WHAT IS COMPUTATIONAL FLUID DYNAMICS ?

The Systematic Application of Computing Systems and Computational Solution Techniques to Mathematical Models Formulated to Describe and Simulate Fluid Dynamic Phenomena.

WHY COMPUTERS (1)

INFORMATION: Valuable Asset/Merchandise

⇒ Need to Create/Manipulate/Store/Transport/..

⇒ Accelerate Via a Machine ⇒ **COMPUTER**

Table 1 Manual vs. Machine Device for Tasks

Task	'Manual'	Machine
Store	Mind/Paper	Disk/Tape/Paper
Create	Mind	CPU
Manipulate	Mind	CPU
Transport	Neurons	Circuit
'Medium'	Carbon	Silicon/Copper

WHY COMPUTERS (2)

Replacement of Human Fuction by Machine Not New !

Table 2 Replacement of Human Function

Function	‘Manual’	‘Machine’
Cut	Teeth	Knife
Lift	Arms	Crane
Transport	Legs	Car/Train/Airplane/..
Process Info	Mind	Computer

WHY SIMULATION (1)

To 'Solve':

- Inquiry
- Prediction (e.g. Performance)
- Understanding (Postdiction) (e.g. of Events)

Options:

- From Experience (Data Base)
- From Experiments (Prototype)
- From Analysis (Simulation)

Remark: All Of These Areas Are Still Progressing !

WHY SIMULATION (2)

- New Products/Unknown Events
  - Extrapolation from Experience Difficult (Non-Linear)
  - Experiments Costly or Impossible
  - Closed-Form Solutions Impossible

<u>But</u>: Failure Compromises Viability of Company/Institution

$\Rightarrow$ NEED SIMULATION

WHY SIMULATION (3)

- Development Costs Compromise Company
  - New Passenger Car: 1 B $
  - New Commercial Plane: 4 B $

- Development Costs Compromise Programs
  - One Underground Nuclear Test: 100 M $

OPTIONS (1)

- Try Out 'As Is'
    - Look/Study
    - Obtain Trends
- Study Database
    - Assemble Relevant Information
    - Make Neural Net
    - Get Error Bounds on Neural Net
    - Obtain Trends

OPTIONS (2)

- Do Experiment
    - Modify/Rebuild Test Chamber
    - Instrument
    - Determine Error Margin
    - Build Model
    - Measure
    - Evaluate
    - Obtain Trends

OPTIONS (3)

- Do Analysis
  - Simplify/Model
    (PDE $\rightarrow$ ODE $\rightarrow$ Formula)
  - Determine Error Margin
  - Solve
  - Obtain Trends

OPTIONS (4)

- Do Computer Simulation/Analysis
  - Specify PDE/ODE
  - Select Numerical Scheme
  - Program and Debug if Required
  - Discretize Domain $(\mathbf{x}, t)$
  - Solve
  - Determine Error Margin (Convergence Study)
  - Evaluate
  - Obtain Trends

Remarks:

- For Complex Systems, All of These Concurrently
- Typical of Technology: Take a Detour to Get There Faster

EXPERIMENTS

- Problems With Experiments
  - Impossible
  - Costly
  - Untimely
  - No Optimization Guidance

EXPERIMENTS IMPOSSIBLE

- Cosmological Events
- Astrophysical Simulations
- Nuclear Weapons
- Fusion Research
- Too Dangerous on Patient
  - Biomedical Drugs/Vaccines
- Too Stressful on Materials
  - Reciprocating Engines
- Too Many Parameters
  - Re, Ma, Fr (Store Separation)

EXPERIMENTS COSTLY

- Prototype $\Rightarrow$
  - Design
  - Engineering
  - Building
  - Measurement
  - Evaluation
  - Experimental Errors
  - Lack of Detailed Insight
  - Time-Delay (Windtunnel Unavailable)
  - Possible Destruction During Measurement
  - Cost of Equipment Increasing

EXPERIMENTS: OTHER CONS

- Experiments: Time-Delay
    - Time to Market Critical
    - Wait for Next Step in Optimization
- Experiments: No Optimization Guidance
    - Optimization Critial for Improvement
    - $\Rightarrow$ Need Sensitivity Analysis
    - $\Rightarrow$ Need Gradients

<u>Remark</u>: Experiments Won't Go Away !

EXPERIMENTS: PROS

- New Developments in Experimental Techniques
    - Laser Doppler Velocimetry
    - Temperature Sensitive Paints
    - Pressure Sensitive Paints
    - Laser Casting (Time-to-Experiment)

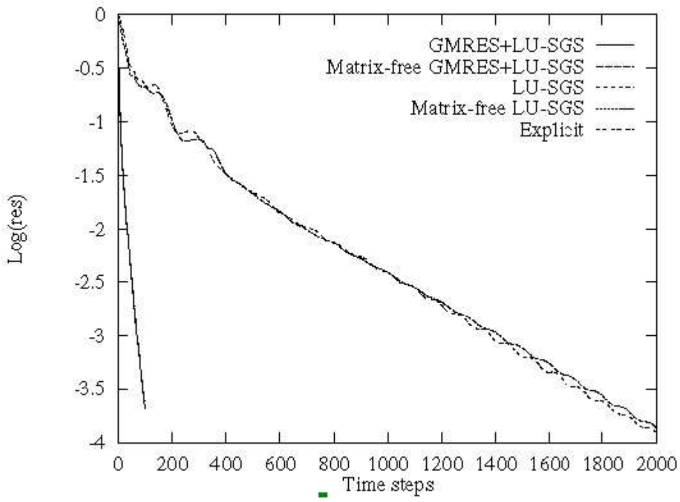
WHY SIMULATION NOW (1)

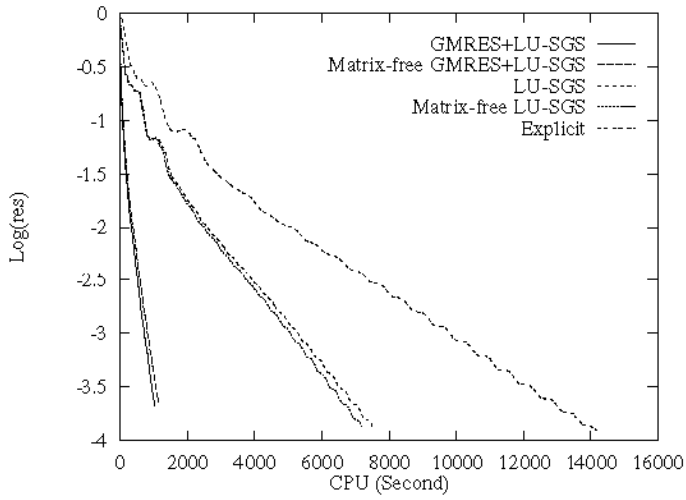
- Algorithmic Improvements Ongoing
    - Limiting (1:15)
    - Multigrid/Implicit Solvers (1:10-1:100)
    - Adaptive Grids (1:10-1:100)
- Model Set-Up Times Decreasing
    - Automatic Grid Generators
    - Link to CAD
    - Better Visualization Tools

IMPLICIT SOLVERS...

ONERA M6 WING:

- `Nelem=740K`
- `Npoin=136K`
- Cray C-90, 1 Processor





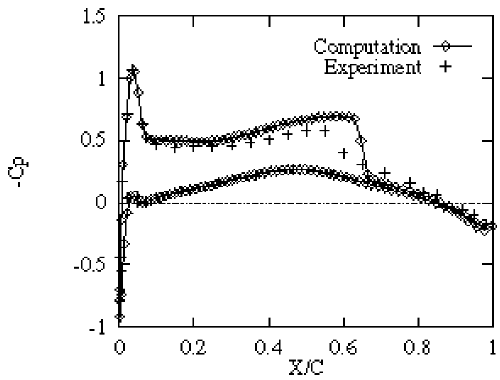


Fig. 2c: Comparison between computed and experimental surface pressure coefficient for wing section at 20% semispan.

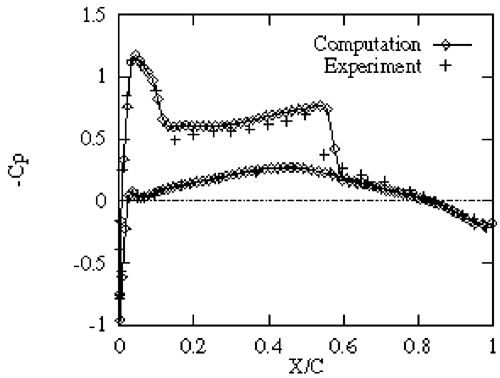


Fig. 2d: Comparison between computed and experimental surface pressure coefficient for wing section at 44% semispan.

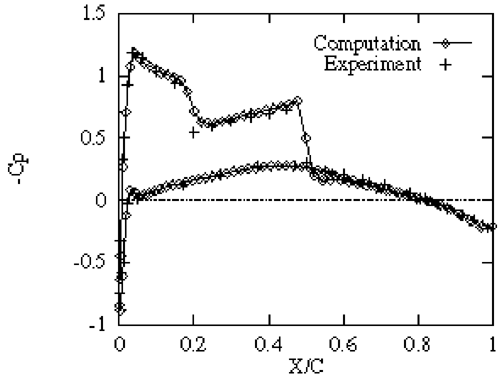


Fig. 2e: Comparison between computed and experimental surface pressure coefficient for wing section at 65% semispan.

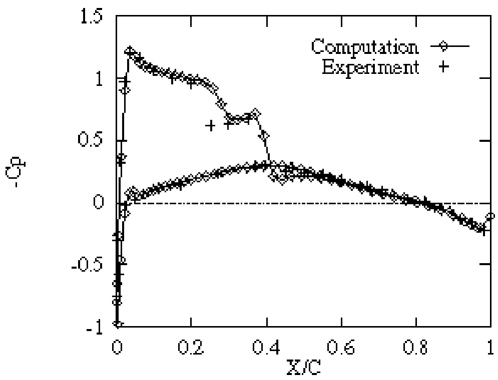


Fig. 2f: Comparison between computed and experimental surface pressure coefficient for wing section at 80% semispan.

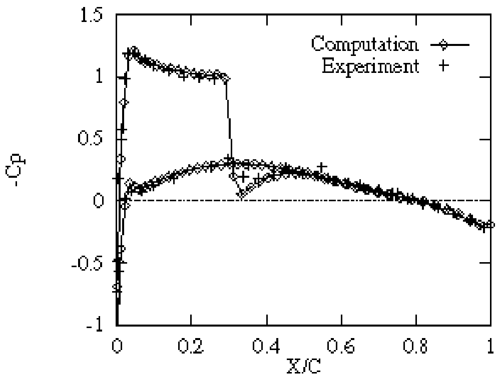


Fig. 2g: Comparison between computed and experimental surface pressure coefficient for wing section at 90% semispan.

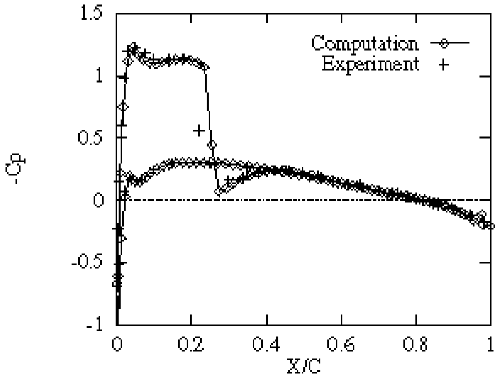
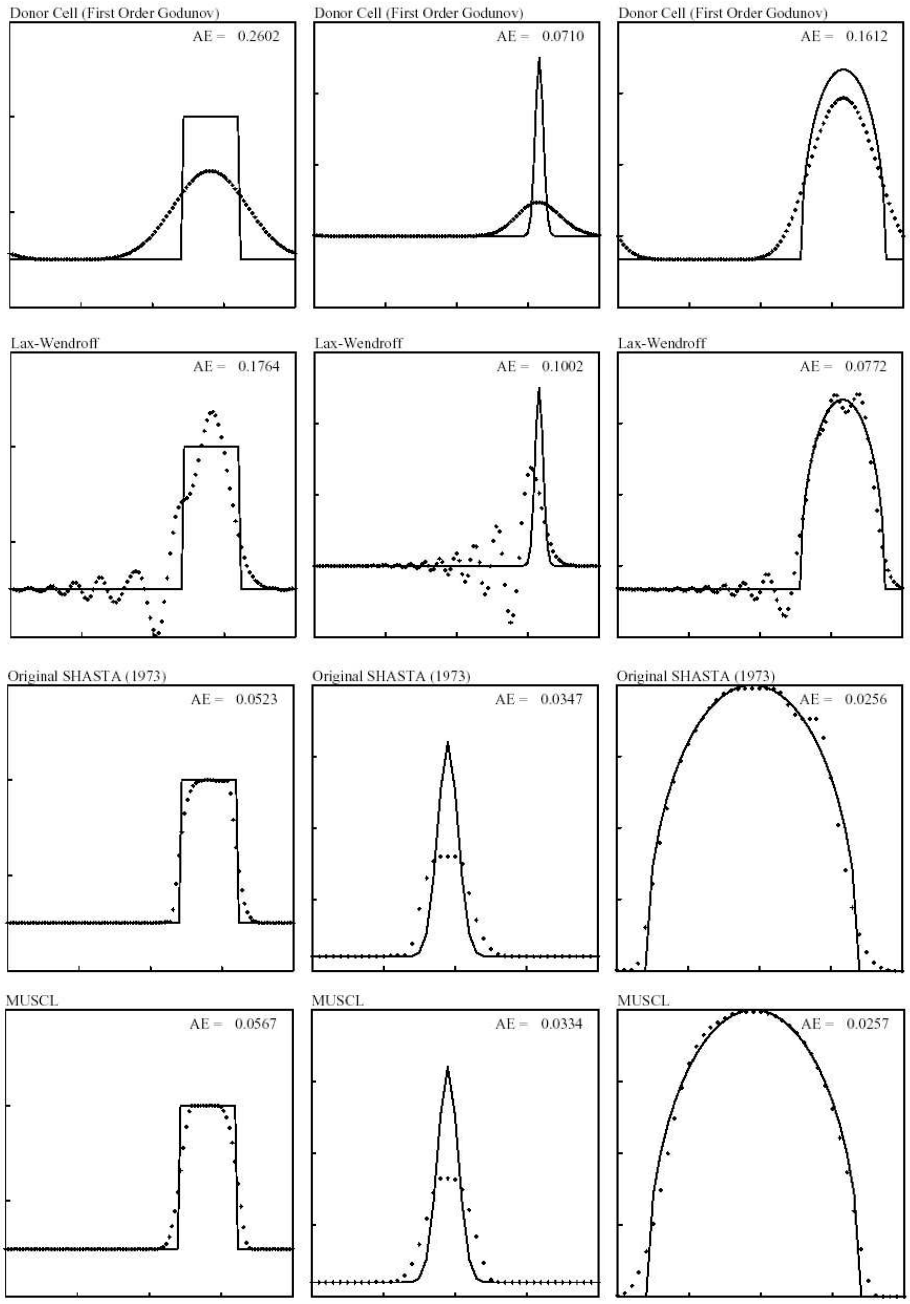


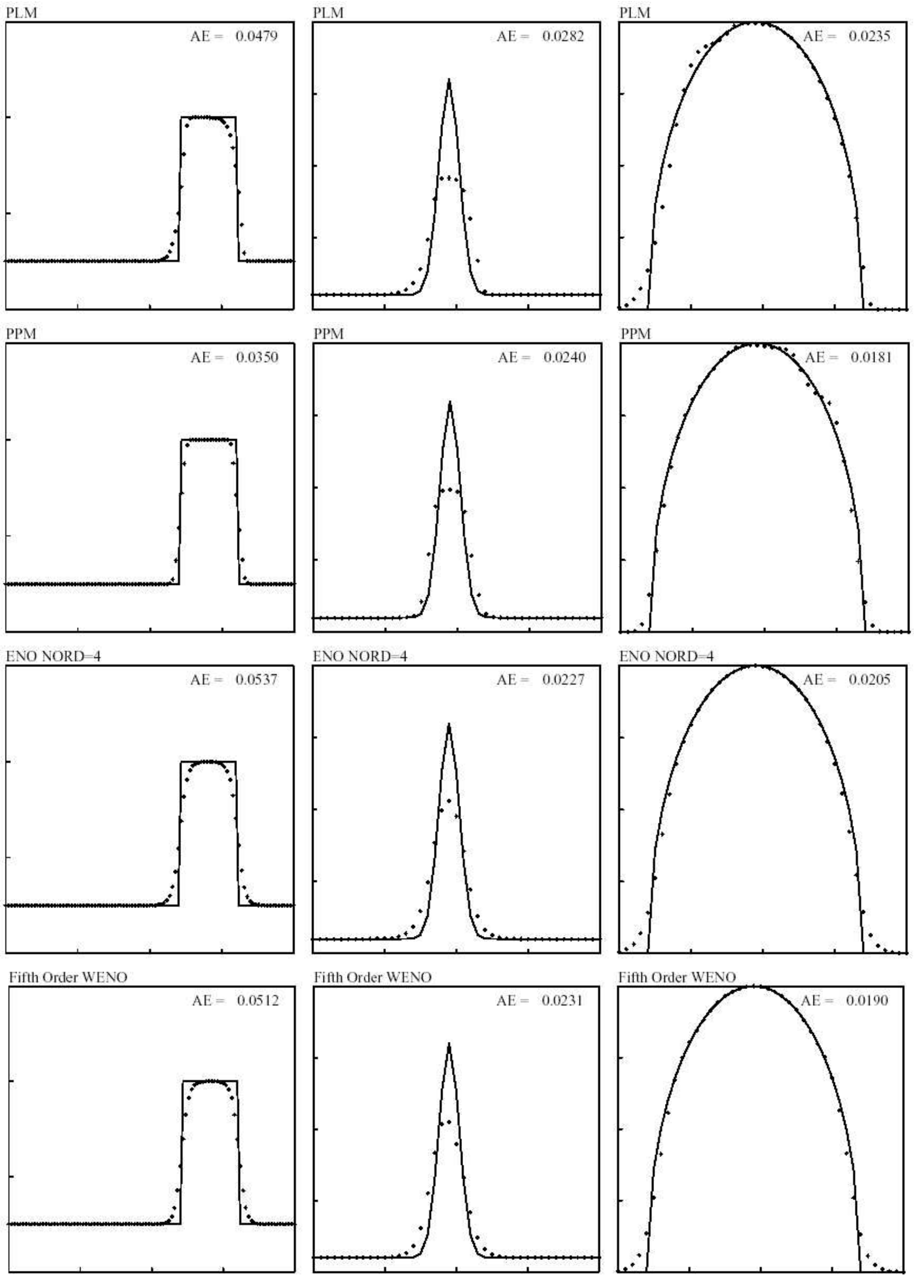
Fig. 2h: Comparison between computed and experimental surface pressure coefficient for wing section at 95% semispan.

LIMITING...



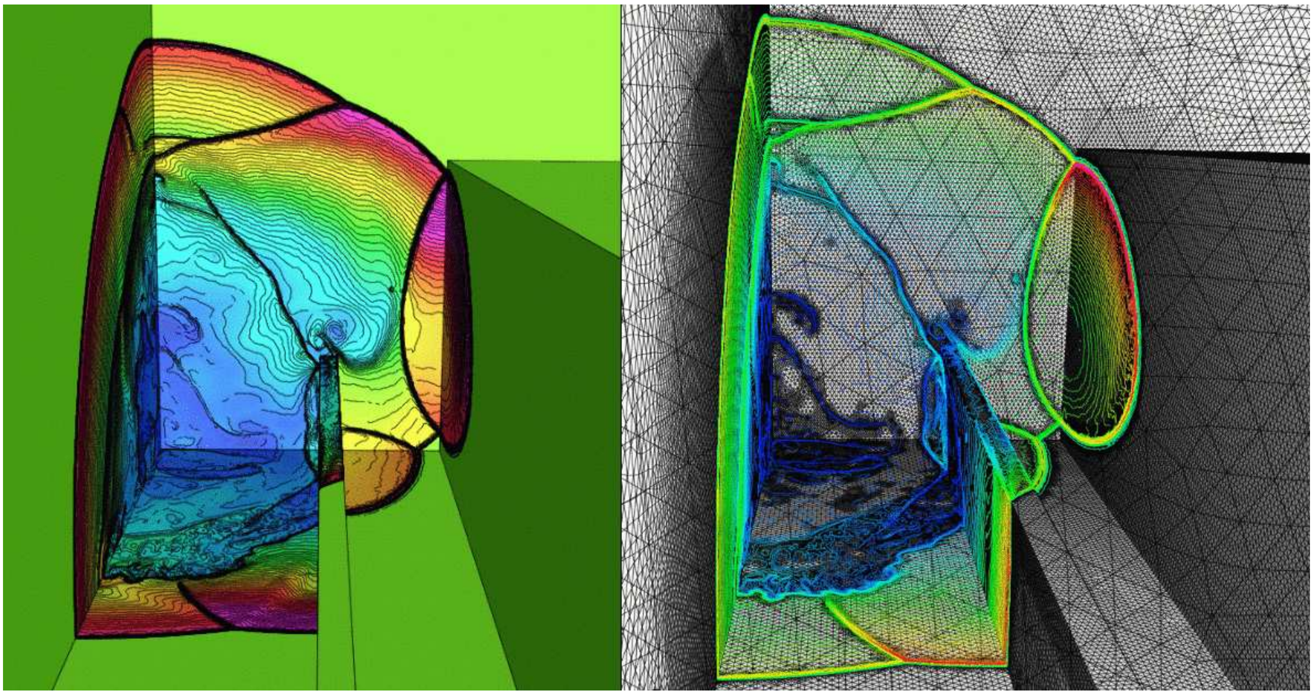
Comparison of Schemes to solve: $u_{,t} + a u_{,x} = 0$

LIMITING...



Comparison of Schemes to solve: $u_{,t} + au_{,x} = 0$

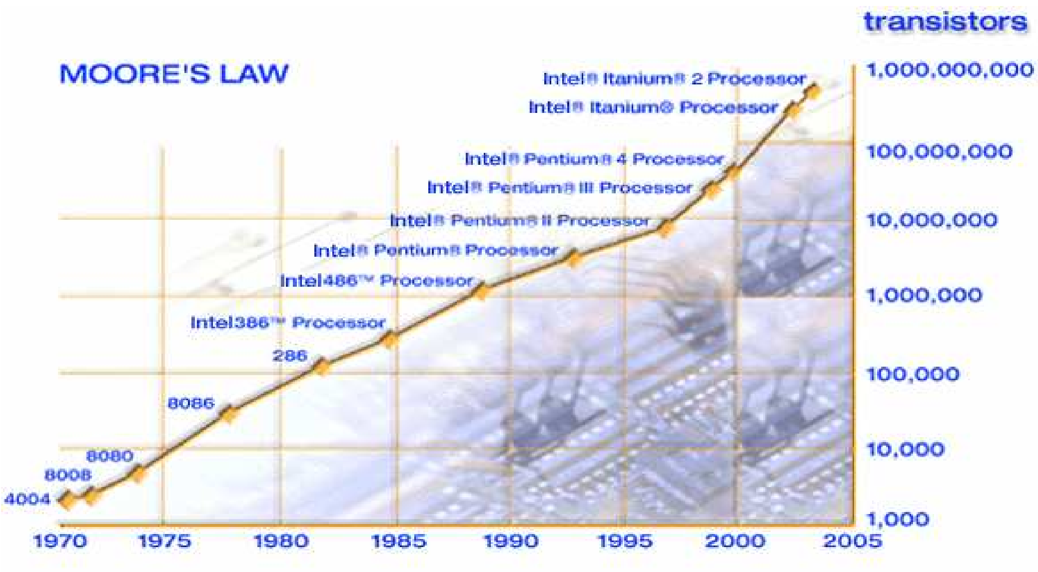
ADAPTIVE MESH REFINEMENT



Shock on Wall: Savings > 1:50

WHY SIMULATION NOW (2)

- Hardware Improvements Ongoing
  - Graphics Engine
  - RISC Architecture
  - CPU Cycle Reduction
  - RAM Increasing
  - Fast Switches



WHY SIMULATION NOW (3)

- Software Improvements Ongoing
  - Unix
  - GL and Open-GL
  - C++
  - CASE Tools
  - MPI/PVM

WHY SIMULATION NOW (4)

Improvements Compounded: $\Rightarrow$

On the Low Side:
$15 \times 10 \times 10 \times 10 \times 10 = 1.5 \cdot 10^5$

On the High Side:
$15 \times 100 \times 100 \times 10 \times 100 = 1.5 \cdot 10^8$

Such Improvements Lead to:

- New Possibilities
- New Fields
- New Markets
- Economic Growth
- ...

PROBLEM SIZE INCREASE (CFD)

Size	Dim	Code	Year	Problem	Machine
$> 10^2$	2-D	FEFLO20	1983	Airfoil	ICL
$> 10^3$	3-D	FEFLO30	1985	Forebody	CYBER-205
$> 10^4$	2-D	FEFLO27	1986	Train	CRAY-XMP
$> 10^5$	3-D	FEFLO72	1989	Train	CRAY-2
$> 10^6$	3-D	FEFLO74	1991	T-62 Tank	CRAY-2
$> 10^7$	3-D	FEFLO96	1994	WTC	CRAY-M90
$> 10^8$	3-D	FEFLO98	1998	Village	Origin 2000

WHY SIMULATION NOW (4)

$\Rightarrow$

In Short: CFD Can Provide:

- Insight
- Discovery
- Understanding

That Are Beyond Theory or Experiments

Consequences:

- New ‘Pillar of Science’
- Birth of ‘Computational Sciences’

CFD: MULTIDISCIPLINARY (1)

- Engineering:
  - reason why
- Physics:
  - relevant phenomena
  - possible approximations
- Mathematics:
  - Classic Analysis (PDEs)
  - Numerical Analysis
  - Discrete Mathematics
- Computer Science:
  - algorithms
  - coding
  - software
  - hardware

CFD: MULTIDISCIPLINARY (2)

- Visualization:
  - optimal algorithms
  - ways of seeing
- User Community:
  - benchmarking
  - education
  - motivation
  - ego (NIHS,..)

CFD CODE

Tool ⇒ service industry

Code properties:

- EU: Ease of Use
- DO: Documentation (Manuals, Help, ..)
- GF: Geometric Flexibility
- TT: Turnaround Time (Set-up to end-result)
- BM: Benchmarking
- AC: Accuracy
- SP: Speed

Customer Base: 3 categories

Gen.Purp./Anal.	Des./Optim.	New Phys.
$O(1)$	$O(1,000)$	$O(10)$
days	seconds	months
EU	SP	AC
DO	TT	BM
GF	GF	SP
TT	AC	TT
BM	BM	GF
AC	EU	EU
SP	DO	DO

PORTING RESEARCH CODES TO AN INDUSTRIAL CONTEXT

Requirements:

- Extensive Manuals and Documentation
- 24-Hour Hot-Line Answering Service
- Hands-on Customer Support Team
- Incorporation of Changes Through Releases & Training

⇒ Change of Focus

⇒ Requires an Organization

SUCCESS STORIES: SUPERCRITICAL WING

Problem:

- Wavedrag Increase in Transonic Regime

Impact:

- Environmental Damage
- Sales ($>$ 50 Bn$)

PDE:

- Potential/Full Potential
- Euler/RANS

Solution Scheme:

- FVM
- Multigrid

Time Per Run:

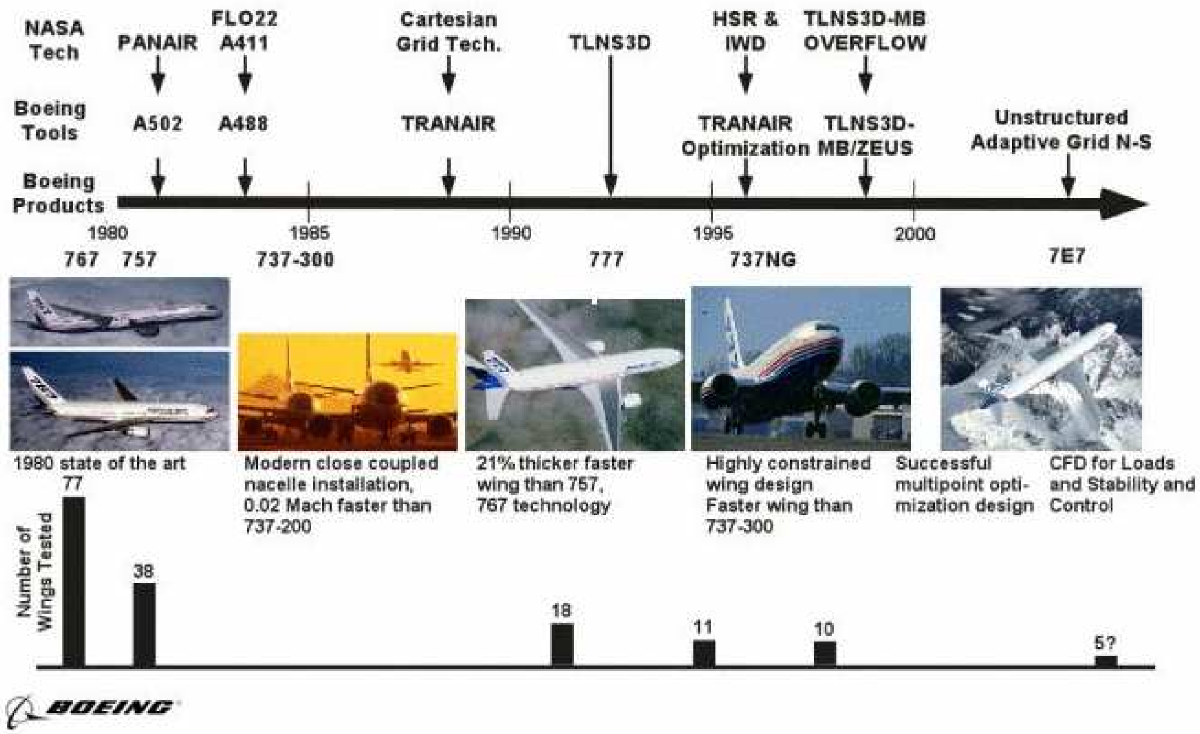
- Several Secs./Mins.

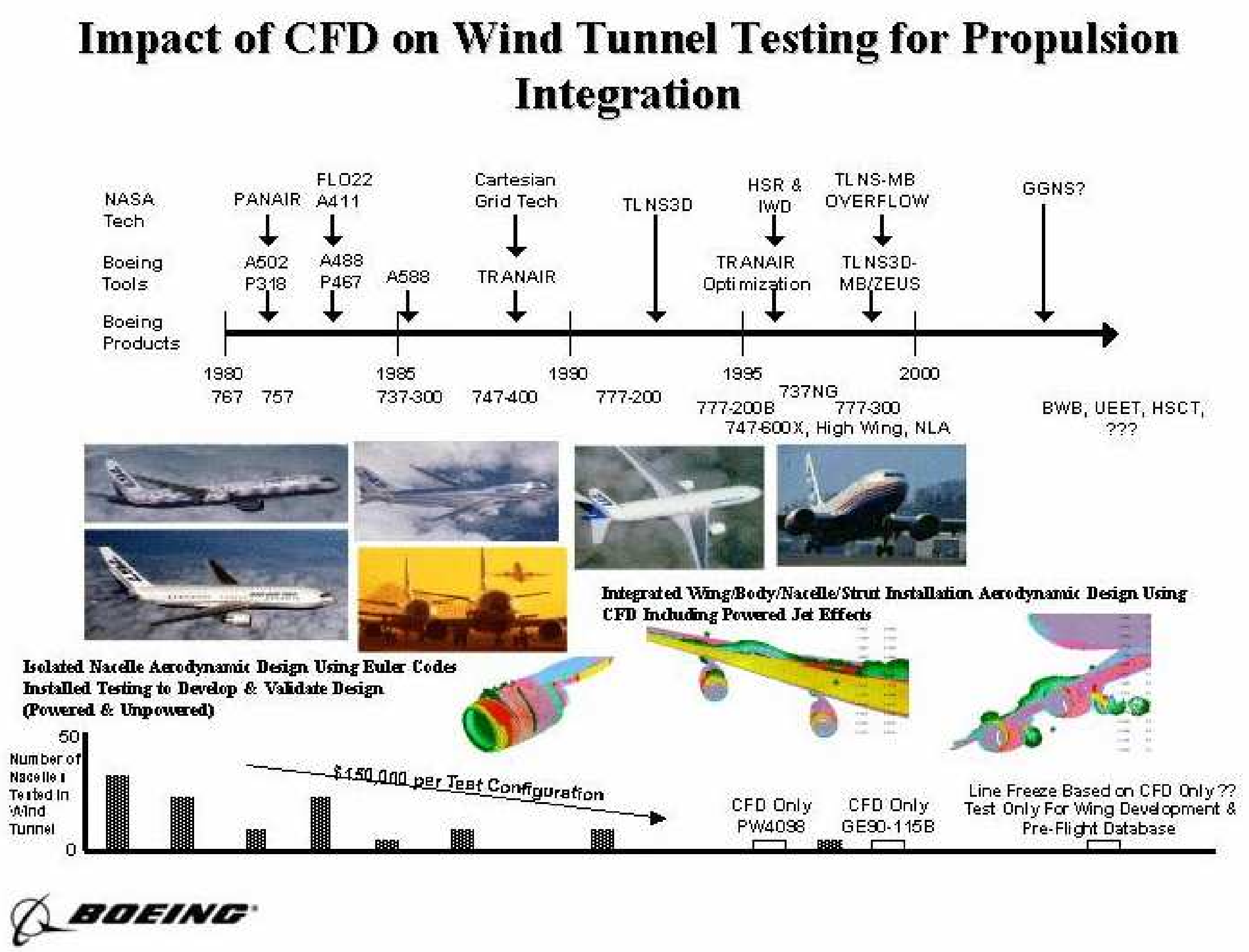
Use:

- $>$ 10,000 Runs/Month (2-D)
- $>$ 100 Runs/Month (3-D)

SUCCESS STORIES: AIRPLANE DESIGN

Impact of CFD on Wind Tunnel Testing for Configuration Lines Development




Impact of CFD on Wind Tunnel Testing for Propulsion Integration
NASA Tech
Boeing Tools
Boeing Products
PANAIR
FLO22
A411
Cartesian Grid Tech
TLNS3D
HSR & IWD
TLNS-MB OVERFLOW
GGNS?
A502 P318
A488 P467
A588
TRANAIR
TRANAIR Optimization
TLNS3D-MB/ZEUS
1980
1985
1990
1995
2000
767 757
737-300
747-400
777-200
777-200B
737NG
777-300
747-600X, High Wing, NLA
BWB, UEET, HSCT, ???
Integrated Wing/Body/Nacelle/Strut Installation Aerodynamic Design Using CFD Including Powered Jet Effects
Isolated Nacelle Aerodynamic Design Using Euler Codes
Installed Testing to Develop & Validate Design
(Powered & Unpowered)
50
Number of Nacelles Tested In Wind Tunnel
0
$150,000 per Test Configuration
CFD Only PW4098
CFD Only GE90-115B
Line Freeze Based on CFD Only??
Test Only For Wing Development & Pre-Flight Database
BOEING

SUCCESS STORIES: TUNDISH FLOWS

Problem:

- Impurities in Steel

Impact:

- Steel Quality
- Sales ($>$ 5 Bn$)

PDE:

- Navier-Stokes
- Non-Newtonian Flows

Solution Scheme:

- FEM

Time Per Run:

- Several Mins./Hours

Use:

- $>$ 10 Runs/Month

PRESENT STATUS (1)

General:

- Well Established
- Extensively Used In:
  - Aerodynamics
  - Hydrodynamics
  - Process Modelling
  - Weapon Design/Assessment

PRESENT STATUS (2)

Physical Models/Complexity:

a) Continuum

- Linear Potential
- Full Potential (Nonlinear)
- Euler
- Reynolds-Averaged Navier-Stokes (RANS)
- Large Eddy
- Direct Simulation of Navier-Stokes (DSNS)
- Multifluid

b) Particles

- Collisionless
- Collisions

c) Particles+Continuum

PRESENT STATUS (3)

Solution Methodologies:

a) Continuum: Grid

- Potential, Euler, Navier-Stokes
- Multifluid
- FDM, FVM, FEM

b) Particles

- Direct Monte-Carlo
- Low Nu-Regime

c) Grid + Particles

- Multiphase Flows
- FDM, FVM, FEM

PRESENT STATUS (4)

Market Size:

Over 5,000 Developers

Over 100,000 Engineers

Software $>$ 80 M$

Hardware $>$ 1 B$