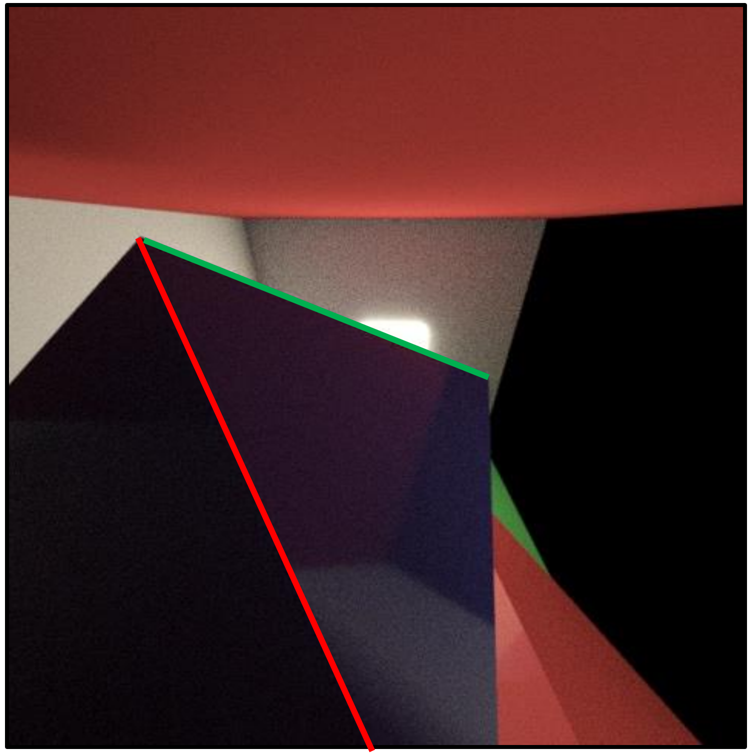
UNBIASED WARPED-AREA SAMPLING FOR DIFFERENTIABLE RENDERING

UCSD CSE 272
Advanced Image Synthesis

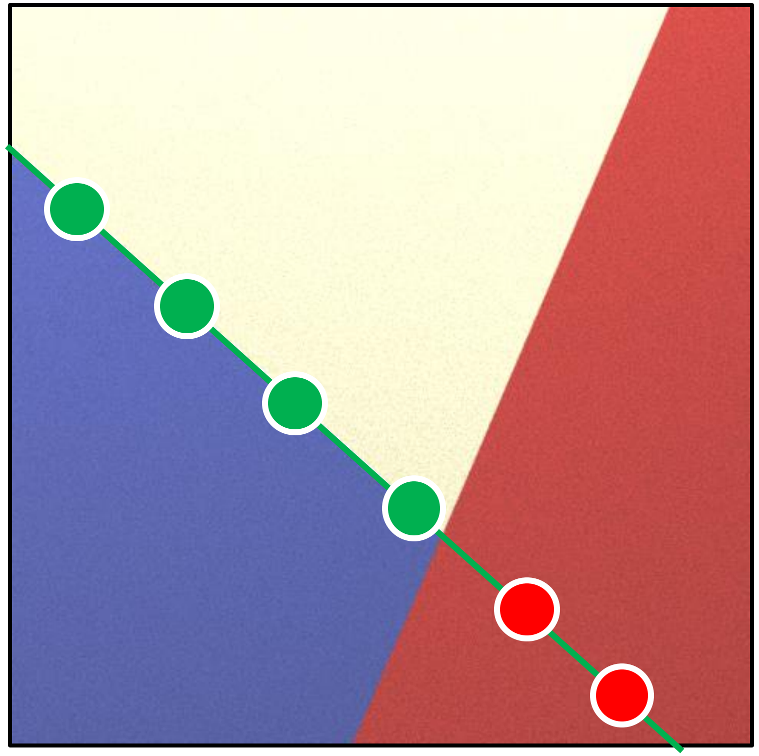
Tzu-Mao Li

with slides from Sai Bangaru

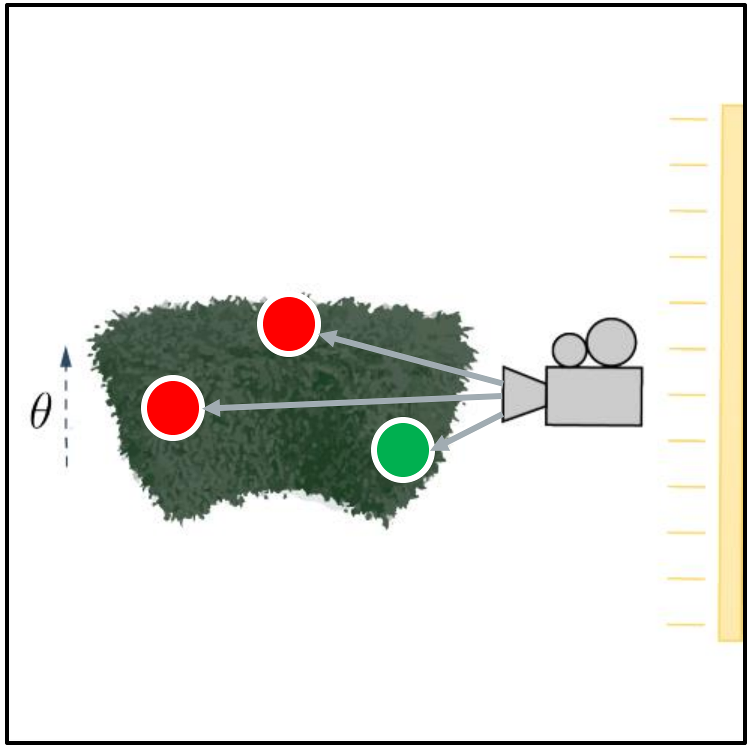
CHALLENGES: EDGE SAMPLING IS HARD!



Silhouette classification

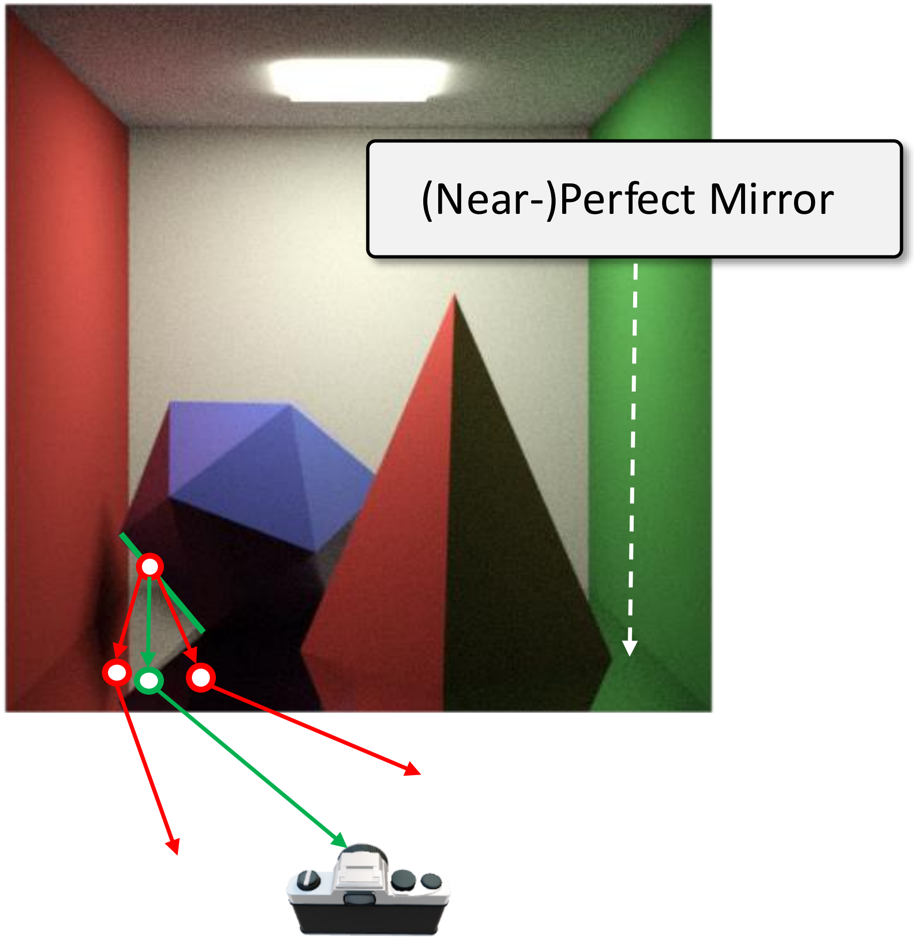


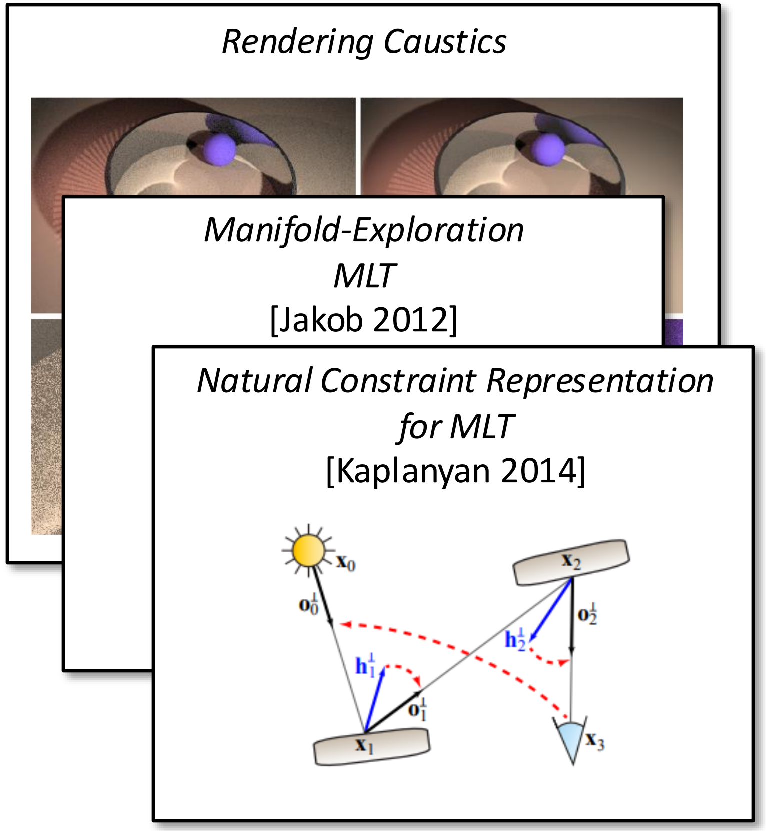
Occlusion



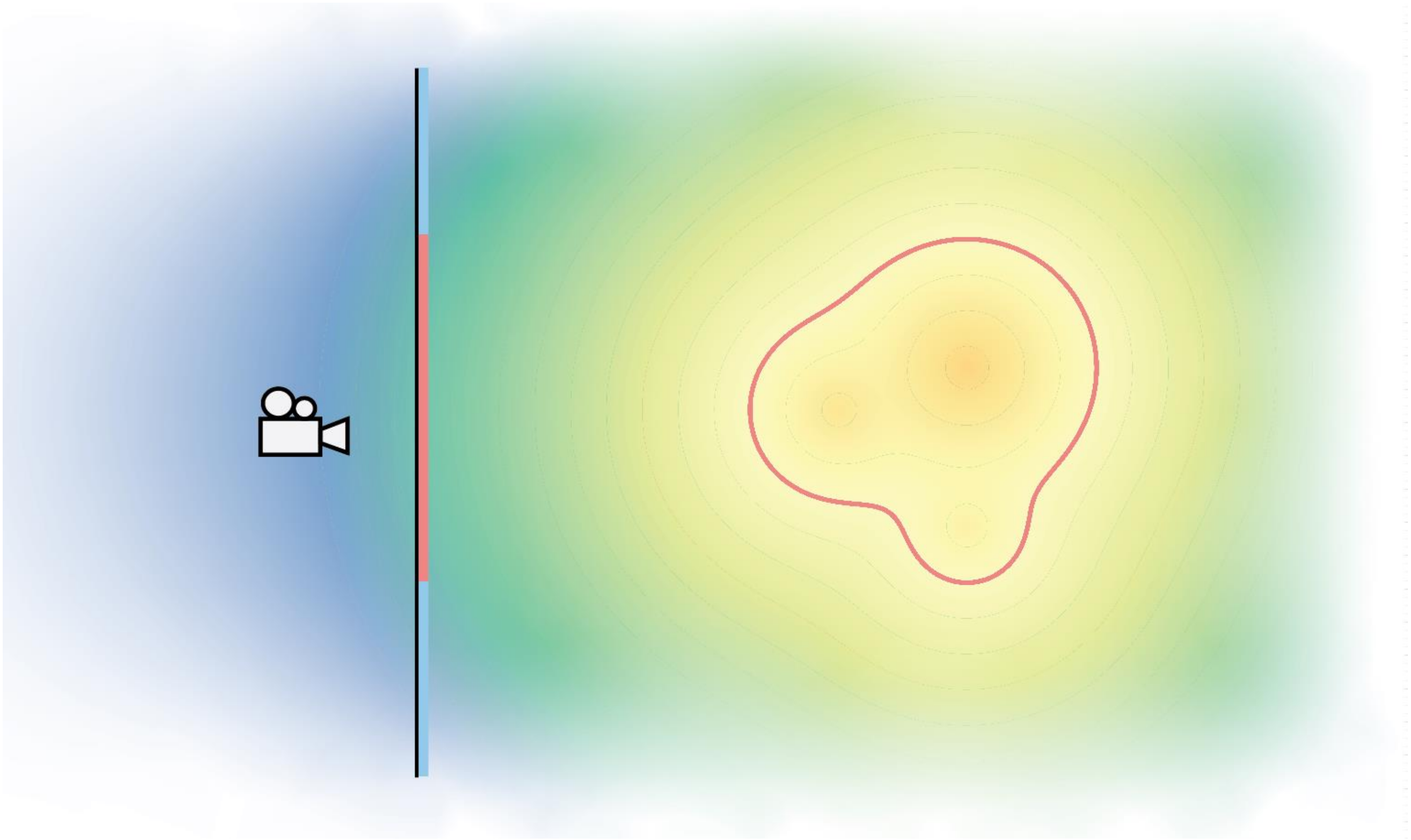
Depth complexity

EDGE SAMPLING HAS TROUBLE WITH SPECULAR REFLECTIONS

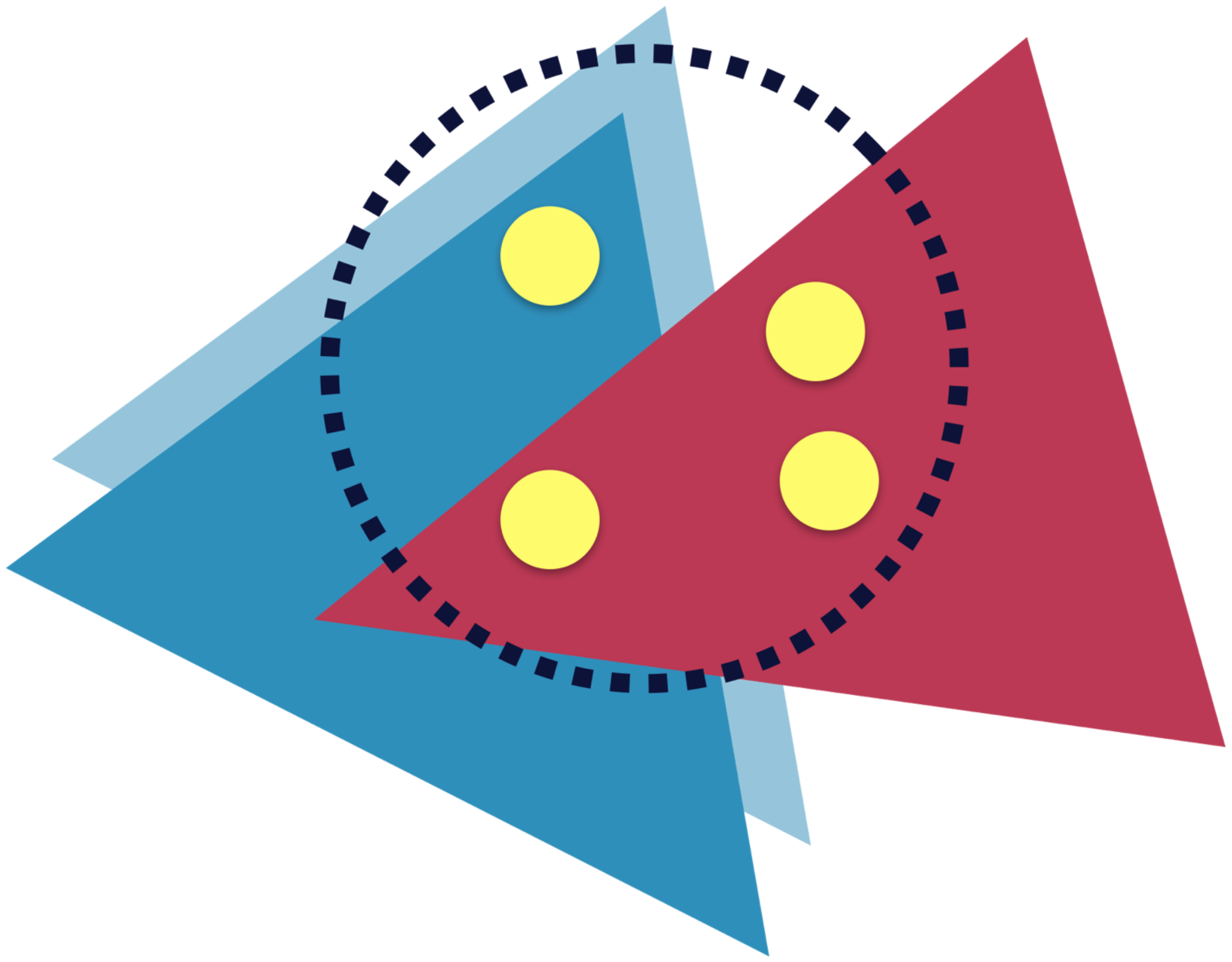




SILHOUETTE EXTRACTION IS DIFFICULT FOR IMPLICIT REPRESENTATIONS



CAN WE DESIGN AN UNBIASED AREA SAMPLING METHOD?



TODAY: WARPED AREA SAMPLING

Unbiased Warped-Area Sampling for Differentiable Rendering

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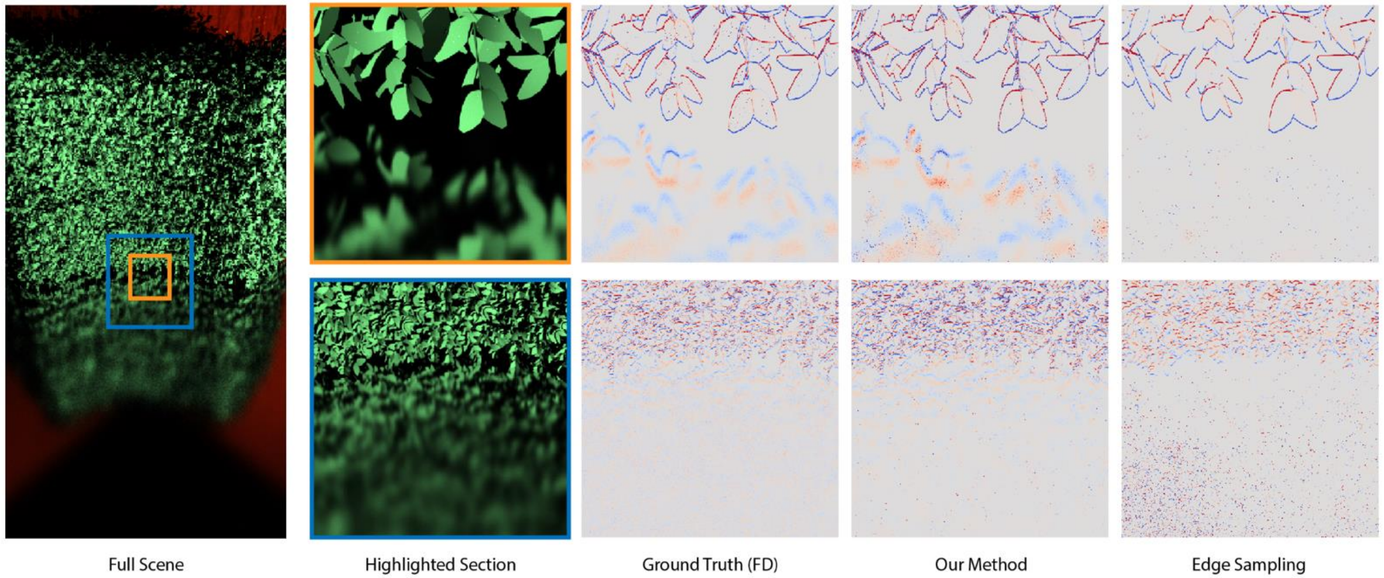
TZU-MAO LI, Massachusetts Institute of Technology
FRÉDO DURAND, Massachusetts Institute of Technology



Differentiable Rendering of Neural SDFs through Reparameterization

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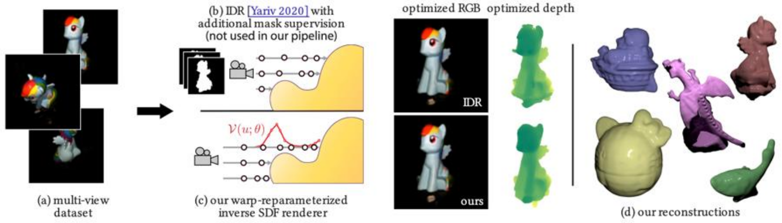

Warped-Area Reparameterization of Differential Path Integrals

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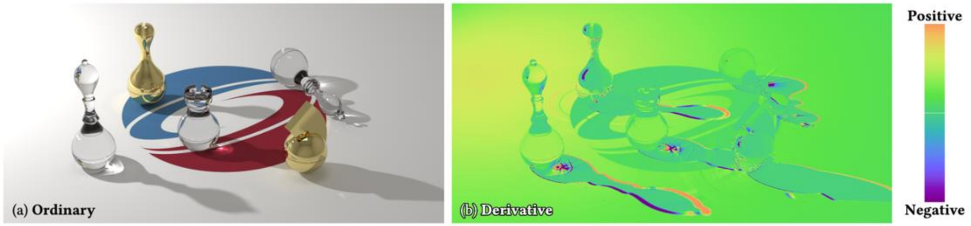
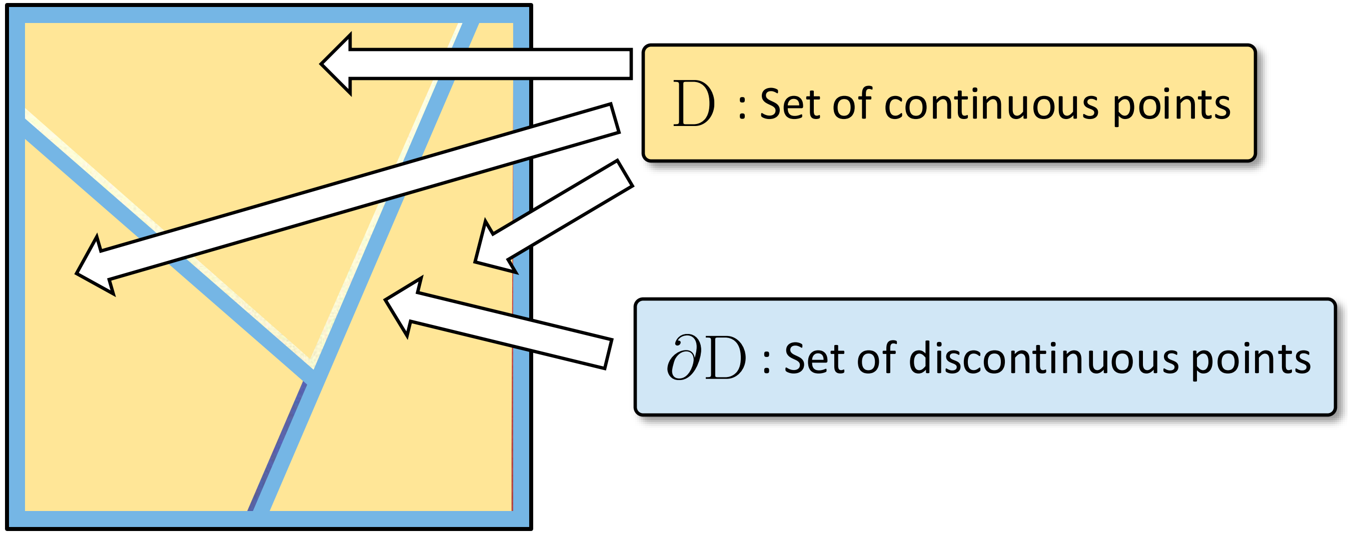
TZU-MAO LI, University of California, San Diego, USA
SHUANG ZHAO, University of California, Irvine, USA



THE REYNOLDS TRANSPORT THEOREM



$$\partial_\theta \int_{\mathrm{D}} f = \int_{\mathrm{D}} \partial_\theta f + \int_{\partial \mathrm{D}} f \vec{\mathbf{v}} \cdot \vec{\mathbf{n}}$$

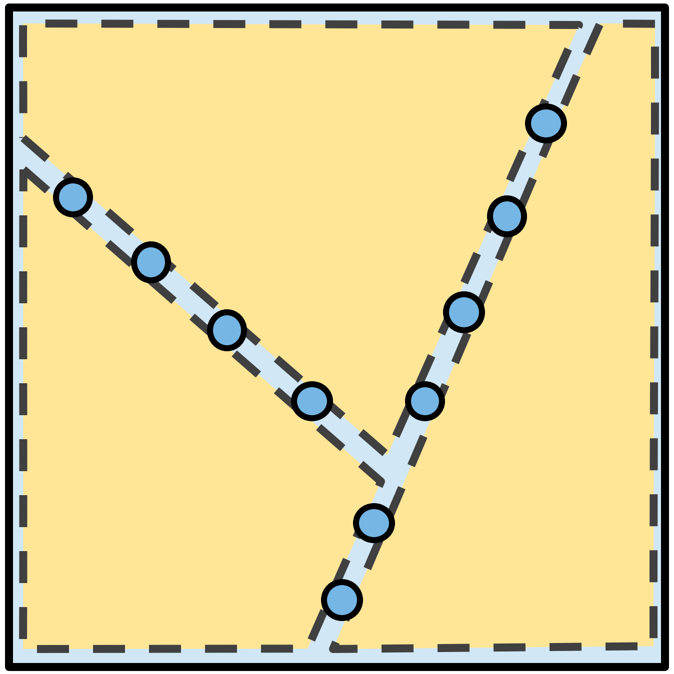
Interior term

Edge term

CONVERTING EDGE SAMPLES TO AREA SAMPLES

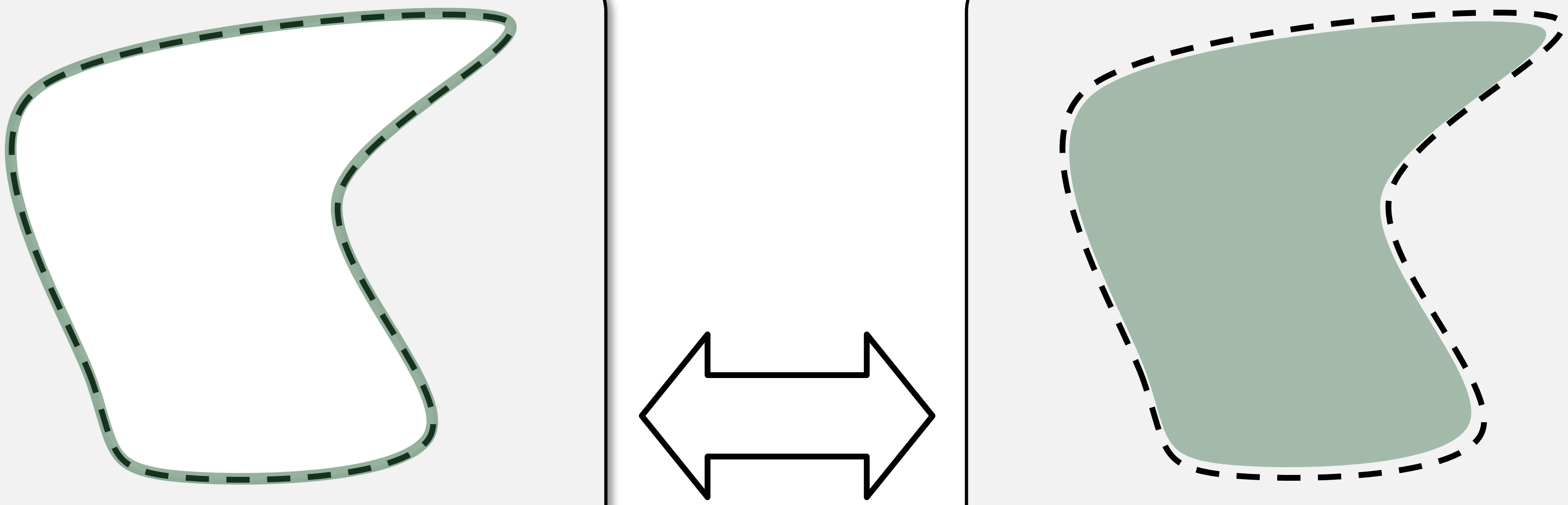
$\int_{\partial D} f\vec{\mathbf{v}} \cdot \vec{\mathbf{n}}$ is estimated through edge samples

Goal: Rewrite $\int_{\partial D} f\vec{\mathbf{v}} \cdot \vec{\mathbf{n}}$ into area integral $\int_{D} g$



THE DIVERGENCE THEOREM

[Gauss 1813]



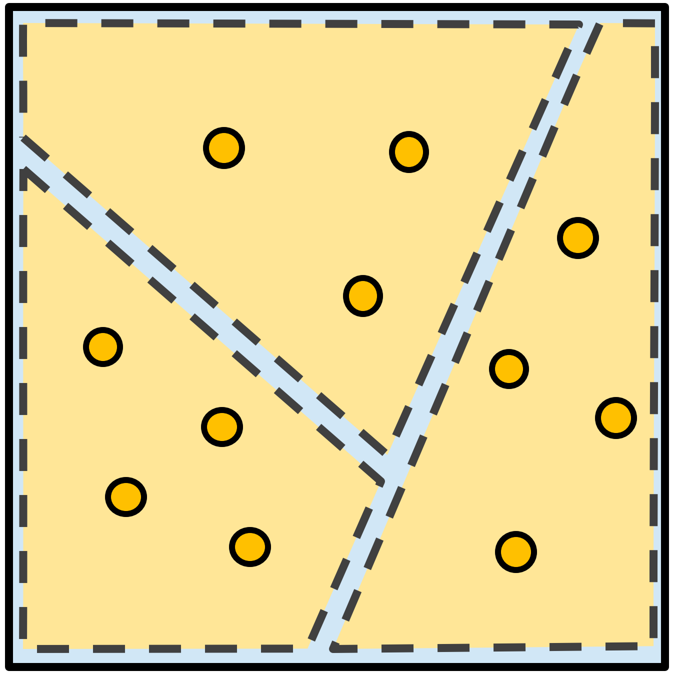
$$\int_{\partial D} \vec{f} \cdot \vec{n} \qquad \Longleftrightarrow \qquad \int_{D} \nabla \cdot \vec{f}$$

APPLYING THE DIVERGENCE THEOREM TO THE EDGE INTEGRAL

Goal: Rewrite $\int_{\partial D} f\vec{\mathbf{v}}\cdot\vec{\mathbf{n}}$ into area integral $\int_{D} g$

Solution: Rewrite $\int_{\partial D} f\vec{\mathbf{v}}\cdot\vec{\mathbf{n}}$ into $\int_{D} \nabla\cdot(\vec{\mathcal{V}}_\theta f)$

$\int_{D} \nabla\cdot(\vec{\mathcal{V}}_\theta f)$ can be estimated through area samples



QUICK RECAP

- Used *Reynolds transport theorem* to find the boundary integral $\int_{\partial \mathrm{D}} f \vec{\mathbf{v}} \cdot \vec{\mathbf{n}}$

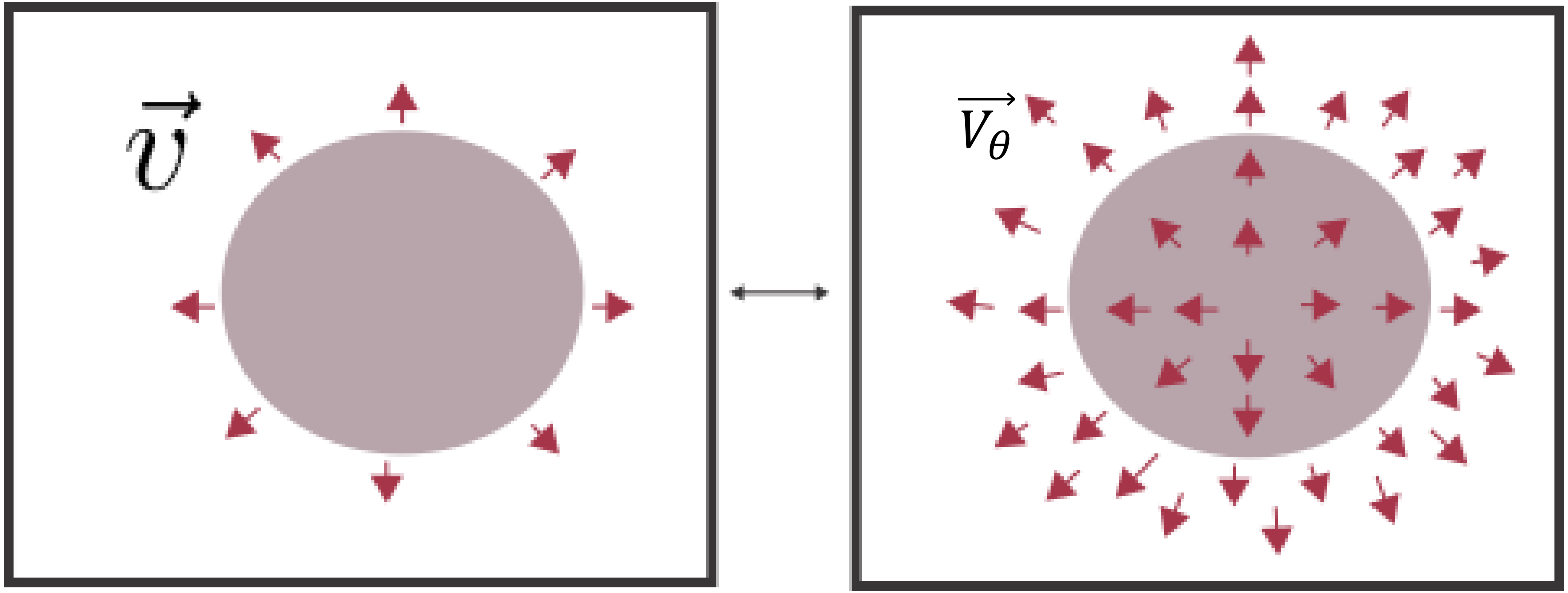
- Rewrote $\int_{\partial \mathrm{D}} f \vec{\mathbf{v}} \cdot \vec{\mathbf{n}}$ to $\int_{\mathrm{D}} \nabla \cdot (\vec{\mathcal{V}}_\theta f)$ using the *divergence theorem*.

- Have to define the *vector field* $\vec{\mathcal{V}}_\theta$ over domain D

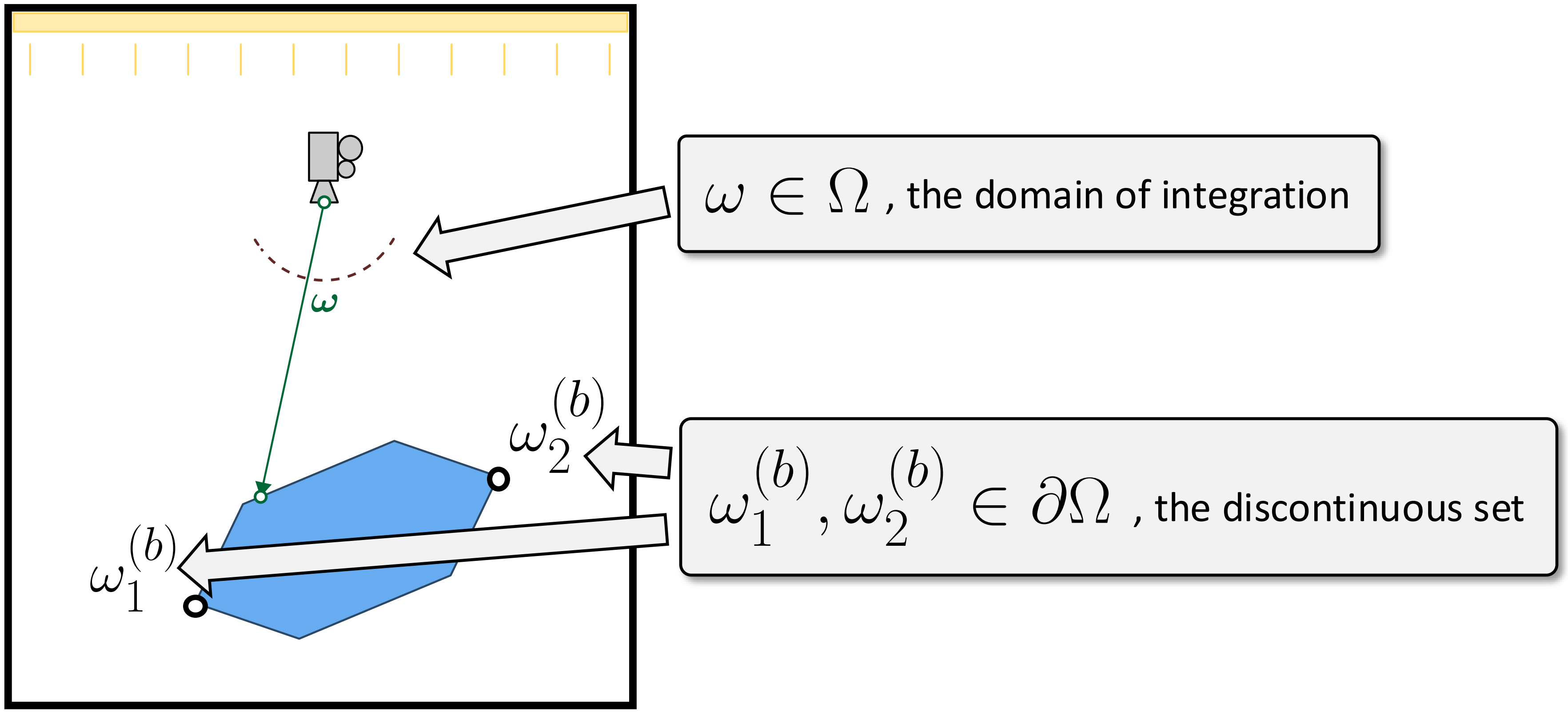
INTUITION

$$\int_{\partial \mathrm{D}} f \vec{\mathbf{v}} \cdot \vec{\mathbf{n}} = \int_{\mathrm{D}} \nabla \cdot (\vec{\mathcal{V}}_\theta f)$$

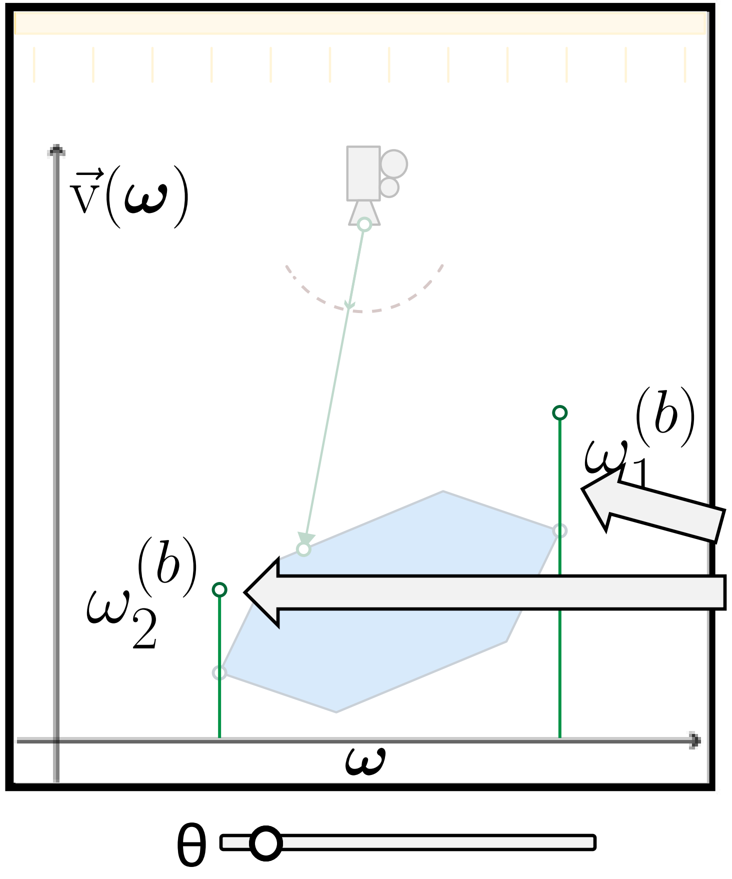
$\overrightarrow{V_\theta}$ continuously interpolates the boundary velocity $\vec{v}$!



A 2D EXAMPLE SCENE

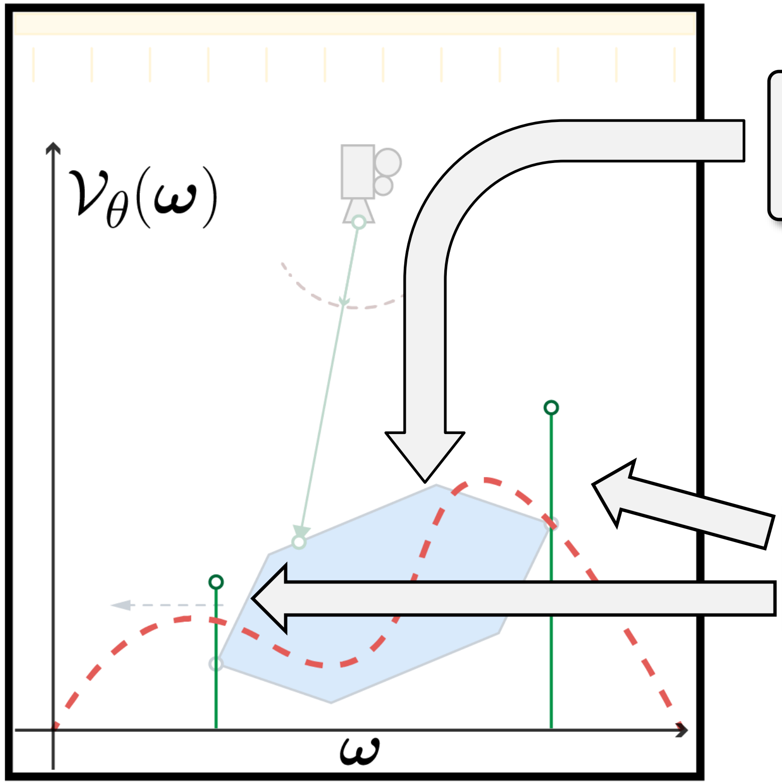


VELOCITY $\vec{\mathbf{V}}$: THE BOUNDARY DERIVATIVE



$\partial_\theta \omega_i^{(b)}$: Derivative of boundary position w.r.t **θ**

WARP FIELD $\mathcal{V}_\theta$: EXTENSION OF $\vec{\mathbf{V}}$ TO ALL POINTS

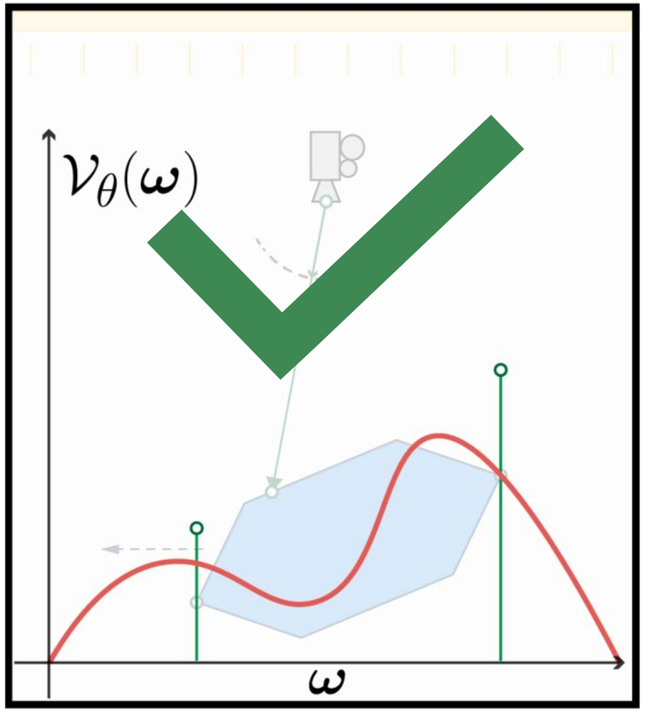


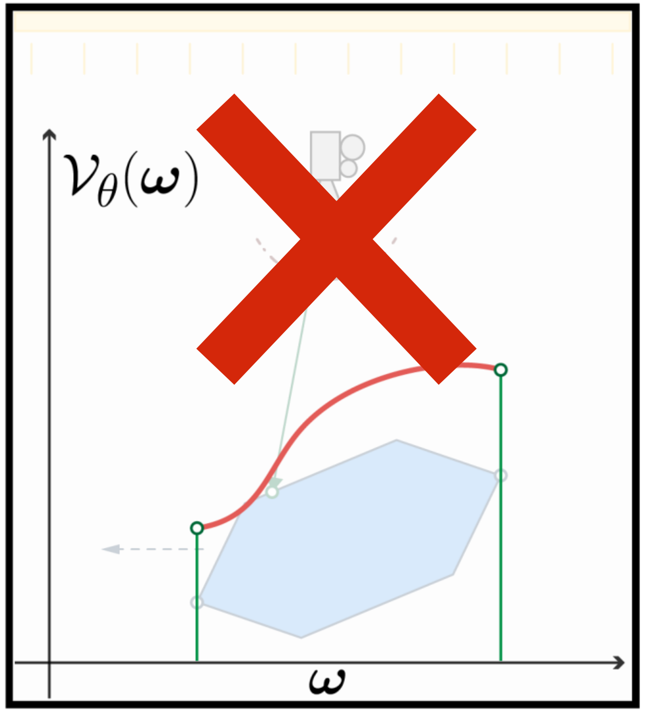
$\mathcal{V}_\theta$: defined over $\boldsymbol{D}$

$\vec{\mathbf{V}}$: defined over $\boldsymbol{\partial D}$

VALIDITY OF $\vec{\mathcal{V}}_\theta$

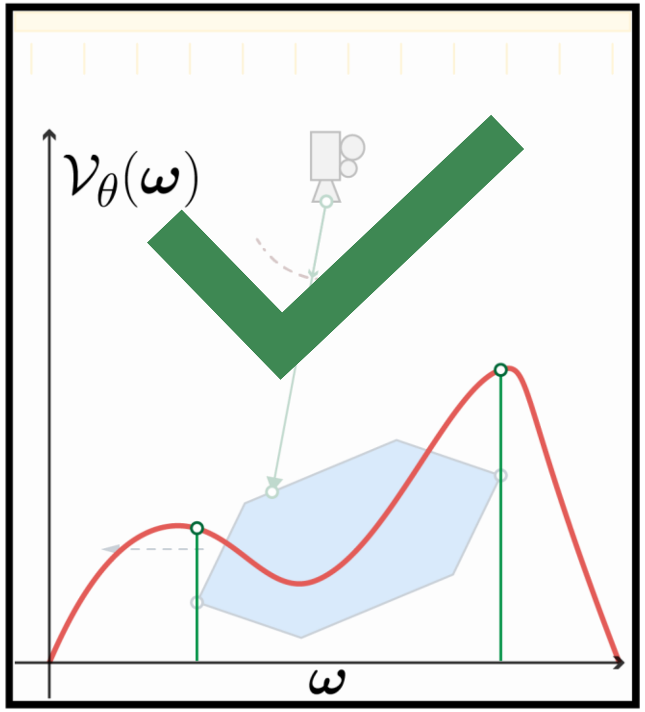
Rule 1: Continuous

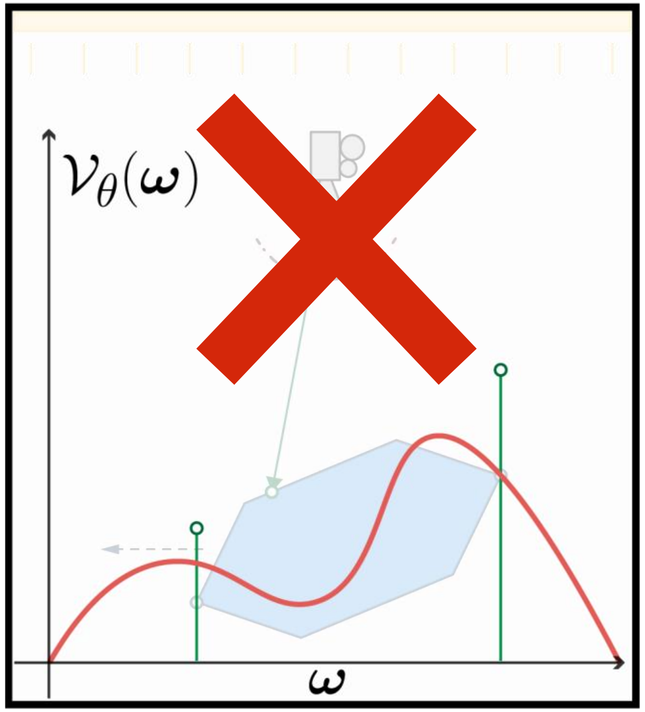




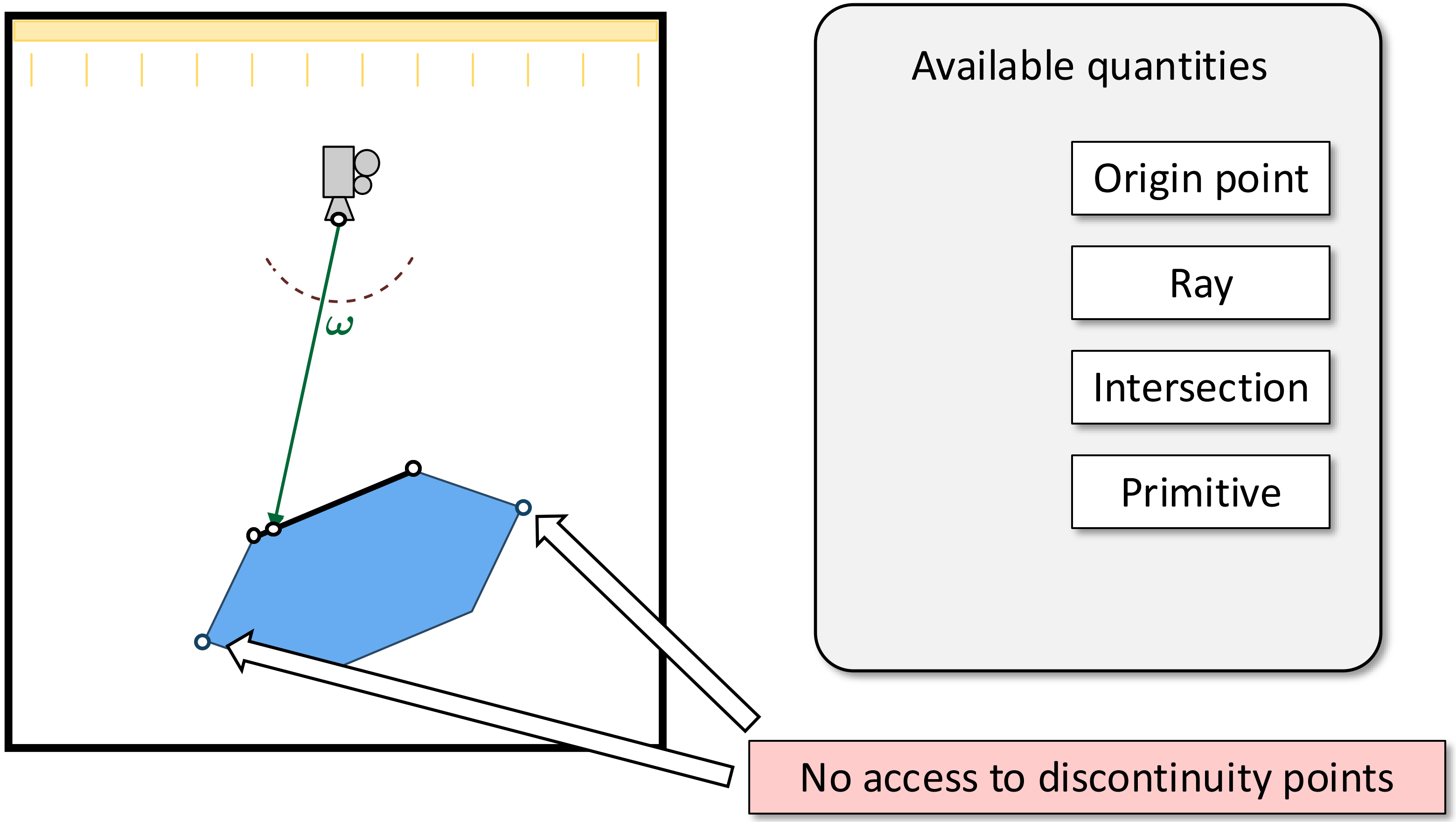
VALIDITY OF $\vec{\mathcal{V}}_\theta$

Rule 2: Boundary Consistent





INTERPOLATION WITHOUT KNOWLEDGE OF BOUNDARIES

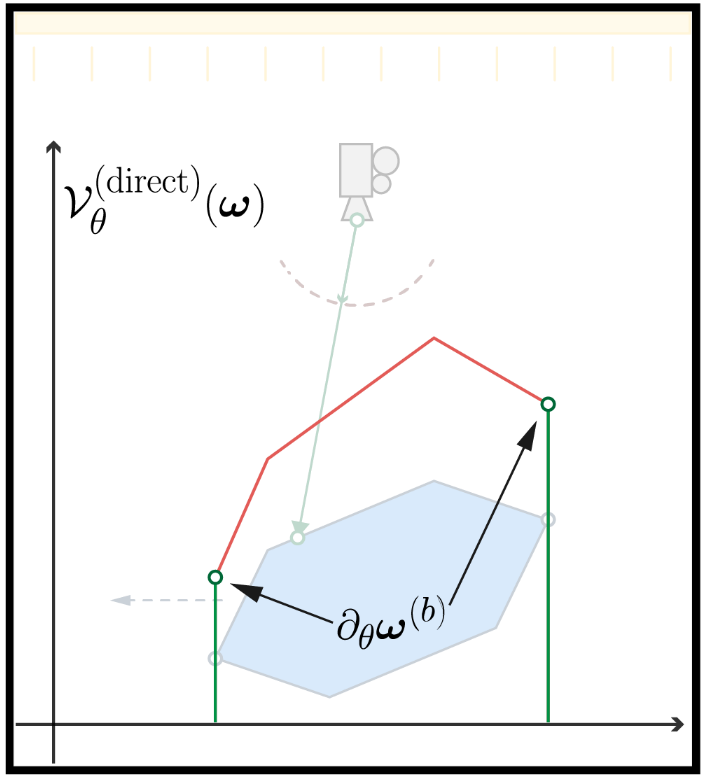


CONSTRUCTING $\vec{\mathcal{V}}_\theta$

Attempt 1 ⟶ Find $\partial_\theta \boldsymbol{\omega}$ through *implicit derivative*

(Incorrect)

$$\mathbf{y} = \textsc{Intersect}(\boldsymbol{\omega}, \theta) \implies \partial_\theta \boldsymbol{\omega} = \frac{\partial_{\boldsymbol{\omega}} \mathbf{y}}{\partial_\theta \mathbf{y}}$$



At all points (not just boundaries)

+ Boundary consistent

- Not continuous

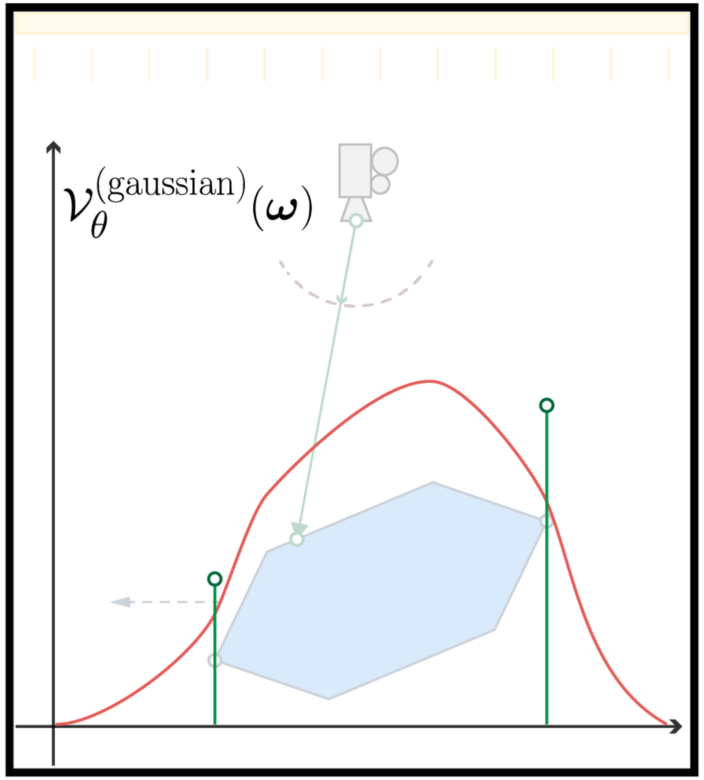
CONSTRUCTING $\vec{\mathcal{V}}_\theta$

Attempt 2 → Filter *Attempt 1* with a Gaussian filter

(Incorrect)

$$\int_{\Omega'} k(\boldsymbol{\omega}, \boldsymbol{\omega}') \frac{\partial_{\boldsymbol{\omega}} \mathbf{y}}{\partial_\theta \mathbf{y}}$$

k(.,.) = Gaussian filter



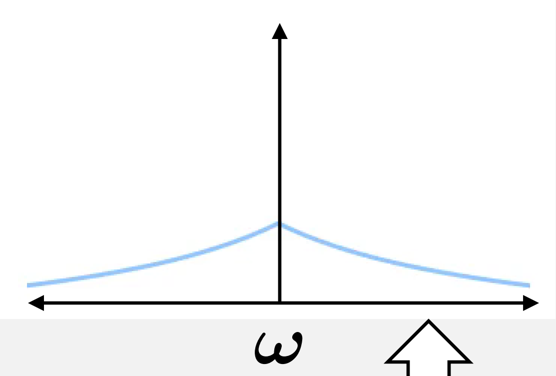
+ Continuous

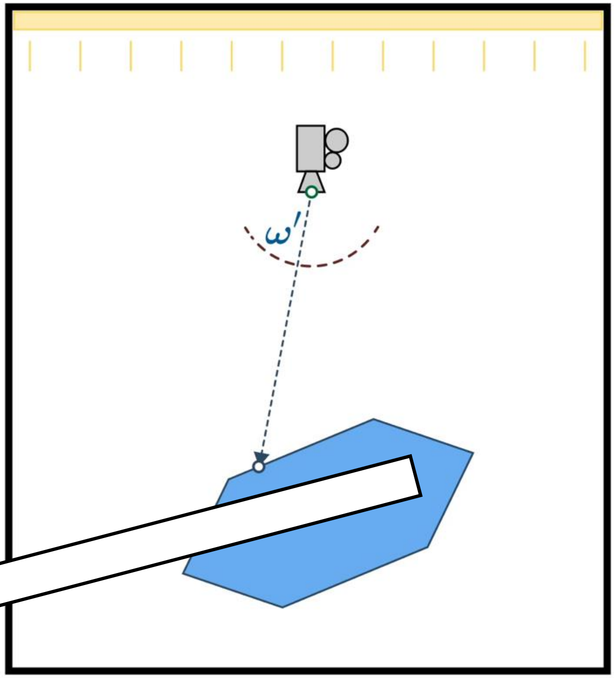
- Not boundary consistent

BOUNDARY-AWARE WEIGHTING

Goal: Find weights $k(\boldsymbol{\omega}, \boldsymbol{\omega}')$ s.t. $\vec{\mathcal{V}}_\theta = \frac{\partial_\omega \mathbf{y}}{\partial_\theta \mathbf{y}}$ at boundaries.

Ideal weighting function

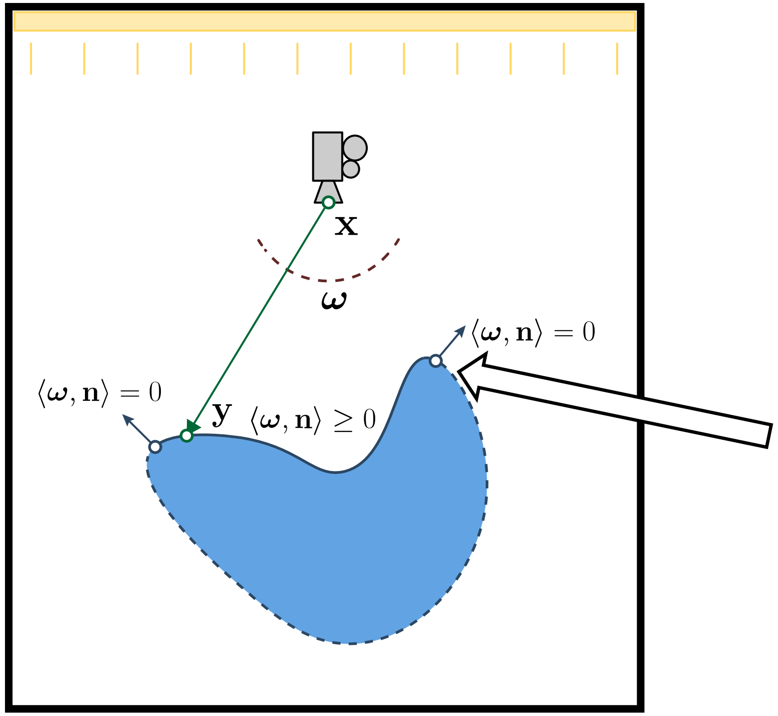




Approach Dirac delta near boundaries

BOUNDARY-AWARE WEIGHTING

Implicit Boundary through *geometric normals*



$$\langle \boldsymbol{\omega}, \mathbf{n} \rangle = 0$$

at boundaries

ry sampling)

boundary
g)

CONSTRUCTING $\vec{\mathcal{V}}_\theta$

Our Approach ⟶ Filter *Attempt 1* with harmonic weights

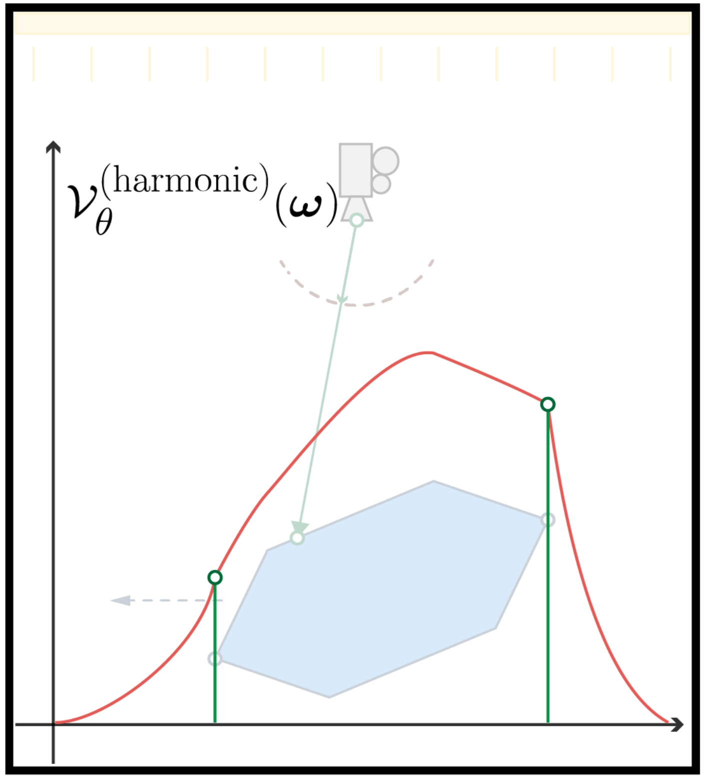
$$k(\boldsymbol{\omega}, \boldsymbol{\omega}') = \frac{1}{\mathcal{D}(\boldsymbol{\omega}, \boldsymbol{\omega}') + \mathcal{B}(\boldsymbol{\omega}')}$$

Distance function

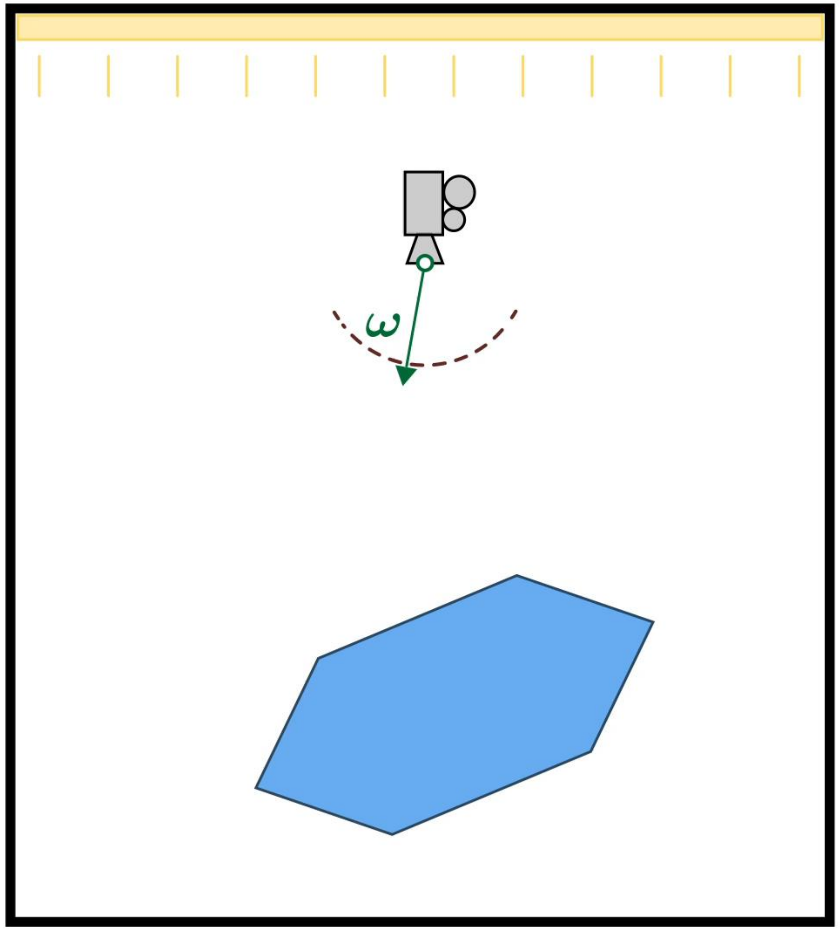
Boundary test

+ Boundary consistent

+ Continuous



COMPUTING $\vec{V}_\theta$



1. Sample **path** using path tracer *(N paths)*

For each bounce:

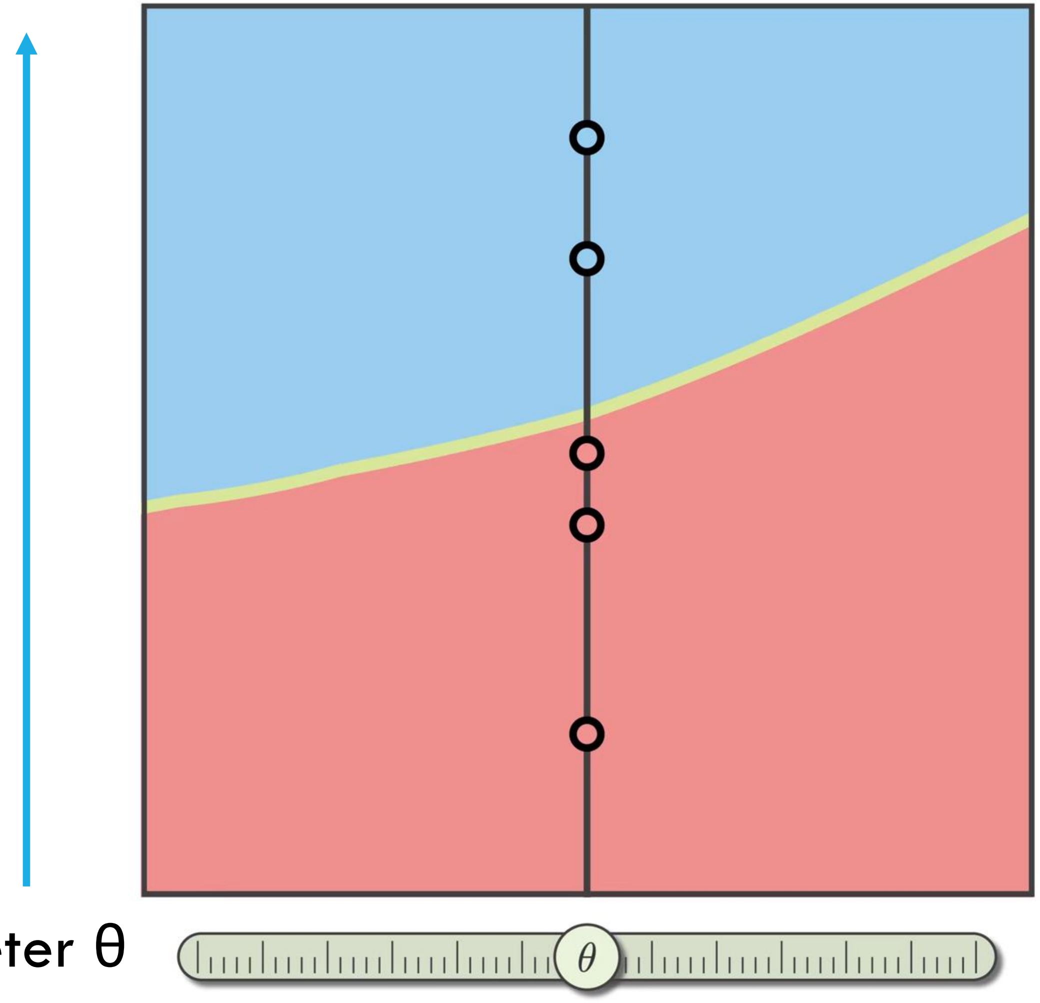
2. Sample **auxiliary** rays *(N' rays)*
3. Compute boundary term ***B()*** locally
4. Compute weight **k(.,.)** and $\partial_\theta \boldsymbol{\omega}$
5. Find weighted mean

QUICK RECAP

- Used *Reynolds transport theorem* to find the boundary integral $\int_{\partial \mathrm{D}} f \vec{\mathbf{v}} \cdot \vec{\mathbf{n}}$
- Rewrote $\int_{\partial \mathrm{D}} f \vec{\mathbf{v}} \cdot \vec{\mathbf{n}}$ to $\int_{\mathrm{D}} \nabla \cdot (\vec{\mathcal{V}}_\theta f)$ using the *divergence theorem*.
- Estimate **consistent** and **continuous** $\vec{\mathcal{V}}_\theta$ over domain D using auxiliary rays

MORE INTUITION: WARPED-AREA SAMPLING CAN BE SEEN AS A CHANGE OF VARIABLE

integration variable u



differentiating parameter θ

TRANSFORM SAMPLES

$$u = T(u'; \theta)$$

MORE INTUITION: WARPED-AREA SAMPLING CAN BE SEEN AS A CHANGE OF VARIABLE

$$\frac{\partial}{\partial\theta}\int_D f\,\mathrm{d}u = \int_D f_\theta + \nabla\cdot\left(\vec{\mathcal{V}}_\theta f\right)\mathrm{d}u$$

MORE INTUITION: WARPED-AREA SAMPLING CAN BE SEEN AS A CHANGE OF VARIABLE

$$\frac{\partial}{\partial\theta}\int_D f\,\mathrm{d}u = \int_D f_\theta + \nabla\cdot\left(\vec{\mathcal{V}}_\theta f\right)\mathrm{d}u$$

$$= \int_D \frac{\partial}{\partial\theta}\left(f\left(T(u';\theta)\right)J_T\right)\mathrm{d}u'$$

MORE INTUITION: WARPED-AREA SAMPLING CAN BE SEEN AS A CHANGE OF VARIABLE

$$\frac{\partial}{\partial \theta} \int_D f \mathrm{d}u = \int_D f_\theta + \nabla \cdot \left(\vec{\mathcal{V}}_\theta f \right) \mathrm{d}u$$

$$= \int_D \frac{\partial}{\partial \theta} \left(f \left(T(u'; \theta) \right) J_T \right) \mathrm{d}u'$$

$$T = u' + (\theta - \theta_0)\, \mathcal{V}_\theta$$

MORE INTUITION: WARPED-AREA SAMPLING CAN BE SEEN AS A CHANGE OF VARIABLE

$$\frac{\partial}{\partial\theta}\int_D f\,\mathrm{d}u = \int_D f_\theta + \nabla\cdot\left(\vec{\mathcal{V}}_\theta f\right)\mathrm{d}u$$

$$= \int_D \frac{\partial}{\partial\theta}\left(f\left(T(u';\theta)\right)J_T\right)\mathrm{d}u'$$

$$T = u' + (\theta - \theta_0)\,\mathcal{V}_\theta$$

connects to previous biased methods

Reparameterizing Discontinuous Integrands for Differentiable Rendering

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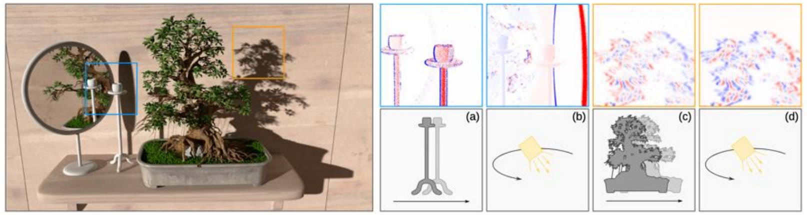


A scene with complex geometry and visibility (1.8M triangles) Gradients with respect to scene parameters that affect visibility

RESULTS

VARIANCE COMPARISON WITH EDGE-SAMPLING

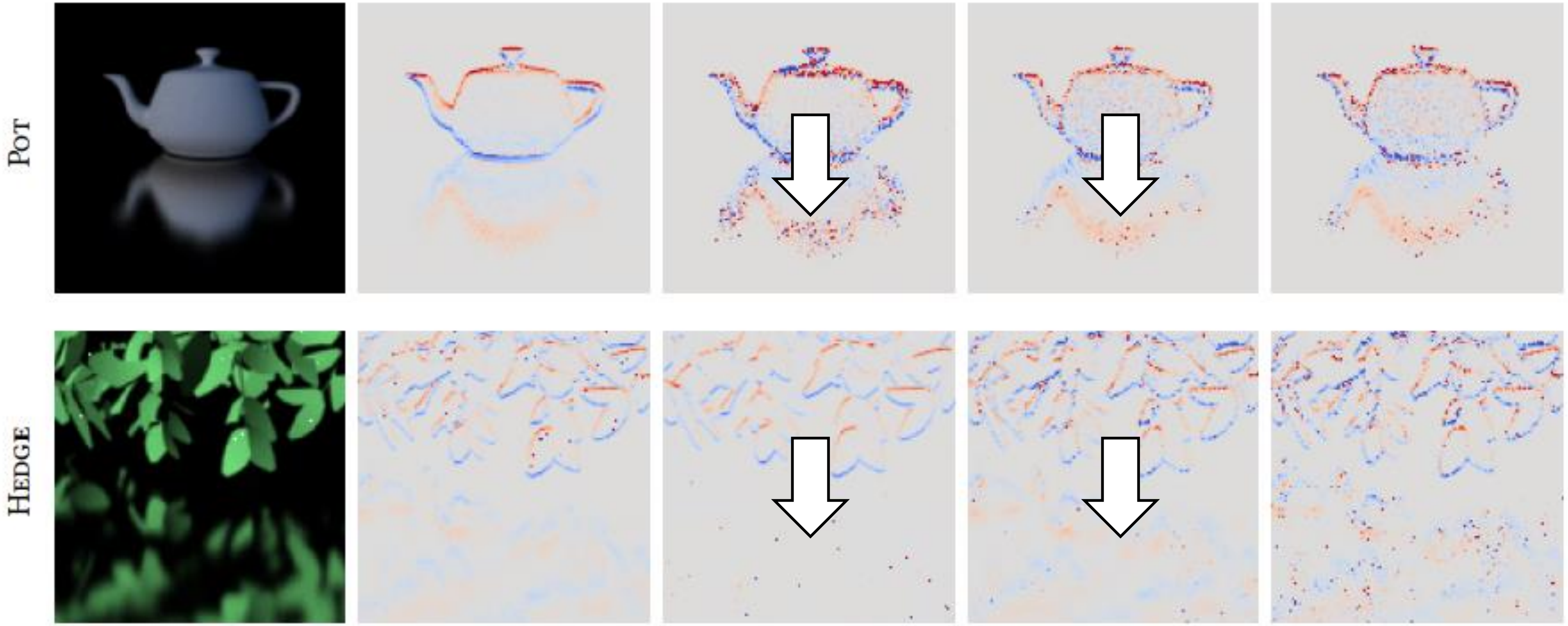
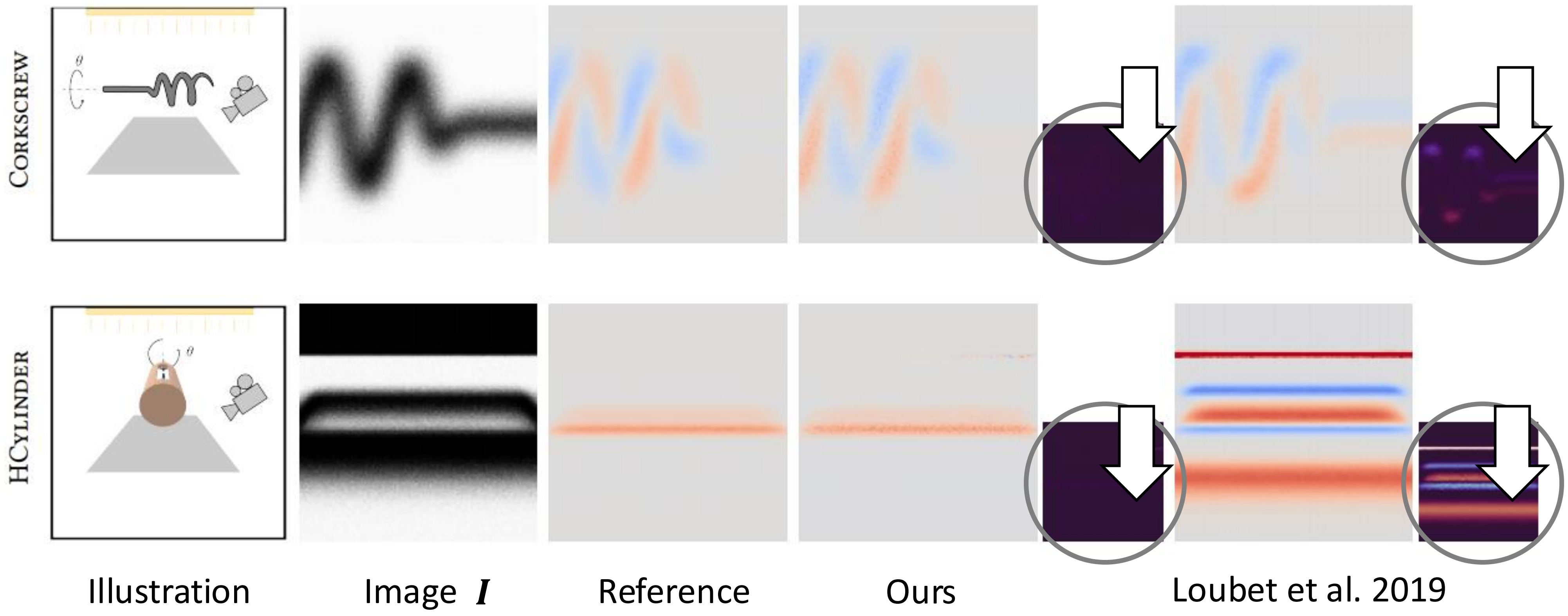


Image I | Reference Derivative | Li et al. 2018 | Ours *without* Russian roulette | Ours *with* Russian roulette

BIAS COMPARISON WITH REPARAMETERIZATION



Rotating cylindrical objects present a complicated scenario for area-sampling

BIAS COMPARISON WITH REPARAMETERIZATION

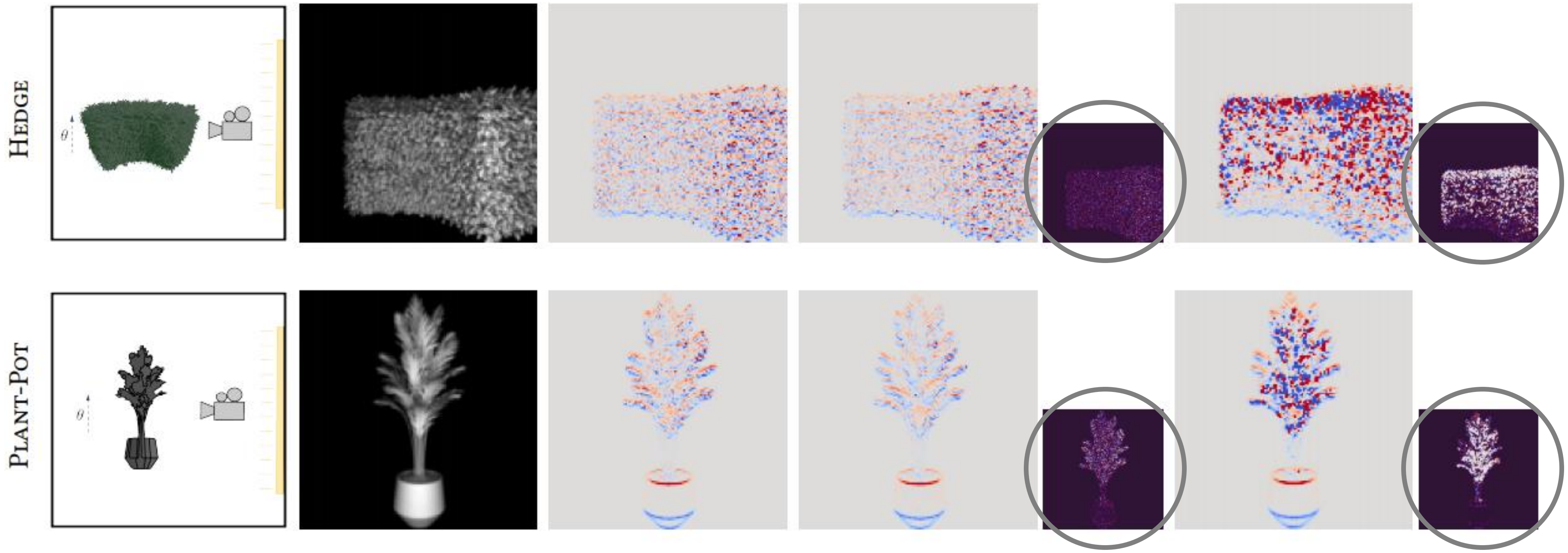
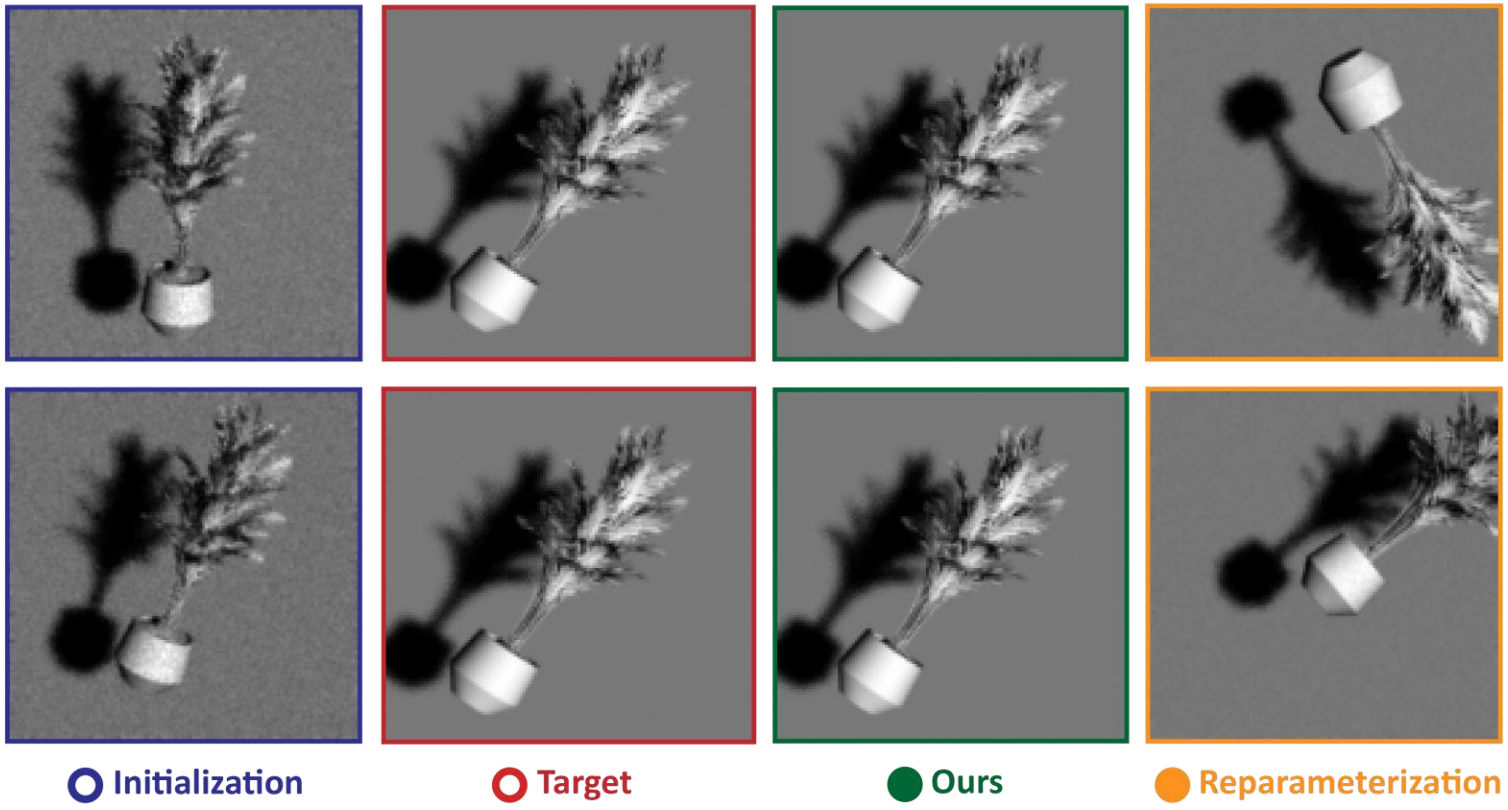
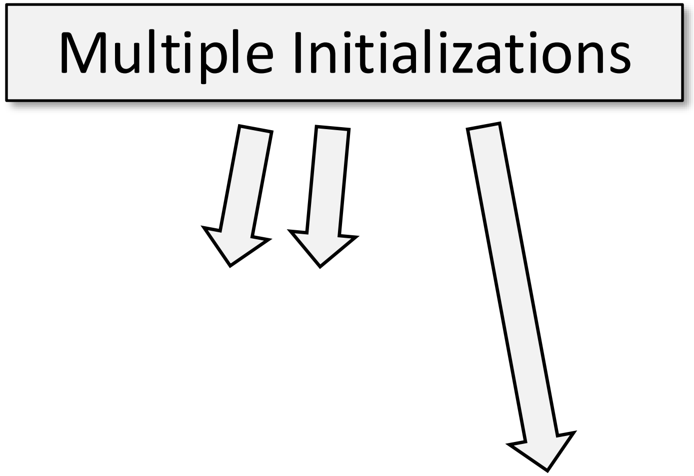


Illustration | Image I | Reference | Ours | Loubet et al. 2019

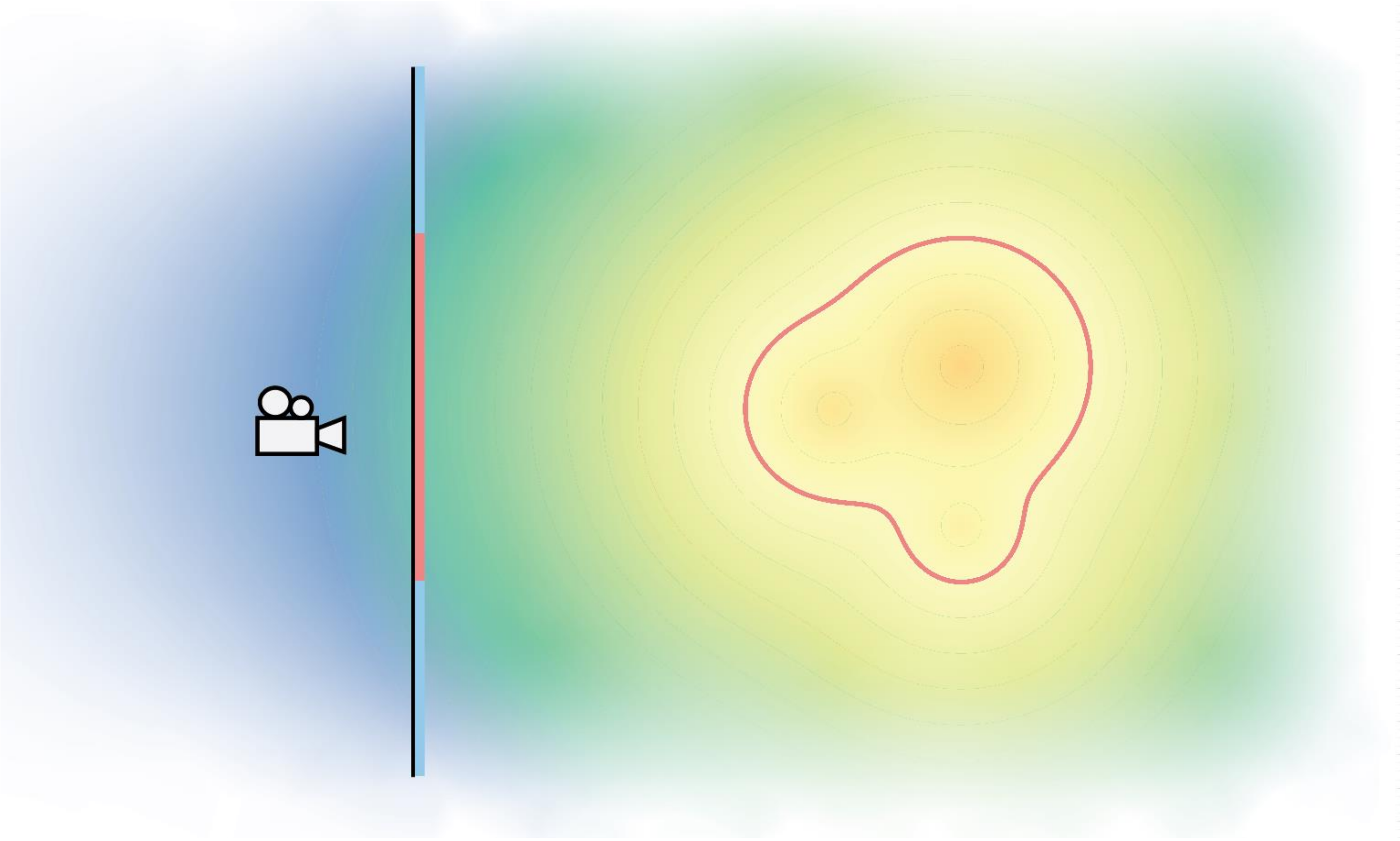
Extremely complex geometry like foliage can cause heuristic to fail

POSE ESTIMATION CAN FAIL WITH BIASED GRADIENTS





WARPED-AREA SAMPLING CAN BE USED FOR SIGNED DISTANCE FIELDS RENDERING



and we can achieve unbiasedness ***without*** auxiliary rays!!

Differentiable Signed Distance Function Rendering

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Differentiable Rendering of Neural SDFs through Reparameterization

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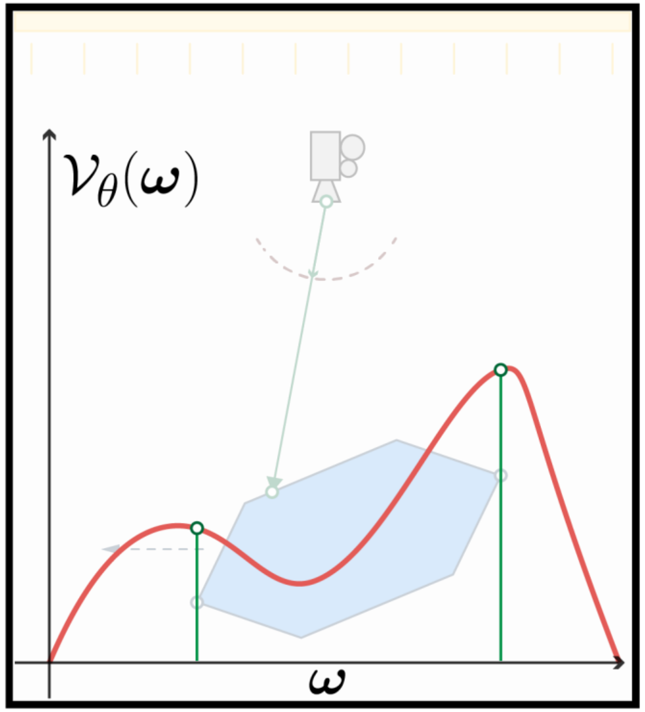
RECALL: THE TWO RULES

Rule 1: Continuous

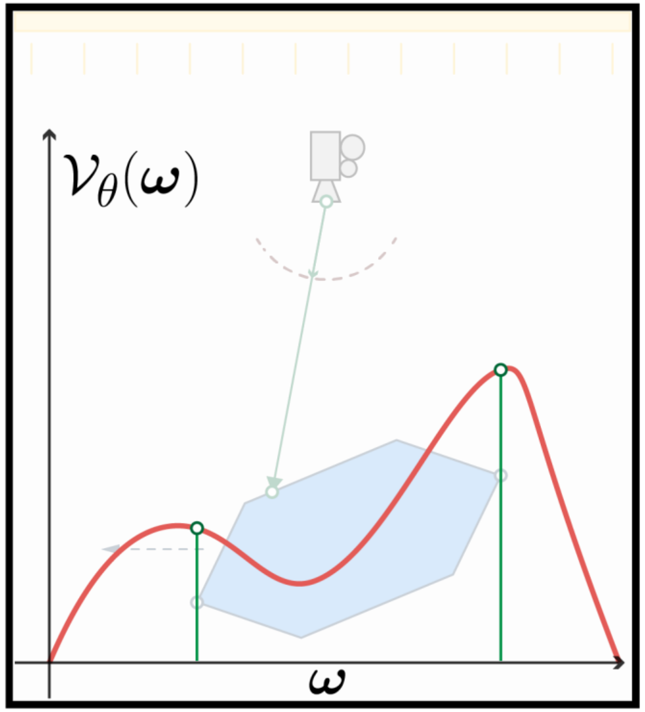
Rule 2: Boundary Consistent



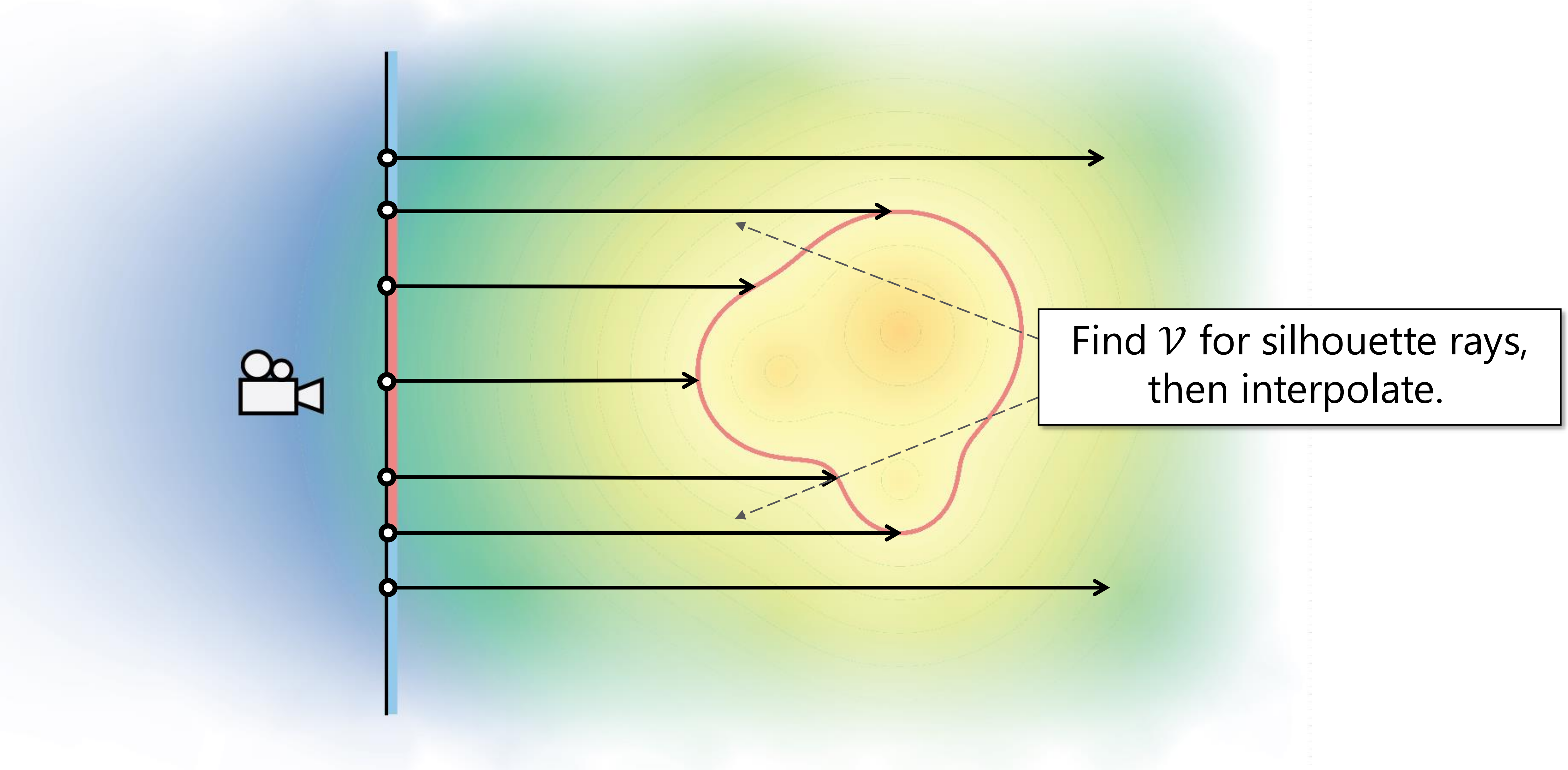
RECALL: THE TWO RULES

Rule 1: Continuous

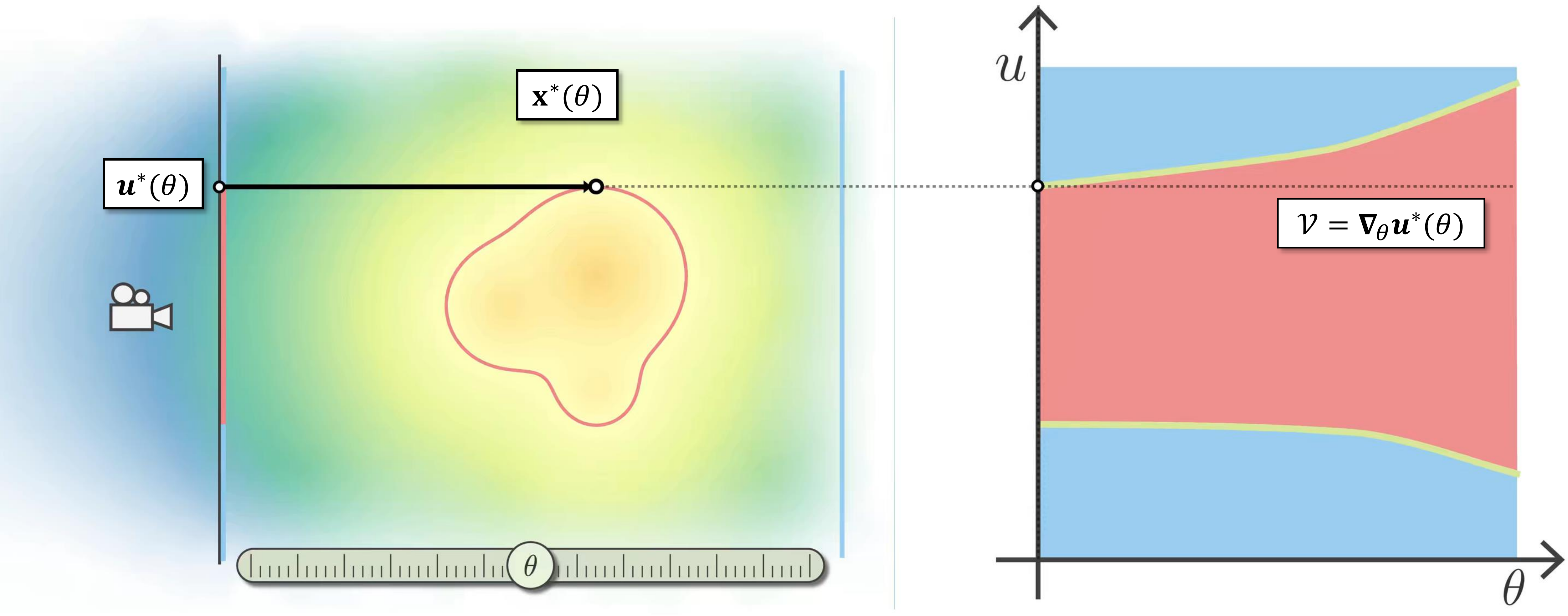
Rule 2: Boundary Consistent



Computing A Consistent $\mathcal{V}(u)$ For An Arbitrary SDF

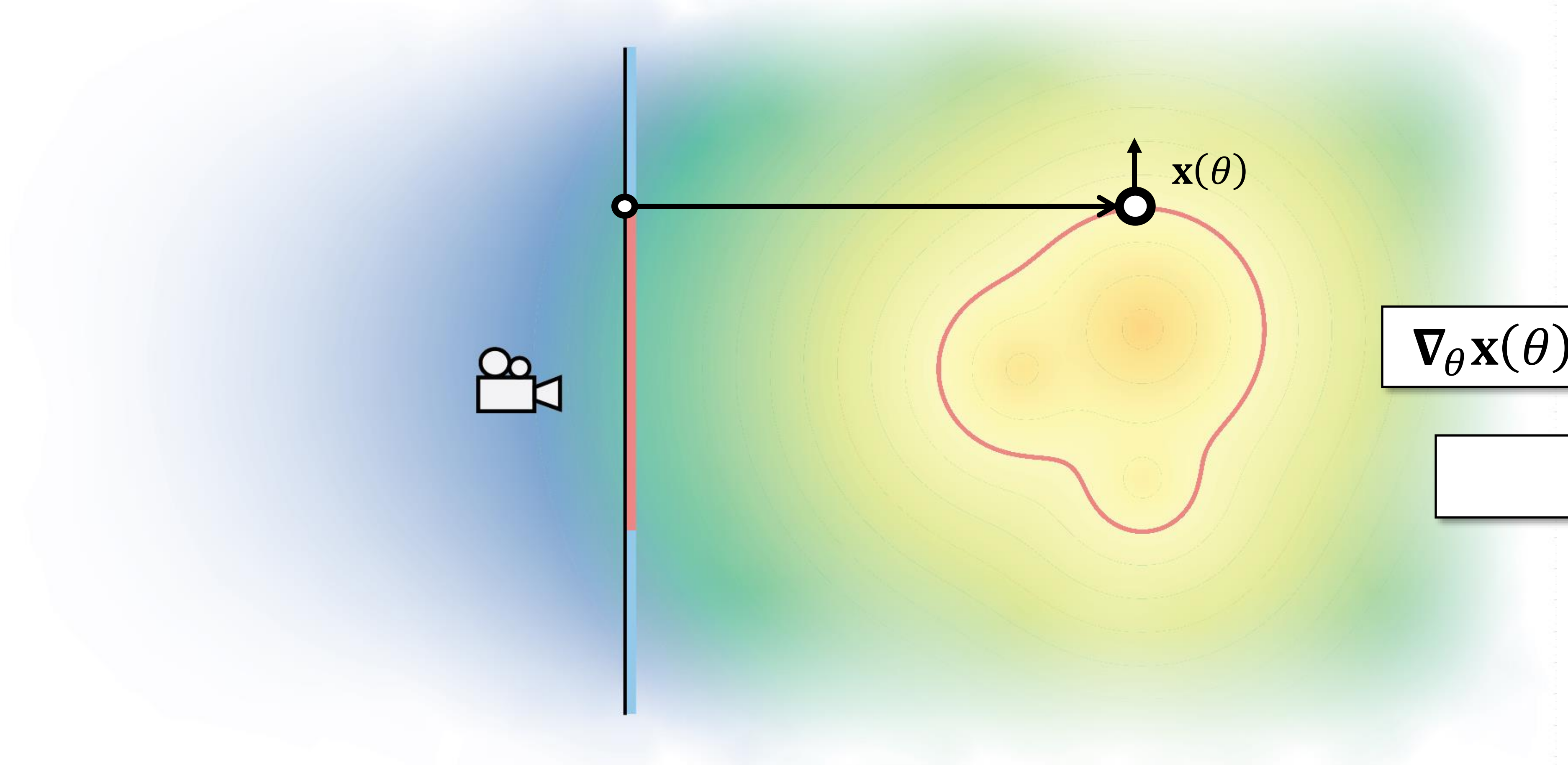


Computing $\mathcal{V}$ By Differentiating The Silhouette Position u^*



Computing $\mathcal{V}$: Implicit Fn. Theorem + Chain Rule

1. **Compute $\nabla_\theta \mathbf{x}^*(\theta)$ using implicit fn. theorem:**
   Derivative of any point in SDF can be computed by differentiating SDF function **f**

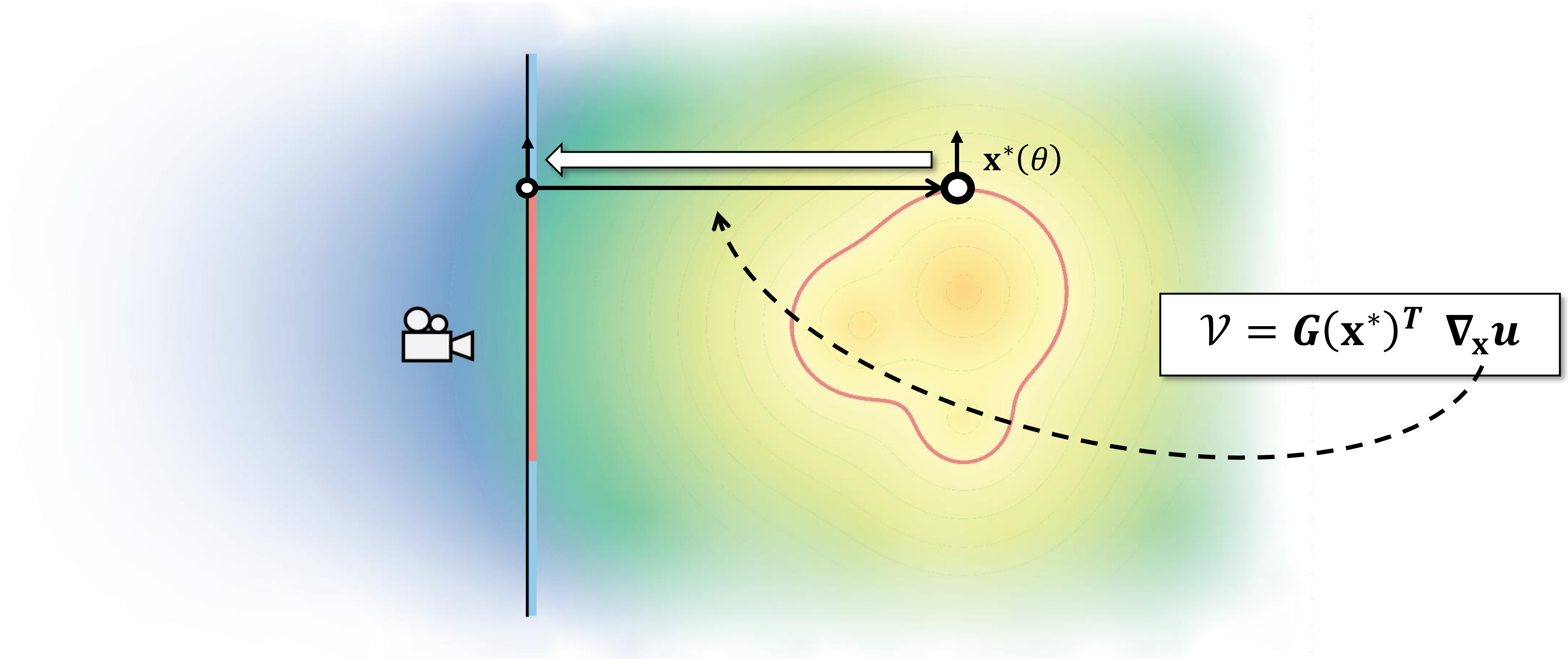


$$\nabla_\theta \mathbf{x}(\theta) = \nabla_{\boldsymbol{\theta}} \boldsymbol{f}(\mathbf{x}; \boldsymbol{\theta}) \cdot \hat{\boldsymbol{n}}$$

$$= \boldsymbol{G}(\mathbf{x})$$

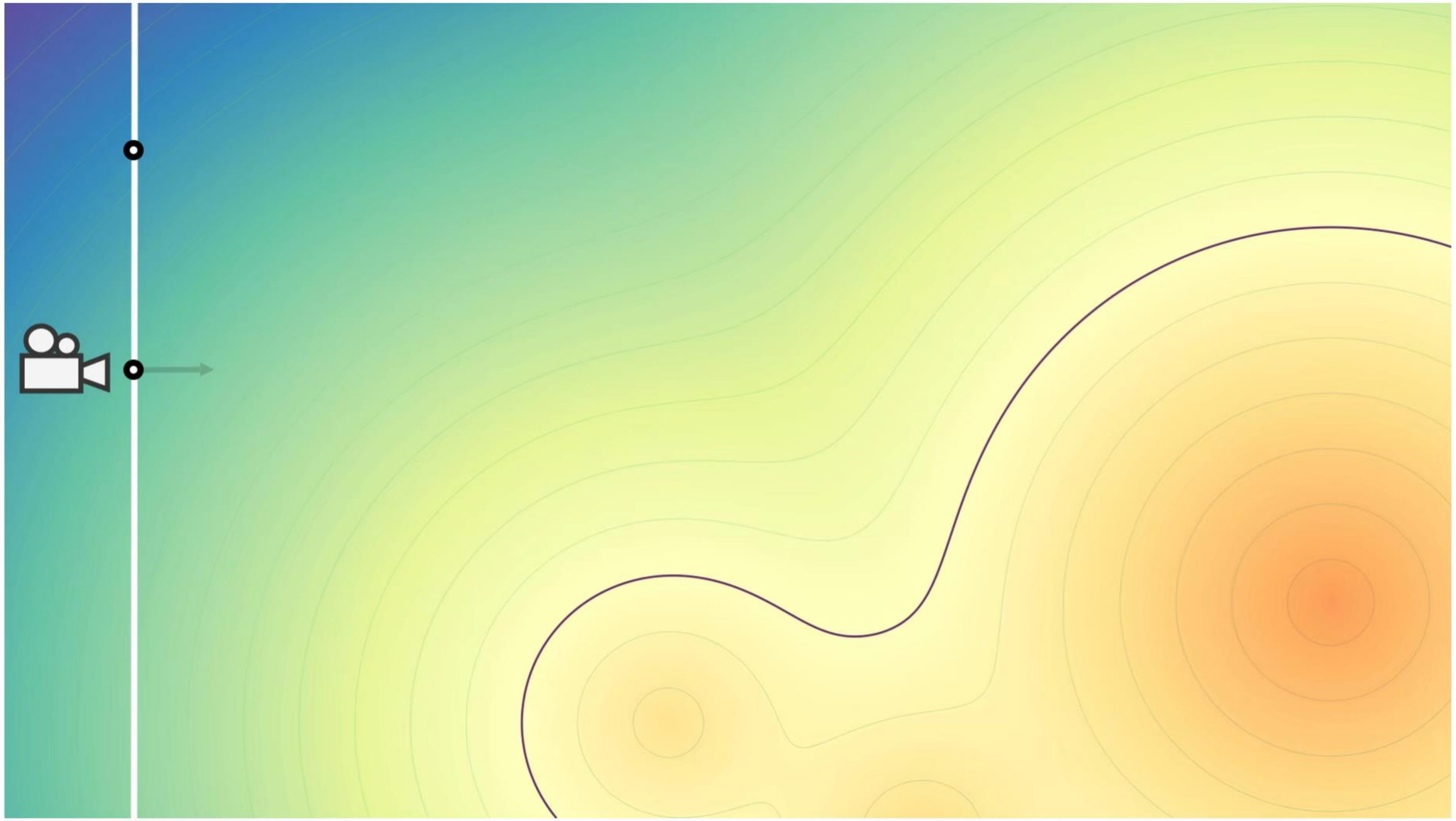
Computing $\mathcal{V}$: Implicit Fn. Theorem + Chain Rule

1. **Compute $\nabla_\theta \mathbf{x}^*(\theta)$ using Implicit Fn. Theorem:**
2. **Propagate $G(\mathbf{x}^*)$ to sample space through chain rule ($u \to \mathbf{x}$):**



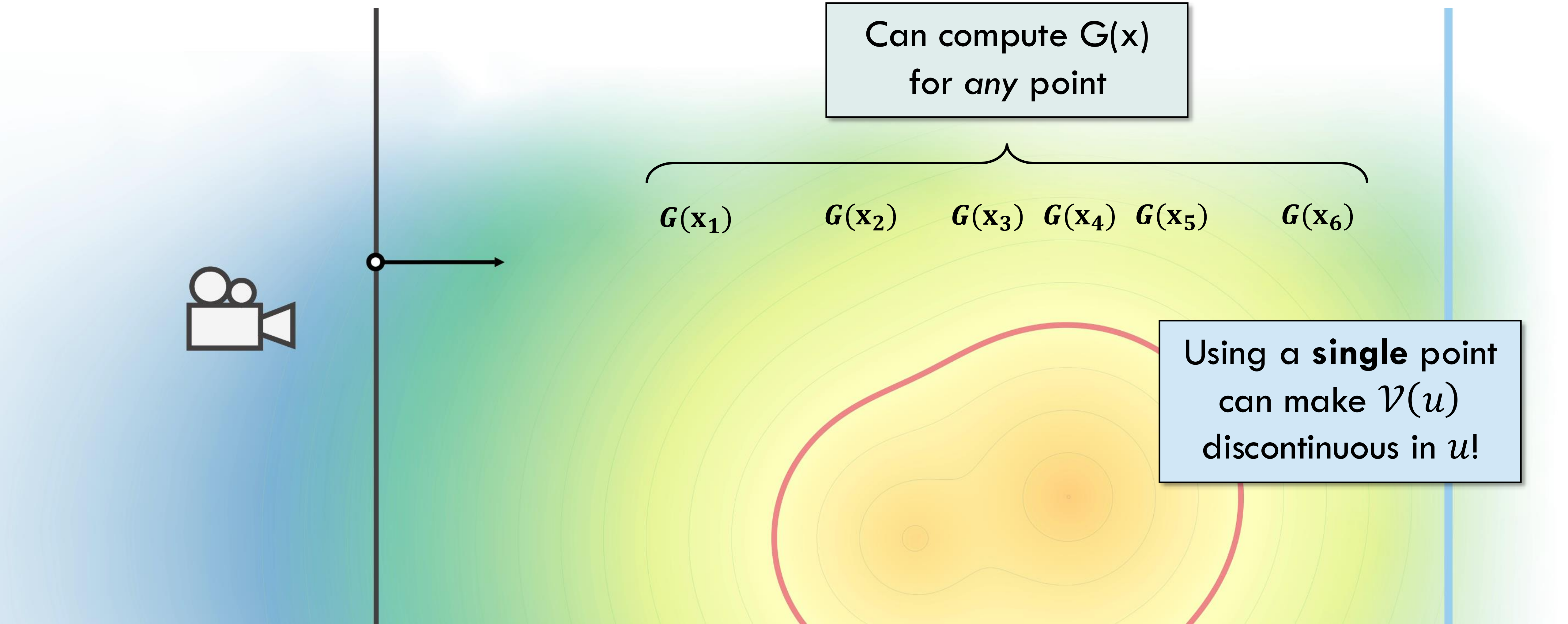
Computing $\mathcal{V}(u)$ For An Arbitrary Ray

Ray-SDF Intersection: Sphere Tracing



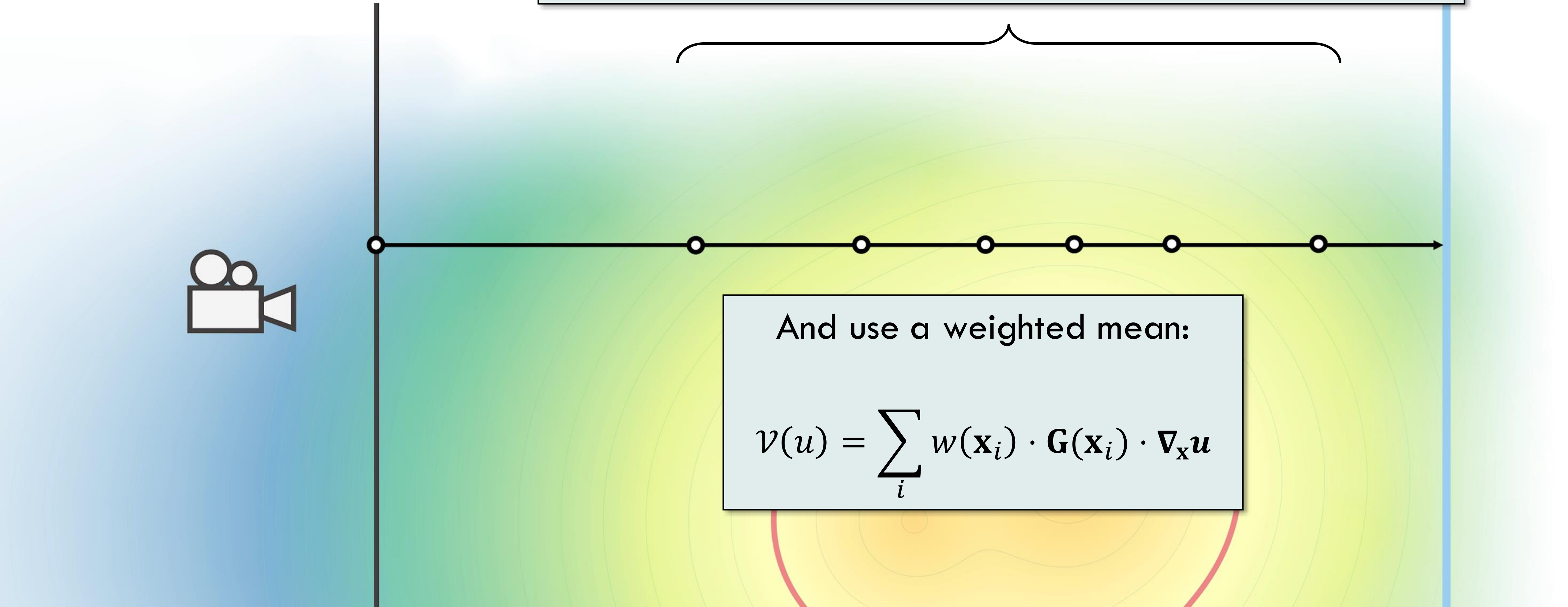
about
ette rays?

Can Compute $\mathcal{V}(u)$ using the Geometry Derivative $G(\mathbf{x})$ of **any** Sphere Tracer point



Computing $\mathcal{V}(u)$ as Weighted Mean of $G(\mathbf{x})$ over Sphere Tracer Points

Solution: Compute silhouette weights w(x)



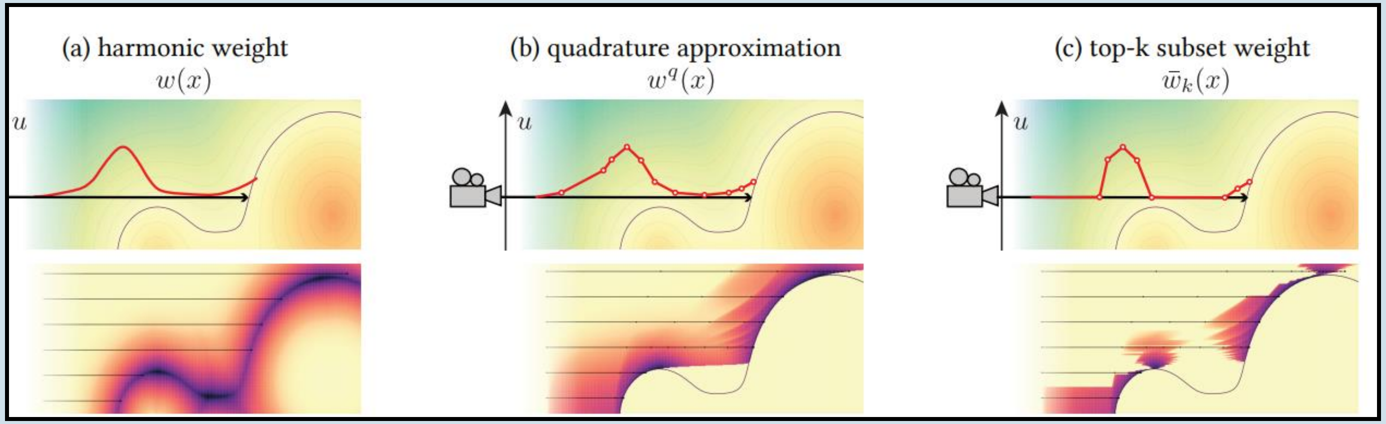
And use a weighted mean:

$$\mathcal{V}(u) = \sum_i w(\mathbf{x}_i) \cdot \mathbf{G}(\mathbf{x}_i) \cdot \nabla_{\mathbf{x}} \boldsymbol{u}$$

Weighted-Mean $\mathcal{V}(u)$ Is Both Consistent And Continuous

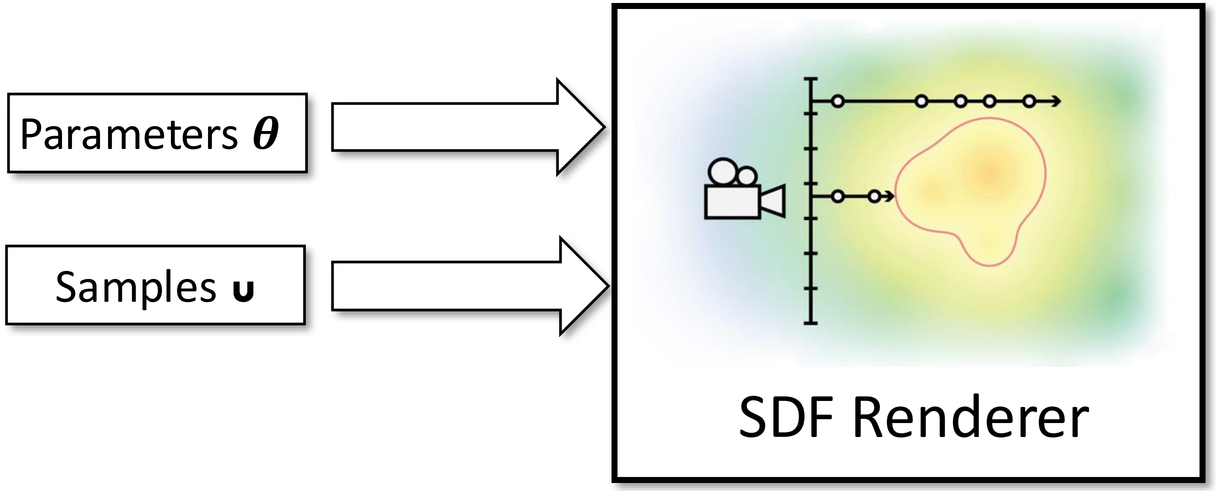
✓ Continuous

See **Paper**: Harmonic & Quadrature Weighting

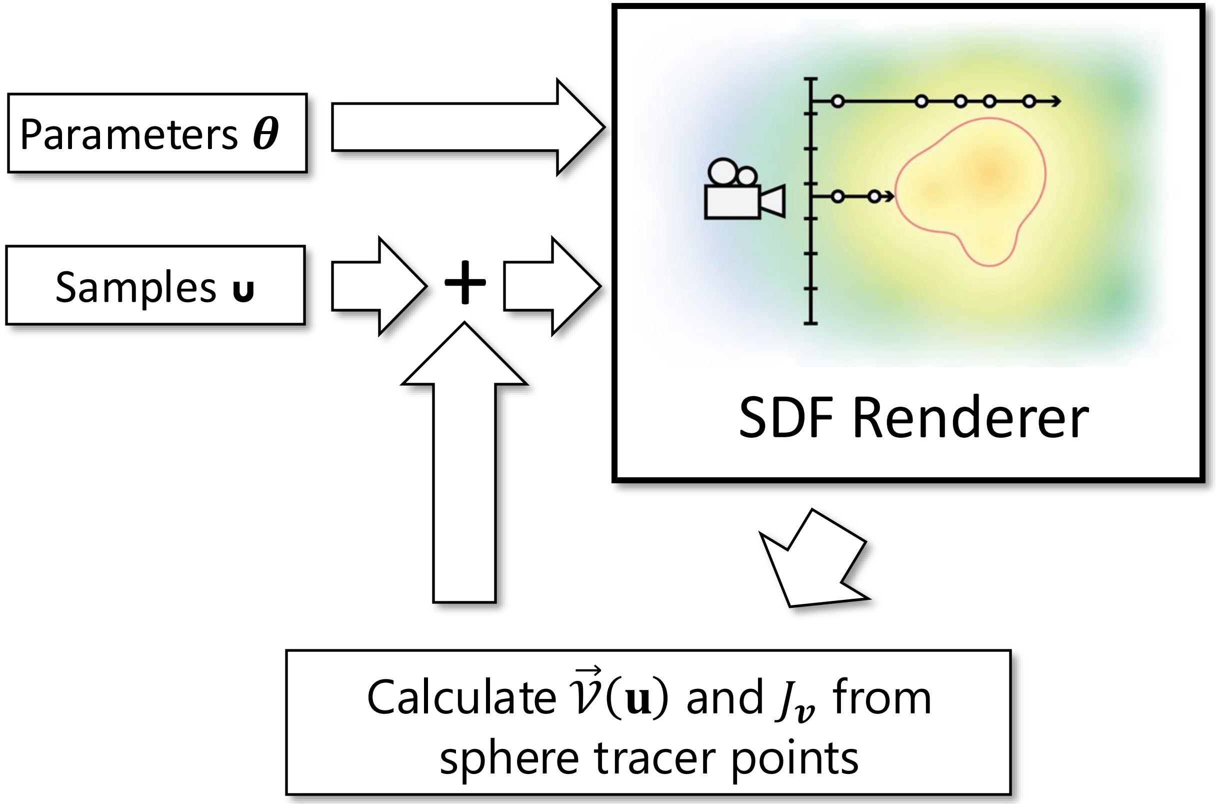


PROJECT PAGE

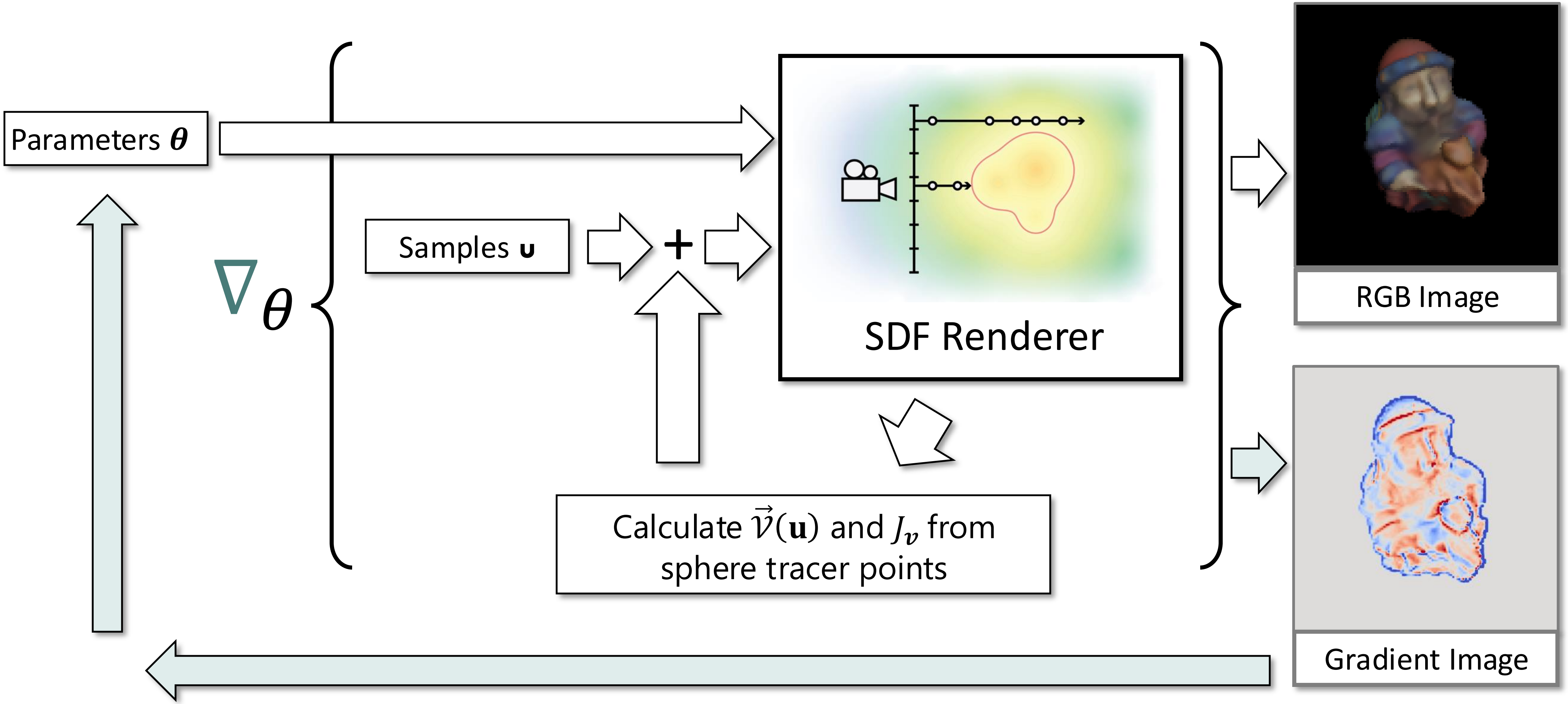
Putting It All Together: First, Render SDF As Usual



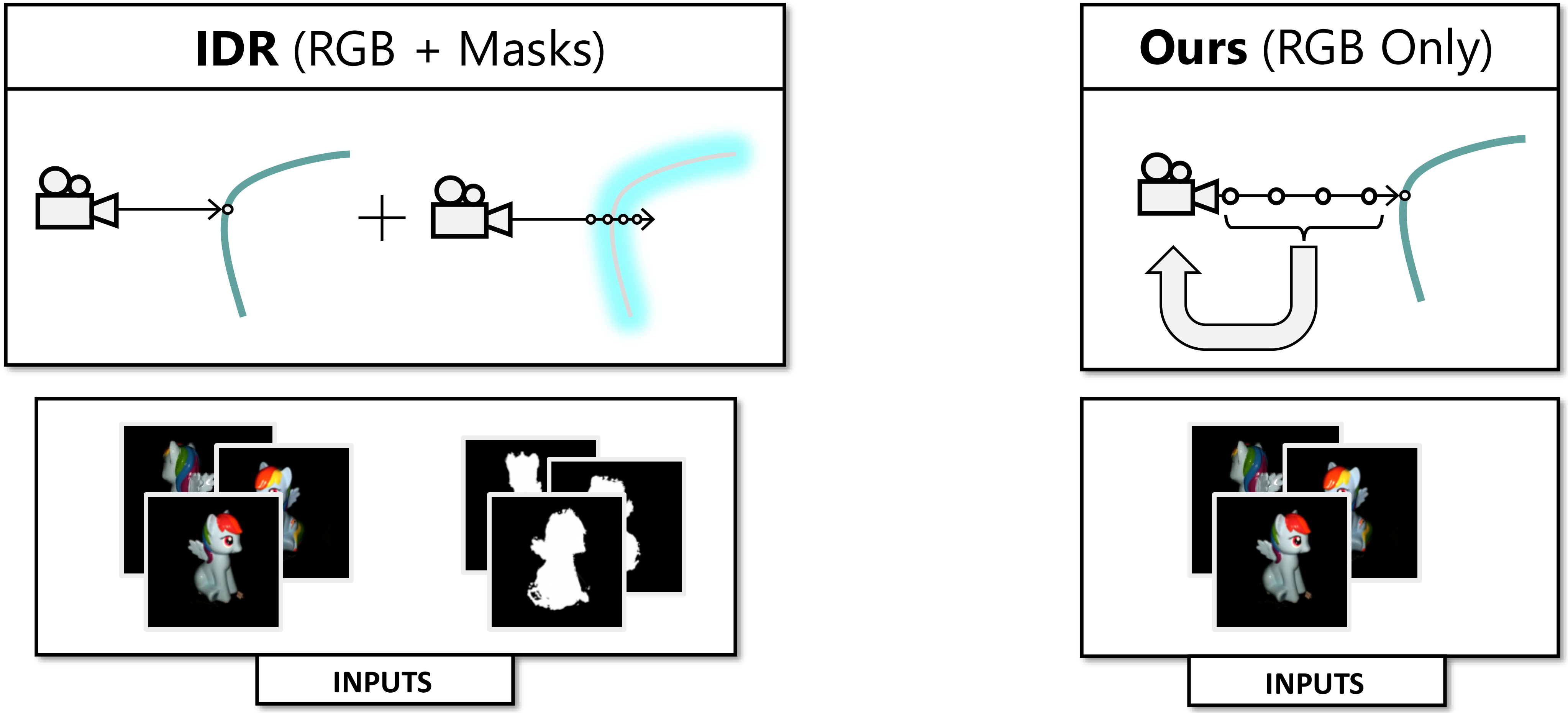
Putting It All Together: Then, Reparameterize Samples



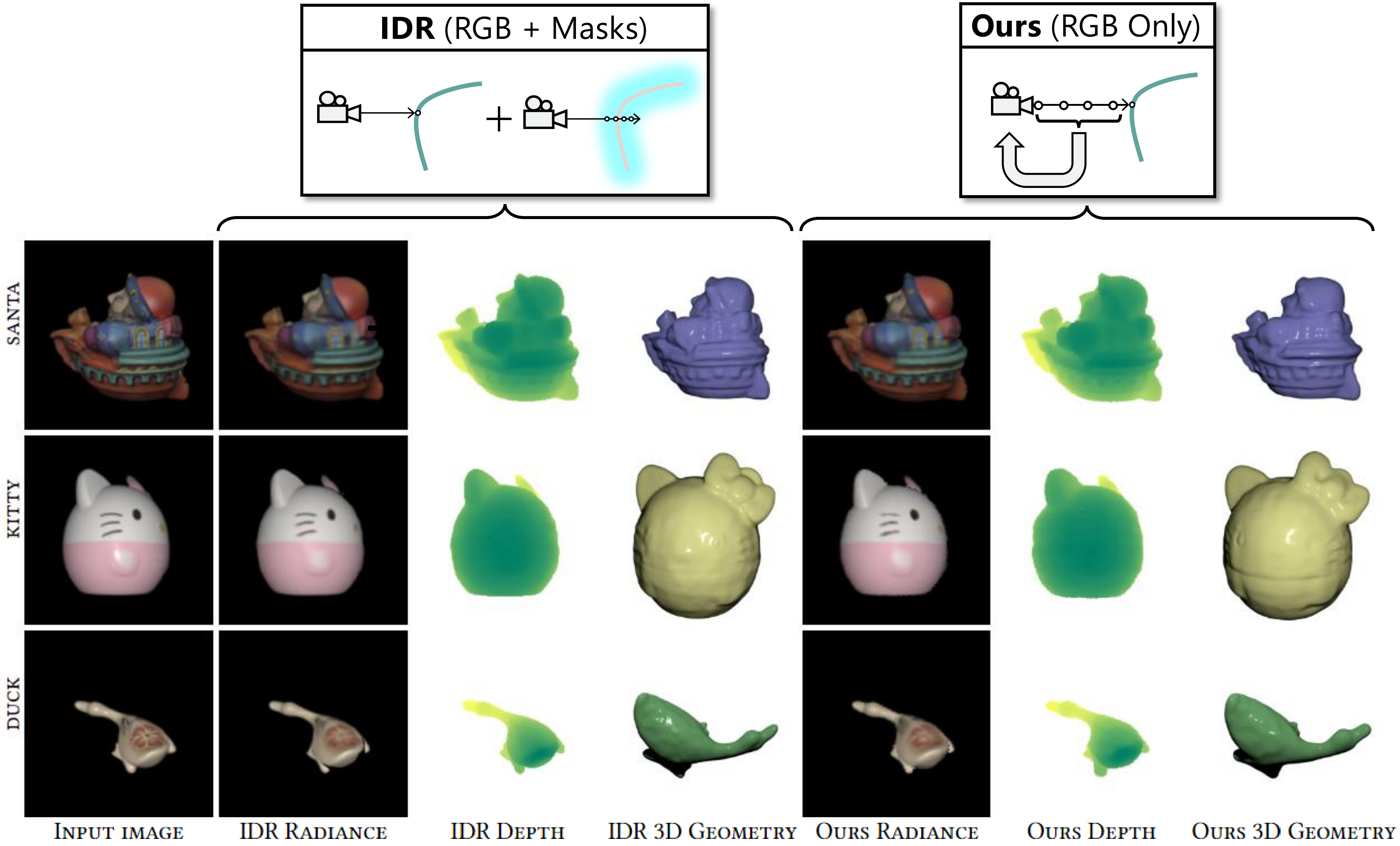
Putting It All Together: Finally, Differentiate With AD



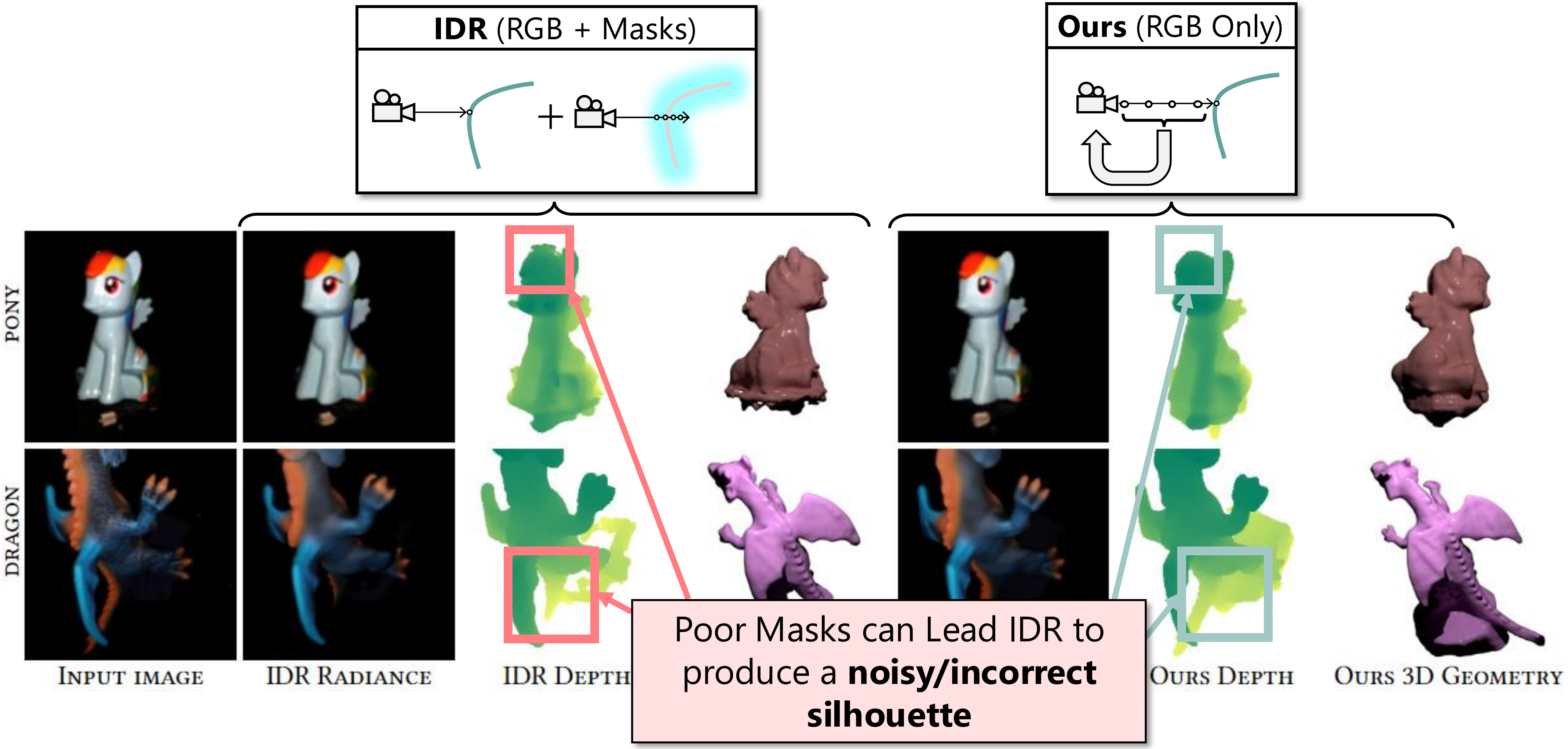
Comparisons Against IDR (Yariv et al. 2020): A Sharp-Surface Model With Segmentation Mask Inputs



Reconstructions On-Par With IDR *Without* Using Masks

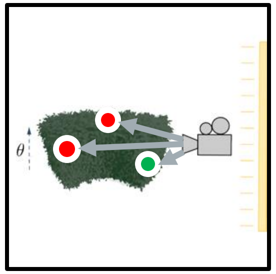


Cleaner Reconstructions Than IDR On Real Data with Poor Segmentation Masks



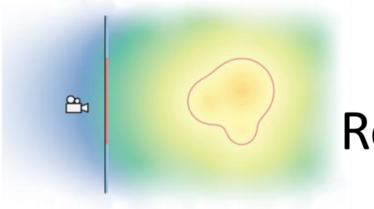
CONCLUSIONS

Problem With **Edge Sampling**



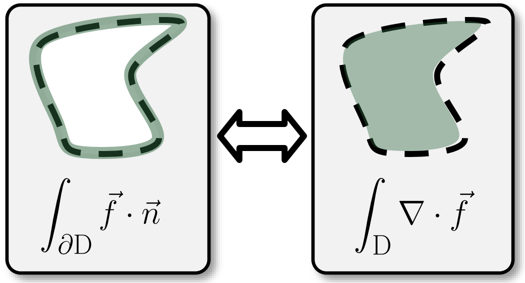
Depth complexity

Specularities

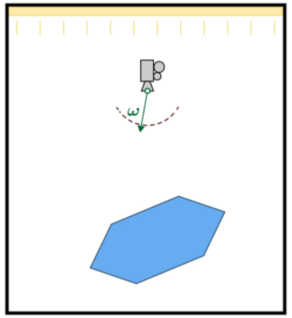


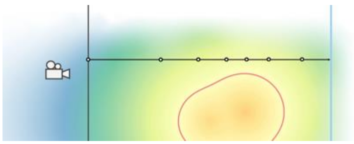
Implicit Representations

Warped-Area Sampling



Convert to Area Sampling

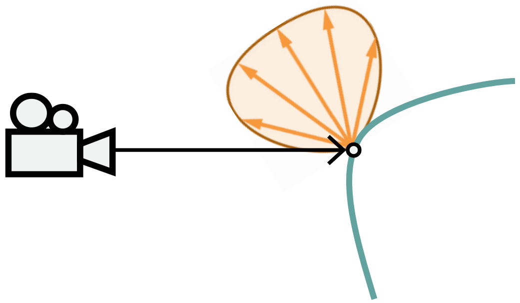




On-the-fly Warp Field Estimation

Future Directions

More SDFs in Physically-based Pipelines



Boundary-Aware Reparameterization For Other Domains