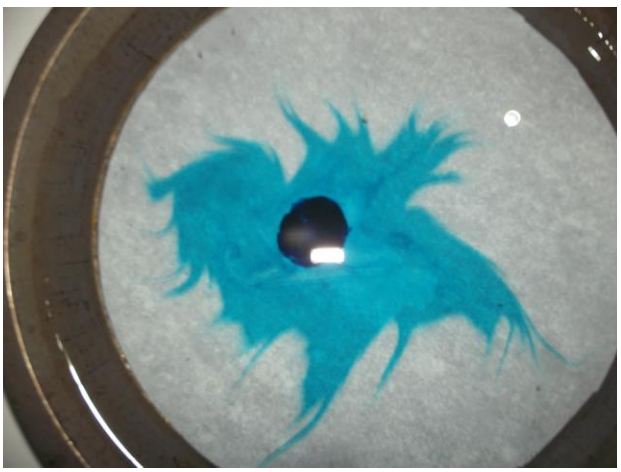
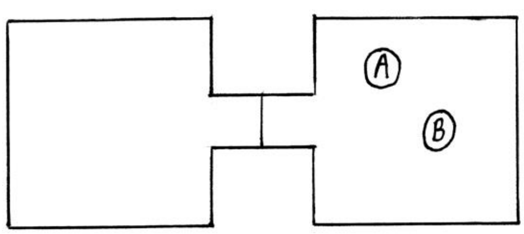
Chemistry Lecture #101: What is Entropy?

Entropy is a measure of how energy is spread out. When energy is concentrated in one area, it spontaneously spreads and diffuses itself across a larger region of space. It is similar to how a drop of food dye placed in water will diffuse and spread through the water.



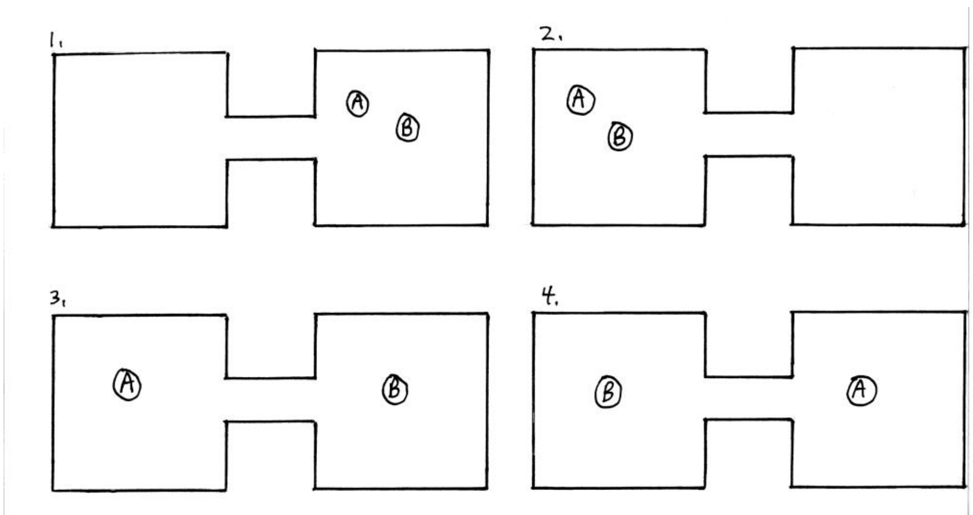
A drop of food dye in a pan of water spreads out and away from the center.

Another example of entropy is the diffusion of gas atoms or molecules. Suppose we have two gas atoms, A and B, on the right side of a closed chamber. This is the initial state. A second chamber is attached on the left.



When a door between the chambers is opened, the atoms are free to move between the chambers. When the atoms move, there are four different ways they can be distributed:

1. Both atoms in the right chamber.
2. Both atoms in the left chamber.
3. Atom A in the left chamber and atom B in the right chamber.
4. Atom B in the left chamber and atom A in the right chamber.



There is a 1 out of 4 chance that both atoms will be on the left (1/4 = 25%). There is a 1 out of 4 or 25% chance that both atoms will be on the right. There is a 2 out of 4 chance that there will be an atom in each chamber (2/4 = 50%). Thus, there is a greater chance that the atoms will be evenly distributed between the chambers compared to being concentrated to one particular side. Likewise, it is more likely that energy will spread out and be distributed, rather than remain concentrated in one area.

Since the atoms are moving, or have kinetic energy, we can see this as an example of kinetic energy being spread over a larger region.

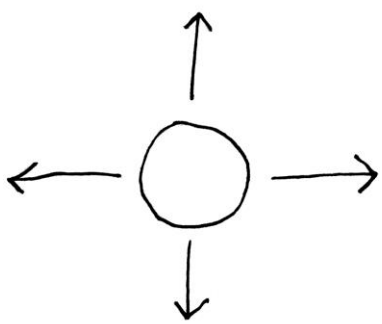
Some books say that entropy increases when there is an increase in the number of ways that energy can be distributed. In our example, the number of ways that energy could be distributed went from 1 to 4 possibilities, so entropy increased.

Another way to look at entropy is to say that it increases when we are less able to predict the location of particles at a particular moment in time. In our example, we initially knew that the two atoms were in the chamber on the right. After we opened the door, the atoms could move, and there were now four possible locations for the atoms. Since the possible locations of the atoms has increased from 1 to 4, we are less able to predict the exact location of the atoms, and therefore have an increase in entropy. Entropy would also increase if the atoms were moving faster.

The most common way that entropy is explained is to say that it is a measurement of disorder or randomness. With our example, the initial randomness of the atoms is low since both atoms are in one location. When they are allowed to move, the possible locations have increased to 4, so our knowledge of where they are is less precise and more random.

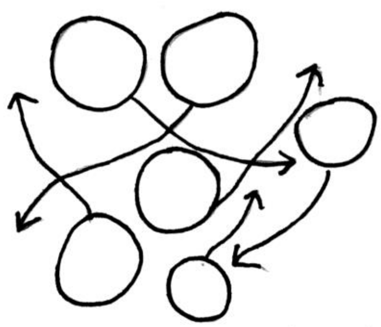
The only time we would know precisely where an atom is located is when an atom is not moving or has no kinetic energy. This would occur if a solid has a temperature of -273 °C or 0 Kelvin, also known as absolute zero. Absolute zero is the complete absence of energy from a substance, and its particles do not move at all. Substances at absolute zero contain no entropy.

But if we add energy to a solid at absolute zero, the atoms will absorb the energy and begin to vibrate. By vibrating, the position of the atoms change slightly, and we know less about their precise locations, thus showing an increase in entropy. Thus, all solids at a temperature above absolute zero contain entropy.



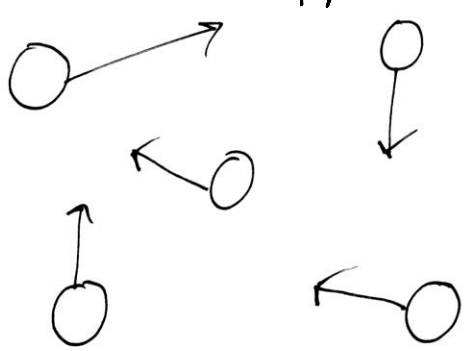
When a particle in a solid vibrates, its position is less precise.

Liquids contain more entropy than solids since the particles of a liquid continuously slide past each other. This makes their positions even more difficult to predict.



Particles in a liquid slide past each other. Liquids have more entropy than solids.

Particles that make up a gas are far apart and moving rapidly. It is very difficult to predict the location of particles under these conditions. Thus, the gaseous state of matter contains the highest amount of entropy.



Gas particles are far apart and move rapidly. Gases have the highest amount of entropy.

Solid → Liquid → Gas

Increasing Entropy →

The entropy content of substances is often listed in charts like the one below. "S" is used to represent entropy.

Thermodynamic Properties (at 25°C and 100.000 kPa)

$\Delta H_f°$ (kJ/mol) $\Delta G_f°$ (kJ/mol) S° (J/mol · K)
(concentration of aqueous solutions is 1*M*)

Substance	$\Delta H_f°$	$\Delta G_f°$	S°	Substance	$\Delta H_f°$	$\Delta G_f°$	S°
Ag(cr)	0	0	42.55	H_3PO_3(aq)	−964.4	—	—
AgCl(cr)	−127.068	−109.789	96.2	H_3PO_4(aq)	−1279.0	−1119.1	110.50
AgCN(cr)	146.0	156.9	107.19	H_2S(g)	−20.63	−33.56	205.79
Al(cr)	0	0	28.33	H_2SO_3(aq)	−608.81	−537.81	232.2
Al_2O_3(cr)	−1675.7	−1582.3	50.92	H_2SO_4(aq)	−909.27	−744.53	20.1
$BaCl_2$(aq)	−871.95	−823.21	122.6	$HgCl_2$(cr)	−224.3	−178.6	—
$BaSO_4$(cr)	−1473.2	−1362.2	132.2	Hg_2Cl_2(cr)	−265.22	−210.745	192.5
Be(cr)	0	0	9.50	Hg_2SO_4(cr)	−743.12	−625.815	200.66
BeO(cr)	−609.6	−580.3	—	I_2(cr)	0	0	116.135
Bi(cr)	0	0	56.74	K(cr)	0	0	64.18
$BiCl_3$(cr)	−379.1	−315.0	177.0	KBr(cr)	−393.798	−380.66	95.90
Bi_2S_3(cr)	−143.1	−140.6	200.4	$KMnO_4$(cr)	−837.2	−737.6	171.71
Br_2(l)	0	0	152.231	KOH(cr)	−424.764	—	—
CH_4(g)	−74.81	−50.72	186.264	LiBr(cr)	−351.213	—	—
C_2H_2(g)	+226.73	+209.20	200.94	LiOH(cr)	−484.93	−438.95	42.80
C_2H_4(g)	+52.26	+68.15	219.56	Mn(cr)	0	0	32.01
C_2H_6(g)	−84.68	−32.82	229.60	$MnCl_2$(aq)	−555.05	−490.8	38.9
CO(g)	−110.525	−137.168	197.674	$Mn(NO_3)_2$(aq)	−635.5	−450.9	218
CO_2(g)	−393.509	−394.359	213.74	MnO_2(cr)	−520.03	−465.14	53.05
CS_2(l)	+89.70	+65.27	151.34	MnS(cr)	−214.2	—	—
Ca(cr)	0	0	41.42	N_2(g)	0	0	191.61
$Ca(OH)_2$(cr)	−986.09	−898.49	—	NH_3(g)	−46.11	−16.45	192.45
Cl_2(g)	0	0	223.066	NH_4Br(cr)	−270.83	−175.2	113
Co_3O_4(cr)	−891	−774	—	NO(g)	+90.25	86.55	210.761
CoO(cr)	−237.94	−214.20	52.97	NO_2(g)	+33.18	+51.31	240.06
Cr_2O_3(cr)	−1139.7	−1058.1	81.2	N_2O(g)	+82.05	+104.20	219.85
CsCl(cr)	−443.04	−414.53	101.17	Na(cr)	0	0	51.21
Cs_2SO_4(cr)	−1443.02	−1323.58	211.92	NaBr(cr)	−361.062	—	—
CuI(cr)	−67.8	−69.5	96.7	NaCl(cr)	−411.153	−384.138	72.13
CuS(cr)	−53.1	−53.6	66.5	$NaNO_3$(aq)	−447.48	—	—
Cu_2S(cr)	−79.5	−86.2	120.9	NaOH(cr)	−425.609	—	—
$CuSO_4$(cr)	−771.36	−661.8	109	Na_2S(aq)	−447.3	—	—
F_2(g)	0	0	202.78	Na_2SO_4(cr)	−1387.08	−1270.16	149.58
$FeCl_3$(cr)	−399.49	—	—	O_2(g)	0	0	205.138
FeO(cr)	−272.0	—	—	P_4O_6(cr)	−1640.1	—	—
Fe_2O_3(cr)	−824.2	−742.2	87.40	P_4O_{10}(cr)	−2984.0	−2697.7	228.86
Fe_3O_4(cr)	−1118.4	−1015.4	146.4	$PbBr_2$(cr)	−278.7	−261.92	161.5
H(g)	+217.965	—	114.713	$PbCl_2$(cr)	−359.41	−314.10	136.0
H_2(g)	0	0	130.684	S(cr)	0	0	31.80
HBr(g)	−36.40	−53.45	198.695	SO_2(g)	−296.830	−300.194	248.22
HCl(g)	−92.307	−95.299	186.908	SO_3(g)	−454.51	−374.21	70.7
HCl(aq)	−167.159	−131.228	56.5	SrO(cr)	−592.0	−561.9	54.4
HCN(aq)	+150.6	+172.4	94.1	Ti(cr)	0	0	30.63
HCHO(g)	−108.57	−102.53	218.77	TiO_2(cr)	−939.7	−884.5	49.92
HCOOH(l)	−424.72	−361.35	128.95	TlI(cr)	−123.8	−125.39	127.6
HF(g)	−271.1	−273.2	173.779	UCl_4(cr)	−1019.2	−930.0	197.1
HI(g)	+26.48	+1.70	206.594	UCl_5(cr)	−1059	−950	242.7
H_2O(l)	−285.830	−237.129	69.91	Zn(cr)	0	0	41.63
H_2O(g)	−241.818	−228.572	188.825	$ZnCl_2$(aq)	−488.19	−409.50	0.8
H_2O_2(l)	—	−120.35	109.6	ZnO(cr)	−348.28	−318.30	43.64
H_3PO_2(l)	−595.4	—	—	$ZnSO_4$(aq)	−1063.15	−891.59	−92.0

Notice that the entropy of $H_2O_{(g)}$ is 188.825 J/mol K, which is greater than that of $H_2O_{(l)}$, which has an entropy of 69.91 J/mol K. Gases have more entropy than liquids.

If the entropy of $H_2O_{(g)}$ is given as S^o = 188.825 J/ mol K, it means that one mole of $H_2O_{(g)}$ at a temperature of 25 °C and a pressure of 100 kPa has an entropy of 188.825 J/K. Notice that the entropy is expressed as a ratio of energy to temperature (J/K).

Knowing the entropy of products and reactants from the thermodynamic properties chart, we can calculate the change in entropy (ΔS^o) that occurs in a chemical reaction, using the formula

$\Delta S^o = \sum S^o(\text{products}) - \sum S^o(\text{reactants})$

ΔS^o = change in entropy for the reaction
$\sum S^o$(products) = sum of the entropies of the products
$\sum S^o$(reactants) = sum of the entropies of the reactants

Find the change in entropy under standard conditions for the reaction

$CH_{4(g)} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(l)}$

Solution

We write down the entropies of products and reactants from the thermodynamic properties chart and add them.

S^O of products (J/mol k)	
$CO_{2(g)}$	= 214
$H_2O_{(l)}$ = 69.9 x 2	= 139.8
$\sum S^o$(products)	=353.8

S^o of reactants (J/mol k)	
$CH_{4(g)}$	= 186
$O_{2(g)}$ = 205 x 2	= 410
$\sum S^o$(reactants)	= 596

Notice that the entropies for $H_2O_{(l)}$ and $O_{2(g)}$ were each multiplied by 2. This is because there is a 2 in front of $H_2O_{(l)}$ and $O_{2(g)}$ in the balanced equation.

We can substitute the product and reactant sums into the equation and solve.

$\Delta S^o = \sum S^o(\text{products}) - \sum S^o(\text{reactants})$

$\Delta S^o = 353.8 - 596$

$\Delta S^o = -242.2$ or -242 J/mol K

-242 J/mol K means that the entropy decreased after the reaction. If the answer had been a positive number, it would mean that the entropy has increased.