This educational seminar provides an introduction to basic concepts of vacuum pressure and gas flow.

Topics of discussions include

- History of Vacuum
- Why we need vacuum
- Pressure and Flow
- Conductance

Brief History of Vacuum Development

Von Guericke
(1602-1686)

Torricelli
(1608-1647)

Pascal
(1622-1666)

Boyle
(1627-1691)

Bernoulli
(1700-1782)

Gay-Lussac
(1778-1851)

Gaede
(1878-1945)

Holweck
(1890-1941)

Varian Brothers
(1898-1961)

Vacuum History (cont'd)

Von Guericke
(1602-1686)

Torricelli
(1608-1647)

- Disputed Galileo's interpretation that 'vacuum force' drew water from a well
- Credited with the invention of the Hg barometer
- Also known for his contribution to Optics and Integral Calculus

Vacuum History (cont'd)


Gaede
(1878-1945)

Holweck
(1890-1941)

- Wolfgang Gaede invented the mercury vapor 'diffusion' pump in 1915
- Gaede (1912) and Holweck (1920s) first proposed pumps based on 'molecular drag'
- 'drag stage' turbo-molecular pumps were not commercialized until the 1980's!


Varian Brothers
(1898-1961)

- Klystron linear vacuum-tube amp invented in 1937; *(radar and microwave network development*)
- Co-inventors of Nuclear Magnetic Resonance (NMR) in 1945-46; *"most significant innovation…"*
- 'sputter-ion' pump invented 1956 (*tube life*)
- Varian Inc. Acquired by **Agilent** in 2010

Why We Need Vacuum?

Move Particles over Long Distances

- High Energy Physics (Particle Accelerators)
- Mass Spectrometry & Electron Microscopes

Create & Maintain 'Clean' Surfaces

- Coating on surfaces (glass, film, semi-conductor)
- Food Packaging

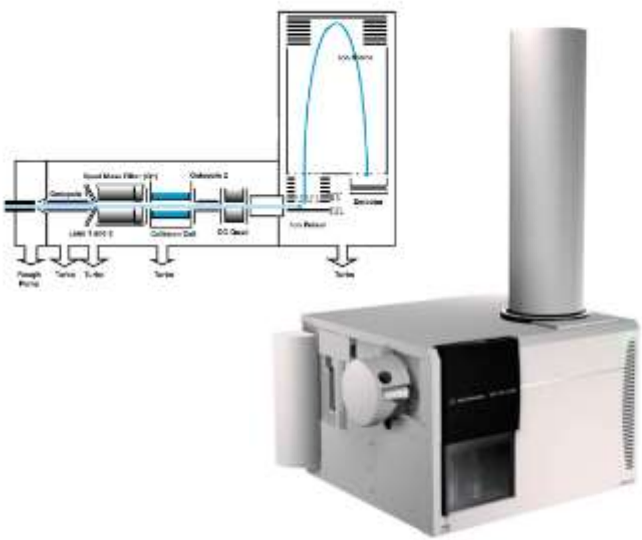
Prevent Electrical Breakdown

- Electrical transformers
- Vacuum Tubes

Moving Particles

CERN Large Hadron Collider (LHC)

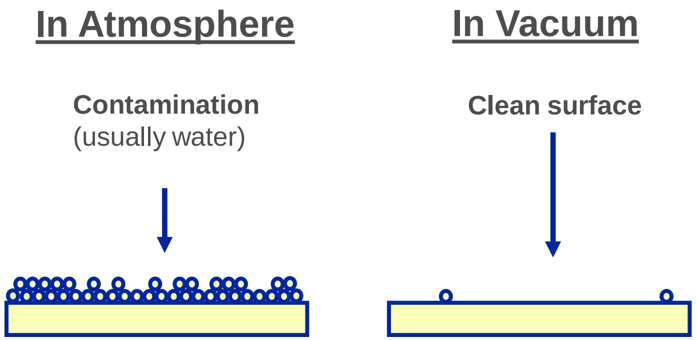
- 11,100 laps/sec around 27 km (17 mile) path
- Beam pipe at approx. 10^{-11} Torr (same as surface of the moon)
- Particles travel at 99.9999% of speed of light
- Vacuum also used as thermal shield for cryo-genic magnets



AGILENT 6500 Series LC-TOF

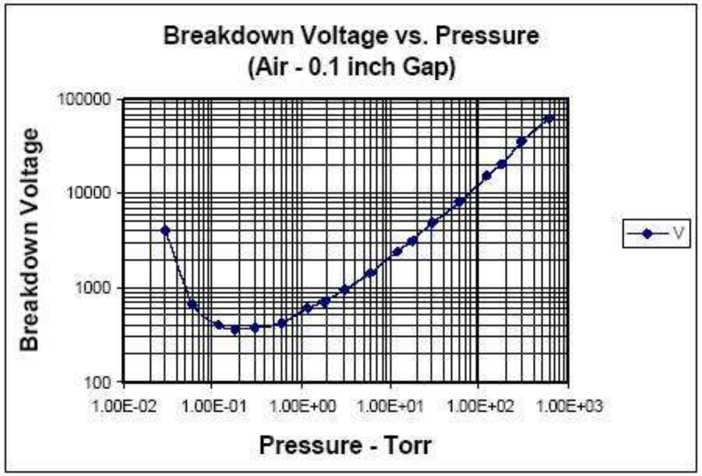
- Approx. 2m flight path (TOF section)
- TOF section pressure ≈10^{-6} Torr
- Vacuum also required for high voltages in the acceleration and collection of ions

Surface Cleanliness & Electrical Isolation



Water Vapor 'Contaminates' Surfaces

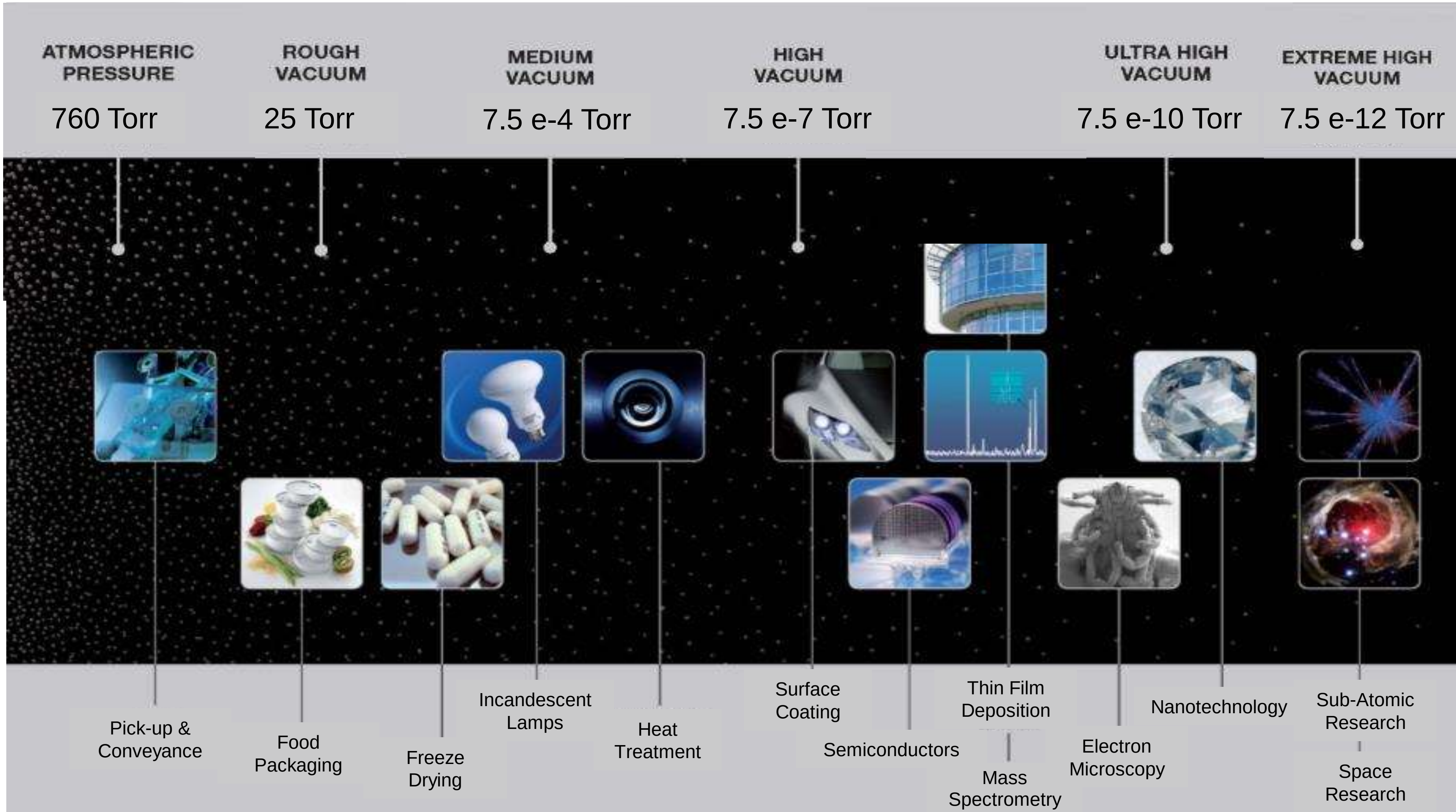
- monolayer of water forms in few seconds at 10^{-6} Torr (vs several HOURS at 10^{-11} Torr)
- Water can bond 'infinitely' to itself!



Breakdown Voltage vs Pressure

- Paschen Curve (F. Paschen, 1889)
- Essential for operation of High Voltage Power amplifier tubes (Radar, X-Ray, Microwave)

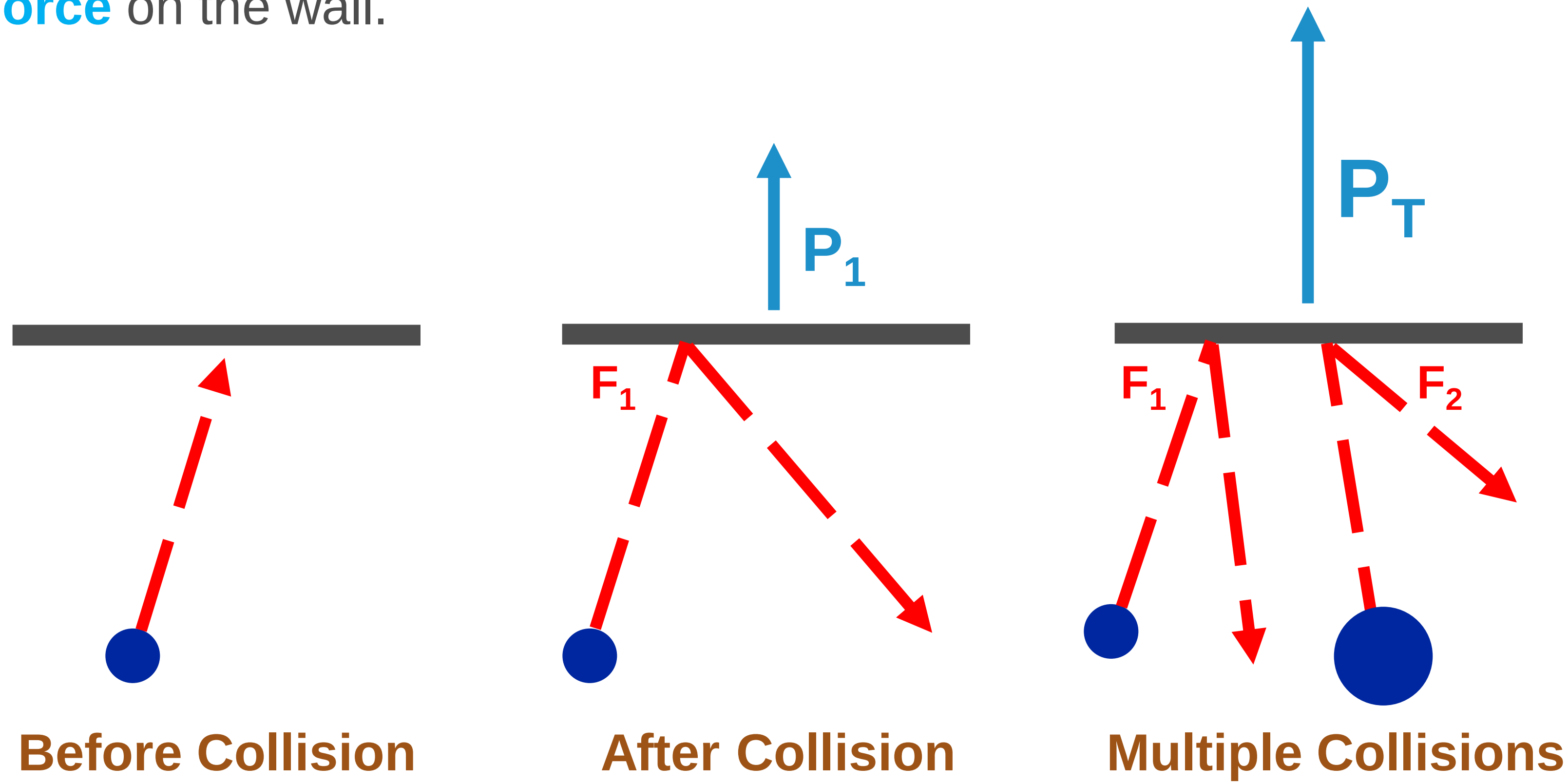
The Range of Vacuum Pressure



Pressure: Molecular Collisions

$$P = F/A$$

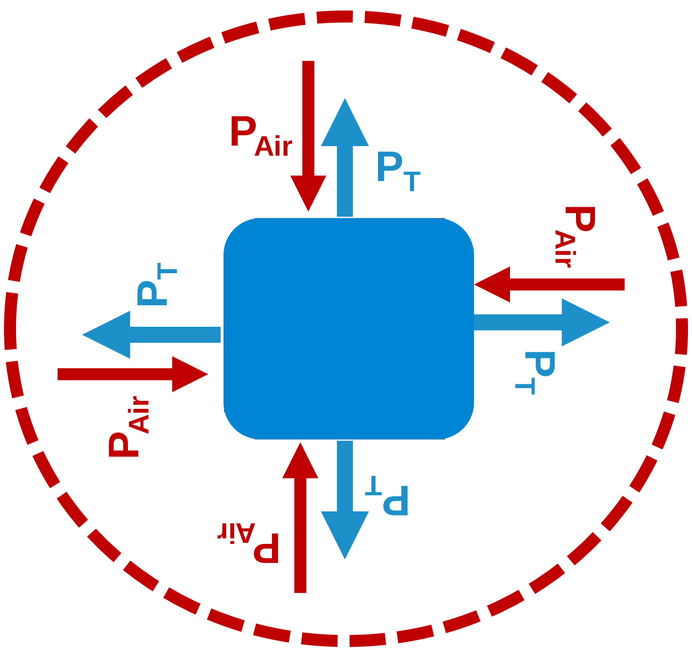
Momentum transfer from a particle hitting a fixed surface creates a **Force** on the wall.



Pressure in a Chamber

Pressure Depends On:

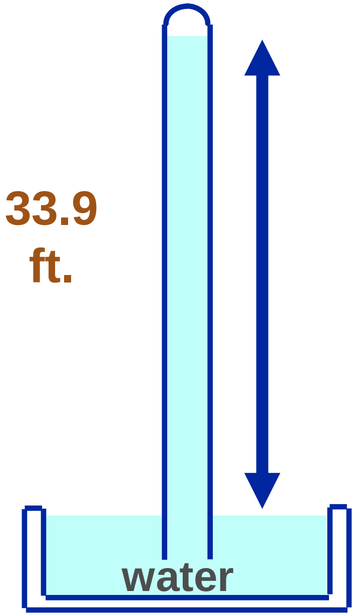
- Number of molecules in the chamber
- Momentum of the molecules (thermal energy)
- Area of the chamber (volume)



Measuring Atmospheric Pressure

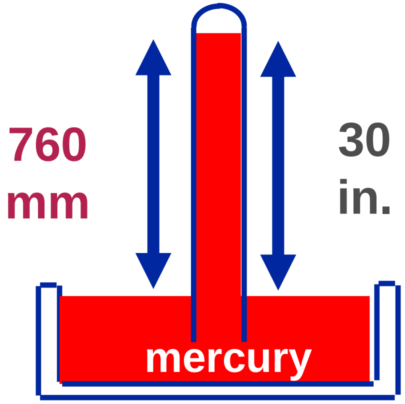
Berti’s Experiment

- 1 In = 0.036 lbs (PSIa)
- 1 Std. ATM = 14.7 PSIa
- Height of column:
  - 14.7/0.036 = 408 In **= 33.9 ft.**



Torricelli's Experiment

- ≈ 14 times heavier than water
- Column is 13 times shorter!
  - 408/14 = 30 In **= 760 mm**



1 std. ATM = 760 Torr

Altitude vs. Pressure

Less Air Molecules

More Air Molecules

Altitude	Pressure (Torr)
1,000 miles	10^{-10}
25 miles	2
10 miles	78
27,500 ft	253
20,000 ft	350
5,000 ft	632
2,000 ft	709
Sea Level	760

Altitude vs. Pressure

Less Air Molecules

More Air Molecules

Altitude	Pressure (Torr)	Particles / cm^3
1,000 miles	10^{-10}	4×10^{6}
25 miles	2	8×10^{16}
10 miles	78	3×10^{18}
27,500 ft	253	1×10^{19}
20,000 ft	350	1.5×10^{19}
5,000 ft	632	2.5×10^{19}
2,000 ft	709	2.8×10^{19}
Sea Level	760	3.0×10^{19}

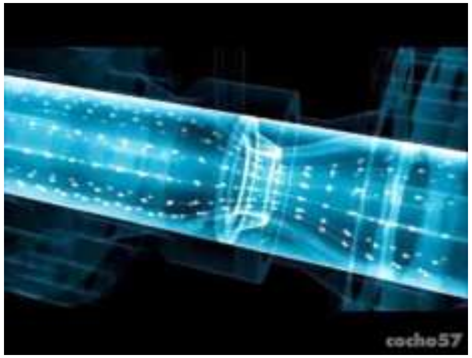
What is Flow?

Unlike SOLIDS, fluids (and gases) do not retain their shape, but adopt the shape of the container.

Fluids will ‘flow’ readily from one place to another with relatively low forces.

While liquids are constrained by ‘body forces’ (gravity and centrifugal), GASES are relatively immune to these:

- Liquids move at ***meters per second*** speeds while gases can move at ***hundreds of meters per second*** with relatively small pressure differences



Gas Flow Regimes

As gas travels from an area of high pressure to one of lower pressure we can describe the motion of the 'fluid' in terms used in fluid dynamics. **BEHAVIOR** of the gas will be different depending on the pressure*.

VISCOUS FLOW (P > 100 mTorr)

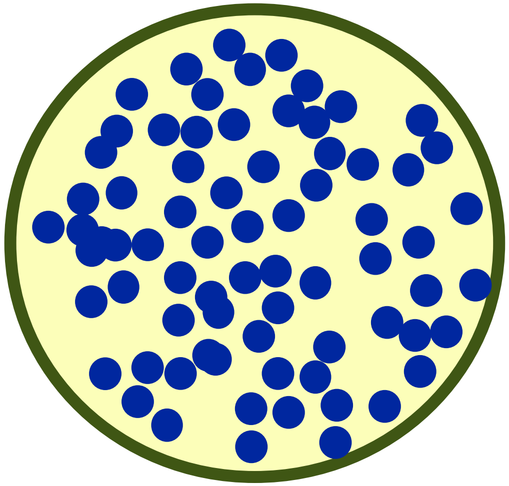
- **Gas behaves like liquid in a tube**
- **Distance between molecules is small**
- **Collisions between gas particles dominate**
- **Flow through momentum transfer**

MOLECULAR FLOW (P < 1 mTorr)

- **Gas molecules behave like discrete particles**
- **Interact with walls more frequently than each other**
- **Minimal collisions between gas particles**

Flow Regimes: Viscous vs Molecular

VISCOUS FLOW
(P > 100 mTorr)



MOLECULAR FLOW
(P < 1 mTorr)

Why We Care: Viscous vs Molecular

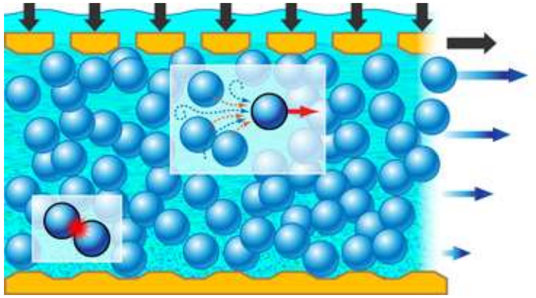
VISCOUS FLOW
(P > 100 mTorr)

MOLECULAR FLOW
(P < 1 mTorr)

Transition Flow (1 -100 mTorr): Life Gets Messy!

Between 100 mTorr (Viscous Flow) and 1 mTorr (Molecular Flow) is the region where gas behavior is less predictable, so we define gas motion as being in **Transition Flow** (also referred to as **Knudsen Flow**).

In reality, flow characteristics are based on the **relationship** between the pressure and the dimensions of the vessel, so characterizing **flow** based on Pressure alone is not technically valid!



Estimates of vacuum pressure in Transition Flow can vary by as much as 50%!

Conductance

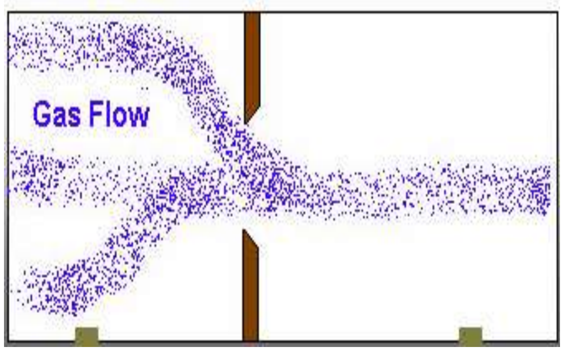
Conductance is the volume of gas per unit time that can move through a region like an orifice or pipe

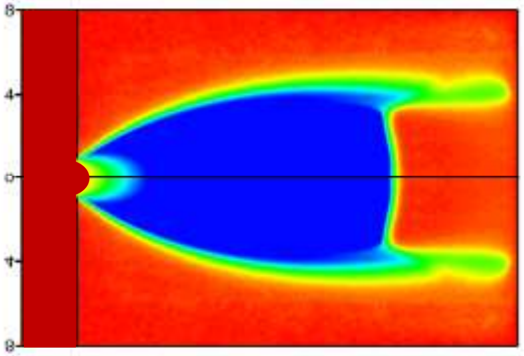
The term “conductance” is assigned to passive components of a system and it is the reciprocal of the resistance to gas flow.

Conductance is expressed in volume units per unit time (L/s)

Conductance in Viscous Flow

ORIFICE conductance in **viscous flow** is extremely complicated to calculate and this is rarely done in practice.





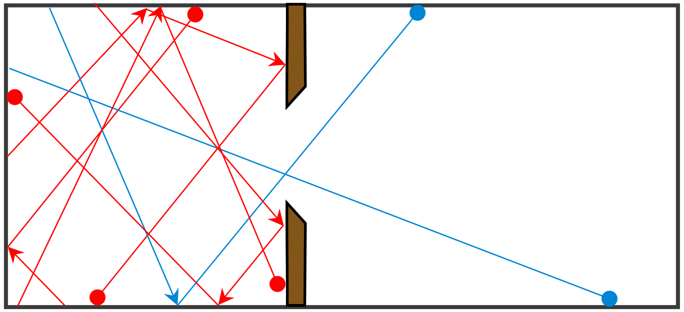
- The Viscous Flow Conductance of a **TUBE** however, is fairly straightforward.

$$C = 180\ D^4 \times P/L \quad (l/sec)$$

D = Diameter of tube in cm
L = Length in cm
P = Pressure in Torr

- Note the Conductance is α to the 4th power of the Diameter of the Tube, and the 1st power of the Pressure (average). Conductance is INVERSELY related to the pipe length (L)

Conductance in Molecular Flow



ORIFICE Conductance (for Air at Room Temperature)

$$C = 11.6 \times A$$ (where A is in cm^2)

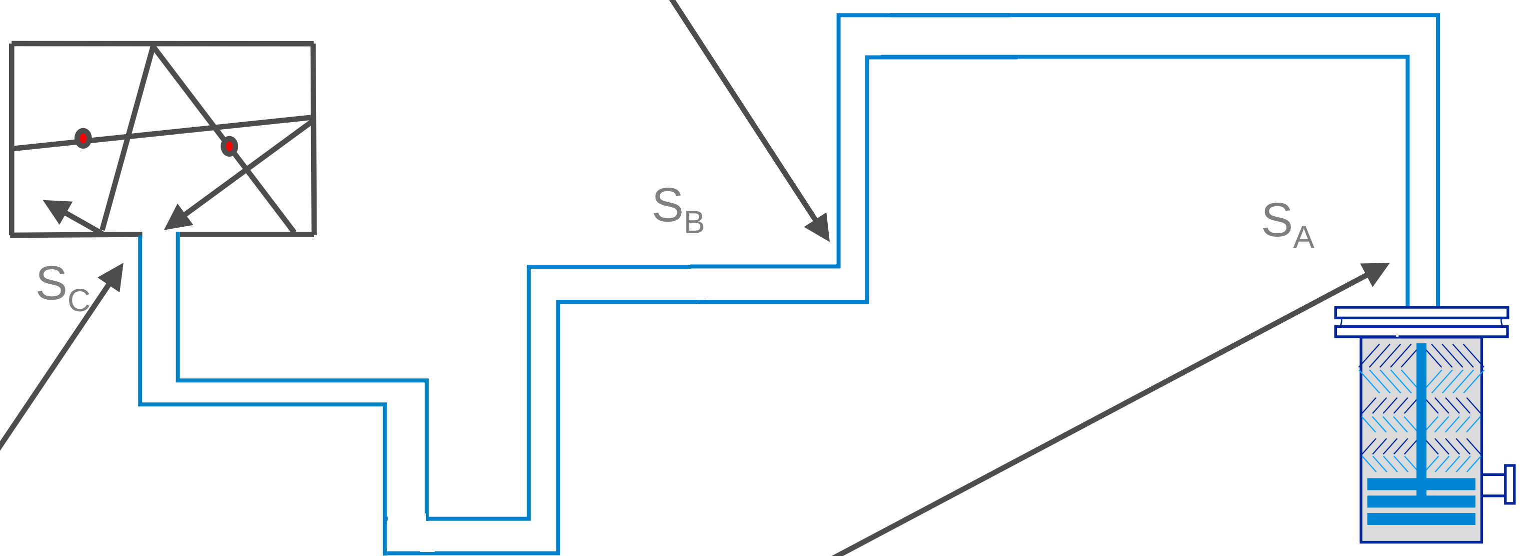
For Short Tubes: $C = \dfrac{11.6\,D^3}{1 + L/D}$

For Longer Tubes ($L > 1.5 \times D$) : $C = \dfrac{12.1\,D^3}{L}$

EXAMPLE: Conductance kills pump speed!

1m Tubing
C = 8 L/sec
S_B= 6.3 L/sec ≈ 5.1 L/sec

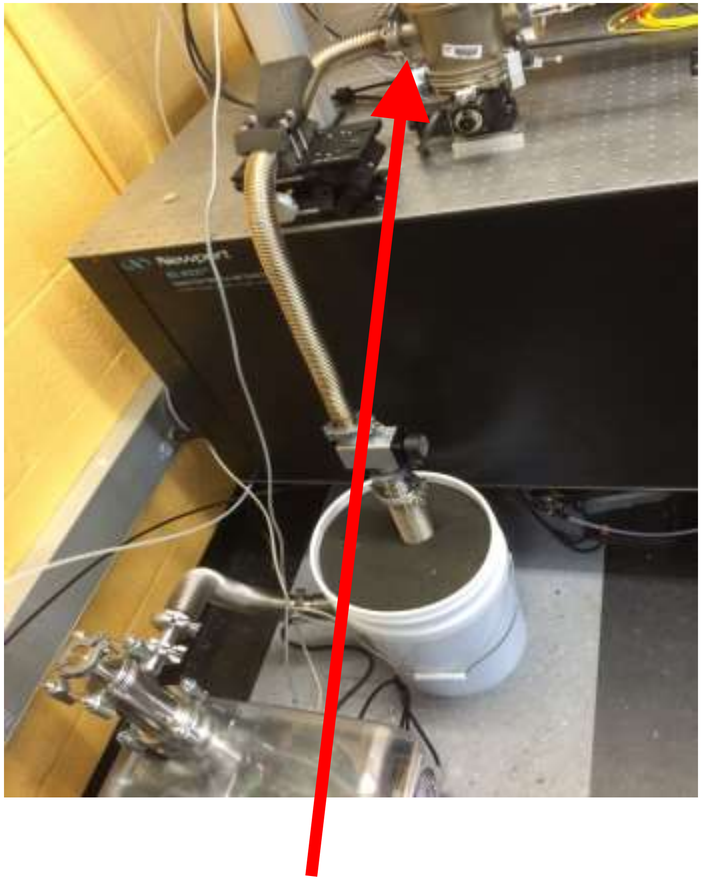
Pump Speed:
S = 67 liters/sec

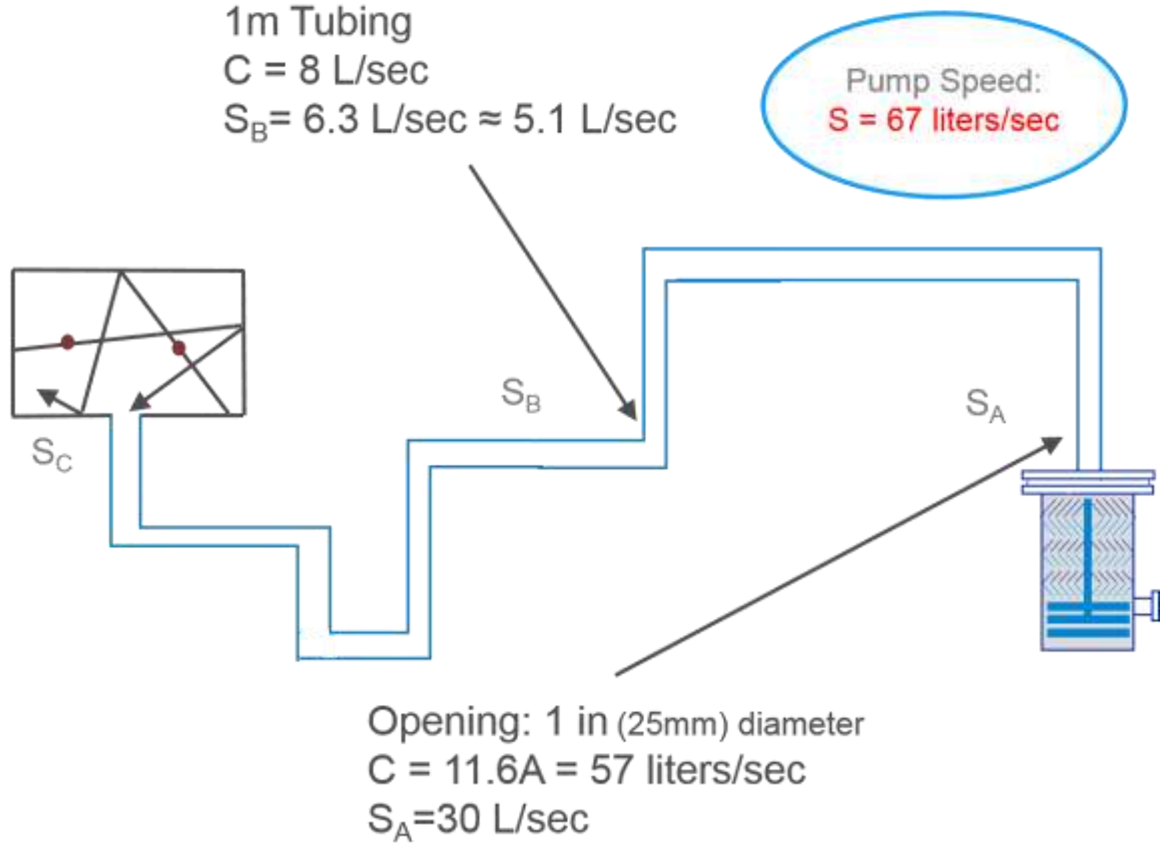


1m Tubing
C = 8 L/sec
S_B= 3.1L/sec ≈ 1.6 L/sec

Opening: 1 in (25mm) diameter
C = 11.6A = 57 liters/sec
S_A=30 L/sec

EXAMPLE: Conductance kills pump speed!





S_{net}= 1.6 L/sec

Summary

Much of the pioneering work in Vacuum was done *hundreds* of years ago (in the time of Galileo).

Vacuum is used in a huge variety of industries - from quantum calculators, to space exploration, to manufacturing of thin film displays and special alloys of metal.

Pressure is the force exerted on a surface through impact of (gas) molecule collisions.

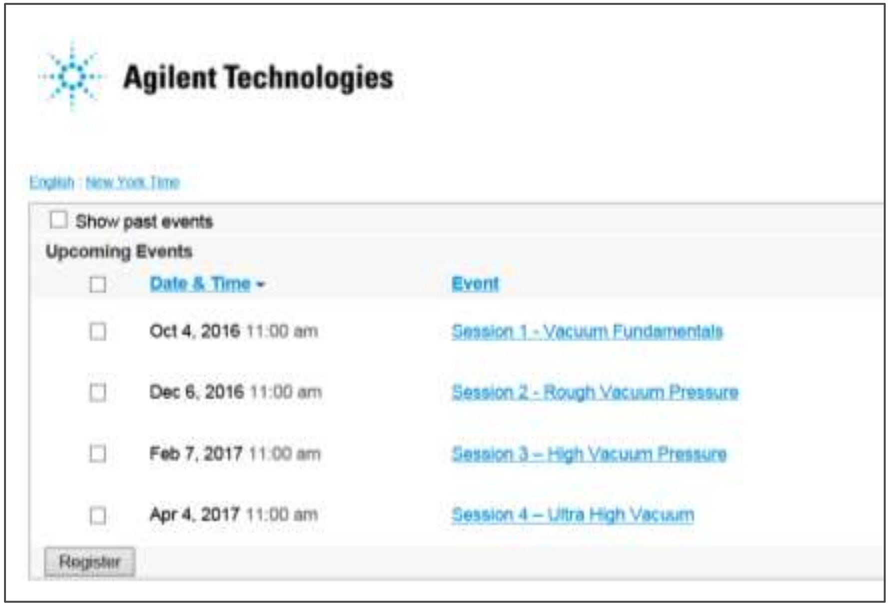
The behavior of gasses in a vessel varies significantly as the pressure changes, and this has a huge impact on how we measure pressure and the type of vacuum pumps needed to achieve **lower** pressure.

Conductance (losses) reduce our ability to pump gas.

Pressure…..How Low Can We Go?

- *Before 1950 we could not measure pressure below 10^{-8} Torr!*
- *By 1964 we could achieve vacuum pressure of around 10^{-14} Torr (Hobson)*
  … no significant advancement on this has happened since!

Next Session: Rough Vacuum Pressure (Dec-6)



Rough Vacuum Pressure Webinar deals with the process of generating, measuring, and maintaining Rough Vacuum Pressure (Atmosphere to approx. 10^-3 Torr).

Concepts such as Conductance, Viscous Flow, and Gas Composition will be discussed in more detail.

Participants will learn about the benefits and drawbacks of different Rough Vacuum pump and Gauge technologies, and what to consider when constructing a vacuum system or troubleshooting leaks in the Rough Vacuum regime.