HANDOUT SET

GENERAL CHEMISTRY I

Periodic Table of the Elements

	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 **H** 1.00794																	2 **He** 4.00262
2	3 **Li** 6.941	4 **Be** 9.0122											5 **B** 10.811	6 **C** 12.011	7 **N** 14.0067	8 **O** 15.9994	9 **F** 18.9984	10 **Ne** 20.179
3	11 **Na** 22.9898	12 **Mg** 24.305											13 **Al** 26.98154	14 **Si** 28.0855	15 **P** 30.97376	16 **S** 32.066	17 **Cl** 35.453	18 **Ar** 39.948
4	19 **K** 39.0983	20 **Ca** 40.078	21 **Sc** 44.9559	22 **Ti** 47.88	23 **V** 50.9415	24 **Cr** 51.9961	25 **Mn** 54.9380	26 **Fe** 55.847	27 **Co** 58.9332	28 **Ni** 58.69	29 **Cu** 63.546	30 **Zn** 65.39	31 **Ga** 69.723	32 **Ge** 72.59	33 **As** 74.9216	34 **Se** 78.96	35 **Br** 79.904	36 **Kr** 83.80
5	37 **Rb** 85.4678	38 **Sr** 87.62	39 **Y** 88.9059	40 **Zr** 91.224	41 **Nb** 92.9064	42 **Mo** 95.94	43 **Tc** (98)	44 **Ru** 101.07	45 **Rh** 102.9055	46 **Pd** 106.42	47 **Ag** 107.8682	48 **Cd** 112.41	49 **In** 114.82	50 **Sn** 118.710	51 **Sb** 121.75	52 **Te** 127.60	53 **I** 126.9045	54 **Xe** 131.29
6	55 **Cs** 132.9054	56 **Ba** 137.34	57 **La*** 138.91	72 **Hf** 178.49	73 **Ta** 180.9479	74 **W** 183.85	75 **Re** 186.207	76 **Os** 190.2	77 **Ir** 192.22	78 **Pt** 195.08	79 **Au** 196.9665	80 **Hg** 200.59	81 **Tl** 204.383	82 **Pb** 207.2	83 **Bi** 208.9804	84 **Po** (209)	85 **At** (210)	86 **Rn** (222)
7	87 **Fr** (223)	88 **Ra** 226.0254	89 **Ac**** 227.0278	104 **Rf** (261)	105 **Db** (262)	106 **Sg** (263)	107 **Bh** (264)	108 **Hs** (265)	109 **Mt** (266)	110 (270)	111 (272)	112 ***** (277)						

*Lanthanides	58 **Ce** 140.12	59 **Pr** 140.9077	60 **Nd** 144.24	61 **Pm** (145)	62 **Sm** 150.36	63 **Eu** 151.96	64 **Gd** 157.25	65 **Tb** 158.925	66 **Dy** 162.50	67 **Ho** 164.930	68 **Er** 167.26	69 **Tm** 168.9342	70 **Yb** 173.04	71 **Lu** 174.967
**Actinides	90 **Th** 232.038	91 **Pa** 231.0659	92 **U** 238.0289	93 **Np** 237.0482	94 **Pu** (244)	95 **Am** (243)	96 **Cm** (247)	97 **Bk** (247)	98 **Cf** (251)	99 **Es** (252)	100 **Fm** (257)	101 **Md** (258)	102 **No** (259)	103 **Lr** (260)

Mass numbers in parenthesis are the mass numbers of the most stable isotopes. As of 1997 elements 110-112 have not been named.
***Peter Armbruster and Sigurd Hofman synthesized a single atom at the Heavy-Ion Research Center in Darmstadt, Germany in 1996. The atom survived for 280 μs after which it decayed to element 110 by loss of an α-particle

Chapter 6

The Gaseous State

THE GASEOUS STATE
CHAPTER 6

INTRODUCTION The behavior of gases is an aspect of chemistry that we give little thought to in our everyday life, but in reality is critical to our survival. Air is a mixture of mostly oxygen and nitrogen, the behaviors of each independently and in the mixture can be modeled by the ideal gas law. Helium balloons float while a balloon with argon will drop quite rapidly. These behaviors can also be modeled with the ideal gas law. Moreover, we can use physics and kinetic molecular theory to develop equations relating basic physical principles to observable phenomena.

GOALS

1. You should be able to relate P, V, T, and n.
2. It is important to be able to do problems involving changes in P, V, T, and n as well as calculate a single observable parameter knowing the others.
3. The ideal gas law can be used in its native form and modified in a variety of ways to solve fundamental problems involving gases such as the molar mass of the gas and the density of a gas.
4. Dalton's law of partial pressures deals with gases in a more experimental and practical way. You must be able to work with pure gases as well as mixtures of gases.
5. Kinetic molecular theory helps us to understand the relationship of microscopic properties and macroscopic properties.
6. You will not be held responsible for non-ideal behavior or Graham's law on the main portion of any exam. These are topics that might be covered for extra credit.

DEFINITIONS

You should have a working knowledge of at least these terms and any others used in lecture.

Pressure and units
Barometer
Barometric pressure
Manometer
Open-end manometer
Closed-end manometer
Boyle's law
Charles' law
Gay-Lussac's law
Ideal gas law
Universal gas constant
Dalton's law
Kelvin temperature
Mole fraction
Partial pressure
Standard temperature and pressure
Kinetic-molecular theory
Root-mean-square velocity
Kinetic energy
Diffusion
Effusion

Robert William Boyle

Britsh chemist, physicist, theologian, natural philosopher
January 27, 1627 – December 31, 1691

Robert Boyle is largely regarded as one of the founders of modern chemistry, and one of the pioneers of the modern scientific method. Himself and alchemist, he lies at a time in history at the transition from alchemy to experimental chemistry and utilized modern methods of scientific discovery. He is best known for the law that bear's his name, which describes the relationship between the absolute pressure and volume of a gas at constant temperature in a closed, flexible system.

From William Faithorne's engraved portrait of Boyle, with his air-pump in the background, 1664 (Sutherland Collection, Ashmolean Museum, Oxford) Ref. http://www.bbk.ac.uk/boyle/

Boyle was a contemporary of Isaac Newton (1642-1726, 1727 New Style). In 1654, Boyle left Ireland to pursue chemical studies at University College, Oxford. While there and with Robert Hooke (1635-1703), he improved the design of Otto van Guricke's (1602-1686) vacuum pump allowing him to perform experiments on the properties of air.

In 1663, Boyle became a charter member of the now-famous Royal Society of London. From 1659 to his death, Boyle was a prolific author of scientific treatises covering natural philosophy, medicine, and religion, and he also published over 40 books. Among his works, *The Sceptical Chymist* is seen as a cornerstone book in the field of chemistry.

Guillaume Amontons

French physicist
August 31, 1663 – October 11, 1705

Guillaume Amontons may be best known for the early studies of static friction, now known as tribology. Isaac Newton (1642-1726, 1727 New Style) would extend Amontons' work to dynamic friction. He is also credited with improvements to the hygrometer to measure humidity, barometer, and thermometer. He also studied mathematics and celestial mechanics.

Amontons investigated the pressure-temperature relationship of gases in closed, rigid containers. Despite the lack of a sufficiently accurate thermometer his results were sufficiently quantitative that he established that the pressure of a gas increases roughly linearly with increasing temperature. This linear relationship was substantiated later by Gay-Lussac (1778-1850). Amontons speculated that a sufficient reduction in temperature would lead to the disappearance of pressure. He is incorrectly credited with the "discovery" of an absolute zero temperature: there is little evidence in his writings that he had more than a fleeting concept of absolute zero temperature. Nevertheless, using the poor instruments of the time (by modern standards), he estimated the theoretical temperature at which the volume of air in his air-thermometer would be reduced to nothing as −240°C, a value exceedingly close to the modern value of absolute zero on the Celsius scale. An accurate estimation of absolute zero temperature would require another century.

Jacques Alexandre César Charles
French inventor, scientist, and balloonist
November 12, 1748 – April 7, 1823

Jacques Charles, with Anne-Jean Robert (1758–1820) and Nicolas-Louis Robert (1760–1820), pioneered the use of hydrogen in unmanned and, ultimately, manned balloons. In 1783, Charles and N.-L. Robert ascended to a height of 550 m (1,800 feet). In June of the same year, the Montgolfier brothers made a flight in a hot air balloon three times higher, so Charles' flight was hardly record-setting but his invention of a valve to release hydrogen from the gas envelope added to control of the lighter-than-air craft.

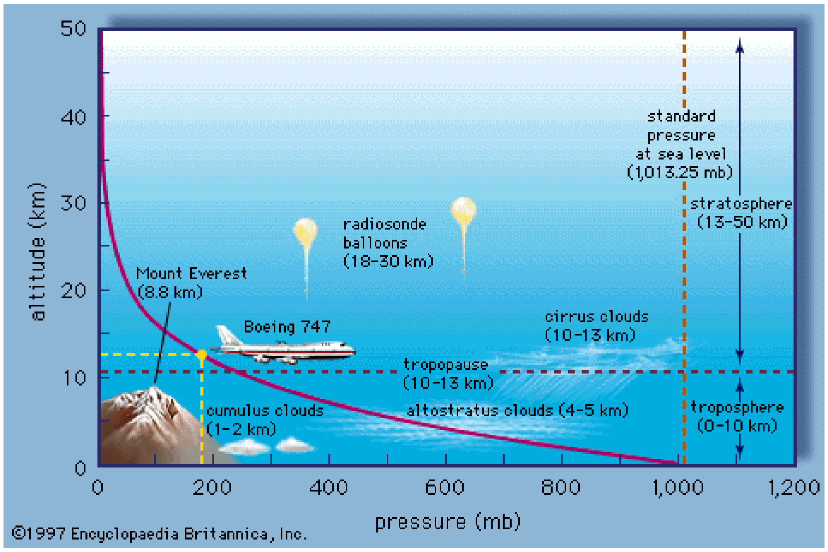
Charles is best known for his work describing how gases expand with increasing temperature. Charles' Law was actually formulated by Joseph Louis Gay-Lussac, but Gay-Lussac credits Jacques Charles for the original work, thus leading to the honorific being afforded to Charles. Charles was elected to the Académie des Sciences in 1795 and appointed to professor of physics at the Conservatoire des Arts et Métiers.

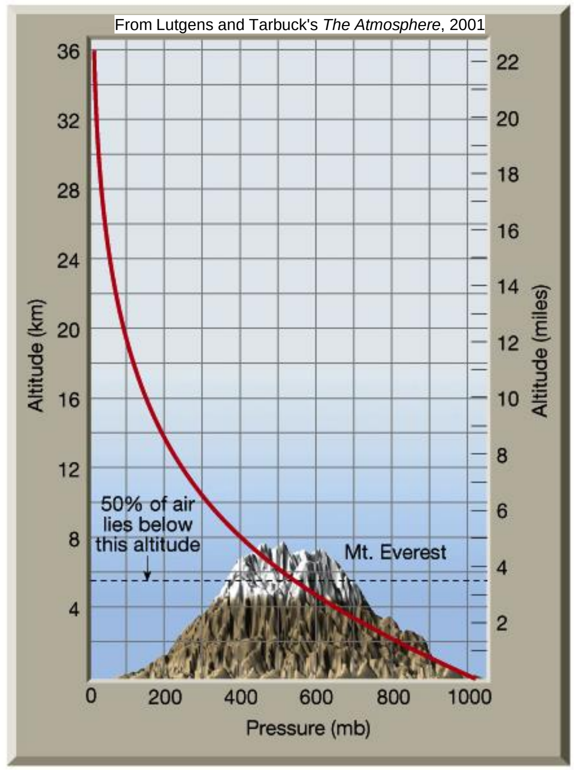
Joseph Louis Gay-Lussac

French chemist
December 6, 1778 - May 9, 1850

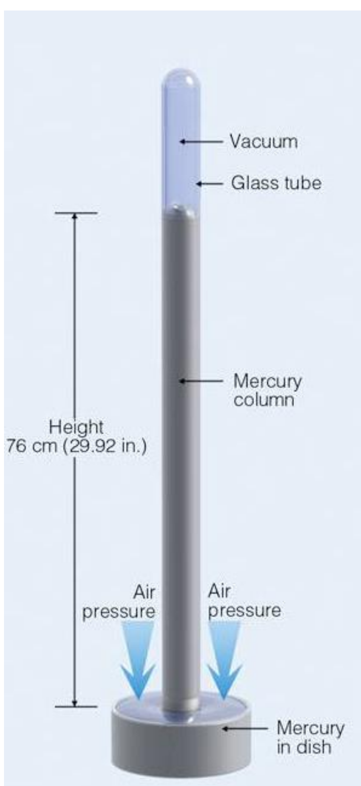
Gay-Lussac was a chemist who also contributed to physics, meteorology, and physiology as well. His early education was under the Catholic Abbey of Bourdeix in Paris and, later, at the École Polytechnique in 1798. Just over 10 years after entering the university, he was appointed a professor of chemistry at the École Polytechnique. He is credited with the co-discovery of boron in 1808 and recognizing iodine as a unique element in 1811. In 1802, he put forth his now-famous law relating the pressure and temperature of a gas in a rigid container: $P = kT$. Notably, Gillaume Amontons' work on the *P-T* relationship of gases preceded Gay-Lussac's but suffered from the lack of accurate thermometers. In 1808, Gay-Lussac's work on combining gas volumes was published.

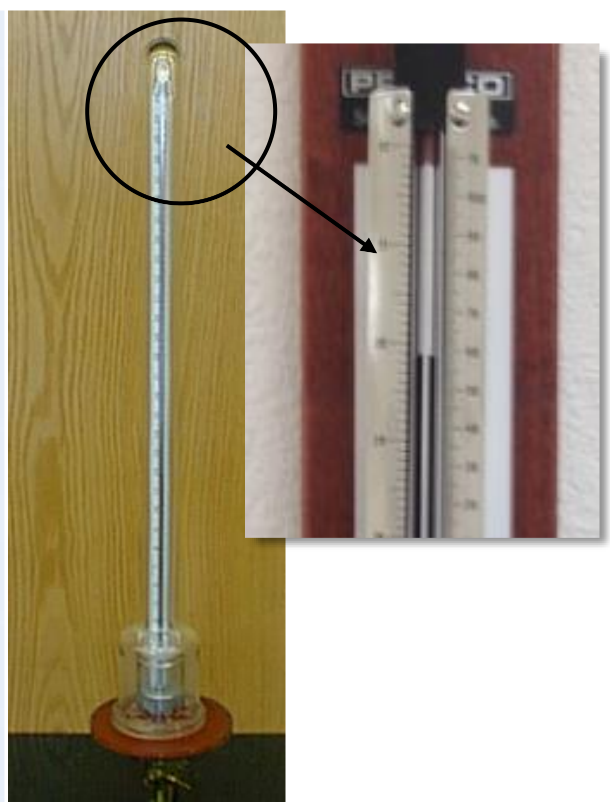
Like Jacques Charles (1748–1823, he was also an accomplished balloonist. In 1804, Gay-Lussac ascended to 7,016 m (23,020 feet) in a balloon, an uncontested altitude record for a short time until beat by Étienne-Gaspard Robert (1763–1837) and Auguste Lhoëst. Legend has it that in another high-altitude flight, Gay-Lussac had to throw overboard several items to lighten the balloon and gain altitude. "One item he sacrificed was an old kitchen chair that he had used as a seat. The chair landed near a peasant girl minding sheep near a village. After considerable debate, the local citizenry and priest decided that the incident was a miracle, but they wondered why God apparently owned such shabby furniture." (klingon.uab.es/soft/Integrat3/GCC7/PTL_LE/BIOS/gaylusac.htm)





The Mercury Barometer





Postulates of the Kinetic Molecular Theory of Gases

1. Gases consist of tiny particles (atoms or molecules).

2. The gas particles are so small, compared to the distances between them, that the volume (size) of the individual particles is assumed to be negligible.

3. The particles are in constant random motion, colliding with the walls of the container. These collisions with the walls cause the pressure exerted by the gas.

4. The particles are assumed to neither attract nor repel each other.

5. The average kinetic energy of the gas particles is directly proportional to the Kelvin temperature of the gas.

Gas Laws I
The Ideal Gas Law

1. What quantity, in moles, of helium are in a 3.0 L Mickey Mouse balloon at Disneyland if the pressure in the balloon is 754 torr and the temperature is 24.2°C?

2. When measured at STP, what volume will 0.35 moles of oxygen gas occupy?

   When warmed to room temperature (25.0°C) and maintained at standard pressure, what will be the new volume?

3. Using the following data, determine the molar mass of the unknown compound.

   The mass of a 255.5 mL flask is 55.144 g (with the mass of the air subtracted out). After filling the flask with an unknown gas at the laboratory barometric pressure, the mass of the flask and gas was measured to be 55.363 g. The barometric pressure was determined to be 742.5 mm Hg using a mercury barometer. The laboratory temperature was 22.4°C.

   What is the molar mass of the gas?

4. A mountaineer blows up a balloon to 3.00 L at sea level where the pressure is 754 mm Hg. He flies to Tibet with his balloon and runs up to 20,000 feet on the way to the top of Mt. Everest, where the pressure is 371 mm Hg. What is the volume of the balloon? (Assume the temperature didn't change.)

5. Your ears are essentially a closed air-space inside your head. Mostly surrounded by bone, there is only one flexible wall enclosing this air-space – the ear drum. The volume inside the air space is not large at only about 1-2 mL. Assuming a volume of 1.0 mL and that you feel pain due to pressure on the ear drum when the volume of the inner ear is reduced by 0.05 mL, what pressure over atmospheric (1.0 atm) is necessary on the ear drum to cause pain? (Report the answer in atm, torr, psi, and Pa)

6. A mountaineer blows up a balloon to 3.00 L at sea level where the pressure is 754 mm Hg and the temperature is 22.0°C. He flies to Tibet with his balloon and runs up to 20,000 feet on the way to the top of Mt. Everest where the pressure is 371 mm Hg and the temperature is -15.5°C. What is the volume of the balloon?

Gas Laws I
The Ideal Gas Law
Additional Problems

1. In an experiment involving Boyle's law, a graph of which data produces a straight line; *P* vs. *V* or *P* vs. 1/V?

2. When a high-diver enters the water after jumping from a diving board, she may descend at much as 10 feet (or more) deep into the pool. At 10 feet, the total pressure on the diver will be 1.3 atm. Assuming that the diver took a deep breath (7.0 L of air in her lungs) at 1.0 atm just before entering the water, what will be the volume of air in her lungs when she gets to 10 feet of depth? Assume that the diver's air spaces (lungs) are completely flexible and she did not exhale while descending.

3. In an experiment involving Amonton's law, a graph of which data produces a straight line; *P* vs. *T* or *P* vs. 1/T?

4. Scuba tanks are given a "Maximum Working Pressure" (MWP) rating (which represents the highest pressure the tank can safely hold at a given temperature) and a “Hydrostatic Test Pressure” (HTP) rating (which represents the highest pressure the tank can hold before it may rupture, and is five-thirds the MWP). In the U.S., the MWP for a tank with an international yoke valve is 206.8 bar at 20.0°C. If the tank is filled to 200.0 bar at 20.0°C, what is the maximum pressure that the tank reaches if left in the sun on a boat, if the tank temperature increases to 39.0°C?

   Does the pressure exceed either (or both) the MWP or HTP? Will the scuba tank rupture?

5. A football is inflated to a pressure of 1.00×10^3 torr in a room at 25°C. If the game is played at 10°C, what will the pressure in the ball be, neglecting any volume change in the ball and assuming that it doesn't leak?

Gas Laws II
Gases in Reaction Stoichiometry

1. What volume of water vapor (measured at 755 mm Hg and 200.0°C) will be produced by the reaction of 32.0 g of oxygen gas with plenty of hydrogen gas?

2. What volume of oxygen gas, measured at 25.0°C and 1.00 atm would be formed by the complete decomposition of 2.00 g of $KClO_3$ (122.55 g/mol) at 250.0°C? (The products of the decomposition reaction are potassium chloride and oxygen gas.)

3. 3.0 L of nitrogen gas are reacted at 250.0°C and 1.5 atm with excess hydrogen gas to form ammonia. What will be the volume of ammonia present when collected and measured at STP assuming the reaction has a 100% yield?

4. Assume for the moment that when green plants inspire CO_2 gas during photosynthesis they produce only glucose for energy storage. Also assume that the photosynthetic reaction by the plant is

$$6\ CO_2(g) + 6\ H_2O(g) \rightarrow C_6H_{12}O_6(s) + 6\ O_2(g)$$

If over a period of time the glucose content of a plant increases by 425 g, what volume of CO_2 was removed from the air? All measurements were made at 22.0°C and 751.5 torr.

Gas Law II
Gases in Reaction Stoichiometry
Additional Problems

1. The amount of NO_2 on a very smoggy day in Houston, TX was measured to be 0.78 ppm (by mass). The barometric pressure was 1011 mbar. Calculate the partial pressure of the NO_2.

   (This problem is a little tougher since you have to calculate the molar mass of air (which also means you have to look up the composition of standard air.)

2. To minimize the possibility of loud and possibly dangerous "backfire", welders using large oxygen-acetylene cutting torches must be careful to prevent the ratio of acetylene (C_2H_2) to oxygen from becoming perfectly stoichiometric. What is the ratio of the pressures of acetylene and oxygen when they are stoichiometrically mixed?

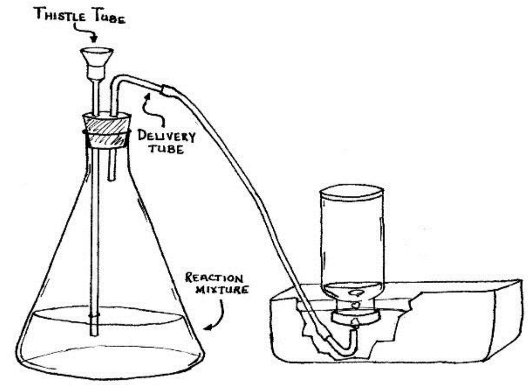
3. Sodium metal reacts with molecular chlorine gas to produce sodium chloride (and a great deal of energy). A closed glass container, fitted with a pressure gauge, has a volume of 3000 mL (±10 mL) and contains chlorine gas at 24.0°C and 1255 torr. On the bottom of the reaction vessel is a 6.90 g lump of sodium metal. The sodium is heated briefly to start the reaction, which continues to completion with no further intervention by the experimenter. The reaction vessel rises in temperature to 47.0°C. Predict the final pressure of the chlorine gas?

Gas Laws III
Dalton's Law of Partial Pressures
in Applied Calculations

1. Air is about 78%$^{v}/_{v}$ N_2 and 21%$^{v}/_{v}$ O_2 (~1%$^{v}/_{v}$ Ar, CO_2, etc. total). Calculate the partial pressure (in mm Hg) of the oxygen gas and nitrogen gas when the total barometric pressure is 1003 mbar. (Recall that 1 atm = 1.01325 bar)

2. A scuba diver will often descend to 16 feet in the ocean where the pressure of the air being breathed is 1.5 atm. What is the partial pressure of the oxygen at this depth?

3. Refer to the gas collection device pictured. What is the partial pressure of the hydrogen gas in the gas collection bottle obtained when the water in the bottle is displaced by hydrogen from the reaction of zinc with hydrochloric acid? The volume of the bottle was measured to be 165 mL, the temperature of the equipment is assumed to be room temperature (23.2°C), and the barometric pressure is 751.9 mm Hg. It may be necessary to estimate or use an approximate value for the vapor pressure of water at this temperature.



4. What is the volume of the H_2 produced if the water vapor is removed?

5. Nitroglycerin explodes according to the equation

$$4\ C_3H_5N_3O_{9(l)} \rightarrow 12\ CO_{2(g)} + 10\ H_2O_{(g)} + 6\ N_{2(g)} + O_{2(g)}$$

What is the total pressure in a 1.0 L closed rigid container (perhaps a hole in the rock in a mine) when 200.0 g of nitroglycerine explodes. Assume for the problem that the temperature of the produced gases are 850°C.

Vapor Pressure of Water
at Several Temperatures

Temperature (°C)	**Vapor Pressure (mm Hg)**
15.0	12.79
16.0	13.63
17.0	14.53
18.0	15.48
19.0	16.48
20.0	17.54
21.0	18.65
22.0	19.83
23.0	21.07
24.0	22.39
25.0	23.76
26.0	25.21
27.0	26.74
28.0	28.35
29.0	30.04
30.0	31.82

Gas Laws III
Dalton's Law of Partial Pressures
Additional Problems

1. The amount of NO_2 on a very smoggy day in Houston, TX was measured to be 0.78 ppmv (parts-per-million by volume). The barometric pressure was 1011 mbar. Calculate the partial pressure of the NO_2.

2. A mixture of cyclopropane gas (C_3H_6) and oxygen gas in a 1.00:4.00 mol ratio is uncommonly used as an anesthetic gas. What mass of each gas is present in a 2.00 L steel container pressurized to 150.0 bar at 25.0°C?

3. “Mixed-air” divers often use standard air (78%N_2, 21%O_2, 1%Ar) which has been enriched to 32%O_2. As the dive tender aboard a marine science research vessel, it is your responsibility to fill scuba tanks with the proper air mix. A 12.5 L (internal volume) scuba tank is pressurized to 2550 psi with standard air. You add pure oxygen to the tank. What must the final pressure be so that the air has a composition of 32%O_2? All measurements are made at 25.0°C.

Mean Free Path in the Kinetic Molecular Theory of Gases

In the kinetic molecular theory of gases the mean free path of particles is the average distance the particle travels between collisions with other moving particles. If the velocities of the particles behave according to the Maxwell distribution, the following relationship applies:

$$l = \frac{kT}{\sqrt{2}\pi d^2 P}$$

where k is the Boltzmann constant (1.381×10^{-23} J/K), T is Kelvin temperature, P is pressure (in Pa), and d is the diameter (in m) of the gas particles.

The table lists some typical mean free path values for dry air (average molar mass 28.97 g/mol, average $d = 3.67 \times 10^{-10}$ m) at different pressures.

Vacuum range	**Pressure in kPa**	**Pressure (torr)**	**Molecules / cm^3**	**Mean free path**
Ambient pressure	101.3	760	2.7×10^{19}	68 nm
Low vacuum	30 – 0.1	225 – 0.75	10^{19} – 10^{16}	0.1 – 100 µm
Medium vacuum	0.1 – 0.01	0.75 – 0.075	10^{16} – 10^{13}	0.1 – 100 mm
High vacuum	10^{-2} – 10^{-6}	0.075 – 7.5×10^{-6}	10^{13} – 10^{9}	10 cm – 1 km
Ultra high vacuum	10^{-6} – 10^{-11}	7.5×10^{-6} – 7.5×10^{-11}	10^{9} – 10^{4}	1 km – 10^5 km
Extremely high vacuum	<10^{-11}	<7.5×10^{-11}	<10^{4}	>10^5 km

Gas Laws IV
Kinetic-Molecular Theory

1. What is the root-mean-squared velocity of nitrogen gas at 25.0°C?

2. What is average kinetic energy of the nitrogen molecules at 25.0°C?

3. What is the average kinetic energy (in J/mol) of SF_6 at 25.0°C? What is the average velocity of SF_6 at this temperature?

4. In a 1-meter-long time-of-flight (TOF) mass spectrometer, a helium ion traversed from the ion source to the ion detector in 12.25 ms. A gas of unknown identity traversed the TOF tube in 188 ms. What is the molar mass of the unknown gas?

5. The escape velocity of a object from Earth's gravitational field is about 25,000 mi/h. In units of miles-per-hour, what is the average velocity of helium at 0°C?

6. At what temperature does the velocity of a helium atom exceed the escape velocity of the Earth?