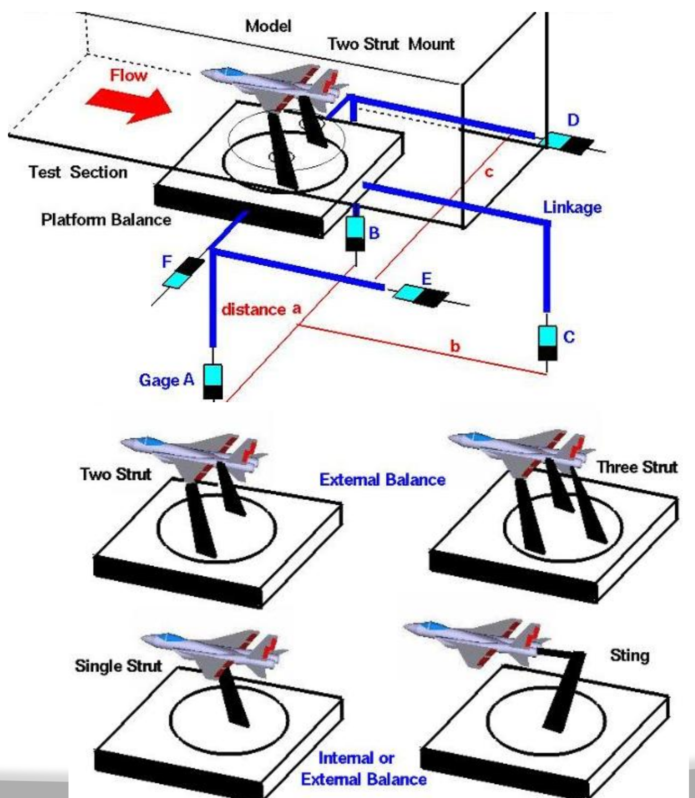
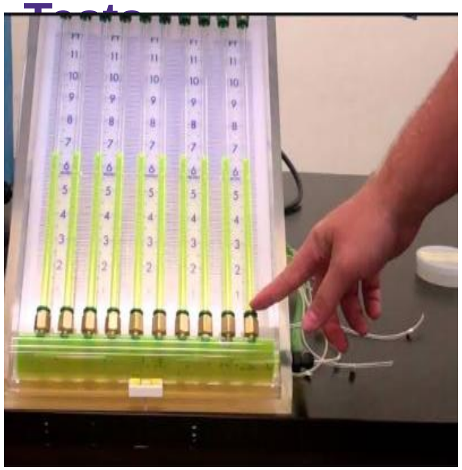
# Unit-I FUNDAMENTALS OF EXPERIMENTS IN AERODYNAMICS

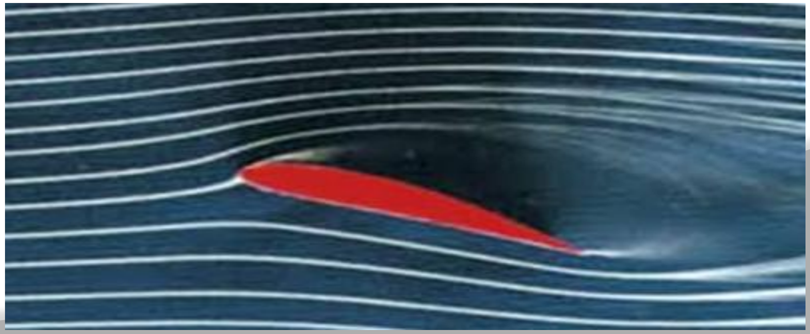
- Forms of Aerodynamic Experiments
- Observations
- Measurement Objectives
- History:
  - Wright Brother‘s Wind Tunnel
- Model Testing
- Wind Tunnel Principles
- Scaling Laws
- Scale Parameters
- Geometric Similarity
- Kinematic Similarity
- Dynamic Similarity
- Wind Tunnels:
- Low Speed Tunnel
- High Speed Tunnels
- Transonic
- Supersonic
- Hypersonic Tunnels
- Shock Tubes
- Special Tunnels:
  - Low Turbulence Tunnels
  - High Reynolds Number Tunnels
  - Environmental Tunnels
  - Automobile Tunnels
- Distinctive Features
- Application

# Forms of Aerodynamic Experiments

- Six component force tests
- Internal balance tests
- Pressure tests
- Flow Visualization Tests





# Observations

Aerodynamic behaviour of Various Geometry

Pressure Behaviour

Control Behaviour

Flow Visualisation Behaviour

# Measurement Objectives

- Various Types  Wind Tunnel
- Various Testing Methods
- Model mounting Methods
- Testing Tools and Application

# Wright Brother‘s Wind Tunnel

**The Wrights large wind tunnel**

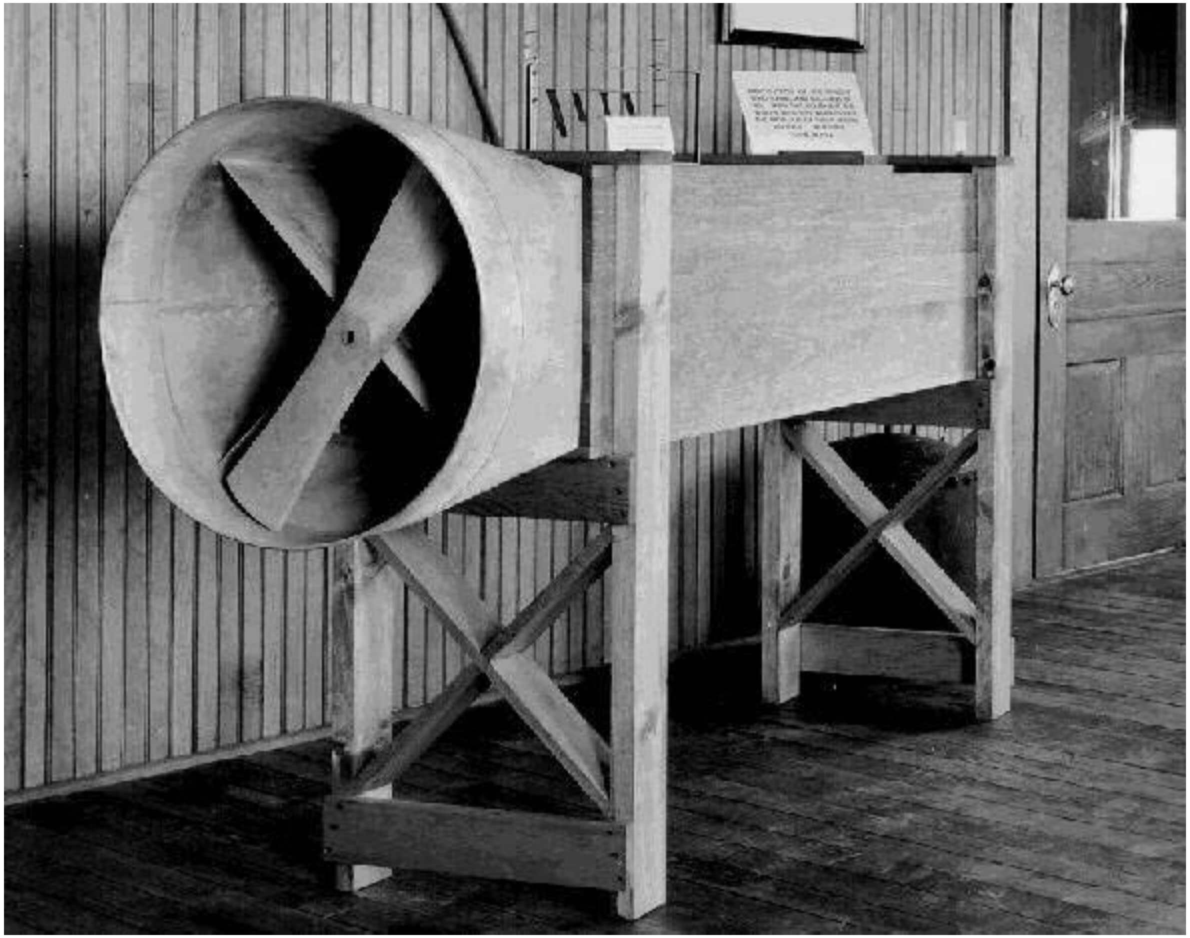
After building and testing a small wind tunnel, the Wright brothers completed a larger, more sophisticated one in October 1901. They used it extensively to carry out aerodynamic research that proved essential in designing their 1903 airplane.

The wind tunnel consisted of a simple wooden box with a square glass window on top for viewing the interior during testing. A fan belted to a one-horsepower engine, which ran the machinery in their bicycle shop, provided an airflow of about 30 miles per hour.

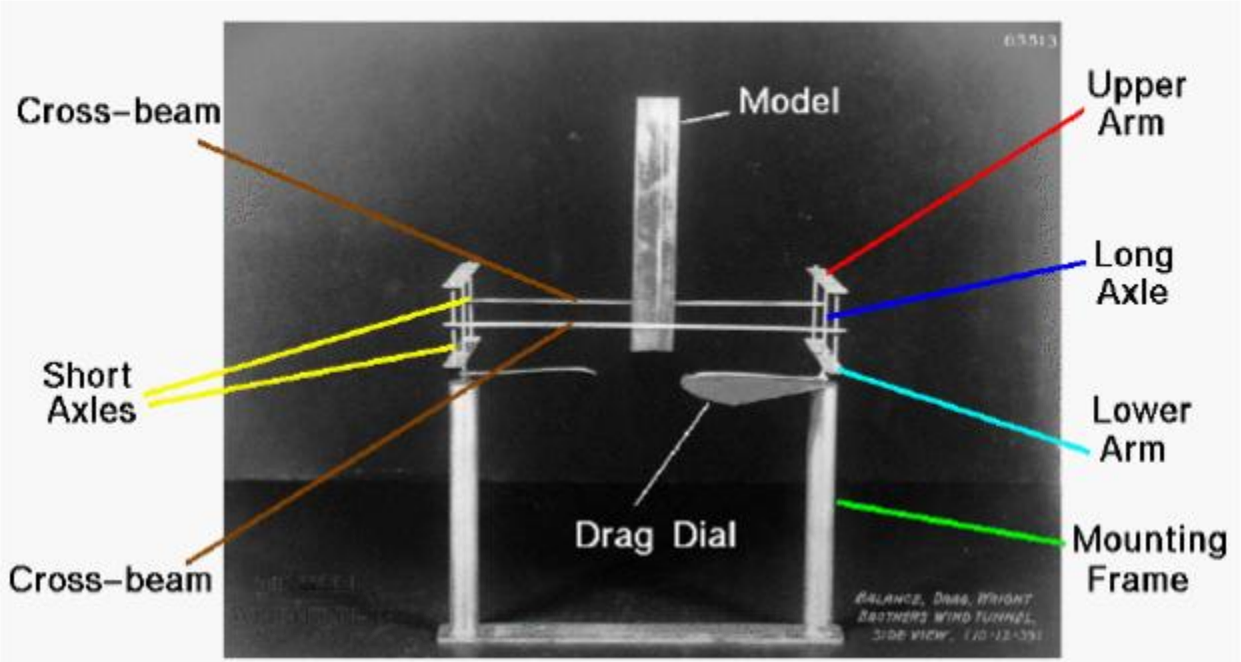
## Wright wind tunnel balances

What made the Wrights' wind tunnel unique were the instruments they designed and built to measure lift and drag. Called balances, after the force-balancing concept, these instruments measured the forces of lift and drag acting on a wing in terms that could be used in the equations.

The balances are made from old hacksaw blades and bicycle spokes. Their crude appearance belies their sophisticated design. Largely the work of Orville, they represent a solid understanding of geometry, mathematics, and aerodynamic forces, and illustrate the Wrights' engineering talents at their finest.



At the end of the summer of 1901, the Wright brothers were frustrated by the flight tests of their 1901 glider. The aircraft was flown frequently up to 300 feet in a single glide. But the aircraft did not perform as well as the brothers had expected. The aircraft only developed 1/3 of the lift which was predicted by the lift equation using Lilienthal's data. During the fall of 1901, the brothers began to question the aerodynamic data on which they were basing their designs. So, they decided to conduct a series of wind tunnel tests to verify the results they were experiencing in flight. They would measure the aerodynamic lift and drag on small models of their wing designs using a wind tunnel in their bicycle shop at Dayton, Ohio. They built two separate **balances** to perform these measurements, one for lift and the other for drag.

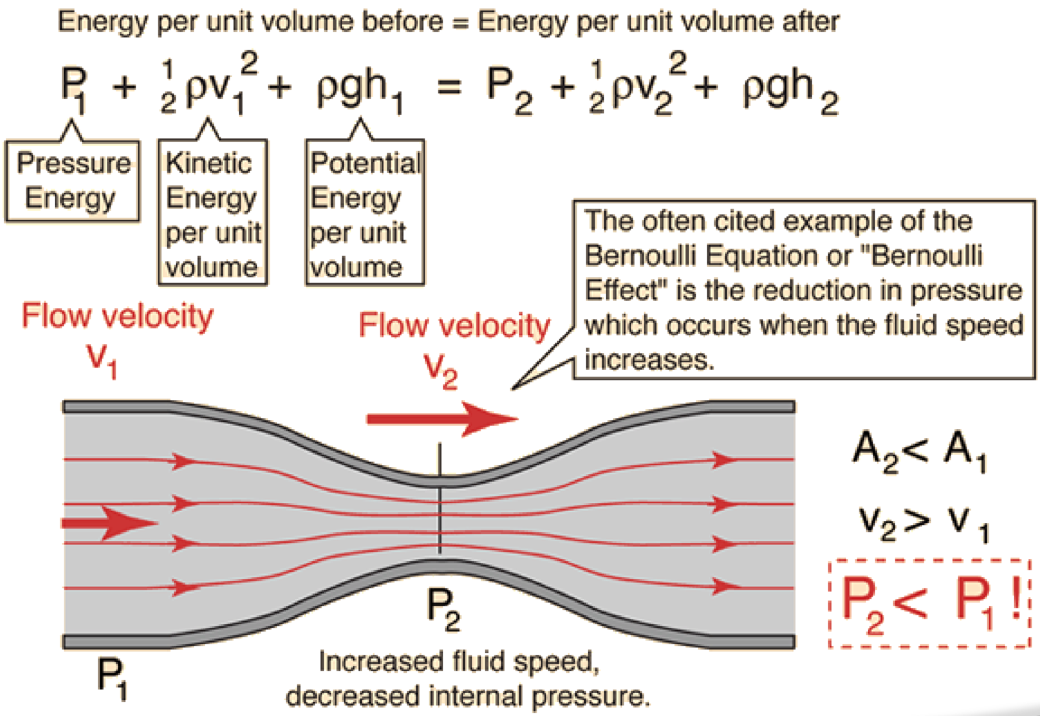

Cross–beam
Model
Upper Arm
Long Axle
Short Axles
Lower Arm
Drag Dial
Mounting Frame
Cross–beam

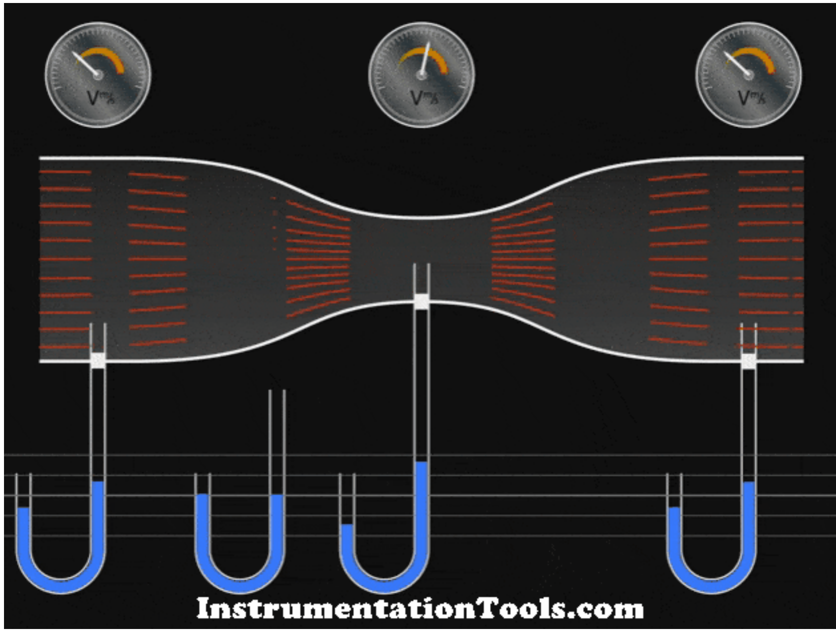
Side View

# Model Testing

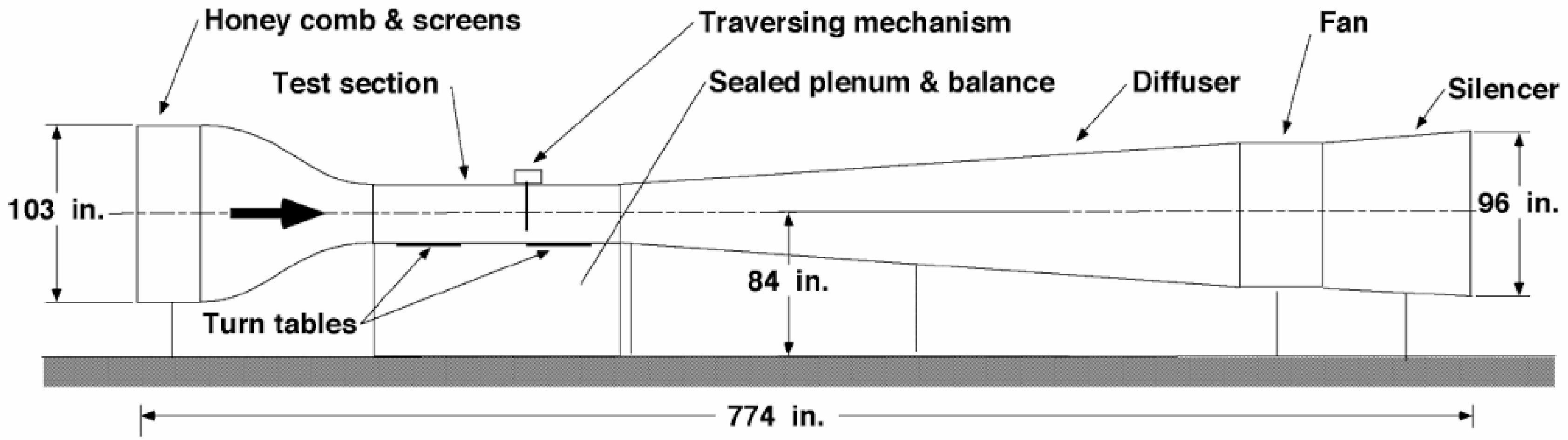
- **Aero Dynamic Force And Moments**
- **Model Size**
- **Model Geometry**

# Wind Tunnel Principles



# Low Speed Wind Tunnel and Major Parts




- Honey comb & Screen
- Contraction
- Test Section
- Diffuser
- Fan or Driving Unit
- Silencer

# Scaling Laws

- Astronomical Scaling ->
  Gravitational forces dominate on an astronomical scale
  (e.g., the earth 1 moves around the sun), but not on smaller scales
- Macro and Micro Scaling
- Geometry Scaling

**Summary**

Two types of scaling laws:

1. **The first type:** Depends on the size of physical objects.
2. **The second type:** **I**nvolves both the size and material properties of the system.

# Scaling Laws

## Scaling in Geometry

Surface and volume are two physical quantities that are frequently involved in micro-device design.

- Volume: related to the mass and weight of a device, which are related to both mechanical and thermal inertial. (thermal inertial: related to the heat capacity of a solid, which is a measure of how fast we can heat or cool a solid. → important in designing a thermal actuator)
- Surface: related to pressure and the buoyant forces in fluid mechanics, as well as heat absorption or dissipation by a solid in convective heat transfer.

# Scaling Laws

Surface to volume ration (S/V ratio)

- $S \propto l^2$ ; $S \propto l^3$
- $S/V \propto l^{-1}$
- - As the size l decreases, its S/V ratio increases

**6.7 Scaling in Fluid Mechanics**

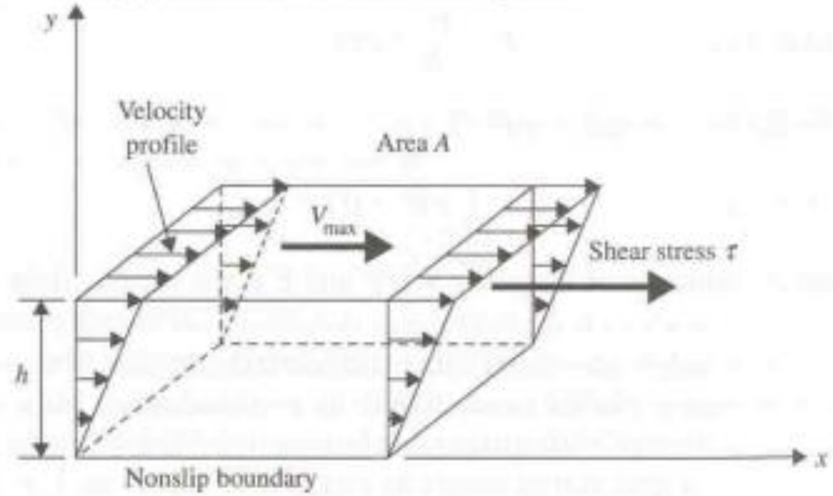
- In Fig. 6.7, moving the top plate to the right induces the motion of the fluid.
  - Newtonian flow: $\tau \propto \frac{d\theta}{dt}$, or $\tau = \mu \frac{d\theta}{dt} = \mu \frac{dV}{dy}$

    where $\tau$: shear stress; $\mu$: coefficient of viscosity (黏滯性); $d\theta/dt$: strain rate; V: fluid velocity.
  - Thus, $\mu = \frac{\tau}{R_s}$ (6.22)

    where $R_s = V_{max}/h$
  - Rate of volumetric fluid flow: $Q = A_s V_{ave}$ (6.23)

    where $A_s$: cross-sectional area for the flow; $V_{ave}$: average velocity of the fluid.

**Figure 6.7** | Velocity profile of a volume of moving fluid.




- Renolds number: $Re = \frac{\rho V L}{\mu}$

  where $\rho$: fluid density; $V$ & $L$: characteristic velocity and length scales of the flow.

  - Re ∝ (inertial forces)/(viscous force)
  - Macro flows: high inertial forces → high Re → turbulence flow
  - Micro flows: high viscosity → low Re → laminar flow

  p.s.: (1) turbulence flow: fluctuating and agitated;

  (2) laminar flow: smooth and steady;

  (3) transition from laminar to turbulent: $10^3 \sim 10^5$

# Scale Parameters

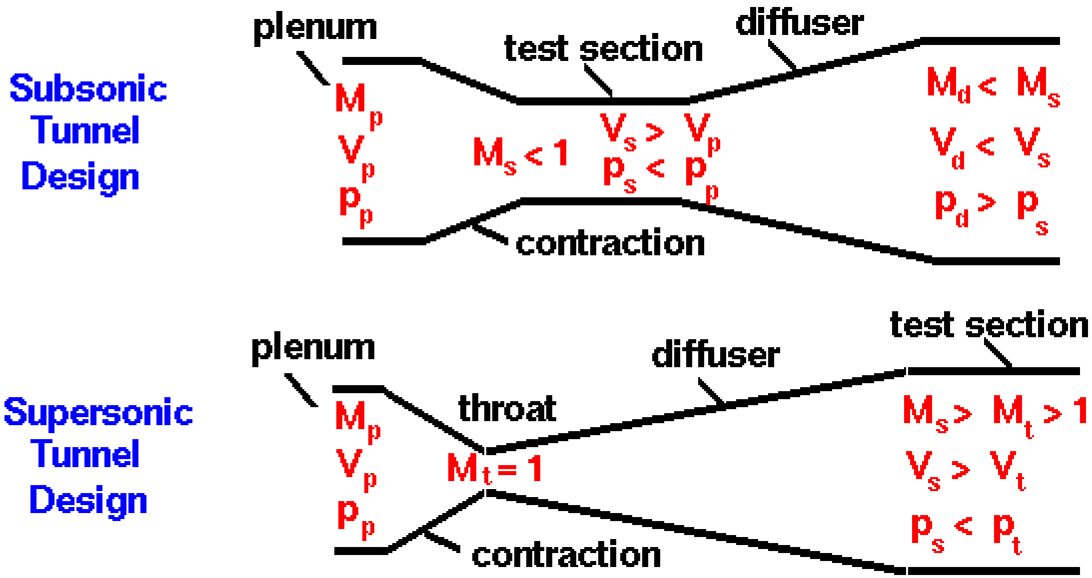
## *Wind Tunnel Design*

Increase in Area:

For subsonic flow ($M < 1$)
velocity decreases & pressure increases

For supersonic flow ($M > 1$)
velocity increases & pressure decreases

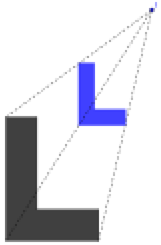
M = Mach
V = velocity
p = pressure
A = area



- Let $f(x)$ be any pdf. The family of pdfs $f(x-\mu)$ indexed by parameter $\mu$ is called the location family with standard pdf $f(x)$ and $\mu$ is the location parameter for the family.
- Equivalently, $\mu$ is a location parameter for $f(x)$ iff the distribution of $X-\mu$ does not depend on $\mu$.

# Example

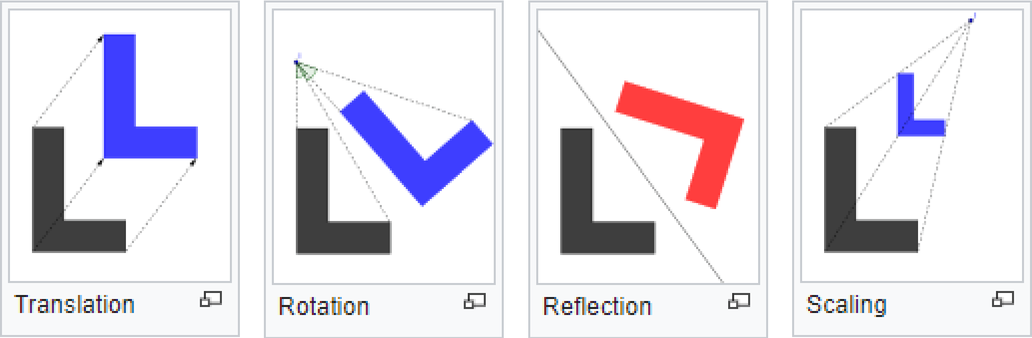
- **If X~N(θ,1), then X-θ~N(0,1) → distribution is independent of θ. → θ is a location parameter.**
- **If X~N(0,θ), then X-θ~N(-θ,θ) → distribution is NOT independent of θ. → θ is NOT a location parameter.**

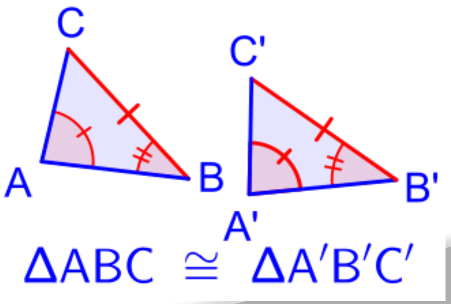




# Geometric Similarity

Two objects are **similar** if they both have the same shape, or one has the same shape as the mirror image of the other. More precisely, one can be obtained from the other by uniformly scaling (enlarging or reducing), possibly with additional translation, rotation and reflection. This means that either object can be rescaled, repositioned, and reflected, so as to coincide precisely with the other object. If two objects are similar, each is congruent to the result of a particular uniform scaling of the other.



# Geometric Similarity

Geometric similarity: *Model scale* $S = L_{WT}/L_{FL}$

Compressibility: *Mach number* $M_{WT} = M_{FL}$; $\left(\frac{V}{a}\right)_{WT} = \left(\frac{V}{a}\right)_{FL}$

Viscous effects: *Reynolds number* $Re_{WT} = Re_{FL}$; $\left(\frac{\rho V L}{\mu}\right)_{WT} = \left(\frac{\rho V L}{\mu}\right)_{FL}$

Wall stagnation temperature ratio: $\left(\frac{T_w}{T_0}\right)_{WT} = \left(\frac{T_w}{T_0}\right)_{FL}$

# Kinematic Similarity & Dynamic Similarity

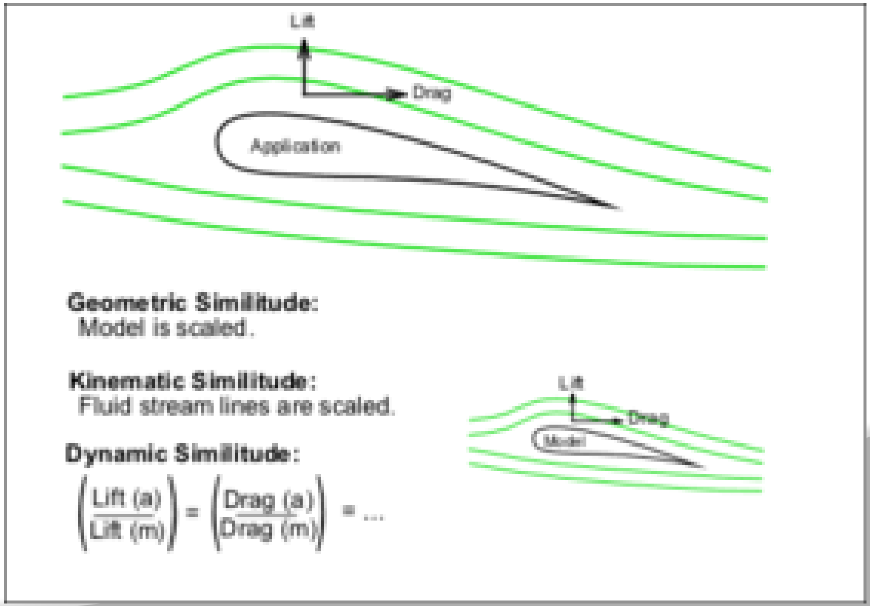
**Kinematic similarity** – fluid flow of both the model and real application must undergo similar time rates of change motions. (fluid streamlines are similar)

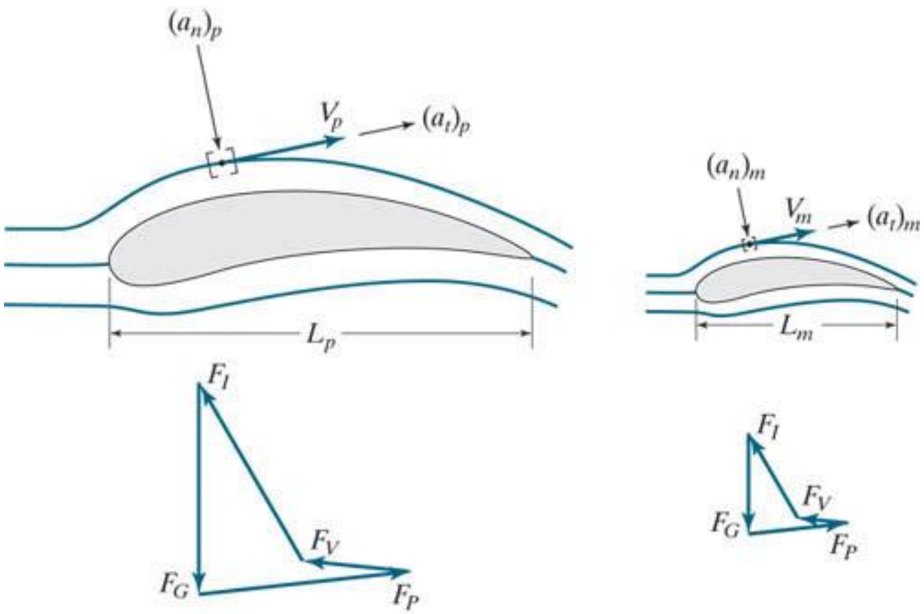
**Dynamic similarity** – ratios of all forces acting on corresponding fluid particles and boundary surfaces **in the** two systems are constant.

## 2. Kinematics similarity

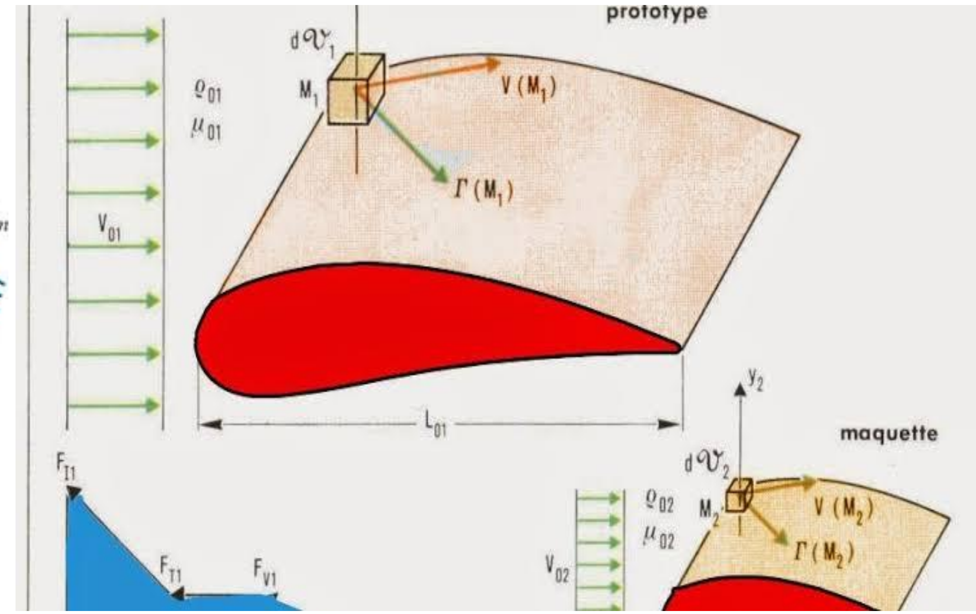
- The kinematic similarity exist between model and prototype, if both of them have identical motions.
- The ratio of the corresponding velocity at corresponding points are equal.

$$V_r = \frac{(V_1)_m}{(V_1)_p} = \frac{(V_2)_m}{(V_2)_p} = \frac{(V_3)_m}{(V_3)_p}$$






(a) Prototype (b) Model



# Dynamic Similarity

The dynamic similarity is said exist between model and prototype if the ratios of corresponding **forces** acting at the corresponding points are equal

$$\frac{F_p}{F_m} = F_r$$

where $F_r$ is Force Ratio

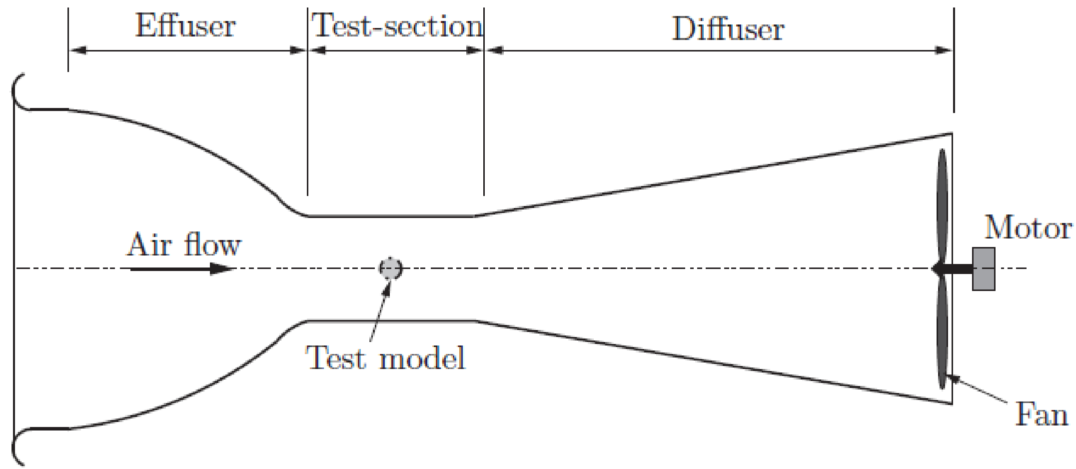
It means for dynamic similarity between the model and prototype, the dimensionless numbers should be same for model and prototype.

## Wind Tunnels:

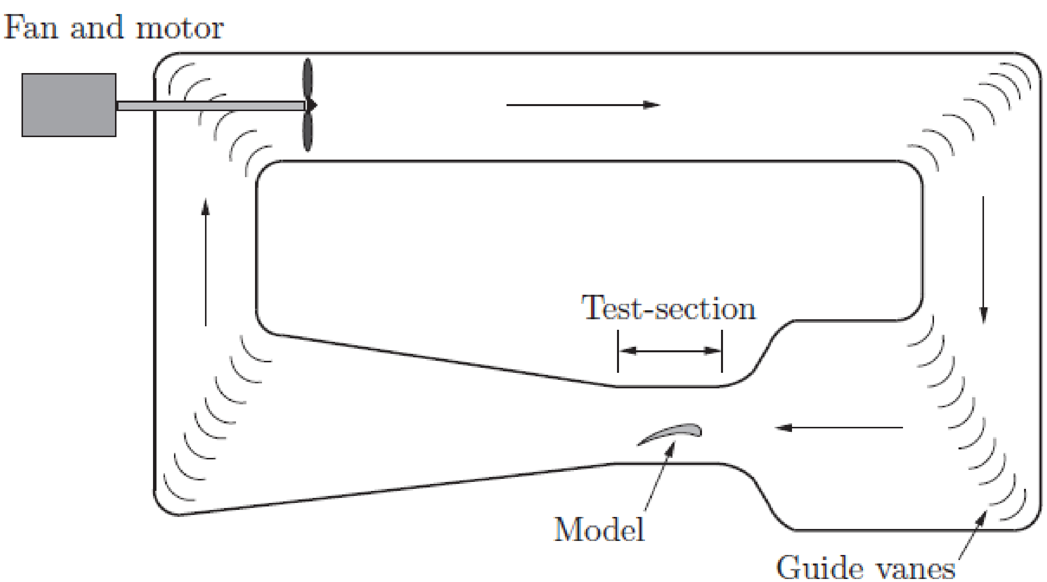
- Low Speed Tunnel
- High Speed Tunnels
- Transonic
- Supersonic
- Hypersonic Tunnels
- Shock Tubes

# Low Speed Tunnel

Open-circuit Tunnels




Closed-circuit Wind Tunnel



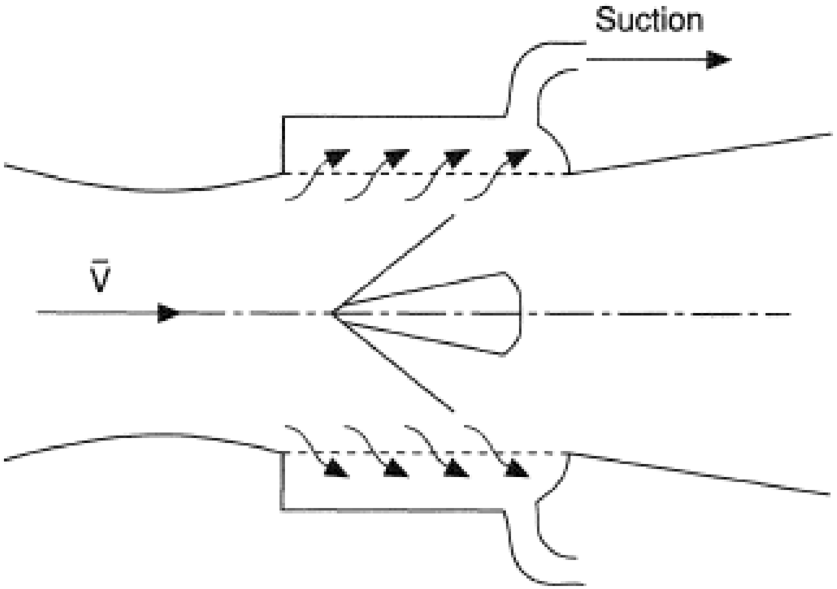
# High Speed Tunnels

1. $0.8 < M < 1.2$ Transonic tunnel
2. $1.2 < M < 5$ Supersonic tunnel
3. $M > 5$ Hypersonic tunnel

$$M = \frac{Pessure\ Force}{Inertia\ Force} = \frac{Speed\ of\ Object}{Speed\ of\ Sound} = \frac{V}{a}$$

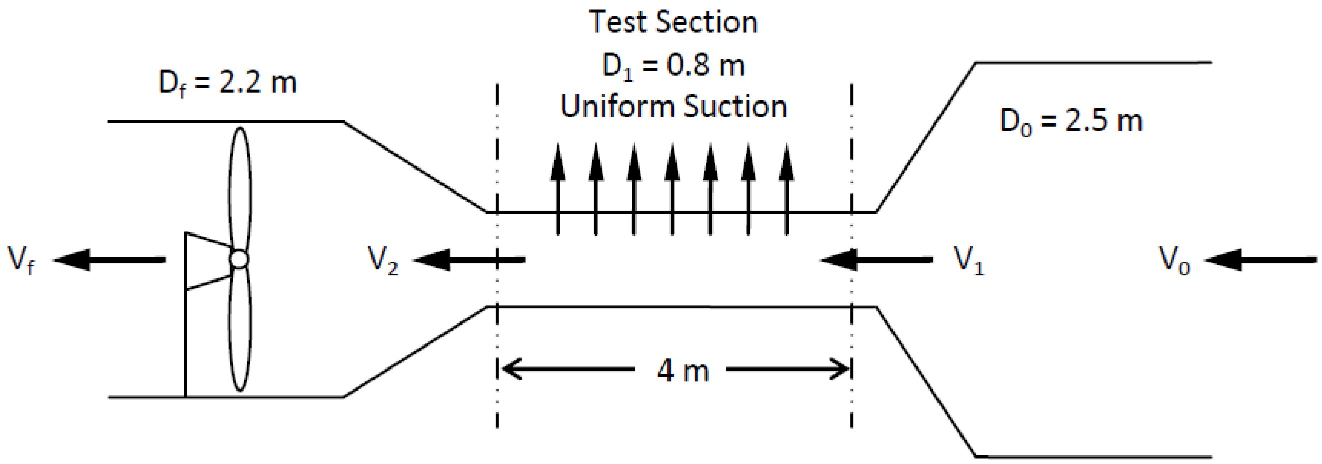
*Where* $a=\sqrt{(\gamma RT)}$

# Transonic Windtunnel



# Transonic Windtunnel

Problem 2. In some wind tunnels, the test section wall is porous or perforated; fluid is sucked out to provide a thin, viscous boundary layer. The wall is 4 m long and contains 800 holes of 6 mm diameter per square meter of area. The suction velocity out of each hold is $V_s$ = 10 m/s, and the test section entrance velocity is $V_1$ = 45 m/s. Assuming incompressible flow of air at 20°C and 1 atm, compute (a) $V_0$, (b) the total wall suction volume flow, (c) $V_2$, and (d) $V_f$.

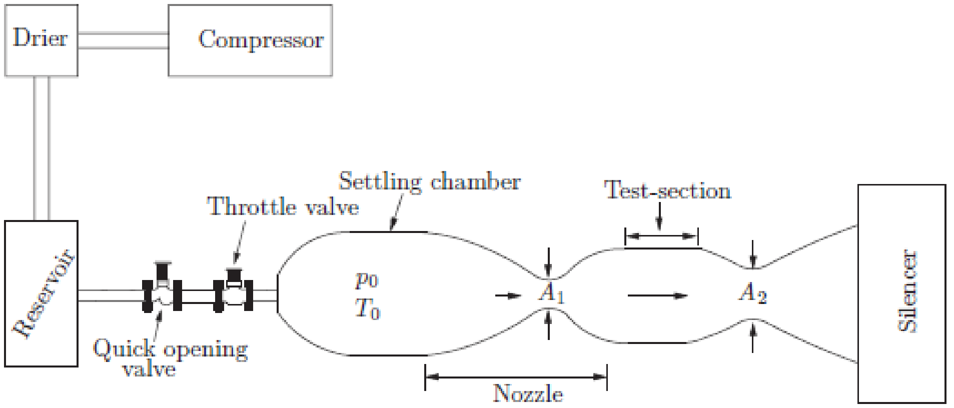


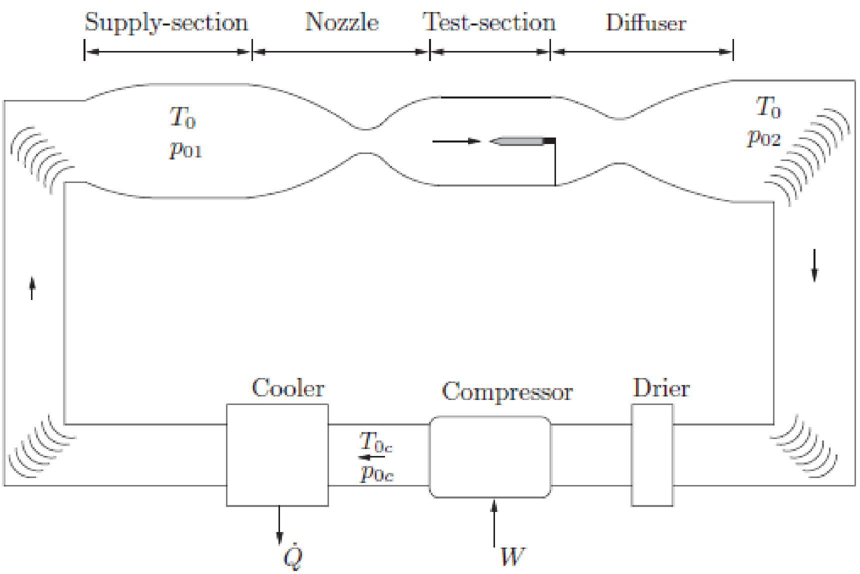
# Supersonic

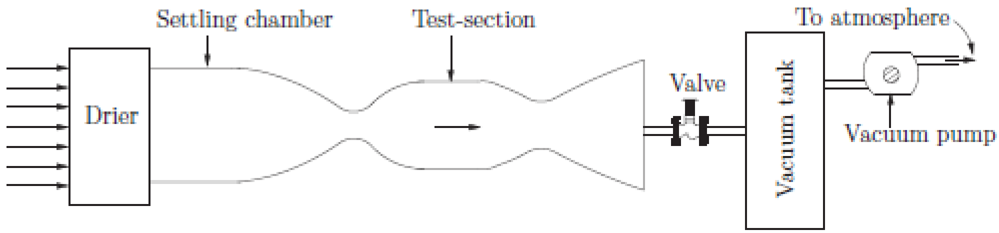
- ❖ Blowdown–Type Wind Tunne

- ❖ Induction–Type Tunnels

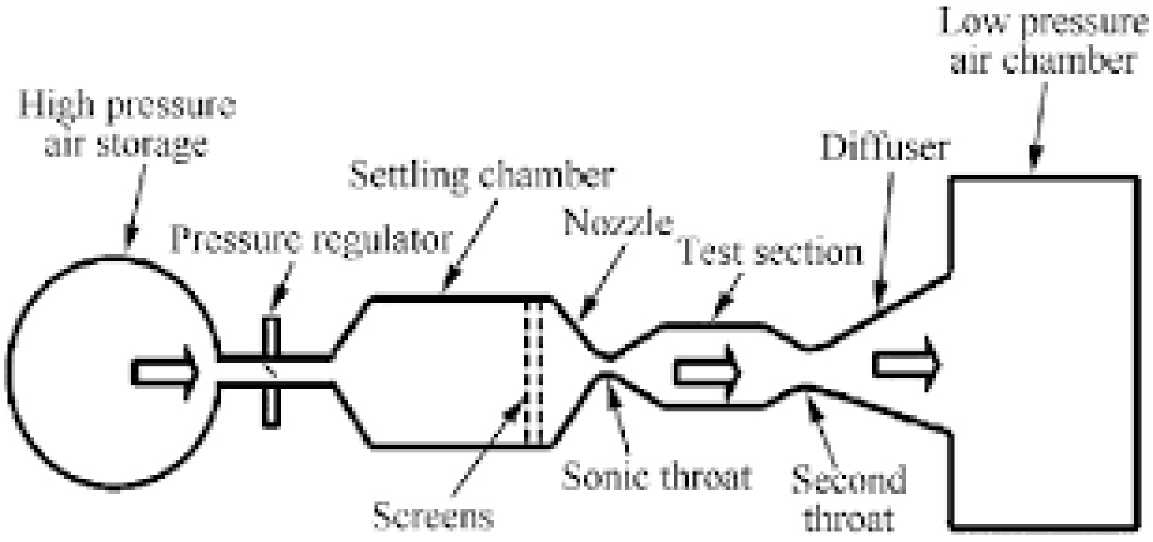
- ❖ Closed-circuit Wind Tunnels



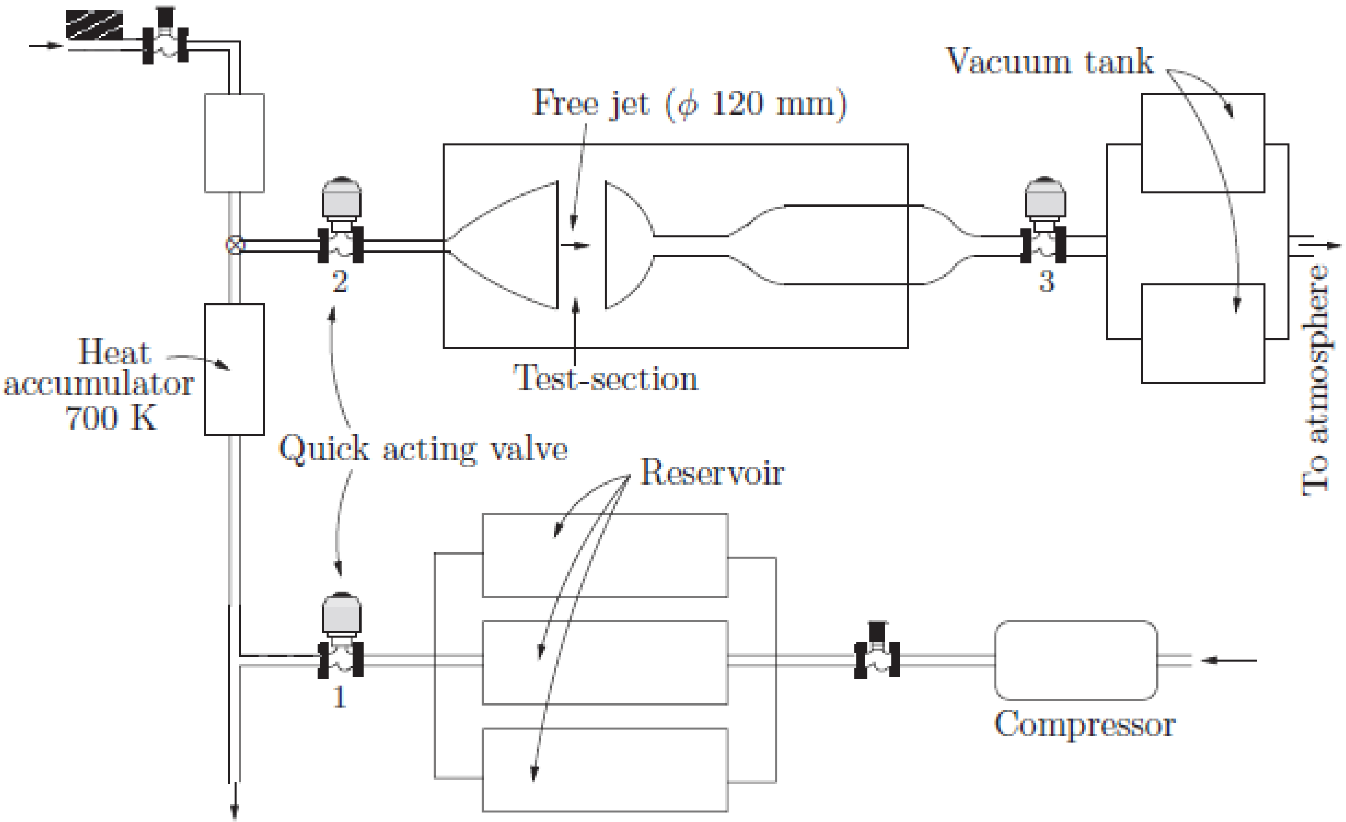



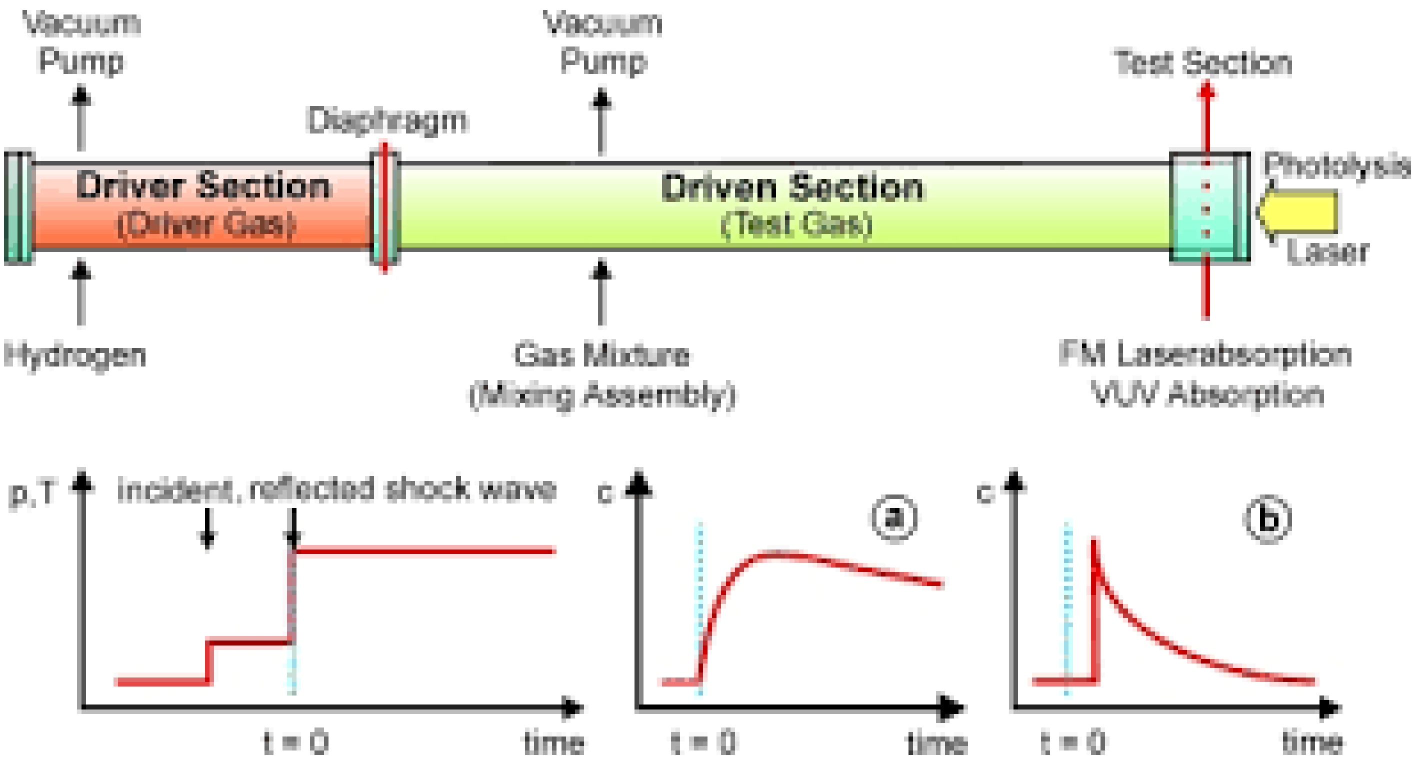
# Blowdown–Type Wind Tunnels



# Hypersonic Tunnels



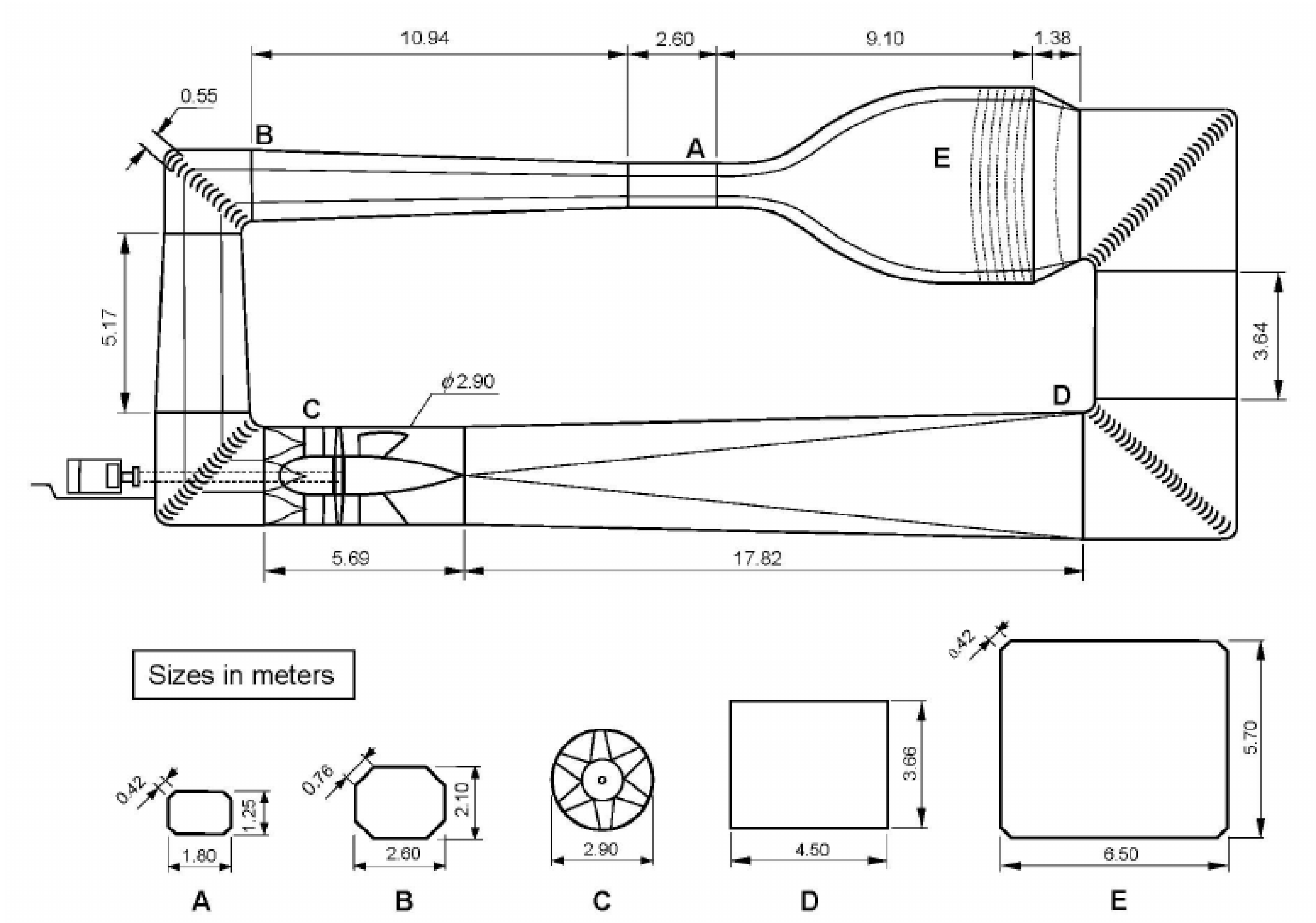
# Shock Tubes


Vacuum Pump
Vacuum Pump
Test Section
Diaphragm
Driver Section
(Driver Gas)
Driven Section
(Test Gas)
Photolysis
Laser
Hydrogen
Gas Mixture
(Mixing Assembly)
FM Laserabsorption
VUV Absorption
p,T
Incident, reflected shock wave
t = 0
time
c
a
t = 0
time
c
b
t = 0
time

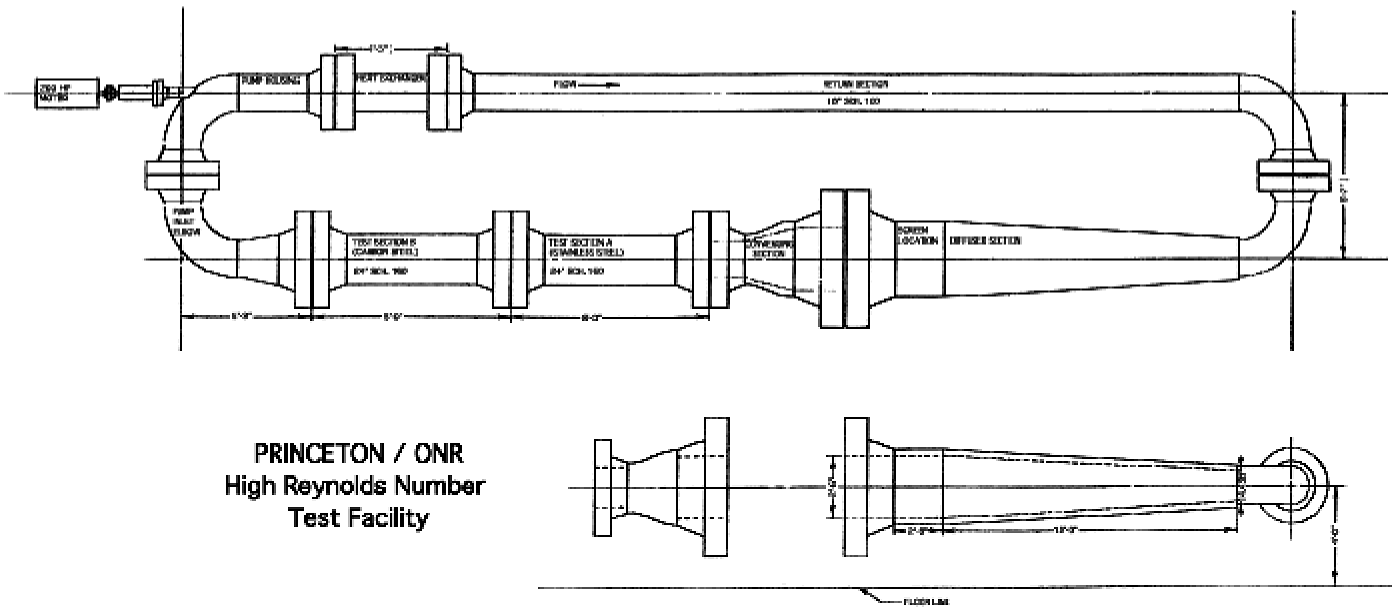
# Special Tunnels:

- **Special Tunnels:**
  - **Low Turbulence Tunnels**
  - **High Reynolds Number Tunnels**
  - **Environmental Tunnels**
  - **Automobile Tunnels**

# Low Turbulence Tunnels

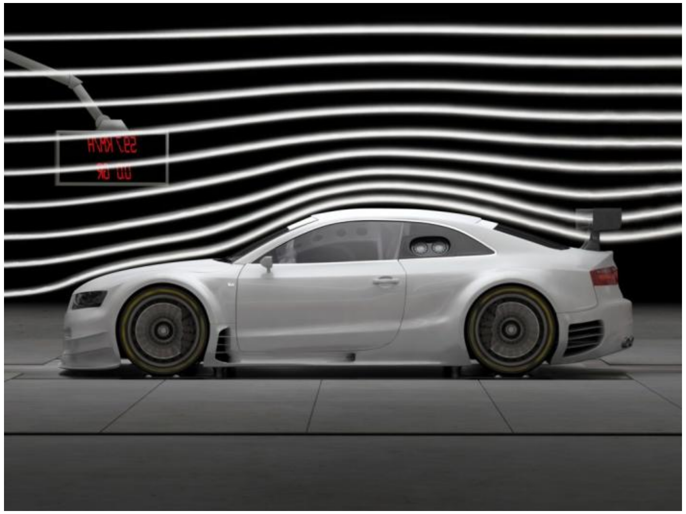


# High Reynolds Number Tunnels

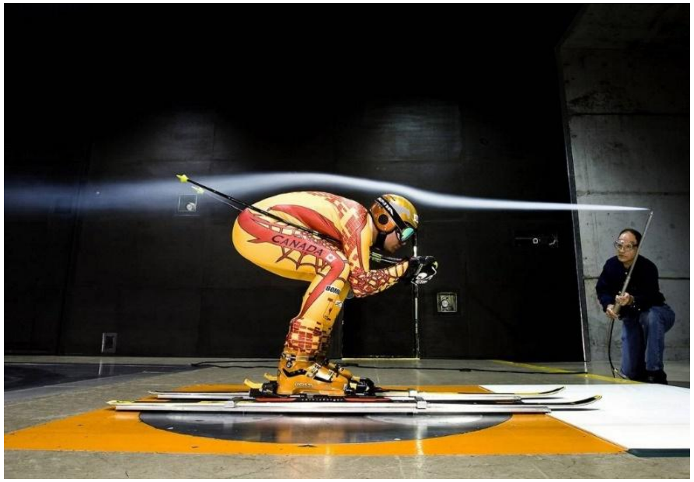


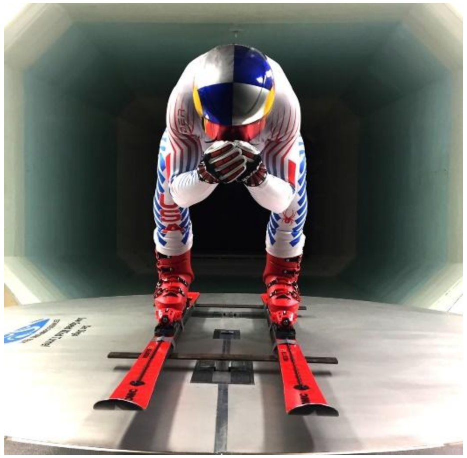
# Environmental Tunnels

# Automobile Tunnels

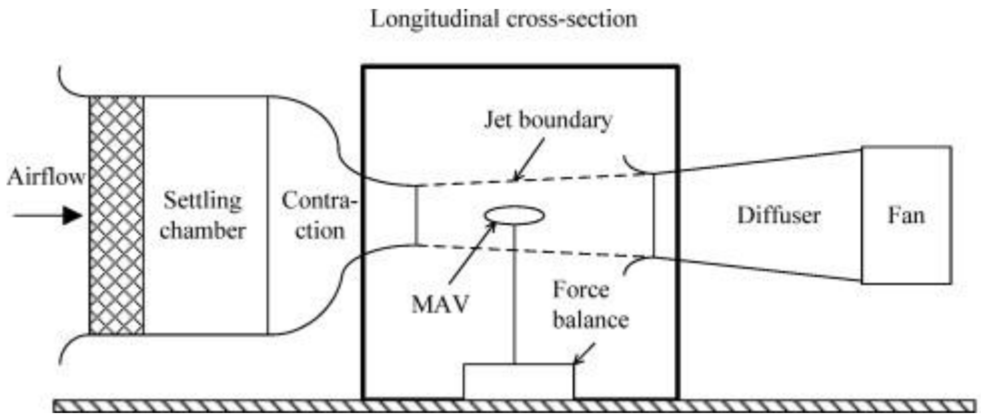


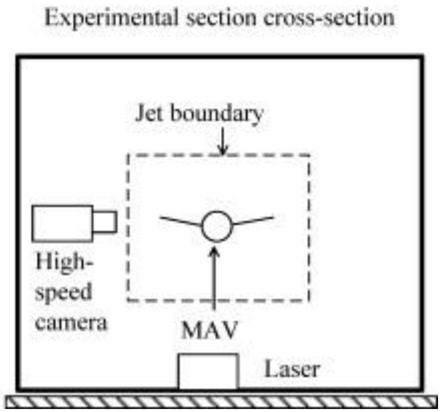
## Application

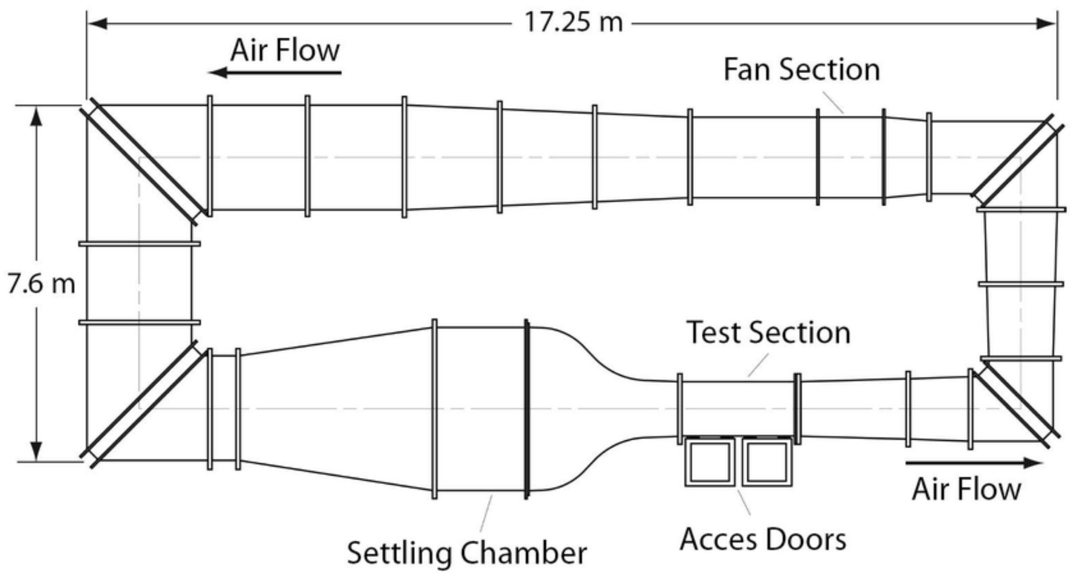




# Low Speed Wind Tunnels



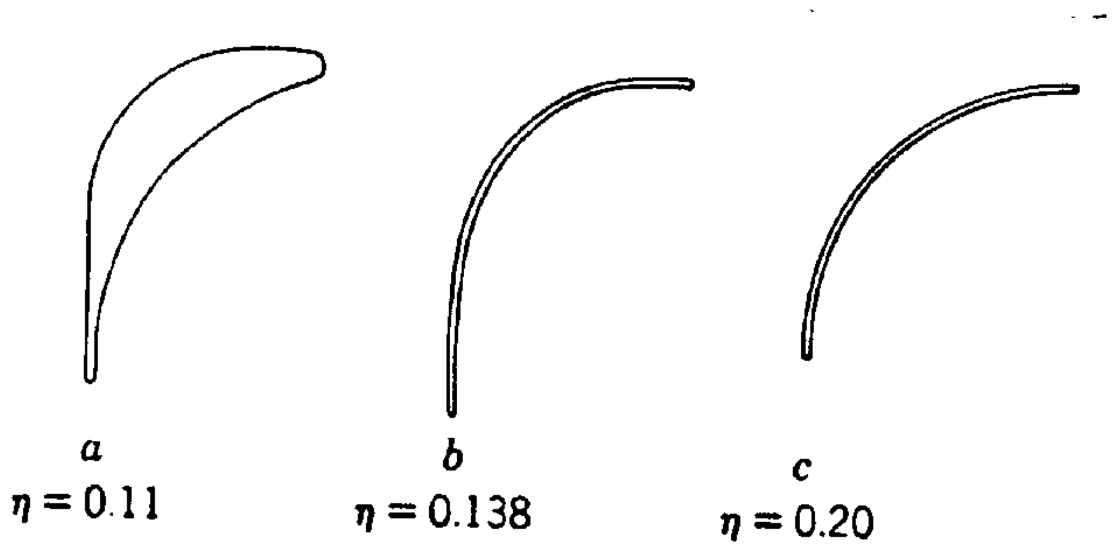



## Principal Components

- Settling Chamber
- Contraction Cone
- Test Section
- Diffuser
- Drive Section.

# Corners

$$\eta = 1.0$$



# Function

Stilling Section - Low speed and uniform flow

Honeycomb - Reduces Large Swirl Component of Incoming Flow

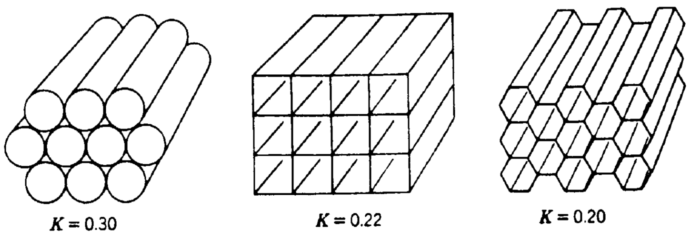



Fig. 2:16 Some honeycombs and their losses.

Screens - Reduce Turbulence [Reduces Eddy size for Faster Decay]
- Used to obtain a uniform test section profile
- Provide a flow resistance for more stable fan operation

# Test Section

Test Section - Design criteria of Test Section Size and Speed Determine Rest of Tunnel Design

Test Section Reynolds Number
Larger JET - Lower Speed - Less Power - More Expensive

Section Shape - Round-Elliptical, Square, Rectangular-Octagonal with flats for windows-mounting platforms
Rectangular with filled corners
Not usable but requies power

For Aerodynamics Testing 7x10 Height/Width Ratio

Test Section Length - L = (1 to 2)w

# Energy Ratio

$$(E.R.)_t = \frac{\text{Jet Energy}}{\sum \text{Circuit Losses}} = \frac{1/2\rho_0 U_0^3 A_0}{\sum \text{Losses}} = \frac{q_0 U_0 A_0}{\eta P}$$

Subscript 0 refers to the test section

P is the motor power

$\eta$ is the fan efficiency

# Design Requirements

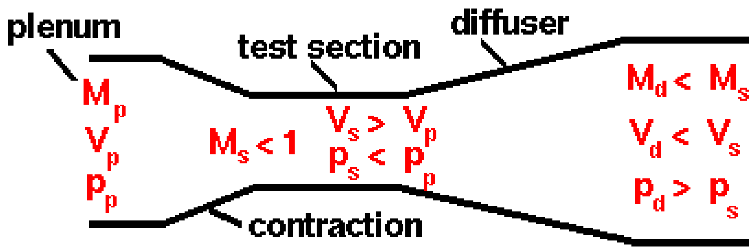
## *Wind Tunnel Design*

**Increase in Area :**

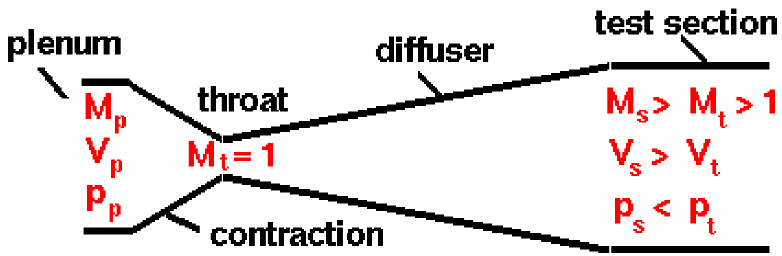
For subsonic flow ( M < 1)
velocity decreases & pressure increases
For supersonic flow ( M > 1)
velocity increases & pressure decreases

M = Mach
V = velocity
p = pressure
A = area

**Subsonic Tunnel Design**




**Supersonic Tunnel Design**



# Losses

$$K = \frac{p_{t1} - p_{t2}}{q}$$

Local Pressure Loss Coefficient

$$K_0 = \frac{p_{t1} - p_{t2}}{q_0} = K \frac{q}{q_0}$$

Pressure Loss Referred to Test Section

$$\Delta E = K_0 1/2 \rho_0 U_0^3 A_0$$

Section Energy Loss

$$(E.R.)_t = \frac{\text{Jet Energy}}{\sum \text{Circuit Losses}} = \frac{1/2 \rho_0 U_0^3 A_0}{\sum \mathrm{K}_0 1/2 \rho_0 U_0^3 A_0} = \frac{1}{\sum K_0}$$

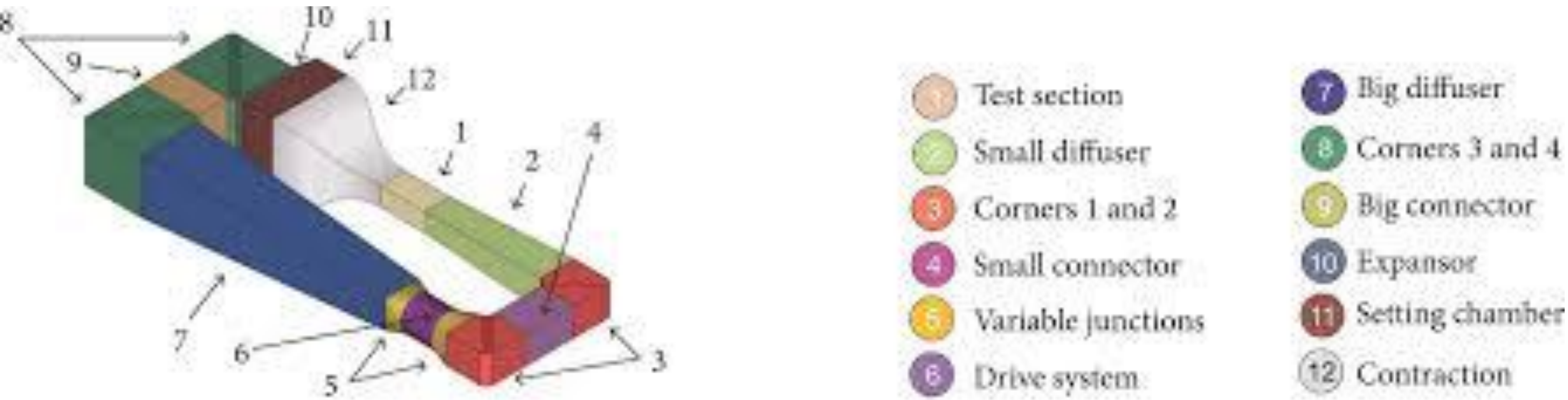
# Constraints And Loss Coefficients.

## Example Open Return Tunnel

| | Section | Ko | % Total Loss |
|---|---|---|---|
| 1 | Inlet Including Screens | .021 | 14.0 |
| 2 | Contraction and Test Section | .013 | 8.6 |
| 3 | Diffuser | .080 | 53.4 |
| 4 | Discharge at Outlet | .036 | 24.0 |
| | **Total** | **.150** | **100.0** |

$$(E.R.)_t = \frac{1}{\sum K_0} = \frac{1}{.150} = 6.67$$

# Wind Tunnel Performance Flow Quality



# Power Losses

$$\text{Reynolds number} = \frac{\text{inertia force}}{\text{viscous force}} = \frac{\rho}{\mu}Vl$$

$$\text{Mach number} = \frac{\text{inertia force}}{\text{elasticity force}} = \frac{V}{a}$$

$$\text{Froude number} = \sqrt{\frac{\text{inertia force}}{\text{gravity force}}} = \sqrt{\frac{V^2}{lg}}$$

# Wind Tunnel Corrections

## Wall Interference

- It is a major concern for wind tunnel design, model shape and experimental techniques
- Wind Tunnel Walls effect the free flow conditions and needs to be corrected in measurements
- It becomes most serious when the airflow began to choke in the transonic range.

$$\text{Blockage Ratio (BR)} = \frac{\text{Projected Area of the Model}}{\text{Projected Area of Wind Tunnel Test Section}}$$

- Models with higher blockage ratios create more wall interference

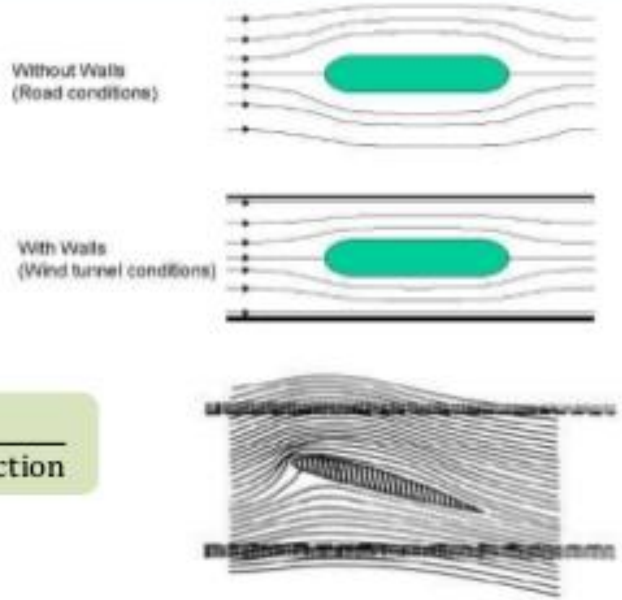
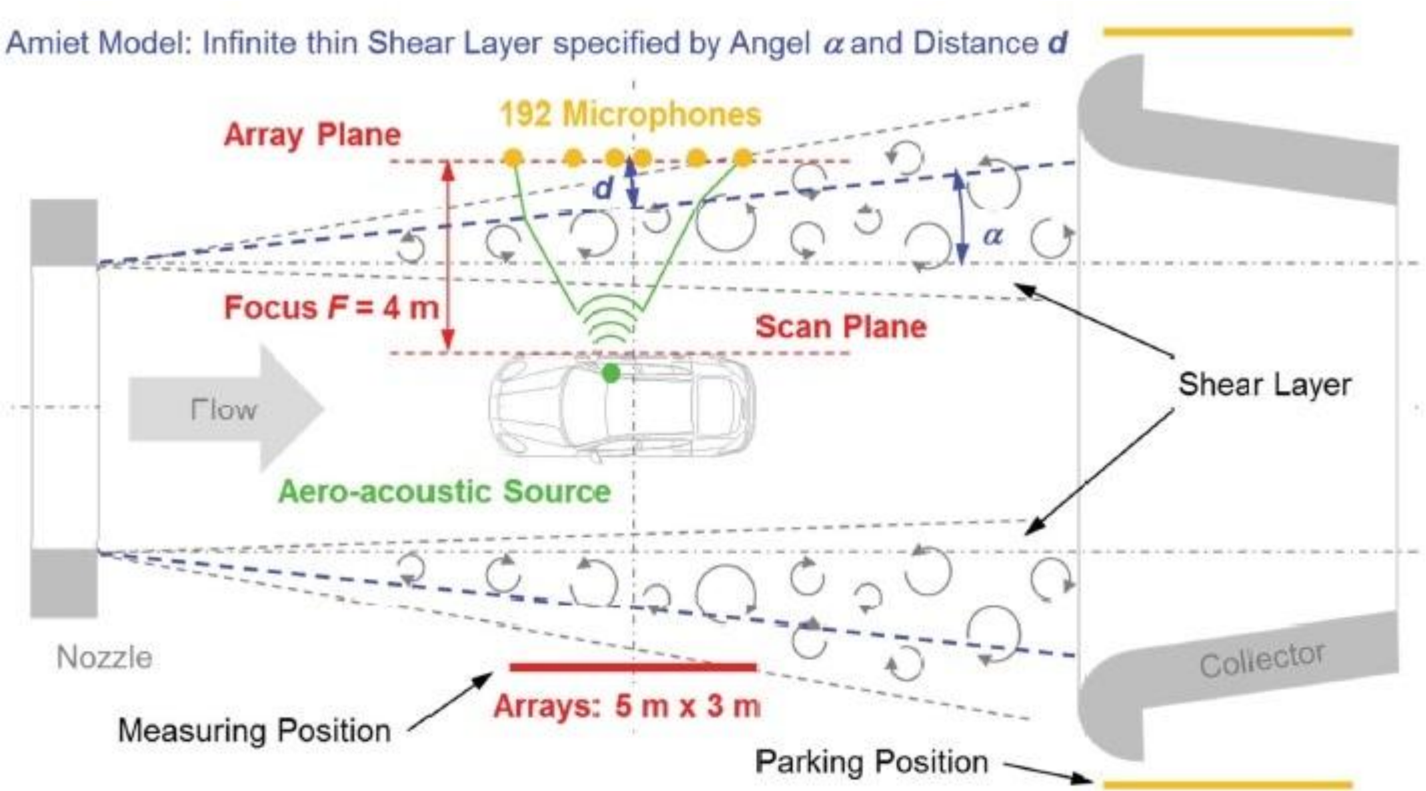
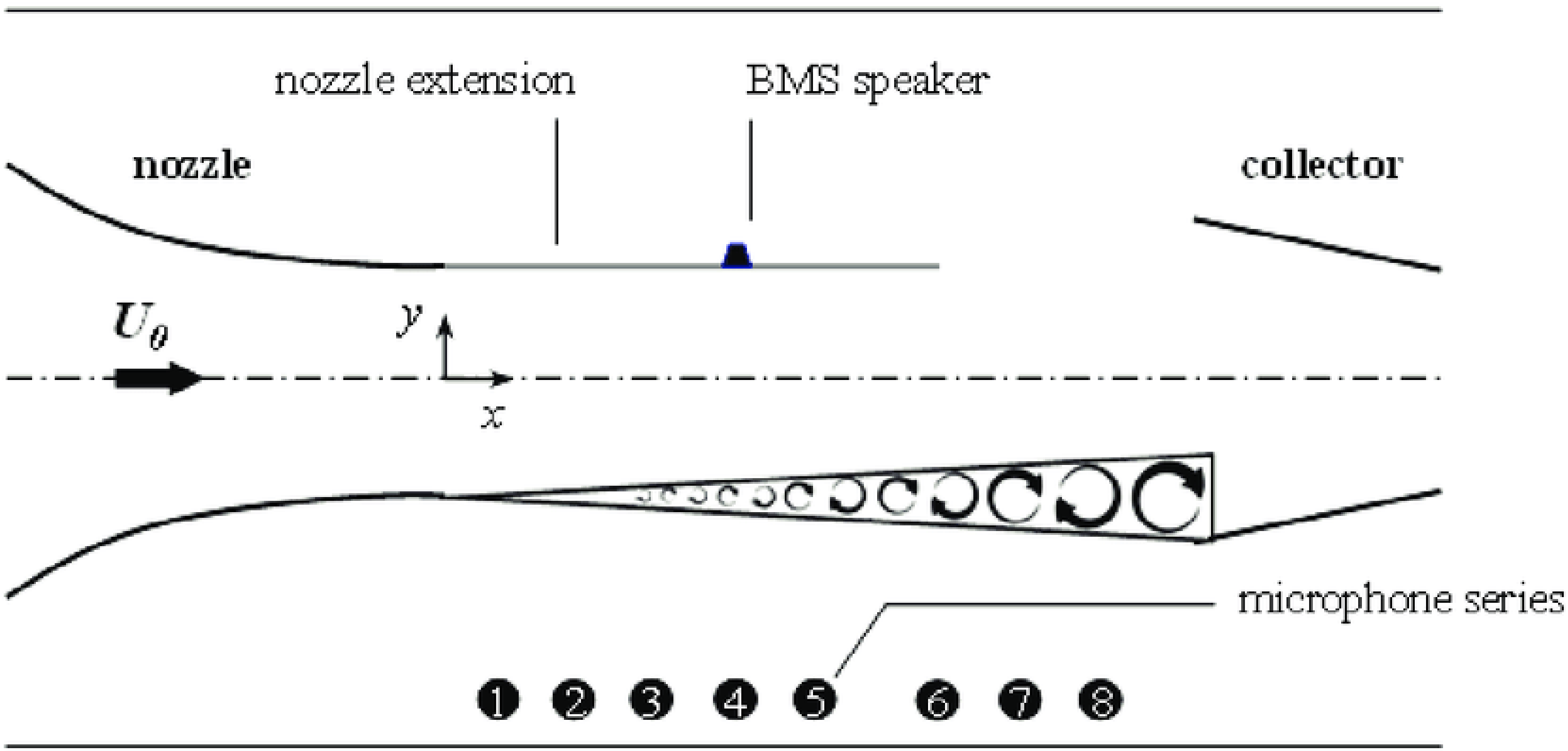



*Figure: Constraining effect of streamlines due to wall interference (Courtesy: NASA)*

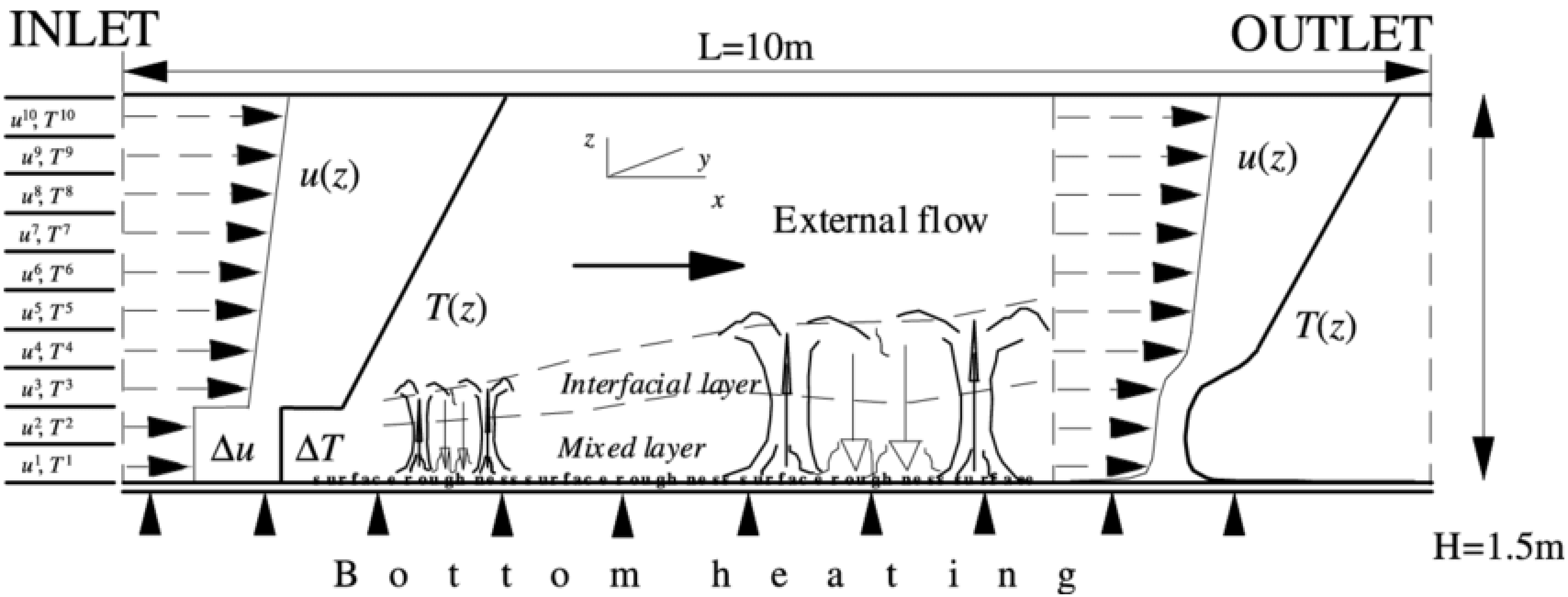
5

# Sources of Inaccuracies

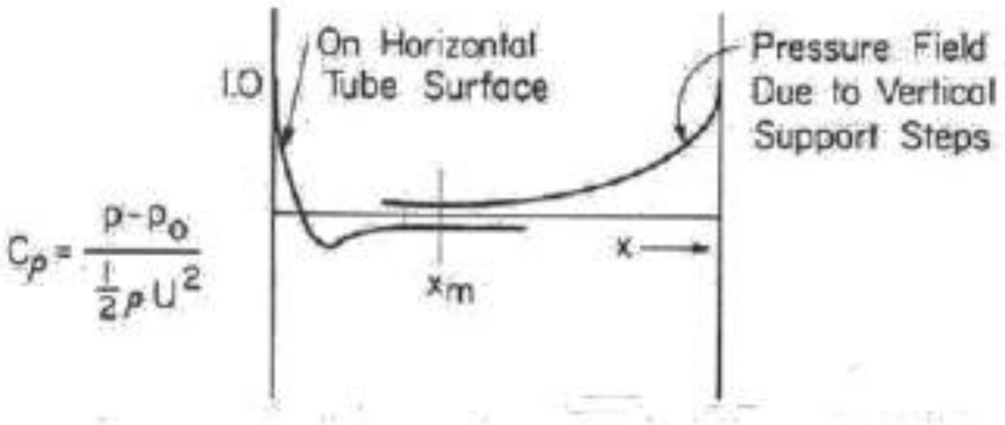



nozzle extension
BMS speaker
nozzle
collector
$U_0$
y
x
microphone series
1 2 3 4 5 6 7 8

# Buoyancy

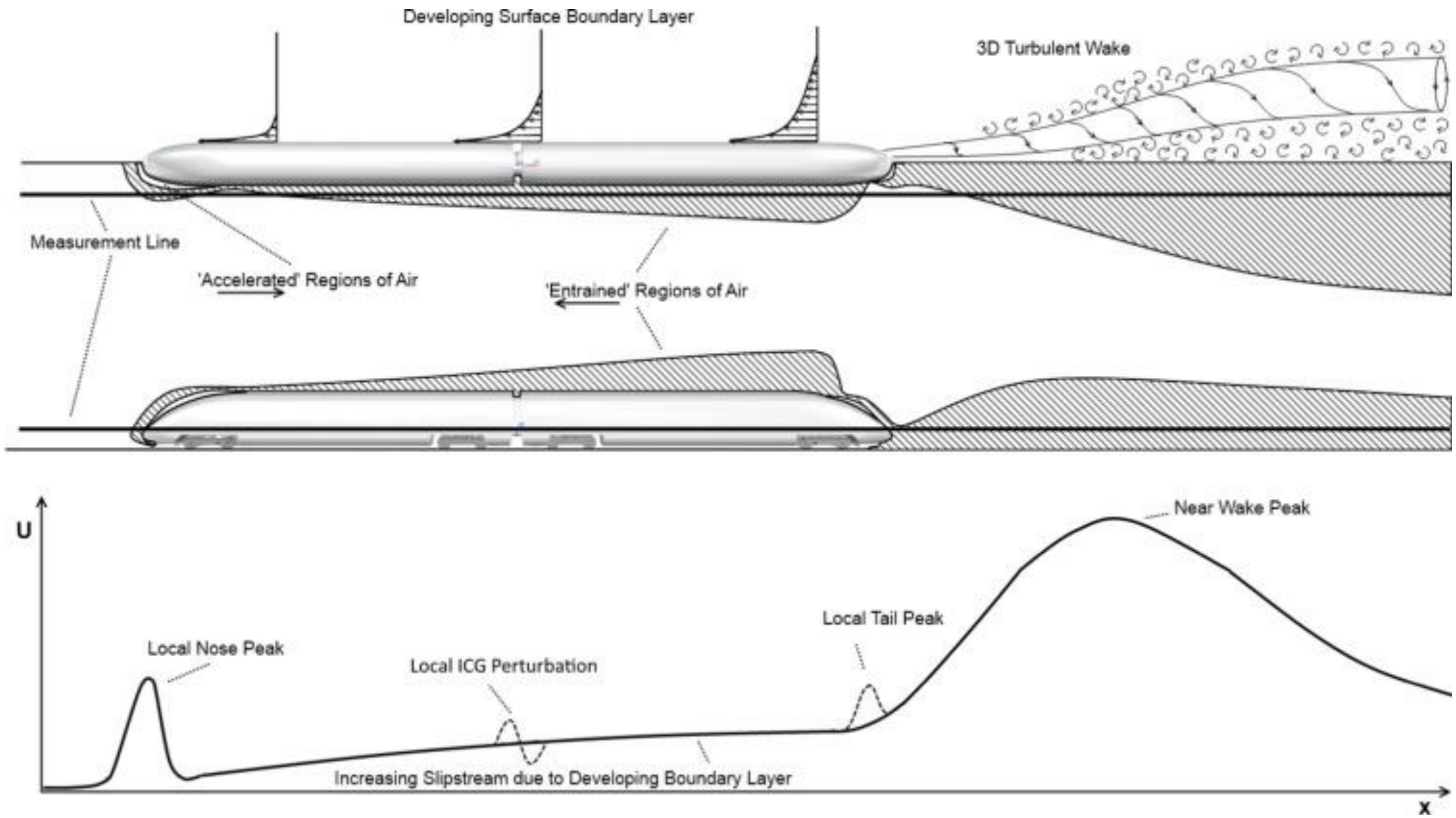

INLET
L=10m
OUTLET
u(z)
T(z)
External flow
Interfacial layer
Mixed layer
Δu
ΔT
H=1.5m
B o t t o m h e a t i n g

# Solid Blockage

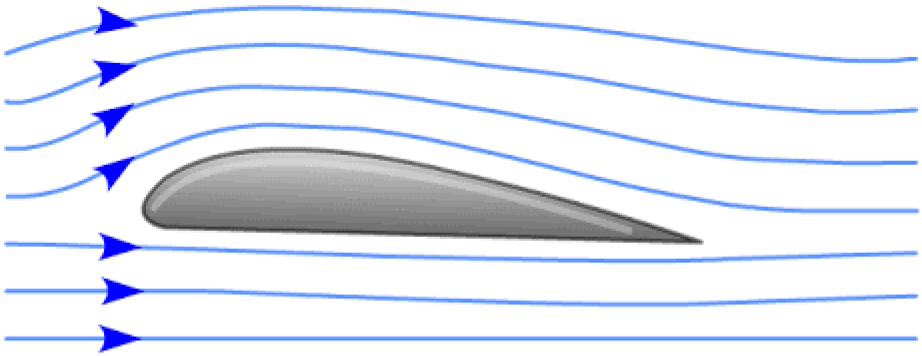



- Nose acceleration and probe support effects may compensate

# Wake Blockage



# Streamline Curvature Causes



The shape of wing forces air to move faster over the top surface.

# WIND TUNNEL BALANCE

## Load Measurement:

1. Low Speed Wind Tunnel Balances
2. Mechanical & Strain Gauge Types
3. Null Displacement Methods & Strain Method
4. Sensitivity
5. Weigh Beams
6. Steel Yard Type
7. Current Balance Type
8. Balance Linkages
9. Levers and Pivots

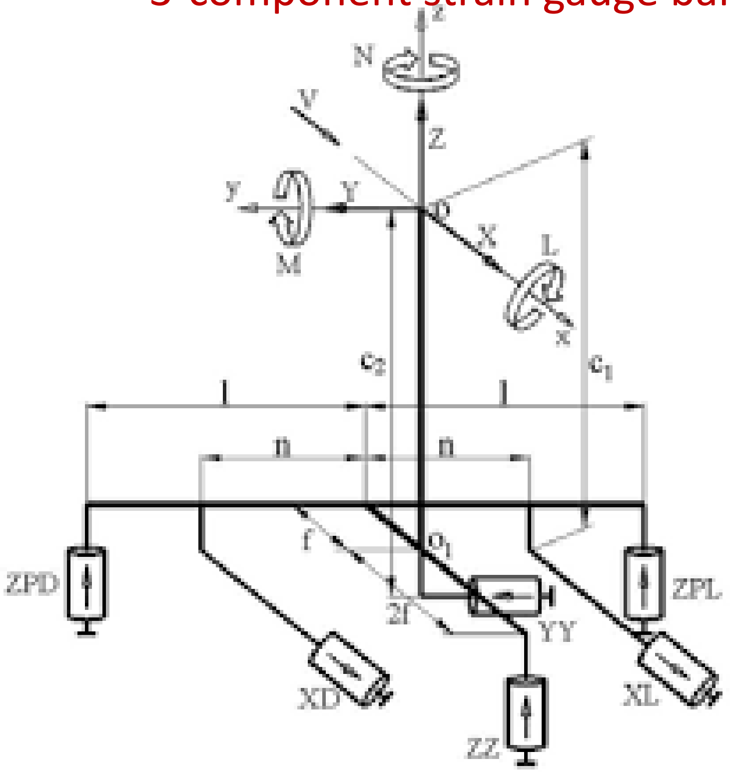
## Model Support

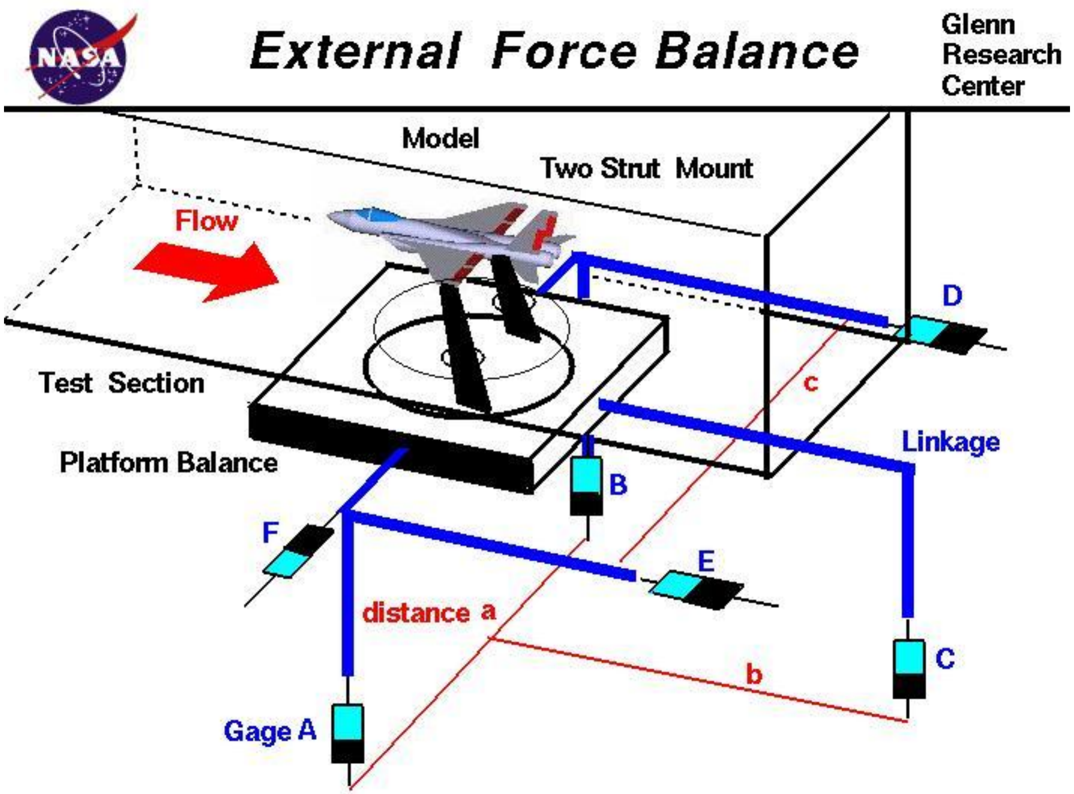
1. Three Point Wire Support
2. Three Point Strut Support
3. Platform Balance
4. Yoke Balance
5. Strain Gauge
6. 3-component Strain Gauge Balance
7. Description and Application

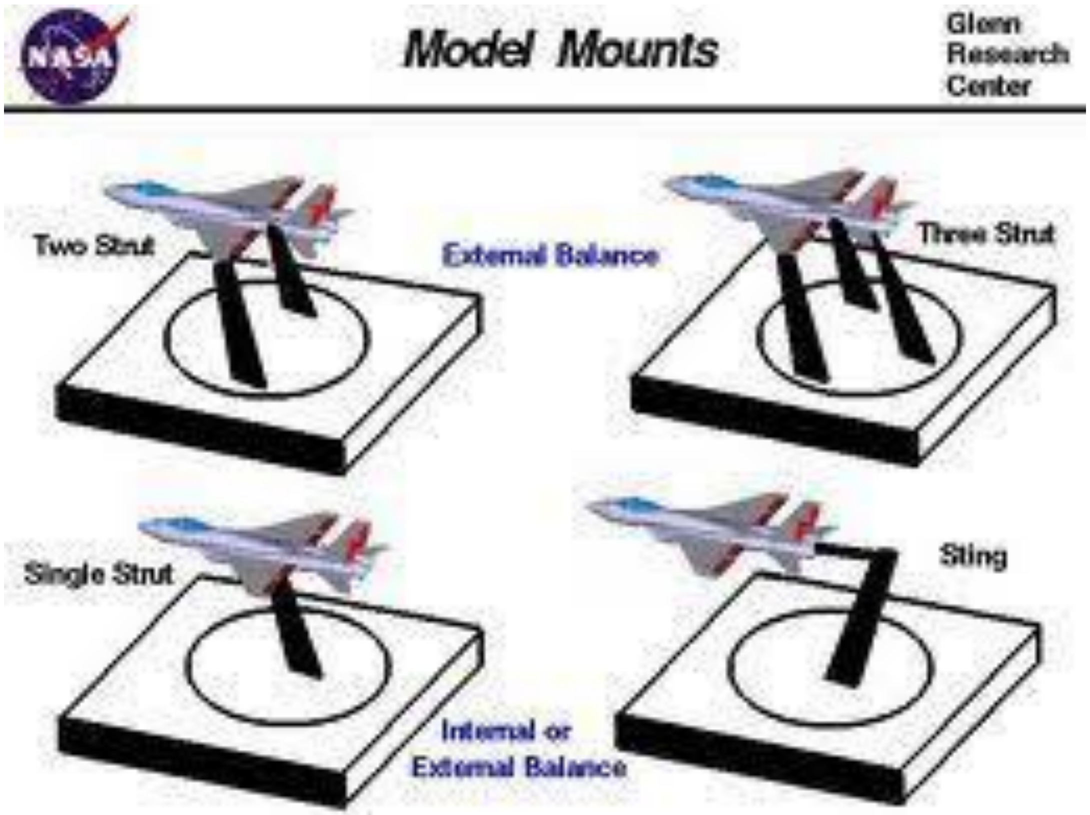
# Balance Linkages, Levers And Pivots

# Model Support Three Point Wire Support

3-component strain gauge balance

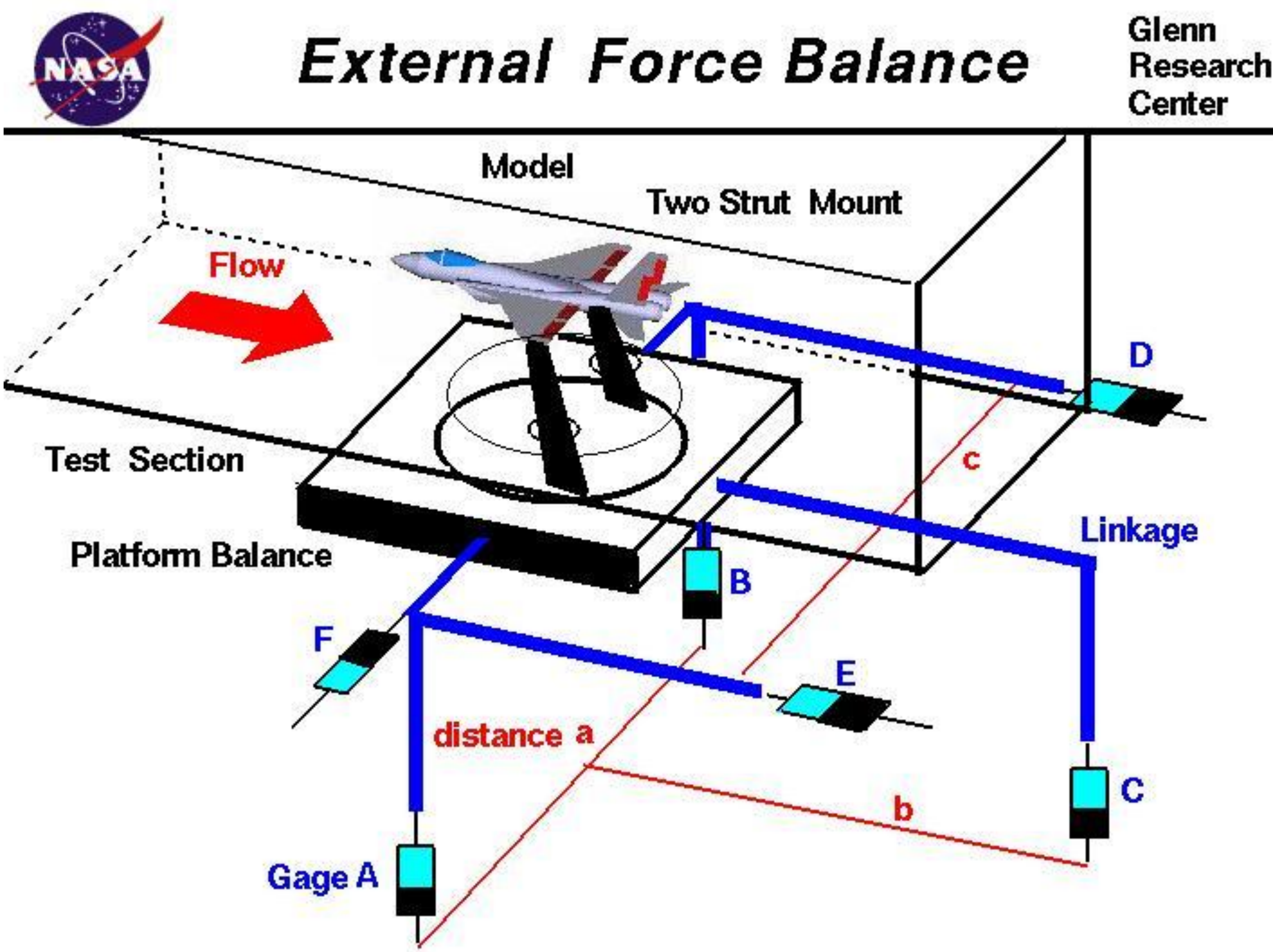



NASA
External Force Balance
Glenn
Research
Center
Model
Two Strut Mount
Flow
Test Section
Platform Balance
D
c
Linkage
B
F
E
distance a
b
C
Gage A

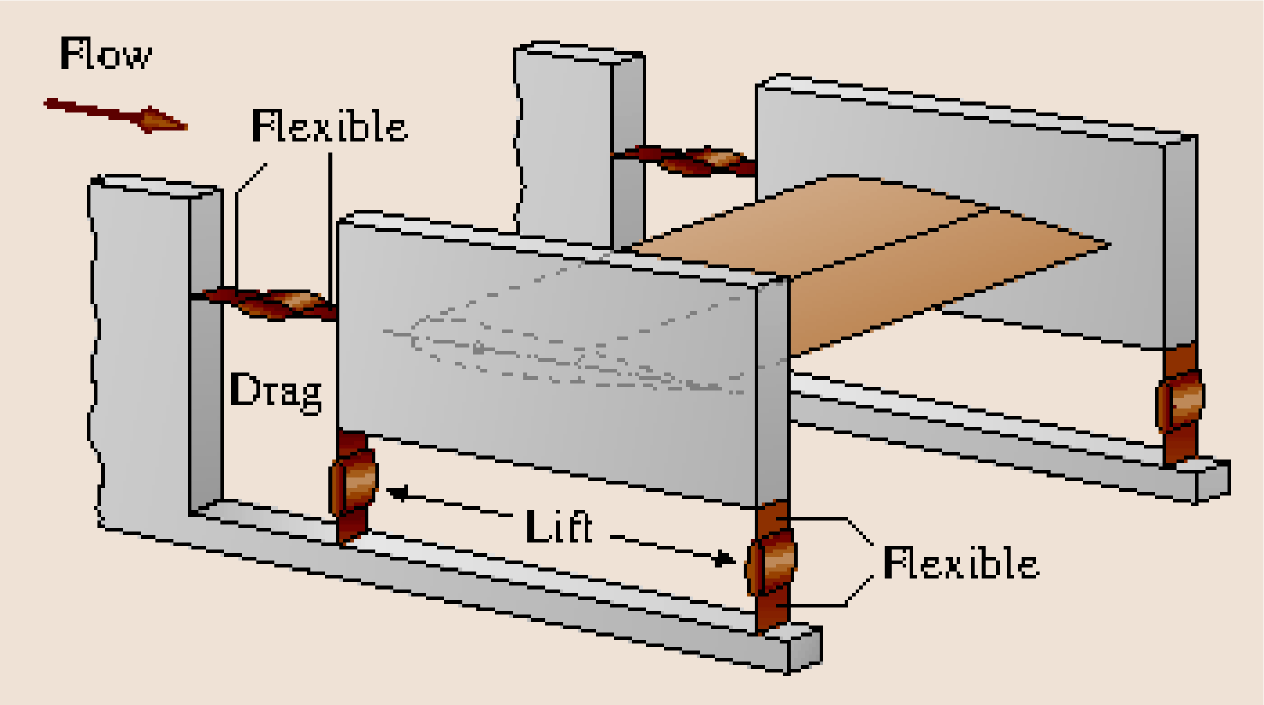

Model Mounts
Glenn
Research
Center
Two Strut
External Balance
Three Strut
Single Strut
Sting
Internal or
External Balance

# Three Point Strut Support

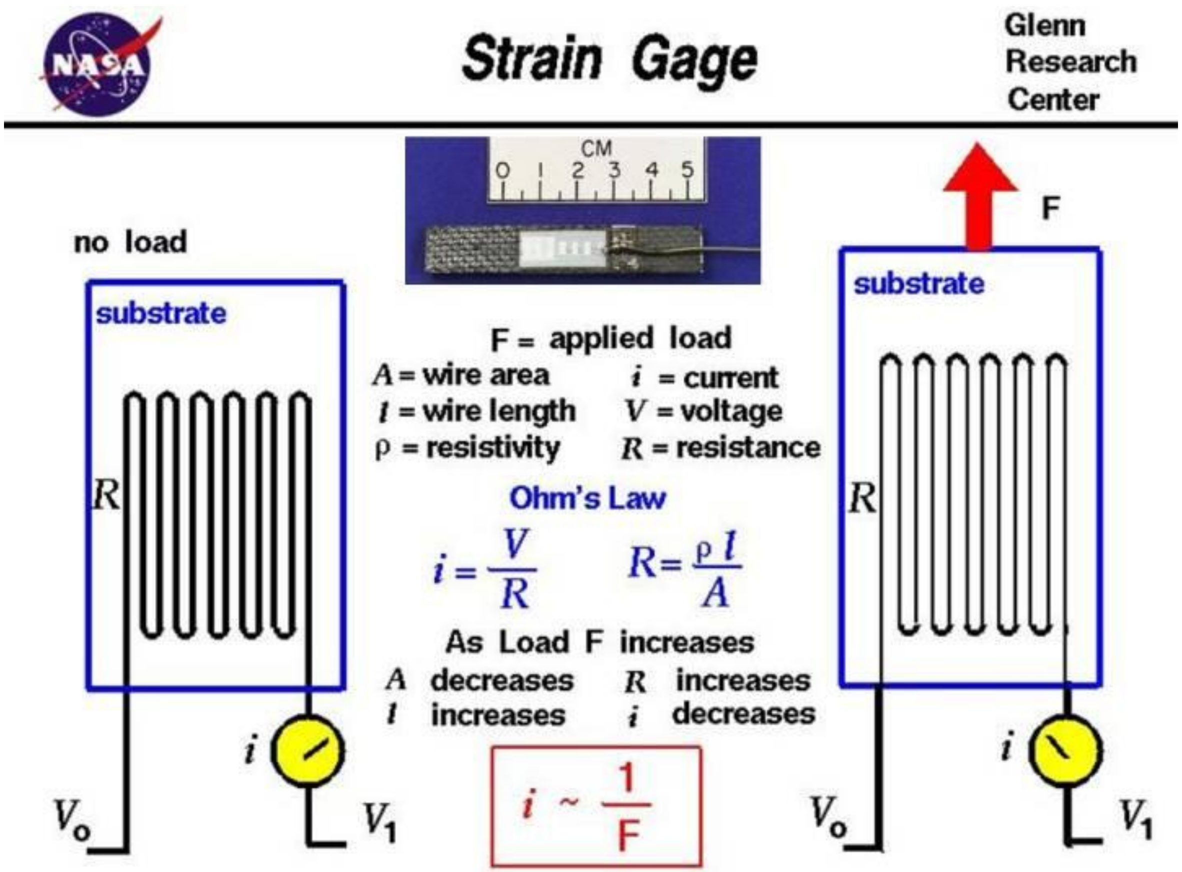
# Platform Balance



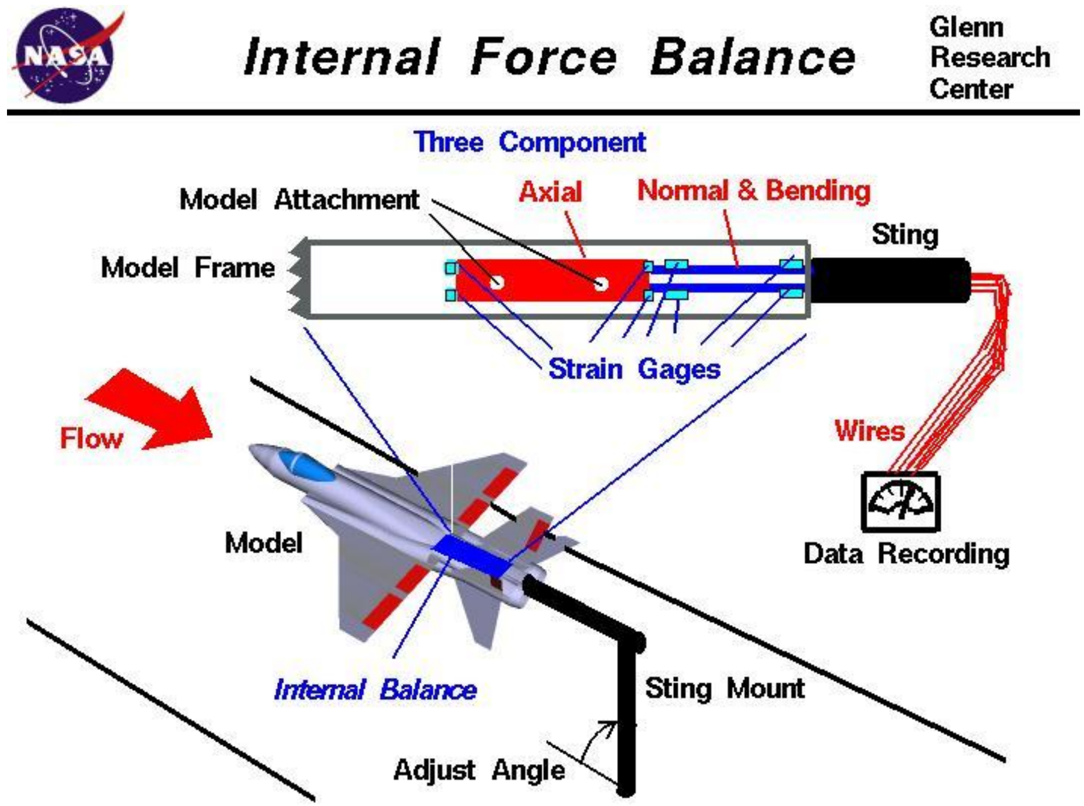
# Yoke Balance



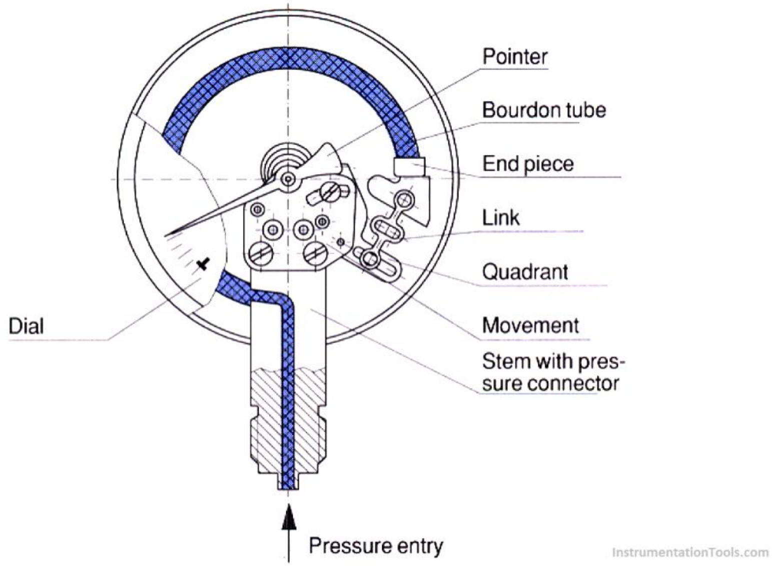
# Strain Gauge

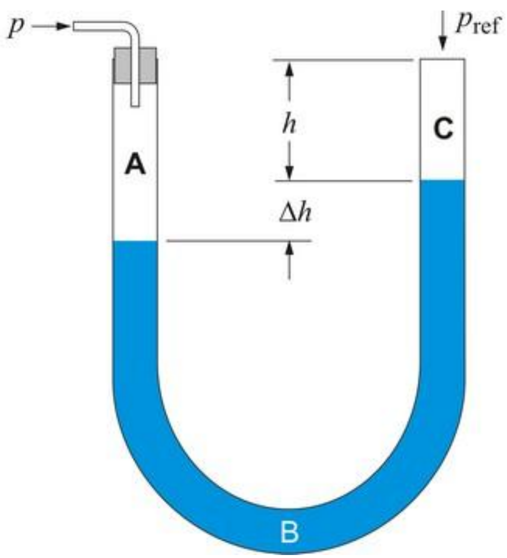


# 3-component Strain Gauge Balance

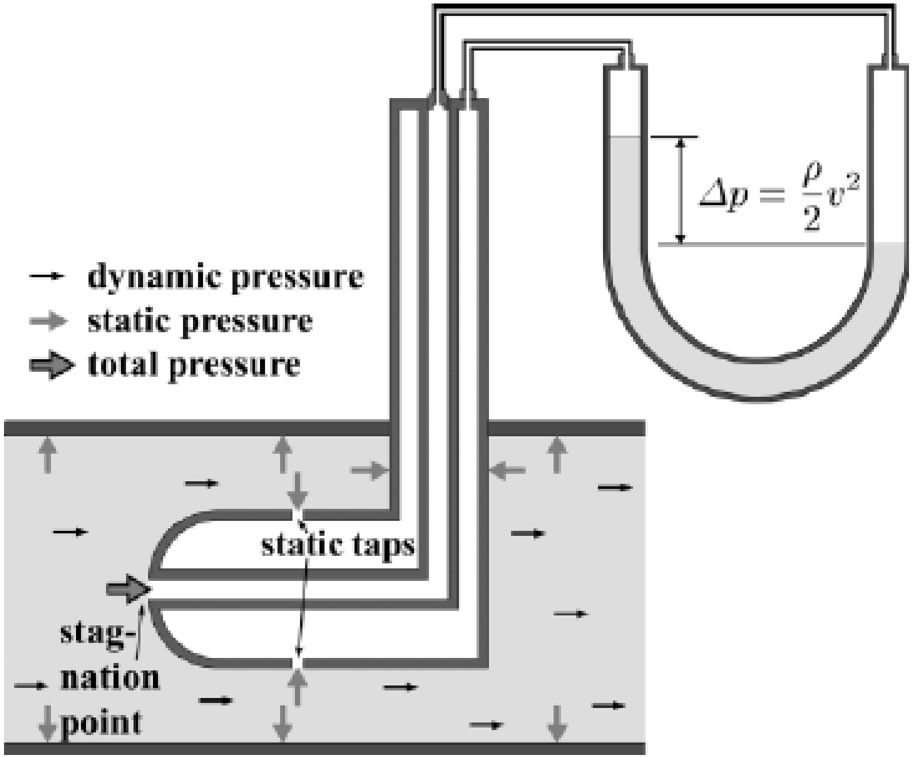


# Pressure

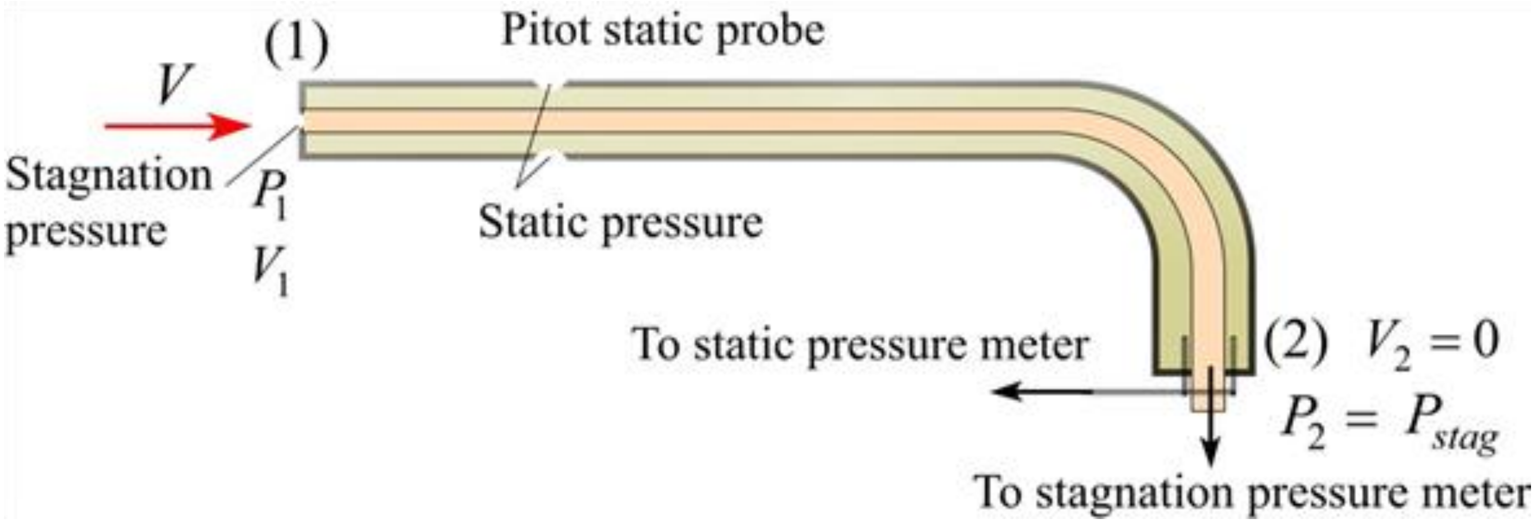

Pointer
Bourdon tube
End piece
Link
Quadrant
Movement
Stem with pressure connector
Dial
Pressure entry
InstrumentationTools.com


p
$p_{ref}$
h
Δh
A
B
C

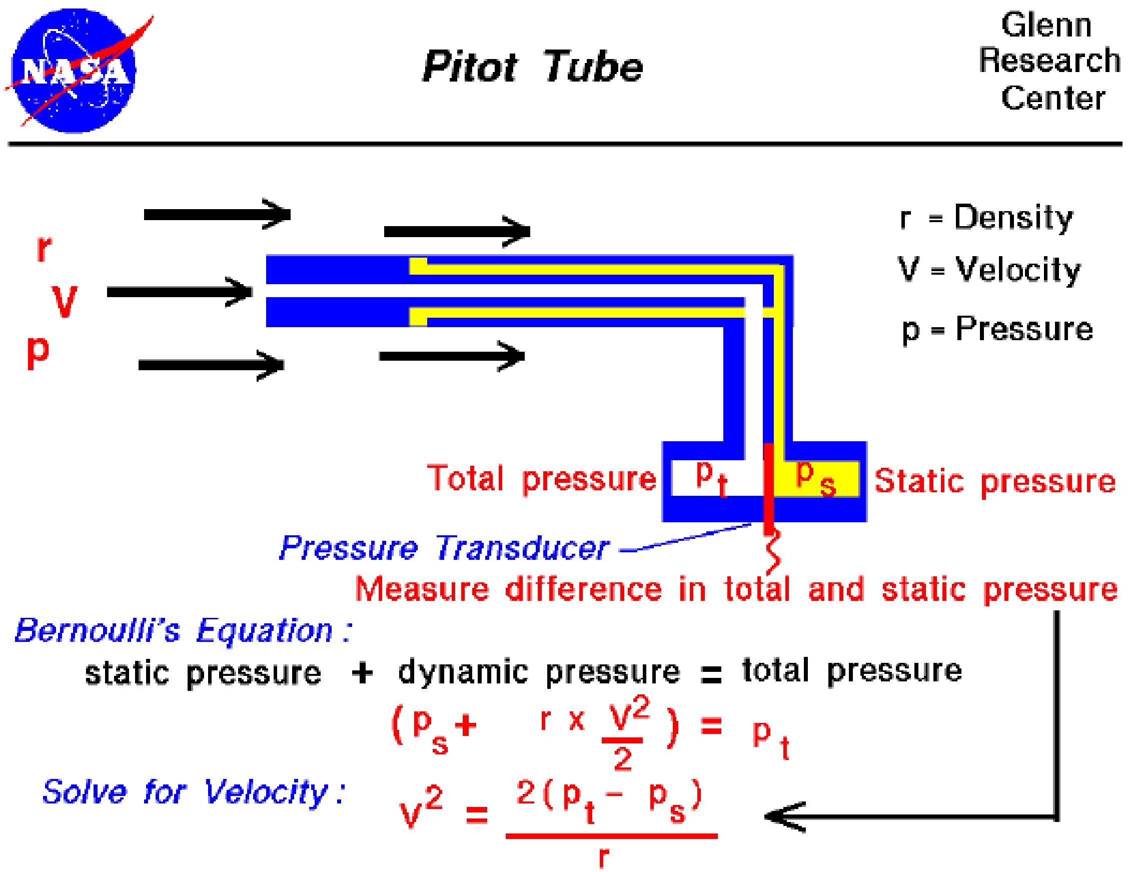
# Static Pressure



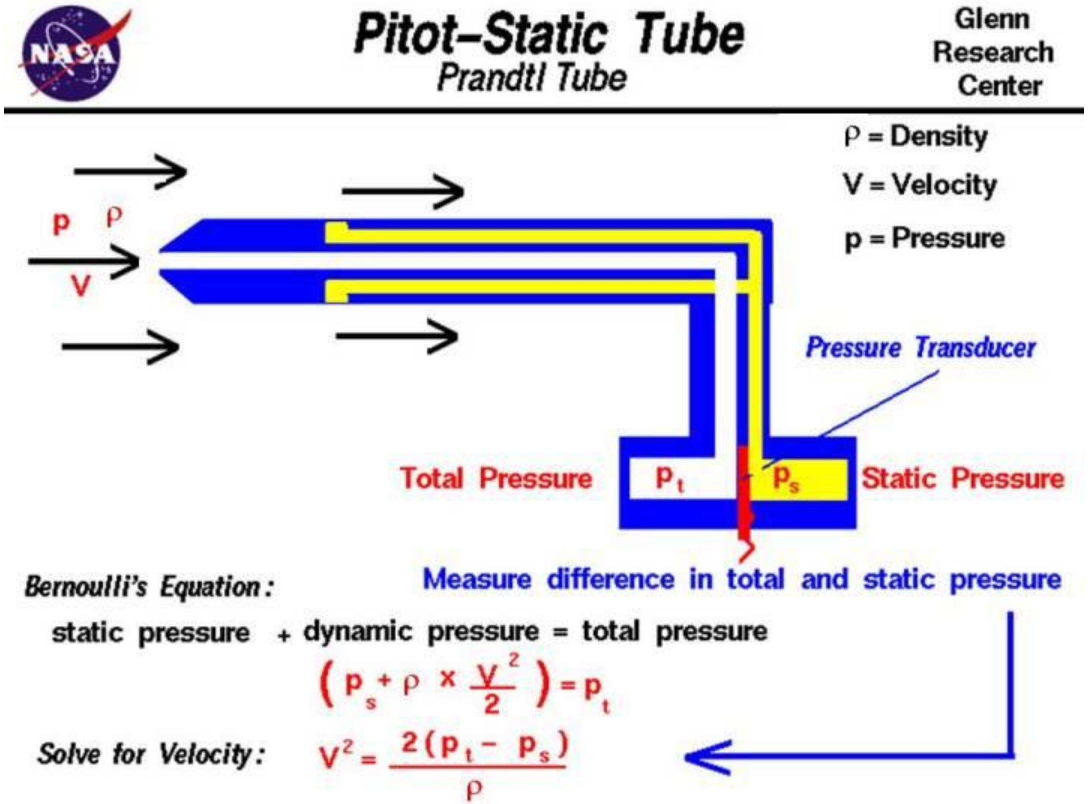
# Surface Pressure Orifice



# Static Probes

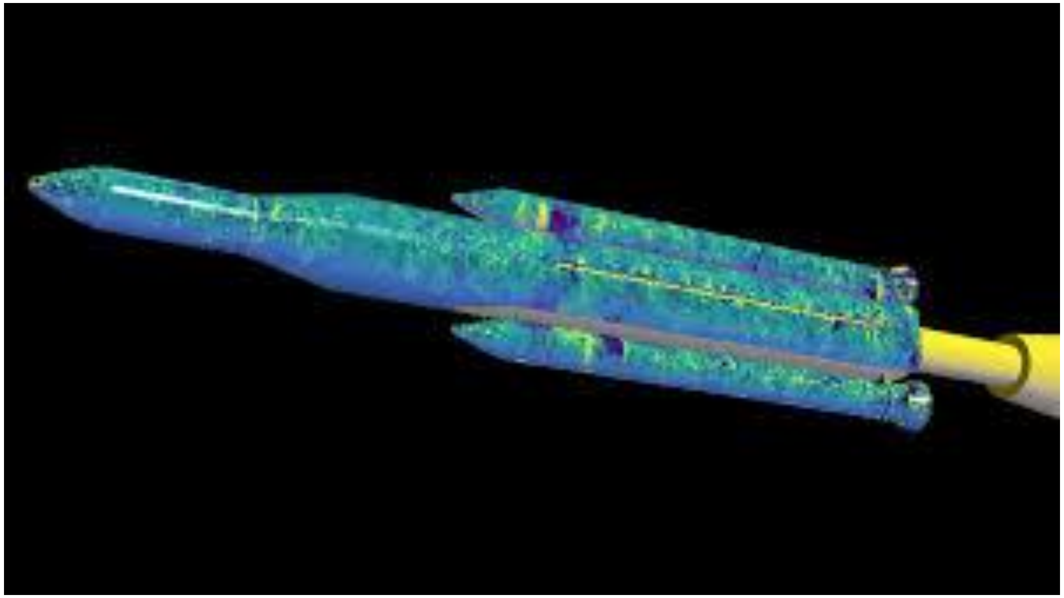


# Pitot Probe For Total Pressure



# Static Pressure and Flow Angularity

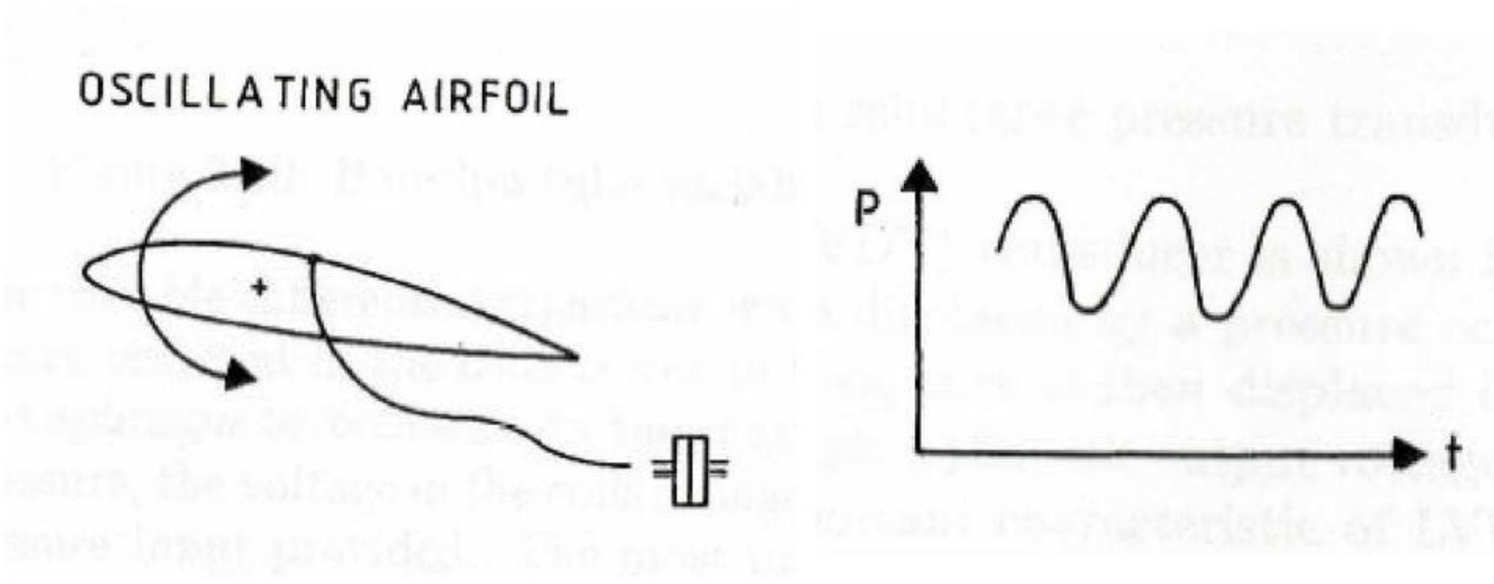
# Pressure Sensitive Paints



# Steady And Unsteady Pressure Measurement

## Unsteady Pressure Measurements

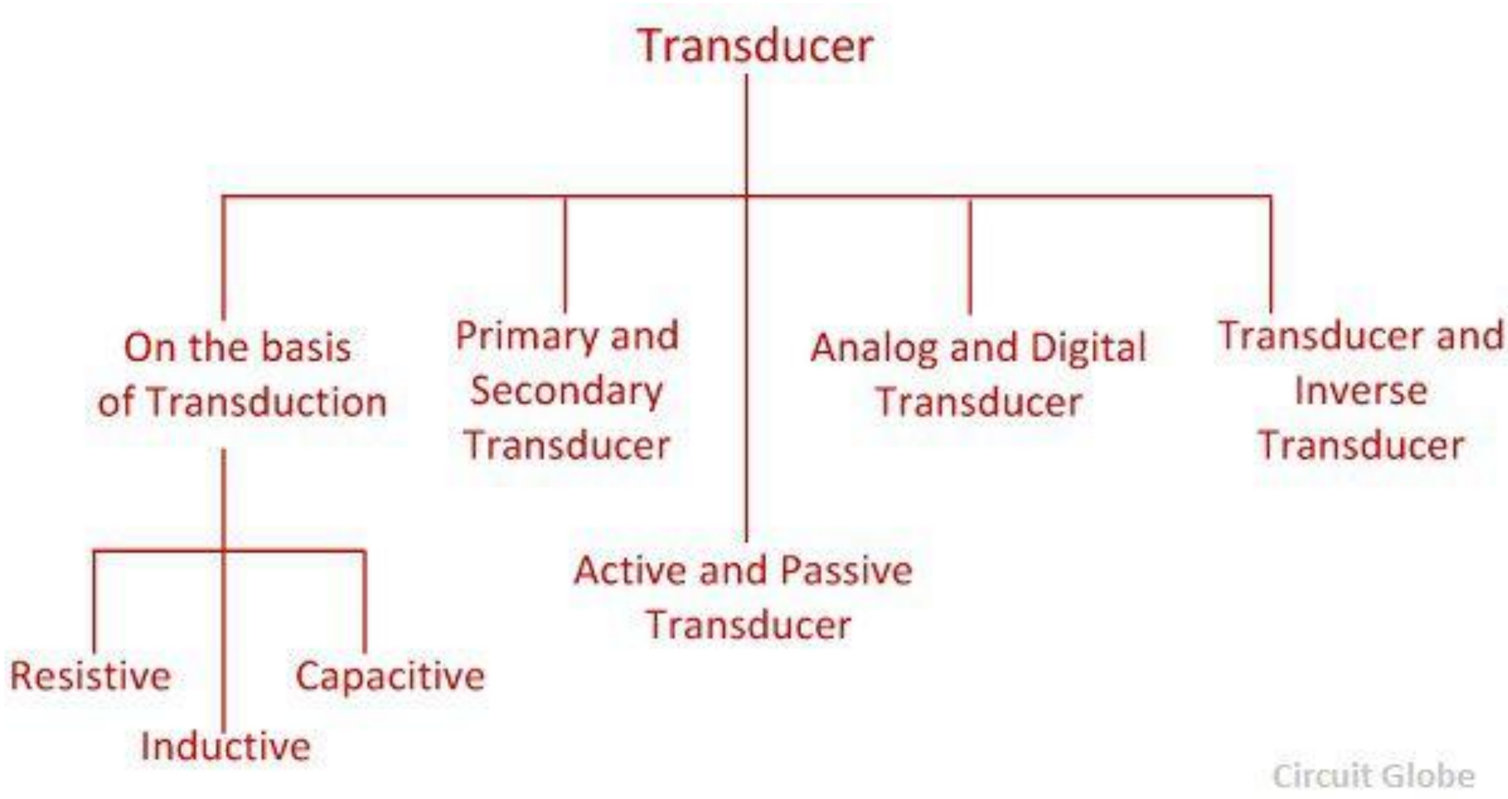
An airfoil (or any other body) immersed in an unsteady mainstream, or a steady mainstream but subjected t of change of incidence, periodic or not (oscillating airfoil, or subjected to a pitch-up maneuver)



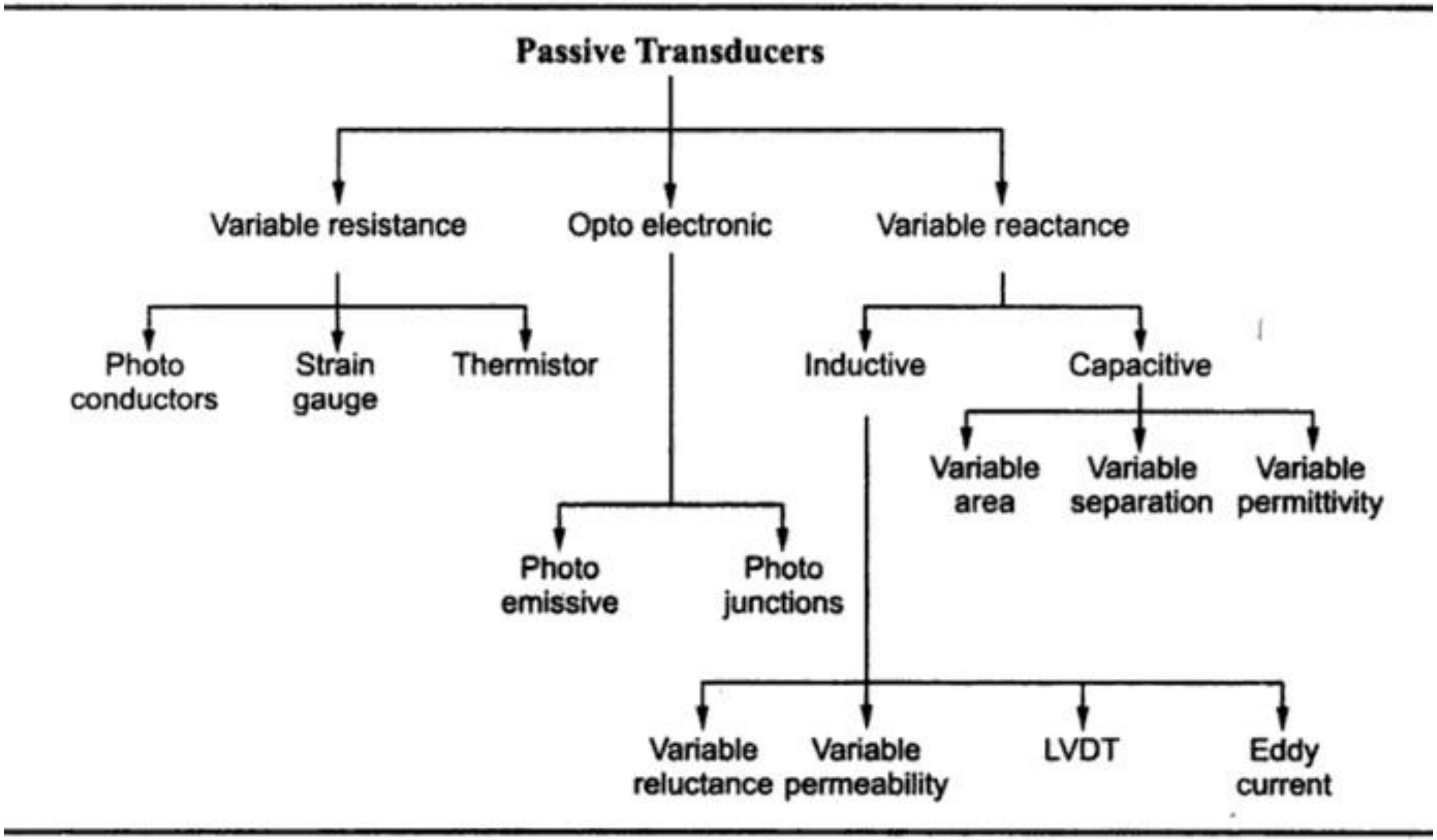

Different cases of occurrence of unsteady pressures

# Various Types of Pressure Probes

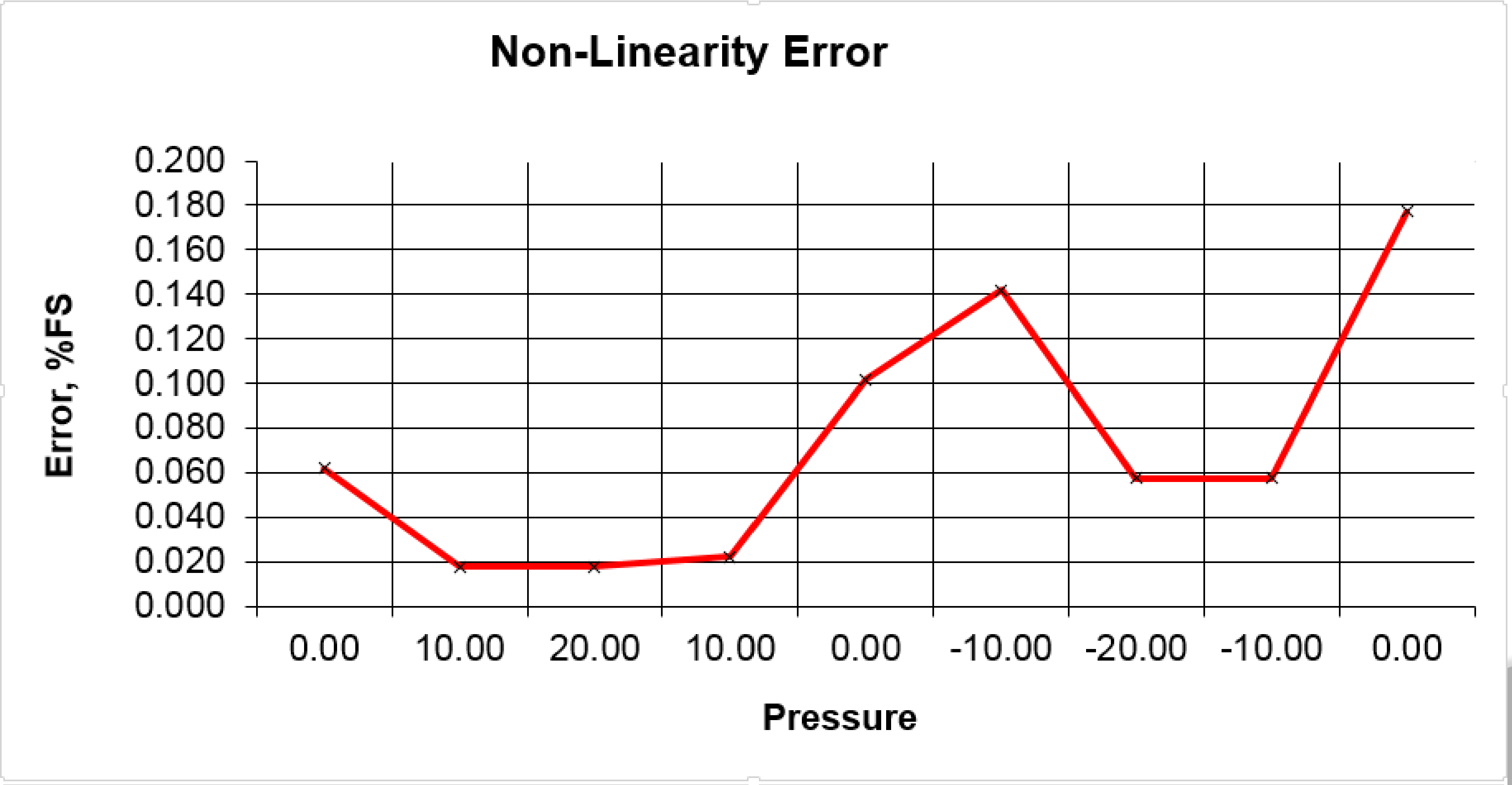
# Transducers



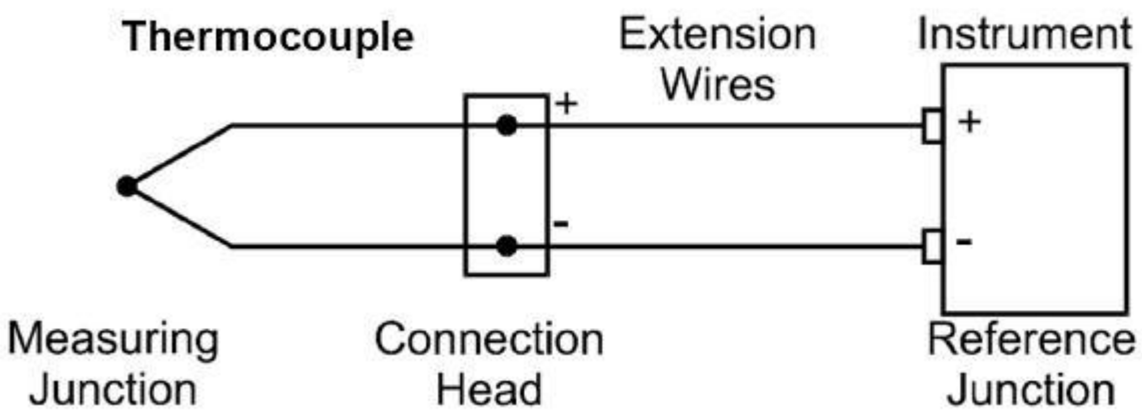
# Transducers



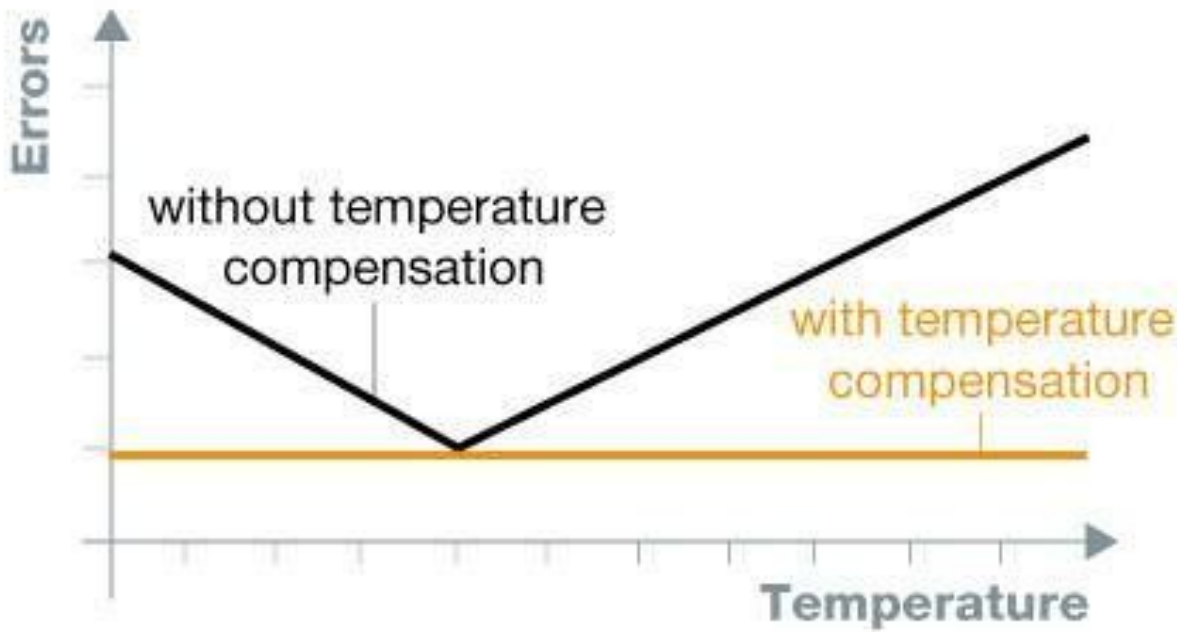
# Errors in Pressure Measurement



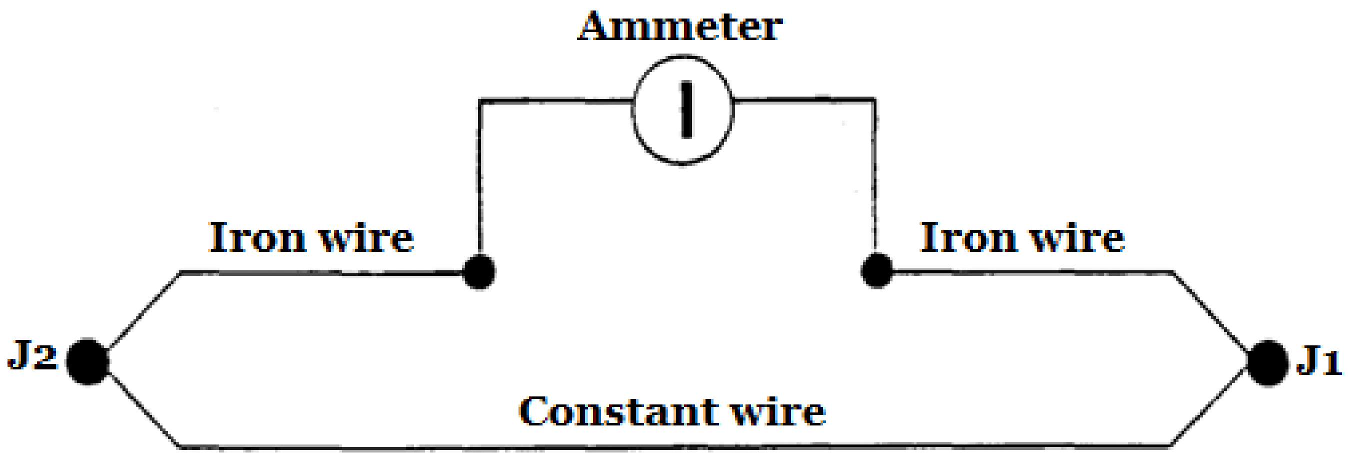
# Temperature





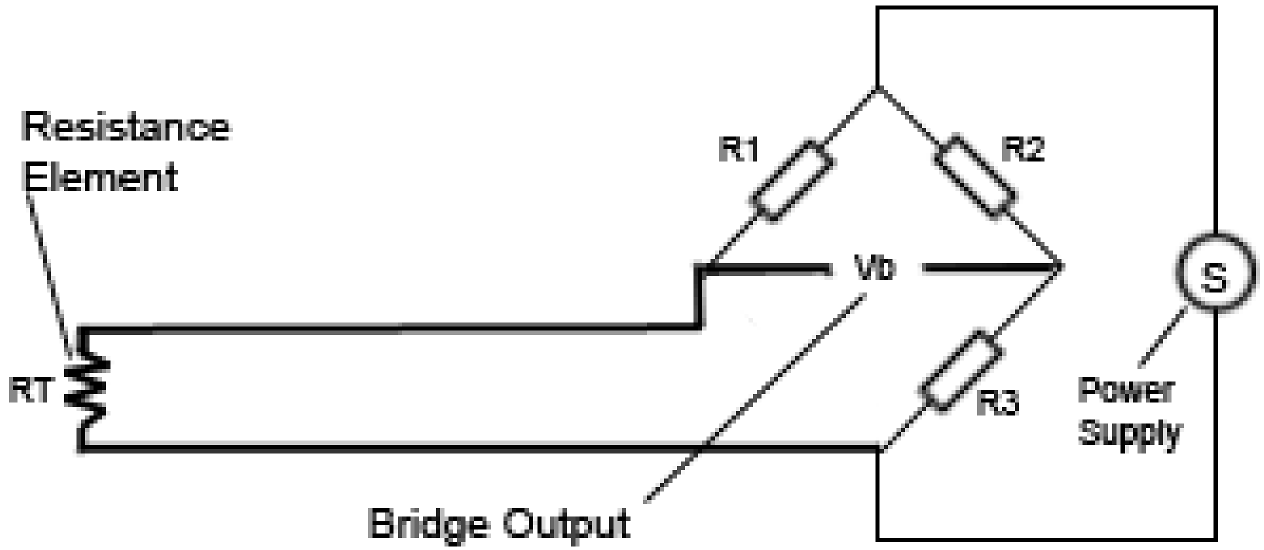

Errors
without temperature compensation
with temperature compensation
Temperature

# Measurement of Temperature using Thermocouples

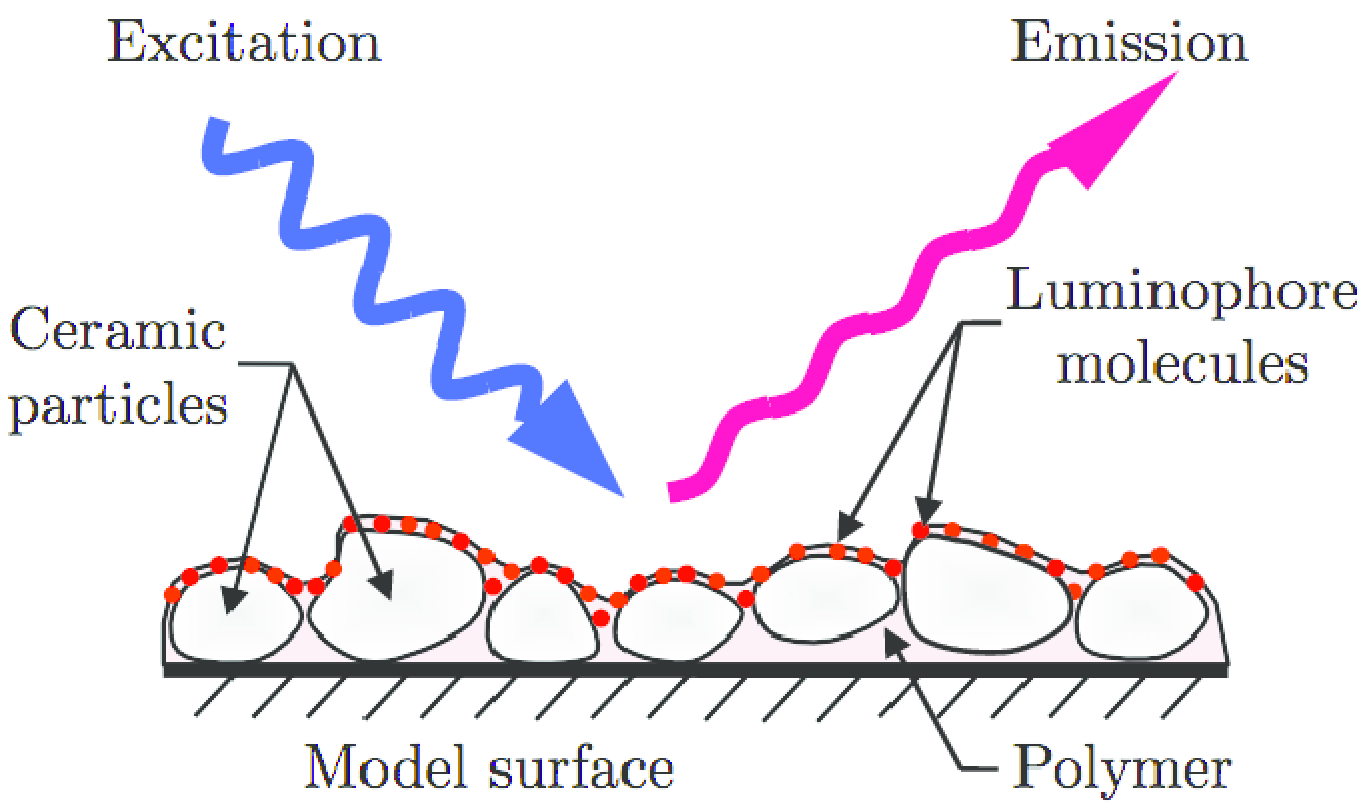



Thermocouple Ammeter

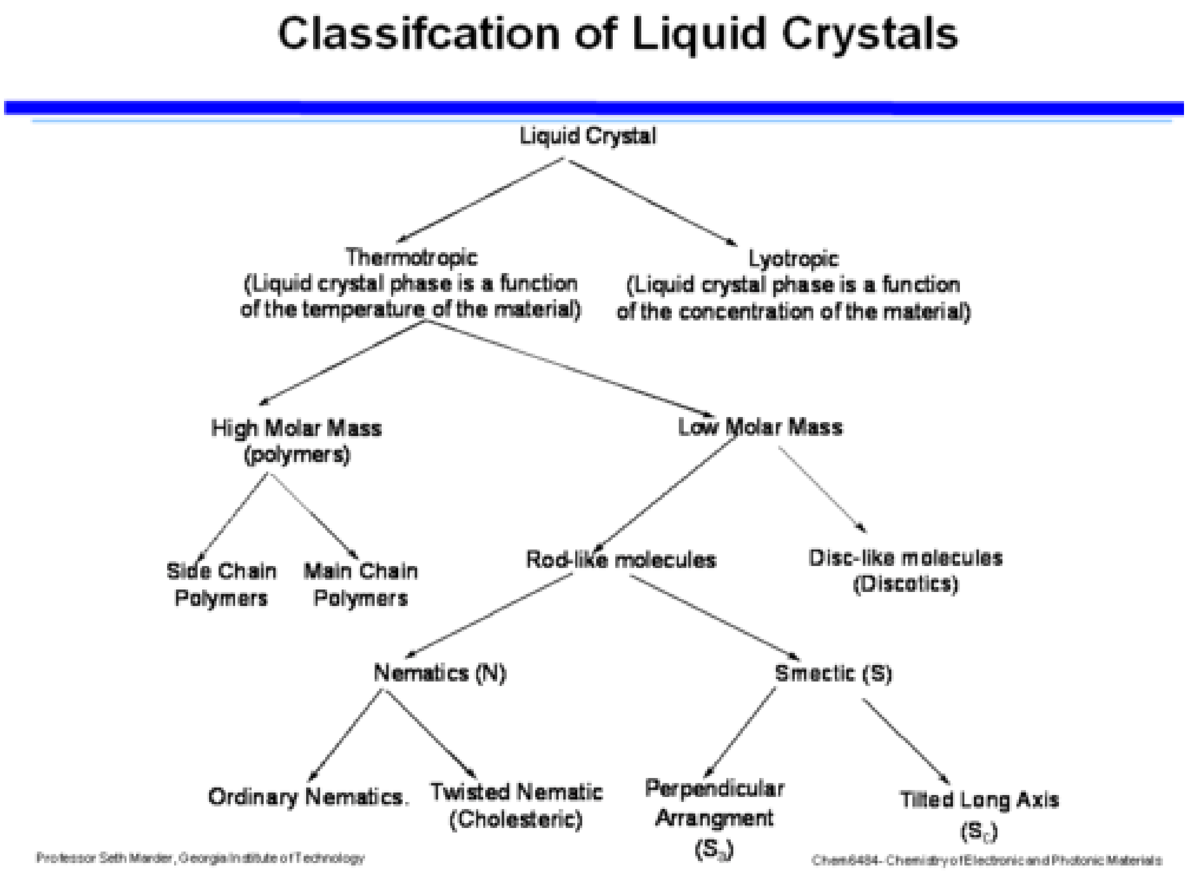
# Resistance Thermometers



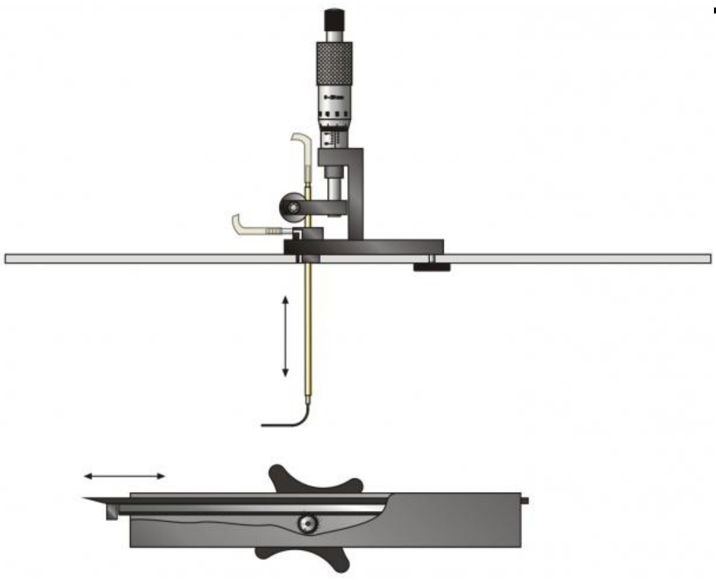
# Temperature Sensitive Paints

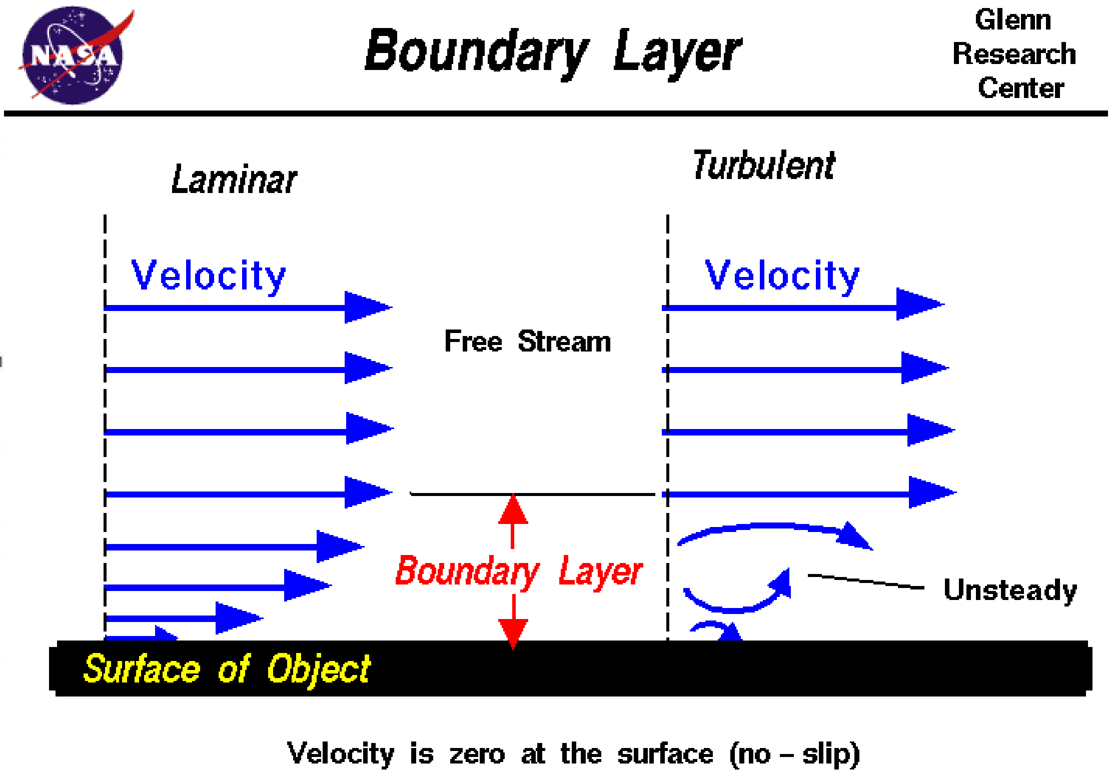


# Liquid Crystals



# Boundary Layer Profile Using Pitot Static Probe

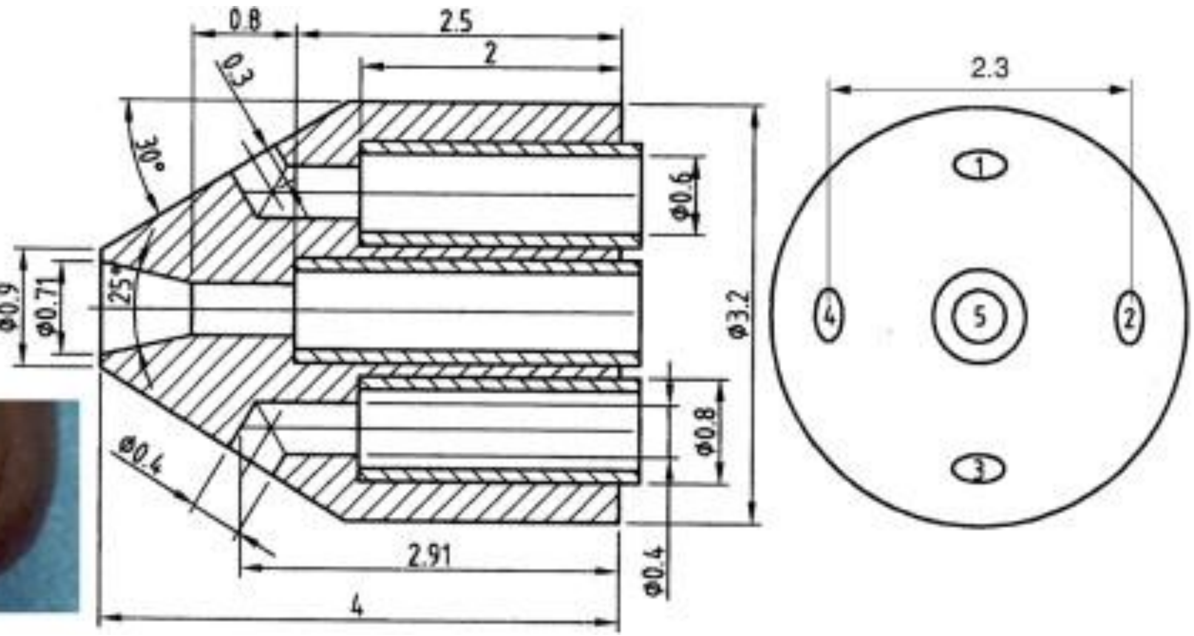




# 5 Hole Probe Yaw Meter

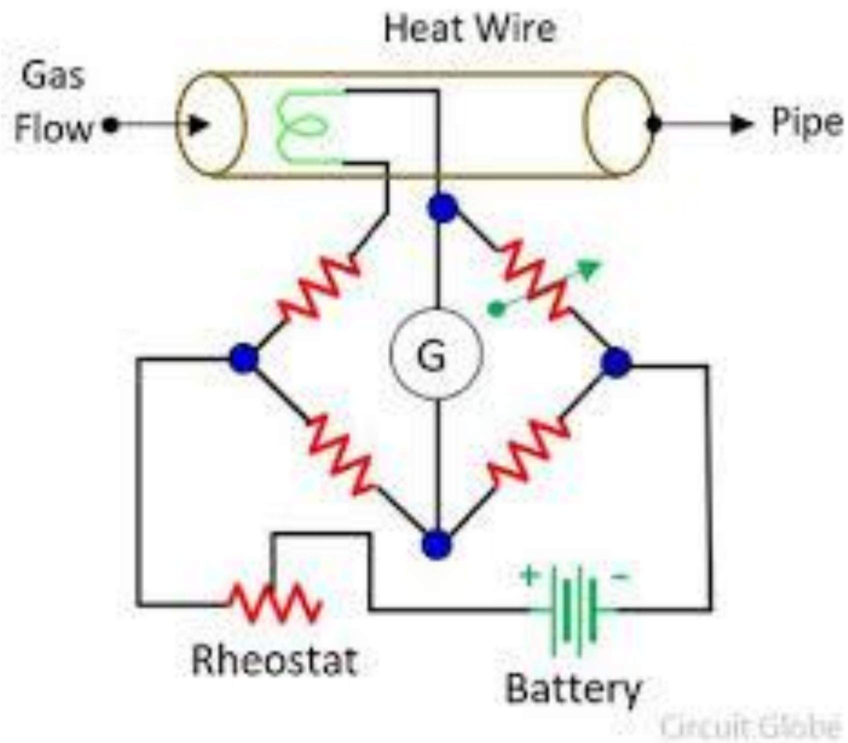
front view

lateral view

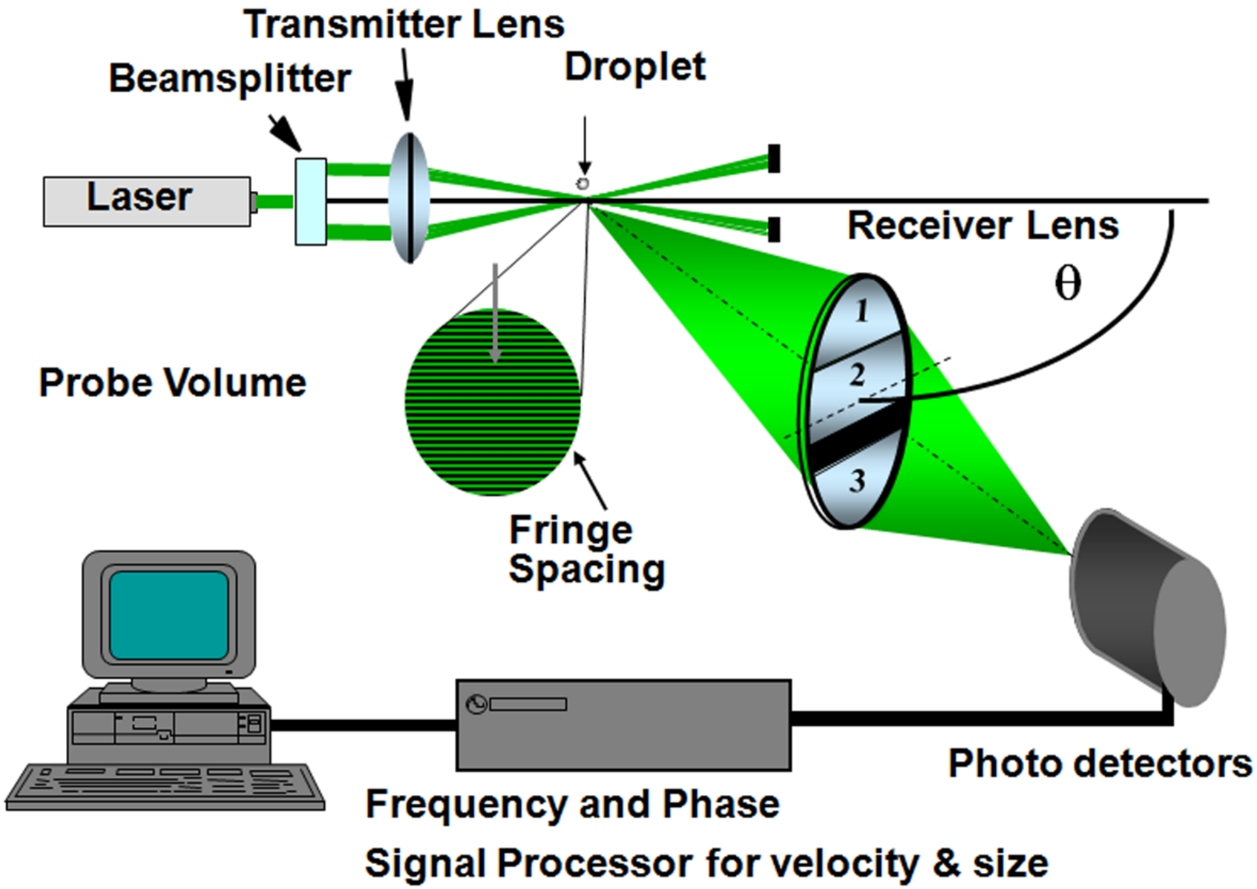


# Total Head Rake

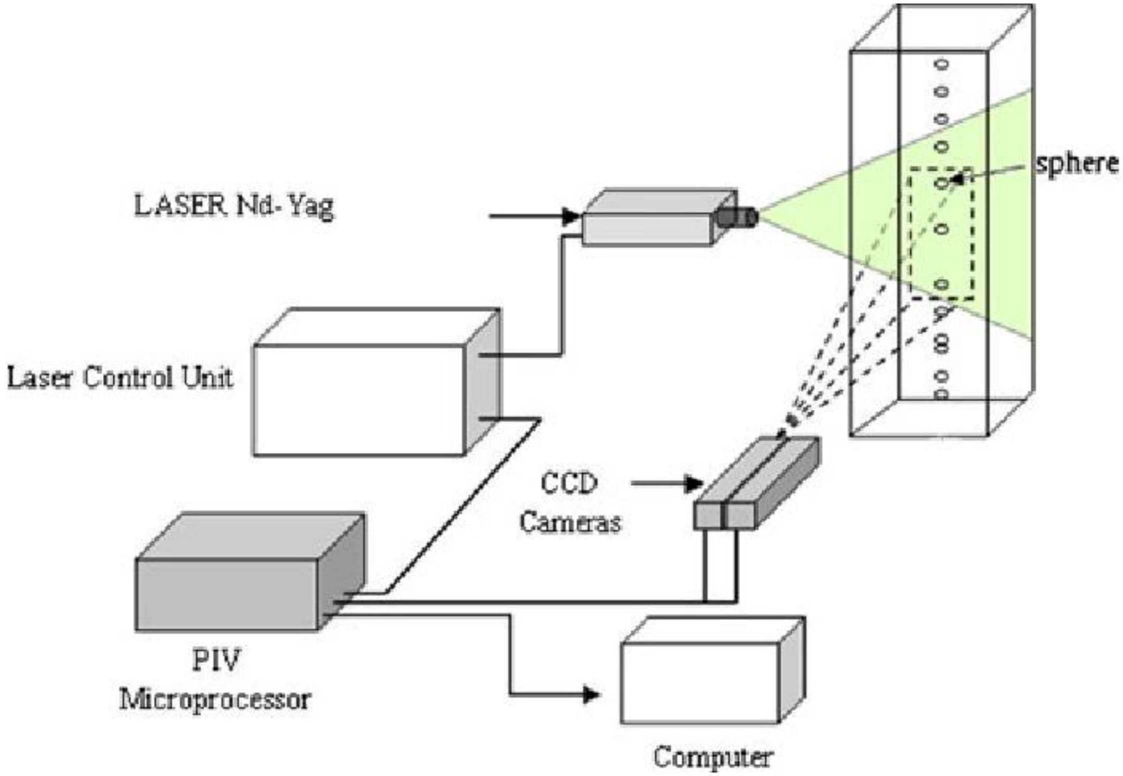
# Hot Wire Anemometry



# Laser Doppler Anemometry



# Particle Image Velocimetry



# Vector Visualization

- Data set is given by a vector component and its magnitude
- often results from study of fluid flow or by looking at derivatives (rate of change) of some quantity
- trying to find out what to see and how!
- Many visualization techniques proposed

# Vector Visualization - Techniques

- **Hedgehogs/glyphs**
- **Particle tracing**
- **stream-, streak-, time- & path-lines**
- **stream-ribbon, stream-surfaces, stream-polygons, stream-tube**
- **hyper-streamlines**
- **Line Integral Convolution**

# Vector Visualization - Origin

- **Where are those methods coming from??**
- **Rich field of Fluid Flow Visualization**
- **Hundreds of years old!!**
- **Modern domain - Computational Field Simulations**

# Flow Visualization

- **Gaseous flow:**
  - **development of cars, aircraft, spacecraft**
  - **design of machines - turbines, combustion engines**
- **Liquid Flow:**
  - **naval applications - ship design**
  - **civil engineering - harbor design, coastal protection**
- **Chemistry - fluid flow in reactor tanks**
- **Medicine - blood vessels, SPECT, fMRI**

# Flow Visualization (2)

- **What is the problem definition?**
- **Given (typically):**
  - **physical position (vector)**
  - **pressure (scalar),**
  - **density (scalar),**
  - **velocity (vector),**
  - **entropy (scalar)**
- **steady flow - vector field stays constant**
- **unsteady - vector field changes with time**

# Flow Visualization - traditionally

- **Traditionally - Experimental Flow Vis**

- **How? - Three basic techniques:**
  - **adding foreign material**
  - **optical techniques**
  - **adding heat and energy**

# Experimental Flow Visualize.

- **Problems:**
  - **the flow is affected by experimental technique**
  - **not all phenomena can be visualized**
  - **expensive (wind tunnels, small scale models)**
  - **time consuming**
- **That's where computer graphics and YOU come in!**

# Vector Field Visualization Techniques

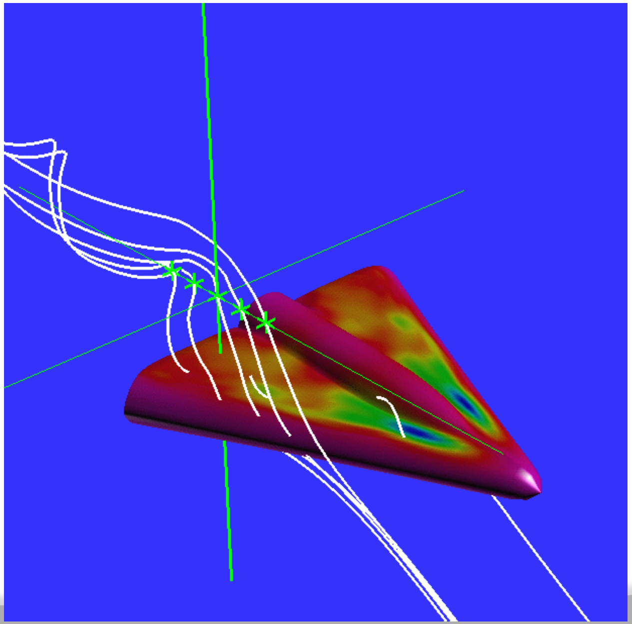
Local technique: Advection based methods -
Display the trajectory starting from a particular location
- streamxxxx
- contours

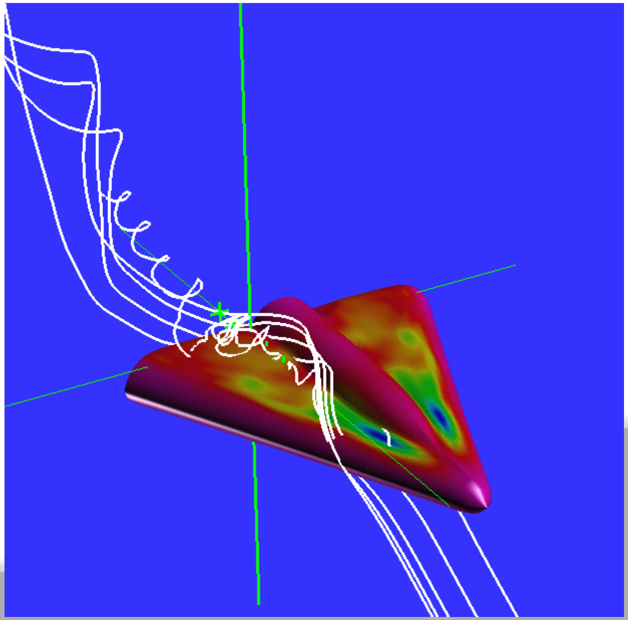
Global technique: Hedgehogs, Line Integral Convolution, Texture Splats etc.
Display the flow direction everywhere in the field

# Local technique - Streamline

• Basic idea: visualizing the flow directions by releasing particles and calculating a series of particle positions based on the vector field -- streamline

$$\frac{d\bar{x}}{ds} = v(\bar{x}, t_0) \quad \text{or} \quad \bar{x} = \bar{x}(s) + \int \bar{v}\, ds$$





# Numerical Integration

$$\frac{d\bar{x}}{ds} = v(\bar{x}, t_0) \quad \text{or} \quad \bar{x} = \bar{x}(s) + \int \bar{v}\, ds$$

- **Euler**

$$\bar{x}(s+\Delta s) = \bar{x}(s) + \bar{v}(\bar{x}(s))\Delta s$$

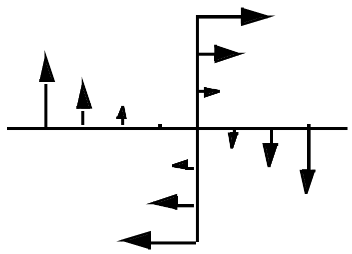
  - **not good enough, need to resort to higherorder methods**

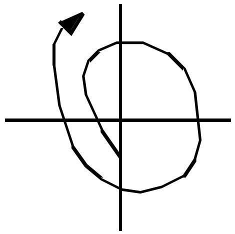
# Numerical Integration

- **2nd order Runge-Kutta**

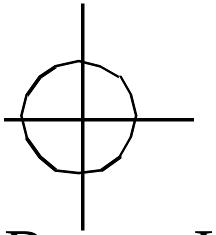
$$\bar{x}^*(s+\Delta s) = \bar{x}(s) + \bar{v}(\bar{x}(s))\Delta s$$

$$\bar{x}(s+\Delta s) = \bar{x}(s) + \frac{\left(\bar{v}(\bar{x}(s)) + \bar{v}\left(\bar{x}^*(s+\Delta s)\right)\right)}{2}\Delta s$$





Euler



Runge-Kutta

# Numerical Integration

- **4th order Runge-Kutta**

$$\bar{x}(s+\Delta s) = \bar{x}_0 + \tfrac{1}{6}\left(\bar{v}(\bar{x}_0) + 2\bar{v}(\bar{x}_1) + 2\bar{v}(\bar{x}_2) + \bar{v}(\bar{x}_3)\right)$$

$$x_0 = \bar{x}(s)$$

$$x_1 = \bar{x}(s) + \tfrac{1}{2}\bar{v}(\bar{x}_0)\Delta s$$

$$x_2 = \bar{x}(s) + \tfrac{1}{2}\bar{v}(\bar{x}_1)\Delta s$$

$$x_3 = \bar{x}(s) + \bar{v}(\bar{x}_2)\Delta s$$

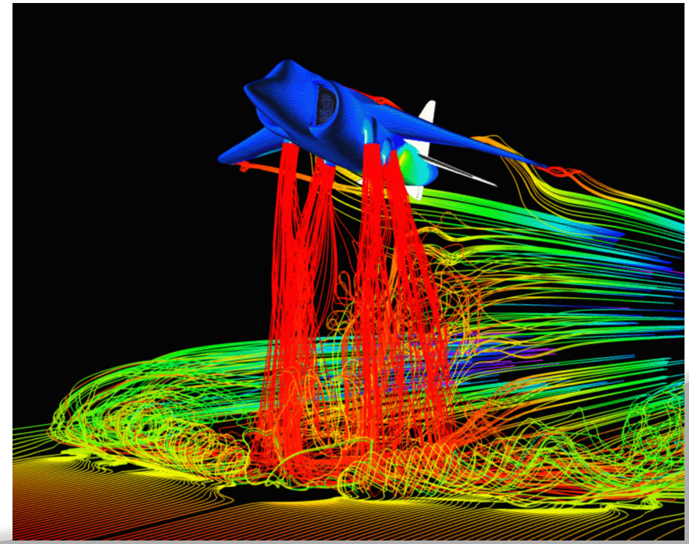
# Streamlines

- Displaying streamlines is a local technique because you can only visualize the flow directions initiated from one or a few particles

- When the number of streamlines is increased, the scene becomes cluttered

- You need to know where to drop the particle seeds

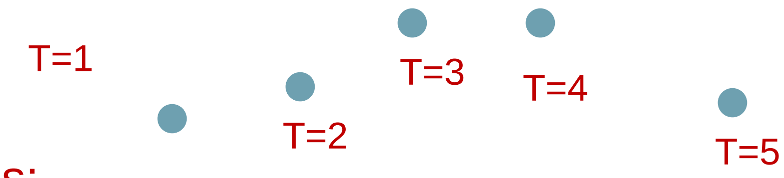
- Streamline computation is expensive



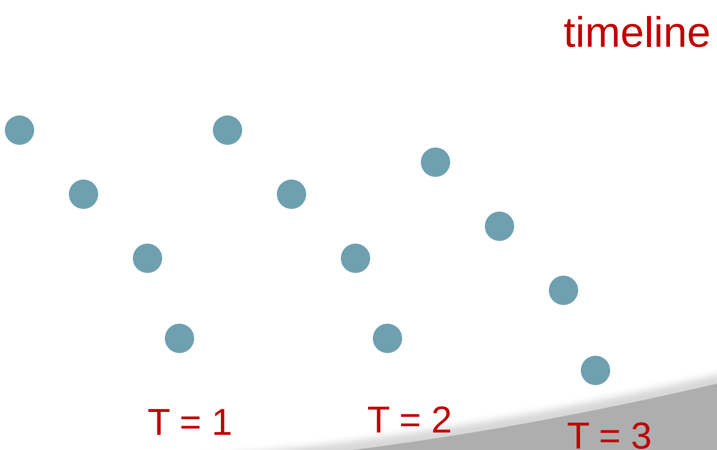
# Pathlines, Timelines

-Extension of streamlines for time-varying data (unsteady flows)

Pathlines:

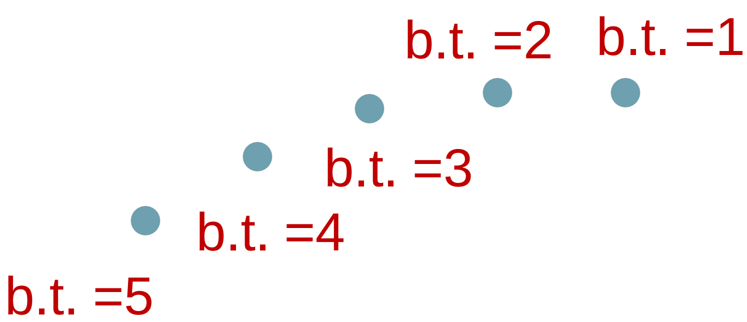



Timelines:

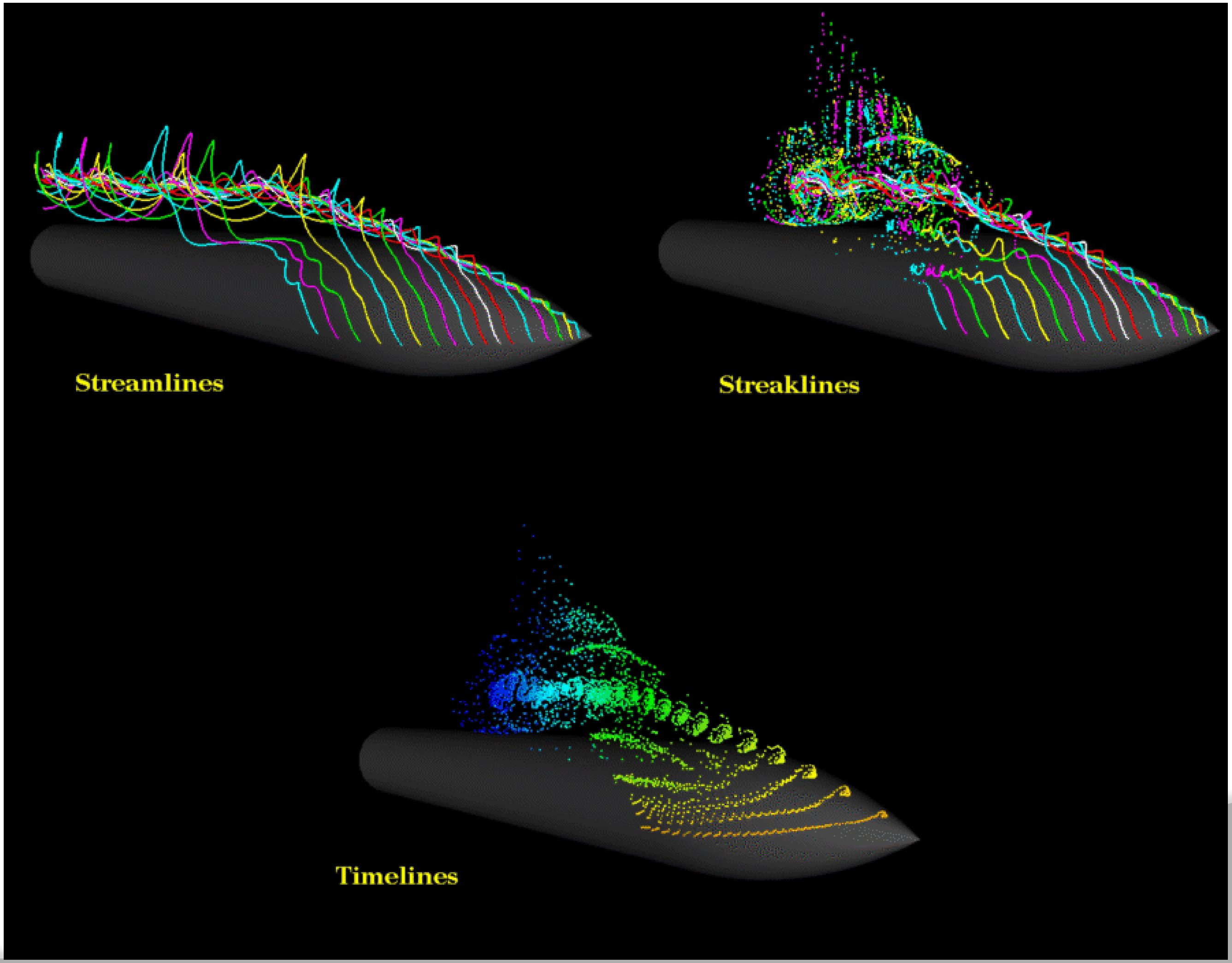


# Streakline

- For unsteady flows also
- Continuously injecting a new particle at each time step, advecting all the existing particles and connect them together into a *streakline*



# Advection methods comparison

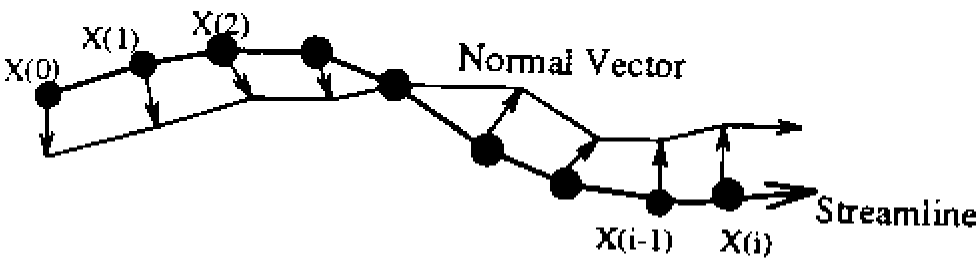


# Stream-ribbon

- We really would like to see vorticities, I.e. places were the flow twists.
- A point primitive or an icon can hardly convey this
- idea: trace neighboring particles and connect them with polygons
- shade those polygons appropriately and one will detect twists

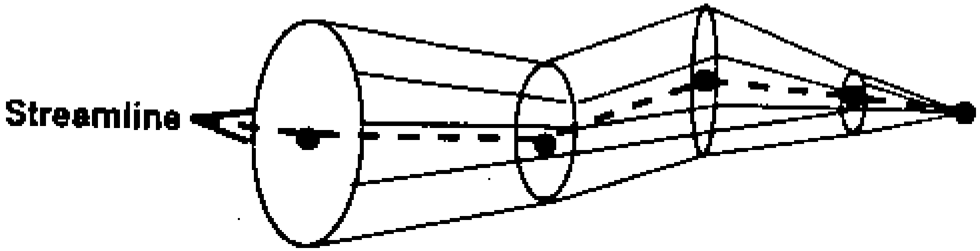
# Stream-ribbon

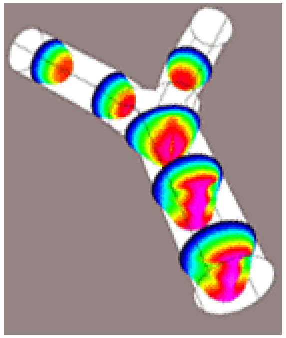
- **Problem - when flow diverges**
- **Solution: Just trace one streamline and a constant size vector with it:**

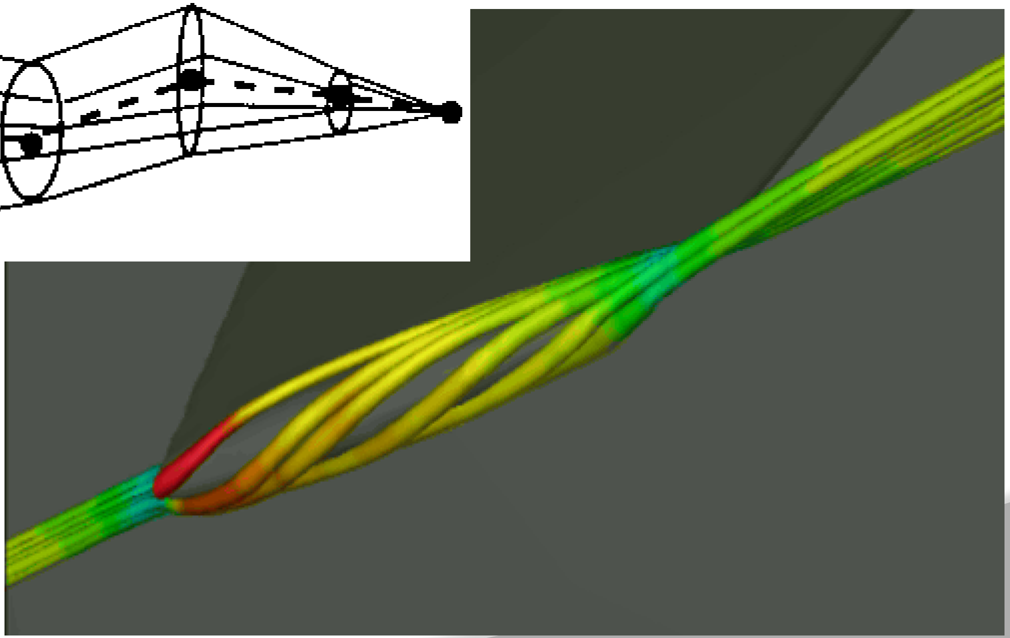


# Stream-tube

- **Generate a stream-line and connect circular crossflow sections along the stream-line**



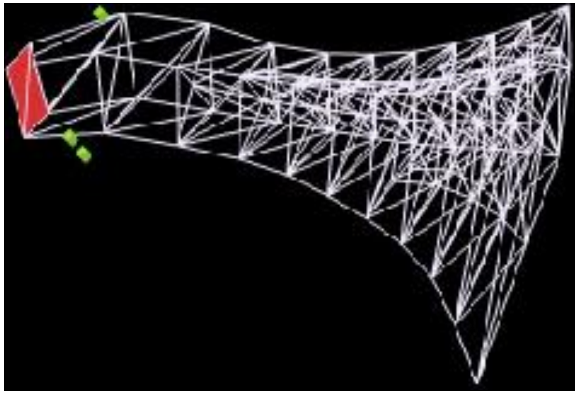


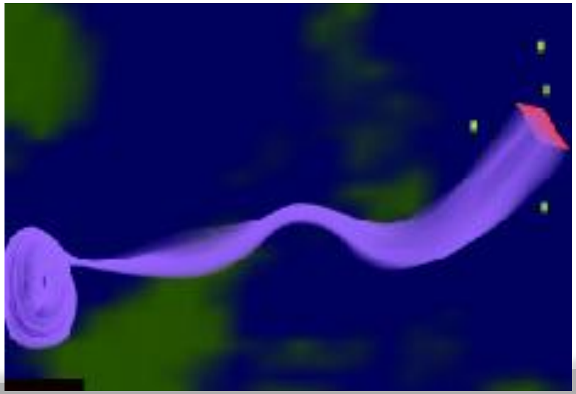
# Stream-balls

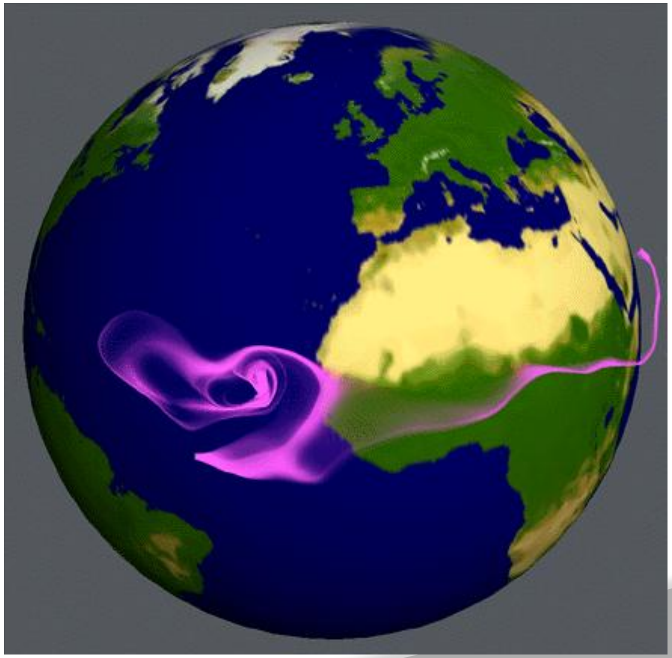
- **Another way to get around diverging stream-lines**
- **simply put implicit surface primitives at particle traces - at places where they are close they'll merge elegantly ...**

# Flow Volumes

- **Instead of tracing a line - trace a small polyhedra**

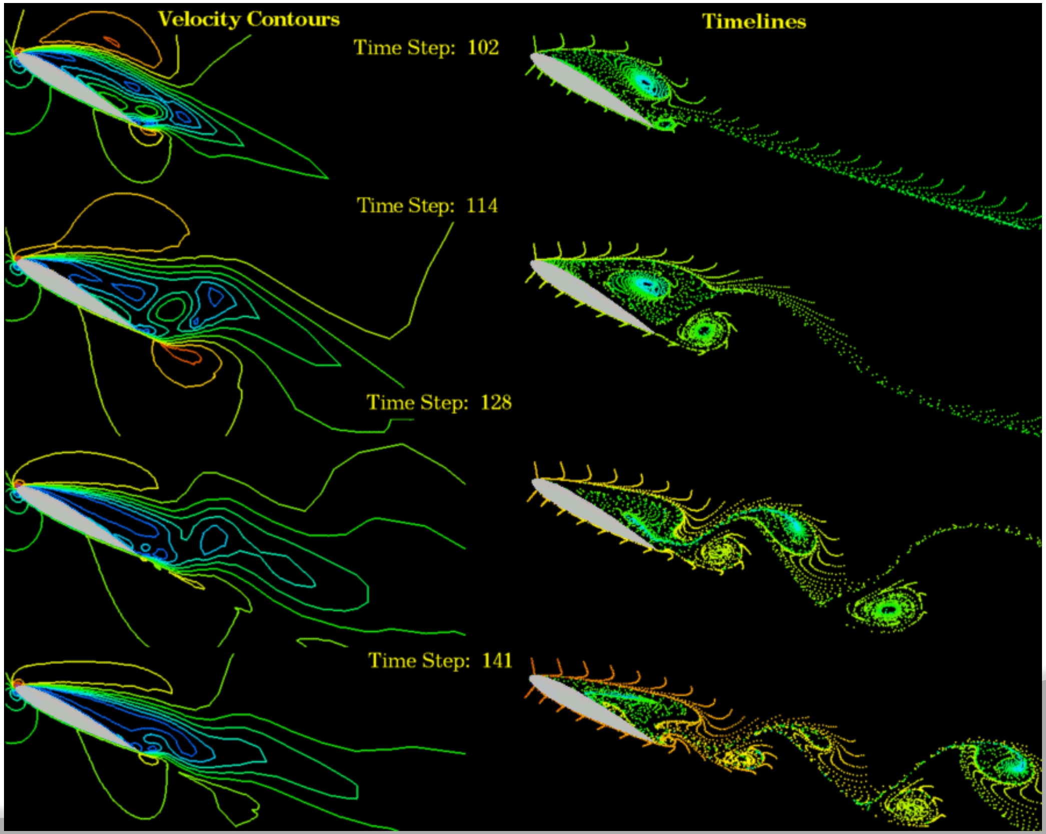






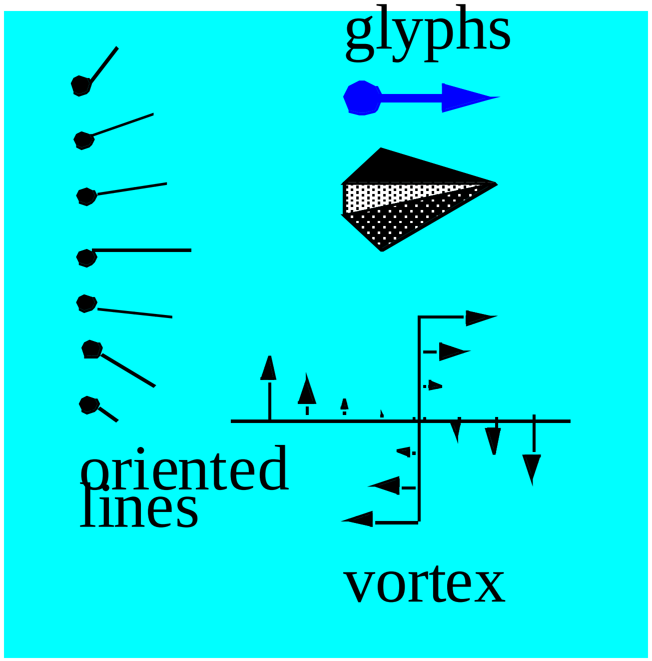
# Contours

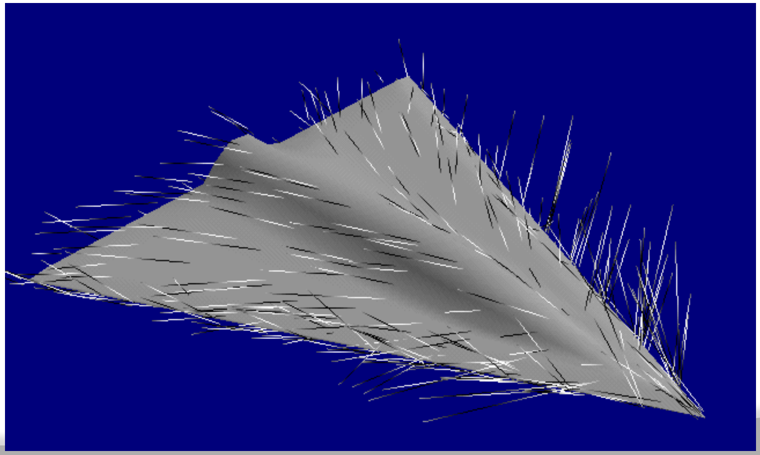
- **Contour lines can measure certain quantities by connecting same values along a line**



# Mappings - Hedgehogs, Glyphs

- **Put "icons" at certain places in the flow**
  - **e.g. arrows - represent direction & magnitude**
- **other primitives are possible**



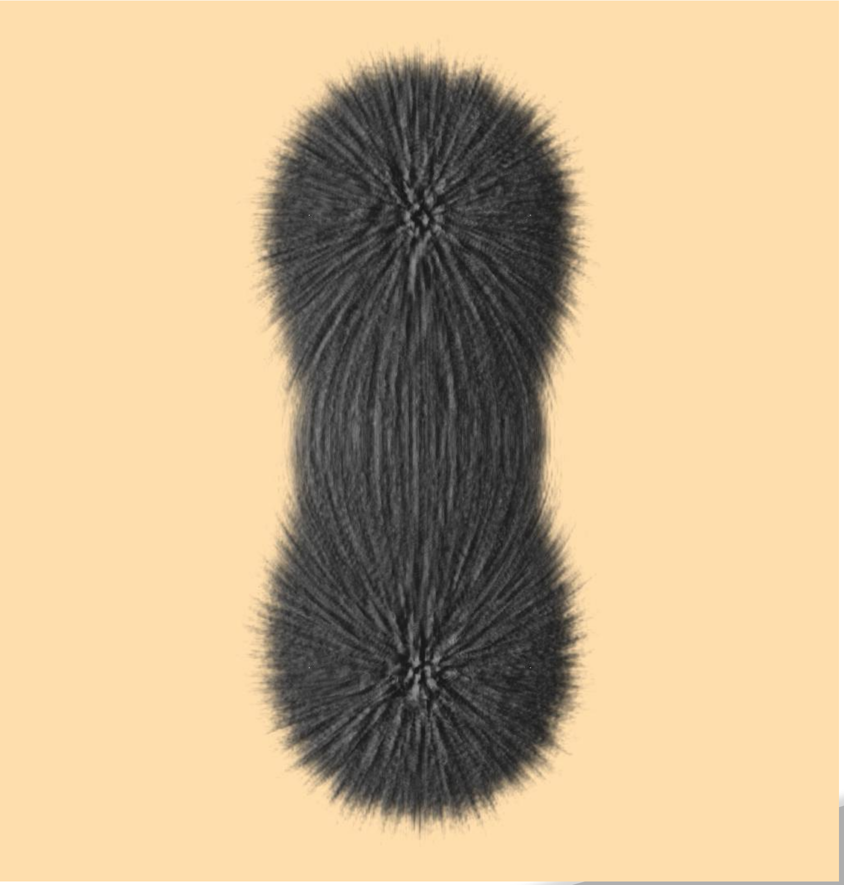



# Mappings - Hedgehogs, Glyphs

- analogous to tufts or vanes from experimental flow visualization
- clutter the image real quick
- maybe ok for 2D
- not very informative

# Global Methods

- **Spot Noise (van Wijk 91)**
- **Line Integral Convolution (Cabral 93)**
- **Texture Splats (Crawfis 93)**

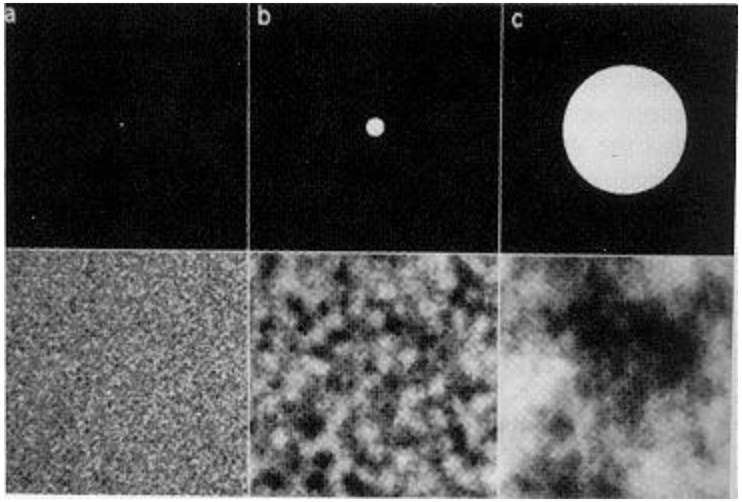


# Spot Noise

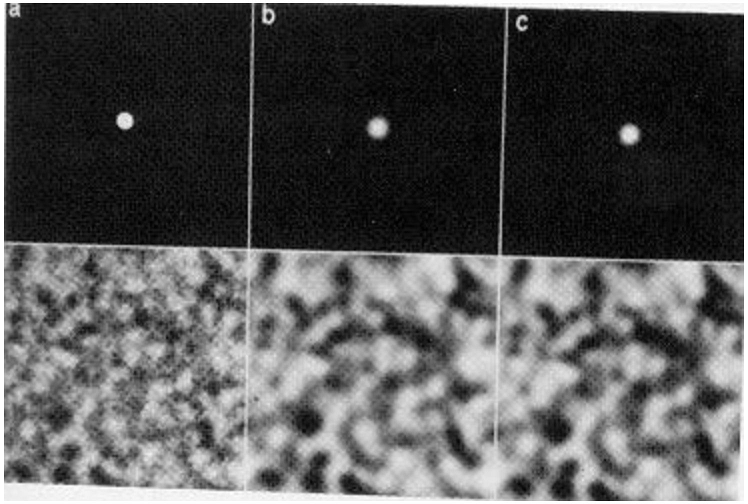
- Uses small motion blurred particles to visualize flows on stream surfaces
- Particles represented as ellipses with their long axes oriented along the direction of the flow
- I.e. we multiply our kernel h with an amplitude and add a phase shift!
- Hence - we convolve a spot kernel in spatial domain with a random sequence (white noise)

# Rendering - Spot Noise

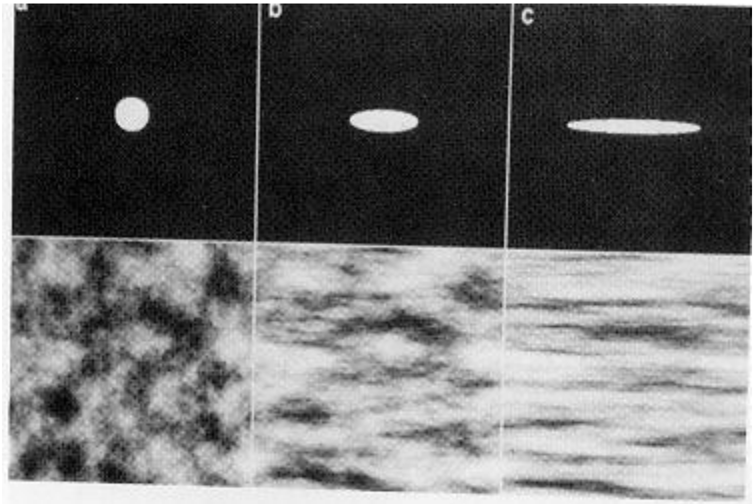
Different size

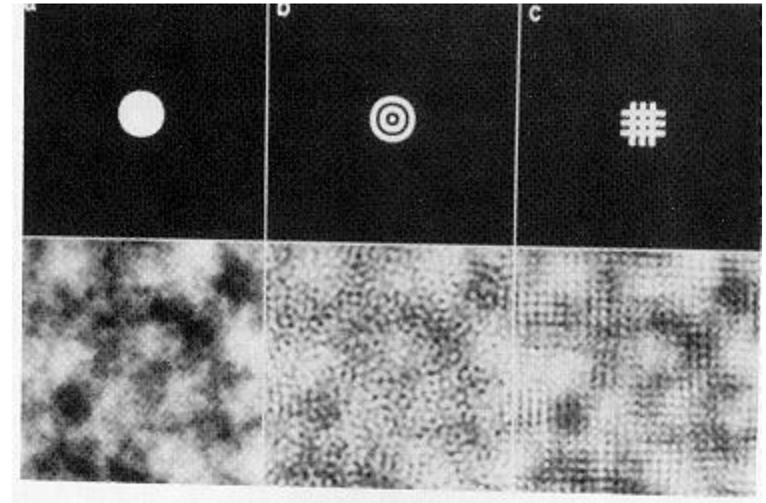


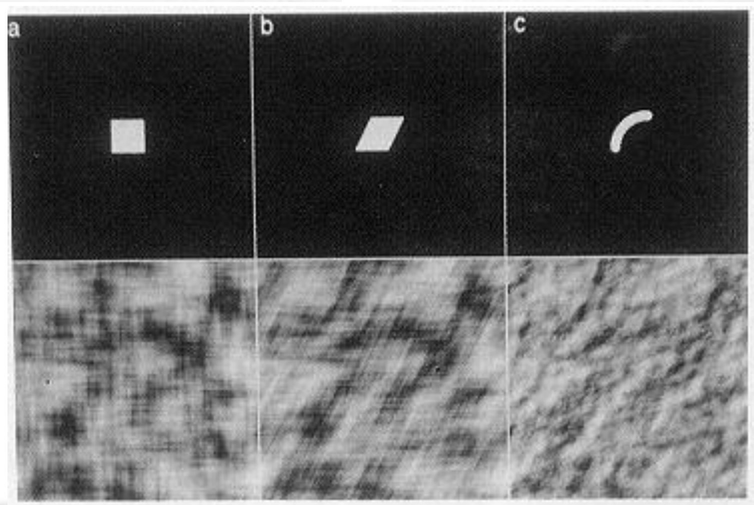

Different profiles



# Rendering - Spot Noise

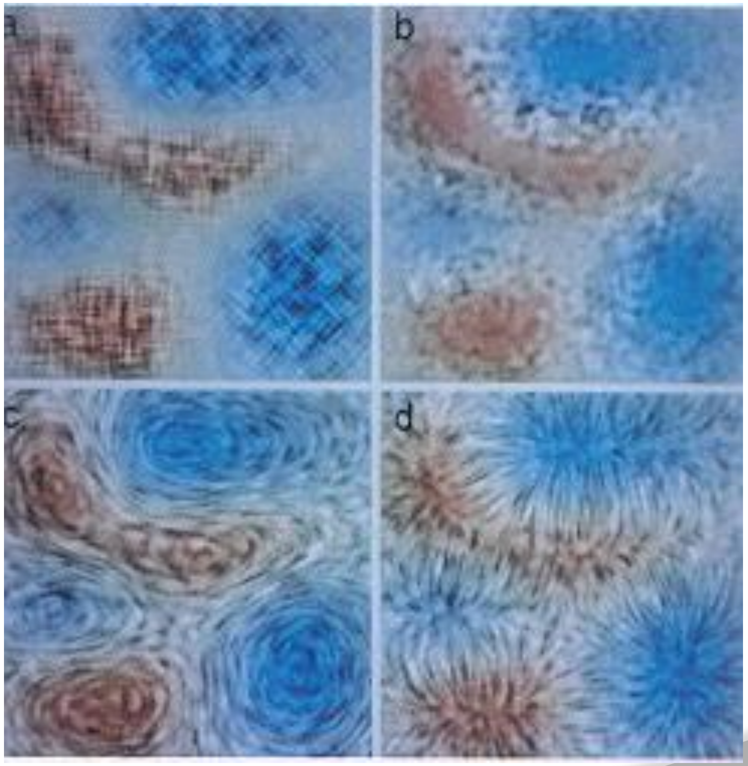


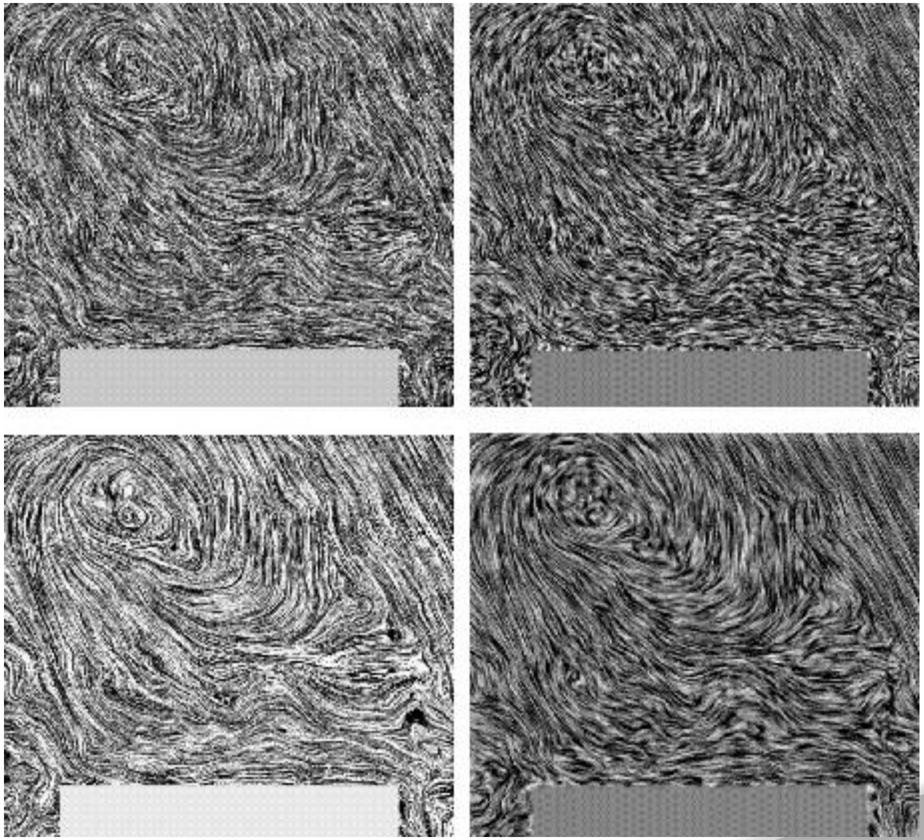
# Rendering - Spot Noise

- **Scalar - use +-shape for positive values, x-shape for negative values**
- **change the size of the spot according to the norm of the gradient**
- **vector data - use an ellipse shaped spot in the direction of the flow ...**



# Rendering - LIC

- **Similar to spot noise**
- **embed a noise texture under the vector field**
- **difference - integrates along a streamline**



LIC Spot Noise

# Texture Splats

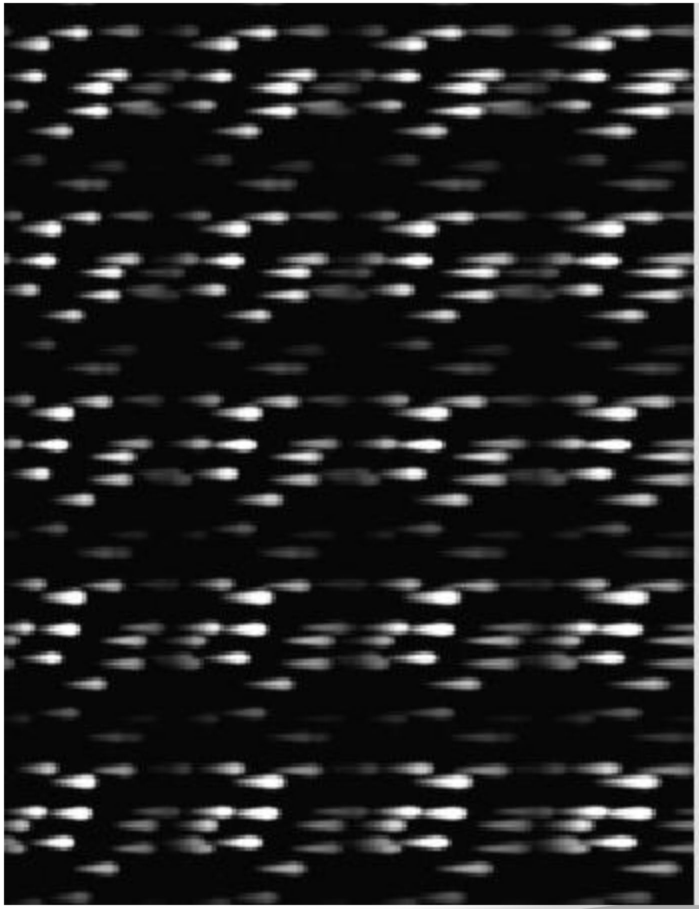
- Crawfis, Max 1993
- extended splatting to visualize vector fields
- used simple idea of “textured vectors” for visualization of vector fields

# Texture Splats - Vector Viz

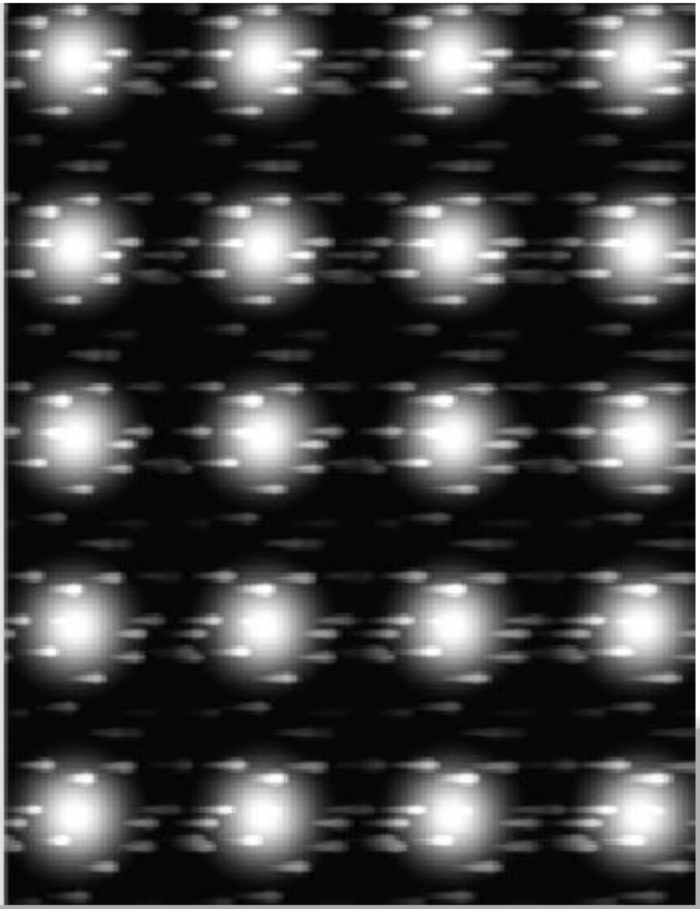
- The splat would be a Gaussian type texture
- how about setting this to an arbitrary image?
- How about setting this to an image including some elongated particles representing the flow in the field?
- Texture must represent whether we are looking at the vector head on or sideways

# Texture Splats

Texture images



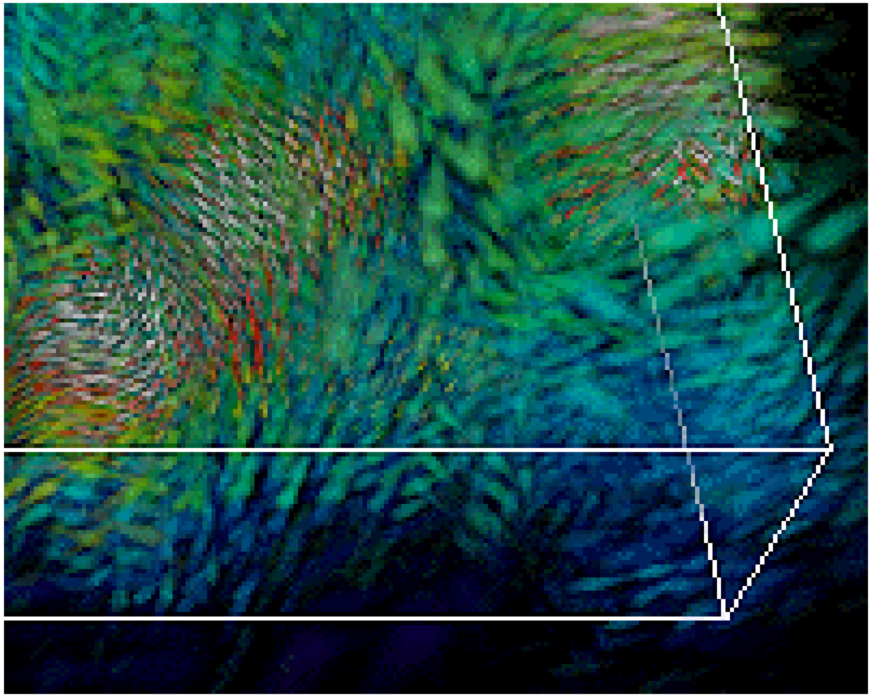
Appropriate opacities

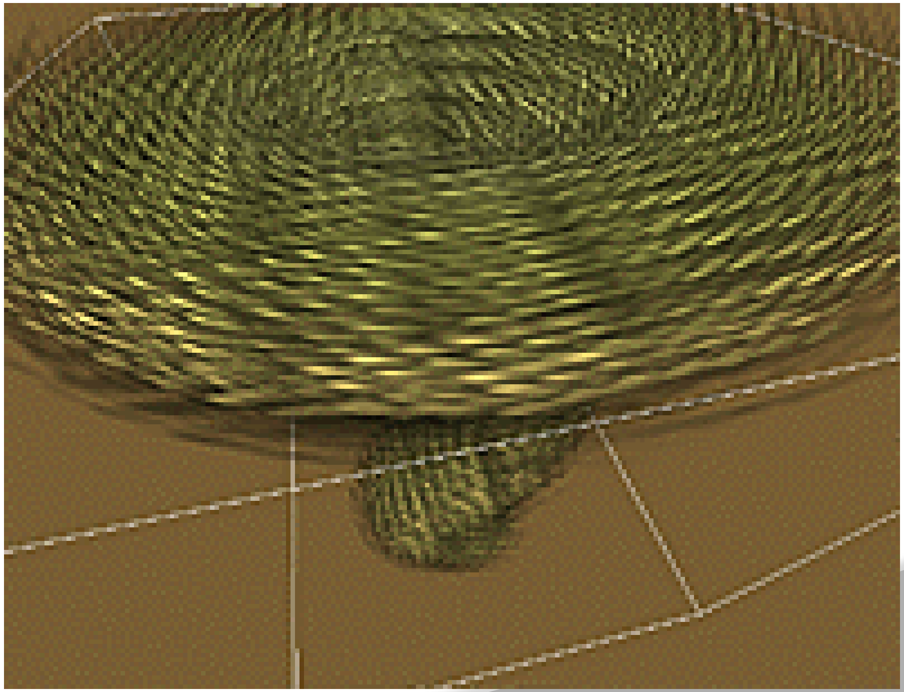


- **How do you get them to “move”?**
- **Just cycle over a periodic number of different textures (rows)**

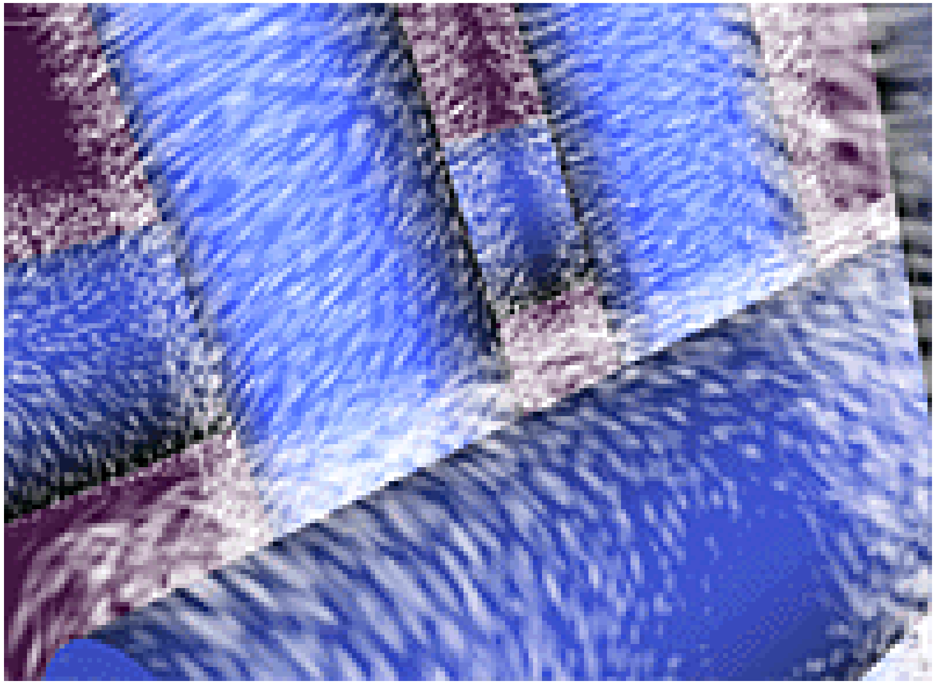
# More global techniques

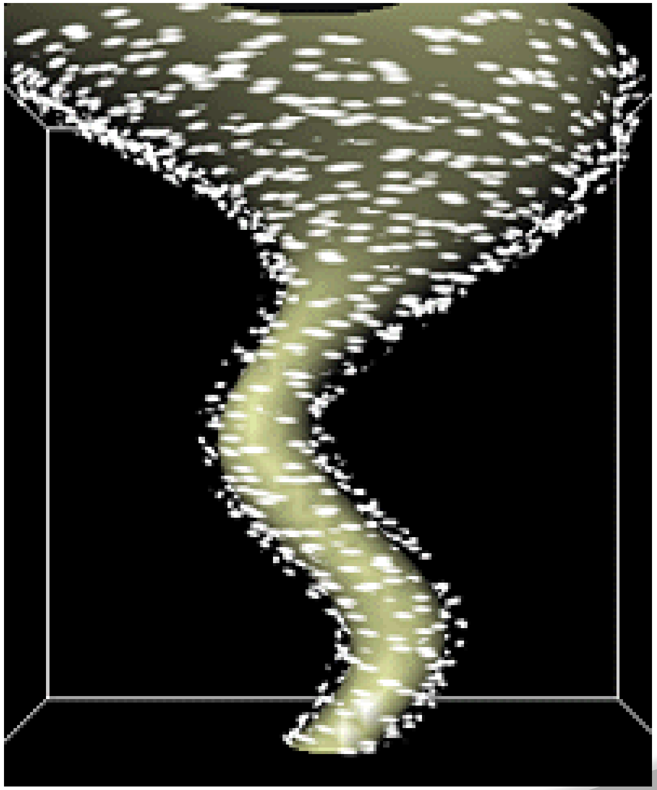
Texture Splats



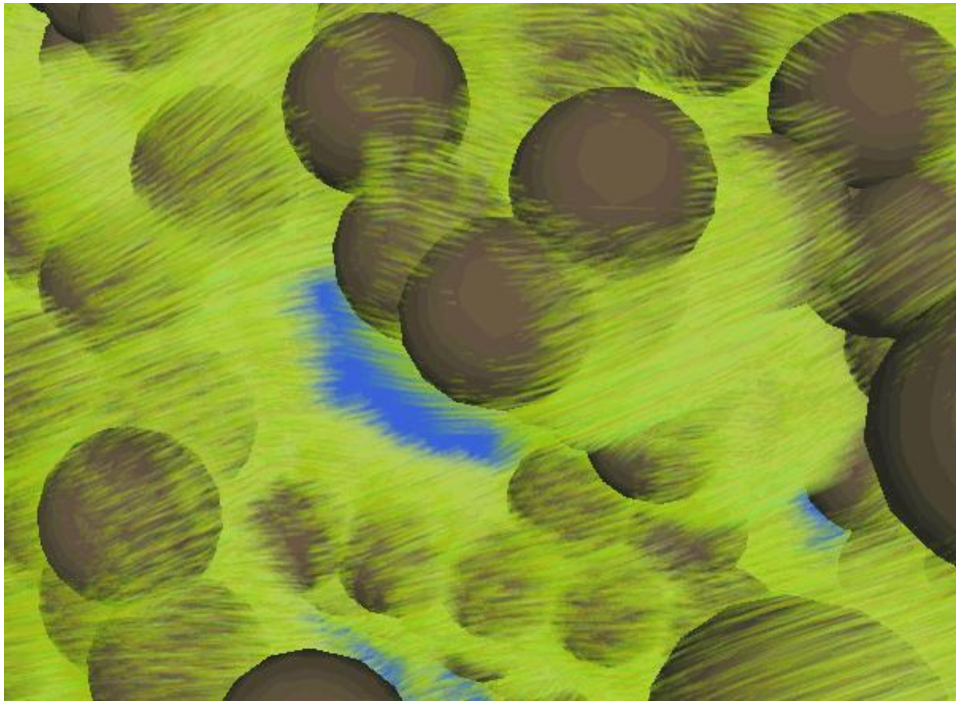


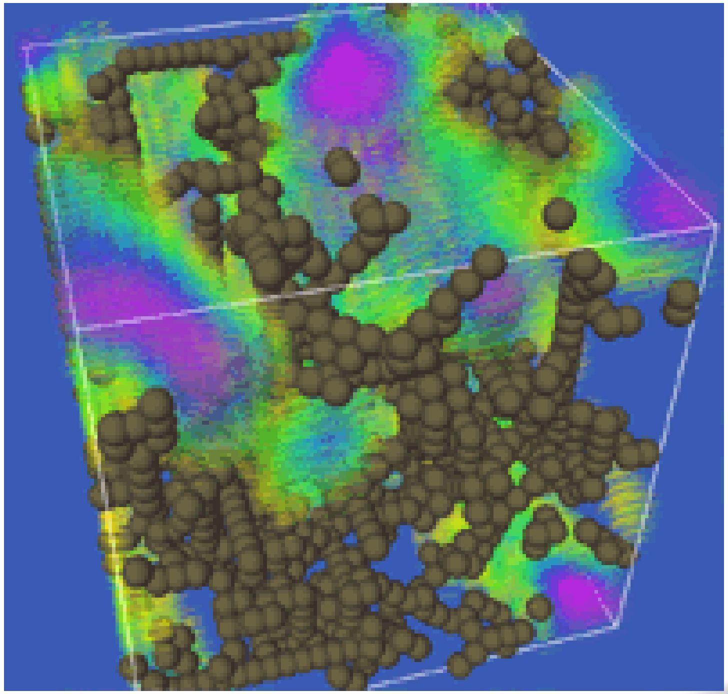
# Spot Noise



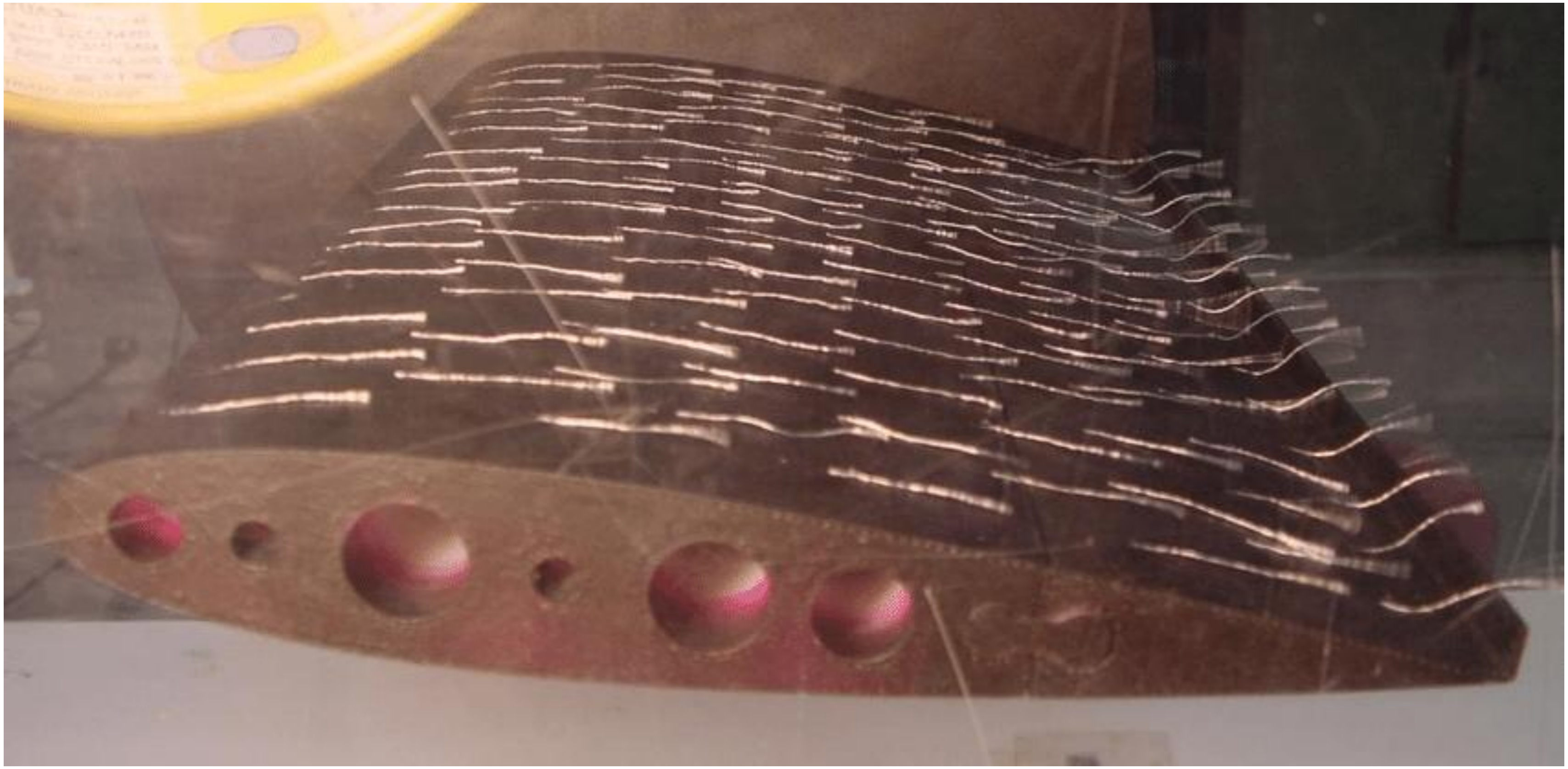


# Line bundles



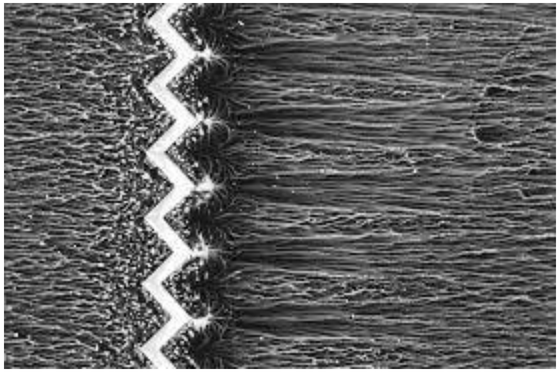


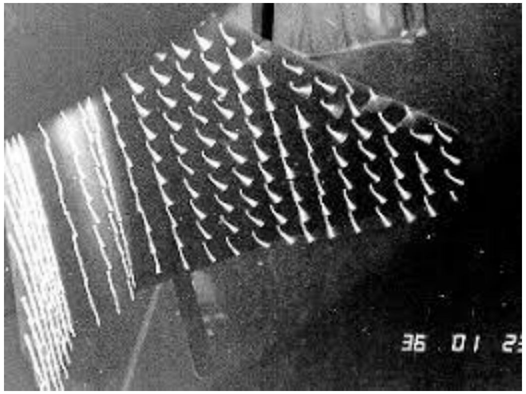
# Time Lines, Tufts

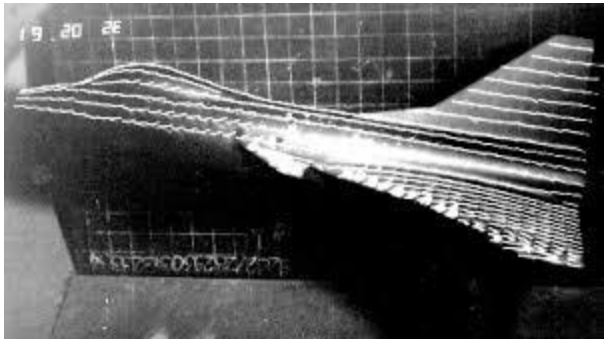


# China Clay

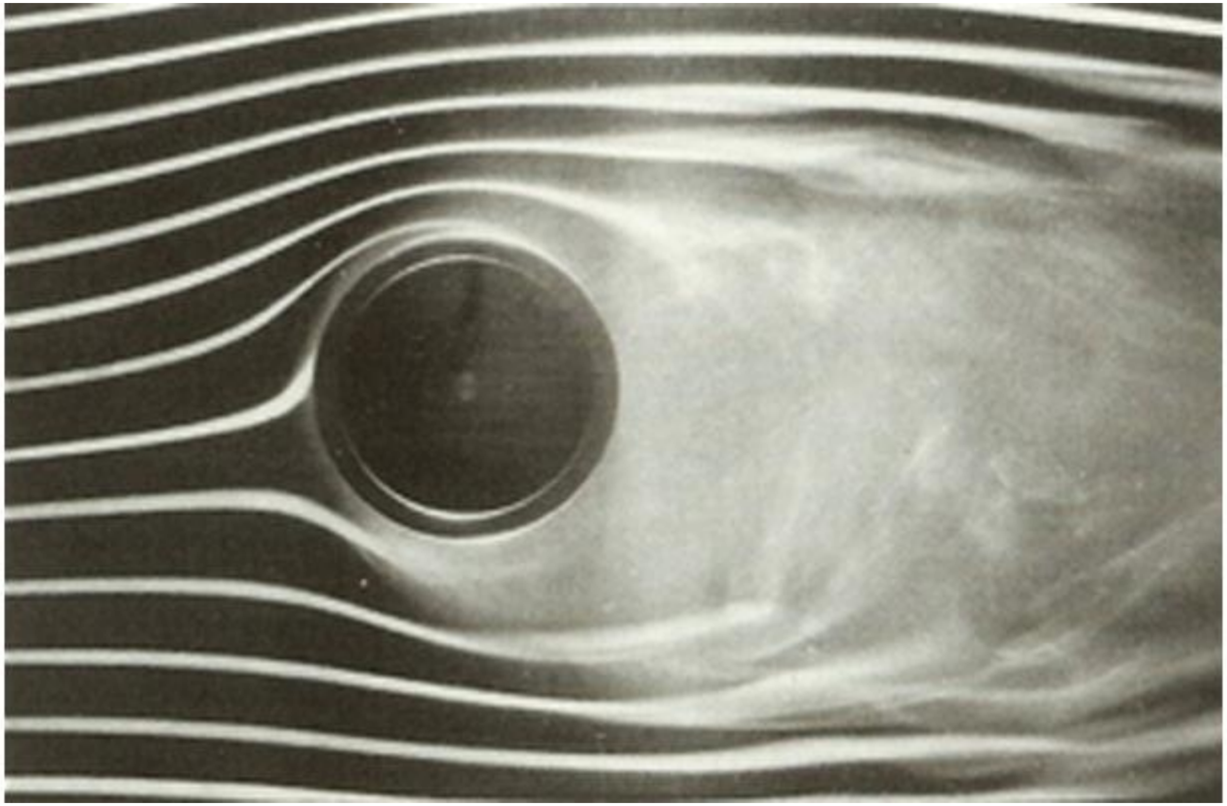
# Oil Film



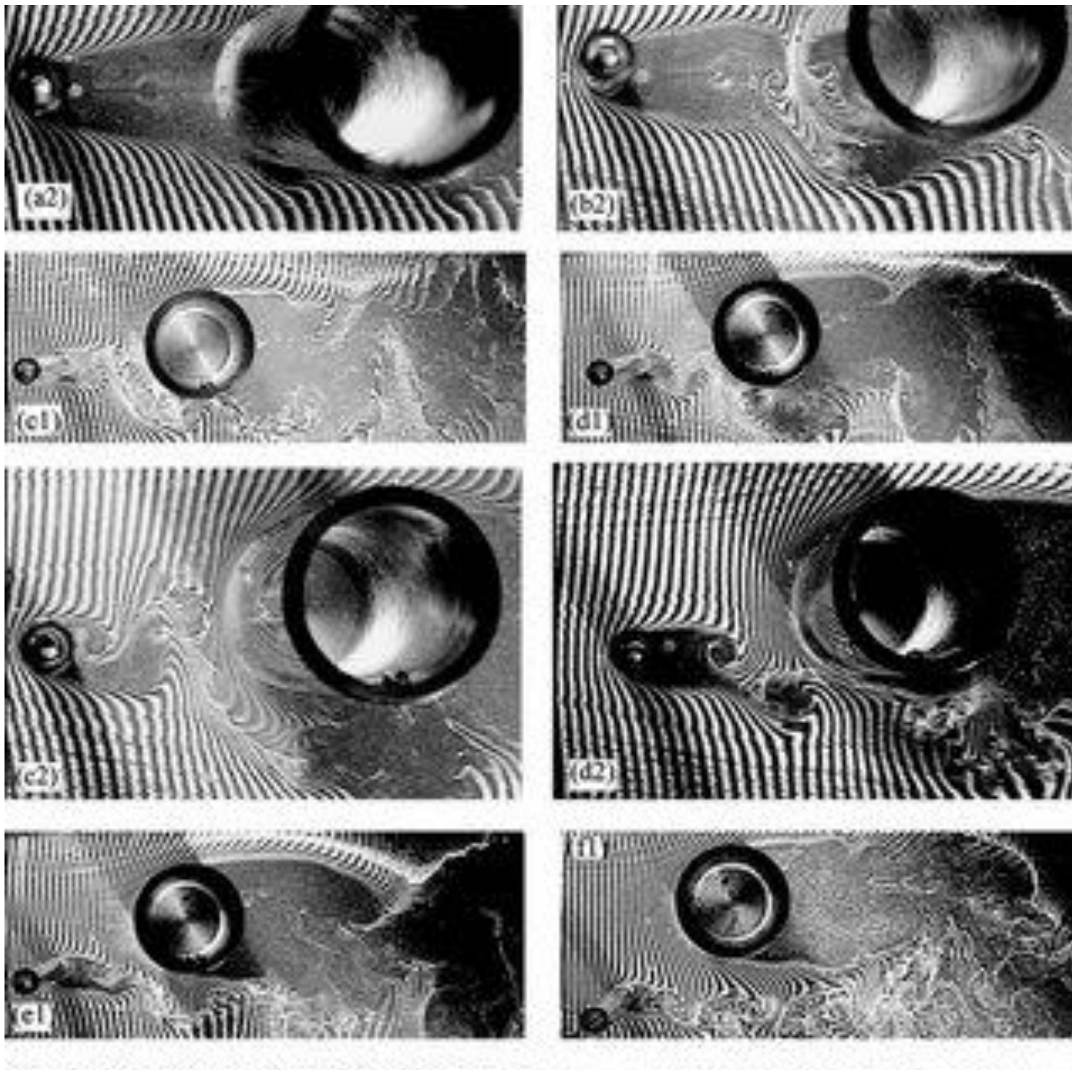




# Smoke



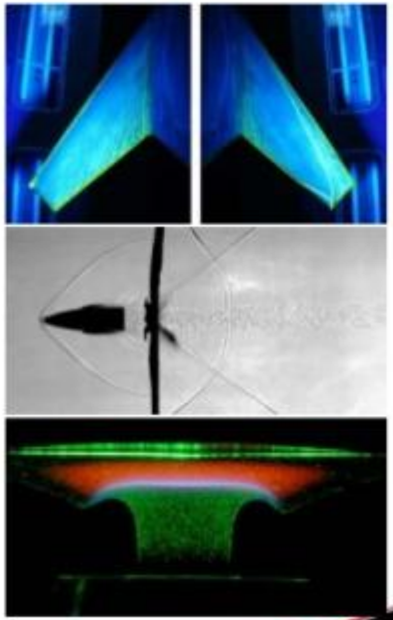
# Hydrogen Bubble



# Optical Methods:

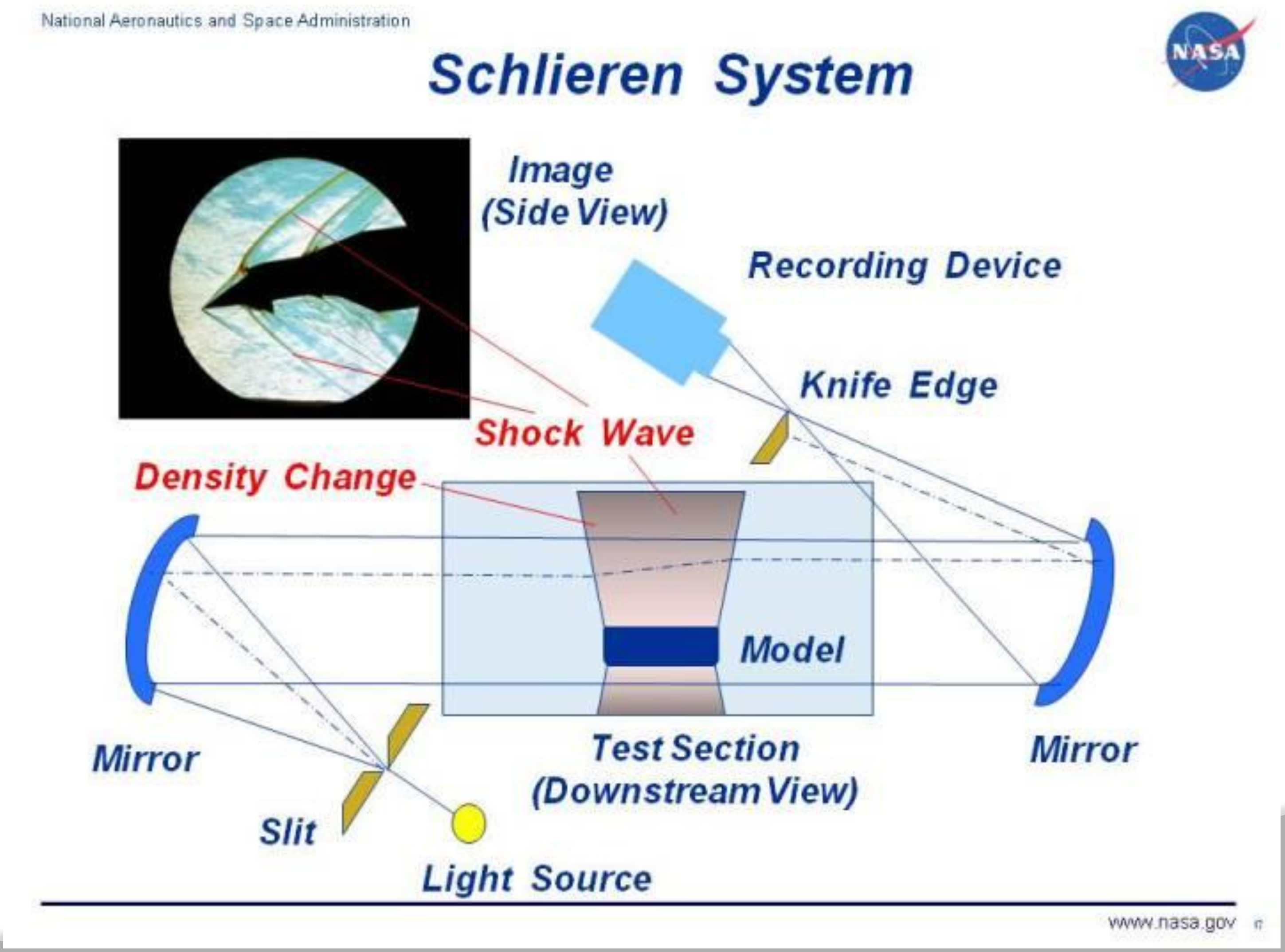
## Flow Visualization Techniques

- Surface Flow Visualization
- Optical Methods
  - Shadowgraph
  - Schlieren
  - Laser Induced Fluorescence
  - ➢ Particle Tracer Method
    - Laser Doppler Velocimetry
    - Particle Image Velocimetry

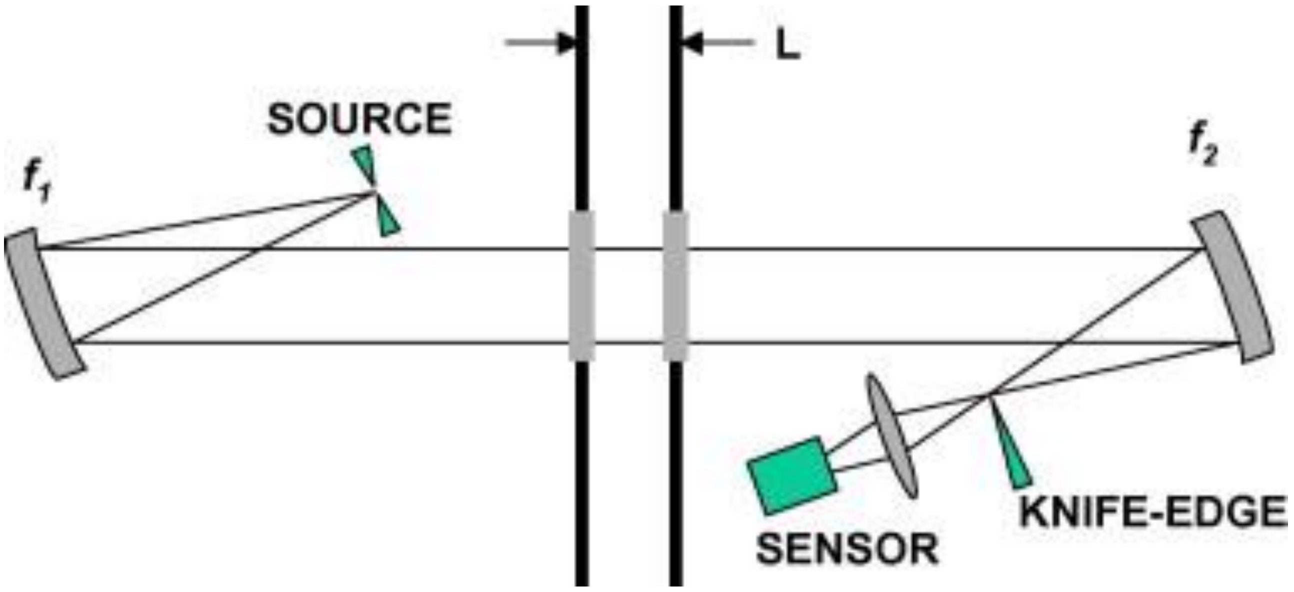


UNIVERSITY OF Cincinnati

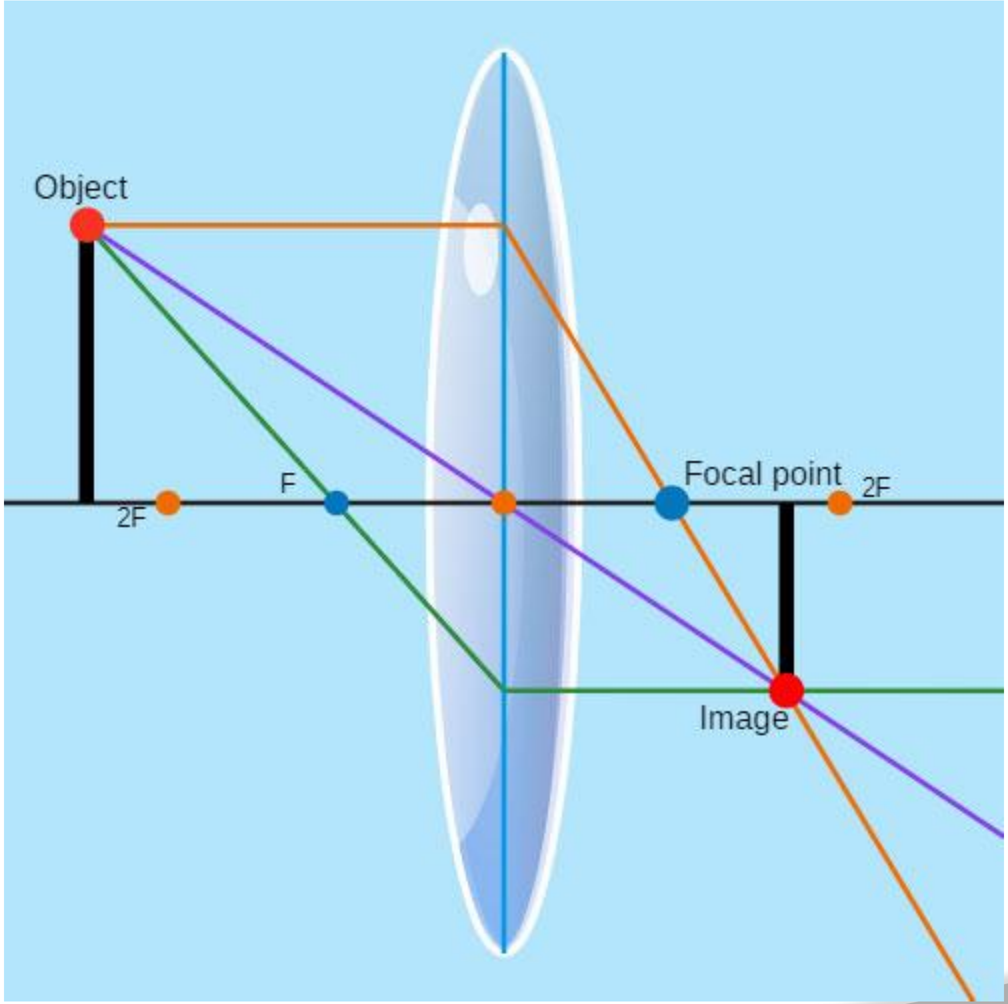
# Density and Refractive Index



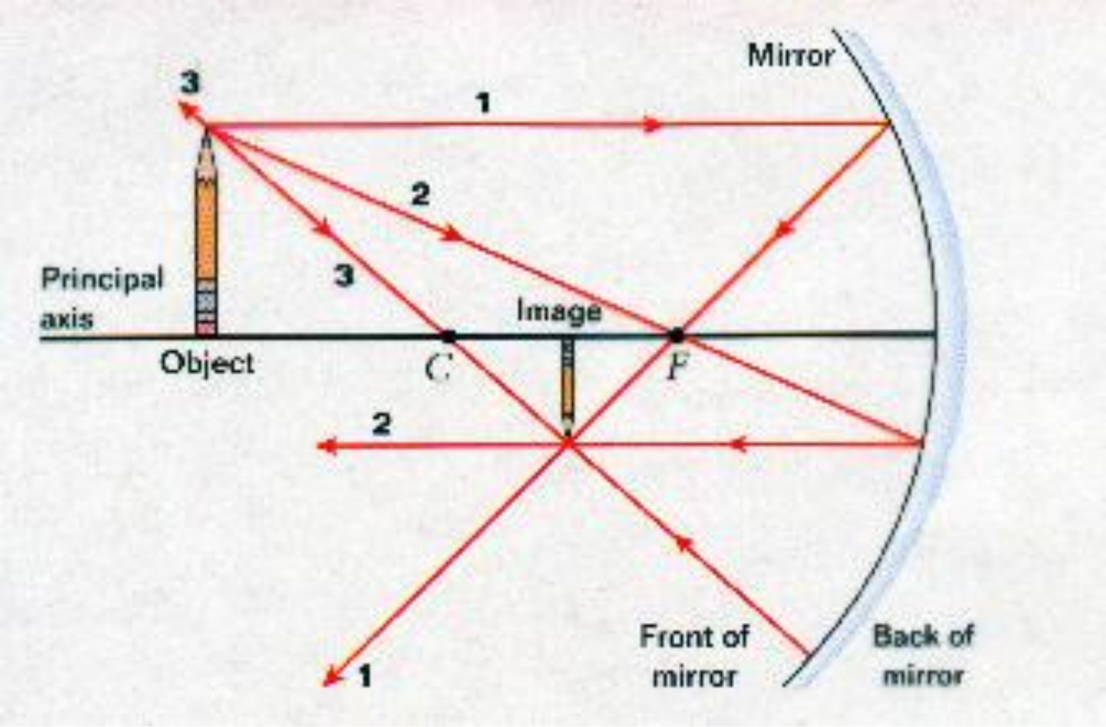
# Schlieren System



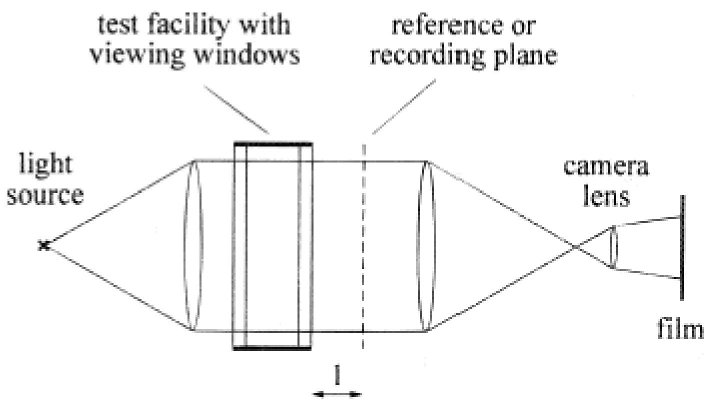
# Convex Lenses

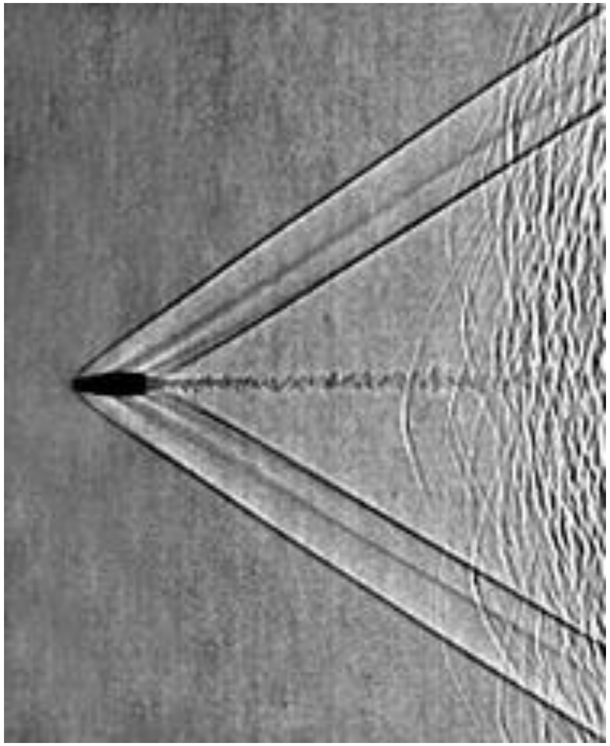


# Concave Mirrors

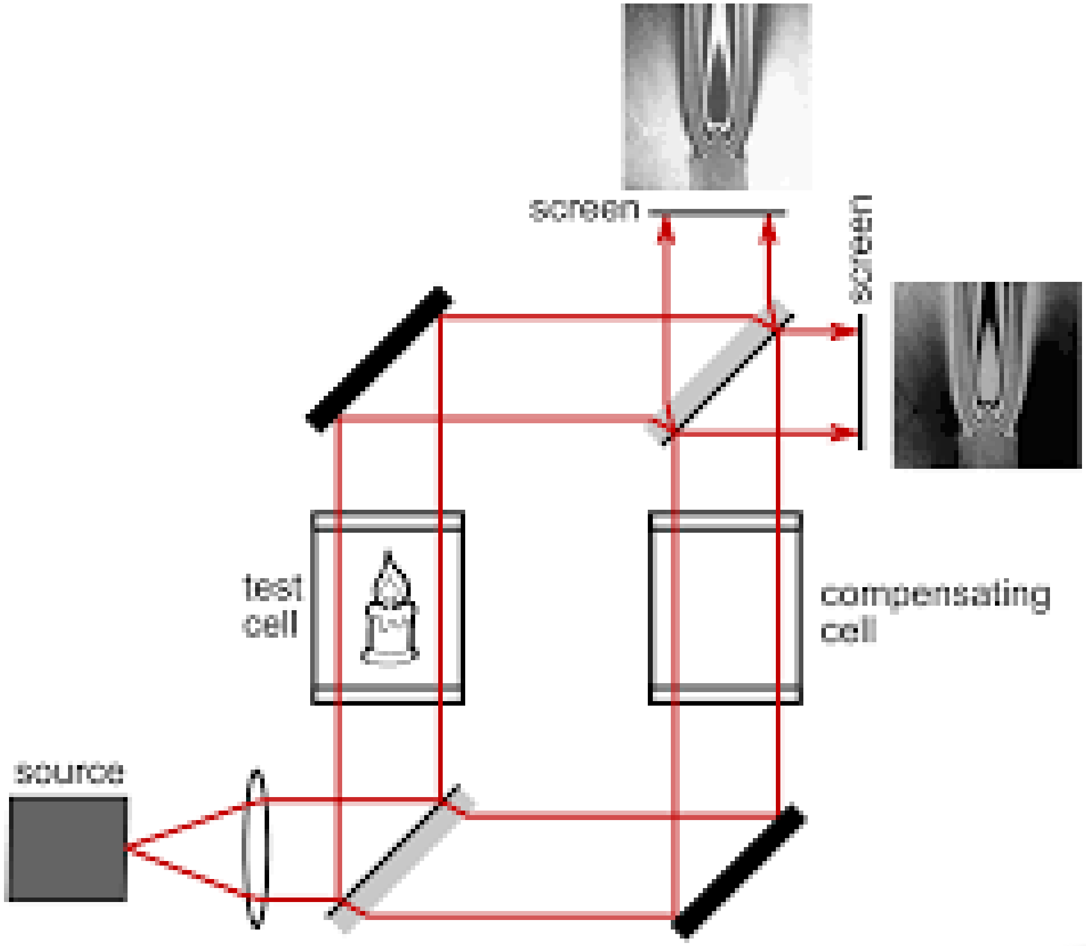


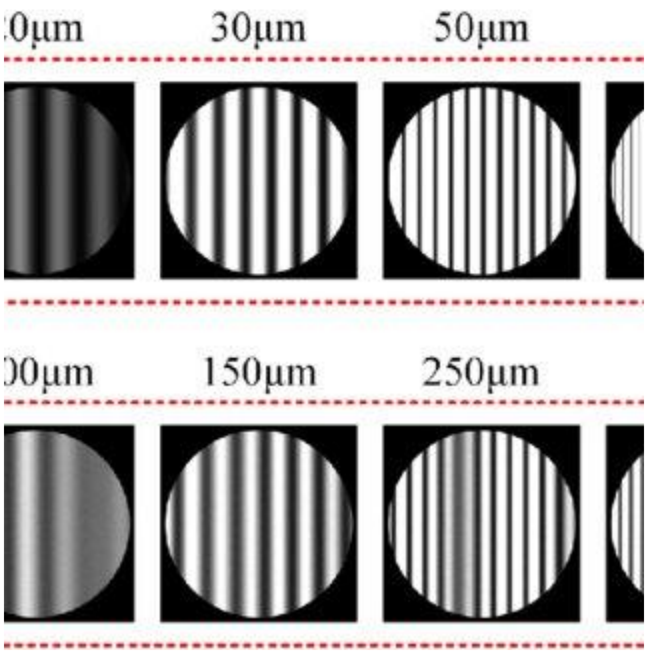
# Shadowgraph



# Interferometry




Thank you