Computational Sciences: The Third Pillar of the Empirical Sciences

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  - Univ. of Paris, VII — Optimization

Outline

- Why ?
- Why Now ?
- Whither Now ?

Outline

- Why ?
  - Creation of Information and Insight
  - Computational Techniques in Science and Engineering
- Why Now ?
- Whither Now ?

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  - Enabling Technologies
  - Typical Case: Computational Fluid Dynamics
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  - Typical Case: Computational Fluid Dynamics
- Whither Now ?
  - Current Status
  - Extrapolations from Current Trends
  - Implications

Why Computational Sciences ?

Why Information/Insight ?

- Curiosity
  - Basic Human Behaviour/Trait
- Need to Predict
  - Engineering Products
  - Intelligence Gathering
- Need to Postdict
  - Explain Experimental Results
  - Forensic Analysis
- Information Age
  - Information: Most Valuable Resource

Information: The Gold of Our Times

- (1) William Gates: Info Enabling (Software)
- (2) Warren Buffett: Info Evaluation (Valuations)
- (3) Carlos Slim Helu: Info Transmission (Hardware)
- (6) Paul Allen: Info Enabling (Software)
- (9) Kenneth Thompson: Media/Entertainment
- (12) Michael Dell: Computers (Hardware)
- (15) Lawrence Ellison: Info Storage/Retrieval (Software)
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- (25) Azim Premji: Info Creation/Processing (Software)
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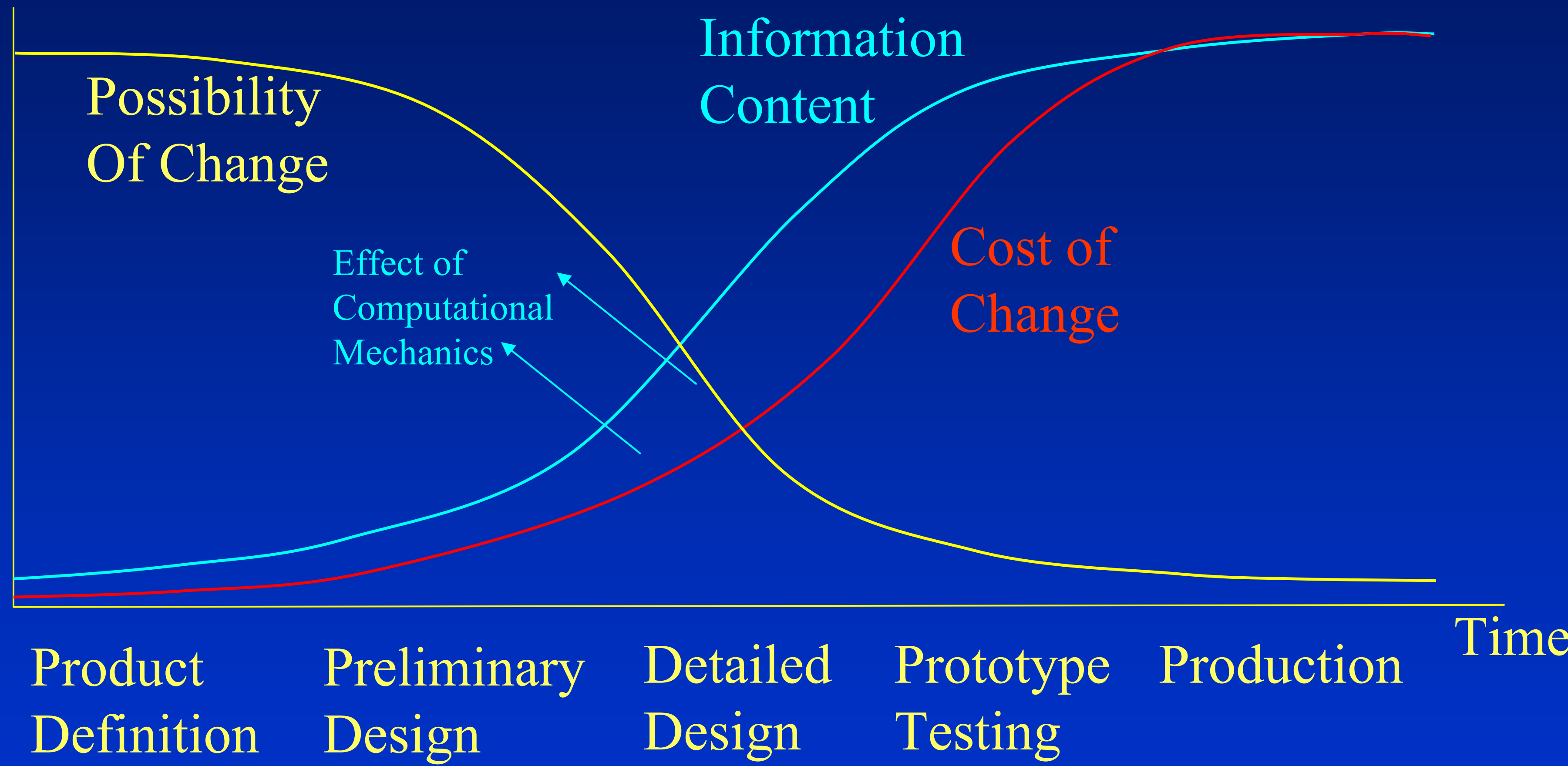
Source: Forbes'06

Product Development Cycle



New Airplane: $20B, New Car: $4B (`Betting the Company')

Creation of Information/Insight

- Data Assimilation (Empirical Relations, Neural Nets)
- Classic Analysis (Partial Differential Equations [PDEs])
- Experiments (Model, Prototype)
- Computational/Numerical Techniques (Simulation)

Classic Analysis

- Derive (Partial/Ordinary Differential) Equations
  - Most Condensed Form of Information
  - Knowledge from Solution of Equations
- If Possible: Solve Equations (Almost Never the Case)
- Simplify Model (PDE → ODE → Formula)
- Determine Error Margin
- Solve
- Obtain Trends
- Summarize: y=f(x)

Famous Equations

- Euler (1760): Inviscid Flows
- Navier (1822) - Stokes (1840) : Viscous Fluids
- Maxwell (1864) : Electromagnetics
- Einstein (1905/1915): $E=mc^2$, General Relativity
- Schrödinger (1925): Quantum Mechanics
- Heisenberg (1927): Uncertainty Principle

Equations

- `Immortality from Equations'
- Closest to Platonic `Ideas'
- `Understanding God'
- `Almost Indescribable Exhilaration When Derived/Found'

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  - Doch Ihr, die echten Göttersöhne, erfreut Euch der lebendig, reichen Schöne…

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But yee, the god's true sons, delight in living, bounteous beauty,
and what floats in wavering appearance, fasten (cement) in lasting thoughts

Problems With Equations

- Solvable Only In Rarest of Cases
- Solvable Only for Very Simple Boundary Conditions
- Example **Fluids**: Only Handful of Exact Solutions
  - Parallel Flow (Channel [Couette], Pipe [Poiseuille])
  - Flow Between Concentric Cylinders
  - Suddenly Accelerated Wall (Stokes' 1st Problem)
  - Flow Near Oscillating Flat Plate (Stokes' 2nd Problem)
  - Stagnation in Plane Flow (Hiemenz)
  - Flow Near Rotating Disk (already ODEs)

- → Need **Numerical Methods** to Solve Them

Experiments

- Modify/Rebuild Test Chamber
- Instrument
- Determine Error Margin
- Build Model
- Measure
- Evaluate
- Obtain Trends
- Summarize: y=f(x)

Famous Experiments

- Galileo (1589): All Objects Fall At Same Speed
- Torricelli (1644): Weight of Air
- Hertz (1886): Radio Waves
- Michelson/Morley (1887): No Ether
- Los Alamos (1945): Atomic Bomb
- Miller-Urey (1953): Creation of Amino acids

- `Immortality from Experiments'
- Unequivocal Truth, `Gold Standard of What Is'

Problems With Experiments

- Impossible
  - Cosmological Events, Nuclear Weapons, Fusion, Biomedical, …
- Inaccurate
  - Real Size/Experiment: Many `Characteristic Numbers' (Re,Ma,Fr)
- Costly
  - Engineering, Wind/Water Tunnel Availability, Test Evaluation
  - Destruction During Testing
- Untimely
  - Time-to-Market Critical
- Lack of Detailed Insight
  - Pressure Probes (0-D), Light Sheets (2-D), MRI (2-D)
- No Optimization Guidance

Why Computational Sciences Now ?

Why Computational Sciences Now ?

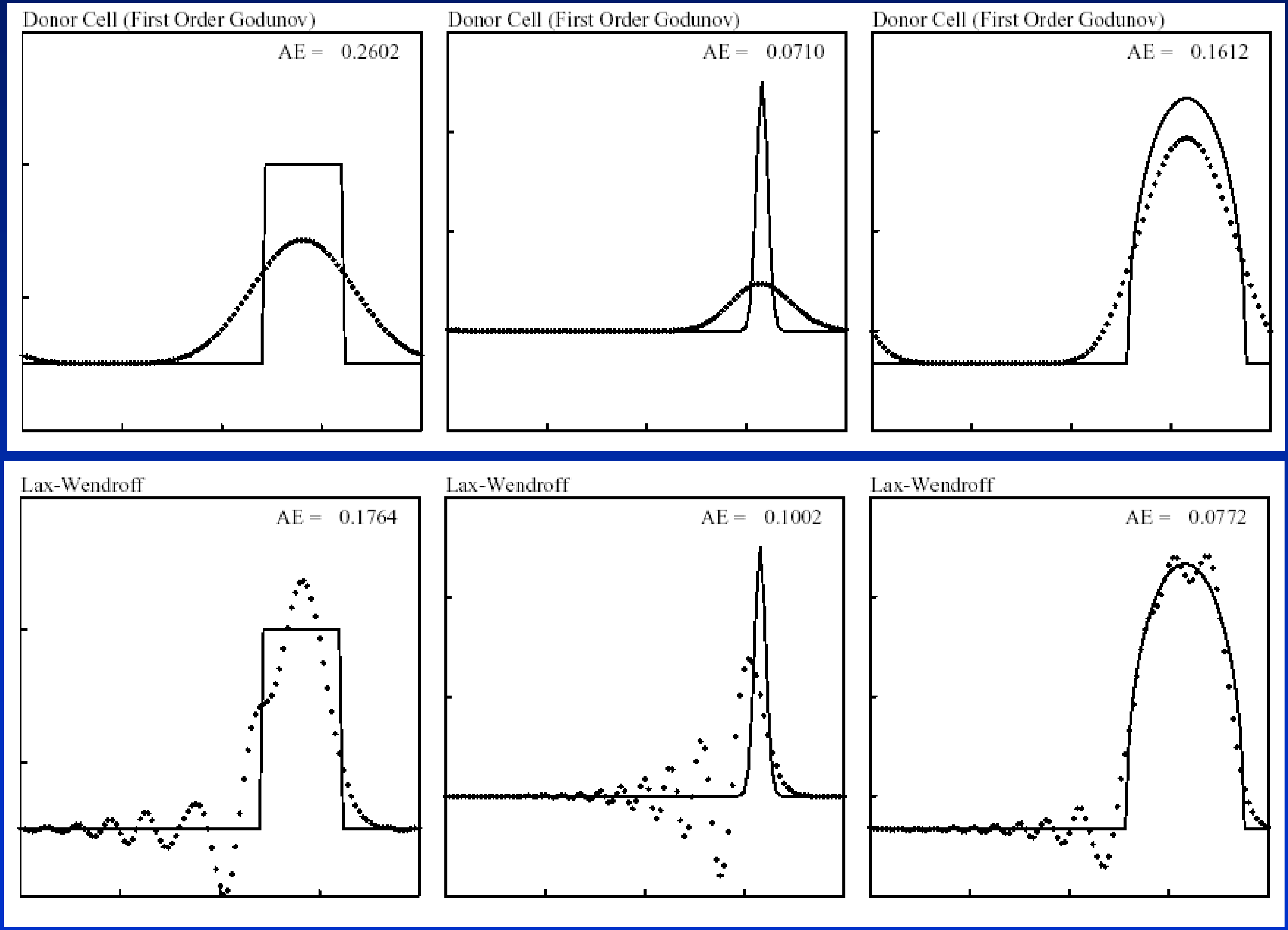
- Enhanced Realism
  - Proper Physics (Fluids: Pot → Euler → RANS → LES → DNS)
  - Multidisciplinary Solvers (CSD, CFD, CTD, CEM, …)
- Algorithmic Improvements
  - Accuracy [Limiters, Order, …]
  - Speed [Multigrid, LU-SGS-GMRES, Adaptive Refinement]
- Reduction of Set-Up Times
  - CAD-Solver Link + Advanced GUIs
  - Automatic Grid Generation
- Advances in Hardware
  - Moore’s Law
  - 3-D Graphics Cards

PDE Solver Bottleneck 1: Advection

- No **Linear** Scheme of Order > 1 Is Monotonicity Preserving (Godunov 1959)
- → Make Schemes **Nonlinear**
- → Limiters, FCT, TVD, LED, …

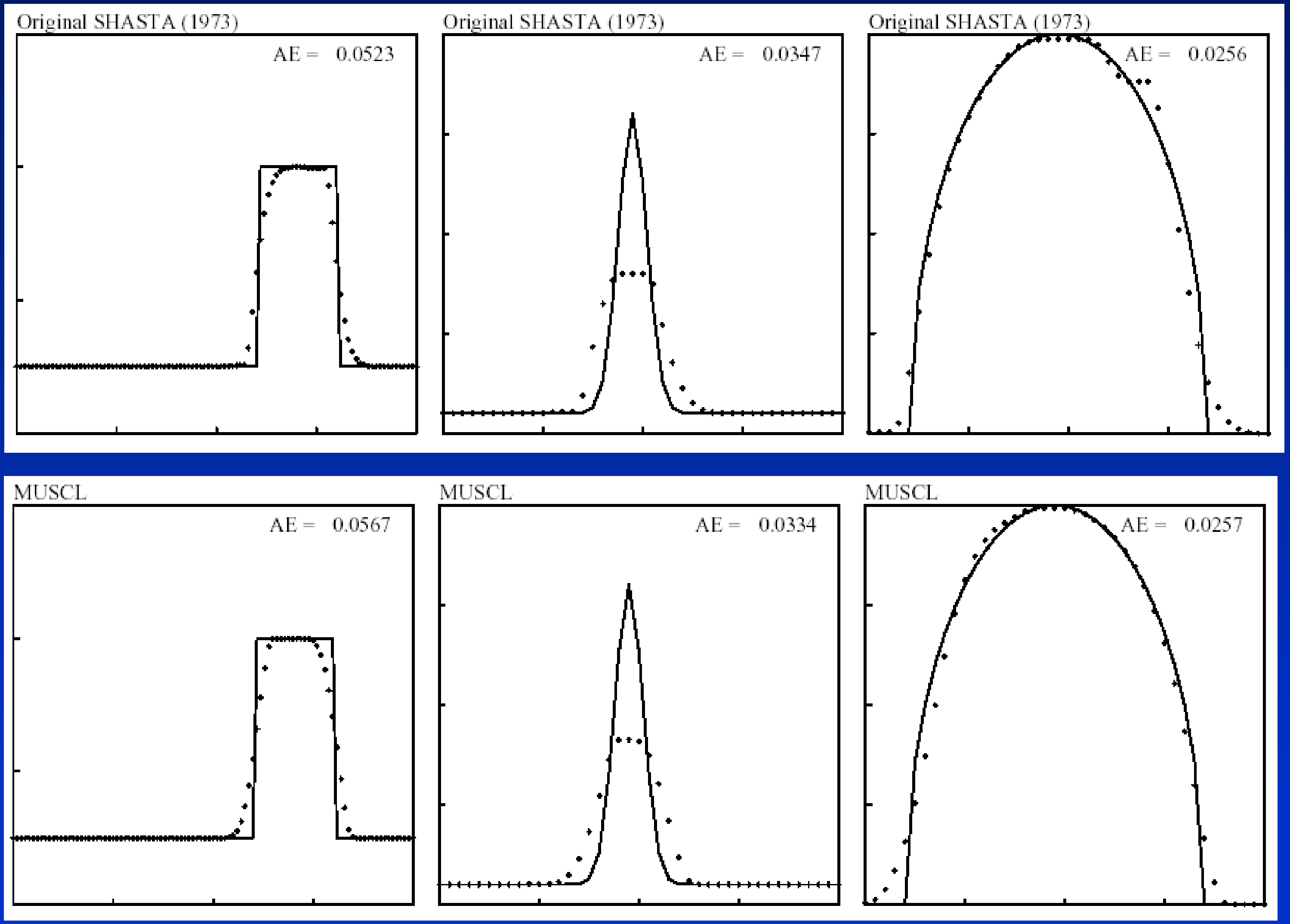
Advection ($u_{,t} + au_{,x} = 0$):1960's

Courtesy S.T. Zalesak



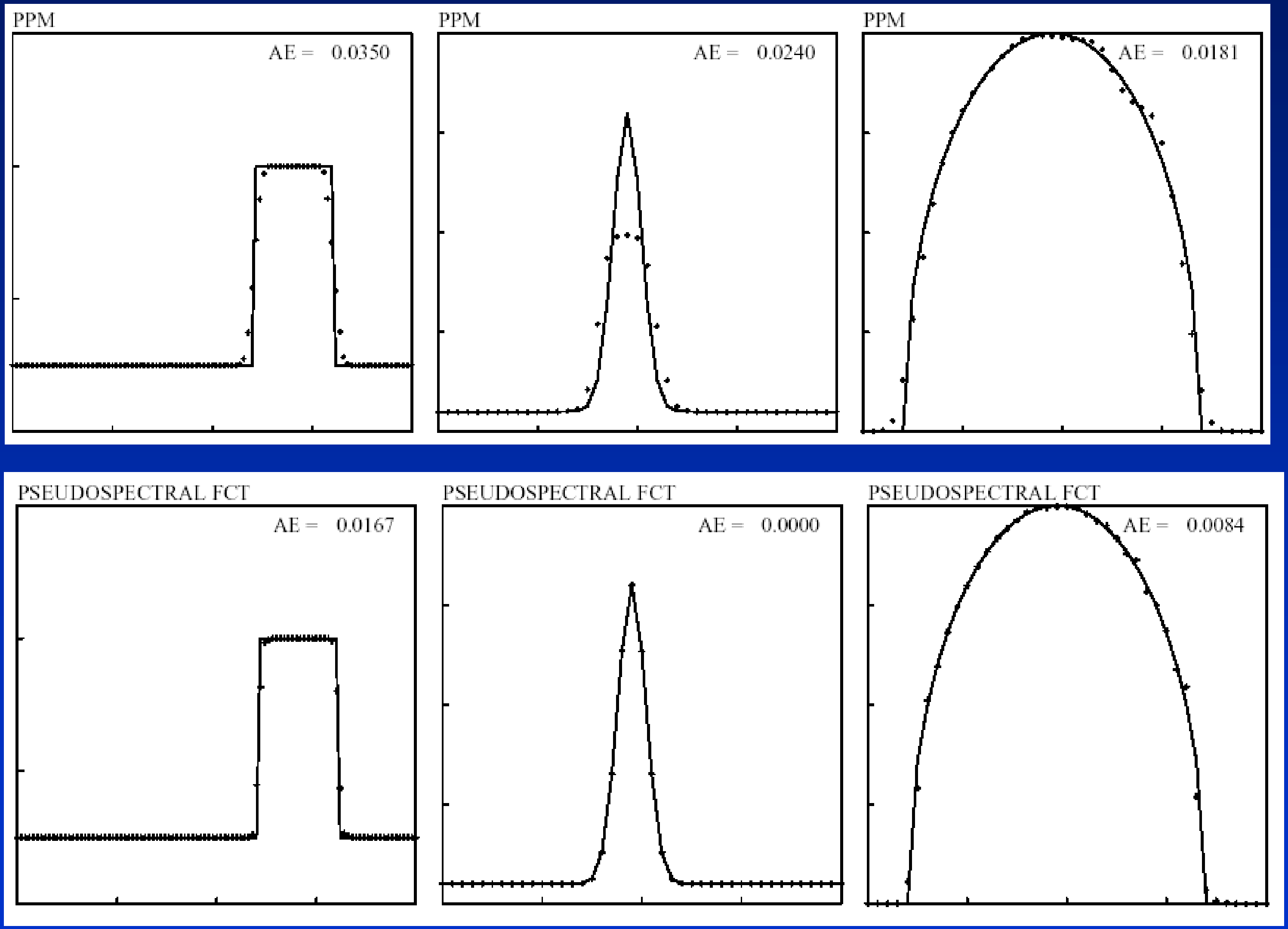
Advection ($u_{,t} + au_{,x} = 0$): 1970's

Courtesy S.T. Zalesak



Advection ($u_{,t} + au_{,x} = 0$): 1980's

Courtesy S.T. Zalesak

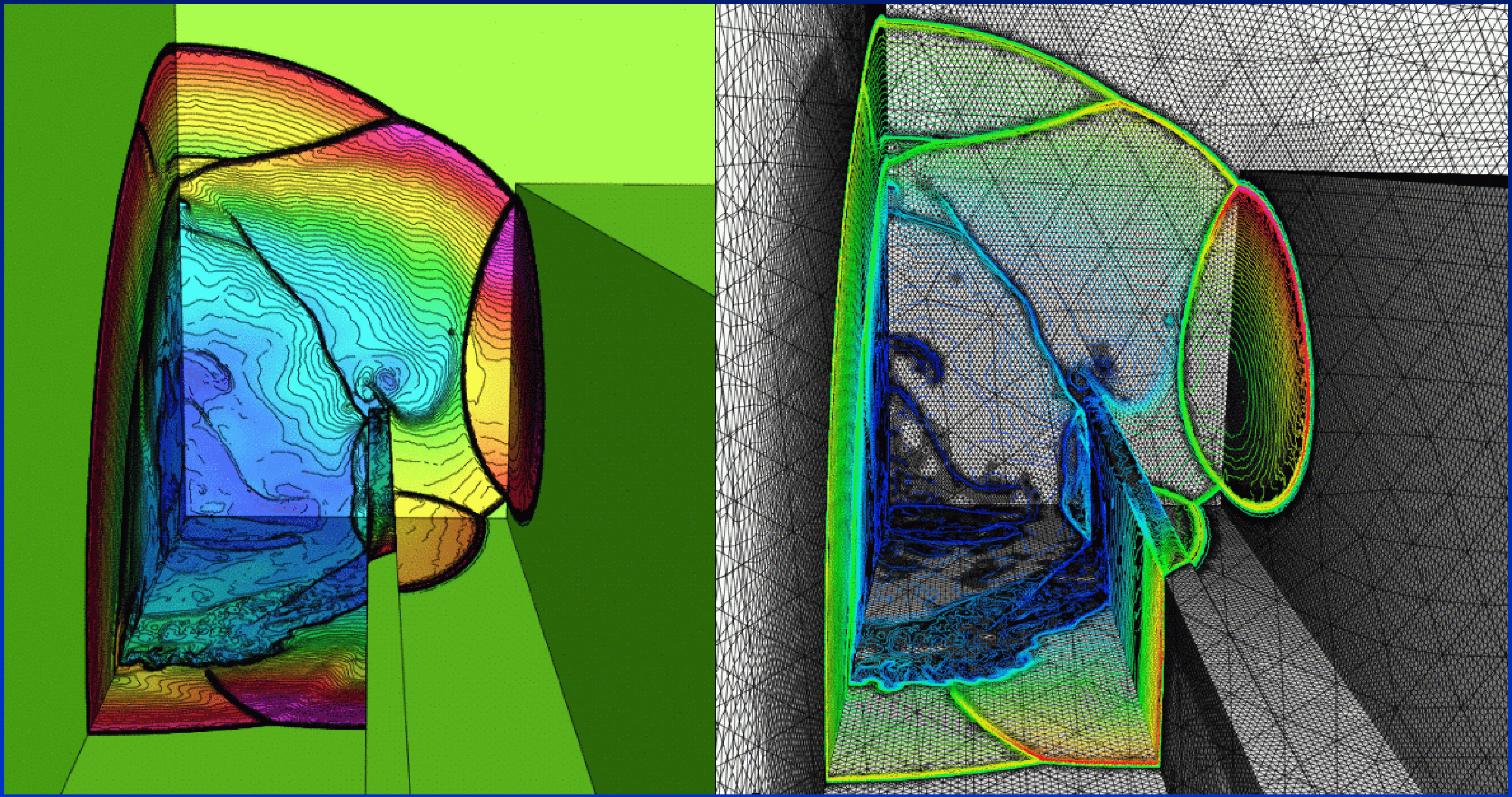


PDE Solver Bottleneck 2: Mesh Size

- Many Problems Are Characterized By Small Regions of Extreme Changes in the Solution, Requiring Small Elements
- ➔ Use a Fine Mesh **Only** in These Regions
- ➔ Adaptive Mesh Refinement

Adaptive Mesh Refinement

Courtesy J.D. Baum

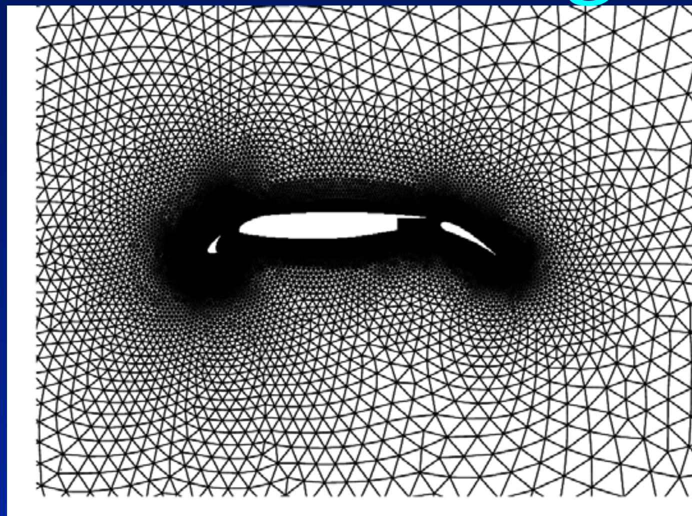


PDE Solver Bottleneck 3: Convergence

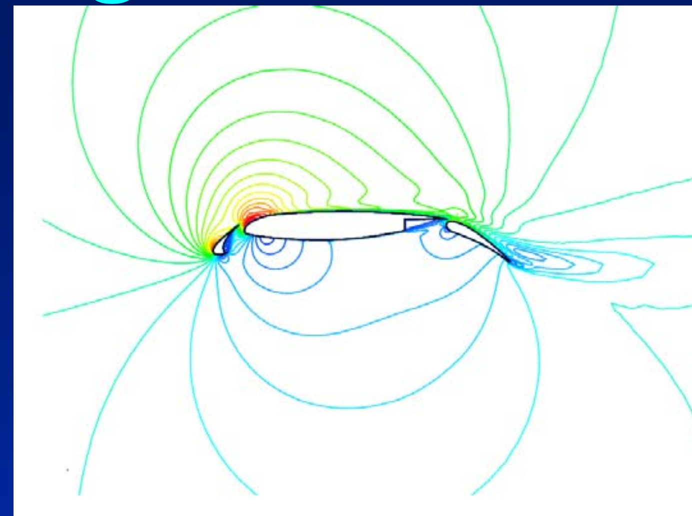
- For Large Problems (>10^7 Points): Iterative Schemes Faster
- Iterations Required for Near-Neighbour RHS Schemes O(Graphsize)
- ➔ Use Series of Coarser Grids (Multigrid)
- ➔ Use `Sweep' RHS Schemes (LU-SGS)

Landing Configuration

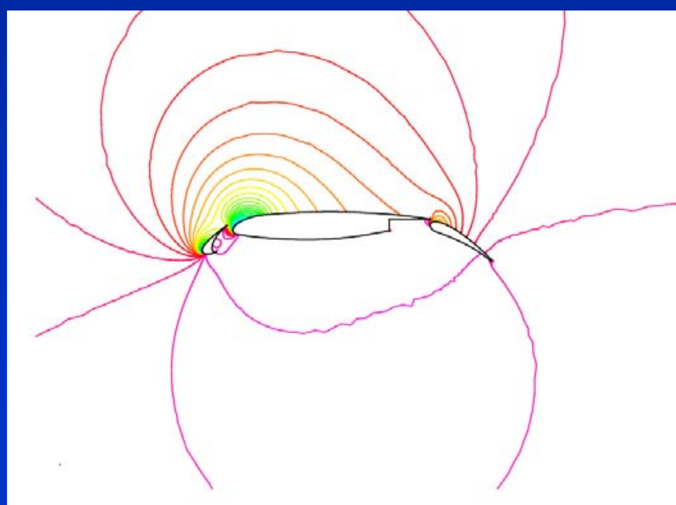
Courtesy H. Luo



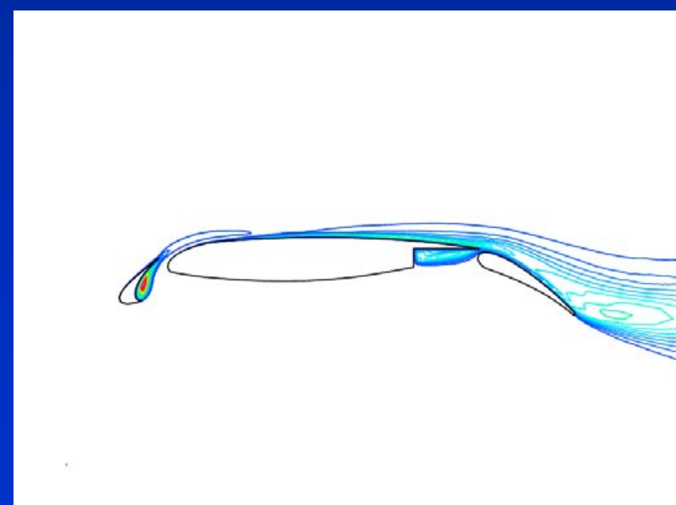
Mesh



Mach-Number

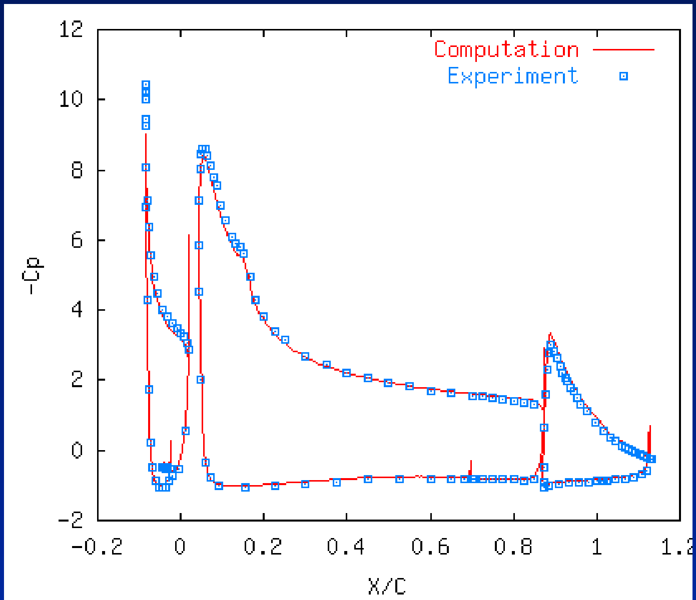


Pressure Contours

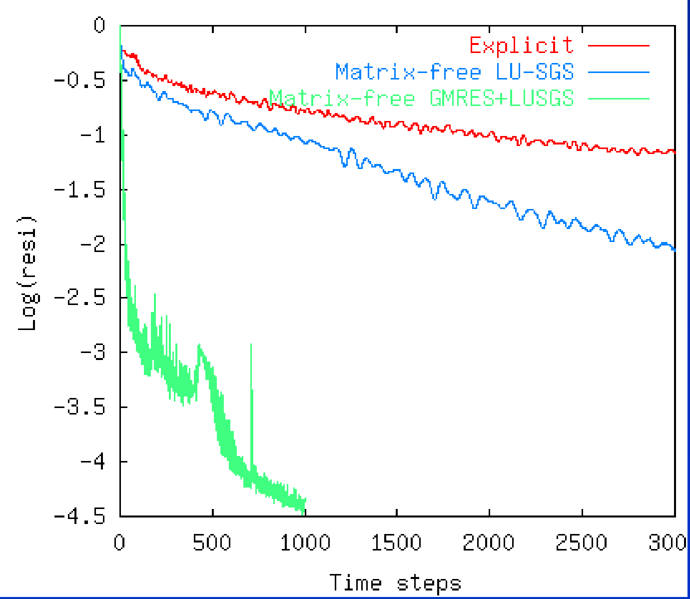


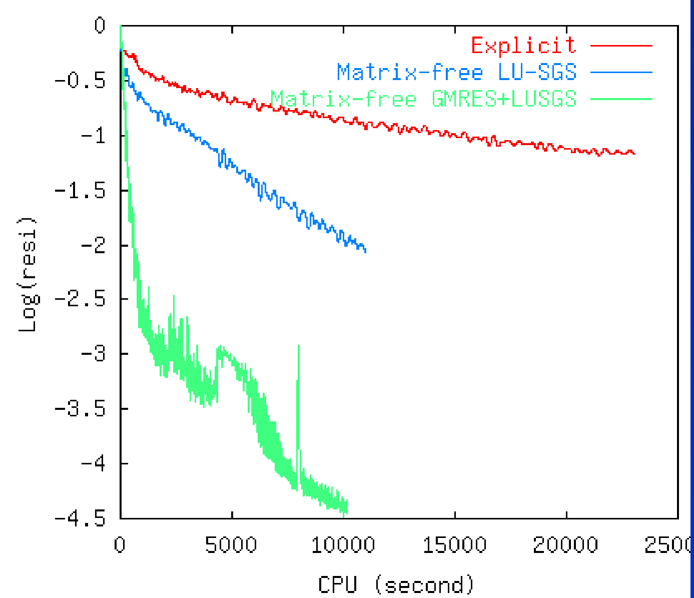
Eddy Viscosity

Landing Configuration

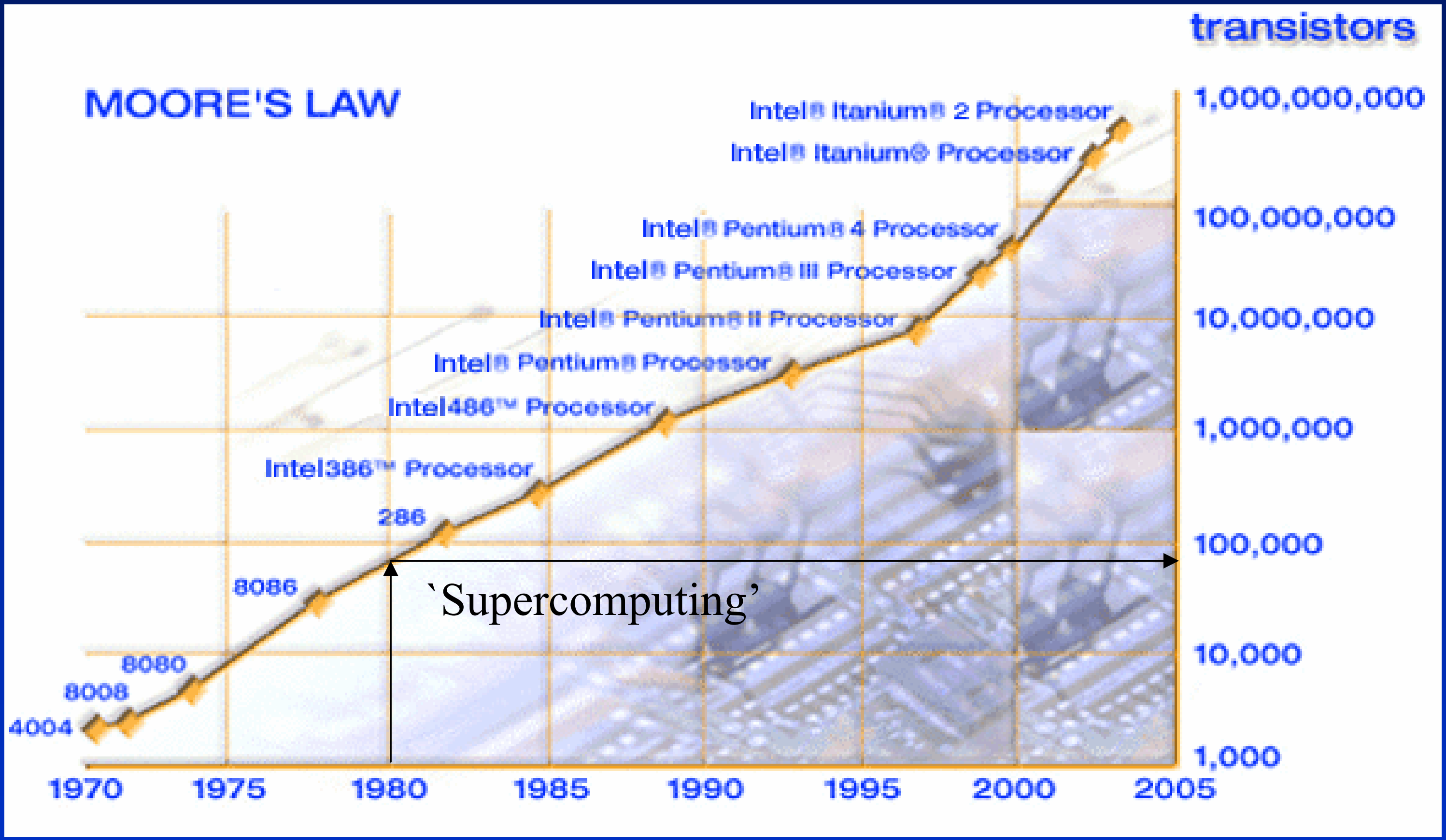


Courtesy H. Luo





Moore's Law (1)



- 35 Years Of Exponential Growth
- Factor 1:10 Every 5 Years

Moore's Law (2)

- More Transistors ➔
  - More Registers
  - More Cache
- Continuing Improvements in:
  - Clockrates
  - Pre-Fetching
  - Branch Prediction
  - Compilers
- ➔ CPU Performance Mirrors Moore's Law
- Prognosis: Will Continue for the Foreseeable Decade

Increase in Problem Size Over Time

Year	Mesh Size	Problem	Code	Algorithm	Machine
1983	$> 10^2$	Airfoil	FEFLO20	TG	ICL
1985	$> 10^3$	Forebody	FEFLO30	TG	Cyber-205
1986	$> 10^4$	Train CSect	FEFLO27	FEM-FCT (El)	Cray-XMP
1989	$> 10^5$	Train	FEFLO72	FEM-FCT (El)	Cray-2
1991	$> 10^6$	T-62 Tank	FEFLO74	FEM-FCT (El)	Cray-2
1994	$> 10^7$	Garage (WTC)	FEFLO96	FEM-FCT (Ed)	Cray-M90
1998	$> 10^8$	Village	FEFLO98	FEM-FCT (Ed)	SGI-O2K

- As of 2003: > 50 Runs/Year in Excess of 300 Mels

Effects of Compounding Improvements

◆ Solvers (Limiters, Order)	$1:10^1$	$1:10^2$
◆ Algorithms (MG, LU-SGS-GMRES,..)	$1:10^1$	$1:10^2$
◆ Hardware (Moore, Parallel, ..)	$1:10^3$	$1:10^6$
◆ Compounded Gains	$1:10^5$	$1:10^{10}$

- Consequences:
  - New Possibilities (`Cambrian Explosion')
  - New Fields (Supercomputing, Computational Sciences)
  - New Markets
  - Economic Growth (Current Comp. Mech. Market: > $10B)

- ➔ Computational Sciences

Computational Sciences

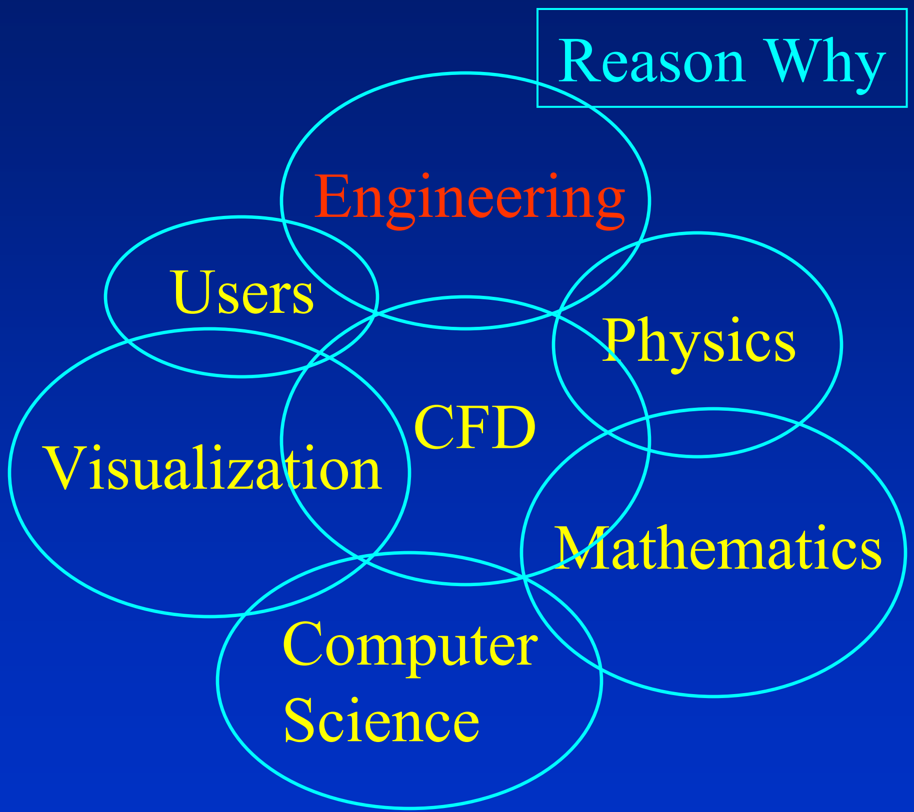
- Mirror Classical Disciplines, But Offer Novelty
- Band that Unites Inter-Disciplinary Endeavours
- Computational Physics / Chemistry / Engineering / …
  - Computational Astronomy
  - Computational Fluid Dynamics
    - Computational: Aerodynamics, Aero-Acoustics, Bubble Dynamics, ..
- Computational Geography / Climate / …
  - Remote Sensing, Seismic Analysis, …
- Computational Economics
  - Computational Finance, Statistics, …
- Computational Social Science
- …

Computer (Virtual) Experiments

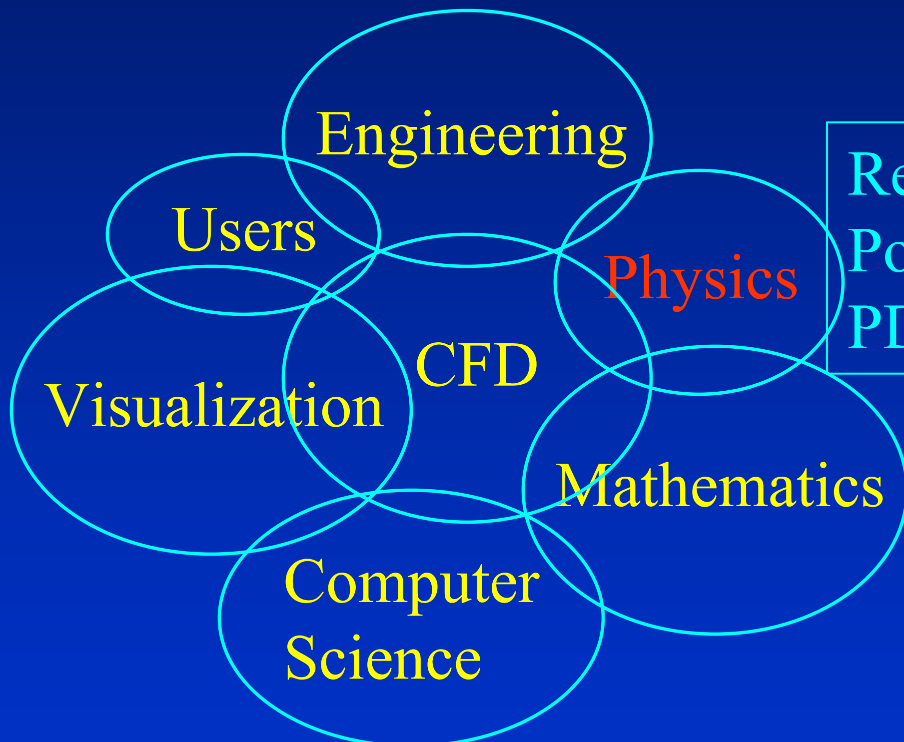
- Possible
  - Unless Physics Unknown (Use: Probe Physical Models)
- Accurate
  - Solves Real Problem, Proper `Characteristic Numbers' (Re,Ma,Fr)
- Cost Competitive
  - Fast Set Up Times
  - Algorithms, Software, Hardware Improving
- Timely
  - Simulate/Compute `Before Bending Tin'
- Detailed Insight
  - 3-D Fields, Many Display Options
- Optimization Guidance

Computational Fluid Dynamics: A Typical Computational Science

CFD: Multidisciplinary Science



CFD: Multidisciplinary Science

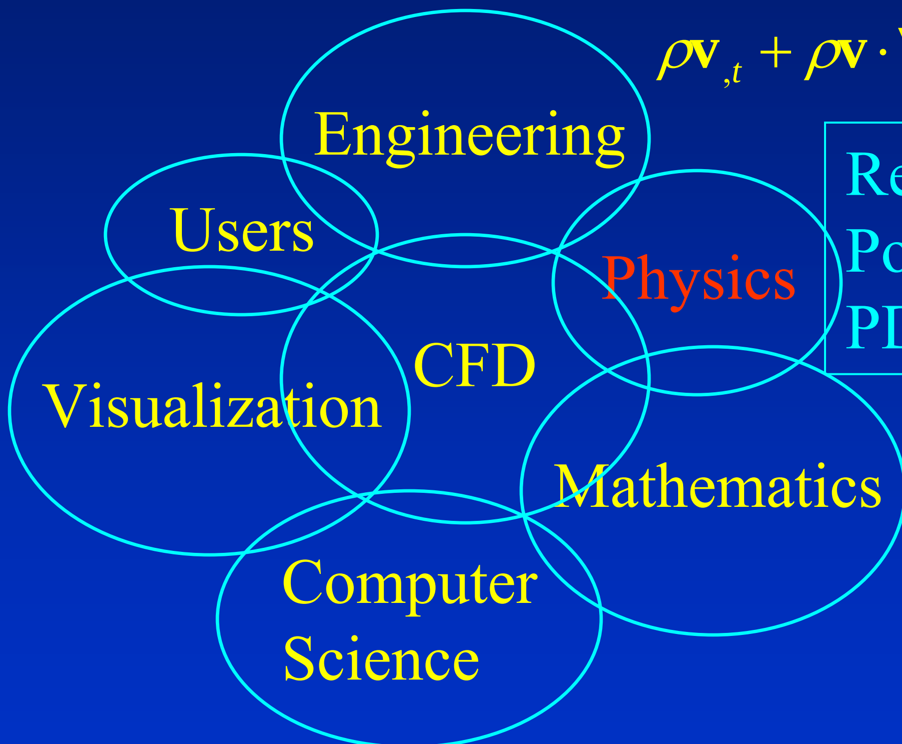


Relevant Phenomena
Possible Approximations
PDEs, ODEs

CFD: Multidisciplinary Science

$$\nabla \cdot \mathbf{v} = 0$$

$$\rho \mathbf{v}_{,t} + \rho \mathbf{v} \cdot \nabla \mathbf{v} + \nabla p = \nabla \mu \nabla \mathbf{v} + \mathrm{f} + \rho \mathbf{g}$$



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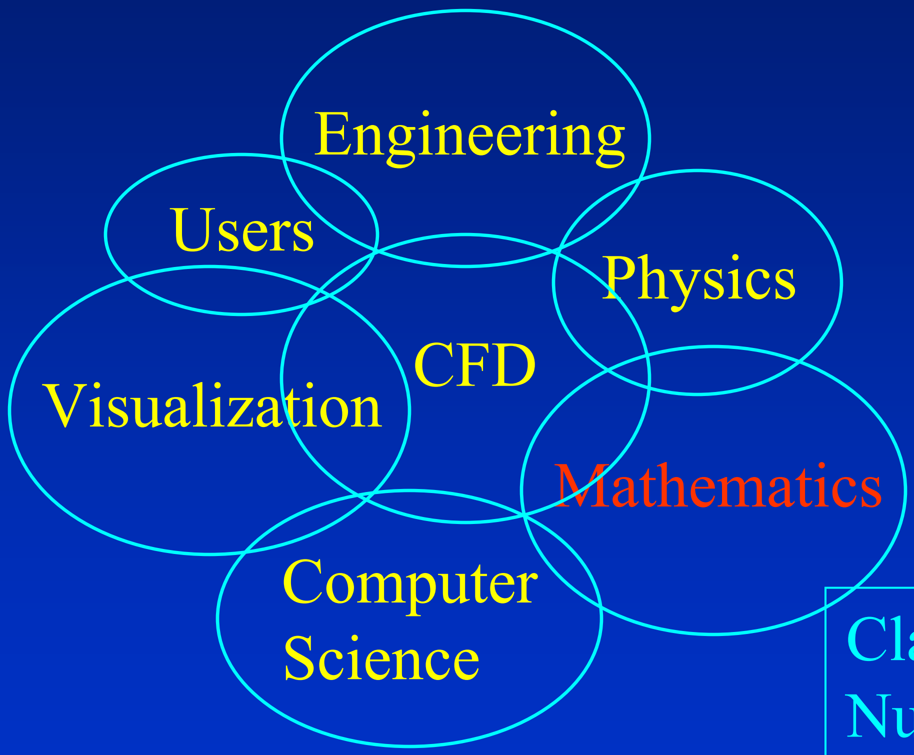
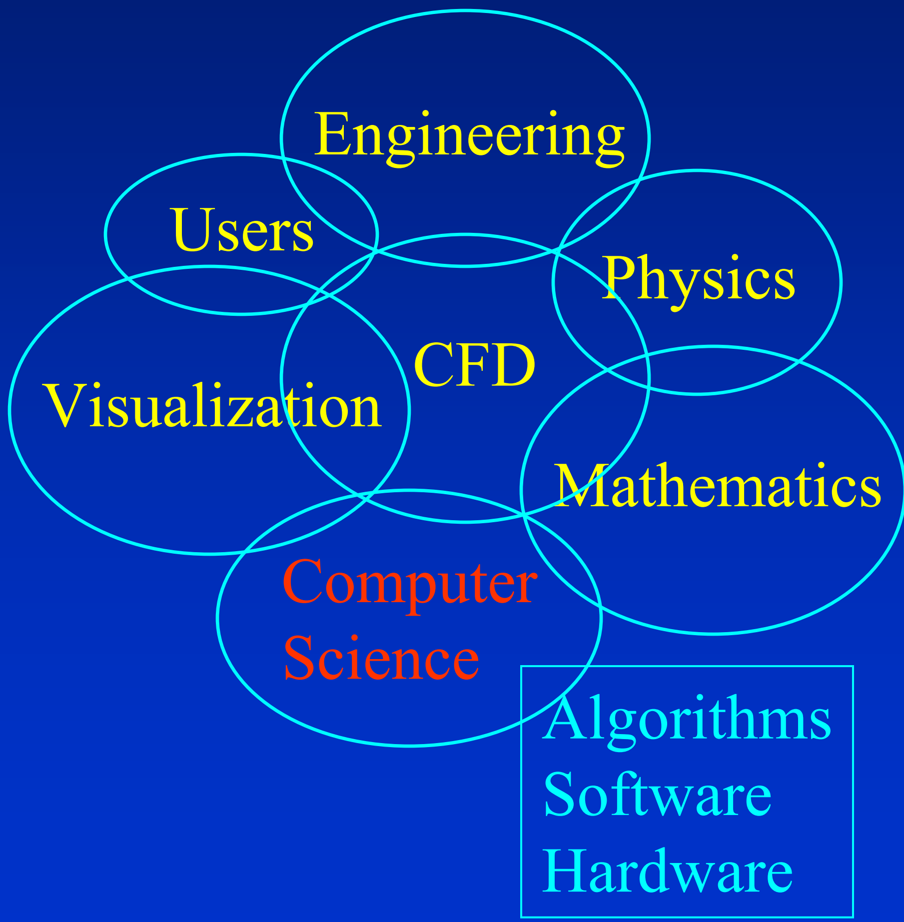


Classic Analysis (PDEs)
Numerical Meth/Analysis
Discrete Mathematics

CFD: Multidisciplinary Science



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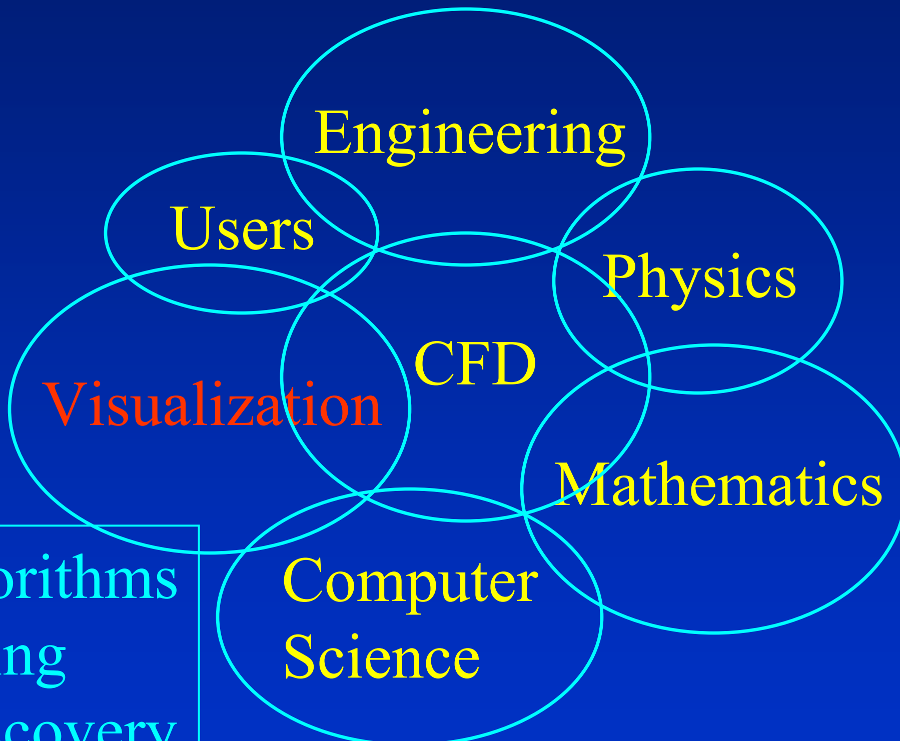
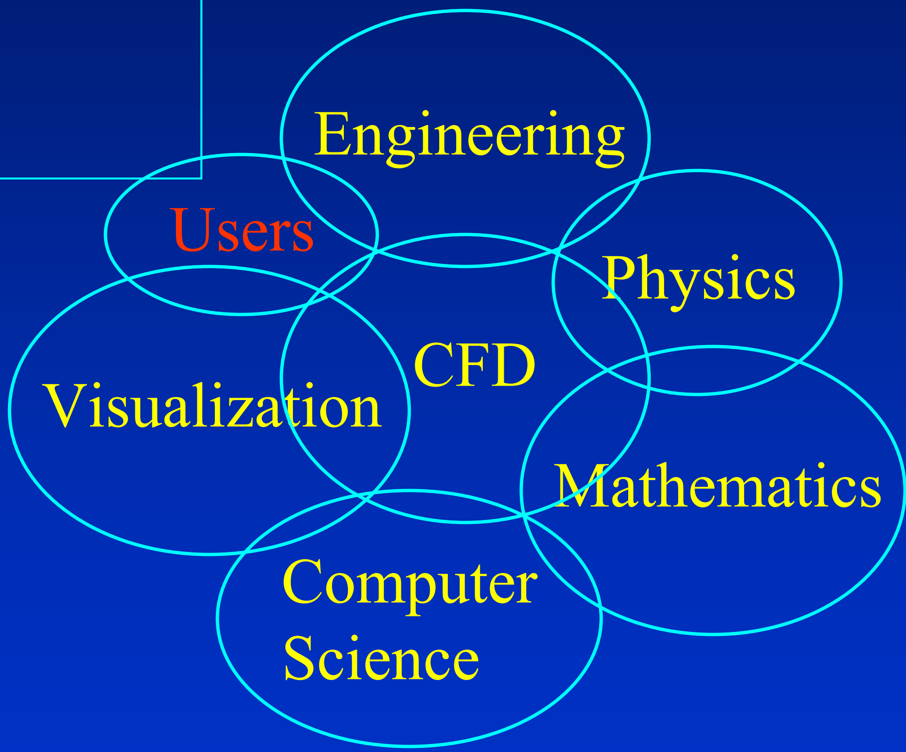


Optimal Algorithms
Ways of Seeing
Tools for Discovery

CFD: Multidisciplinary Science

Benchmarking/QA
Education
Motivation
NIH…



CFD: Multidisciplinary Science

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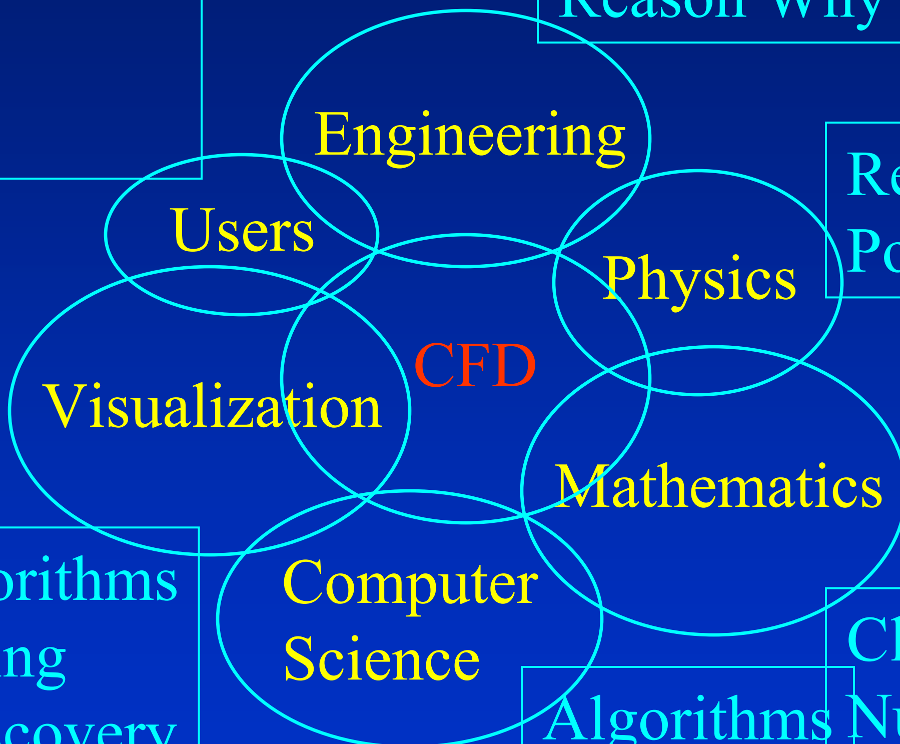
Reason Why



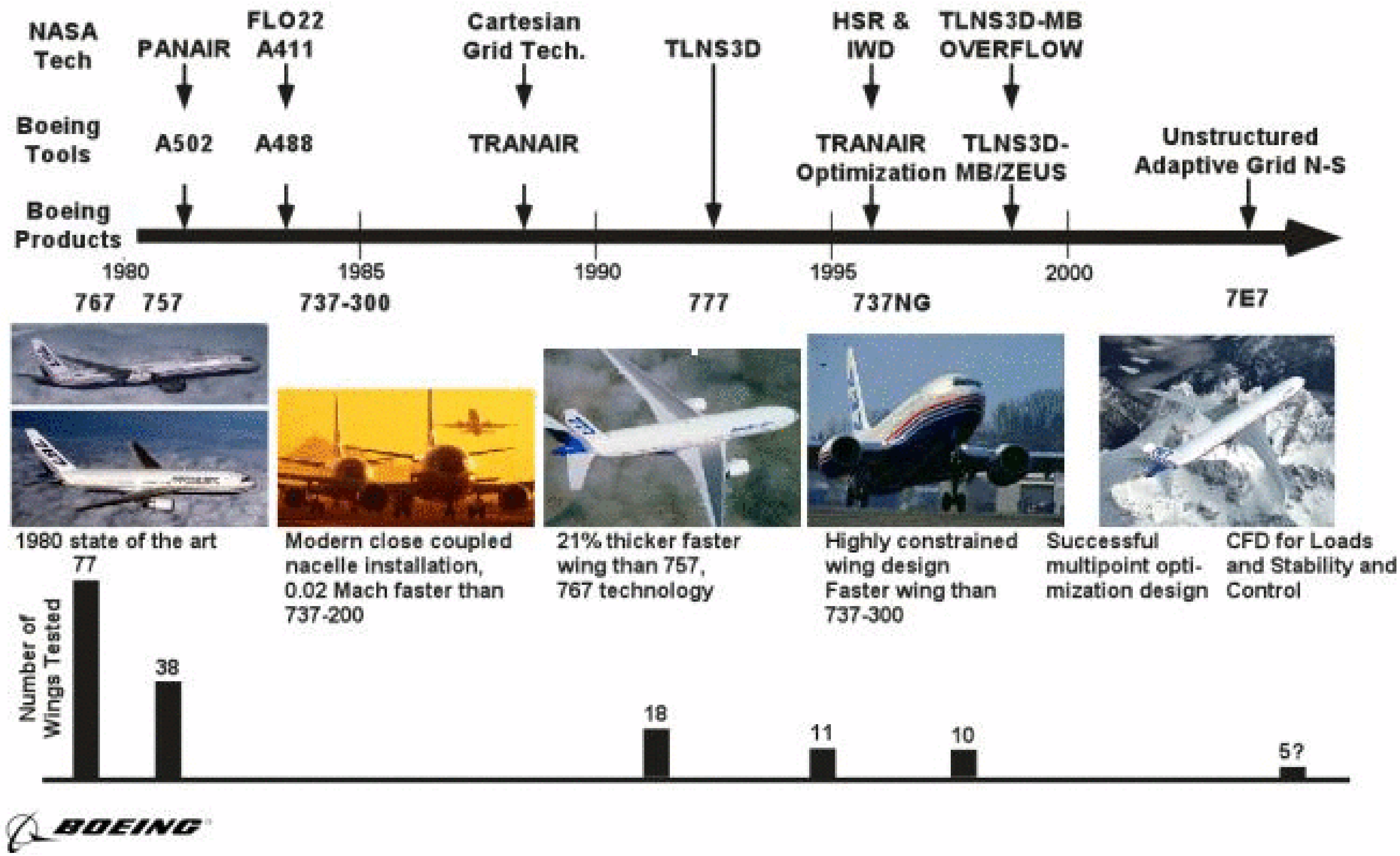
Relevant Phenomena
Possible Approximations

Optimal Algorithms
Ways of Seeing
Tools for Discovery

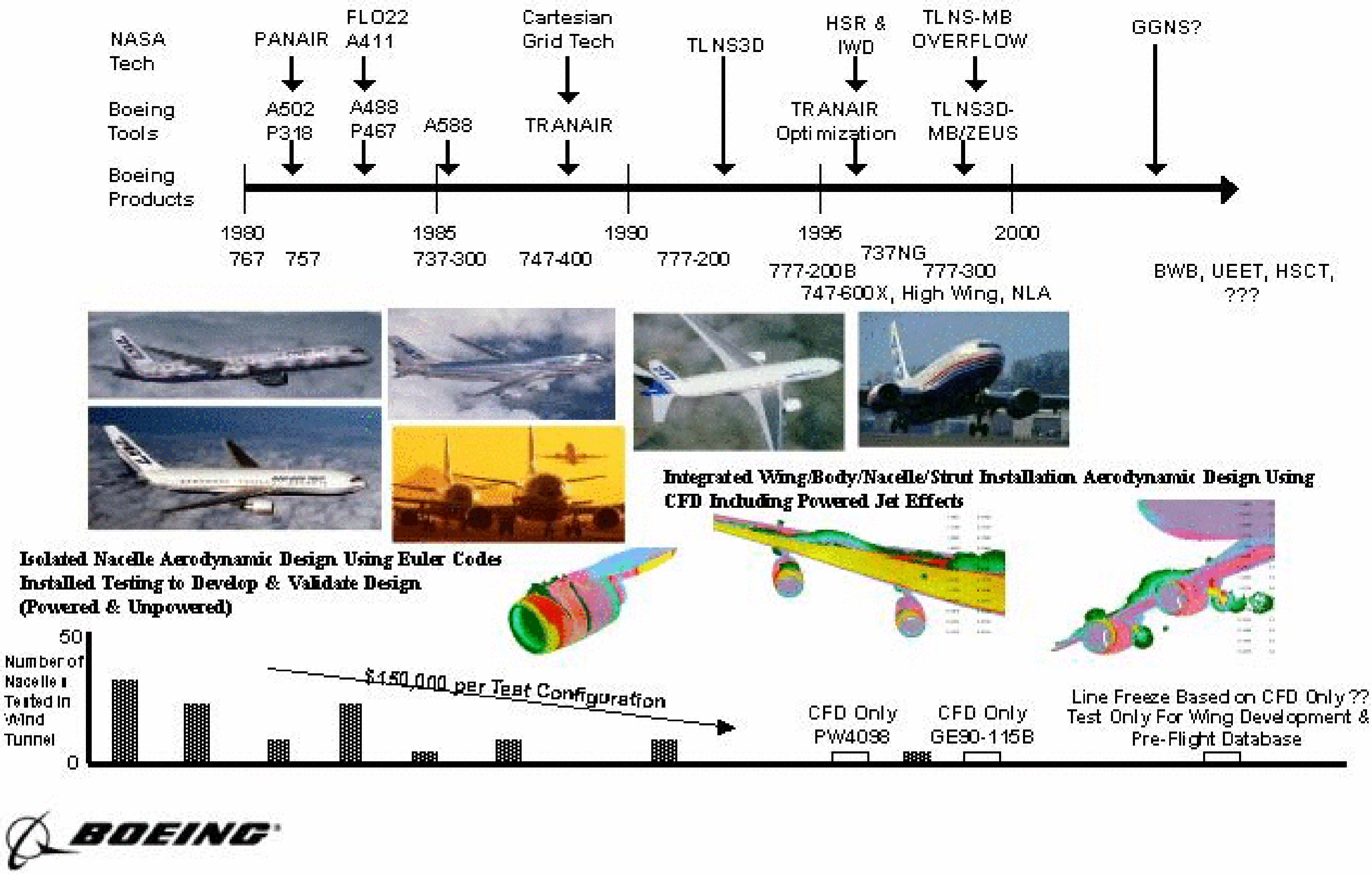
Algorithms
Software
Hardware

Classic Analysis (PDEs)
Numerical Meth/Analysis
Discrete Mathematics

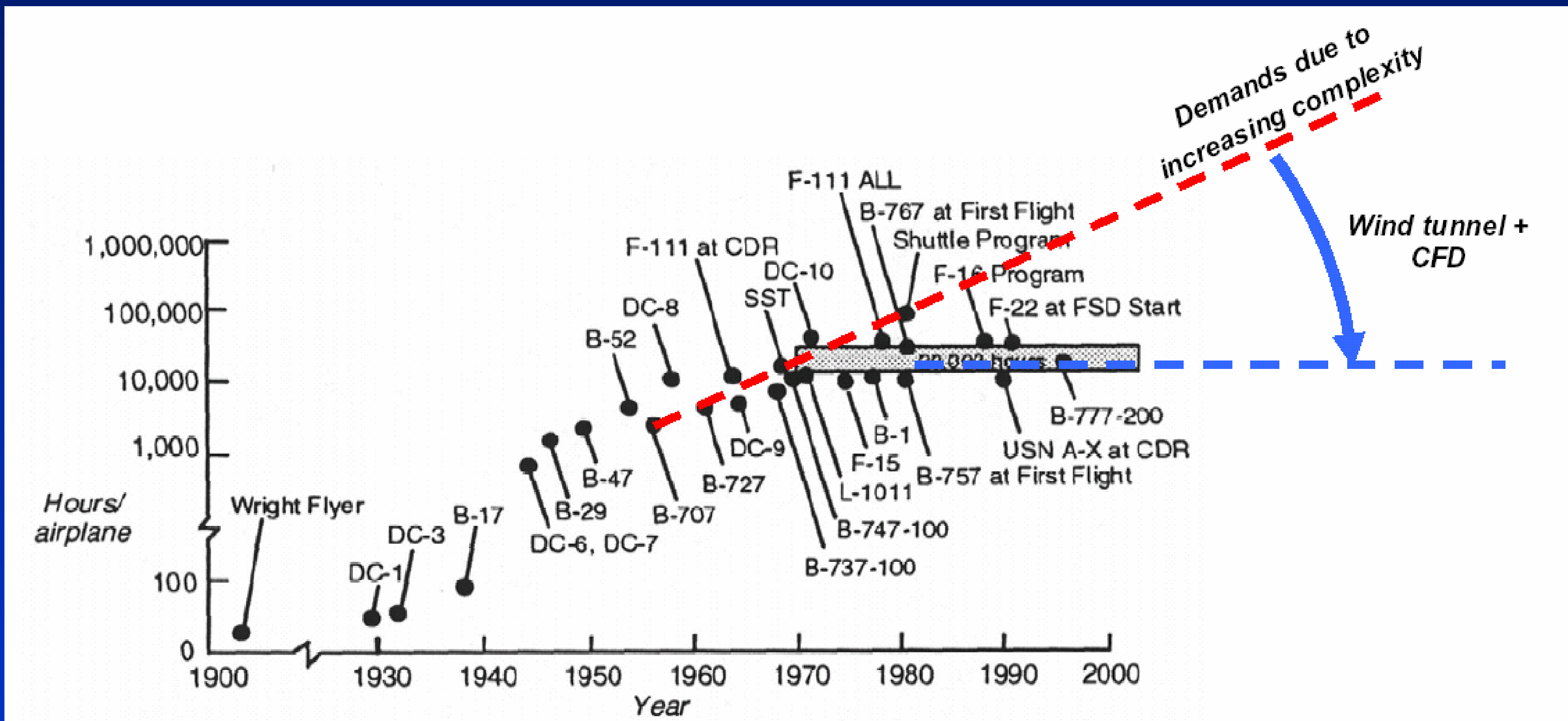
Impact of CFD on Wind Tunnel Testing for Configuration Lines Development



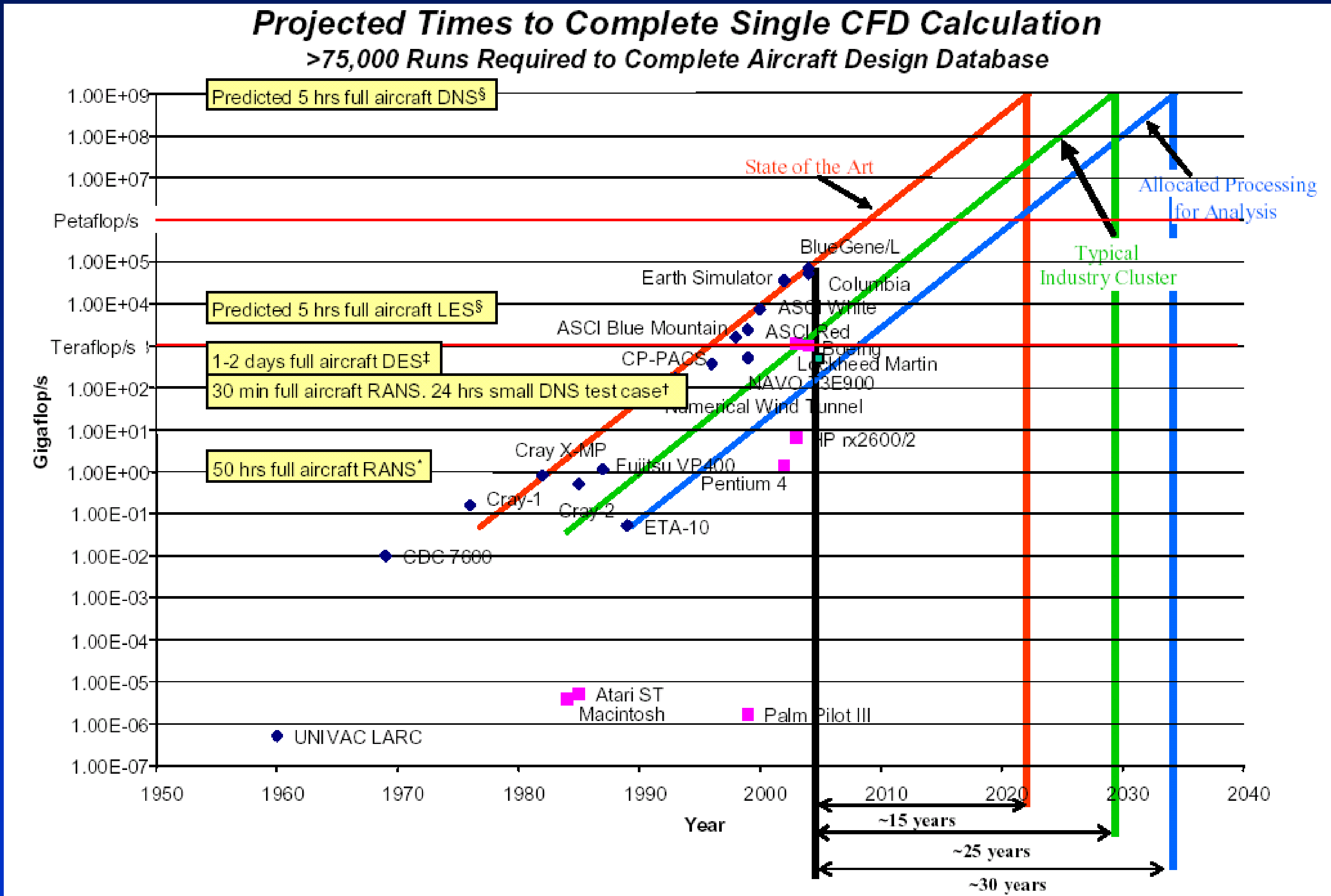
Impact of CFD on Wind Tunnel Testing for Propulsion Integration



Impact of CFD on Wing Design



Source: Figure 9. *DOD Aeronautical Test Facilities Assessment*, March 1997



Projected Times to Complete Single CFD Calculation
>75,000 Runs Required to Complete Aircraft Design Database
Predicted 5 hrs full aircraft DNS§
Predicted 5 hrs full aircraft LES§
1-2 days full aircraft DES‡
30 min full aircraft RANS. 24 hrs small DNS test case†
50 hrs full aircraft RANS*
State of the Art
Allocated Processing for Analysis
Typical Industry Cluster
Petaflop/s
Teraflop/s
Gigaflop/s
Year
BlueGene/L
Earth Simulator
Columbia
ASCI White
ASCI Blue Mountain
ASCI Red
CP-PACS
Boeing
Lockheed Martin
NAVO T3E900
Numerical Wind Tunnel
HP rx2600/2
Cray X-MP
Fujitsu VP400
Pentium 4
Cray-1
Cray-2
ETA-10
CDC 7600
Atari ST
Macintosh
Palm Pilot III
UNIVAC LARC
~15 years
~25 years
~30 years

Discoveries/Developments Attributable to Computational Sciences

- Chaos Theory
- Wavelets
- Supercritical Airfoil
- Current Generation of Semiconductor Wafers
- Clinical Relevance of Haemodynamics on Aneurysm Rupture
- …

Software Development in the Engineering Process

Project
↓
Objectives (Performance, Cost, …)
↓
Optimization (Critical Parameters, …)
↓
Disciplines (CSD, CFD, CTD, CEM, CDM, …)
↓
Problem Definition (Models, PDEs, BCs, …)
↓
Grid
↓
Solver
↓
Data Reduction

Historic Development Line

Trends in Computational Sciences

Trends in Computational Sciences

- Caution: Future Predicted From Present
  - Typical Human Behaviour
  - Proper Unless Disruptive Technology Event Occurs
  - Chaos Part of Living Beings

- Computational Sciences Comprised Of/Influenced By:
  - Engineering
  - Physics
  - Numerics
  - Hardware
  - Software Packages
  - Pre/Post
  - Experimental Facilities

Trends: Science/Engineering (1)

- Computational Sciences Used Extensively
- Software Vendors Part of Process/Supply Chain
  - Expectations Continually Raised
  - In-House Culture Formed
  - New Features Demanded From User Base
- Software Packages: Healthy Mix; e.g. CFD:
  - Commercial: Fluent, Star-CD, CFX, AMI, PAM-Flow, CFDRC, ..
  - Government/Open Source: ETBFCT, Xfoil, Arc2D/3D, Cart3D, ..
  - In-House Industry/Lab/University Codes: FLO-Series, FEFLO, …
  - → Further Penetration Driven by Competition (Niche-Option)
- Packages: Many Levels of Fidelity
  - CFD: Potential → Euler → RANS → LES → DNS
  - → Risk of Over-Simplification [Consequences Costly]

Trends: Science/Engineering (2)

- Software Packages: High Degree of Maturity
  - GUIs
  - Pre-Processors (Data Import/Repair)
  - Grid Generators
  - Field/Adjoint Solvers
  - Adaptive Refinement Modules
  - Body/Surface/Mesh Motion Modules
  - Link to Other Discipline/Metier Codes
  - Link to Optimization Packages
  - Post-Processing
  - Benchmarking
  - Training + Support
  - Quality Assurance and Staged Releases
  - Consulting Services

Trends: Physics

- In All Fields: Increased Realism
  - Bridging Continuum and Atomistic Scales
- Flows:
  - Euler/Navier-Stokes Equations Well Established
  - Acoustic Fluctuations: 10^{-6} of Ambient
  - Combustion: Many Species, Parameters Not Always Known
  - Multiphase: Computational Bubble Dynamics
- Structures:
  - Continuum Equations Well Established
  - Failure/Cracking/Spalation/…
  - Treatment of Discontinua (Concrete, Composites, …)

Trends: Numerics

- Solver Research Spans 5 Decades
  - Problem Areas: Advection, Divergence, Stiffness, Stability
  - Identified and Addressed (Many Variations)
- Standard/Core Components of Field Solvers
  - Nonlinear Advection Schemes (Limitors) [1:16]
  - Preconditioning [1:10]
  - Multigrid [1:10]
  - GMRES [1:10]
  - Adaptive Refinement [1:5-1:50]
  - Parallel Computing [1:10-1:100]
- New Hardware → New Algorithms/Numerics

Trends: Hardware

- Moore's Law (1:2 Every 18 Months, 1:10 Every 5 Years)
- ➔ Today's Supercomputer Problem Will Reach PC in 15 Years
- Current PCs: 10^7 Elements ➔ 10^8 in 5 Years
- Current SCs: 10^{10} Elements ➔ 10^{11} in 5 Years
- Programmable GPU/FPGA

PDE Solvers: Current Bottlenecks

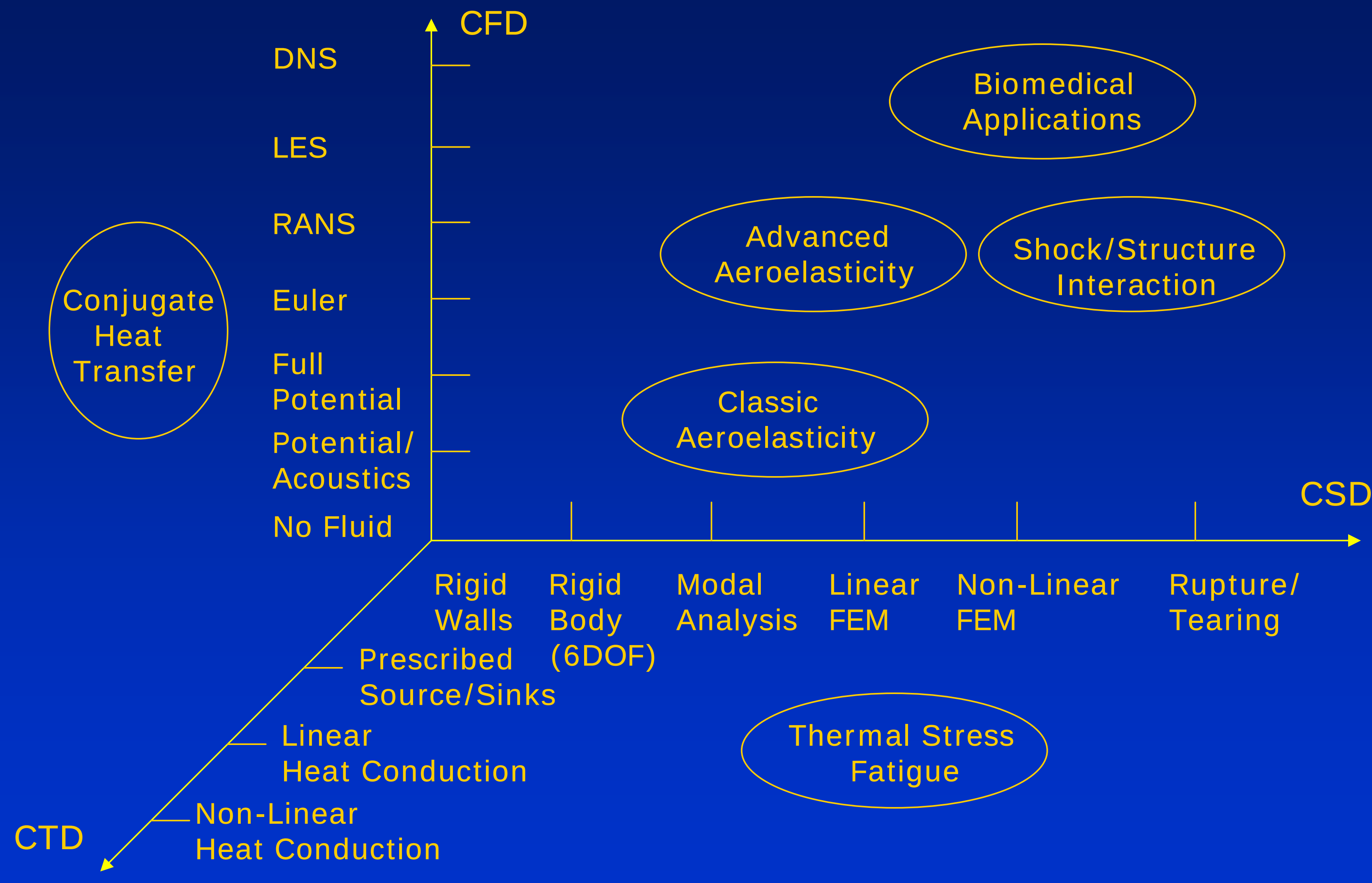
- Pre-Processing:
  - CAD Cleanup for Dirty, Complex Geometries (e.g. Car)
- Grid Generation:
  - Optimal Boundary Layer Grids (Walls, Wakes)
  - Grids with 10^{10} Elements (City Center)
- Flow Solvers:
  - Reliable Implicit Solvers (Dynamics of Numerics)
- Post-Processing:
  - Time-Accurate Particle Tracing for Large Grids
  - Data Mining for Design/Optimization Runs
- Optimization:
  - Hierarchical Data Representation and Design Procedures
  - Li-Huyse-Padula Theorem (➔ Robust Design is Expensive)

Extrapolations

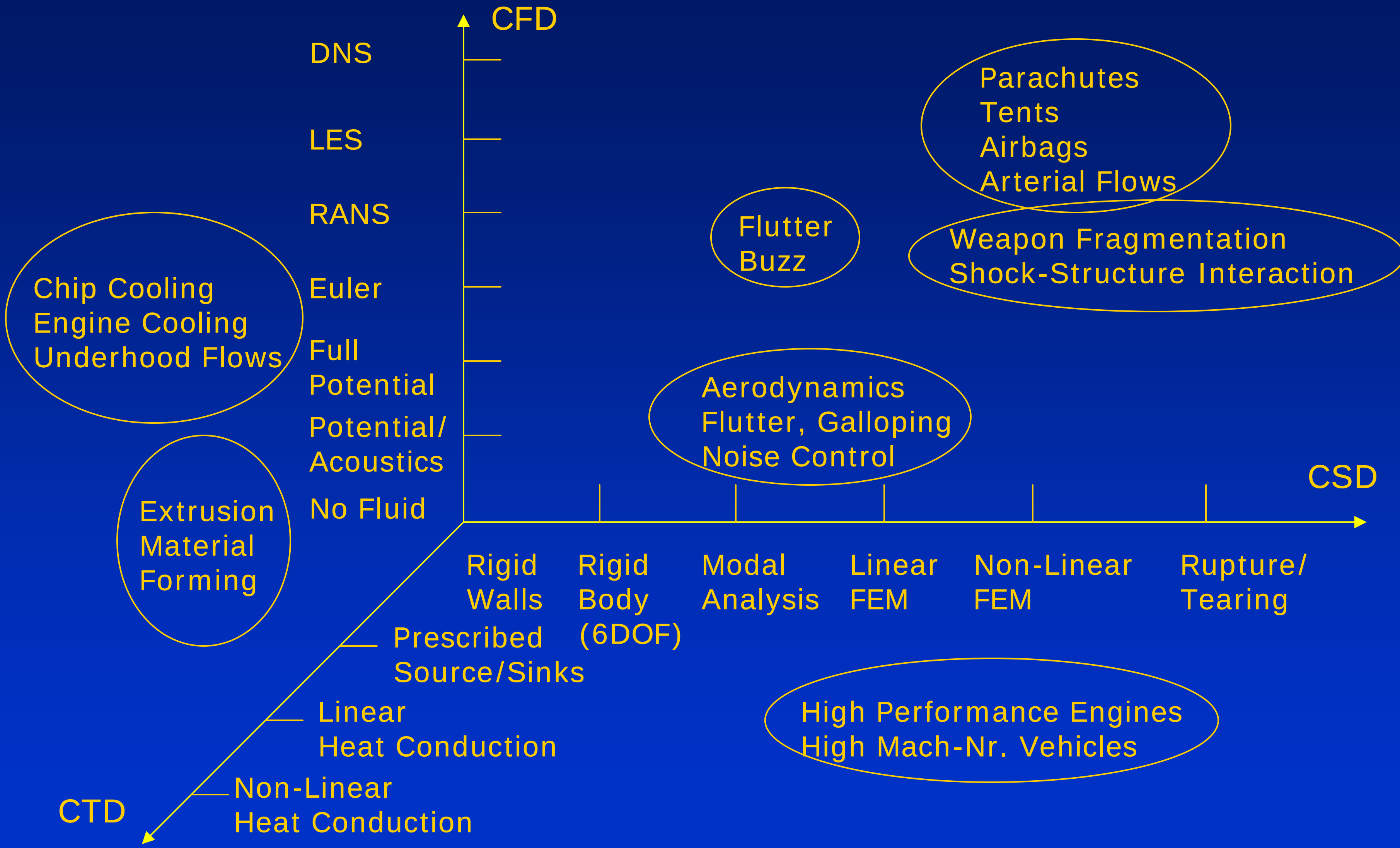
Extrapolation 1: Realism

- Physical Representation:
  - Coupling of Phases (e.g. bubbly flows, cavitation)
  - Coupling of Spatial Scales (atomistic-continuum)
  - Coupling of Temporal Scales (e.g. long-term effects)
  - Coupling of Disciplines (e.g. fluid-structure-thermal-control)
  - Coupling of Fields (e.g. fluid mechanics, chemistry, biology)
- Geometry Representation:
  - Direct Link to CAD (Digital Product Line)
  - Automatic Abstraction Tools
  - Fast and Reliable Image-to-CAD, Image-to-Grid

CFD/CSD/CTD Space



CFD/CSD/CTD Space



Extrapolation 2: Concurrent Use of Algorithms/Codes

Example: Weapons Effect Simulations

Stage	Problem Size	Key CFD Algorithm	Coupling
Store Mounting	O(50Mels)	LU-SGS-GMRES	Modal
Store Separation	O(50Mels)	LU-SGS-GMRES	Lin. FEM
Detonation/Fragm.	O(20Mels)	FEM-FCT	Impact
Blast/Frags	O(1Bels)	FEM-FCT	Impact
Chem/Bio Release	O(50Bels)	Inco/Proj/Transport	Climate

Extrapolation 3: User Qualification

- Computational Packages: Vast Range of Models/Options
- → Need to Decide:
  - Required Model for Relevant Physics
  - Suitable Geometry Representation for Physics
  - Appropriate Grid Resolution
  - Suitable Solver
  - Relevant Diagnostics
- → Need Highly Qualified Individual
  - → May See Considerable Outsourcing
  - Market for Higher Education Institutions

Extrapolation 4: Solution Quality

- Next Logical Demand After Physics and Realism
- Accuracy:
  - Presently Done via Specific Comparisons with Experiments
  - Convergence Studies (Solution of PDE/Model)
  - Adaptive Mesh/Timestep Refinement [Perhaps]
  - Certifiable Solution (e.g. c_d=0.3+/-0.01)

Extrapolation 5: Solution Sensitivity

- Next Logical Demand After Physics, Realism, Accuracy
- Sensitivity:
  - Determine Influence of:
    - Physical Constants
    - Model Parameters
    - Boundary Conditions
    - Geometry, ..
    - Mesh Resolution, Time Steps, Numerical Scheme, …
  - Options:
    - Sensitivity Equations
    - Polynomial Chaos
    - Automatic Differentiation
    - Monte Carlo

Extrapolation 6: Design of Experiments

- Ability to Compute → Ability to Predict
- Experiments: Costly, 1-Shot
- → Need to Make Sure Experiment is Successful

- → Use Computing/Simulation To:
  - Predict
  - Instrument
  - Evaluate

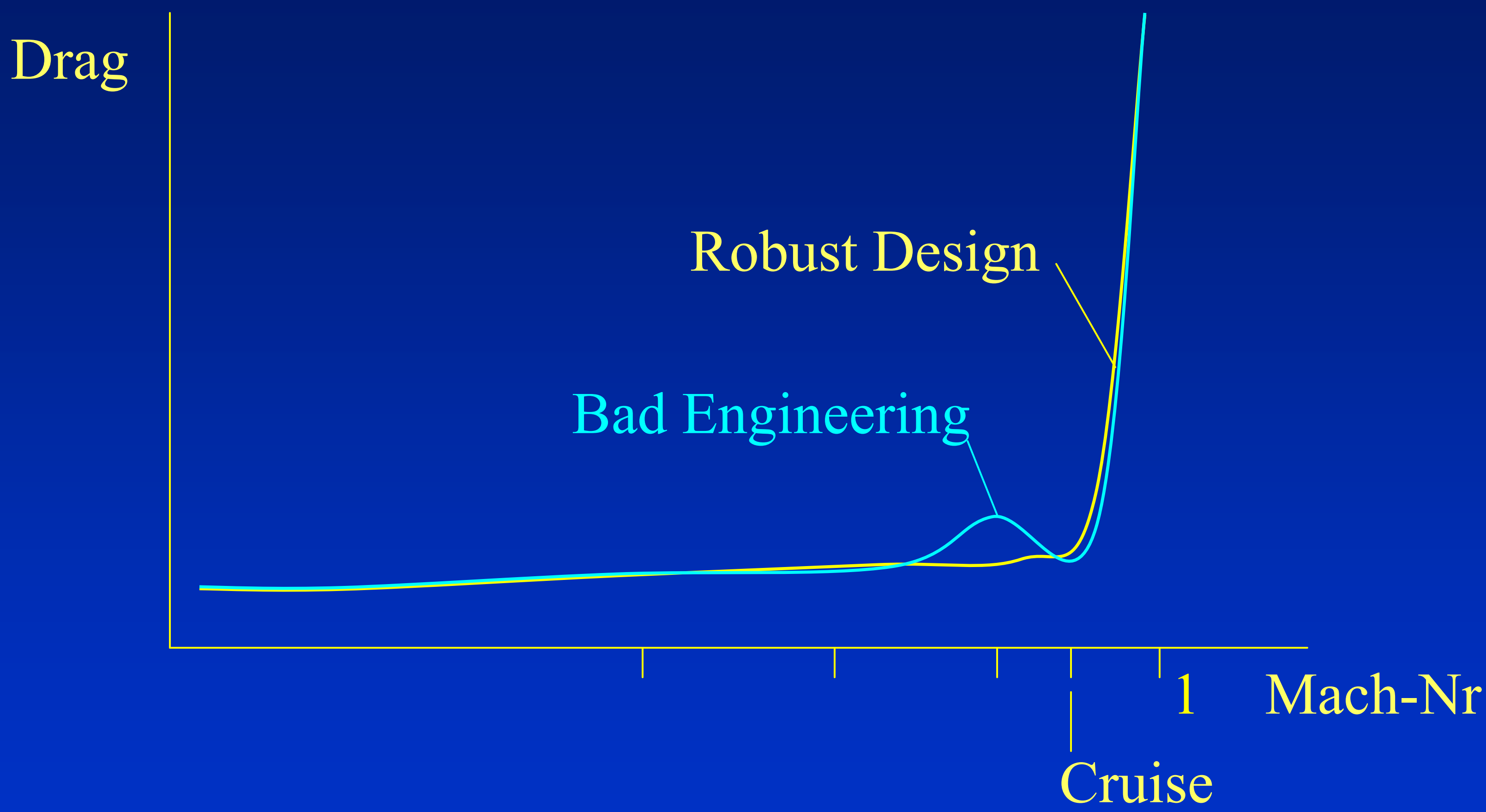
  Experiments

- Presently, 90% of Blast-Structure Runs are Pre-Experiment

Extrapolation 7: Design/Optimization

- Ability to Compute → Ability to Optimize
  - Shapes
  - Processes
- Important Differentiator w.r.t. Experiments
- Industry/Science Penetration Limited But Increasing
- Several Outstanding Issues
  - Definition of Optimality
  - Optimization Strategies
  - Hierarchical Design
  - Integration Into Process
  - Li-Huyse-Padula Theorem (→ Robust Design is Expensive)

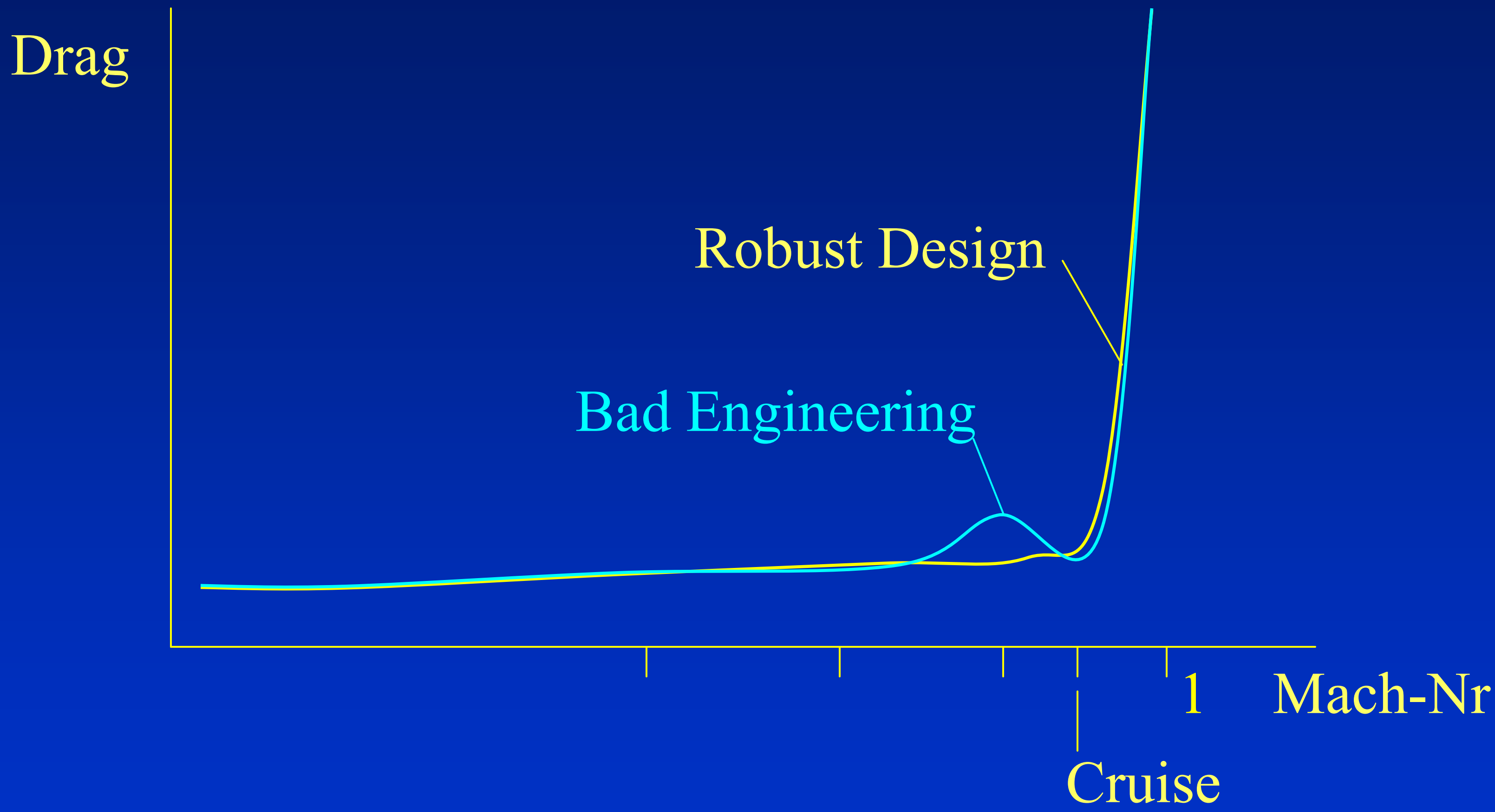
Robust Design: Wings



Li-Huyse-Padula Theorem:
Nr. of Design Conditions = O(Nr. of Design Variables)

Robust Design: Wings

B-777 Wing: > 7,000 Design Variables



Li-Huyse-Padula Theorem:

Nr. of Design Conditions = O(Nr. of Design Variables)

Extrapolation 8: Use of Hardware

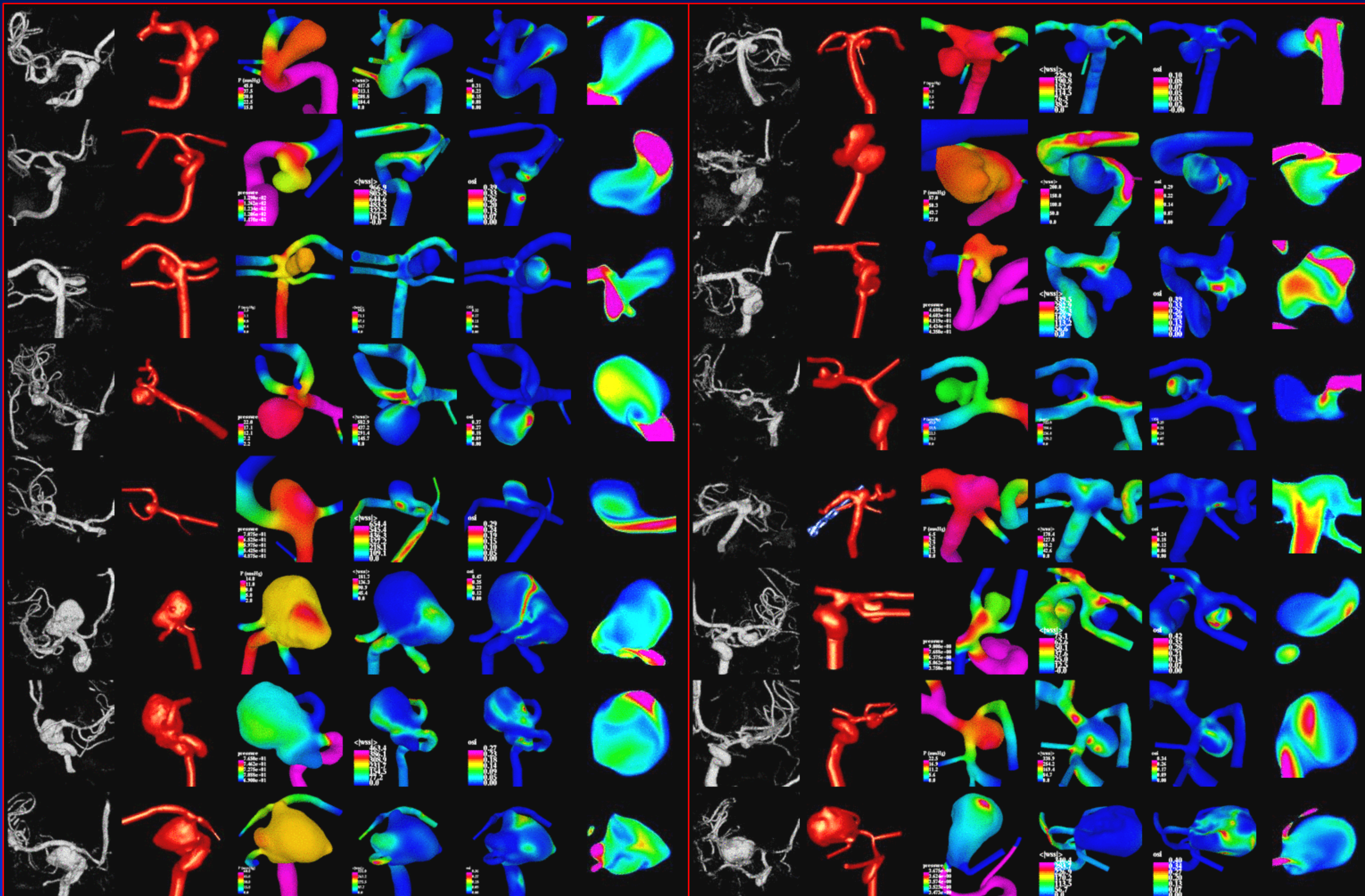
- Low-Cost Parameter Scoping Runs: < 50Mels
  - Linux Farms
  - Able to Fit Individual Run on Each Processor
  - Ideal for Scoping Runs
  - Data Reduction/Database Management
  - Danger: Bad/Missing Data in So Much Data
- High-Fidelity Engineering Runs: < 500Mels
  - Leading-Edge Stand-Alone Computer
  - > 10 Gflops
  - > 100 Gbyte RAM [100Mels]
  - Appearing at Present (e.g. 128 proc Shared Altix/SP5)
- Very Large Runs: O(50Bels)
  - Leading Edge MPP Machine

Extrapolation 9: Evolving Work Environment

- Computing/Simulation as Virtual Experiment
  - Many (!!) Runs
- Minimal User Input for Many Runs
  - Scoping/ Stochastics/ Envelopes →
  - Parametric Definition of Problem
- Distributed Computing
  - Automatic Search for Available Resources
- Data Assimilation
  - Distributed Data Acquisition and Plotting
- Data → Information → Intelligence → Decision
  - Presentation Protocols
  - Link to Data Banks

Database of Aneurysm Models

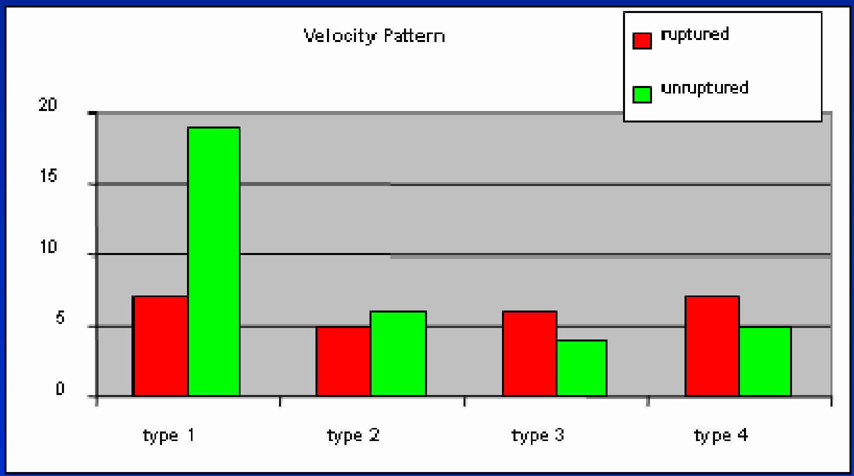
Courtesy J.R. Cebral



Haemodynamic Characteristics & Rupture

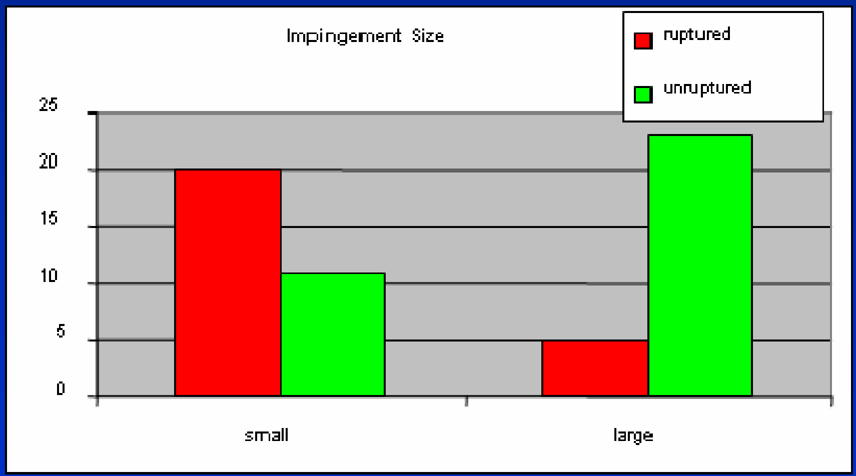
- Observed Large Variety of Flow Patterns
- Flow Patterns not Easily Predictable the Simple Measures
- Sample of 62 Aneurysms:

Flow Type



80% unruptured => type 1
75% ruptured => type > 1

Impingement Size



90% large impingement => unruptured
80% ruptured => small impingement
Statistically significant to 95% confidence

Extrapolation 10: Instant Computing

- CFD Embedded into Product/Process Chain
  - Interactive Design (What If ?)
  - Process Control (Manufacturing) [Silicon Wafers]
  - Flight Mechanics (Optimal Morphed Wing)
  - Battlefield Strategies (On the Fly Targeting)
  - Patient-Specific, Evolving Medical Devices
  - Response to Natural/Man-Made Disaster
  - …

Visions of the World

What Is Real ? Limitations:

- Experiments: When Possible:
  - Measuring Device (Predisposed Output, Predisposed Error)
  - Uncertainty (Heisenberg)
- Analysis: When Possible:
  - `Description of Nature' Used (PDEs, Particles, …)
  - Realistic Boundary Conditions
- Virtual Experiments:
  - `Description of Nature' Used (PDEs, Particles, …)
  - Boundary Conditions
  - Numerics Employed
  - Degrees of Freedom (Mesh Size)
  - Possible (Predisposed) Output/Visualization

The World as Equation

- Flow = Conservation of Mass and Momentum
- Navier (1822) - Stokes (1840) - Equations

$$\nabla \cdot \mathbf{v} = 0$$

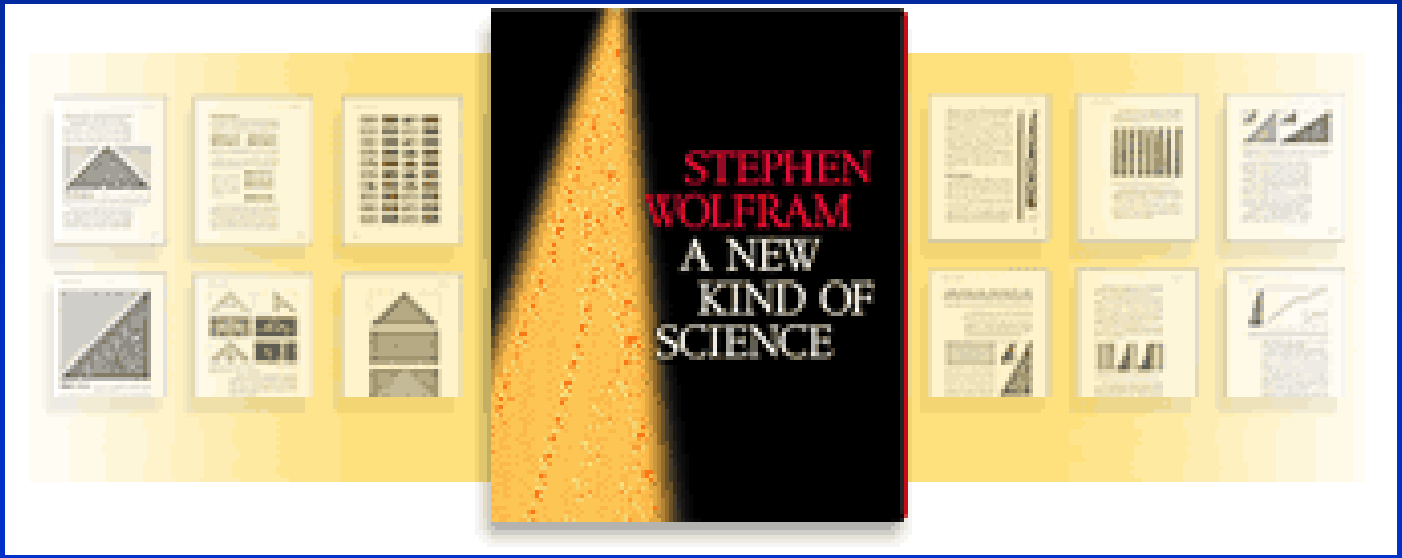
$$\rho \mathbf{v}_{,t} + \rho \mathbf{v} \cdot \nabla \mathbf{v} + \nabla p = \nabla \mu \nabla \mathbf{v} + \mathrm{f} + \rho \mathbf{g}$$

ρ: Density	g: Gravity Vector
v: Velocity	p: Pressure
μ: Viscosity	f : External Force/Source Term

- Existence ? Stability ?
- Turbulence ?

The World as Algorithm

- Descriptive Power of Algorithms Infinite
- Numbers/Processes/Phenomena from Algorithms
- ➔ The World As Algorithm
  - Which ?
  - Insight ?



Outlook (1)

- Computational Sciences: Always Interdisciplinary
- 3-4 Decades of Development
- Software: Public/Commercial/Open/…
- Highly Specialized `Solutions' Emerging
- Multidisciplinary Optimization
- Multi-Length/Time Scale Optimization
- Embedded in Many Products/Processes
- Physics-Based Virtual Reality

Outlook (2)

- Experiments Preceded by Lengthy CFD/CSD/… Runs
- Biased Insight

- Computational Sciences: New `Pillar' of Empirical Sciences
- New Way of Seeing Reality
- New Way of Measuring/Seeing/Undestanding/Going Where We Could Not Before

- Task for Philosophy:
  - ➔ Sequel to Kant's: Kritik der Reinen Vernunft ?

Outlook (3)

- Nietzsche, Zarathrustra, Preamble:
  - Die Erde ist dann klein geworden, und auf ihr hüpft der letzte Mensch, der alles klein macht. Sein Geschlecht ist unaustilgbar, wie der Erdfloh; der letzte Mensch lebt am längsten.

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The earth has then become small, and on it hops the last (kind of) human, the one that makes all things small; his stock is uneradicateable, like the flea; the last human lives the longest.

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  - Doch Ihr, die echten Göttersöhne, erfreut Euch der lebendig, reichen Schöne…

  Und was in schwankender Erscheinung schwebt, befestiget in dauernden Gedanken

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But yee, the god's true sons, delight in living, bounteous beauty,
and what floats in wavering appearance, fasten (cement) in lasting thoughts