Recovering Real-world Reflectance Properties and Shading from HDR Imagery








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Introduction

- Given an HDR video capture, its poses and a 3D reconstruction of the scene:
  - Use HDR textures to estimate albedo and shading *per surface element*
  - Calculate ideal target frames (TF) for each object in the scene given an object segmentation
  - Use each objects TF to estimate it's non-diffuse material

➡ Enables faithful reconstructions

➡ Plausible scene relighting

➡ Visually accurate rendering of virtual objects

Camera Capture

Proposed

Background - Rendering equation

Rendering Equation [Kajiya 1986]

$$I(p) = L_{\mathrm{o}}(x, \omega_o) = \int_{\mathcal{H}^2} f_{\mathrm{r}}(x, \omega, \omega_o) L(x, \omega) \langle \omega, n \rangle \, \mathrm{d}\omega$$

$I(p)$: image I a pixel $p \in \mathbb{R}^2$

$L_o(x, \omega_o)$: Observed radiance L_o at $x \in \mathbb{R}^3$ in viewing direction $\omega_{\mathrm{o}} \in \mathcal{H}^2$

$\mathcal{H}^2$: Upper hemisphere

f_{r}: Bidirectional Reflectance Distribution Function (BRDF)

L: Incoming radiance at $x \in \mathbb{R}^3$ from direction $\omega \in \mathcal{H}^2$

$\langle \omega, n \rangle$: Dot-product between incident direction ω and surface normal n

Approach - BRDF

We use a dichromatic BRDF [Shafer 1985], i.e.

$$f_r(x, \omega, \omega_o) = f_{\mathrm{d}}(x) + f_{\mathrm{nd}}(x, \omega, \omega_o)$$

$f_{\mathrm{d}}(x)$: Albedo $\rho(x)$ at surface point $x \in \mathbb{R}^3$: $f_{\mathrm{d}}(x; \rho) = \rho(x)$

$f_{\mathrm{nd}}(x, \omega, \omega_o)$: Non-diffuse microfacet BRDF [Torrance and Sparrow 1967] with parameters roughness φ and specular ψ, $f_{\mathrm{nd}}(x, \omega, \omega_o; \varphi, \psi)$:

$$f_{\mathrm{nd}}(\varphi, \psi) = G(\varphi) D(\varphi) F(\psi)$$

$$G(\varphi) = G_1(\langle n, \omega \rangle, \varphi) G_1(\langle n, \omega_{\mathrm{o}} \rangle, \varphi); \quad G_1(x, y) = \frac{1}{x + \sqrt{x^2 + y^2 - x^2 y^2}}$$

$$D(\varphi) = \frac{\varphi^2}{\pi(1 + (\varphi^2 - 1)\langle n, h \rangle^2)^2}; \quad h = \frac{\omega + \omega_{\mathrm{o}}}{\|\omega + \omega_{\mathrm{o}}\|}$$

$$F(\psi) = \psi + (1 - \psi)(1 - \langle \omega, h \rangle)^5$$

Approach - Reformulation Rendering Equation

Plugging the BRDF model into the rendering equation gives:

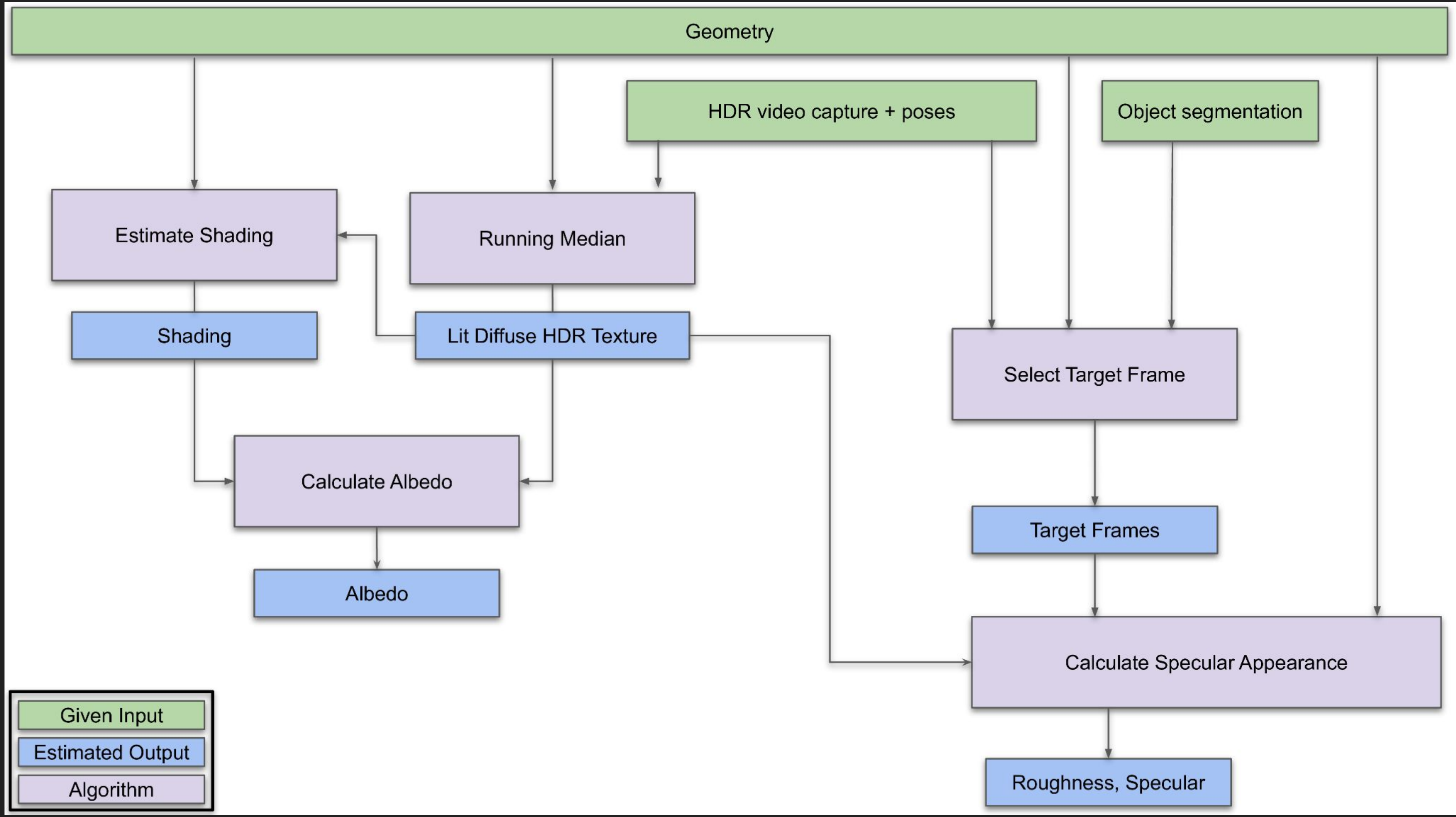
$$L_{\mathrm{o}}(x, \omega_o) = L_{\mathrm{d}}(x) + L_{\mathrm{nd}}(x, \omega_o)$$

$$L_{\mathrm{d}}(x) = \rho(x) \int_{\mathcal{H}^2} L(x, \omega) \langle \omega, n \rangle \, \mathrm{d}\omega$$

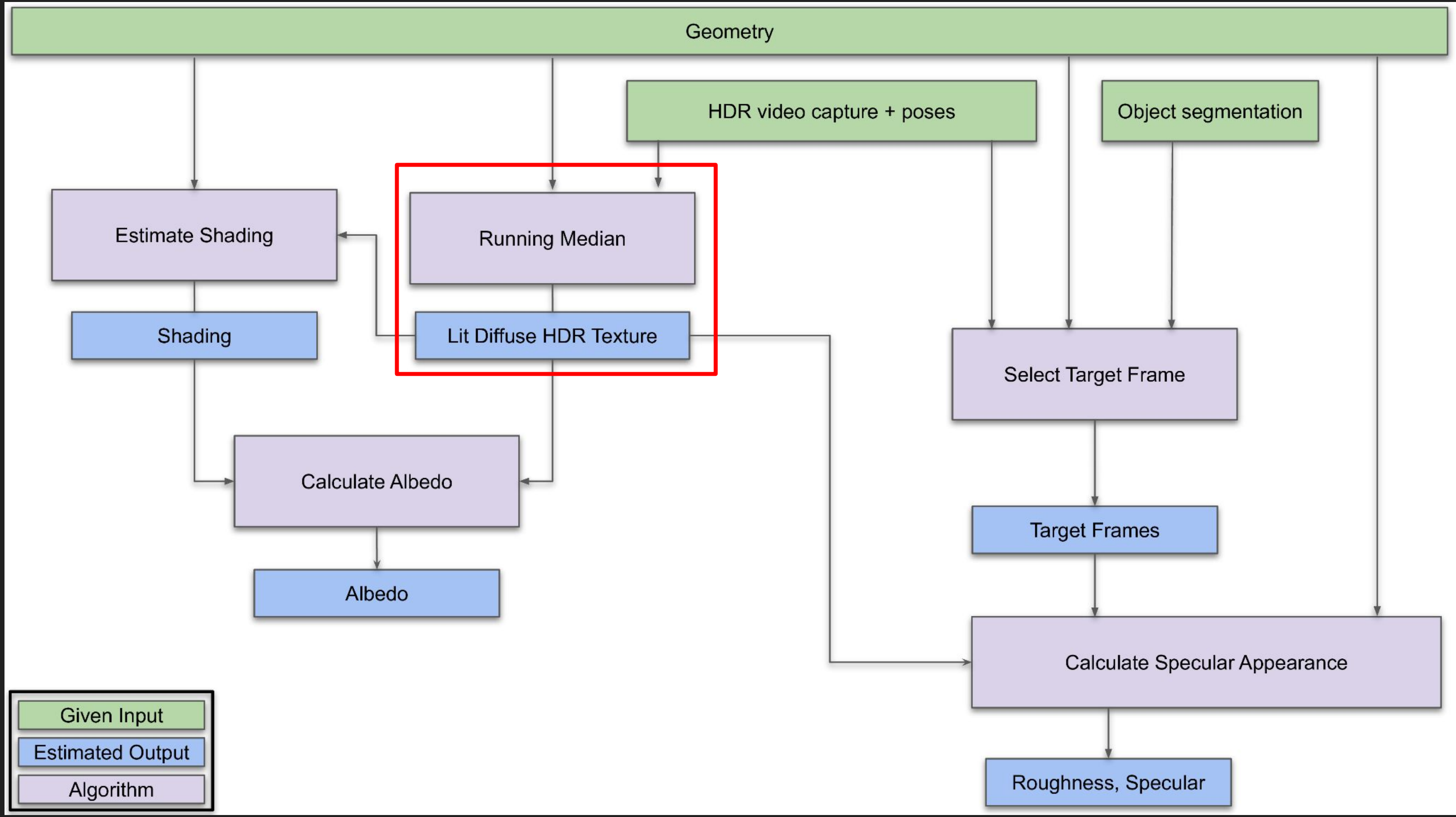
$$L_{\mathrm{nd}}(x, \omega_o) = \int_{\mathcal{H}^2} f_{\mathrm{nd}}(x, \omega, \omega_o; \varphi, \psi) L(x, \omega) \langle \omega, n \rangle \, \mathrm{d}\omega$$

We solve for $L_{\mathrm{d}}, \rho, \varphi$, and ψ for each surface element of a complete indoor scan

Approach - Proposed Overall Algorithm



Approach - Lit Diffuse HDR Texture L_{d}



Approach - Lit Diffuse HDR Texture L_d

Running mean on HDR 16-bit data results in artifacts

Mean with artifacts

Use median instead of mean [Riviere et al. 2016]

- All values have to be stored for median calculation
- => Very expensive, memory demanding, time consuming

=> Estimate an approximation of the median using the P-Square algorithm [Jain and Chlamtac 1985]

Approach - Running Average on HDR data

Mean

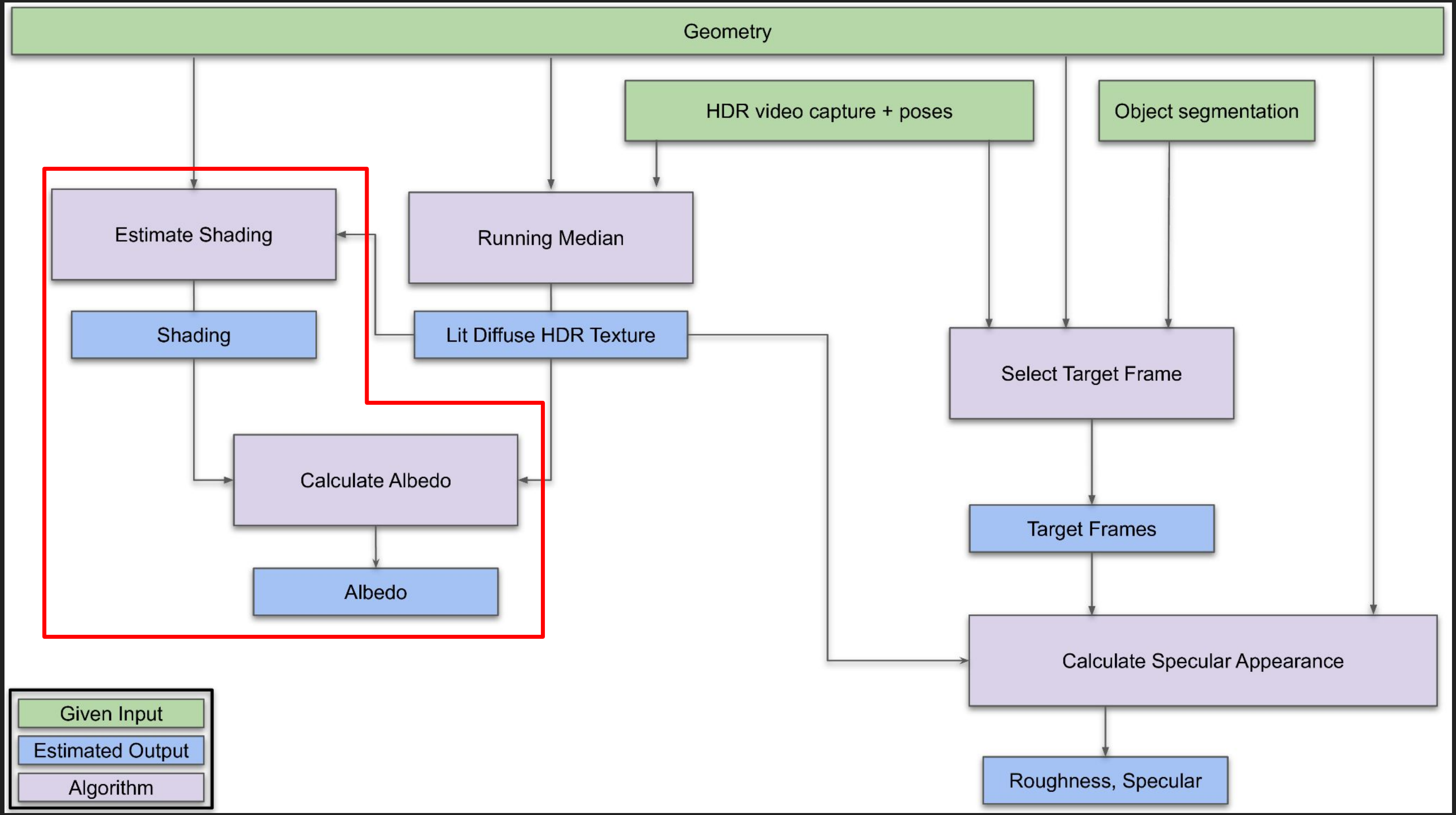
Median

Approach - Lit Diffuse HDR Texture L_d

=> Assume median texture equals diffuse radiance L_d, and we call it *Lit diffuse HDR texture*

Median texture = L_d = Lit diffuse HDR texture

Approach - Shading and Albedo Reconstruction



Approach - Shading and Albedo Reconstruction

$$L_{\mathrm{o}}(x, \omega_o) = L_{\mathrm{d}}(x) + L_{\mathrm{nd}}(x, \omega_o)$$

$$L_{\mathrm{d}}(x) = f_{\mathrm{d}}(x; \rho) \int_{\mathcal{H}^2} L(x, \omega) \langle \omega, n \rangle \, \mathrm{d}\omega$$

$$L_{\mathrm{nd}}(x, \omega_o) = \int_{\mathcal{H}^2} f_{\mathrm{nd}}(x, \omega, \omega_o; \varphi, \psi) L(x, \omega) \langle \omega, n \rangle \, \mathrm{d}\omega$$

Approach - Shading and Albedo Reconstruction

$$\overbrace{L_{\mathrm{d}}(x)}^{\text{Median Texture}} = \overbrace{\rho(x)}^{\text{Albedo}} \cdot \overbrace{S(x)}^{\text{Shading}}$$

$$S(x) = \int_{\mathcal{H}^2} L(x, \omega) \langle \omega, n \rangle \, \mathrm{d}\omega$$

Solve for albedo with

$$\rho(x) = \frac{L_{\mathrm{d}}(x)}{S(x)}$$

Approach - Estimate Shading

$$S(x) = \int_{\mathcal{H}^2} L(x, \omega) \langle \omega, n \rangle \, \mathrm{d}\omega \approx \sum_{i=1}^{N} L(x, \omega_i) \langle \omega_i, n \rangle$$

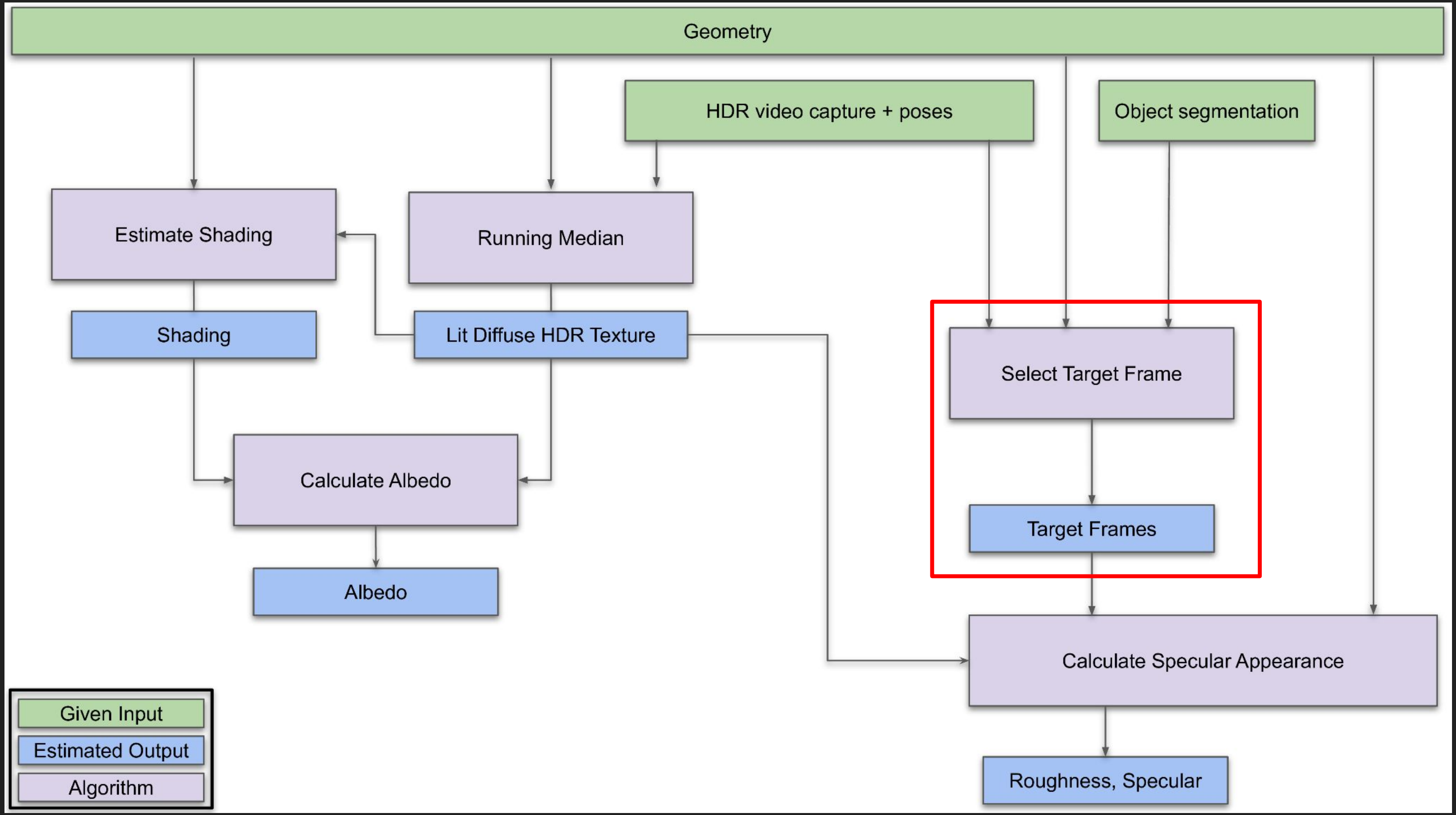
- Cast N rays $(x, \omega_i), i = 1, \ldots, N$, at each surface point $x \in \mathbb{R}^3$ in direction $\omega_i \in \mathcal{H}^2$
- At each rays hitpoint $\tilde{x}_i \in \mathbb{R}^3$: $L(x, \omega_i) = L_\mathrm{d}(\tilde{x}_i)$

L_d

$N = 100$ samples

$N = 10000$ samples

Approach - Target Frame Calculation



Approach - Target Frame Calculation

Use *only one* target frame for each object

- Less computational complexity
- Fast

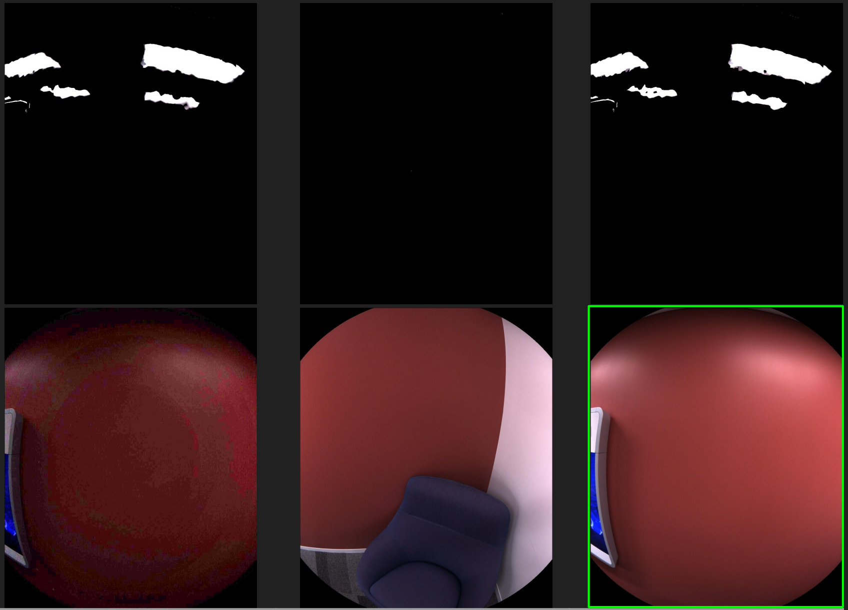
Target frame should fulfill:

- $\mathcal{A}_1$: High chance of specular highlight caused by direct illumination
- $\mathcal{A}_2$: HDR capture consists of valid pixels, i.e. not over-/under-saturated

Approach - Target Frame Calculation

Rendered Specularity

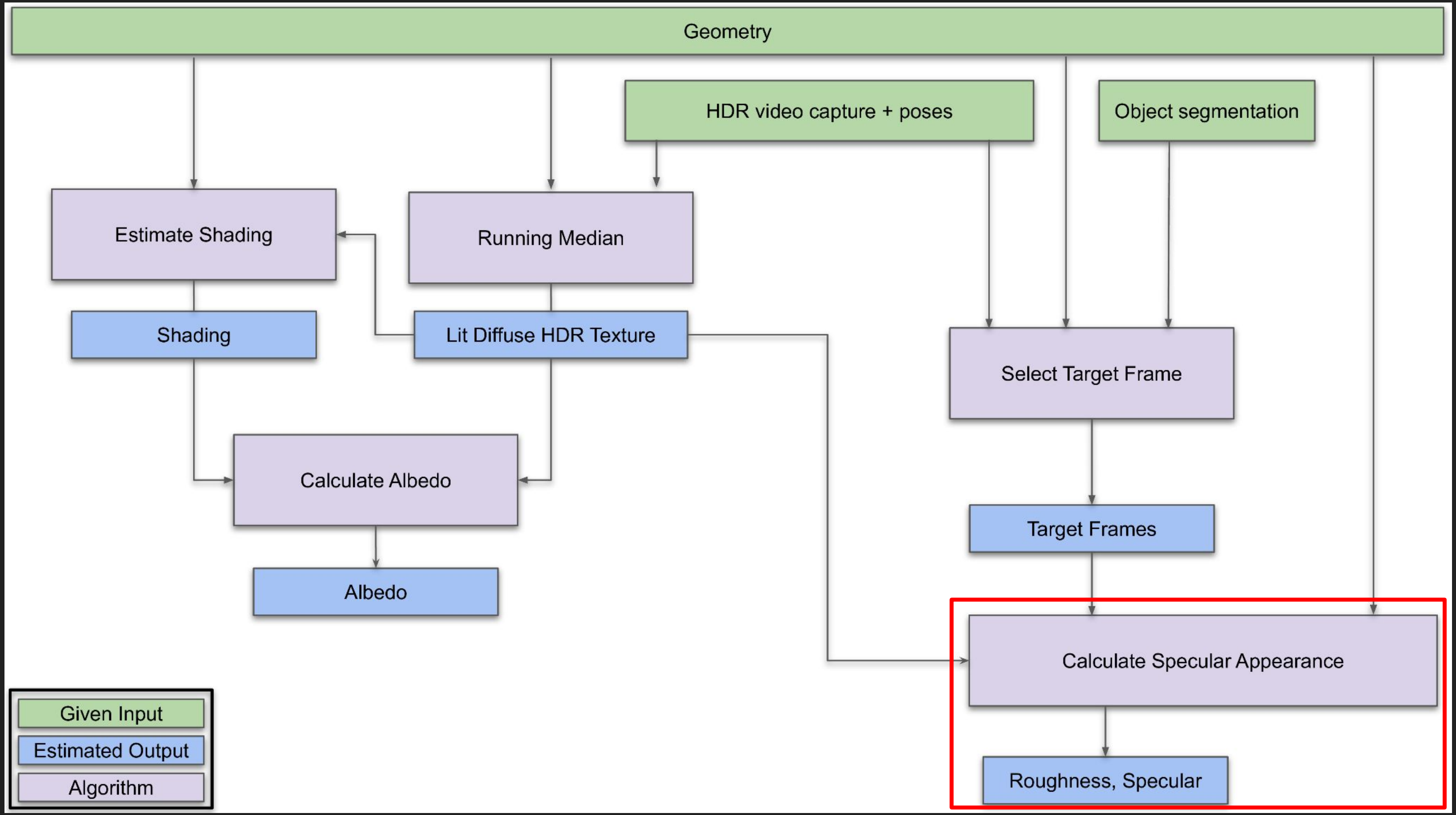
Observation



Target Frame

$\mathcal{A}_1$	✔	✘ (no specularities)	✔
$\mathcal{A}_2$	✘ (under-saturated)	✔	✔
TF	✘	✘	✔

Approach - Roughness and Specular Estimation



Approach - Roughness and Specular Estimation

Goal: Estimate i-th object non-diffuse material parameters φ^i, ψ^i

$$I^i(p) = I^i_{\mathrm{d}}(p) + I^i_{\mathrm{nd}}(p; \varphi^i, \psi^i)$$

$$\min_{\varphi^i, \psi^i \in [0,1]} \sum_{p \in \Omega^i} \| I^i(p) - (I^i_{\mathrm{d}}(p) + I^i_{\mathrm{nd}}(p; \varphi^i, \psi^i)) \|^2, \quad \forall i$$

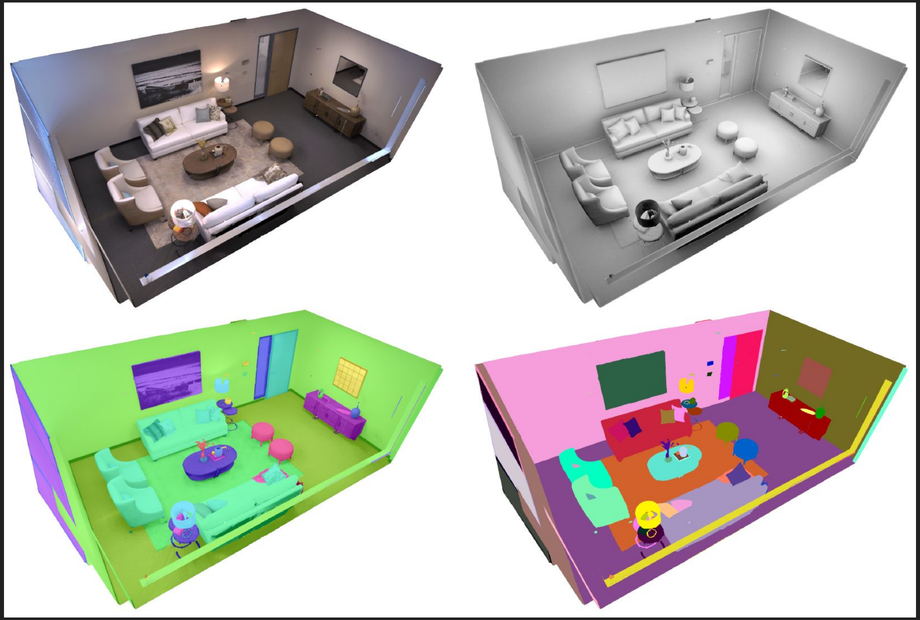
=> Grid search in φ^i, with nested least squares optimization in ψ^i

Experiments

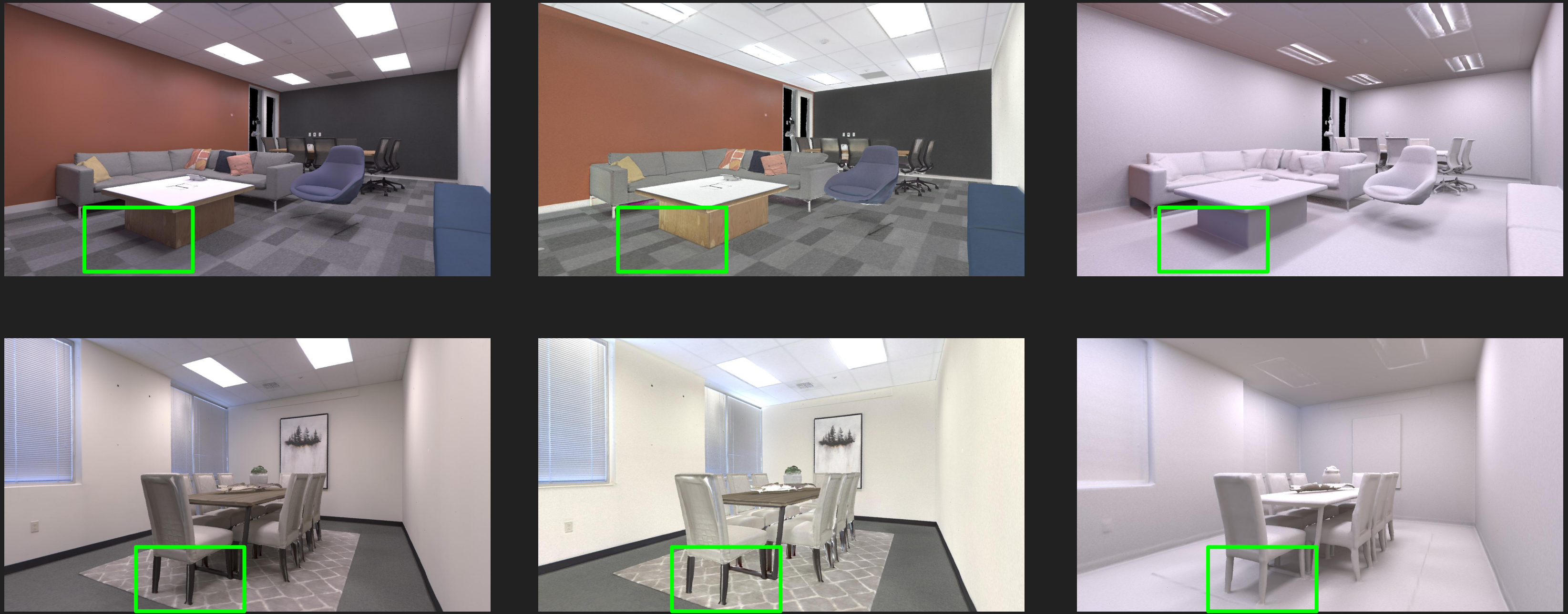
Real-world data set “Replica” [Straub et al. 2019] used for quantitative and qualitative evaluation

Provides:

- Geometry of complete 3D scenes
- HDR video
- Per frame camera poses
- Object instance segmentation



Experiments - Shading and Albedo Validation

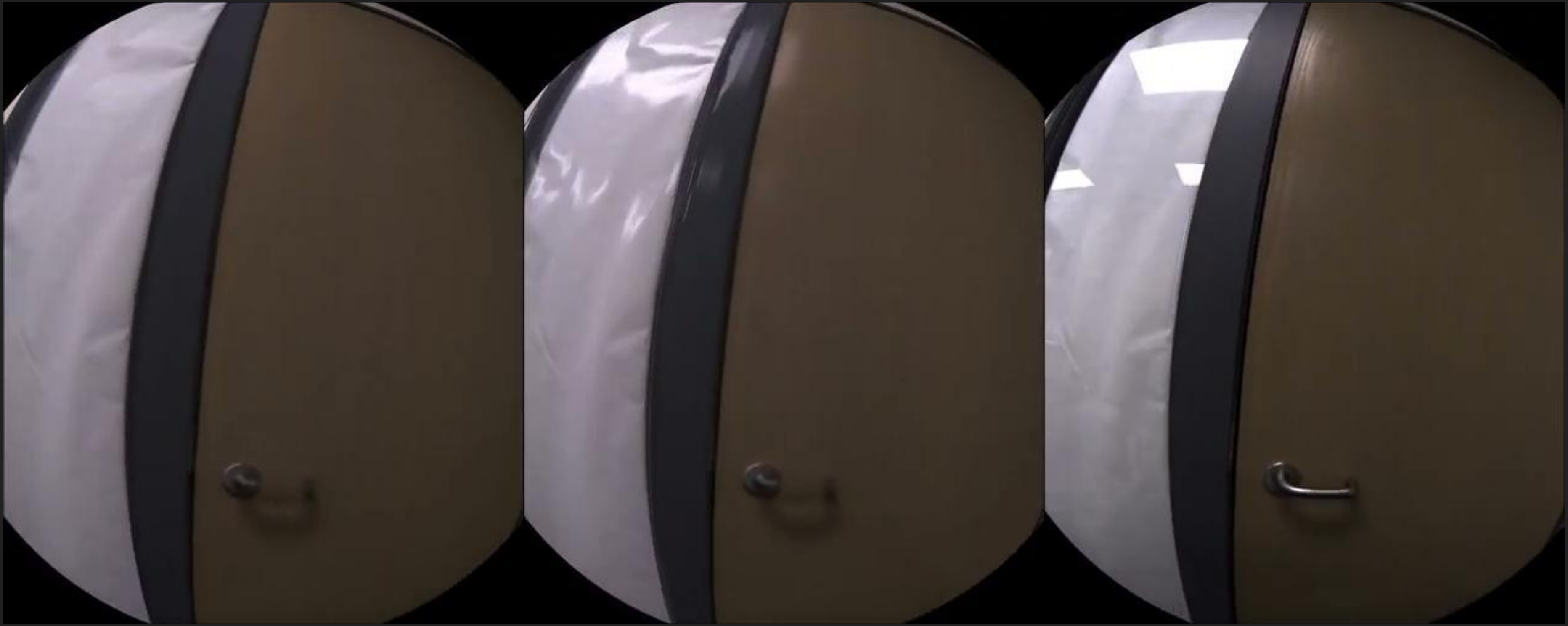


Office 3

Room 2

Input Albedo Shading

Experiments - Specular Appearance Validation



Lit Diffuse HDR Texture | Proposed | Ground Truth Video Capture

Experiments - Relighting

Conclusion

- Calculate lit diffuse HDR texture
- Calculate albedo and shading per surface element
- Automatically calculate target frame for every object
- Calculate specular appearance parameters for every object