Turbulence Modeling: Roadblocks,
and the Potential for Machine Learning
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An Old-Fashioned Framework for Machine Learning in Turbulence Modeling

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Outline

- Our aim is to provide guidance for Machine-Learning (ML) actors in modeling…
  - and also for “traditional” actors!
- We have the concept of “Turbulence Culture”
  - It takes many years to acquire
  - It mingles rigor and intuition, making it hard to teach
  - We have our controversies, and more than a few fallacies
  - Nobody reads the textbooks anymore
- We have concerns over the ~ 5 years of ML literature
  - No new “general purpose” model produced
    - No trace of ML at the Turbulence-Modeling Resource (TMR)!
  - Many papers accepted, but often the product is “not a model”
    - The correction is “$\beta(x, y)$” and/or is very narrow-based
    - A hidden Neural Network was used
    - Invalid quantities are used, such as the mean velocity
    - More subtle flaws are common, such as a failure at the Edge of the Turbulent Region (ETR)
  - Rules are needed
- Creating and “planting” a new general-purpose model is a very large task
- A Paradigm Change is possible, of course…

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Turbulence Modeling Culture

- Turbulence defeats theory
  - We have a collection of facts, and good approximations
  - They accumulated over a century
- The Navier-Stokes equations describe turbulence
  - Direct Numerical Simulation would take infinite CPU power
- Reynolds-Averaging is correct, but…
  - The unsolvable Closure Problem stops “systematic development”
    - Algebra used to be blamed for lack of progress
- Simple empirical models are in service 24/7
  - Each was set by hand using a very small number of Turbulence Facts
  - They have a very small number of adjustable constants
  - Their one area of clear success is the simple boundary layer
  - It is crucial to understand the intent of each term
    - People propose to me “making the car faster in a straight line by fitting bigger brakes”
- We now have Big Data, “billions of turbulence facts” for ML to exploit
  - But not billions of constants
- Below, we list “hard” and “soft” constraints on a model

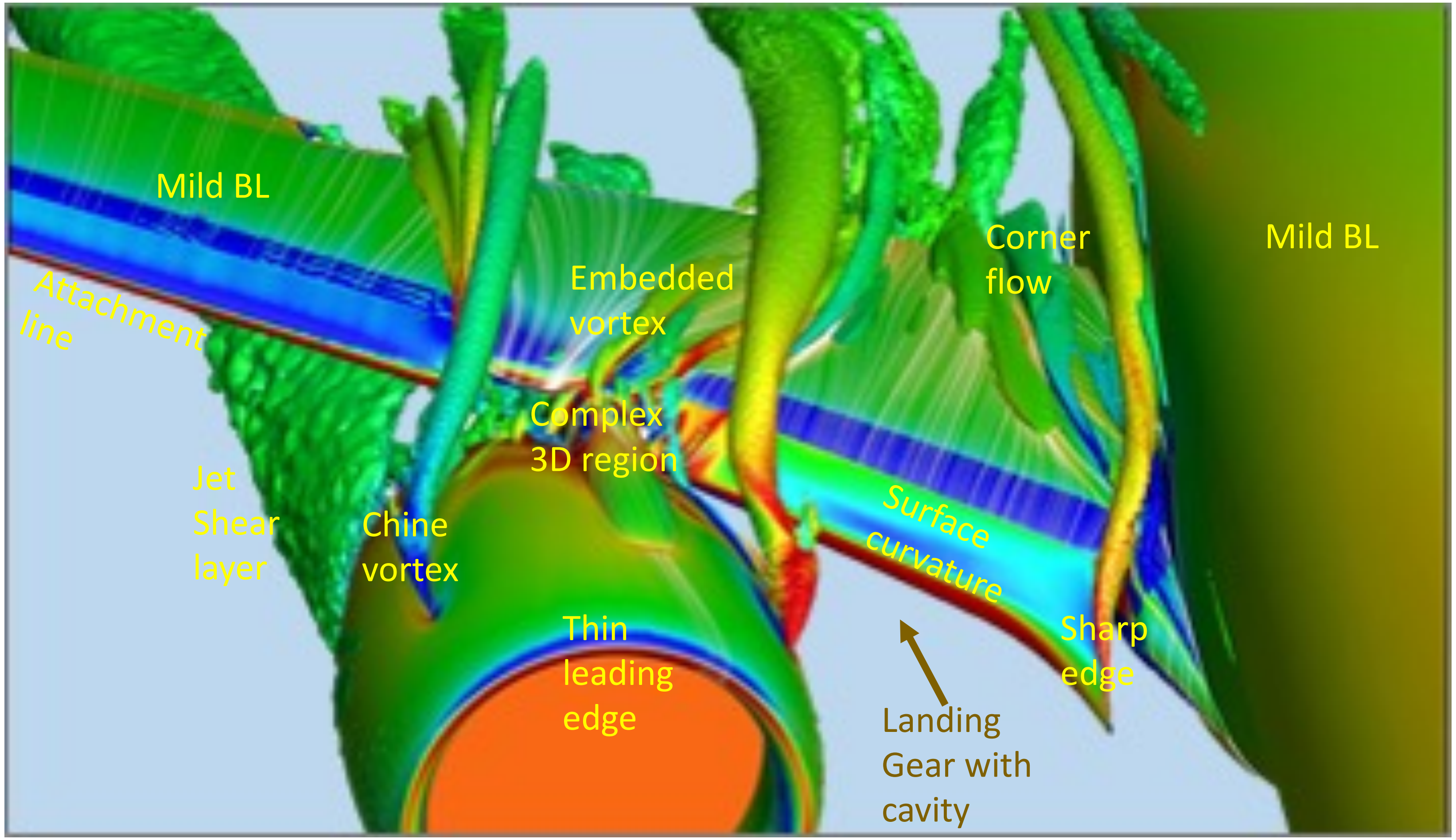
Turbulence Modeling Culture

- The community needs a model that "tries to do everything"
  - Call this "Universal" or "General," although very far from perfect
  - Specialized and "zonal" models are of limited value
    - Unless it is for "unusual needs," such as hypersonics
  - This is especially true if we expect a breakthrough from large Machine-Learning efforts
- The model needs to be fully described in the paper
  - PDE's, wall and freestream boundary conditions
    - This is a mild problem with for-profit CFD companies
  - Do not rely on a "hidden" Neural Network
  - There must be an easy way to obtain Fully Turbulent operation
  - Modern models need to be compatible with Hybrid RANS-LES Methods (HRLM)
- Grid-resolution needs must be reasonable and demonstrated
  - The operation count must be moderate
  - The damage to iterative convergence must be moderate; machine-zero convergence is expected
- In free shear flows, the molecular viscosity cannot appear
  - Kolmogorov energy cascade is from large eddies to viscous eddies
- You cannot ignore the simple boundary layer
  - The Karman Constant cannot be 0.6… or unknown!
  - The TBL controls viscous drag, and also separation, especially in HRLM mode

Universality? Generality?

- ➢ "One model" is applied to numerous different flow modules in a single solution
- ➢ Industrial practice is not zonal (meaning, having zones set by user)

Vortex
At tip

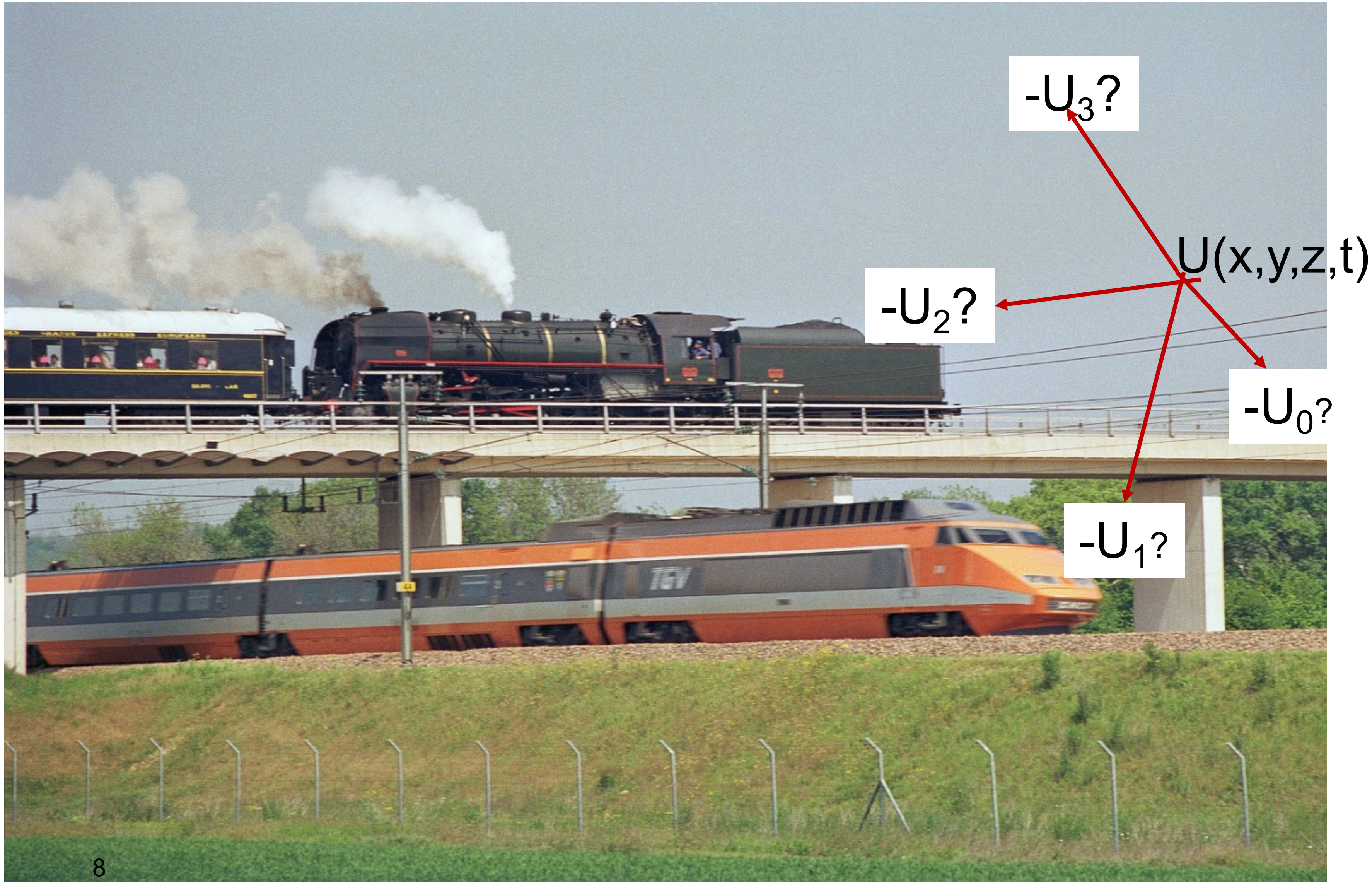


Courtesy J. Slotnick and Airbus! Wall pressure and streamlines, field vorticity

Hard Constraints

- Turbulence is Galilean Invariant
  - The model must also be: do not use the velocity!
    - Very limited exceptions for very-near-wall physics
  - More subtle issues: streamline curvature and pressure gradient
  - Turbulence does not know a flow is “steady”
- The model must be independent of the direction of the axes
  - There is no such thing as “normal” and “shear” Reynolds Stresses
    - The statement “the normal stresses are equal” means nothing
- No numbers linked to “the flow” such as freestream velocity
- The model must give accurate skin friction in simple BL
- The model must be robust in ETR terms

Four Possible Reference Frames

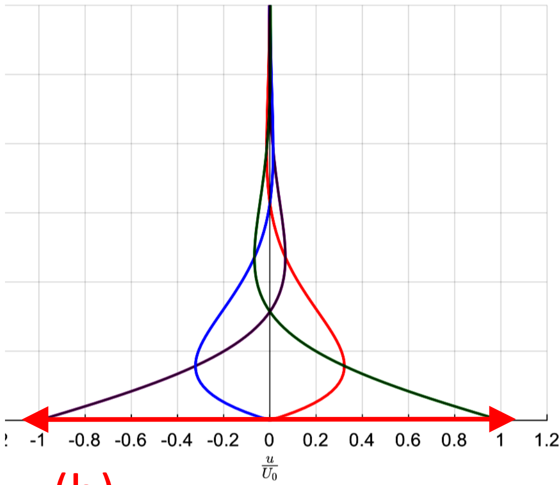


Acceleration as Feature in a Turbulence Model: Invalid

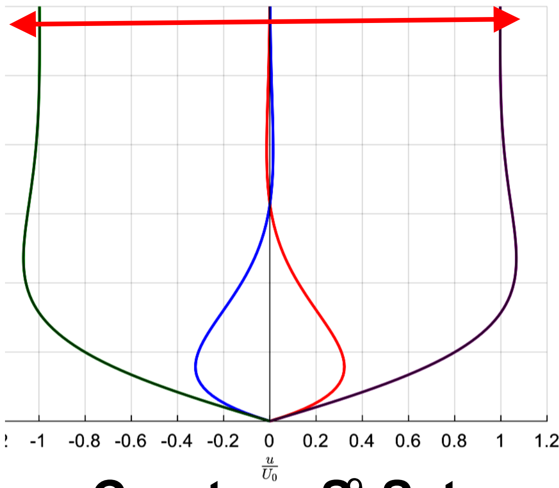
- I have been on this since 1999 (with Speziale)
- The pressure gradient controls transition, separation…
  - What better quantity to introduce?
- The issue is unsteady flows
  - Stokes' Second Problem:
  - Boundary layer with oscillating (air mass – wall) velocity difference $\Delta U = U_0 \cos(\omega t)$
- Use reference frame of air mass (a), or of the wall (b)
- The two flows have different acceleration and pressure gradients
- They have exactly the same turbulence!
- In Real Life, consider vortex shedding, blade passing, etc.

- The pressure gradient in steady flow is really the flux of vorticity across the wall, $\mu \partial \omega / \partial n$. This is valid
- This flux propagates upwards to create inflection points, and so on
- Unfortunately, it's not a local quantity

(a)



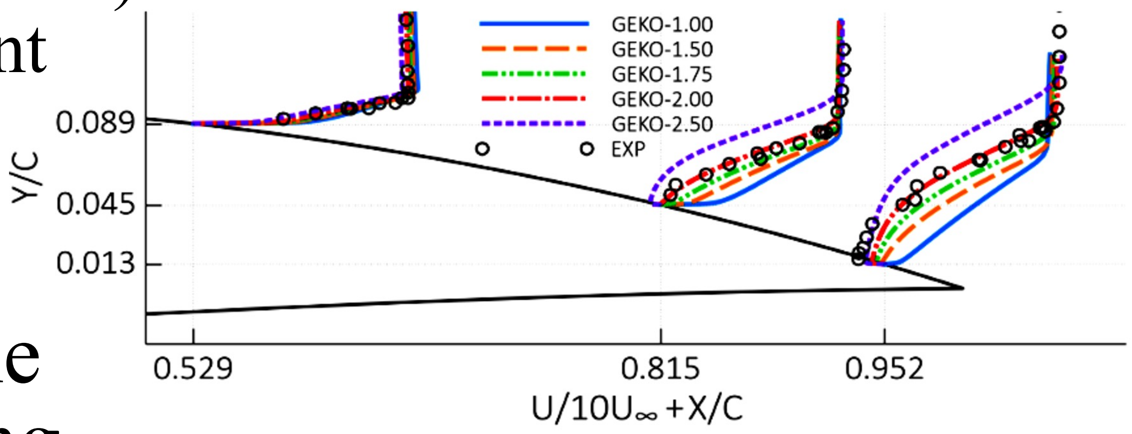
(b)



Courtesy S. Sato

GEKO "Generalized k-omega" Model of Menter

- In my opinion, this is a radical concept
- The formulas have not been published. It's coded only in ANSYS-Fluent
  - However, the concept is clearly explained
- The user has SIX adjustable parameters, now "field variables"
  - Goal is to have at the user's discretion a "single model" that spans the behavior of many models
    - Similar to "going from k-ε to SST," but even wider
  - Each parameter controls a particular effect, e.g., separation, jet width, or corner vortices (like having QCR on and off)
  - They can take different values in different regions
  - Notable application: thick wind-turbine airfoils

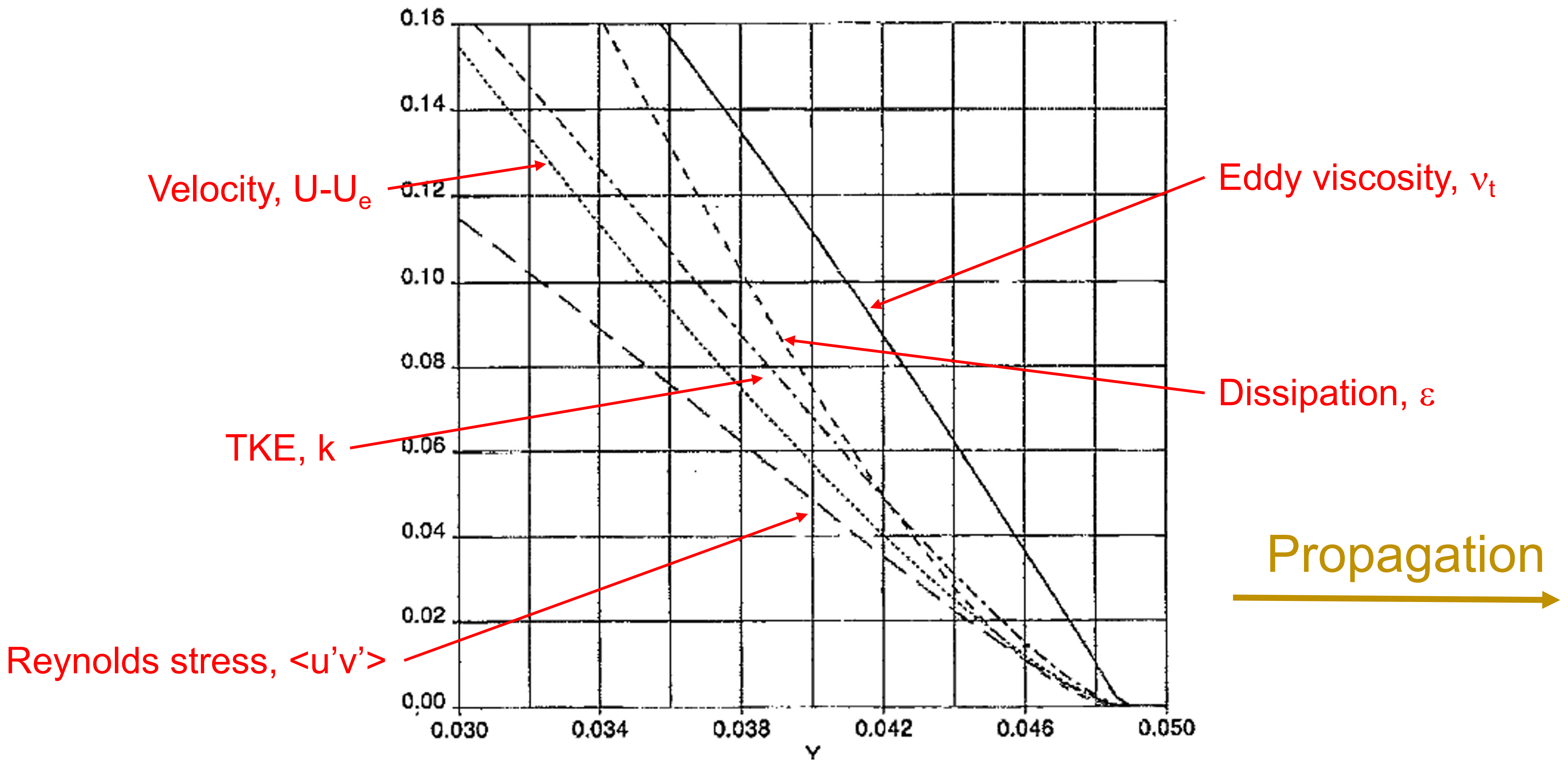


- Model is constrained to give the same flat-plate boundary layer with any setting
  - Boeing secret versions of SA satisfy exactly the same constraint!

The Edge of the Turbulent Region, or ETR (1)

- External flows have clean, inviscid, irrotational, non-turbulent fluid
  - The turbulent variables are essentially zero there
  - They must not influence the turbulent layers
  - k-ω and Baldwin-Barth fail this test, and are not used much
    - Wilcox in his 2006 edition did not really solve it
- A few actors have paid attention:
  - Menter, SA, Cazalbou, Kok, DLR, Abe
- At the core of this issue is the "Turbulent Ramp"
  - It must propagate slowly into the clean fluid
  - This region is dominated by the diffusion terms
  - The situation with slope discontinuities is not perfect, but is acceptable
  - Two-equation models also have excessive decay from the inflow values
    - Separate issue…

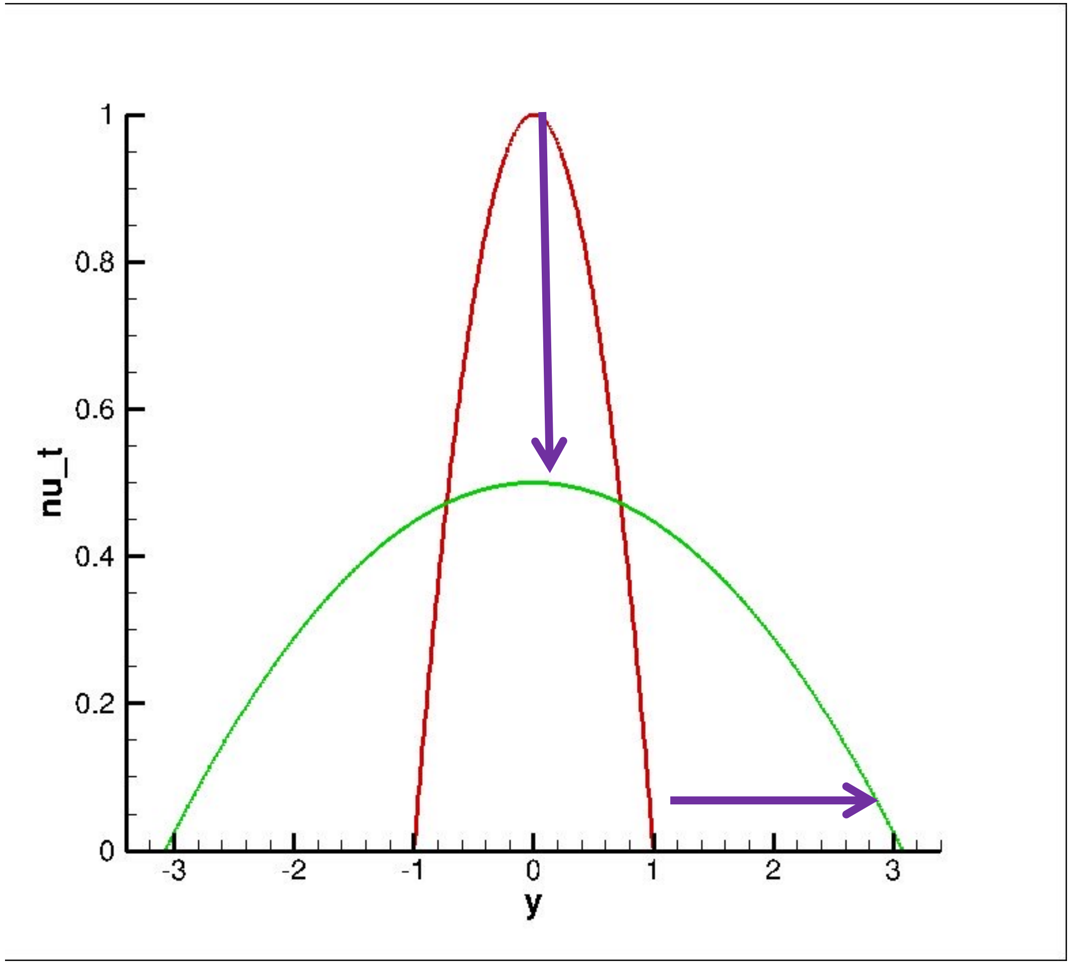
Turbulent Ramp of *k*-*ε* Model



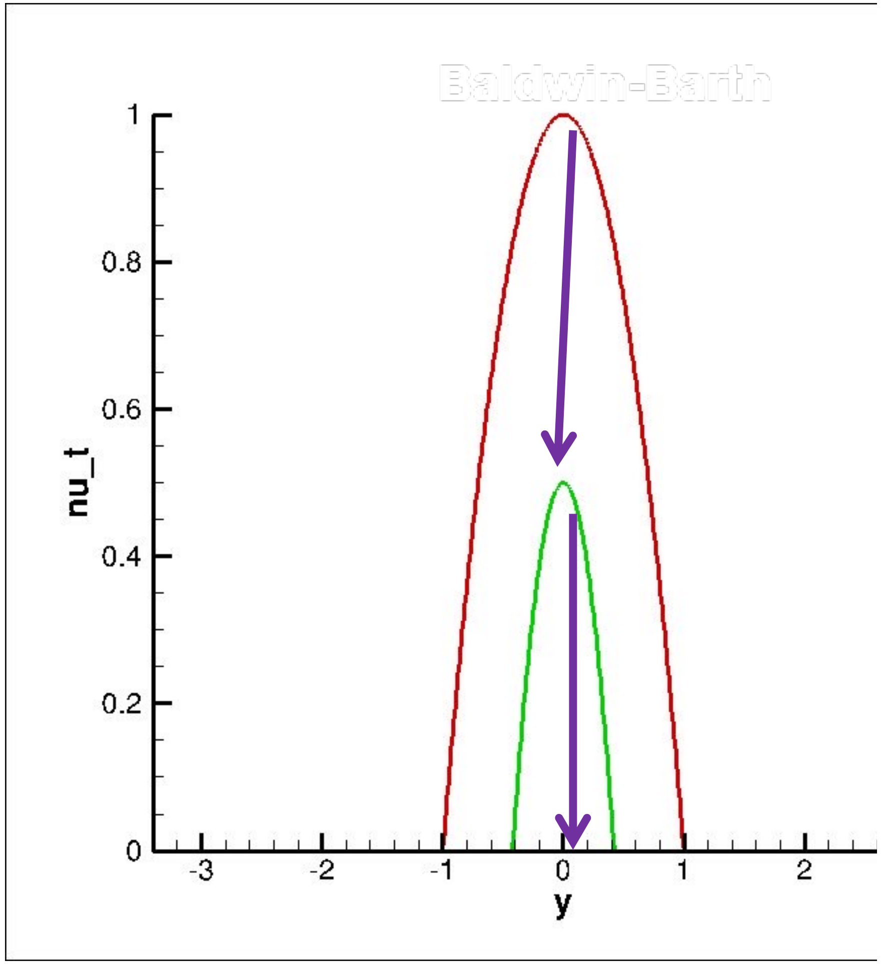
Cazalbou, Spalart & Bradshaw

Exact Solutions of the Diffusion Terms Only

Spalart-Allmaras, c_{b2} = 0.622



Baldwin-Barth, c_{b2} = -2



These parabolas also work in cylindrical and spherical coordinates!

The Edge of the Turbulent Region, or ETR (2)

- The ETR problem in a model can be hidden by coarse grids
  - It normally prevents grid convergence, unless high ambient ("freestream") values are used
    - There are no guidelines to pick such values
  - There are ways to detect the problem:
    - Run case with different ambient values, all small, and run with very fine grids
- Solve the Ramp Problem analytically
  - Only the diffusion terms are needed
  - This involves non-trivial "weak solutions" to the PDEs, such as

$$k = k_0 H(ct - y) \left| \frac{ct - y}{\delta_0} \right|^{\sigma_k/(2\sigma_k - \sigma_\epsilon)}$$

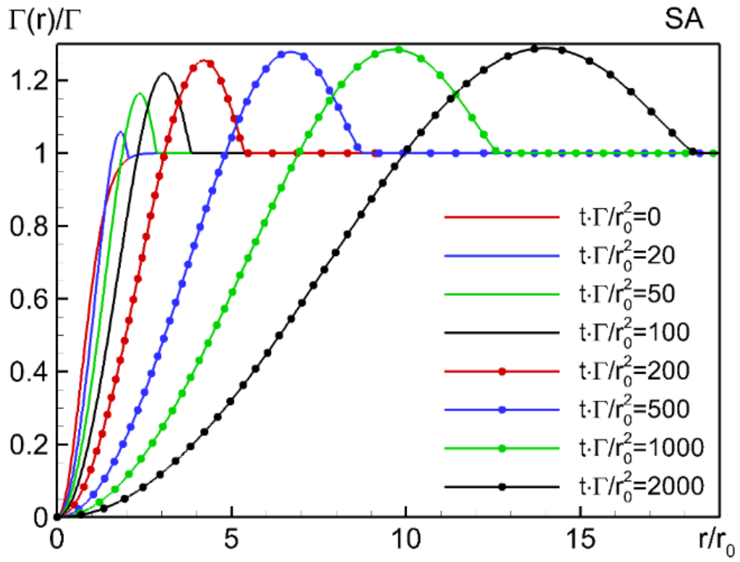
  - confirmed by fine-grid numerical solutions
- The von-Karman length scale L_{VK} goes to 0 linearly at the ETR, and then, $1/L_{VK}$ is used…
  - Von Karman meant if for the near-wall region
- It is very unlikely that a data-driven approach can address this

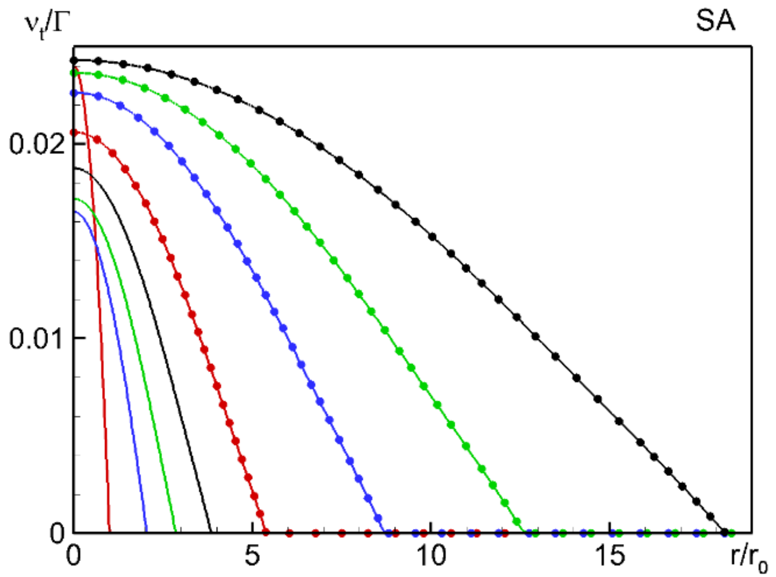
Soft Constraints, Often Violated

- Do not use the wall distance
  - It is not in the exact equations
  - It is costly, and accuracy problems are easy to create
  - It is not fully smooth
- Avoid non-smooth functions such a min and max
  - These prevent high-order convergence
  - Same for singular boundary conditions, such as $O(1/y^2)$
- Produce a realizable stress tensor
  - This is "nice" but not crucial
- Avoid high derivatives
  - Problematic for finite-element solvers
- Allow exactly zero values
- Avoid non-smooth solutions, with slope jumps in ν_t
  - No solution was ever found for SA, or any other model
- Respect the exact terms, such as the production of TKE
- Make turbulence die out in a mature vortex
  - Recent work with Garbaruk

Turbulence in a Mature Vortex?

- Govindaraju & Saffman 1971, Zeman 1995, Spalart & Garbaruk 2018
- Let an isolated 2D vortex become self-similar (it works for mixing layer)
- If it sustains turbulence, it creates a circulation overshoot!
  - i.e., opposite vorticity appears out of nowhere
  - Origin is the conflict between conserving circulation and angular momentum
  - G & S proved this rigorously, outside turbulence modeling (just self-similarity)





- Guilty: SA92, SST92, k-ε, k-ω, EARSM
- Innocent: SARC, SST-RC suppress the eddy viscosity

Turbulence in a Mature Vortex?

man 1995, Spalart & Garbaruk 2018

self-similar (it works for mixing layer)

a circulation overshoot!

now

ving

turb

RSM

ss the eddy viscosity

Reflections on Machine Learning

- Avoid bombastic ("ronflant" in French) titles such as:
  - "Physics-Informed Machine Learning Approach for Augmenting Turbulence Models: A Comprehensive Framework"
  - 100 years ago, Prandtl and Taylor knew a lot about the physics!
- Remember the "calling for universality"
- Remember a correction that is a function "β(x,y)" in a single flow can be "instructive for a human modeler," but does not constitute a model
  - It is not clear how AI can choose which term to correct with β (e.g. production? destruction?)
- Writing that "a Neural Network was trained, and gave these results" does not give a model
  - The exception: Weatheritt & Sandberg. No NN, and specific PDE's from Genetic-Expression Programming
- The selection of the input quantities ("features") is the core challenge
  - $\frac{\partial U_i}{\partial x_j}$; S_{ij} versus Ω_{ij}; invariants and powers of $\frac{\partial U_i}{\partial x_j}$; d; n_i; $\frac{DS_{ij}}{Dt}$ (in RC and in Olsen's Lag models); etc.
  - It is not clear how AI can do this
- Will AI be the "architect," or only in charge of "subtasks?"
- The author has no promising ideas to offer
  - Politely giving his opinion on bad new ideas is not much fun