Status and future prospects of turbulence modeling in CFD

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Outline

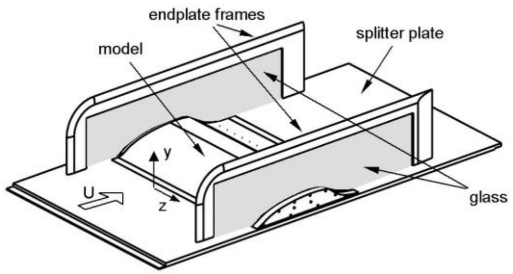
- Current status of Reynolds-Averaged Navier-Stokes (RANS) turbulence modeling
  - The NASA challenge
- U Mich/NASA Turbulence Modeling Symposium (7/2017)
  - http://turbgate.engin.umich.edu/symposium/
- Some lessons from the High Lift Prediction Workshop 3 (HiLiftPW-3)
- Prospects for RANS, Large-Eddy Simulation (LES), and hybrid RANS/LES
- Impact of other disciplines
- Recommendations

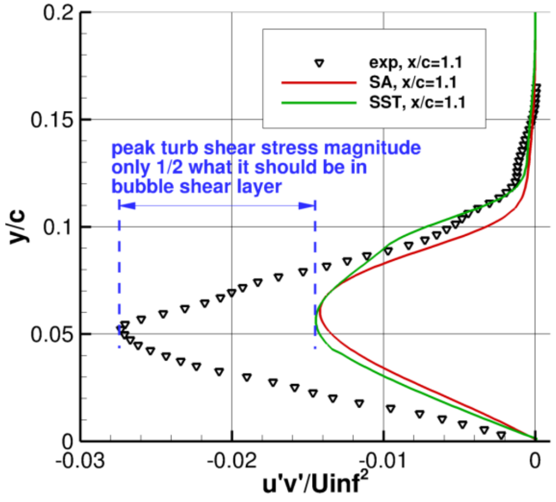
The NASA 40% Challenge

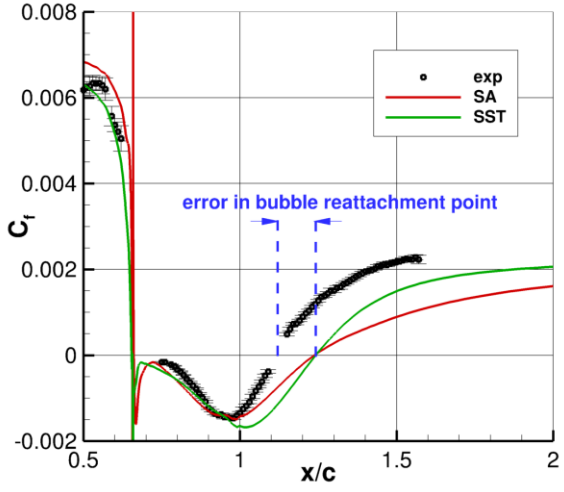
- Transformational Tools and Technologies (TTT) Project defined a Technical Challenge to:
  - Identify and down-select critical turbulence, transition, and numerical method technologies for 40% reduction in predictive error against standard test cases for turbulent separated flows, evolution of free shear flows and shock-boundary layer interactions on state-of-the-art high performance computing hardware.
  - Test cases included: 2D NASA Hump, Axisymmetric transonic bump, Compressible mixing layer, Round jet, Axisymmetric compression corner, many others.
  - https://turbmodels.larc.nasa.gov/StandardTestCasesFinal6.pdf
  - Time frame: by early 2018.
  - Workshop to be held at NASA Langley in March 2018.

Examples from the NASA 40% Challenge

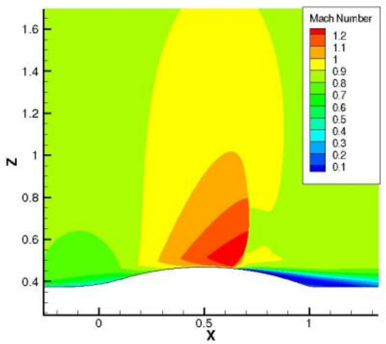
2D NASA Hump

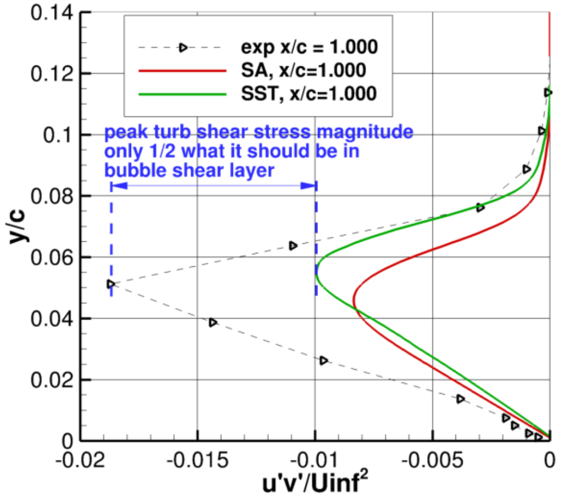




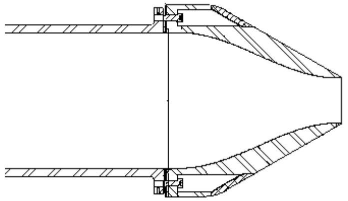


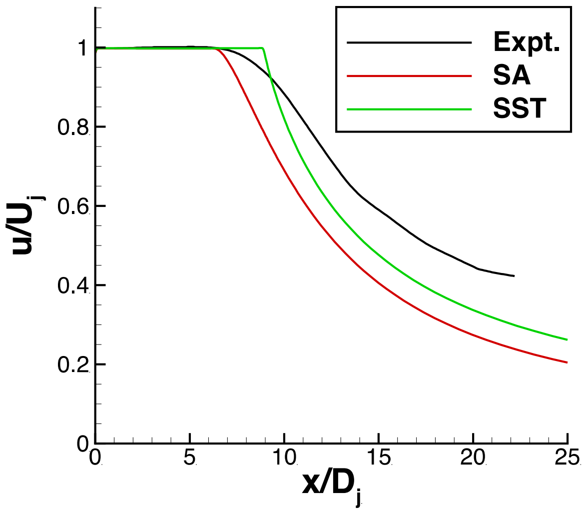
Axisymmetric Transonic Bump





Round Jet

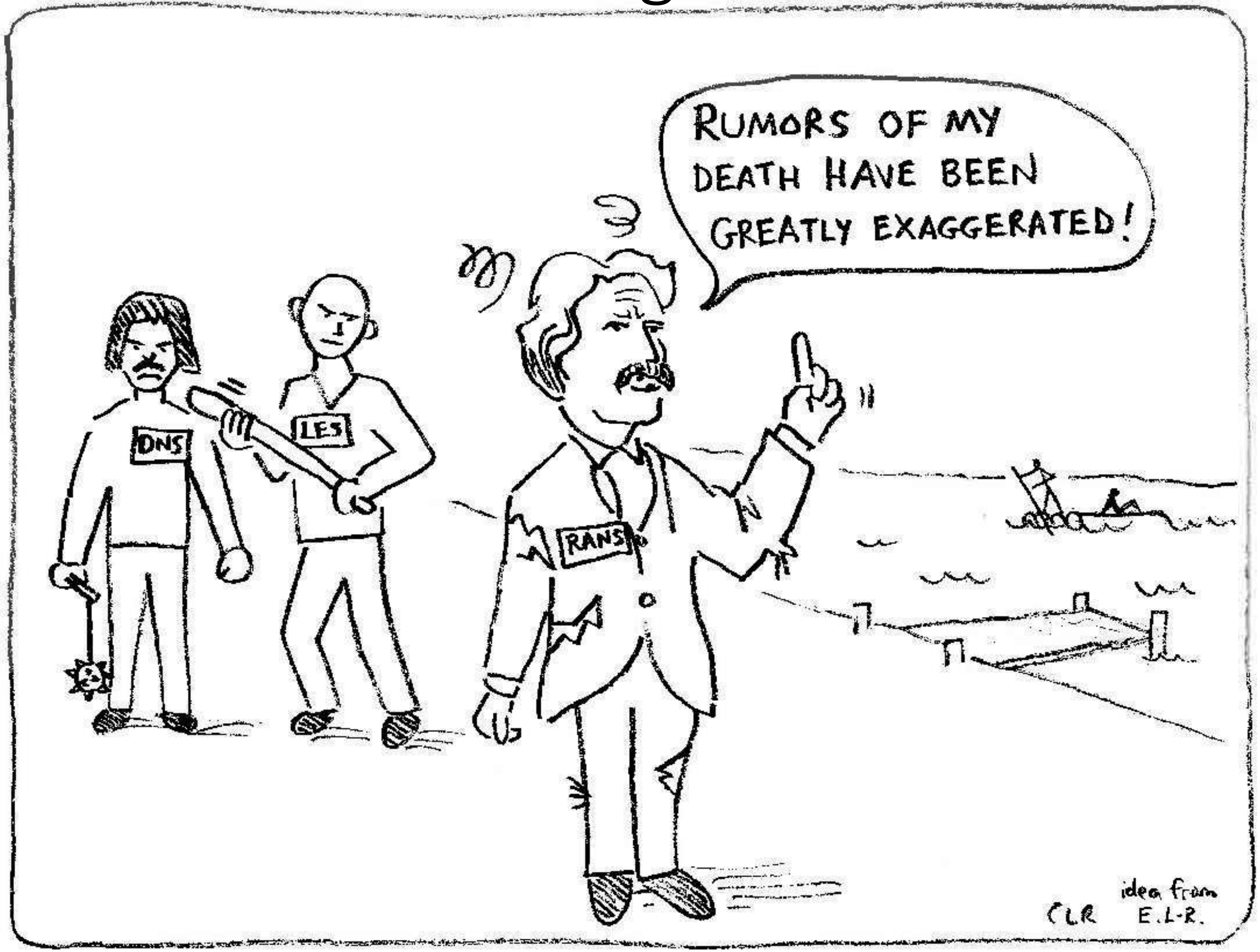




RANS Turbulence Modeling

- Existing RANS models fail for many flows.
  - And the "concept" of RANS may be invalid for many situations (e.g., wake region of cylinder viewed as a time-averaged problem).
  - See Spalart's "Philosophies and Fallacies" paper PIAS 74(2015),1-15.
- Has RANS model development stagnated, or is it merely waiting for the next great idea?
- Is there an unseen "ultimate barrier" that is preventing further significant progress?

RANS Turbulence Modeling



RANS Turbulence Modeling

UM/NASA Symposium

- July 11-13, 2017 in Ann Arbor, MI
- 32 participant talks
- 88 attendees
- Over 8 hours of discussion time: speculation, open exchange of views
- Overall:
  - Good exchange of ideas, fostered new alliances.
  - Concept of “ultimate barrier” introduced and discussed.
  - Particular focus on exploring uncertainty quantification (UQ) and data-driven modeling as applied to turbulence modeling.
  - Summary available in NASA/TM-2017-219682, Nov 2017.

UM/NASA Symposium

- Do we still need RANS-based turbulence models?
  - For industry, the answer is **<u>YES</u>** (most industrial users are probably decades away from any routine use of scale-resolving simulations).
    - Requirement to execute thousands of parametric explorations and design runs.
    - Computations over the full flight envelope.
    - Additional areas in which CFD (much less RANS) has not even penetrated – this includes conceptual design, trajectory prediction, robust design, etc.
  - Strong desire for RANS model improvements, not just in the near-term.
  - LES & DNS will continue to penetrate in many practical contexts & be invaluable for insight/discovery.
    - Can they play a greater role in RANS model improvement?

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- Expectations and ultimate barrier in RANS modeling
  - Most view RANS as unacceptable for flows with massive separation, assuming such a flow is treated as simply time-averaged.
  - But where is the line of acceptable/unacceptable?
    - How good is “good enough”? 20% error, 5% error, 0.1% error?
  - If there is a barrier and if today’s best models have not reached it, then what should be done to approach it, how complex a model is needed, what data is needed, and so on?
  - The ultimate-barrier argument is mainly about the lack of physics (loss of information) in Reynolds-averaging.

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- Uncertainty quantification
  - Robust uncertainty estimates for RANS are crucial, but difficult.
  - Quantifying uncertainty by assuming ranges for turbulence model closure coefficients is probably not very reliable, mainly because the models themselves are highly uncertain.
    - Due to the inherent loss of information in the Reynolds averaged representation, model structure, and modeling assumptions.

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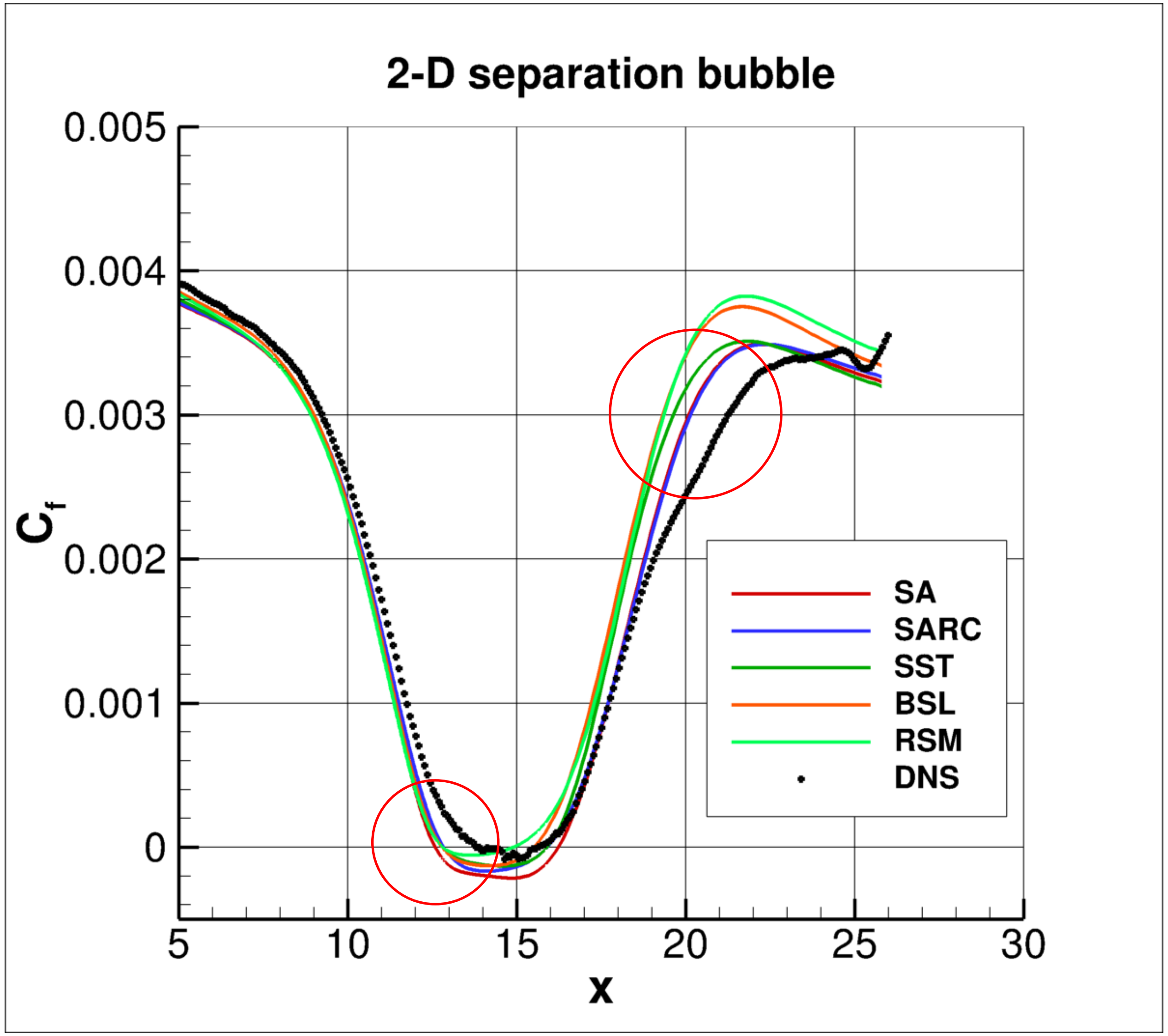
- Uncertainty quantification, cont'd



In this example, all RANS models are similarly "off" in these regions. Merely varying closure coefficients likely would not address the fundamental reason for RANS disagreement.

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- Uncertainty quantification, cont'd
  - Inadequate grid resolution, imperfect geometric fidelity, boundary condition uncertainty, and lack of code verification also contribute to CFD prediction uncertainties, and can easily mask the true deficiencies of turbulence models.
  - Model-form uncertainty quantification is in its infancy (how to quantify "unknown unknowns"?)

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- Data-driven modeling
  - Attendees were brought up to speed regarding this very new research area.
  - Karthik Duraisamy to speak later today on this subject.
  - Main points:
    - Does not constitute a new philosophy; rather, data-driven modeling brings in a new set of tools that allows for a more formal and comprehensive use of data.
    - A closed, universally accurate turbulence model is not waiting to be “discovered.”
    - The success of data-driven modeling is highly dependent on the choices made during the process. This includes the data used in the process, priors for inference, features in machine learning, etc. In this sense, the data-driven modeling process is no different from the traditional way of creating a turbulence model.
    - A broader community effort is needed.

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- Experiments
  - In many cases, the skin friction is one of the most desirable quantities needed for CFD validation, but also is one of the most challenging to measure.
  - Desperate need for an up-to-date, vetted, evolving catalog of peer-reviewed experiments, rated for their usefulness and completeness. This catalog would need to be constantly tracked and updated with experiments that use newer technology.
  - There has been a gradual (much-needed) evolution toward emphasis on quantifying boundary conditions (inflow turbulence, back pressure, etc.) and other details more carefully; i.e., experiments specifically designed for the purpose of CFD validation.

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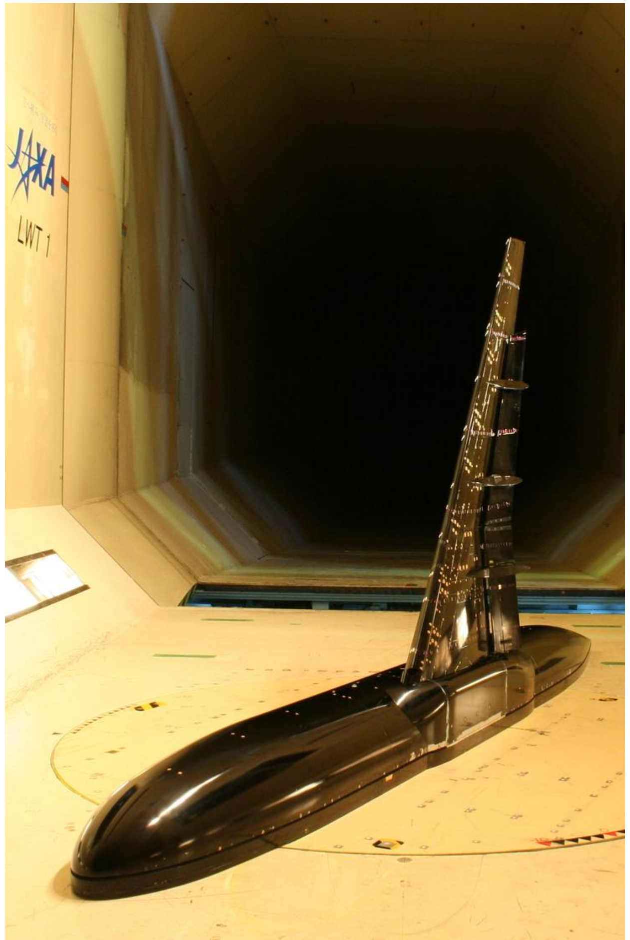
- Philosophy
  - Reynolds Stress Transport (RST) models
    - Still not widely used.
    - As a class, they have more potential; but they are hard to calibrate, typically more difficult to run, and (for aero applications) have not yet proven to be worth the effort in general.
    - In the latest High Lift Prediction Workshop (HiLiftPW-3), only one entry (out of 79) used an RST model; 51 used SA or variant.
  - Global vs. zonal models
    - Preference for global, but may not be realistic in interdisciplinary flows (example: flow separation + thermal mixing).
  - In 3D complex flows, sufficient grid convergence is not easily demonstrable.
  - Transition often has an impact.

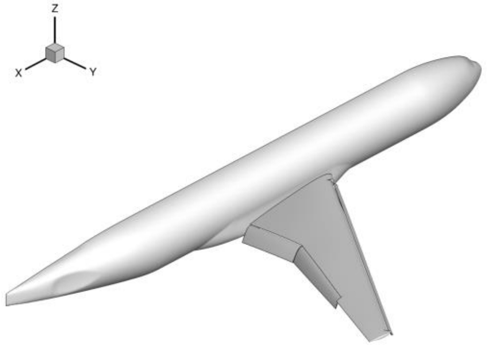
Lessons from HiLiftPW-3

- HL-CRM case explored grid convergence.
- JSM explored effect of nacelle/pylon installation.
- A 2-D verification case was also included.

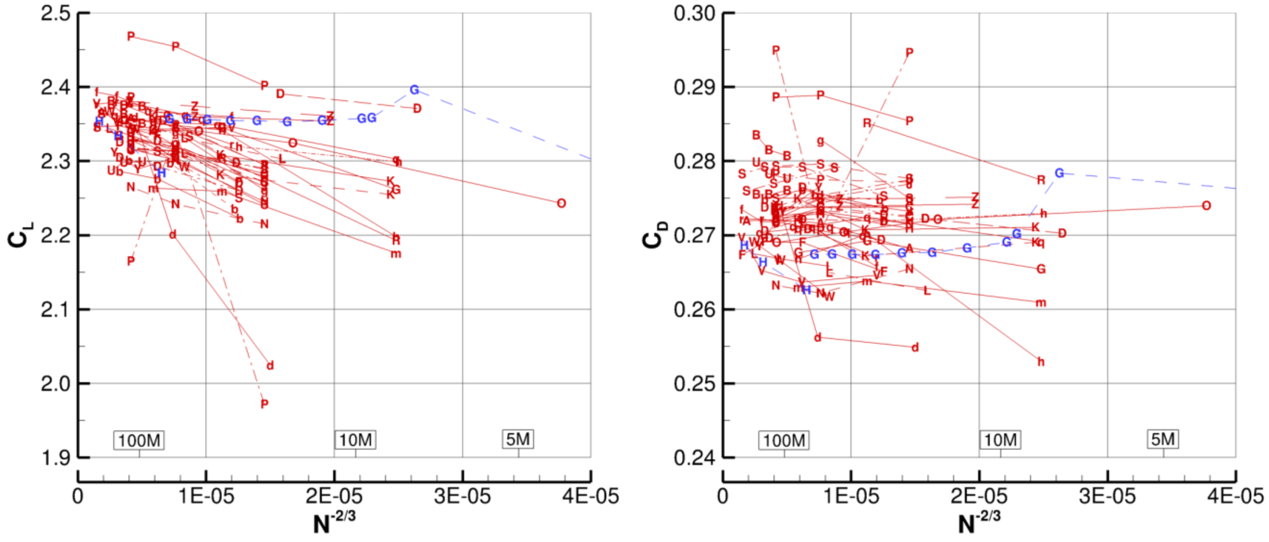


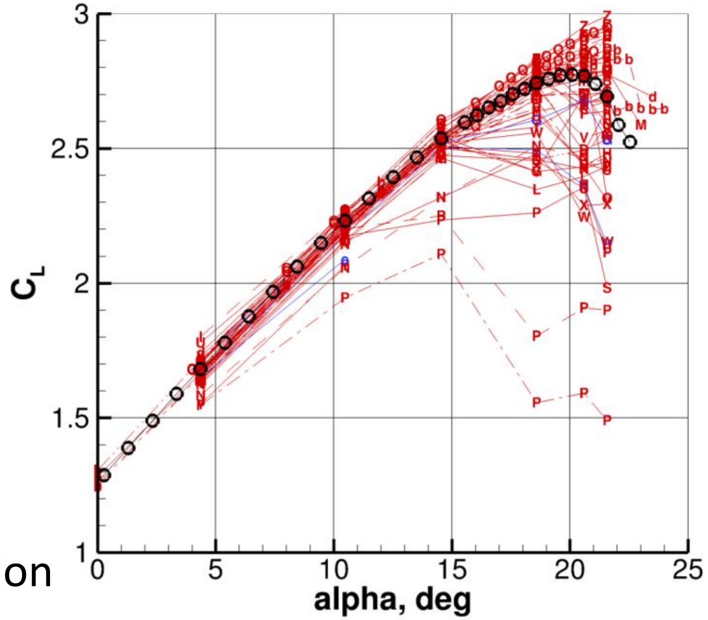
HiLiftPW-3 results

HL-CRM



JSM



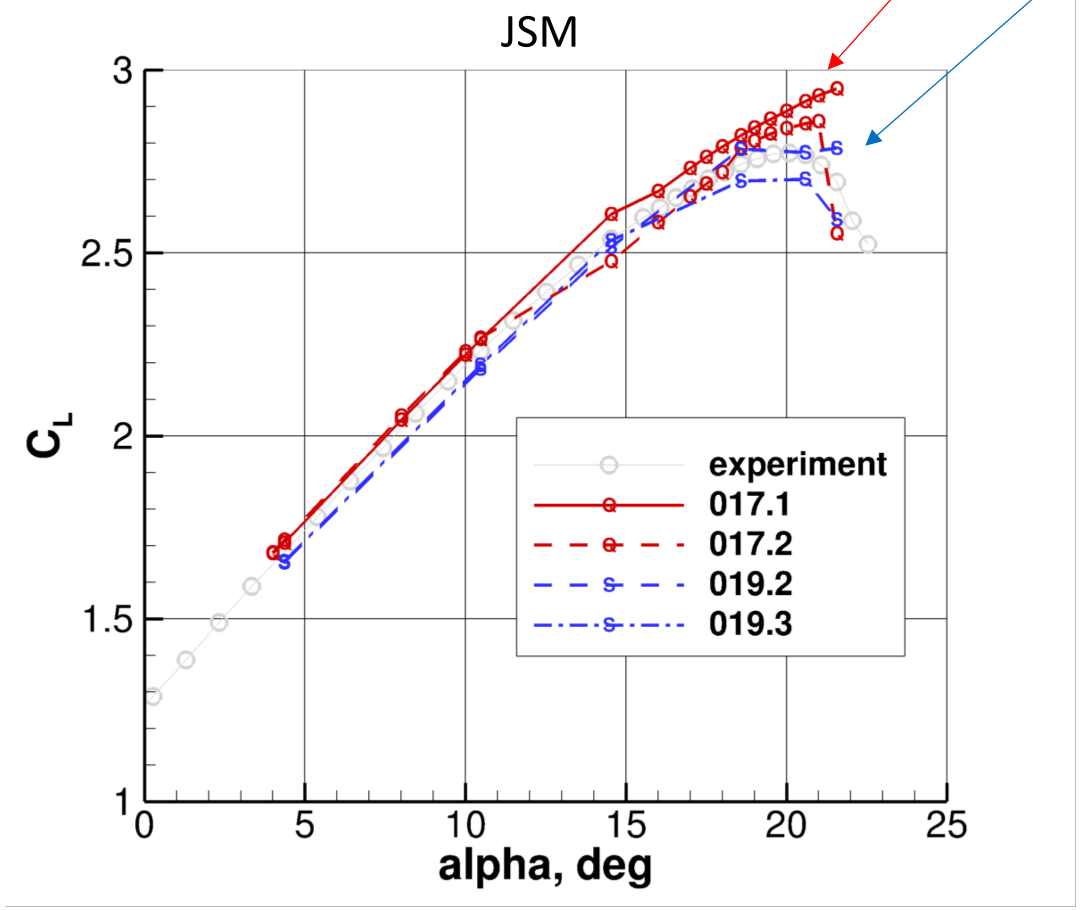


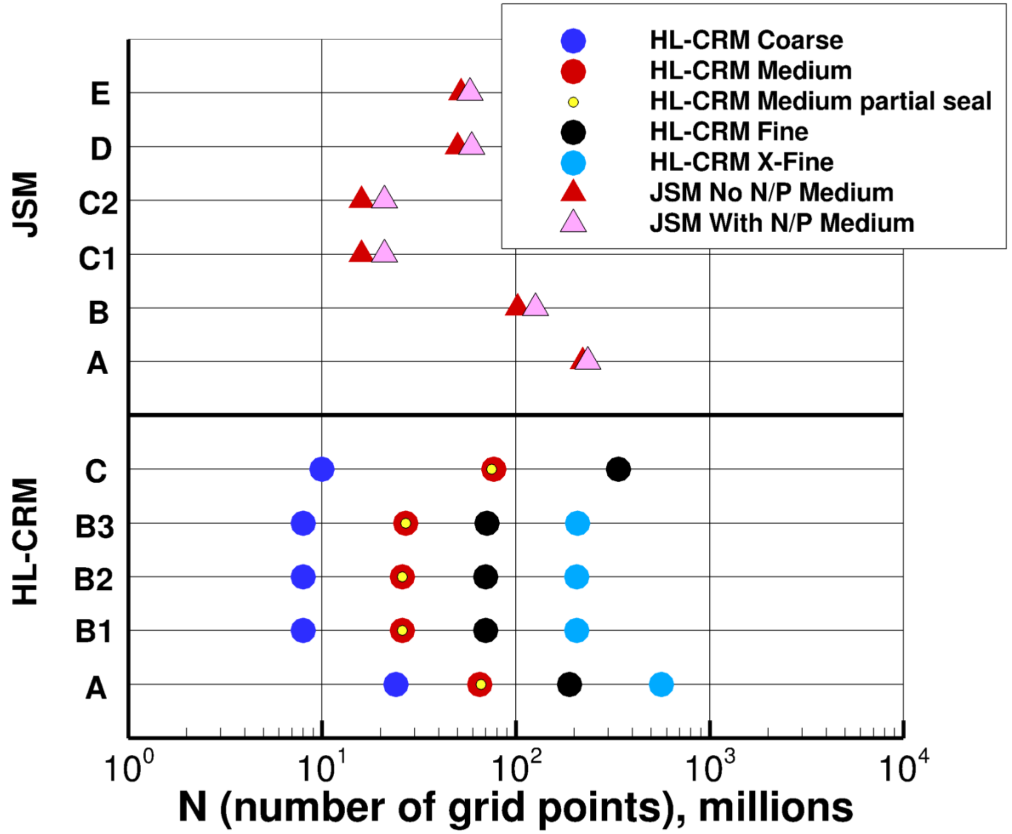
Issue of possible multiple solutions for RANS when separation is present (AIAA Paper 2013-0663)

HiLiftPW-3 results

Same code & model, different grid

Same code & model, different grid



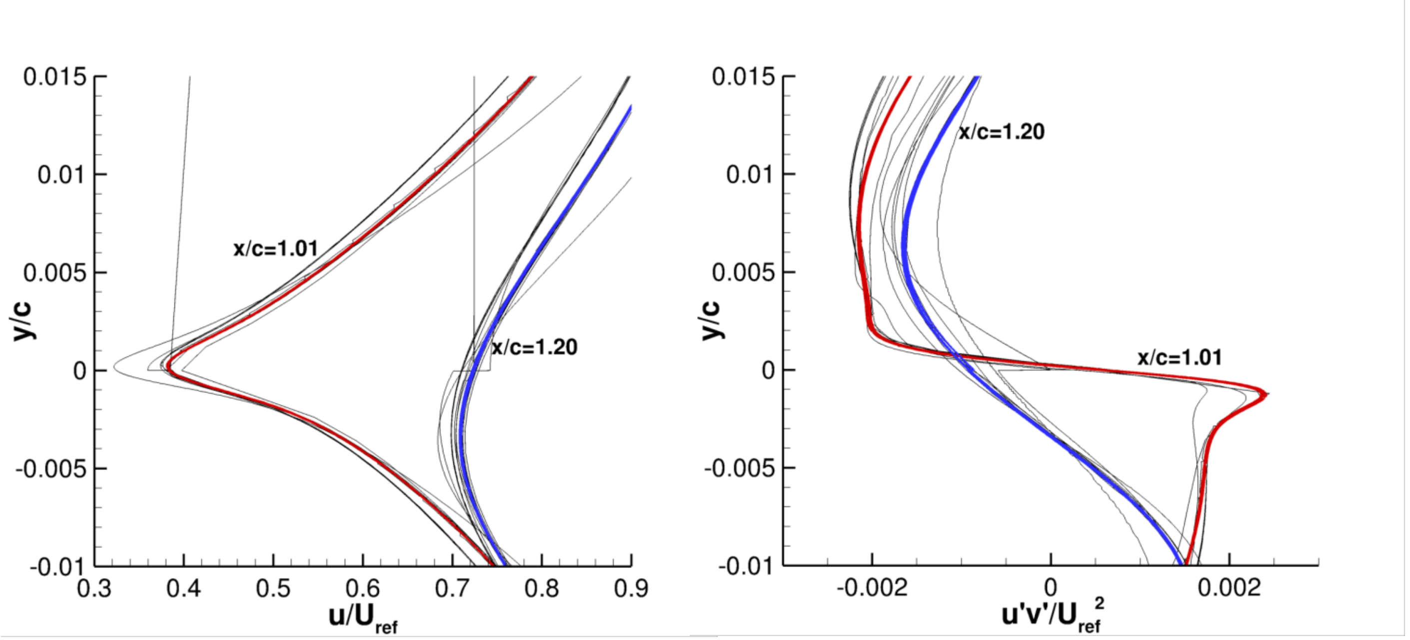


- Grids had effect near $C_{L,max}$
- “Medium” grid sizes still typically less than 100 million points

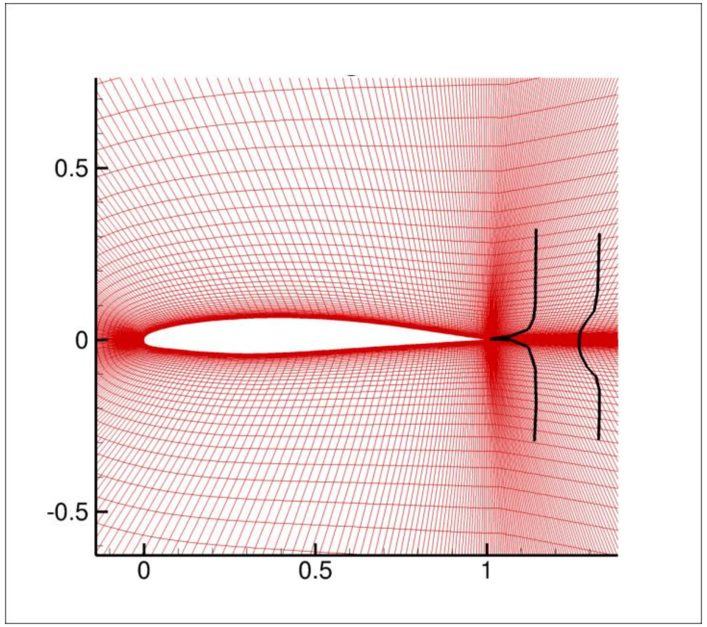
The important role of verification*

2-D verification case

*Software implementation accurately represents developer's description of the model**



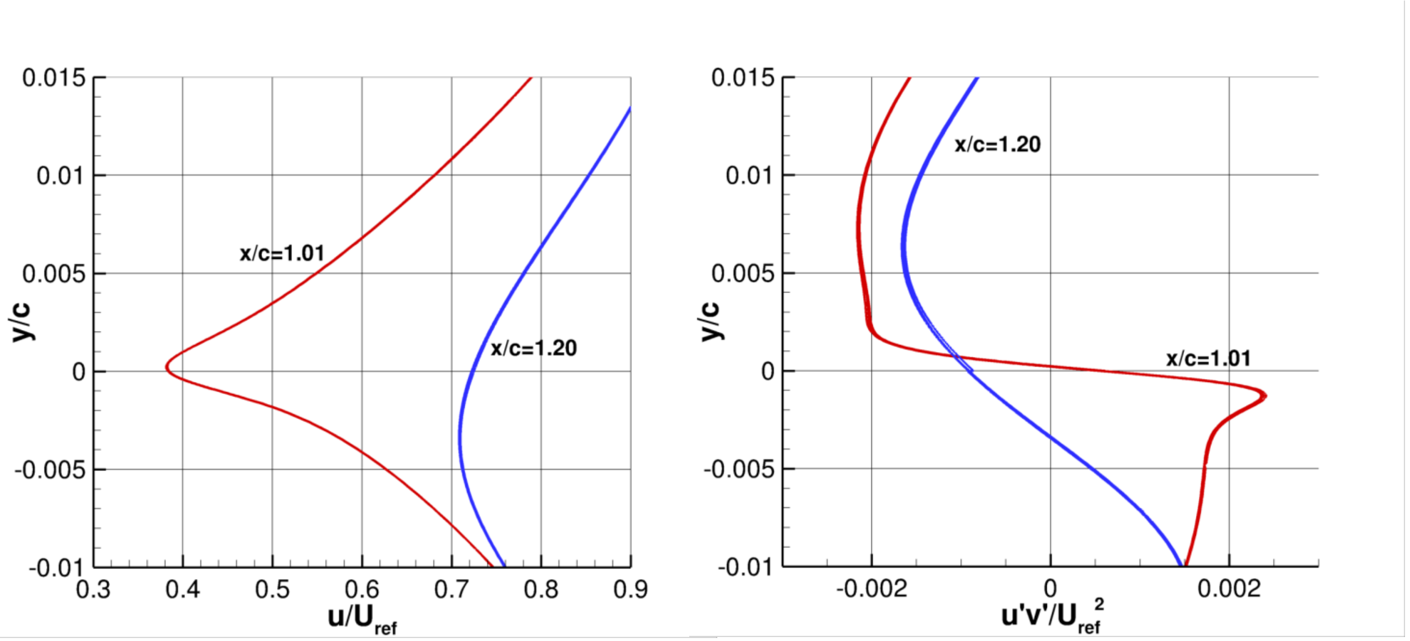
VERIF/2DANW case from TMR website: https://turbmodels.larc.nasa.gov



The important role of verification

2-D verification case

8 different codes produce nearly identical results for SA model



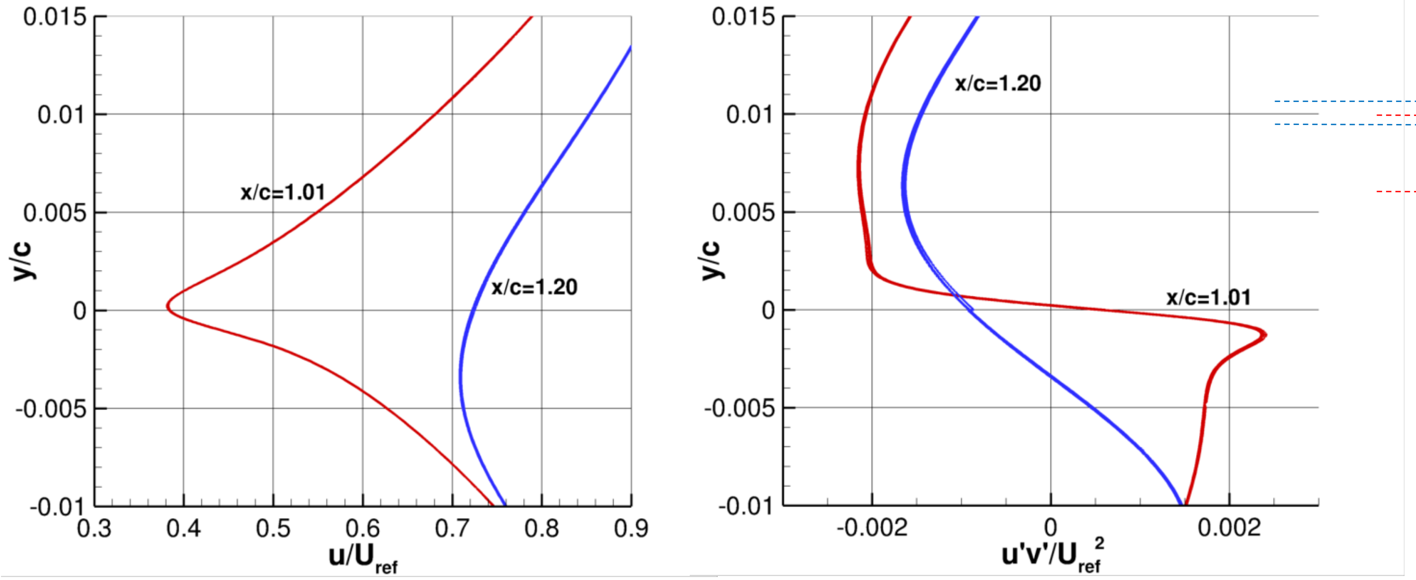
VERIF/2DANW case from TMR website: https://turbmodels.larc.nasa.gov

In the verification case, only 30% of the CFD codes that participated with the SA turbulence model were fully verified.

The important role of verification

2-D verification case

8 different codes produce nearly identical results for SA model



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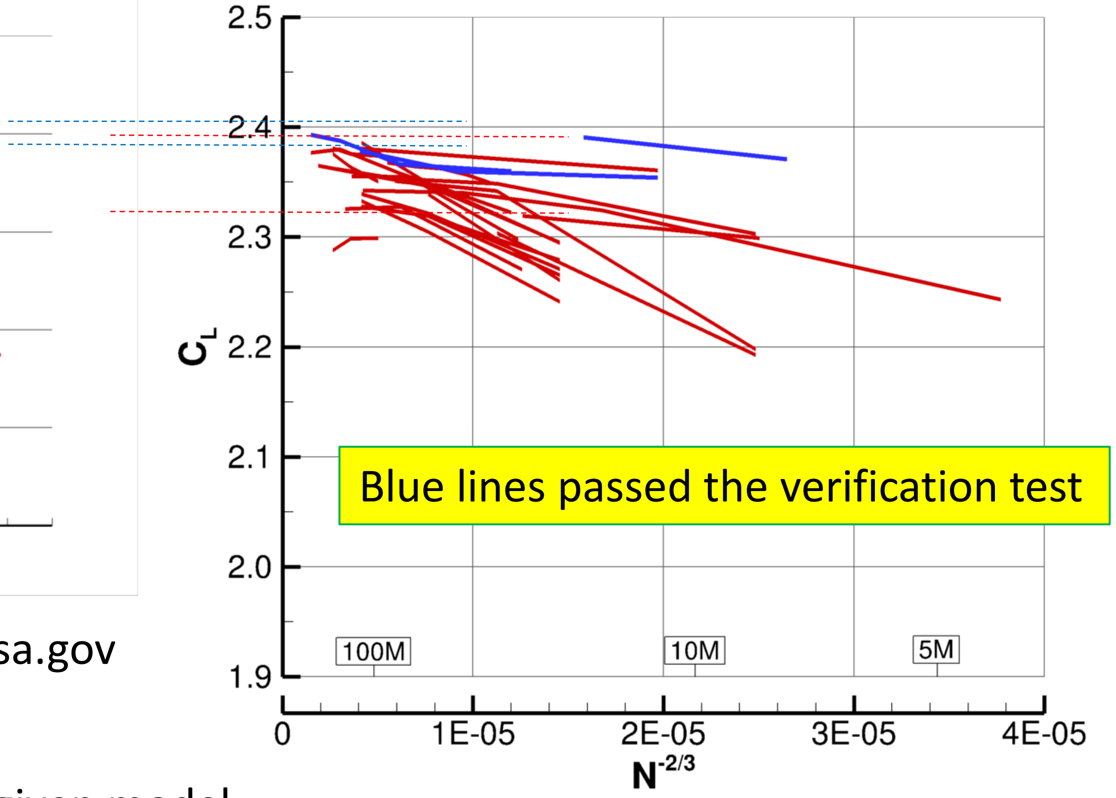
HL-CRM

SA models only



Verification removes one possible source of CFD uncertainty, for a given model.

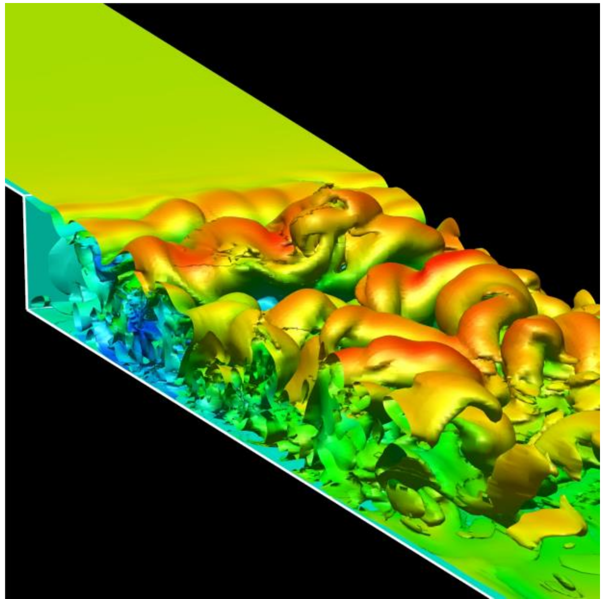
Other sources: grid (size, extent, adherence to geometry), BCs, iterative convergence.

Prospects/needs for RANS

- RANS has apparently made only minor progress in the last 20 years.
  - RST models implemented & verified in multiple codes.
  - Some other new models have emerged (still not as widely used as SA & SST variants):
    - 1 eq: WA-2017.
    - 2 eq: k-kL, EASMs & other nonlinear models.
    - Other: Lag models, elliptic blending models, transition models.
  - It would be beneficial to choose the most promising models & bring community efforts to bear on them.
    - Document, create verification cases, verify in multiple codes, then apply to multiple classes of validation cases in a systematic fashion.
    - Verification cases are still needed for SA-RC-QCR2000.

Prospects/needs for LES and hybrid RANS/LES

- LES, WMLES, hybrid models are under development, in <u>many</u> forms.
  - This class is difficult to get a handle on, because there are so many different methods out there.
  - Much user expertise is typically needed.
  - “Worms” always look nice, but what is the quality of the simulation?
  - VERIFICATION of these methods is much more difficult, but is still crucial.
  - The website http://wmles.umd.edu/ is working toward providing commonality & verification for WMLES.



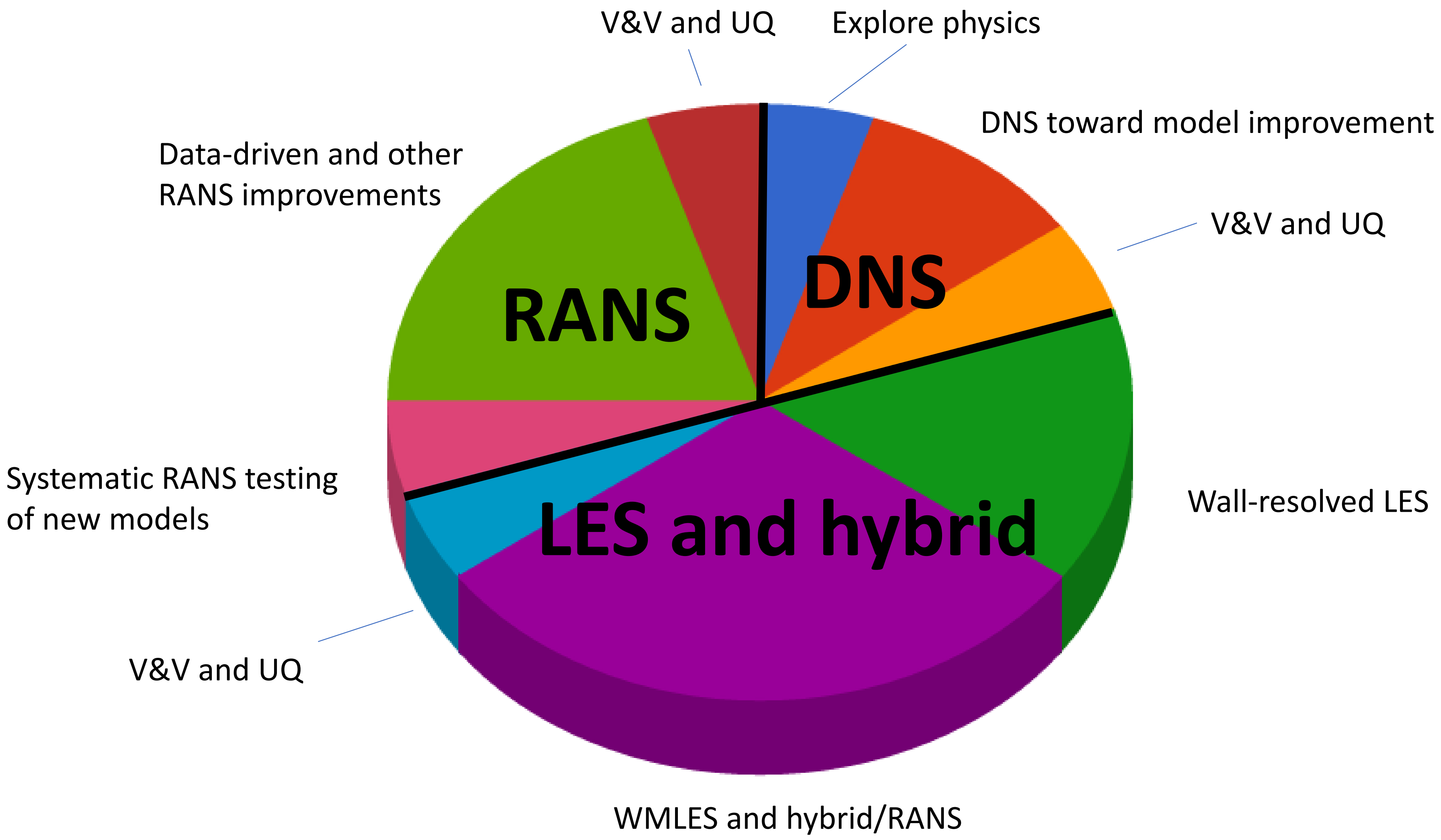
Impact of other disciplines

- HPC
  - Engineers are currently bumping up against resource limits, even for RANS!
  - Need to be able to routinely run on grids of order 1-10 billion points, or more.
  - Code developers need fast & easy access to thousands of cores (not just for production runs).
- Numerical algorithms
  - Low dissipation & dispersion is especially important for scale-resolving simulations (stability, accuracy).
  - Higher order may be beneficial.
  - Good algorithms also crucial for efficiently attaining iteratively fully-converged solutions.
- Physical modeling
  - New experiments specifically designed for CFD validation may teach us things.
    - Separated flows.
    - Compressible mixing layers.
    - Corner flows.
  - Targeted DNS may also offer physical insights to turbulence modelers.
  - But are we losing modelers? (less interest, fewer new students being trained).

Turbulence research: what should be done?

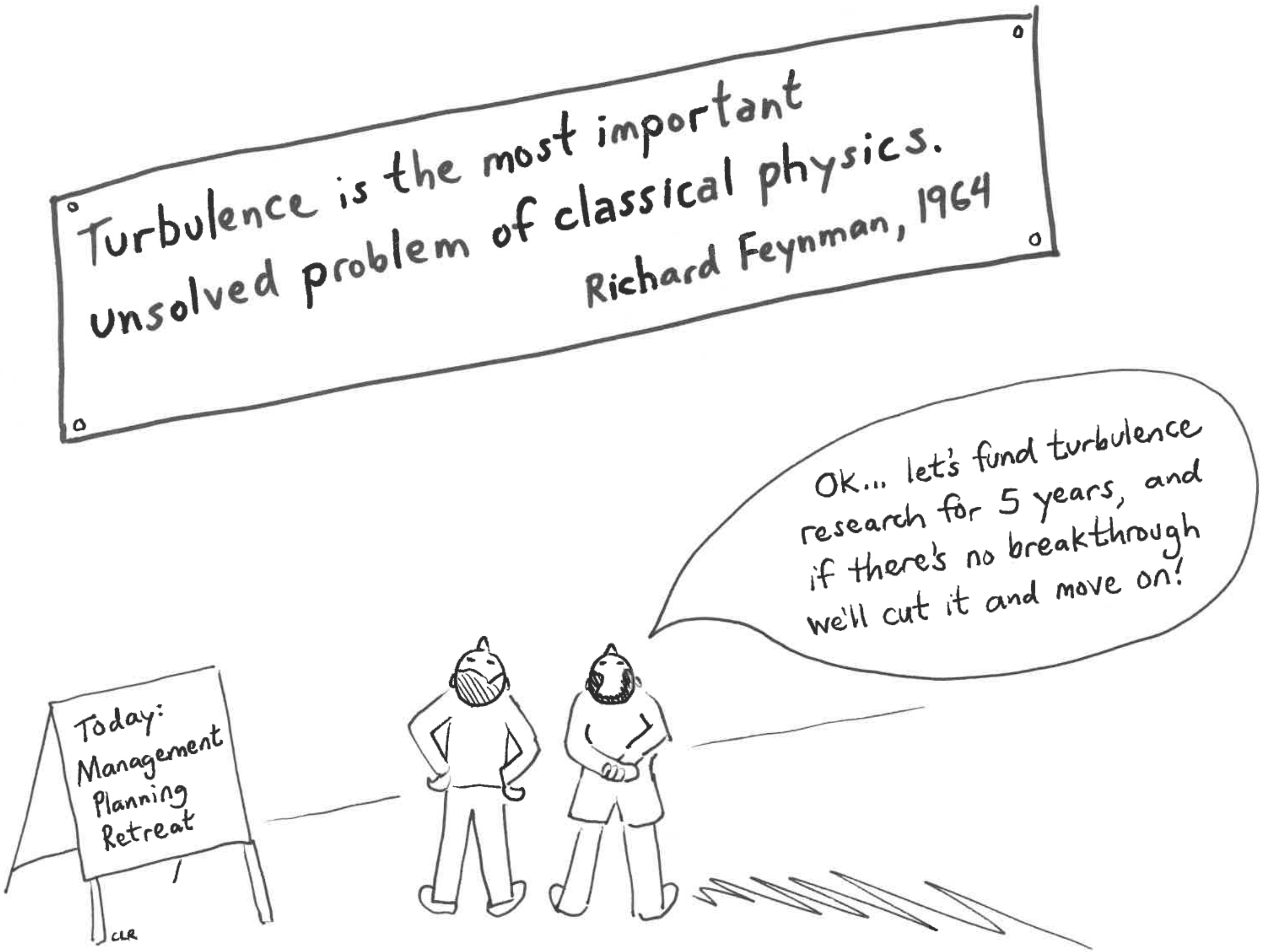
- Experiments:
  - Work together to jointly agree on best 3-D validation experiments, and what to measure (always including uncertainty estimates).
    - Redo some useful “classic” experiments (e.g., Bachalo-Johnson transonic bump).
- Develop <u>portfolio</u> of turbulence research across disciplines, e.g.:
  - DNS
    - Explore flow physics
    - DNS toward improvement of RANS, LES, and hybrid models
    - V&V and UQ!
  - LES and hybrid
    - LES (wall-resolved)
    - WMLES and Hybrid RANS/LES
    - V&V and UQ!
  - RANS
    - Systematic implementation/testing of promising new models
    - Data-driven methods and other research into improvements for existing models
    - V&V and UQ!

Turbulence research: what should be done?



Turbulence research: what should be done?

- V&V and UQ need to be better integrated throughout.
- **Modeling** and **numerical algorithms** are tightly coupled.
- **Numerical algorithms** and **HPC** are also coupled.
- But: danger of spreading too thin within a single organization (e.g., NASA).
  - Need a community of collaborators.
  - Groups like the AIAA Turbulence Model Benchmarking Working Group (TMBWG) are well poised to help bring researchers together.
    - They are also working to help plot a turbulence modeling roadmap.
  - The 2017 Umich/NASA Symposium was helpful; regular meetings/symposia are needed.


Turbulence is the most important unsolved problem of classical physics.
Richard Feynman, 1964
Ok... let's fund turbulence research for 5 years, and if there's no breakthrough we'll cut it and move on!
Today: Management Planning Retreat
CLR


Oh, those are just our Turbulence Modelers ... playing in their SANDBOX as usual.
DANGER QUICKSAND!
CLR

End

Backup

Overview

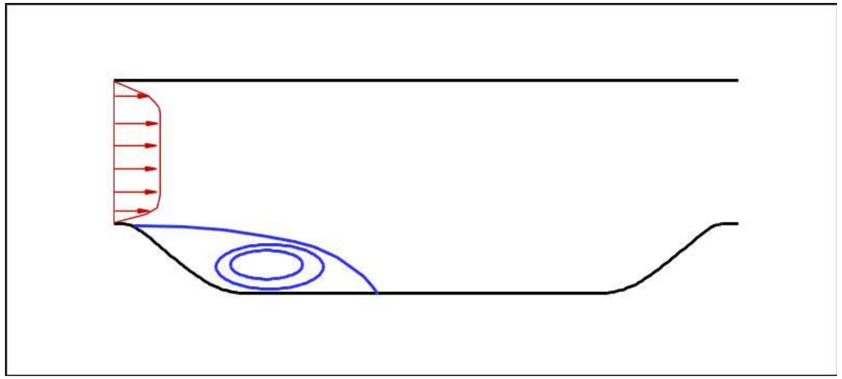
- Future prospects for turbulent flow simulations and how these may be enabled by advances in other fundamental disciplines such as physical modeling, numerical algorithms, and High Performance Computing (HPC).
- Some of this talk is based on turbulence model-related discussions held during a recent University of Michigan / NASA Symposium.

Turbulence Modeling

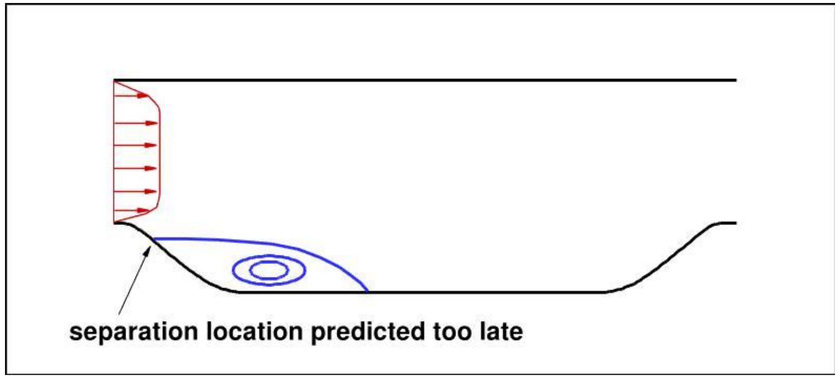
RANS Turbulence Modeling

Smooth-body separated flow

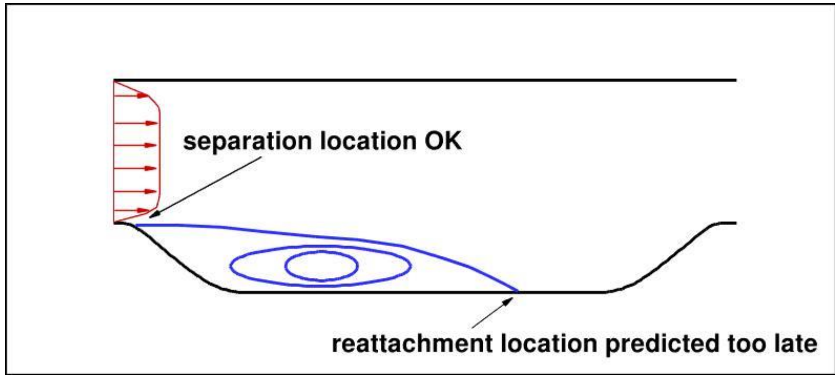
Correct result



Incorrect result typical with k-epsilon



Incorrect result typical with SA, SST, k-omega



See, e.g., ERCOFTAC SIG 15 workshops, AIAA-2014-0201

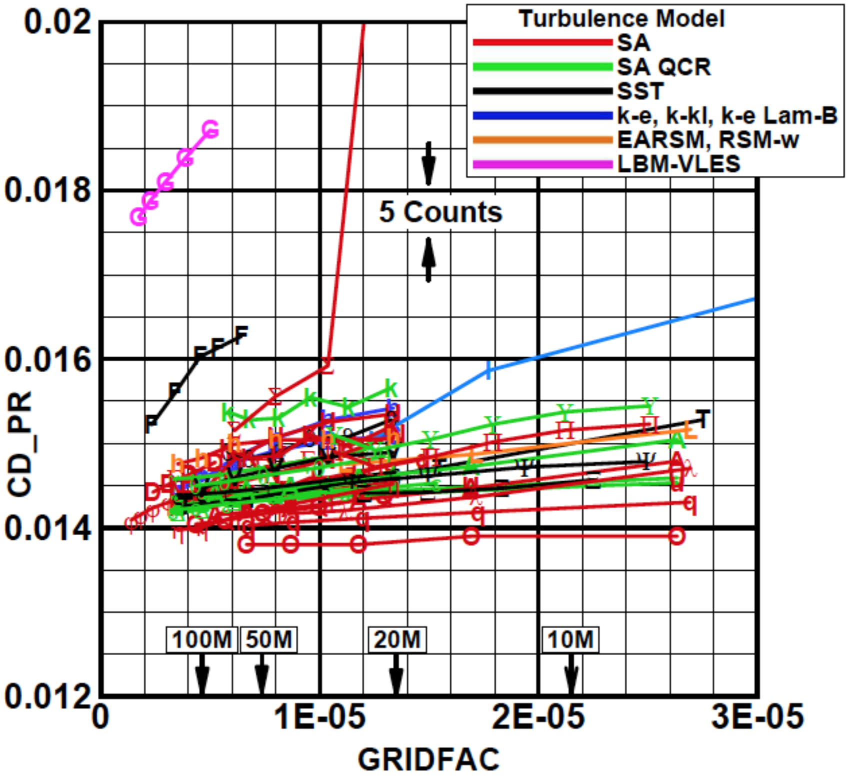
Philosophy

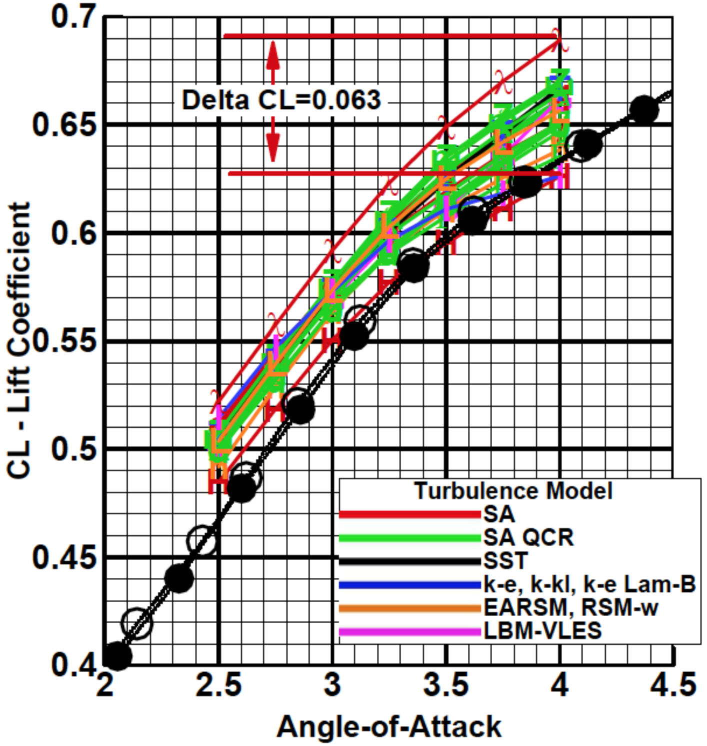
- Controversy over well-posedness of Unsteady RANS (URANS)
  - Lack of distinction between models aimed at RANS vs. URANS?
  - No separation of scales between resolved and modeled turbulence.
  - Is there a clear averaging/filtering operator?
  - Is there a scale defined implicitly by a model's prediction of k and epsilon?
  - Ensemble averaging vs. time averaging.

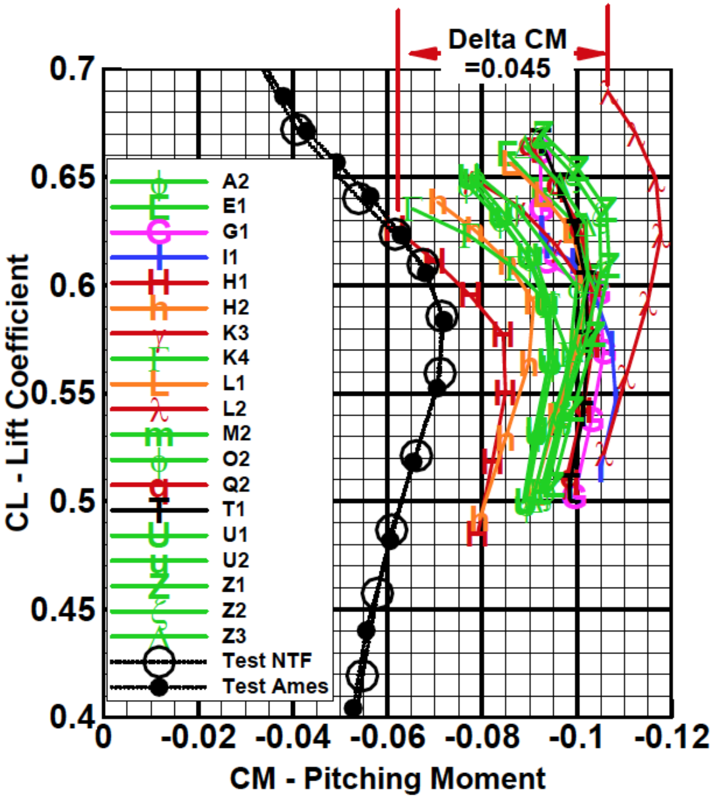
Other recent workshops

- DPW-6
  - Solutions were generally tighter than past workshops (about 10 drag counts at cruise condition, ignoring outliers).
  - Buffet study “fan” of CFD solutions gets progressively wider with increasing angle-of-attack.
  - Questions about whether steady RANS or URANS will be appropriate for buffet, or if need to employ scale-resolving methods.
  - Grid adaption methods were promising; mainstreaming them encouraged.
  - Importance of verification was highlighted, using an NACA 0012 airfoil case.

DPW-6 results from AIAA-2017-1208







Prospects for RANS, LES, and hybrid RANS/LES

- From Spalart's "Philosophies and Fallacies" paper PIAS 74(2015),1-15:
  - CFD numerics work well with local models (where formulation of the model only involves turbulence variables & derivatives of the velocity field at one point).
    - Nonlocal models are more difficult to implement.
    - In unstructured grids & massively parallel computers, communication with non-neighbors is costly.
  - Minimum distance function, higher velocity derivatives can introduce nonlocality and some history effects in an empirical manner (e.g., SA-RC).
  - Systematic vs. empirical philosophy of modeling.
    - Closure problem (is it possible/practical to model individual unknown terms accurately?)
    - In practice, in systematic method, there is still MUCH empiricism.
    - Empirical method: relies on modeler intuition & tuning for certain flows; risk of proliferation.
  - Domain of application of RANS will shrink to primarily boundary layers, with scale-resolving methods elsewhere (ZONAL).

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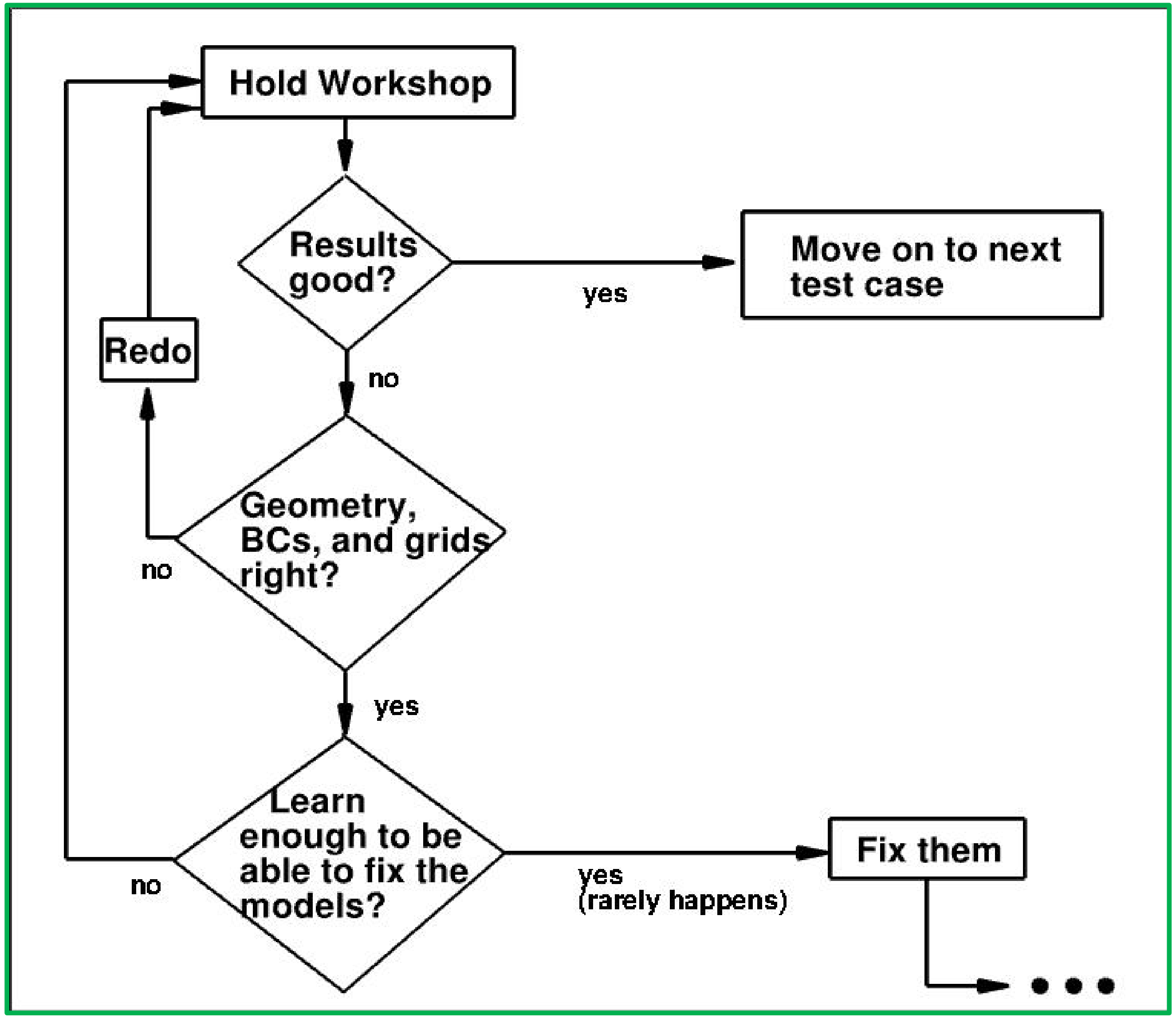
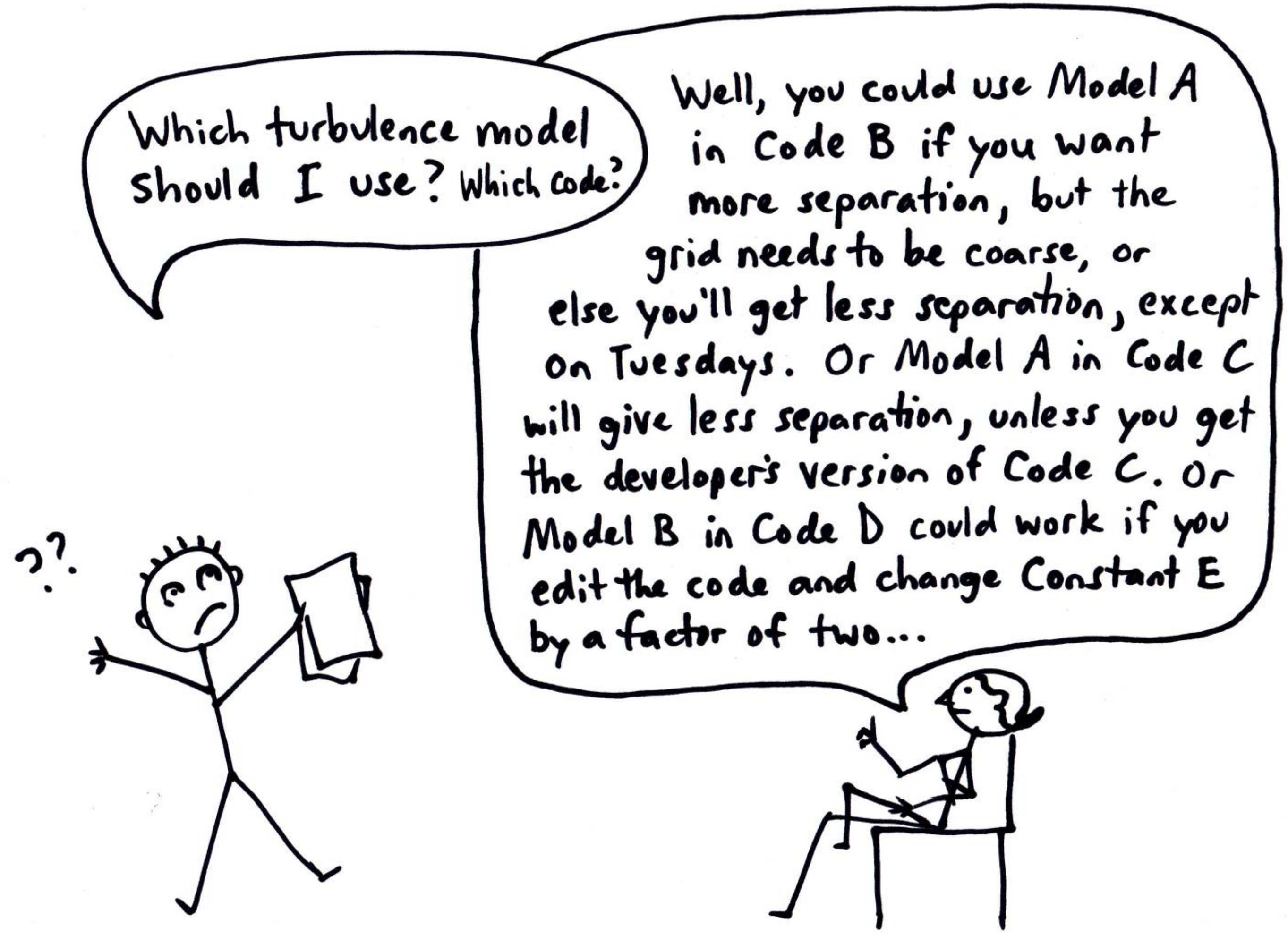
- What can the community do?
  - Regarding RANS research, opinions varied:
    - Focus less on improving existing models, and more on UQ.
    - Continue to chip away at RANS (some: at RST level; others: at 1 or 2 equation level).
      - Less experts in the field means more collaboration is needed.
      - Can data-driven modeling yield fruit?
      - Maintain balanced portfolio (do not go completely over to LES-related research)
  - Experiments:
    - Work together to jointly agree on best 3-D validation experiments.
      - Perhaps redo some ”classic” experiments (e.g., Bachalo-Johnson transonic bump).
    - What data is most useful to measure?
      - Skin friction.
      - Reynolds stresses.
      - Differences between budget terms are probably more important than individual terms, and many of the terms themselves cannot be easily measured in any case.
  - Numerics:
    - High Performance Computing (HPC) is needed to help accelerate the trend toward larger 3-D grids, more time-accurate applications, and more scale-resolving capability.
    - Integrate automatic anisotropic grid adaption into standard practice.

The important role of verification



The important role of verification

Move from this…



The important role of verification

Toward this…