AE-705: Introduction to Flight

Bernoulli, Coandă & Mach

Three Giants of Fluid Mechanics

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VIT Vellore

WHO WAS BERNOULLI ?

"...there is no philosophy which is not founded upon knowledge of phenomena, but to get any profit from this knowledge it is absolutely necessary to be a mathematician."

DANIEL BERNOULLI

Early Life

Source:http://bernoullisprinciple.weebly.com/uploads/6/6/7/8/6678503/1009873.jpeg

Academics

Life in Saint Petersburg

Return to Basel

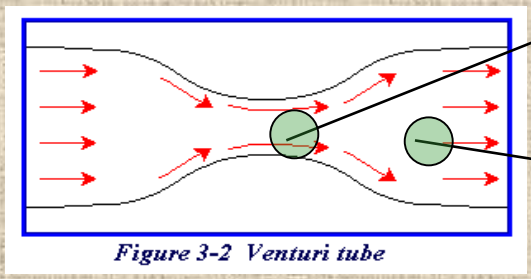
Daniel Bernoulli[1700-1782]

Source:https://static1.squarespace.com/static/530bb0b9e4b0f4676186966d/531fd317e4b0db5158a50c15/531fd317e4b0db5158a50c14/1394405054069/260px-Daniel_Bernoulli_001.jpg

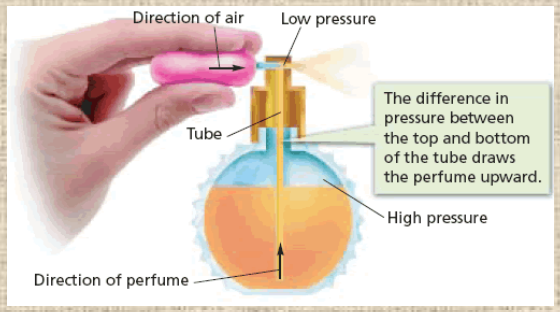
Exercitationes quaedam Mathematicae

Hydrodynamica

BERNOULLI EQUATION

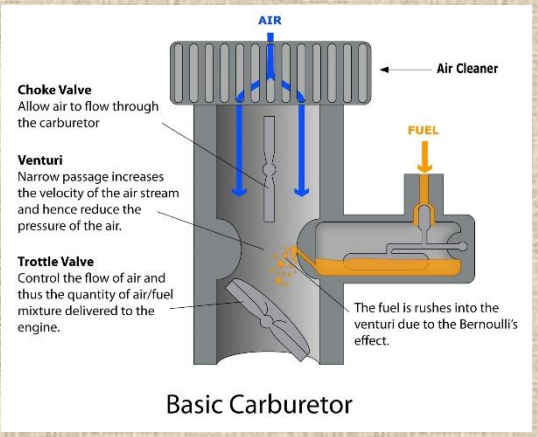


Source: http://www.allstar.fiu.edu/aerojava/images/pic3-2.gif

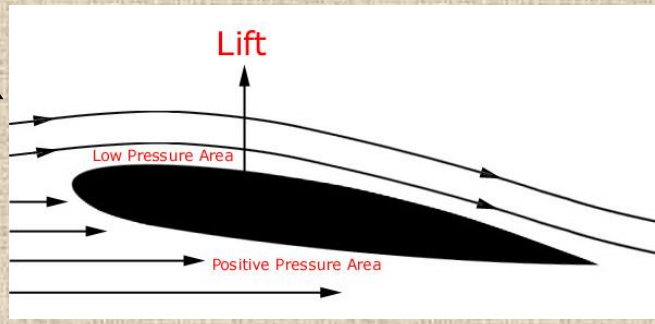


Source: http://mycampus.nationalhighschool.com/doc/sc/physical%20science/ebook/products/0-13-190327-6/sx7097a3.gif

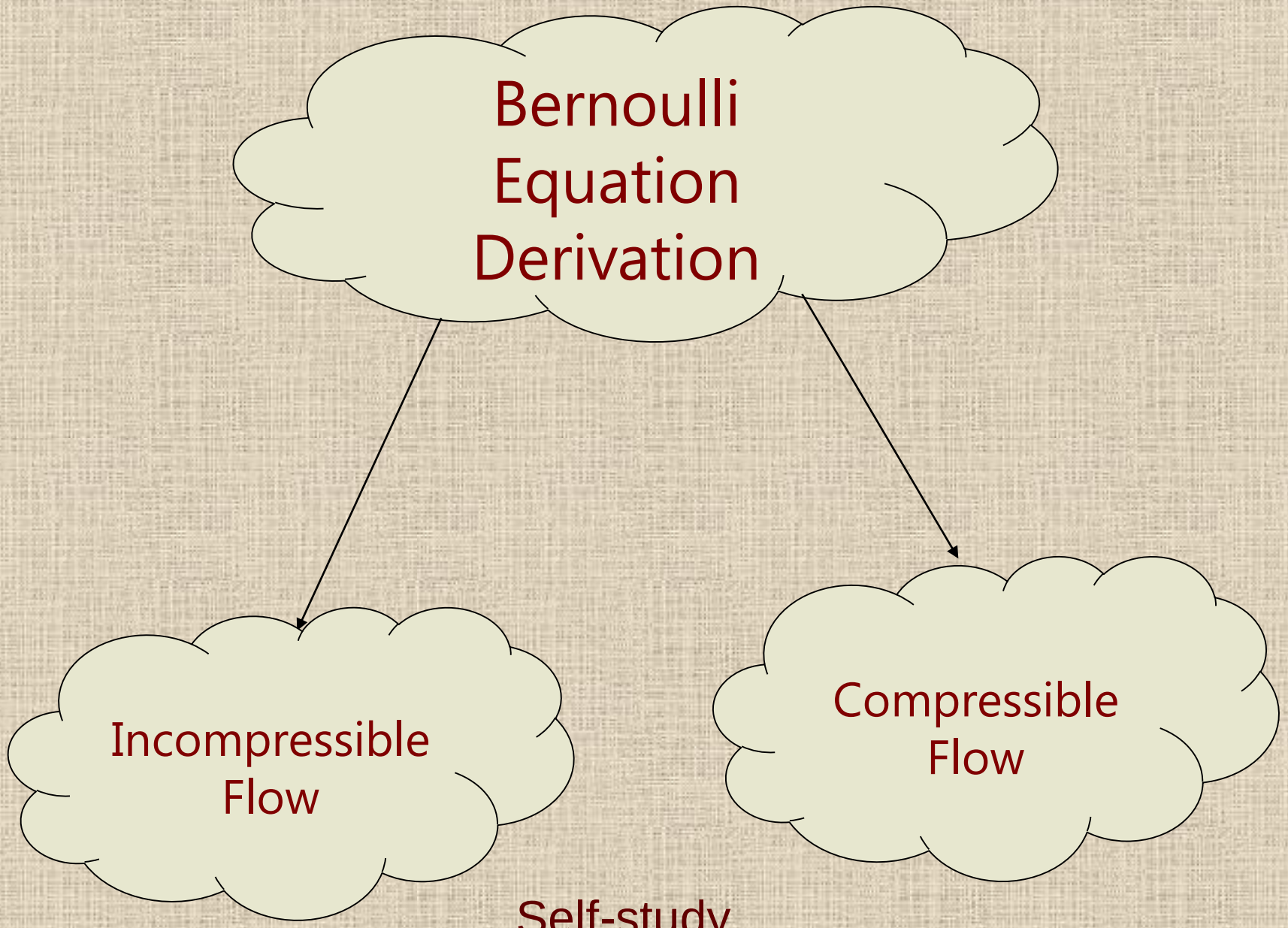
Bernoulli Equation Applications



Source: http://3.bp.blogspot.com/-puEhlmJyfgw/UcGHZFFy9vI/AAAAAAAABuk/vAwPTeYc6m8/s1600/Carburetor-01.png

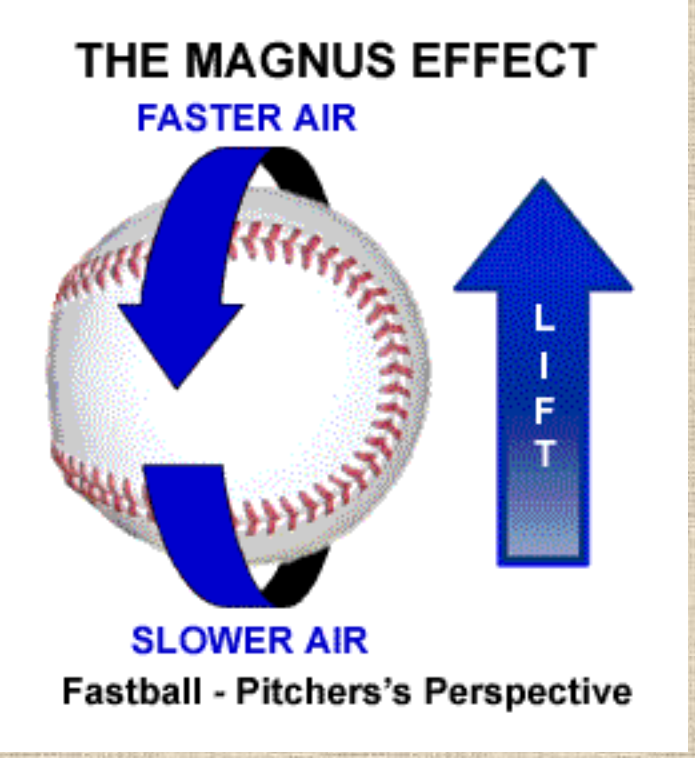


Source: http://www.aviation-history.com/theory/airfoil-6a.jpg


Bernoulli
Equation
Derivation
Incompressible
Flow
Compressible
Flow

Self-study

MAGNUS EFFECT



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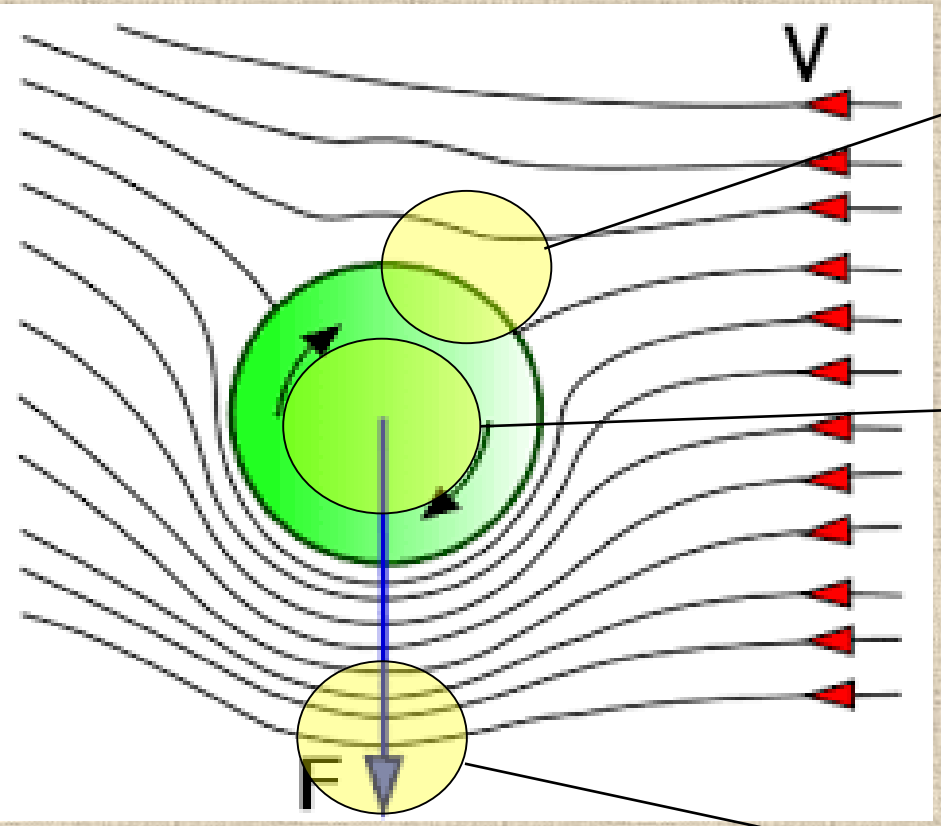
Spinning object moving through a fluid creates a pressure difference between its sides

Difference in pressure curves the object and changes its trajectory

Source: https://previews.123rf.com/images/chudtsankov/chudtsankov1308/chudtsankov130800439/21699409-Smiling-Mad-Scientist-Or-Professor-Holding-A-Frog-Stock-Vector-doctor-mad-cartoon.jpg

Source: https://www.youtube.com/watch?v=2OSrvzNW9FE

MAGNUS EFFECT



Source: http://schema-root.org/science/physics/effects/magnus/magnus_effect.png

relative motion between the spinning body and the fluid

spinning cylindrical or spherical solid immersed in a fluid

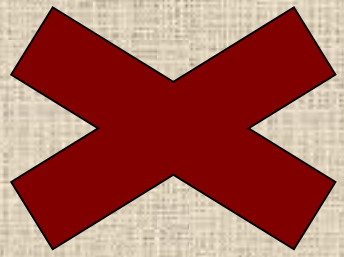
generation of a sidewise force

Source: https://www.youtube.com/watch?v=YIPO3W081Hw

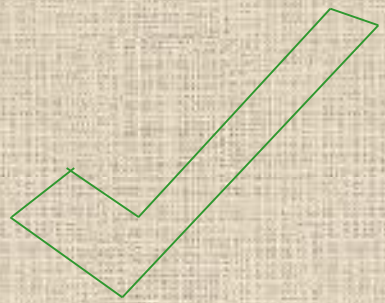
Source: https://static.vecteezy.com/system/resources/previews/000/077/164/non_2x/cartoon-scientist-vector.jpg

Question

Why does this happen?

Bernoulli Principle 

Or

Coandă Effect 

History and Applications

COANDĂ EFFECT

Source: http://ampress.ro/wp-content/uploads/2015/04/coand%C4%83.jpg

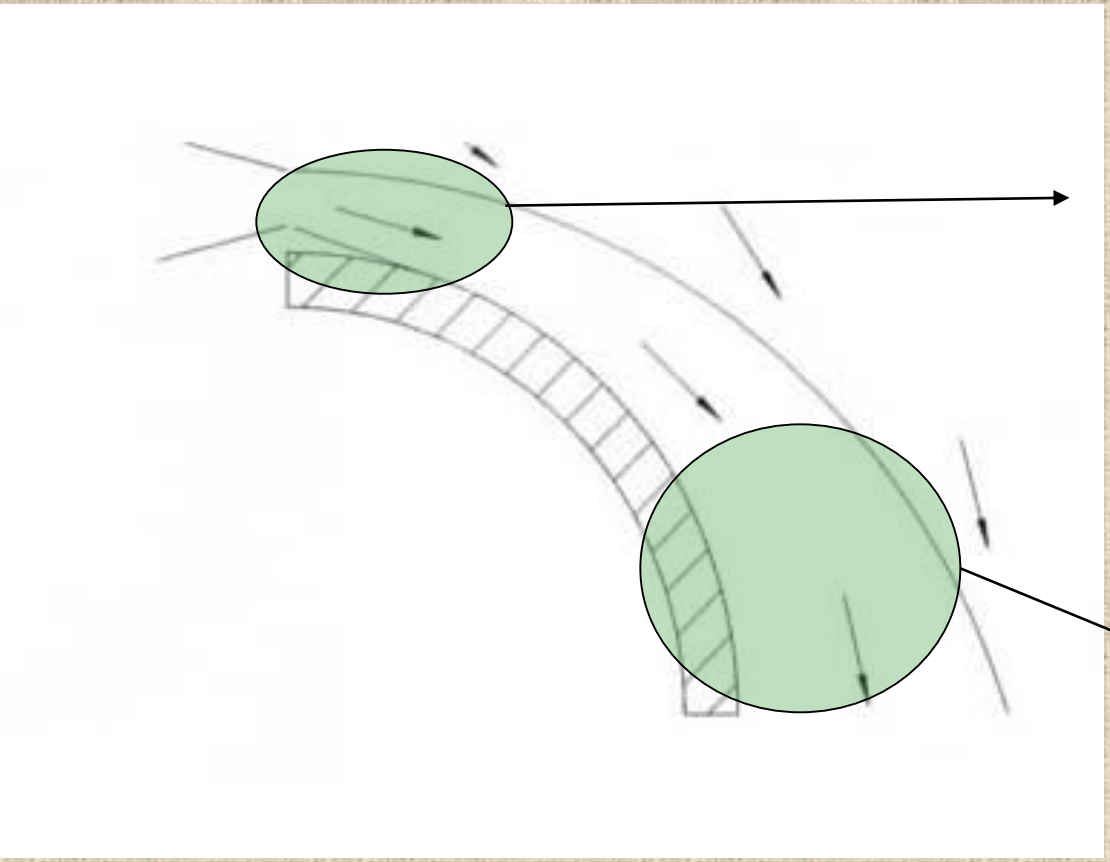
Henri Coandă [1886-1972]

- born in Bucharest, Romania
- interested in the technical problems of flight
- designed and piloted the first jet plane known as the **Coandă-1910**

Source: https://upload.wikimedia.org/wikipedia/commons/thumb/f/f8/Coanda_1910.png/300px-Coanda_1910.png

- In 1930, he discovered the Coandă effect

Coandă Effect



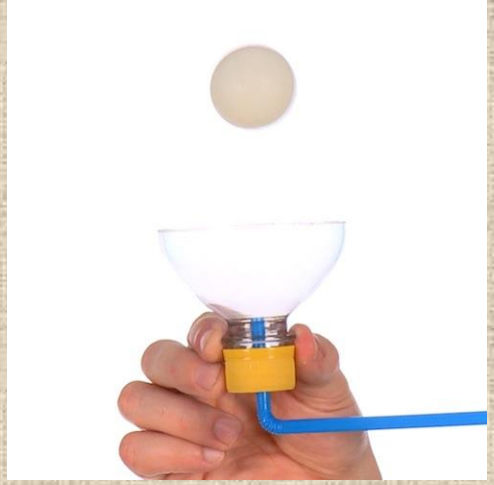
jet flow attaches itself to a nearby surface

Jet remains attached even when the surface curves away

Source: http://www.thermofluids.co.uk/images/coandaeffect2.jpg

Let's understand Coandă Effect with an **experiment**

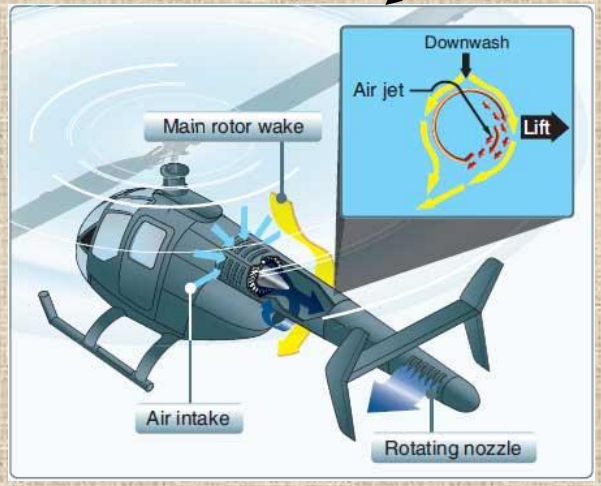
Source: https://thumbs.dreamstime.com/z/cartoon-boy-idea-28030171.jpg



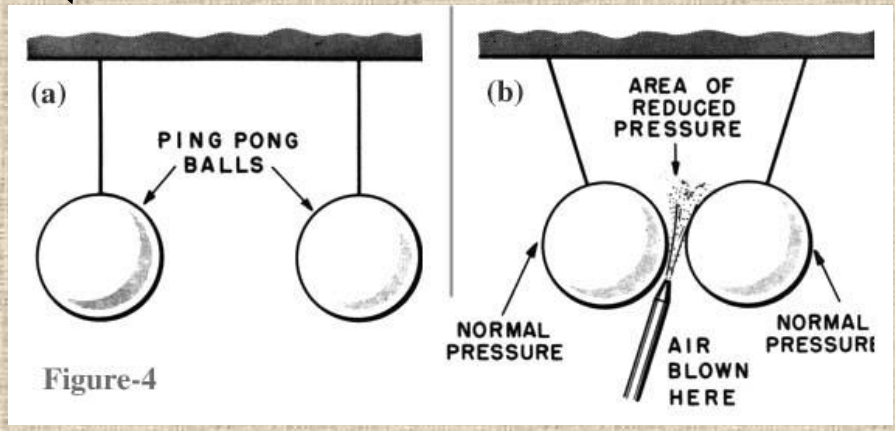
Source: https://s-media-cache-ak0.pinimg.com/originals/38/2e/b7/382eb7839f80b65202c32fa3c4f642c8.jpg

Source: http://www.discoverhover.org/infoinstructors/images/cans.jpg

Coandă Effect Applications

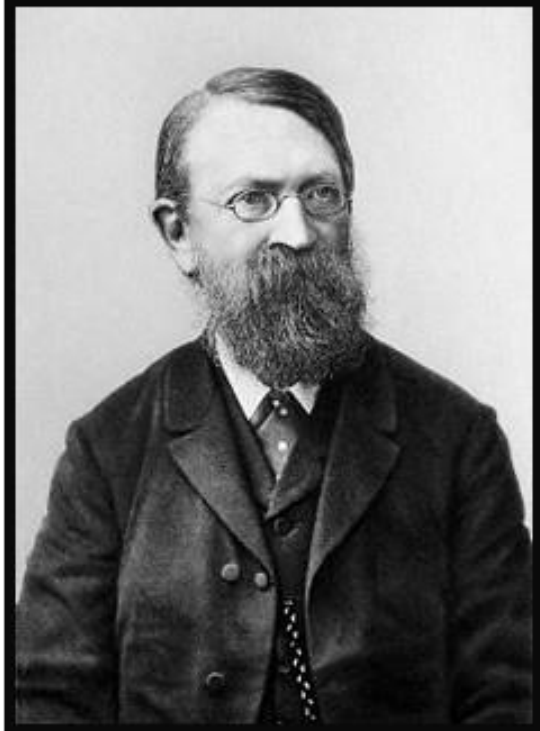


Source: http://www.danubewings.com/wp-content/uploads/2015/11/4-14.jpg



Source: http://www.aethro-kinematics.com/Ping-pong.jpg

Coandă Effect Saucer



The presentations and conceptions of the average man of the world are formed and dominated, not by the full and pure desire for knowledge as an end in itself, but by the struggle to adapt himself favourably to the conditions of life.

(Ernst Mach)

izquotes.com

History, Regimes, Applications and Shock Waves

MACH NUMBER

Mach Number

Source:http://www.kbvp.com/sites/default/files/images/F18F%20pushing%20the%20mach.preview.jpg

$$M = \frac{v}{a}$$

v: Local Flow Velocity

a: Speed of Sound in the medium

- Dimensionless number
- Determines the behaviour of fluid at $v > a$

Source:http://www.aerospaceweb.org/question/history/mach/ackeret.jpg

Significance of Mach Number

Source:http://i178.photobucket.com/albums/w276/scd718/Aircraft/f14d2cm.jpg

- At high speeds →

  Aircraft compresses air around it

- Local density of the air varies

- Varying Density →

  Alters the net force on the aircraft

As per Conservation of Momentum $\rho V dV = -dP$

Assuming Isentropic flow $\frac{dP}{P} = \gamma \frac{d\rho}{\rho}$

$$dP = \gamma \frac{P}{\rho} d\rho$$

$$= \gamma RT d\rho$$

$$dP = \gamma \frac{P}{\rho} d\rho = \gamma RT d\rho$$

$$dP = a^2 d\rho$$

Combining with momentum equation

$$\rho V dV = -a^2 d\rho$$

$$-\boldsymbol{M^2} \frac{\boldsymbol{dV}}{\boldsymbol{V}} = \frac{\boldsymbol{d\rho}}{\boldsymbol{\rho}}$$

If

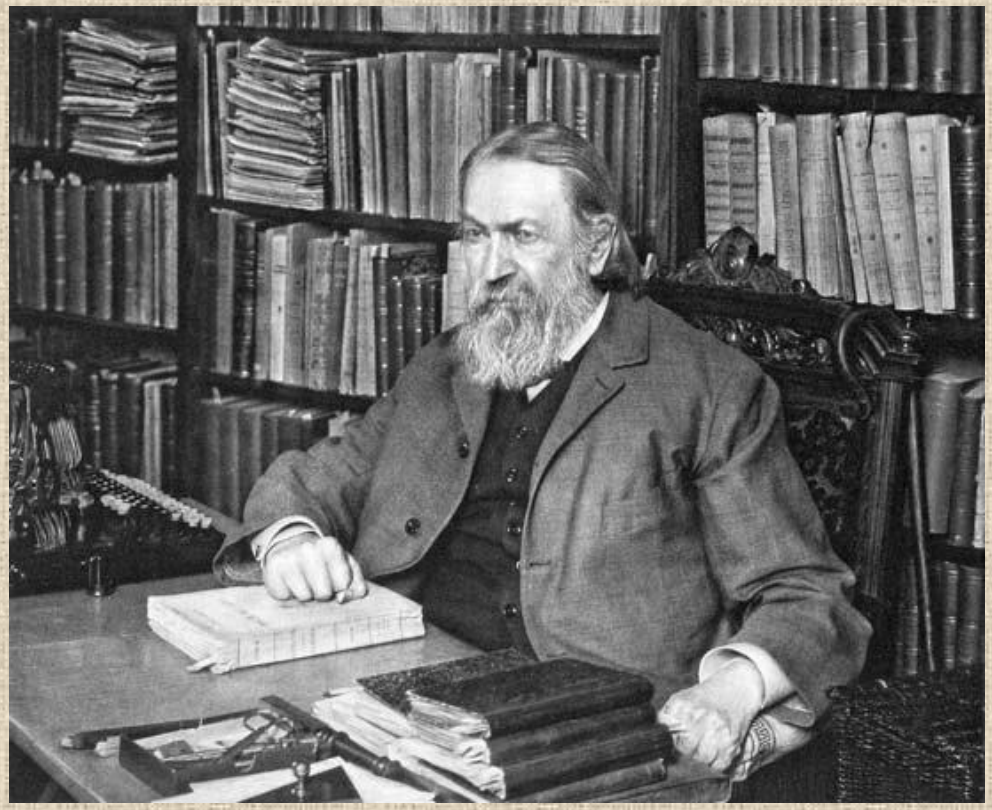
M<1 → ρ~constant

M~1 → dρ~dV

M>1 → dρ>dV by a factor of **M²**

Source: https://www.grc.nasa.gov/www/k-12/airplane/machrole.html

HISTORY OF MACH NUMBER



Source:https://media1.britannica.com/eb-media/69/68569-004-0B1898D2.jpg

Ernst Mach , February 18, 1838 to February 19, 1916

He was an Austrian physicist and philosopher, noted for his contributions to physics such as the Mach number and the study of shock waves. As a philosopher of science, he was a major influence on logical positivism and through his criticism of Newton, a forerunner of Einstein's relativity.

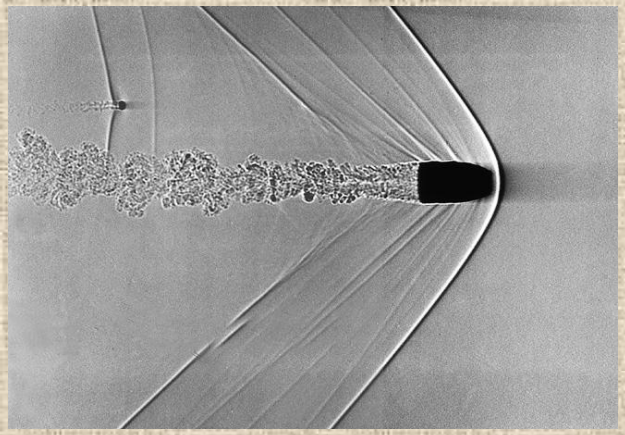
"...Science always has its origin in the adaptation of thought to some definite field of experience"

ERNST MACH

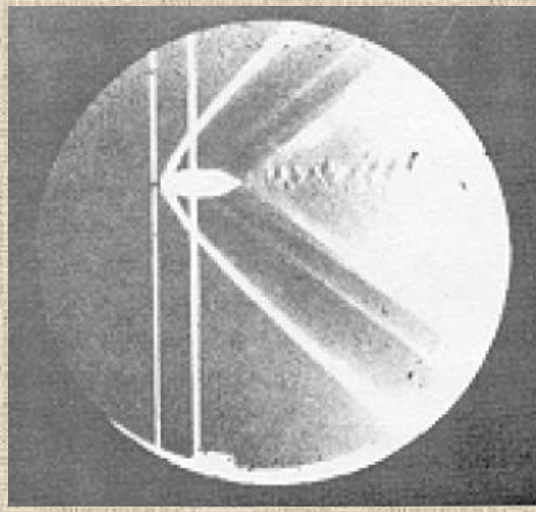
Ernst Mach [1838-1916]

Source:https://upload.wikimedia.org/wikipedia/commons/thumb/b/be/Ernst_Mach_01.jpg/648px-Ernst_Mach_01.jpg

- First to understand the fundamental principles of supersonic flow



Source:https://www.wired.com/wp-content/uploads/images_blogs/wiredscience/2011/06/supersonic-bullet_660.jpg

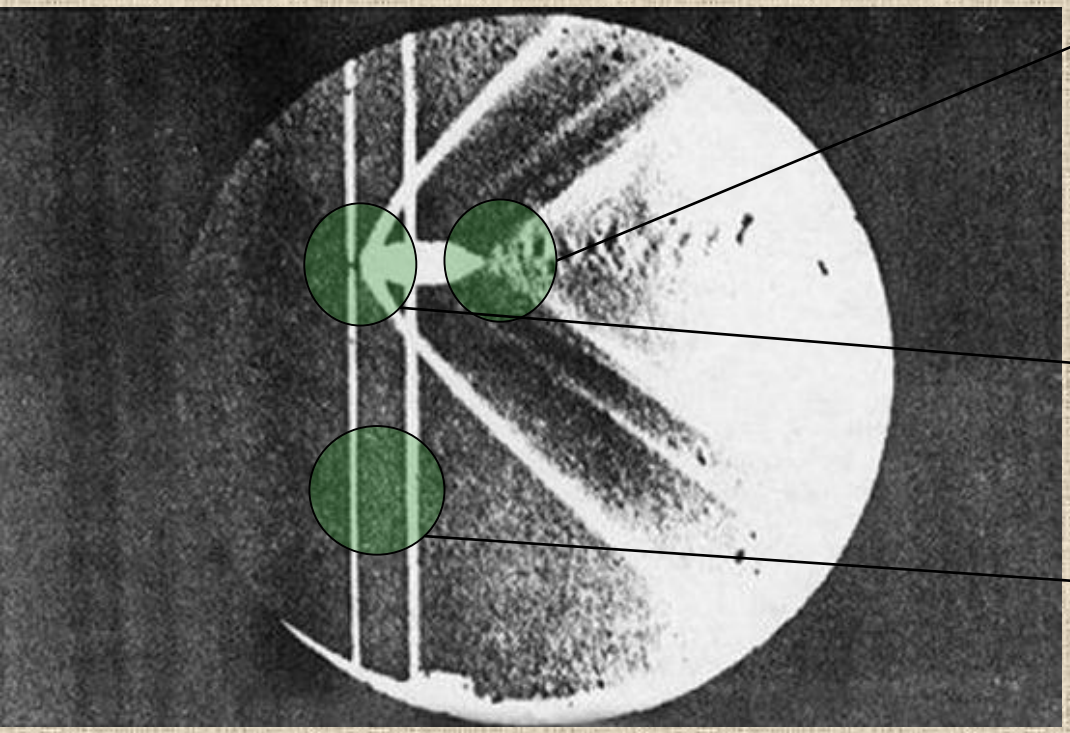


Source: Anderson, J. D., Jr. *History of High Speed Flight and its Technical Development.*, AIAA Paper 2000-02, 30th ASM&E, Reno, NV, 2000

- Revolutionary paper *Photographische Fixierung der durch Projektile in der Luft eingeleiten Vorgange*, presented before the Academy of Sciences in Vienna in 1887

SUPERSONIC BULLET EXPERIMENT

- Demonstrated the existence of the shock waves
- Mach photographed shock waves formed by a bullet traveling faster than the speed of sound



weaker shock wave created at the aft end of the bullet

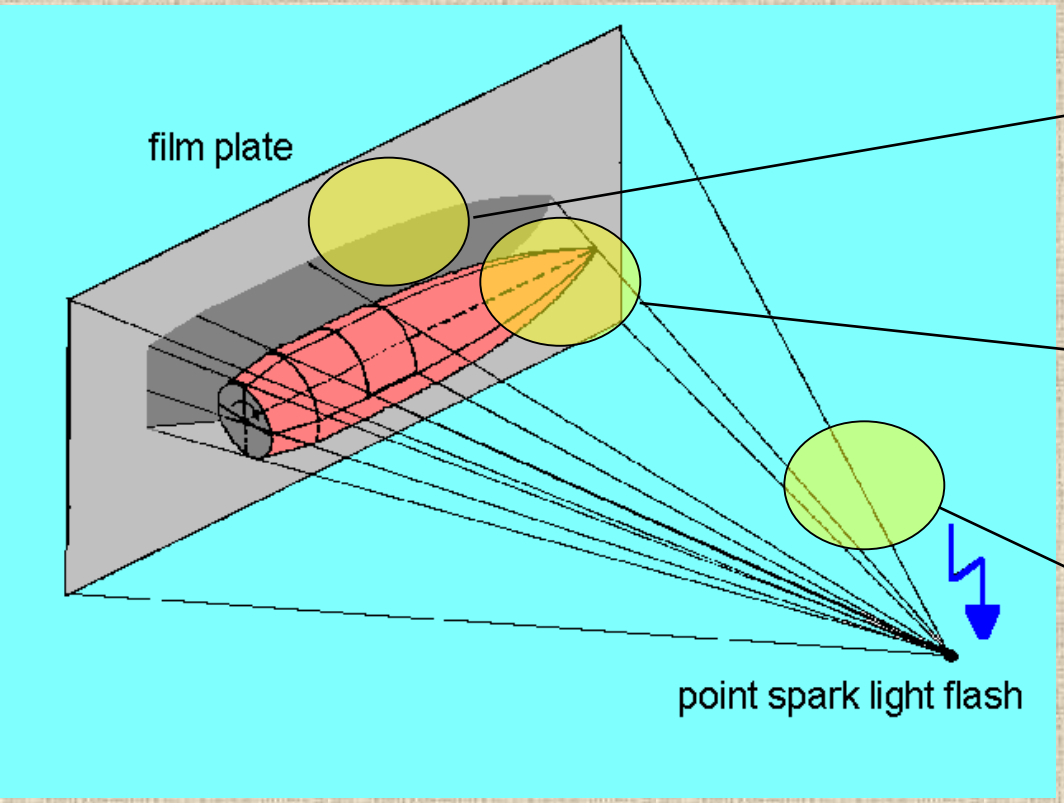
strong shock wave formed by the nose of the bullet

lines made by the trip wires that triggered the camera

Source:http://www.aerospaceweb.org/question/history/mach/bullet.jpg

SUPERSONIC BULLET EXPERIMENT

A shadowgraph was used to obtain the photo



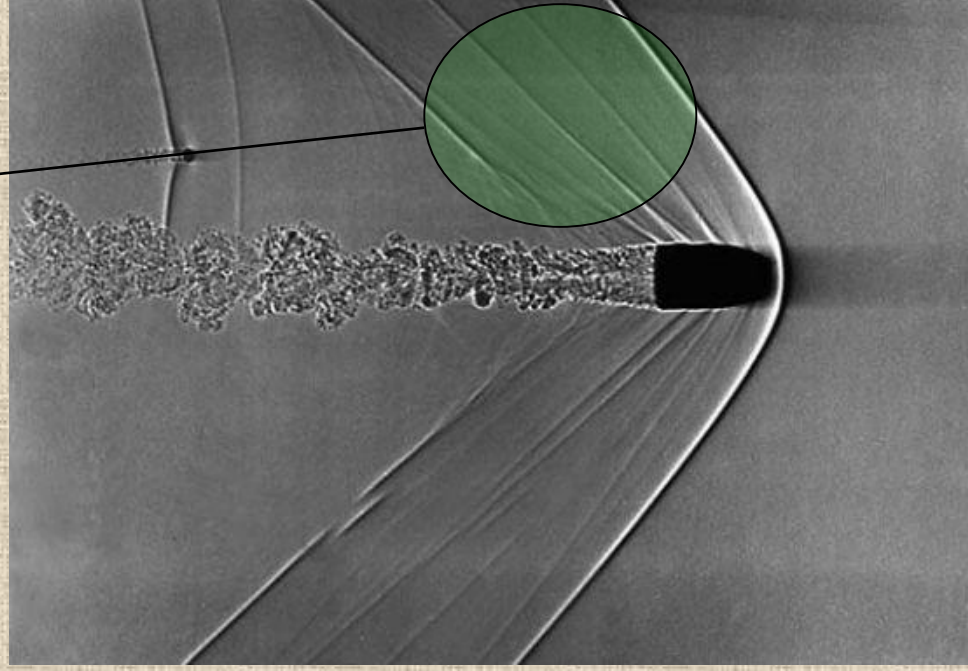
Light waves are refracted and create shadows on screen

Light reflected onto a screen or Film plate

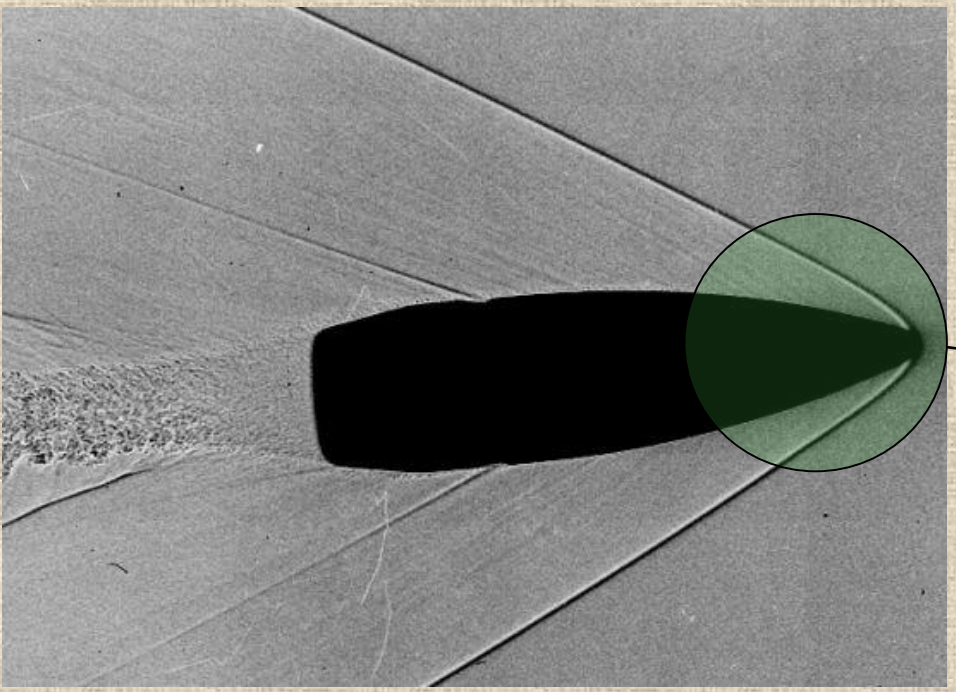
Light was passed through

Source:http://www.aerospaceweb.org/question/history/mach/shadowgraph.gif

Shock waves create changes in temperature and air flow



Source:http://www.aerospaceweb.org/question/history/mach/shadowgraph.gif

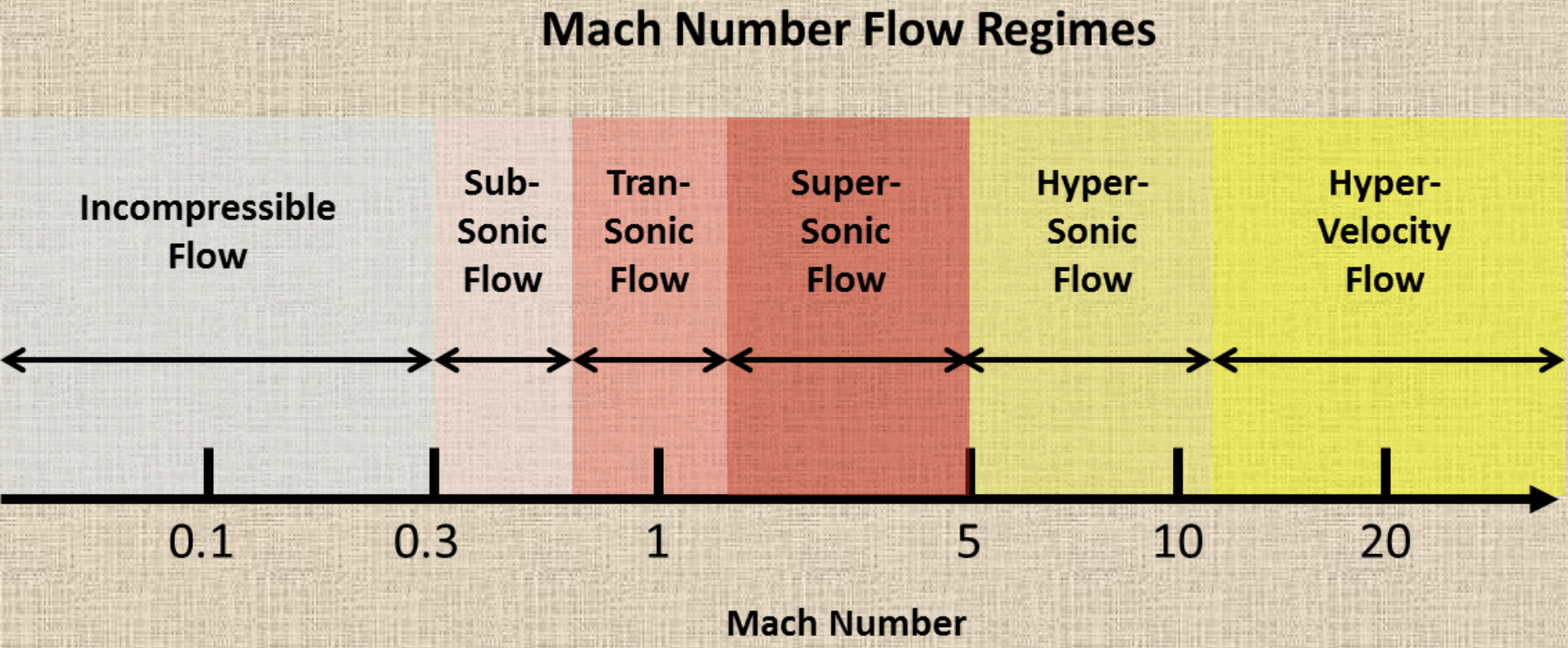


Shadows created on the screen

Source:http://www.aerospaceweb.org/question/aerodynamics/bullet/bullet2.jpg

MACH REGIMES

Division of flight regimes based on Mach number



Source:https://upload.wikimedia.org/wikipedia/commons/9/95/Mach_Number_Flow_Regimes.png

SUBSONIC FLOW

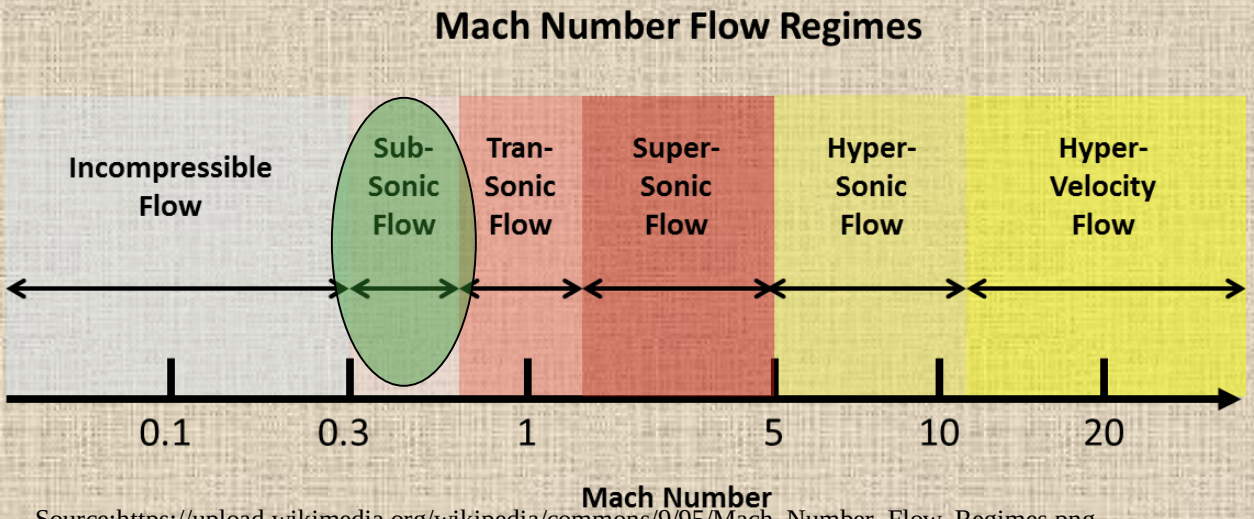
- Aircraft with high aspect ratio wings and rounded features

Source:http://1j5jsm2mvi7w2f7x4m23n116.wpengine.netdna-cdn.com/wp-content/uploads/2015/07/ALH-jetbuyfeatured.jpg

Grumman OV-1 Mohawk

Source:http://i.dailymail.co.uk/i/pix/2016/10/15/01/0A34186C000005DC-3839195-image-a-2_1476489689898.jpg

Focke-Wulf Fw 190



Source:https://upload.wikimedia.org/wikipedia/commons/9/95/Mach_Number_Flow_Regimes.png

TRANSONIC FLOW

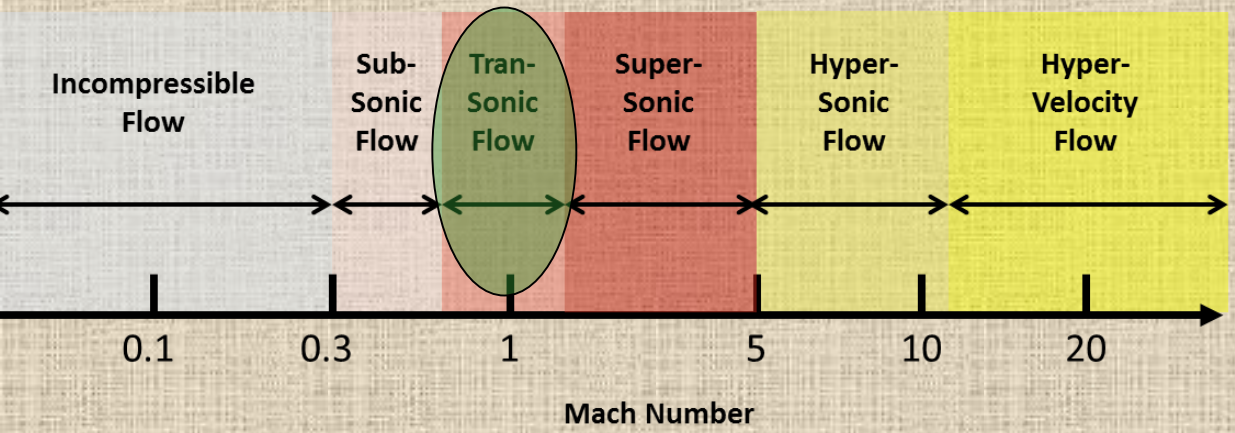
- Region which divides the subsonic and supersonic flows

Source: http://www.airbusgroup.com/int/en/group-vision/what-we-do.html

Airbus A350-1000

Source:http://www.boeing.com/resources/boeingdotcom/commercial/747/assets/images/marquee-747.jpg

Boeing 747-8



Source:https://upload.wikimedia.org/wikipedia/commons/9/95/Mach_Number_Flow_Regimes.png

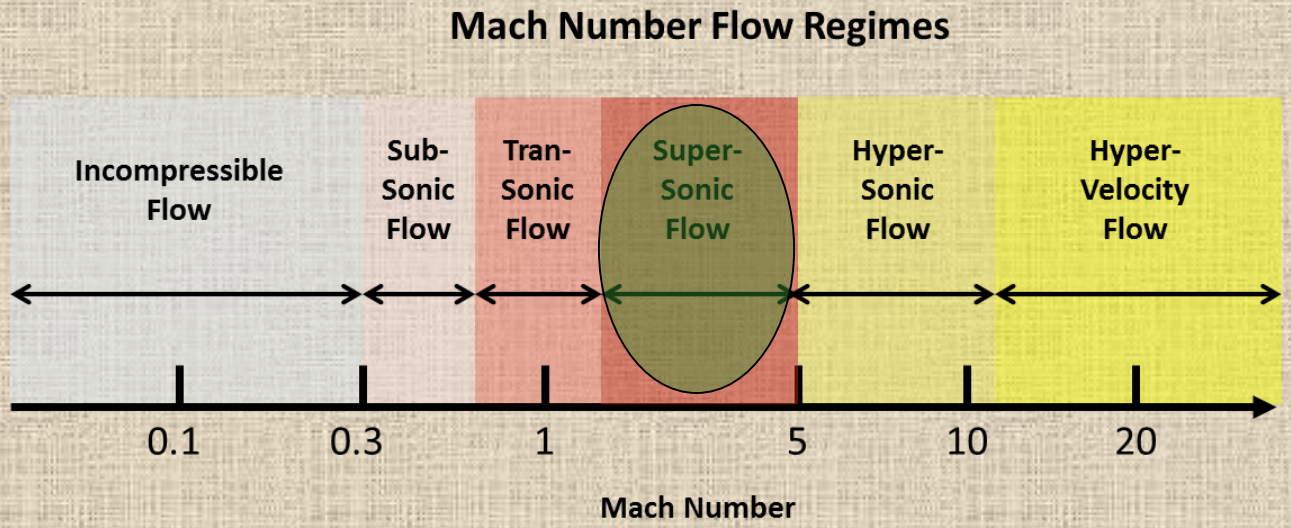
SUPERSONIC FLOW

Source:http://i.dailymail.co.uk/i/pix/2015/01/05/246C29D000000578-0-image-a-5_1420466801321.jpg

Boeing F/A-18E/F Super Hornet

Source:http://images.indianexpress.com/2016/07/tejas-oped-2-759.jpg

HAL Tejas



Source:https://upload.wikimedia.org/wikipedia/commons/9/95/Mach_Number_Flow_Regimes.png

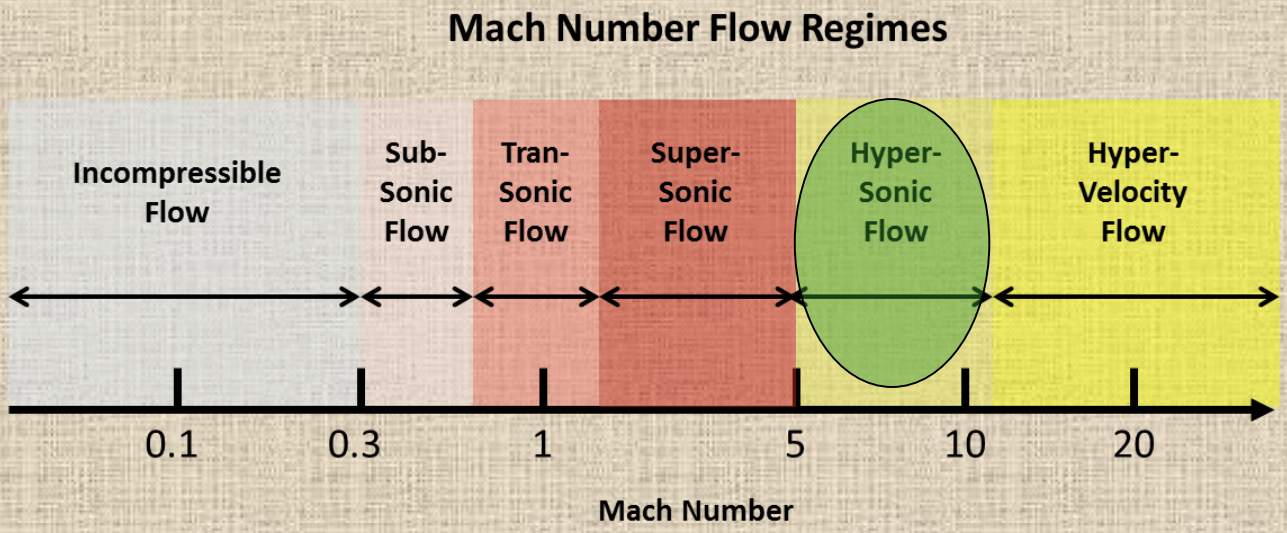
HYPERSONIC FLOW

Source:https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcT9tDN-en0h0yQjy0sQncQ_gYL7ai8RO7ySmh8Q_p5mqjeQrNsl

X-43 A Scramjet

Source:https://static.turbosquid.com/Preview/2014/05/21__10_53_06/rend02.jpg1e5d7a4d-c39f-4237-bc41-b4073ce4880bOriginal.jpg

Boeing X-51A (WaveRider)



Source:https://upload.wikimedia.org/wikipedia/commons/9/95/Mach_Number_Flow_Regimes.pngc

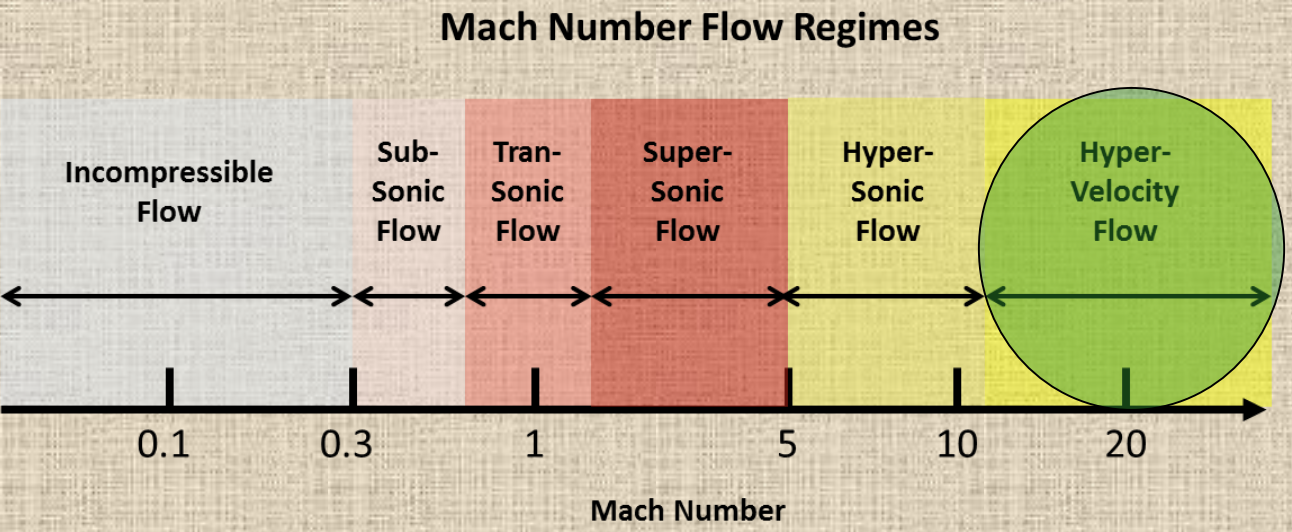
HYPER VELOCITY FLOW

Source:http://www.space-rockets.com/photo/launch1.jpg

Pathfinder

Source:https://www.nasa.gov/sites/default/files/orion-d4-liftoff-ingalls.jpg

ULA Delta IV



Source:https://upload.wikimedia.org/wikipedia/commons/9/95/Mach_Number_Flow_Regimes.pngc

Mach Number of aircrafts, spacecraft and missiles

Source:https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcT9tDN-en0h0yQjy0sQncQ_gYL7ai8RO7ySmh8Q_p5mqjeQrNsl

X-43 A Scramjet

- Mach 9.6
- Highest speed aircraft

Source:https://upload.wikimedia.org/wikipedia/commons/thumb/2/20/AGM-84_Harpoon_launched_from_USS_Leahy_%28CG-16%29.jpg/330px-AGM-84_Harpoon_launched_from_USS_Leahy_%28CG-16%29.jpg

Exocet missile

- Mach 3-5

Source:https://upload.wikimedia.org/wikipedia/commons/thumb/3/34/Skylab-73-HC-440HR.jpg/220px-Skylab-73-HC-440HR.jpg

Saturn V

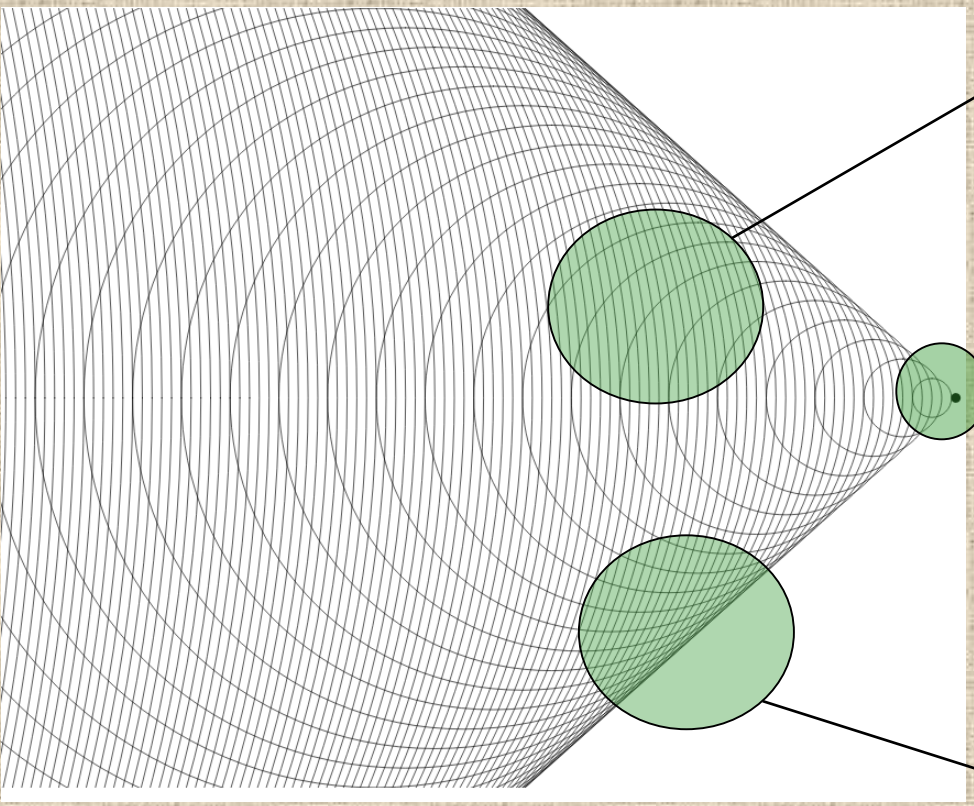
- Mach 13

MACH WAVES

- $V_{mach\ waves} > V_{sound}$
- sudden change in stress, density and temperature

$$V_{shock\ wave} \uparrow \leftrightarrow Amplitude \uparrow$$

FORMATION OF SHOCK WAVES



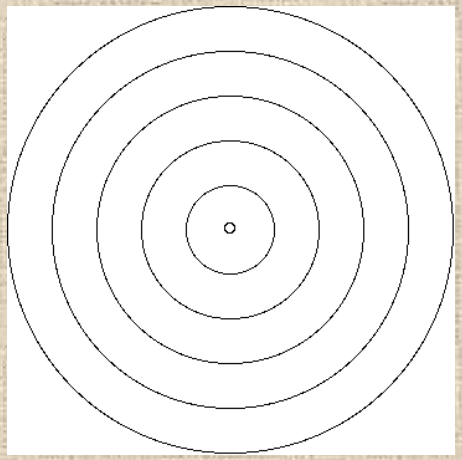
Source: http://physics.info/shock/

the wave fronts lag behind the source in a cone-shaped region

source

edge of the cone forms a supersonic wave front called a "**shock wave**".

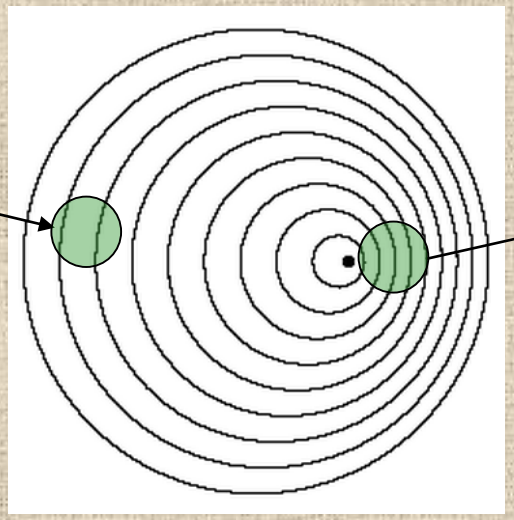
when ($v > v_a$)



Source: http://www.exo.net/~pauld/workshops/ligo/dopplercircles.gif

Stationary sound wave

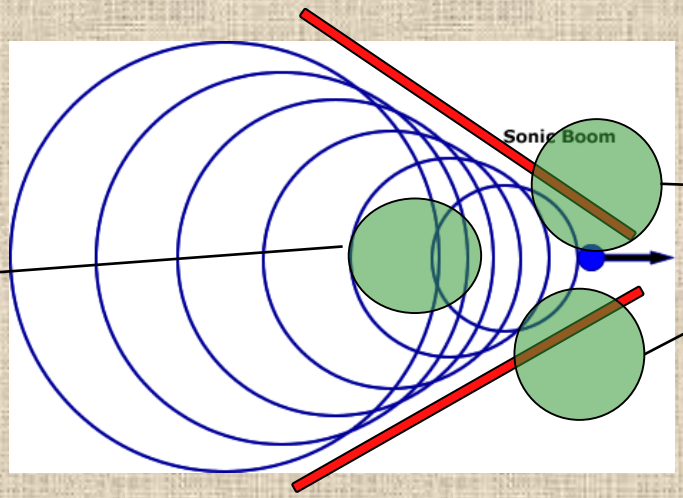
Doppler effect takes place and $\lambda_1 < \lambda_2$



Source: https://uprepcharlie.files.wordpress.com/2013/05/circles.png/

Subsonic sound wave

Wave crests overlap one another



Large amplitude shock wave generated

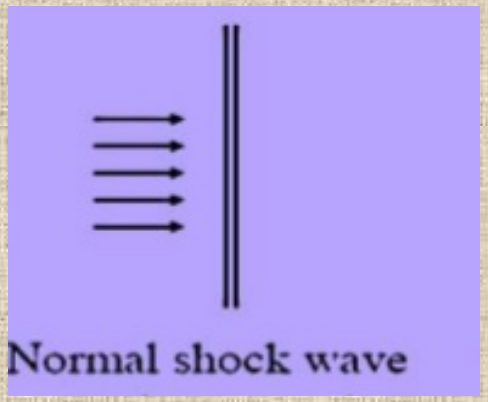
Source: http://www.school-for-champions.com/science/images/sound_traveling_faster_sonic_boom.gif

Supersonic sound wave

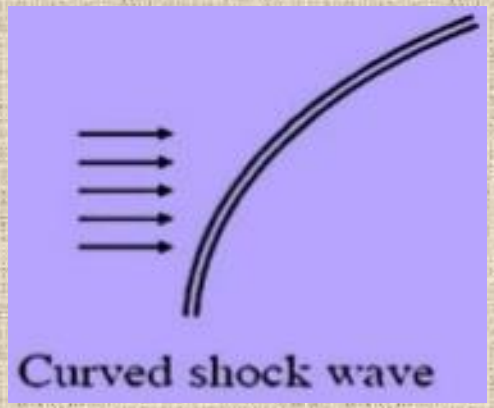
Types of shock waves

Normal Shock

Shock wave ⊥ flow direction

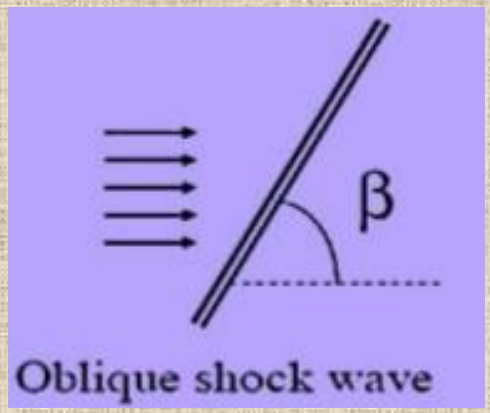


Curved Shock



Oblique Shock

- Shock wave not ⊥ flow direction
- Decreases with Mach number



Source: https://www.slideshare.net/asiflemon7/presentation-on-shockwave-phenomena

SONIC BOOM

Source: https://www.youtube.com/watch?v=x6DUbxCpszU

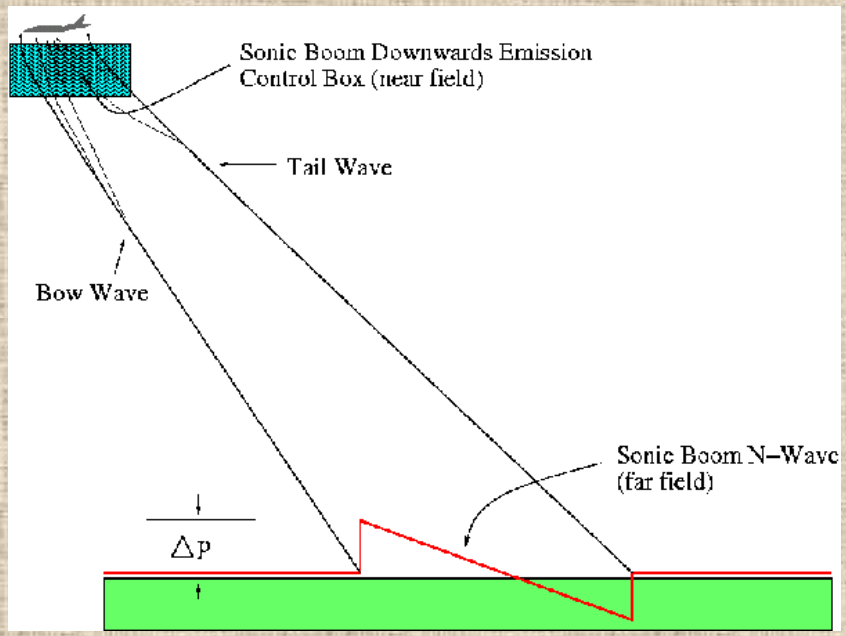
Source: https://img.buzzfeed.com/buzzfeed-static/static/2015-02/23/11/enhanced/webdr03/original-19818-1424710169-33.png?downsize=715:*&output-format=auto&output-quality=auto

SONIC BOOM

Source: https://www.scienceabc.com/wp-content/uploads/2017/04/Military-jet-plane-sonic-boom.jpg

- Loud noise created by shock wave
- Coherent addition of wave → creation of strong sum wave

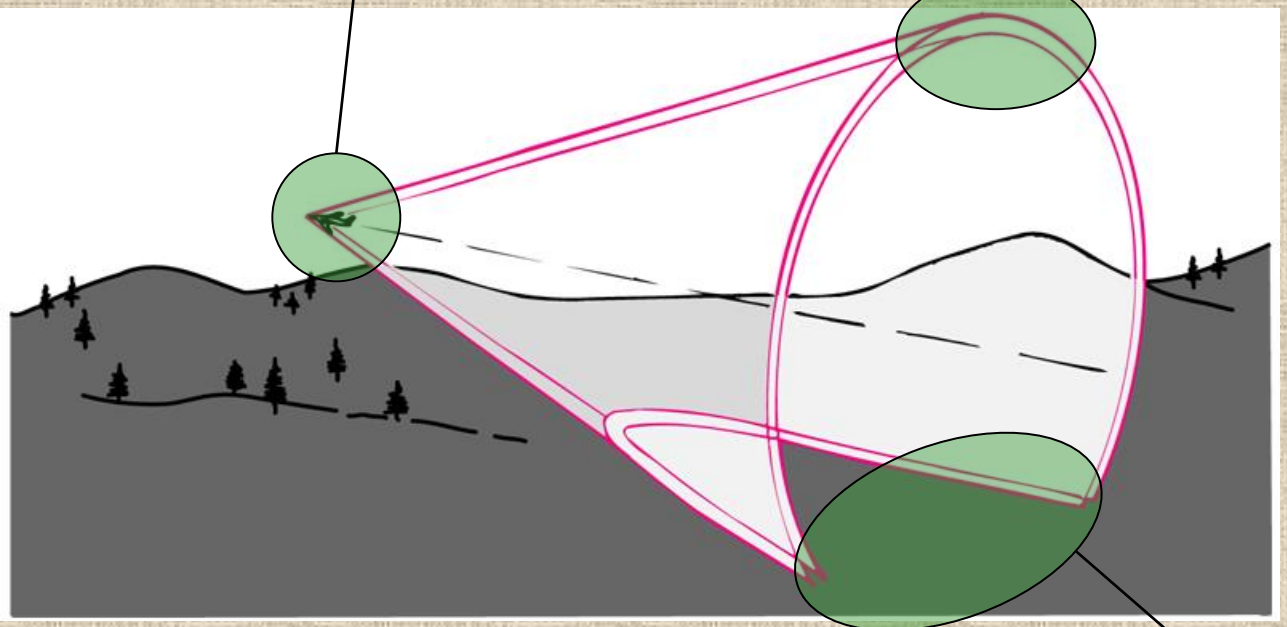
- Boom experienced when there is a sudden change in pressure
- Overall pressure profile known as *N-wave*



Source: https://qph.ec.quoracdn.net/main-qimg-c921e1f0659b74c8de6eece7fff7eadc

A conical pressure wave front is produced called **Mach Cone**

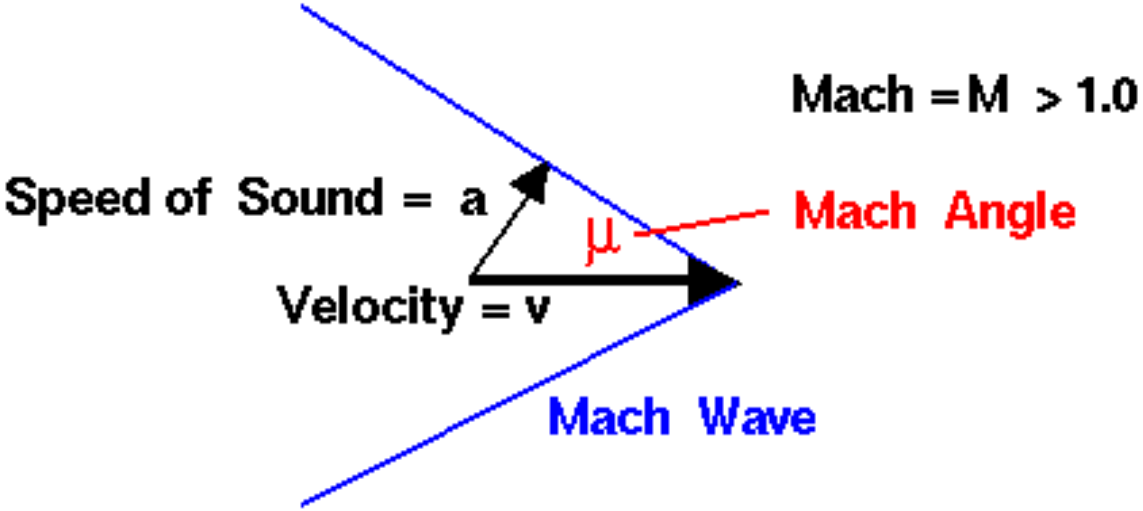
Plane at supersonic speeds



Source: http://w3.shorecrest.org/~Lisa_Peck/Physics/syllabus/soundlight/ch25waves/ch25wave_images/sonicboom.jpg

Mach cone meets the ground creating a hyperbolic area called **Boom Carpet**

Mach Angle



Source: https://www.grc.nasa.gov/www/k-12/airplane/machang.html

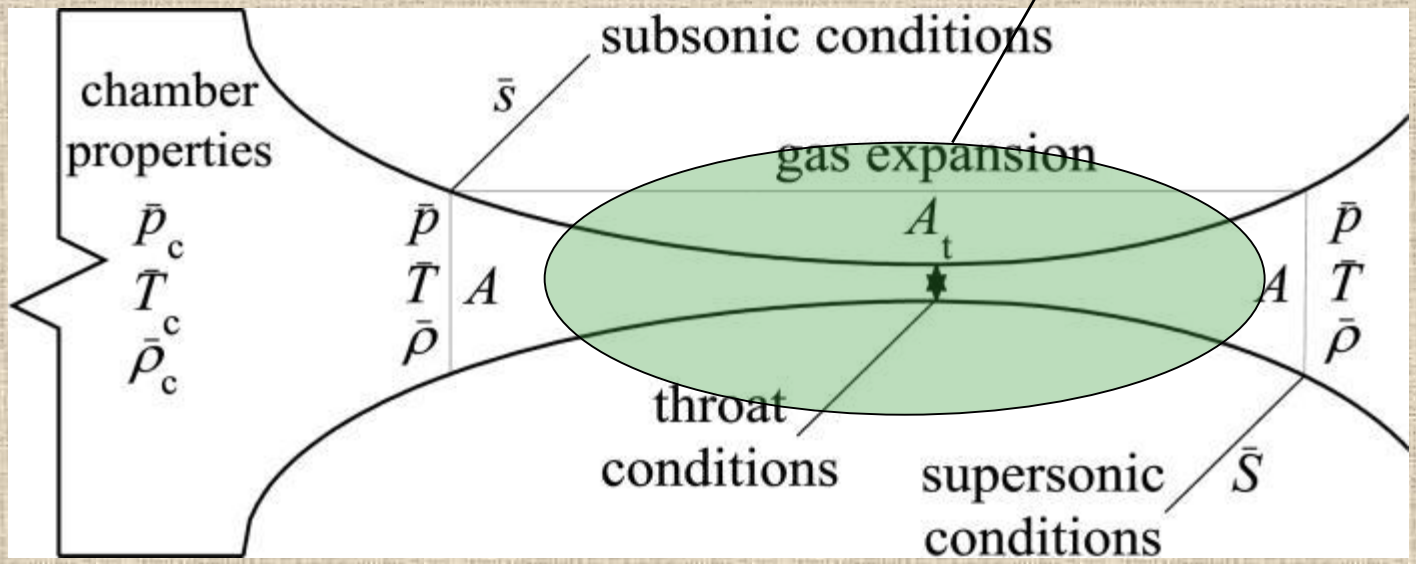
Mach angle is the angle a shock wave makes with the direction of motion

$$\sin \mu = \frac{a}{v} \rightarrow \sin \mu = \frac{1}{M} \rightarrow \mu = \sin^{-1} \frac{1}{M}$$

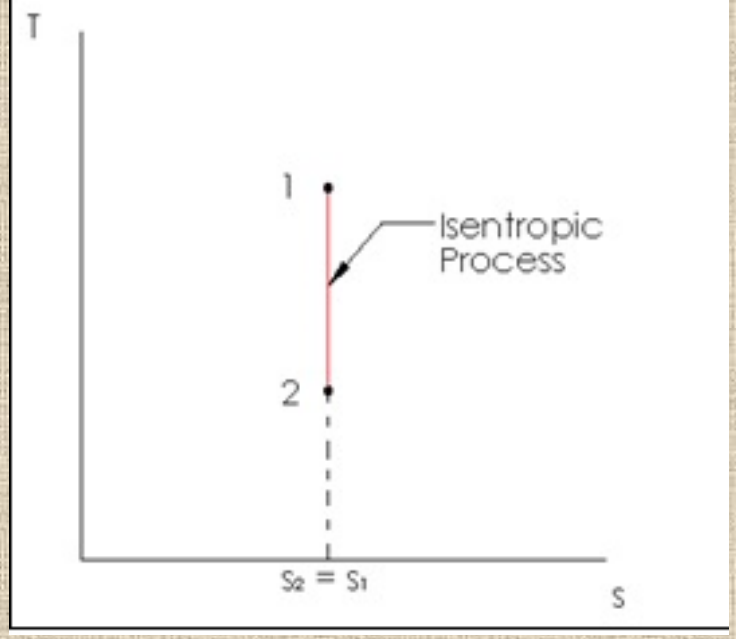
ISENTROPIC FLOW

- Reversible flow at constant value of entropy
- Sound waves creation → isentropic process
- change in flow variables→ small and gradual

Isentropic flow through nozzle



Source: http://gasturbinespower.asmedigitalcollection.asme.org/data/journals/jetpez/27186/031201_1_1.jpeg

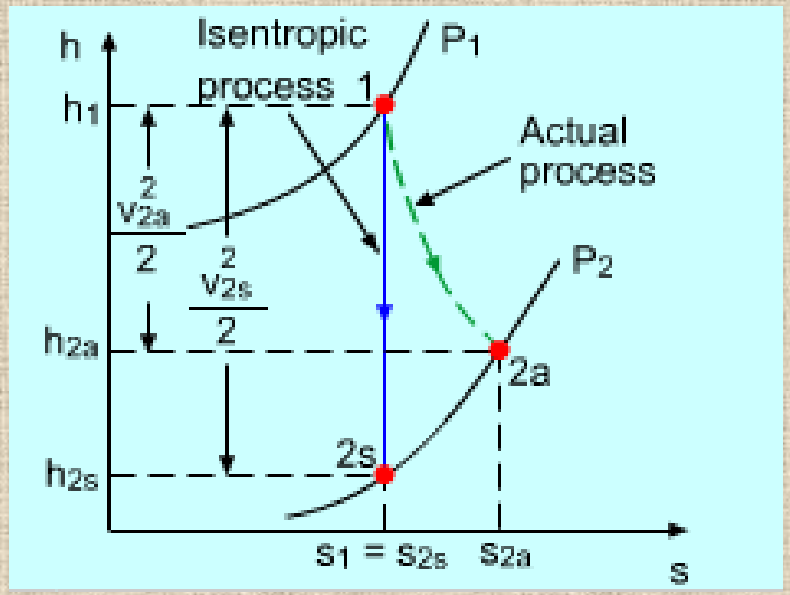


Source: http://engineering-references.sbainvent.com/thermodynamics/pictures/isentropic-process.jpg

T-S Diagram

- energy can be exchanged with the flow → as long as it doesn't happen as heat exchange.
- Example: an isentropic expansion or compression

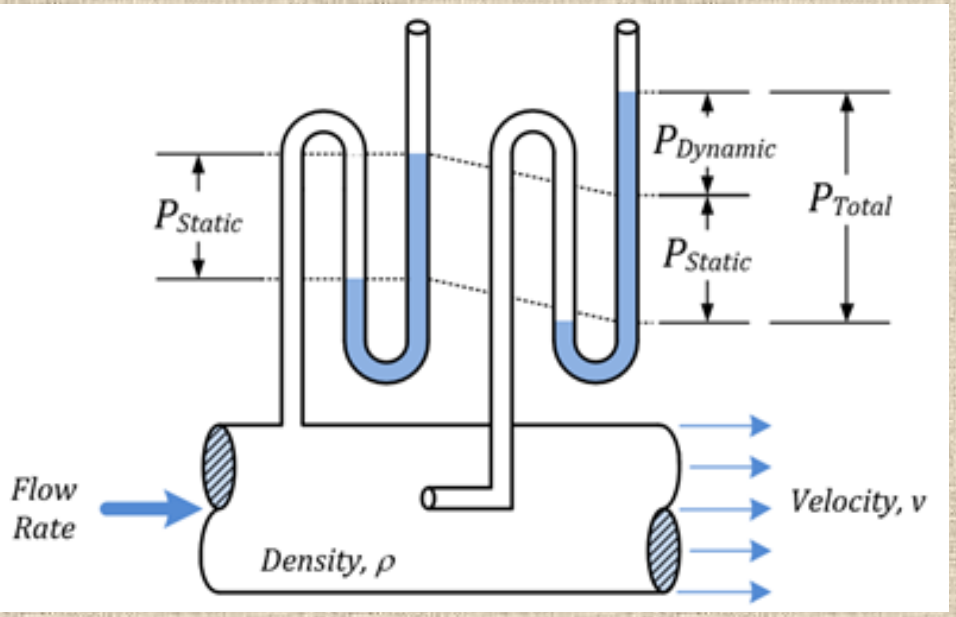
- No heat is added to the flow
- No energy transformations occur due to friction or dissipative effects



Source: http://www.ecourses.ou.edu/ebook/thermodynamics/ch06/sec065/media/th060508p.gif

h-s Diagram

TOTAL PRESSURE

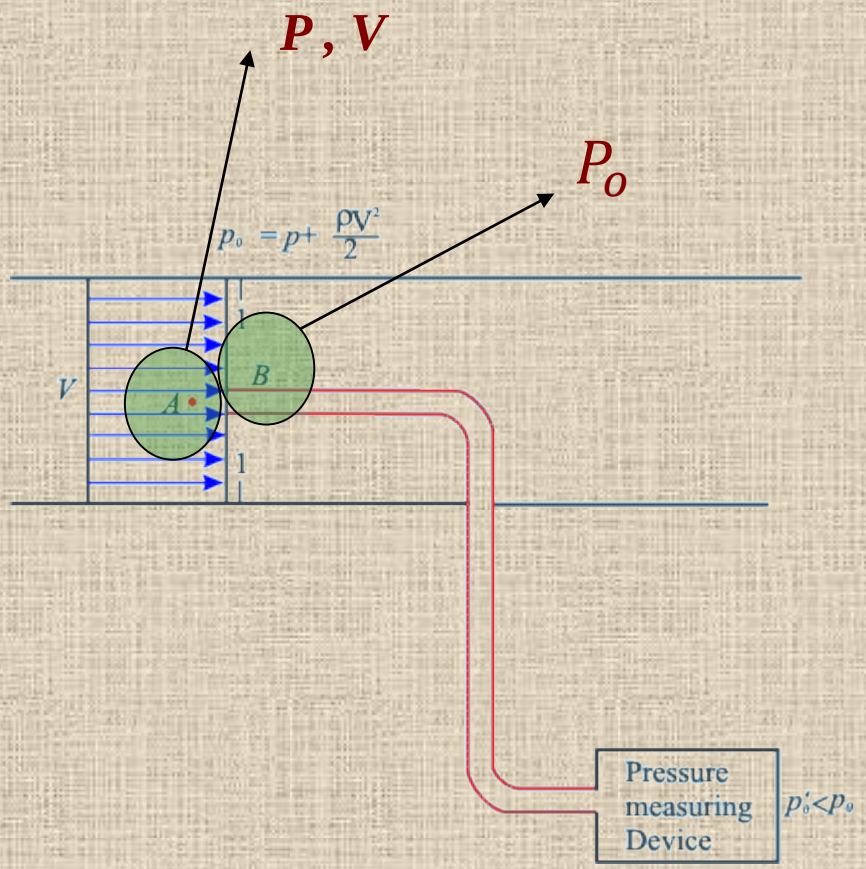


Source: https://eng-software.com/media/1771/pressure2.png?width=400px&height=256px

- Pressure developed if the fluid were brought to rest isentropically
- The entire kinetic energy of the fluid particle is utilized to increase its pressure only
- This is possible only in an isentropic process

$$P_{total} = P_{static} + P_{dynamic}$$

Assuming incompressible flow



Source: http://www.nptel.ac.in/courses/112104118/lecture-16/images/fig_16.2.gif

Applying Bernoulli at A and B

$$P_o = P + \frac{\rho V^2}{2}$$

Static pressure

Dynamic Pressure

$$V = \sqrt{2\left(\frac{P_o - P}{\rho}\right)}$$

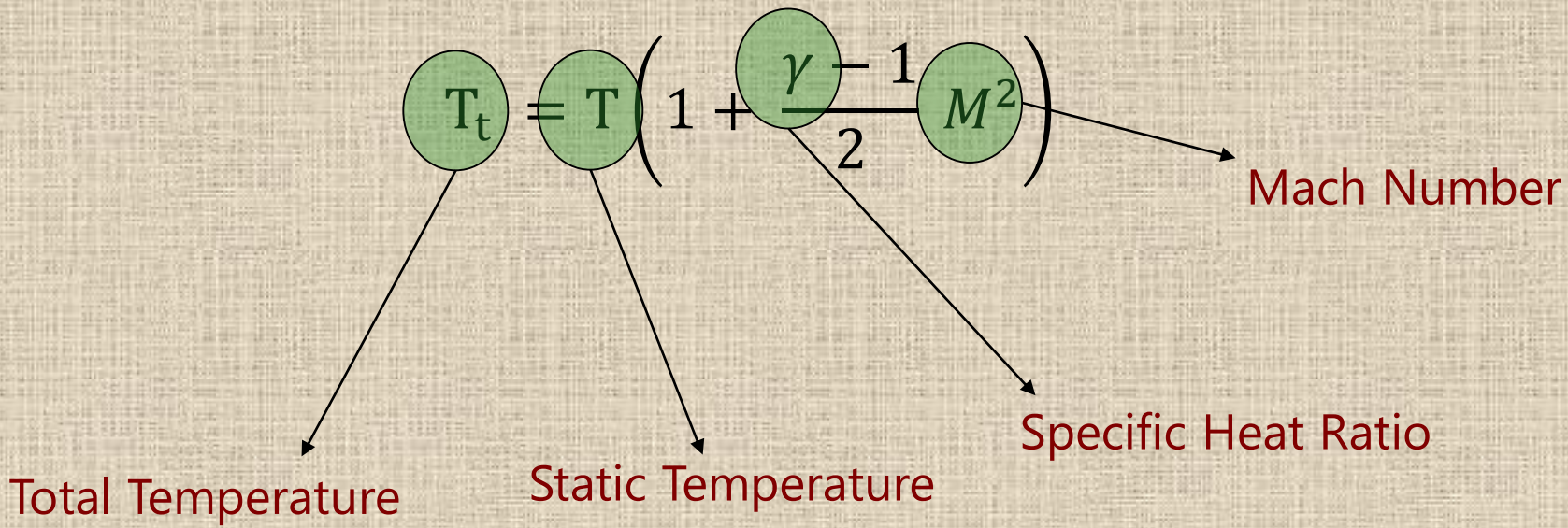
TOTAL TEMPERATURE

Source: https://wahlco.com/wp-content/uploads/2016/01/stagnation-thermocouple.jpg

- Temperature developed when the moving flow is isentropically brought to a halt
- depends on the Mach number of the flow
- T_{total} is the sum of the static temperature and the dynamic temperature
- total temperature measured using thermocouples

$$T_{total} = T_{static} + T_{dynamic}$$

Assuming Isentropic flow, the relation between Total and Static temperature is



Also

$$\frac{P}{P_o} = \left(\frac{T}{T_t}\right)^{\frac{\gamma}{\gamma-1}}$$

Total Pressure