Accelerating flow physics: a background to some strange effects in fluids

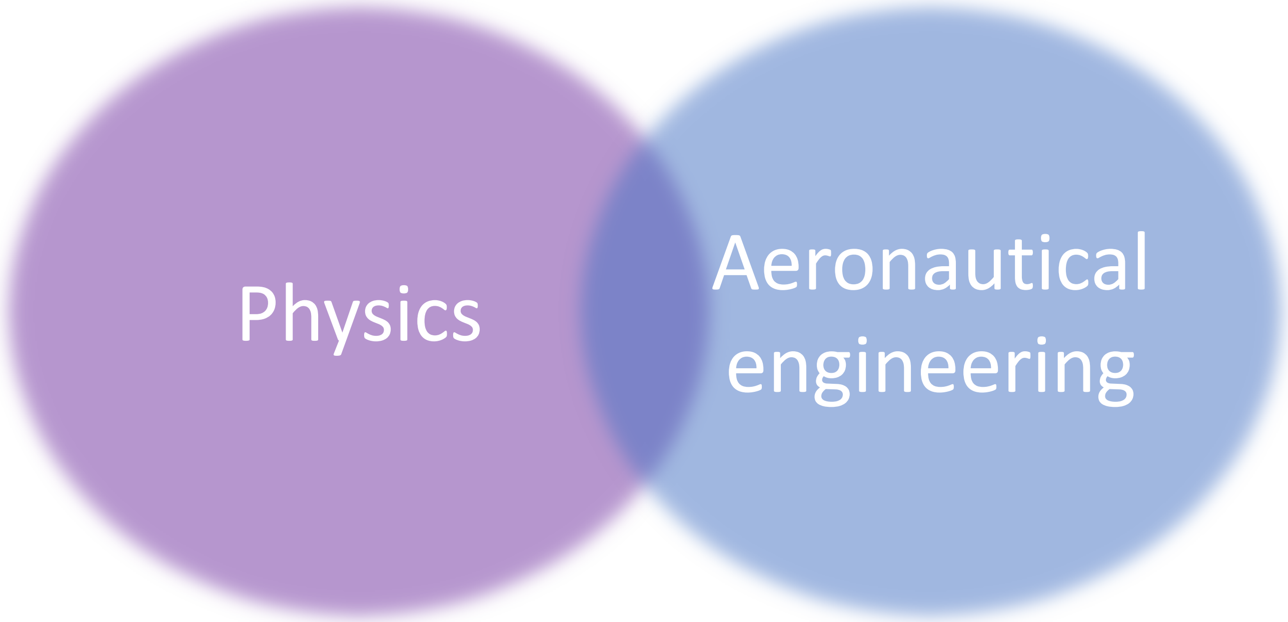
Irvy (Igle) Gledhill

School of Mechanical, Industrial and Aeronautical Engineering

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

100 1922 2022

- This is about classical physics in the applied environment, and unusual topic at physics conferences.



“fluids are just plasmas with all the difficult fields taken out”

- A physicist in engineering: an “applied theoretical physicist”?
- plasma simulation:
- Wave instabilities, plasma confinement (UCLA, John Dawson), space shuttle outgassing (Stanford, Oscar Buneman, Owen Storey)
- computational fluid dynamics:
- Cellular automata, Computational Fluid Dynamics (CSIR South Africa)
- Computational physics in collaboration across fields:
  - Methane explosions in coal mines, ocean breakwater engineering;
  - Molecular modelling for *M. tuberculosis* treatment, HIV treatment; modelling non-linear optics for protection of eyes from lasers
- New interest: accelerating flight

The fine print for this talk

- Understanding aerodynamics when accelerations are significant
- This is not a history of flow physics or aerodynamics: it is a background with one thread, that of acceleration
- 2022/2023: centenary of the International Union of Pure and Applied Physics

100 years of flow physics

- Acceleration … Against the background of the development of flow physics
  - The practical past
  - The golden age of theory
  - The expansion of experiments
  - The contribution of Computational Fluid Dynamics – "CFD"
  - Next!
- Fluid behaviour in non-intuitive and non-linear
- Not easy to predict
- Sometimes counter-intuitive
- But often beautiful

- Reasonably well understood:
  - Steady flow
  - Time-dependent flow over constant-velocity objects
  - Aeroelasticity
  - Turbines and helicopter blades; small oscillations
  - Internal flow: pipes and engines
  - Multi-phase flow
  - Multi-physics models
- Not well understood:
  - Turbulence, of course!
  - Accelerating flight

Accelerating flight in the transonic range

- Transonic: near the speed of sound, Mach number near 1
- Compressibility is important
- An example: The Bloodhound Supersonic Car
- Flying at zero altitude

Acknowledgement
https://www.youtube.com/watch?v=krcLNgLcF9Q

The Practical Past

Water has dominated the flow of humanity

Economies, migrations and legends

- https://en.wikipedia.org/wiki/Wah_Gardens By Umer23459 - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=72569360

- https://www.sahistory.org.za/article/mapungubwe

Mapungubwe, South Africa

- One of South Africa's First Peoples
- Settled 1200 to 1290 CE (Common Era)
- Rich flood plain, similar to the Nile
- Abandoned c1400 CE
- Apparently because of a local change of climate
- Hydraulic engineering would have been useful…

- https://www.peaceparks.org/unesco-director-visits-mapungubwe/

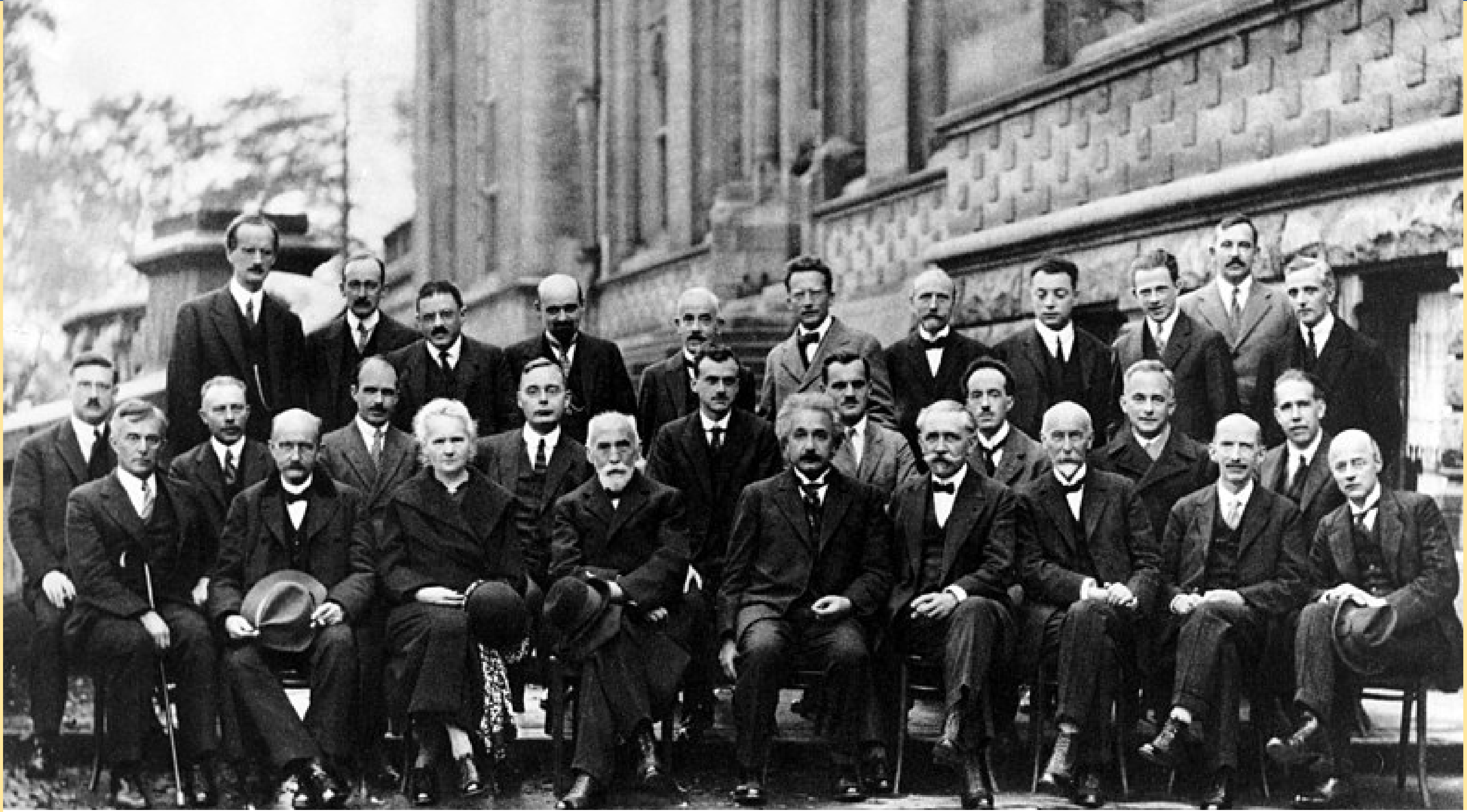
The Golden Age of Theory

Before 1922 and lasting into the 1950's

The golden age of theory

- By 1922/23, the Navier-Stokes relations
  - conservation of mass, momentum and energy in a fluid
  - well established.
- Constitutive relations and equation of state established
- Their non-linear nature gave rise to many approximate forms of soluble equations, and elegant solutions:
  - Potential flow, inviscid
  - Stokes flow, dominated by viscosity
  - Boundary layer flow, along a wall
  - Pipe flow: Poisson flow

L: Debye
L: Langmuir



A. Piccard, E. Henriot, P. Ehrenfest, E. Herzen, Th. de Donder, E. Schrödinger, J. E. Verschaffelt, W. Pauli, W. Heisenberg, R. H. Fowler, L. Brillouin;
P. Debye, M. Knudsen, W.L. Bragg, H. A. Kramers, P. A. M. Dirac, A. H. Compton, L. de Broglie, M. Born, N. Bohr;
I. Langmuir, M. Planck, M. Curie, H.A . Lorentz, A. Einstein, P. Langevin, Ch.-E. Guye, C. T. R. Wilson, O. W. Richardson
Fifth Solvay conference participants, 1927. Institut International de Physique Solvay in Leopold Park.
https://en.wikipedia.org/wiki/Solvay_Conference

UIPPA

IUPAP

1922

The Thirteen

1. Belgium
2. Canada
3. Denmark
4. France
5. Holland
6. Japan
7. Norway
8. Poland
9. Spain
10. Switzerland
11. United Kingdom
12. United States of America
13. Union of South Africa

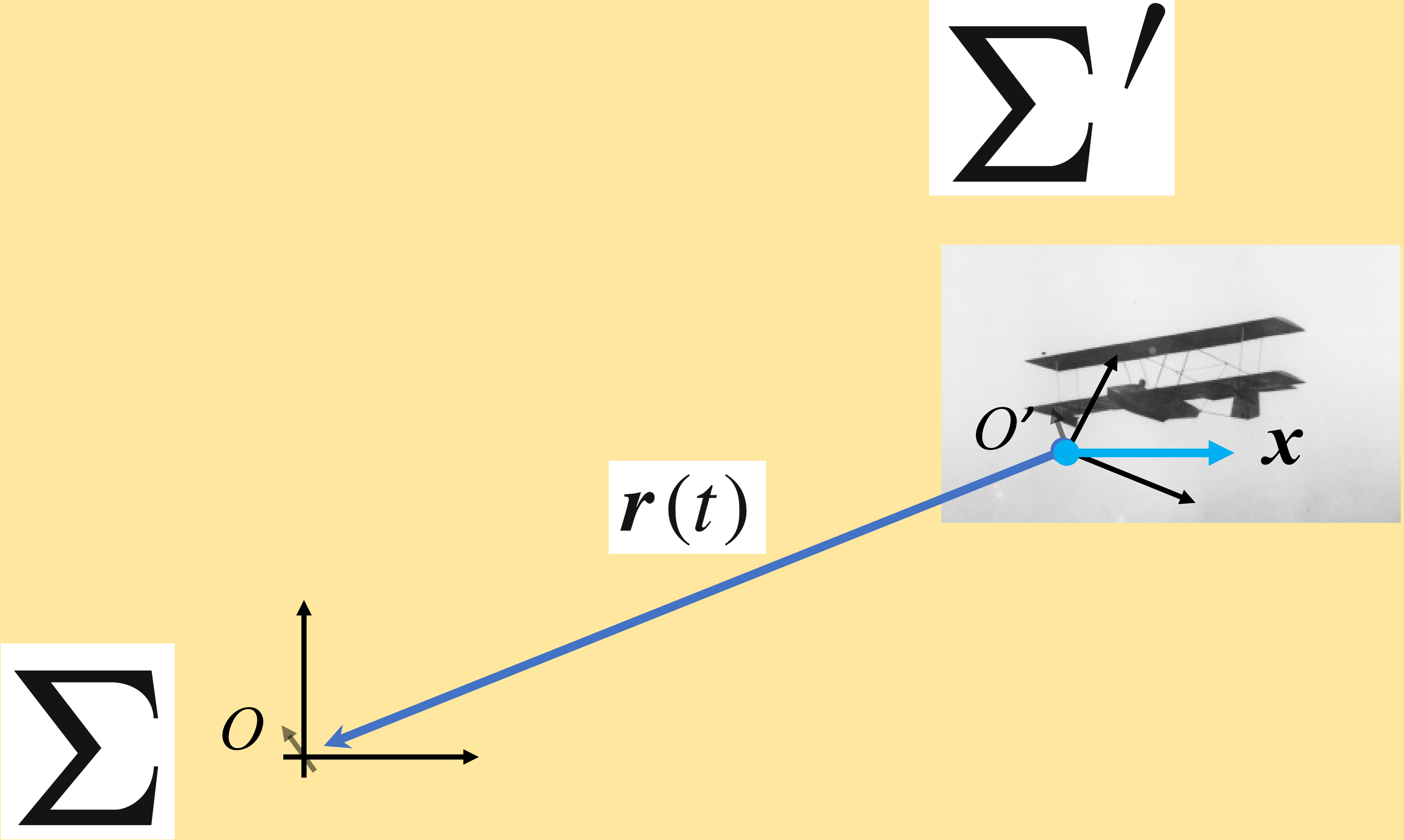
The Ten

W. Bragg, president
M. Brillouin
O.M. Corbino
M. Knudsen
M. Leblanc
R.A. Millikan
H. Nagaoka
E. Van Aubel, vice-présidents
H. Abraham, secretary

https://iupap.org/who-we-are/history

Accelerating flight

- The Navier-Stokes equations include a body force, usually gravity
- were, over the years, transformed into rotating frames
  - Interest in weather and oceans
- transformed into an arbitrarily relative, non-inertial frame in various ways

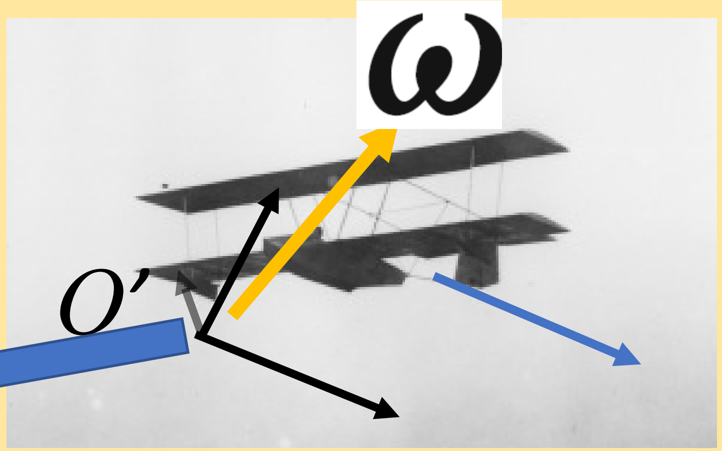

Σ′
O’
x
r(t)
Σ
O

Accelerating flight

Σ'

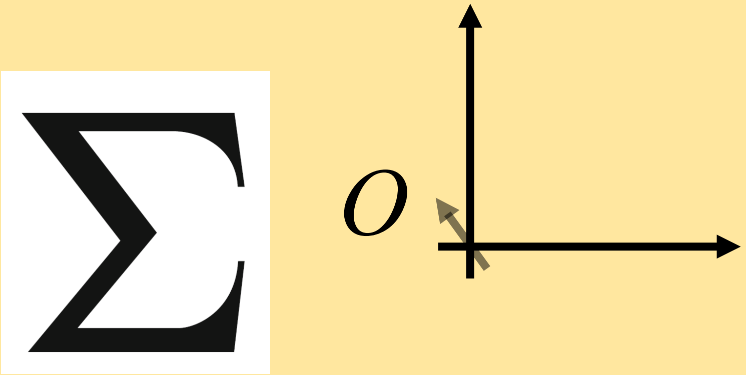
- Interframe velocity:

relative velocity of two points $\boldsymbol{u}$



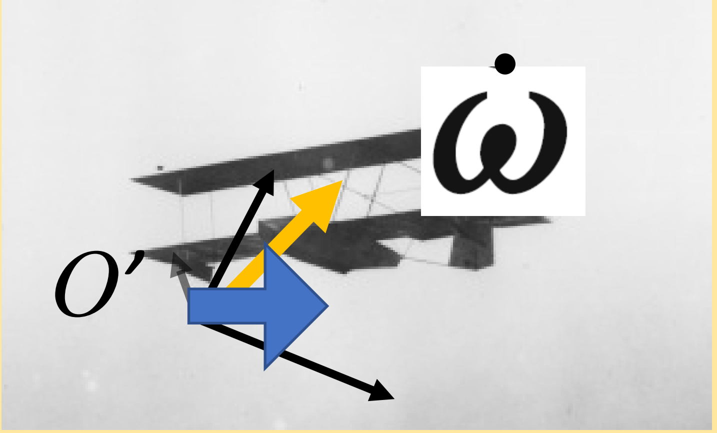
$\dot{\boldsymbol{r}}(t)$

$\boldsymbol{v}$ fluid velocity



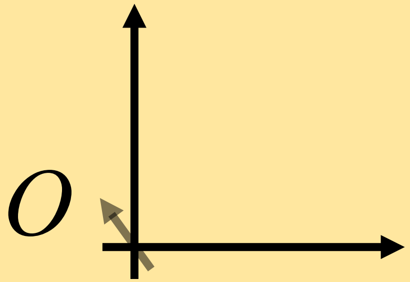
Accelerating flight

Σ'



$\ddot{r}$

Σ



Conservation of

- Mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

- Momentum

$$\frac{\partial}{\partial t}(\rho \boldsymbol{v}) + \nabla \cdot [\rho \boldsymbol{v} \otimes \boldsymbol{v} + p\boldsymbol{I} - \boldsymbol{\tau}]$$
$$= -\rho \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \boldsymbol{x}) - 2\rho \boldsymbol{\omega} \times \boldsymbol{v} - \rho \dot{\boldsymbol{\omega}} \times \boldsymbol{x} - \rho \ddot{\boldsymbol{r}} + \rho \boldsymbol{g}$$

- Energy

$$\frac{\partial}{\partial t}\rho E^* + \nabla \cdot [\rho \boldsymbol{v} E^* + p\boldsymbol{v} - \boldsymbol{\tau} \cdot \boldsymbol{v} - \kappa \nabla T]$$
$$= q_H + \rho \boldsymbol{v} \cdot \boldsymbol{g} - \rho (\boldsymbol{v} + \boldsymbol{u}) \cdot \ddot{\boldsymbol{r}} - \rho (\boldsymbol{v} + \boldsymbol{u}) \cdot (\dot{\boldsymbol{\omega}} \times \boldsymbol{x})$$

using

Generalised Rothalpy

(convenient form)

$$E^* = e + \frac{\|\boldsymbol{u}\|^2 - \|\boldsymbol{v}\|^2}{2}$$

This form:
Gledhill *et al.*, Aerosp. Sci. Tech. **13** 197 2009
Gledhill *et al.,* Theor. Comp. Fluid Dynamics **30** 449 2016

Lecture by J. Noir at WITGAF Cargese, Corsica, 2019 https://witgaf2019.sciencesconf.org/data/pages/Noir1.pdf

Taylor-Proudman theorem

In a fluid that is

Inviscid,

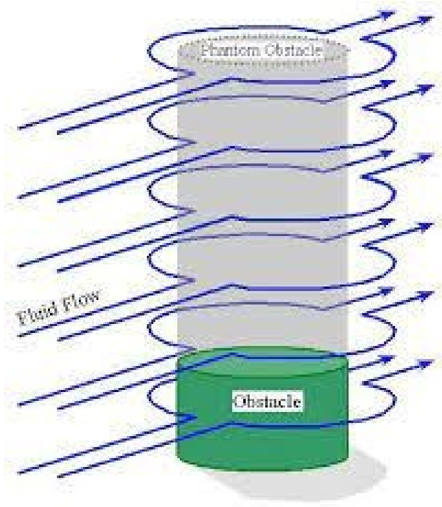
Incompressible,

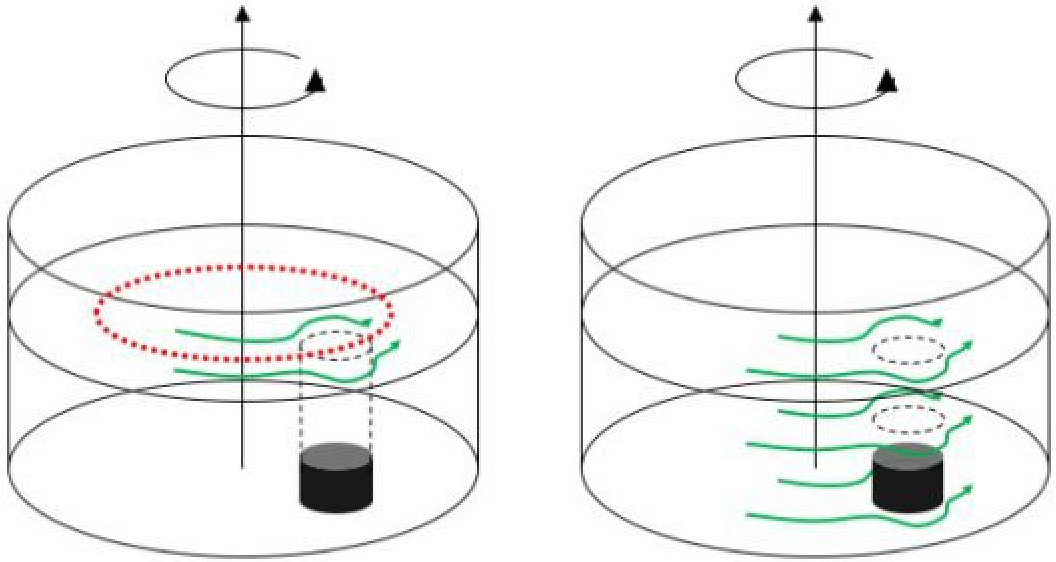
Dominated by Coriolis effect, i.e.

Rotating with Rossby number

$$Ro = \frac{Lv}{2\omega} \ll 1$$

…fluid velocity will be uniform along any line parallel to the axis of rotation





http://weathertank.mit.edu/links/projects/taylor-columns-introduction

https://mirjamglessmer.com/2019/09/11/taylor-column-in-a-tank/

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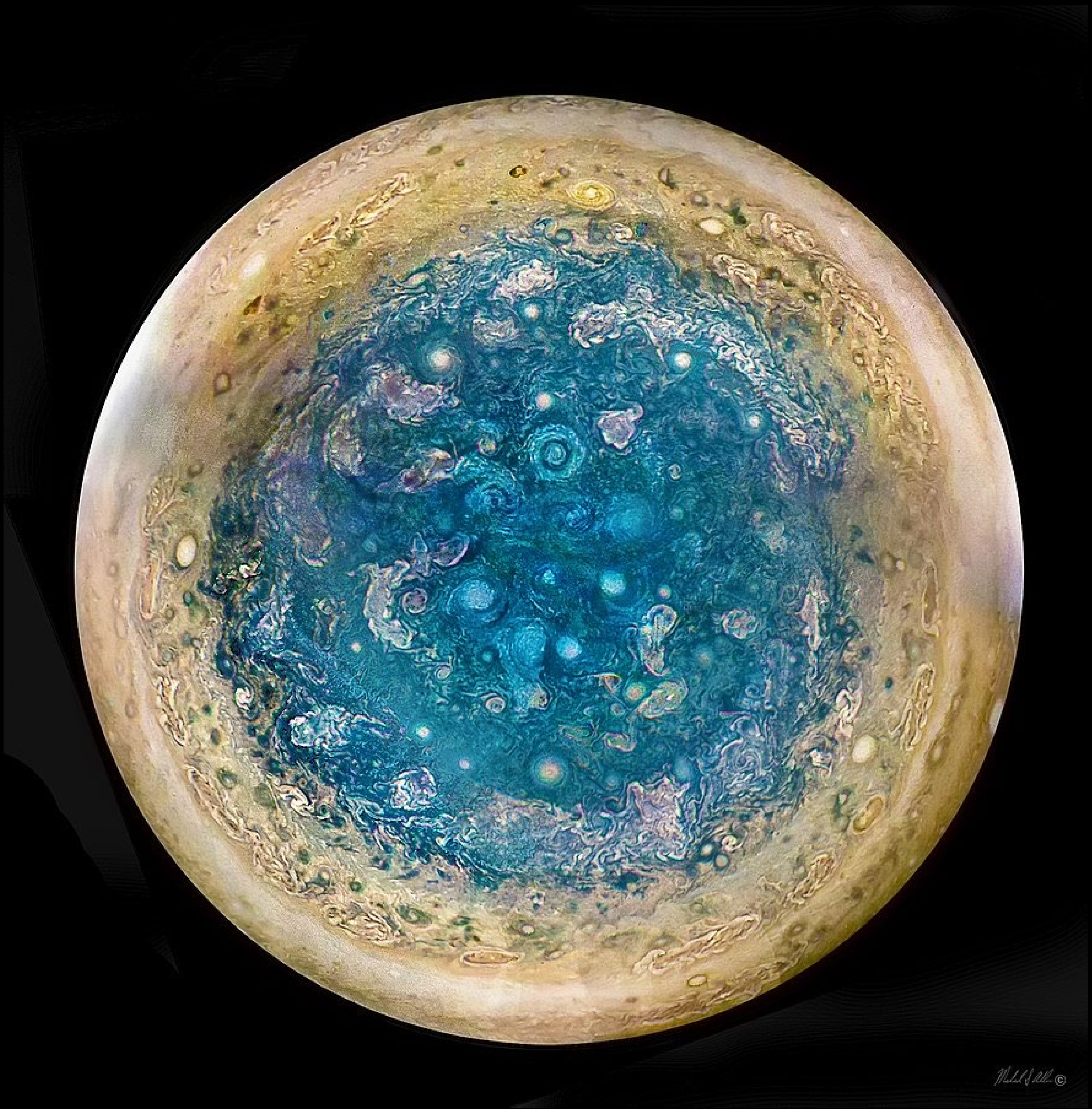
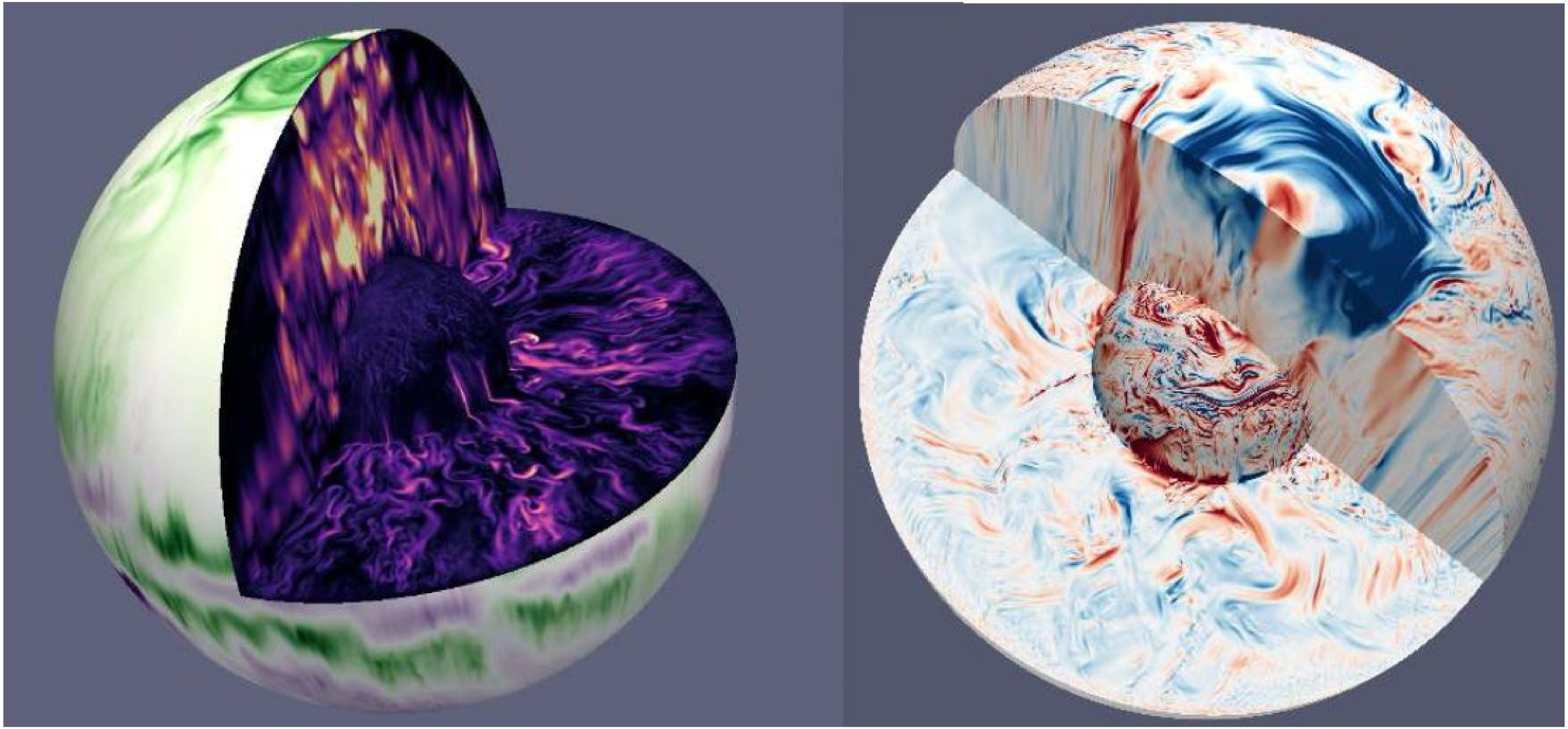
Lecture by J. Noir at WITGAF Cargese, Corsica, 2019 https://witgaf2019.sciencesconf.org/data/pages/Noir1.pdf

- Taylor columns
- Demonstrated by G.I. Taylor in 1923
- Previously demonstrated by Kelvin, Perry
- Previously derived by Hough, Proudman

Lecture by J. Noir at WITGAF Cargese, Corsica, 2019 https://witgaf2019.sciencesconf.org/data/pages/Noir1.pdf

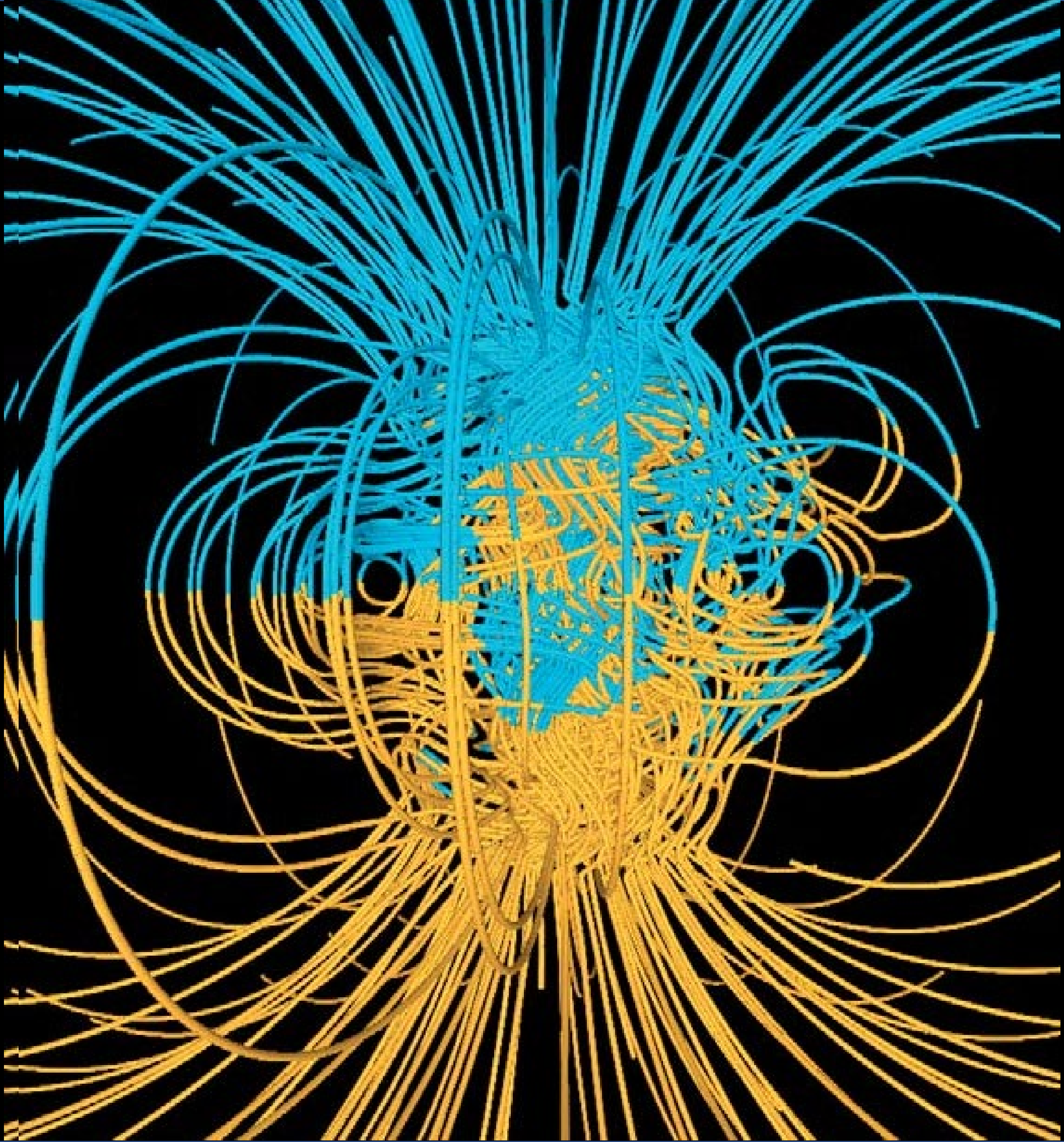


Credit: NASA



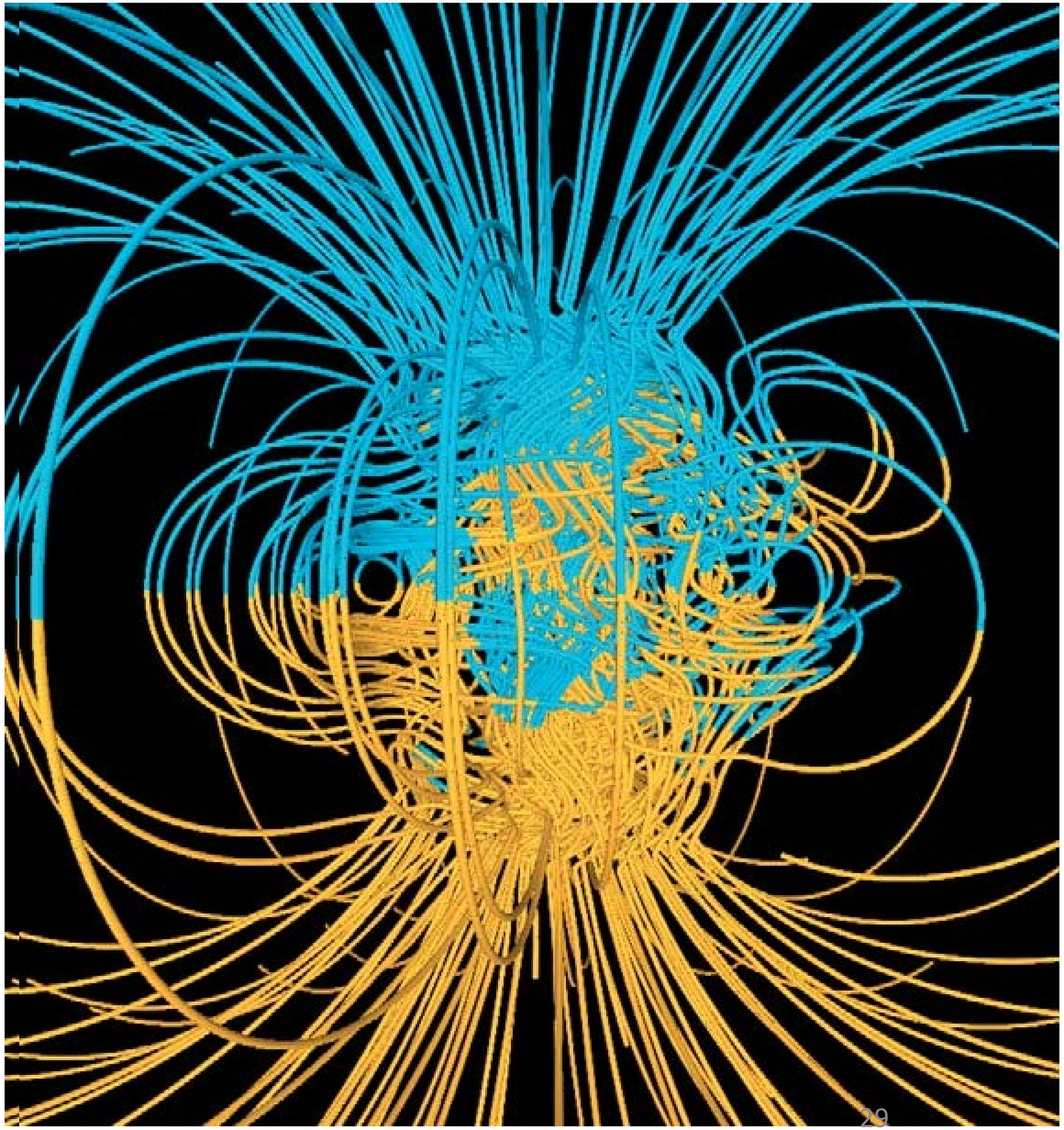
courtesy of Nathanael Schaeffer, rotating convection simulations performed with XSHELL

Lecture by J. Noir at WITGAF Cargese, Corsica, 2019 https://witgaf2019.sciencesconf.org/data/pages/Noir1.pdf

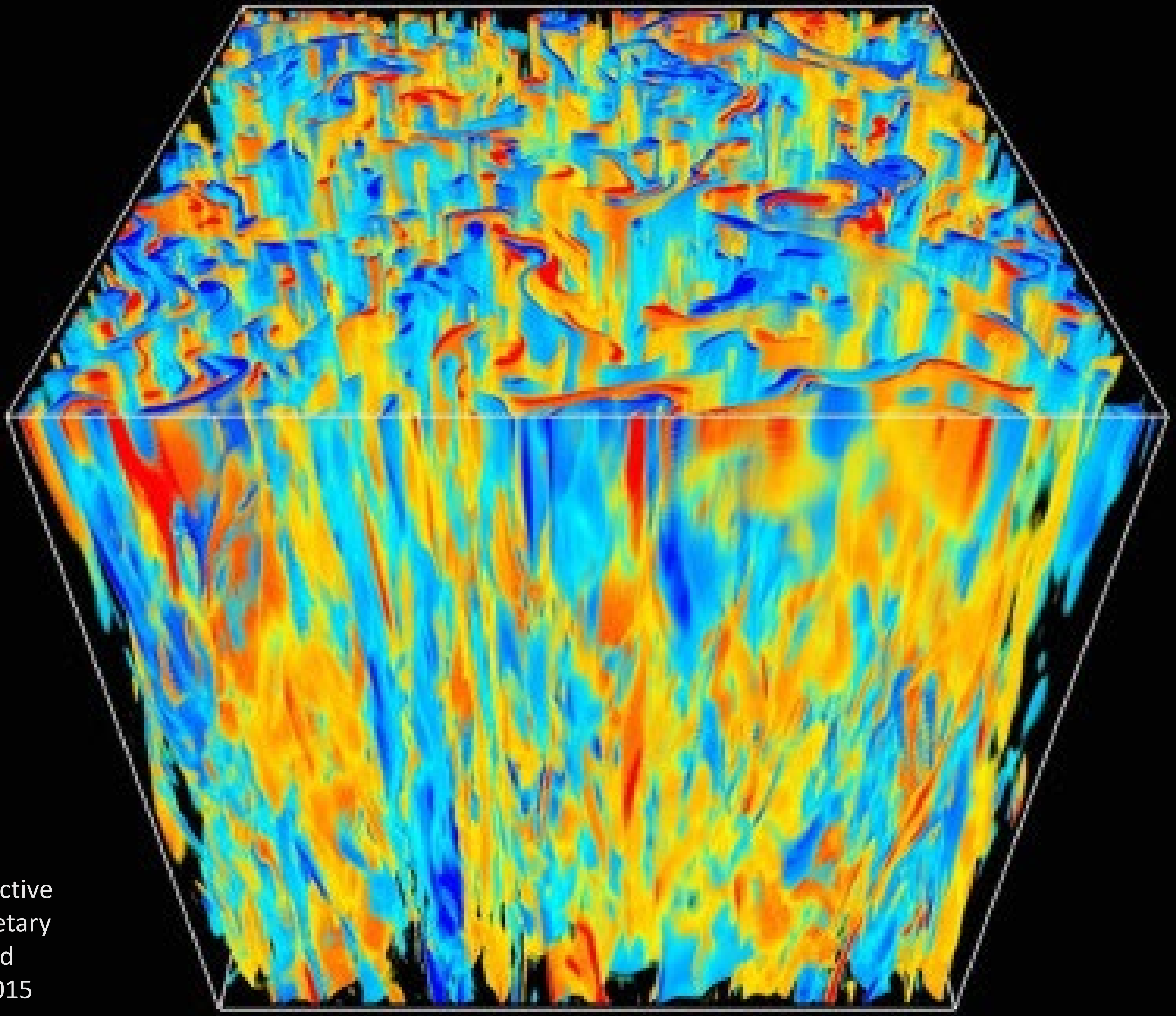


Notes: physics in Glatzmaier and Roberts, *Physics of the Earth and Planetary Interiors* 91 631995 https://websites.pmc.ucsc.edu/~glatz/book.html https://solidearth.jpl.nasa.gov/PAGES/mag01.html

Of course it's more complicated in MHD…

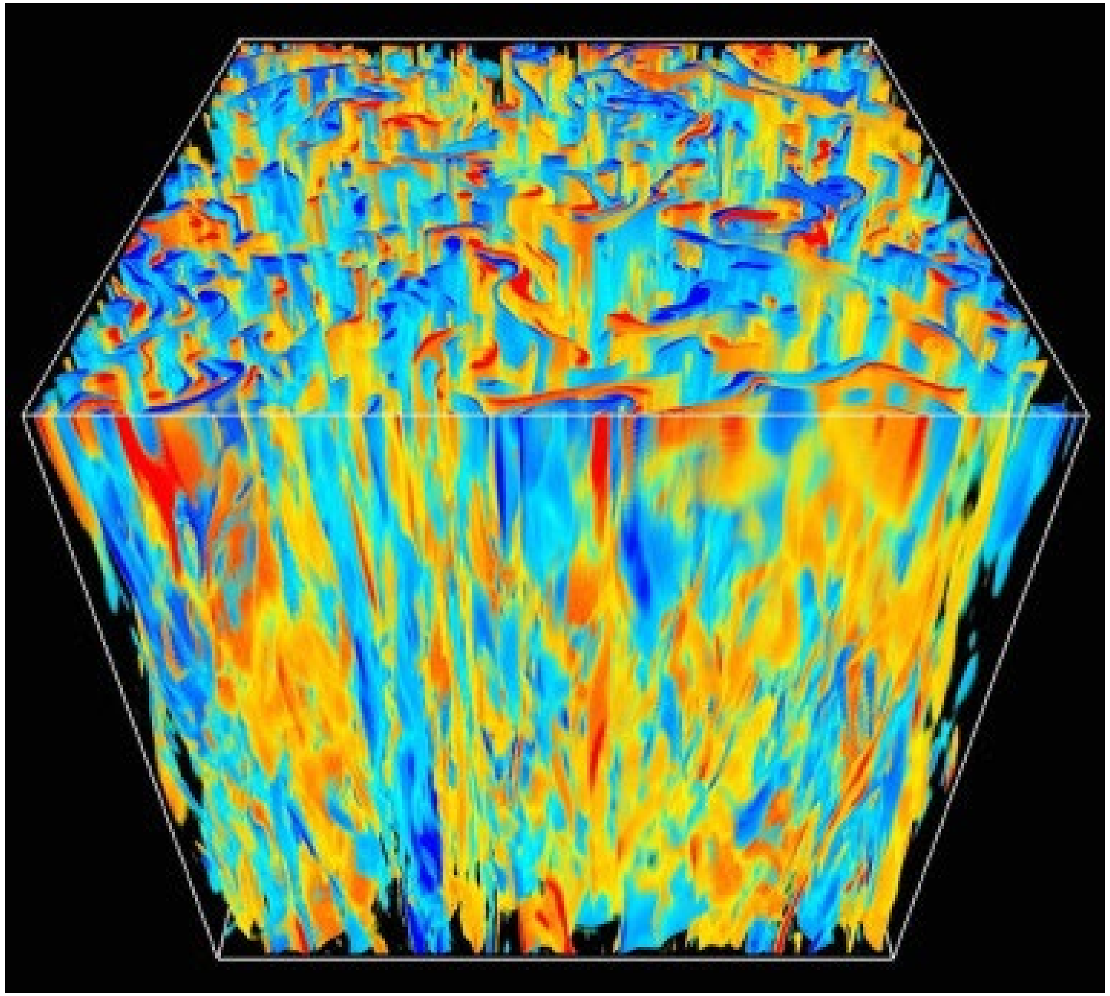


- A snapshot of the simulated geomagnetic field produced by Glatzmaier and Roberts (1995). A set of magnetic lines of force illustrated the 3D structure of the field, which is intense and complicated inside the fluid core and smooth and dipole-dominated outside the core. The rotation axis of the model Earth is vertical in the illustration and yellow lines represent outward directed field and blue line represent inward directed field. The field is sheared around the 'tangent cylinder' to the inner-core equator
- Notes: physics in Glatzmaier and Roberts, *Physics of the Earth and Planetary Interiors* 91 631995
- https://websites.pmc.ucsc.edu/~glatz/book.html
- https://solidearth.jpl.nasa.gov/PAGES/mag01.html

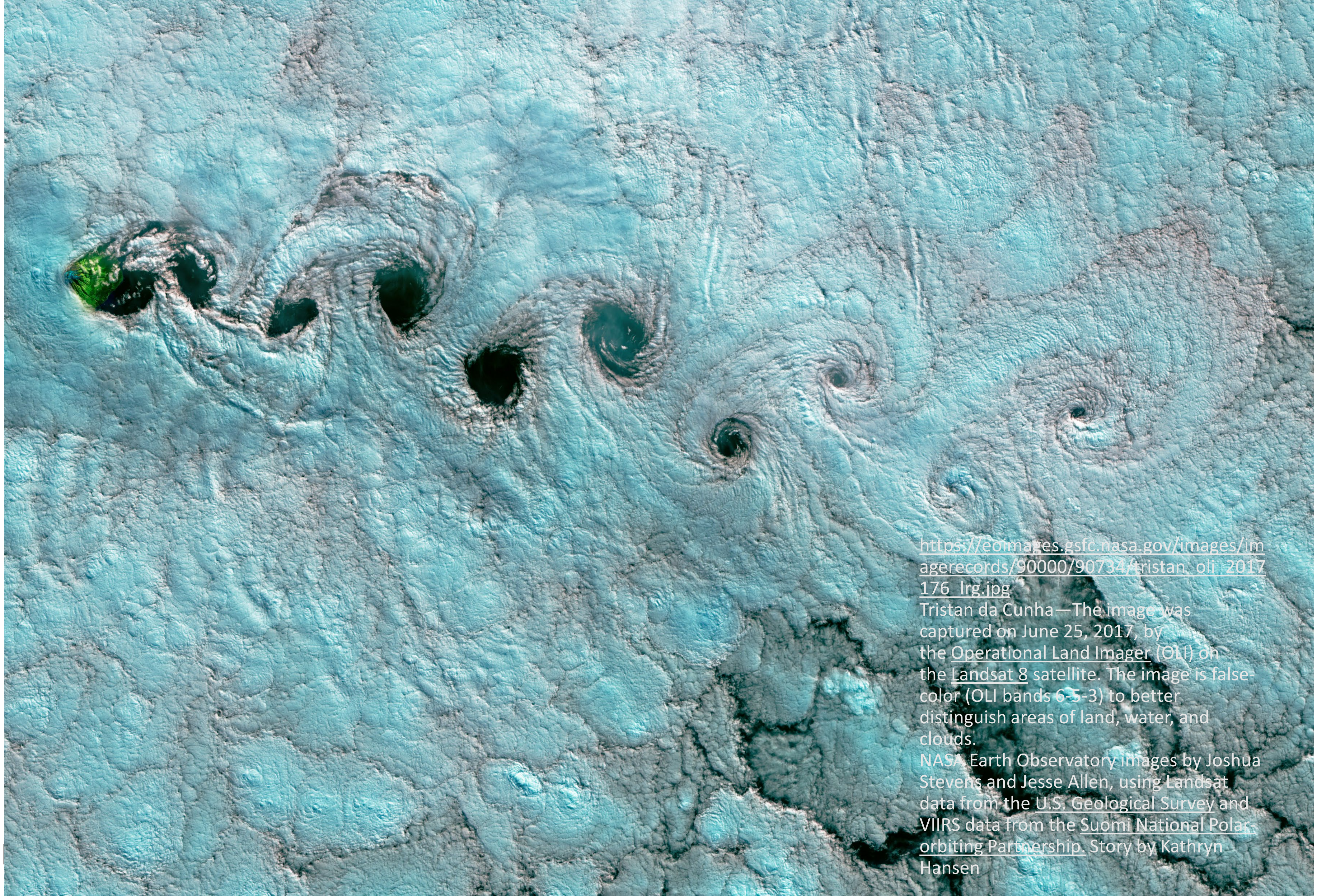


Aurnou *et al.,* Rotating convective turbulence in Earth and planetary cores, Physics of the Earth and Planetary Interiors, **246** 52 2015

Add turbulence…

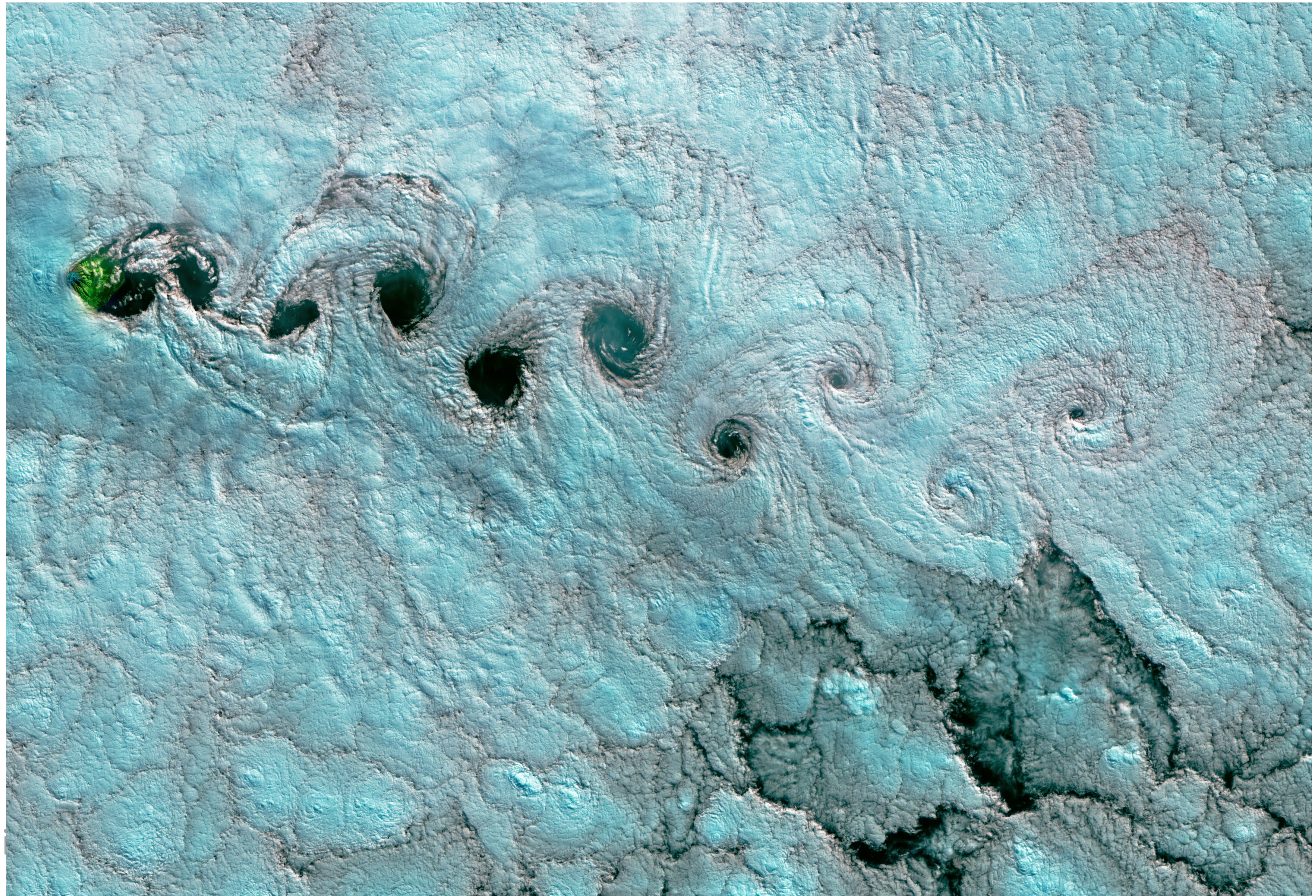


- Notes
- Oblique view of the axial vorticity field in an asymptotically-reduced rotating convection model with Pr=0.0235, a value comparable to that of many liquid metals. The flow is in the geostrophic turbulent regime.
- Aurnou *et al.,* Rotating convective turbulence in Earth and planetary cores, Physics of the Earth and Planetary Interiors, **246** 52 2015



https://eoimages.gsfc.nasa.gov/images/imagerecords/90000/90734/tristan_oli_2017176_lrg.jpg
Tristan da Cunha—The image was captured on June 25, 2017, by the Operational Land Imager (OLI) on the Landsat 8 satellite. The image is false-color (OLI bands 6-5-3) to better distinguish areas of land, water, and clouds.
NASA Earth Observatory images by Joshua Stevens and Jesse Allen, using Landsat data from the U.S. Geological Survey and VIIRS data from the Suomi National Polar-orbiting Partnership. Story by Kathryn Hansen

Non-linearity of the NS equations leaps out in von Kármán vortex streets



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NASA Earth Observatory images by Joshua Stevens and Jesse Allen, using Landsat data from the U.S. Geological Survey and VIIRS data from the Suomi National Polar-orbiting Partnership. Story by Kathryn Hansen

The expansion of experiments

Wind tunnels and why they don’t model accelerating flight

- By NASA/photographer unknown - Great Images in NASA Description, Public Domain, https://commons.wikimedia.org/w/index.php?curid=6450057

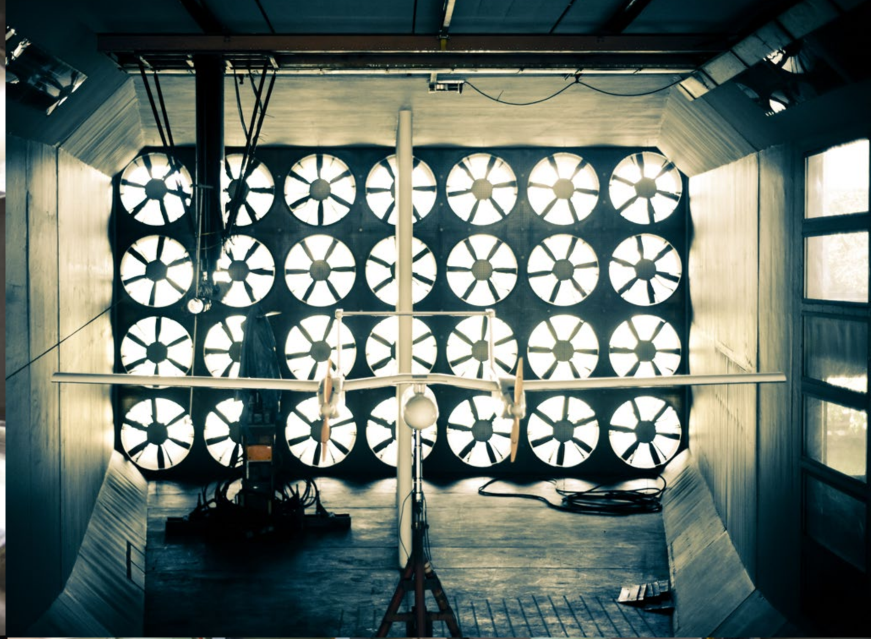
Before 1922: the bicycle

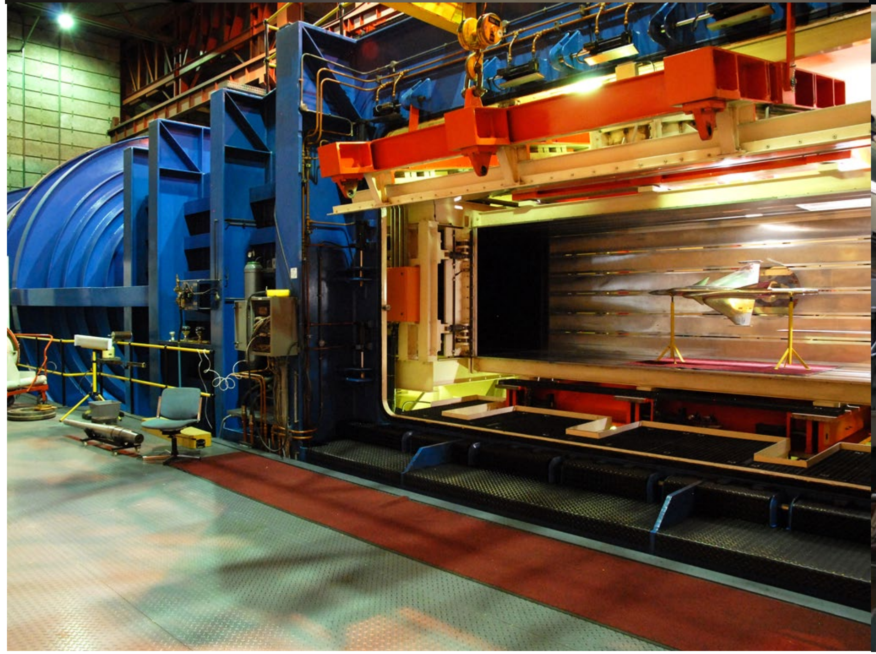
- Before 1902: Wilbur (1867-1912) and Orville (1871-1948) Wright ran a bicycle business.
- Built wind tunnel without walls = apparatus on a bicycle, balance two airfoils to find optimum
- Built a lift balance and a drag balance

Credit From the Collections of The Henry Ford.
https://www.thehenryford.org/collections-and-research/digital-collections/artifact/149448/

- replica of the Wright Brothers' wind tunnel at the Virginia Air & Space Museum in Hampton, VA. The entry of the tunnel was called the 'goesinta' by the brothers and the exit was dubbed the 'goesouta.'
- https://en.wikipedia.org/wiki/Wind_tunnel#/media/File:WB_Wind_Tunnel.jpg

- “Low” speed
  - Subsonic M<1
  - 120 kmh^{-1}
  - Incompressible behaviour
  - No shocks
- Transonic
  - “Medium” speed
  - M ~ 1
  - Shocks appear
- Supersonic
  - Attached and detached shocks





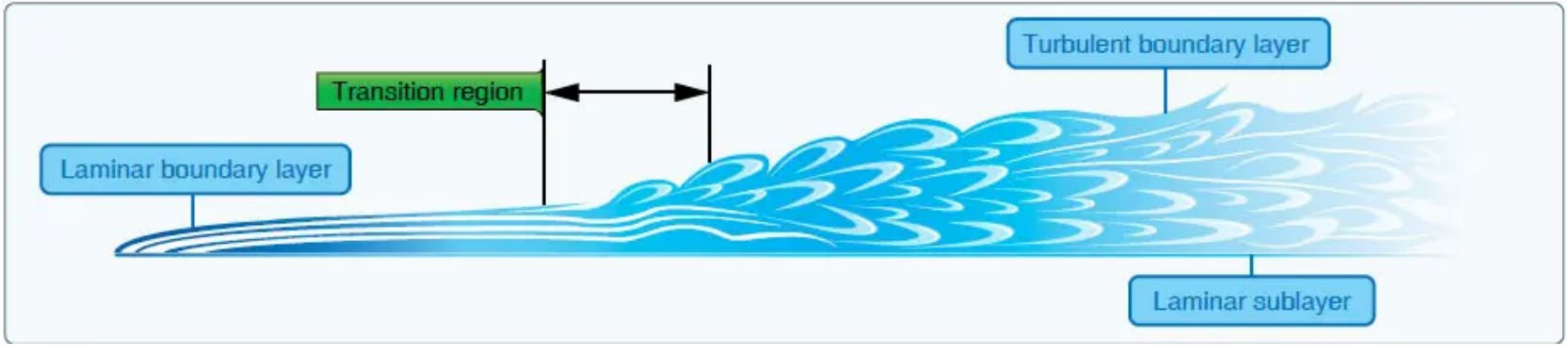
https://www.csir.co.za/suite-wind-tunnels

A problem for accelerating flight modelling

- But – accelerating the flow in a wind tunnel is not equivalent to accelerating an aircraft in flight
- Wind-tunnel startup requires a pressure gradient
- Accelerating flight takes place in stagnant air

- A problem for finding validation data.

Boundary layers



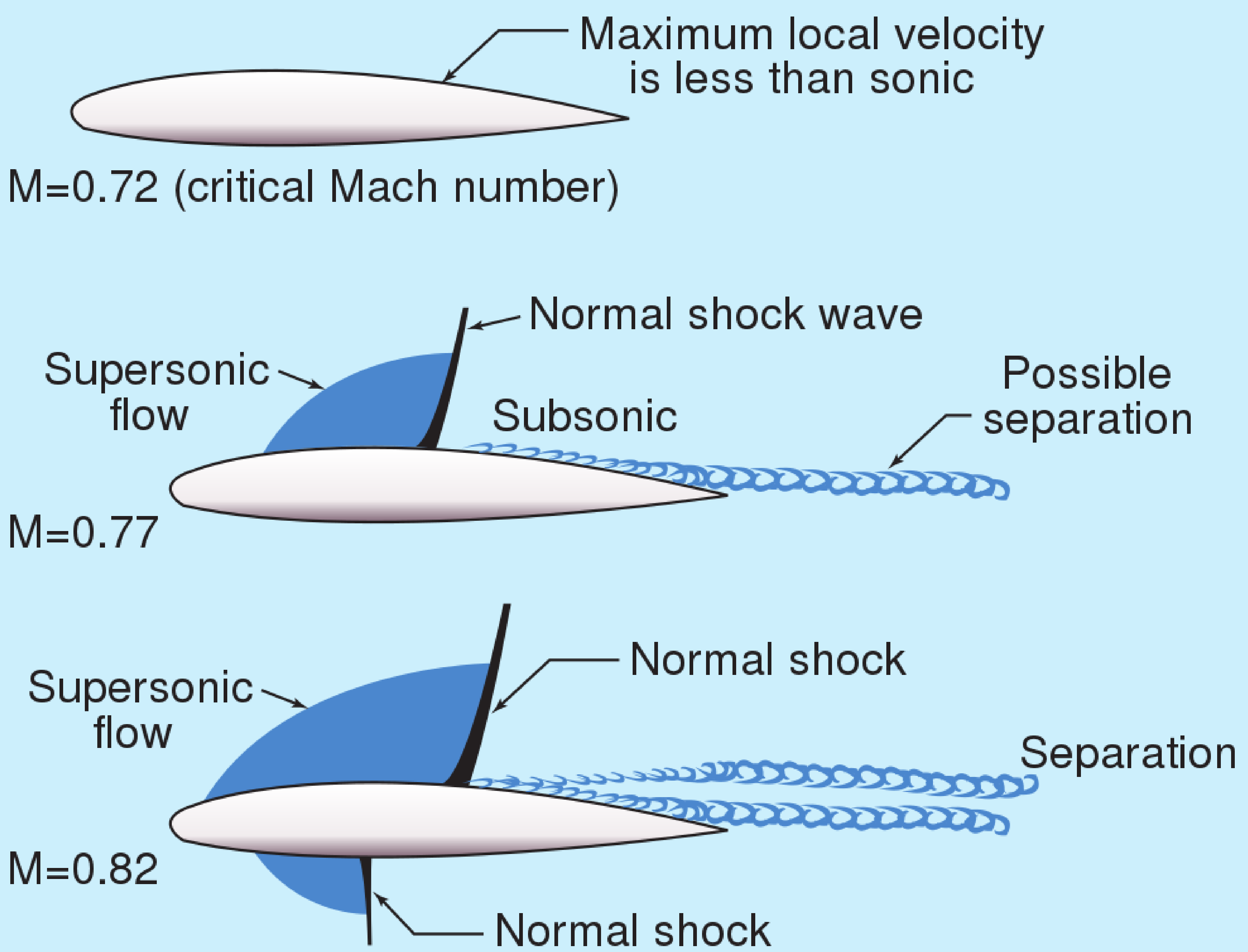
- https://www.flightliteracy.com/high-speed-flight-part-two-boundary-layer-and-shock-waves/

Shock waves

- Propagating disturbance that moves faster than the local speed of sound c
- Sonic boom
- Fluid properties: density, pressure, flow velocity **v**, flow Mach number M = **v/c**, temperature, entropy

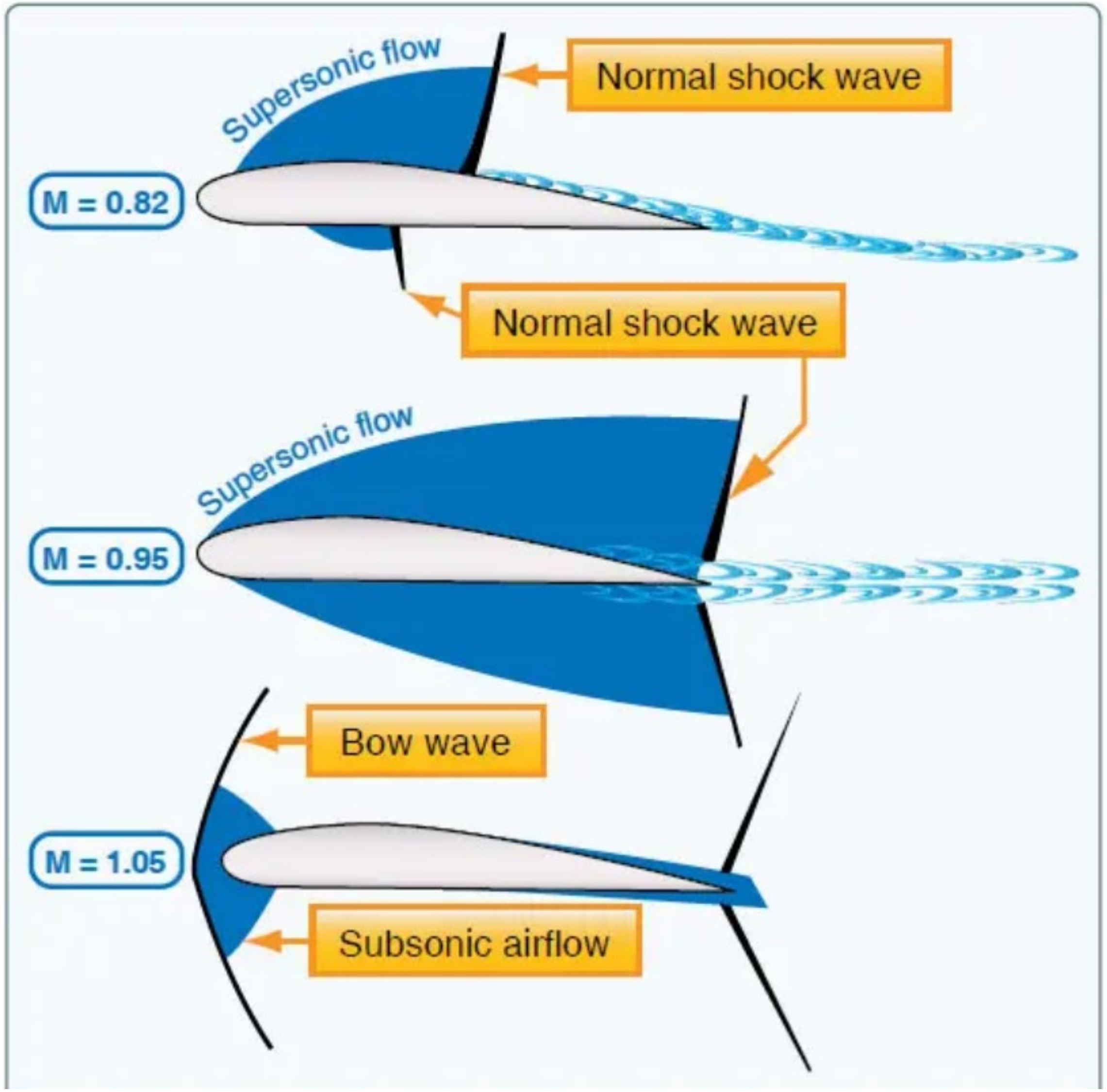
- Shock wave in air: about 200 nm thick

Shocks



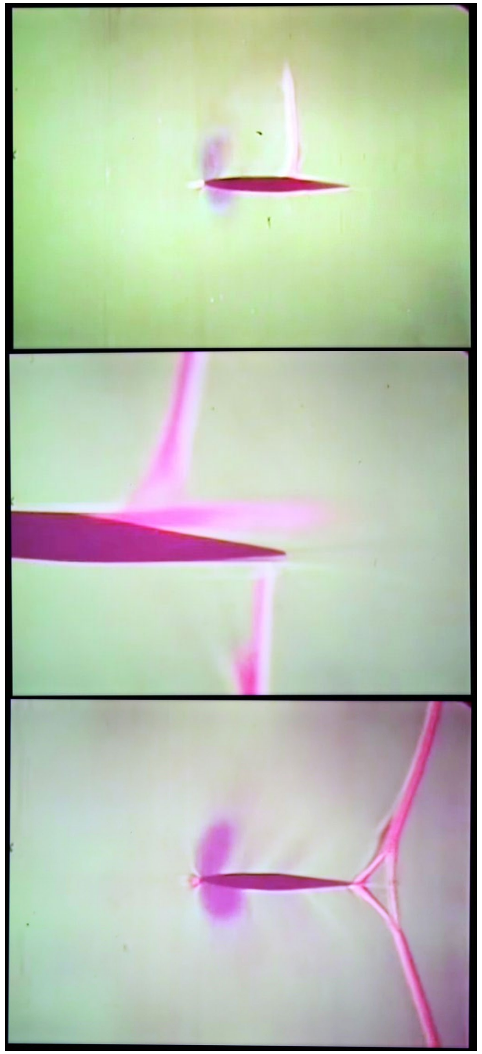
https://en.wikipedia.org/wiki/Shock_wave#/media/File:Transonic_flow_patterns.svg public domain

Shocks cont.



- https://www.flightliteracy.com/high-speed-flight-part-two-boundary-layer-and-shock-waves/

Shocks on airfoils



- Shocks cause flow separation: reverse flow
- Critical Mach number **v/c, c** is speed of sound (!)
- Far from an aircraft: sonic boom
- Treat as a discontinuous solution of the NS equations

Images G Morrow, Quora, https://www.quora.com/What-causes-shockwaves-to-form-on-an-airfoil-when-the-airflow-is-supersonic-Why-does-this-cause-flow-separation

First supersonic flight, X-1, 1947
Test flight is an experiment

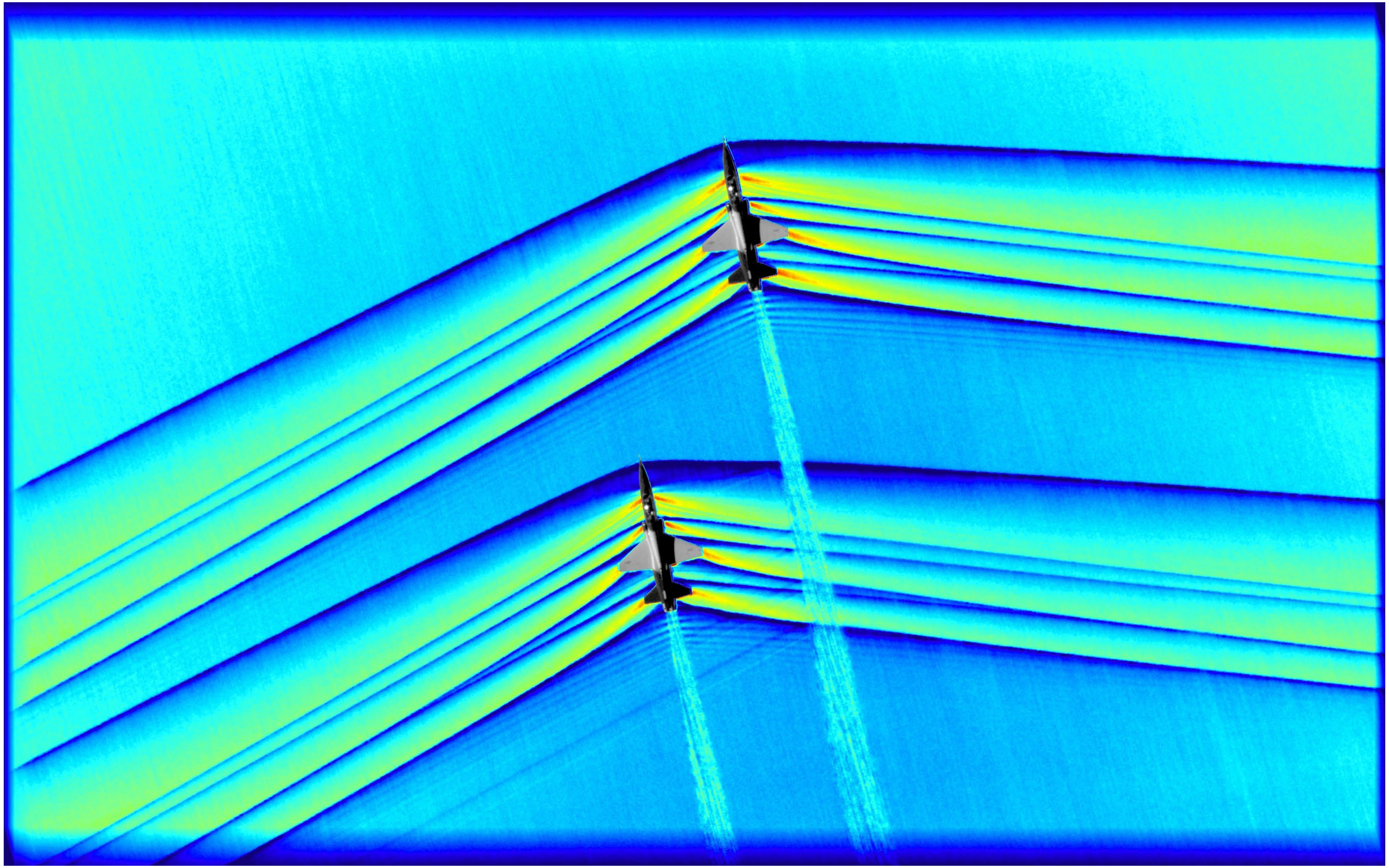
https://commons.wikimedia.org/w/index.php?curid=111134

youtube.com/watch?v=HekbC6Pl4_Y

Why does this matter?

- Shock wave may be over an aileron – loss of control
- Buffeting
- “Compressibility lockup”

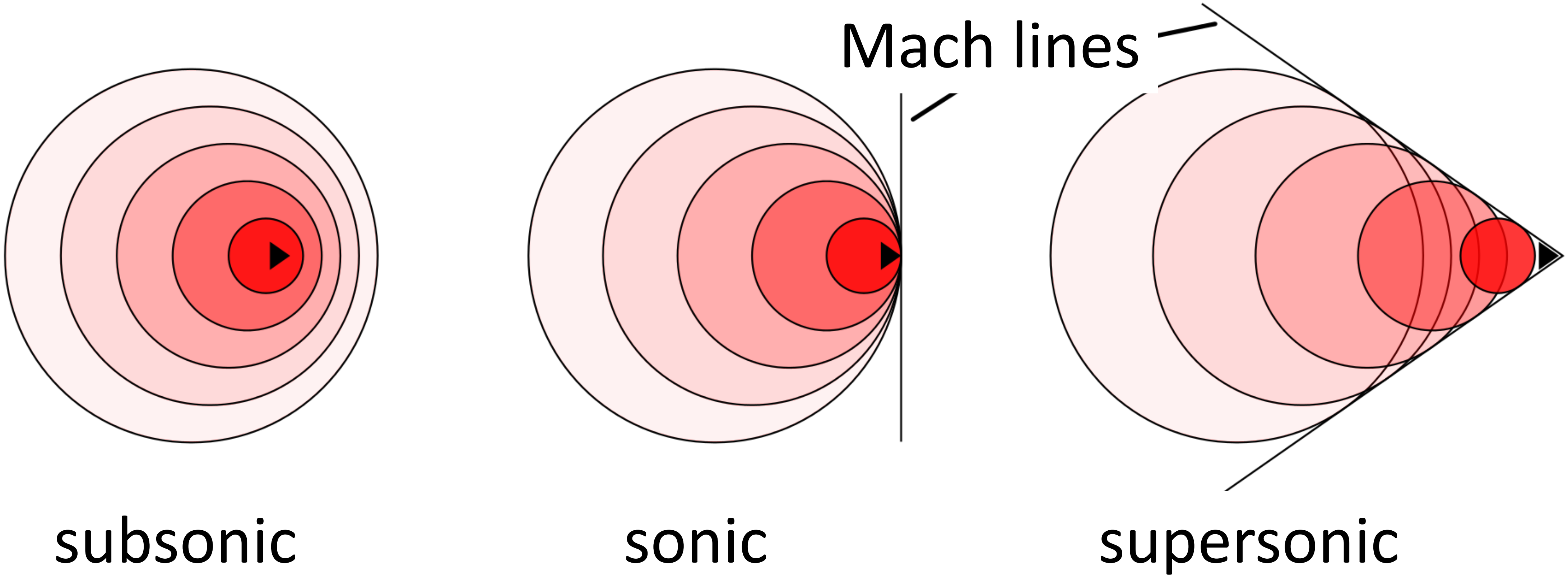
- Image: *U.S. Navy* photo by ENSIGN JOHN GAY
- **AN F/A -18 HORNET BREAKS THE SOUND BARRIER** in the skies over the Pacific Ocean.



NASA flights to capture background schlieren of two supersonic T-38 aircraft

https://www.nasa.gov/sites/default/files/styles/image_card_4x3_ratio/public/thumbnails/image/f4_p3_rgb_planedrop.jpg

Mach lines



- Pbroks13 https://en.wikipedia.org/wiki/Sound_barrier#/media/File:Sound_barrier_chart.svg

Mach waves for acceleration

- 1953, Lilliy
- Weak waves interfere to form shock waves
- The sonic boom
- Hydraulic analogy trials

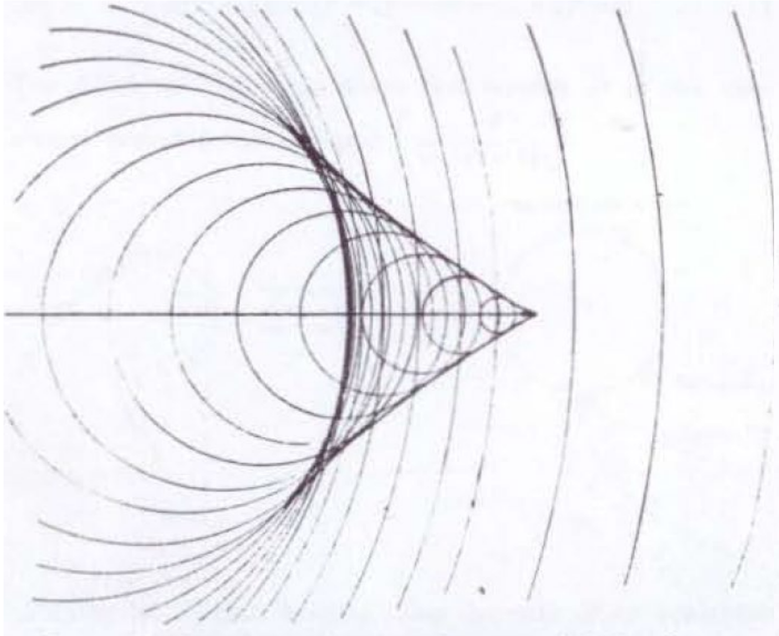


FIGURE 7. Source accelerating along a straight line from subsonic to supersonic speed.

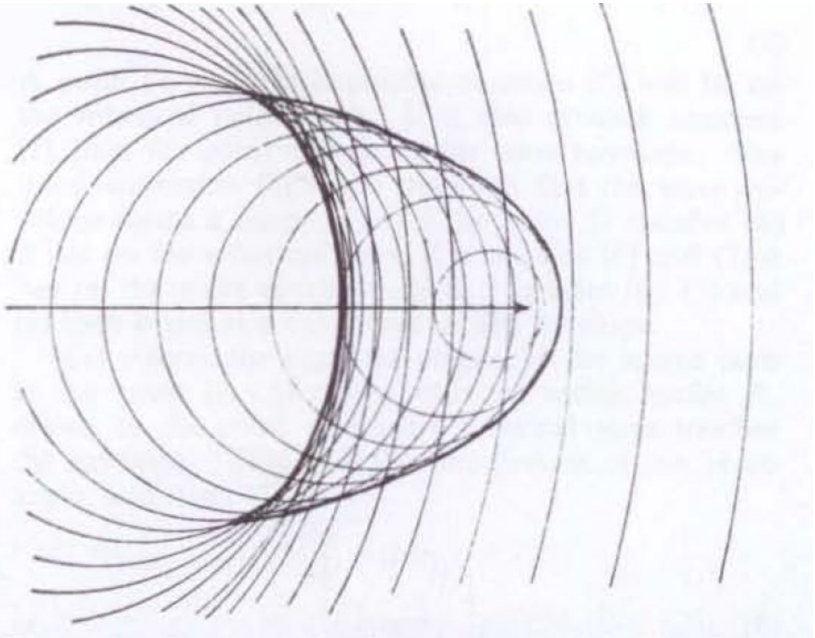
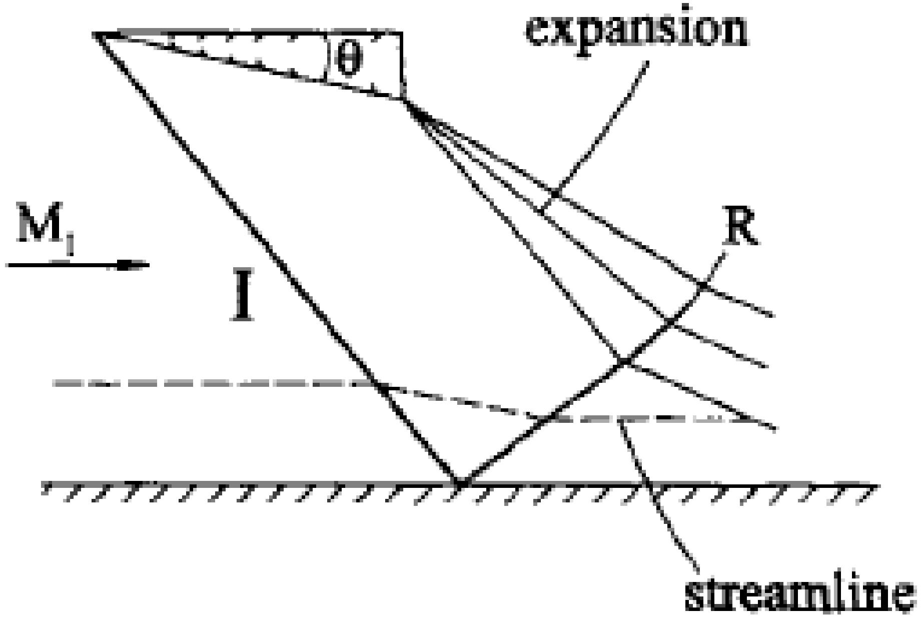
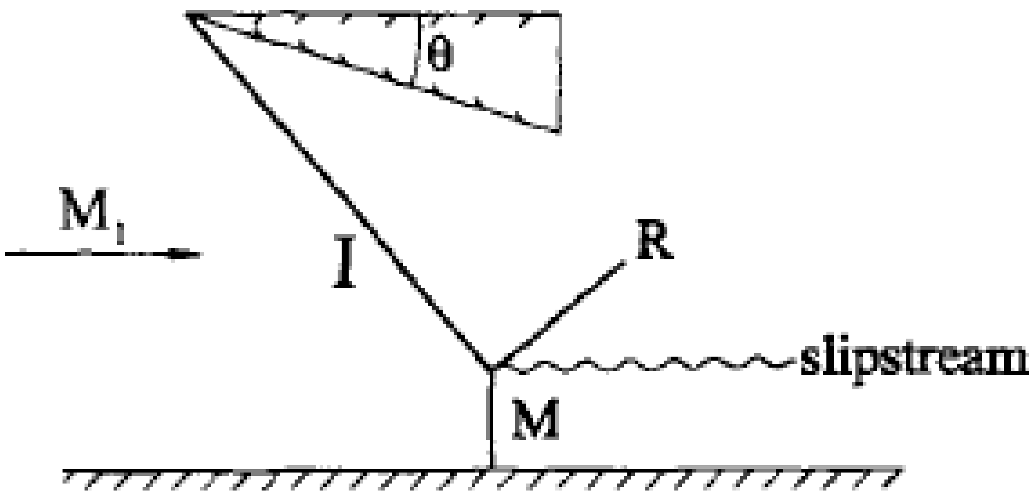


FIGURE 8. Source accelerating along a straight line from subsonic to supersonic and then retarding to subsonic speed.

Lilley, G.M., Westley, R., Yates, A.H., Busing, J.R.: Some aspects of noise from supersonic aircraft. J. R. Aeronaut. Soc. Coll. Aeronaut. Rep. **57**, 396–414 (1953)

Regular reflection and Mach reflection



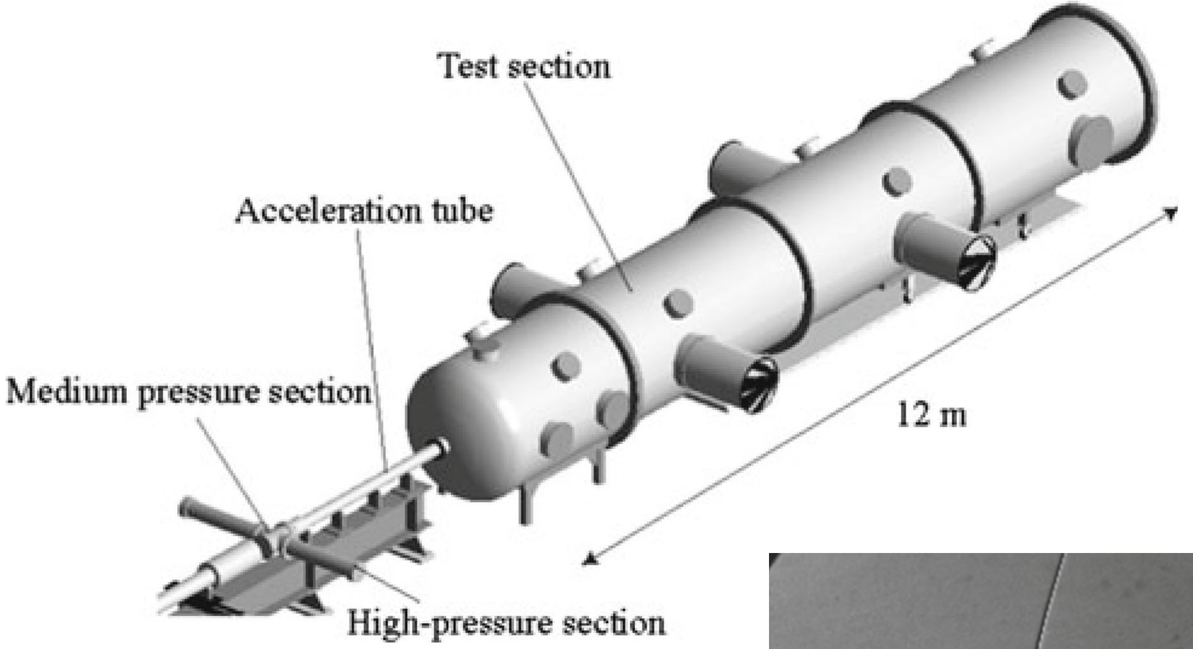


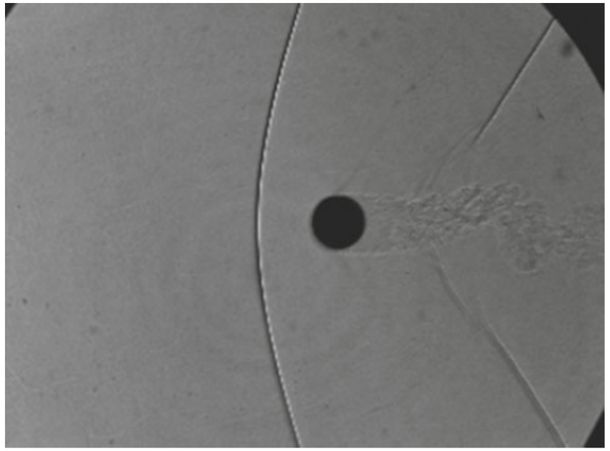
- G. Ben-Dor, O. Igra, and T. Elperin, *Handbook of Shock Waves,*. Academic Press, 2000.

Ballistic range puzzle: shocks in subsonic flow?

- Free flight
- Ballistic range: spheres travel at M ≈1

- High speed camera: frame rate 125 000 s^{-1}
- exposure 1 μs
- The shock standoff distance is unexpectedly large





Saito *et al.,* Shock Waves, **21** 483 2011

Rocket sleds

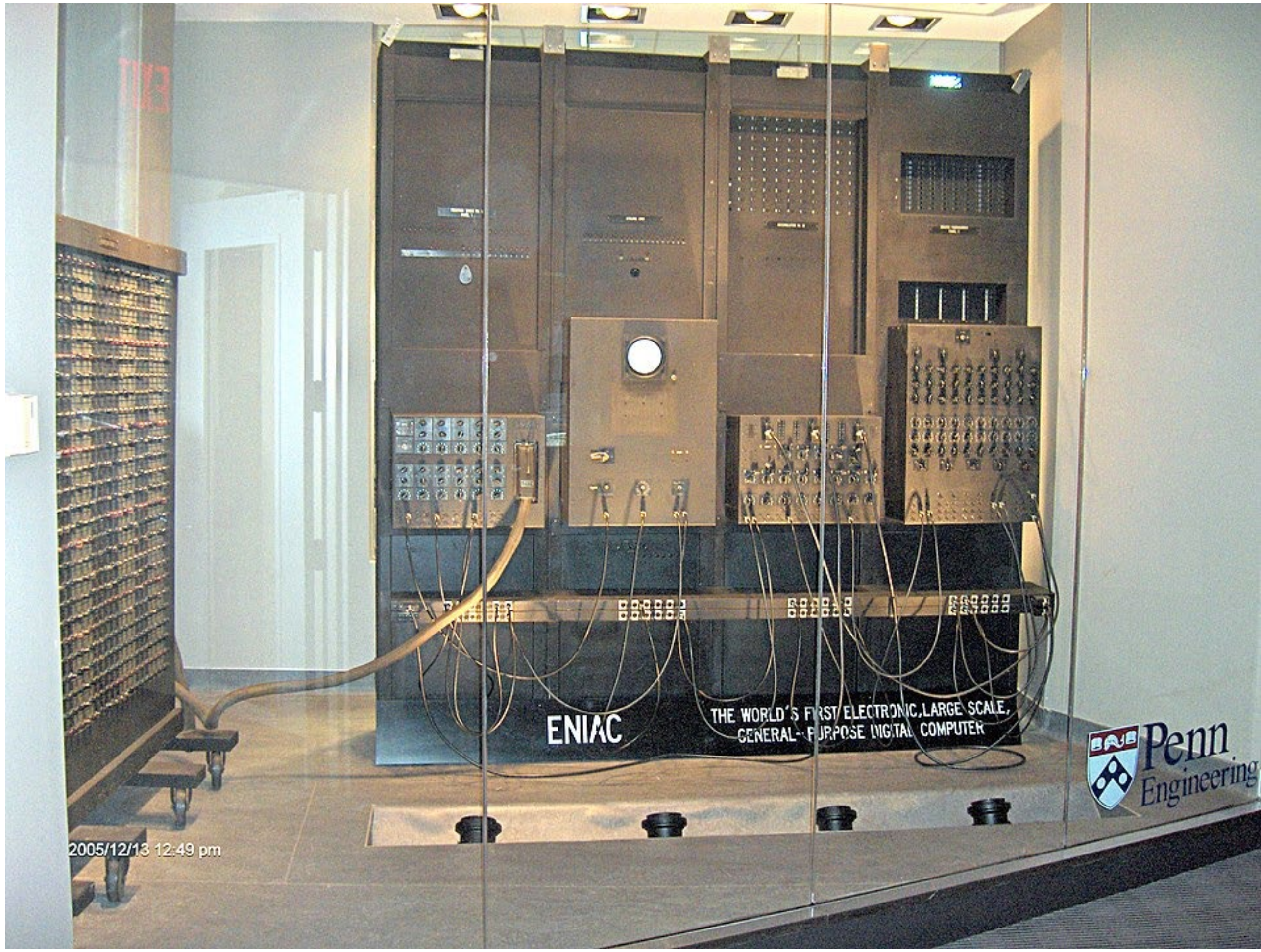
- Data not always available
- Pendine facility UK

The contribution of Computational Fluid Dynamics – “CFD”

Early computing – but not the whole history

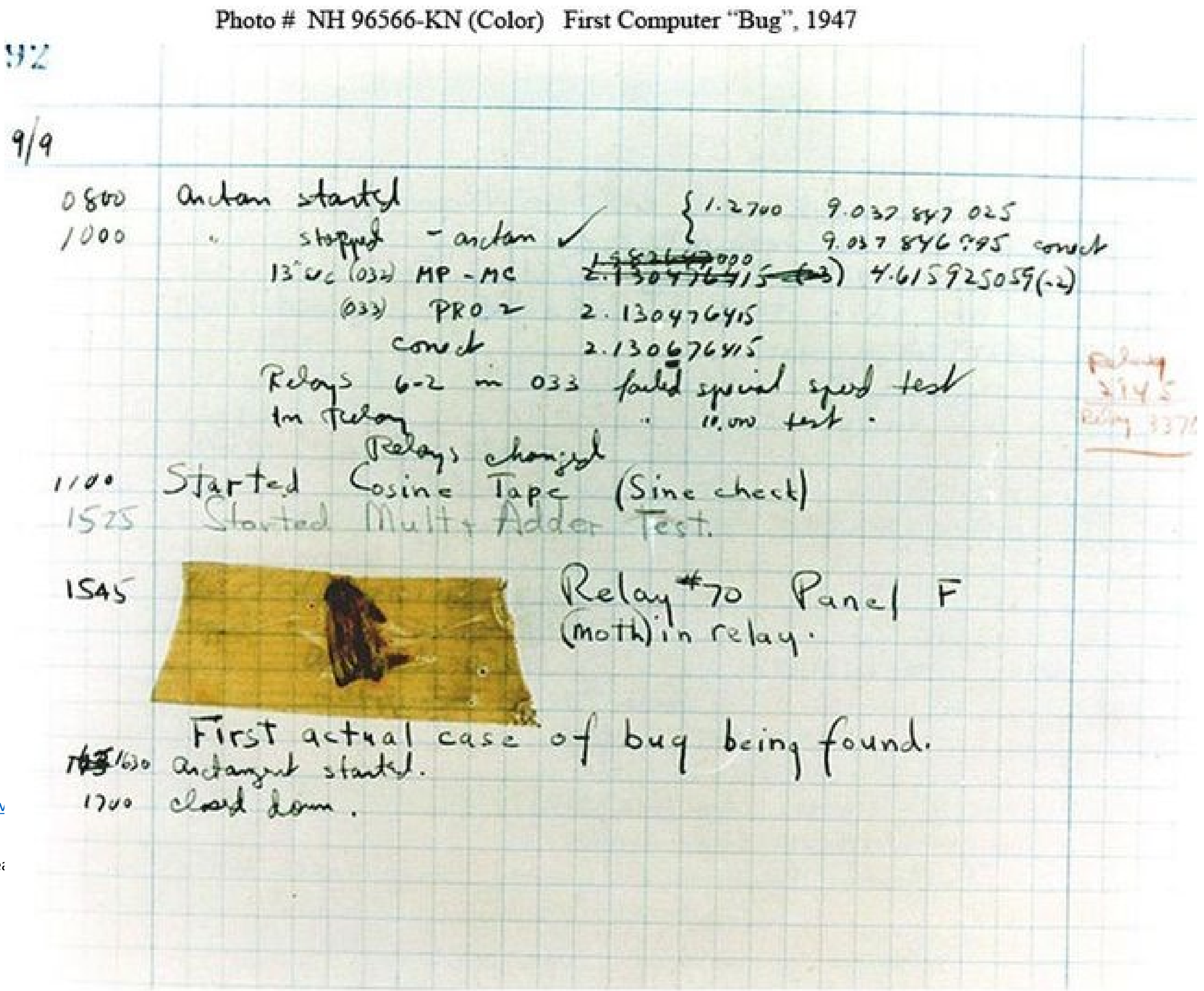
Early Computational Fluid Dynamics (CFD)

- 1940's: ENIAC and weather prediction
- John von Neumann and Stanislaw Ulam, Monte Carlo methods
- 1950's Particle-in-Cell methods for plasmas: Buneman, Dawson, Hockney, Birdsall, Morse



- https://commons.wikimedia.org/w/index.php?curid=6557095

First reported bug



- https://www.nationalgeographic.org/thisday/sep9/worlds-first-computer-bug/#:~:text=On%20September%209%2C%201947%2C%20a,their%20computer%20at%20Harv d%20University.
- 9 September 1947, Harvard, 15:45 Relay # 70, Panel F, of the Mark II Aiken Relay Calculator Tea reported the bug; History reported by Grace Hopper, PhD maths Yale 1923, , invented the first English-language data-processing compiler,an author of COBOL
- https://commons.wikimedia.org/wiki/File:First_Computer_Bug,_1945.jpg

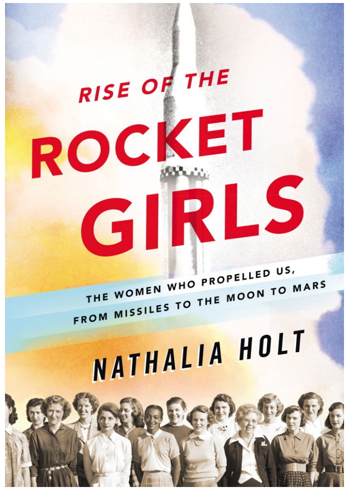
Computers

- 1940’s Buneman: analytical machine at Harwell
- 1940’s Buneman: the travelling wave tube analysis, fields and 17 electrons to each student

1936-1958 Jet Propulsion Laboratory computers

- https://www.space.com/34619-women-computers-of-nasa-jpl.html

1936-1958 Jet Propulsion Laboratory computers



- https://www.space.com/34619-women-computers-of-nasa-jpl.html
- Credits NASA/JPL-Caltech, Rise of the Rocket Girls Little, Brown and Co.
- JPL 1953 group photo includes Janez Lawson

Cards

First Open Source Poisson Solver?

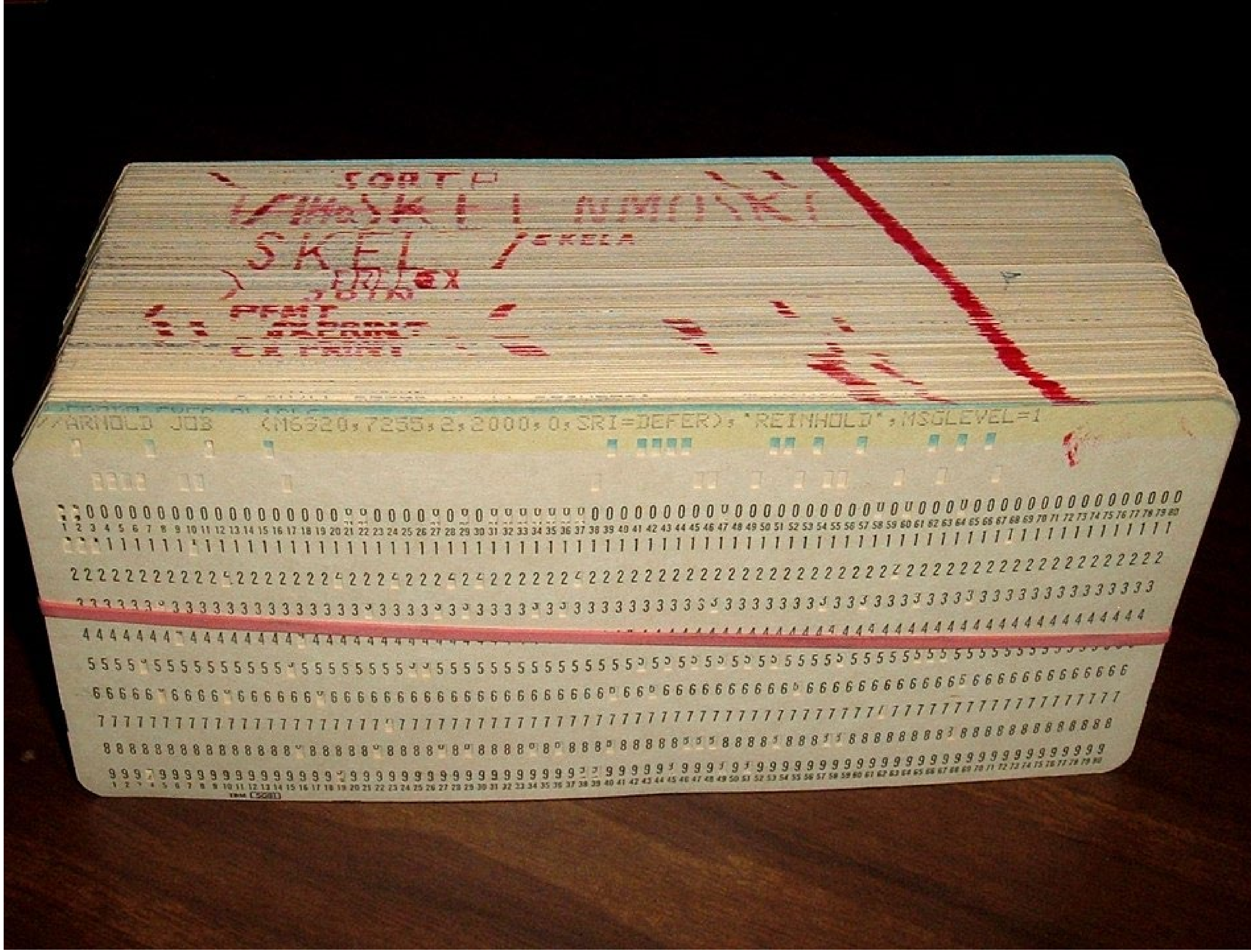


Image of punch cards
By ArnoldReinhold - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=16041053

The contribution of Computational Fluid Dynamics – CFD

- Plasmas: PDEs are MHD; particle-in-cell (superparticles)
- Fluids: PDEs are CFD; SPH (superparticles), Cellular Automata
- Multi-physics: boundary conditions…

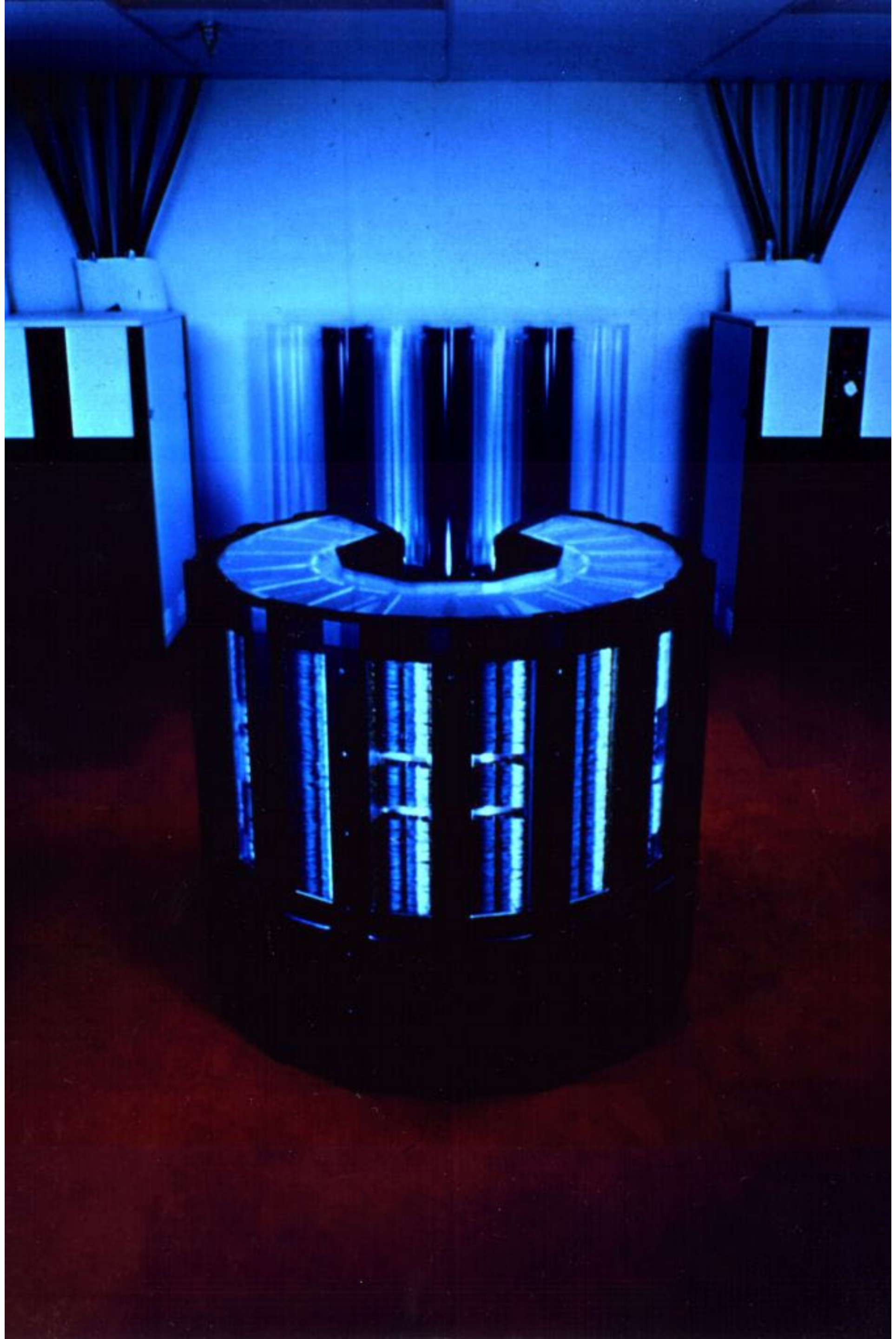
Super computing

- 1980’s Cray X-MP
- The light nanosecond

- http://www.craysupercomputers.com/crayxmp.htm
- https://en.wikipedia.org/wiki/Connection_Machine#/media/File:Computer_Museum_of_America_(51).jpg CC BY-SA 3.0
- File:Computer Museum of America (51).jpg

Super computing

- 1980's Cray II
- FFT (Fortran, assembler)

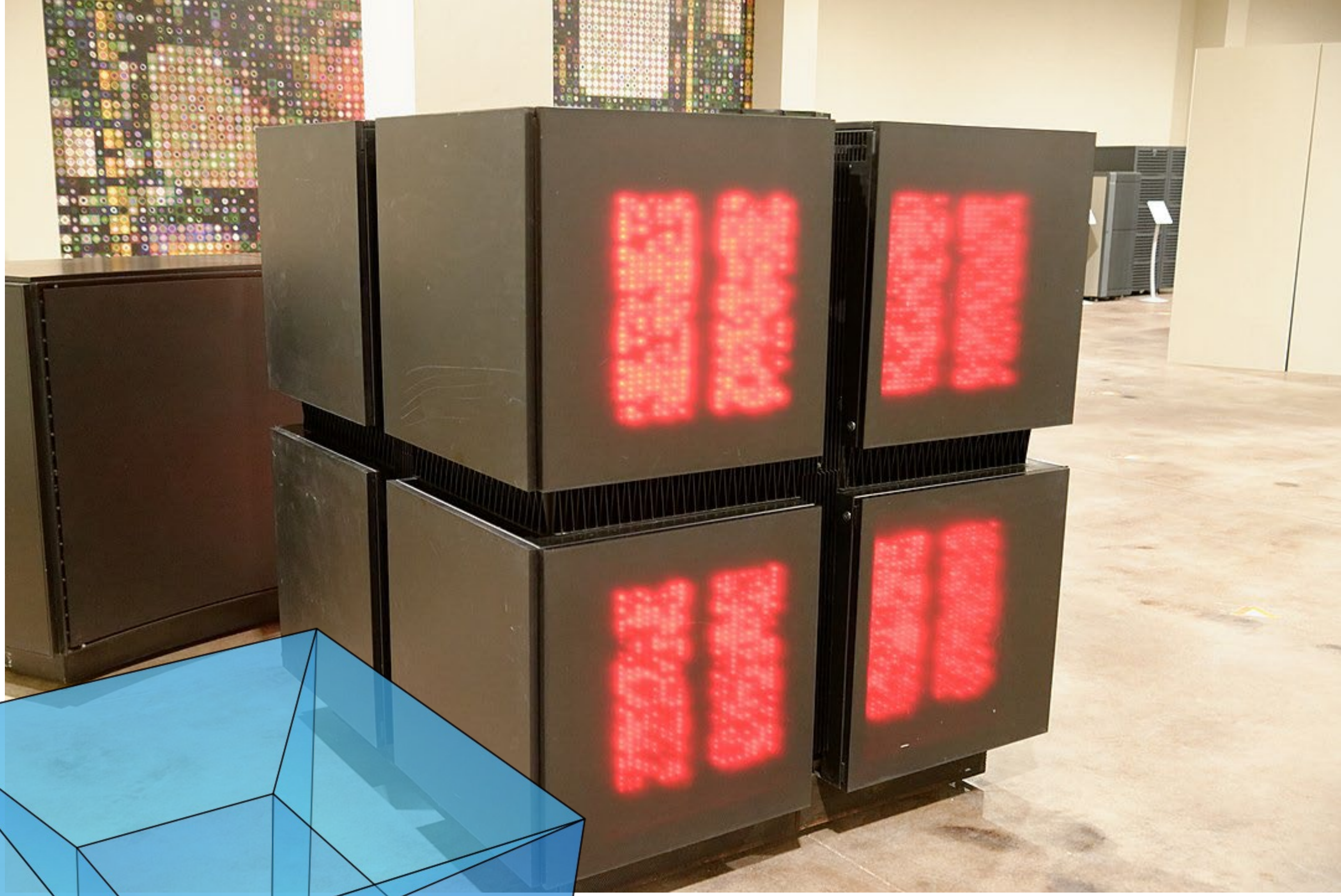


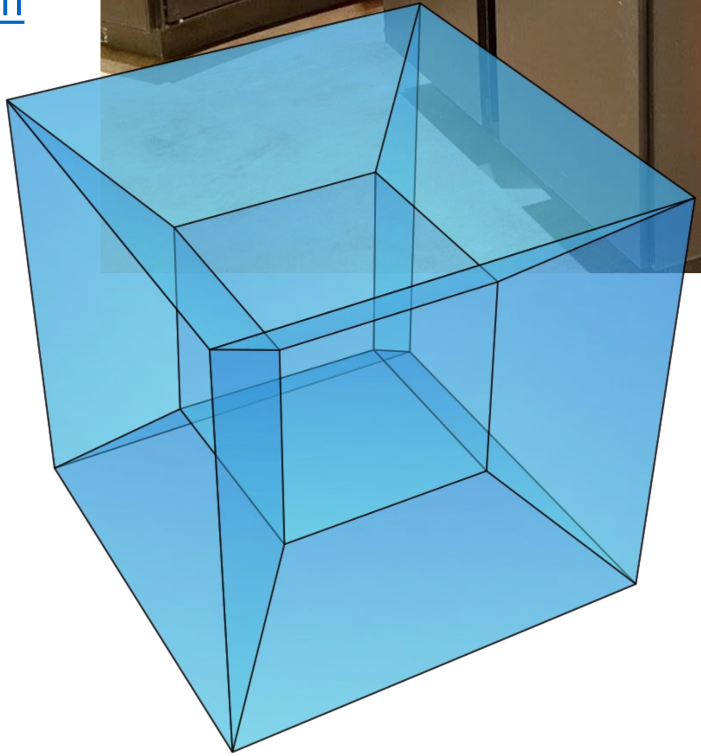
- http://www.craysupercomputers.com/crayxmp.htm

Parallel processing

1980’s: the age of parallel processing
http://www.craysupercomputers.com/crayxmp.htm

Thinking Machines Connection Machine

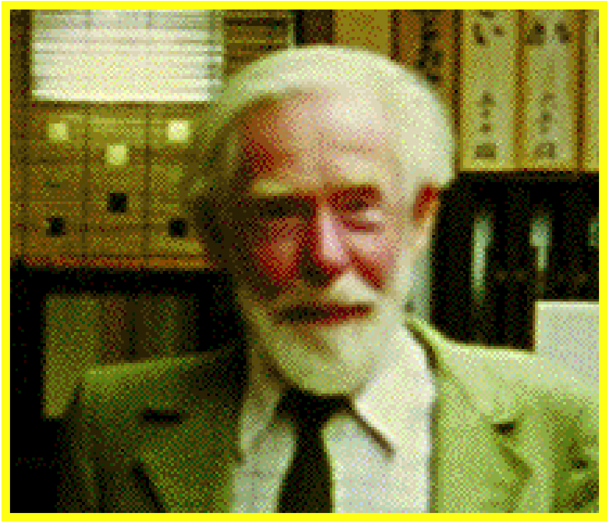


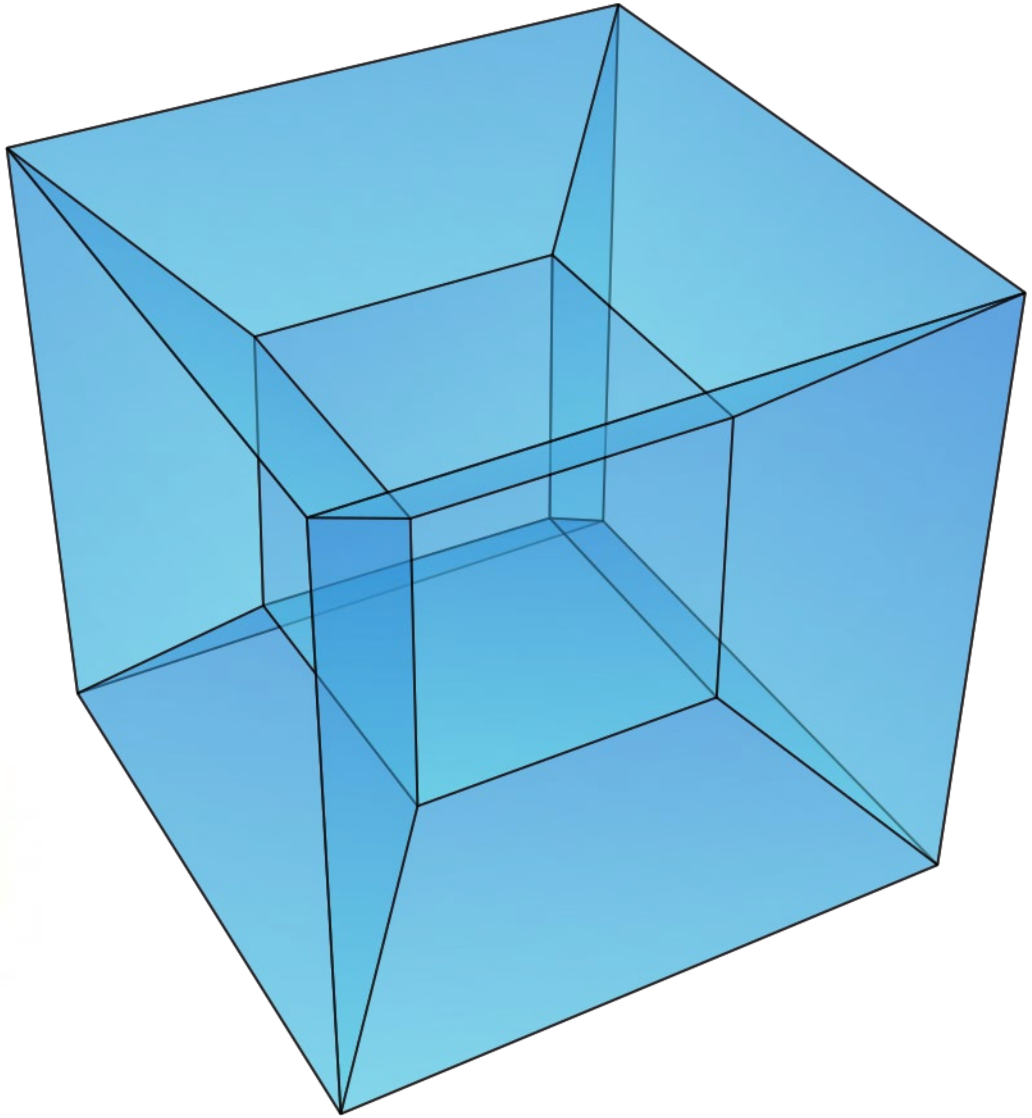


By Judson McCranie, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=81284520

Parallel processing

Oscar Buneman and visualisation

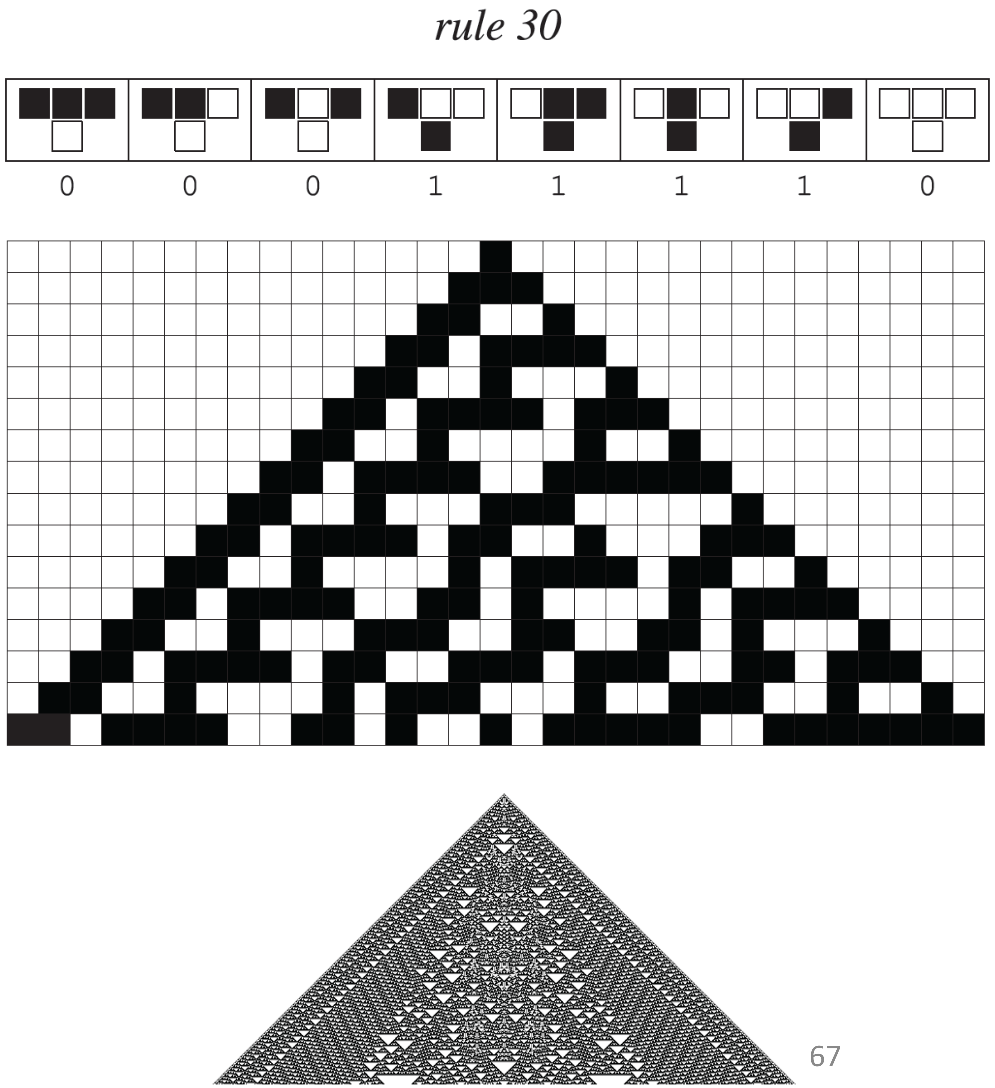




https://www.physics.ucla.edu/icnsp/buneman.htm

From Cellular Automata to the Lattice Gas

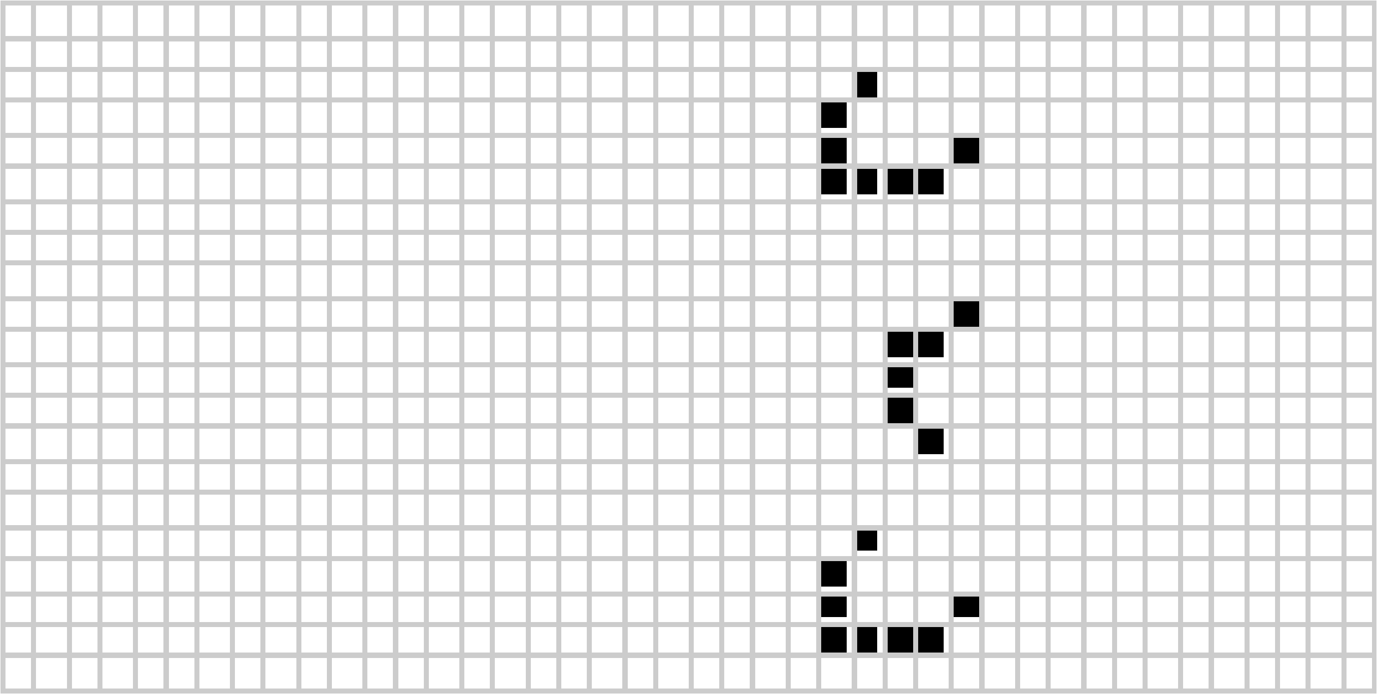
- a collection of "coloured" cells
- on a grid of specified shape
- that evolves through a number of discrete time steps
- according to a set of rules based on the states of neighbouring cells.
- The rules are applied iteratively for as many time steps as desired



- https://mathworld.wolfram.com/CellularAutomaton.html

From Cellular Automata to the Lattice Gas

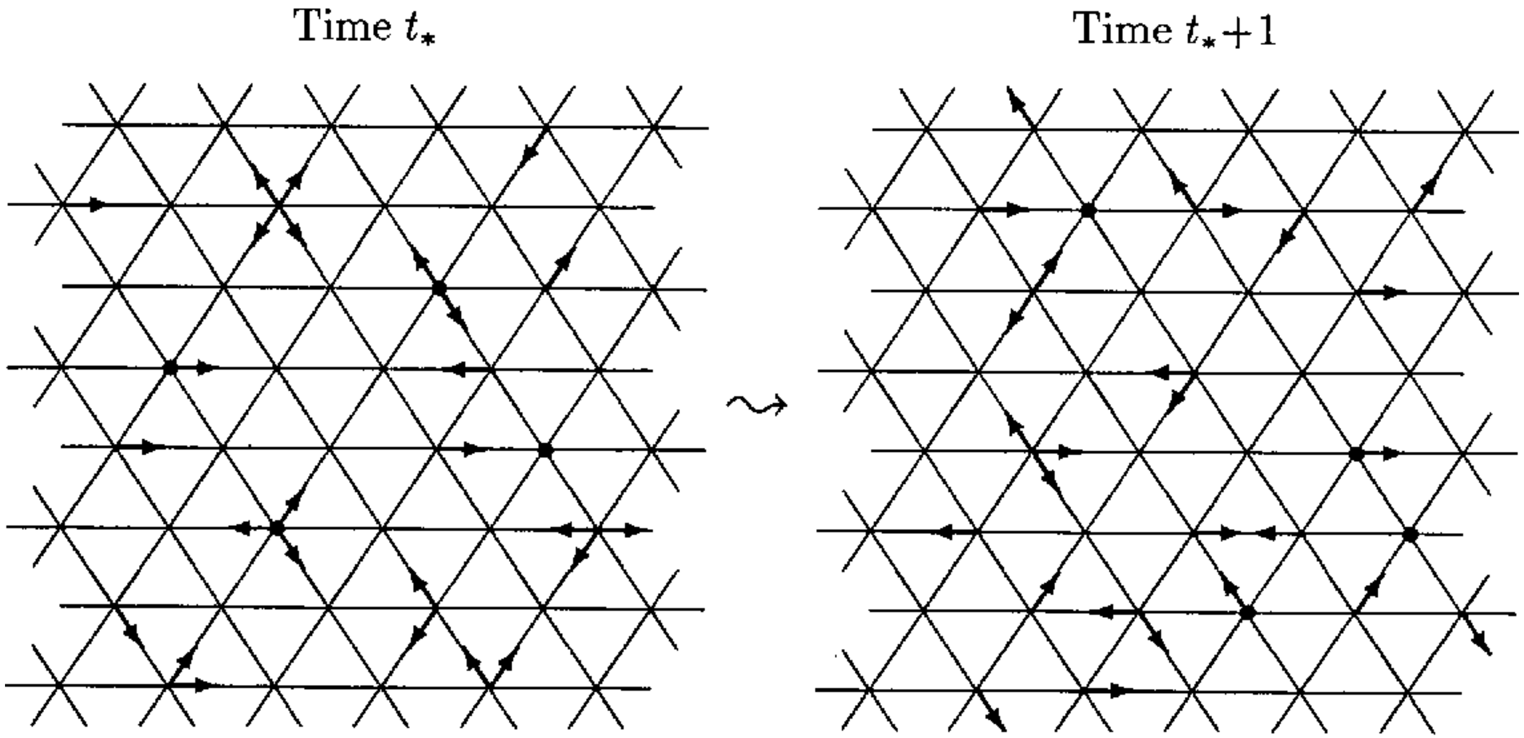
- Conway's game of life, discovered by J. H. Conway in 1970



- https://mathworld.wolfram.com/CellularAutomaton.html

Lattice gases mimic fluids: Lattice Boltzmann methods

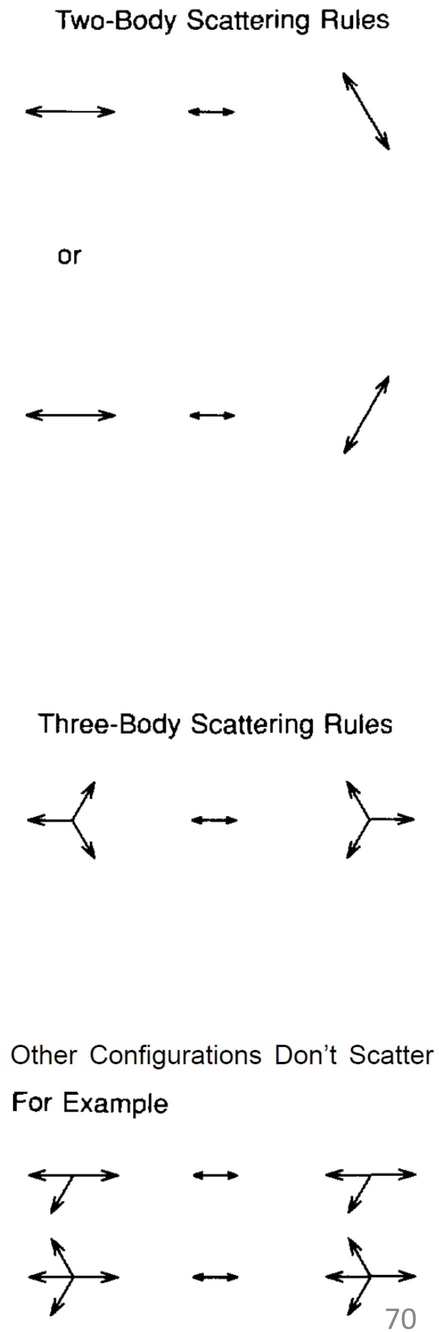
- Triangular lattice
- Each node has particles
- All particles hop to next node each time step



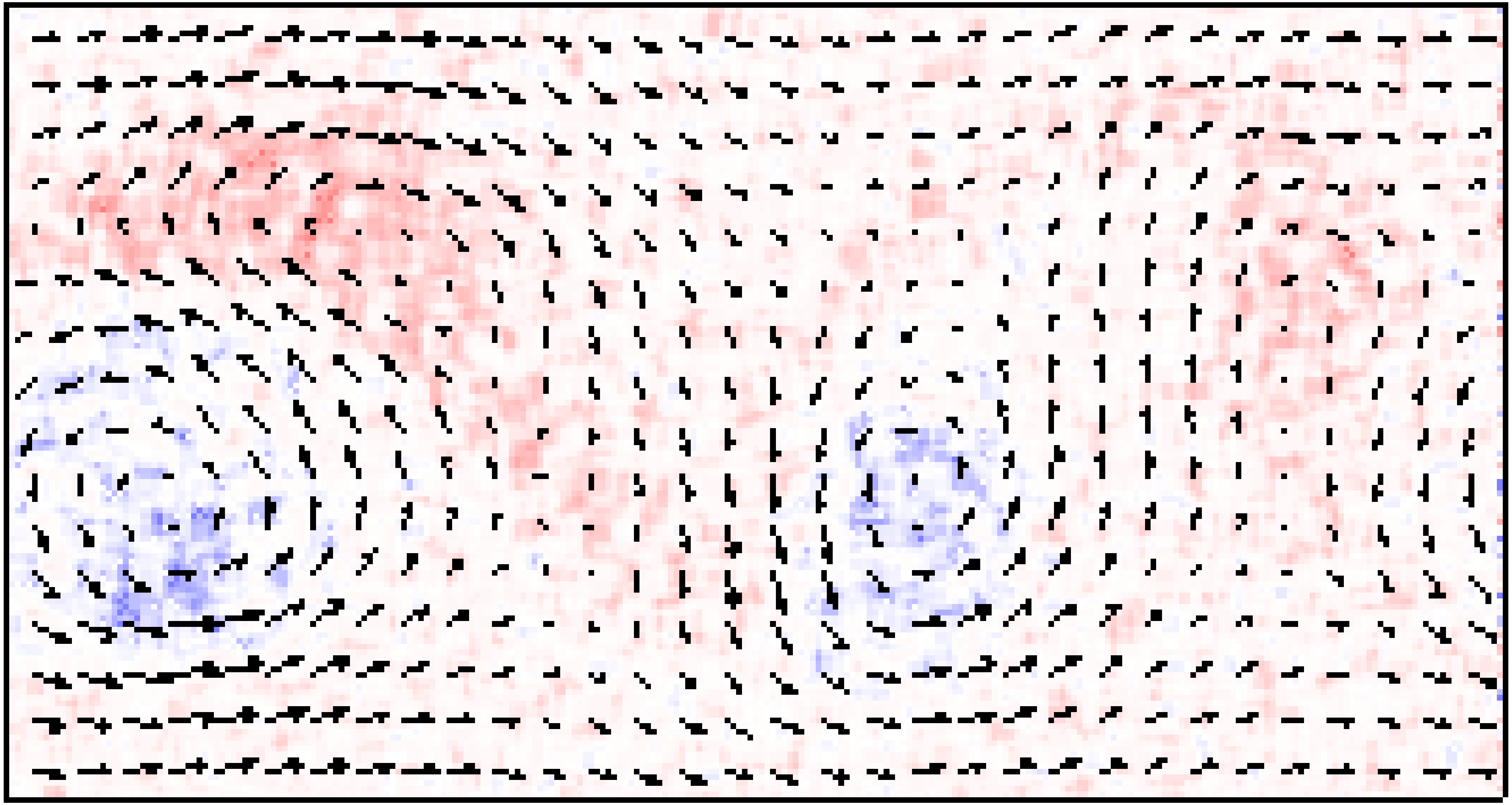
- Images B Hasslacher LosAlamos Science 1987, B Wylie PhD Thesis U Edinburgh 1990

Lattice gases mimic fluids: Lattice Boltzmann methods

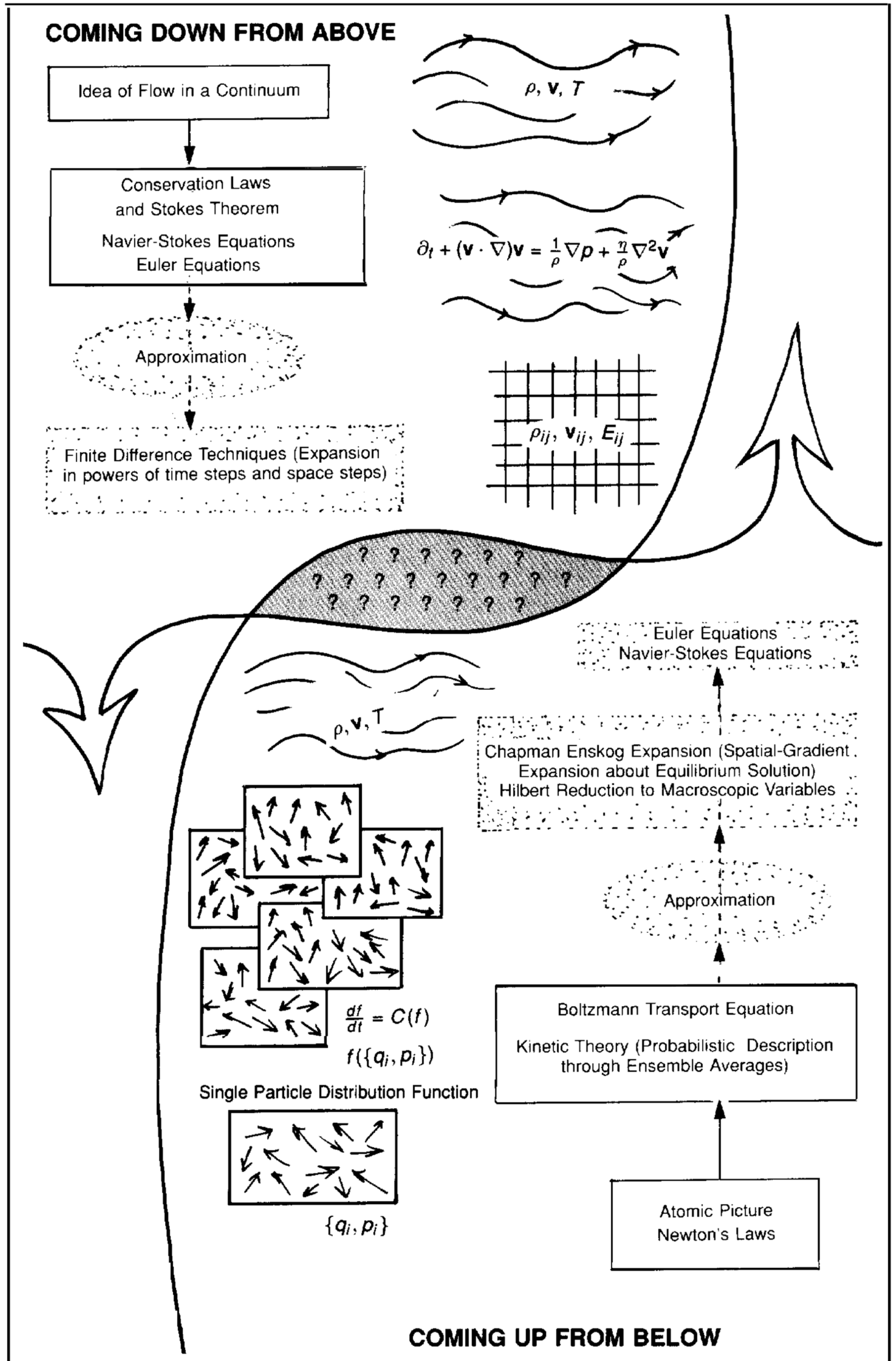
- Do the statistical mechanics: Chapman-Enskog expansion gives Boltzmann equation, and the Navier-Stokes equation can be recovered with an anisotropic viscosity depending on lattice geometry and collision rules
- Run as a cellular automaton using bits only
- Or run as local particle distributions



- Images B Hasslacher LosAlamos Science 1987, B Wylie PhD Thesis U Edinburgh 1990



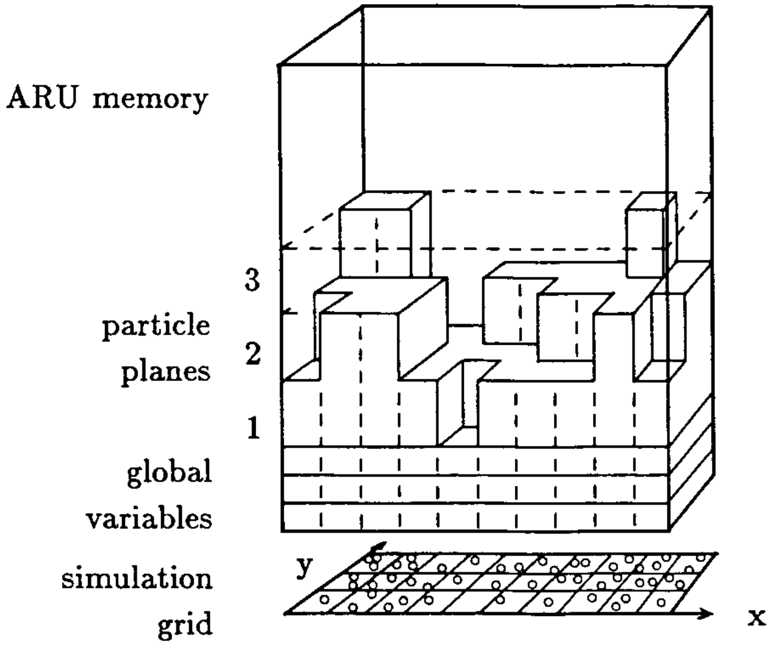
- http://www.ai.mit.edu/projects/im/broch/lat1.html



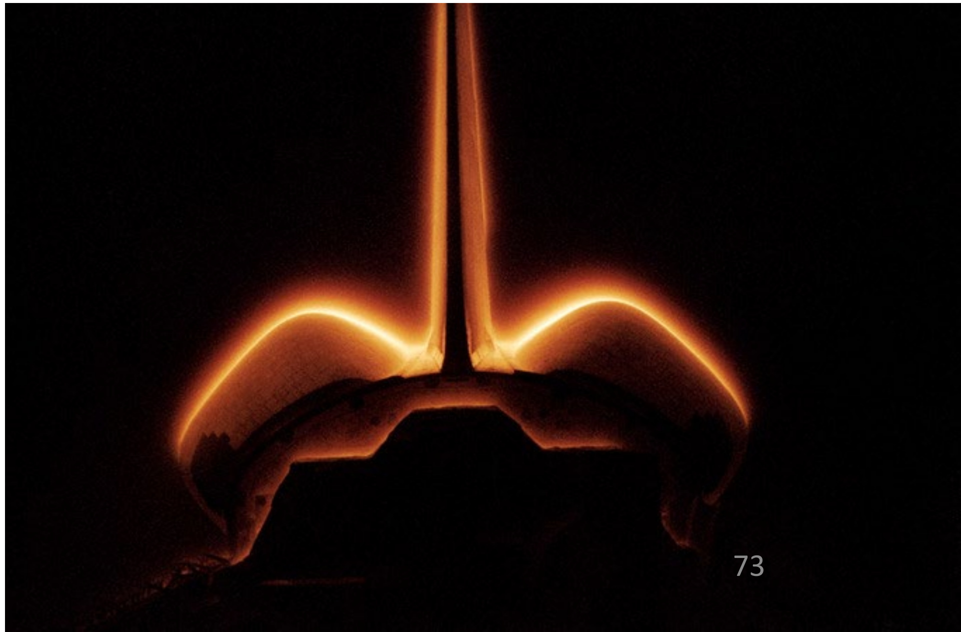
- https://www.osti.gov/servlets/purl/6590163
- Hasslacher Los Alamos Science 1987

Massive parallelism in lockstep

- 1980's Goodyear Massively Parallel Processor
- 16 384 Single-Instruction Multiple Data processors in Mapping particle data to memory
- Space Shuttle glowing on ram surfaces,
- Whistler instability, galaxy evolution
- NASA Ames, MPP, change the particles and fields
- 2D grid of 16 384 (2^{14}) processors in lockstep
- IF by masking



- Gledhill and Storey, Frontiers of Massively Parallel Scientific Computation, p 37-46, NASA Goddard Space Flight Centre, Greenbelt, Maryland, 1986
- https://courses.lumenlearning.com/introchem/chapter/glow-of-space-shuttles/ O+NO→NO_2^*



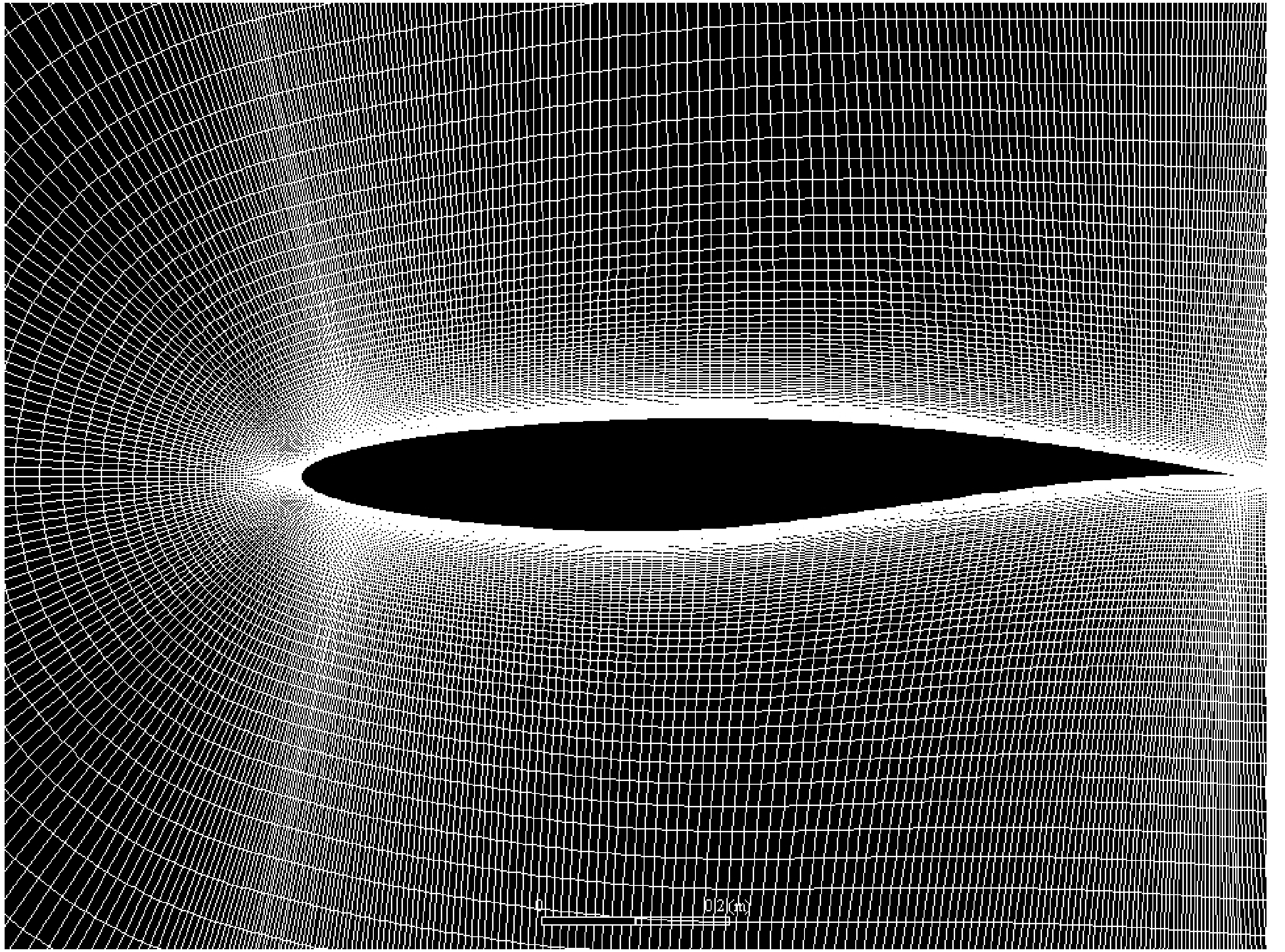
Early aeronautics

- Panel methods: Euler equations, Green’s function method, discretised model
- Panel plus boundary layer: Eppler and Drela for airfoil and wing design
- Subsonic flow reasonably well modelled
- 3D Potential codes: Jameson, Courant Institute, 1977
- Discretisation

CFD and acceleration: shocks

- Airfoil,
- Discrete grid
- Capture boundary layer
- ~ 1 µm transonic!
- Boundary conditions:

  Riemann boundary conditions to prevent reflection of shocks; Must be many typical lengths away



- discretisation grids Cartesian, unstructured, hybrid; multi-grid acceleration, adaptive grids; moving overset grids, adaptive unstructured grids
- Finite difference, finite volume, finite element; boundary element methods
- Transient flow; aeroelastic solid-fluid coupling
- Decades of development of algorithms and grids!
- At shocks: Gibbs phenomenon - overshoot and oscillation, or undershoot and smoothing; limiters and heuristics
- Gridless methods: SPH – Smooth Particle Hydrodynamics

2022

- **Subsonic**: elliptical equations, incompressible, few problems
- **Supersonic**: hyperbolic equations, characteristic solution often useful, few problems

- **Transonic**: critically dependent on small features of geometry and on gridding that captures the flow features “grid the flow, not the geometry”
- Transient cases often run for days “work expands to fill the time available”
- Transonic accelerating flight: now in scope of resources

The Problem

- Predicting Turbulence.
- Direct Navier-Stokes simulation down to the inner turbulence scale has been done
- Formerly a factory for manufacturing PhD theses
- Now: usually run three models in validation phase and choose the most appropriate
- Large Eddy Simulation: expensive, informative

Aerofoils in ground effect at transonic speeds

- Subsonic, M_{crit} reached sooner in ground effect, lift was larger up to shock formation, flowfields sensitive to changes in any variable; shock on lower surface destablised pitch - dangerous

- Transonic speeds

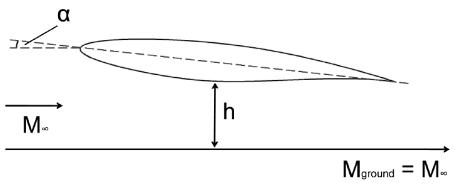


Figure 2. Parameters for an aerofoil in ground effect.

- Doig *et al.,* The Aeronautical Journal, **116**, 407, 2012
- Keogh *et al.*, J. Wind Eng. Ind. Aerodyn. **154** 34, 2016

Figure 1. A US Navy Blue Angel demonstration aircraft during a Mach 0·95 pass, highlighting shock/surface interaction (with permission: Matt Niesen).

Destabilising shock in Ground effect

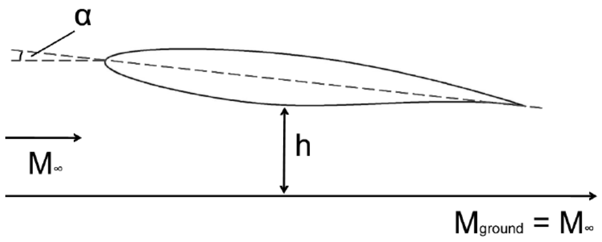
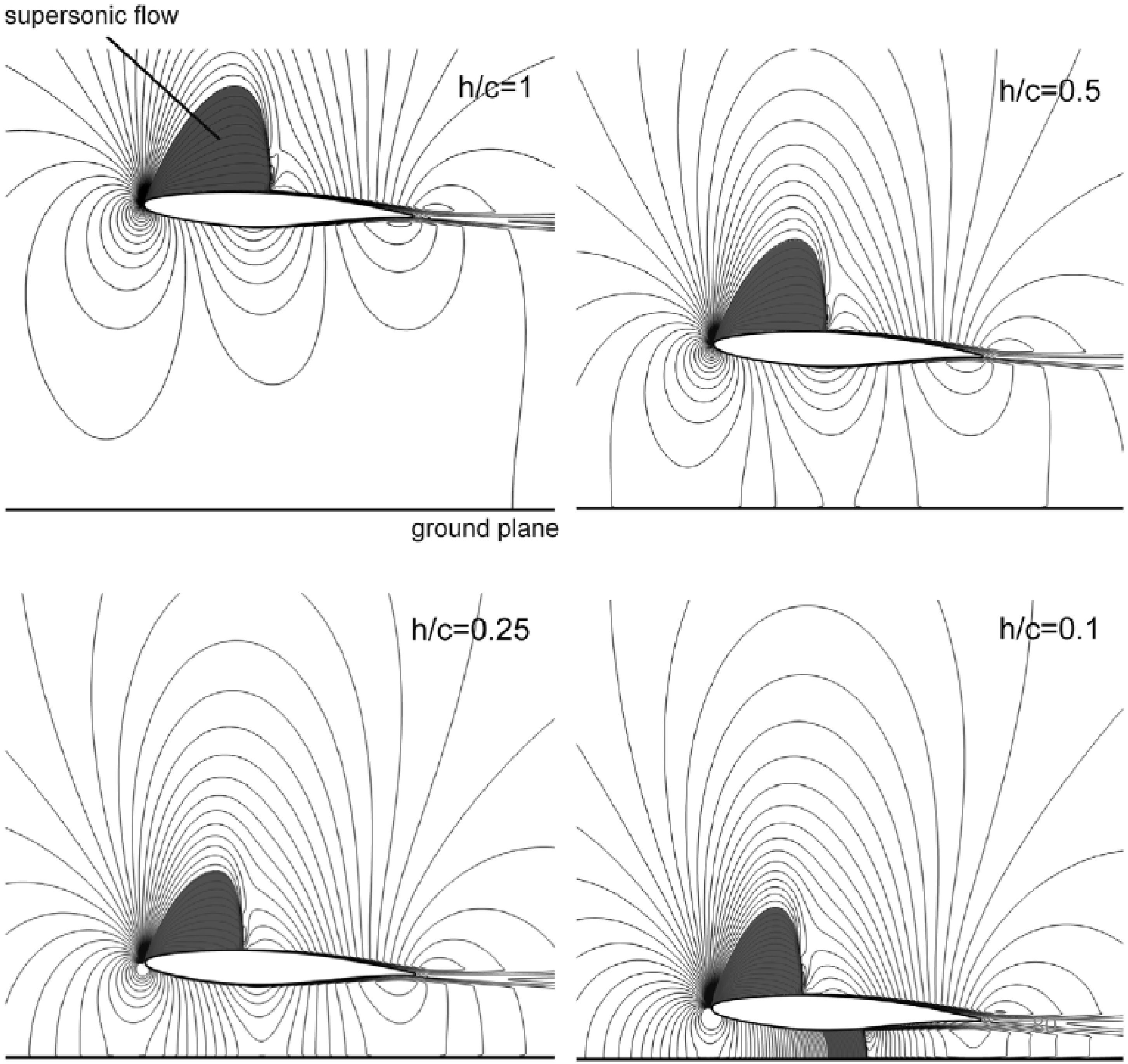


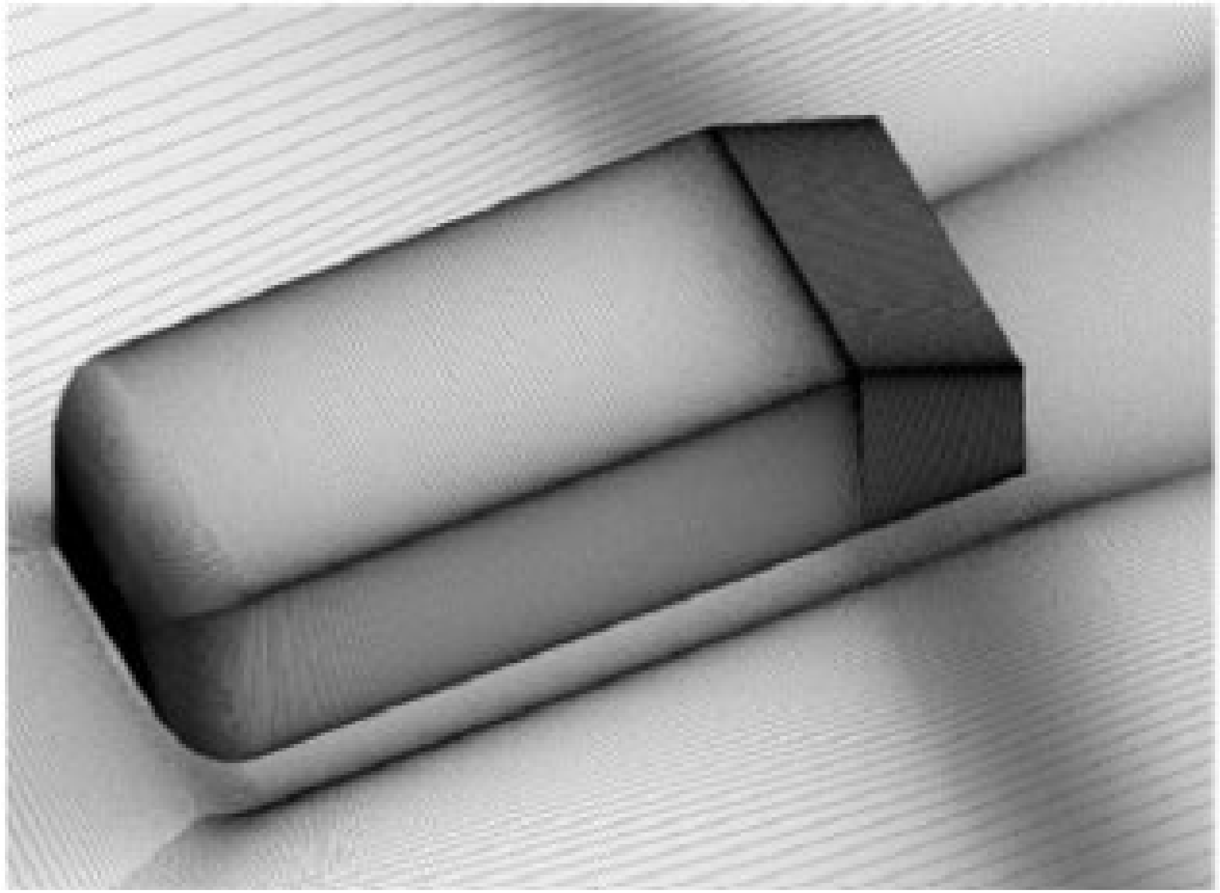
Figure 2. Parameters for an aerofoil in ground effect.

- Doig *et al.,* The Aeronautical Journal, **116**, 407, 2(
- Keogh *et al.*, J. Wind Eng. Ind. Aerodyn. **154** 34, 2



Back to simulation of flight at low altitude

- Ahmed body: standard vehicle
- Turns and aerodynamic effect on stability
- Large Eddy Simulation
- Experimental data existed for validation



- Keogh *et al.*, J. Wind Eng. Ind. Aerodyn. **154** 34, 2016

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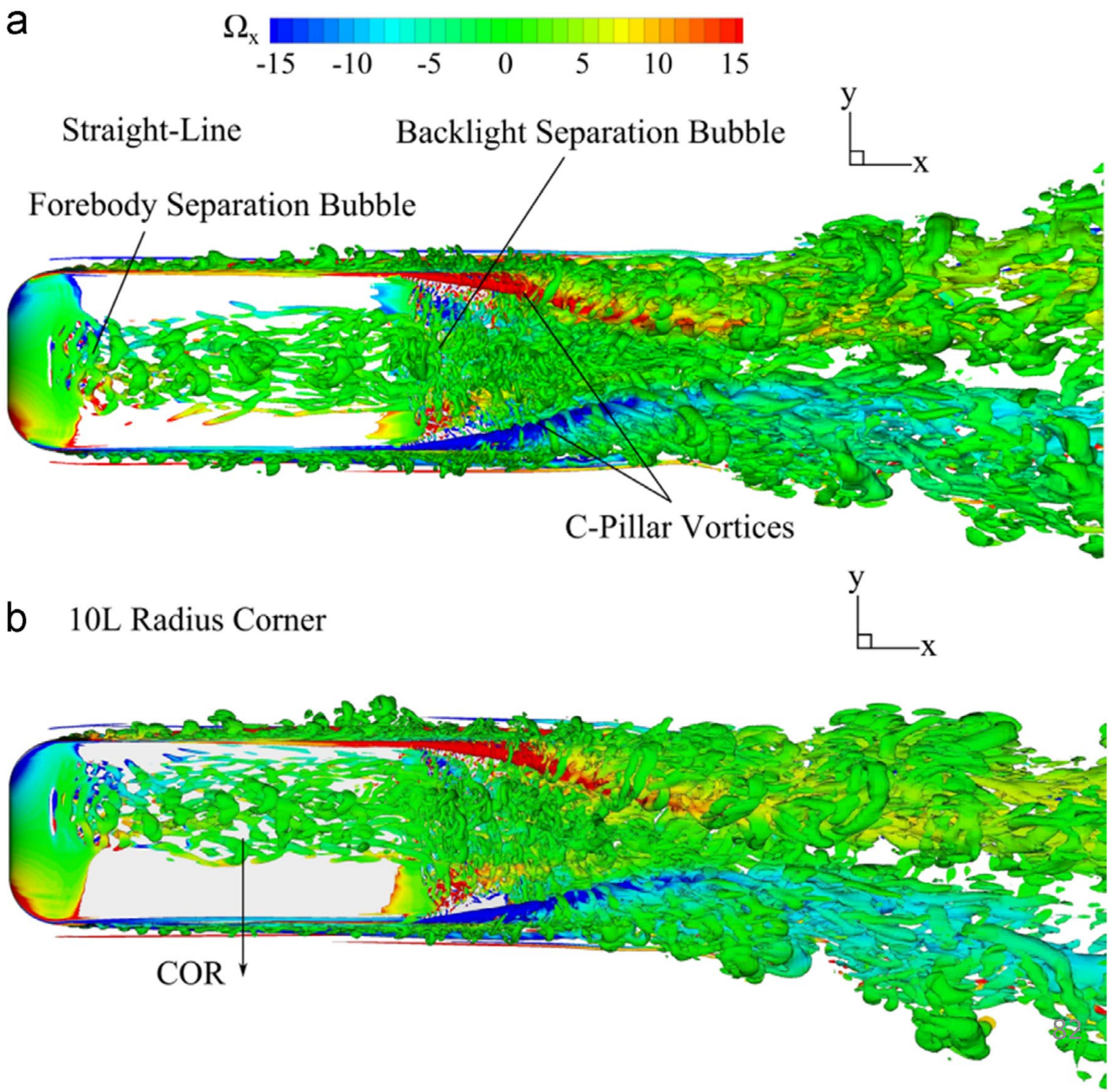


- Keogh *et al.*, J. Wind Eng. Ind. Aerodyn. **154** 34, 2016

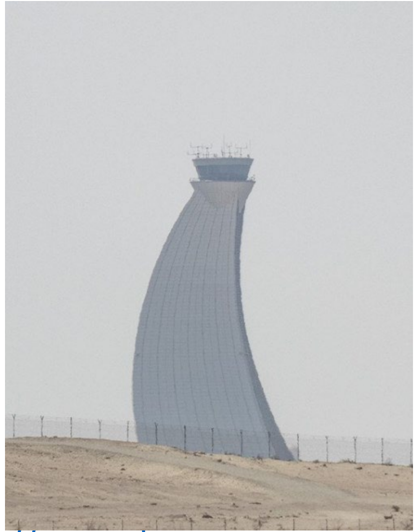
$$\Sigma'$$

Absolute frame

Inertial frame

- Fly the aircraft grid through an inertial frame
- For each point on the grid, $x(t)$
- Boundaries: $v=0$

$$\Sigma$$



Relative frame

Non-inertial frame

- Add all the source terms
- Include acceleration of fluid in every fluid element
- Boundaries: flow accelerated

https://www.skyscrapercenter.com/building/abu-dhabi-international-airport-air-traffic-control-tower/30422; https://unsplash.com/s/photos/aircraft

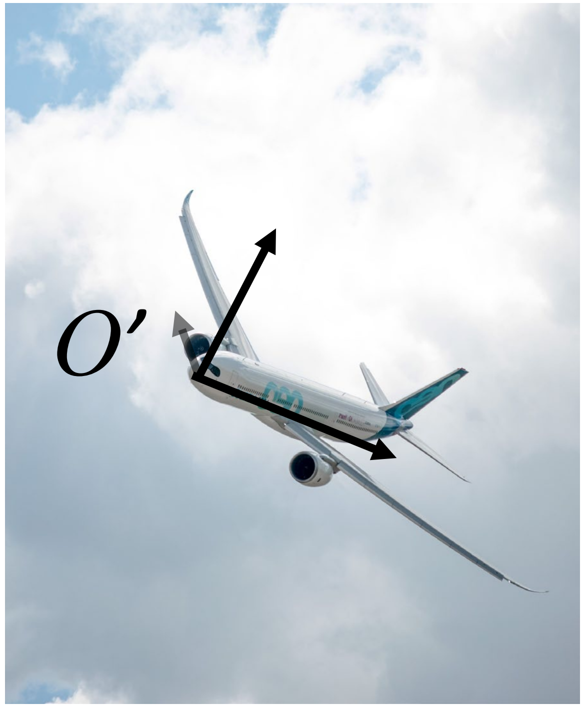
Σ'

Absolute frame

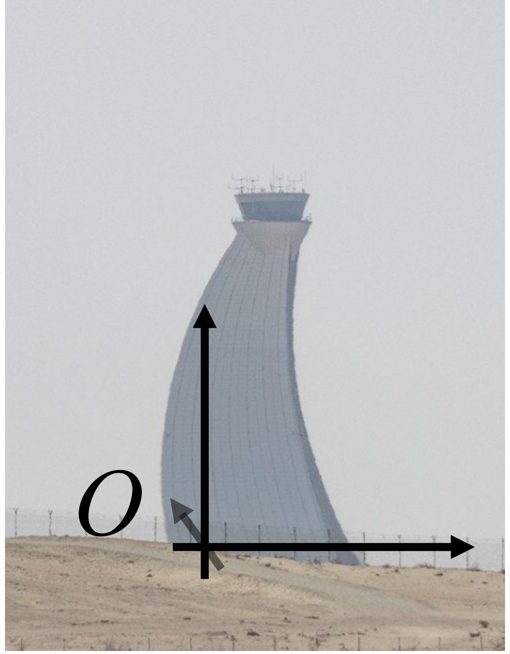
Inertial frame

Relative frame

Non-inertial frame



Σ



https://www.skyscrapercenter.com/building/abu-dhabi-international-airport-air-traffic-control-tower/30422;
https://unsplash.com/s/photos/aircraft

Vectors in Σ'

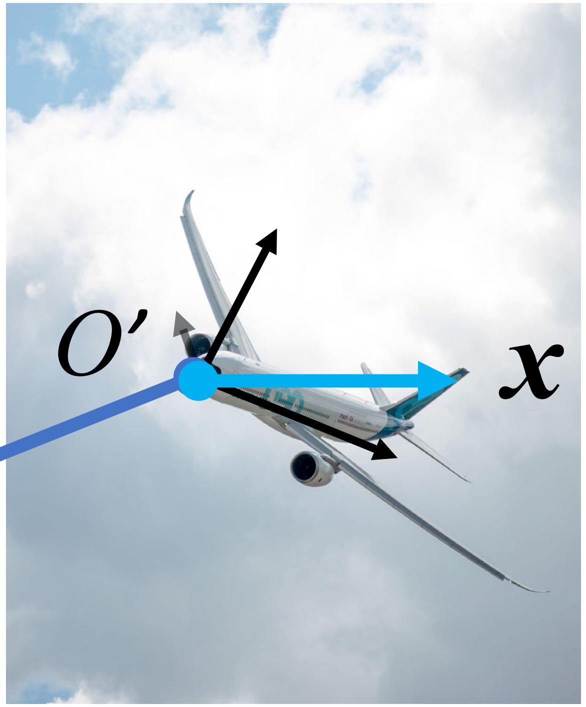
Absolute frame

Inertial frame

Relative frame

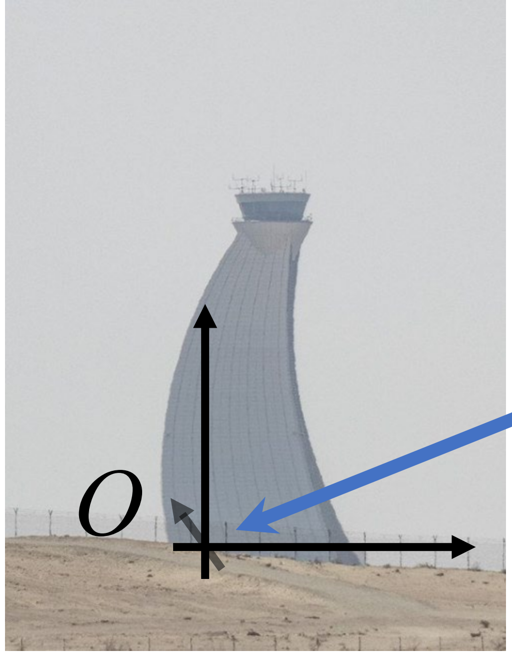
Non-inertial frame

Σ'



$\boldsymbol{r}(t)$

Σ



https://www.skyscrapercenter.com/building/abu-dhabi-international-airport-air-traffic-control-tower/30422; https://unsplash.com/s/photos/aircraft

Vectors in Σ'

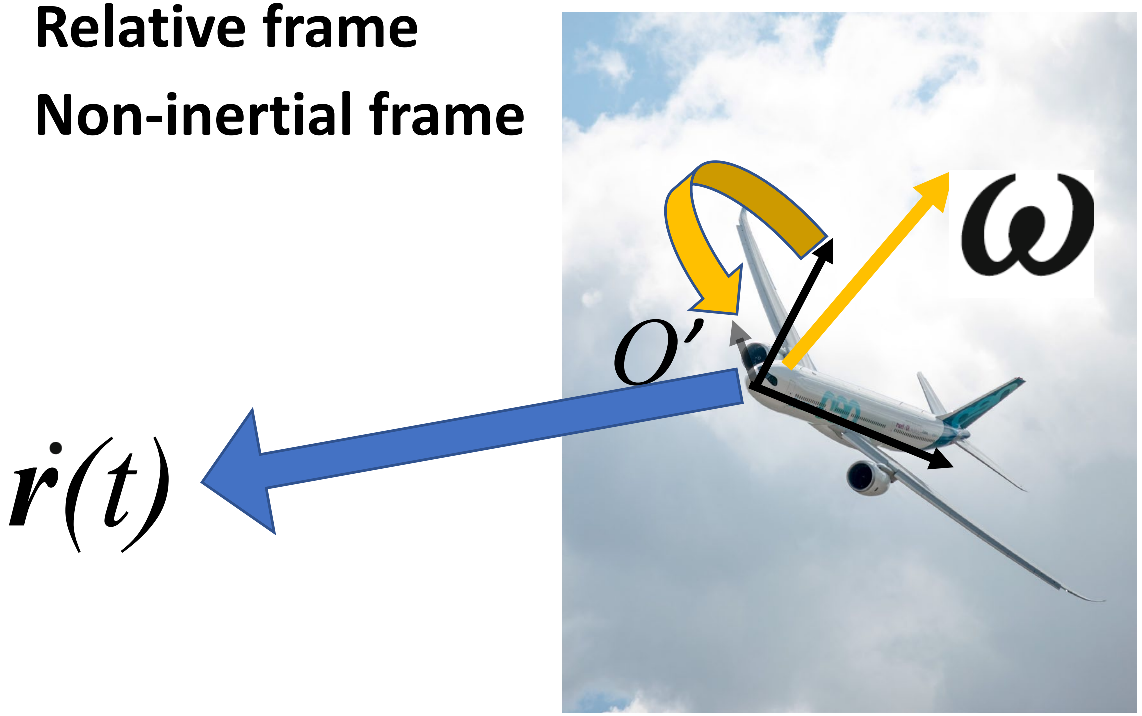
Σ'

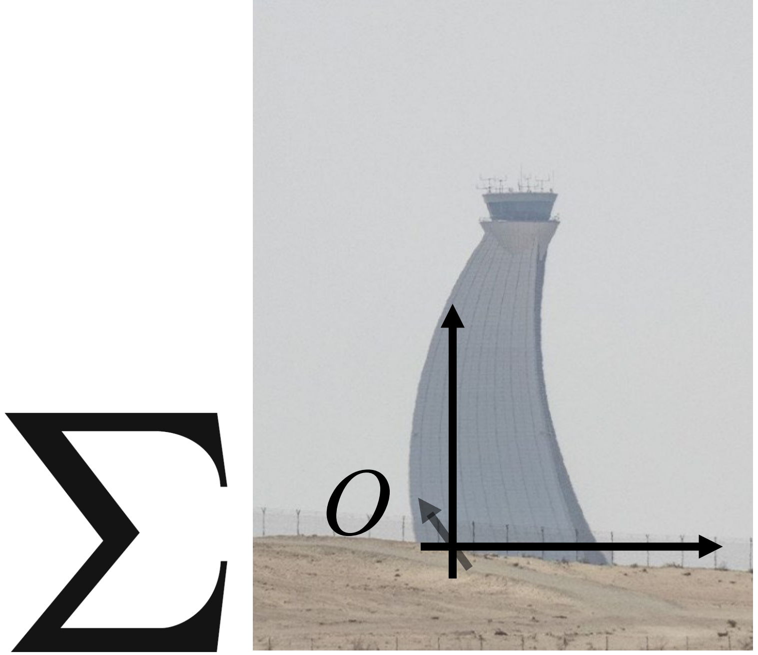
Absolute frame

Inertial frame

Relative frame

Non-inertial frame





- Interframe velocity $\boldsymbol{u}$

https://www.skyscrapercenter.com/building/abu-dhabi-international-airport-air-traffic-control-tower/30422; https://unsplash.com/s/photos/aircraft

Vectors in Σ'

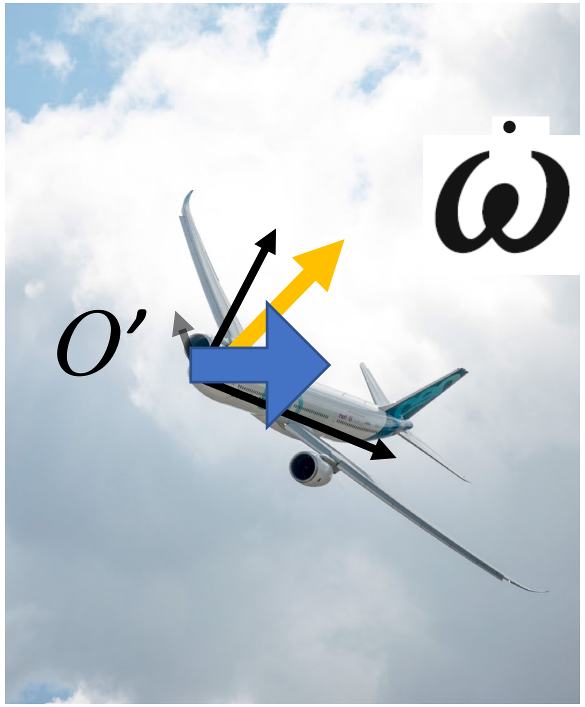
Σ'

Absolute frame

Inertial frame

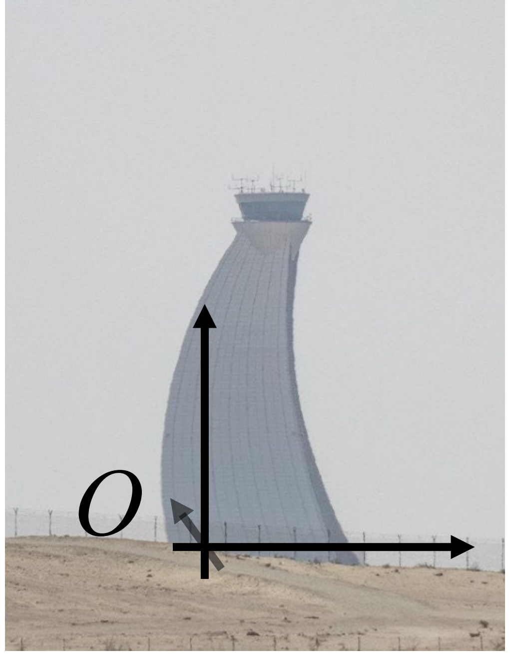
Relative frame

Non-inertial frame



$\ddot{r}$

Σ



- Interframe velocity

https://www.skyscrapercenter.com/building/abu-dhabi-international-airport-air-traffic-control-tower/30422; https://unsplash.com/s/photos/aircraft

Invariants under transform

- Density
- Pressure
- Temperature
- Position, velocity, acceleration are transformed

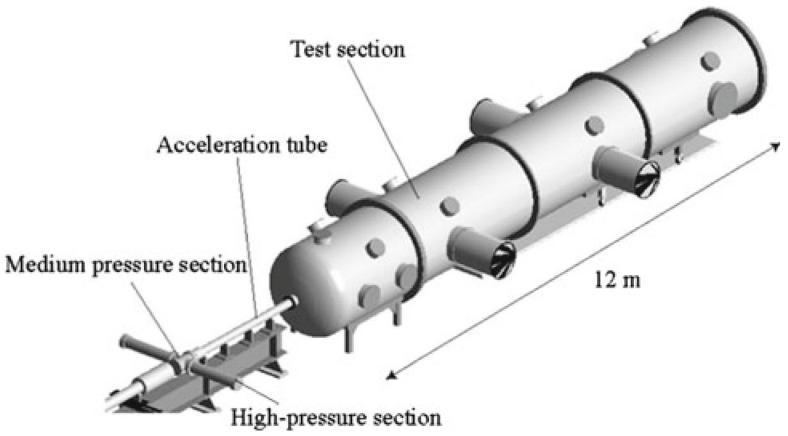
The search for validation data

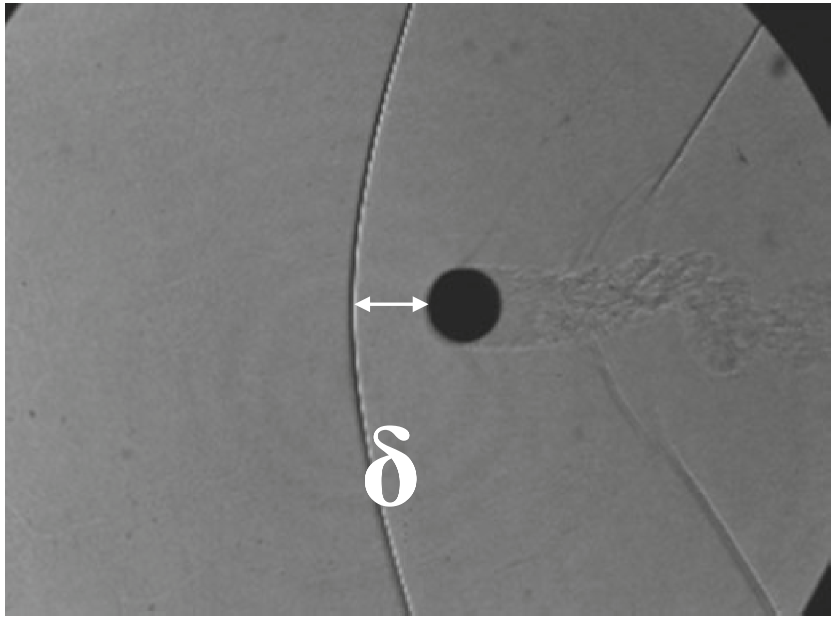
- Wind tunnel data can only support steady flight
- Ballistic range
- Rocket range
- Land Speed record

Ballistic range puzzle: shocks in subsonic flow?

- Free flight
- Ballistic range: spheres travel at M ≈1

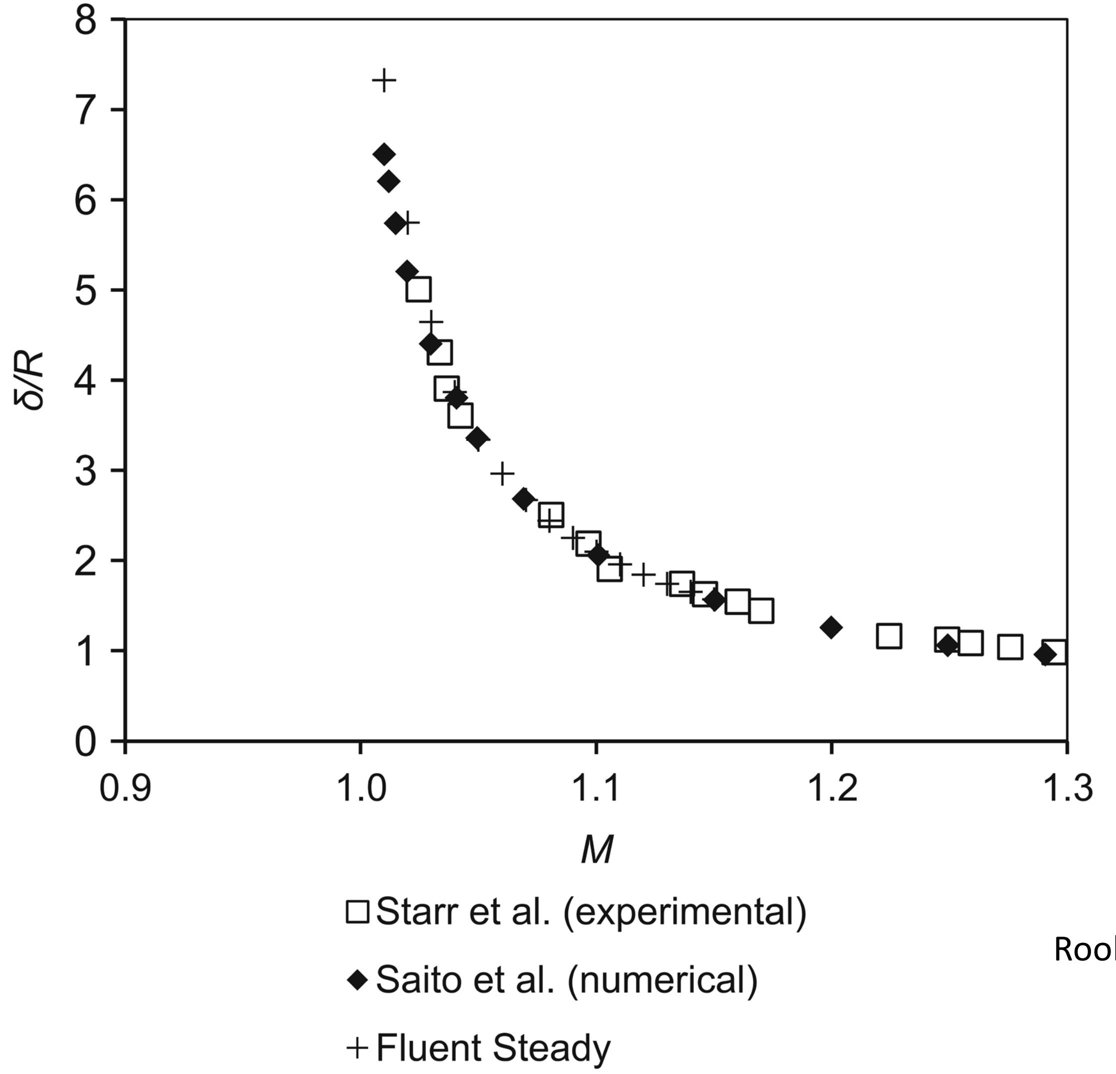
- High speed camera: frame rate 125 000 s-1 exposure 1 μs
- The shock standoff distance **δ** is unexpectedly large





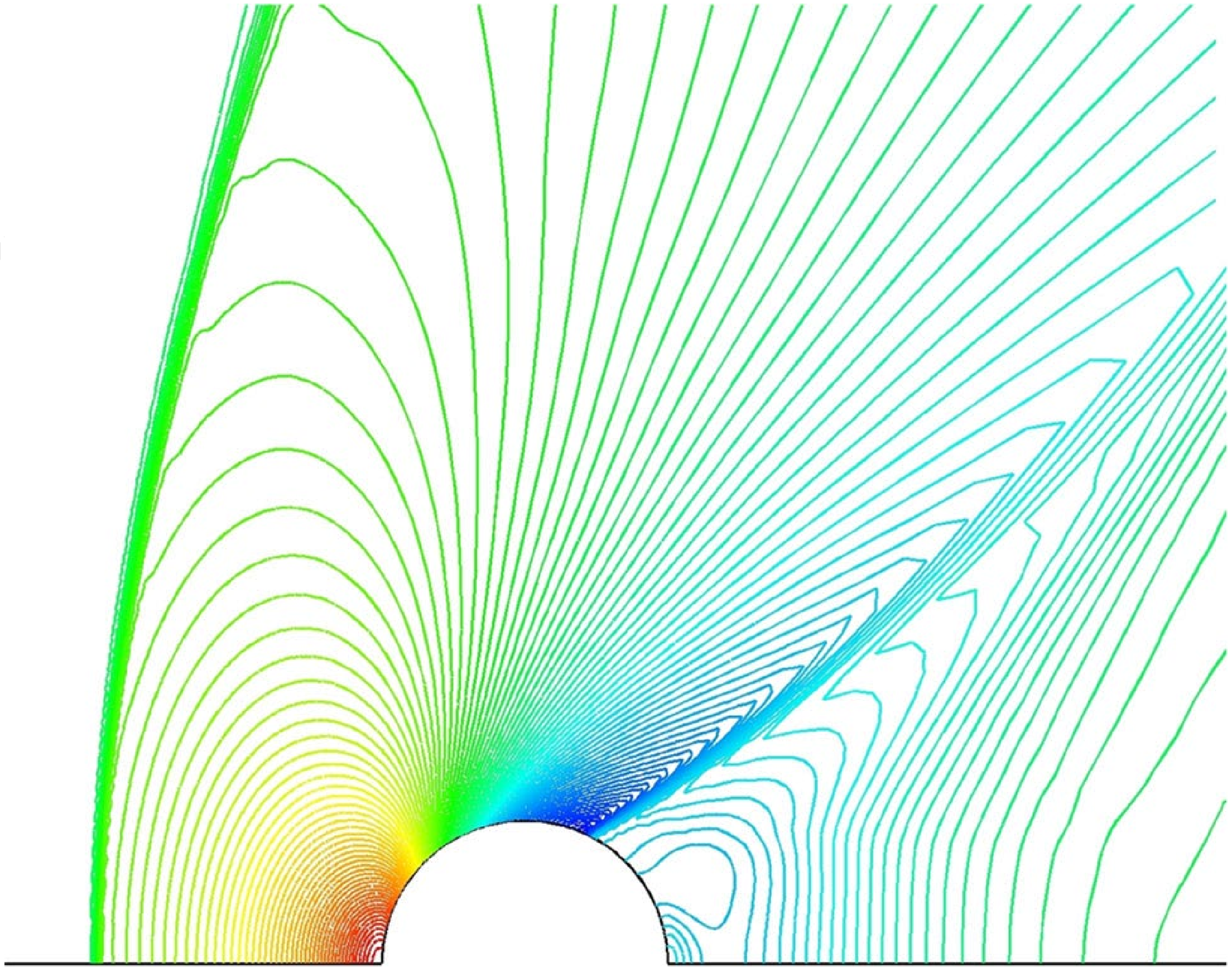
Saito *et al.,* Shock Waves, **21** 483 2011

Steady sphere velocity validation



Roohani *et al*. Sock Waves **30,** 115, 2020

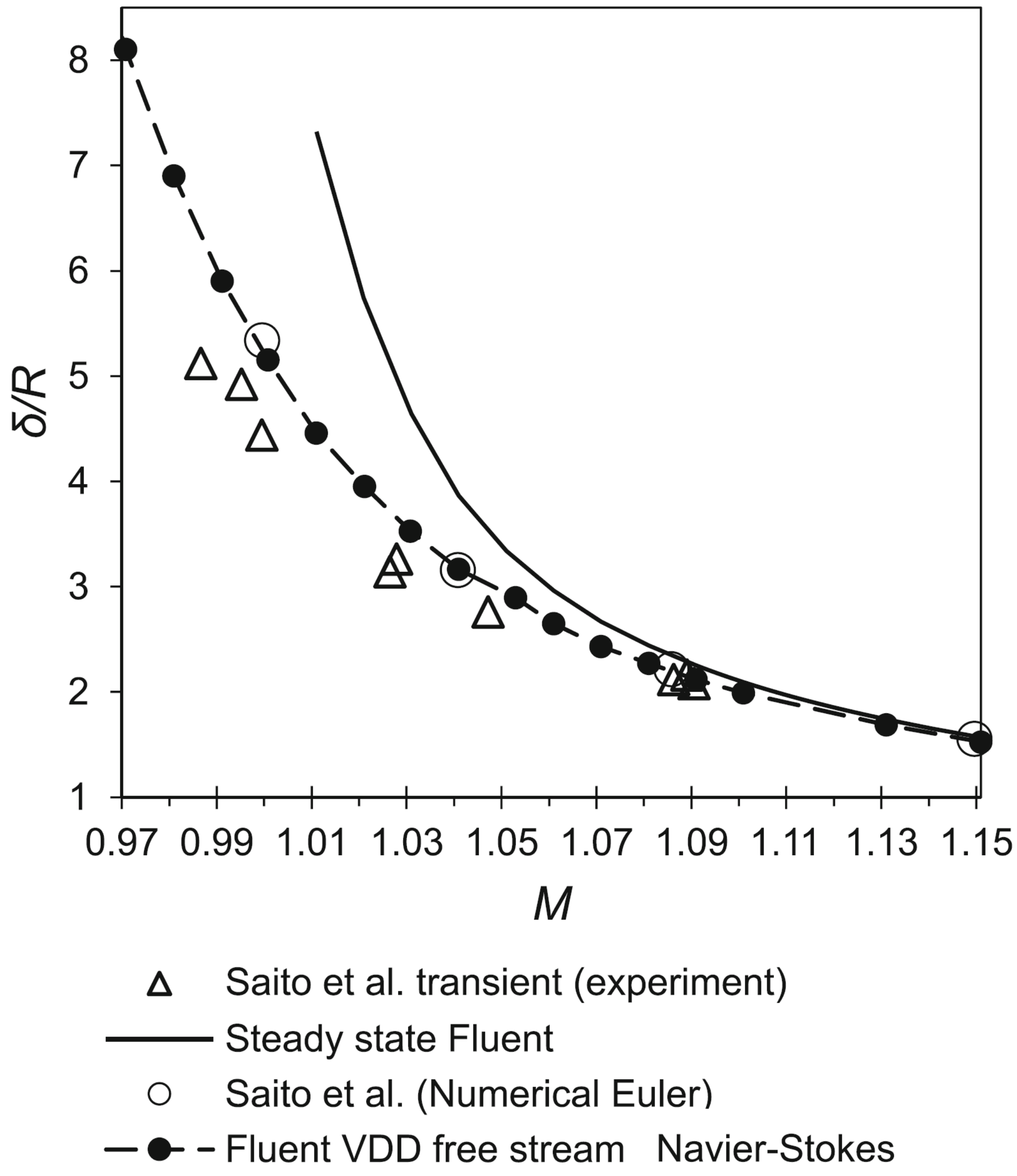
- Contours of static pressure in Pa a Mach number 1.10 while
- Simulated in relative frame with source term
- decelerating from *M*0 = 1.25 with velocity-dependent drag



- Roohani *et al.,* Shock Waves **30**, 115, 2020

Velocity dependent drag

- Validation of method
- In constant velocity sphere cases, no shocks exist below M = 1
- But there are clear shocks in the subsonic case in CFD and the experiment



Roohani *et al*. Sock Waves **30,** 115, 2020

Airfoil case

- Left: steady flight at
- Right: deceleration

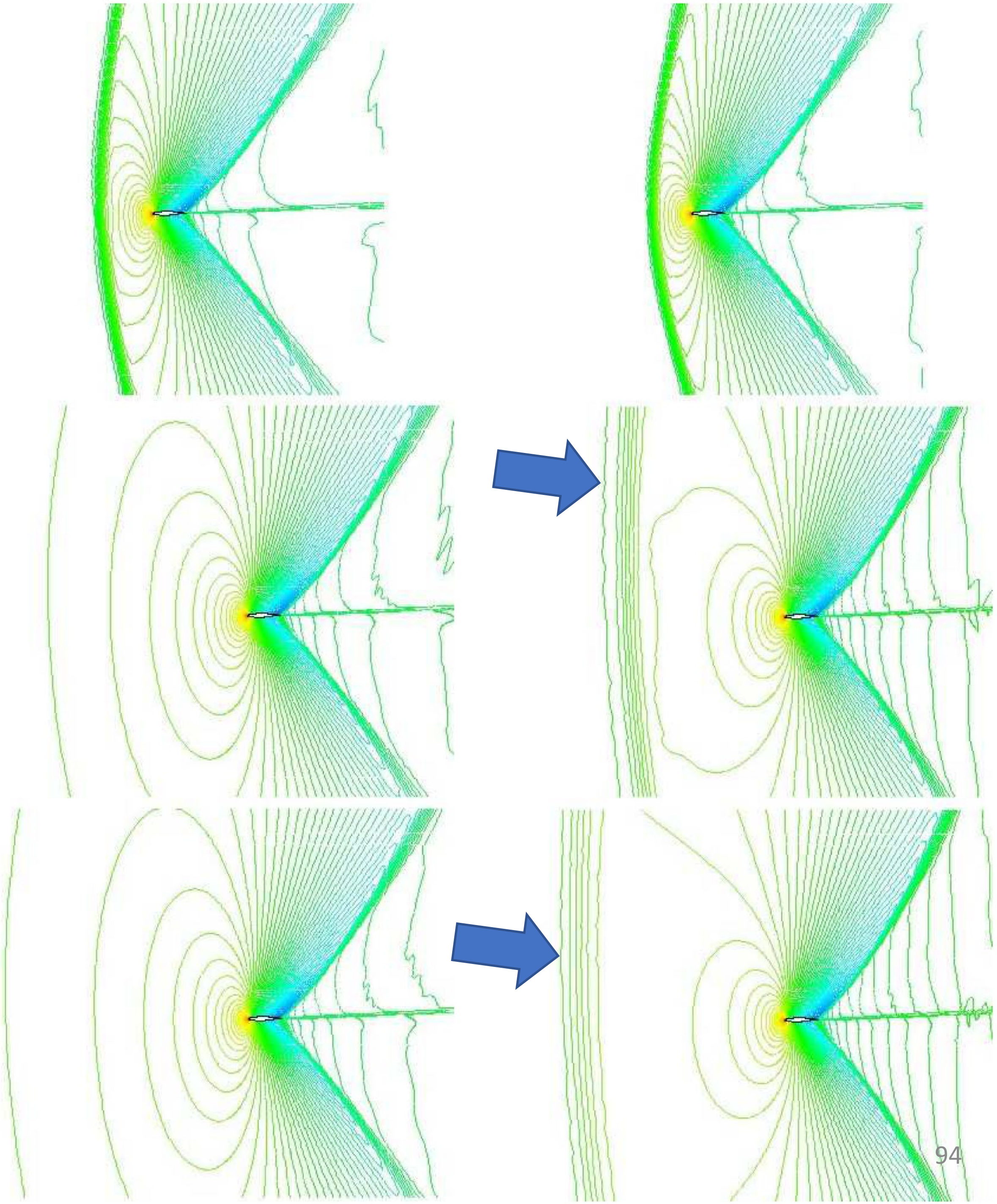
$\ddot{r}$ = -86.77 ms^{-1}

M = 1.10, 1.00, 0.98

M = 1.10

M = 1.00

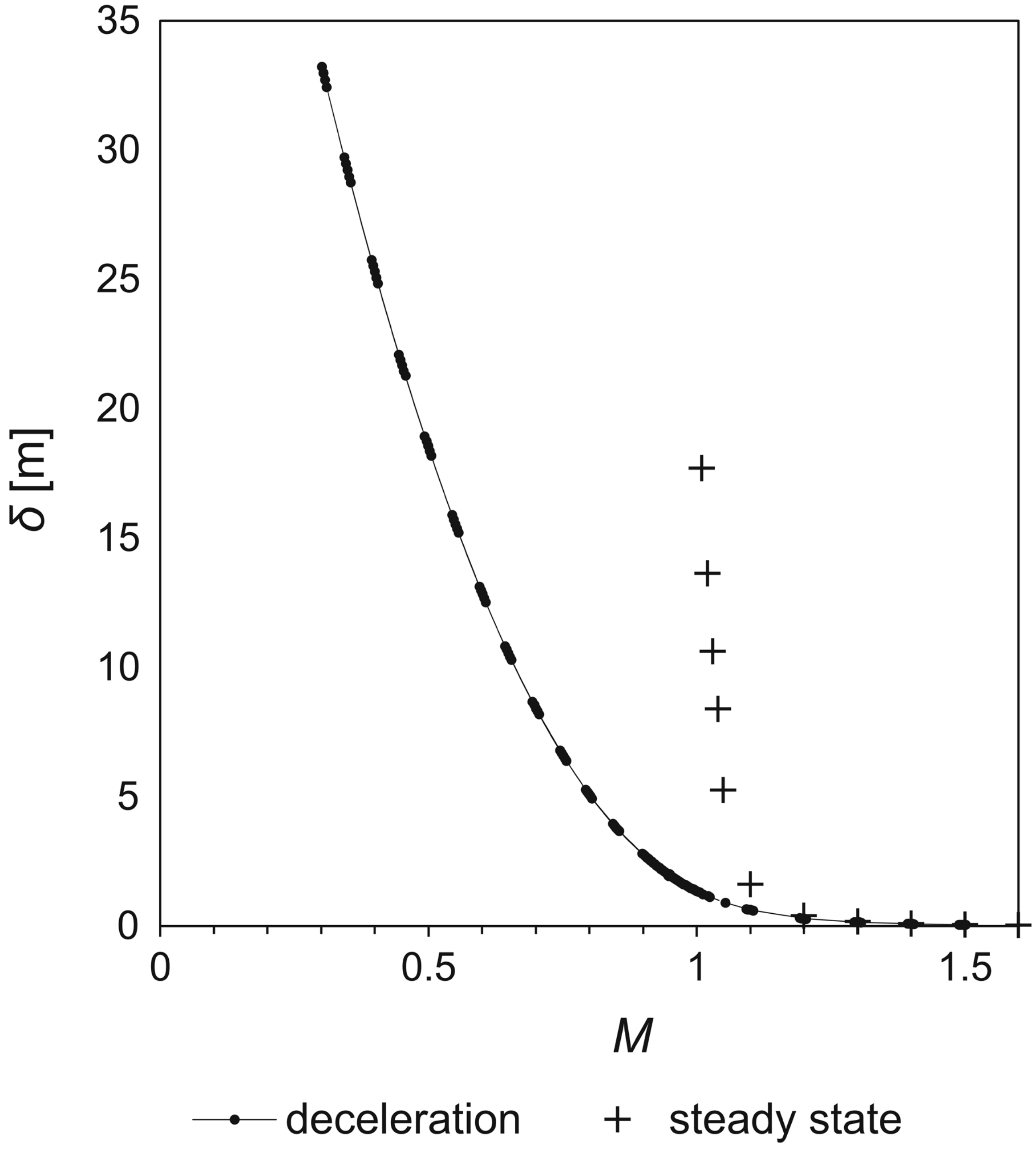
M = 0.98



Roohani and Skews, *27th Int. Symp. on Shock Waves,* 2008.

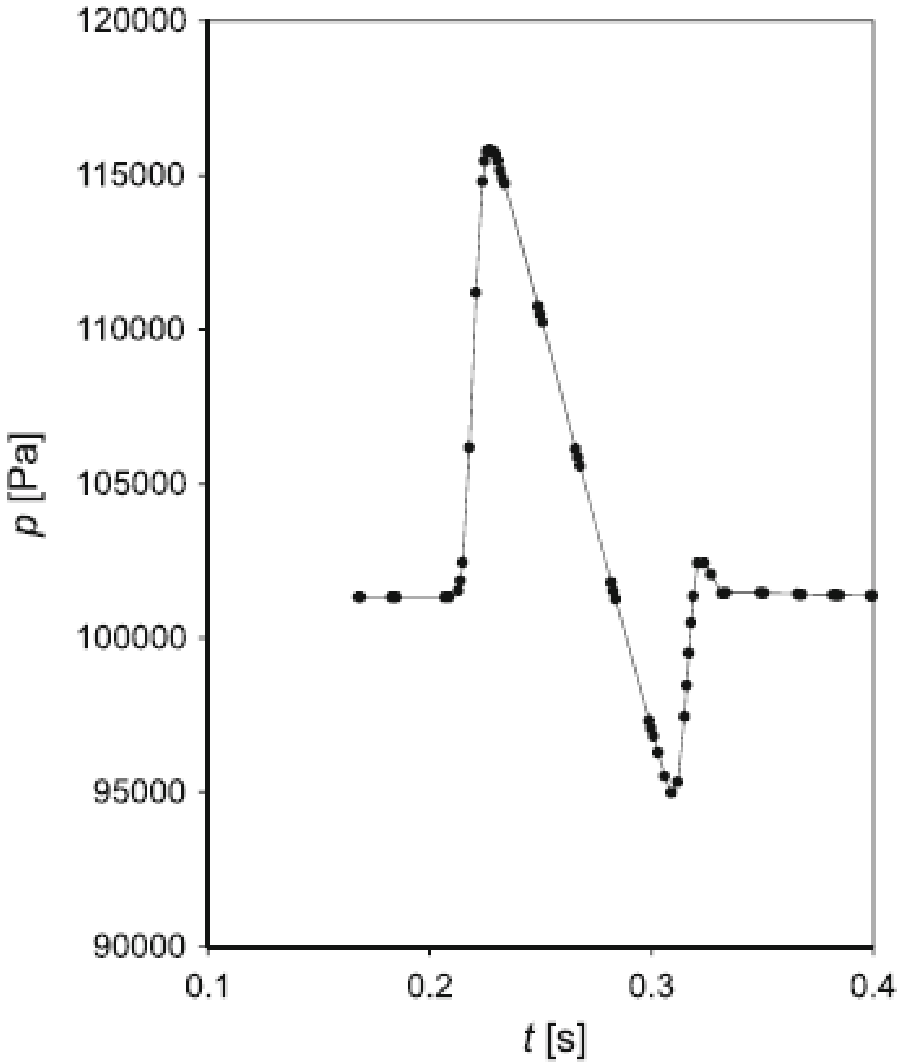
Controversy

- Detached shocks exist for drag deceleration for M<1, down to below M ~ 0.6, airfoil (RAE2822 profile)
- Shock propagating at M~1, sphere at M<1
- Classic example of flow history and entrenched thinking
  - Roohani *et al.*, Shock Waves **30** 115 2020



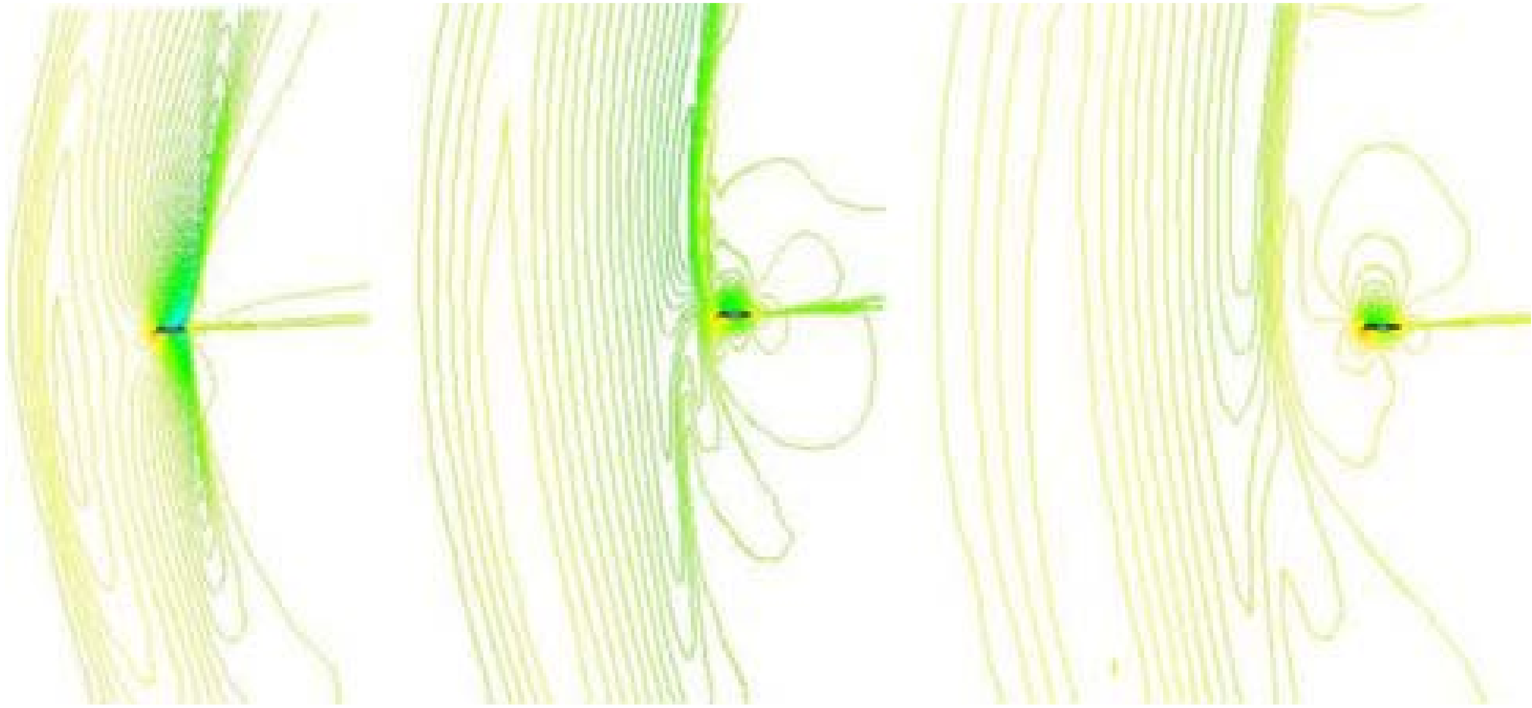
Controversy

- Turns out to be equivalent to blast wave behaviour



- Roohani *et al.*, Shock Waves **30** 115 2020

Shocks overtake the airfoil



M = 0.82 M = 0.70 M = 0.64

- Deceleration of −1,041ms^{-2}
- density contour plots
  - Roohani and Skews, Shock Waves **19** 297 2009

Shocks overtake the airfoil

Image https://www.ironman4x4.com/blog-posts/keeping-dust-out-of-your-4x4/

Supersonic Cars: Bloodhound LSR – Land Speed Record



- up to 3g of acceleration and -4g of deceleration
- flow physics of accelerating and decelerating subsonic, transonic and supersonic flow at ground level
  - Acknowledgements B.J. Evans
  - https://axleaddict.com/cars/Thrust-SSC-More-than-1000-kmph-Car
  - https://24htech.asia/?#thrust-ssc-is-so-fast-it-creates-sonic-booms-s80144.html

Supersonic Cars: Bloodhound LSR – Land Speed Record



- Thrust SSC: 763mph (1,227km/h) 1997 Black Rock Desert, Nevada, USA
- RAF Pilot Andy Green
- Bloodhound target: new record; 800 mph
  - Acknowledgements B.J. Evans
  - https://axleaddict.com/cars/Thrust-SSC-More-than-1000-kmph-Car
  - https://24htech.asia/?#thrust-ssc-is-so-fast-it-creates-sonic-booms-s80144.html

Haksteenpan

- Found by searching on google earth for flattest large area with suitable surface and access

Bloodhound SSC

- Tyre check at Technical Centre, Bristol. UK, 2016
- A high-speed collaboration
- On hold: COVD-19
- funding

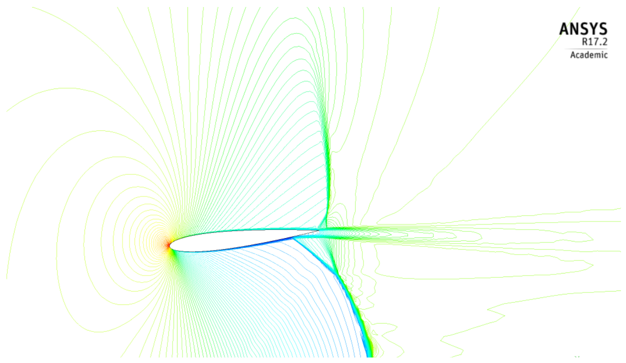
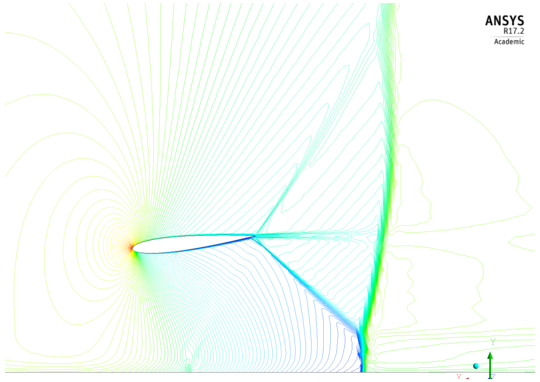
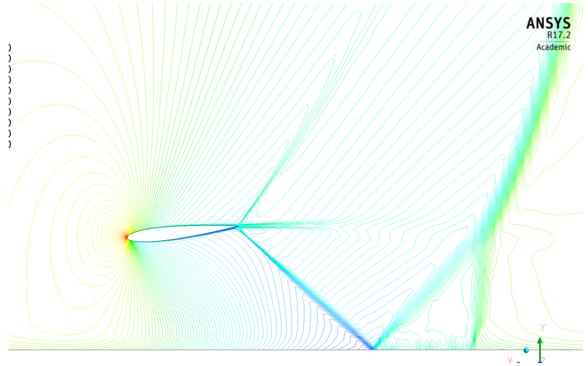
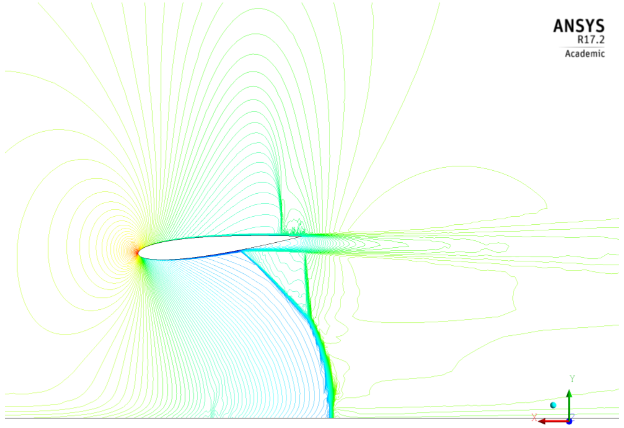
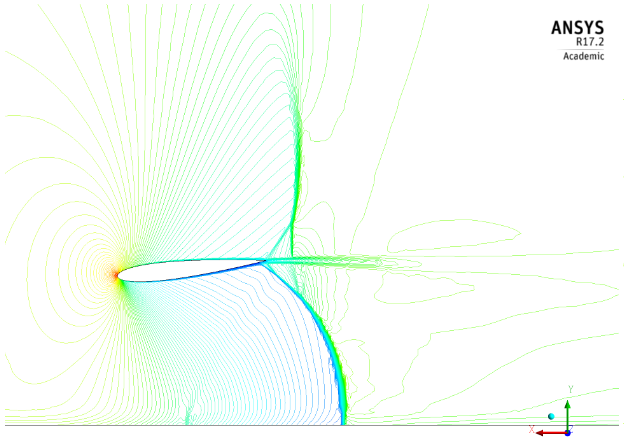
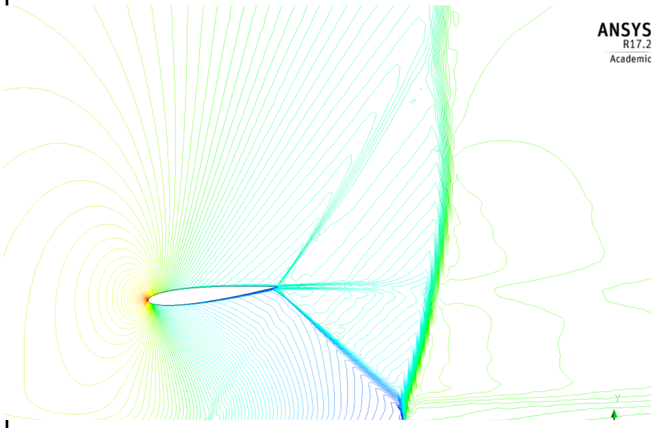
Image: author

critical items

- Wheel contact with ground
- Airbrakes and parachute
- Dust drag – the car takes an estimated 3 tons of dust with it (added mass!)

- Gust sensitivity
- Shocks under the car: dangerous pitching
- Anomalies in rocket sled testing
- Validation data!

Aerofoil in ground effect with shocks at transonic speeds – with linear acceleration

Mach number	**0.85**	**0.90**	**0.95**
Steady velocity			
Acceleratin g: 175 g			

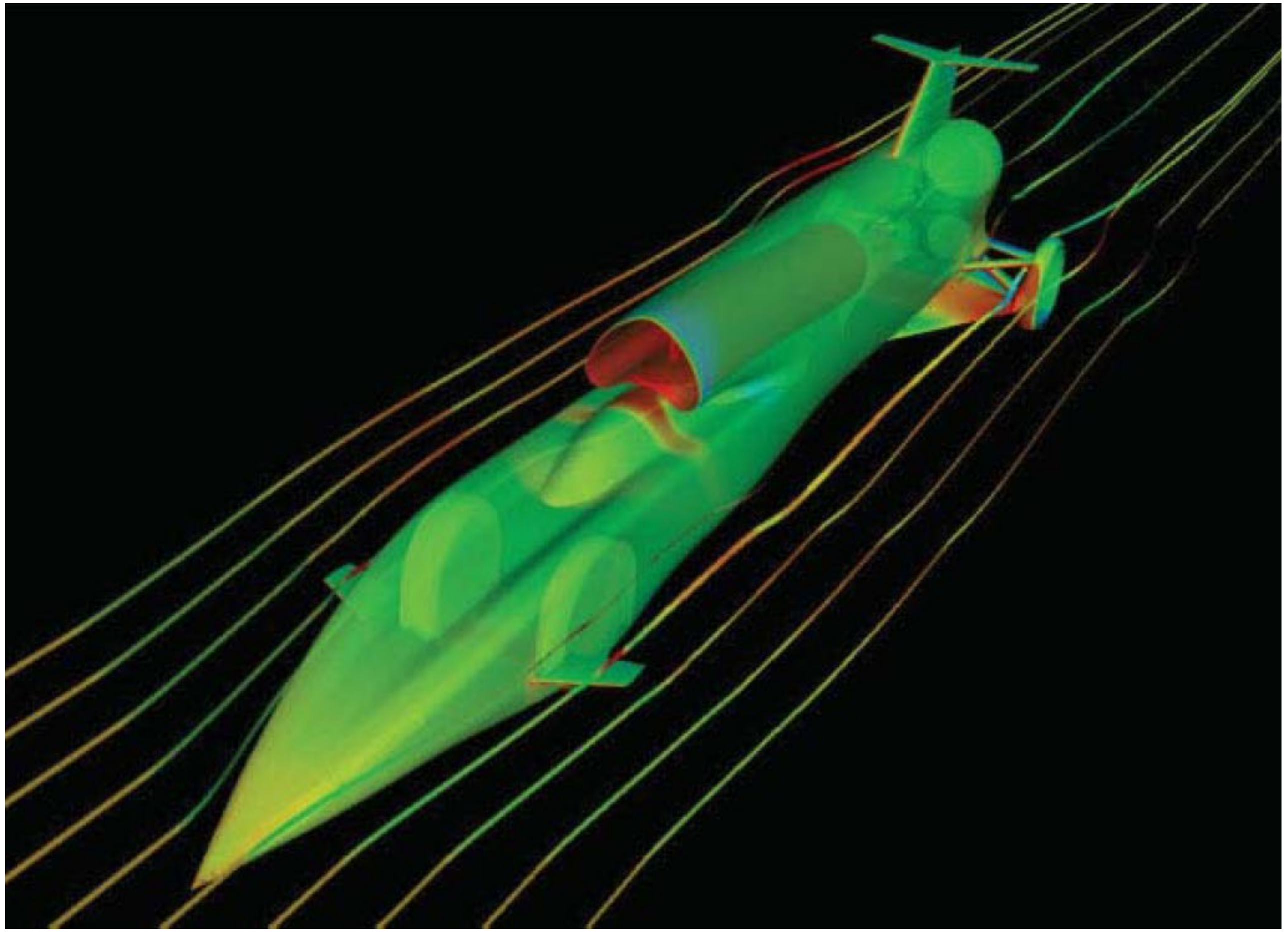
Morrow *et al.,* 23rd International Shock Interaction Symposium9 - 13 July 2018

Pressure distribution (surface) and streamlines (velocity colours)

In-house finite volume code,

HLLC convective flux function and the Spalart– Allmaras turbulence model, on unstructured hybrid meshes

Evans *et al.,* Numerical Methods for Partial Differential Equations **27** 141 2011



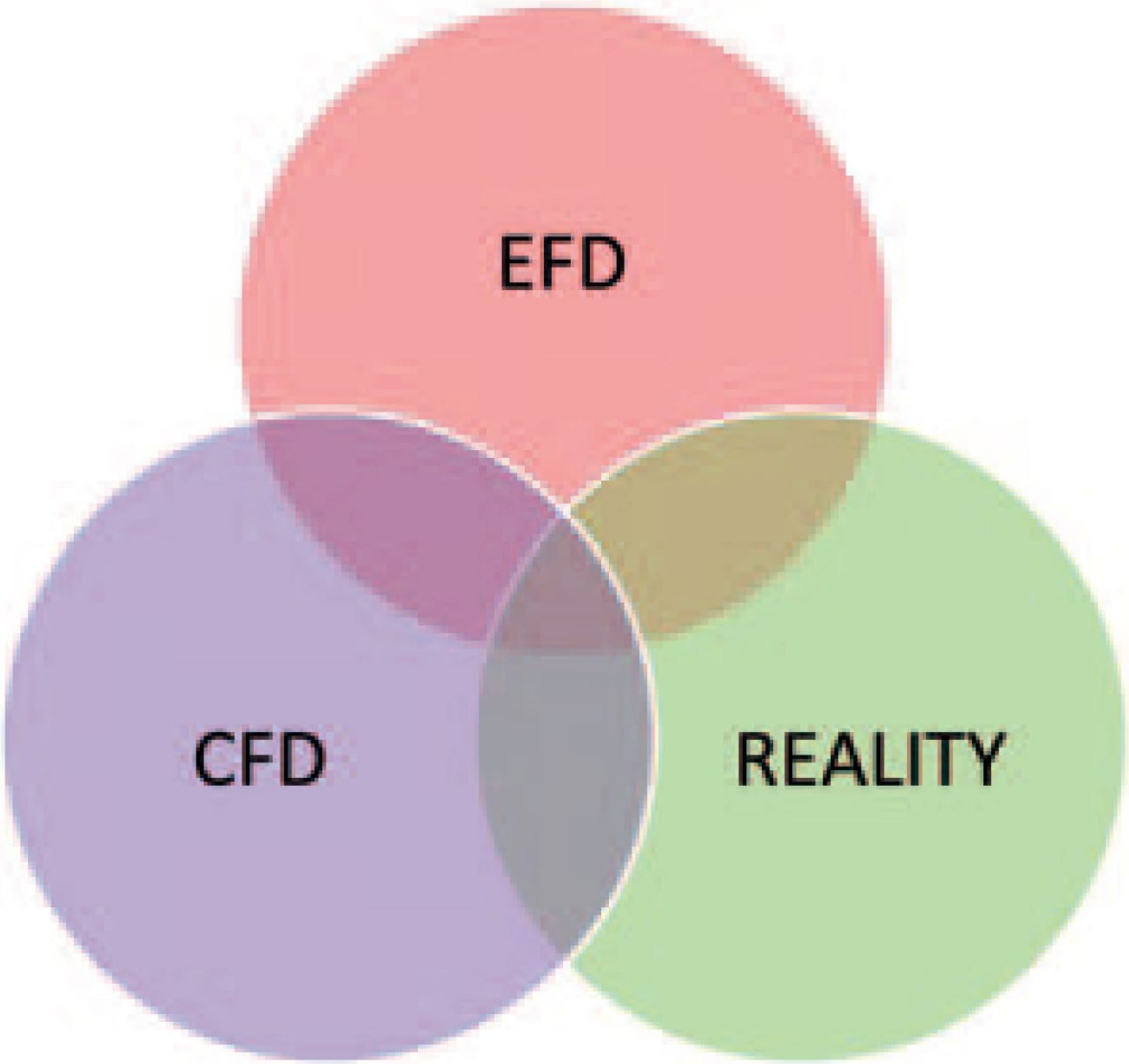
- Jet: Rolls Royce EJ200 jet engine from the Eurofighter Typhoon jet fighter
- Wheel design: solid, inspired by boat hull

- 2017
- 628mph (1010km/h)
- Data for validating CFD models (Swansea University)
- Needs a rocket fitted for next trial
- Designed to pursue the 1,000mph (1,609km/h) record M ~ 1.4
- Constraint: all wheels must maintain contact with the ground

https://www.bloodhoundlsr.com/

Next!

- CFD
- Aviation
  - the constraint is passenger movement on the ground, not the aerodynamics
  - Pandemic(s) and Climate Change are certainly affecting travel and collaboration
  - AI? Software and pilots have a controversy
  - Increasing manoeuvre for aircraft and drones
- Computing and CFD
  - Models expand, multi-physics
  - Quantum computing?? Enable Boltzmann models; classical CFD is deterministic and compute-hungry
  - Keep an open mind, but don’t let you brains drop out



• Barber *et al.*, J. Aeronautical Engineering **226** 602 (2012)

Acknowledgements

- **Sweden**: U. Uppsala Jan Nordström, FFA Karl Forsberg, Peter Eliasson, Ola Hamner
- **Japan**: Muroran Inst. Tech: Prof. T. Saito, Nagoya University: Prof. Akihiro Sasoh, Yuki Yamashita
- **UK**: Swansea U.: Ben Evans
- **South Africa**: U. Witwatersrand: Beric Skews, Hamed Roohani, Sean Morrow, Irshaad Mahomed