CorticalFlow++: Boosting Cortical Surface Reconstruction Accuracy, Regularity, and Interoperability

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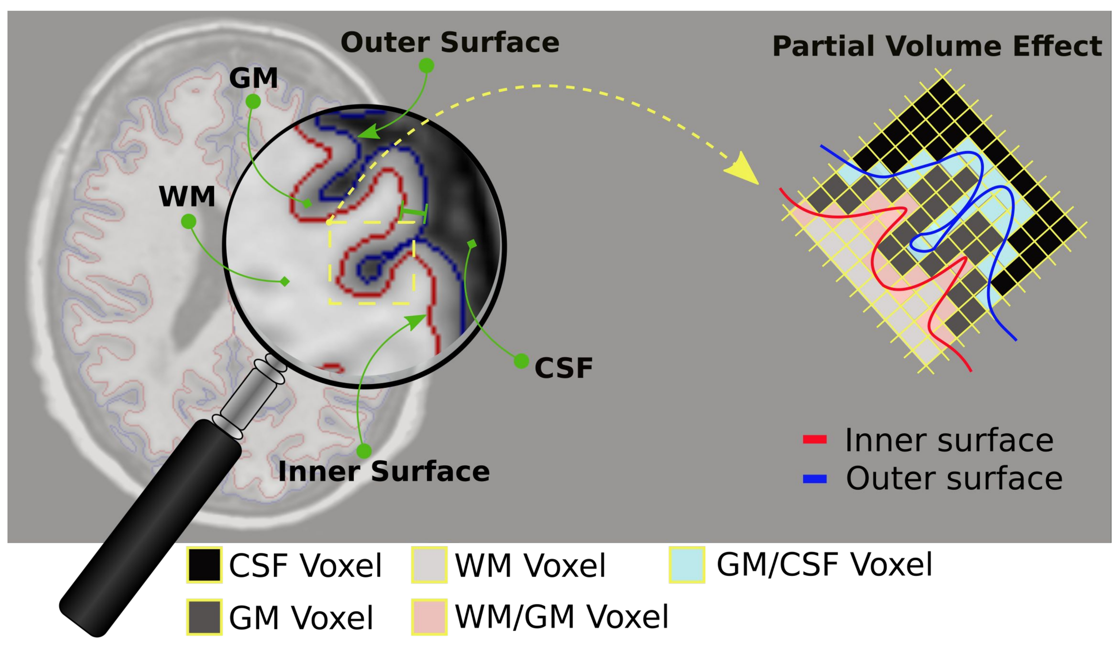
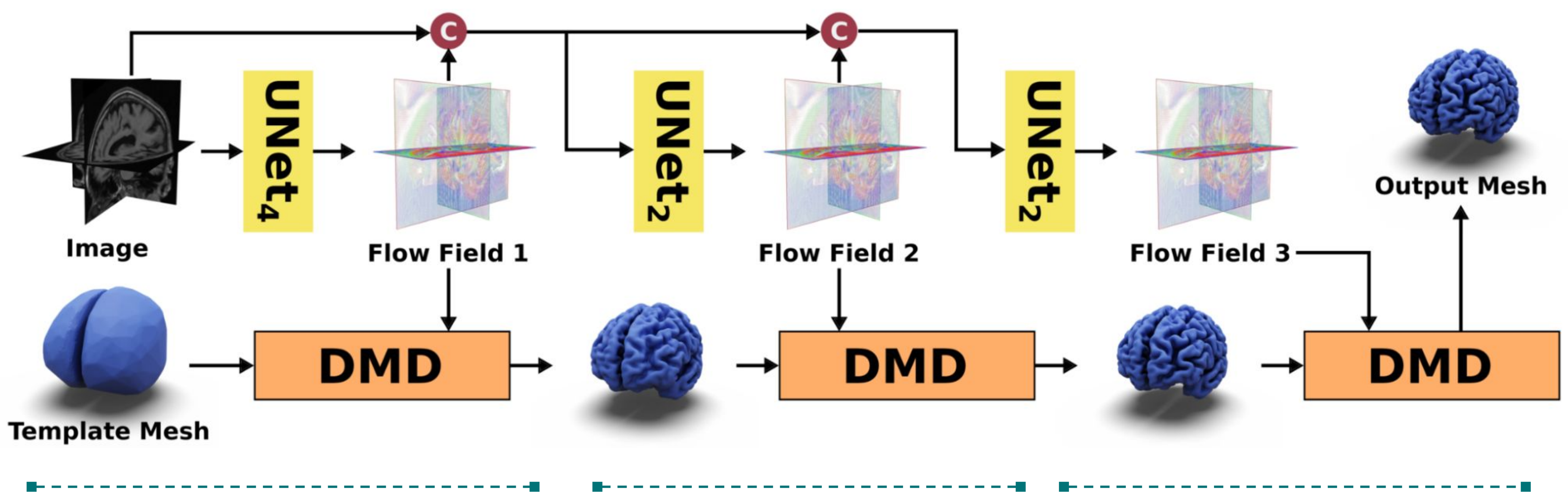
This work improves CorticalFlow's accuracy, regularity, and interoperability with existing surface analysis tools without severely degrading its inference time and GPU memory consumption.

1) Cortical Surface Reconstruction from MRI (CSR):



2) CorticalFlow Model



$$\mathrm{CF}^{i+1}_{\theta_{i+1}}(\mathbf{I}, \mathcal{T}_{i+1}) = \mathrm{DMD}\Big(\mathrm{UNet}^{i+1}_{\theta_{i+1}}(\mathbf{U}_1^\frown \cdots \mathbf{U}_i^\frown \mathbf{I}), \mathrm{CF}^{i}_{\theta_i}(\mathbf{I}, \mathcal{T}_{i+1})\Big)$$

$$\mathrm{CF}^{1}_{\theta_1}(\mathbf{I}, \mathcal{T}_1) = \mathrm{DMD}\Big(\mathrm{UNet}^{1}_{\theta_1}(\mathbf{I}), \mathcal{T}_1\Big)$$

3a) Higher Order ODE Solver

DMD modules compute per vertex diffeomorphic mappings Φ from the predicted flow field **U** by solving the flow ODE,

$$\frac{d\Phi(s;\mathbf{x})}{ds} = \mathbf{U}\left(\Phi(s;\mathbf{x})\right), \text{with} \quad \Phi(0;\mathbf{x}) = x$$

CorticalFlow uses the forward **Euler** method,

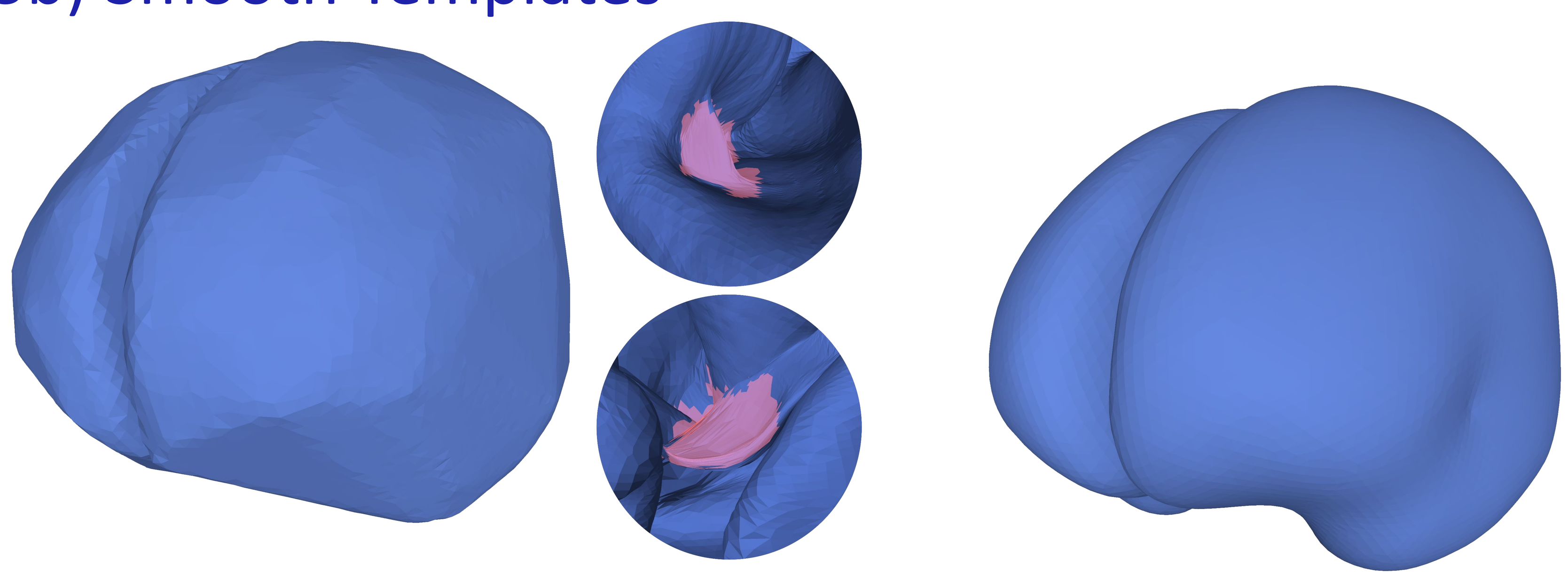
$$\hat{\Phi}(h, \mathbf{x}) = \mathbf{x} + h\mathbf{U}(\mathbf{x}),$$

While **CorticalFlow++** uses the **RK4** method:

$$\hat{\hat{\Phi}}(h, \mathbf{x}) = \mathbf{x} + \frac{1}{6}[k_1 + 2k_2 + 2k_3 + k_4]$$

$$k_1 = \mathbf{U}(\mathbf{x}) \quad k_2 = \mathbf{U}\left(\mathbf{x} + h\frac{k_1}{2}\right) \quad k_3 = \mathbf{U}\left(\mathbf{x} + h\frac{k_2}{2}\right) \quad k_4 = \mathbf{U}(\mathbf{x} + hk_3)$$

3b) Smooth Templates



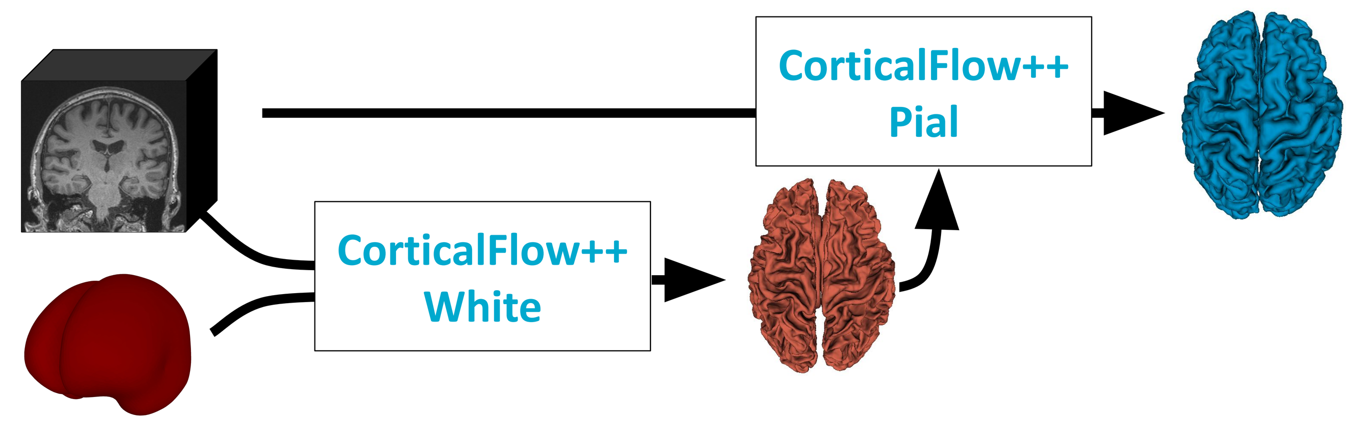
CorticalFlow's template and generated mesh artifacts — **CorticalFlow++'s template**

Procedure:

1. Compute a **signed distance grid** for every training mesh.
2. Threshold and compute the **binary union** of these grids.
3. Use **marching cubes** algorithm to obtain a coarse mesh.
4. Smooth the coarse mesh by applying **laplacian smoothing**.
5. Remesh using **delaunay triangulation**.

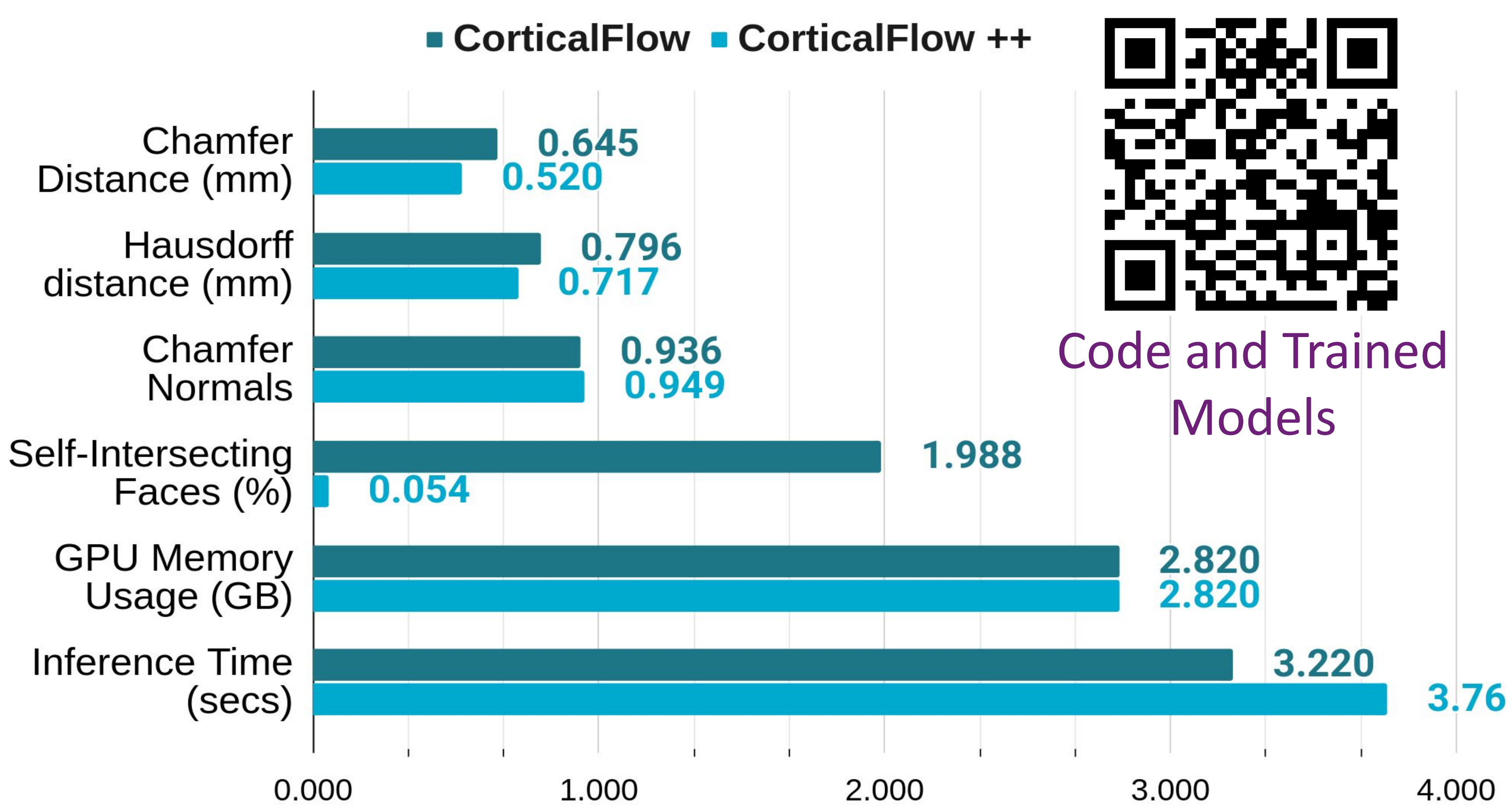
3c) White To Pial Surface Morphing

CorticalFlow deforms separate template meshes leading to reconstructed meshes **without a one-to-one mapping** between the vertices in the white and pial surfaces. Instead, **CorticalFlow++** predicts pial surfaces by deforming its corresponding **predicted white surface**.



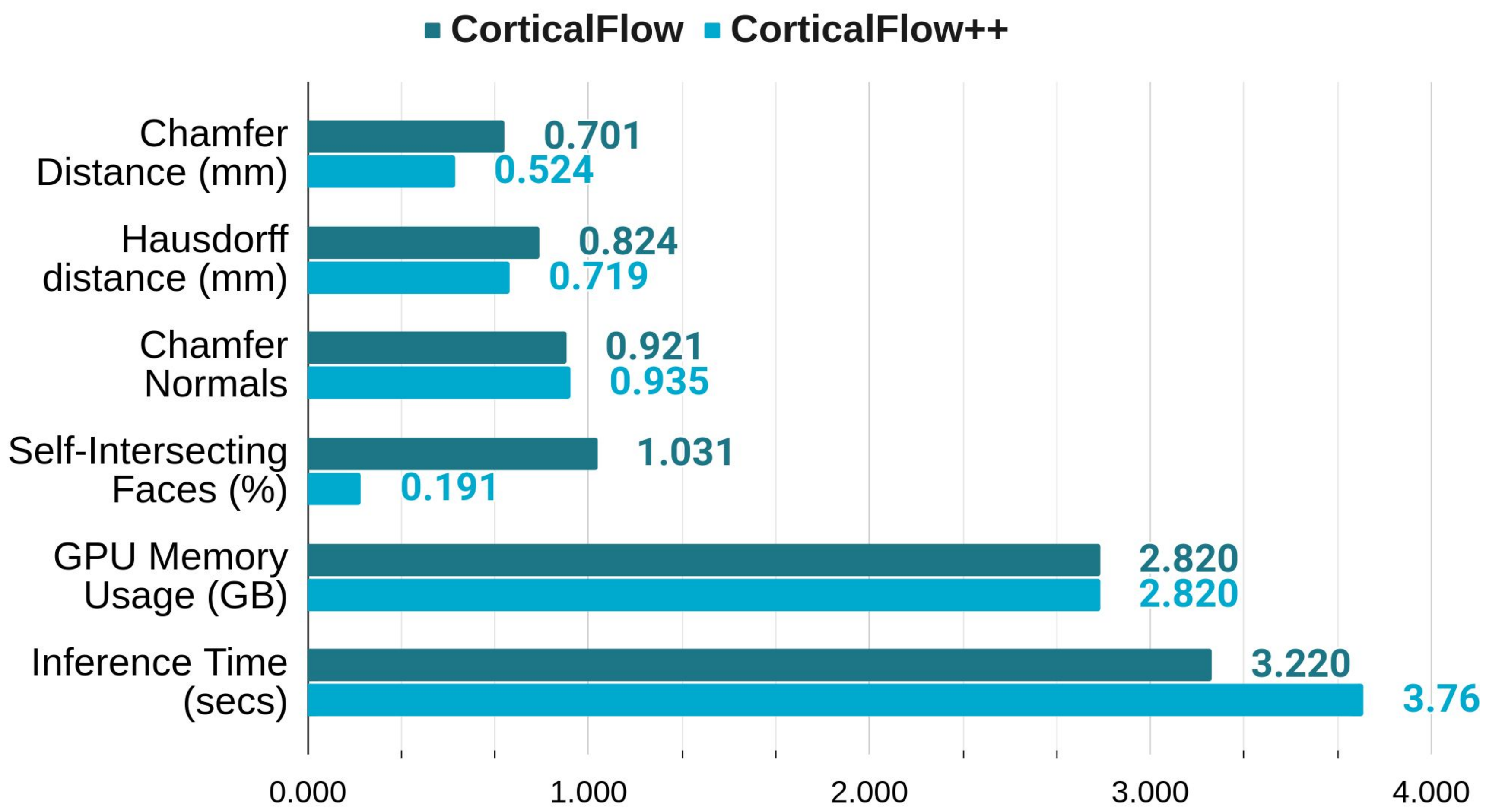
4) Results:

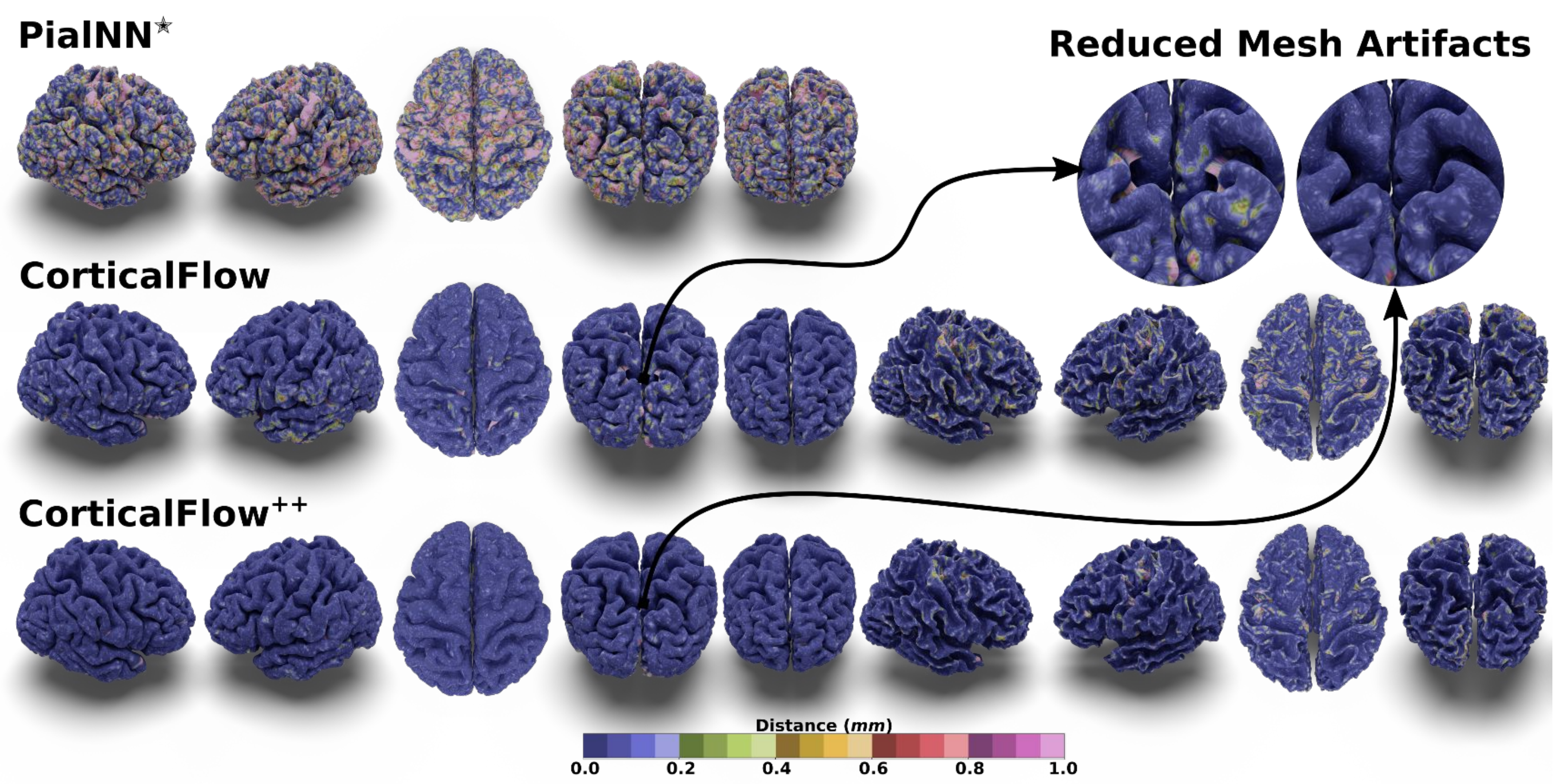
ADNI Benchmark



Code and Trained Models

OASIS3 (Out-Of-Train Distribution)





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