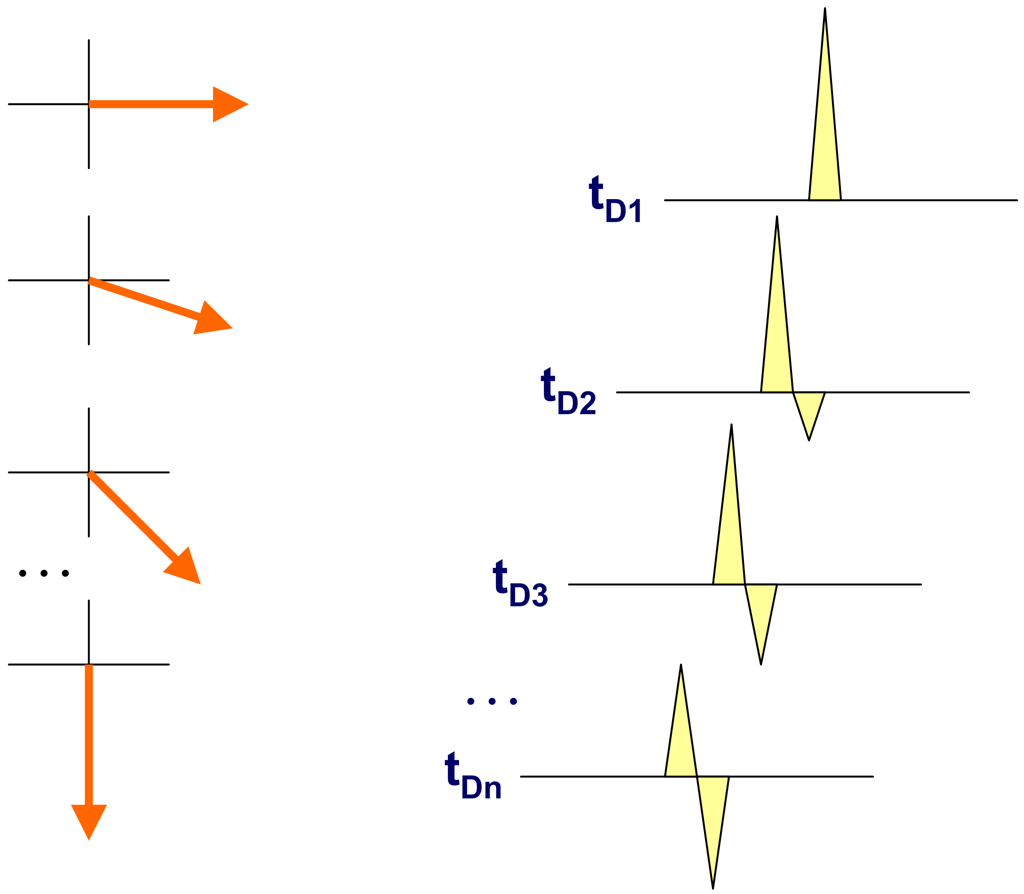
2D NMR spectroscopy

- So far we have been dealing with multiple pulses but a single dimension - that is, 1D spectra. We have seen, however, that a multiple pulse sequence can give different spectra which depend on the delay times we use.

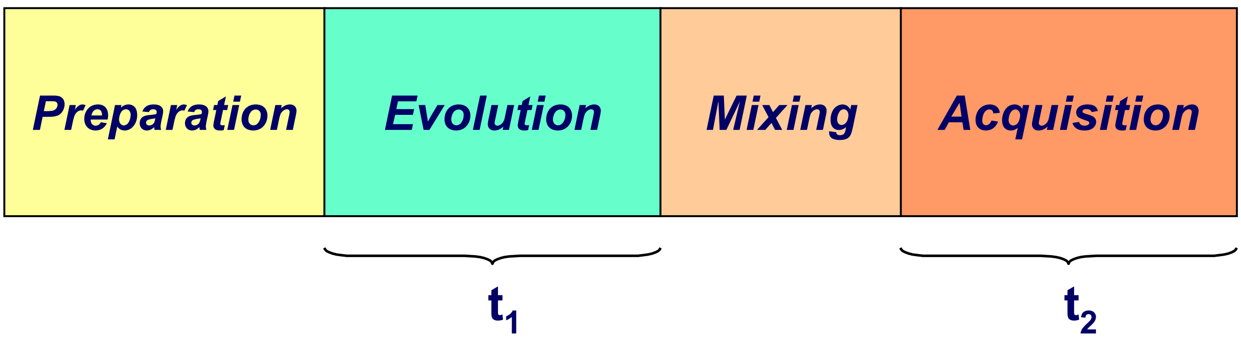
- The 'basic' 2D spectrum would involve repeating a multiple pulse 1D sequence with a systematic variation of the delay time $\mathbf{t_D}$, and then plotting everything stacked. A very simple example would be varying the time before acquisition:



- We now have ***two time domains***, one that appears during the acquisition as usual, and one that originates from the variable delay.

2D NMR basics

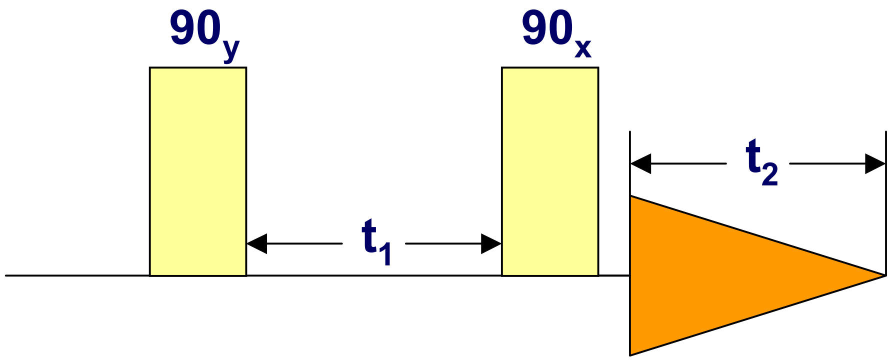
- There is some renaming that we need to do to be more in synch with the literature:
    - The first perturbation of the system (pulse) will now be called the ***preparation*** of the spin system.
    - The variable $\mathbf{t_D}$ is renamed the ***evolution time***, $\mathbf{t_1}$.
    - We have a ***mixing*** event, in which information from one part of the spin system is relayed to other parts.
    - Finally, we have an ***acquisition period*** ($\mathbf{t_2}$) as with all 1D experiments.
- Schematically, we can draw it like this:



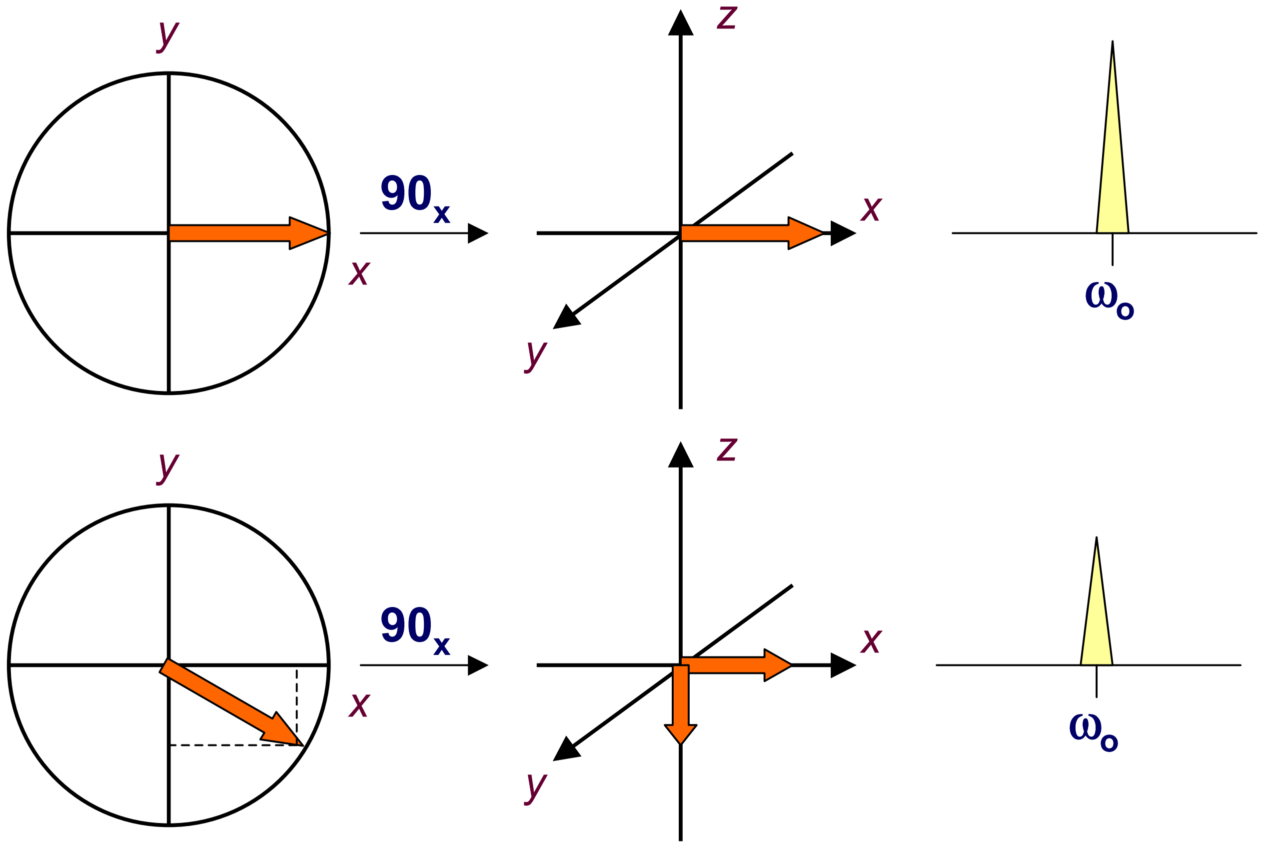
- $\mathbf{t_1}$ is the variable delay time, and $\mathbf{t_2}$ is the normal acquisition time. We can envision having $\mathbf{f_1}$ and $\mathbf{f_2}$, for both frequencies…
- We'll see that this format is basically the same for all 2D pulse sequences and experiments.

A rudimentary 2D experiment

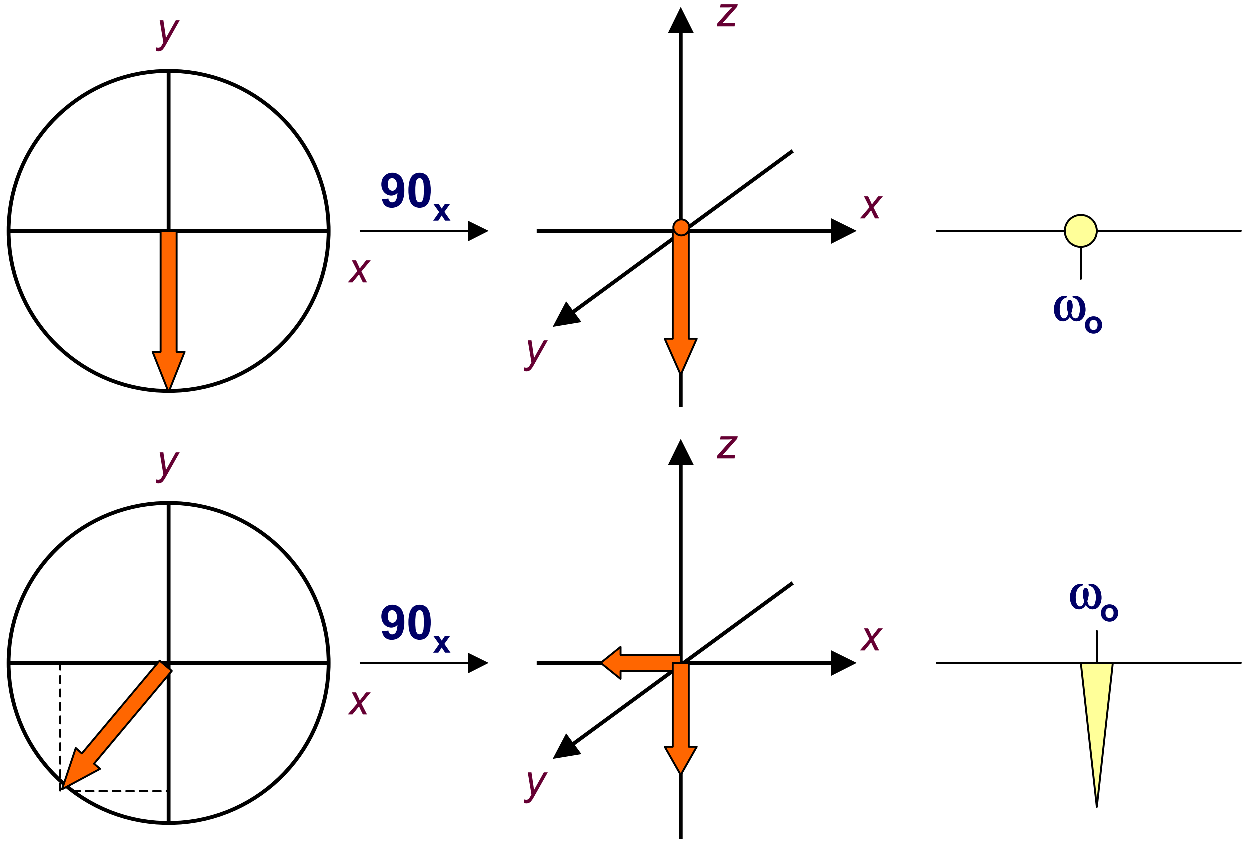
- We'll see how it works with the backbone of what will become the ***COSY*** pulse sequence. Think of this pulses, were $\mathbf{t_1}$ is the preparation time:



- We'll analyze it for an off-resonance (ω_o) singlet for a bunch of different $\mathbf{t_1}$ values. Starting after the first π **/ 2** pulse:



The rudimentary 2D (continued)

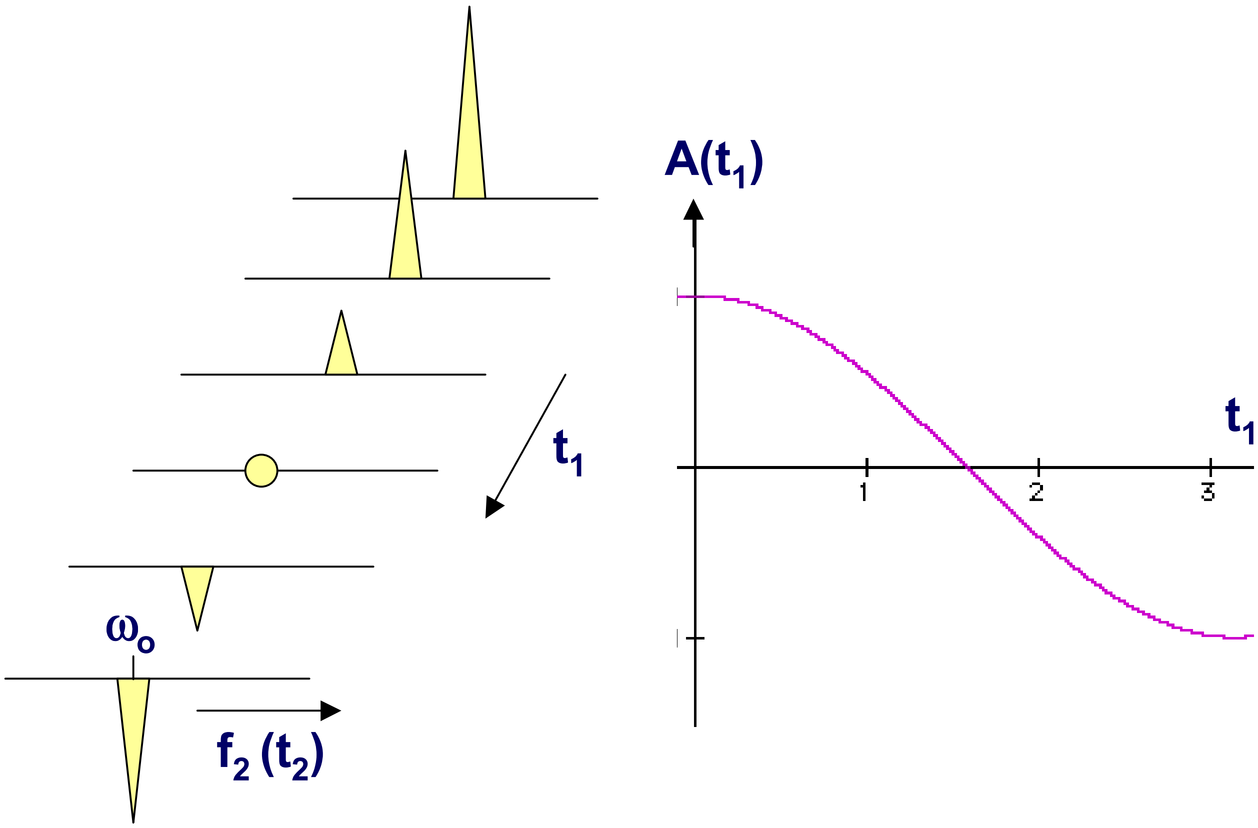


- The second **π / 2** pulse acts only on the **y** axis component of the magnetization of the **<xy>** plane.
- The **x** axis component is not affected, but its amplitude will depend on the frequency of the line.

$$A(t_1) = A_o * \cos(\omega_o * t_1)$$

The rudimentary 2D (…)

- If we plot all the spectra in a ***stacked plot***, we get:



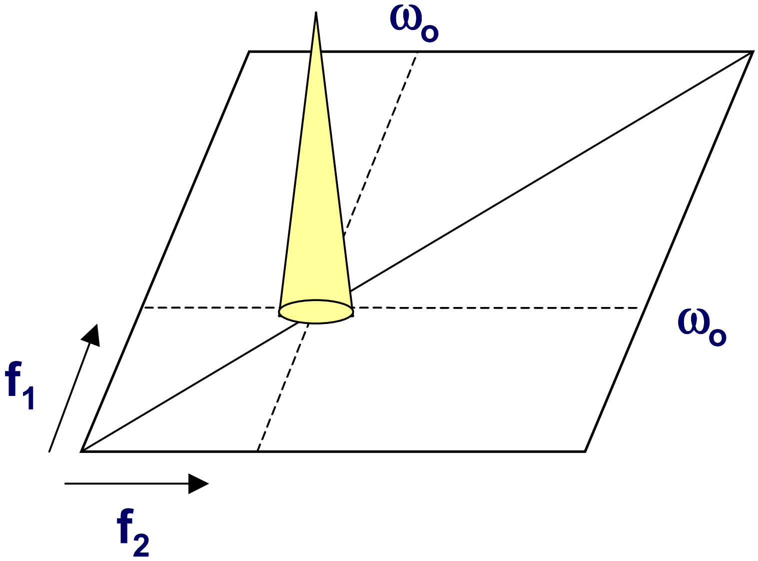
- Now, we have frequency data in one axis (**f_2**, which came from **t_2**), and time domain data in the other (**t_1**).

- Since the variation of the amplitude in the **t_1** domain is also periodic, we can build a pseudo FID if we look at the points for each of the frequencies or lines in **f_2**.

- One thing that we are overlooking here is that during all the pulsing and waiting and pulsing, the signal will also be affected by **T_1** and **T_2** relaxation.

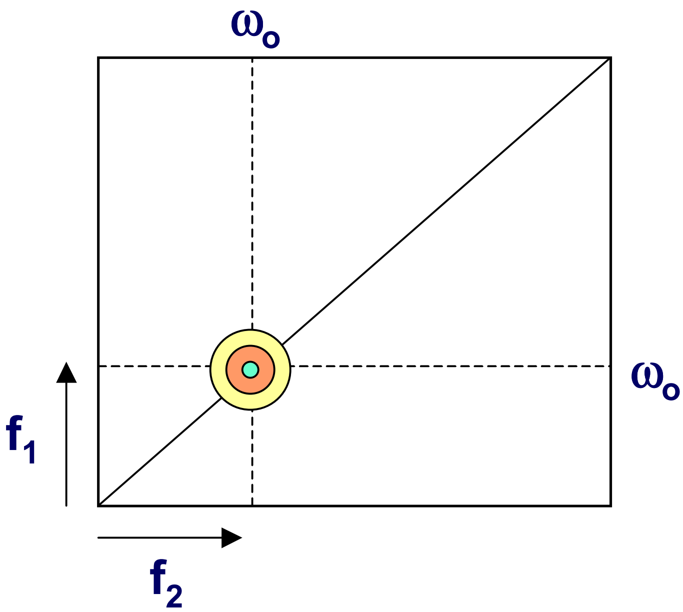
The rudimentary 2D (…)

- Now we have FIDs in $\mathbf{t_1}$, so we can do a ***second Fourier transformation*** in the $\mathbf{t_1}$ domain (the first one was in the $\mathbf{t_2}$ domain), and obtain a ***two-dimensional spectrum***:



- We have a ***cross-peak*** where the two lines intercept in the 2D map, in this case on the ***diagonal***.

- If we had a real spectrum with a lot of signals it would be a royal mess. We look it from above, and draw it as a ***contour plot*** - we chop all the peaks with planes at different heights.

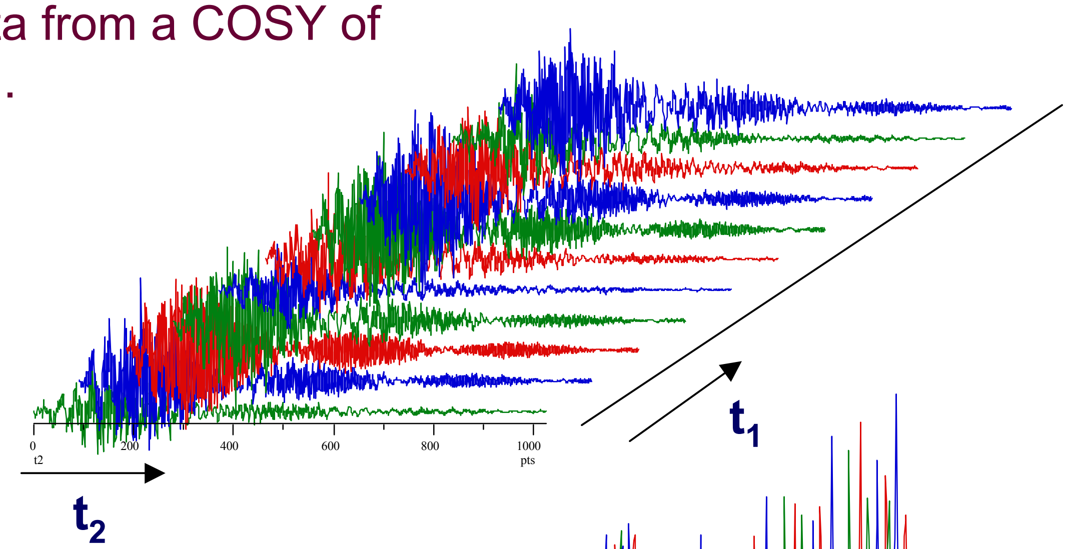


- Each slice is color-coded depending on the height of the peak.

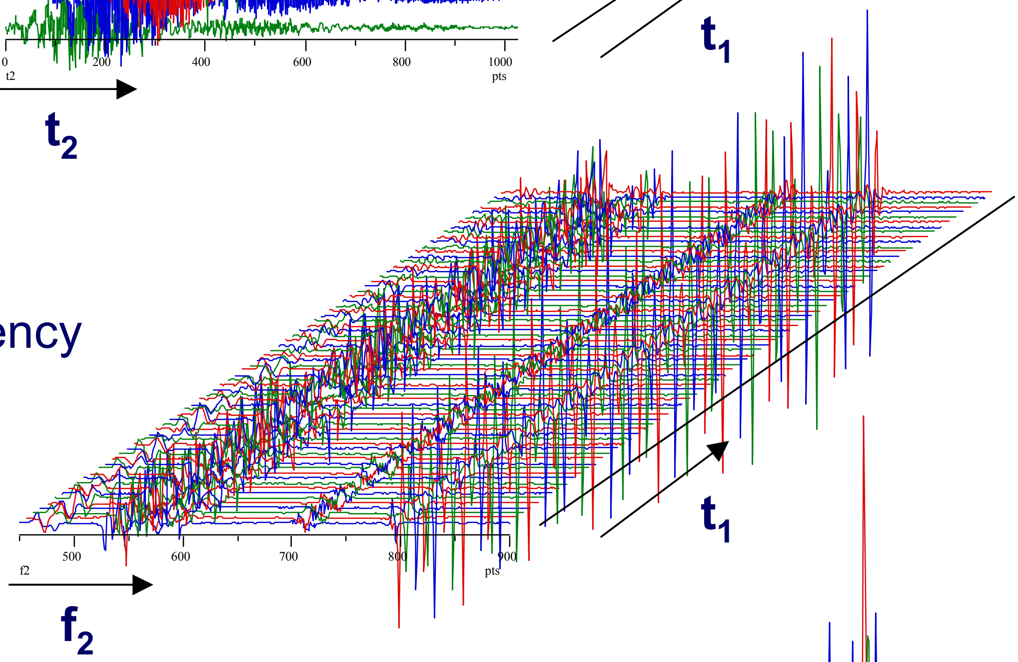
The same with some real data

- This is data from a COSY of pulegone...

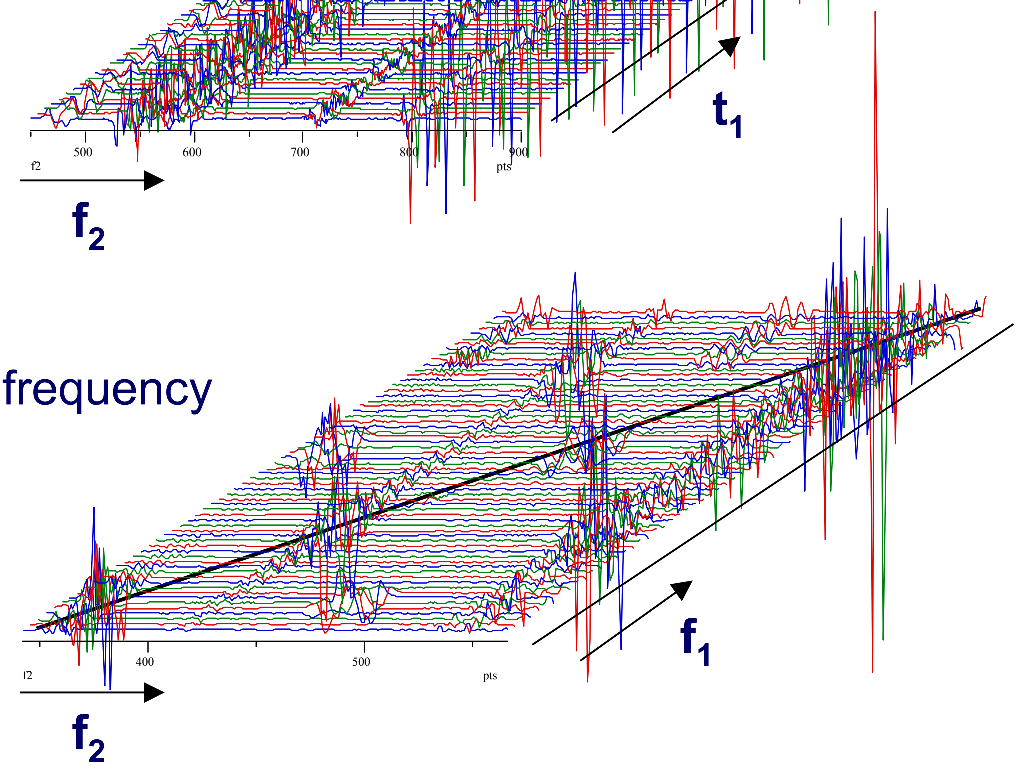
time - time



time - frequency

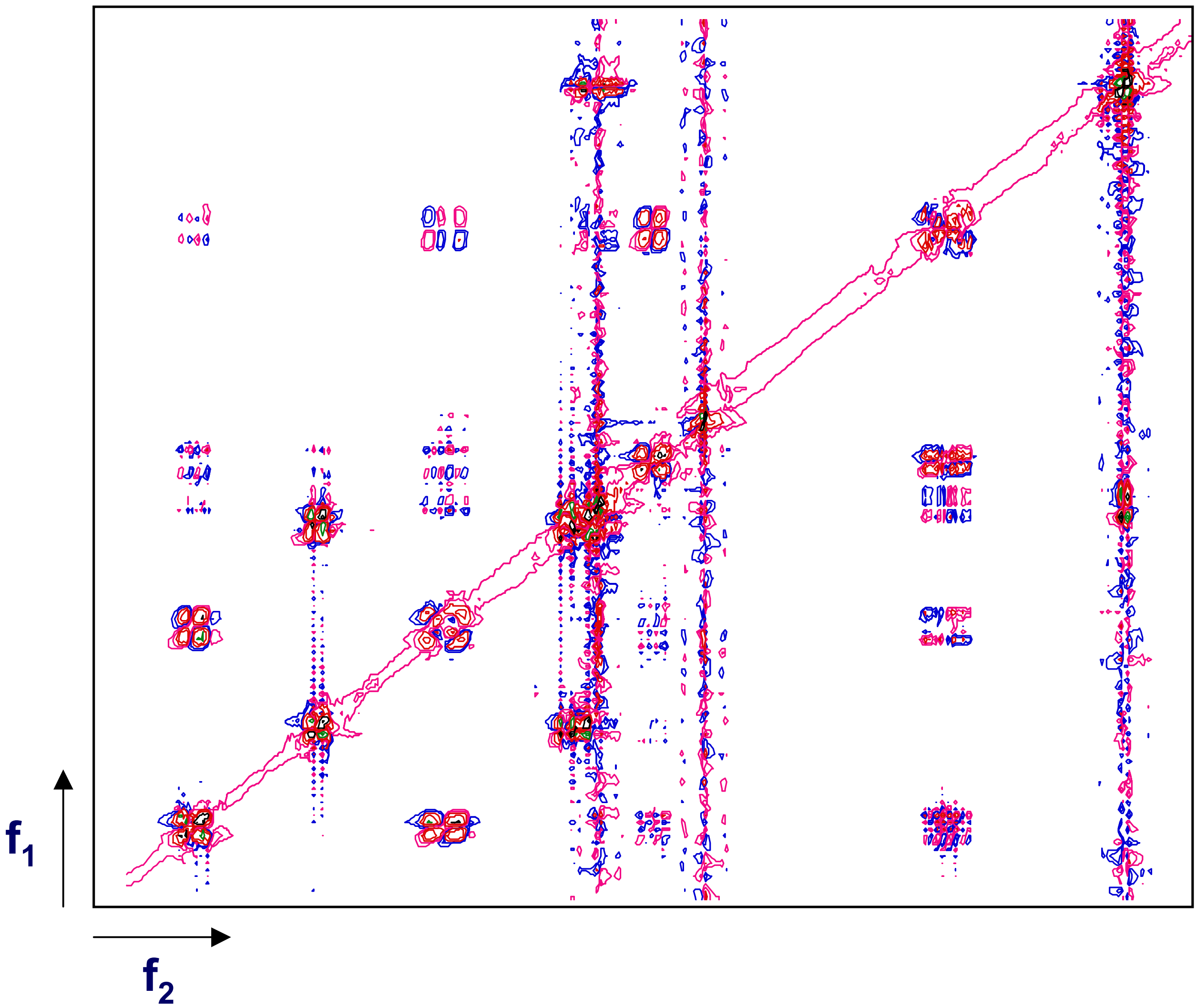


frequency - frequency



The same with some real data

• Now the ***contour-plot*** showing all the ***cross-peaks***:



• OK, were the heck did all the ***off-diagonal*** peaks came from, and what do they mean?

• I’ll do the best I can to explain it, but again, there will be several black-box events. We really need a mathematical description to explain COSY rigorously.

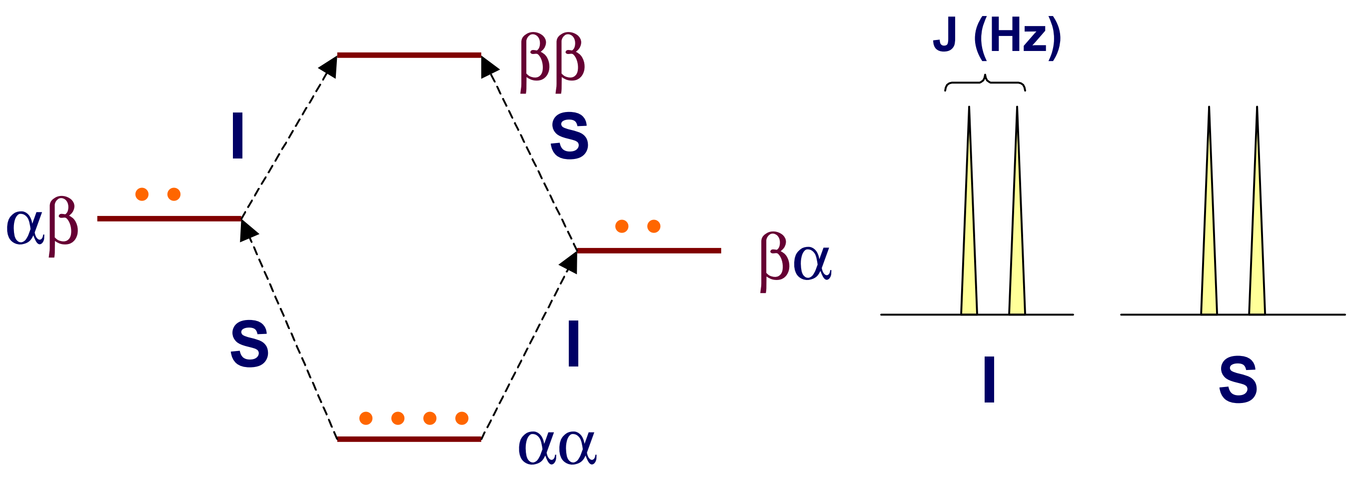
Homonuclear correlation - COSY

- ***COSY*** stands for ***COrrelation SpectroscopY***, and for this particular case in which we are dealing with homonuclear couplings, ***homonuclear correlation spectroscopy***.

- In our development of the 2D idea we considered an isolated spin not coupled to any other spin. Obviously, this is not really useful.

- What COSY is good for is to tell which spin is connected to which other spin. The off-diagonal peaks are this, and they indicate that those two peaks in the diagonal are coupled.

- With this basic idea we'll try to see the effect of the COSY $\mathbf{90_y - t_1 - 90_y - t_1}$ pulse sequence on a pair of coupled spins. If we recall the 2 spin-system energy diagram:



- We see that if we are looking at **I** and apply both **π / 2** pulses, (a pseudo **π** pulse) we will invert some of the population of spin **S**, and this will have an effect on **I** (polarization transfer).

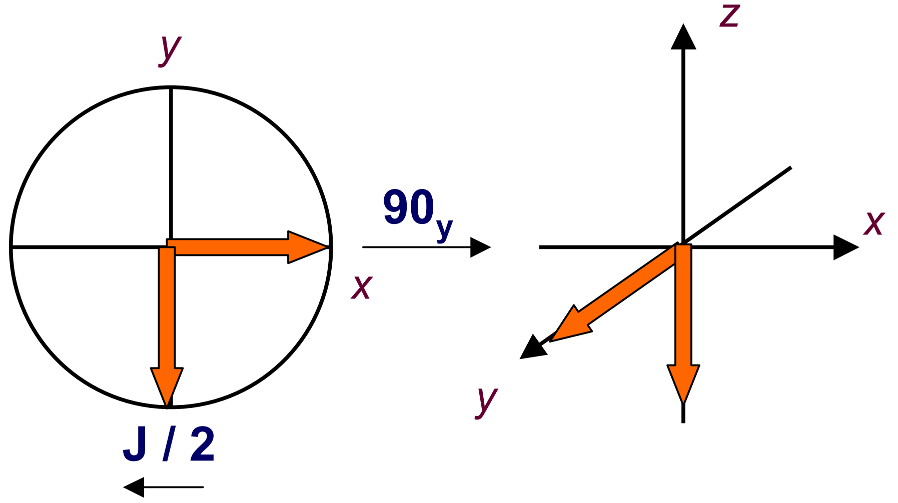
Homonuclear correlation (continued)

- Since the **I** to **S** or **S** to **I** polarization transfers are the same, we'll explain it for **I** to **S** and assume we get the same for **S** to **I**. We first perturb **I** and analyze what happens to **S**.

- After the first **π / 2**, we have the two **I** vectors in the x axis, one moving at ω_I **+ J / 2** and the other at ω_I **- J / 2**. The effect of the second pulse is that it will put the components of the magnetization aligned with **y** on the **-z** axis, which means a partial inversion of the **I** populations.

- For **t_1 = 0**, we have complete inversion of the **I** spins (it is a π pulse and the signal intensity of **S** does not change. For all other times we will have a change on the **S** intensity that depends periodically on the resonance frequency of **I**.

- The variation of the population inversion for **I** depends on the cosine (or sine) of its resonance frequency. Considering that we are on-resonance with one of the lines and if **t_1 = 1 / 4 J**:

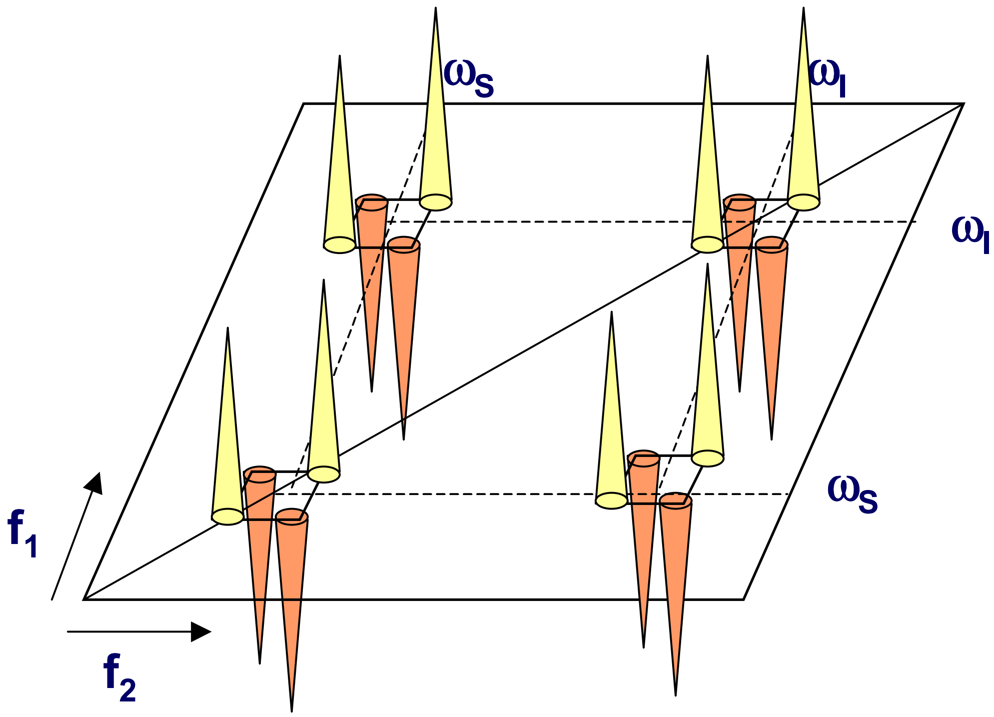


Homonuclear correlation (…)

- If we do it really general (nothing on-resonance), we would come to this relationship for the change of the **S** signal (after the **π / 2** pulse) as a function of the **I** resonance frequency and **J_{IS}** coupling:

$$A_S(t_1,t_2) = A_o * \sin(\omega_I * t_1) * \sin(J_{IS} * t_1) * \sin(\omega_S * t_2) * \sin(J_{IS} * t_2)$$

- After Fourier transformation on **t_1** and **t_2** , and considering also the **I** spin, we get:



- This is the typical pattern for a doublet in a ***phase-sensitive*** COSY. The sines make the signals dispersive in **f_1** and **f_2**.

Summary of COSY

- The 2D spectrum has cross peaks on the diagonal as well as off the diagonal.

- Everything is doubled, because we have **I** to **S** as well as **S** to **I** polarization transfer.

- Exactly on the diagonal we see the normal 1D spectrum. Off the diagonal we see all connected or coupled transitions.

Next class

- Heteronuclear correlation spectroscopy (HETCOR).

- Brief discussion on the mid-term assignment.