Air Vehicle Design

AOE 4065 – 4066

II. Air Vehicle Design Fundamentals

Course Module A9

Use of Software Tools

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AOE 4065-4066:
Capstone Air Vehicle Design (AVD) Course Modules (CMs)

Overview of AVD Courses

I. Foundational Elements

F1. Design: *An Engineering Discipline*

F2. Systems and Systems Thinking

F3. Basics of Systems Engineering

F4. Decision Making with Ethics and Integrity

II. Air Vehicle Design Fundamentals

A1. Purpose & Process

Conceptual Design

A2. Understand the Problem

A3. Solve the Problem

A4. Initial Sizing: *Takeoff Weight Estimation*

A5. Initial Sizing: *Wing Loading and Thrust Loading Estimation*

A6. Cost Considerations

A7. Concept to Configuration: *Key Considerations*

A7A. Configuration Layout: *Drawings & Loft*

Conceptual & Preliminary Design

A8. Trade Studies

A9. Use of Software Tools

A10. Preliminary Design: *Baseline Design Refinement & Validation*

III. Project Management Topics

P1. Basics of Project Management and Project Planning

P2. Project Organization

P3. Roles & Responsibilities of Team Members

P4. Project Execution: *Teamwork for Success*

P5. Project Risk Management

P6. Delivering Effective Oral Presentations

P7. Writing Effective Design Reports

Disclaimer

Prof. Pradeep Raj, Aerospace and Ocean Engineering, Virginia Tech, collected and compiled material contained herein from publicly available sources solely for educational purposes during the 2012-2024 time frame.

Although a good-faith attempt is made to cite all sources of material, we regret any inadvertent omissions.

CRUCIALLY IMPORTANT

CMs only introduce key topics and highlight some important concepts and ideas…but without sufficient detail.

We must use lots of Reference Material* to add the necessary details!

(*see Appendix in the Overview CM)

Outline

A9. Use of Software Tools

A9.1 Why use software tools?

A9.2 Recommended software

A9.3 Pervasive use of CFD

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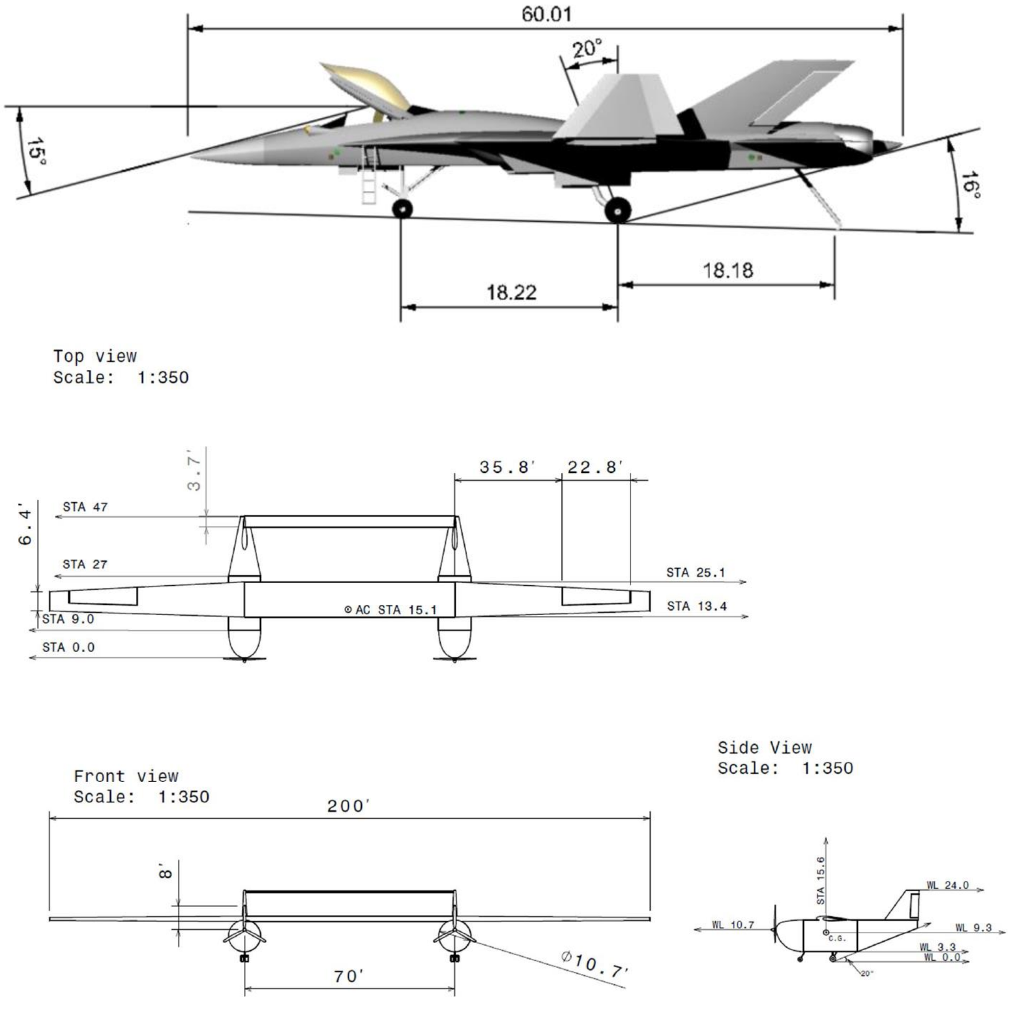
Why Use Software Tools?

Just because we can?

No, we should not use them just because we can.

We must <u>know</u> the purpose!



We should use them because…

- we can perform functions with
  - ✓ Higher efficiency
  - ✓ Increased productivity
  - ✓ Reduced time
  - ✓ Reduced cost
  - ✓ Fewer errors
- we can explore more design options
- we can spend **more time for creative thinking**
- …

They take out the drudgery <u>IF</u> used judiciously

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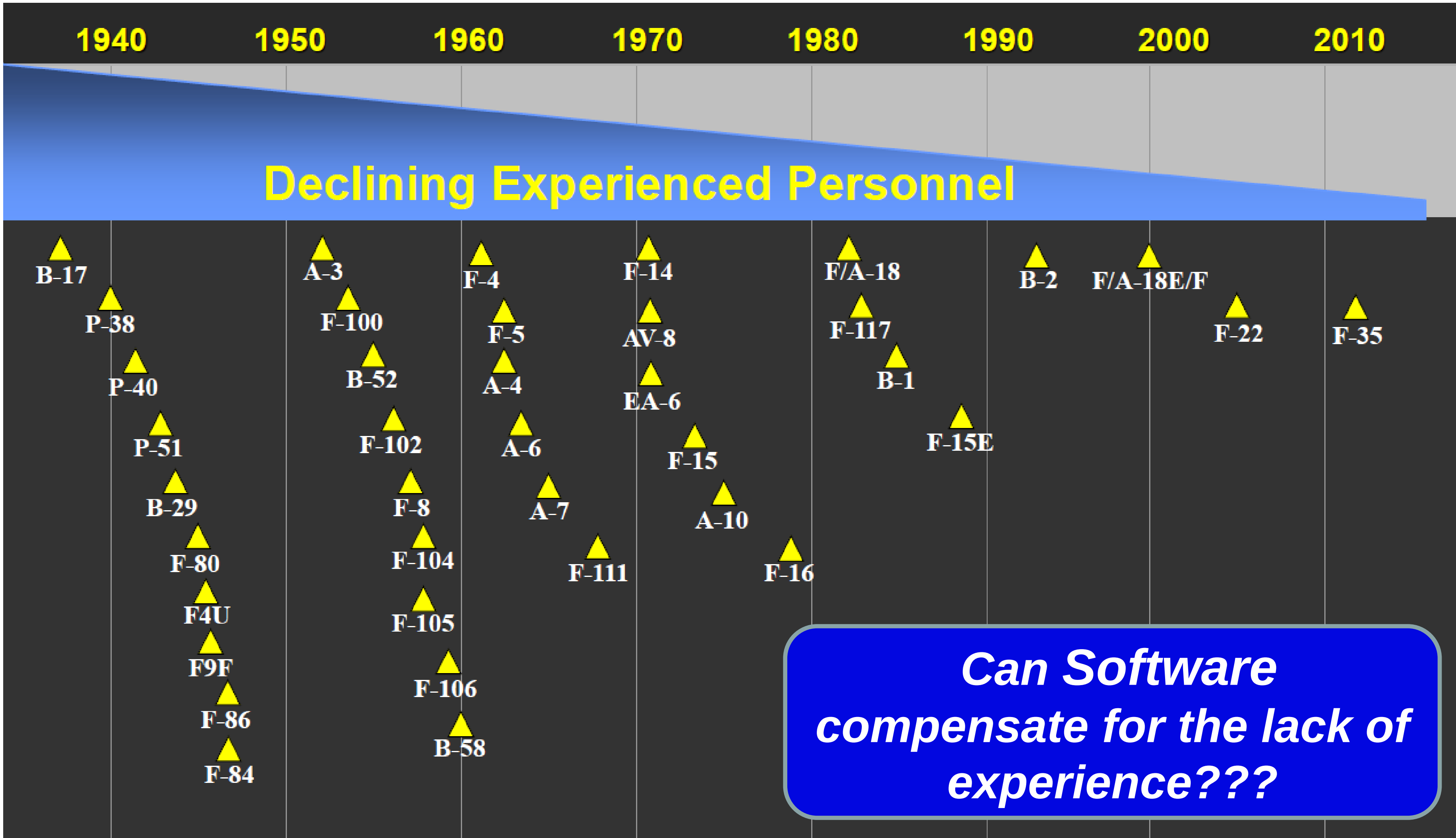
A Critical Workforce Challenge

(Defense Industry Example)

*Limited Opportunities for Engineers to Gain Experience**



Can Software compensate for the lack of experience???

**Learn from their own mistakes!*

Before Using Any Software Tool, Ask:

"DO WE KNOW WHY WE'RE USING IT?"

"New engineers today have an overdependence on computers. They have a tendency to believe everything the computers tell them. You throw in a bunch of numbers and out comes the answer, and therefore it must be right. **Just because it comes out on a computer printout doesn't make it right**."

Benjamin Cosgrove (1926-2006)
Sr. Vice President of Engineering, Boeing Commercial Airplanes

I should be able to go to a wing designer and say to him or her, "We need to change the gross weight by 5%. How does that change the bending moment of the new wing?" If that person runs a calculation on the back of the envelope and says it'll do this, that's fine with me. But when someone says I'll give you the answer in three days when it comes out of the computer, that's an overdependence. **You've got to have practical thinking people who know what they're doing**."

A Talented Engineer Can Do Wonders Even Without Computers

Two Key Aspects of All Software: *Verification & Validation*

No Bugs!

- Is the software solving the *problem right*? VERIFICATION
- Is the software solving the *right problem*? VALIDATION

How faithfully do our predictions mimic reality?

You must consider BOTH aspects when writing your own code.

What We Simulate Is Not Reality Itself, But Reality Determined by Our Software.

Beware of a "Validated Code"

- **An Example: CFD Vendors Typically Offer *'Validated Codes'***
  - Implies that *simulation results can be trusted because they accurately predict the real flow characteristics.*
- **Traditional Code Validation Approach**
  - Correlate computed and test results for a *select set of* test cases.
- **But Traditional Code Validation is of Limited Value**
  - Even extensive correlations of computed and test results on geometries and flow conditions ***that differ substantially from those being considered for design*** are of limited value.
  - Too Many Potential Traps: *Generation of grid-converged solutions; availability of on- and off-surface measured data from the same test; Reynolds number scaling of test data; accurate matching of boundary conditions; user proficiency; etc., etc., etc.*

'Validated Code' – A Misnomer

Measure of Merit of Software Tools

- **'Effectiveness' is the Measure of Merit of Software Tools in *Aircraft Design Environment;* it is best defined as**

$$Effectiveness = Quality \times Acceptance$$

  - ***"Q" (Quality)* Factor**
    - **Credibiity of data produced by the tools** (Can we trust the data/ results?)
  - ***"A" (Acceptance)* Factors**
    - **Turnaround time** (Elapsed Time) **from go-ahead to data delivery**
    - **Cost of producing data** (Labor Hours plus H/W-S/W related expenses)
- **Desired State**
    - *Rapid Turnaround*
    - *Low Cost*
    - *Credible Data*

Simultaneously!

Watch for software portability and compatibility as well

Note: E = Q x A is applicable to many systems, not just software

Outline

A9. Use of Software Tools

A Rich Source of Software Suites for Aircraft Design

https://archive.aoe.vt.edu/mason/Mason_f/MRsoft.html

Current Software

Aerocal Pak #1	Takeoff Distance Calculation*
stand alone NACA 1135*	Landing Gear Integration
Standard atmosphere	Propulsion
Airplane Design and Sizing • Nicolai's sizing program(s)* • OpenVSP • CEASIOM • Dan Raymer's Aircraft Design Pages	*Geometry* • Airfoil generation: NACA 4&5 Series*, foilgen • Airfoil generation: NACA 6&6A Series*, LADSON • Planform Analysis*, WingPlanAnal • A Zip file with a collection of airfoils.
Lifting Line Theory • Simple Lifting Line Theory* • Utah State Lifting Line and Aero Analysis	Skin Friction/Form Factor Drag* friction
Induced drag • Induced Drag for a single planar wing*, LIDRAG • Induced Drag for nonplanar lifting systems*, idrag • Induced Drag for simple nonplanar lifting systems, with camber line design*, LamDes2	*Vortex Lattice Methods* • Vortex lattice analysis and design: VLMpc* • Vortex lattice analysis and design: VLM 4.997 (manual only) • Vortex lattice analysis code in MATLAB: Tornado • An extended vortex lattice code from Prof. Drela at MIT and Harold Youngren: AVL
Airfoil Aerodynamics • Vortex lattice design to find the 2D camber line for a given chordload*, DESCAM • Subsonic Airfoil Analysis and Design: XFOIL 6.9 • Subsonic Airfoil Analysis and Design: Pablo • Subsonic Airfoil Analysis and Design: JavaFoil • Transonic airfoil analysis: TSFOIL2*	*Supersonic Aerodynamics* • Supersonic aerodynamics of arrow wings* • Minimum drag and area distribution* • Harris Wave Drag computation (manual and data sets only) • Supersonic cone at zero angle of attack
Stability and Control • Control Power Assessment* • Lateral/Directional estimates and Engine Out* • DigitalDATCOM stability and control estimation (sample input files only) • Single engine minimum control speed	*Cryogenic Wind Tunnel Testing* • Transonic Testing Background • A Spreadsheet Calculator

* - executable available

Online Databases for Aircraft Design

- ***Airfoildb:*** *http://www.airfoildb.com*
- ***Airfoiltools:*** *http://www.airfoiltools.com*
- ***Hexcel:*** *http://www.hexcel.com/Resources/Calculator*
- ***Edraw:*** *http://www.edrawsoft.com/*

Software Suites for Synthesis/Sizing

PARAMETRIC GEOMETRY MODELS

- ***OpenVSP (Vehicle Sketch Pad)***
  http://www.openvsp.org/download.php

- ***SOLIDWORKS***
  http://www.solidworks.com/sw/products/3d-cad/

- ***Rhinoceros***
  https://www.rhino3d.com/…

PERFORMANCE AND SIZING

- ***FLOPS***
  https://software.nasa.gov/software/LAR-18934-1

- ***Pacelab APD***
  http://www.pace.de/products/preliminary-design/pacelab-apd.html

Software Suites for Analysis

AERODYNAMICS

- ***FRICTION, LIDRAG, IDRAG, LAMDES, AWAVE, VLM, AVL,… and many more methods!***
  https://archive.aoe.vt.edu/mason/Mason_f/MRsoft.html
  https://www.cambridge.org/us/academic/subjects/engineering/aerospace-engineering/applied-computational-aerodynamics-modern-engineering-approach?format=HB&isbn=9781107053748
- ***XFLR5:*** *http://www.xflr5.tech/xflr5.htm*
- ***XFOIL:*** *http://web.mit.edu/drela/Public/web/xfoil*
- ***VSPAero:*** *http://openvsp.org/wiki/lib/exe/fetch.php?media=vsp_aircraft_analysis_user_manual.pdf*
- ***Tornado:*** *http://tornado.redhammer.se/*
- ***Genesis:*** *https://www.hpcmpcreategenesis.org/*
- ***STAR-CCM+:*** *https://www.plm.automation.siemens.com/global/en/products/simcenter/STAR-CCM.html*
- ***OpenFOAM:*** *http://www.openfoam.org/download/*

STABILITY & CONTROL

- ***DigitalDATCOM:*** *http://www.pdas.com/datcom.html*
- ***AVL:*** *http://web.mit.edu/drela/Public/web/avl/*

Software Suites for Analysis

PROPELLERS

- ***QPROP:*** *https://web.mit.edu/drela/Public/web/qprop/*
- ***XROTOR:*** *https://web.mit.edu/drela/Public/web/xrotor/*

STRUCTURES

- ***SOLIDWORKS Simulation:*** *https://www.solidworks.com/domain/simulation*
- ***ANSYS:*** *https://www.ansys.com/products/structures*

NOISE

- ***ANOPP2:*** *NASA software*

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Recognize Stages of Proficiency

1. Innocent	Has never heard of X
2. Aware	Has read an article about X
3. Apprentice	Has attended a class on X
4. Practitioner	Has practiced X and is ready to use it on a real project
5. Journeyman	Uses X naturally and automatically
6. Master	Has internalized X and knows when to break the rules!

Outline

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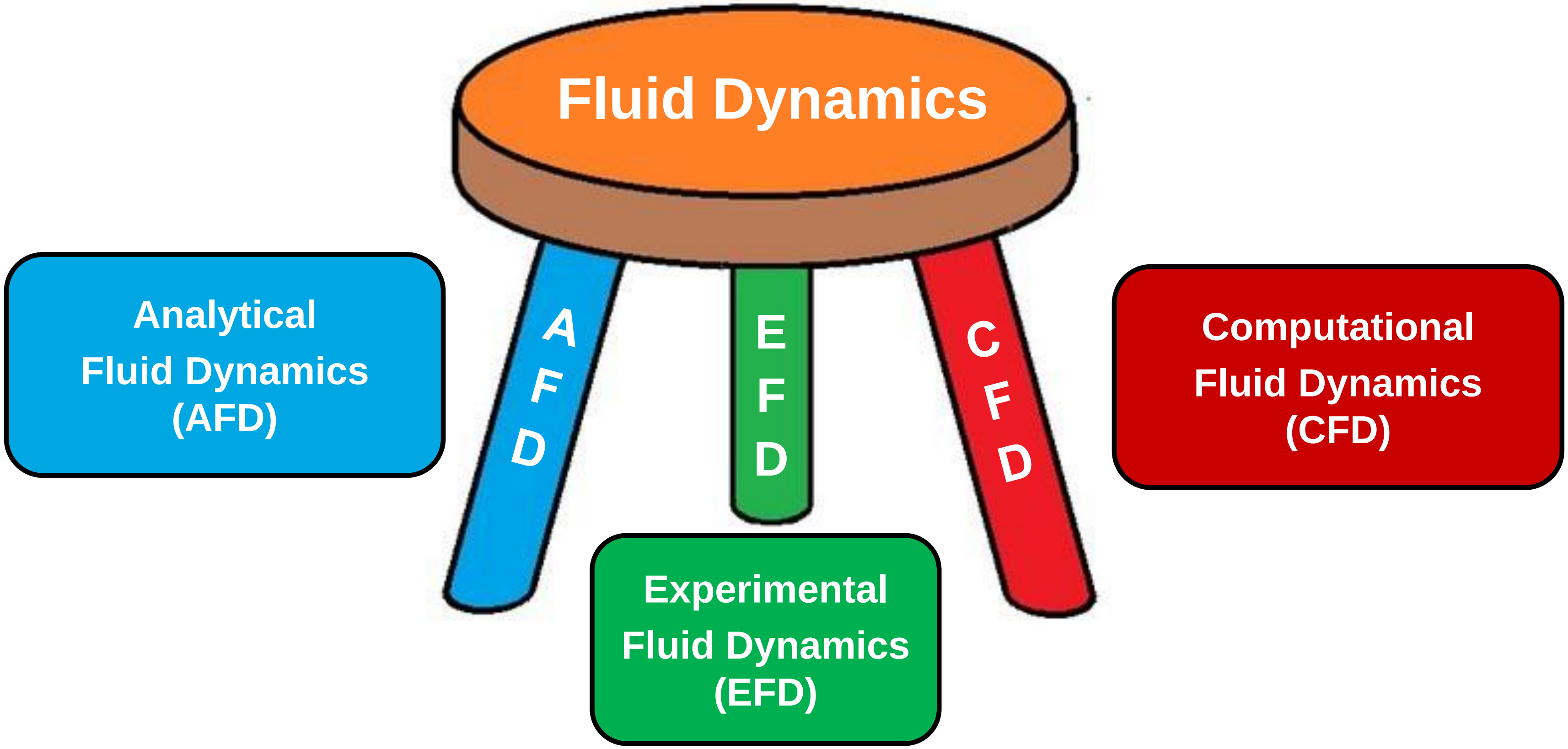
A9.3 Pervasive use of CFD

Computational Fluid Dynamics (CFD):
A Subdiscipline of Fluid Dynamics

Fluid Dynamics: The branch of applied science concerned with the movement of fluids (liquids and gases).*



Aerodynamics: *A subset of Fluid Dynamics with air as the fluid.*

Synergistic Use of AFD, EFD, and CFD is Essential for Comprehensive Understanding of Fluid Dynamics

*American Heritage Dictionary definition

EFD and CFD:

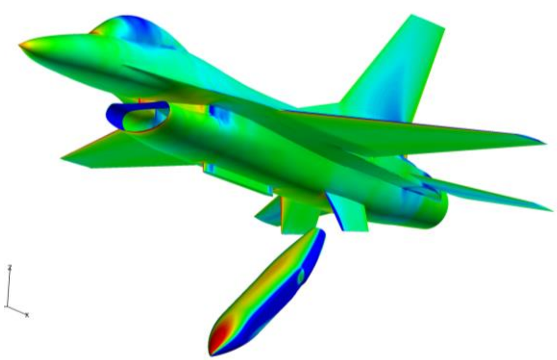
Two Primary Means of Aerodynamic Simulations Today

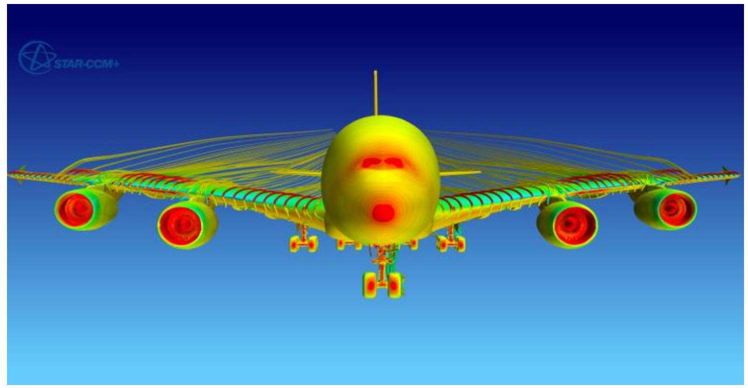
	EFD (Experimental Fluid Dynamics)	CFD (Computational Fluid Dynamics)
Strengths	• Perceived as "Real" • Credible data ▪ Quantified uncertainties • Large excursions per entry	• Low cost • Quick turnaround • No scale effects • No wall interference effects • No support interference effects • Can model aeroelastic distortions • Applicable to ***all*** flight conditions
Weaknesses	• Higher cost, longer elapsed time • Scale effects • Wall interference effects • Support interference effects • Aeroelastic distortions • Not practical for ***some*** flight conditions	• Perceived as "Virtual" • Lack of credibility due to ▪ Computational uncertainties caused by limitations or deficiencies in Numerical Modeling and Flow Physics Modeling

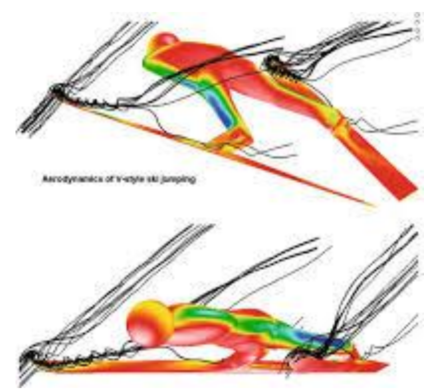
Highly Complementary Strengths

CFD for Engineering Design

CFD is used to simulate flow about bodies moving through a fluid by solving governing mathematical equations on digital computers.







CFD Use is Now a Necessity—Not a Luxury—for Engineering Design of Air Vehicles

Image Source: Internet

CFD Plays a Crucial Role in Engineering Design of Flight Vehicles

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- **Generates Aerodynamic Data to Support Flight Vehicle Design**
  - New Vehicles ("*clean-sheet" designs*)
  - Derivative Vehicles (*improvements, upgrades and/or modifications*)
- **Enables Multidisciplinary Analysis, Design & Optimization (MADO) Environments to Create Quality, Affordable Flight Vehicles**
  - CFD offers the *most practical* (probably the only?) *means* of producing data required for rapid design closure through extensive multidisciplinary trade-offs
  - CFD affords timely and cost-effective evaluation of the impact of geometric changes on performance, and of sensitivity of performance to *numerous* design variables
  - *CFD provides inverse design and shape optimization capability that most clearly differentiates it from wind tunnels*

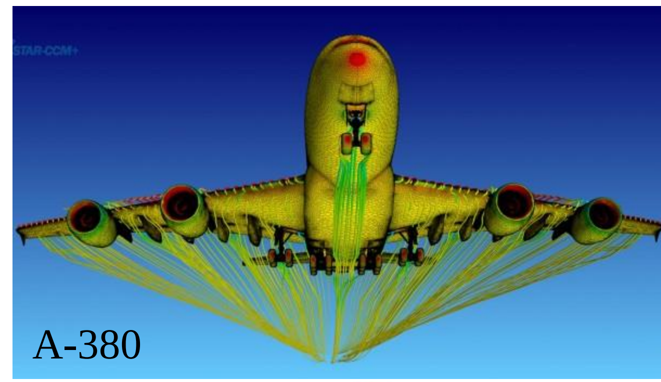
CFD Provides Required Aerodynamic Data to Meet Flight Vehicle Design Needs

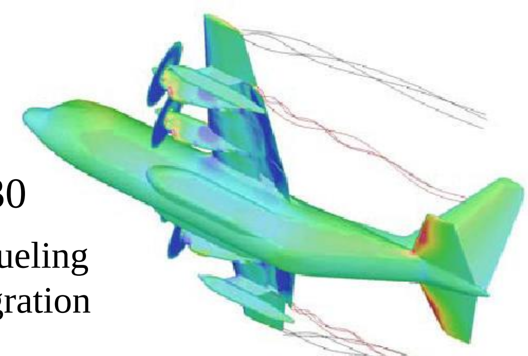
Source: Refs. 1.13 – 1.21

Pervasive CFD Use in Flight Vehicle Design

- **New Vehicles ("clean-sheet" designs)**
  - *Outer Mold Line (OML) Design:* Forces, moments, and surface pressure distributions
  - *Shape Optimization*: Sensitivity of aerodynamic data to design variables
  - *Flight Performance Prediction:* Data to validate take-off, climb, cruise, maneuver, descent, landing
  - *Airframe Propulsion Integration:* Data to minimize installation losses
  - *System Integration:* Off-body flow field for safe carriage and deployment of stores & weapons
  - *Structural Design*: Steady and unsteady flight loads
  - *Flight Control System Design*: Stability & Control coefficients and rate derivatives
  - Etc.
- **Derivative Vehicles (improvements, upgrades and/or modifications)**
  - Aerodynamic data to assess impact of shape change on performance when integrating new or improved subsystems to upgrade current product or design a derivative


Quieter Supersonic Aircraft


A-380


KC-130

New Refueling Pod Integration

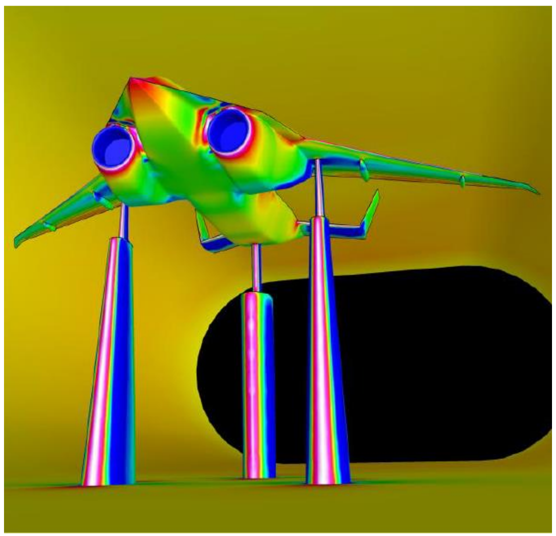
Success Hinges on Credible Data On Time & On Budget

Source: Refs. 1.13 – 1.18

CFD Produces Data!

Computational Fluid Dynamics (CFD) offers a powerful *means* of *simulating fluid flows*, à la wind tunnels, about bodies of arbitrary shape.

CFD Simulation



Both use a 3-step process

1. Build a model

2. Blow air on it

3. Gather and interpret data

(Data include forces, moments, and flow quantities—on and off the surface)

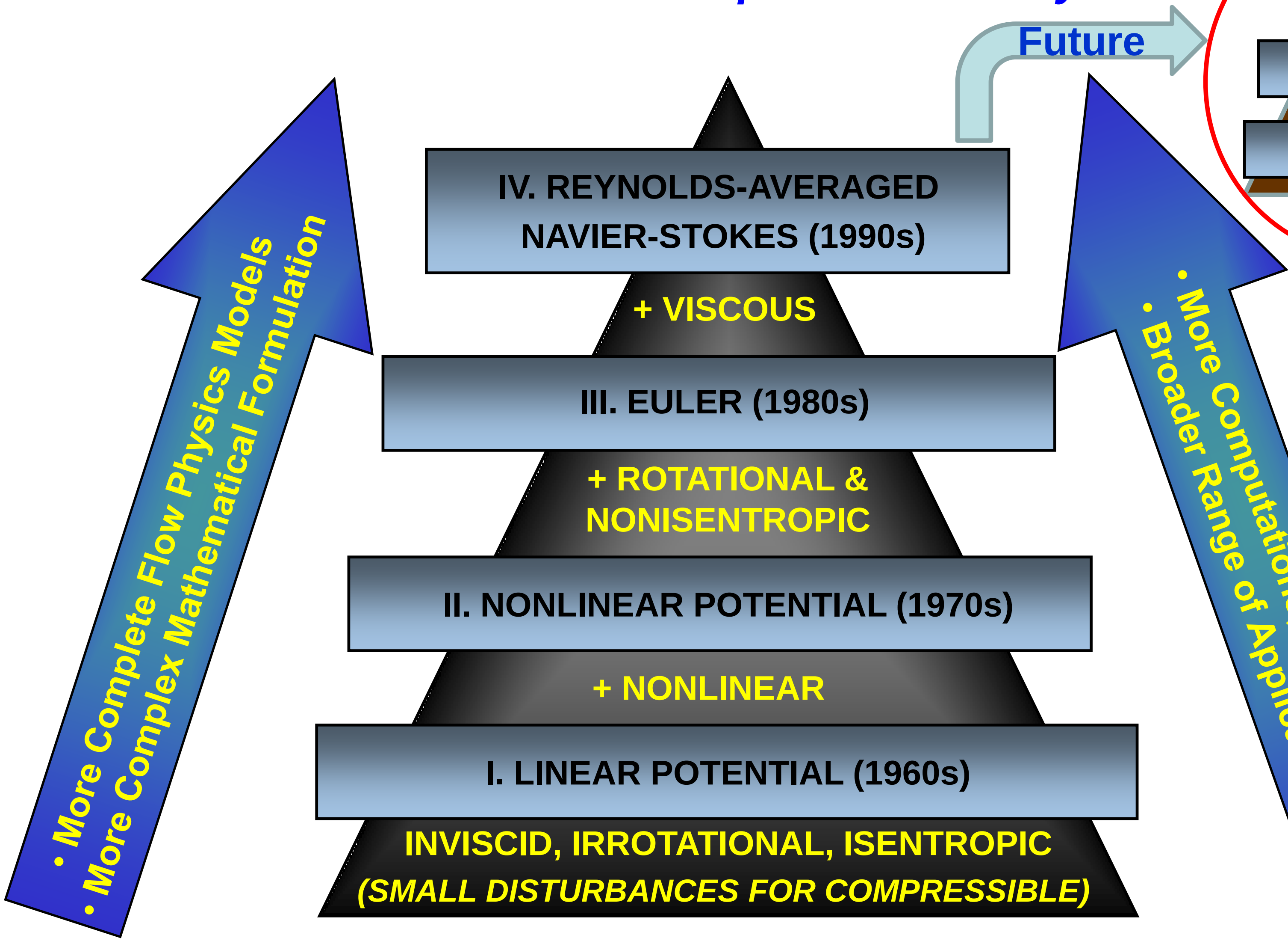
Wind-tunnel Simulation

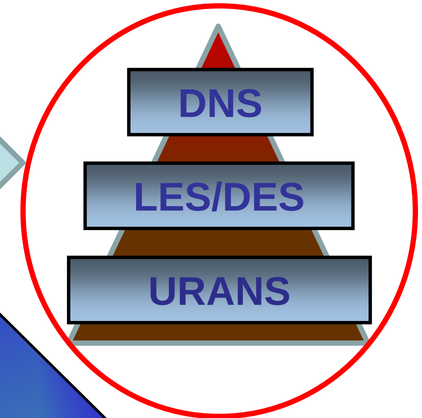
Solving Engineering Problems in Aircraft Design Needs Aerodynamic Data, But…
Don't Confuse Data with Solutions!

Image Source: Hooker et al (AIAA-2013-1098)

CFD Evolution

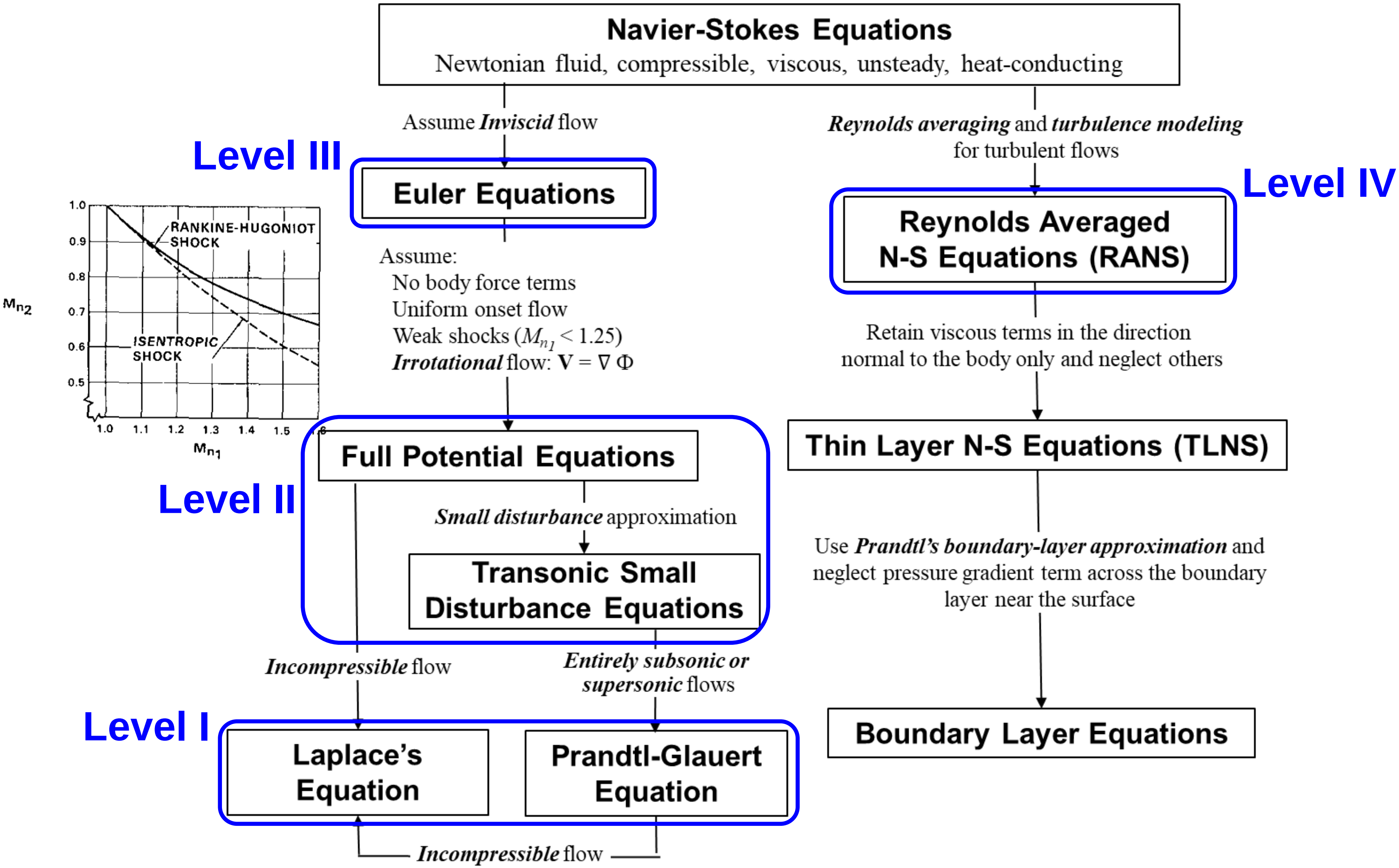
Four Levels of Capabilities Today





60+ Years of Dramatic Advances Since the 1950s

Approximations of N-S Equations Mapped to Four Levels of CFD



Adapted from Fig. 2-10, Configuration Aerodynamics by W.H. Mason

Full Aircraft RANS Simulations:

Reasonably Quick & Affordable Since the Year 2000

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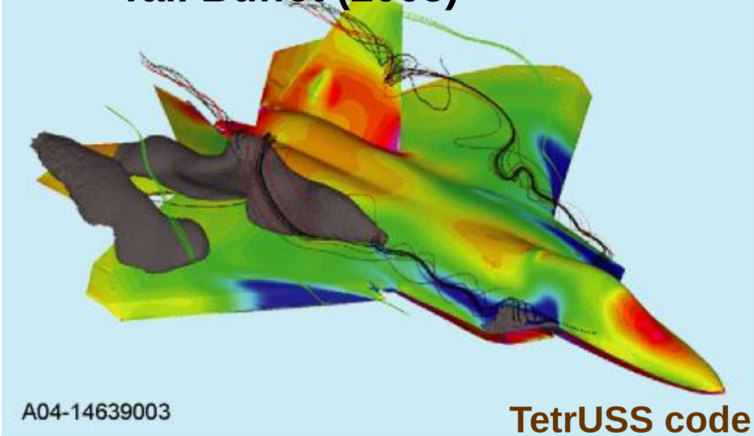
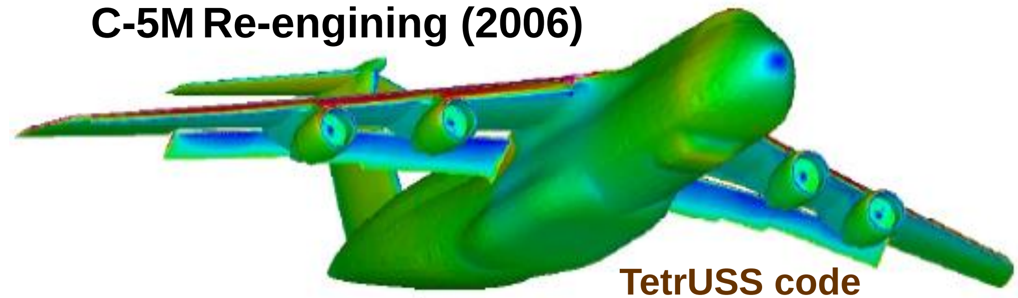
F-22 Tail Buffet (2005)



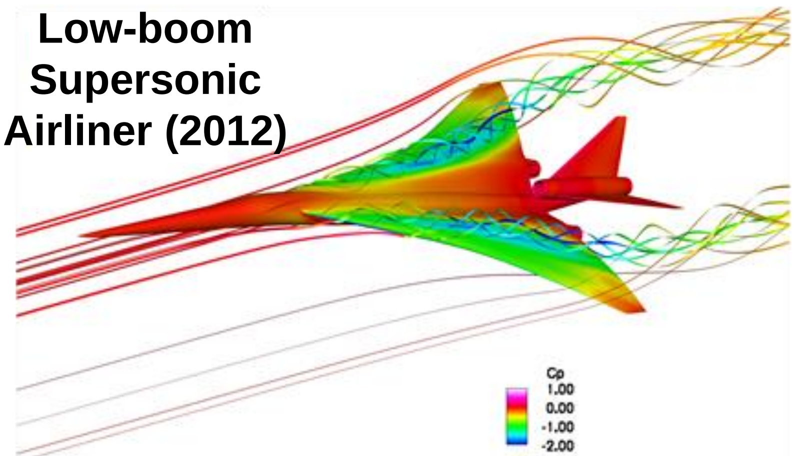
TetrUSS code

C-5M Re-engining (2006)



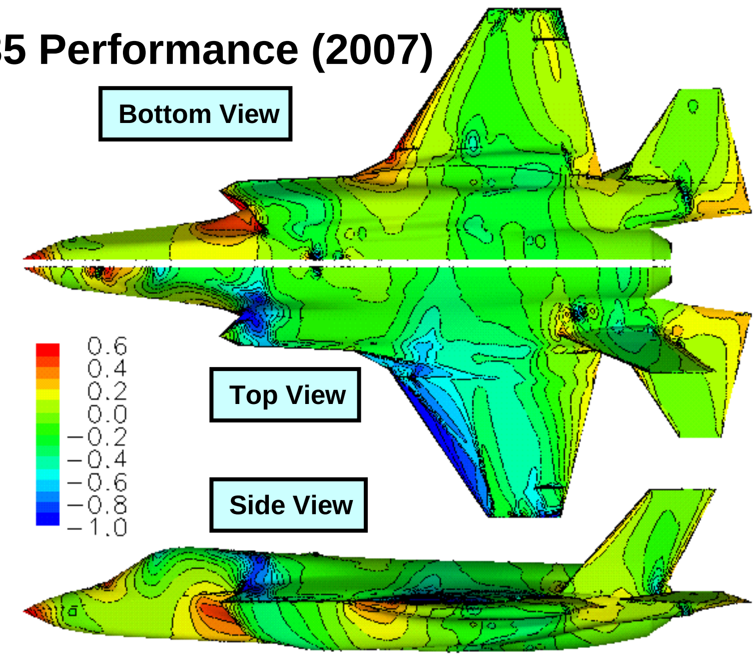
TetrUSS code

Low-boom Supersonic Airliner (2012)



CFD++ code

F-35 Performance (2007)



Falcon code

What is the 'Effectiveness' of RANS-based CFD?

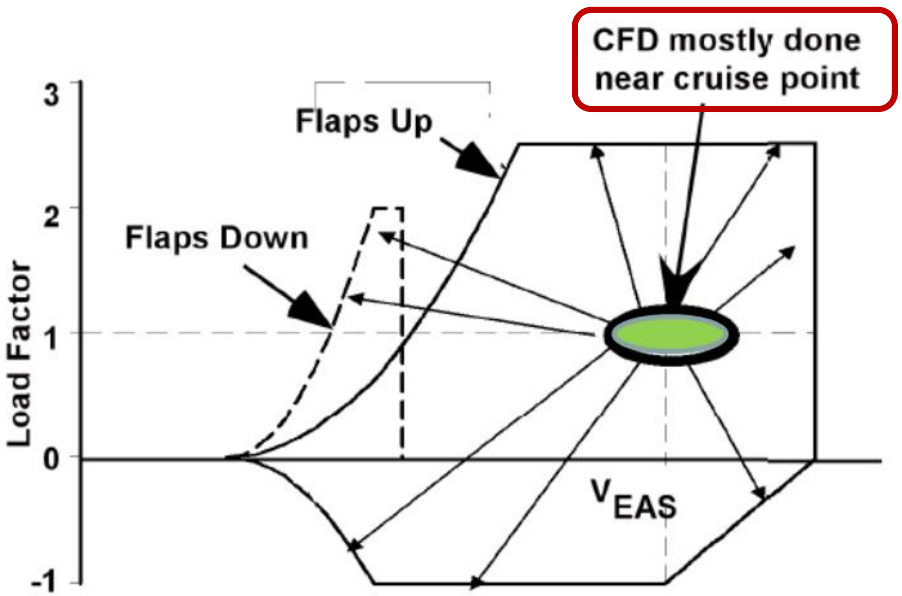
Effectiveness of RANS CFD:
Less than Satisfactory

2005

The Aeronautical Journal, Vol. 109

Tinoco, Bogue, Kao, Yu, Li, and Ball

"The major impact of CFD, delivered to date at Boeing, has mainly been related to its application to *high speed cruise*."



2014

NASA/CR-2014-218178

CFD Vision 2030 Study: A Path to Revolutionary Computational Aerosciences

Slotnick	*Boeing R&T*
Khodadoust	*Boeing R&T*
Alonso	*Stanford University*
Darmofal	*MIT*
Gropp	*NCSA*
Lurie	*Pratt & Whitney*
Mavriplis	*Univ. of Wyoming*

"…the well-known limitations of RANS methods for separated flows have confined reliable use of CFD to a small region of the flight envelope or operating design space."

RANS Simulations of *Complex* Flows

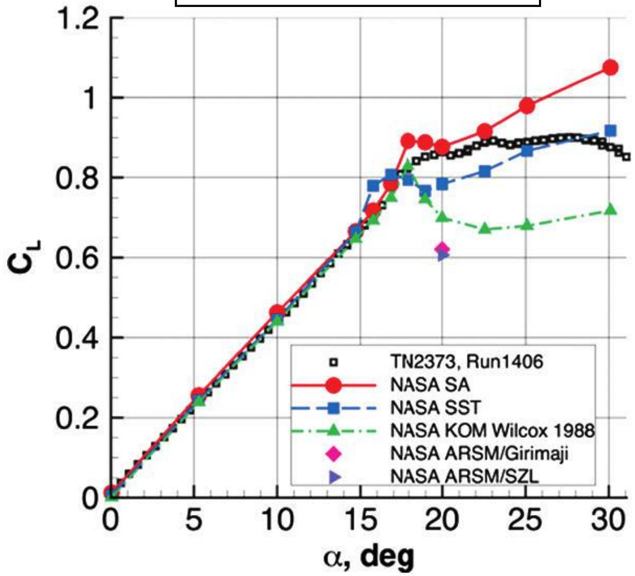
(dominated by separation and free vortices)

Predictions Not Credible!

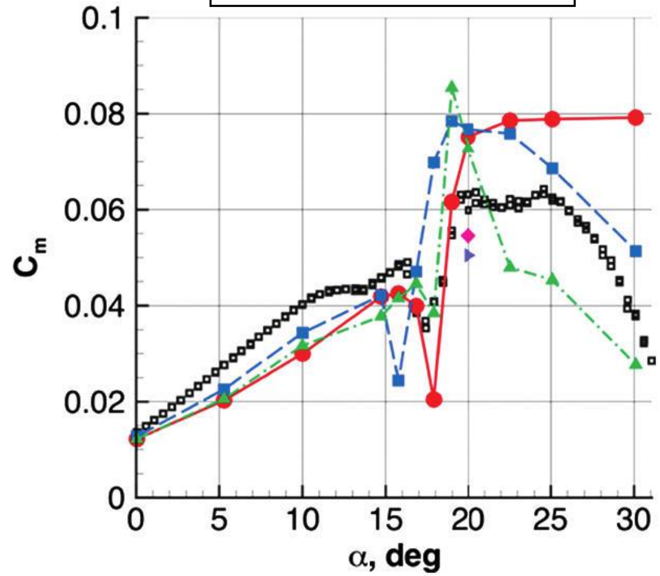
NASA TetrUSS simulations by Frink et al, *AIAA Journal of Aircraft, 2012*

NATO RTO AVT-161
Stability **A**nd **C**ontrol **CON**figuration (SACCON)

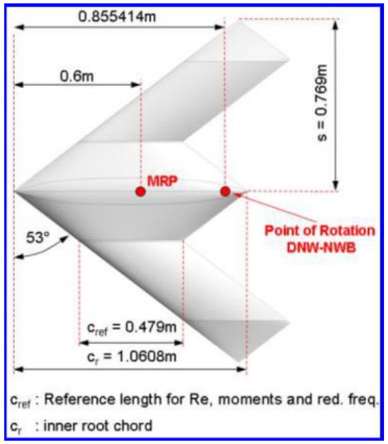
C_L vs. α



C_M vs. α



M = 0.149
Re = 1.6x10^6



Wide variation in predicted data from *five* state-of-the-art turbulence models!

Laminar-to-turbulent transition modeling: yet another challenge!

"All Models are False, Some are Useful!"

Source: Ref. 124

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Why Less Than Satisfactory Effectiveness of RANS CFD ?

A Major Factor: Turbulence Modeling Deficiencies!

"It is quite clear that no model is universal, giving good results for all flows of interest."

– Peter Bradshaw, FRS

Imperial College & Stanford, 1999

"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 really rather optimistic."

Sir Horace Lamb

Address to British Association for the Advancement of Science

London, U.K., 1932

(1849-1934)

Accurate Modeling of Complex, Multiscale, Nonlinear Phenomena with a Few Free Parameters is an Extremely Long Shot Indeed

RANS Methods: *Overarching Challenge*

RANS predictions are not credible* especially for simulations of complex flows dominated by *separation* and *free vortices*!

**How faithfully predictions mimic the real world?*

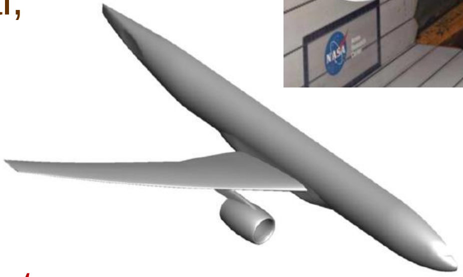
- **Most problematic when designing novel configurations**
  - If RANS simulations predict flow separation or free vortices, are the data credible enough to invest additional time and effort for configuration redesign?
  - If expensive and time consuming wind-tunnel testing must be done for further validation—doesn't it defeat the purpose of using RANS simulations in the first place for a cost-effective design process?

Assessing and Overcoming this Challenge has been a Constant Focus of ACA Community since early 2000s

Assessment of RANS Predictions: *Absolute (Total) Drag*

AIAA CFD Drag Prediction Workshops (DPWs)

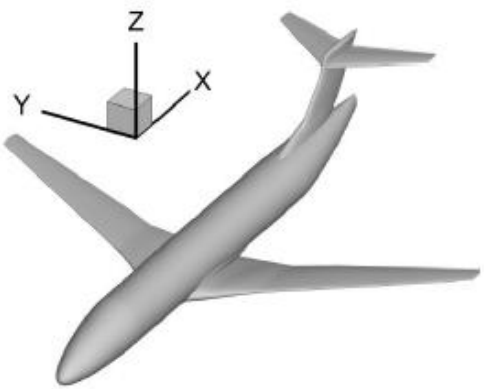
- **Formally initiated in 2000**; seven (7) workshops to date: 2001, 2003, 2006, 2009, 2012, 2016, and 2022; numerous publications
- **Primary Goal:** *Assess state-of-the-art CFD methods as practical aerodynamic tools for the prediction of forces and moments on industry-relevant geometries, with a focus on absolute drag.*
- **Test Cases:** *Variants of commercial transport wing-body configurations; transonic flows; many meshes and flow-solvers; multiple turbulence models*
- **Interesting Findings from the 6th DPW in** Tinoco et al, *Journal of Aircraft, 55 (4), 2018*
  - **NASA Common Research Model (CRM) Wing-Body**: *Solutions exhibited "tighter" convergence of total drag with a spread of less than 10 counts [1 count = 0.0001]*
  - **NASA CRM Wing-Body-Nacelle-Pylon**: *Drag increment predicted within the uncertainty of the test data…this is of significant importance to industry design processes*
  - **NASA CRM Wing-Body Static Aeroelastic Effect:** *Higher lift predicted at a given angle of attack, and more negative (nose down) pitching moment at a given lift coefficient than observed in test data.*

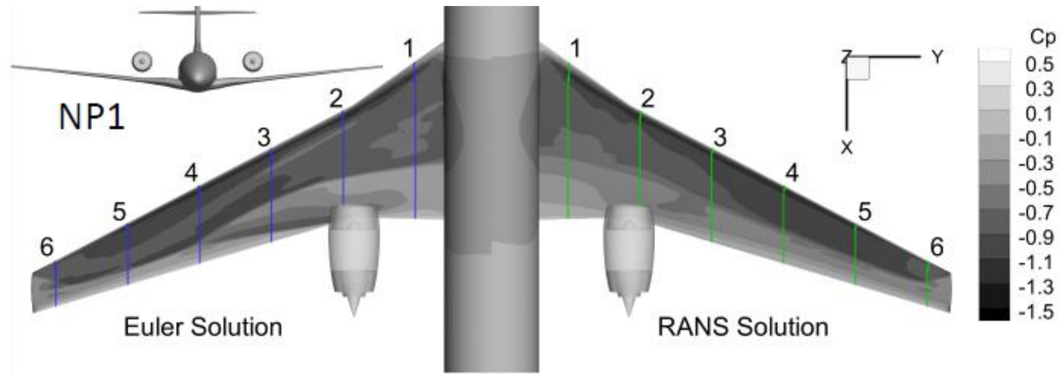


Importance of Accurate Prediction Cannot Be Over Emphasized!

Source: Ref. 6.1.6

Skin Friction Estimation Using *FRICTION*#: *A Comparison with USM** (a *RANS* code)

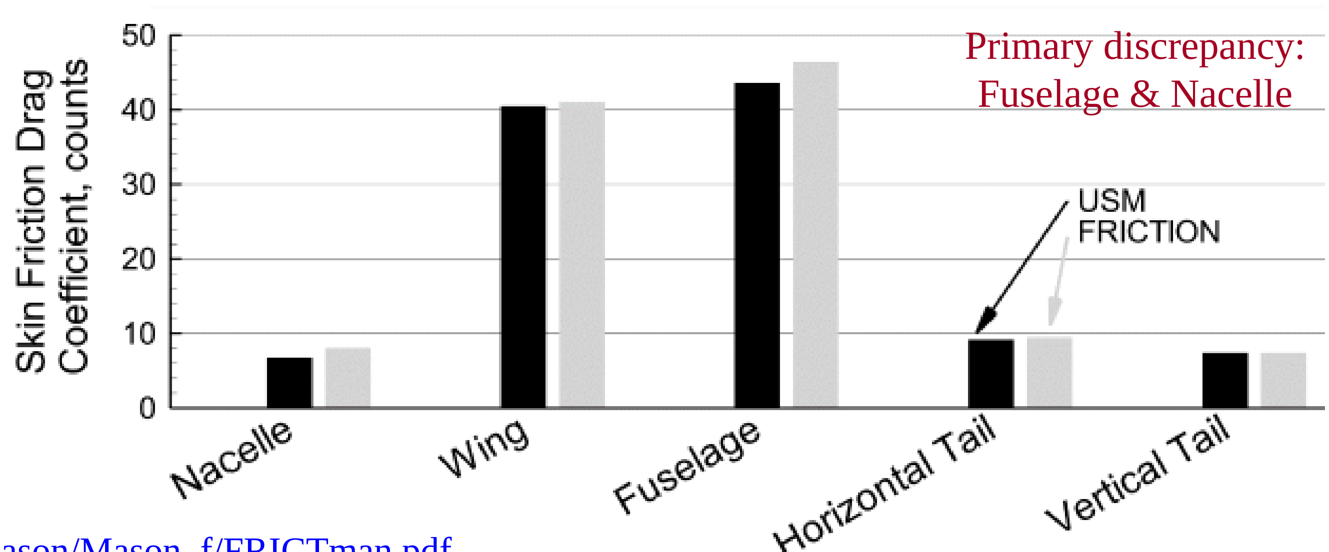




M = 0.8

Re = 27 million

C_L = 0.5



Primary discrepancy:
Fuselage & Nacelle

#https://archive.aoe.vt.edu/mason/Mason_f/FRICTman.pdf

*https://doi.org/10.2514/2.324 [AIAA Journal, 36(11), 1998, pp 1975-1982]

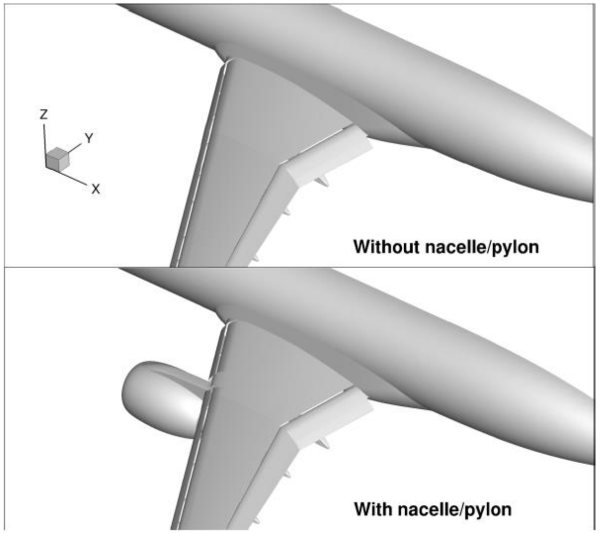
"FRICTION overestimated the viscous drag by between 2 and 5 drag counts, which is remarkably accurate." – Nat Blaesser

Source: NJ Blaesser, PhD dissertation, VT 2019

Assessment of RANS Effectiveness: *Prediction of High-Lift Characteristics*

AIAA High Lift Prediction Workshops (HLPWs)

- Formally initiated in 2009; four (4) workshops to date: 2010, 2013, 2017, and 2022; numerous publications
- Primary Goal: *Assess the numerical prediction capability (mesh, numerics, turbulence modeling, high-performance computing requirements, etc.) of current-generation CFD technology for swept, medium/high-aspect ratio wings in landing/takeoff (high lift) configurations*
- Test Cases: *Variants of commercial transport configurations; subsonic flows; variety of grid systems and flow solvers; multiple turbulence models*
- Interesting Findings from 3rd HiLiftPW: Rumsey et al, *AIAA 2018-1258*
  - JAXA Standard Model High-lift Configuration with and without Pylon/Nacelle
    - ✓ *Fairly tight clustering of results in the linear lift-curve range, and very large scatter in results near maximum lift*
    - ✓ *Differences between nacelle/pylon on and off were well predicted in general*
    - ✓ *Significant influence of grid for the solutions near maximum lift*
    - ✓ *Transition model results were inconsistent near maximum lift; reasonable results for the wrong reasons!*



What's the Dominant Contributor to Error in RANS Solutions?

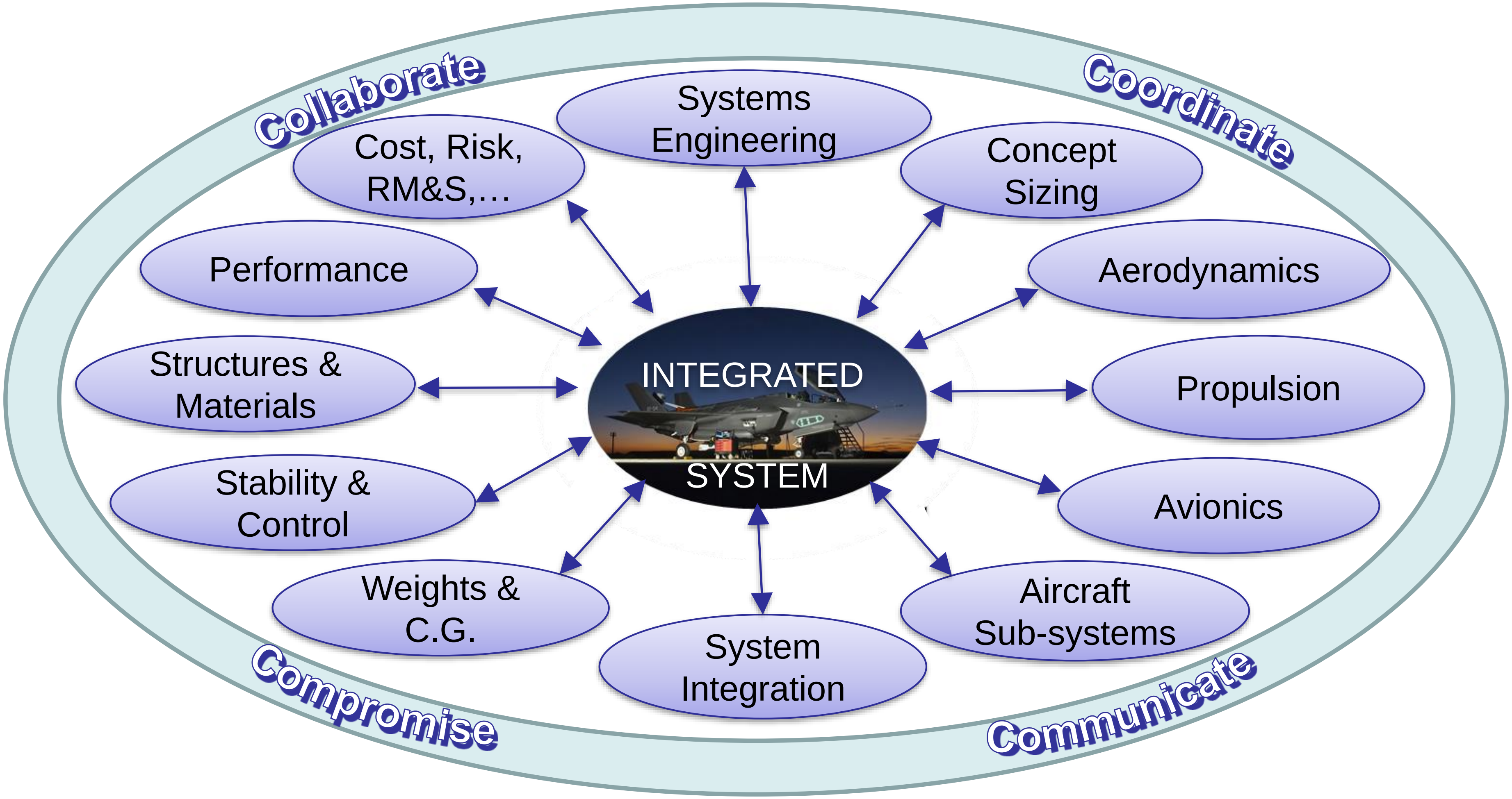
Is it the Mesh, the Solver, or the Turbulence Model?

Interesting Findings from Statistical Analysis: Ollivier-Gooch, *AIAA 2019-1334*

- *Approach:* 39 datasets from Third High-Lift Prediction Workshop (2017) and 31 datasets from Fifth Drag Prediction Workshop (2016) matched into groups based on three primary variables: mesh, flow solver, and turbulence model.
- *Qualitative Conclusions* based on crude statistical analysis due to sparse amount of data in each group.
  - Mesh and turbulence model appear to have about equally large impacts on outputs.
    - ✓ Results of different mesh sets with the same flow solver and turbulence model differed about as much as the average results for the three groups varied from each other!
  - Even with relatively fine meshes used, there are still flow features resolved by some meshes and not others.
  - Flow solver is at least as big a difference as other factors.
    - ✓ Community needs to do a better job of *verification* of numerical model and turbulence model implementations.
  - User selected input parameters can cause significant variation in output values.
    - ✓ Improved user training can help.

Epilogue

Capstone Aircraft Design Project



Disciplinary "experts" must provide advice and ***data***—*on time and on budget*—to configuration designer who integrates it all into an innovative configuration.

Software Tools Are Essential to Producing Data