AOE 4144: Applied CFD

1. Introduction

The 1st of 12 lectures by Prof. Raj to share his perspective on effective application of computational aerodynamics to aircraft design.

Each lecture contains excerpts from the presentation shown below describing his exciting journey on a long and winding road for more than five decades!

Reflections on the Effectiveness of Applied Computational Aerodynamics for Aircraft Design

https://www.aoe.vt.edu/people/emeritus/raj/personal-page/reflections-on-ACA-effectiveness.html

Pradeep Raj, Ph.D.
Collegiate Professor Emeritus
Kevin T. Crofton Department of Aerospace and Ocean Engineering
Virginia Tech, Blacksburg, Virginia, USA
http://www.aoe.vt.edu/people/emeritus/raj.html

Program Management Director, Lockheed Martin (Retired)
Deputy Director, Technology Development & Integration
The Skunk Works®, Palmdale, California, USA

Advanced Development Programs

LOCKHEED MARTIN

COLLEGE OF ENGINEERING
KEVIN T. CROFTON DEPARTMENT OF AEROSPACE AND OCEAN ENGINEERING
VIRGINIA TECH

ABOUT THE LECTURER

Pradeep Raj

- **Virginia Tech, Blacksburg, Virginia (2012-present)**
  - **Professor (2012–2017); Collegiate Professor (2017-2024); Collegiate Professor Emeritus (2024-present)**
    - **Air Vehicle Design, Applied Aerodynamics**
- **Lockheed Martin (1979–2011)**
  - **Technical (1979-1999): Aeronautics Company, California & Georgia**
  - **Management (1999-2000): Aeronautics Co., Georgia; Leadership (2000-2011): Advanced Development Programs, Skunk Works®, Palmdale, California**
- **UMR*, Rolla, Missouri**
  - **Asst. Prof. (1978–79)**

  **now Missouri S&T University*
- **Ga Tech, Atlanta, Georgia**
  - **Ph.D. Aerospace Engineering (1976)**
- **ISU, Ames, Iowa**
  - **Research Assistant Professor (1976–78)**
- **IISc, Bangalore, India**
  - **M.E. Aeronautical Engr. (1972)**
  - **B.E. Elec. Technology (1970)**
- ***AIAA Fellow (2011)*** ***Fellow RAeS (2016)*** ***FIAE (1991)***

Image Source: Internet

An Aside: "Why Join VT After Retiring From LM?"

Clarence Leonard "Kelly" Johnson (1910-1990)

Legendary Aircraft Designer

Founder of World-renowned Skunk Works®

"Hang with young people; they mostly have it right"

ABOUT THE LECTURES

These lectures are excerpted from the author's presentation entitled
**"Reflections on the Effectiveness of
Applied Computational Aerodynamics for Aircraft Design"**

The URL of the current version of the full presentation is:
https://www.aoe.vt.edu/people/emeritus/raj/personal-page/reflections-on-ACA-effectiveness.html

In this presentation, the author places the evolution of Applied Computational Aerodynamics (ACA) as well as its capabilities and shortcomings in a historical context. But it is NOT a history of ACA. Instead, he shares his perspective on how we got to where we are today, and how we get to where we need to be tomorrow.

This is a much expanded version of the Lead presentation:
Applied Computational Aerodynamics: *An Unending Quest for Effectiveness*
Royal Aeronautical Society Applied Aerodynamics Conference
The Future of Aerodynamics, Bristol, U.K., July 24-26, 2018

MOTIVATION

The primary motivation is to convince budding and practicing engineers using CFD to predict aerodynamic characteristics of aircraft (and of other objects moving through the air) that they must dispel their mistaken notion:

CFD is a commodity now, so we just need to learn to use it for generating aerodynamic data

- Yes, we know that CFD may be considered a commodity today since users can choose from a large number of either commercial or open-source CFD software for aerodynamic flow simulation
- When I assumed the primary responsibility of teaching aircraft design courses at Virginia Tech in 2012, it became apparent rather quickly that
  - a large number of students—just a few months shy of being professionals—used CFD as a "black box", i.e., choosing default input parameters and generating aerodynamic data
  - students instinctively trusted the data, and almost never asked: *"So what that we can predict aerodynamic characteristics, do the predictions replicate reality?"*

Computational Aerodynamics Engineers Must Learn to Ask and Answer the "So What?" Question!

SCOPE

To present a relatively complete yet concise perspective on

- ***the evolution of applied computational aerodynamics (ACA),***
- ***the impressive capabilities of today's ACA for meeting flight vehicle design needs,***
- ***the less-than-satisfactory effectiveness of ACA for meeting design needs due to serious shortcomings, and***
- ***the future prospects for fully effective ACA capabilities.***

The perspective reflects Raj's 50+ years of related experience in aerospace industry and academia.

So what?

All it suggests is that Raj is OLD.

True, but "age has its privileges!"

Más sabe el diablo por viejo que por diablo.

The devil knows more from being old than from being a devil.

"With age comes wisdom, but sometimes age comes alone!"

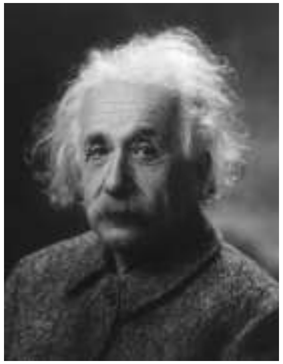
-- Oscar Wilde

An Aside on *Experience*

"experience is direct observation of, or participation in, events as a basis of knowledge"—*Merriam-Webster dictionary*

"experience is knowledge or skill in a particular job or activity that you have gained because you have done that job or activity for a long time—*Collins online dictionary*

Albert Einstein



14 Mar 1879 – 18 Apr 1955

"The only source of knowledge is experience."

C.S. Lewis

29 Nov 1898 – 22 Nov 1963

"Experience: that most brutal of teachers. But you learn, my God do you learn."

Randy Pausch

23 Oct 1960 – 25 Jul 2008

"Experience is what you get when you don't get what you wanted. And it can be the most valuable thing you have to offer."

Knowledge from experiences is crucial to developing wisdom you need to make good decisions; you can't get wise overnight from books alone.

This 'old devil' has much to offer…whether or not you agree with everything he has to say!

Image & Quotes Source: Internet

Topics

Preface

1. Introduction

2. Genesis of Fluid Dynamics *(Antiquity to 1750)*

3. Fluid Dynamics as a Mathematical Science *(1750–1900)*

4. Emergence of Computational Fluid Dynamics *(1900–1950)*

5. Evolution of Applied Computational Aerodynamics *(1950–2000)*

5.1 Infancy through Adolescence (1950–1980)

Level I: Linear Potential Methods (LPMs)

Level II: Nonlinear Potential Methods (NPMs)

5.2 Pursuit of Effectiveness (1980–2000)

Level III: Euler Methods

Level IV: Reynolds-Averaged Navier-Stokes (RANS) Methods

6. ACA Effectiveness: Status and Prospects *(2000 and Beyond)*

6.1 Assessment of Effectiveness (2000–2020)

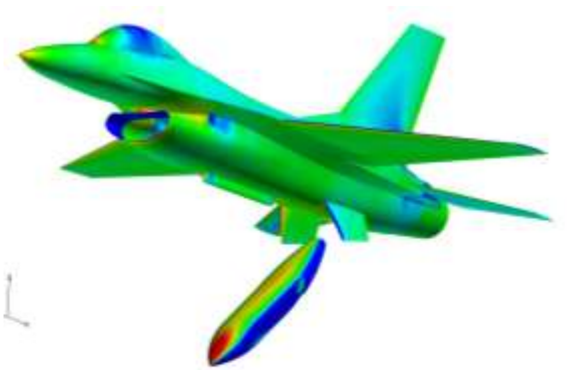
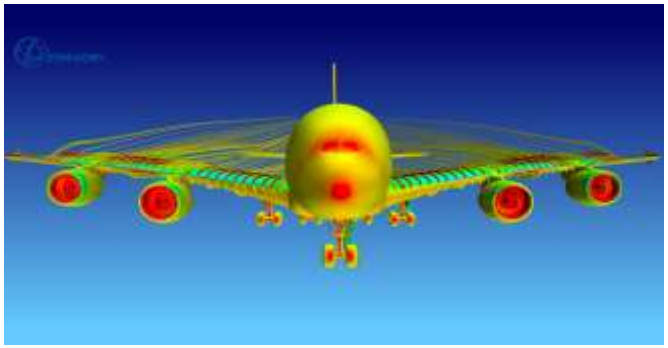
6.2 Prospects for Fully Effective ACA (Beyond 2020)

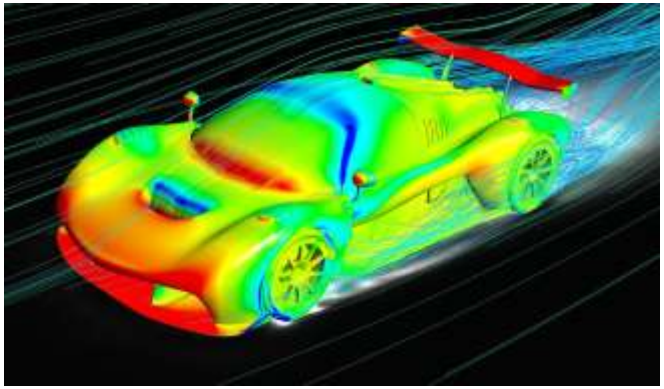
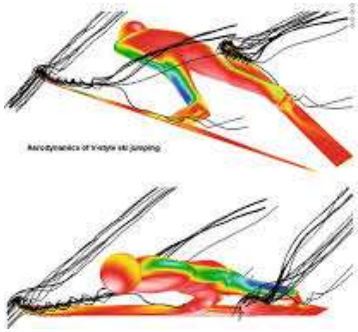
7. Closing Remarks

Appendix A. An Approach for ACA Effectiveness Assessment

Applied Computational Aerodynamics (ACA)

ACA** is an engineering discipline that deals with the application of **C**omputational **F**luid **D**ynamics (CFD) to the **analysis** and **design** of arbitrarily shaped objects moving through the **air.

Computational Aerodynamics is CFD when the fluid is air.

ACA puts CFD to *practical use* as opposed to CFD being only theoretical.

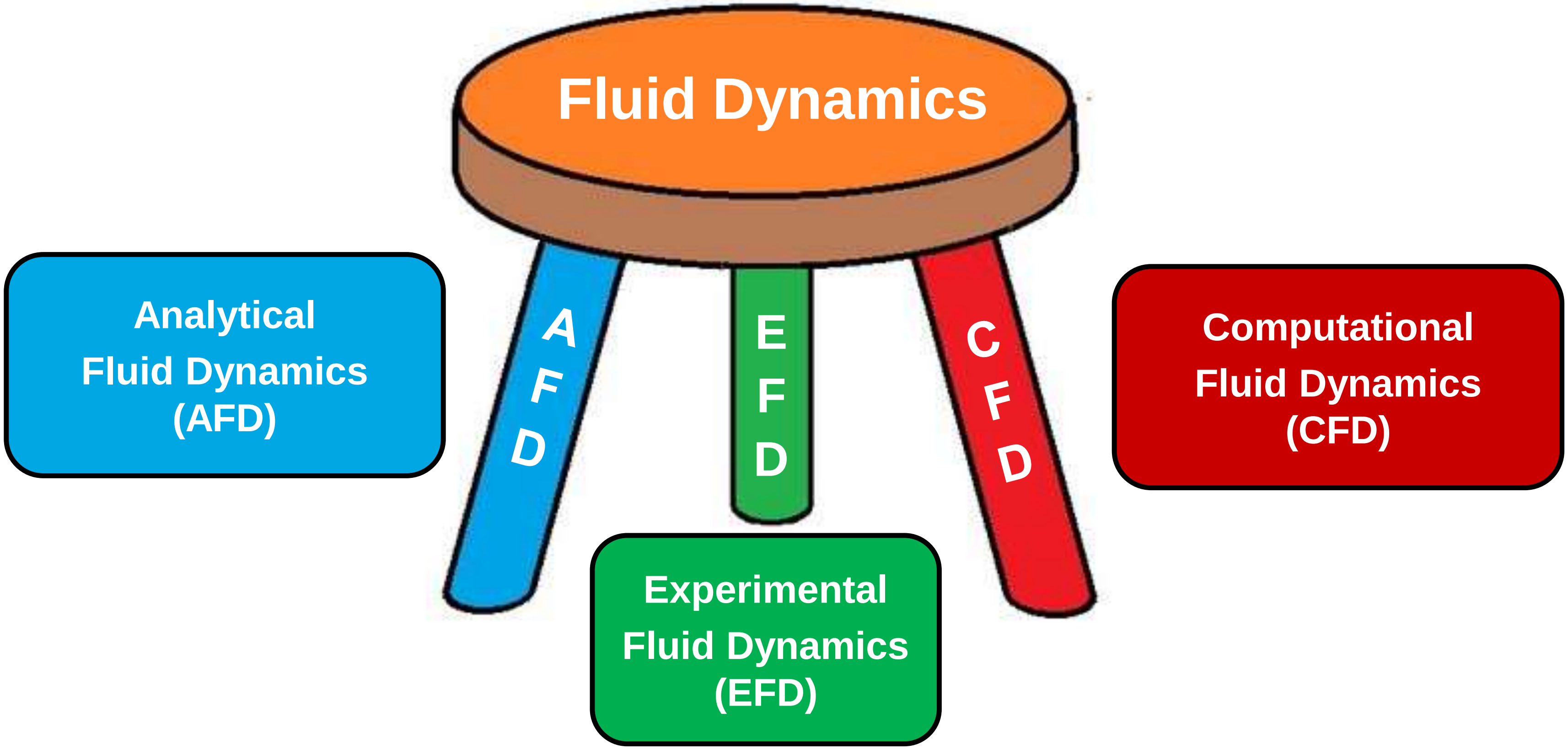
Adapted from https://dictionary.cambridge.org/us/dictionary/english/applied

Image Source: Internet

Computational Fluid Dynamics (CFD)

The Newest Subdiscipline of Fluid Dynamics

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



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

CFD Ingredients

Governing Equations: Mathematical Formulations of Fluid Flow
(*Partial differential equations in continuous domain*)

Computer Platforms
(Digital computers to run computer programs, and for data processing & storage)

CFD

Numerical Models of Governing Equations
(*Difference equations in discretized domain*)

Computer Programs
(Software suite based on algorithms to solve the difference equations)

Today's CFD offers a powerful suite of numerical models, computer programs, and associated tools & processes for simulating fluid flows using digital computer platforms

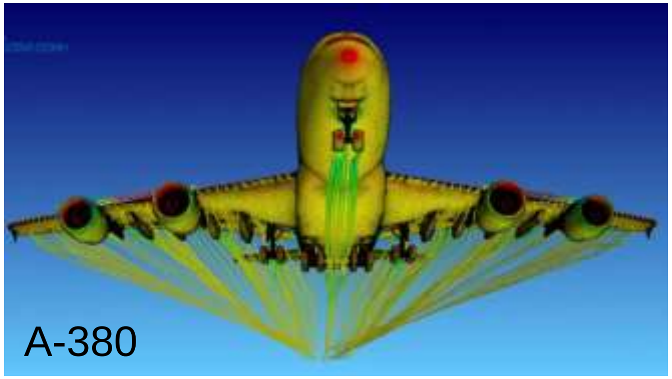
Overarching Goal of ACA

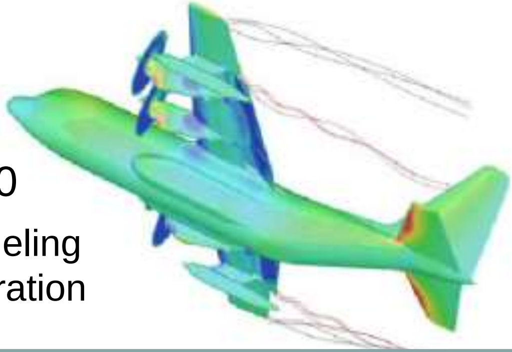
The goal of applied computational aerodynamics (ACA) is to generate credible solutions of practical aerodynamic problems via aerodynamic analysis and design using computational fluid dynamics (CFD), and to deliver the solutions—on time and on budget—to engineers who are tasked with designing systems that move through the air, such as aircraft.

ACA is No Longer a Luxury, But a Necessity, to Support Engineering Design of All Types of Systems that Move Through the Air

Pervasive Use of ACA in Air 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:* Validate take-off, climb, cruise, maneuver, descent, landing
  - *Airframe Propulsion Integration:* 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)**
  - Assess impact of shape change on flight performance when integrating new or improved subsystems to upgrade current product or design a derivative





KC-130

New Refueling Pod Integration

Indispensable for Engineering Design of Flight Vehicles

Source: Refs. 1.1 – 1.6

Effectiveness

"The ability of producing a desired result or a desired output"

Richardson, 1910

*"Both for engineering and for many of the less exact sciences, such as biology, there is a demand for **rapid** **methods,** easy to be understood and **applicable to unusual equations and irregular bodies**. If they can be **accurate**, so much the better; but **1 per cent, would suffice** for many purposes."*

Hess and Smith, 1967

*"**Prospective users**…rarely interested in whether or not an accurate solution of an idealized problem can be obtained, but are concerned with **how well the calculated flow agrees with the real flow**."*

Miranda, 1982

*"The **effectiveness** of computational aerodynamics **depends not only on the** **accuracy** of the codes **but** to a very large degree—perhaps more than is generally appreciated—**on their robustness, ease and economy of use.***

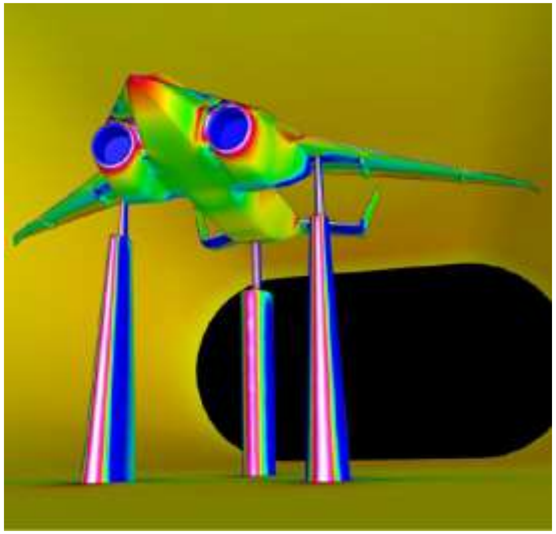
Deliver Accurate Solutions, Rapidly and Affordably

Image Source: Refs. 1.7 thru 1.9

CFD and ACA are *NOT* Synonymous

CFD *Produces Data*.

Computational Fluid Dynamics (CFD) offers a powerful *means* of *generating aerodynamic data*, à la wind tunnels, for bodies moving through air.



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)

ACA Produces Solutions!

Applied Computational Aerodynamics (ACA) is all about using CFD to deliver credible *solutions of engineering problems* to designers.

Aerodynamic Data is Needed to Solve Engineering Problems, But Don't Confuse Data with Solutions!

Image Source: Ref. 1.10

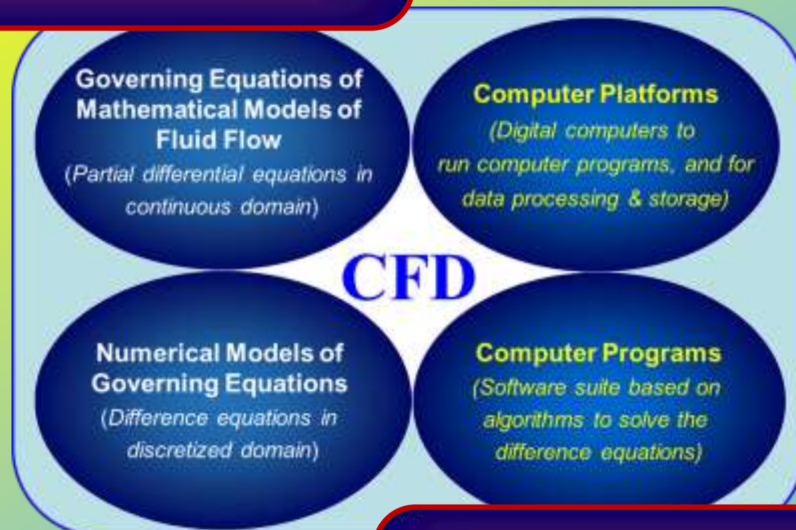
Relationship of CFD to ACA

CFD is to ACA as Airplane is to Air Transportation!

ACA

Customer

Engineering design problems, resources, and constraints



Value

Meeting customer needs and expectations

ACA Uses CFD to Create Value for the Customer

Don't We Already Know a Lot About CFD and ACA?

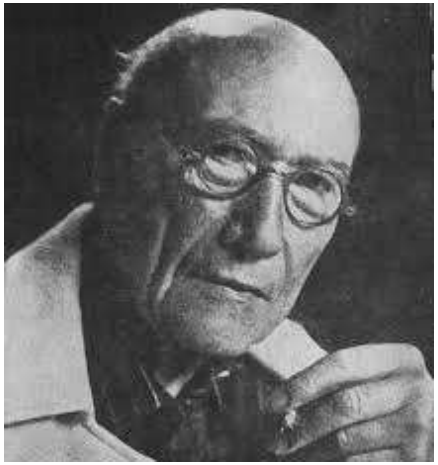
Yes, everything has been said!

Then Why Say It Again?

Source: Refs. 1.11 to 1.18

Everything has been said before, but since nobody listens we have to keep going back and beginning all over again.

André Gide



French author
Nobel Prize in Literature (1947)
22 November 1869 – 19 February 1951

- It is extremely difficult, if not impossible, for a single book to do justice to the multiple facets of CFD and ACA including theoretical aspects and practical applications.
- **The current status and future prospects of the effectiveness of ACA for aircraft design are our main focus areas.**
- The intention is *to* ***COMPLEMENT, NOT DUPLICATE,*** what is extensively covered in many excellent CFD and ACA books.

Source: Ref. 1.19

Objective & Approach

To discuss how we got to today's ACA (applied computational aerodynamics) which has less than satisfactory effectiveness, and how we get to fully effective ACA tomorrow that can best meet the needs of engineering design of aircraft.

We shall examine evolution of CFD (computational fluid dynamics) as a sub-discipline of Fluid Dynamics, and its application to aerodynamic problems.

Since CFD is applicable to a broad range of problems in science and engineering, we use a highly simplified taxonomy of CFD applications to distinguish applications for scientific studies from those for engineering:

CFD Applications

Scientific Studies

- Turbulence
- Acoustics
- Combustion
- …

Engineering Studies

- Increased aerodynamic efficiency
- Reduced environmental noise
- Improveddpropulsor efficiency
- …

Next, We Briefly Address Three Topics To Place the Material in the Following Sections in Proper Context

"Engineering isn't Science!"

Theodore von Kármán

<u>Scientists discover</u> the world that exists; *<u>engineers create</u>* the world that never was.

Hungarian-American mathematician, aerospace engineer, and physicist; Univ. of Göttingen; RWTH Aachen; Caltech; VKI for Fluid Dynamics

11 May1881 – 6 May 1963

Eugene E. Covert

American aerodynamics and aeronautics specialist, MIT

6 Feb 1926 – 15 Jan 2015

<u>*Engineering is*</u> in the end <u>*about making something*</u>.

The Core Purpose of Engineering: Apply Knowledge and Skills to Develop New Devices

Image Source: Internet

"An Engineer's Mentality"

"In essence, the current engineering education paradigm consists of giving the students all the data at the top of the page, and the solution (?) consists of rearranging the data on the bottom of the page and handing it in as a "worked" assignment. In many years in industry I never encountered anything even remotely close to this process. "

"In my experience, *the overwhelming majority of the engineering problem is gathering information and interpreting results.* *Although this is the engineering problem it almost never occurs in our science-based engineering education system*."

"**Engineering design** may be the student's only exposure to this process. The student response in evaluations comes across as "problem statements too vague." If that's the case with these problems, we have not yet helped the students develop an engineer's mentality."

William H. Mason
AIAA Paper 92-2661

William H. Mason

Professor Emeritus, Virginia Tech
Co-author of an ACA textbook
Engineer Grumman Corp.
19 Jan 1947 - 27 Mar 2019

Note: Highlighting by the author of this presentation.

Source: Ref. 1.20

"An Engineer's Reality"

"One of the **characteristics of engineers which** I have frequently observed, and which **must be guarded against is** the ***search for exact answers***, and the feeling of frustration if the exact answer is not forthcoming. This probably stems from the many years of high school and college training where the answer is always to be found in the back of the book, and the feeling of elation which comes when, after trying several solutions, and looking furtively at the answer, the latest trial finally works.

Unfortunately, ***in real life, there are no exact or final answers***. In a job, which must go ahead at a rapid pace, we cannot withhold judgment "until all the facts are in". Rarely is all the evidence at hand. Decisions must be made, and action taken, before complete knowledge can be acquired.

I have for some time thought that ***a few of our present day ills stem from this childish faith in the existence of perfect answers***. It requires a degree of maturity to realize that all solutions are partial ones."

Adm. Hyman G. Rickover (1900–1986)

"Father of the Nuclear Navy," 63 Years of Active Duty in US Navy

Lecture on *Administering a Large Military Development Project* delivered to U.S. Naval Postgraduate School, Monterey, CA, 15 March 1954

Note: Highlighting by the author of this presentation.

Source: http://hdl.handle.net/10945/59370

Engineering Design of Aircraft

Designing An Object: *A Creative Act*

But Creativity Alone May Produce Useless/Impractical Artifacts

The Coffeepot for Masochists

The Camouflage Cup
(cut out plastic cup)

The Uncomfortable Wine Glass

Engineering Design is "Creativity with Purpose!"

"Engineering Design is an iterative decision-making activity performed by team of engineers to produce plans by which resources are converted, preferably optimally, into systems or devices to meet human need."

-- T.T. Woodson, *Introduction to Engineering Design*, 1966

Source: https://www.pinterest.com/laragtorres/impossible-objects/

Engineering Design Process

Adapted from "*The Mechanical Design Process*" by David G. Ullman

- **In engineering design, designer uses *three types of knowledge***
  - **A. knowledge to generate ideas**—comes from experience and natural ability
  - **B. knowledge to evaluate ideas**—comes from domain-specific knowledge
  - **C. knowledge to make decisions and structure the design process**—largely independent of domain-specific knowledge

- **Six basic actions are taken to solve any design problem**
  1) **Establish the need—**what is to be solved
  2) **Plan—**how to solve it
  3) **Understand the problem—**what the requirements are, and what existing solutions for similar problems are
  4) **Generate alternative solutions**
  5) **Evaluate the alternative solutions—**compare them to design requirements and to each other
  6) **Decide on acceptable solutions**

This Model Works for Entire Product or a Small Piece of It

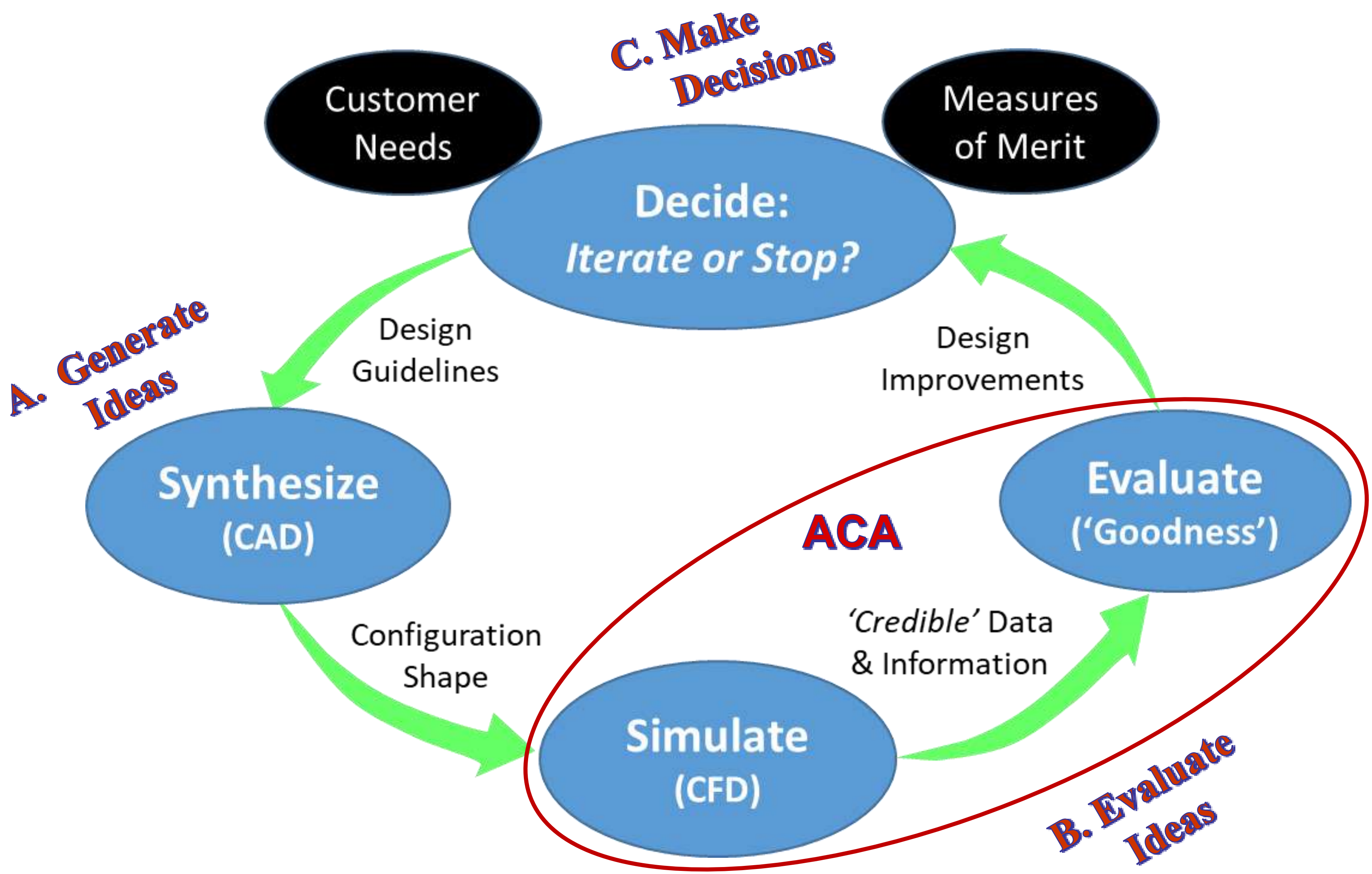
In the Hands of Good Designers, the Engineering Design Process has Delivered…

…An Impressive Array of Aircraft With Phenomenal Performance!

Fully Effective ACA

Role of ACA in Aircraft Design

"A Simplified Aerodynamic Design Loop"



Fully Effective ACA

Ability to deliver credible solutions* of aerodynamic problems using CFD—on time and on budget—to support engineering design

**how faithfully the solutions replicate reality*

Miranda, in *AIAA 82-0018*, defined Effectiveness as a product of two factors:

$$Effectiveness = Quality \times Acceptance$$

"Quality" *(how well the results replicate reality)*

Credibility of the results of the comp aero simulation of flows about arbitrarily shaped configurations

"Acceptance" (*on time, on budget delivery of results*)

Ease of use; short turnaround time (elapsed time from go-ahead to delivery); low cost (labor hours & H/W+S/W costs)

Effectiveness of today's ACA is less than satisfactory due to shortcomings in credibility of results.

Luis R. Miranda

Manager
Computational Aerodynamics
Lockheed-California Co.

Fully Effective ACA Requires Simultaneous Maximization of Both Quality and Acceptance Factors

Pervasive Use of ACA in Engineering Design of Aircraft Drives the Pursuit of Fully Effective ACA

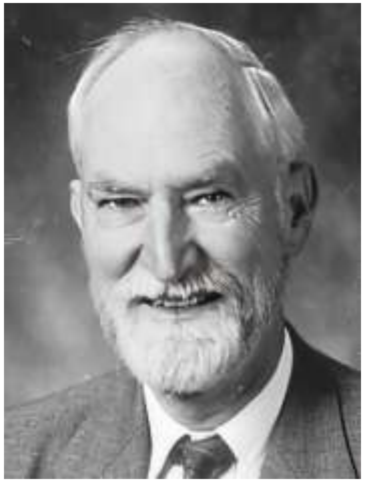
Source: Ref. 1.4, 1.21 thru 1.25

Pursuit of Value with CFD

"…the value of CFD is directly related to its **contribution to RATE OF LEARNING during the process of designing an airplane**. Higher rates of learning lead to better designs. Rate of learning is comprised of the product of two terms, namely (i) **learning per design cycle**, **multiplied by** (ii) the **number of design cycles** that can be executed in a given amount of time. Earlier developments in CFD tended to focus on the former and to ignore or discount the latter. But the teachings of the 1990s created a greater focus on the latter, with the result that the processes in use for designing airplanes today are improving at a rate that is unprecedented."

On The Pursuit of Value with CFD
Frontiers of Computational Fluid Dynamics
World Scientific Publishing Co., November 1998, pp. 417-427

Paul E. Rubbert



Boeing Company (1960-1997)
Technical Fellow, Director of CFD
AIAA Fellow, Member NAE
18 Feb 1937 - 23 Dec 2020

Two areas of interest:
1. the conduct and management of research for effectiveness
2. the continued development and exploitation of computational fluid dynamics.

Note: Highlighting by Raj.

Lecture 1:
Overarching Takeaways

CFD Produces Data, ACA Produces Solutions.
Don't Confuse Data with Solutions!

CFD is to ACA as Airplane is to
Air Transportation!

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