Robust Neural Distance Fields using 1-Lipschitz Neural Networks

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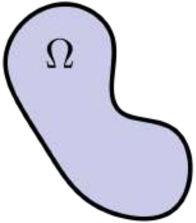
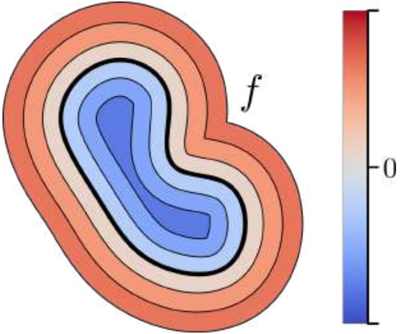
Implicit Representation of Geometry

Represent a compact object $\Omega \subset \mathbb{R}^n$ as a level set of a continuous function:

$$\Omega = \{x \in \mathbb{R}^n \mid f(x) \leqslant 0\}$$

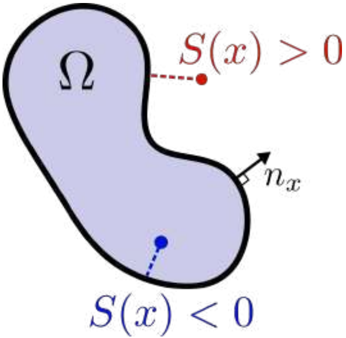




Signed Distance Function

The SDF of Ω is the function S defined as:

$$S(x) = \begin{cases} -d(x, \partial\Omega) & \text{if } x \in \Omega \\ d(x, \partial\Omega) & \text{otherwise} \end{cases}$$



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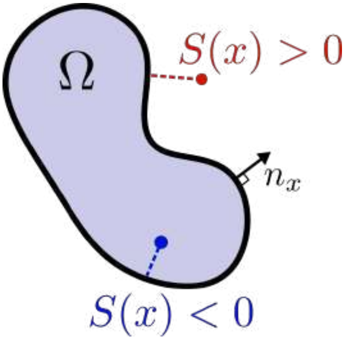
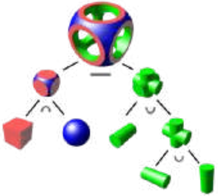
S is the solution to the **Eikonal** equation:

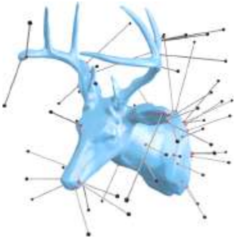
$$\begin{cases} ||\nabla S(x)|| &= 1, & \forall x \in \mathbb{R}^n \\ S(x) &= 0, & \forall x \in \partial\Omega \\ \nabla S(x) &= n_x, & \forall x \in \partial\Omega \end{cases}$$



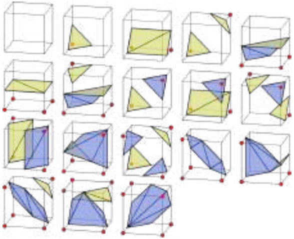
Applications



Constructive Solid Geometry
[Ricci (1973)]

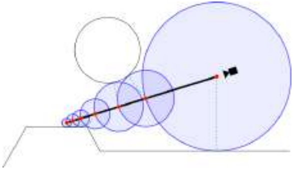


Closest Point Query
[Sharp and Jacobson (2022)]

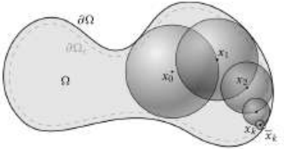


Marching Cubes
[Lorensen and Cline (1987)]

Rendering
Snail shader by Inigo Quilez



Empty Sphere Query
[Hart (1995)]



Monte-Carlo Simulation
[Sawhney and Crane (2020)]

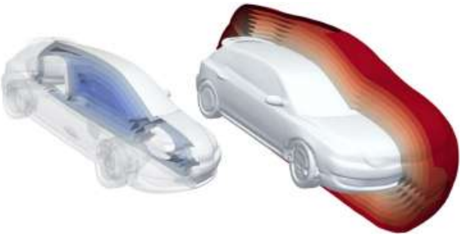
Signed Distance Function

Simple shapes:
Direct approach

```
float sdHexagram( in vec2 p, in float r )
{
    const vec4 k = vec4(-0.5,0.8660254038,0.5773502692,1.7320508076);
    p = abs(p);
    p -= 2.0*min(dot(k.xy,p),0.0)*k.xy;
    p -= 2.0*min(dot(k.yx,p),0.0)*k.yx;
    p -= vec2(clamp(p.x,r*k.z,r*k.w),r);
    return length(p)*sign(p.y);
}
```

https://iquilezles.org/articles/distfunctions2d/

Complex shapes:
Neural Distance Fields



[Gropp et al. (2020)]

Approximate a solution of the Eikonal equation

Neural Distance Fields

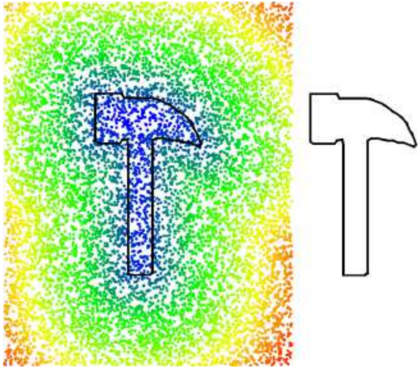
Neural Distance Fields: State of the Art Approach

- Define a neural network f_θ with parameters $\theta \in \mathbb{R}^K$
- Optimize over θ to minimize some loss function

$$\mathcal{L}_{fit} = \mathbb{E}_{x \in \mathbb{R}^n} \left[(f_\theta(x) - S(x))^2 \right]$$

$$\mathcal{L}_{normal} = \mathbb{E}_{x \in \partial\Omega} \left[(\nabla f_\theta(x) - n_x)^2 \right]$$

$$\mathcal{L}_{eikonal} = \mathbb{E}_{x \in \mathbb{R}^n} \left[(||\nabla f_\theta(x)|| - 1)^2 \right]$$



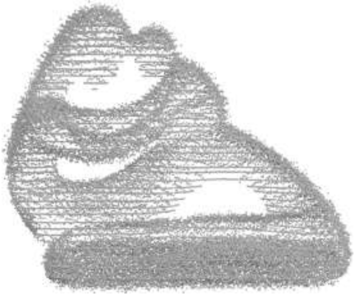
Dataset $\{(x_i, S(x_i))\}$

Neural Distance Fields: Limitations

Ground truth distances may not be available in practice.

Triangle soup

Incomplete point cloud

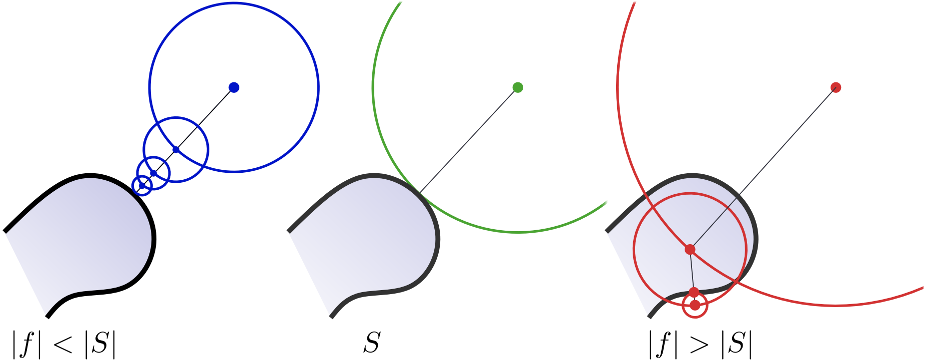


Noisy point cloud

Neural Distance Fields: Limitations

f_θ does not exactly satisfy the Eikonal equation

Geometric queries are guaranteed only if $||\nabla f_\theta|| \leqslant 1$
i.e. f_θ should be **1-Lipschitz**.



Robust Neural Distance Fields using 1-Lipschitz Neural Networks

1-Lipschitz Neural Networks

- A (feed-forward) neural network f_θ is a sequence of *layers*: $f_L \circ ... \circ f_1$
- Specifying an architecture defines a functional space $\mathcal{F} = \{ f_\theta \mid \theta \in \mathbb{R}^K \}$

[1] *"A Unified Algebraic Perspective on Lipschitz Neural Networks"*, Araujo et al., ICLR (2023)

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1-Lipschitz Layer[1]

$$x \mapsto x - 2WD^{-1}\sigma(W^T x + b)$$

where:

$$\sigma(x) = ReLU(x) = \max(x, 0)$$

$$D = \text{diag}\left(\sum_j |(W^T W)_{ij} \exp(q_j - q_i)|\right)$$

Parameters to optimize: W, b, q

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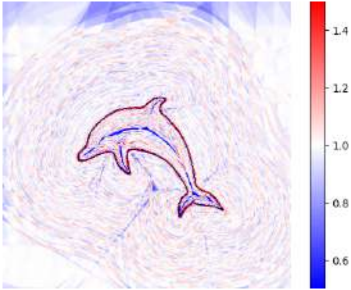
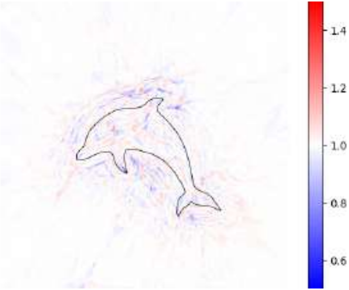
Plot of Gradient Norm



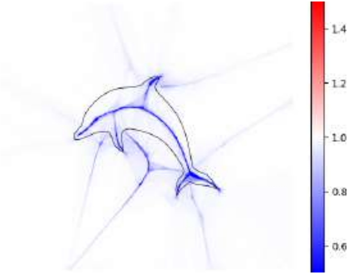
$\min \mathcal{L}_{fit}$

$\max ||\nabla f_\theta|| =$ **13.8**



$\min \mathcal{L}_{fit} + 0.1\mathcal{L}_{eikonal}$

$\max ||\nabla f_\theta|| =$ **1.4**



$\min \mathcal{L}_{fit}$ with
Lipschitz architecture

$\max ||\nabla f_\theta|| =$ **0.998**

Learning a Distance Field without Ground Truth

Learning a SDF from occupancy labels with Lipschitz networks

Suppose we can determine $y : \mathbb{R}^n \to \{-1, 1\}$ defined as:

$$y(x) = \begin{cases} -1 \text{ if } x \in \Omega \\ 1 \text{ if } x \notin \Omega \end{cases}$$

[1] *"Achieving Robustness in Classification Using Optimal Transport with Hinge Regularization"*, Serrurier et al., CVPR (2021)

[2] *"Robust One-Class Classification with Signed Distance Function Using 1-Lipschitz Neural Networks"*, Bethune et al., ICML (2023)

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hinge-Kantorovich-Rubinstein loss[2]

$$\mathcal{L}_{hKR} = \mathbb{E}_x \left[-y f_\theta(x) \right] + \lambda \mathbb{E}_x \left[\max(0, m - y f_\theta(x)) \right], \quad m, \lambda > 0$$

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$f^* = \text{argmin}_\theta \, \mathcal{L}_{hKR}$ over 1-Lipschitz functions is a SDF up to margin parameter m[3]

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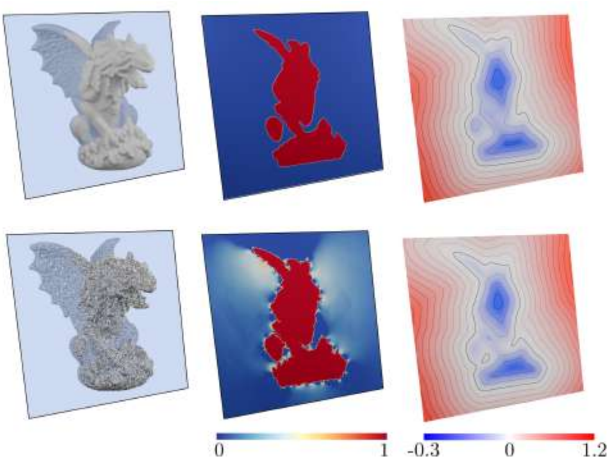
Generalized Winding Number for Inside/Outside Partitioning

$$w_{\partial\Omega}(x) = \frac{1}{4\pi} \int_{\partial\Omega} d\Theta(x)$$

$w \in \{0, 1\}$ for manifolds
$w \in [0, 1]$ for point clouds[4]



[1] *"Fast Winding Numbers for Soups and Clouds"*, Barill et al., ACM Transactions on Graphics (2018)

Overview of the method

1. **Input:** Point cloud or triangle soup representing $\partial\Omega$
2. Sample points x_i uniformly in a loose box around Ω
3. Use the winding number to assign $y_i \in \{-1, 1\}$ to x_i
4. Minimize $\mathcal{L}_{hKR}$ over (x_i, y_i) for some 1-Lipschitz architecture

Input

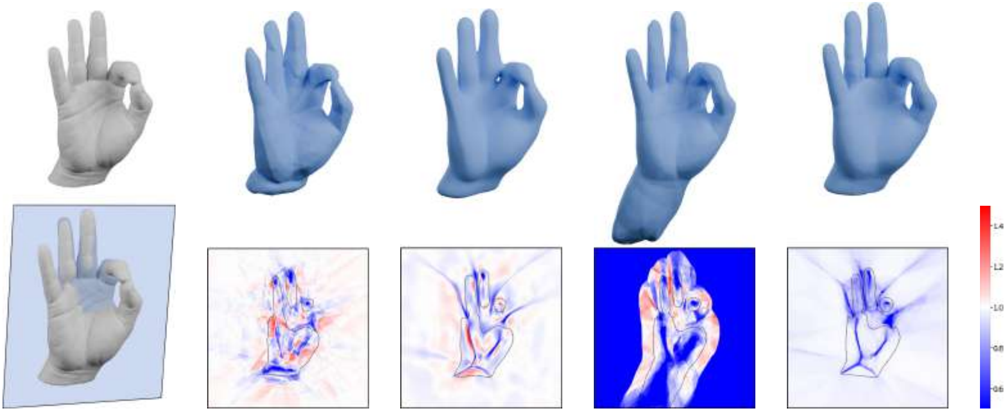
Samples

0 level set

SDF

Results

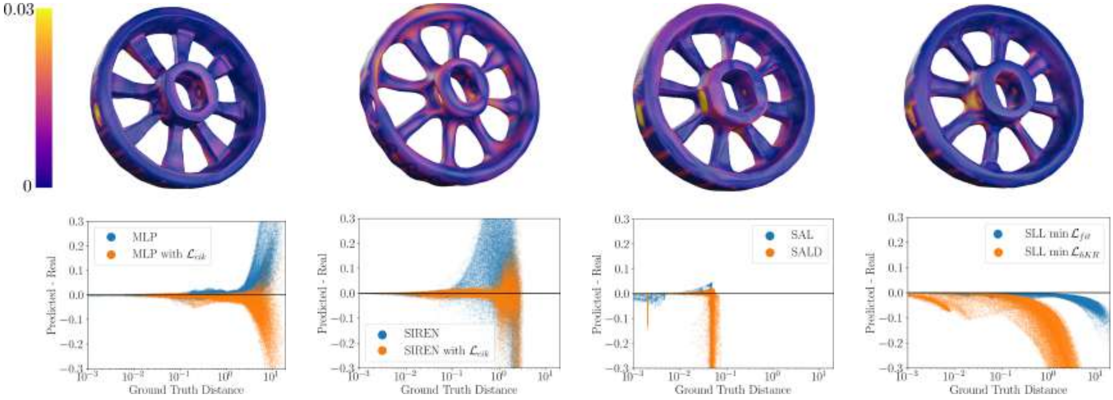
Surface Reconstruction and Gradient Correctness



Ground Truth | MLP[1] | SIREN[2] | SALD[3] | Ours

[1] *"On the Effectiveness of Weight-Encoded Neural Implicit 3D Shapes"*, Davies et al., (2021)
[2] *"Implicit Neural Representations with Periodic Activation Functions"*, Sitzmann et al., NeuRIPS (2020)
[3] *"SALD: Sign Agnostic Learning with Derivatives"*, Atzmon and Lipman, ICLR (2020)

Our Methods Always Underestimates the True Distance



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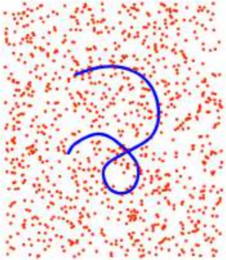
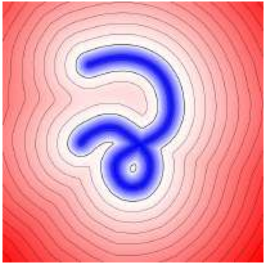
Unsigned Distance Function for Curves and Open Surfaces

Take $y = -1$ on $\partial\Omega$ and $y = 1$ on $\mathbb{R}^n \backslash \partial\Omega$. Loss margin m acts as a thickness parameter.



Input point cloud

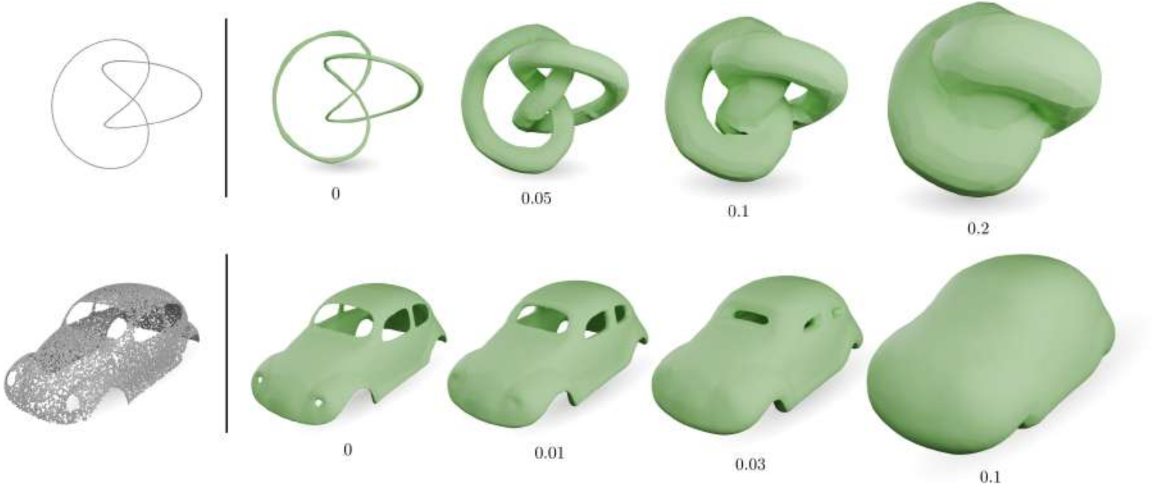


$m = 10^{-1}$

$m = 10^{-2}$

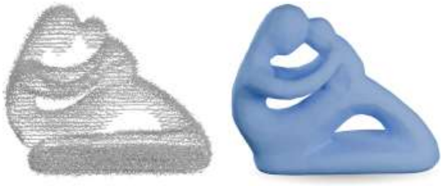
$m = 10^{-3}$

Unsigned Distance Function for Curves and Open Surfaces

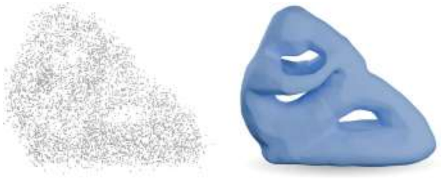


SDF reconstruction with no ground truth

With holes

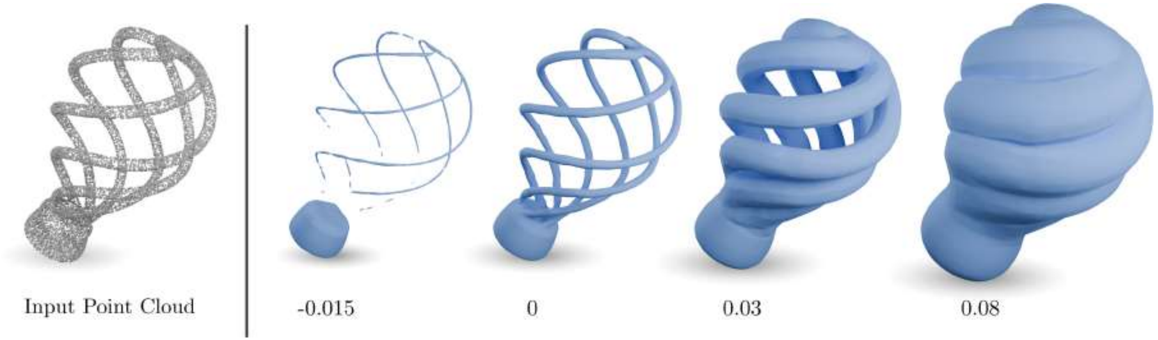


Simulated Lidar



Noisy

Sparse (500 pts)



Merci pour votre attention !

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