# Combining SU2 and Graph Neural Networks for Fluid Flow Prediction

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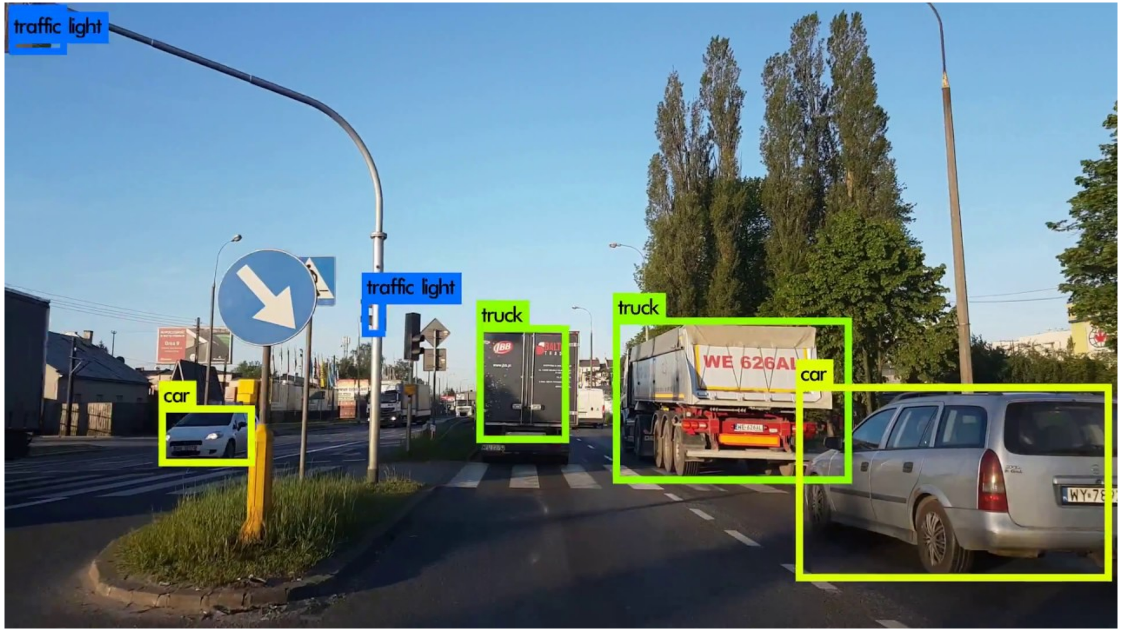
Carnegie Mellon University

SU2 foundation

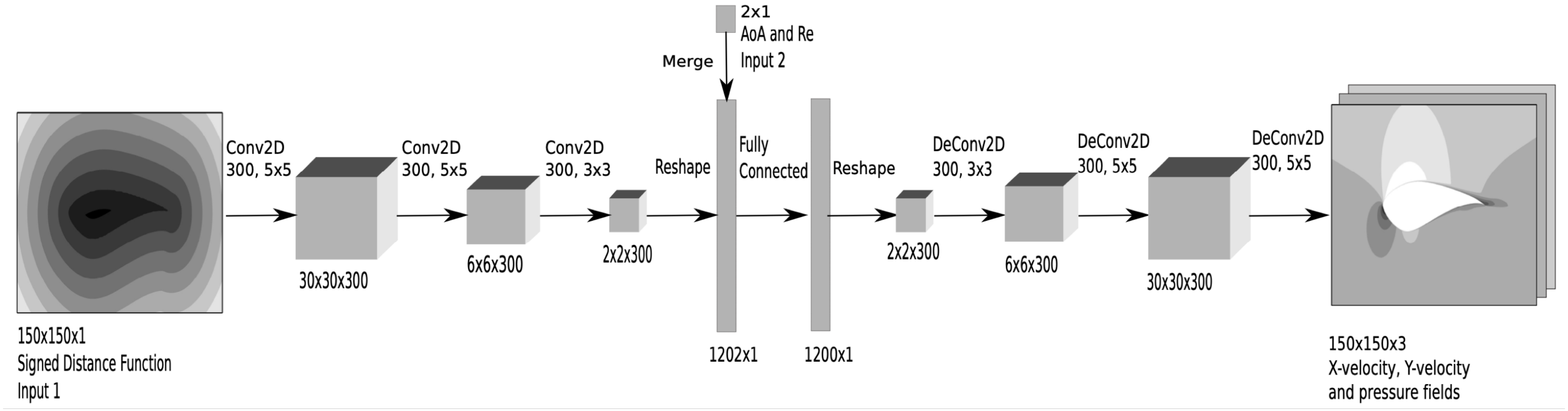
BOSCH

# Successes of Deep Learning

Learning complex input-output relations

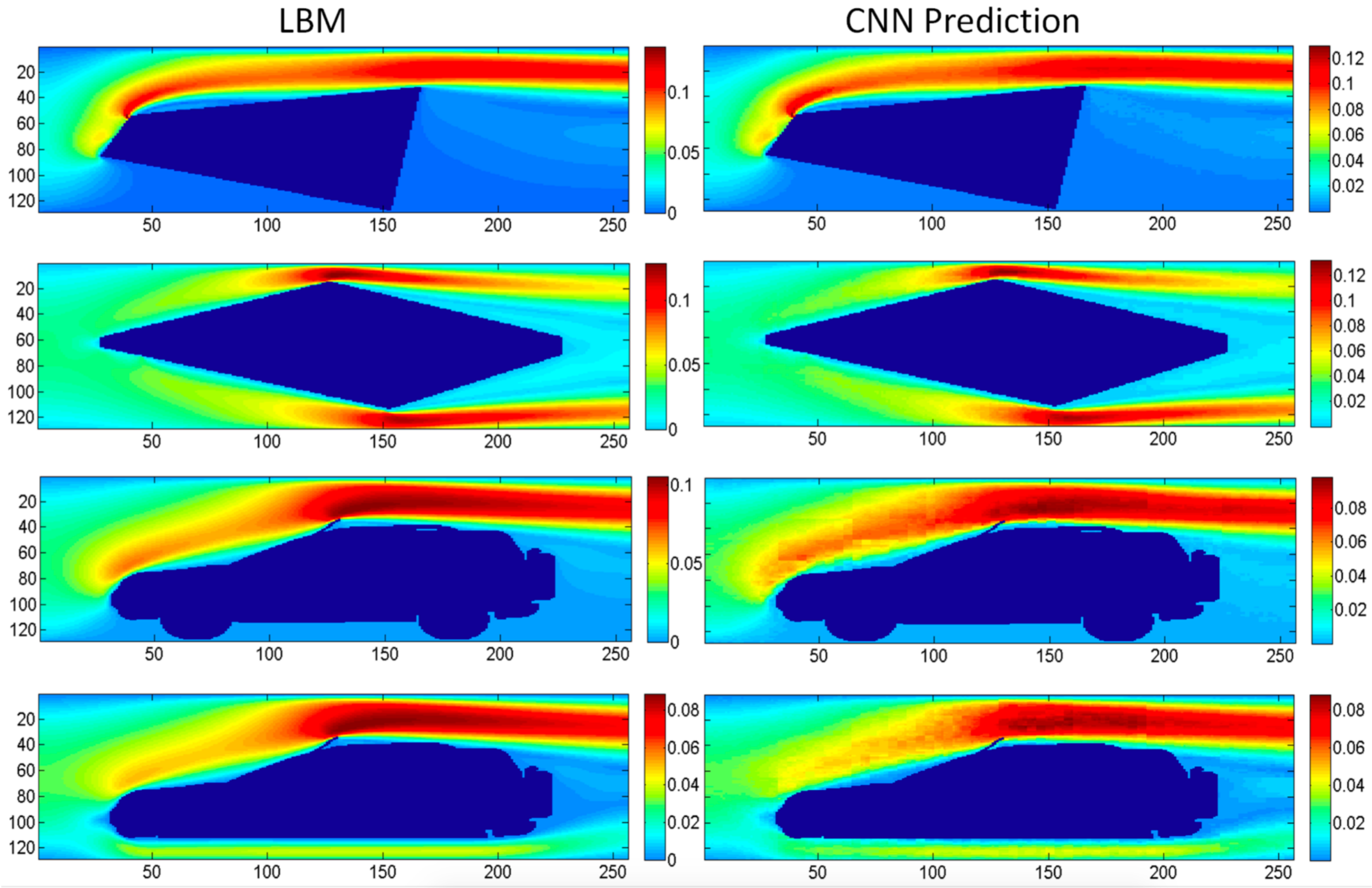
# Machine learning and CFD




Y. Afshar et al., *Prediction of Aerodynamic Flow Fields Using Convolutional Neural Networks*, 2019

# Machine learning and CFD

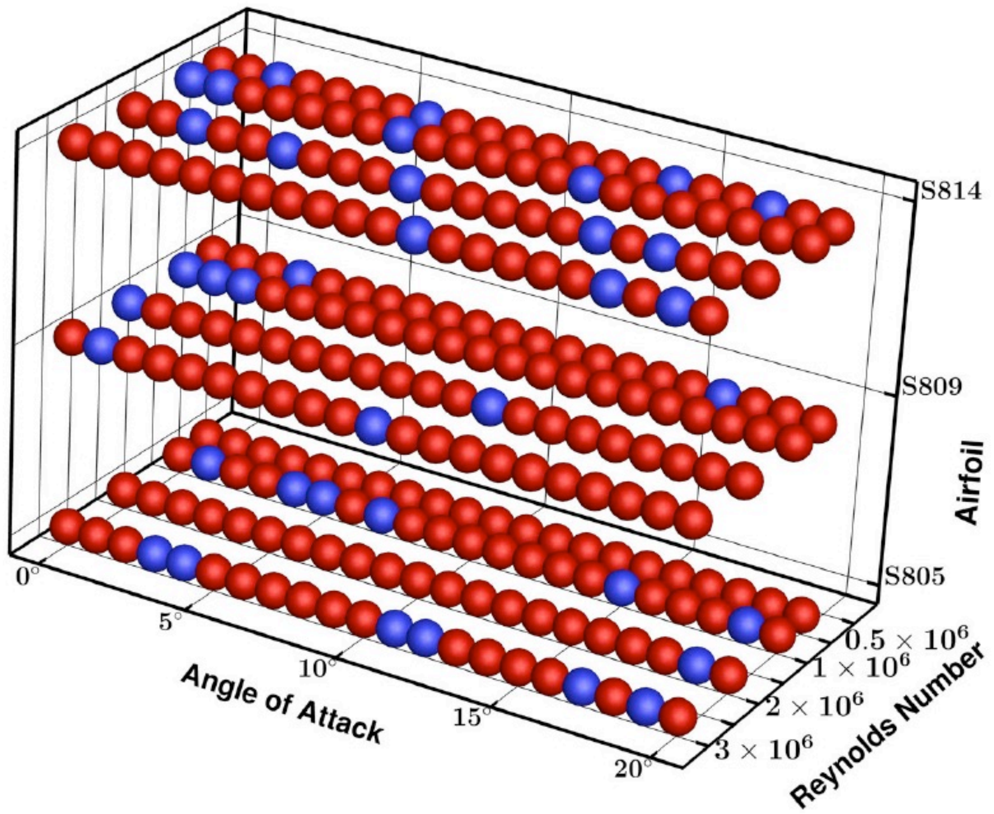
Standard Convolutional networks can only be applied to regular grids




X. Guo, W. Li & F. Iorio, *Convolutional Neural Networks for Steady Flow Approximation*, 2016

# Machine learning and CFD

Works well on data within the distribution seen during training



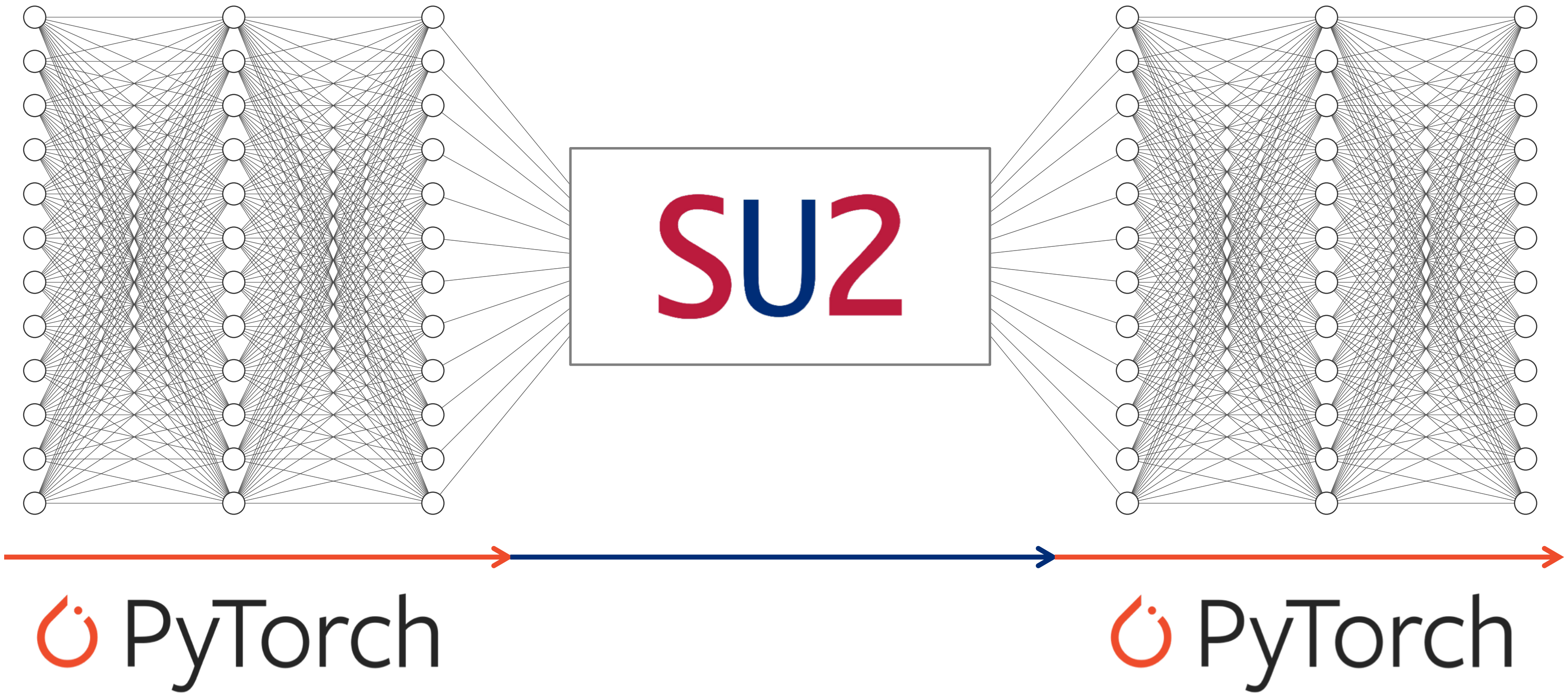

Y. Afshar et al., *Prediction of Aerodynamic Flow Fields Using Convolutional Neural Networks*, 2019

# Combining SU2 and Graph Networks

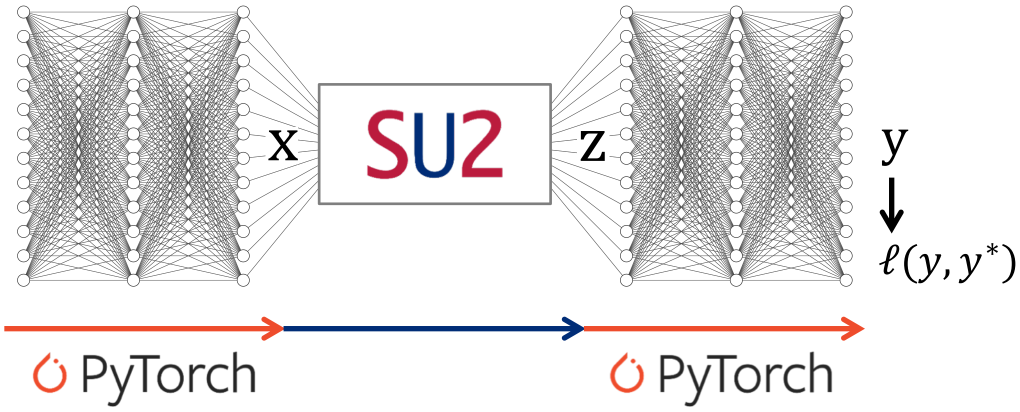
- Operate directly on non-uniform meshes using graph networks

- Embed differentiable CFD solver into deep learning model for better generalization

# Schematic pipeline



# Interface overview



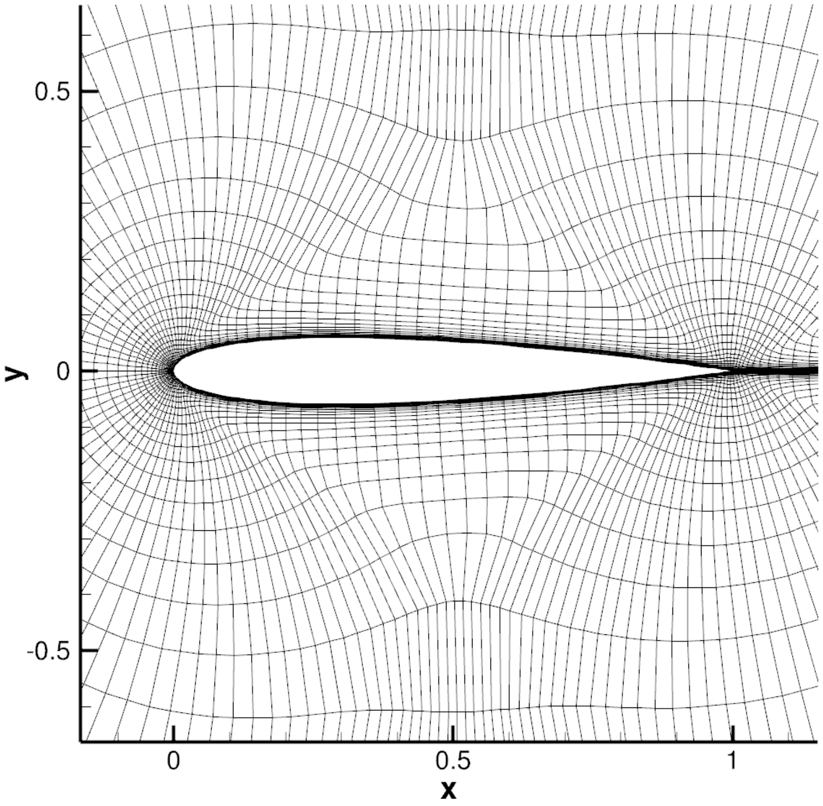

- Config file

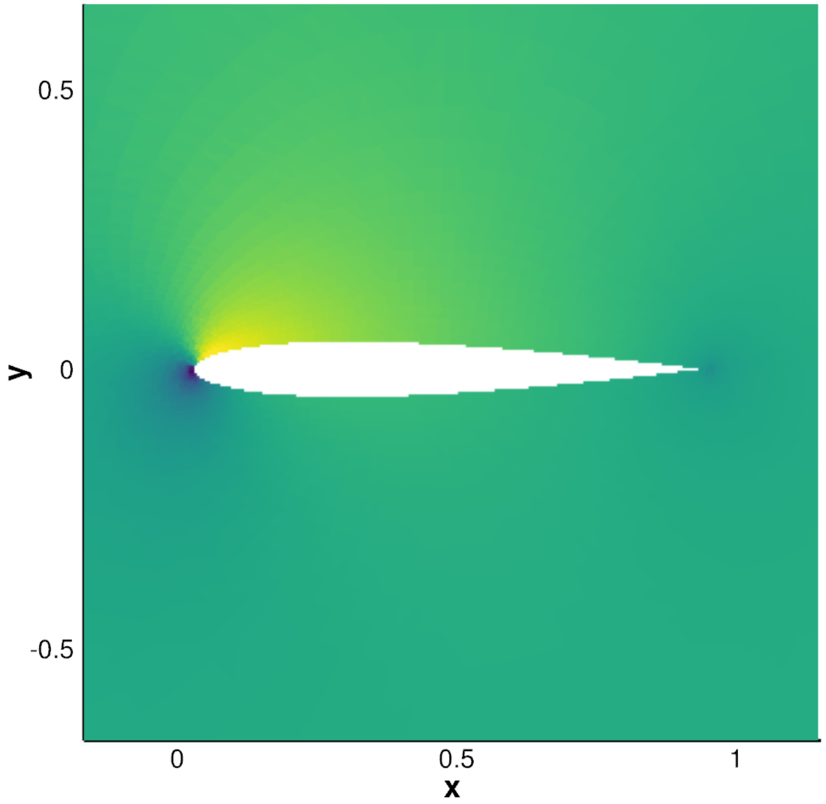
```
% Regular config file…

DIFF_INPUTS = MESH_X, MESH_Y
DIFF_OUTPUTS = VEL_X, VEL_Y, PRESS
```

- Python

```
import torch
from su2_function import SU2Function
# process some data in torch
x = torch.operation(data)
# input into SU2 and run simulation
su2 = SU2Function(config_file)
z = su2(x)
# process more in torch
y = torch.operation(z)
# set loss and get gradients
loss = torch.nn.MSELoss(y, y_star)
loss.backward() # dloss/dx available
```

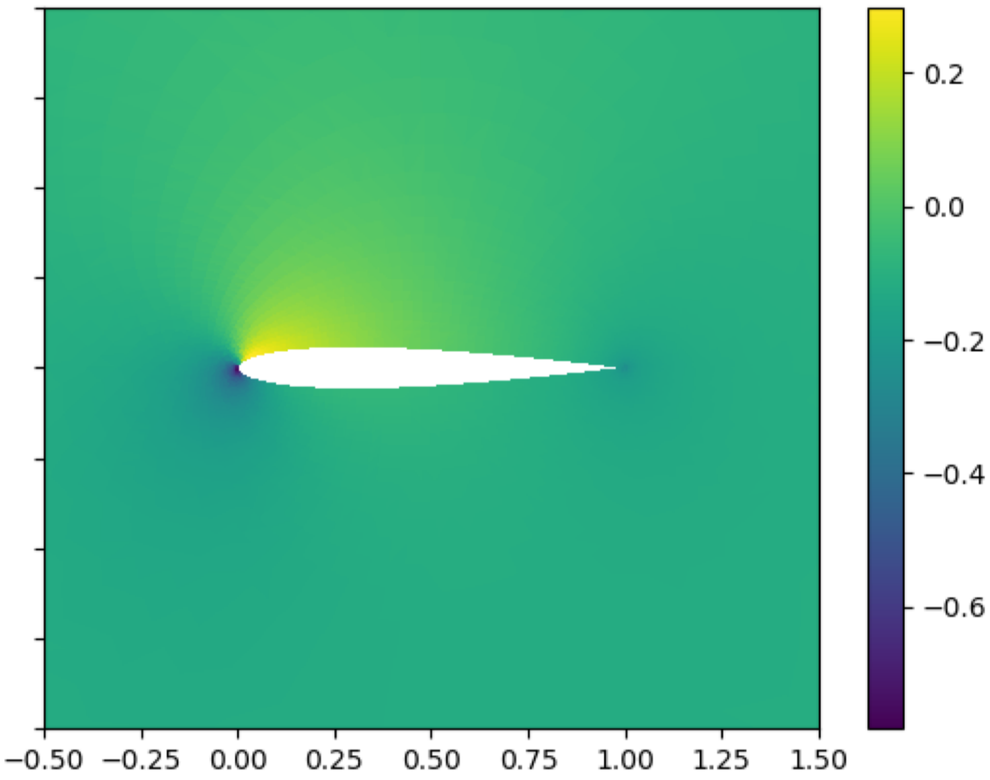
# Simulating flow around an airfoil

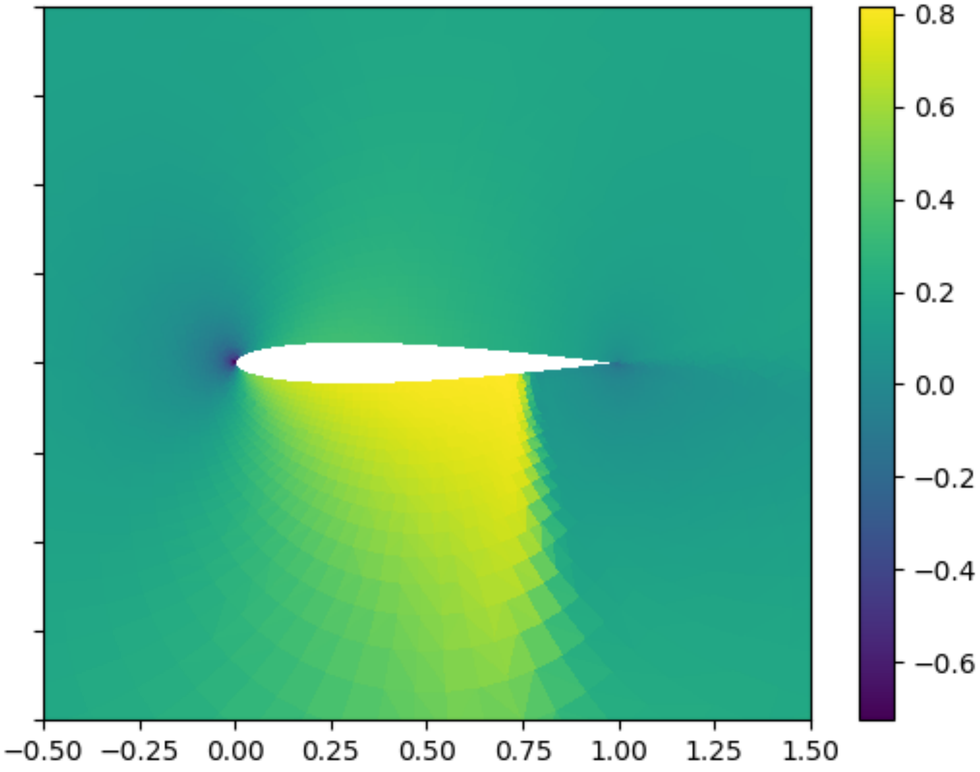


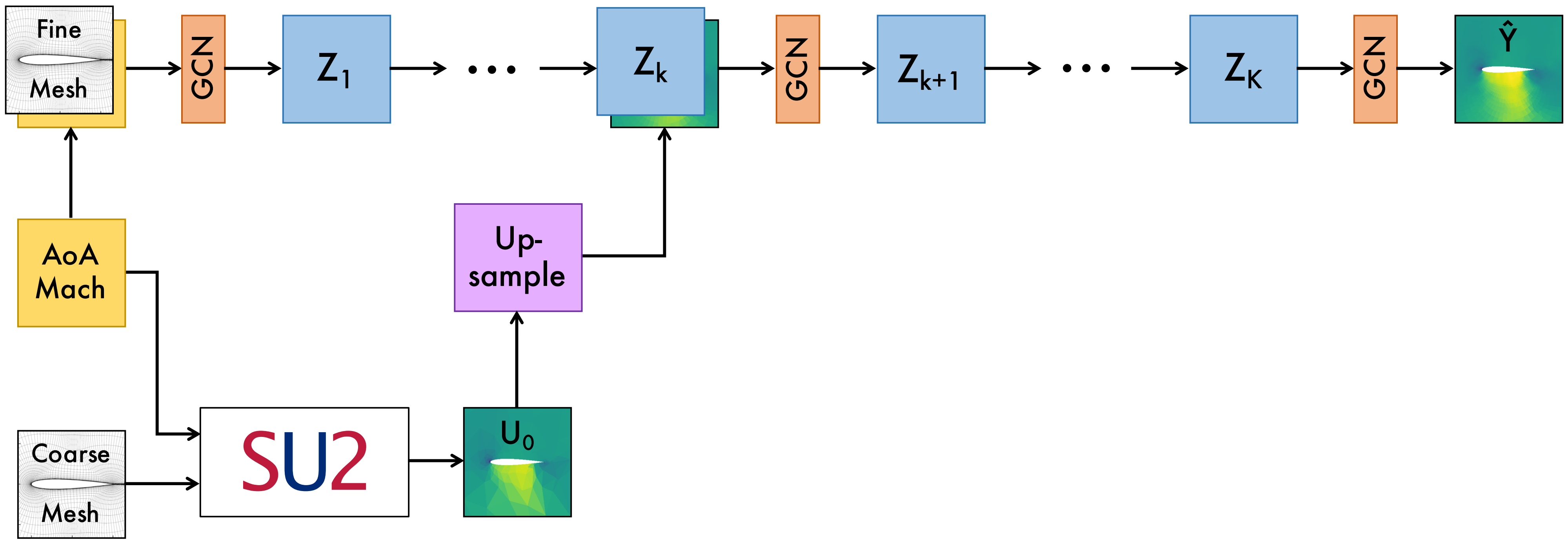
# Physical Parameters

$$\text{AoA} \in \{-10, -9, \ldots, 9, 10\}$$
$$\text{Mach} \in [0.2, 0.8]$$

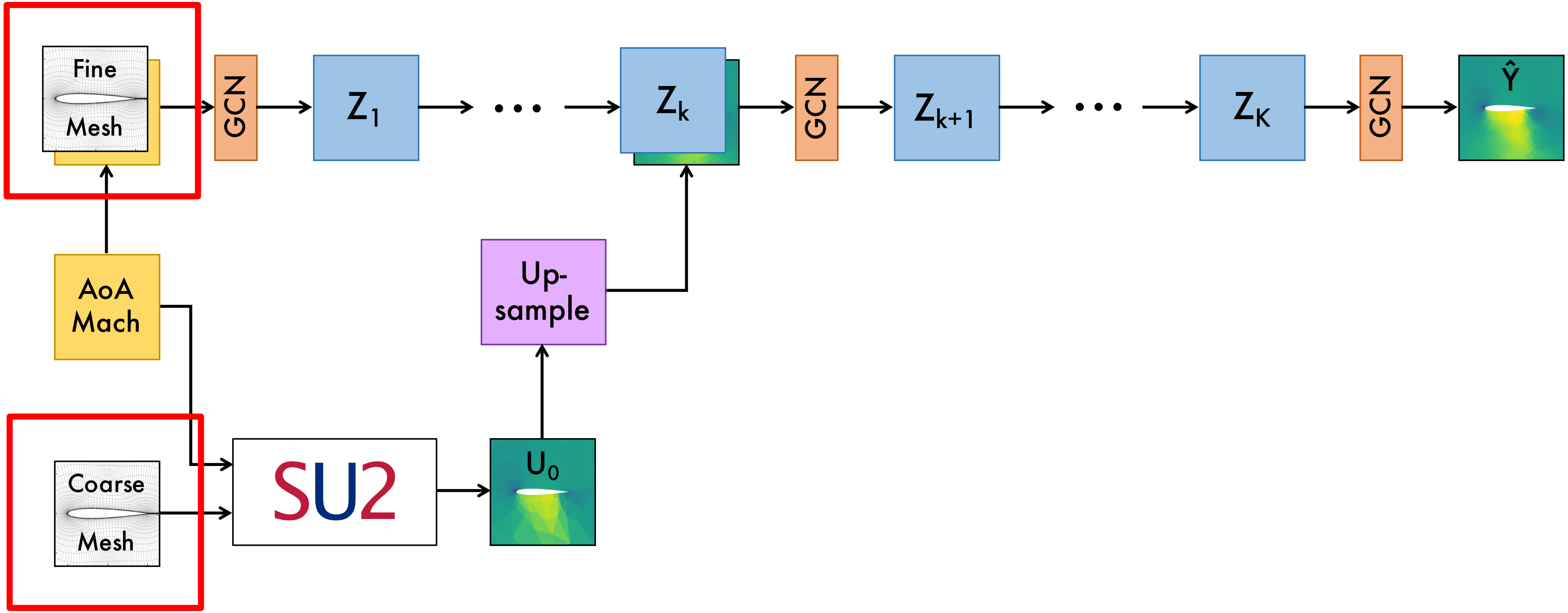


# CFD-GCN

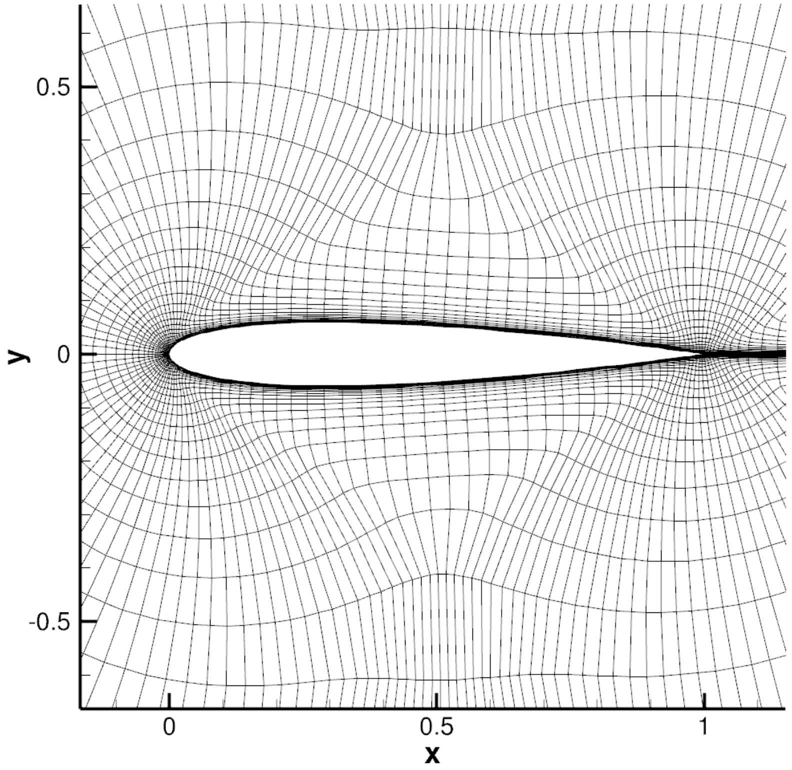

Fine
Mesh
GCN
$Z_1$
• • •
$Z_k$
GCN
$Z_{k+1}$
• • •
$Z_K$
GCN
$\hat{Y}$
AoA
Mach
Up-
sample
Coarse
Mesh
SU2
$U_0$

# CFD-GCN

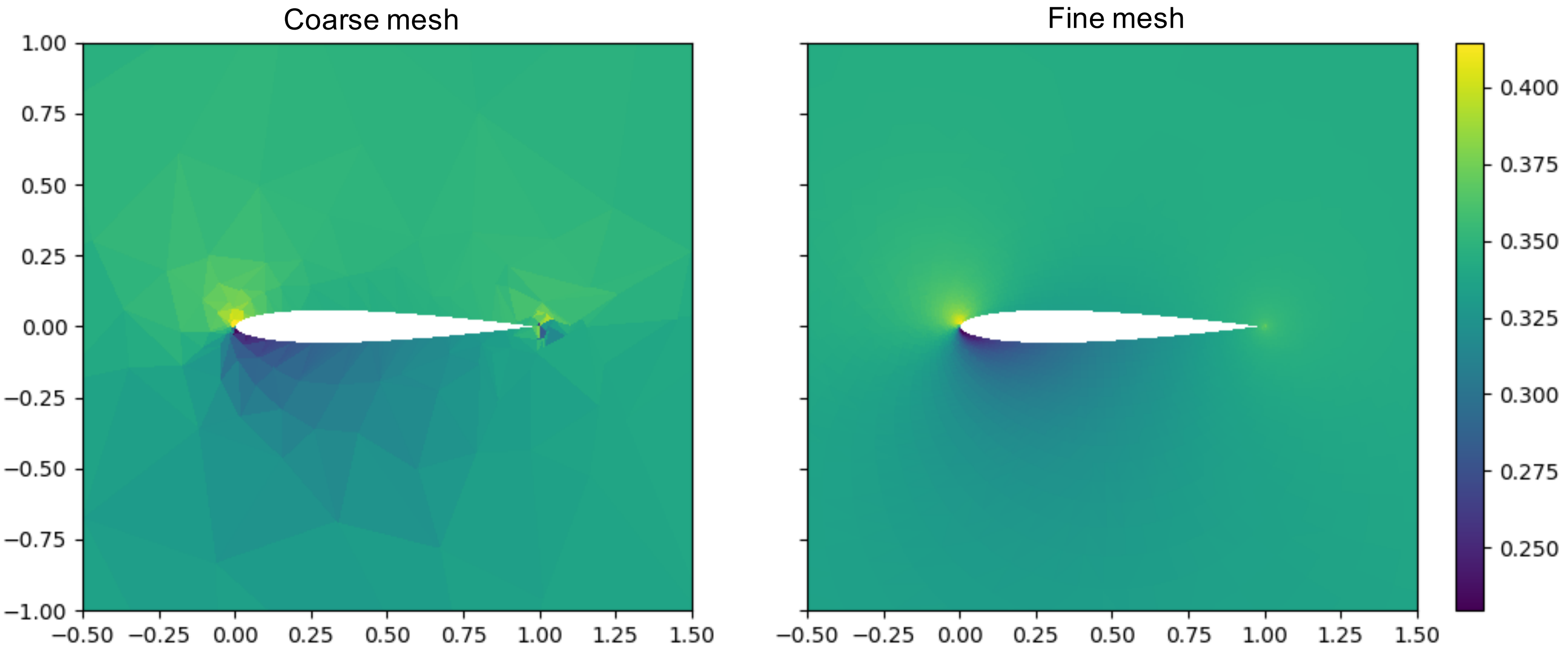


Fine
Mesh
GCN
$Z_1$
$Z_k$
GCN
$Z_{k+1}$
$Z_K$
GCN
$\hat{Y}$
AoA
Mach
Up-
sample
Coarse
Mesh
SU2
$U_0$

# Airfoil Mesh



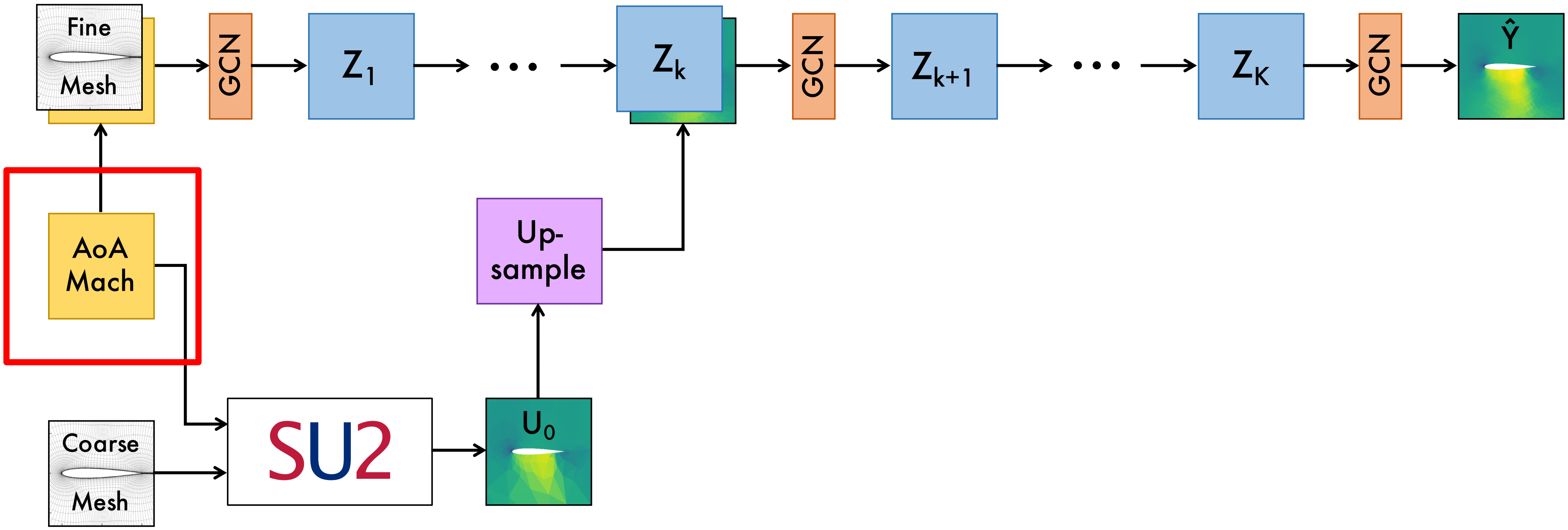
# Coarse and Fine Meshes




$\approx$ 300 nodes

$\approx$ 6000 nodes

# CFD-GCN



Fine
Mesh
GCN
$Z_1$
$Z_k$
GCN
$Z_{k+1}$
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AoA
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Coarse
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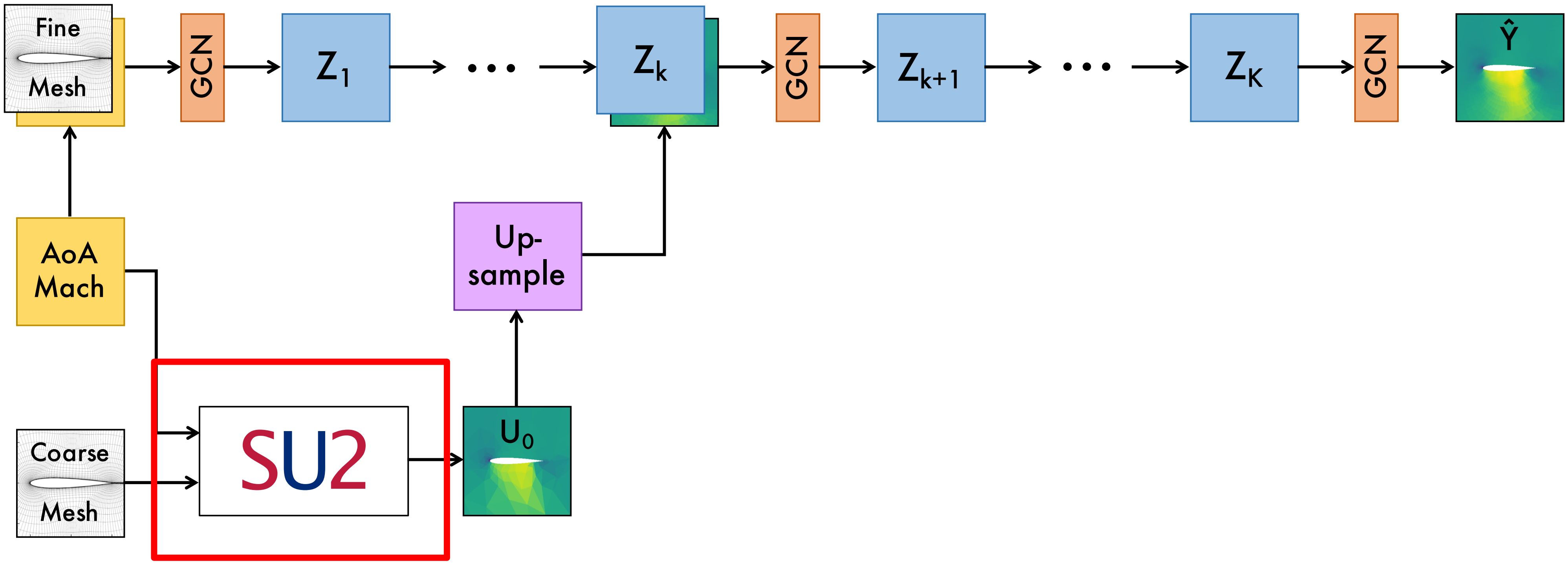

Fine Mesh
GCN
$Z_1$
$Z_k$
GCN
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GCN
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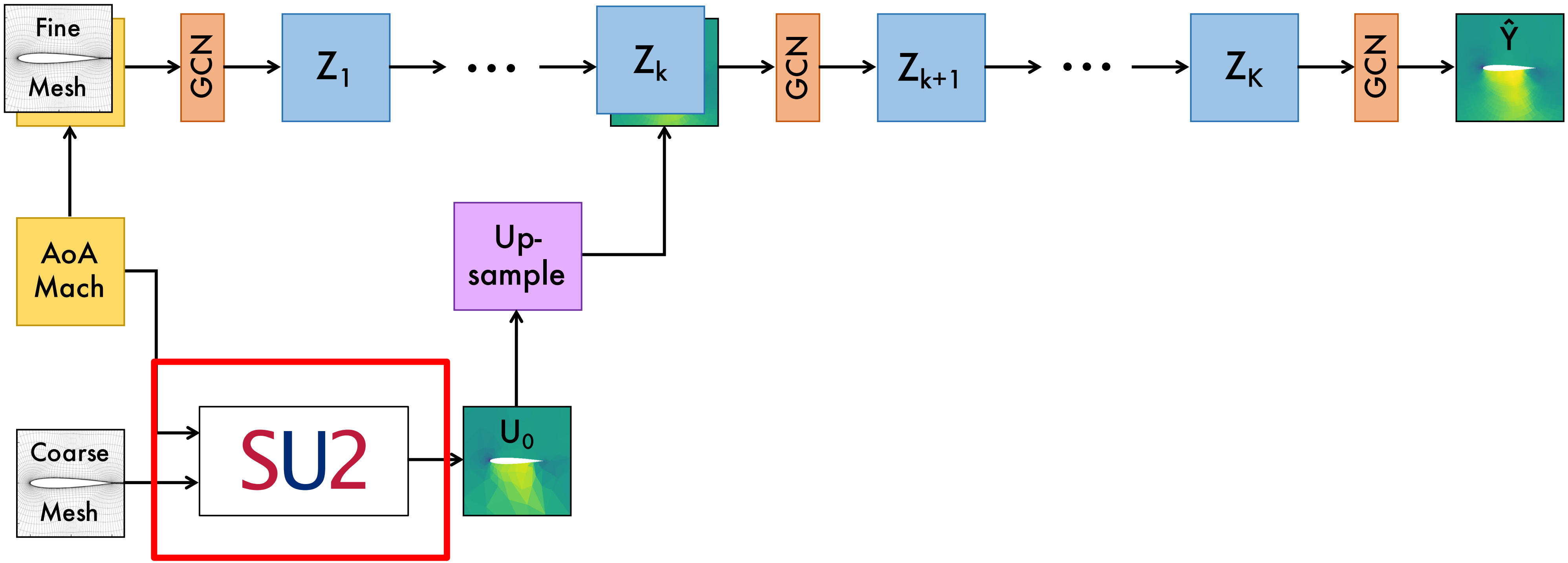
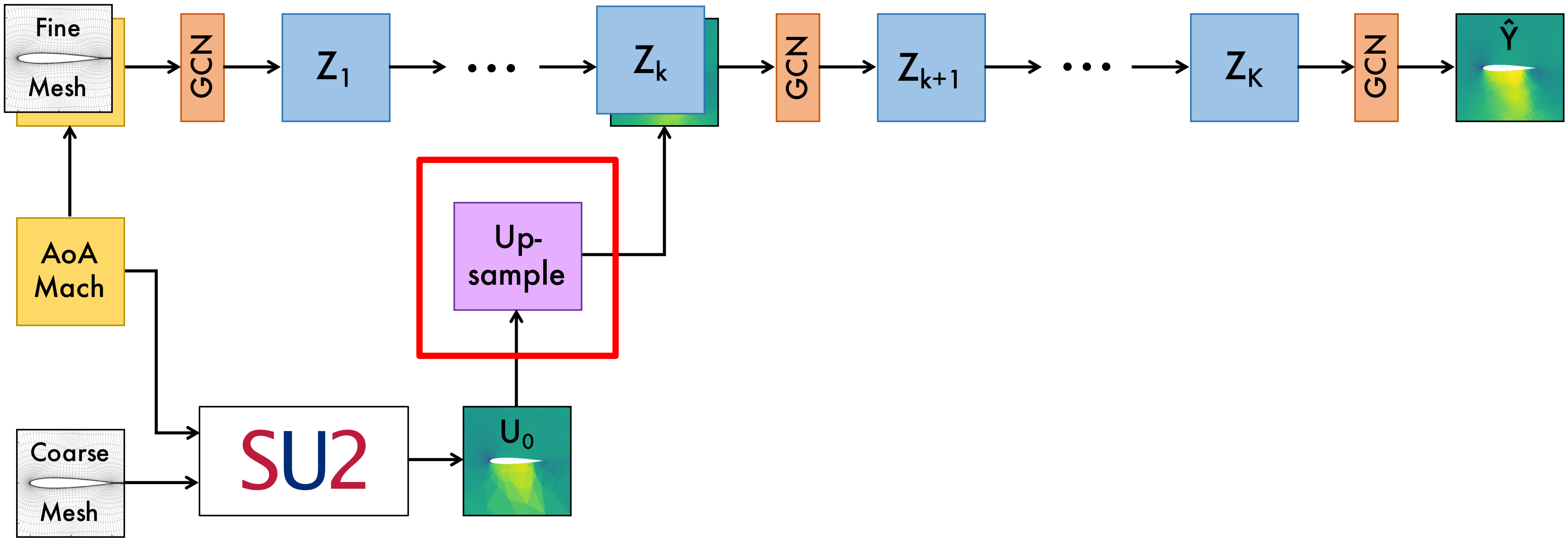
AoA
Mach
Up-sample
Coarse Mesh
SU2
$U_0$

# CFD-GCN



Fine
Mesh
GCN
Z1
Zk
GCN
Zk+1
ZK
GCN
Ŷ
AoA
Mach
Up-
sample
Coarse
Mesh
SU2
U0

# CFD-GCN



Fine
Mesh
GCN
$Z_1$
$Z_k$
GCN
$Z_{k+1}$
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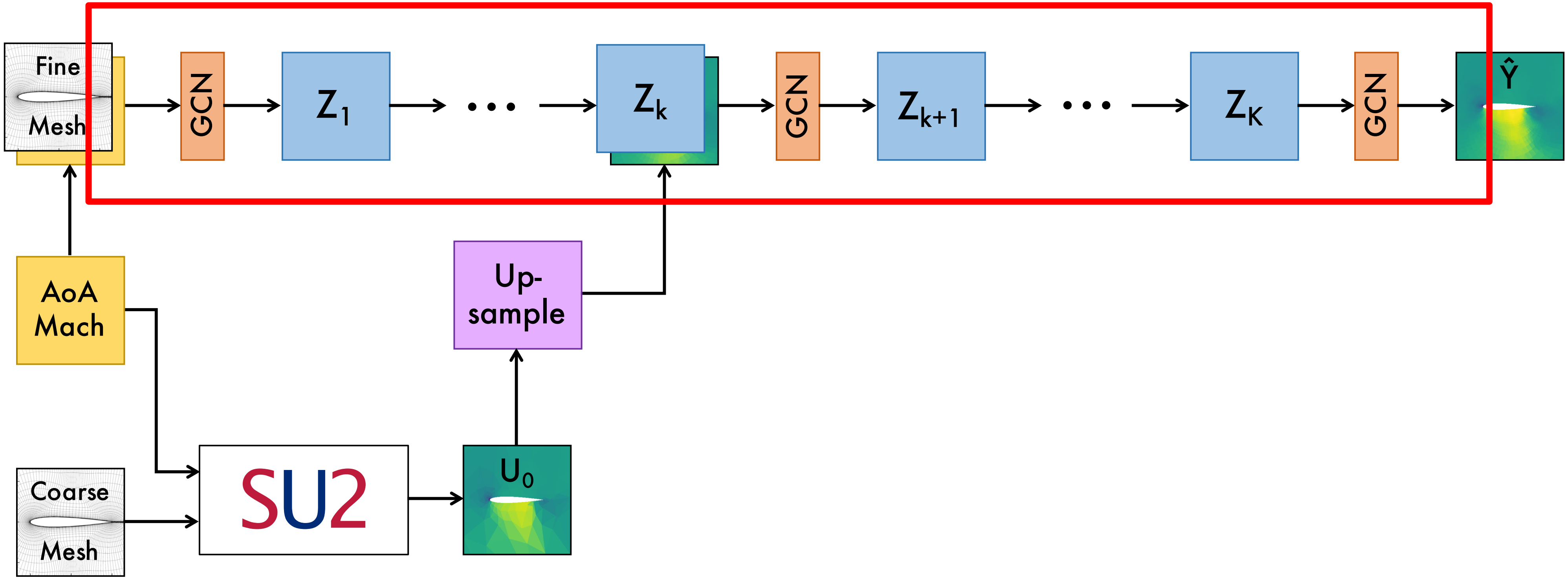
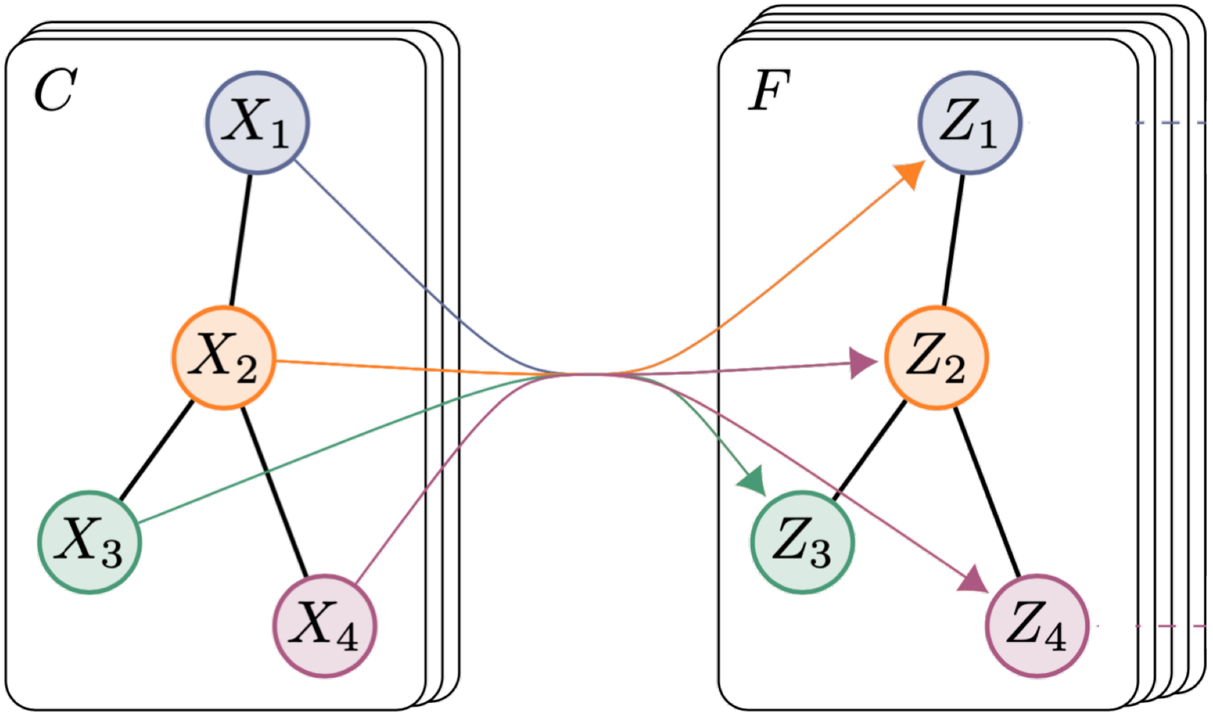


Fine Mesh
GCN
$Z_1$
• • •
$Z_k$
GCN
$Z_{k+1}$
• • •
$Z_K$
GCN
$\hat{Y}$
AoA Mach
Up-sample
Coarse Mesh
SU2
$U_0$

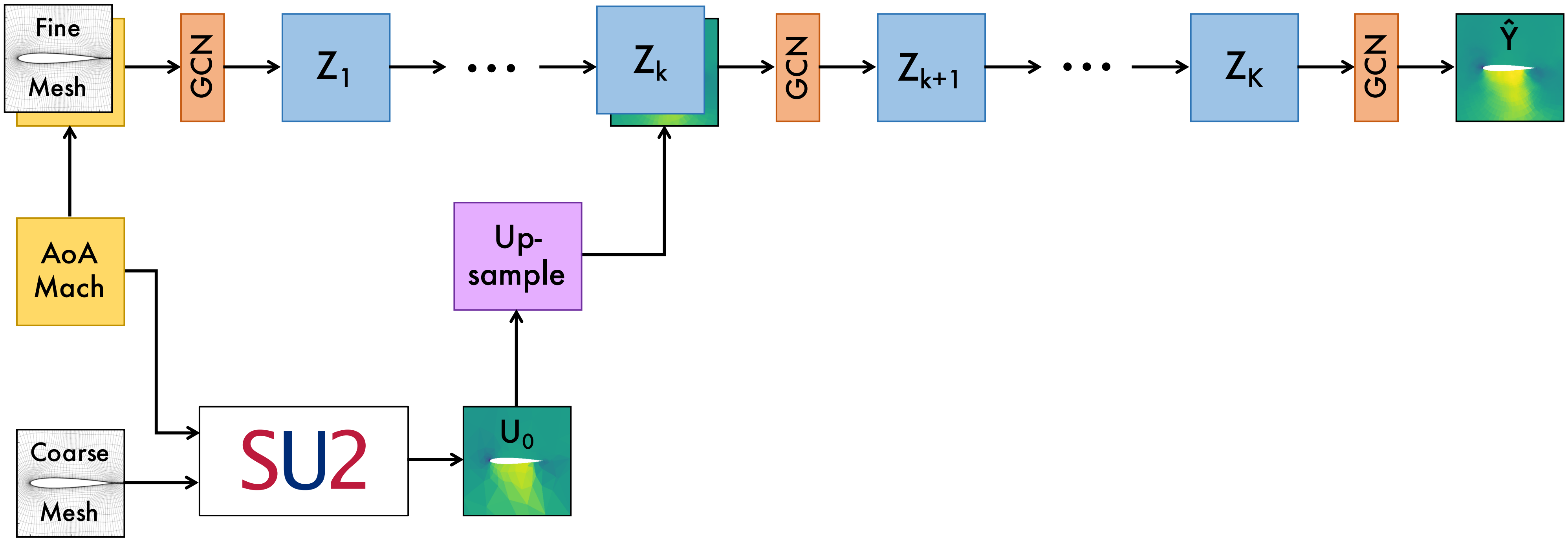
# GCN Layer

$$Z = \mathrm{GCN}(X) \coloneqq \tilde{A}\, X\, W + b$$

$X \in \mathbb{R}^{N \times C}$ $\quad$ $Z \in \mathbb{R}^{N \times F}$

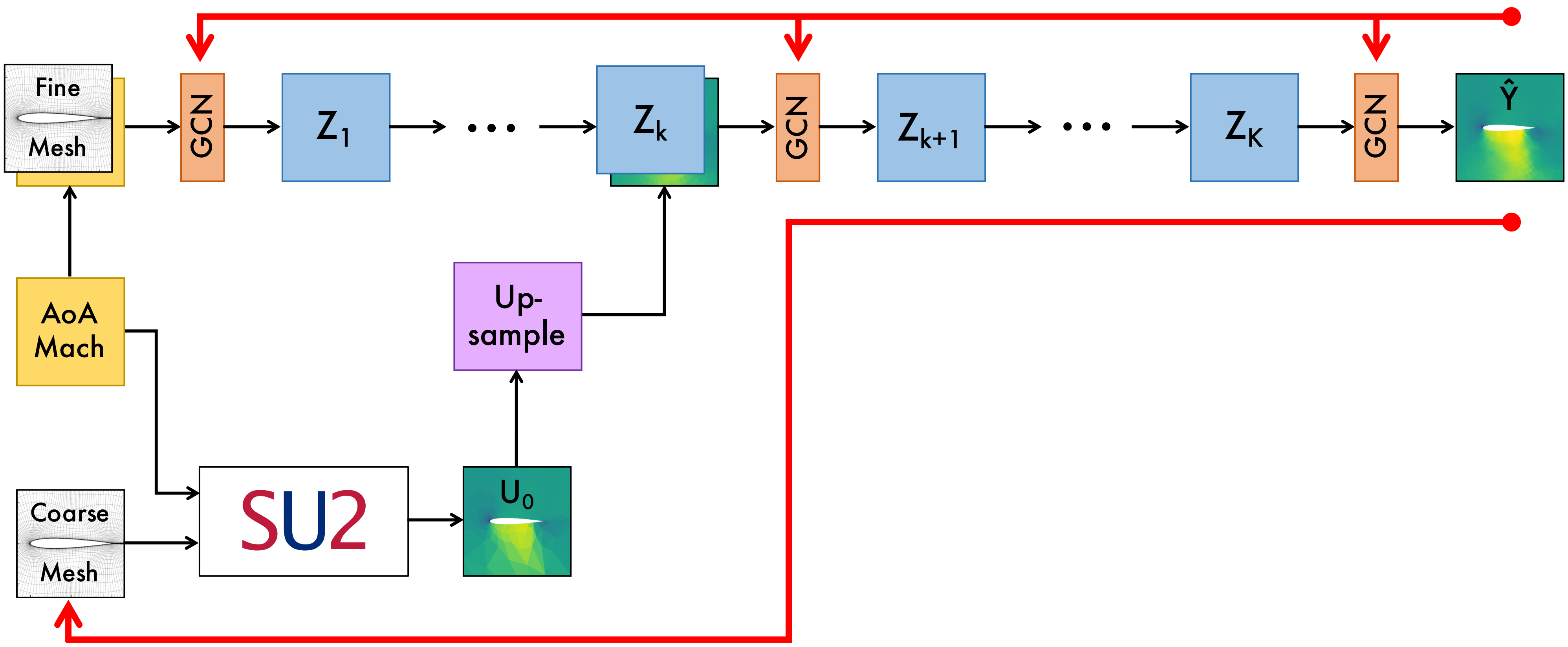


# CFD-GCN

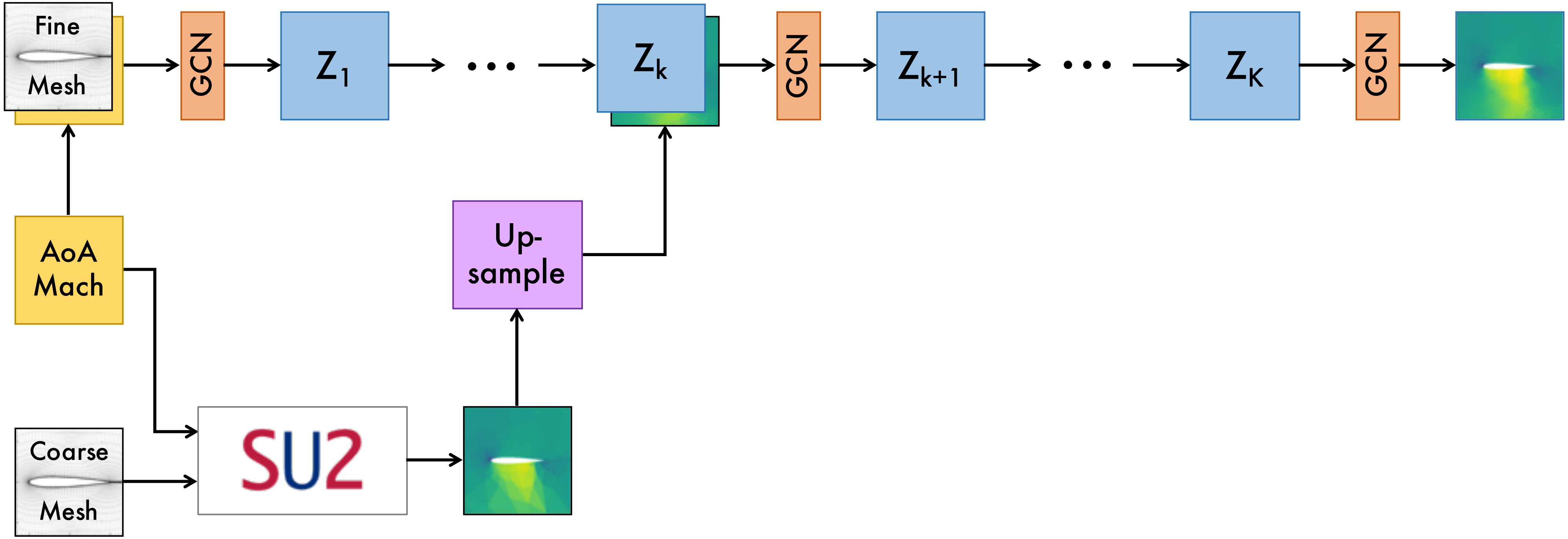


Fine Mesh
GCN
$Z_1$
. . .
$Z_k$
GCN
$Z_{k+1}$
. . .
$Z_K$
GCN
$\hat{Y}$
AoA Mach
Up-sample
Coarse Mesh
SU2
$U_0$

# CFD-GCN Backpropagation

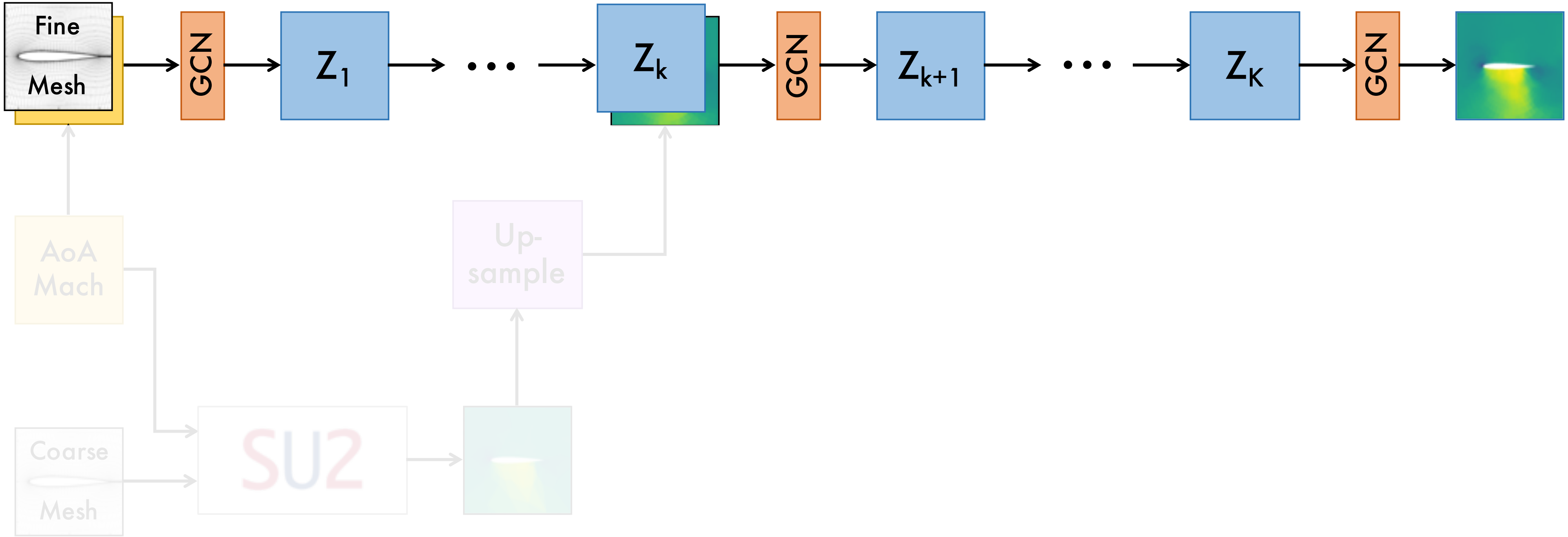


# CFD-GCN

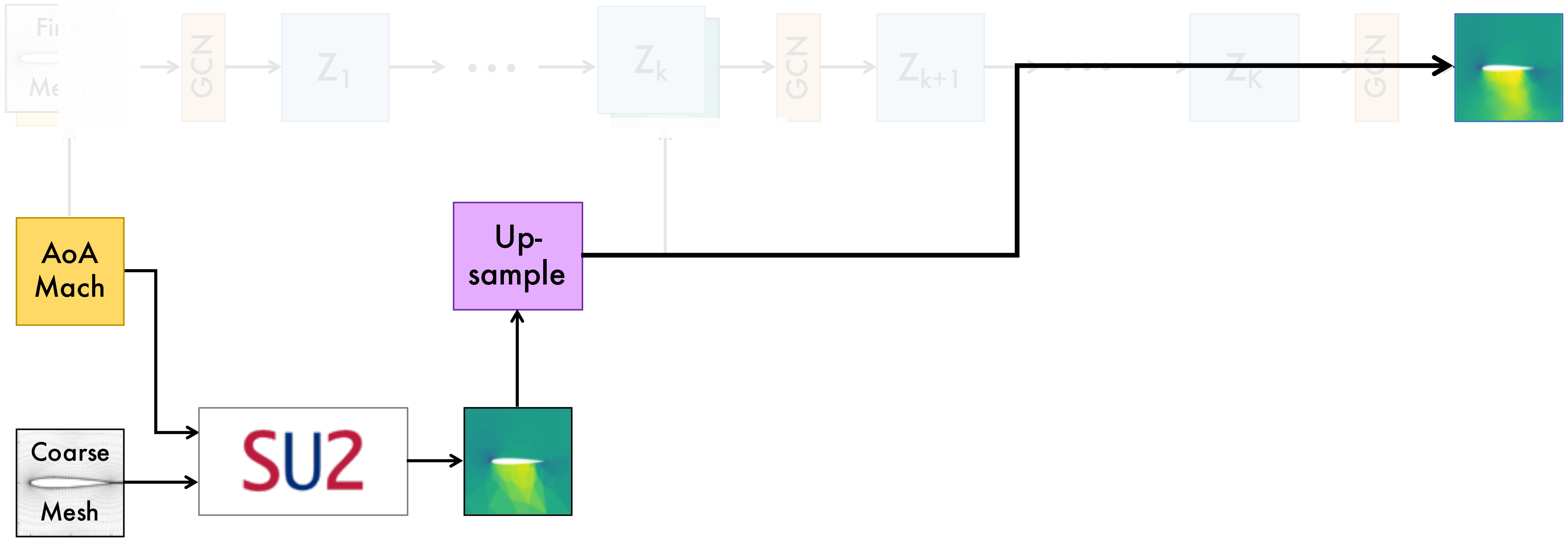


Fine
Mesh
GCN
$Z_1$
• • •
$Z_k$
GCN
$Z_{k+1}$
• • •
$Z_K$
GCN
AoA
Mach
Up-
sample
SU2
Coarse
Mesh

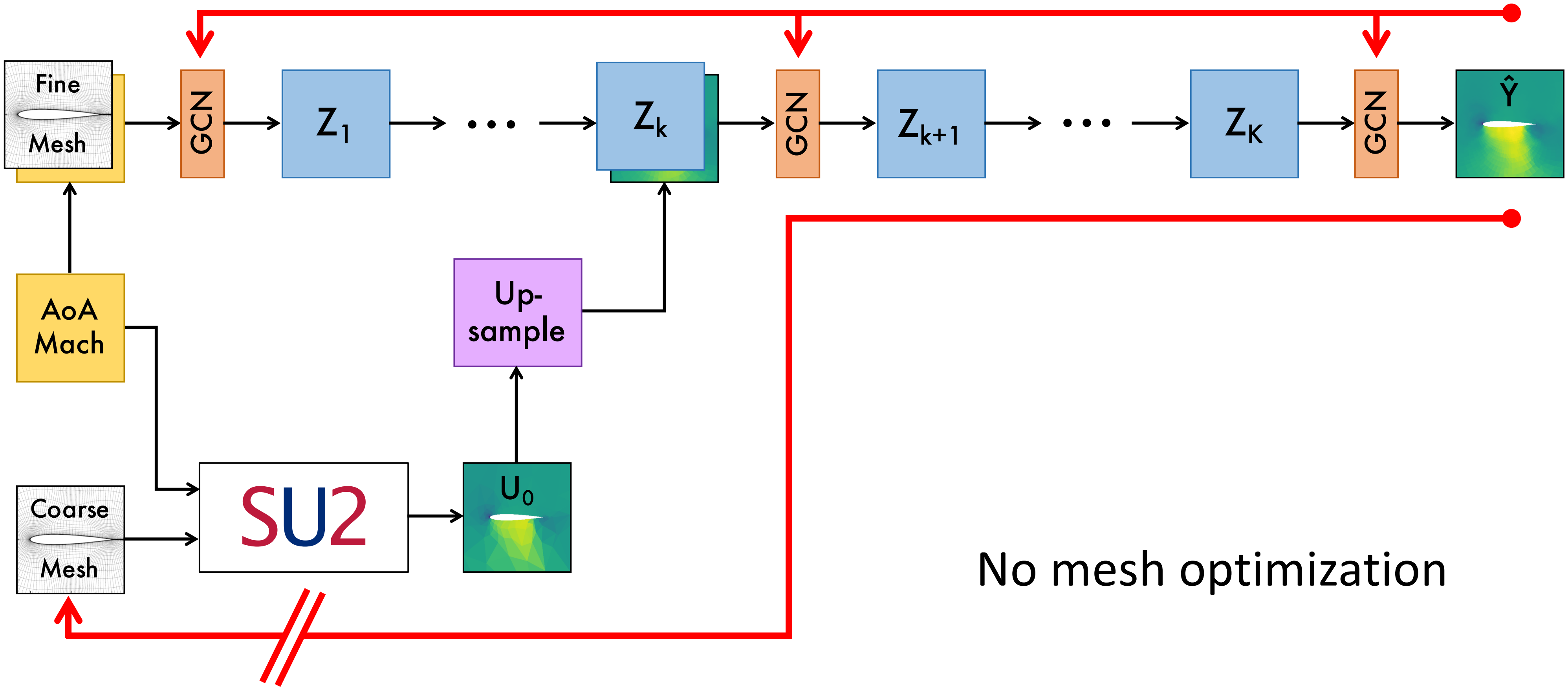
# GCN Baseline



# Upsampled Coarse Model (UCM) Baseline

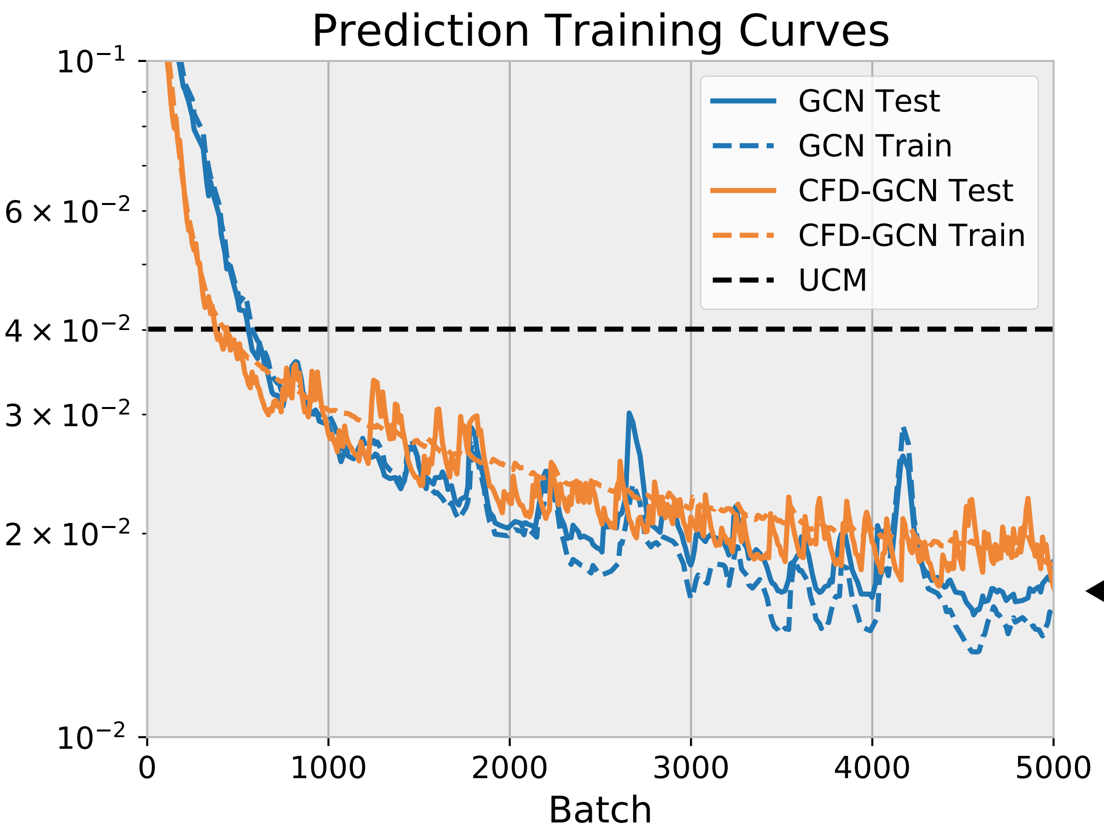


# Frozen Mesh Baseline



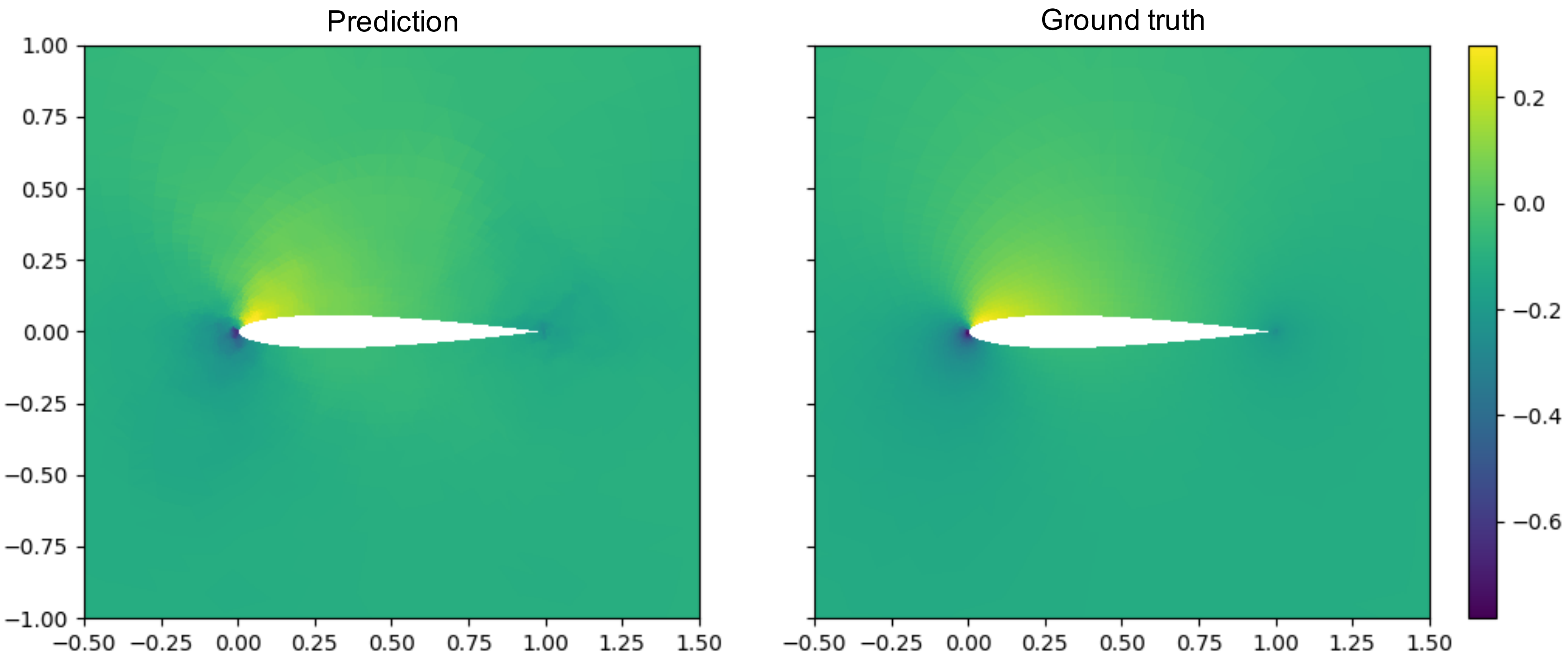

No mesh optimization

# Prediction Results




Similar performance between GCN and CFD-GCN, with slight edge to GCN due to overfitting

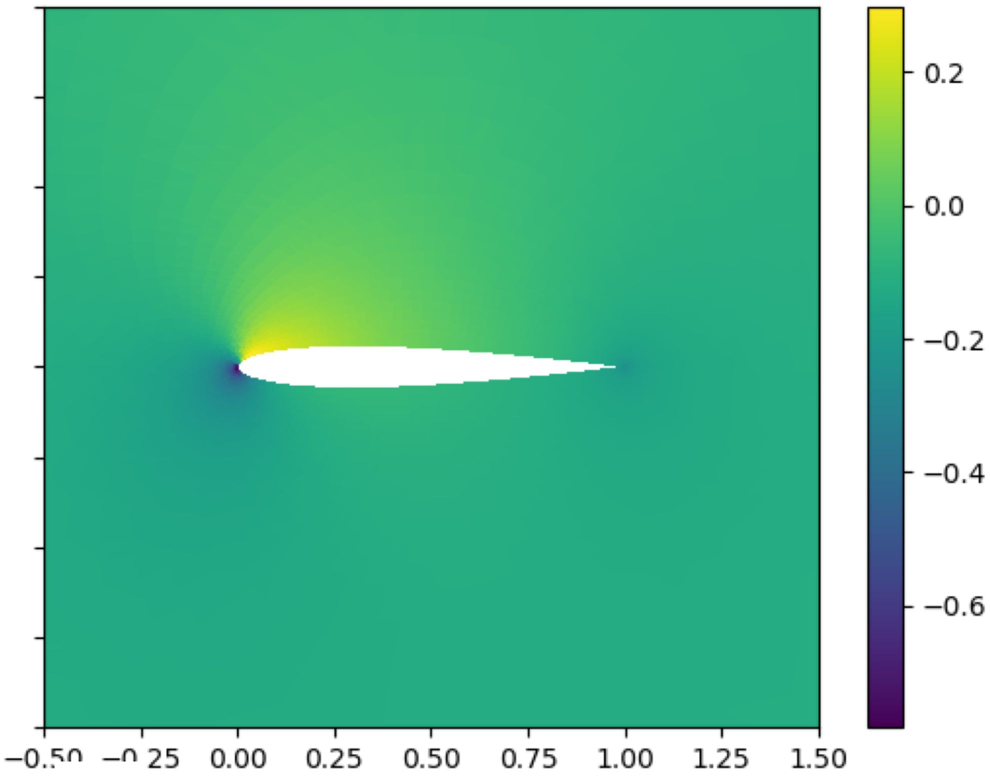
# Prediction Results



# Generalization Task

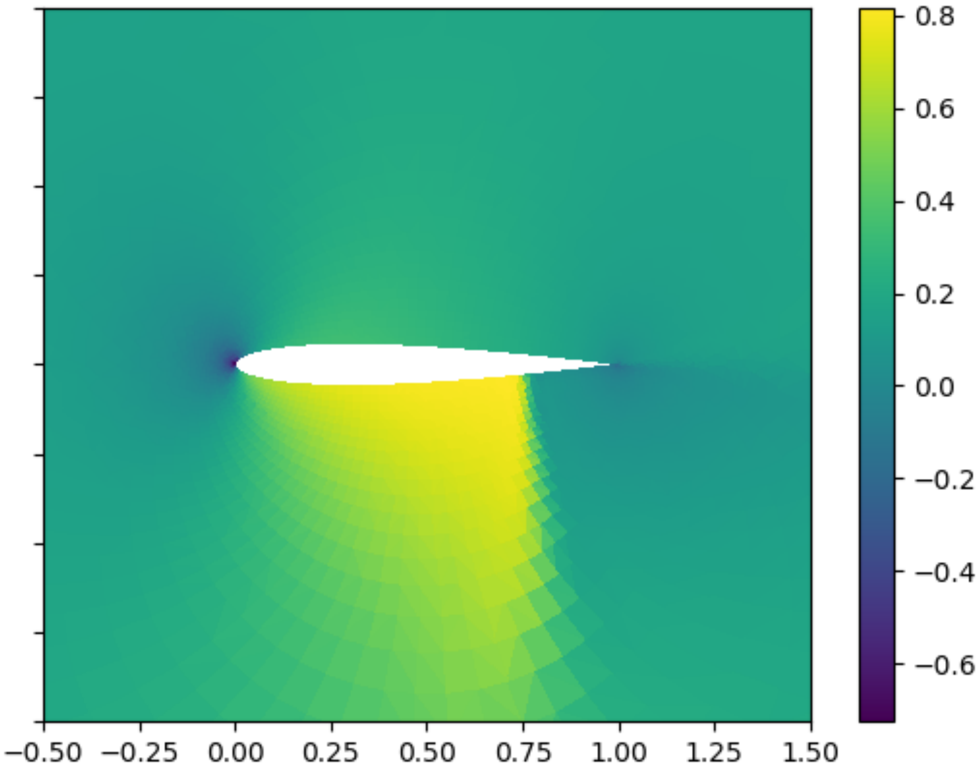
## Training set

Mach $< 0.5$

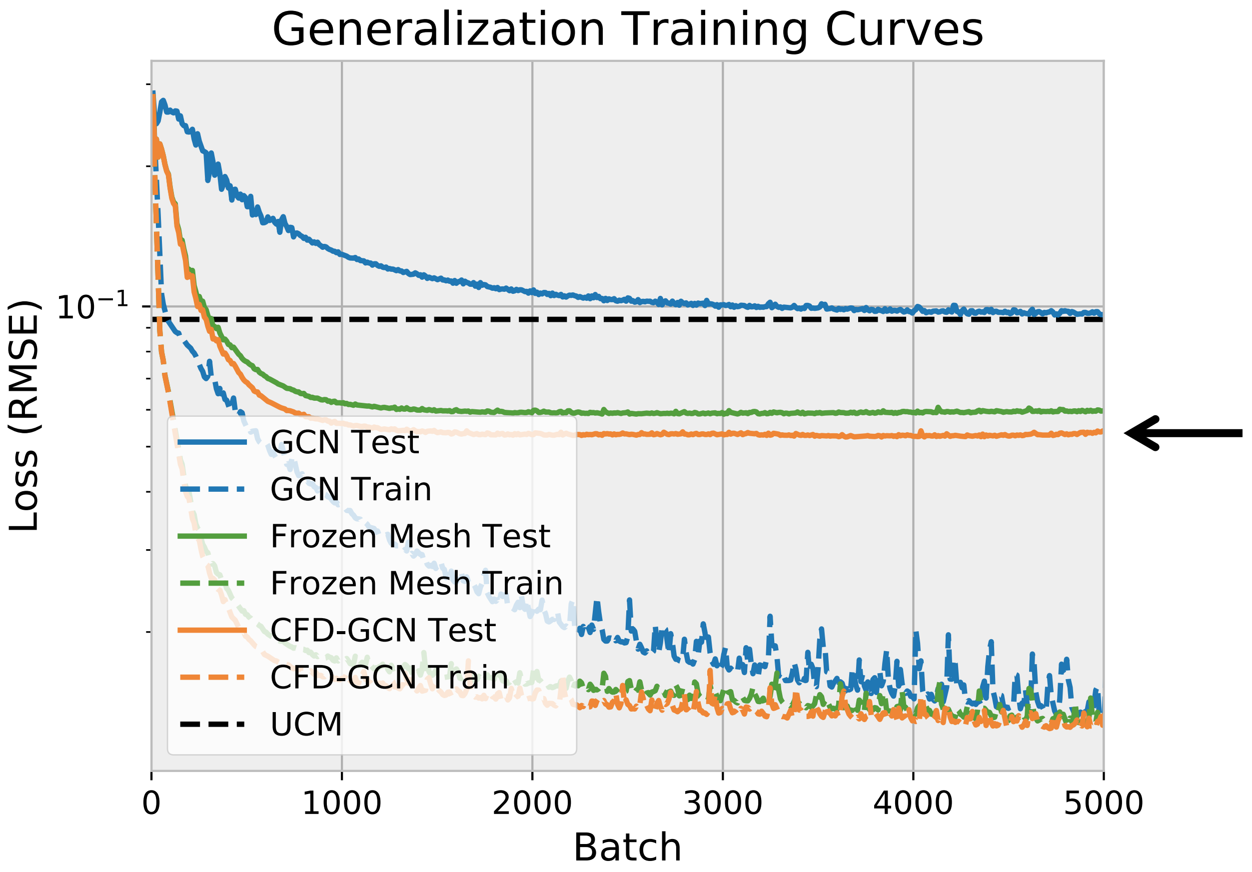



## Test set

Mach $> 0.5$



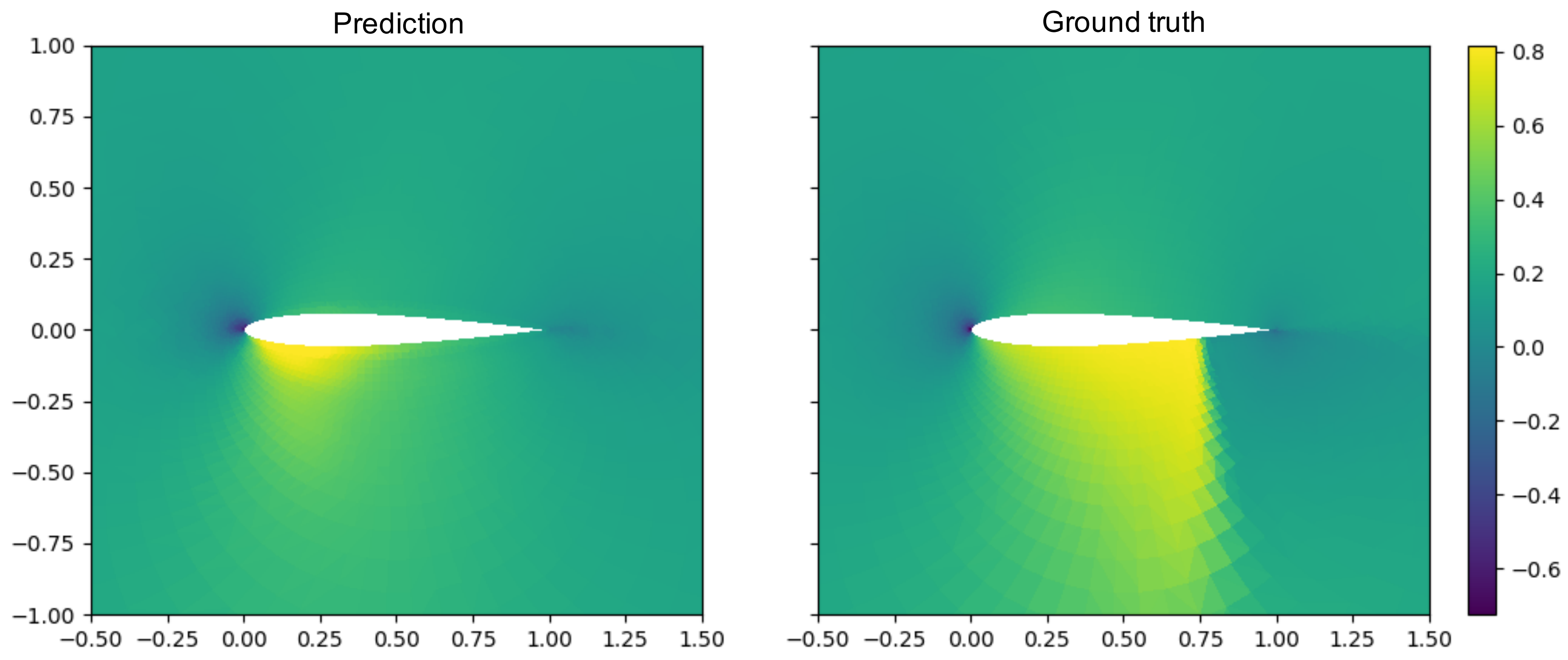
# Generalization Results




CFD-GCN outperforms all baselines when generalizing to unseen conditions

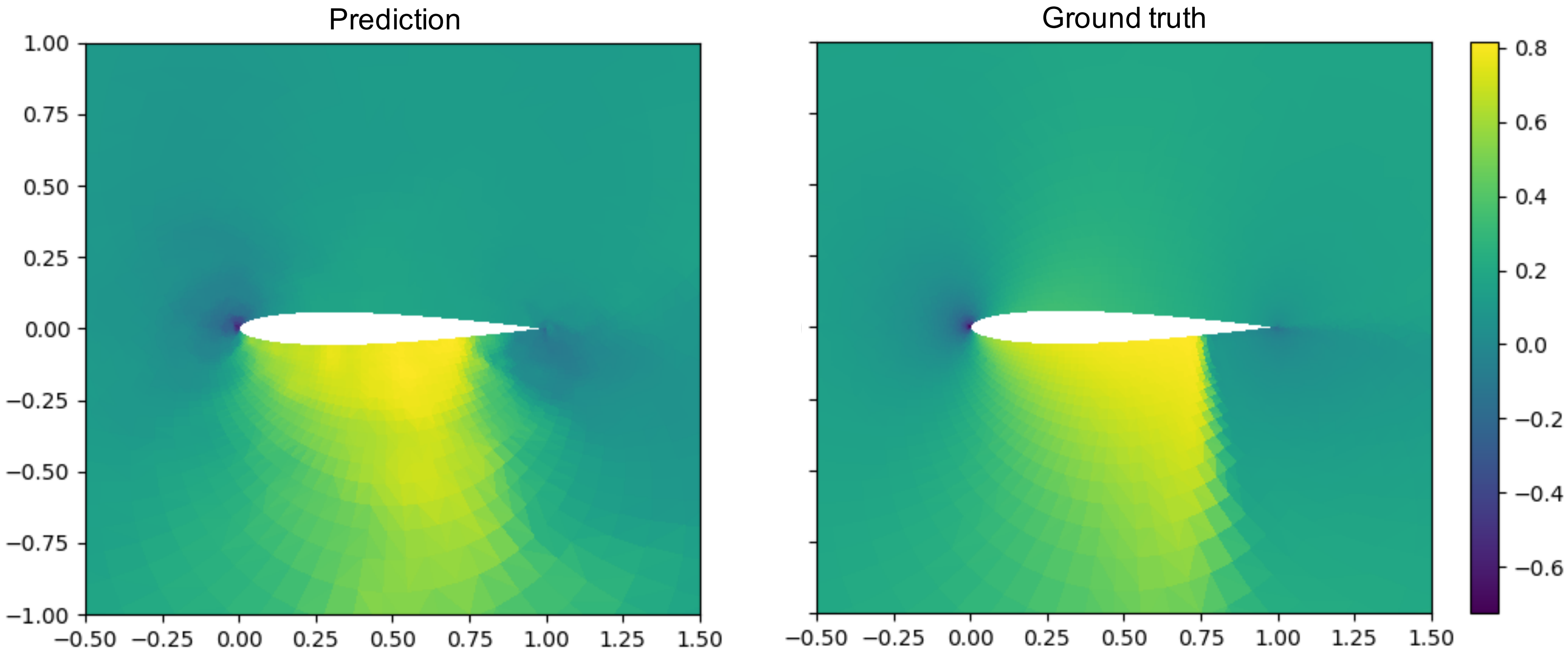
# Generalization Results

- GCN Baseline



# Generalization Results

- CFD-GCN



# Timing Results

| Model | Run Time |
| --- | --- |
| CFD-GCN | 3s |
| Fine Mesh Simulation | 189s |

# Summary

- By combining a coarse CFD simulation and GCN layers, the CFD-GCN model
  - Operates directly on meshes
  - Runs faster than a full CFD simulation
  - Achieves better generalization than a pure GCN model

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Thank you!