SIGGRAPH 2015

Xroads of Discovery

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The 42nd International Conference and Exhibition on Computer Graphics and Interactive Techniques

Optimizing PBR

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Talk Overview

- PBR challenges on Mobile
- What hardware are we optimizing for?
- Faster BRDF
- Linear/Gamma
- Environment Reflections

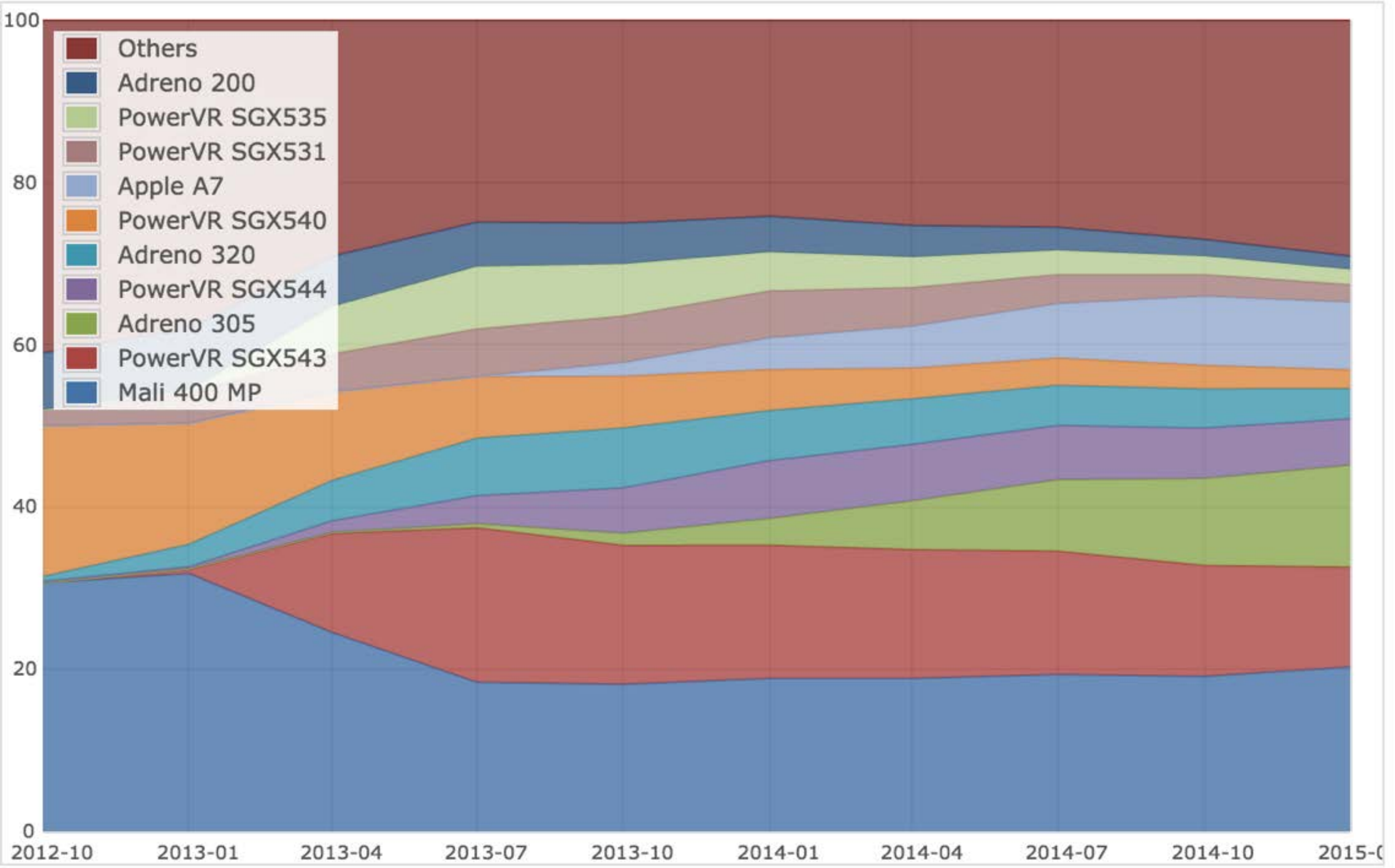
PBR challenges on Mobile

- Performance
- Many GPUs, many architectures, many peculiarities
- Gamma/Linear workflows
- Lack of high quality texture compression formats
  - ASTC - light at the end of the tunnel

PBR challenges on Mobile

- Shader compilers are still not as good as on PC
- Scalar (more recent) vs vector pipeline
- texCUBElod
- FP32 vs FP16 precision
- Lots of shader variations!

Optimization Target



based on # of apps running Unity

Performance

	PowerVR	NVIDIA	Qualcomm	ARM
4 ~ 8 GFlops **0.2 ~ 1 GP/s**	**SGX535** iPad, iPhone4	**Tegra2**	**Adreno2xx**	**Mali400 MPx** SGS3 (I9300) SGS2 (I9100)
16 GFlops **2 ~ 3 GP/s**	**SGX54x** iPad2/3, iPhone4s, iPhone5	**Tegra3**	**Adreno305** SGS4 mini (I9195)	
100 GFlops **4 GP/s**	**G6x30** iPadAir, iPhone5s	**Tegra4**	**Adreno3x0** Nexus 4, Nexus 5	MaliT628
250 GFlops **4 ~ 8 GP/s**	**G6x50** iPadAir2, iPhone6	**K1, X1** Nexus 9, Shield Tablet	**Adreno420**	MaliT760 SGS6

- Huge performance leap in every generation

Market Share

	PowerVR		NVIDIA		Qualcomm		ARM	
4 ~ 8 GFlops 0.2 ~ 1 GP/s	SGX535	3.5%	Tegra2	1.0%	**Adreno2xx**	**9%**	**Mali400 MPx**	**19%**
16 GFlops 2 ~ 3 GP/s	**SGX54x**	**15.4%**	Tegra3	0.9%	**Adreno305**	**7.1%**		
100 GFlops 4 GP/s	**G6x30**	**6.0%**	Tegra4	0.0%	**Adreno3x0**	**10.3%**	MaliT628	0.5%
250 GFlops 4 ~ 8 GP/s	G6x50	0.3%	K1, X1	0.0%	Adreno420	0.1%	MaliT760	0.0%

- Green - GPU with significant market share
- TIP: new devices >10x faster than what most people have in their pocket!

Optimization Tiers

	PowerVR		NVIDIA		Qualcomm		ARM	
Low-end Tier	SGX535	3.5%	Tegra2	1.0%	Adreno2xx	9%		
Mid Tier	SGX54x	15.4%	Tegra3	0.9%	Adreno305	7.1%	Mali400 MPx	19%
	G6x30	6.0%	Tegra4	0.0%	Adreno3x0	10.3%	MaliT628	0.5%
High-end Tier	G6x50	0.3%	K1, X1	0.0%	Adreno420	0.1%	MaliT760	0.0%

- iOS, Android and Windows combined

Important GPU characteristics for PBR

- Ratio between math (ALU) and fetching texture (TEX)
- Scalar or vector architecture
- Precision

	PowerVR		NVIDIA		Qualcomm		ARM	
16 GFlops	SGX54x	**16** FLOPs / 1 TEX **FP16 *** **vector**					Mali400 MPx	**16** FLOPs / 1 TEX **FP16 only** **vector**
70 GFlops	SGX554	**32** FLOPs / 1 TEX **FP16 *** **vector**			Adreno3xx	16? FLOPs / 1 TEX FP32/FP16 scalar	MaliT604	**16*** FLOPs / 1 TEX FP32-FP16 wide **vector**
>100 GFlops	G6x30	**48** FLOPs / 1 TEX FP32-FP16 scalar	K1	**48** FLOPs / 1 TEX FP32 only scalar			MaliT628	**32*** FLOPs / 1 TEX FP32-FP16 wide **vector**
>200 GFlops	G6x50	**64** FLOPs / 1 TEX FP32-FP16 scalar	X1	**64/128** FLOPs / 1 TEX FP32-FP16 scalar	Adreno4x0	**32** FLOPs / 1 TEX FP32-FP16 scalar	MaliT760	**>68** FLOPs / 1 TEX FP32-FP16 wide **vector**

- Unofficial numbers, some based on our measurements. Numbers might be wrong! Numbers are peak values.
- **TEX** - bilinear texture fetch
- **FP32-FP16** - supports both precision, likely to be faster in FP16
- **FP16 *** - definitely faster in FP16, but certain complex operations (EXP, LOG, etc) will be executed in FP32 anyway
- **wide vector** - FP16 are likely to be executed as 8-way vectors

Important GPU characteristics for PBR

- FP16 (“FP16 only” & “FP16 *”)
  - PBS is more prone to artifacts @ low precision
  - Check your epsilons (1e-4 is OK, 1e-5 is not!)
  - Sometimes need additional clamping due to precision overflows
- Vector pipeline might need different optimizations
- ALU/TEX differs a lot for high-end vs low-end GPUs

Optimizing for High-end tier

	PowerVR		NVIDIA		Qualcomm		ARM	
	SGX535	3.5%	Tegra2	1.0%	Adreno2xx	9%	Mali400 MPx	19%
	SGX54x	15.4%	Tegra3	0.9%	Adreno305	7.1%		
High-end Tier	G6x30	6.0%	Tegra4	0.0%	Adreno3x0	10.3%	MaliT628	0.5%
	G6x50	0.3%	K1, X1	0.0%	Adreno420	0.1%	MaliT760	0.0%

Optimizing BRDF for Mobile

$$I_{spec} = \frac{D(N \cdot H, roughness) \cdot G(N \cdot V, N \cdot L, roughness) \cdot F(L \cdot H, specColor)}{4 \cdot (N \cdot V) \cdot (N \cdot L)} \cdot N \cdot L$$

- Specular micro-facet equation
- D: Distribution Term
    - **GGX** vs **Normalized Blinn-Phong** vs **SG** approx.
- V: Visibility term

$$V = \frac{G(N \cdot V, N \cdot L, roughness)}{4 \cdot (N \cdot V) \cdot (N \cdot L)}$$

- F: Fresnel term

GGX vs BlinnPhong

- GGX - more simple ops (ADD, MUL), but only 1 complex (RCP)

$$GGX=\frac{roughness^4}{\pi\cdot\left((N\cdot H)^2\,(roughness^4-1)+1\right)^2}$$

- Normalized Phong - several complex ops (RCP, EXP, LOG)

$$Phong=\frac{1}{\pi\cdot roughness^4}\cdot(N\cdot H)^{\left(\frac{2}{roughness^4}-2\right)}$$

  - even SG approximation (RCP, EXP)

Simple vs Complex op

- PowerVR G6x00 asm
  (Phong example)
- Can do many ops / cycle, but only 1 complex!
- Most other architectures complex op = latency

```
23    : fmad ft0, i0, r22, r9
        fmul ft1, c71, r13
        pck.f32 ft2
        tstgz.f32 ftt, _, ft0
        mov i0.e0.e1.e2.e3, i3, ftt, ft0, ft1

24    : flog i0, i0.abs

25    : fmul ft0, i1, i2
        fmul ft1, i0, i3          cycle
        mov i3, ft0;
        mov i0, ft1;

26    : fexp i0, i0               another cycle

27    : fadd ft0, i3, r23
        fmul ft1, i0, r23
        mov i2, ft0;
        mov i1, ft1;
```

Geometric / Visibility term

- Smith adopted for GGX $V_{Smith} = \frac{1}{((N.L).(1\text{-}k)+k)((N.V).(1\text{-}k)+k)}$
- Kelemen and Szirmay-Kalos (KSK) $V_{SKS} = \frac{1}{(L.H)(L.H)}$
  - does not take roughness into account!
- Fix for KSK (J. Hable)

$$V_{SKSm} = \frac{1}{(L.H)^2.(1\text{-}roughness^2)+roughness^2}$$

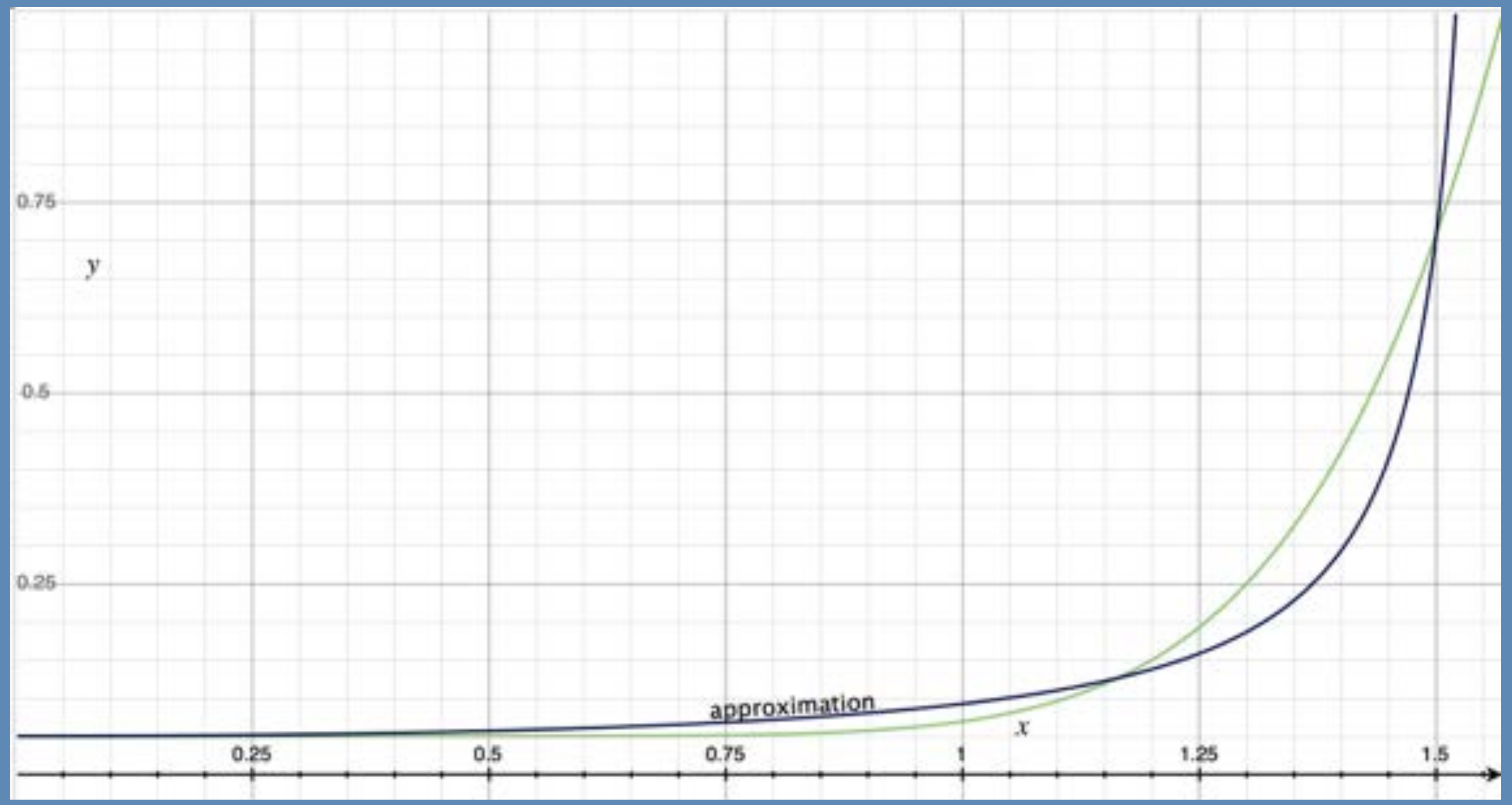
- Dependent only on **L•H** and Roughness!

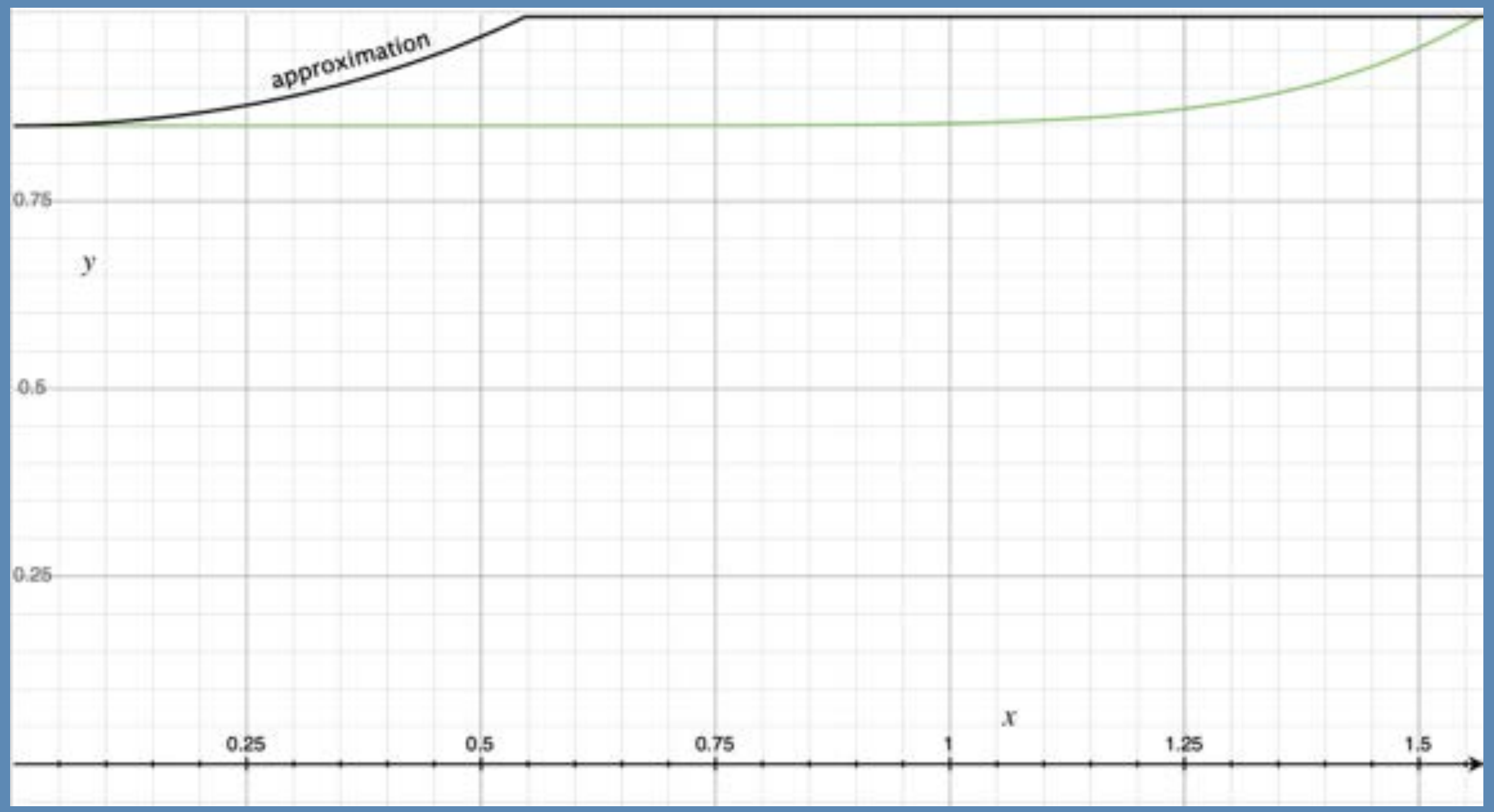
Fresnel term

- Approximation suggested by C. Schüler:

$$F = \frac{specColor}{L \cdot H}$$

- Dielectrics - **OK**
  (reflectance 0.02 ~ 0.15)
- Conductors aka Metals - average value OK
  (reflectance 0.7 ~ 1.0)
  - **has wrong shape**, but Fresnel is almost flat for Metals anyway
- Goes to +Infinity instead of 1





Fresnel term

$$F = \frac{specColor}{L \cdot H}$$

- Will not use Schüler approximation directly
- Just inspiration that specColor can be post multiplied
  - Great for scalar pipeline!

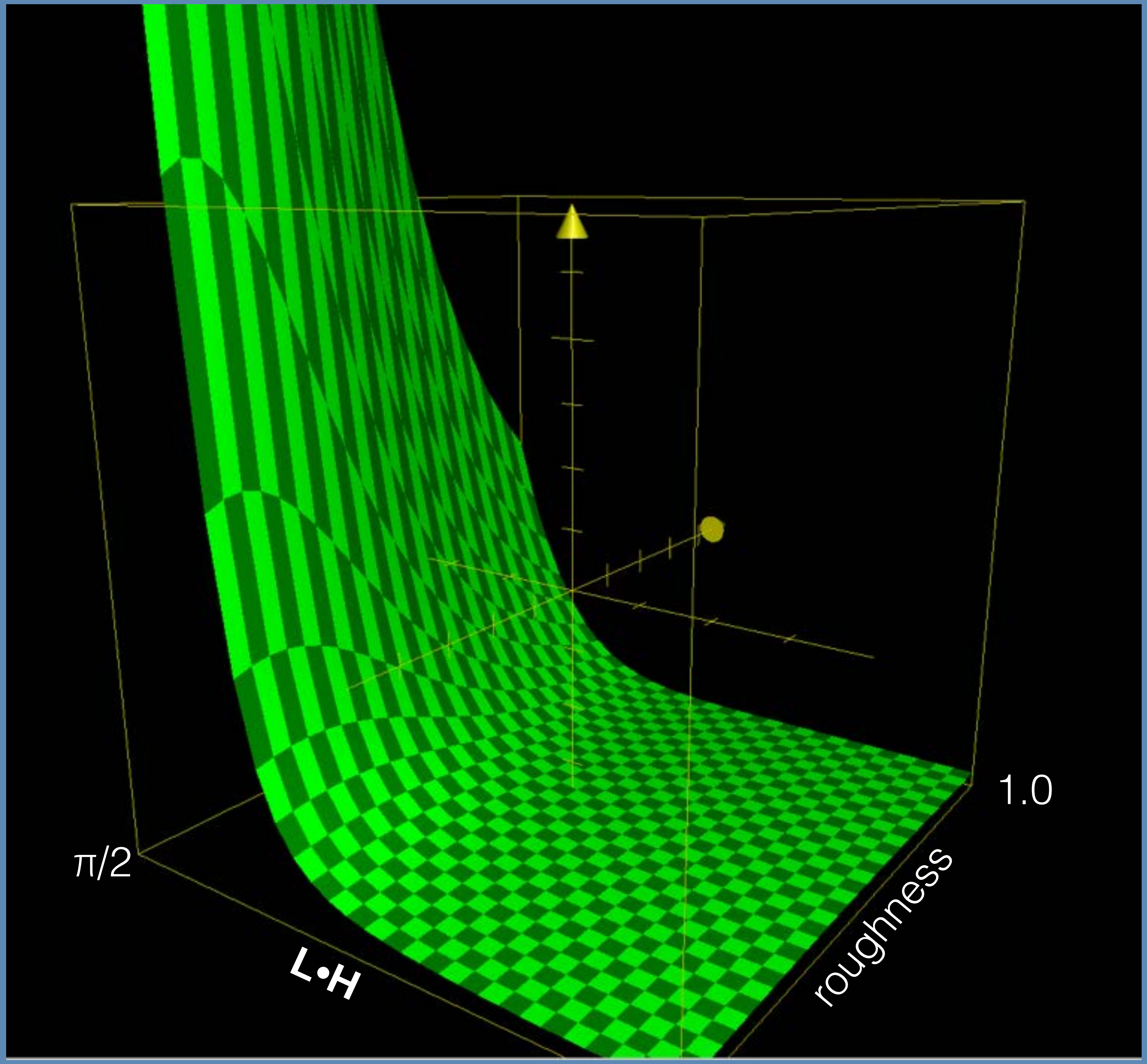
V*F together

- Modified KSK and Schlick Fresnel depend on **L•H**

- Fuse them together

$$V.F = \frac{(1\text{-}L.H)^5}{(L.H)^2.(1\text{-}roughness^2)+roughness^2}$$

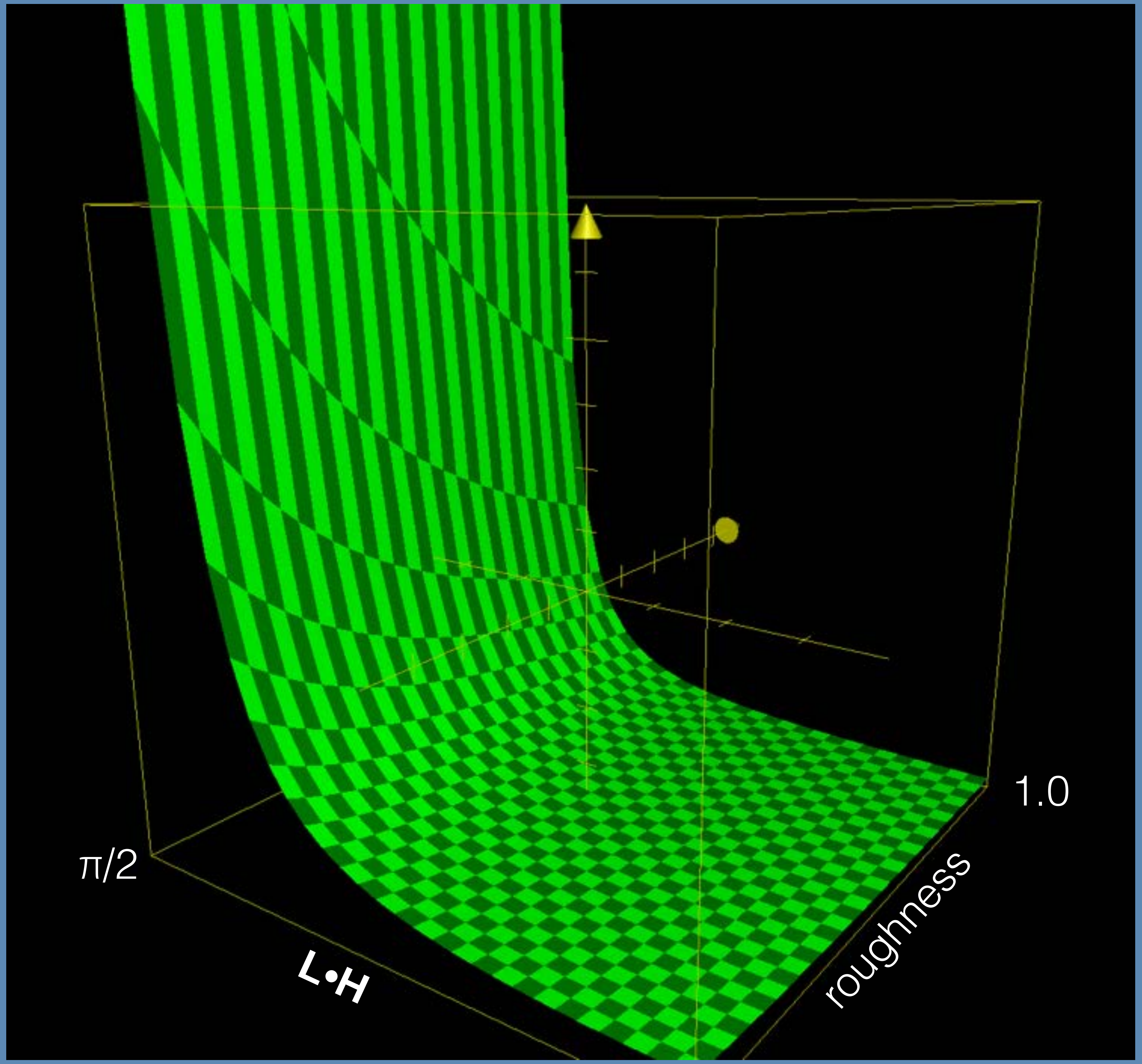
- Cheaper approximation?



Approximate V*F

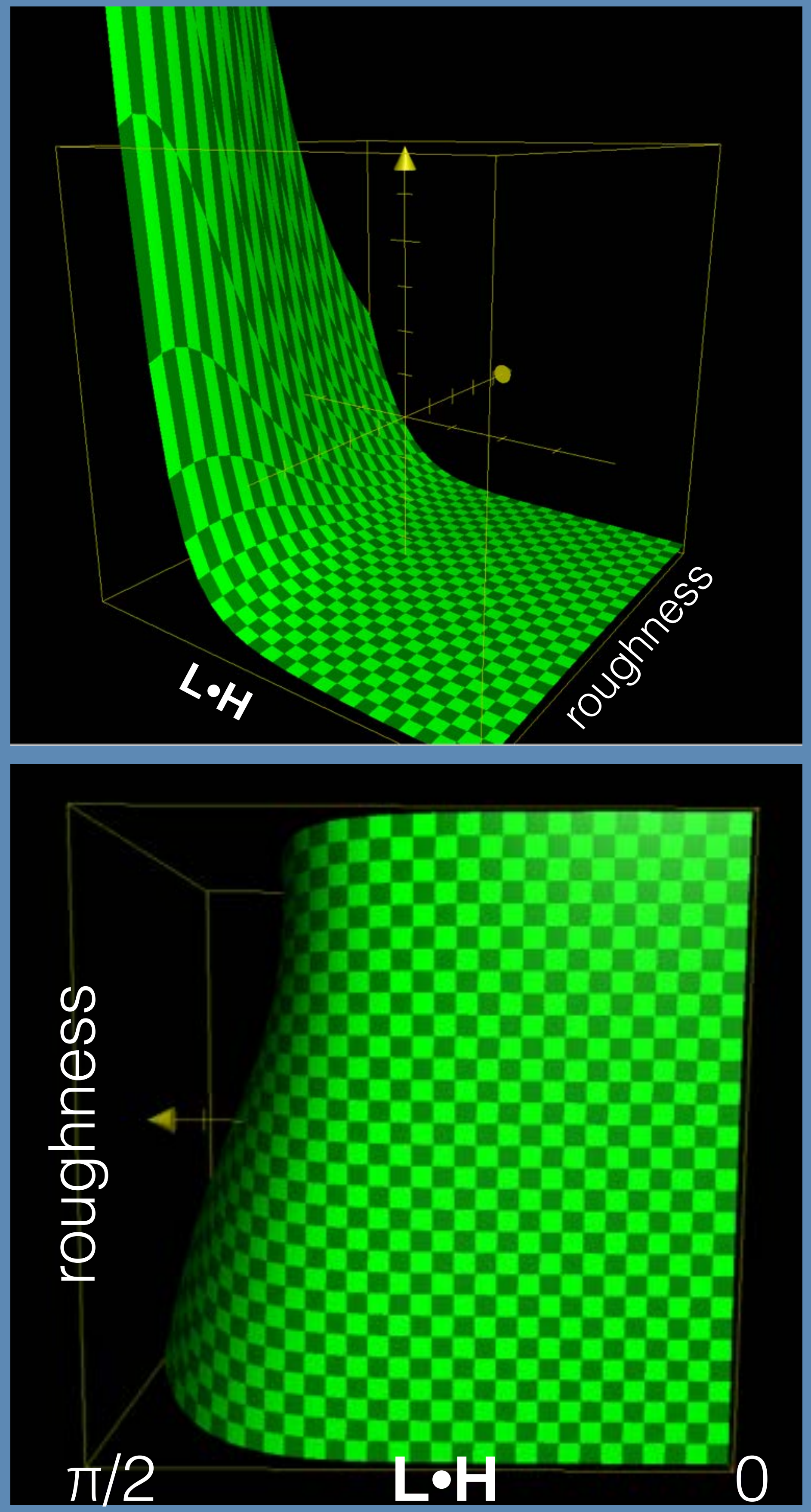
- Not an algebraic simplification
- Fitting similar curve

$$V \cdot F_{approx} = \frac{1}{(L \cdot H)^2 \cdot (roughness + 0.5)} \cdot specColor$$

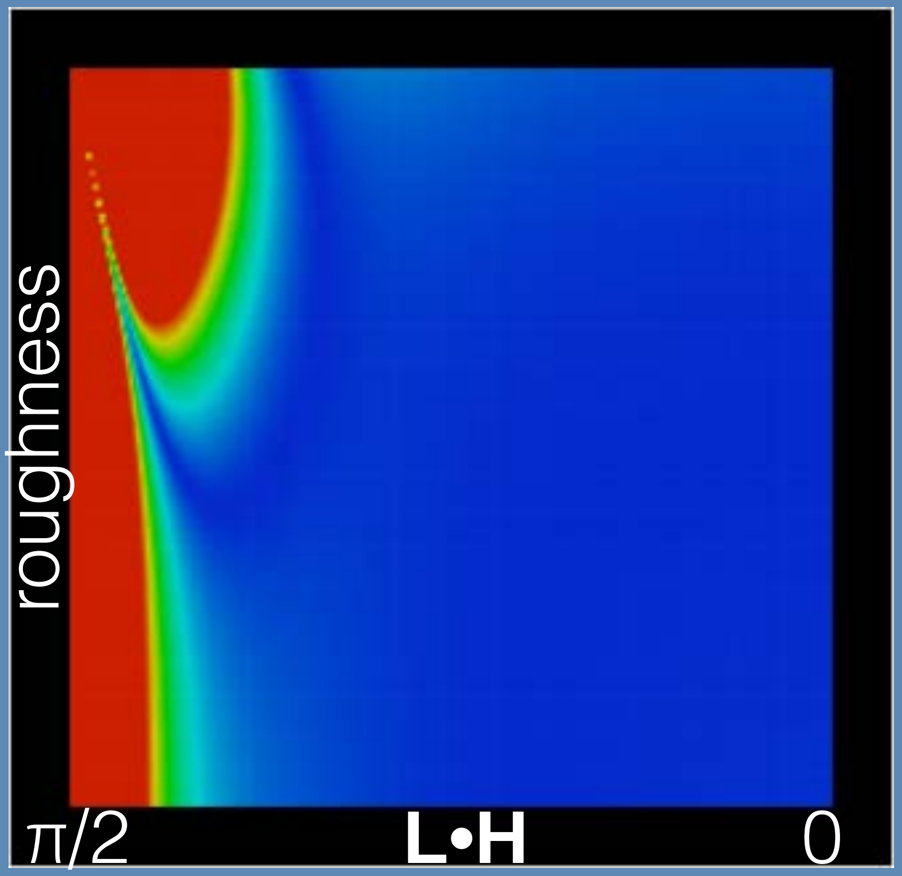


Approximation Results

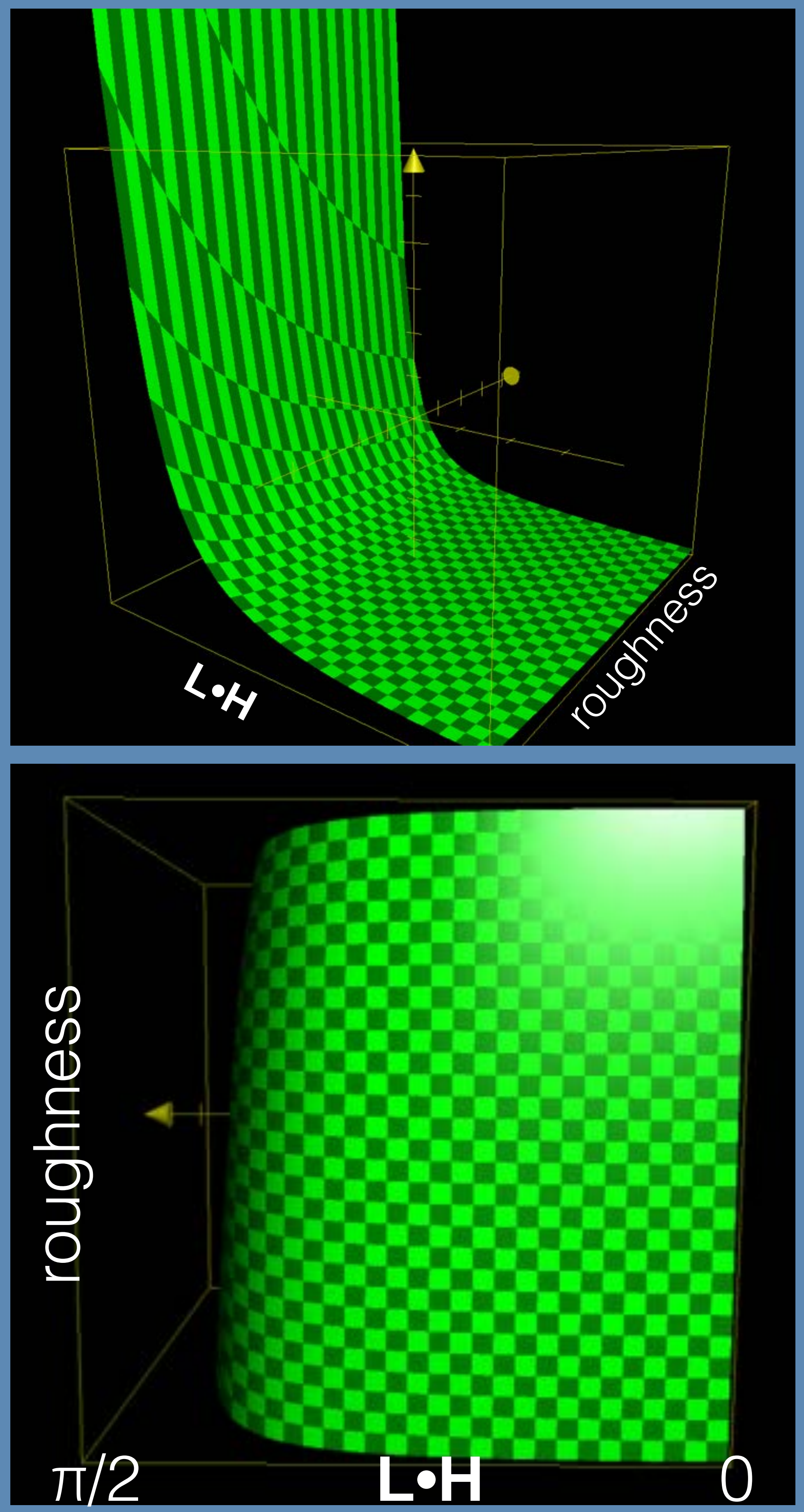
Original (Modified KSK, Fresnel)



Errors



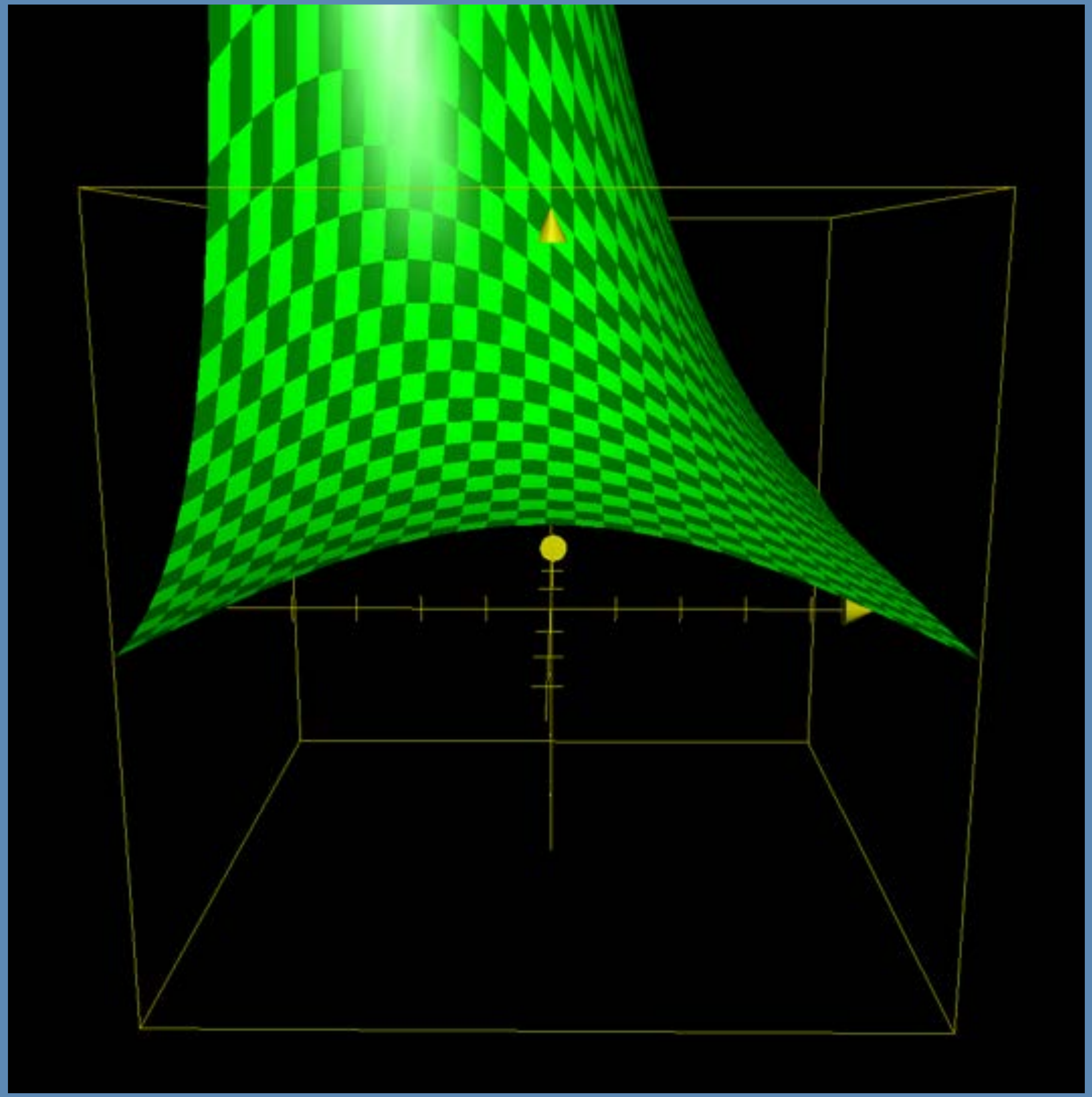
Our approximation



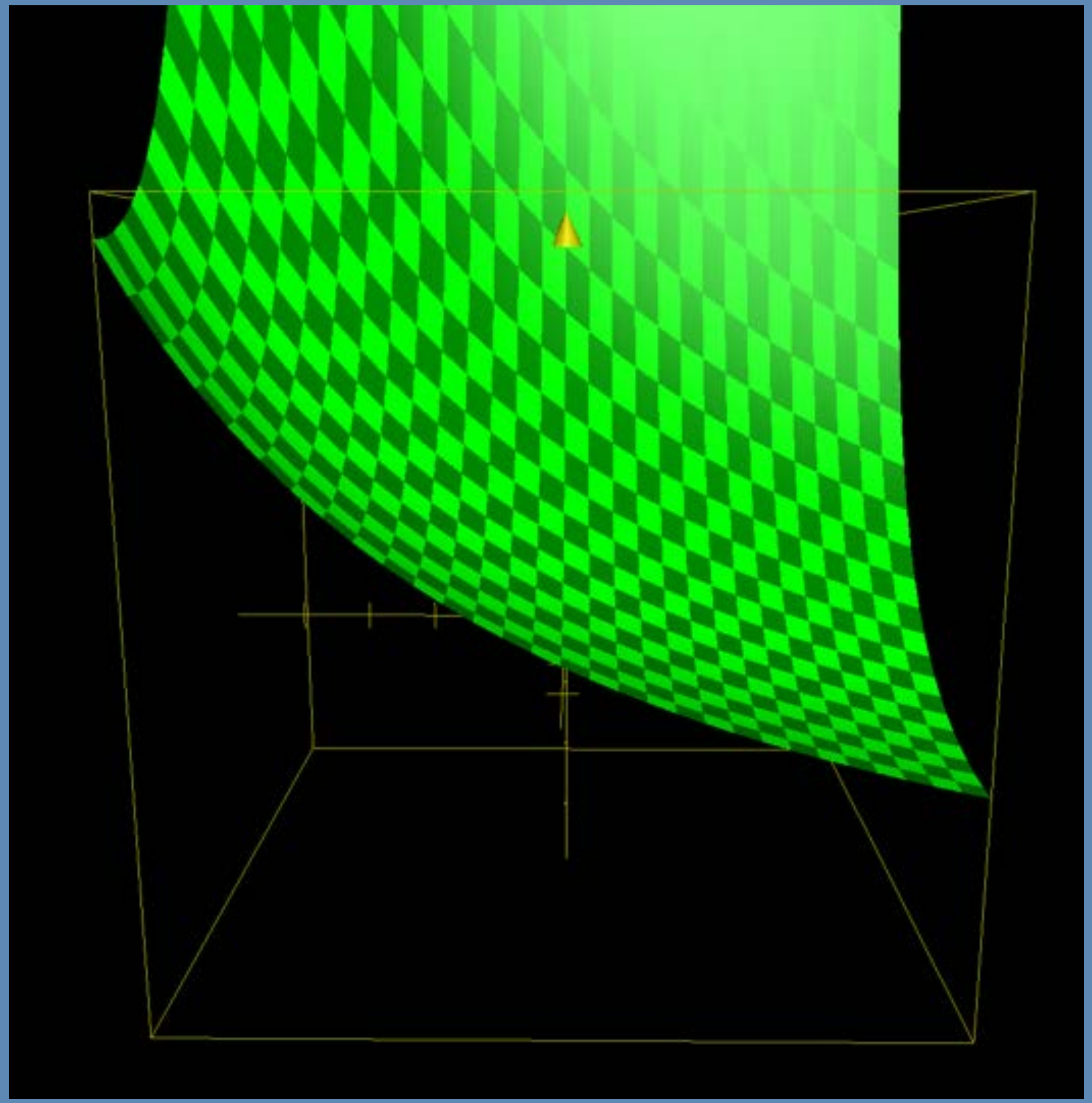
Approximate V*F

- Good for Dielectrics, but diverge for Metals

Original (Modified KSK, Fresnel)



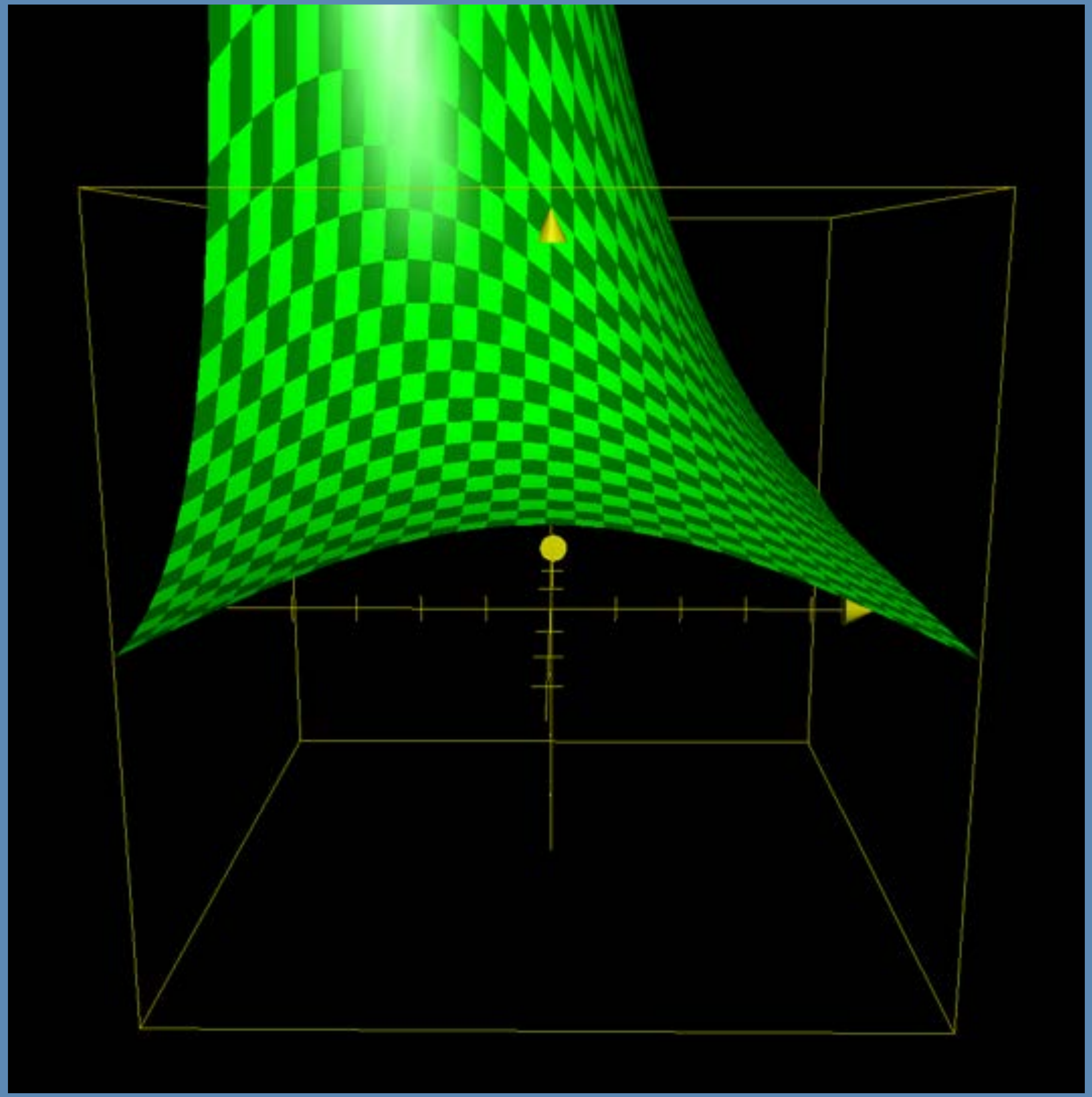
Our approximation



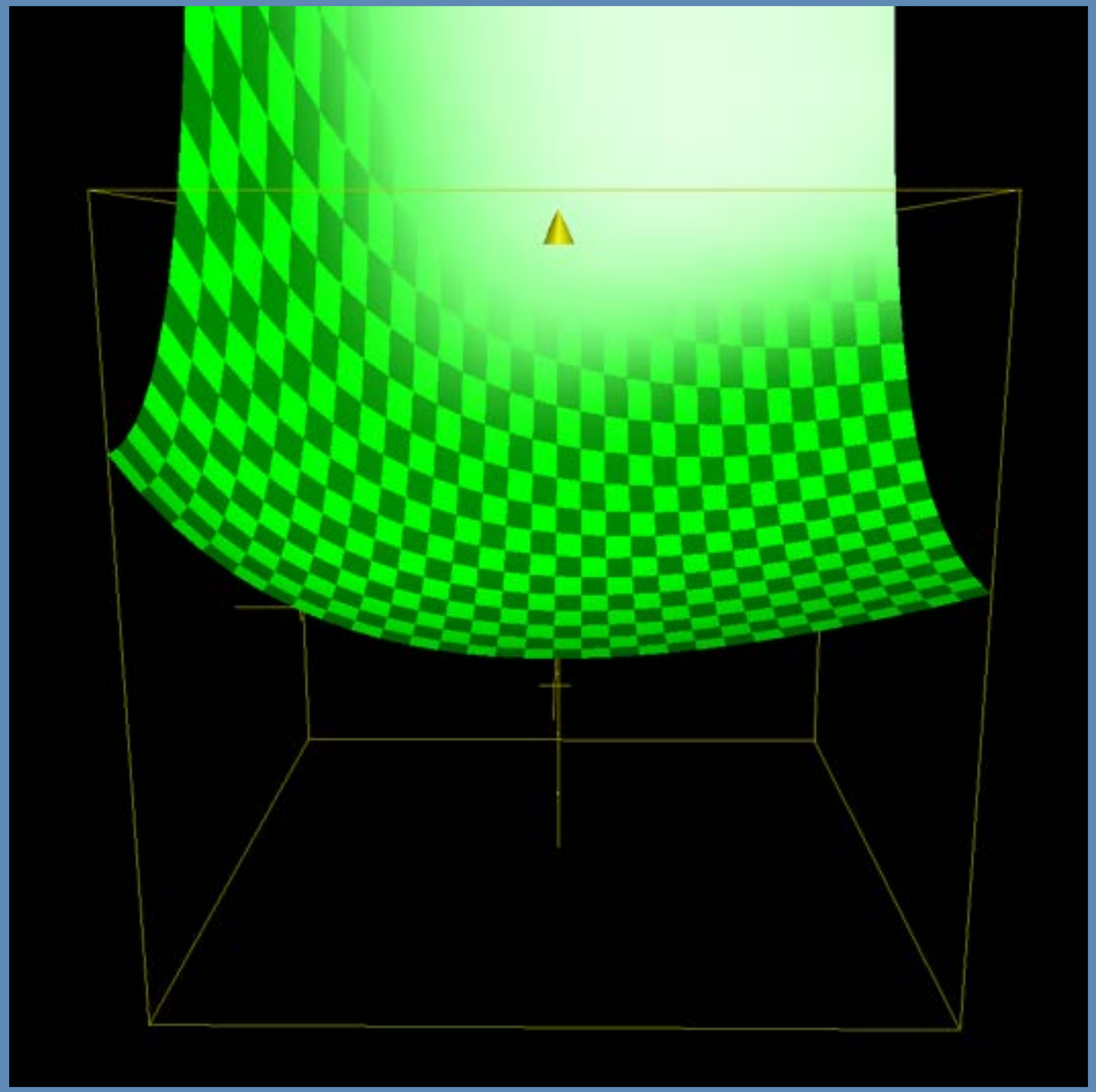
Approximate V*F

- Can be improved with couple more ops, but does not matter in practice

Original (Modified KSK, Fresnel)



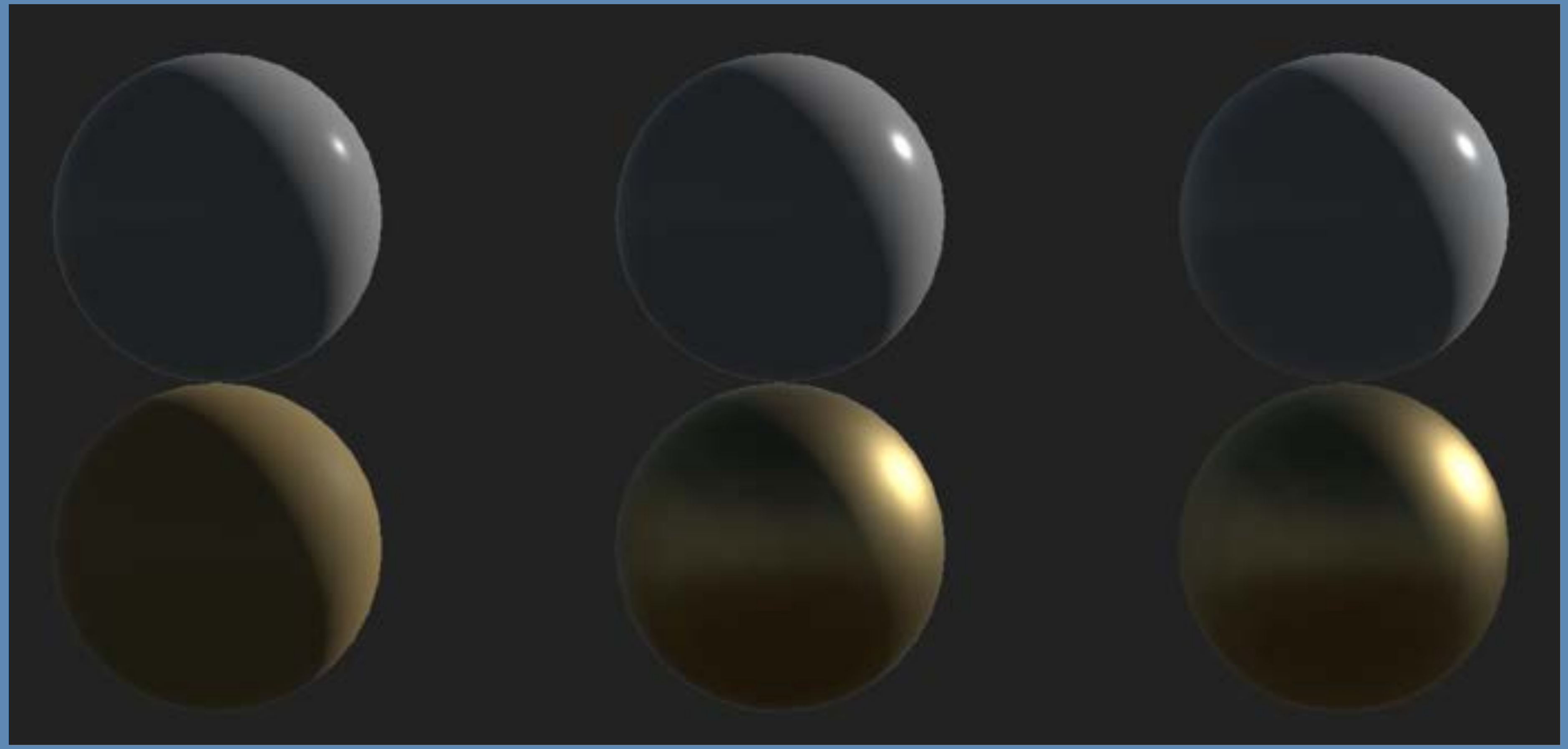
Our approximation*



Comparison of Visibility Terms

Implicit+Fresnel **Smith**+Fresnel **Our Approximation**

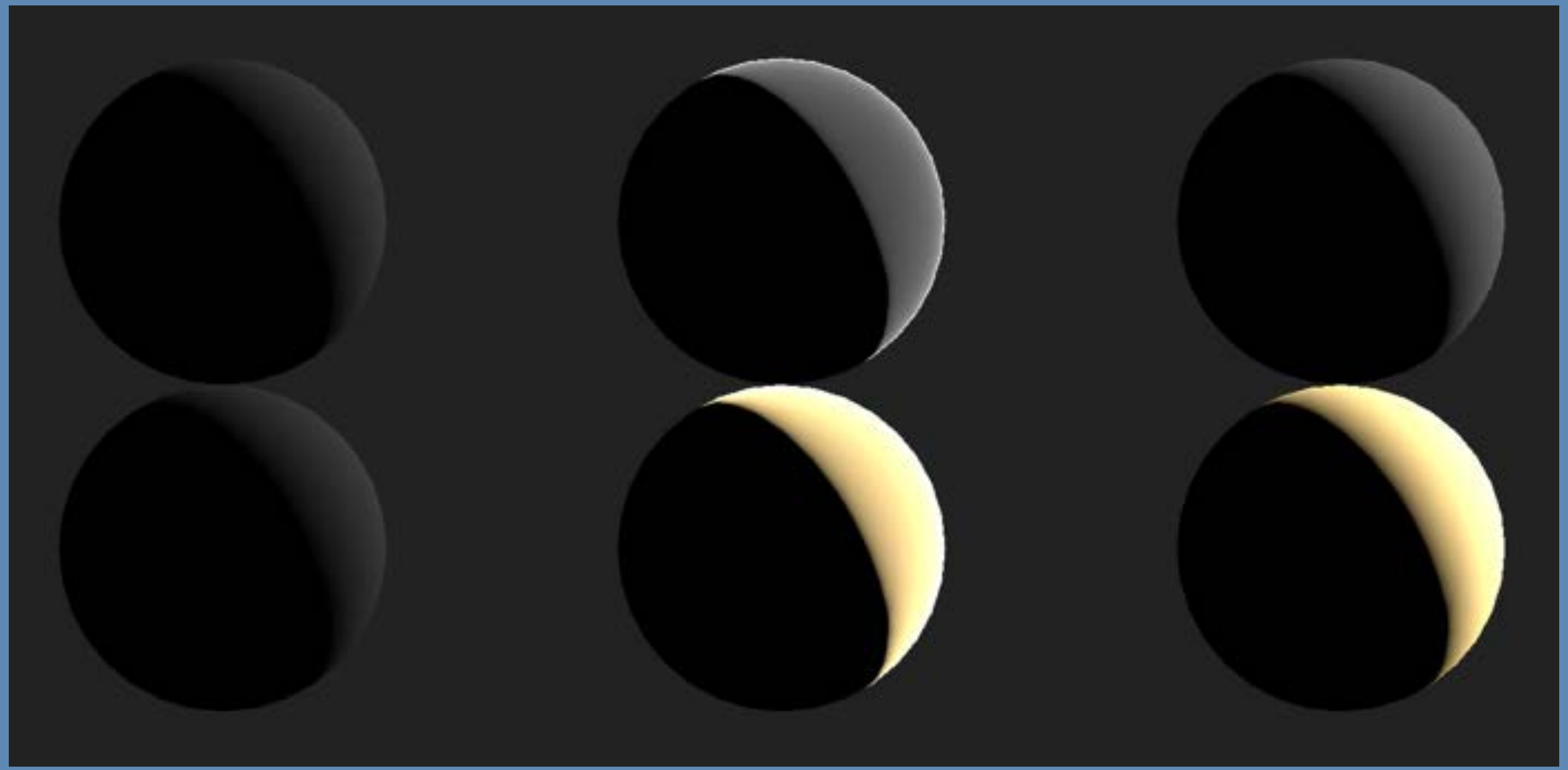
Complete lighting



Plastic

Metal

V*F terms only



Plastic

Metal

Final Specular BRDF

$$BRDF_{spec} = \frac{roughness^4}{4 \cdot \pi \cdot \left((N \cdot H)^2 \left(roughness^4 - 1 \right) + 1 \right)^2 \cdot (L \cdot H)^2 (roughness + 0.5)} \cdot specColor$$

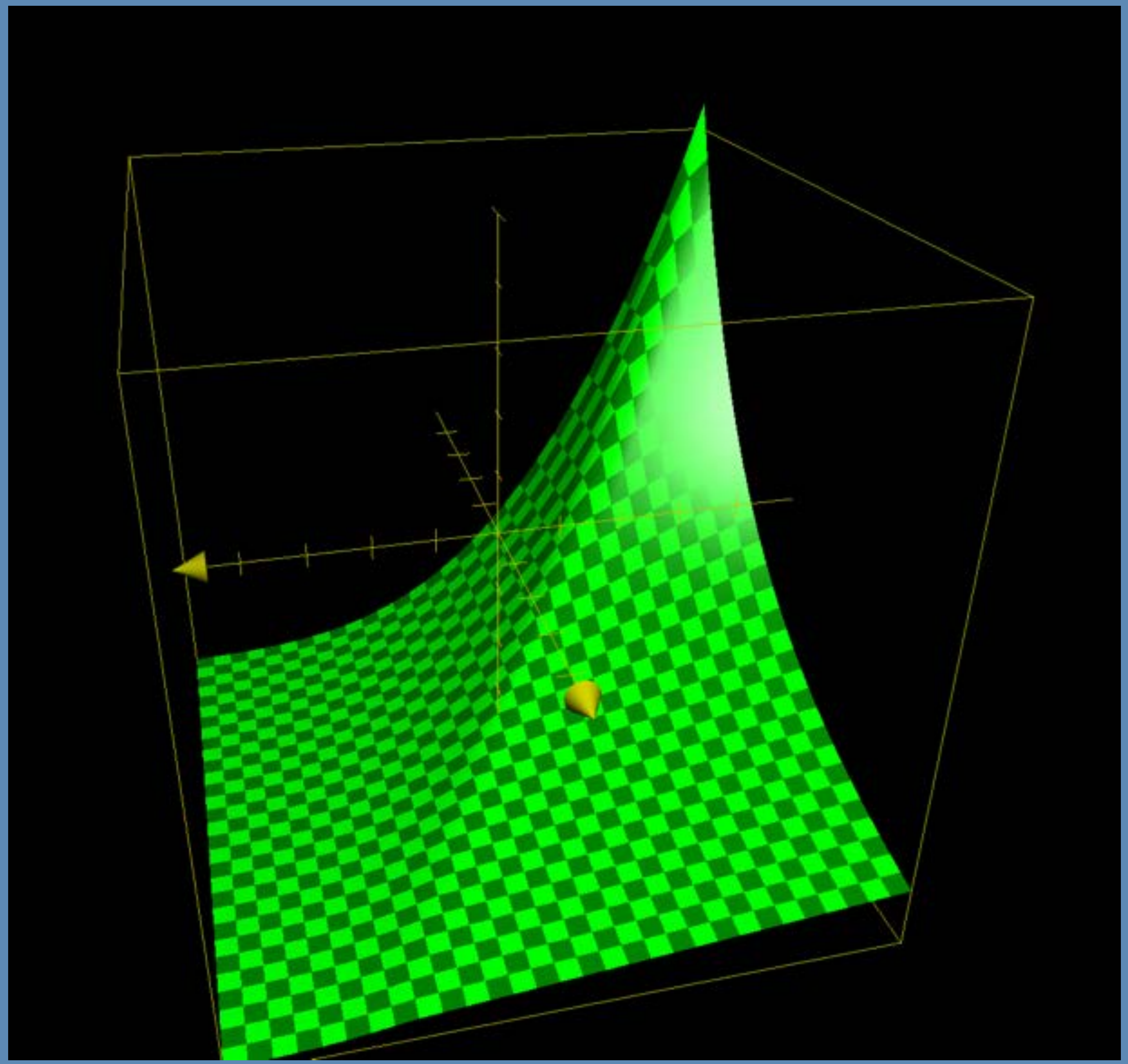
- Just 1 division
- Good for scalar pipeline

Environment BRDF

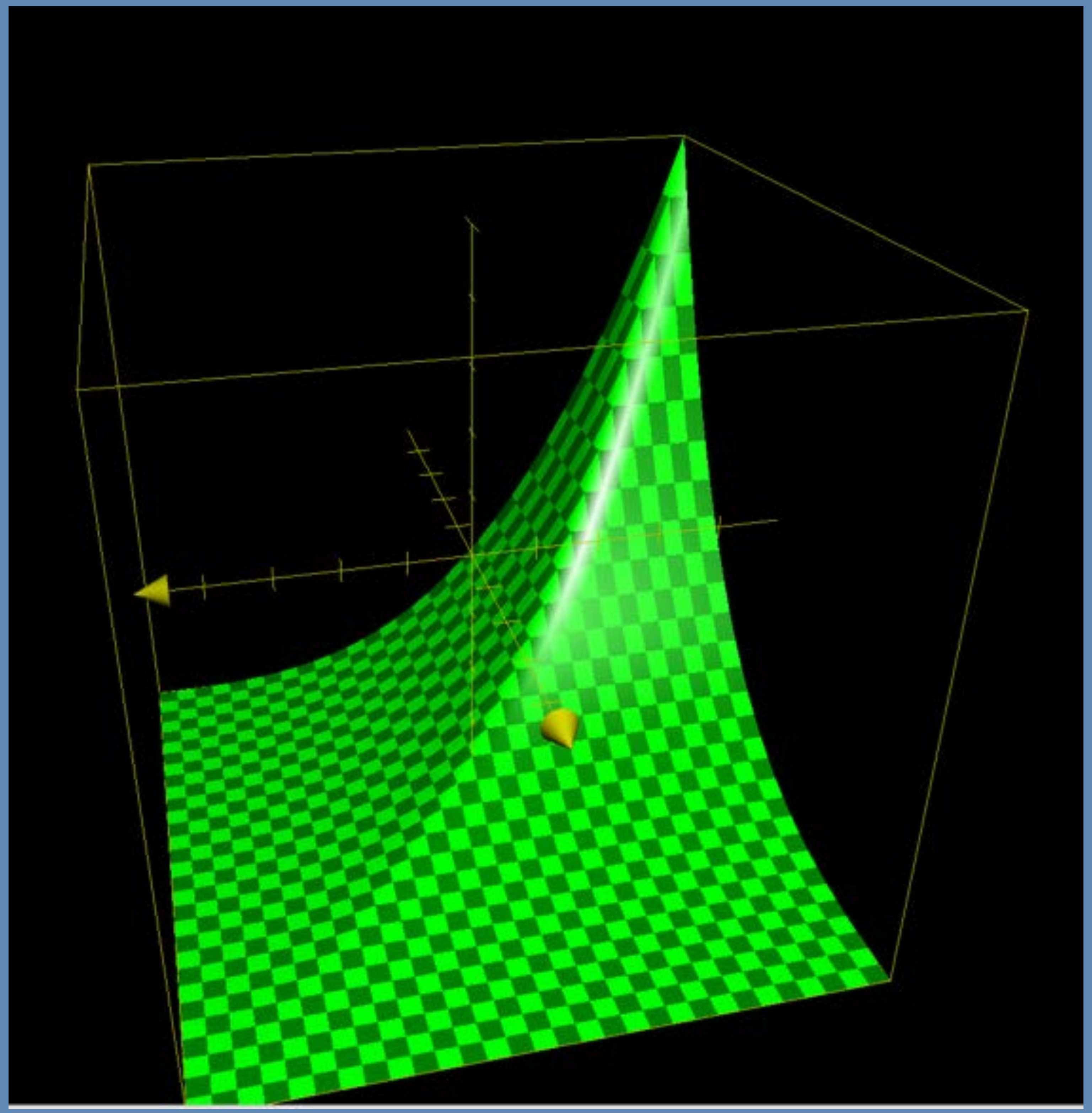
- B. Karis approximation based on D. Lazarov work
- Just refitted with simpler function

$$BRDF_{env} = (1 - \max(roughness, N \cdot V))^3 + spec\mathrm{Color}$$

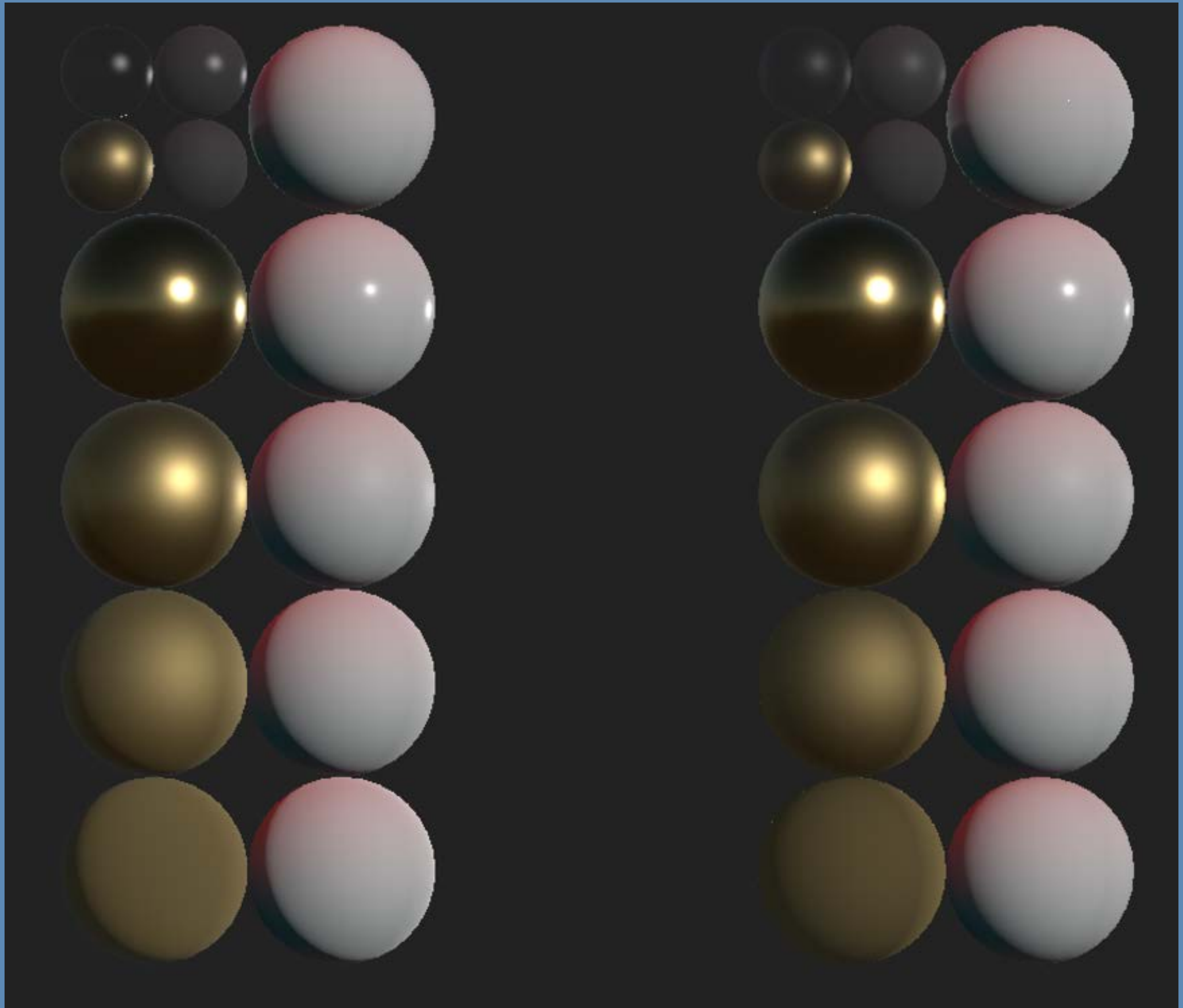
Environment BRDF



$(1\text{-max}(roughness, N{\cdot}V))^3$



Putting everything together



Putting everything together

	ImgTech G6x00 (scalar)	ImgTech SGX554 (vector)	QCOM Adreno305 (scalar)	ARM MaliT760 (vector)	ARM Mali400MP4 (vector)
old-school-non-PBR unnormalized BinnPhong	141%	172%	154%	140%	
normalized BlinnPhong, Smith **(baseline)**	100%	100%	100%	100%	100%
proposed version GGX	**114%**	**126%**	**118%**	**111%**	**271%**

- Percentages are used to make test runs on different screen resolutions easily comparable.
- Measured with a scene consisting of 50K vertices fully covering screen with >3x overdraw rate.

Optimizing for Mid tier

PowerVR		NVIDIA		Qualcomm		ARM	
SGX535	3.5%	Tegra2	1.0%	Adreno2xx	9%		
SGX54x	15.4%	Tegra3	0.9%	Adreno305	7.1%	Mali400 MPx	19%
G6x30	6.0%	Tegra4	0.0%	Adreno3x0	10.3%	MaliT628	0.5%
G6x50	0.3%	K1, X1	0.0%	Adreno420	0.1%	MaliT760	0.0%

Mid Tier

Per-vertex lighting

- Medium-end hardware:
  - Lower bandwidth, GFLOPs are meh
- Diffuse and ambient per-vertex
- Specular per-pixel
- Environment reflection vector per-vertex
- Specular in Tangent space - saves matrix-vector transformation

Optimizing for Low-end

Low-end Tier

PowerVR		NVIDIA		Qualcomm		ARM	
SGX535	3.5%	Tegra2	1.0%	Adreno2xx	9%		
SGX54x	15.4%	Tegra3	0.9%	Adreno305	7.1%	Mali400 MPx	19%
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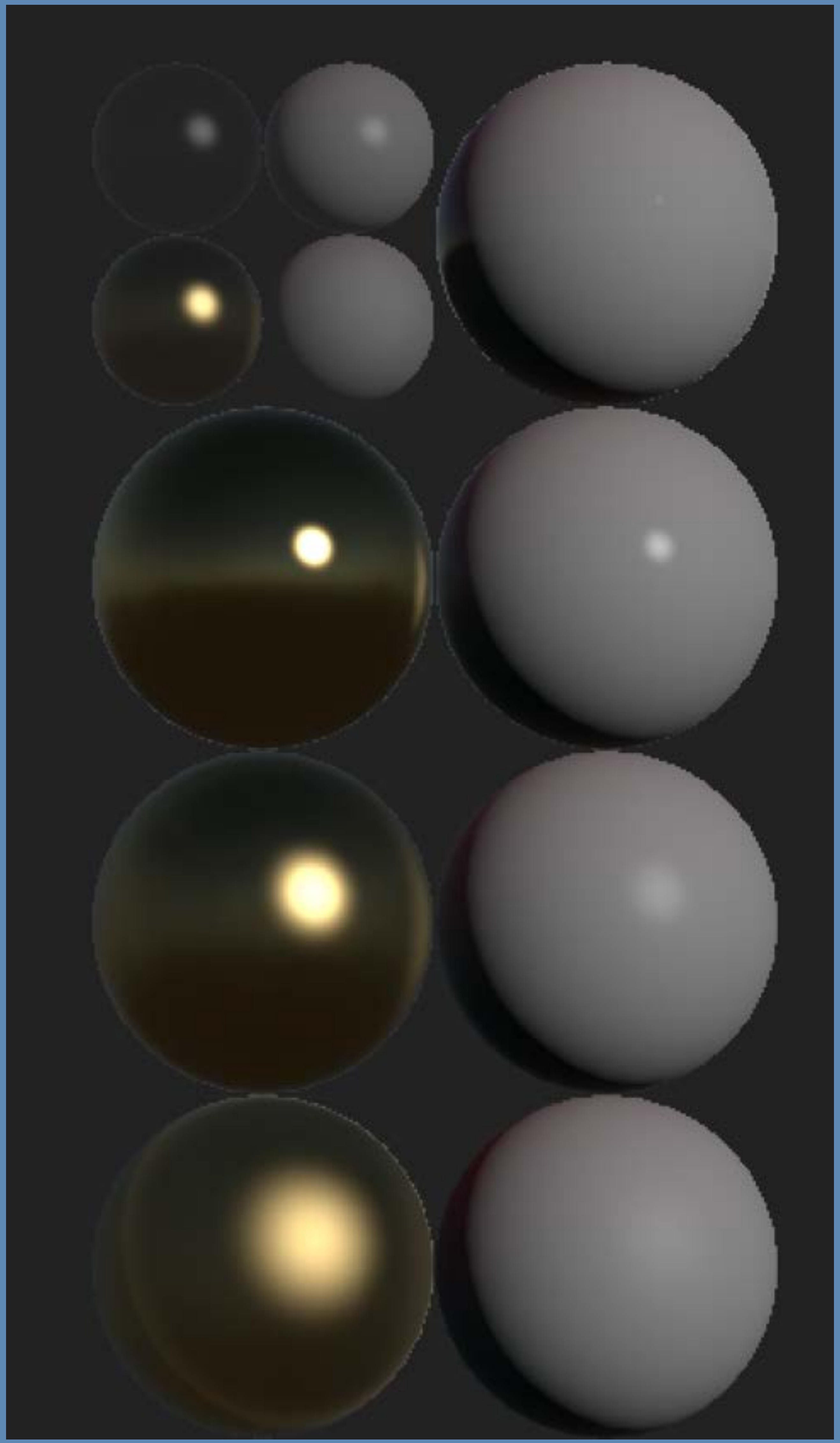
LUT

- Low-end hardware:
  - Low ALU/TEX ratio
- Specular intensity in LUT
  - <**N•H**, Roughness>
- Remember implicit Geometric term!
  - I = BRDF * **N•L**
- **N•H** is cosine - highlights are really crammed

LUT specular

- Store 1/16 intensity in LUT
- **R•L** instead on **N•H** saves couple of ops
  - suggested by B.Karis
- Warp LUT /w **R•L⁴** to get more space for highlights



- PBR challenges on Mobile
- What hardware are we optimizing for?
- Faster BRDF
- **Linear/Gamma**
- **Environment Reflections**

Linear/Gamma

- Linear lighting
  - hard on older GPUs
  - has additional cost
- Gamma and Linear will never look the same, but we can aim for:
  - consistent base light intensity
  - consistent highlight size

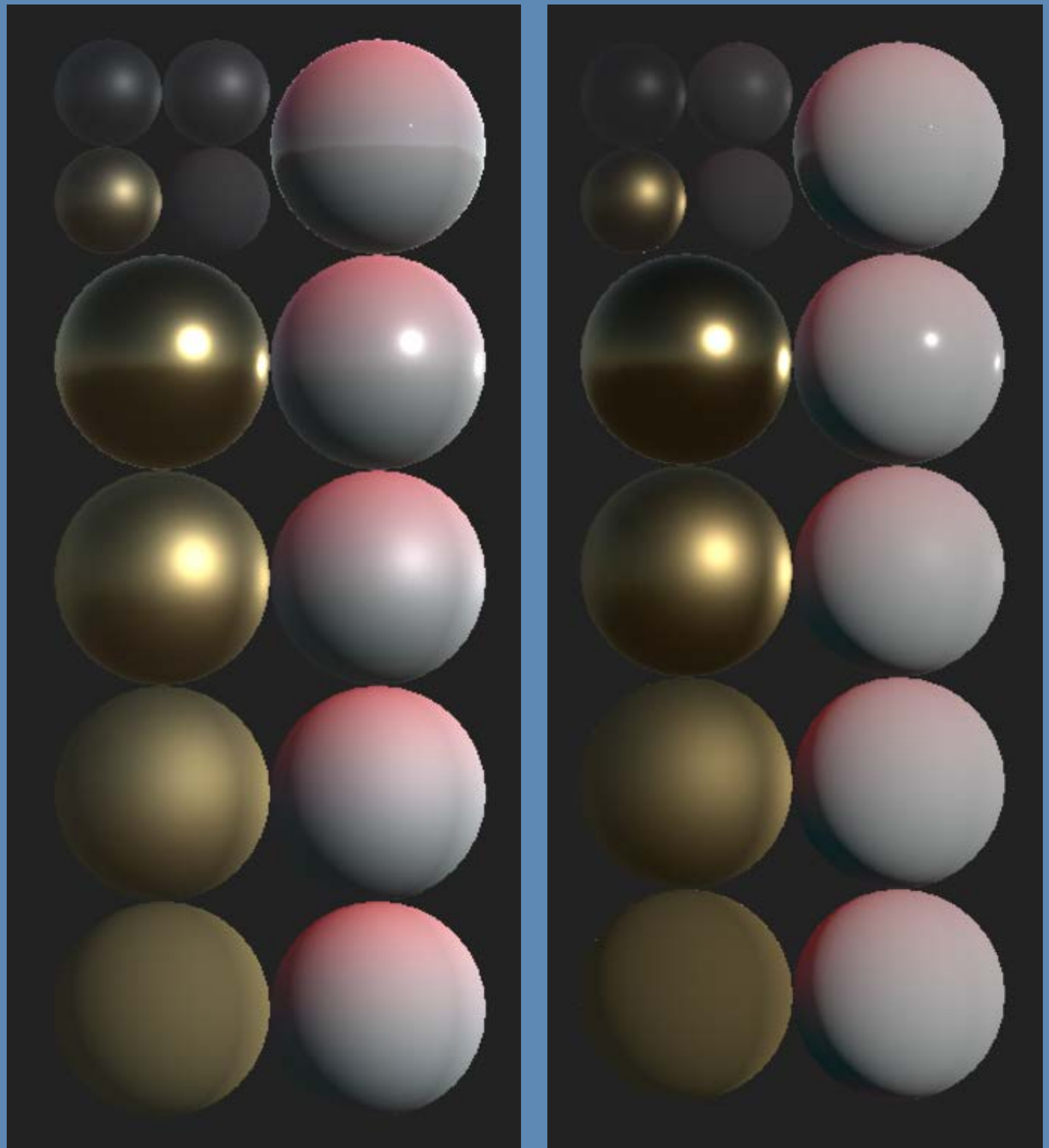
Hack for Gamma to “match” Linear

- Approximate gamma with 2.0
- “Fixup” just **specular intensity**:
  - Keep parameters (Roughness) for specular part of equation in Linear
  - Evaluate specular intensity as in Linear space
  - Convert resulting specular intensity to sRGB space before applying colors:
    = *sqrt (specIntensity_Linear) * specColor_sRGB*

Pros of Gamma hack

- No need to uncompress colors/textures from sRGB to Linear
- Roughness is Linear already
  - usually stored in Alpha channel
- Potentially long latency op (INVSQRT) is NOT at the end of the shader
  - cost can be hidden by other ops

Gamma vs Linear



Environment reflections

- texCUBElod can be really expensive sometimes
  - G6xx0 - high-end mobile GPU!
  - optional extension on ES2.0
- G6xx0: use dynamic branches to pick 2 closest mips and lerp
  - slightly faster!

texCUBElod

- Lerp 2 extreme mips
  - ugly, but fast
- 3-way lerp:
  hardcoded highest mip#
  middle mip#
  2nd order SH
  - for middle you can cut mip levels (/w extension) and hardcode to a very large number

Thanks

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Dominykas Kiauleikis

Sakari Pitkänen

References

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7. Robert Cook and Kenneth Torrance, “A reflectance model for computer graphics”

Bonus Slides

OpenGL ES3.0

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250 GFlops 4 ~ 8 GP/s	**G6x50** iPadAir2, iPhone6	**K1, X1** Nexus 9, Shield Tablet	**Adreno420**	**MaliT760** SGS6

- Green - GPU with ES3.0 support
- TIP: you can’t just use ES2.0 / ES3.0 to determine performance of GPU

Low-end with large share

	PowerVR		NVIDIA		Qualcomm		ARM	
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- Yellow - Low-end with large share, but most in APAC and Latin America
- And you still need to support iPhone4

Textures

- Lack of uncorrelated 4 channel compression
  - Consider Roughness in a separate texture
  - Pairing Roughness with Specular/Metal instead of Albedo or Normals since former is low frequency & low variance data

Textures

- Lack of HDR compression
    - IBL, Lightmaps: RGB*2 instead of RGBm/HDR
    - IBL: uncompressed HDR cubemaps
    - An awful tradeoff :(