The US Particle Accelerator School
Vacuum Fundamentals

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Your Instructor

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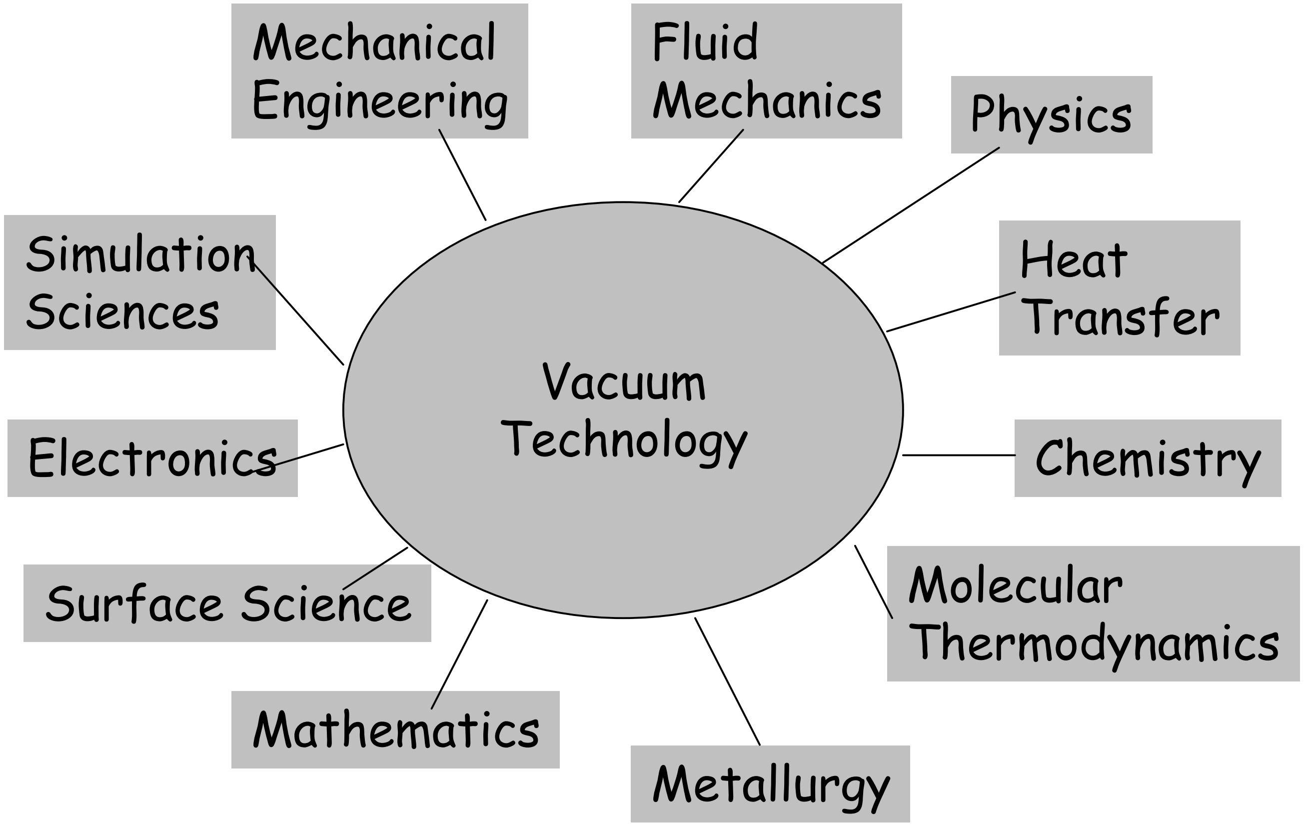
Vacuum is a highly interdisciplinary subject



Vacuum Technology

Mechanical Engineering

Fluid Mechanics

Physics

Heat Transfer

Chemistry

Molecular Thermodynamics

Metallurgy

Mathematics

Surface Science

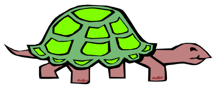
Electronics

Simulation Sciences

Kinetic behavior of gas molecules

The behavior of a collection of gas molecules in a vessel is dependent upon the pressure, temperature and composition of the gas.

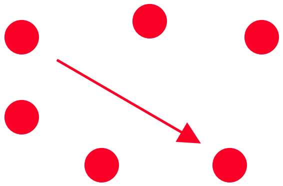
Velocity of gas molecules.



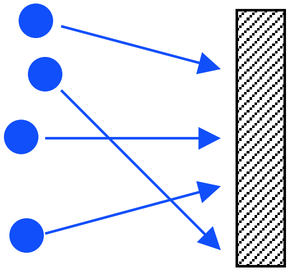
Kr

He

Mean free path



Impingement rate



Gas Laws

Charles' Law

volume vs temperature

Boyle's Law

pressure vs volume

Combined or General Gas Law

pressure vs temperature vs volume

Avogadro's Law

volume vs amount

Ideal Gas Law

pressure vs temperature
vs volume vs amount

These laws apply to all molecules and atoms regardless of their size

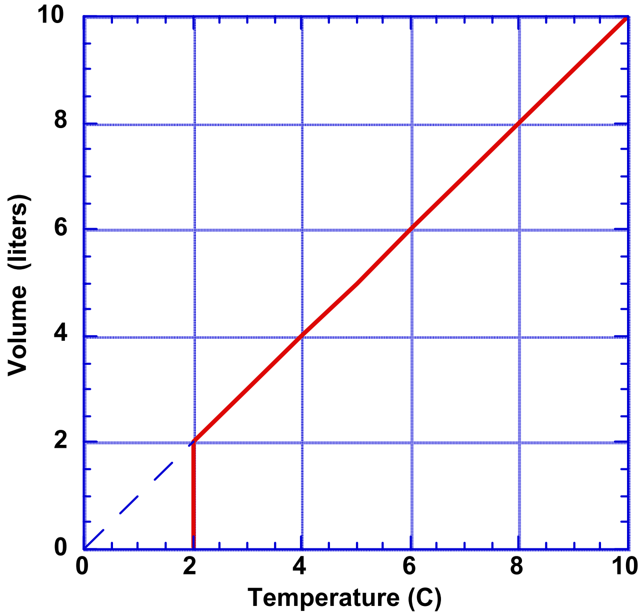
Charles's Law

The volume of a fixed amount of gas at a fixed pressure will vary proportionally with absolute temperature.

$$V \propto T$$

$$\frac{V}{T} = \text{constant}$$

$$\left(\frac{V_1}{T_1}\right) = \left(\frac{V_2}{T_2}\right)$$



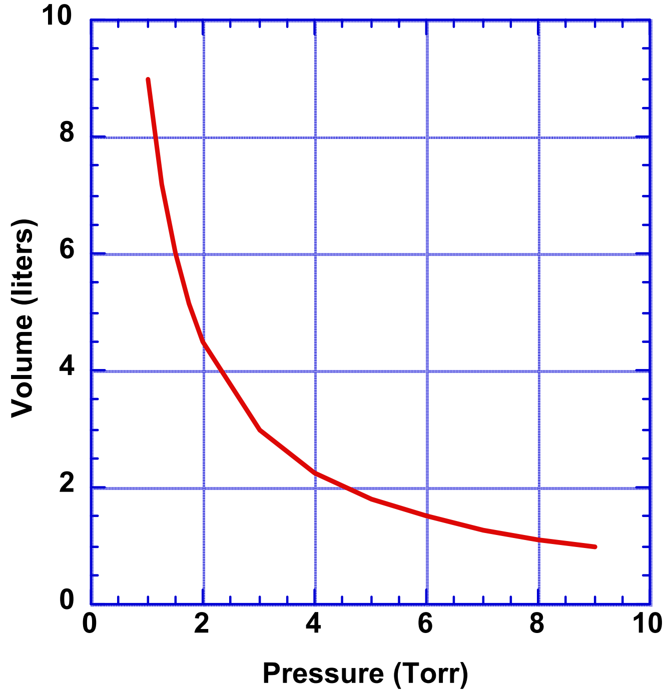
Boyle's Law

For a fixed amount of gas at a fixed temperature, its pressure is inversely proportional to its volume.

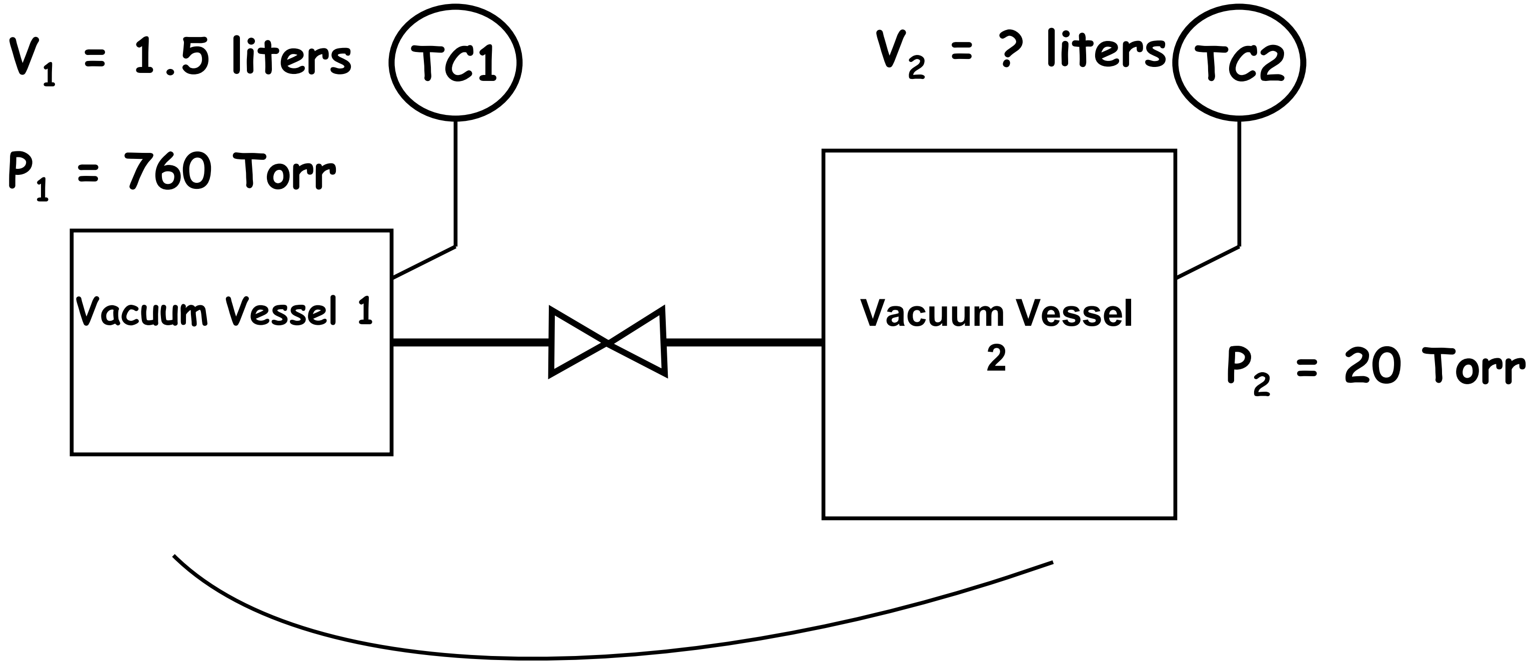
$$V \propto \frac{1}{P}$$

$$PV = \text{constant}$$

$$P_1V_1 = P_2V_2$$



Finding volume of a vessel with Boyle's Law



V_1 = 1.5 liters

P_1 = 760 Torr

TC1

Vacuum Vessel 1

V_2 = ? liters

TC2

Vacuum Vessel 2

P_2 = 20 Torr

Combined Gas Law

Provides relationship between pressure, volume, and temperature for a fixed amount of gas.

$$\frac{PV}{T} = \text{constant}$$

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

Example of combined gas law

P_1 = 100 Torr P_2 = 200 Torr
V_1 = 200 liters V_2 = 80 liters
T_1 = 293 K T_2 = ? K

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

$$\frac{(100\ \text{Torr})(200\ \text{liters})}{293\ \text{K}} = \frac{(200\ \text{Torr})(80\ \text{liters})}{T_2}$$

$$T_2 = 234\ \text{K}$$

Avogadro's Law

The Volume occupied by any gas, at a fixed temperature and pressure, is proportional to the number of moles of that gas.

$$V \propto n$$

N_o = Avogadros' Number = 6.02×10^{23} particles = 1 mole

Ideal Gas Law

Provides relationship between pressure, volume, Temperature, and amount of gas.

$$PV = nRT$$

R = 0.08206 Atm-liter/ K-mole
= 62.36 Torr-liter/K-mole

Units in Gas Law calculations

Gas law calculations may be performed using a variety of pressure units (Torr, Bars, ATM, PSI, Pa, etc.) but the pressure units must remain consistent through the calculation.

$$t = \frac{V}{S_t} \ln \frac{P_1}{P_2} \left(\frac{\text{Torr}}{\text{Torr}} \right)$$

Temperature must be in absolute units (K,R).

Pressure unit conversions

To convert from:
Multiply by: To:

Atm	Torr	760
Pascal	Torr	7.5×10^{-3}
mBar	Torr	0.750
PSI	Torr	51.7

Maxwell's Distribution Law

Maxwell determined that for a large population of one type of molecule, there would be a distribution of velocities. There is not be one uniform velocity.

$$N_v = 4\pi N\left(\frac{m}{2\pi kT}\right)^{\frac{3}{2}} v^2 e^{\left(\frac{-mv^2}{2kT}\right)} dv$$

where $N_v dv$ = the number of molecules found in the velocity interval between v and v + dv

v = velocity of the gas molecules (m/sec)

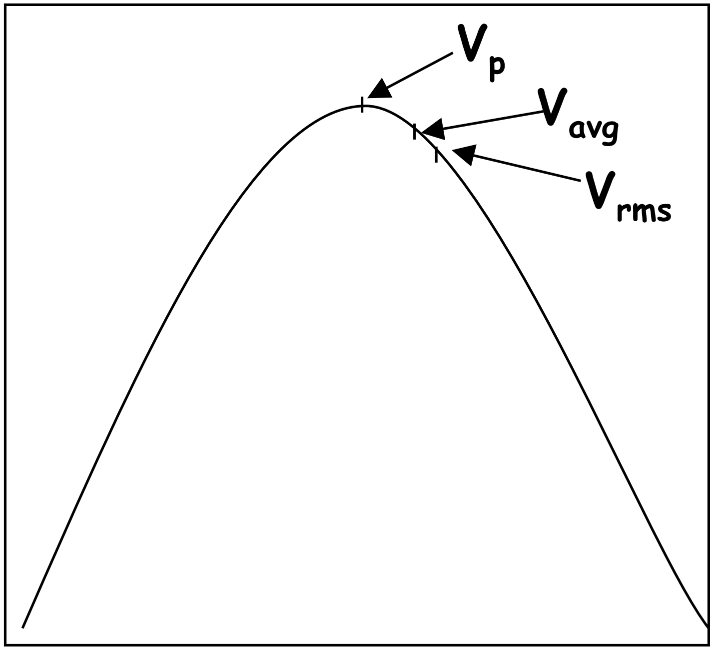
N = the total number of gas molecules

k = Boltzmann's constant (1.38×10^{-23} J/K)

m = mass of the molecule (kg)

T = Temperature (K)

A Typical Maxwell Velocity Distribution



$$v_{rms} = \text{root mean square velocity}$$

$$\approx 1.7\left(\frac{kT}{m}\right)^{\frac{1}{2}} \propto \left(\frac{T}{M}\right)^{\frac{1}{2}}$$

$$v_{avg} = \text{average velocity of populatio}$$

$$\approx 0.98 v_{rms}$$

$$v_p = \text{most probable velocity}$$

$$\approx 0.82 v_{rms}$$

Velocity of gas molecules

The velocity of gas molecules is independent of the pressure of the gas, and depends only on the molecular weight of the gas and its absolute temperature.

$$\bar{V} = 1.455 \times 10^4 \sqrt{\frac{T}{M}}$$

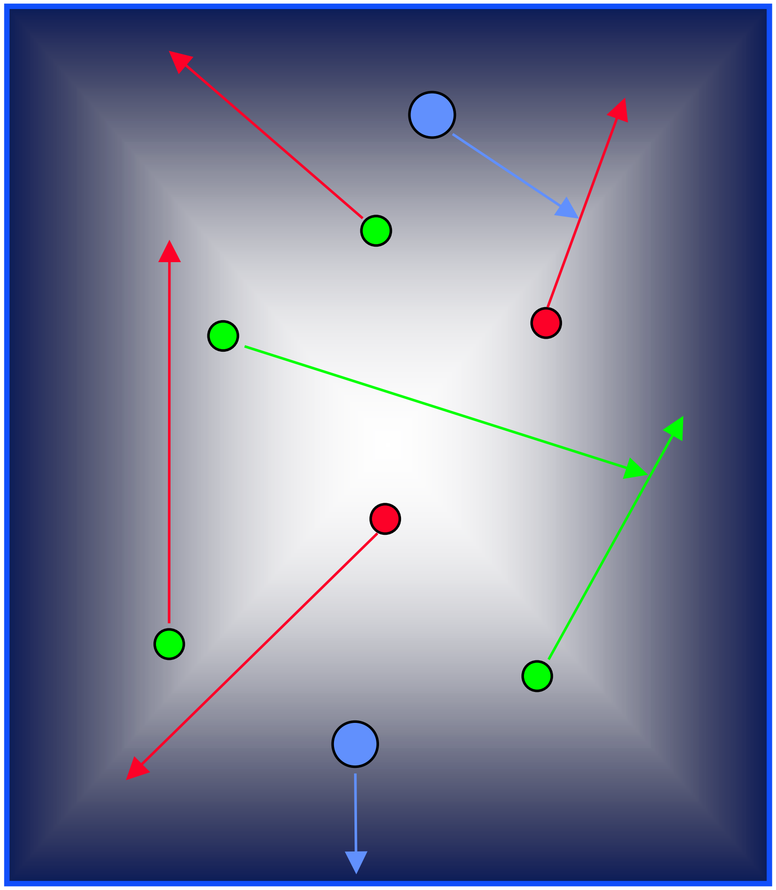
$\bar{V}$ = average velocity (cm/sec)
T = absolute temperature (K)
M = molecular weight of gas, (g/mole)

Mean free path

The mean free path is the average distance that a gas molecule can travel before colliding with another gas molecule.

Mean Free Path is determined by:

- Size of molecule
- Pressure
- Temperature



Mean Free Path Equation

$$\lambda_i = \frac{kT}{\sqrt{2}\pi P d_i^2}$$

λ_i = mean free path of gas species "i" ($^{cm}/_{sec}$)
k = Boltzmann's constant (1.38 x 10^{-23} Joules/K)
T = Temperature (K)
P = Pressure (Pa)
d_i = gas species diameter (cm)

Gas Flow

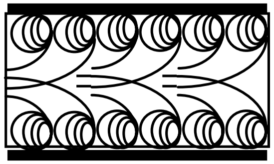
The flow of gases in a vacuum system is divided into three regimes. These regimes are defined by specific value ranges of a dimension-less parameter know as the Knudsen number.

$$K_n = \frac{\lambda_a}{a}$$

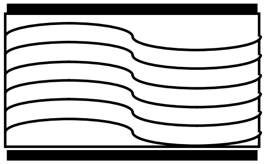
λ_a = mean free path
a = characteristic dimension of flow channel
(typically a pipe radius)

Gas Flow

Viscous Flow : $Kn = \frac{\lambda_a}{a} < 0.01$



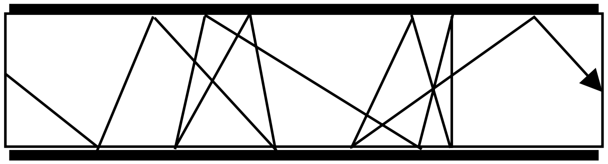
Turbulent



Laminar

Transition Flow : $0.01 < Kn < 1.0$

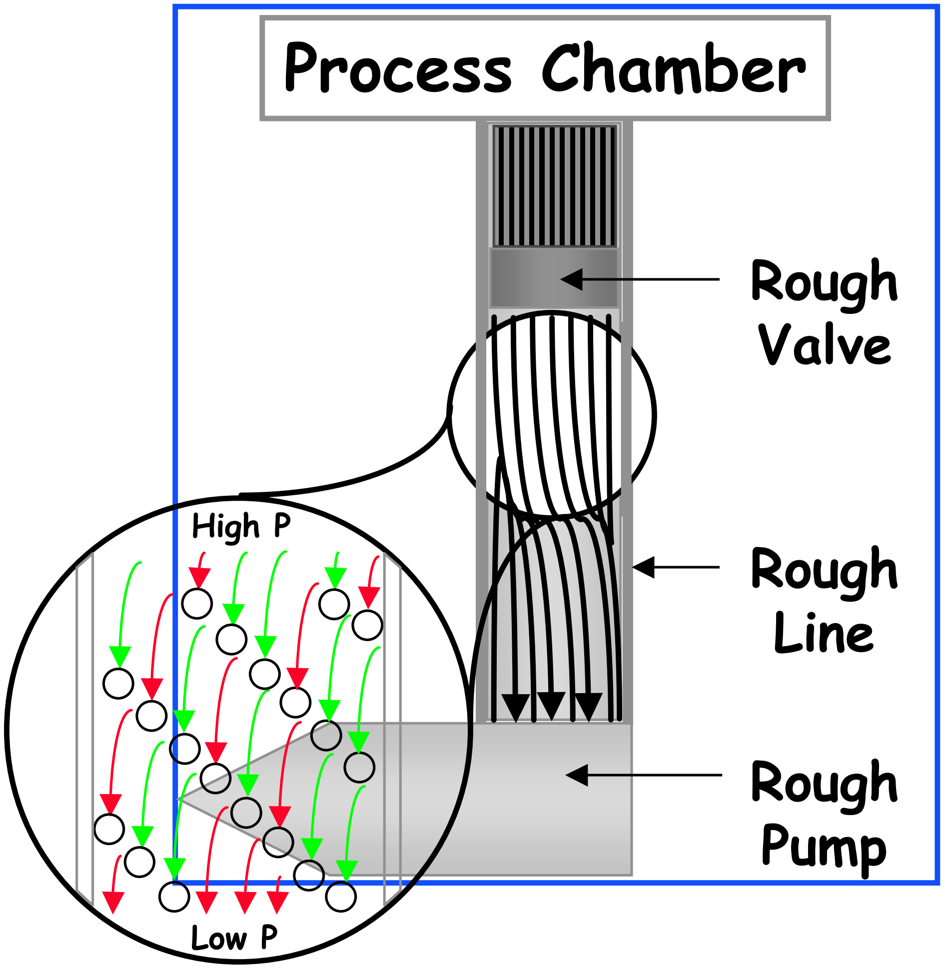
Molecular Flow : $Kn > 1.0$



Molecular

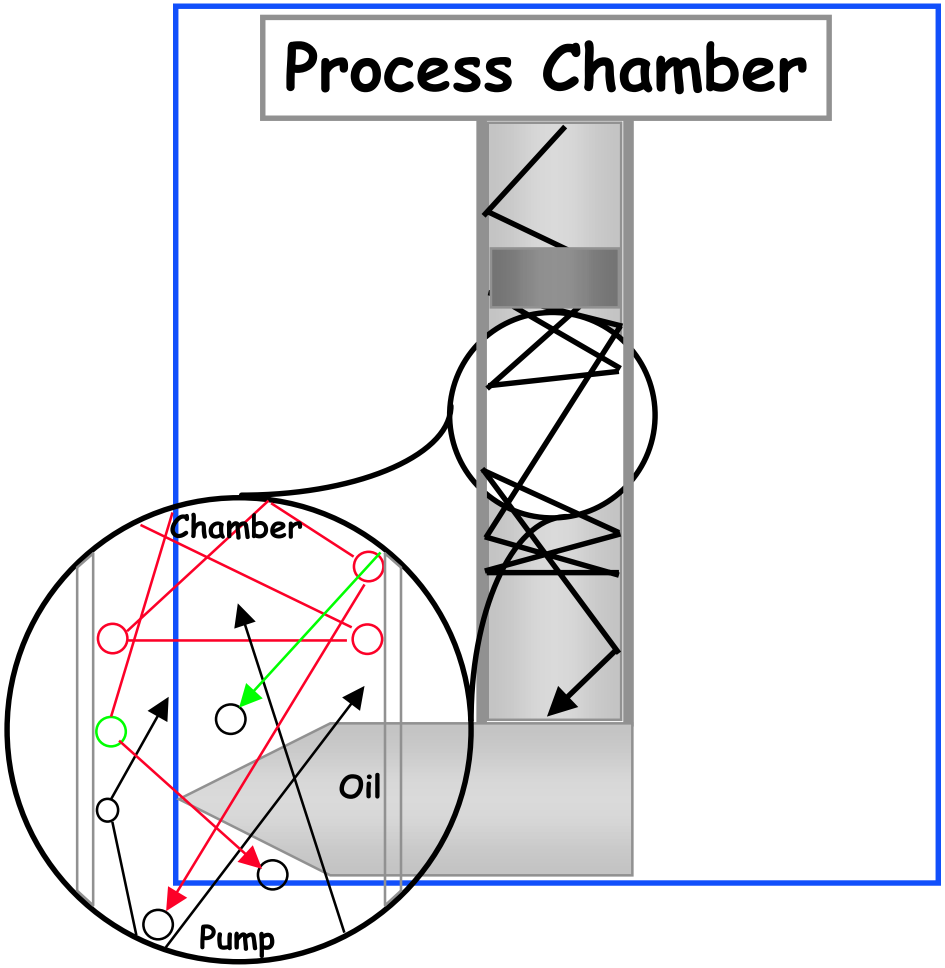
Viscous Flow

- **Viscous Flow**
  - Molecules travel in uniform motion toward lower pressure
  - Random motion of a molecule is influenced in the direction of the mass flow
  - Molecular motion “against” mass flow unlikely



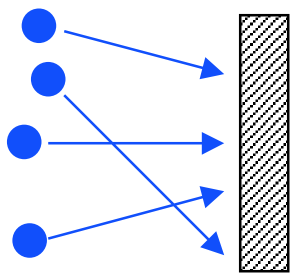
Molecular Flow

- **Molecular Flow**
  Molecules move randomly in either direction - to or away from rough pump and vacuum pump
  - Oil molecules will Backstream (move up the rough line) in this flow regime



Gas Flux Density incident on a Surface (impingement rate)

$$\upsilon = N\left(\frac{kT}{2\pi m}\right)^{1/2}$$



$$\text{where } N = \frac{PN_o}{RT}$$

$$= \text{density of molecules per } m^3$$

$$\upsilon = 10^3\,\frac{PN_o}{RT}\left(\frac{kT}{2\pi m}\right)^{1/2}$$

liters/m³ conversion

Gas Flux Density (Impingement rate)

The number of gas molecule collisions with the inner surface of a container is given by:

$$\upsilon = 3.5 \times 10^{22} \frac{P}{\sqrt{MT}}$$

u = particle flux density (molecules/sec cm^2)
P = pressure (Torr)
M = molecular weight of gas (g/mole)
T = absolute temperature (K)

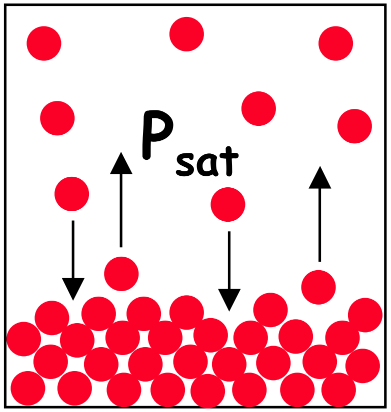
Residence time

Residence time is the average amount of time a molecule stays on a surface, and is a function of the molecular weight of the gas and the temperature of the surface.

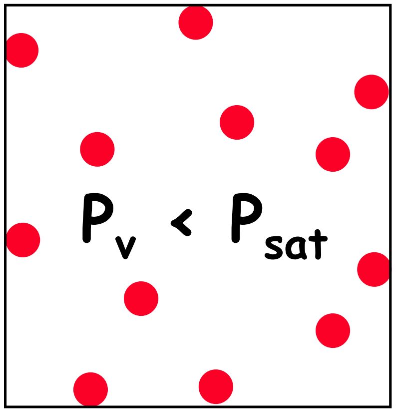
$$t = t_o e^{\left(\frac{Q}{RT}\right)}$$

where t_o = residence time (sec)
Q = activation energy
T = temperature (K)

Vapor Pressure



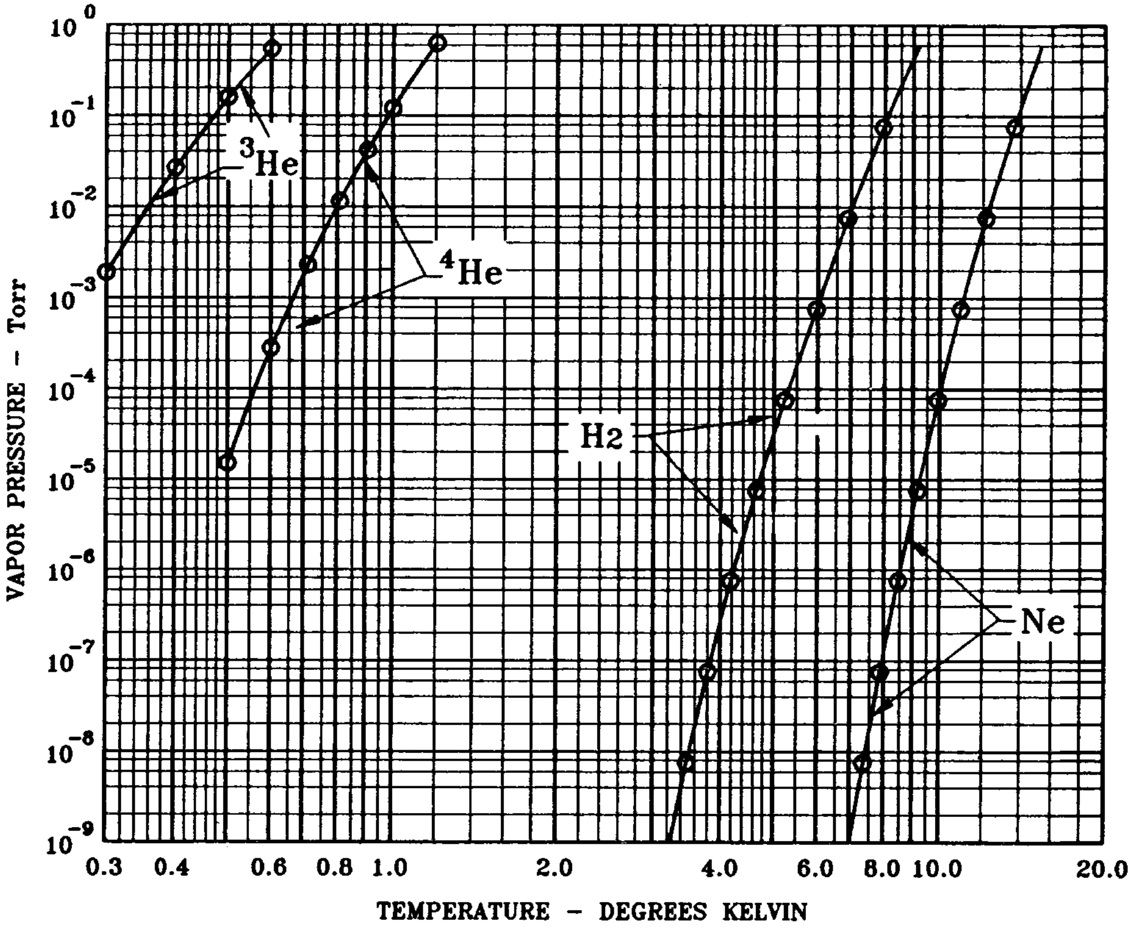
In this case, the gas above the bulk is considered to be saturated.



In this case, there is not sufficient bulk material to support a saturation vapor pressure

- Vapor pressure is an important concept as it relates to cryopumps.
- At thermal equilibrium the net flux of particles at the surface of bulk material is zero.
- Each element has a specific saturation pressure for a given temperature.
  The saturation pressure is also referred to as the saturation vapor pressure, equilibrium vapor pressure, or just vapor pressure.

Vapor Pressure Curve



Pumping Speed

Defined as a measure of volumetric displacement (liters/sec, cu.feet/minute, cu.meters/minute)

- It is the volume of gas flowing past a point per unit time.
- Pumping speed is independent of pressure.
- Pumping speed is an abstract concept used to describe the behavior of gas in a vacuum system.

$$S = \frac{dV}{dt}$$

Throughput

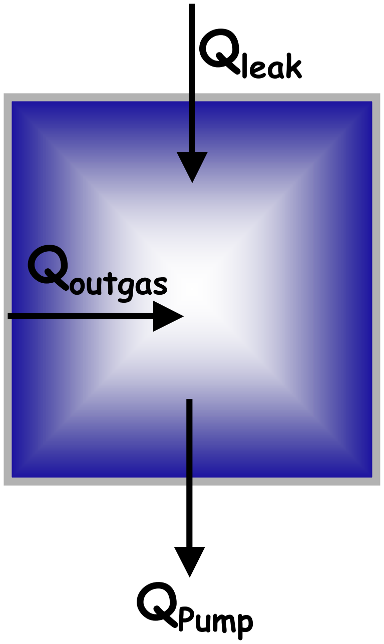
Defined as a measure of gas flow rate (Torr liters/sec)

- For constant pumping speed throughput varies with pressure:

$$Q = \frac{d(PV)}{dt} = SP$$

- Under dynamic conditions:

$$\frac{d(PV)}{dt} = Q - S(P - P_o)$$



Conductance

Defined as a measure of ease with which abstract volumes can pass from one place in a vacuum system to another.

- Conductance is an abstract concept used to describe the behavior of gas in a vacuum system.
- Conductance is specific to a particular geometrical configuration.
- Conductance is specific to the actual gas species and temperature.
- When the mean free path of a gas species in a system is less than the dimensions of the system the conductance is pressure dependent.

Conductance under Molecular Flow

Aperture

$$C = 3.64\sqrt{\frac{T}{M}}\,A \qquad \text{(liters/sec)}$$

where A = the aperture area (cm^2)
T = Temperature (K)
M = molecular weight (grams/mole)

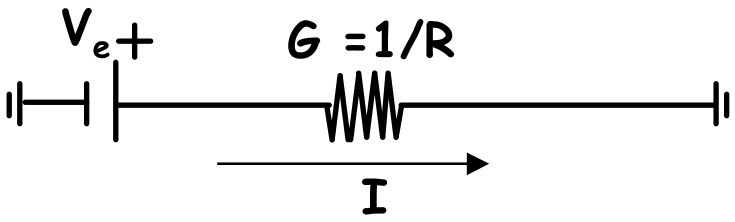
Long Tubes ($L \geq 10D$)

$$C = 3.81\sqrt{\frac{T}{M}}\,\frac{D^3}{L} \qquad \text{(liters/sec)}$$

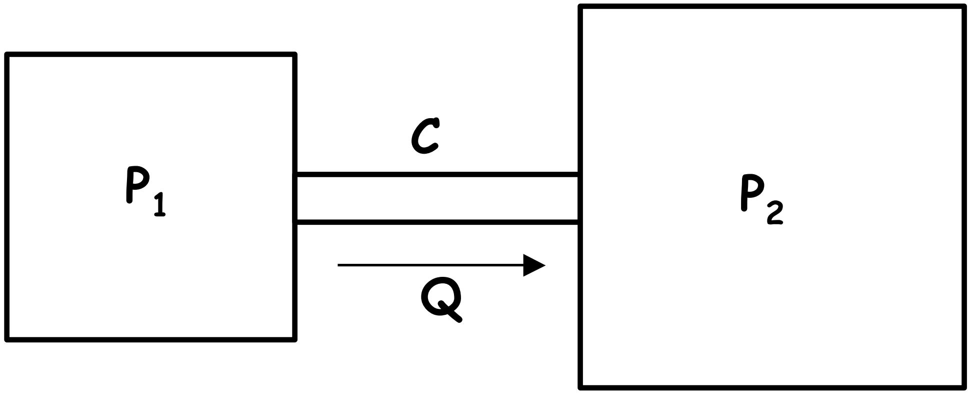
where D = pipe diameter (cm)
L = pipe length (cm)

Electrical Analogy (Ohm's Law)

A vacuum system operating in the molecular flow regime can be thought of in terms of an electrical circuit.

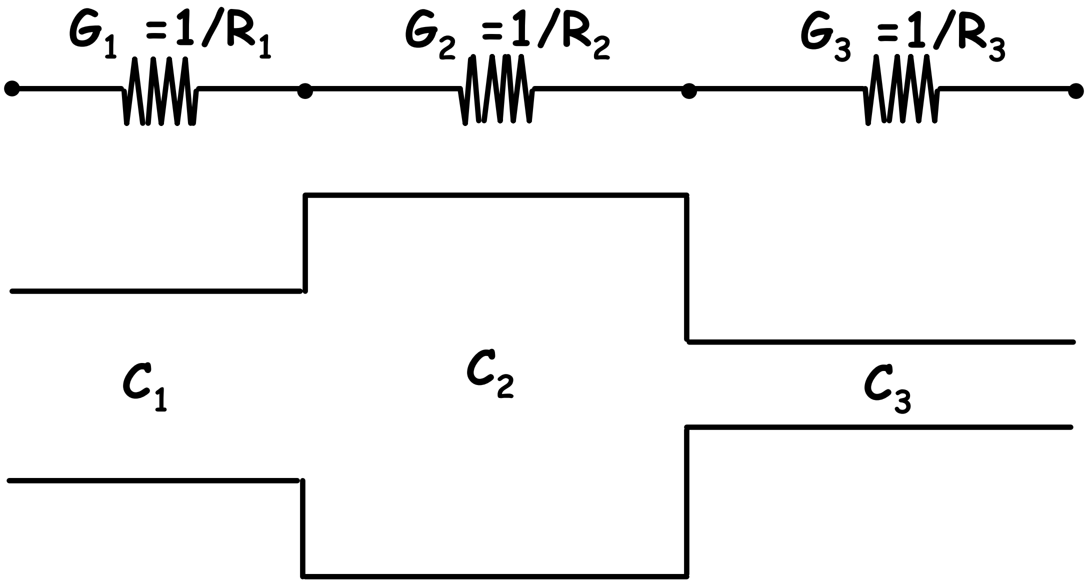


$$I = GV_e$$



$$Q = C(P_1 - P_2)$$

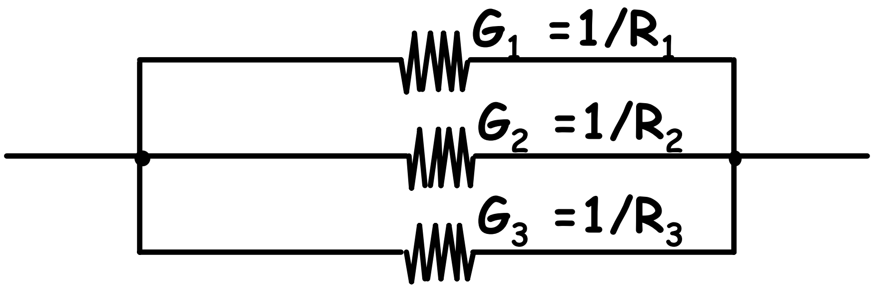
Electrical Analogy (continued)
Conductances in Series



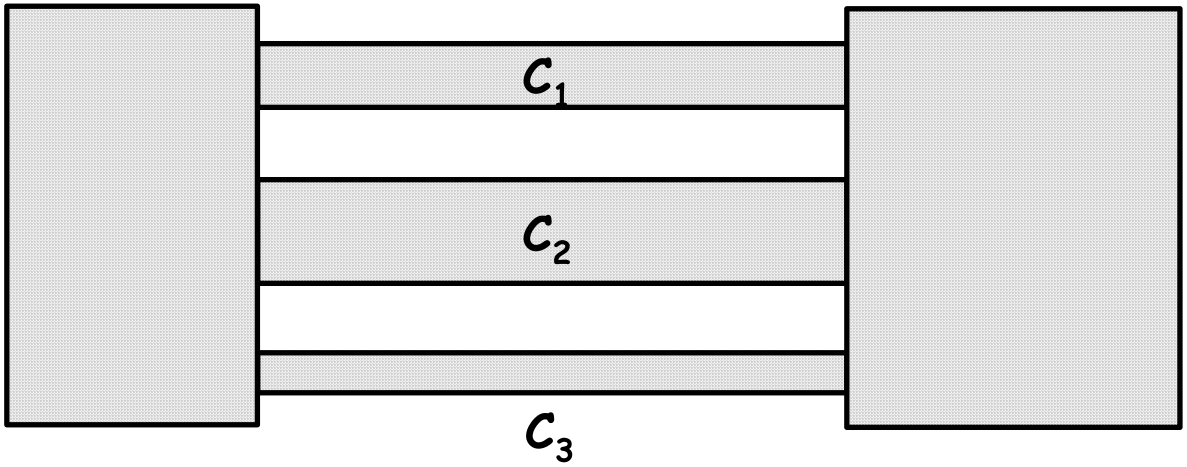
$$\frac{1}{G_e} = \frac{1}{G_1} + \frac{1}{G_2} + \frac{1}{G_3}$$

$$\frac{1}{C_{Total}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

Electrical Analogy (continued)
Conductances in Parallel



$$G_e = G_1 + G_2 + G_3$$



$$C_{Total} = C_1 + C_2 + C_3$$

Dalton's Law

The partial pressures of gases in a mixture behave independently according to the ideal gas laws.

$$P_{Total} = P_{N_2} + P_{O_2} + P_{Ar} + P_{CO_2} + \ldots\ldots + P_n$$

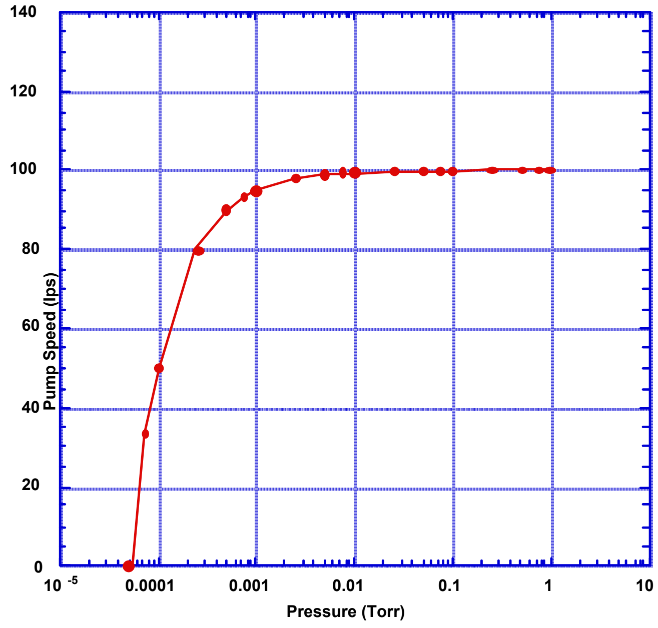
$$P_{Total} = \frac{Q_{N_2}}{S_{N_2}} + \frac{Q_{O_2}}{S_{O_2}} + \frac{Q_{Ar}}{S_{Ar}} + \frac{Q_{CO_2}}{S_{CO_2}} \ldots\ldots + \frac{Q_n}{S_n}$$

Variable Pumping Speed

All pumps have both high and low applicable pressure limits.

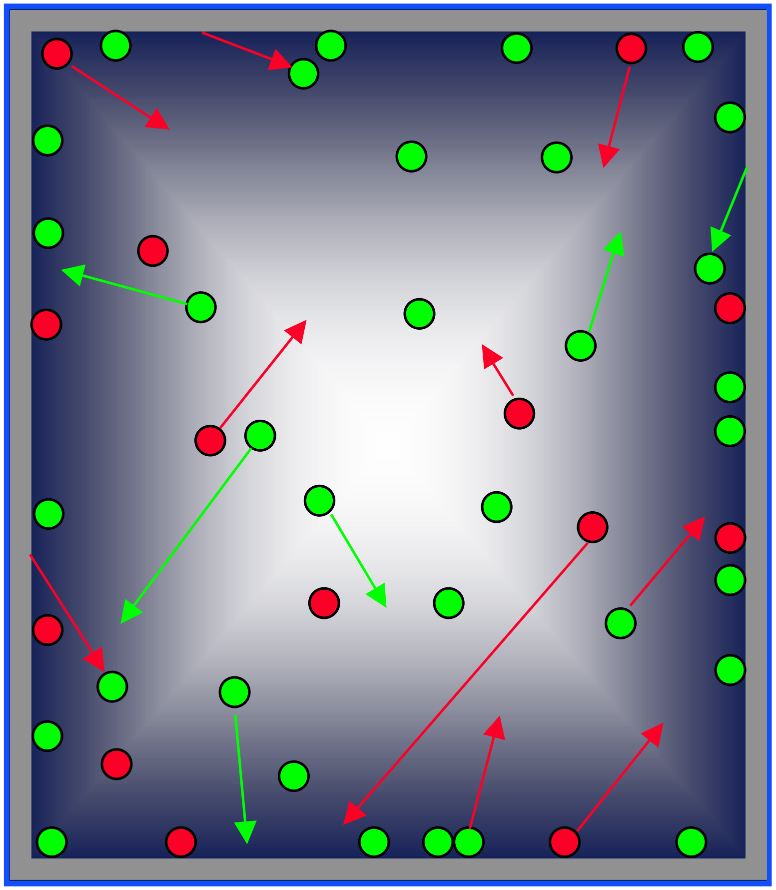
- Base or blank-off pressure (P_B) is the minimum pressure a pump will achieve
- At base pressure pumping speed is zero

$$S = S_{max}\left(1 - \frac{P_B}{P}\right)$$



Adsorption and desorption (outgassing)

- **Adsorption** is the arrival of gas molecules on a surface
  - Adsorbed gas molecules exist as molecular layers and in some ways behave like a sheet of liquid
  - Rule of thumb – one monolayer consists of ~10^{15} molecules (atoms) per cm^2
- **Residence time** is the amount of time a gas molecule stays on a surface
- **Desorption** is the departure of gas molecules from a surface
  - The rate of desorption is a function of the activation energy of the sorbent and the temperature of the surface



Adsorbed gases affect material properties

- 1 monolayer of adsorbed gas influences bonding, wettability, and surface chemical reactions
- 1 to 10 monolayers of adsorbed gas affect lubrication and electrical conduction
- 1 to 200 monolayers of adsorbed gas change the absorption of light by a surface
- 200 to 2000 monolayers affect the visual color of surfaces

Permeation is the transfer of a fluid through a solid

- Material combination (fluid & solid)
- Temperature
- Permeation thickness
- Area
- Pressure differential