Physics 5D - Heat, Thermodynamics, and Kinetic Theory

Homework will be posted at the Phys5D website http://physics.ucsc.edu/~joel/Phys5D. Solutions are due at the beginning of class. Late homework will not be accepted since solutions will be posted on the class website (password: Entropy) just after the homework is due, so that you can see how to do the problems while they are still fresh in your mind.

Course Schedule

Date	Topic	Readings
1. Sept 30	Temperature, Thermal Expansion, Ideal Gas Law	17.1-17.10
2. Oct 7	Kinetic Theory of Gases, Changes of Phase	18.1-18.5
3. Oct 14	Mean Free Path, Internal Energy of Gases	18.6-19.3
4. Oct 21	Heat and the 1st Law of Thermodynamics	19.4-19.9
5. Oct 28	Heat Transfer; Heat Engines, Carnot Cycle	19.10-20.2
6. Nov 4	Midterm Exam (in class, one page of notes allowed)	
7. Nov 18	The 2nd Law of Thermodynamics, Heat Pumps	20.3-20.5
8. Nov 25	Entropy, Disorder, Statistical Interpretation of 2nd Law	20.6-20.10
9. Dec 2	Thermodynamics of Earth and Cosmos; Overview of the Course	
10. Dec 11	Final Exam (5-8 pm, in class, two pages of notes allowed)	

Website for homeworks: http://physics.ucsc.edu/~joel/Phys5D

Physics 5D Homework Set #1 Fall 2013

DUE at the beginning of class Monday October 7

To earn full credit on homework problems, you must exhibit the steps that lead to your final result. The homework grades will be based on the clarity of your method of solution as well as on your final answer.

Problems:

1. Giancoli, Chapter 17, problem 21.

2. Giancoli, Chapter 17, problem 28.

3. Giancoli, Chapter 17, problem 32. (Assume that air is an ideal gas.)

4. Giancoli, Chapter 17, problem 54.

5. Giancoli, Chapter 17, problem 56. (Note: ℓ_0 is the diameter of the molecules.)

General Problems:

6. Giancoli, Chapter 17, problem 62.

7. Giancoli, Chapter 17, problem 73. (The force = pressure x area of the air is equal to its weight ≈ Mg, where M is the mass of all the air and $g \approx 9.8$ m/s^2. Assume that air is about 80% nitrogen molecules and 20% oxygen molecules.)

8. Giancoli, Chapter 17, problem 80. (Assume that helium is an ideal gas.)

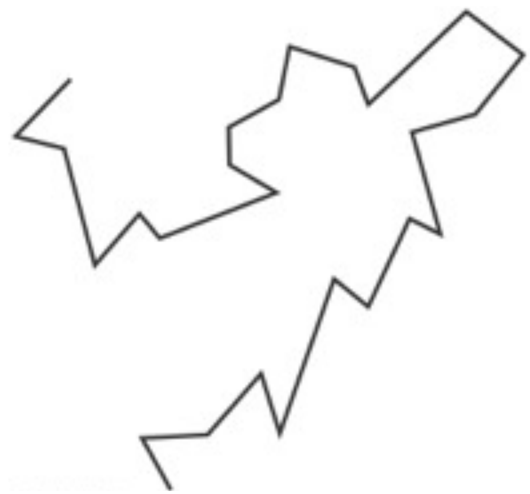
Giancoli - Chapter 17 Temperature, Thermal Expansion, and the Ideal Gas Law

17-1 Atomic Theory of Matter

Atomic and molecular **masses** are measured in unified **atomic mass units** (**u**). This unit is defined so that the **carbon-12** atom has a mass of exactly **12.0000 u**. Expressed in kilograms:

$$1 \text{ u} = 1.6605 \times 10^{-27} \text{ kg}.$$

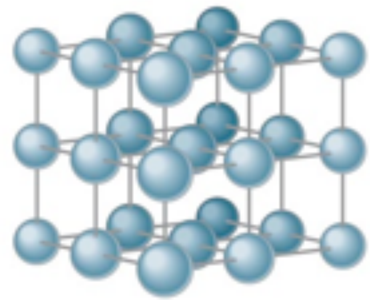
Brownian motion is the jittery motion of tiny flecks in water. Einstein showed in 1905 that this is the result of **collisions** with **individual** water molecules.



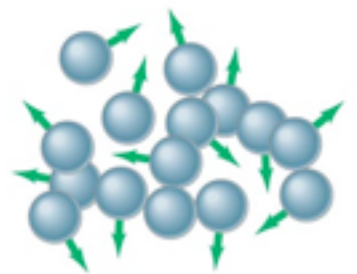
17-1 Atomic Theory of Matter

On a **microscopic** scale, molecules in **solids** are held in place by chemical bonds, in **liquids** there are bonds but molecules are able to move, while in **gases** there are only weak forces between molecules.

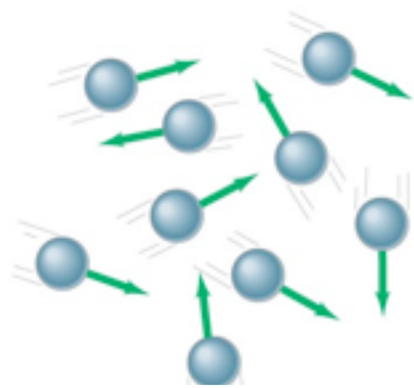
solids



liquids



gases



Thermometers are instruments designed to measure temperature. In order to do this, they take advantage of some **property** of matter that **changes** with temperature.

Early thermometers:

Thermometer chronology:

Galileo thermoscope 1593

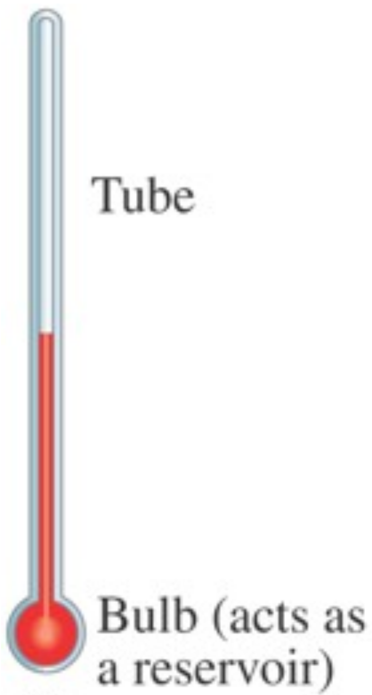
Daniel Fahrenheit's
alcohol thermometer 1709
mercury thermometer 1714

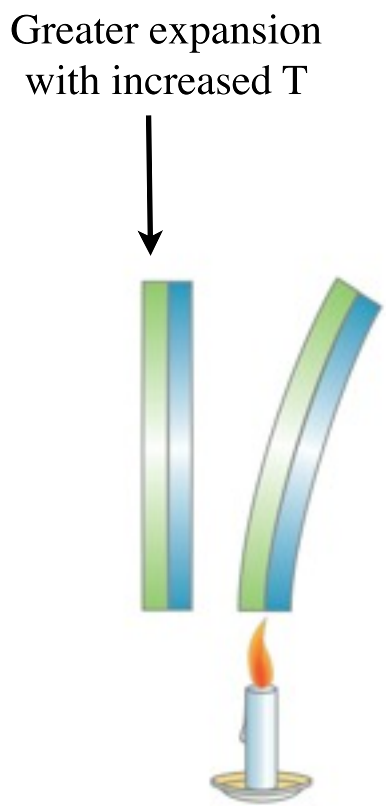
Anders Celsius 1742

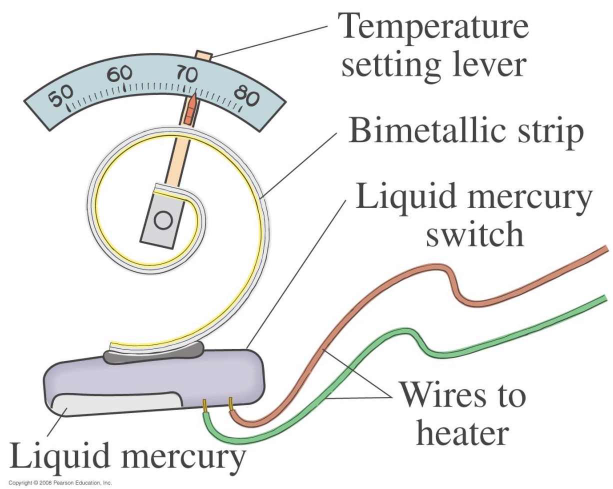
Lord Kelvin's
absolute scale 1848

17-2 Temperature and Thermometers

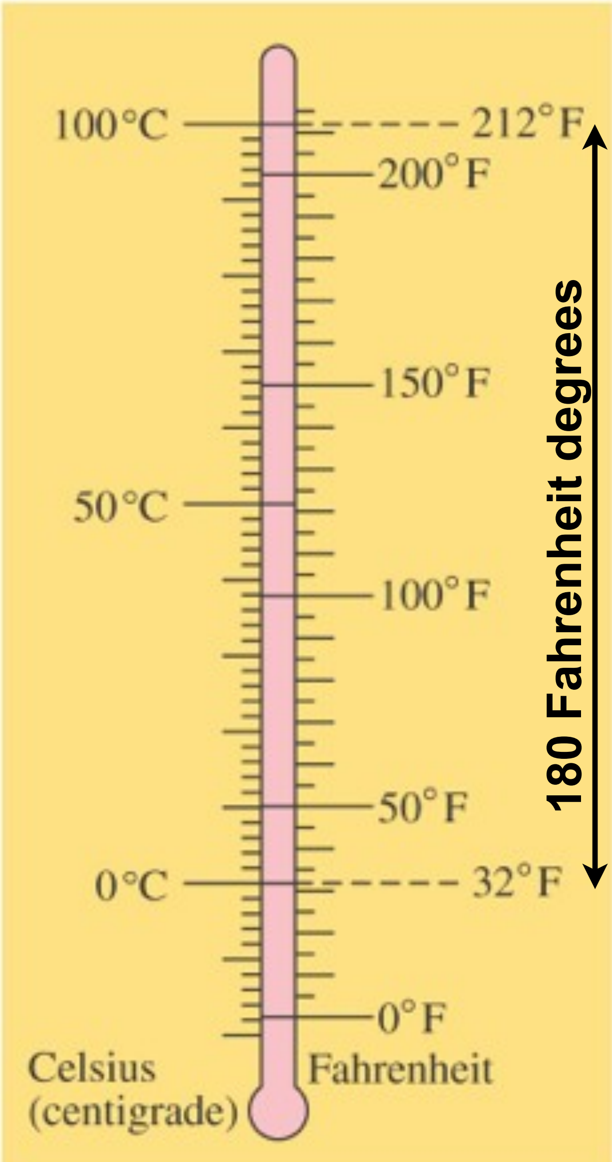
Common thermometers used today include the liquid-in-glass type and the bimetallic strip.







17-2 Temperature and Thermometers



Temperature is generally measured using either the **Fahrenheit** or the **Celsius / Kelvin** scales.

The **freezing** point of water is **0°C**, or **32°F**; the **boiling** point of water is **100°C**, or **212°F**

T_F °F = 32 °F + 1.8 T_C

$T_K = T_C + 273.15$ K

Absolute zero = 0 K

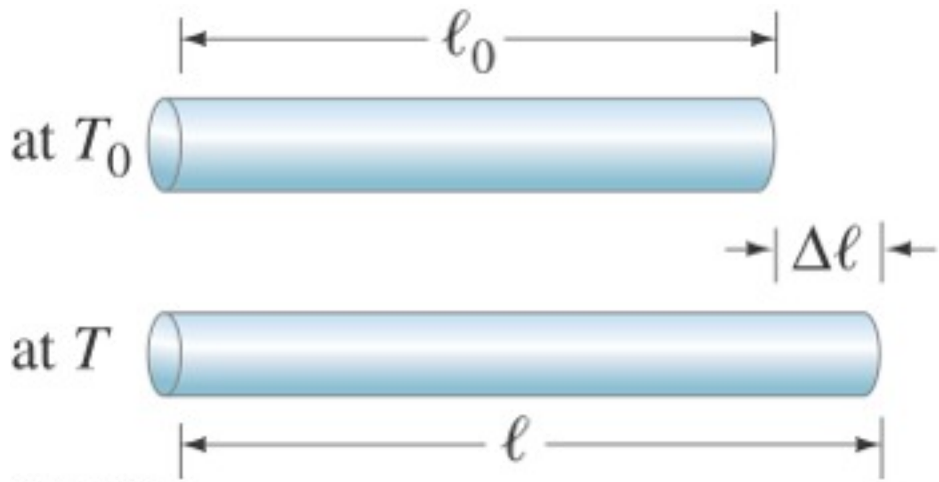
= −273.15 °C

17-3 Thermal Equilibrium and the Zeroth Law of Thermodynamics

Two objects placed in **thermal contact** will eventually come to the **same** temperature. When they do, we say they are in **thermal equilibrium**.

The **zeroth** law of thermodynamics says that if two objects are each in equilibrium with a **third** object, they are also in thermal equilibrium with each other.

17-4 Thermal Expansion



Linear expansion occurs when an object is heated.

$$\ell = \ell_0(1 + \alpha \Delta T)$$

Here, **α** is the **coefficient of linear expansion**.

Example: $\alpha_{Al} = 25\mathrm{x}10^{-6}$, so if $\Delta T = 100$C, an aluminum bar grows in length by a factor 1.0025

17-4 Thermal Expansion

Volume expansion is similar, except that it is relevant for **liquids** and **gases** as well as solids:

$$\Delta V = \beta V_0 \Delta T.$$

Here, β is the coefficient of **volume** expansion.

For **uniform** solids, $\beta \approx 3\alpha$ because each of the 3 dimensions expands by the same factor α:

$$\Delta V = \ell_0{}^3 [(1 + \alpha \Delta T)^3 - 1] = \ell_0{}^3 3\alpha \Delta T$$

neglecting terms of order $(\alpha \Delta T)^2$.

17-4 Thermal Expansion

TABLE 17–1 Coefficients of Expansion, near 20°C

Material	Coefficient of Linear Expansion, α $(C°)^{-1}$	Coefficient of Volume Expansion, β $(C°)^{-1}$
Solids		
Aluminum	25×10^{-6}	75×10^{-6}
Brass	19×10^{-6}	56×10^{-6}
Copper	17×10^{-6}	50×10^{-6}
Gold	14×10^{-6}	42×10^{-6}
Iron or steel	12×10^{-6}	35×10^{-6}
Lead	29×10^{-6}	87×10^{-6}
Glass (Pyrex®)	3×10^{-6}	9×10^{-6}
Glass (ordinary)	9×10^{-6}	27×10^{-6}
Quartz	0.4×10^{-6}	1×10^{-6}
Concrete and brick	$\approx 12 \times 10^{-6}$	$\approx 36 \times 10^{-6}$
Marble	$1.4–3.5 \times 10^{-6}$	$4–10 \times 10^{-6}$
Liquids		
Gasoline		950×10^{-6}
Mercury		180×10^{-6}
Ethyl alcohol		1100×10^{-6}
Glycerin		500×10^{-6}
Water		210×10^{-6}
Gases		
Air (and most other gases at atmospheric pressure)		3400×10^{-6}

Larger than for solids

Does a hole in a piece of metal get bigger or smaller when the metal is heated?

A. Bigger, because the distance between every two points expands.

B. Smaller, because the surrounding metal expands into the hole.

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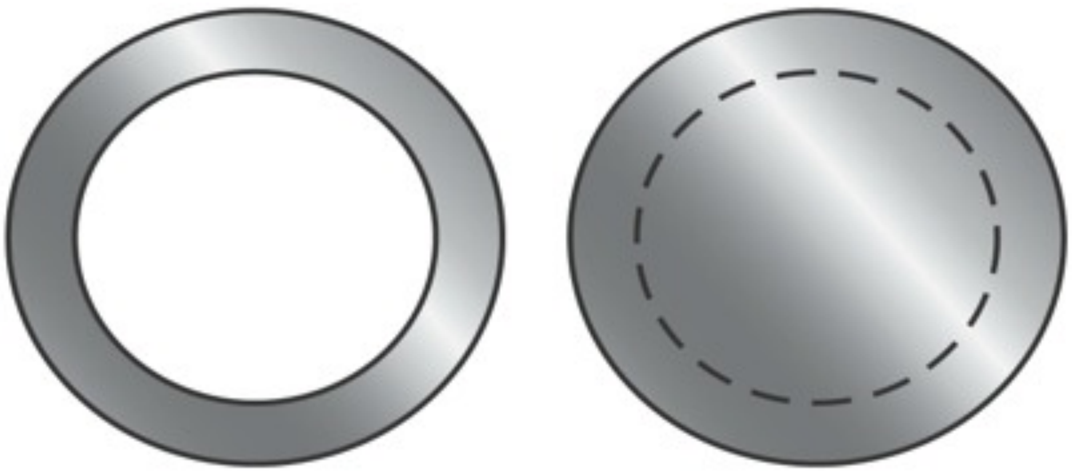


17-4 Thermal Expansion

Example 17-7: Gas tank in the Sun.

The 70-liter (L) steel gas tank of a car is filled to the top with gasoline at 20°C. The car sits in the Sun and the tank reaches a temperature of 40°C (104°F). How much gasoline do you expect to overflow from the tank?

17-4 Thermal Expansion

Example 17-7: Gas tank in the Sun.

The 70-liter (L) steel gas tank of a car is filled to the top with gasoline at 20°C. The car sits in the Sun and the tank reaches a temperature of 40°C (104°F). How much gasoline do you expect to overflow from the tank?

Answer: The coefficient of volume expansion of gasoline is $\beta = 0.00095/°\mathrm{C}$, so the expansion of the gasoline is

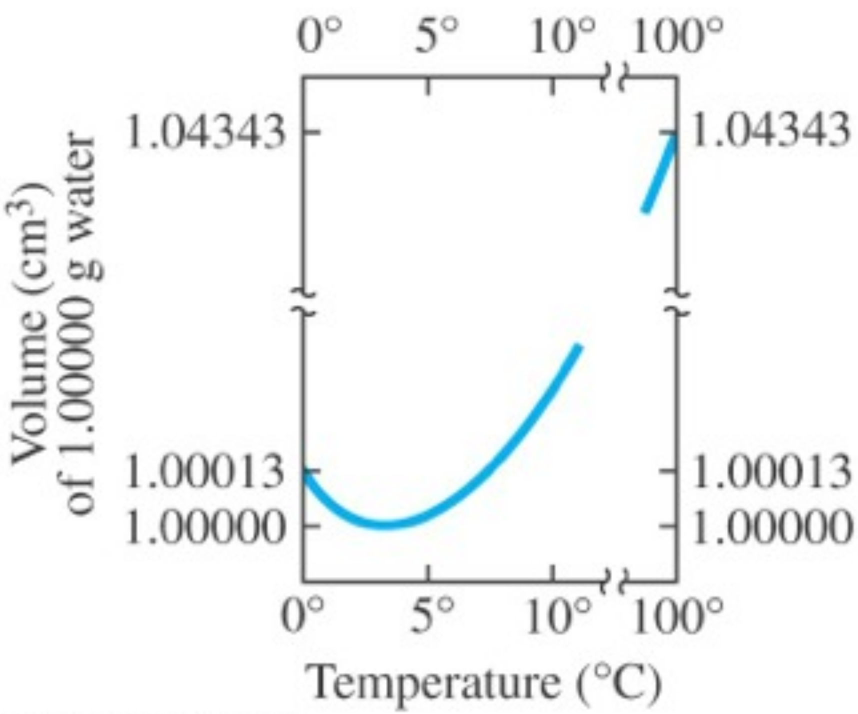
$$\Delta V = \beta V_0 \Delta T = (0.00095/°\mathrm{C})\,(70\ \mathrm{L})\ 20°\mathrm{C}$$

$$= 1.3\ \mathrm{L}$$

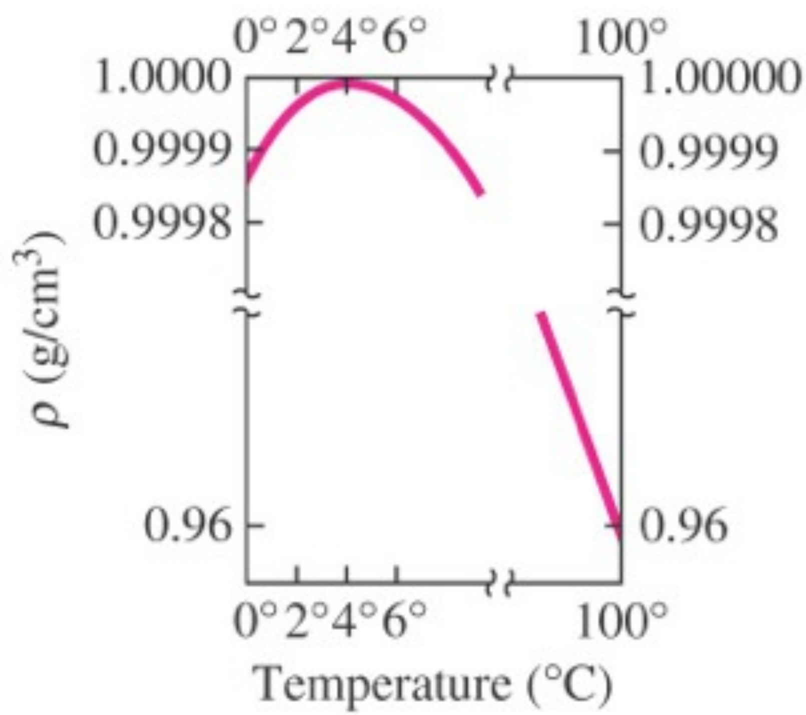
17-4 Thermal Expansion

Water behaves differently from most other solids—its **minimum** volume occurs when its temperature is 4°C. As it cools further, it **expands**, as anyone who leaves a bottle in the freezer to cool and then forgets about it can testify.

Volume



Density



When water above 4 ºC is heated, the buoyant force on an object of constant volume immersed in it

- A. increases.
- B. is unchanged.
- C. decreases.

When water above 4 ºC is heated, the buoyant force on an object of constant volume immersed in it

- A. increases.
- B. is unchanged.
- C. decreases, since

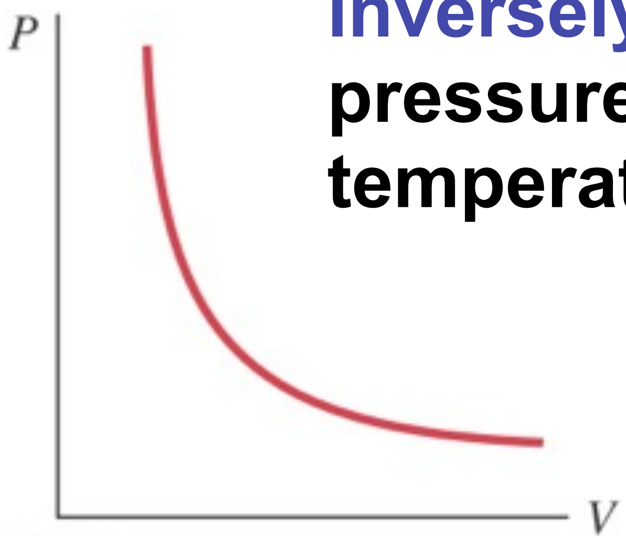
F_B = weight of displaced fluid decreases

Galileo Thermometer

17-6 The Gas Laws and Absolute Temperature

The relationship between the volume, pressure, temperature, and mass of a gas is called an **equation of state**.

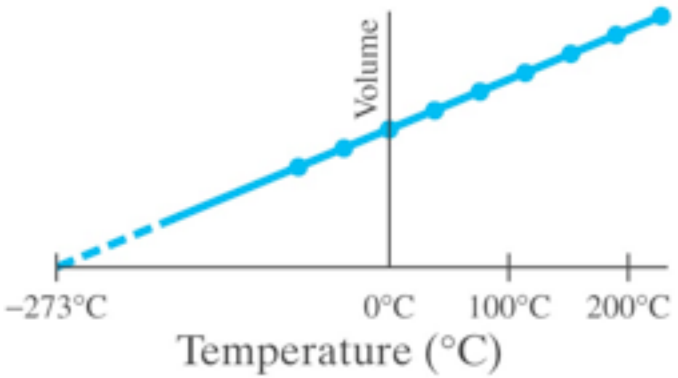
$$\boxed{V \propto \frac{1}{P}}$$

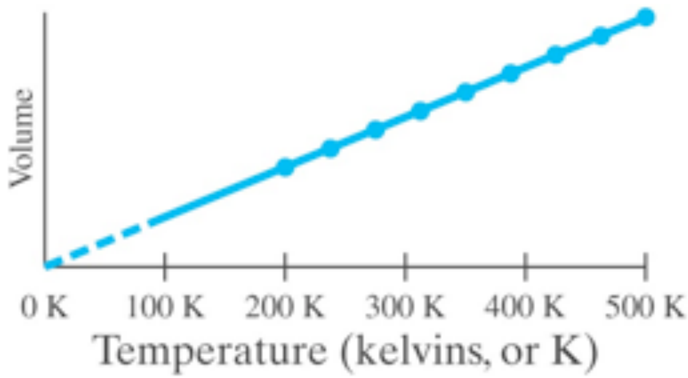


Boyle's law: the **volume** of a given amount of gas is inversely proportional to **pressure** as long as the **temperature** is constant.

Robert Boyle (1627-1691)
Founder of modern chemistry

17-6 The Gas Laws and Absolute Temperature





$$\boxed{V \propto T}$$

The **volume** is linearly proportional to the **temperature**, as long as the temperature is somewhat above the **condensation point** and the **pressure** is constant. Extrapolating, the volume becomes zero at −273.15°C; this temperature is called **absolute zero**

Guillaume Amontons, 1702
Jacques Charles, 1787
Joseph Gay-Lussac, 1808

17-6 The Gas Laws and Absolute Temperature

The concept of absolute zero allows us to define a third temperature scale—the absolute, or **Kelvin**, scale. This scale starts with **0 K** at **absolute zero**, but otherwise is the same as the Celsius scale. Therefore, the **freezing** point of water is 273.15 K, and the **boiling** point is 373.15 K.

Finally, when the **volume** is constant, the **pressure** is directly proportional to the **temperature**.

$$\boxed{P \propto T}$$

Gay-Lussac's Law

17-7 The Ideal Gas Law

We can combine the three relations just stated into a **single** relation:

$$PV \propto T.$$

What about the **amount** of gas present? If the **temperature** and **pressure** are constant, the **volume** is proportional to the **mass** ***m*** of gas:

$$\boxed{PV \propto mT}.$$

17-7 The Ideal Gas Law

A **mole** (mol) is defined as the number of **grams** of a substance that is numerically equal to the **molecular mass** of the substance:

1 mol H_2 has a mass of 2 g.

1 mol Ne has a mass of 20 g.

1 mol CO_2 has a mass of 44 g.

The number of moles (mol) in a certain mass of material:

$$n\ (\text{mole}) = \frac{\text{mass (grams)}}{\text{molecular mass (g/mol)}}.$$

17-7 The Ideal Gas Law

We can now write the **ideal gas law**:

$$PV = nRT,$$

Amadeo Avogadro

where n is the number of **moles** and R is the **universal gas constant**.

$$\begin{aligned} R &= 8.314\,\mathrm{J/(mol\cdot K)} \\ &= 0.0821\,\mathrm{(L\cdot atm)/(mol\cdot K)} \\ &= 1.99\,\mathrm{calories/(mol\cdot K)}. \end{aligned}$$

Note: PV has units of Force x Distance = Energy

ConcepTest Nitrogen and Oxygen I

Which has more molecules—a mole of nitrogen (N_2) gas or a mole of oxygen (O_2) gas?

1) oxygen
2) nitrogen
3) both the same

ConcepTest Nitrogen and Oxygen I

Which has more molecules—a mole of nitrogen (N_2) gas or a mole of oxygen (O_2) gas?

1) oxygen
2) nitrogen
3) both the same

A mole is defined as a quantity of gas molecules equal to Avogadro's number (6.02×10^{23}). This value is independent of the type of gas.

ConcepTest Nitrogen and Oxygen II

Which weighs more—a mole of nitrogen (N_2) gas or a mole of oxygen (O_2) gas?

1) oxygen
2) nitrogen
3) both the same

ConcepTest Nitrogen and Oxygen II

Which weighs more—a mole of nitrogen (N_2) gas or a mole of oxygen (O_2) gas?

1) oxygen
2) nitrogen
3) both the same

The oxygen molecules have a molecular mass of 32, and the nitrogen molecules have a molecular mass of 28.

Follow-up: Which one will take up more space?

17-8 Problem Solving with the Ideal Gas Law

Standard temperature and pressure (STP):

T = 273 K (0°C)

P = 1.00 atm = 1.013×10^5 N/m^2 = 101.3 kPa.

Determine the volume of 1.00 mol of any gas, assuming it behaves like an ideal gas, at STP.

$$V = RT/P = (8.314\ \text{J/mol K})\ (273\text{K}) / (1.013 \times 10^5\ \text{N/m}^2)$$

$$= 22.4 \times 10^{-2}\ \text{m}^3 = 22.4\ \text{L}$$

17-8 Problem Solving with the Ideal Gas Law

Example 17-12: Mass of air in a room.

Estimate the mass of air in a room whose dimensions are 5 m x 3 m x 2.5 m high, at STP.

17-8 Problem Solving with the Ideal Gas Law

Example 17-12: Mass of air in a room.

Estimate the mass of air in a room whose dimensions are 5 m x 3 m x 2.5 m high, at STP.

Answer: The volume is 5 x 3 x 2.5 m^3 = 37.5 m^3

= 37500 L

Since 22.4 L is one mole at STP, there are 37500/22.4 = 1700 moles in the room. Since air is about 20% 0_2 and 80% N_2, its average molecular mass is 0.2(32) + 0.8(28) = 28.8. Thus the mass of air in the room is 1700 x 28.8g = 48900 g = **49 kg**

ConcepTest Ideal Gas Law

Two cylinders at the same temperature contain the same gas. If B has twice the volume and half the number of moles as A, how does the pressure in B compare with the pressure in A?

1) $P_B = \frac{1}{2} P_A$

2) $P_B = 2 P_A$

3) $P_B = \frac{1}{4} P_A$

4) $P_B = 4 P_A$

5) $P_B = P_A$

ConcepTest Ideal Gas Law

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5) $P_B = P_A$

Ideal gas law: $PV = nRT$ or $P = nRT/V$

Because B has a factor of twice the volume, it has a factor of two less the pressure. But B also has half the amount of gas, so that is another factor of two reduction in pressure. Thus, B must have only one-quarter the pressure of A.

17-8 Problem Solving with the Ideal Gas Law

- **Volume** of 1 mol of an ideal gas is **22.4 L**
- If the amount of gas does not change:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}.$$

- Always measure *T* in **kelvins**
- *P* must be the **absolute** pressure

Note: absolute pressure = gauge pressure + 1 Atm

1 Atm = 101 kPa = 14.7 psi = 760 mmHg (torr)

17-8 Problem Solving with the Ideal Gas Law

Example 17-13: Check tires cold.

An automobile tire is filled to a gauge pressure of 200 kPa (= 29 psi) at 10°C. After a drive of 100 km, the temperature within the tire rises to 40°C. What is the pressure within the tire now?

$P_1 = (200 + 101)\text{ kPa} = 301\text{ kPa}$
$T_1 = 283\text{ K}, T_2 = 313\text{ K}.$

Assume V = constant. Then
$P_2 V_1 / T_2 = P_1 V_1 / T_1$ or
$P_2 = P_1 (T_2 / T_1) = 301\text{ kPa } (313/283)$
$= 333$ kPa absolute pressure
$= 233$ kPa gauge pressure
$= 34$ psi

17-9 Ideal Gas Law in Terms of Molecules: Avogadro's Number

Since the gas constant is **universal**, the **number** of molecules in one mole is the same for all gases. That number is called **Avogadro's number**:

$$N_A = 6.02 \times 10^{23}.$$

Amadeo Avogadro

This was first measured (and named) by Jean Babtiste Perrin in 1909, using Einstein's 1905 analysis of Brownian motion.

Perrin

17-9 Ideal Gas Law in Terms of Molecules: Avogadro's Number

Therefore we can write:

$$PV = nRT = \frac{N}{N_A} RT,$$

or

$$\boxed{PV = NkT,}$$

where k is called **Boltzmann's constant**.

$$k = \frac{R}{N_A} = \frac{8.314\ \mathrm{J/mol \cdot K}}{6.02 \times 10^{23}/\mathrm{mol}} = 1.38 \times 10^{-23}\ \mathrm{J/K}.$$

1592 Galileo's thermoscope

1643 Torricelli makes first barometer

1662 Boyle's Law Published

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

1702 Amontons' Experiment

$$V \propto T$$

1714 Fahrenheit's Thermometer

1734 Bernoulli's KMT

$$P \propto T$$

1787 Charles' Law

1801 Dalton's Law of Partial Pressure

1802 Gay-Lussac's Balloon Ride

1811 Avogadro's Principle Published

The ideal gas law is

$$PV = nRT,$$

where n is the number of moles and R is the universal gas constant

$$\begin{aligned} R &= 8.314\,\mathrm{J/(mol \cdot K)} \\ &= 0.0821\,\mathrm{(L \cdot atm)/(mol \cdot K)} \\ &= 1.99\,\mathrm{calories/(mol \cdot K)}. \end{aligned}$$

or $PV = NkT$ **where k is Boltzmann's constant N is the number of molecules, and N_A is Avogadro's number**

$$k = \frac{R}{N_A} = \frac{8.314\,\mathrm{J/mol \cdot K}}{6.02 \times 10^{23}/\mathrm{mol}} = 1.38 \times 10^{-23}\,\mathrm{J/K}.$$

17-9 Ideal Gas Law in Terms of Molecules: Avogadro's Number

Example 17-14: Hydrogen atom mass.

Use Avogadro's number to determine the mass of a hydrogen atom.

17-9 Ideal Gas Law in Terms of Molecules: Avogadro's Number

Example 17-14: Hydrogen atom mass.

Use Avogadro's number to determine the mass of a hydrogen atom.

Answer: $1.008\text{g} / 6.02\text{x}10^{23} = 1.67\text{x}10^{-24}$ g

17-9 Ideal Gas Law in Terms of Molecules: Avogadro's Number

Example 17-14: Hydrogen atom mass.

Use Avogadro's number to determine the mass of a hydrogen atom.

Answer: $1\text{g} / 6.02\text{x}10^{23} = 1.7\text{x}10^{-24}$ g

Example 17-15: How many molecules in one breath?

Estimate how many molecules you breathe in with a 1.0-L breath of air.

17-9 Ideal Gas Law in Terms of Molecules: Avogadro's Number

Example 17-14: Hydrogen atom mass.

Use Avogadro's number to determine the mass of a hydrogen atom.

Answer: $1\text{g} / 6.02\times10^{23} = 1.7\times10^{-24}$ g

Example 17-15: How many molecules in one breath?

Estimate how many molecules you breathe in with a 1.0-L breath of air.

Answer: $6.02\times10^{23} / 22.4 = 2.7\times10^{22}$ molecules

17-10 Ideal Gas Temperature Scale—a Standard

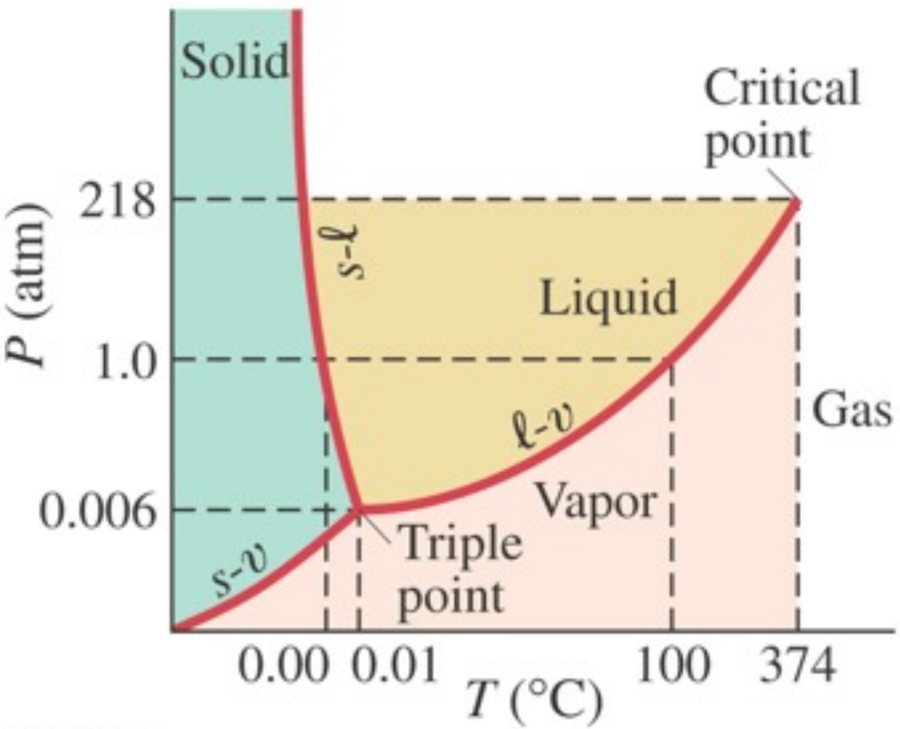
This standard uses the constant-volume gas thermometer and the ideal gas law. There are two fixed points:

Absolute zero—the pressure is zero here

The triple point of water (where all three phases coexist), is defined to be 273.16 K—the pressure there is 4.58 torr.

18-3 Real Gases and Changes of Phase

A *PT* diagram is called a **phase diagram**; it shows all three phases of matter. The solid-liquid transition is **melting** or **freezing**; the liquid-vapor one is **boiling** or **condensing**; and the solid-vapor one is **sublimation**.



Phase diagram of water (note nonlinear axes).

P_{tp} = 4.58 torr
= 0.0604 atm
T_{tp} = 273.16 K

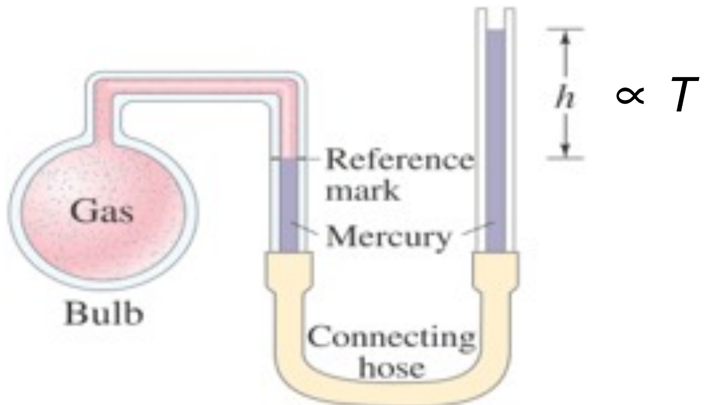
17-10 Ideal Gas Temperature Scale—a Standard

Then the temperature is defined as:

$$T = (273.16\,\mathrm{K})\left(\frac{P}{P_{tp}}\right), \quad \text{where } P_{tp} = 4.58 \text{ torr}$$

In order to determine temperature using a real gas, the pressure must be as low as possible so it behaves like an ideal gas.

constant-volume gas thermometer



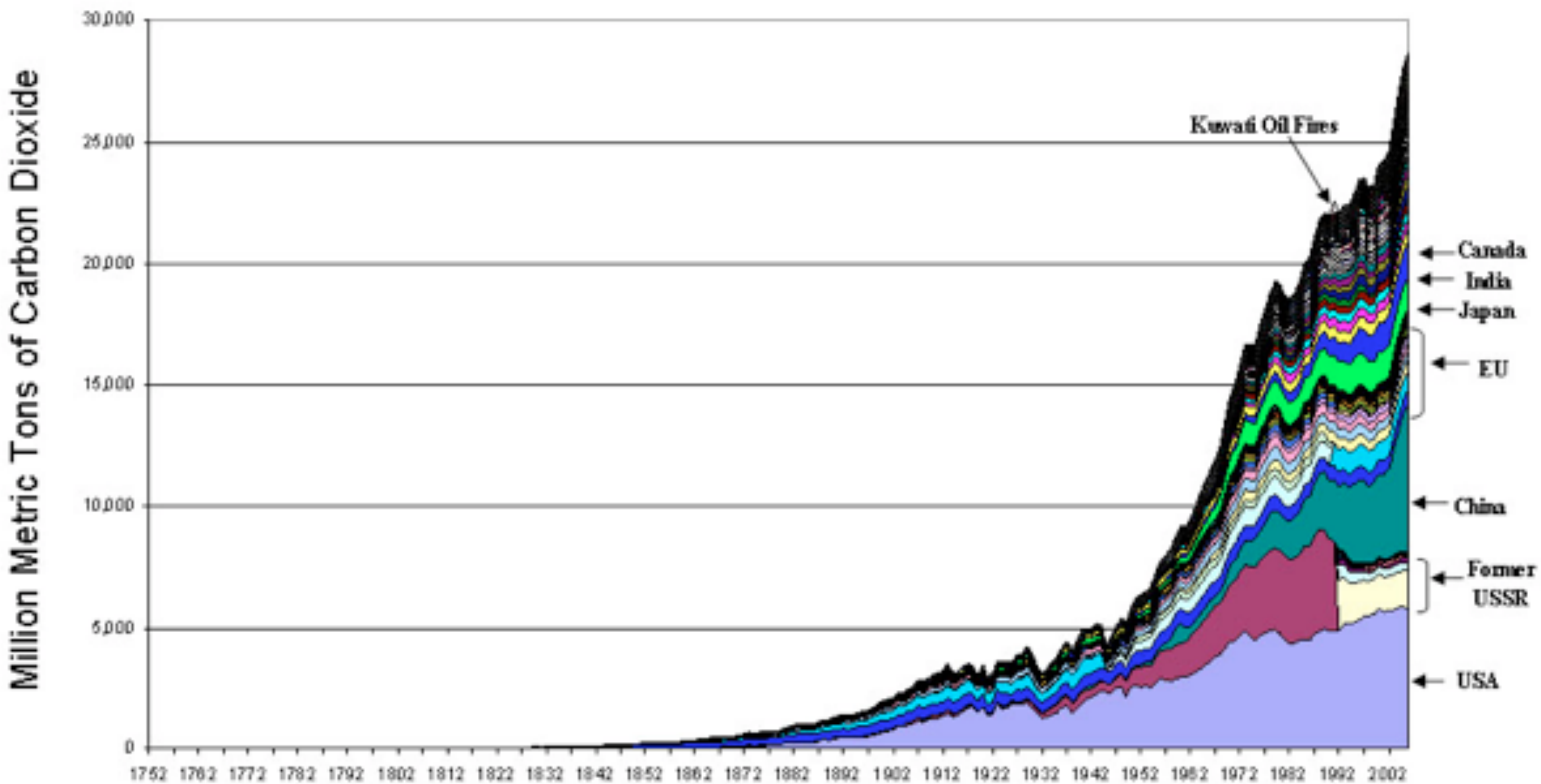
Example: Carbon Dioxide in the Atmosphere

Amount of CO_2 in Atmosphere:

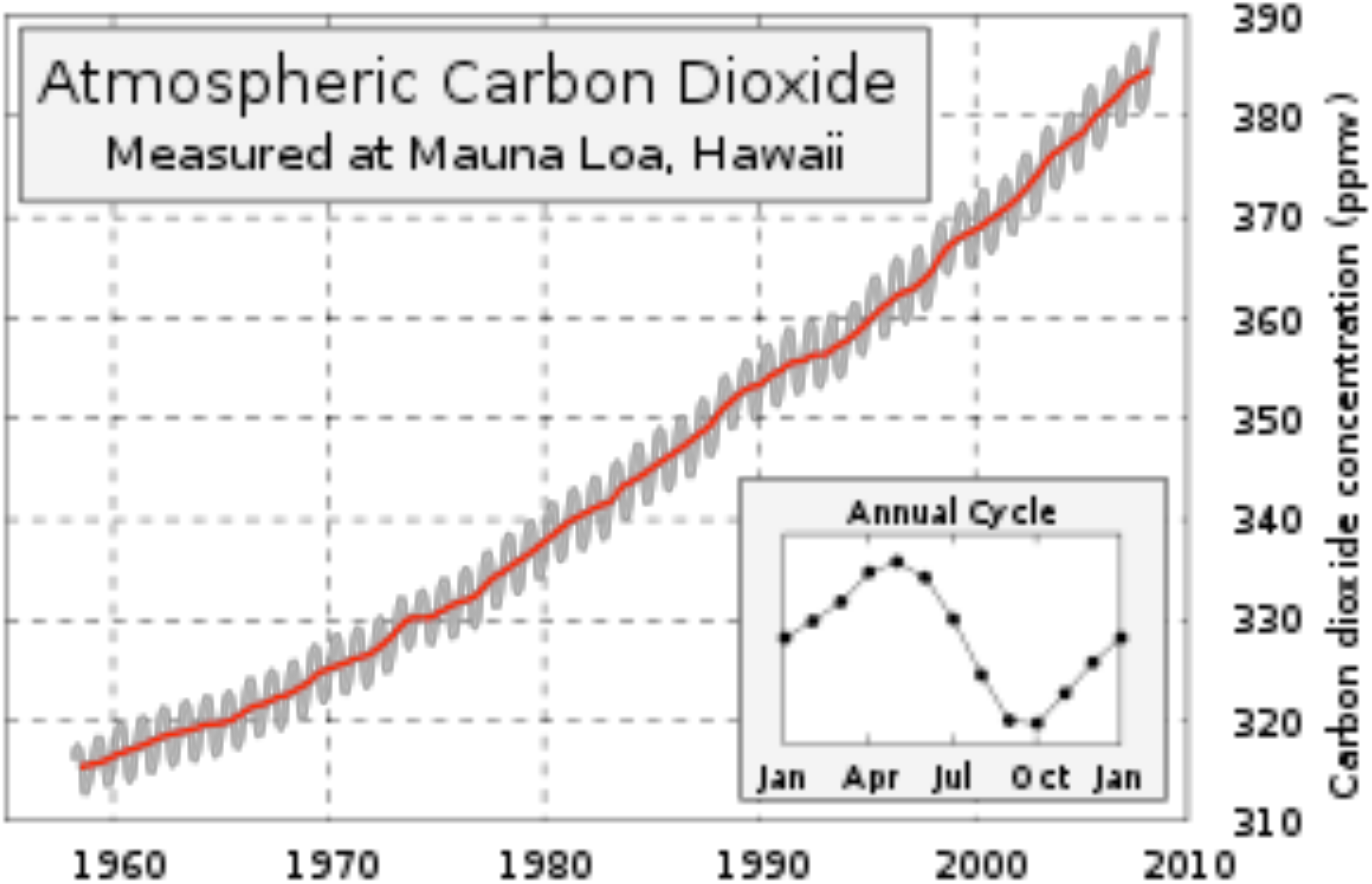
about 400 ppm by volume, 600 ppm by mass

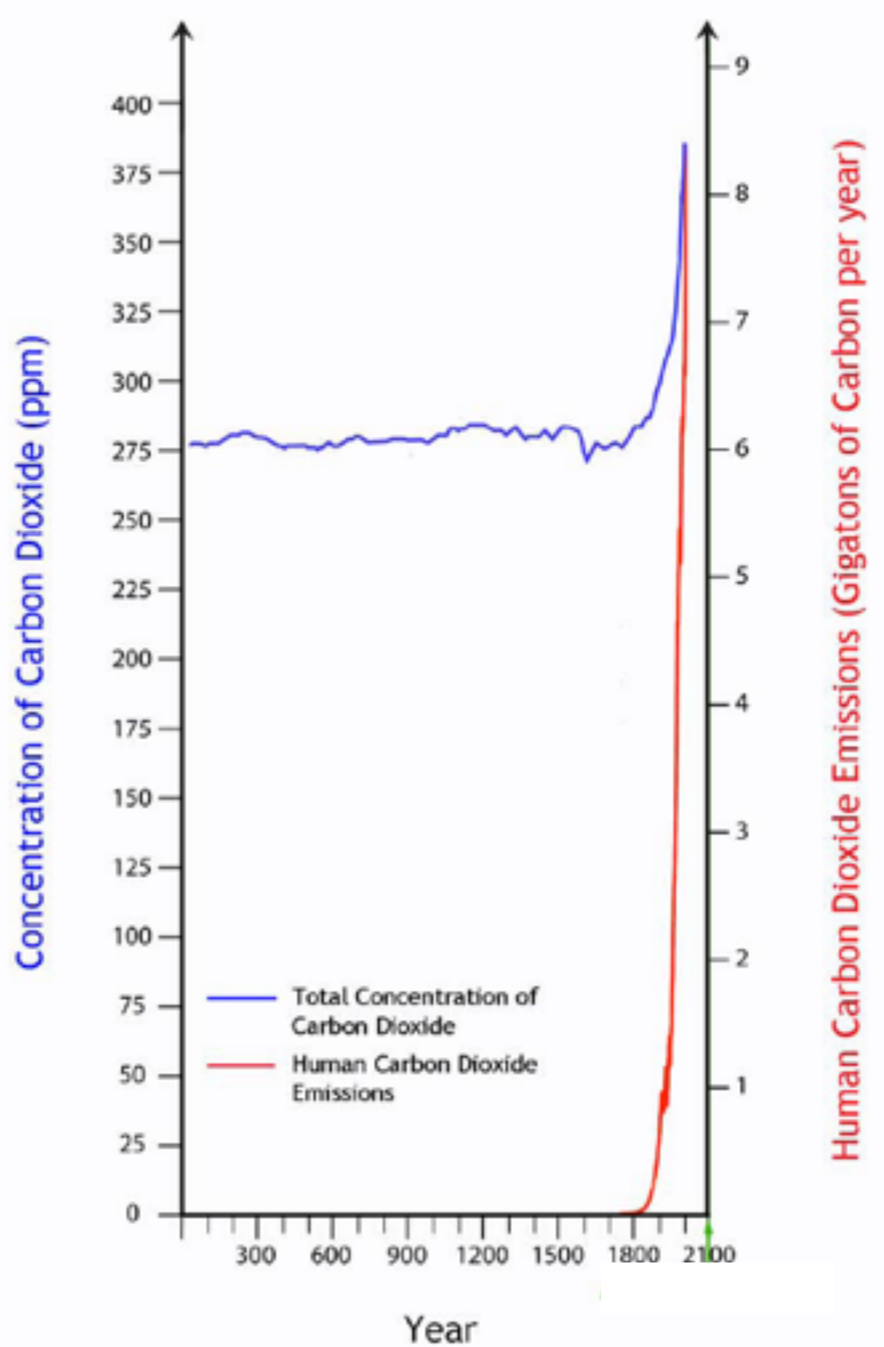
$(6x10^{-4})(5x10^{18}$ kg) = $3x10^{15}$ kg = 3000 GT

Human production = 30 GT/yr = 1% of atm !



Human production = 30 GT/yr = 1% of atm = 4 ppm
Annual increase is now about 2 ppm, so about 1/2 of human production stays in the atmosphere.





If we continue with business as usual, we will continue to double CO_2 production every 30 years, leading to over 500 ppm in the atmosphere by 2040, almost double the pre-industrial level. The corresponding rise in temperature is ~2 to 3K, about 2 to 3x what we have seen so far.