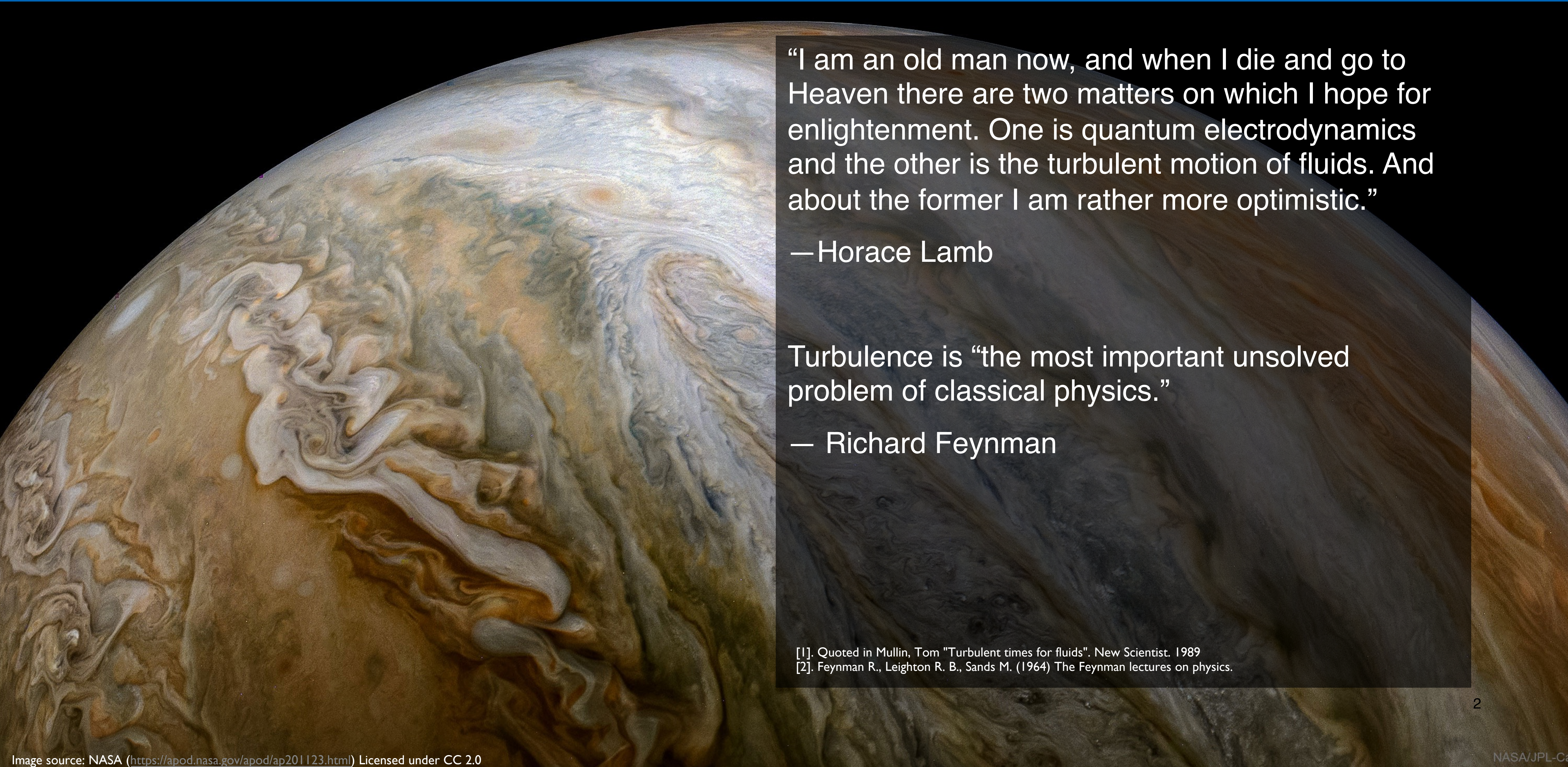
Turbulence and Its Impact on EDL

By Clark Pederson

Entry, Descent, and Landing Summer Seminars

June 27th, 2024

Introduction to Turbulence



"I am an old man now, and when I die and go to Heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics and the other is the turbulent motion of fluids. And about the former I am rather more optimistic."

—Horace Lamb

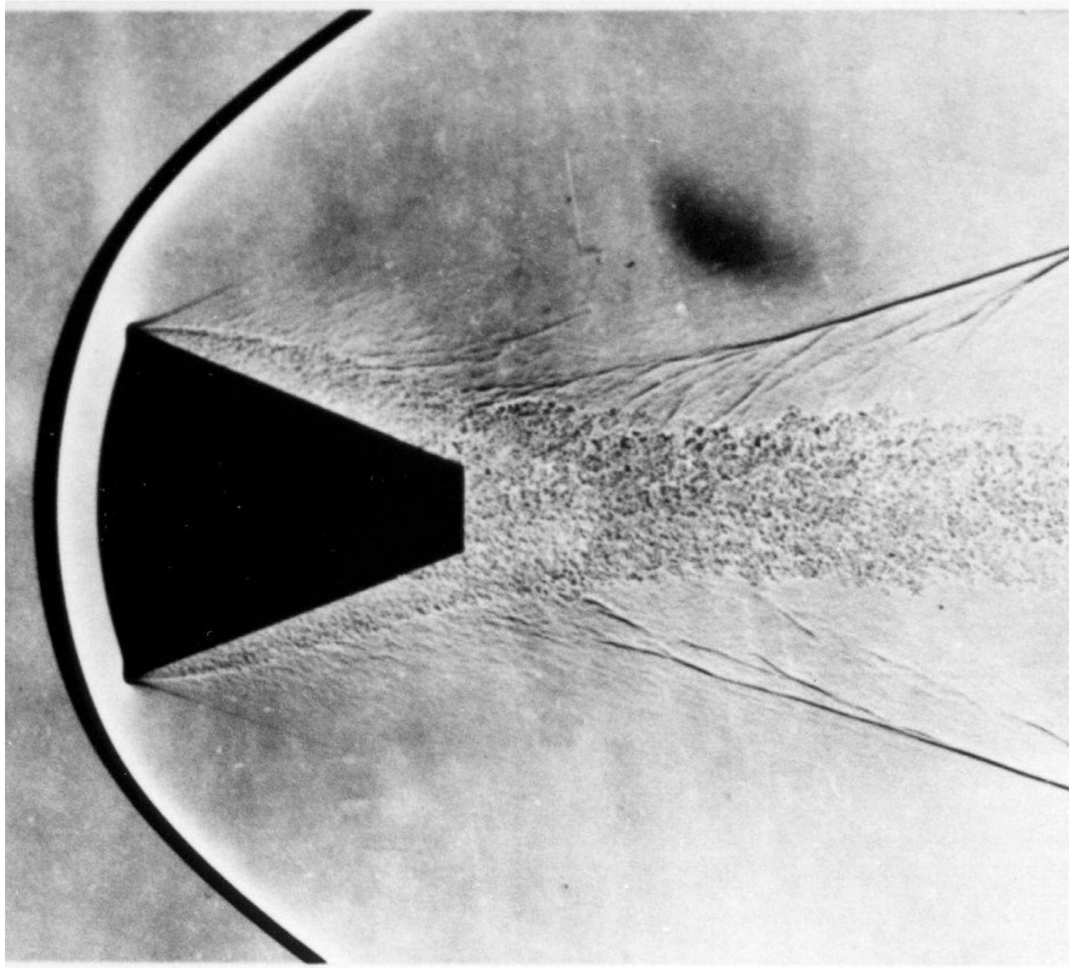
Turbulence is "the most important unsolved problem of classical physics."

— Richard Feynman

[1]. Quoted in Mullin, Tom "Turbulent times for fluids". New Scientist. 1989
[2]. Feynman R., Leighton R. B., Sands M. (1964) The Feynman lectures on physics.

What Is Turbulence?

- Davidson [1] defines turbulence as the chaotic, three-dimensional advection of vortices.
- Turbulence is somewhat nebulous, but we can identify it based on its characteristics:
  - Enhanced diffusion: of mass, momentum, and energy. Turbulent diffusion can be several orders of magnitude larger than viscous diffusion.
  - Wide range of scales: The range of lengthscales varies as $Re^{3/4}$, where Re is the Reynolds number.
  - Chaotic: The instantaneous details are sensitive to small perturbations.
  - Vortical structures: Turbulence can be explained as vortex stretching and vortex tilting.
  - Three-dimensional

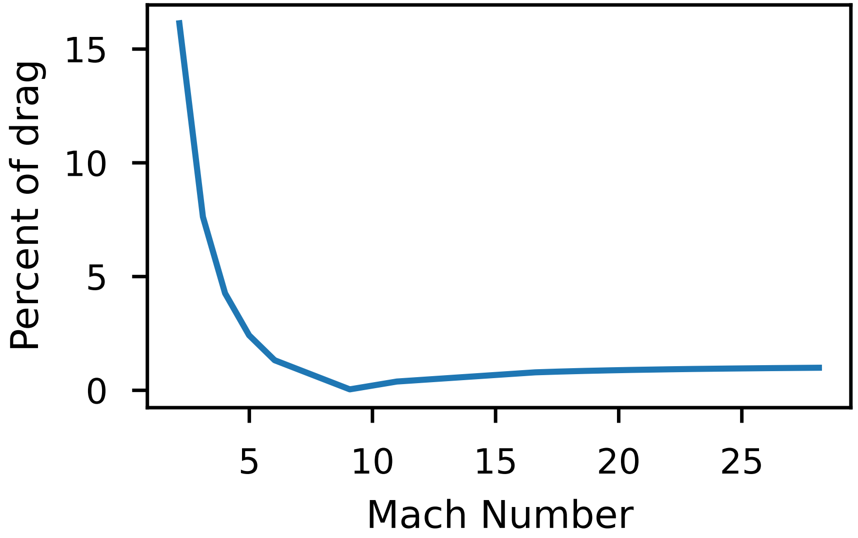


Shadowgraph of an early Mercury concept vehicle from 1957.
Source: NASA

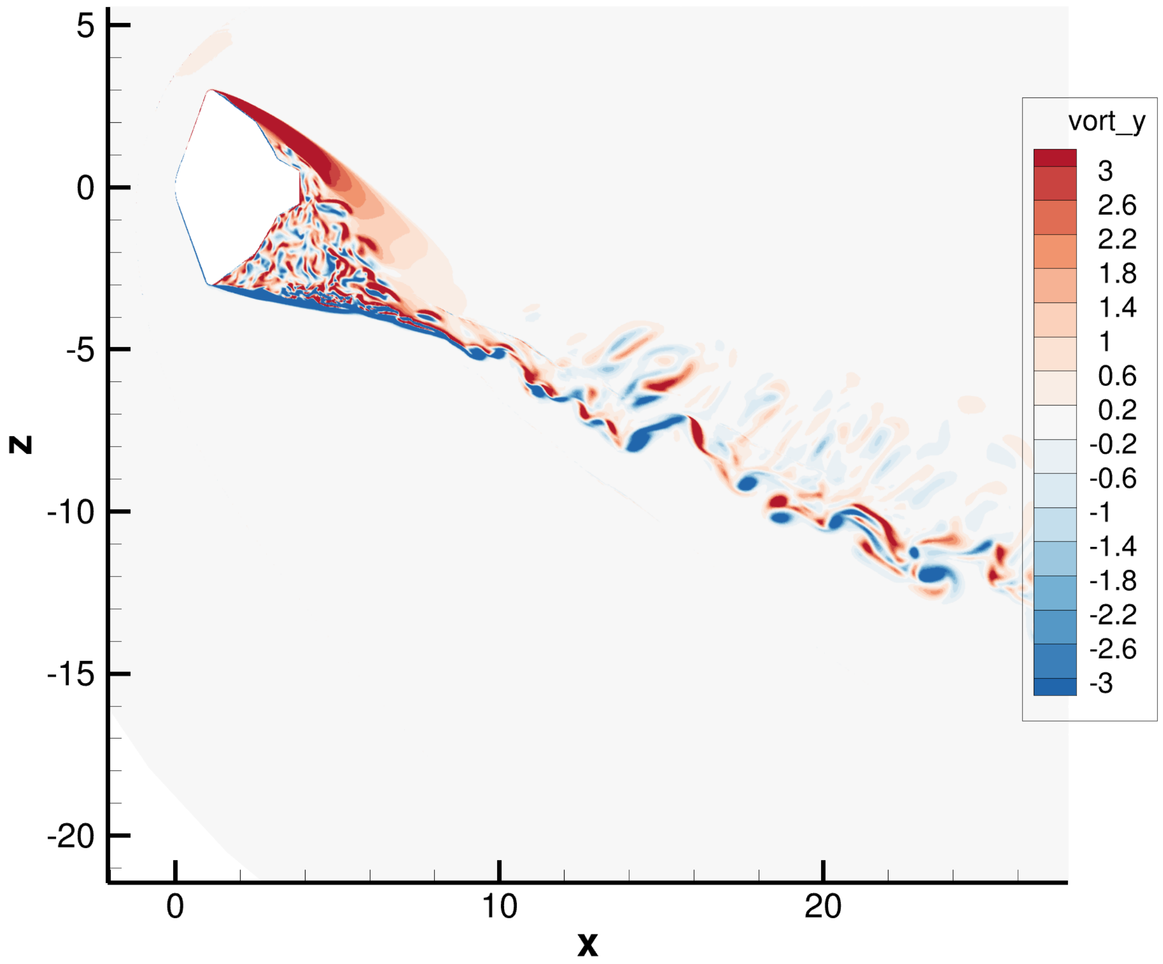
[1] Davidson, Peter Alan. *Turbulence: an introduction for scientists and engineers*. Oxford university press, 2015.

Backshell Drag on Entry Capsules

- Backshell drag is a significant portion of drag for a blunt-body capsule below Mach 5.
- Turbulent thickens the wake shear layer, which can lead to lower wake pressures and higher drag.

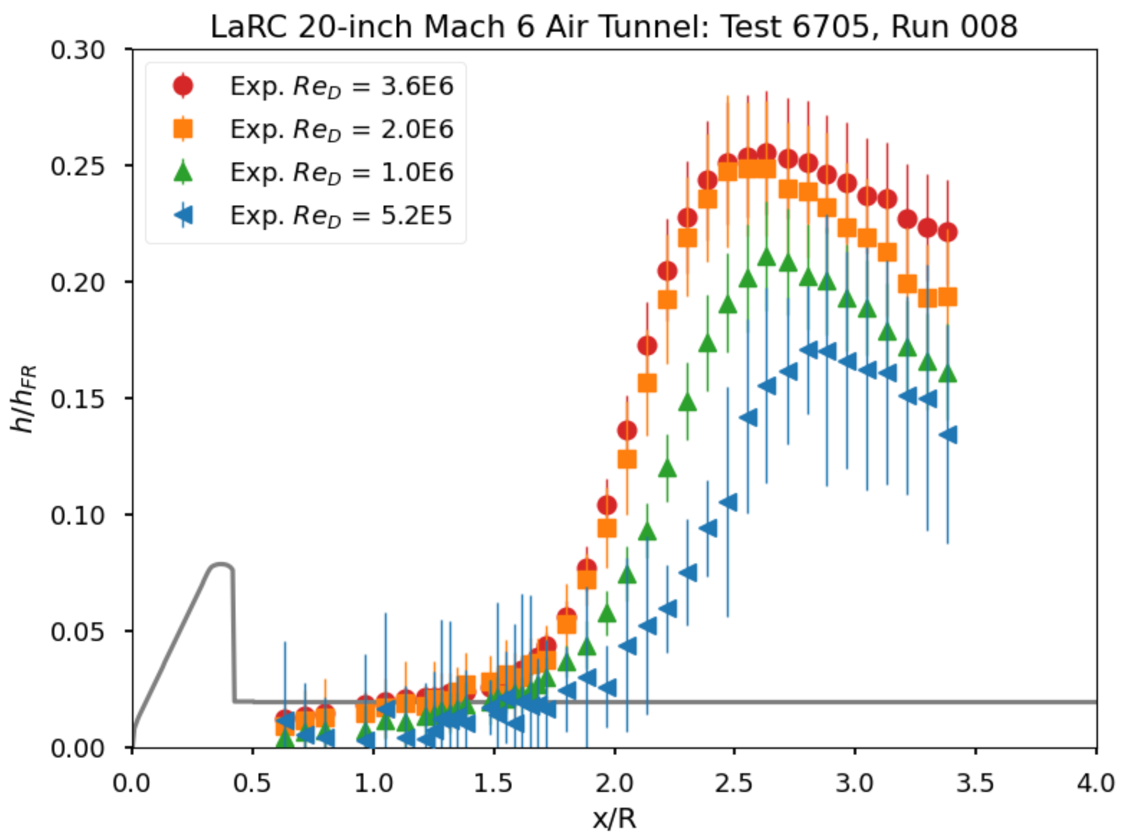


Contribution of wake drag to overall drag on a Mars Science Laboratory capsule.

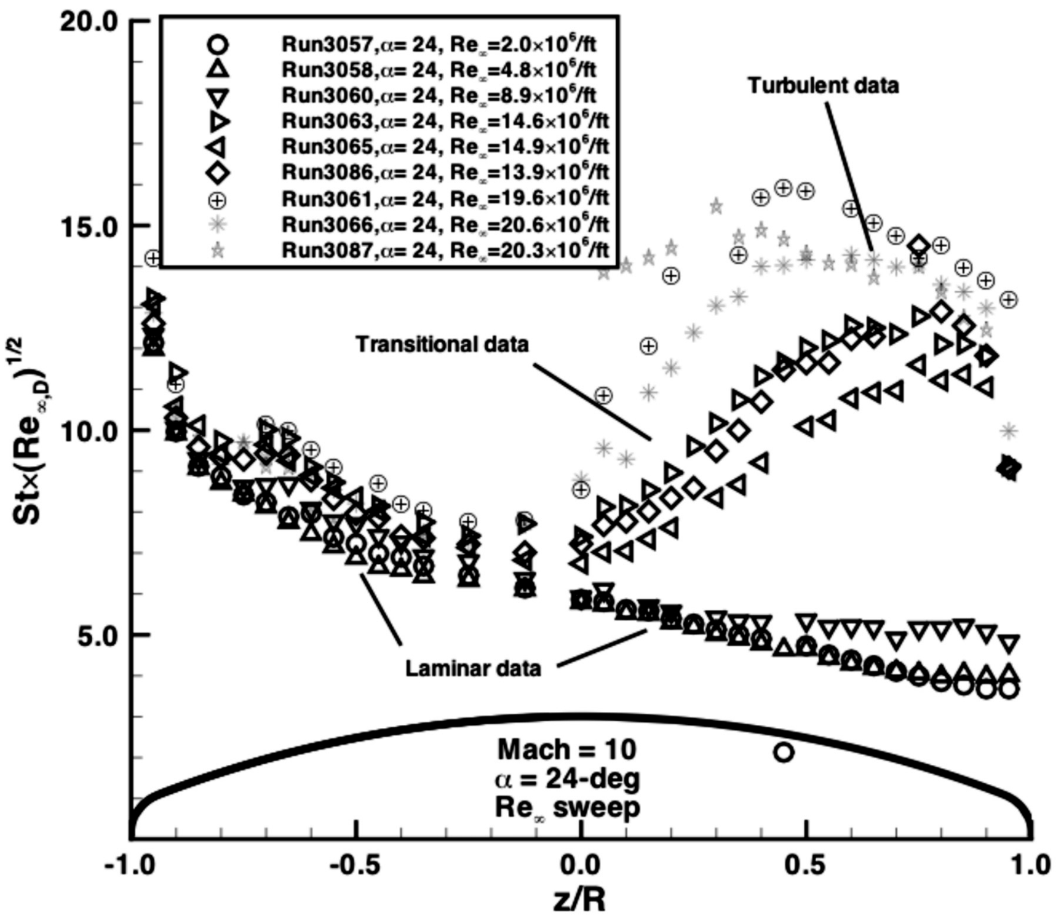


Vorticity in the wake of a Mars Science Laboratory capsule at Mach 2. Simulated using DDES.

Heating Augmentation



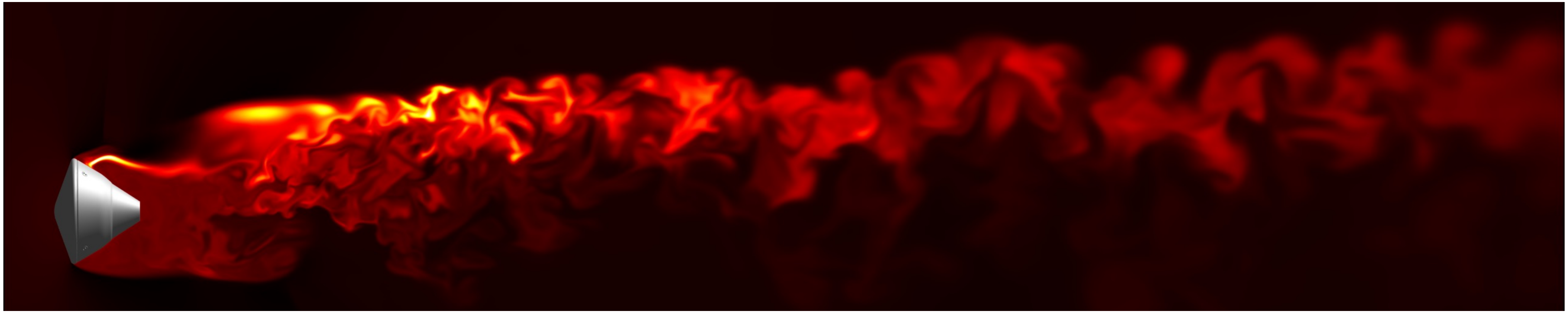
Heating observed in the wake of a 70-degree sphere cone.



Heating observed during experimental tests on the Orion CEV
By Hollis et al., https://doi.org/10.2514/1.38579. Used with permission.

Reaction Control Systems

- Jets in crossflow are highly unstable and usually turbulent.
- RCS can change the lift, drag, or pitching in complex ways by changing the local flowfield.
- Dyakonov et al. [2] showed that the RCS system on the Phoenix lander could have a control reversal in yaw.



[2] Dyakonov et al., *Analysis of the Effectiveness of Phoenix Entry Reaction Control System*, JSR 2011

Modeling Introduction

Why do we need models? What models do we need?

Why do we need models? The closure problem

Consider the momentum equation for a thin shear layer:

$$\frac{\partial \rho u}{\partial t} + \frac{\partial \rho u^2}{\partial x} + \frac{\partial \rho u v}{\partial y} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial y}\left(\mu \frac{\partial u}{\partial y}\right)$$

We can separate variables into average parts and fluctuations about the average:

$$p = \bar{p} + p'$$

$$u = \tilde{u} + u''$$

Where $\langle p \rangle = \bar{p}$ is an average and $\tilde{u} \equiv \langle \rho u \rangle / \langle \rho \rangle$ is a mass-weighted (aka Favre) average.

That gives us a new equation:

$$\frac{\partial \bar{\rho}\tilde{u}}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}\tilde{u}}{\partial x} + \frac{\partial \bar{\rho}\tilde{u}\tilde{v}}{\partial y} = -\frac{\partial \bar{p}}{\partial x} + \frac{\partial}{\partial y}\left(\bar{\mu}\frac{\partial \tilde{u}}{\partial y} - \langle \rho u'' v'' \rangle\right) + \frac{\partial}{\partial y}\left(\left\langle \mu \frac{\partial u''}{\partial y} \right\rangle\right)$$

$\tau_{12} = -\langle \rho u'' v'' \rangle$ is a component of the Reynolds Stress tensor. It is an unknown and varies spatially with the solution variables. The full tensor is symmetric, so it has 3 independent components in 2D.

In a full 2D flow, we end up with five equations and eight unknowns:

- Equations: 1 mass, 2 momentum, 1 energy, 1 equation of state
- Unknowns: $\bar{\rho}$, $\tilde{u}$, $\bar{\rho}$, $\tilde{E}$, $\bar{p}$, τ_{11}, τ_{12}, τ_{22}

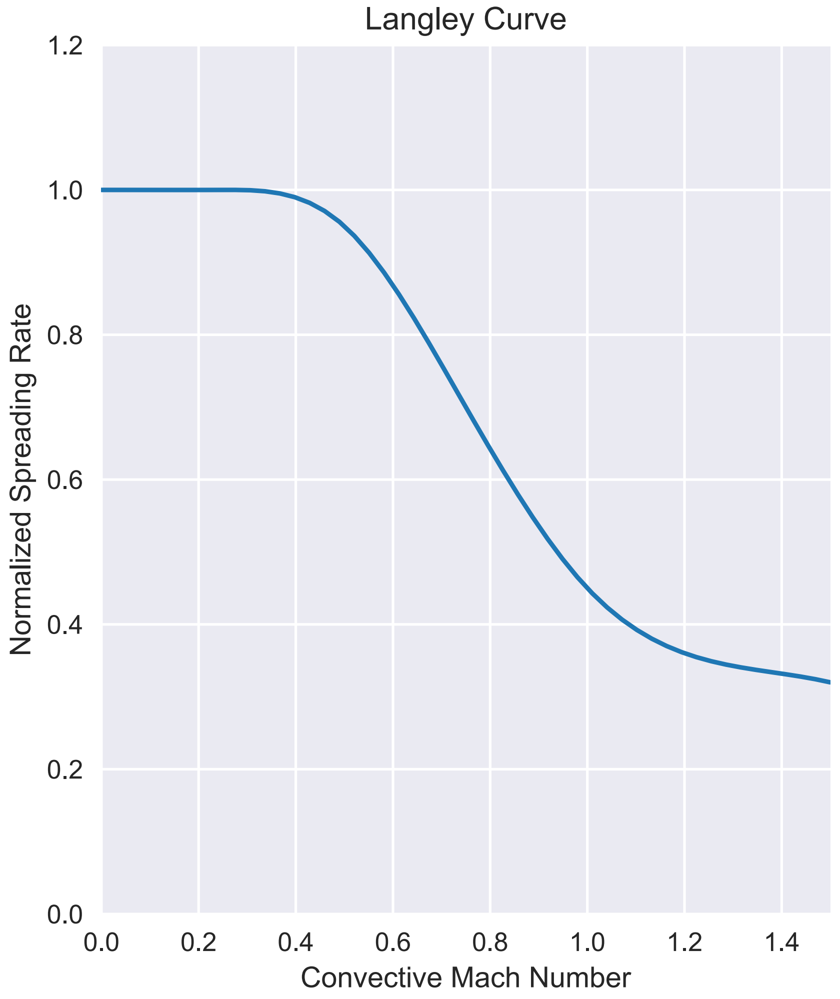
We have more unknowns than equations, so we need to a way to model the unknown with the known.

Philosophical Semantics

- Do we understand turbulence?
- Turbulence is well-understood in some ways.
  - We know the governing equations—the Navier Stokes equations are highly reliable.
  - We can run a computer simulation with the unsteady Navier Stokes equations and see exactly what's happening with the turbulent flow.
- The problem is not a "physics" problem, but a "modeling" or "engineering" problem.
  - There is a fundamental loss of information when we move from the full, well-understood physics to a mean description.
  - Modeling attempts to fill in that loss of information.
  - We are trying to describe a complex, chaotic behavior with simple, understandable models.

How Does Compressibility Affect Turbulence?

- We need to distinguish between *variable-density* effects and true *compressibility* effects
- Some effects can be explained with variable-density calculations:
  - For example: decrease in skin friction with increasing Mach number
  - Morkovin's hypothesis: "the essential dynamics of these shear flows will follow the incompressible pattern" [3].
- Other effects cannot be explained merely by variations in density:
  - Decreased spreading rate of mixing layers with increasing Mach number



[3] Morkovin, M.V. "Effects of compressibility on turbulent flows." *Mécanique de la Turbulence*. CNRS, pp. 367-380

Turbulence Modeling Overview

- "All models are wrong, but some are useful." [4]
- Sreenivasan [5] stated that a good model has two hallmarks:
  1. Wide applicability
  2. Well-understood limitations
- What type of answer do you need? That determines the best turbulence model:

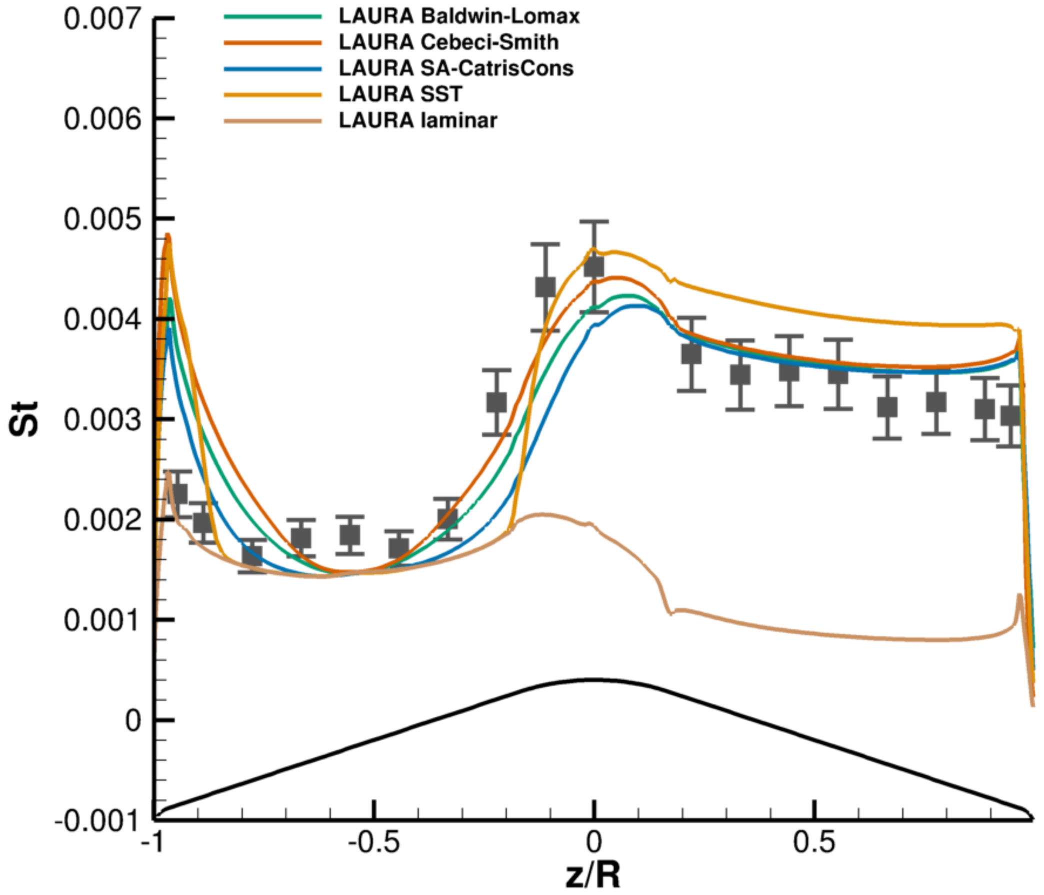
Quantity of Interest	Level of Fidelity in Simulation / Turbulence Modeling
Heating/Drag at high Mach numbers (M > 6)	May be able to safely ignore
Heating on attached boundary layers	Simple models
Drag/lift at intermediate Mach numbers	Simple models
Heating/pressure in a wake	Advanced models
RCS interactions / retro-propulsion	Advanced models
Dynamic pitching coefficients	Unsteady sims and advanced models

[4] Box, George. *Empirical Model-Building and Response Surfaces, 1987*
[5] Sreenivasan, K.R. "The turbulent boundary layer". *Frontiers in Experimental Fluid Mechanics*, pp. 159-20. 1989

Mean Flow Simulations and Models

Algebraic Models

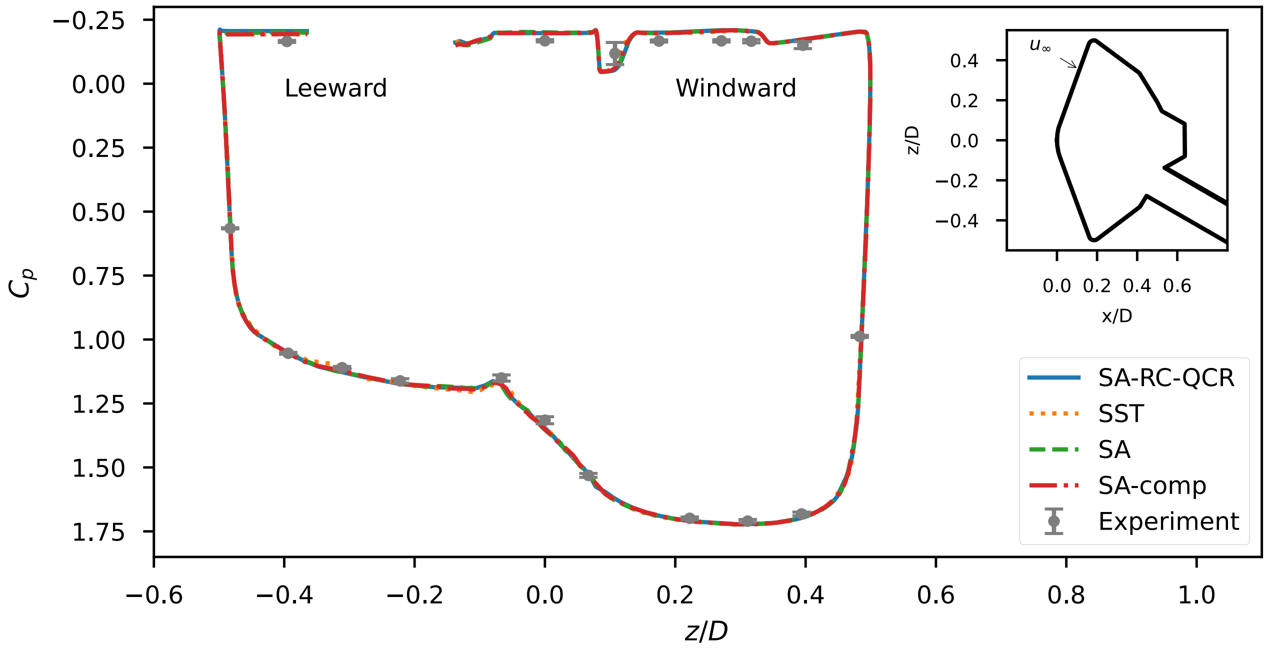
- The eddy viscosity is modeled with an algebraic formula.
- Examples include the Cebeci-Smith and the Baldwin-Lomax model.
- Depend on boundary-layer assumptions; not valid for separated flows
- Still very useful for one key reason: They work well across a wide range of Mach numbers, without explicit corrections for compressibility.



Comparison of CFD predictions with experiment for an MSL heatshield. Conditions are Mach 7.75 , Re_D = 15E6, and α = 20°

PDE-based RANS Models

- The eddy viscosity is solved using extra solution variables, which are used to calculate an eddy viscosity
  - For example, $\mu_t = \rho k/\omega$ with PDEs for k and ω
- You now have extra PDEs to solve, along with the Reynolds-Averaged Navier Stokes equations
- Generally, models fall into three categories:
  - One-equation, Spalart-Allmaras models
  - Two-equation, K-Omega models
    - SST
    - Wilcox
  - Two-equation, K-Epsilon models
- K-Omega models generally perform well for many high-speed flows. But… every model has its limitations.



Known Strengths and Weaknesses of RANS Models

RANS models (algebraic and PDE-based) have the following strengths and weaknesses:

Strengths

- Simplicity
- Low computational cost
- Works well for:
  - Attached boundary layers with:
    - Favorable pressure gradients
    - Mild adverse pressure gradients
  - Free shear flows (e.g., jets and wakes) at low turbulent Mach numbers

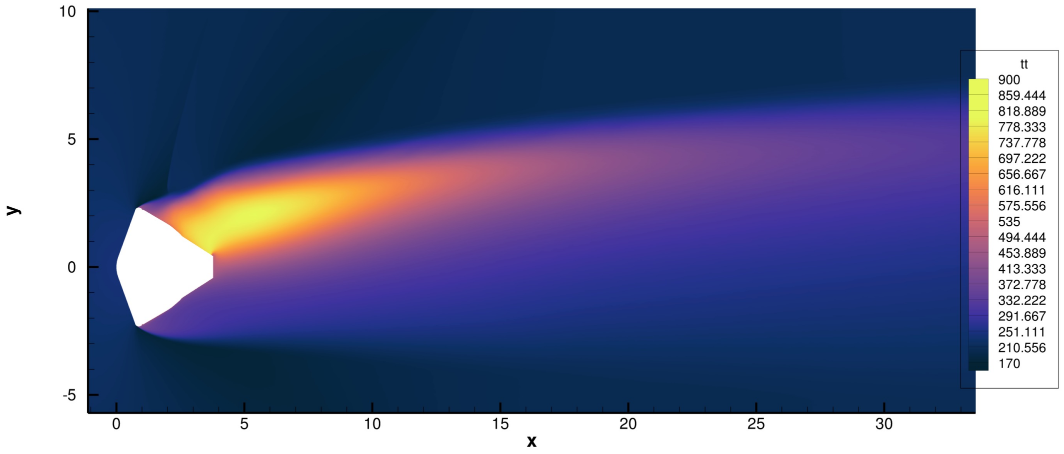
Weaknesses

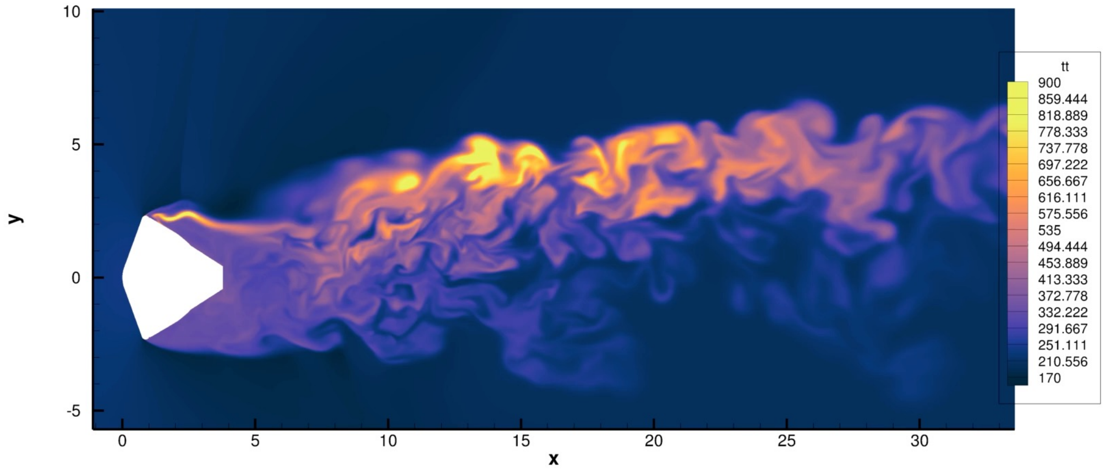
- Fundamental loss of information: turbulence is modeled only with the mean solution
- Poor predictive accuracy for:
  - Separated flows (e.g., wakes)
  - Jets in crossflow
  - Shock boundary-layer interactions
  - Free-shear flows with high turbulent Mach numbers

Scale-Resolving Simulations

Two Fundamentally Different Problems

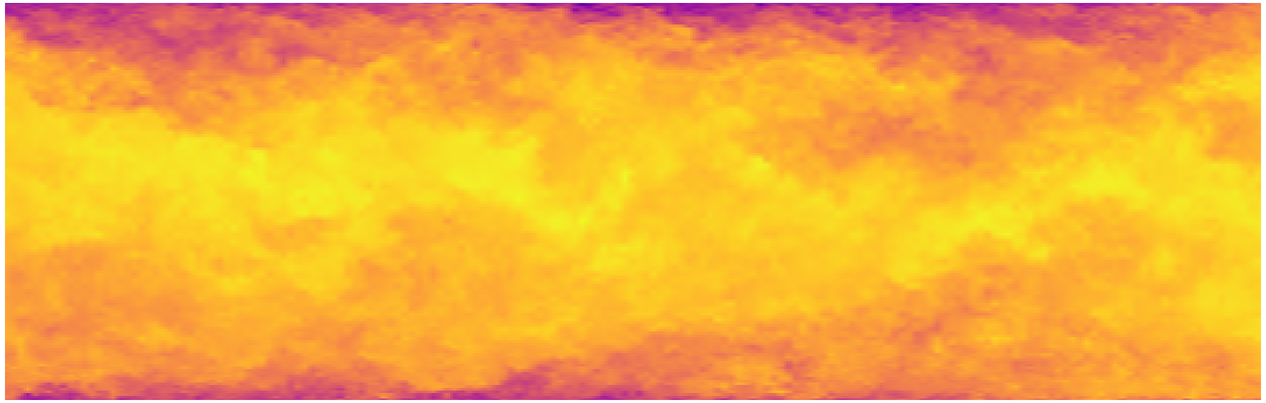
Average Solutions and RANS Models	Unsteady Solutions and Scale-Resolving Sims
Your solution represents the mean flow.	You have an unsteady solution, representing the solution at moments in time.
The turbulent fluctuations are modeled.	At least some of the turbulent fluctuations are directly represented in your simulation.
You can use time-marching, but you only care about arriving at a steady solution.	Time-marching at a global timestep is necessary.
Mean quantities (like lift or drag) can be computed from the final solution.	Mean quantities are computed using an average over a time period.





Direct Numerical Simulation

- Solve the unsteady Navier-Stokes equations directly *with no turbulence model*.
- Use high-order numerics, a fine grid, and short timesteps to resolve everything down to the viscous scales.
- All the turbulent scales are resolved; none are modeled.
- It is an alternative to experiments for high-fidelity data.
- You should never call a simulation "DNS" just because you did not use a turbulence model and you ran with unsteady timestepping.
  - Your grid and timesteps must be small enough to resolve the viscosity-dominated length- and timescales.
  - "Under-resolved DNS" is an oxymoron.



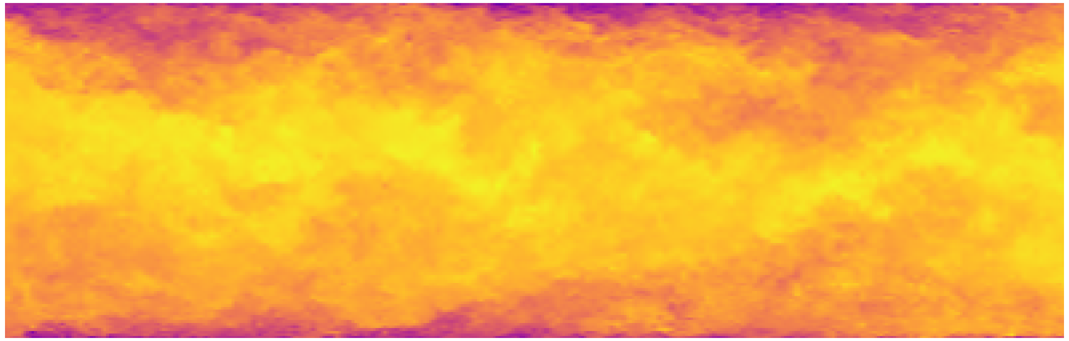
Streamwise velocity in a channel flow DNS at Re_τ=5200 by Lee and Moser

- Cost scales roughly as $Re^{2.6}$ [6], where Re is the Reynolds number.
- Impractical for most applied problems on large geometries.
- Feasible for applied problems only if computer chips continue to improve for 30-50 years.

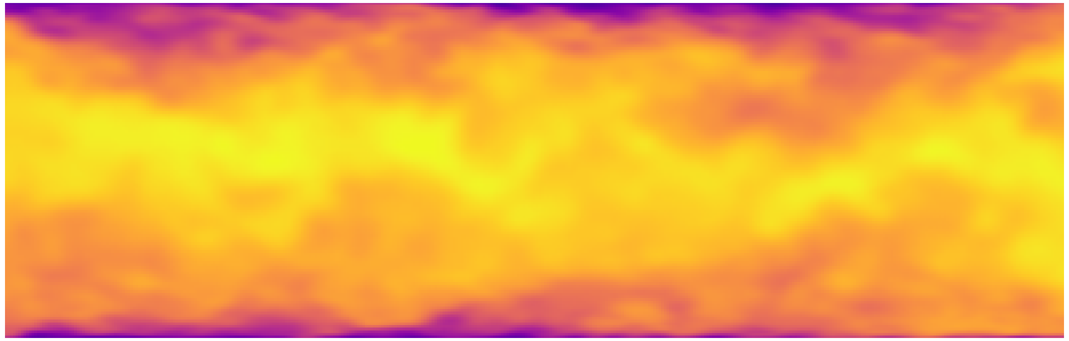
[6] Choi and Moin. *Grid-point requirements for large eddy simulation: Chapman's estimates revisited.* Phys. Fluids 2012

Large Eddy Simulations

- The majority of the kinetic energy in a flow is in the largest scales.
- The smallest scales are isotropic and simpler to model.
- We can model the filtered solution, where only the largest scales are resolved and the smallest scales are filtered out.
- We use a model for the effect of the small, unresolved scales on the largest scales.
- Cost scales as $Re^{1.9}$ [7] for wall-bounded flows
  - Better, but still expensive



Streamwise velocity

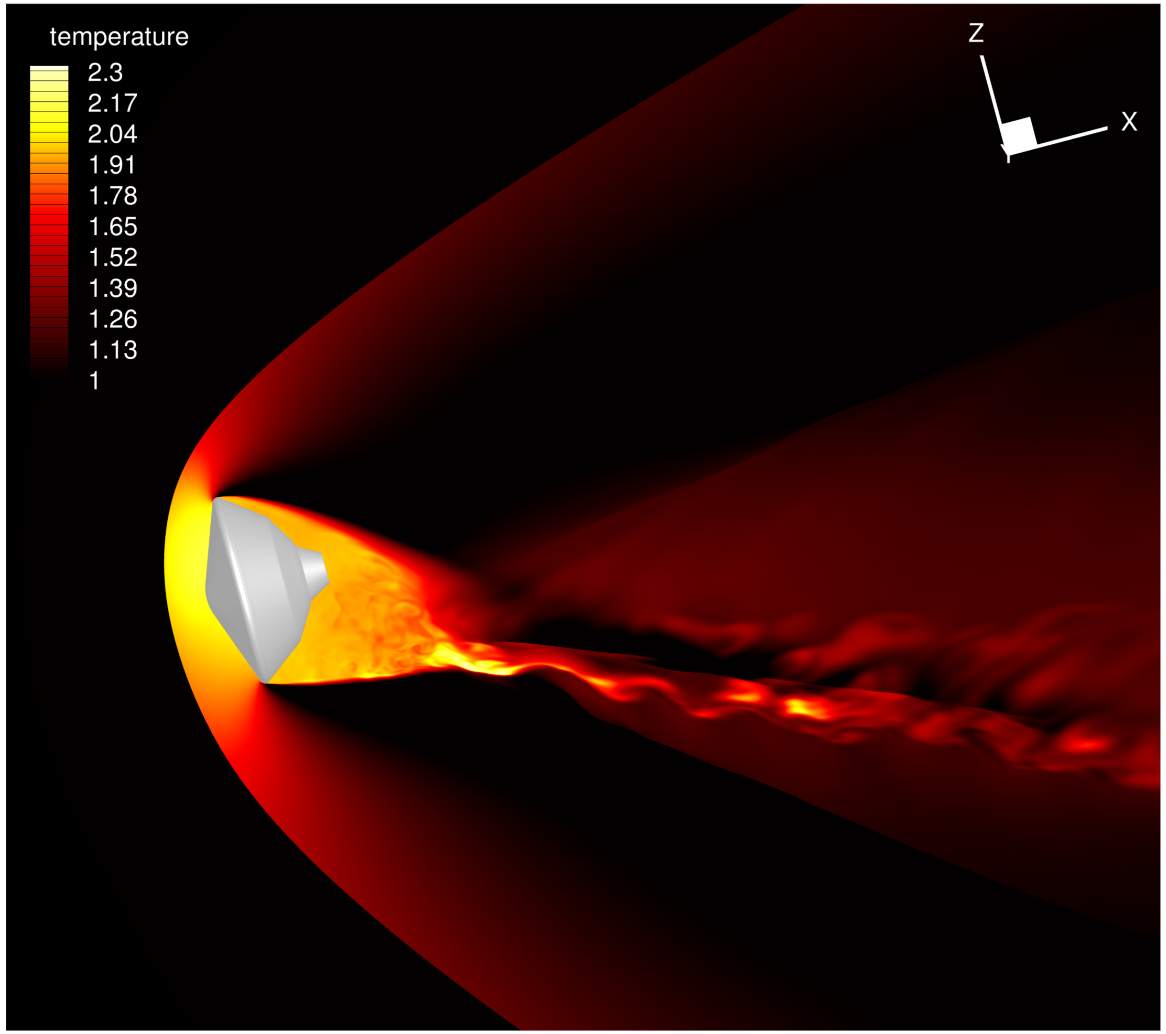


Velocity with a Gaussian Filter

[7] Choi and Moin. *Grid-point requirements for large eddy simulation: Chapman's estimates revisited.* Phys. Fluids 2012

Hybrid RANS/LES and WMLES

- Near a wall, the largest energy-containing eddies can be very small.
  - This makes wall-resolving LES very expensive.
  - What if we model these scales, instead of directly resolving them?
- Two families with a lot of overlap:
  - Hybrid RANS/LES
    - Use a RANS model where its accuracy is sufficient
    - Switch to LES where higher fidelity is needed.
    - Examples include DES, DDES, IDDES
  - Wall-modeled LES
    - Use LES everywhere in the domain
    - Add a boundary condition that models the effect of the coarsely-resolved near-wall eddies.



Known Strengths and Weaknesses of Scale-Resolving Sims

Scale-resolving simulations have the following strengths and weaknesses:

Strengths

- Better accuracy than RANS in:
  - adverse pressure gradients
  - separated flows
- Allow investigation of unsteady phenomenon, such as dynamic pitch stability or acoustics

Weaknesses

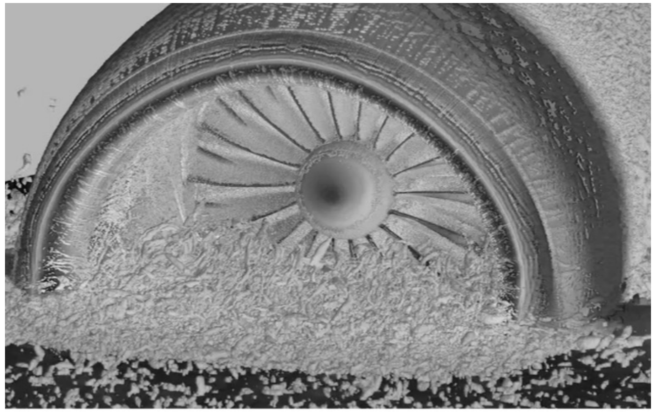
- Computational cost is higher than RANS due to timestepping requirements
- Several common models such as DES are sensitive to grid topology
- Hybrid RANS/LES:
  - Predictions can be sensitive to model parameters
  - Models can be robust to under-resolved grids and give a bad solution with no clear warning.
- WMLES:
  - Still evolving
  - Current state-of-art has questionable predictive accuracy [8]
  - Extensions for rough walls, etc. still being developed and tested

[8] Larsson et al. "High fidelity CFD verification workshop 2024", 2023, https://doi.org/10.2514/6.2023-1241

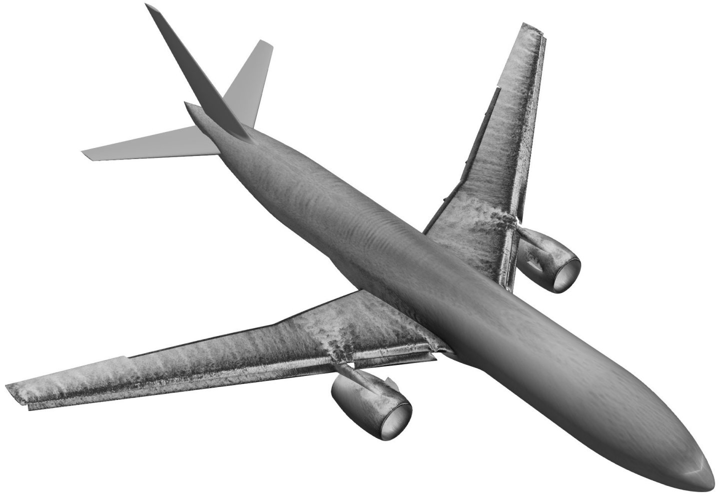
Building-Block Flow Model for Wall-Modeled LES

Research by Dr. Adrian Lozano-Duran under a NASA Early Career Faculty Grant

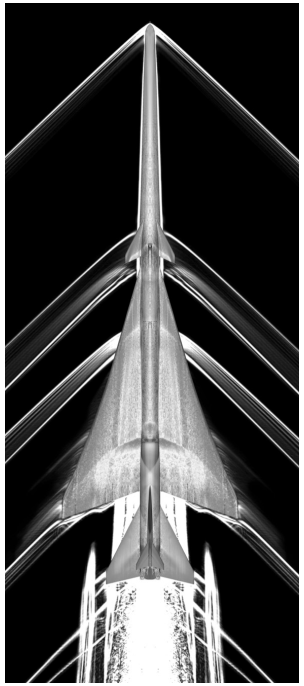
How to devise a **one** closure model for WMLES accurate across multiple flow physics?



NASA BL-ingesting inlet distortion tolerant fan



NASA Common Research Model



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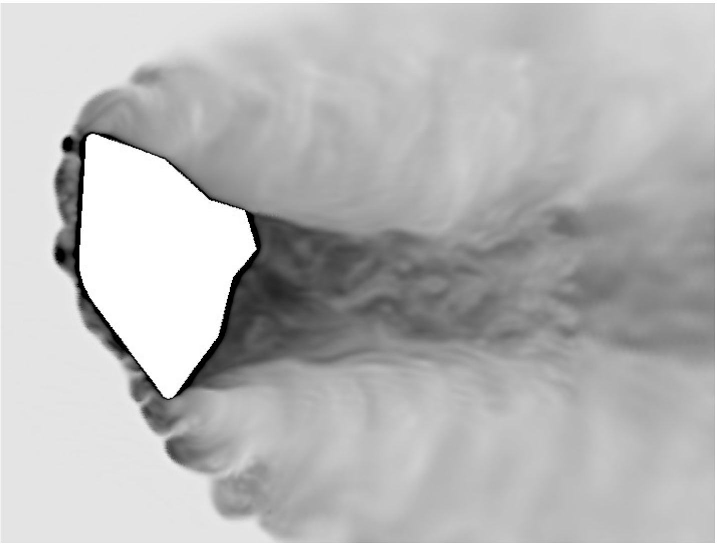
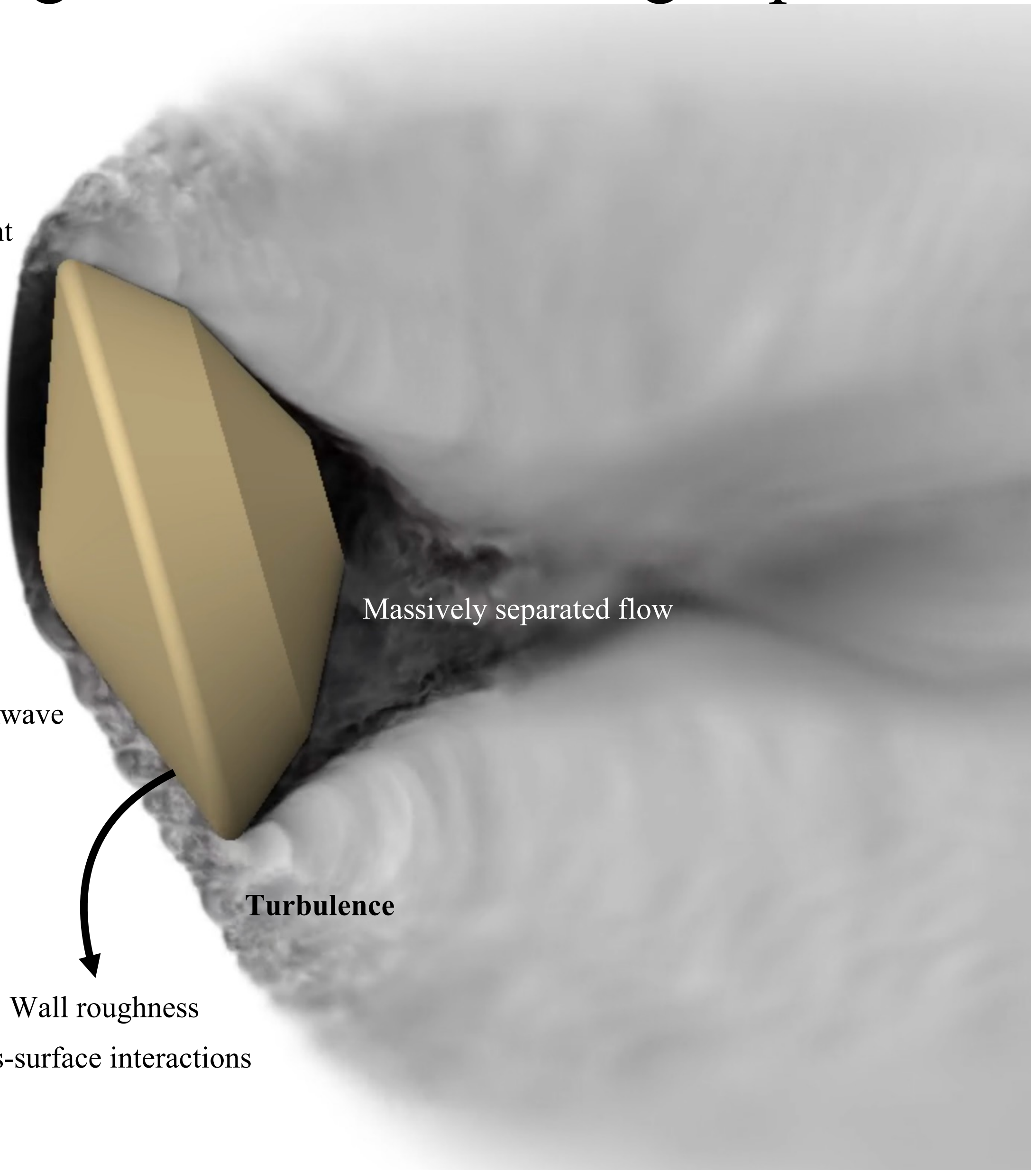


Mars Science Laboratory EDL vehicle

The Building-Block Model Project:
One wall+SGS model accurate for multiple flow physics, rather than many specialized models each good at one flow regime

Challenges in WMLES of high-speed aerodynamics



Challenges:

Future payloads for space exploration might imply:

- larger shells → higher Reynolds number at high speeds
- laminar-to-turbulent transition
- turbulent flow under strong pressure gradients
- massively separated flow
- gas-surface interactions
- wall roughness due to ablation
- unsteady shockwaves
- chemical reactions and ionization
- …

Limitations:

Current tools do not account for all flow phenomena simultaneously and/or rely heavily on simple models, experimental correlations, and extrapolation

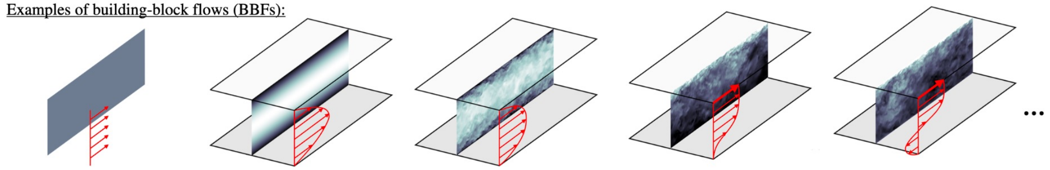
Goal: Building-block-flow model (BFM)

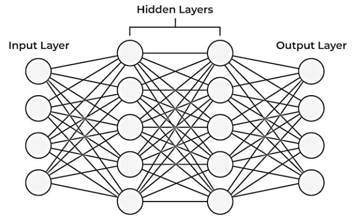
Devise closure model for WMLES simulation able to

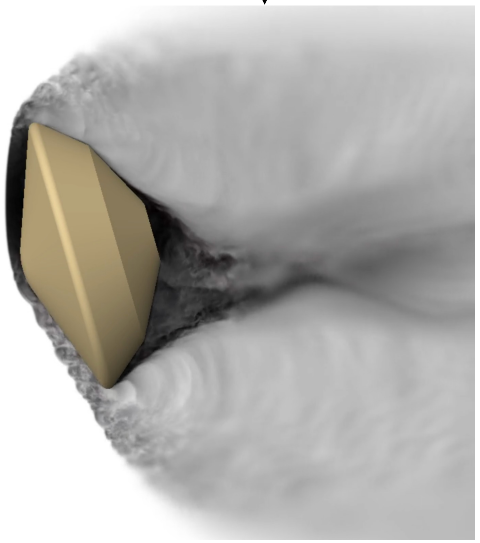
- **Account for different flow physics**
  - Laminar flow
  - Turbulence under zero, favorable, and adverse pressure-gradients
  - Separation
  - Shockwaves
  - Wall roughness
- **Integrate wall and SGS model into one entity**
- **Scalable to additional flow physics in future if needed:**
  - Chemical reactions, ionization, gas-surface interactions
- **Consistent with numerical schemes / grids**
- **Provide confidence score in the prediction**
- **Applicable to complex geometries**

The idea

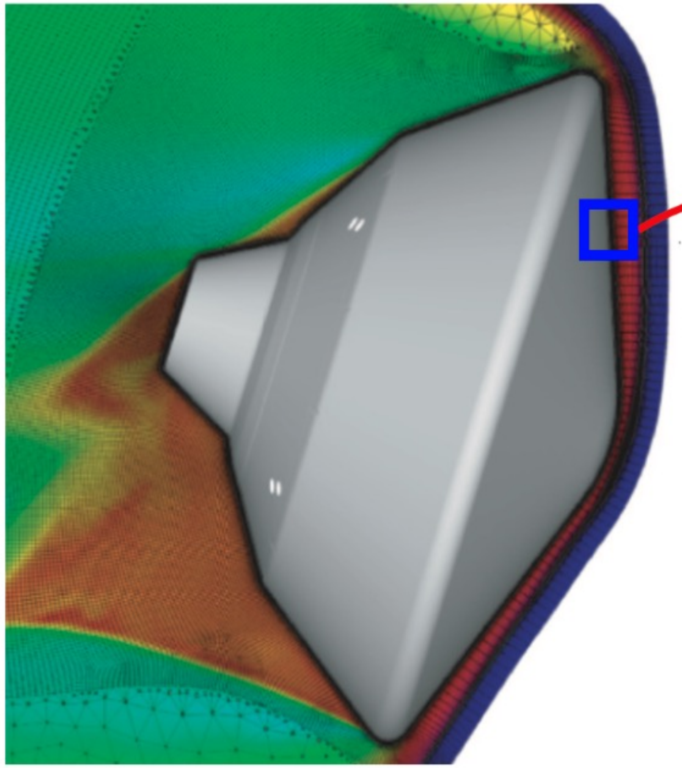
Use a collection of simple flows containing essential flow physics to formulate generalizable subgrid-scale/wall models







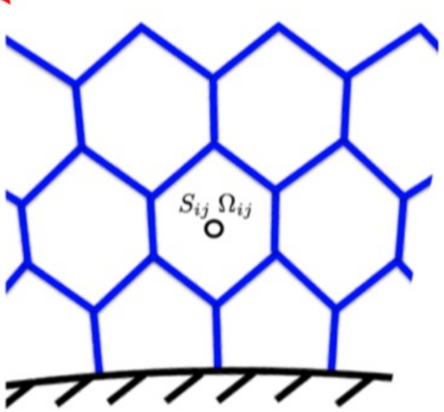
BFM neural network architecture

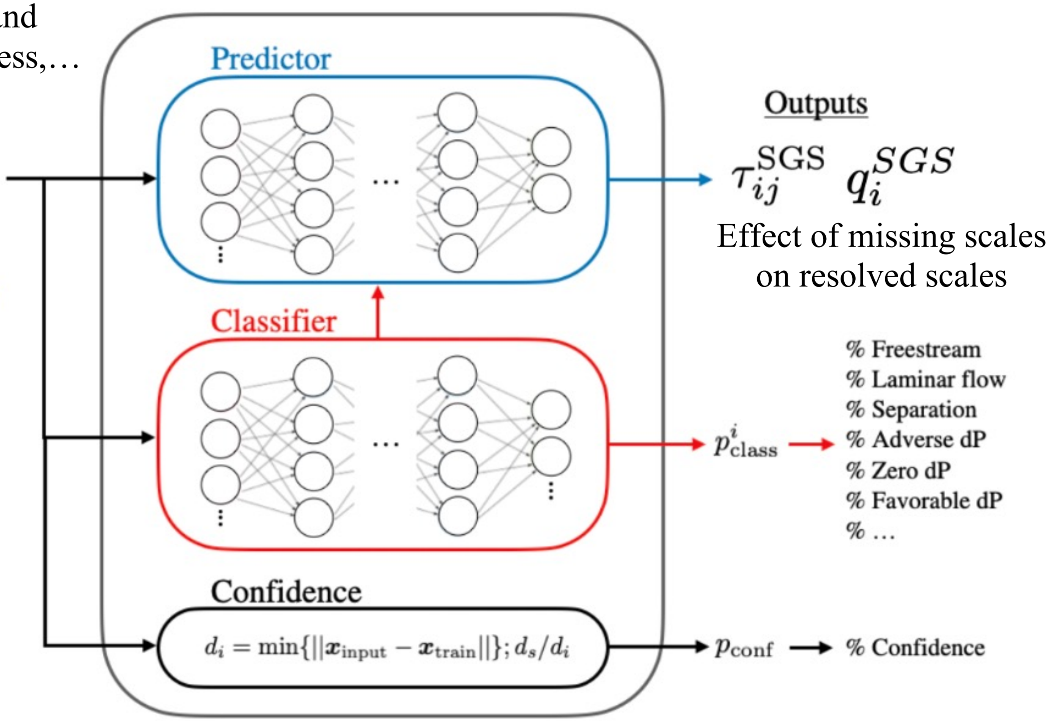


Local inputs based on velocity and temperature gradients, wall roughness,…

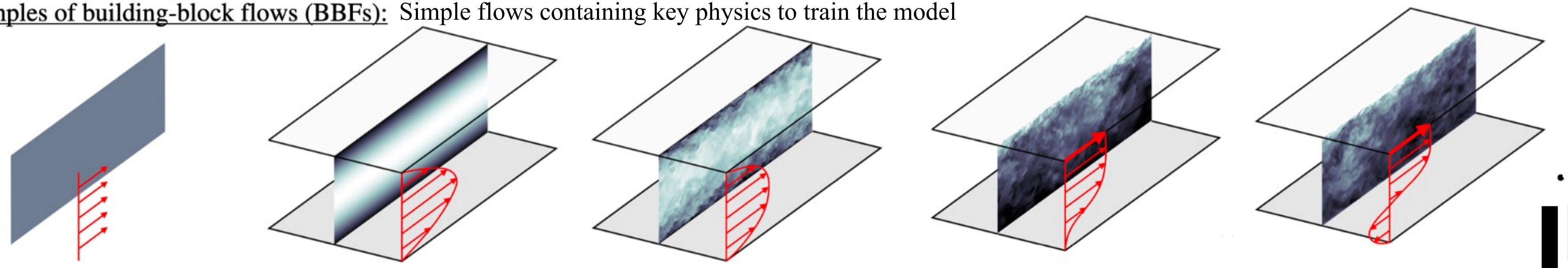
Inputs

$(I_1, I_2, \ldots, \boldsymbol{\theta}, \boldsymbol{\Gamma})$





<u>Examples of building-block flows (BBFs):</u> Simple flows containing key physics to train the model



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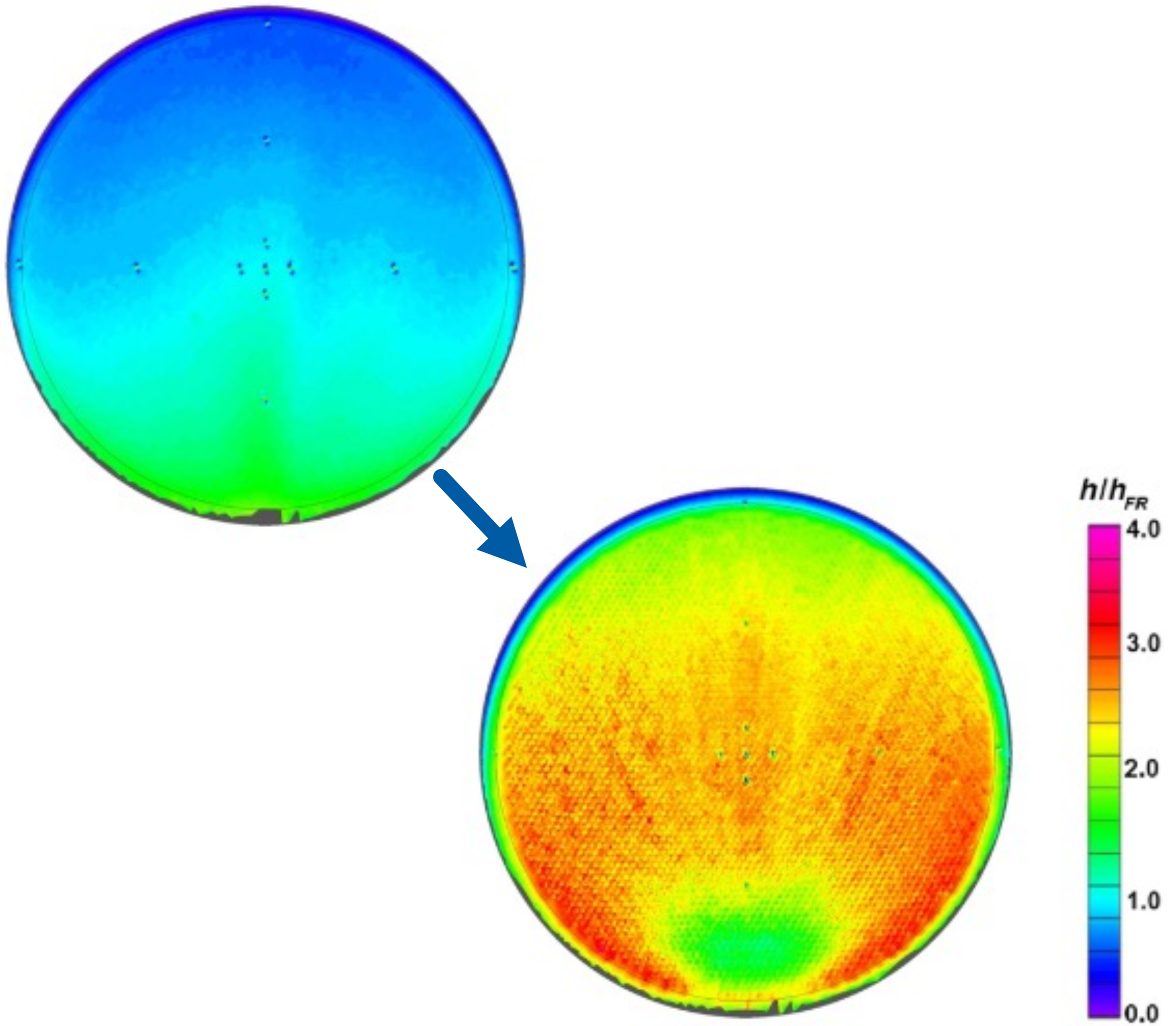
Looking to the Future

New research directions and general advice

Effect of Roughness

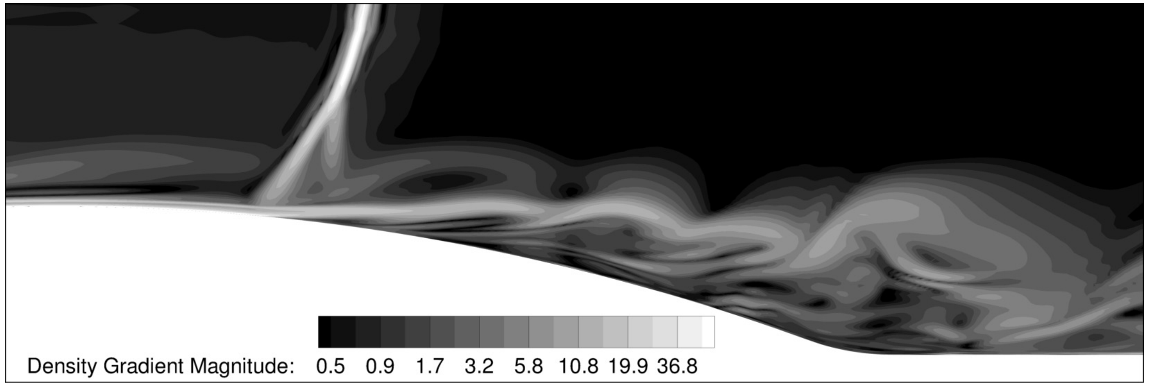
- We cannot assume that vehicles have “smooth walls” during atmospheric entry.
- How is turbulence affected by roughness?
- Different types of uniform roughness:
  - Woven thermal protection systems (TPS)
  - Ablated surfaces
  - Damaged TPS
- Discrete features can also enhance turbulence
  - Tile boundaries
  - Blocked TPS
- Brian Hollis and his collaborators have gathered a massive amount of experimental data on roughness effects at Mach 6 and Mach 10



Effect of hexcomb-pattern roughness on heating.
From Hollis 2021, https://doi.org/10.2514/1.A34791. Used with permission

Overcoming the Weaknesses of Hybrid RANS/LES

- DES works well for many use cases, but has several weaknesses
- Solid turbulence theory can be used to improve the reliability and the accuracy of hybrid RANS/LES
  - Gives correct eddy viscosity on cells of arbitrary aspect ratios
  - Avoids modeled stress depletion
  - Actively manage the amount of resolved fluctuations
- Interesting new modeling ideas:
  - Active Model Split by Haering, Oliver, and Moser
  - Dynamic Hybrid RANS/LES Model by Bhushan and Walters
  - Active HTLES by Mehta, Manceau, Duffal, and de Laage de Meux

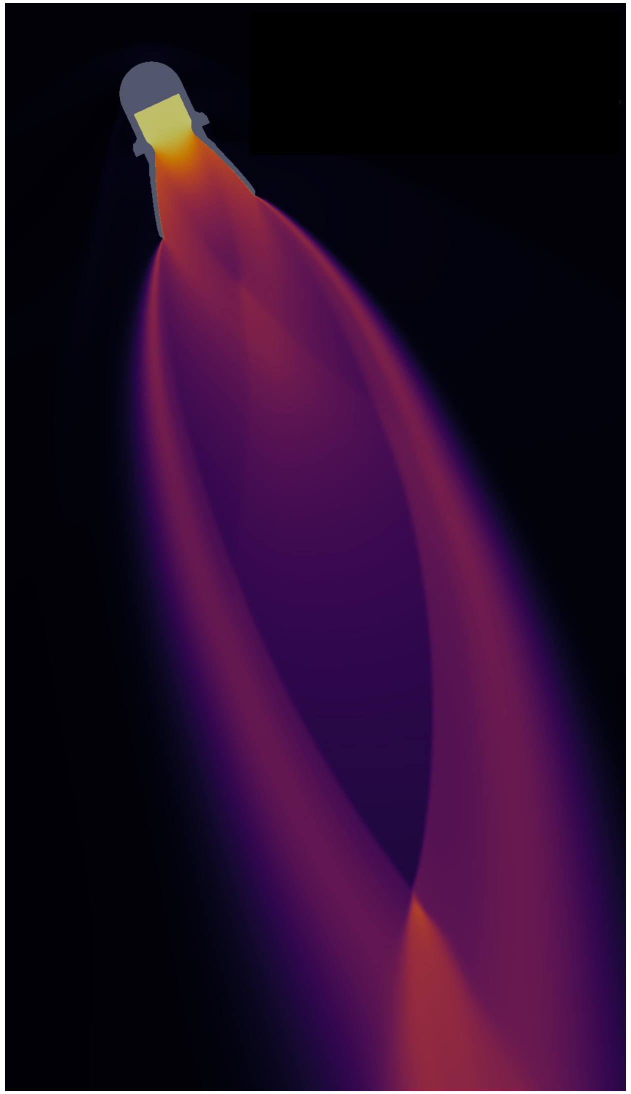


Density gradients in the Bachalo Johnson transonic axisymmetric bump

Other Areas of Research

These subjects are active areas of research:

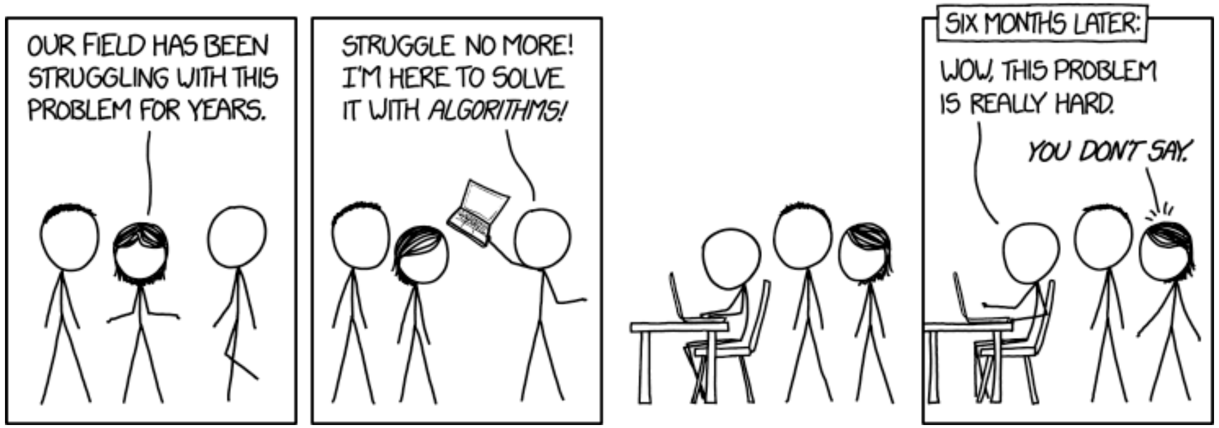
- Boundary layer transition
- Correlations for high enthalpy, heated, or strongly cooled boundary layers
- Rotation/curvature effects in compressible flows
- Cavity flows
- Interactions between chemistry and turbulence



Temperature in a slice through the symmetry plane of a rocket motor.

Attempts to Tame Turbulence

- Over the past 100 years, many advances have been made in mathematics and physics and then applied to the "turbulence problem"
  - Chaos theory and nonlinear dynamics
  - Information theory
  - Supercomputing
  - Perturbation methods
  - Renormalization group theory
  - Proper orthogonal decomposition (POD)
- Each has helped advance the field, but none have solved the hard problems.
- As new techniques emerge (such as deep neural networks) optimism should be tempered by experience.



"Here to Help," by Randall Munroe, https://xkcd.com/1831/

Where Can I Learn More?

These resources are listed as useful references and are not intended as a formal endorsement.

Books

- Wilcox, David C. *Turbulence modeling for CFD*. Vol. 2. La Canada, CA: DCW industries, 1998.
- Smits, Alexander J., and Jean-Paul Dussauge. *Turbulent shear layers in supersonic flow*. Springer Science & Business Media, 2006.
- Durbin, Paul A., and BA Pettersson Reif. *Statistical theory and modeling for turbulent flows*. John Wiley & Sons, 2011.
- Pope, S. B. *Turbulent Flows*. Cambridge University Press, 2000.

Websites

- Turbulence Modeling Resource, https://turbmodels.larc.nasa.gov/
- Larsson, Johan, "Modeling and Prediction of High-Speed Boundary Layers", AMS Seminar, https://youtu.be/1IG-UN3UaDQ

Review articles

- Durbin, Paul A. "Some recent developments in turbulence closure modeling." *Annual Review of Fluid Mechanics* 50 (2018): 77-103.
- Fröhlich, Jochen, and Dominic Von Terzi. "Hybrid LES/RANS methods for the simulation of turbulent flows." *Progress in Aerospace Sciences* 44, no. 5 (2008): 349-377.
- Candler, Graham V., Pramod K. Subbareddy, and Joseph M. Brock. "Advances in computational fluid dynamics methods for hypersonic flows." *Journal of Spacecraft and Rockets* 52, no. 1 (2015): 17-28.

Questions?