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Using Machine Learning for Error Detection in Turbulent Flow Simulations

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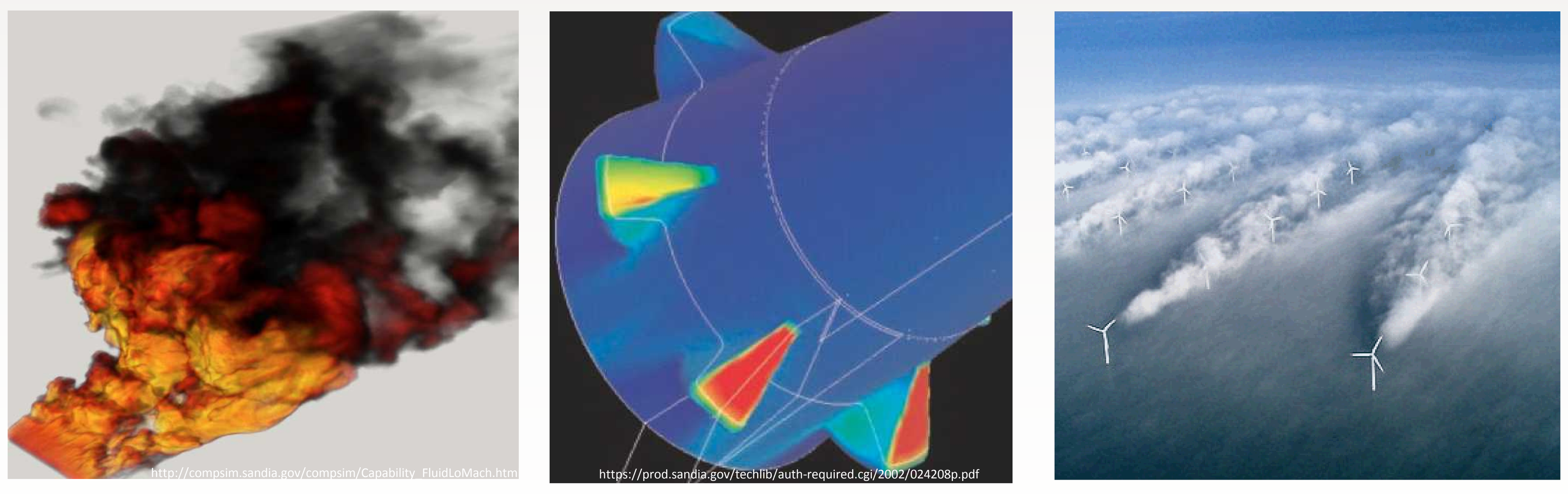
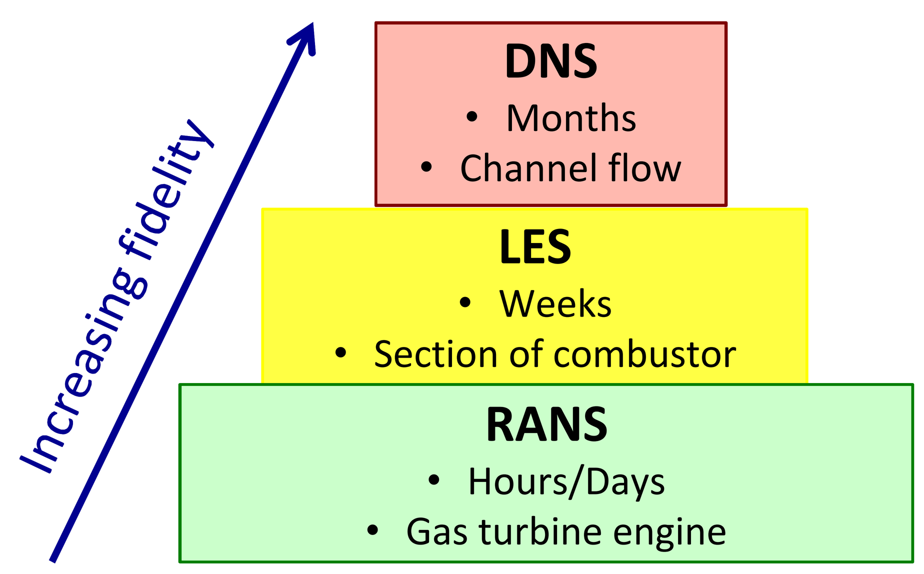
Overview

- Turbulent flows are chaotic, three-dimensional, and occur at a continuum of scales
- Direct Numerical Simulation (DNS) of these flows is very computational expensive
- Reynolds Averaged Navier Stokes (RANS) uses empirical models for the turbulence
  - Significantly more computationally efficient than DNS
  - Often has high uncertainty because of "missing physics" in the empirical models
  - If experimental or higher fidelity simulation results are not available for validation, there is no reliable method for evaluating RANS accuracy.
- In the present project, machine learning methods are used to identify regions of high RANS model form uncertainty.

Turbulence Simulations



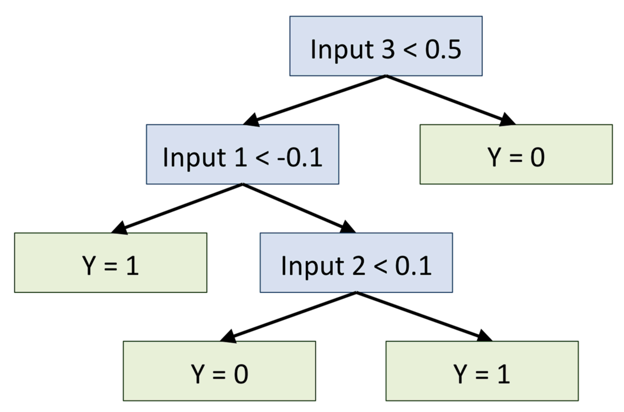
- Turbulent flows are ubiquitous in nature and in applications of interest at Sandia

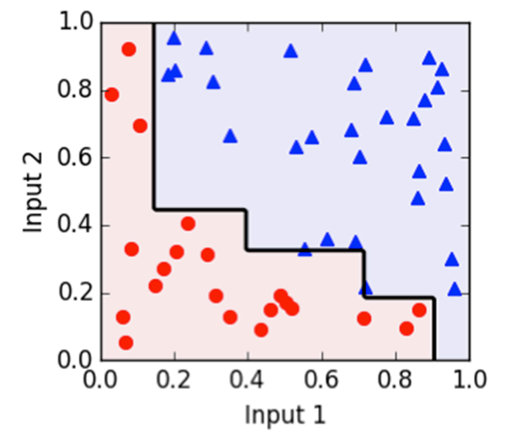


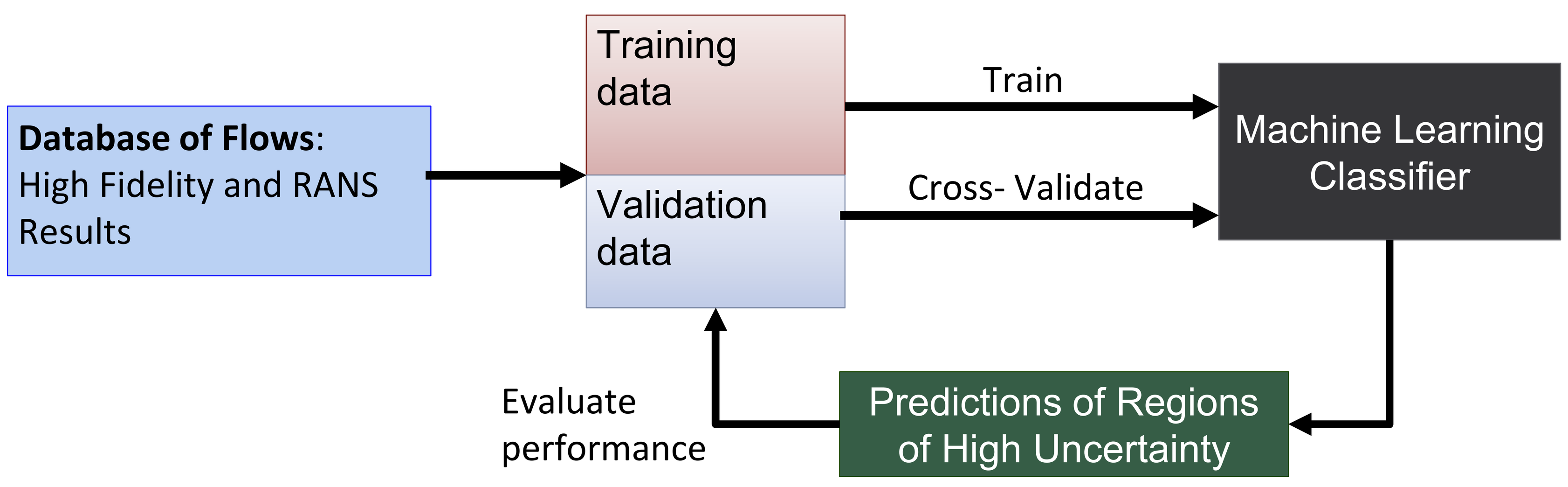
- RANS is more computationally efficient than DNS or LES
- RANS is prone to model form uncertainty where its underlying assumptions are violated
- There is no reliable method for determining when RANS models will fail

Machine Learning

- Set of data-driven algorithms for regression, classification, clustering
- *E.g.*: linear regression, support vector machines, neural networks
- Have been broadly applied in finance, software engineering, retail
- **For this application: use binary classifiers to flag regions of high RANS uncertainty on a point-by-point basis**

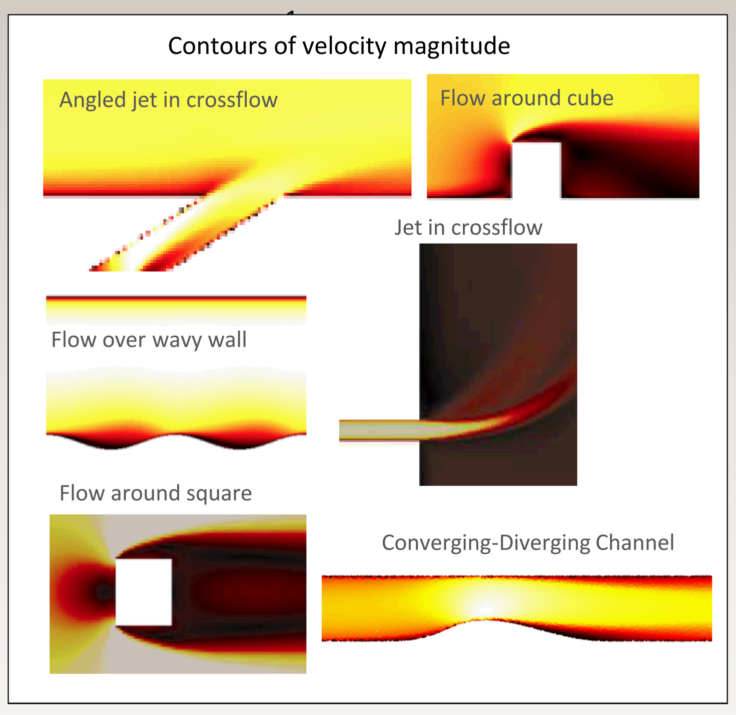






Database of Flows

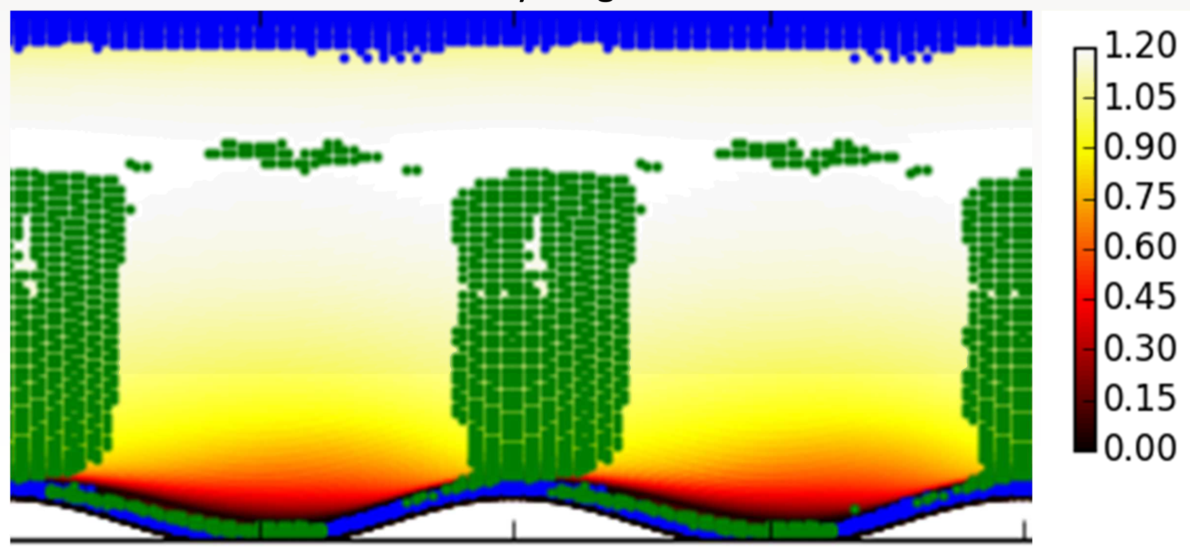
- Building block flows
- Both RANS and high fidelity (DNS or well-resolved LES) data



Inputs and Outputs

- Inputs: Local flow variables from RANS
  - Non-dimensional, rotationally invariant
- Outputs: Binary prediction of whether underlying model assumption is violated
  - Examined Boussinesq hypothesis assumptions: linearity, isotropy, and non-negativity

Results

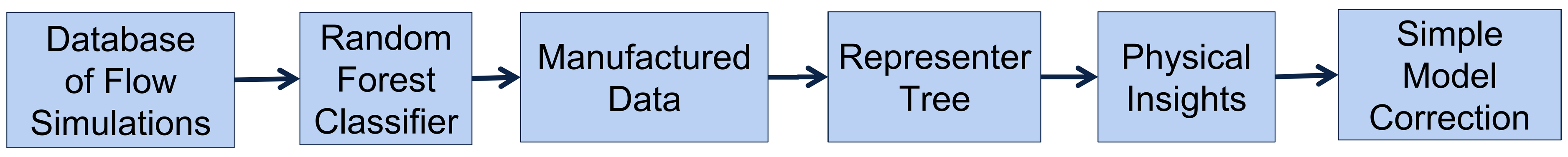


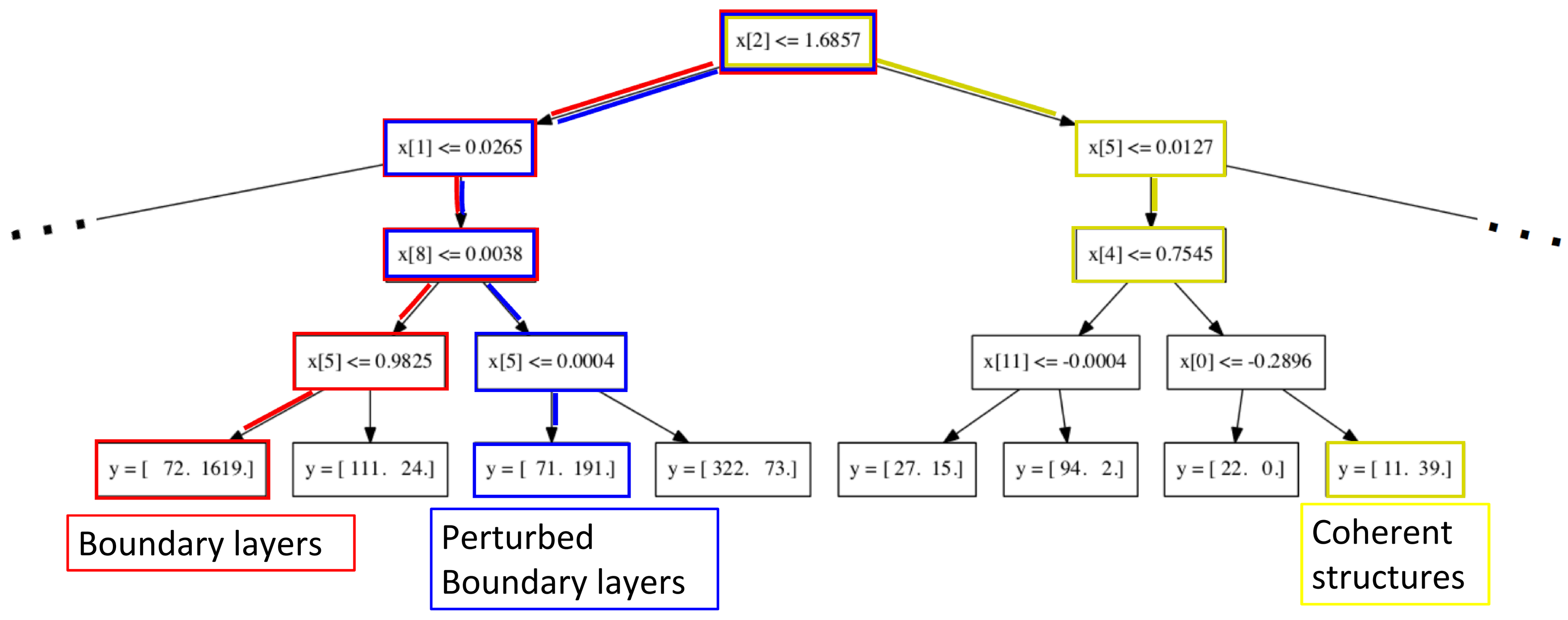
Blue: Classifier predicts isotropy assumption violated
Green: Classifier predicts linearity assumption violated

- Classifiers are 3 X more accurate than best previously available
- Machine learning algorithms can process high-dimensional data, resulting in more accurate classifiers

Rule Extraction

- How do we get insight into our "black box" machine learning model?





Impacts

- Classifiers for RANS model uncertainty can transform the way RANS results are post-processed and understood
  - Clarify when RANS simulations are predictive [1]
  - Enable adaptive modeling corrections
  - Inform experimental design
  - Improve switching functions for hybrid RANS-LES simulations
- Developing strategies for using machine learning algorithms on physical systems

Acknowledgments and References

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1. J. Ling and J. Templeton, "Evaluation of machine learning algorithms for prediction of regions of high Reynolds averaged Navier Stokes uncertainty," Physics of Fluids, (2015).
2. J. Ling, "Using Machine Learning to Understand and Mitigate Model Form Uncertainty in Turbulence Models," IEEE ICMLA, (2015).