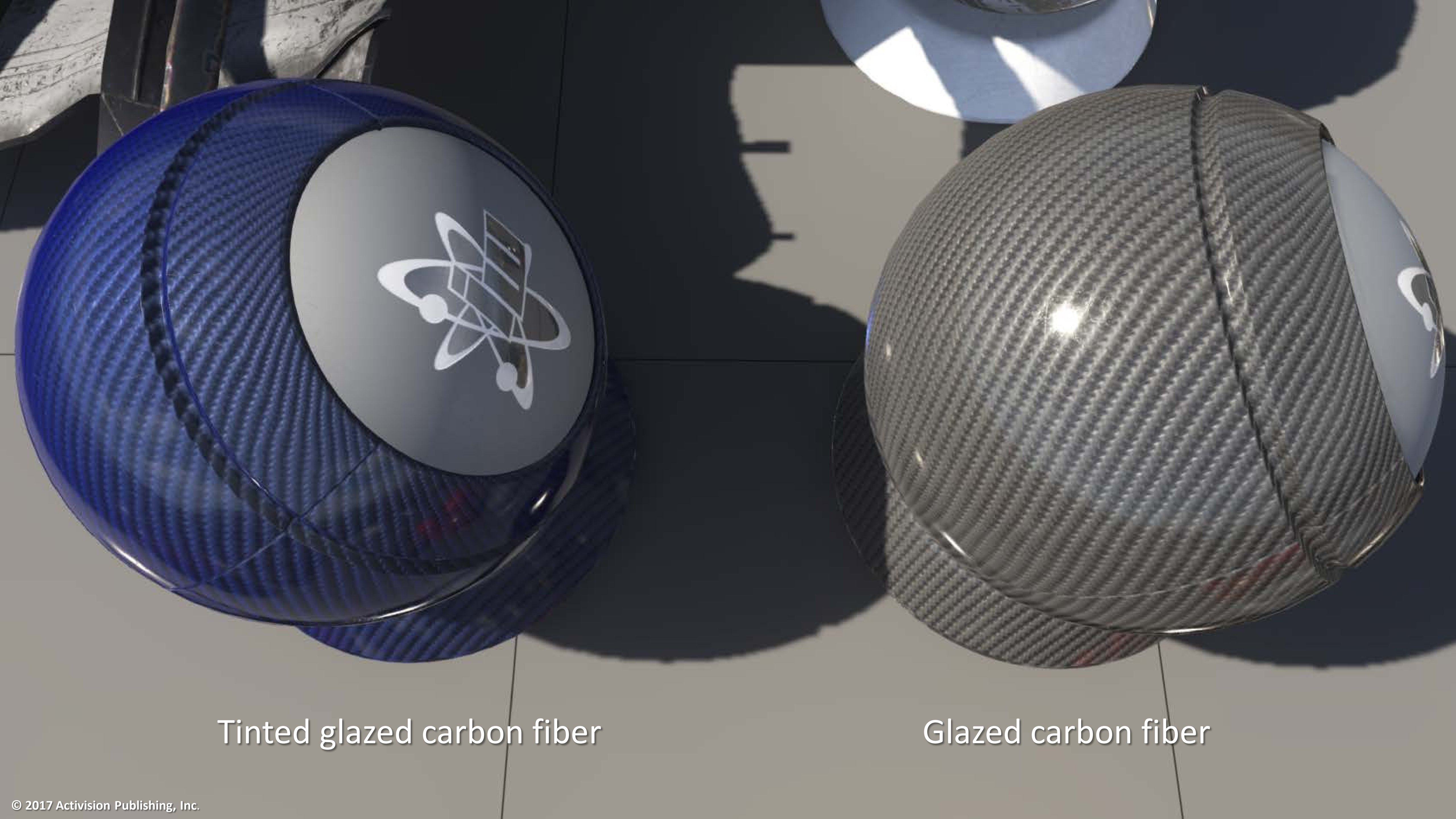



Wood
Lacquered wood


Metallic paint


Carbon fiber
Glazed carbon fiber


Carbon fiber
Glazed carbon fiber

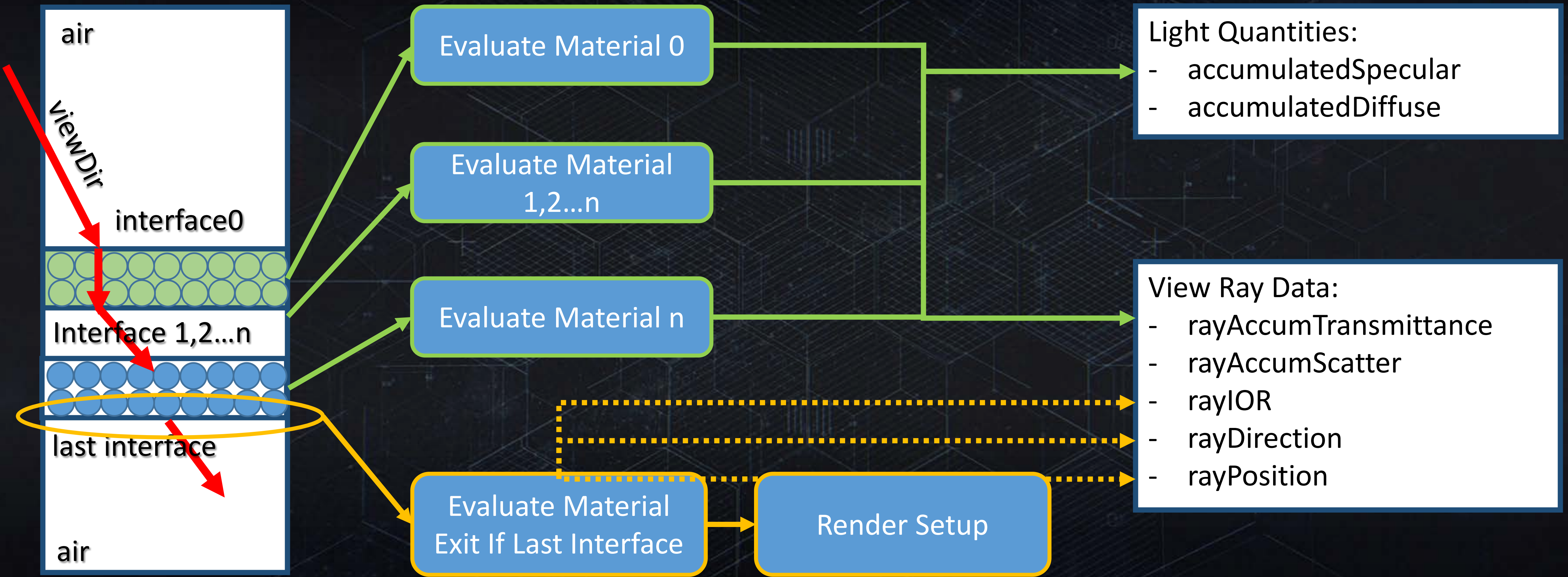


Tinted glazed carbon fiber

Glazed carbon fiber

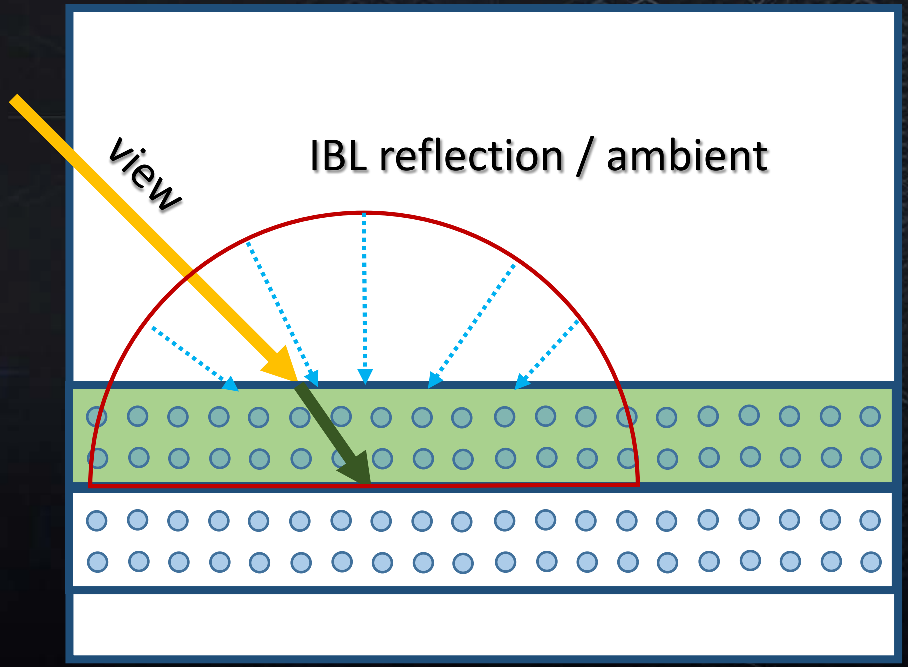
Multilayered Material Compilation

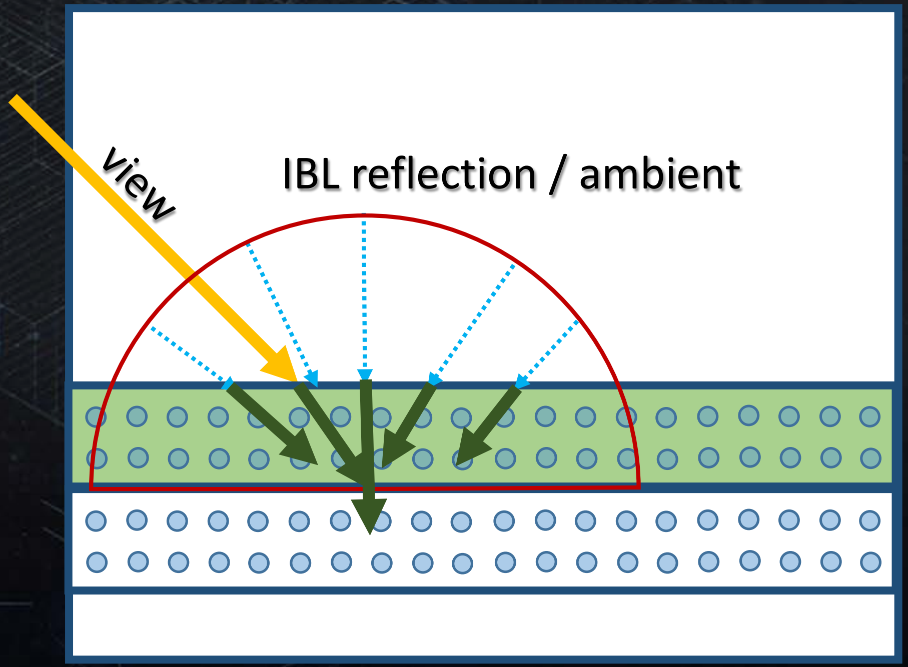
Path-Based Material Evaluation



Absorption

- Ray accumulates absorption for ‘view path’ during IBL stage
  - Incoming IBL lighting re-uses accumulated ‘view path’ absorption (optimization)
  - Pre-integrating integral is future research

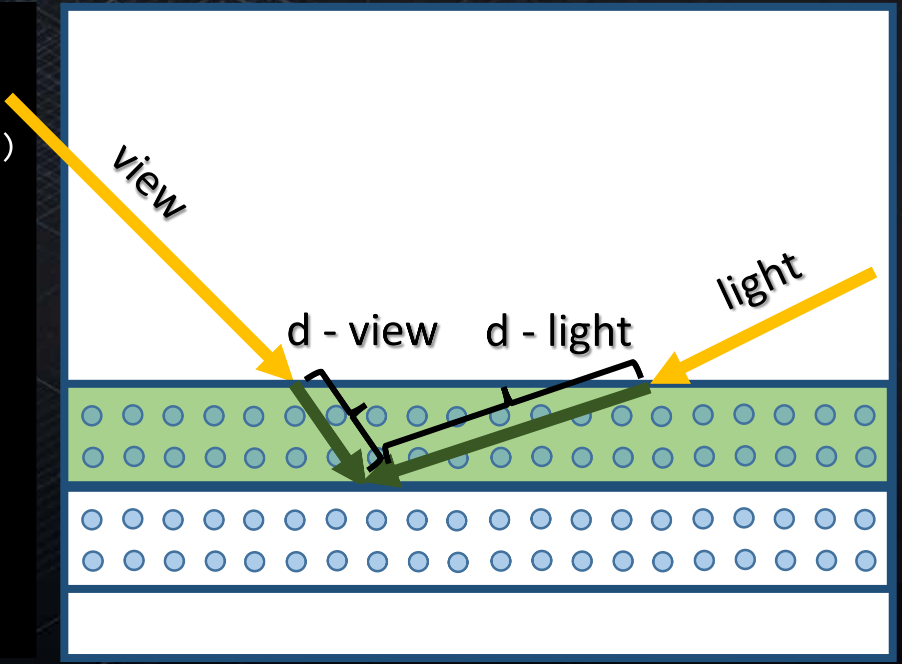




Absorption

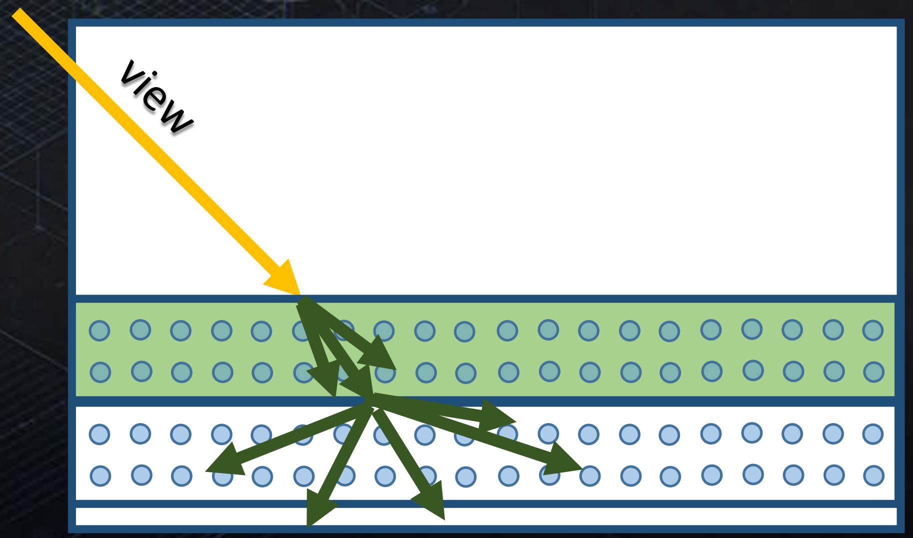
- Absorption of ‘light path’ is accumulated during direct lighting stage per light
  - Combined with ‘view path’ absorption
  - Beer-Lambert law [CHA15]

```
float3 DirectAbsorption( float NdotV, float NdotL, float3 alpha, float d )
{
    float3 color;
    float denom = max( NdotL * NdotV, 0.001f );
    color = exp( -alpha * ( d * ( ( NdotL + NdotV ) / denom) ) );
    return color;
}
```

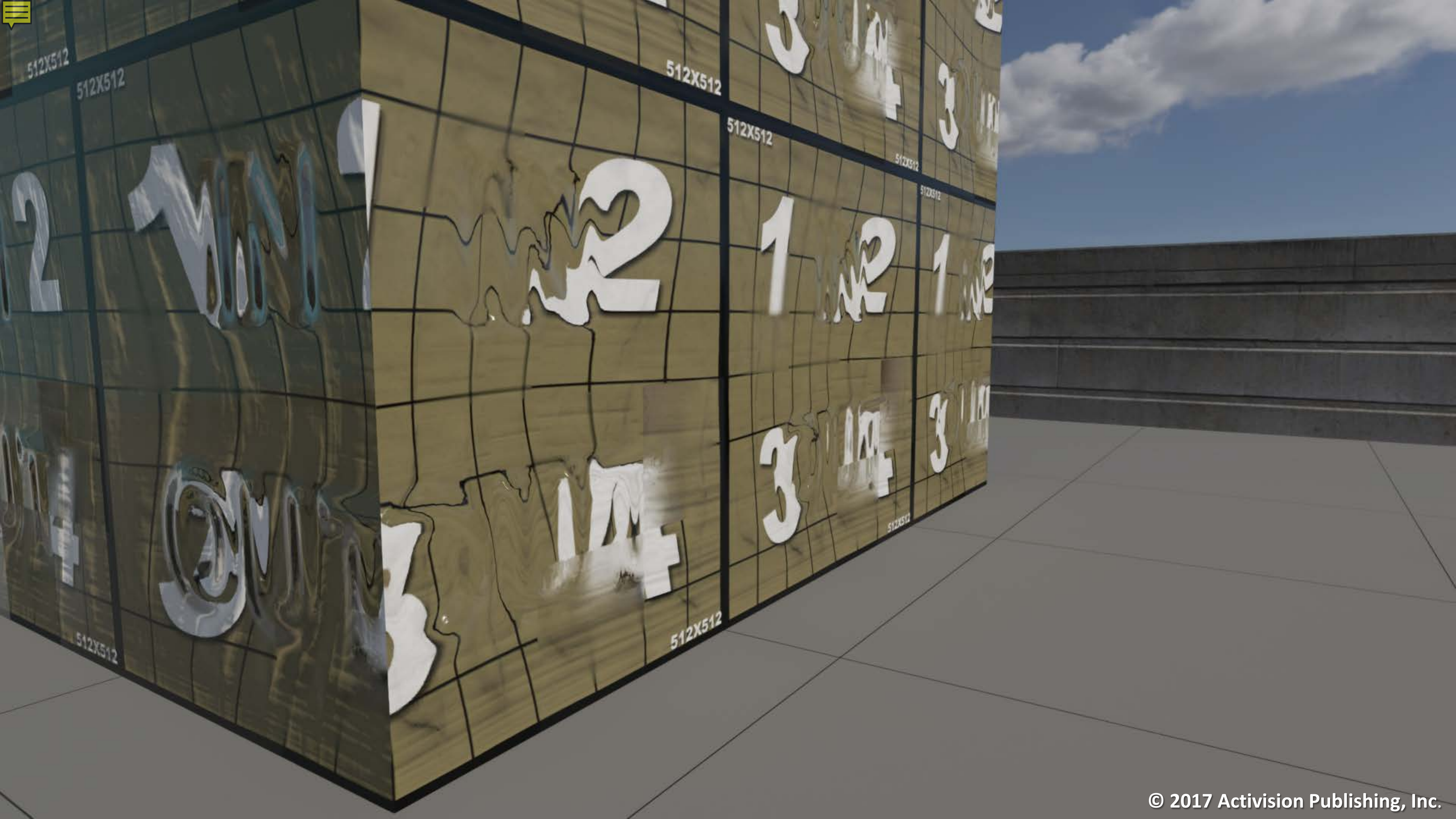


Scattering

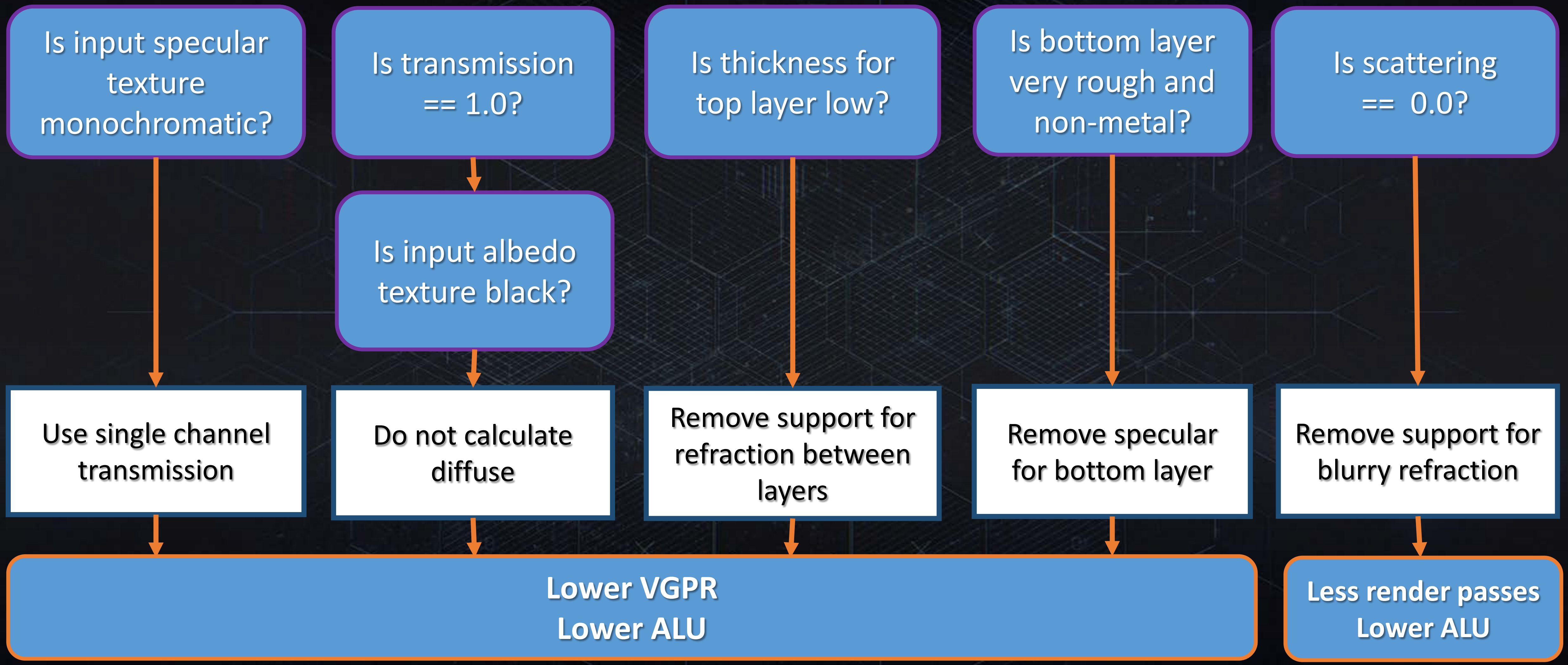
- 'View'/'Light' 'path' accumulates scattering as PDF width [KAR13]
  - Interface _roughness_ + medium _scattering_ * macro _thickness_
- 'View path' scattering changes evaluated surface footprint
  - BRDF anti-aliasing techniques provide a way to evaluate larger footprint of surface BRDF [HAN07][HIL12]
  - Calculate projected area of scattering PDF at _thickness_ distance
  - Calculate mip-map offset from area
  - Offset base mip-map picked by hardware




512X512
512X512
512X512
512X512
512X512
512X512
2
1
2
1
3
4
3
4
3


512X512

Example material compiler auto-optimizations

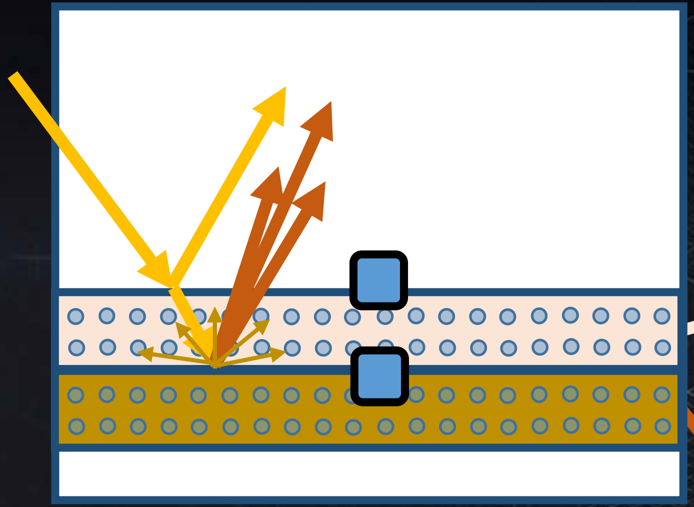


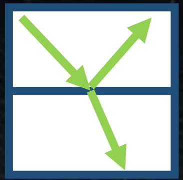
Material optimizations

- Material Compiler auto-optimizations are crucial for performance
  - Shader LOD
- Forward+ shader flow optimized for VGPRs
  - [loop] for each light, [loop] for each layer
- Single world space position for rendering systems
  - Reflection probes search and blending
    - Multiple reflection probe samples with mipLevel[layerScatteringMip]
  - Culled lights list lookup
  - Tetrahedron grid global illumination lookup
  - Multiple reflection probe samples with mipLevel[layerScatteringMip]

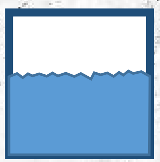
Various Forward+ material shaders generated by material compiler			
Material	**Fullscreen render time (PS4 @1080p)**	**VGPR Count**	**Effective ALU ops (with 1 light source)**
Colored metal	1.51 ms	64	515
Thin film covered color metal	1.67 ms	64	543
Carbon fiber	1.24 ms	64	445
Naïve Glazed Carbon Fiber	3.30 ms	128	980
Optimized Glazed Carbon Fiber	2.12 ms	84	707
Double-layered Ice w/ scattering	2.06 ms	84	714
Glass HW Blend	2.07 ms	64	724
Glass HW Dual Blend	2.17 ms	64	741
Glass SS Refraction	2.35 ms + 0.3 ms fixed pass	64	813

Art Material Setup



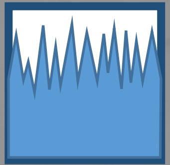


Albedo Color: none (optimization)
Specular Color: non-metal
Transmittance: 1.0 (optimization)
Absorption: 0.98 0.89 0.83

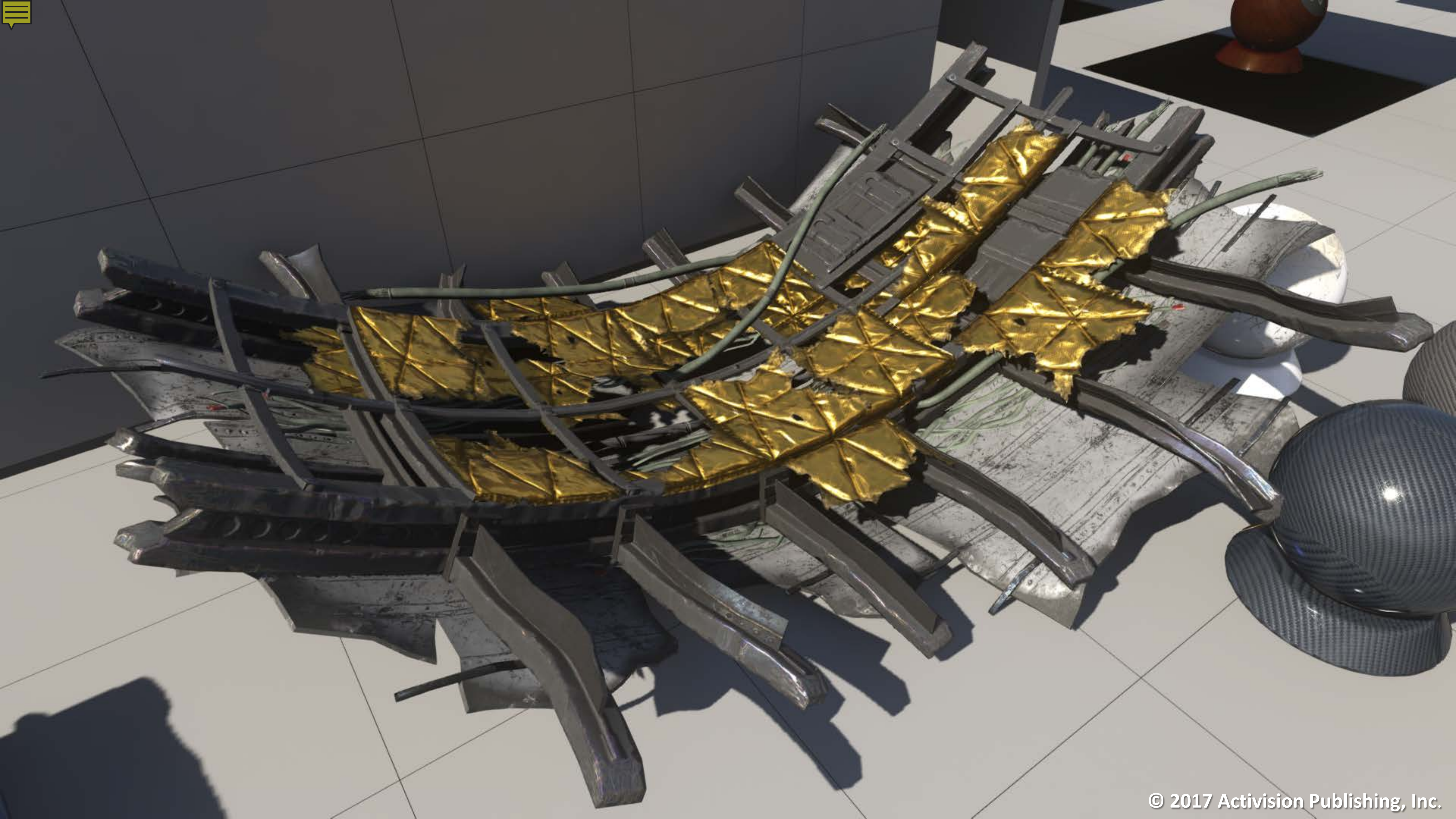


Roughness: low

Albedo Color : wood texture
Specular Color : non-metal
Transmittance : 0.0



Roughness: high




KENDALL BALLISTICS WEAPON SYSTEM
X10


BARRACKS

Thin Film


Heat treated pipe with oily layer
© 2017 Activision Publishing, Inc.


Soap bubble
© 2017 Activision Publishing, Inc.


Chemically treated aluminum
© 2017 Activision Publishing, Inc.

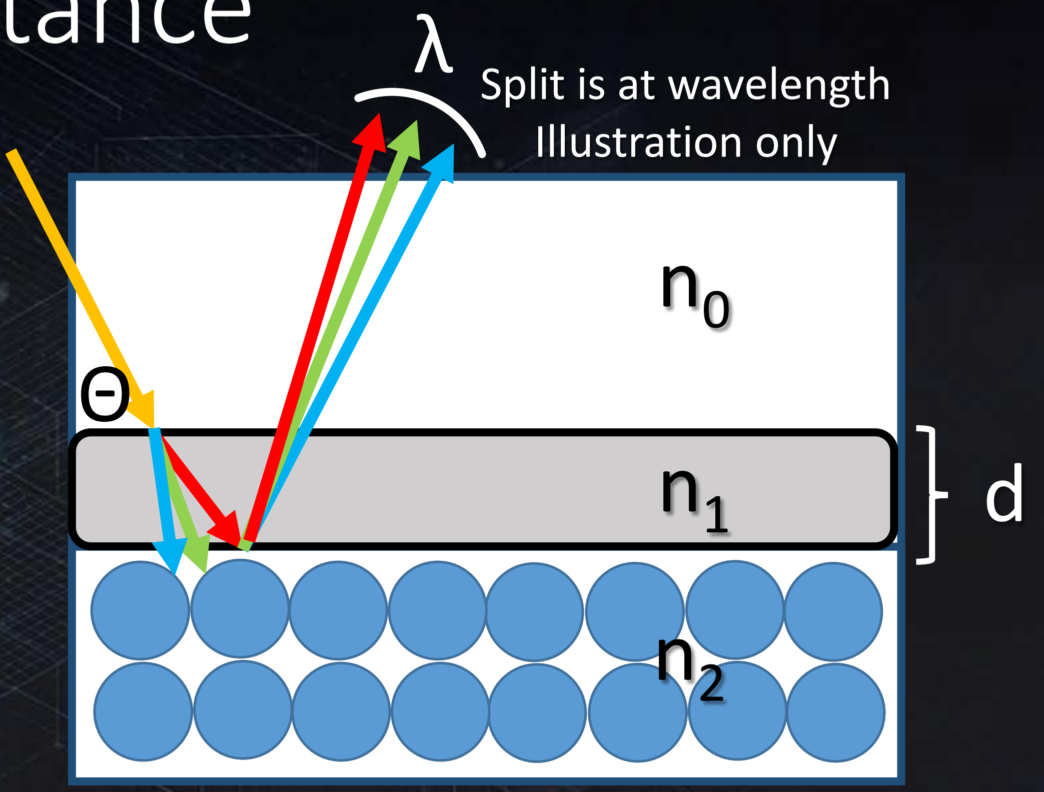
Thin Film Layer

No thin film Layer

Natural oily thin film layer

Thin film reflectance

- Thin film reflectance is a function of wavelength, incidence angle, thickness and layer IORs [HAA07]
- Very rough, but physically motivated approximation to thin film interference. Driven with existing material definition.
- Run time application uses precomputed reflectance colors for D65 light [HAA07]
- Single modulated wavelength sampling
  - Better approximations [BEL17]



$$s_{i,j} = FresnelR_s(n_i, n_j, \theta) \qquad \delta = 4\pi\cos(\theta_{transmitted}) * n_1 * d/\lambda \qquad p_{i,j} = FresnelR_p(n_i, n_j, \theta)$$

$$F_s = ((s_{0,1})^2 + (s_{1,2})^2 + 2 * s_{0,1} * s_{1,2} * \cos(\delta))/(1 + (s_{0,1} * s_{1,2})^2 + 2 * s_{0,1} * s_{1,2} * \cos(\delta))$$

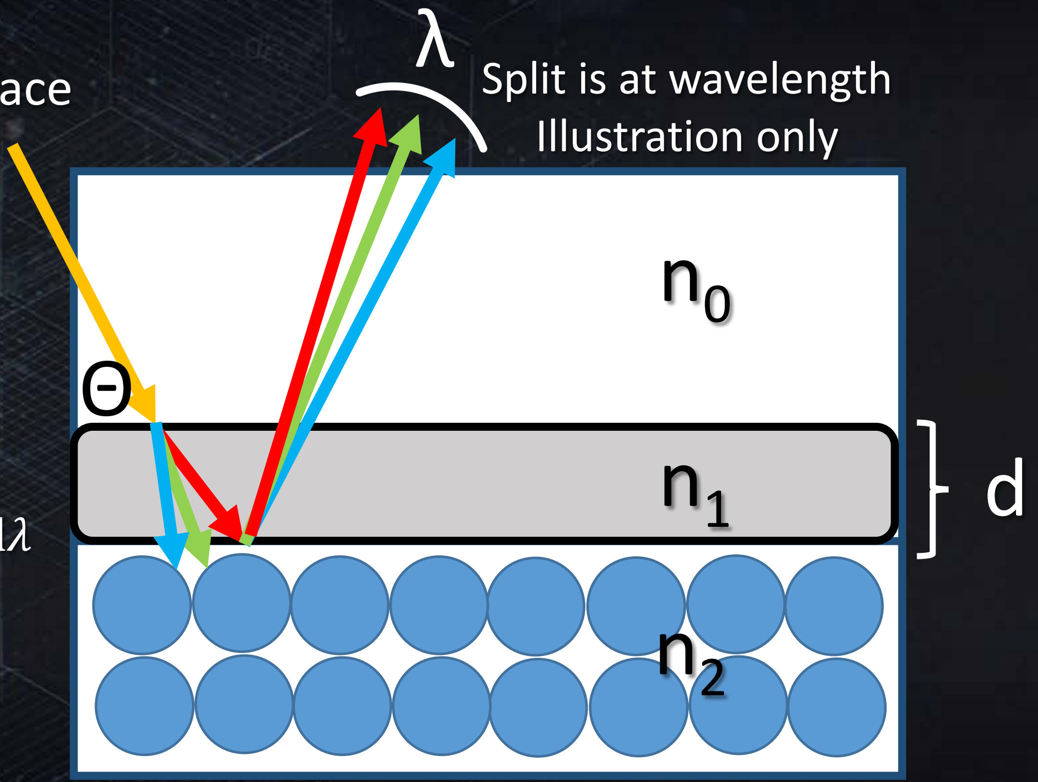
$$F_p = ((p_{0,1})^2 + (p_{1,2})^2 + 2 * p_{0,1} * p_{1,2} * \cos(\delta))/(1 + (p_{0,1} * p_{1,2})^2 + 2 * p_{0,1} * p_{1,2} * \cos(\delta))$$

$$ThinFilm = (F_s + F_p)/2$$

Thin film approximation

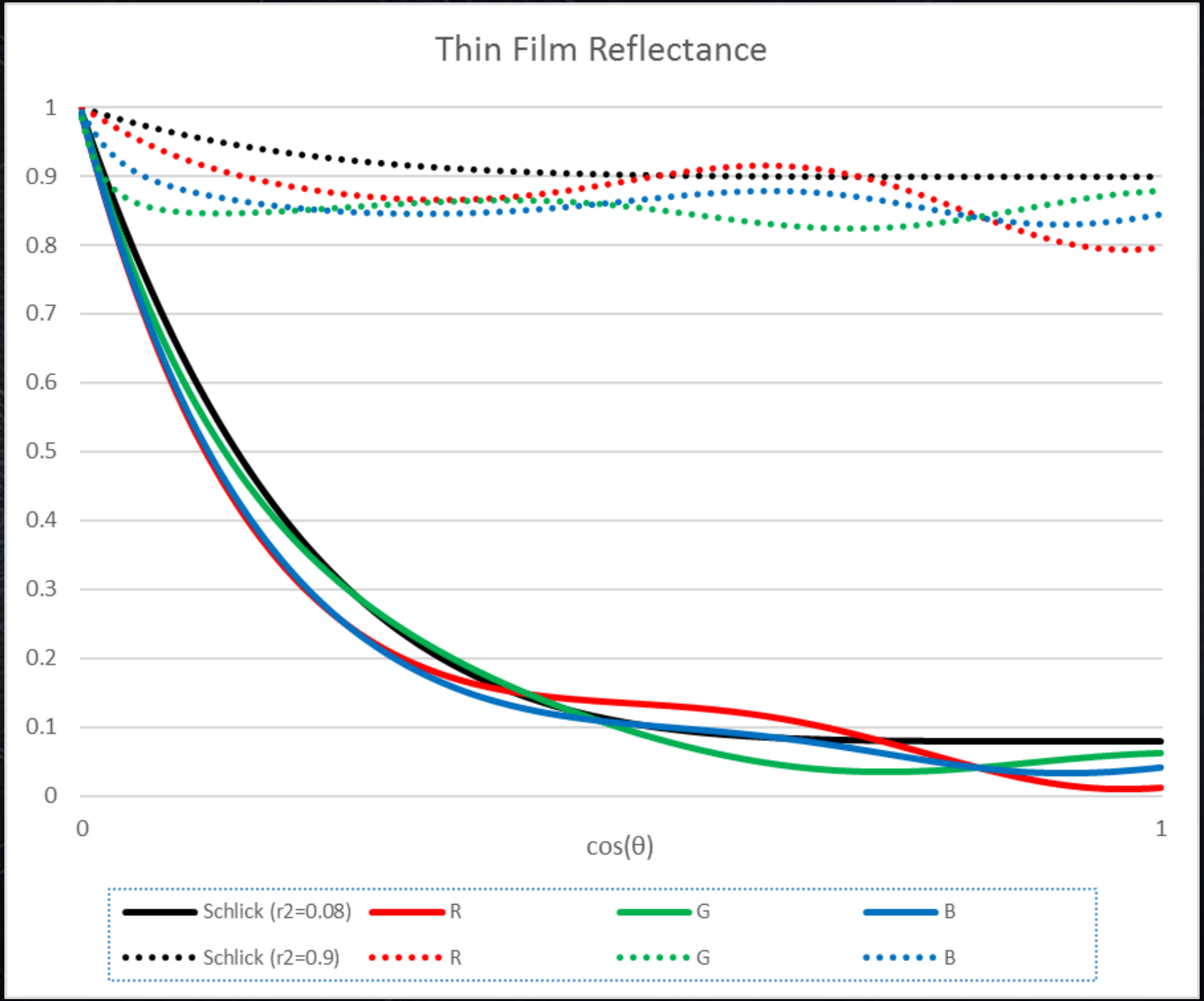
- Thin film approximation allows for varying reflectance/IOR of the bottom layer
- IORs derived from specular reflectance for air/surface interface
  - $r_i = ((n_i - n_0)/(n_i + n_0))^2$
- Assume
  - n_0 = 1.0 (air)
  - r_1 = 0.04 (dielectric with average specular reflectance)
- $ThinFilm_{R,G,B}(d, \cos(\theta), r_1, r_2) =$

  $\int Illuminant(\lambda) * CMF_{R,G,B}(\lambda) * ThinFilm(\lambda, d, \cos(\theta), r_1, r_2)\mathrm{d}\lambda$
- 2D texture lookup stores reflectance convolved as offset to (Schlick) Fresnel
  - $ThinFilm_{R,G,B}(d, \cos(\theta), r_1, k) - Schlick(k, \cos(\theta))$
  - k – const correlation factor for r_1 / r_2



Thin film approximation rationale

- Plot of Fresnel for bottom surface and RGB reflectance vs cos(Θ) for fixed thickness, film IOR and bottom surface IOR
- When the bottom surface IOR is varied, the difference between the RGB curves and the Fresnel curve remains approximately proportional at non-glancing angles.

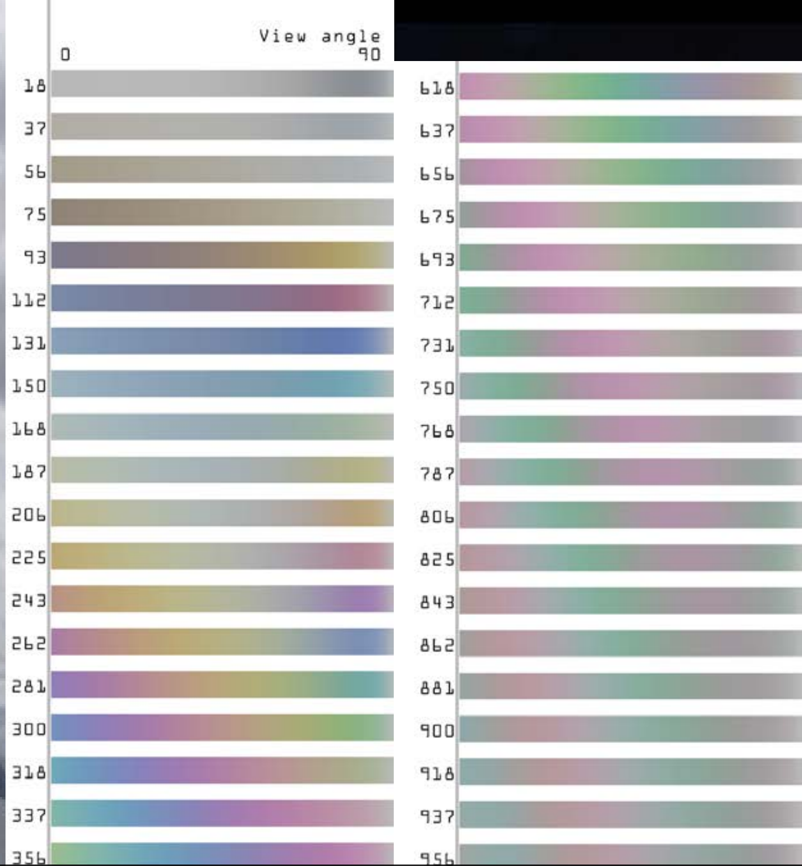


Thin film approximation

$$ThinFilm_{r,g,b}(\mathrm{d}, \cos(\theta), r_1, r_2) \approx$$

$$Schlick(\, r_2, \cos(\theta)) + (ThinFilm_{r,g,b}(d, \cos(\theta)\,, r_1, k) - Schlick(k, \cos(\theta))) * \bar{P}(r_2, r_3)$$

- $\bar{P}$ was chosen by observing difference between thin film reflectance and bottom surface reflectance at $\cos(\theta) = 1.$
- Let $P(r1, r2) = \sup_{\forall \lambda, d}(|ThinFilm(\lambda, d, 0, r_1, r_2) - r_2|)$. ThinFilm reflectance is periodic for $\frac{d}{\lambda}$, so this is easy to compute.
- Choose k such that P(r1,k) is maximized and normalize $\bar{P}(r_1, r_2) = P(r_1, r_2)/P(r_1, k)$
- For our chosen value of r_1, $\bar{P}$ ends up being roughly parabolic with max at $k \approx 0.5$. Accuracy was not a huge concern for this feature, so we simplified things even further and set $\bar{P}(r_1, r_2) = 4 * r_2 * (1 - r_2)$




```
float3 ApplyThinFilm( float3 fresnel, float NdotL, float2 thicknessAndIntensity, float3 specSample ){
    float3 lutSample = thinFilmLUT.SampleLevel( linear, float2( thicknessAndIntensity.x, NdotL ), 0 ).rgb - 0.5f;
    float3 intensity = thicknessAndIntensity.y * 4.0f * ( specSample * ( 1.0f - specSample ) );
    return saturate( lutSample * intensity + fresnel );}

float3 PhysicallyBased_GetPrimaryFresnelWithSpecColor( SurfaceAttributes surfaceAttributes, float dotH ){
    float3 primaryFresnel = SchlickPrimaryFresnel( abs( dotH ), surfaceAttributes.specColor );
    return = ApplyThinFilm( primaryFresnel, abs( dotH ), surfaceAttributes.thinFilmThicknessAndIntensity,
                                                          surfaceAttributes.specColor ); }
```

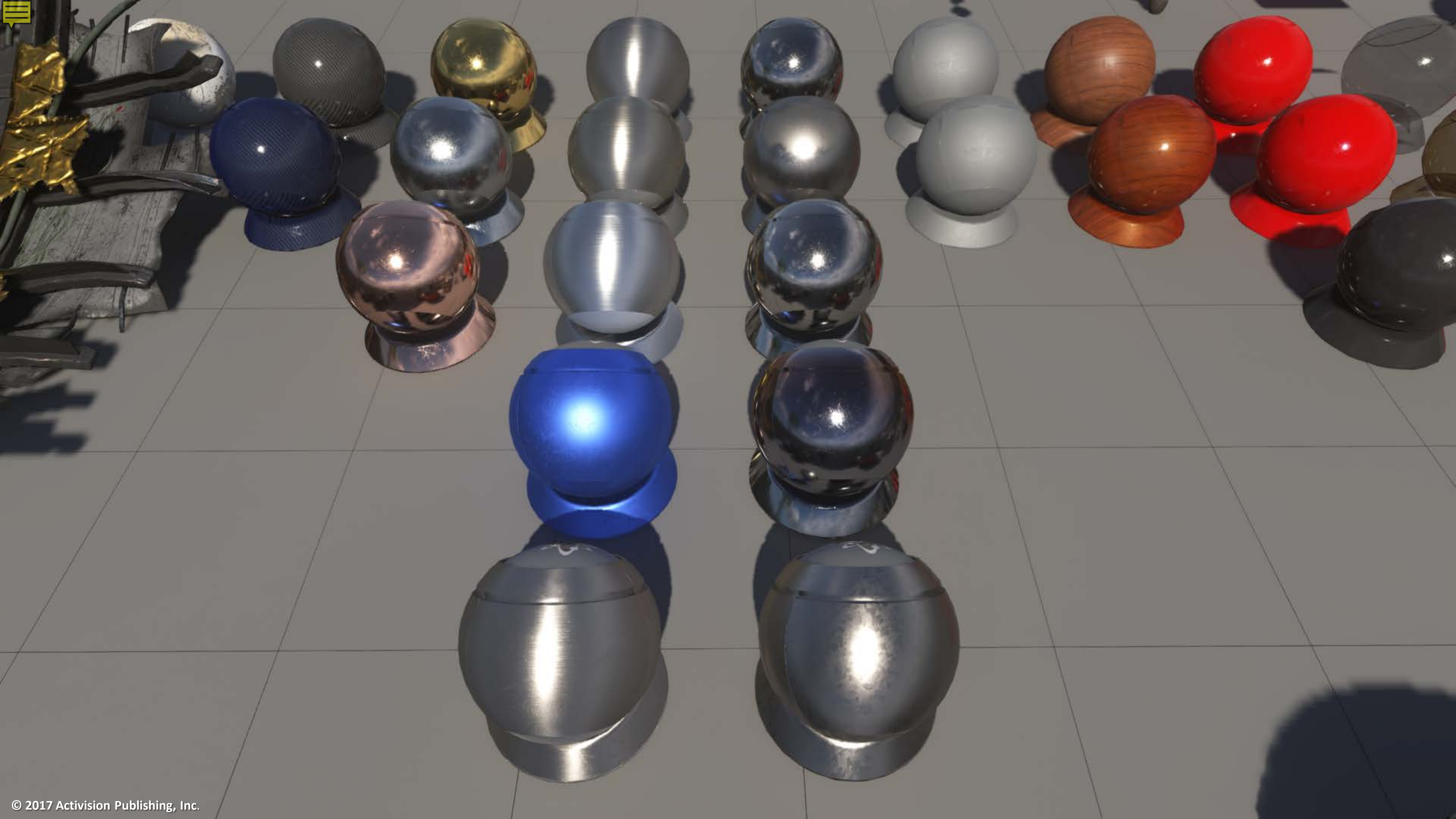
- Art controls
  - Intensity texture
  - Thickness texture
  - Min / max thickness range
  - Custom LUT

74-76

112-113

280-282

400-1200



Future Research

- Multi-scattering [HEI16]
- Scattering between surfaces [DUP16]
- Approximating complex BRDFs with multilayer Material Compiler
  - TRT hair shading
  - Path based shading/lighting models
- Getting closer to movie industry material shaders and quality [HER17]
  - Not far away in terms of feature set
  - “**Pixar’s Foundation for Materials: PxrSurface and PxrMarschnerHair**”

Rendering Presentations 2017

- EGSR
  - Ambient Dice — Michal Iwanicki
- Siggraph
  - Indirect Lighting in COD: Infinite Warfare — Michal Iwanicki
  - Dynamic Temporal Supersampling and Anti-Aliasing — Jorge Jimenez
  - Improved Culling for Tiled and Clustered Rendering — Michal Drobot
  - Practical Multilayered PBR rendering — Michal Drobot
- Microsoft XFest 2017
  - Optimizing the Renderer of Call of Duty: Infinite Warfare — Michal Drobot

research.activision.com


JOIN US
www.activisionblizzard.com/careers

Special Thanks

- Tech Art
  - Kyle McKisic
  - Olin Georgescu
- Code
  - Adam Micciulla
    - amicciulla@gmail.com

PBS Course Organisers:

Stephen Hill

Stephen McAuley

Additional Thanks

- IW Rendering Team
  - Anthony Carotenuto, Rulon Raymond, Peter Pon, Mike Esposito, Vishal Kashyap, Felipe Gomez
- Activision Central Tech
- Infinity Ward
- Sledgehammer Games
- Treyarch
- Raven

research.activision.com

Q&A

michal@infinityward.com
@MichalDrobot

CALL OF DUTY INFINITE WARFARE

References 1/2

[ADA03] “Real-time Rendering of Woven Clothes”, Neeharika Adabala, Nadia Magnenat-Thalmann, Guangzheng Fei, VRST 2003

[BEL17] “A Practical Extension to Microfacet Theory for the Modelling of Varying Iridescence”, Laurent Belcour and Pascal Barla, Siggraph 2017

[BUR12] “Physically-Based Shading at Disney”, Brent Burley, Siggraph 2012

[BUR15] “Extending the Disney BRDF to BSDF with Integrated Subsurface Scattering”, Brent Burley, Siggraph 2015

[CHA15] “Real-World Measurements for Call of Duty: Advanced Warfare”, Danny Chan, Siggraph 2015

[DRO10] “Quadtree Displacement Mapping with Height Blending”, Michal Drobot, GDC Europe 2009

[DRO17] “Rendering of Call of Duty: Infinite Warfare”, Michal Drobot, *Digital Dragons 2017*

[DUP16] “Additional Progress Towards the Unification of Microfacet and Microflake Theories”, Jonathan Dupuy, Eric Heitz and Eugene d’Eon, EGSR 2016

[HAA07] “Thin Film Rendering”, Tomas Bernhard Haarde and Pall Ragnar Palsson, DTU/ITU Master Thesis, 2007

[HAN07] “Frequency Domain Normal Map Filtering”, Charles Han, Bo Sun, Ravi Ramamoorthi and Eitan Grinspun, Siggraph 2007

[HER17] “Pixar’s Foundation for Materials: PxrSurface and PxrMarschnerHair”, Christophe Hery and Junyi Ling, Siggraph 2017

References 2/2

[HAN07] “Frequency Domain Normal Map Filtering”, Charles Han, Bo Sun, Ravi Ramamoorthi and Eitan Grinspun, Siggraph 2007

[HER17] “Pixar’s Foundation for Materials: PxrSurface and PxrMarschnerHair”, Christophe Hery and Junyi Ling, Siggraph 2017

[HIL12] “Rock-Solid Shading: Image Stability Without Sacrificing Detail”, Dan Baker and Stephen Hill, Siggraph 2016

[HEI14] “Understanding the Masking-Shadowing Function in Microfacet-Based BRDFs”, Eric Heitz, Journal of Computer Graphics Techniques Vol. 3, No. 2, 2014

[HEI16] “Multiple-Scattering Microfacet BSDFs with the Smith Model”, Eric Heitz, Johannes Hanika, Eugene d’Eon and Carsten Dachsbacher

[KAR13] “Real shading in Unreal Engine 4”, Brian Karis, Siggraph 2013

[MAN16] “Fast Filtering of Reflection Probes”, Josiah Manson and Peter-Pike Sloan, EGSR 2016

[MAX14] “Pushing the limits of realism of materials”, Atilla Akin, Maxwell Render Team, blog entry

[SCH12] “Recent Advances in Physically-Based Appearance Modeling of Cloth”, Kai Schroder, Shuang Zhao and Arno Zinke, 2012

[STA15] “Stochastic Screen-Space Reflections”, Tomasz Stachowiak and Yasin Uludag, Siggraph 2015

[WEI07] “Arbitrarily Layered Micro-Facet Surfaces”, Andrea Weidlich and Alexander Wilkie