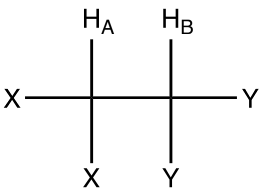
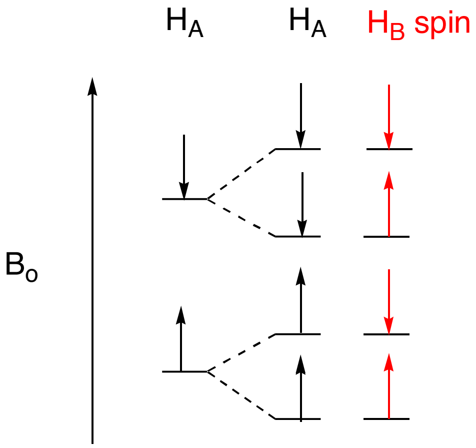
Review from last class

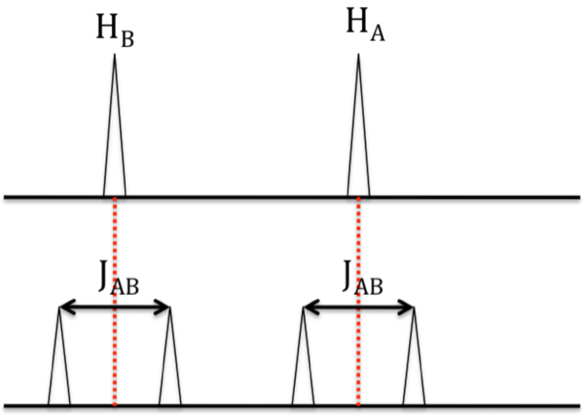
Spin-Spin Splitting (Coupling)



X≠Y

H_A is not a singlet due to the influence of H_B on its spin, and vice versa. This diagram shows the energy for H_A, and the spins for H_B are shown (in red) only to show the effect on H_A





J_{AB} = **Coupling constant** between atoms A and B, measured in Hertz (Hz)

The H_A coupling constant corresponds to the energy differences caused by the H_B proton in alignment with and in opposition to the field. This energy difference is equal to the effect that the H_A proton has on H_B, so both of these coupling constants are equal.

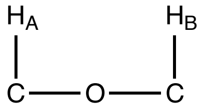
The coupled signal is centered around the same chemical shift value that the signal would have if there were no coupling.

Limitations of Coupling

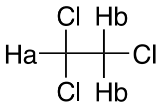
1. 2 to 3 bonds separating nuclei (coupling is typically not seen between nuclei that are further apart than 3 bonds)
2. Usually no coupling across O, N, S, C=O

Note: there are exceptions to these rules (e.g. Aromatic systems)

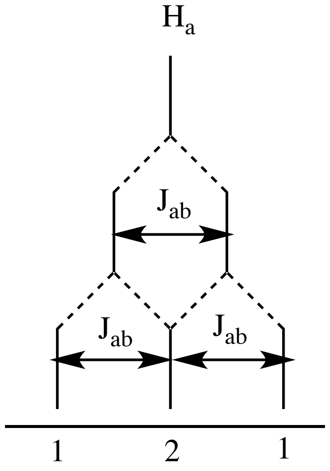
Example: In the following structure, H_A and H_B would not couple due to the oxygen



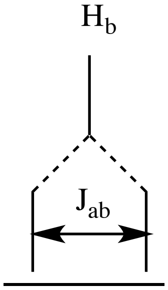
Example of coupling: Ha is downfield of Hb



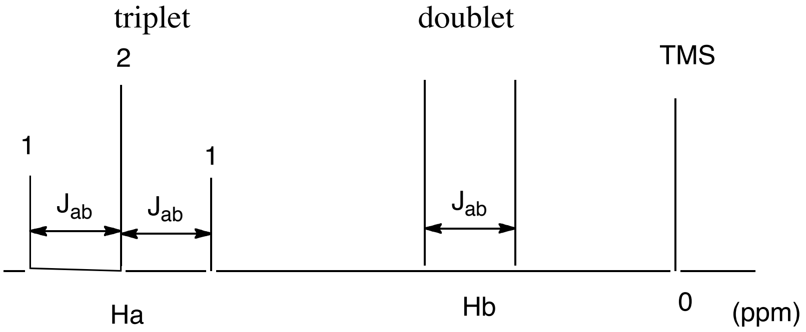
1,1,2-trichloroethane
achiral (not chiral)



triplet



doublet



Integration:	1	:	2
(relative intensity)	(1Ha)	:	(2 Hb)

Pascal's Triangle

1
1 1
1 2 1
1 3 3 1
1 4 6 4 1

Above represents intensities of singlet, doublet (1 to 1), triplet (1 to 2 to 1), quartet (1 to 3 to 3 to 1), quintet (1 to 4 to 6 to 4 to 1)

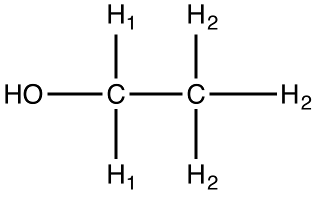
Signal multiplicity can be described by the rule 2nI + 1

Where I = spin and n = the number of equivalent hydrogens that are nearby (2 or 3 bonds away from the hydrogen that is being examined)

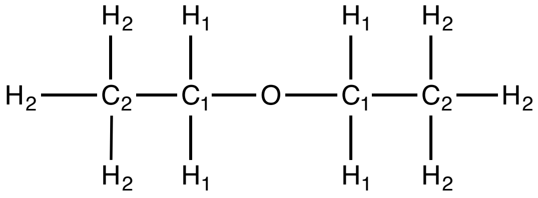
Since I = ½ for 1H, this rule can be simplified to the n + 1 rule

- The number of lines for a signal is equal to the number of neighbouring hydrogens + 1

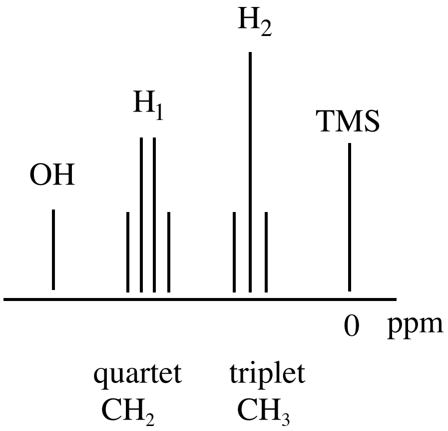
Consider examples below and the types of hydrogens (a and b)

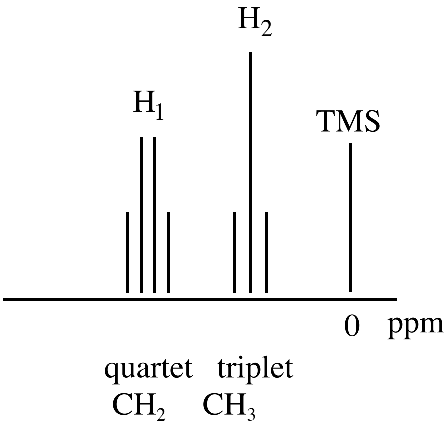


Ethanol



Diethyl ether





Intensity (area ratio) would be 2:3

Intensity would be 4:6 or 2:3

No stereogenic centers present. No coupling across oxygen.

Both molecules should have 2 sets of signals.

The intensity (of the entire coupled signal) is determined by the number of hydrogens that make the particular signal. For example, the quartet above is for the CH_2 which is a total of 2 hydrogens, while the triplet is for the CH_3 which is a total of 3 hydrogens.

Note: In the diethyl ether example, carbon (1) is attached to the oxygen, which means the methylene (1) is more deshielded and more downfield. However, the methyl (2) is not attached to the oxygen, meaning the methyl (2) is much less deshielded and less downfield.

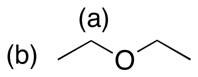
Carbon NMR

^{12}C has 6 protons and 6 neutrons	no nuclear spin, invisible in NMR
^{13}C has 6 protons and 7 neutrons	spin = ½, stable isotope, occurs naturally in 1.1% abundance
^{14}C has 6 protons and 8 neutrons	radioactive, half life is $t_{1/2}$ = 5730 years

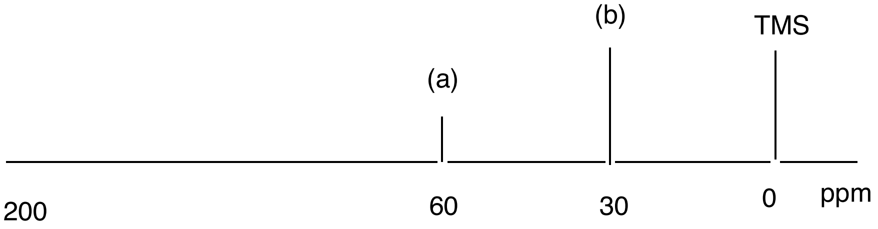
^{13}C has an odd number of neutrons, therefore it has nuclear spin and is NMR active. ^{12}C and ^{14}C both have an even number of neutrons and an even number of protons and are not NMR active (they have no nuclear spin and cannot be seen by NMR).

^1H-Broad Band Decoupling

A ^{13}C NMR spectrum is run decoupled (this means to irradiate all protons so that there is no ^1H spin-spin coupling to ^{13}C). As a result the ^{13}C signals are singlets, which simplifies interpretation.

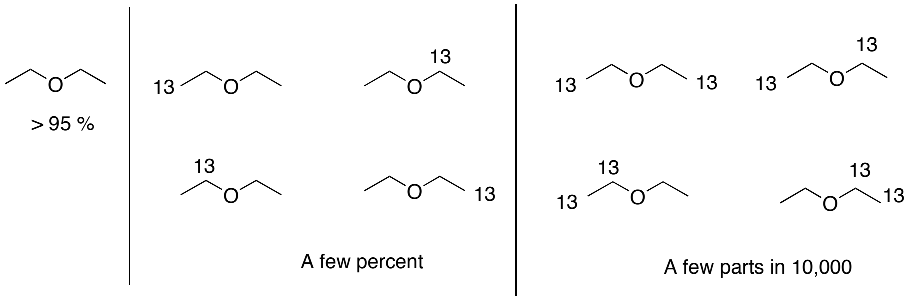


diethyl ether



There are two different types of carbon in diethyl ether, therefore one would expect to see two different signals. Each appears as a singlet in the proton (^{1}H) decoupled (that is irradiated) carbon-13 spectrum.

There is no ^{13}C-^{13}C spin-spin coupling because the chance of there being two ^{13}C's next to each other is 0.01 x 0.01 = 0.0001 or one part in 10,000, which is too small to detect easily.



The integration of ^{13}C NMR spectra is not common.
In ^{1}H NMR spectra, the relative area of the peaks indicates how many H's are present.
In ^{13}C NMR spectra, the intensity or area of the peak cannot be used to calculate the relative number of carbons because of relaxation effects and transfer of energy from decoupled hydrogens.

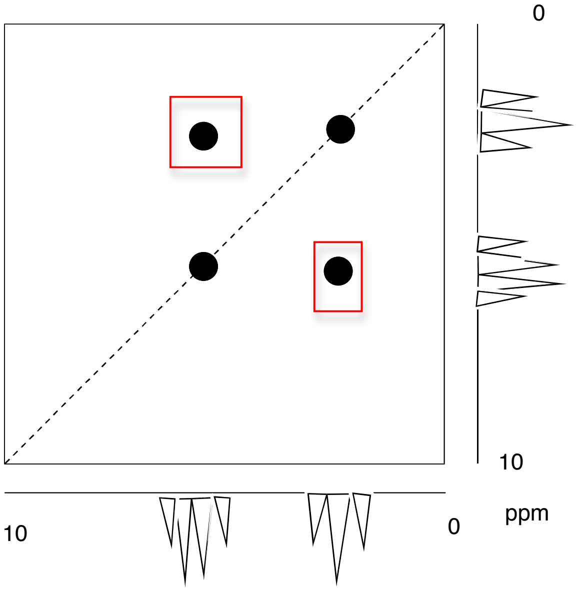
2-D NMR

Two major types of experiments:

1. Through bonds energy transfer (dependent on coupling constants, J)
2. Through space energy transfer (NOE = Nuclear Overhauser Effect)

Correlation Spectroscopy (COSY) (a through bond experiment)

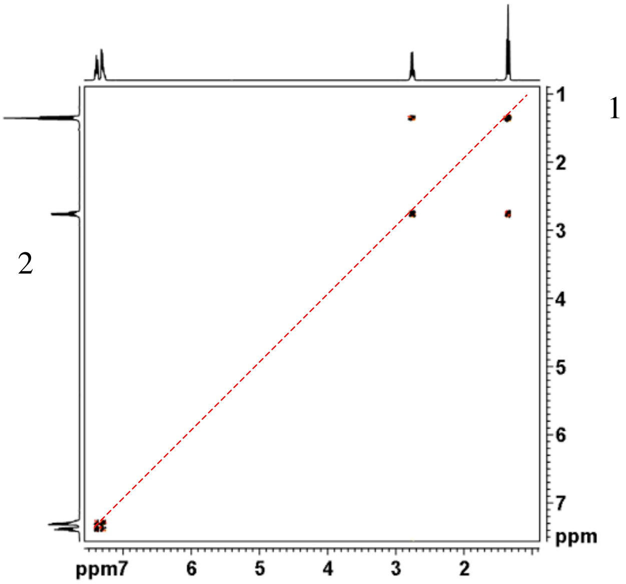
Shown below is a COSY spectrum of **diethyl ether**.

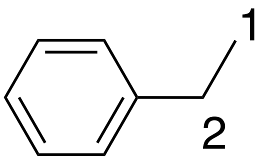


Diagonal signals (autocorrelation) are just the hydrogens of each group seeing each other (e.g. The three hydrogens of a methyl group).

The off diagonal cross peaks show that the triplet and the quartet signals correlate to each other and the hydrogens that are responsible for those signals are on adjacent atoms (i.e. coupled) in the molecule. For a simple molecule like diethyl ether, this is trivial and can be seen from the one-dimensional spectrum. However, in complex molecules with many signals, the connectivity of coupled hydrogens can be determined.

Example 2: COSY of ethylbenzene





Protons labeled 1 are the methyl group, and are correlated to the methylene protons labeled 2 - as see by the dots off of the diagonal. The aromatic protons at 7 ppm are not coupled to these but couple to themselves

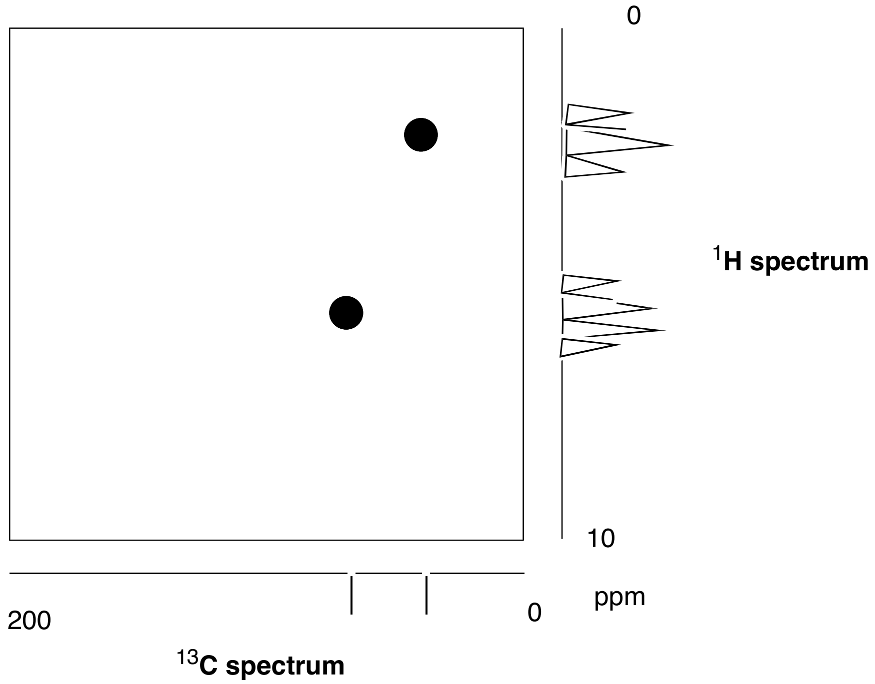
Heteronuclear Correlation Spectroscopy (HETCOR) (a through bond experiment)

An example of a HETCOR experiment is Heteronuclear Multiple Quantum Coherence (HMQC)

Shown below is the HETCOR spectra of diethyl ether ($CH_3CH_2OCH_2CH_3$).

HETCOR gives the connectivity of carbons and hydrogens

This technique correlates the ^{1}H NMR spectrum with the ^{13}C NMR spectrum. It allows connectivity patterns to be established in conjunction with COSY. In other words, COSY tells which hydrogens are adjacent to each other and HETCOR allows the connection to their respective carbons.
Unlike COSY, there is **no diagonal** in HETCOR experiments.

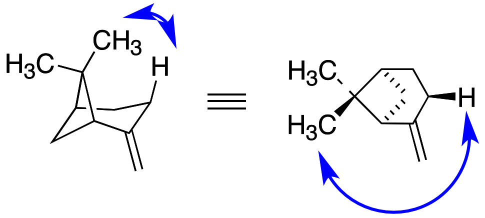


The carbon at 30 ppm correlates to the hydrogens at 1 ppm. The carbon at 60 ppm correlates to the hydrogens at 4 ppm. "Correlation" in HETCOR can only be 1 bond away. In COSY the protons can be "correlated" to other protons up to 3 bonds away.

Nuclear Overhauser Effect (NOE) (a through space experiment)

An NOE effect is an energy transfer between two nuclei (e.g. protons) through space. The effect drops off proportionally to $1/r^6$ where r = internuclear distance

β-pinene - Two drawings of the same molecule:



For better understanding of this structure, please see additional graphics page on our web site (www.chem.ualberta.ca/~vederas then click on basic organic chemistry) or use models available from first floor chemistry storeroom

This technique allows you to distinguish between the two methyl groups in β-pinene (major constituent of turpentine). If the single diastereotopic H shown on the methylene is irradiated, it will transfer energy via the NOE effect to the closest methyl group and produce an enhanced signal. This will be shown by that one methyl group peak in the NMR spectrum becoming more intense. Irradiation of that same methyl will analogously enhance the methylene hydrogen shown. The more distant methyl will not show this NOE effect. This technique is useful for determining the 3-D orientation (structure) of molecules, including proteins. 3-D structures of proteins with molecular weight of 50,000 and thousands of atoms have been determined by advanced versions of the NOE method.