Advanced NMR & Imaging

Lecture 2: Principles of Magnetic Resonance Imaging

Bibliography for the Course

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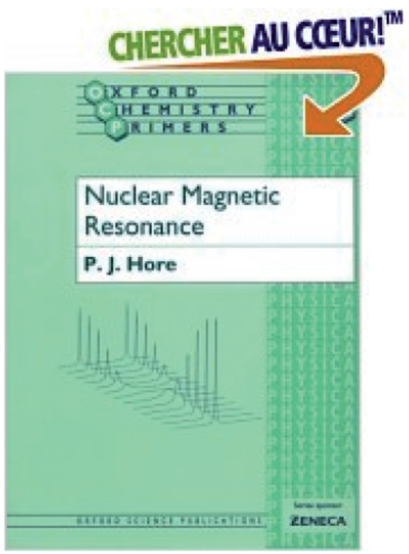
Bibliography for the Course



Nuclear Magnetic Resonance (Broché)

de P. J. Hore (Auteur) "Molecules are inconveniently small-too small to be observed and studied directly ..." (plus)
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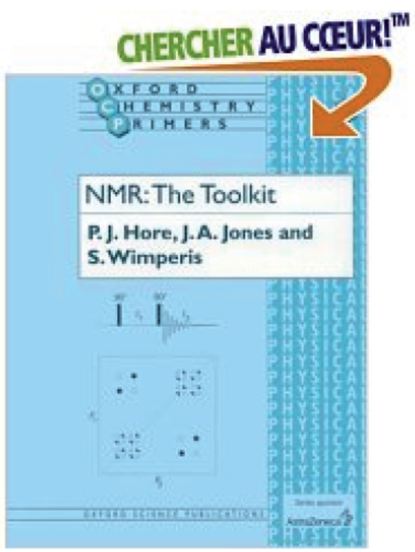

Nmr: The Toolkit (Broché)

de Peter Hore (Auteur), Jonathan Jones (Auteur), Stephen Wimperis (Auteur) "The so-called vector model of NMR spectroscopy is an essential weapon in the armoury of every practising NMR spectroscopist because it provides the sort of..." (plus)
Aucun commentaire client existant. Soyez le premier.

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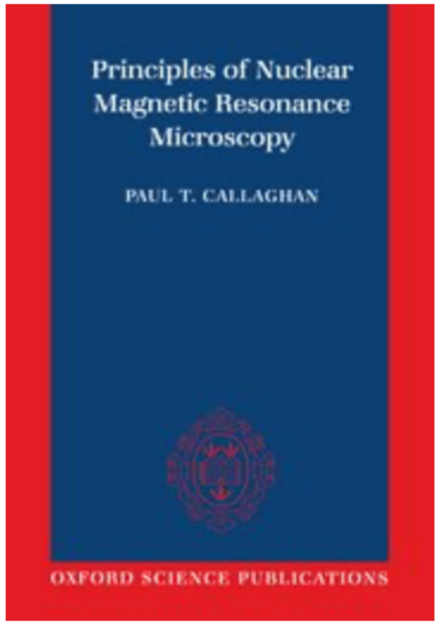
Bibliography for the Course

for magnetic resonance imaging



Principles of Nuclear Magnetic Resonance Microscopy

The late Paul T. Callaghan

Clarendon Press

This highly successful book, details the underlying principles behind the use of magnetic field gradients to image molecular distribution and ...

and many, many, many other textbooks and internet based resources….

Objectives

- Understand how NMR spectra can reflect spatial distributions
- Understand the role of magnetic field gradients
- Understand the notion of inverse (k) space and how to acquire image data in several dimensions

The Zeeman Effect

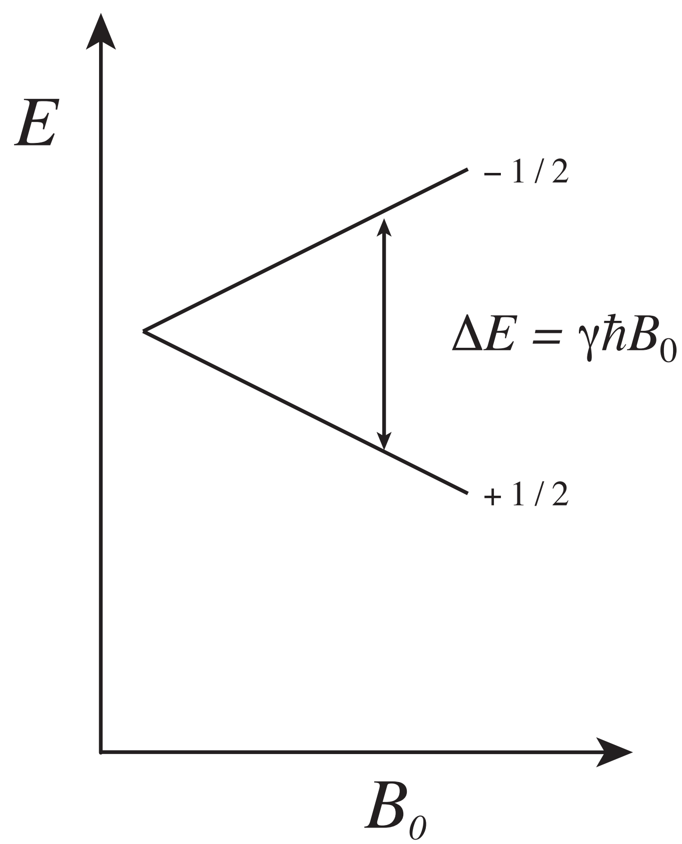
The NMR experiment consists in putting a sample in a magnetic field and observing the consequent transitions between energy levels of the nucleus whose degeneracy is lifted by the field.

The property is (nuclear) SPIN (quantum number m), and m can take values

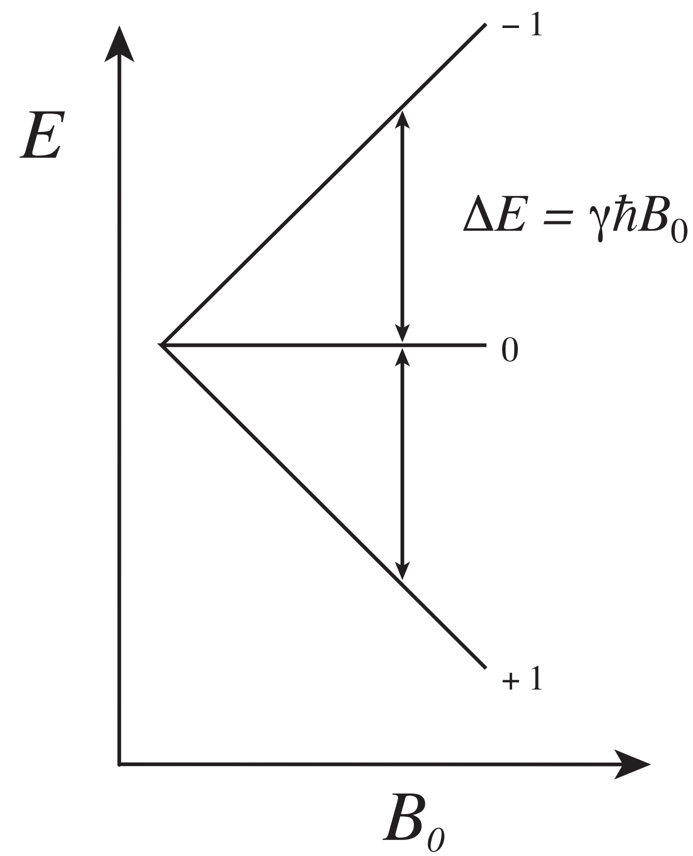
0, 1/2, 1, 3/2, 2, 5/2 ....

The Zeeman Effect

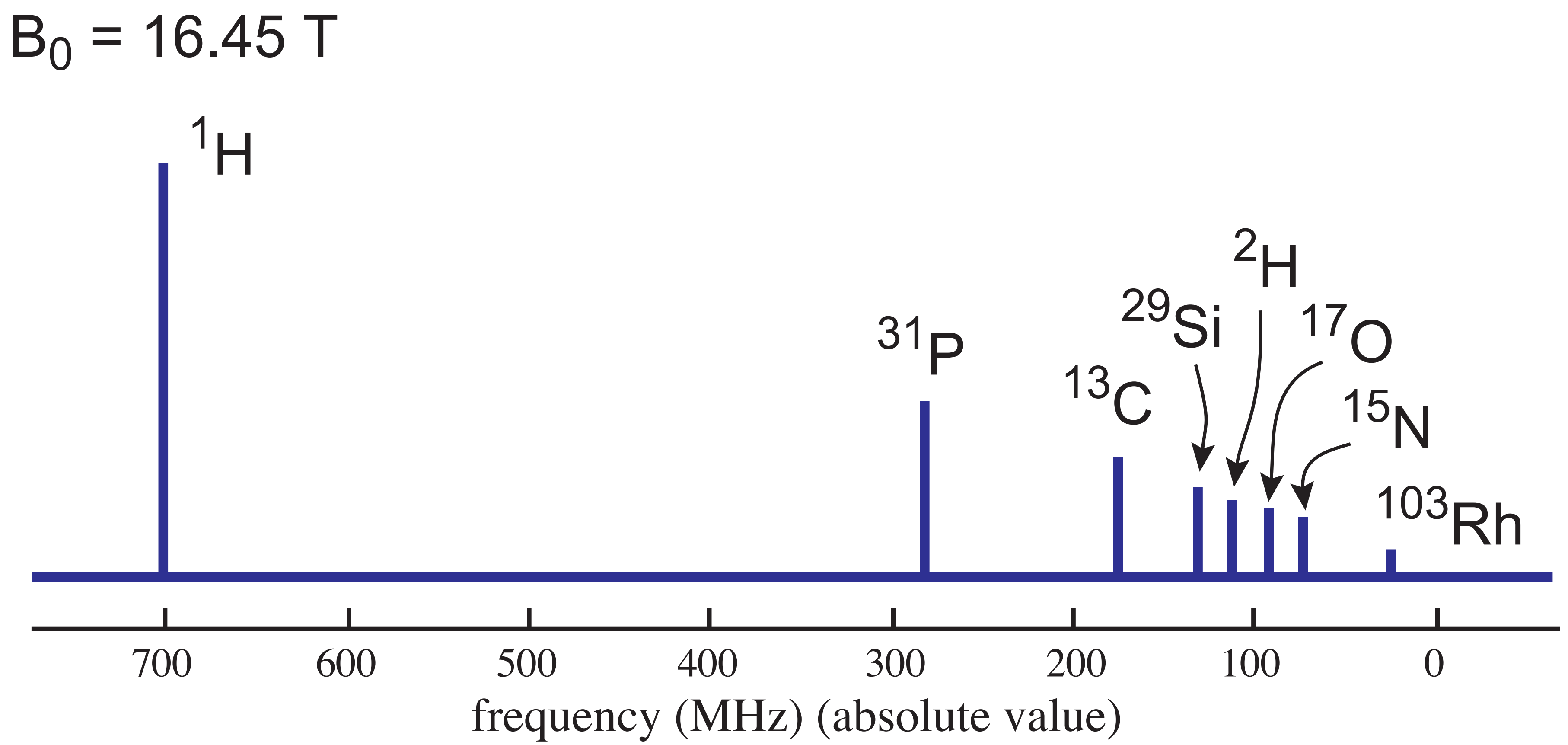
spin *I* = 1/2



spin *I* = 1



The Zeeman Effect

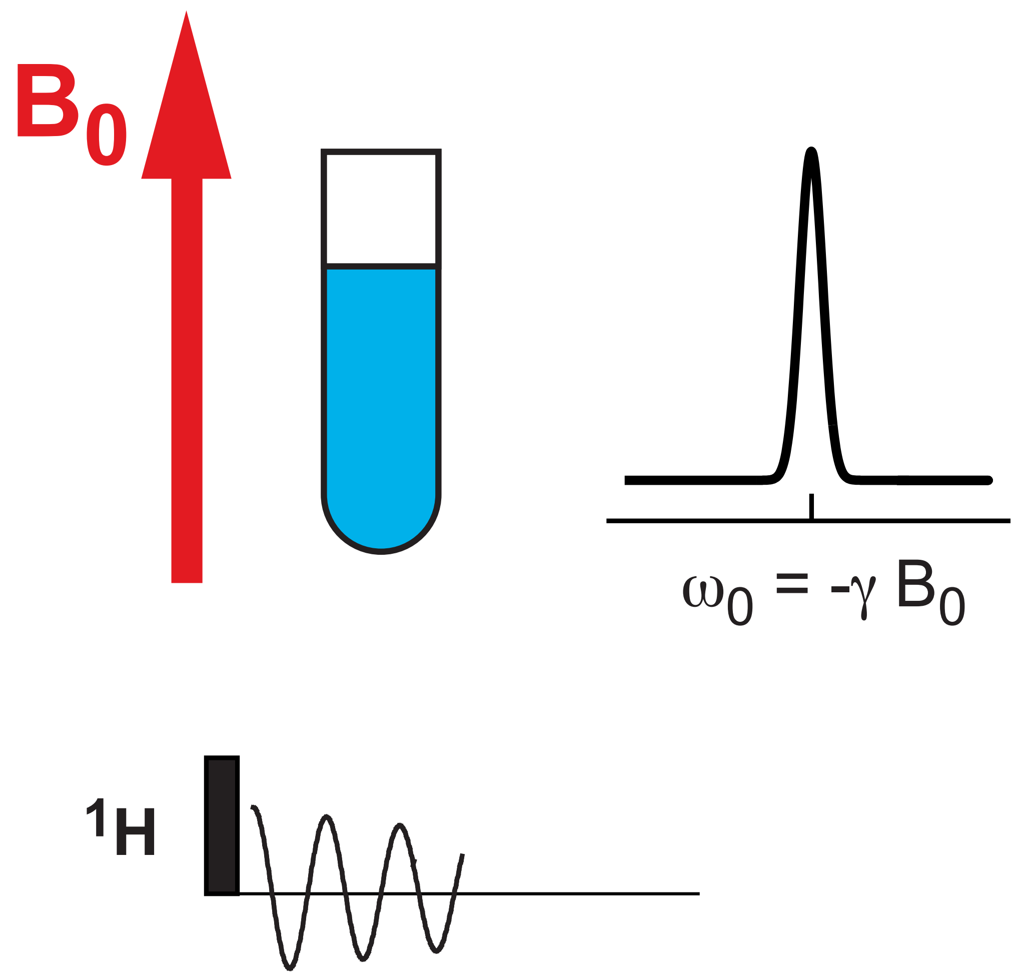


The Larmor Theorem states that the motion of a magnetic moment in a magnetic field (B_0) is a precession around that field at a frequency

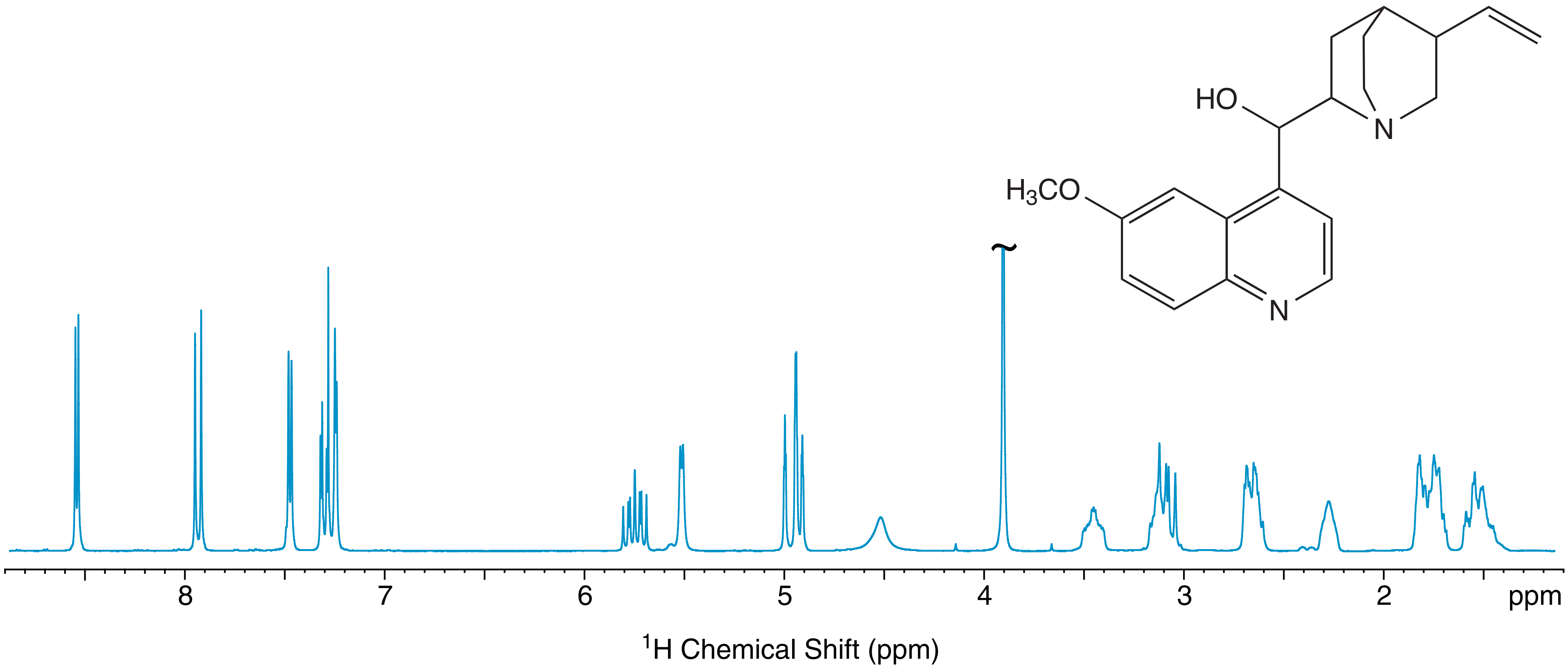
$$\omega_0 = -\gamma B_0$$

Principles of Magnetic Resonance Imaging

Spectroscopy



Principles of Magnetic Resonance Imaging

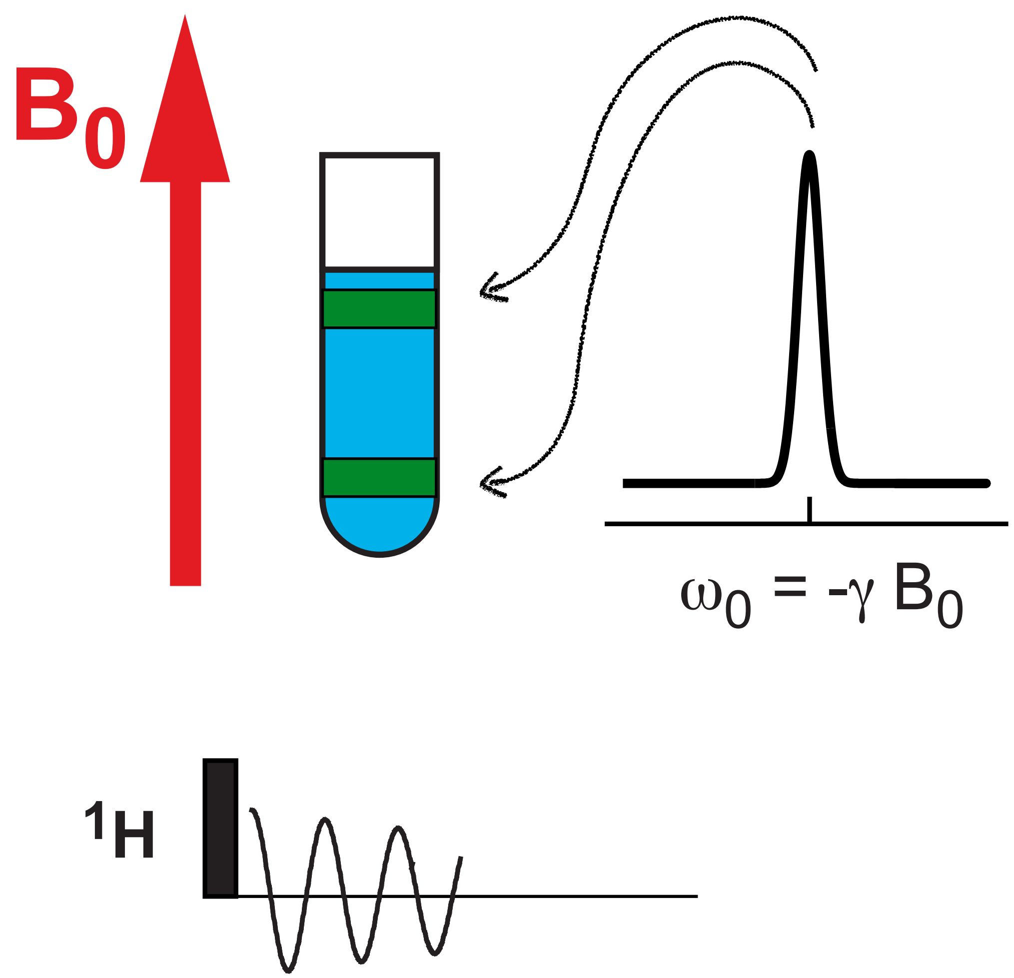


In spectroscopy, we adjust the homogeneity of the magnetic field so that all the molecules in the whole sample experience exactly the same field to within < 1 Hz (0.002 ppm).

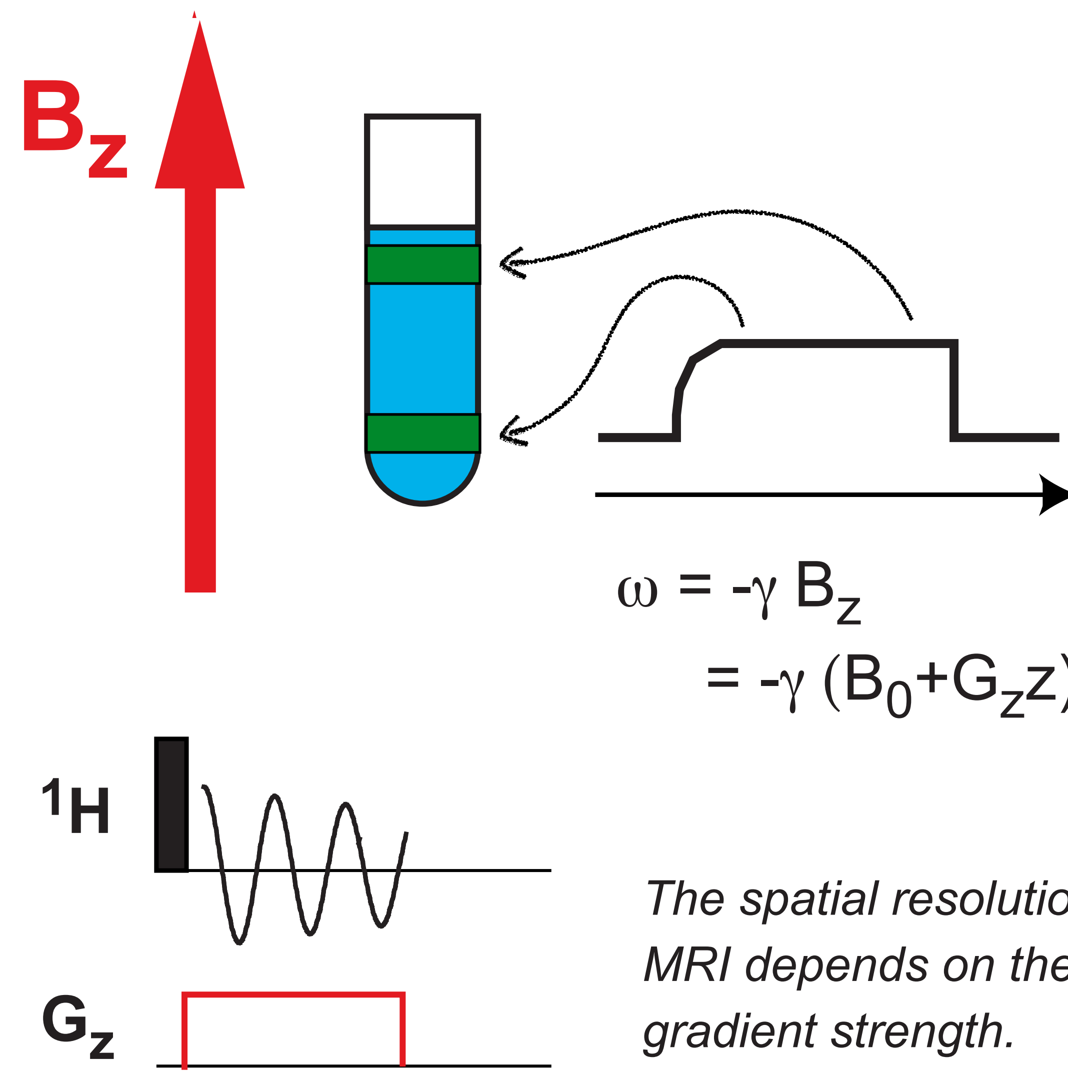
This allows resolution of very small differences in resonance frequencies, due to different shielding of different nuclei by their electrons (chemical shifts), or due to the spin states of other nearby nuclei (J-couplings).

Principles of Magnetic Resonance Imaging

Spectroscopy



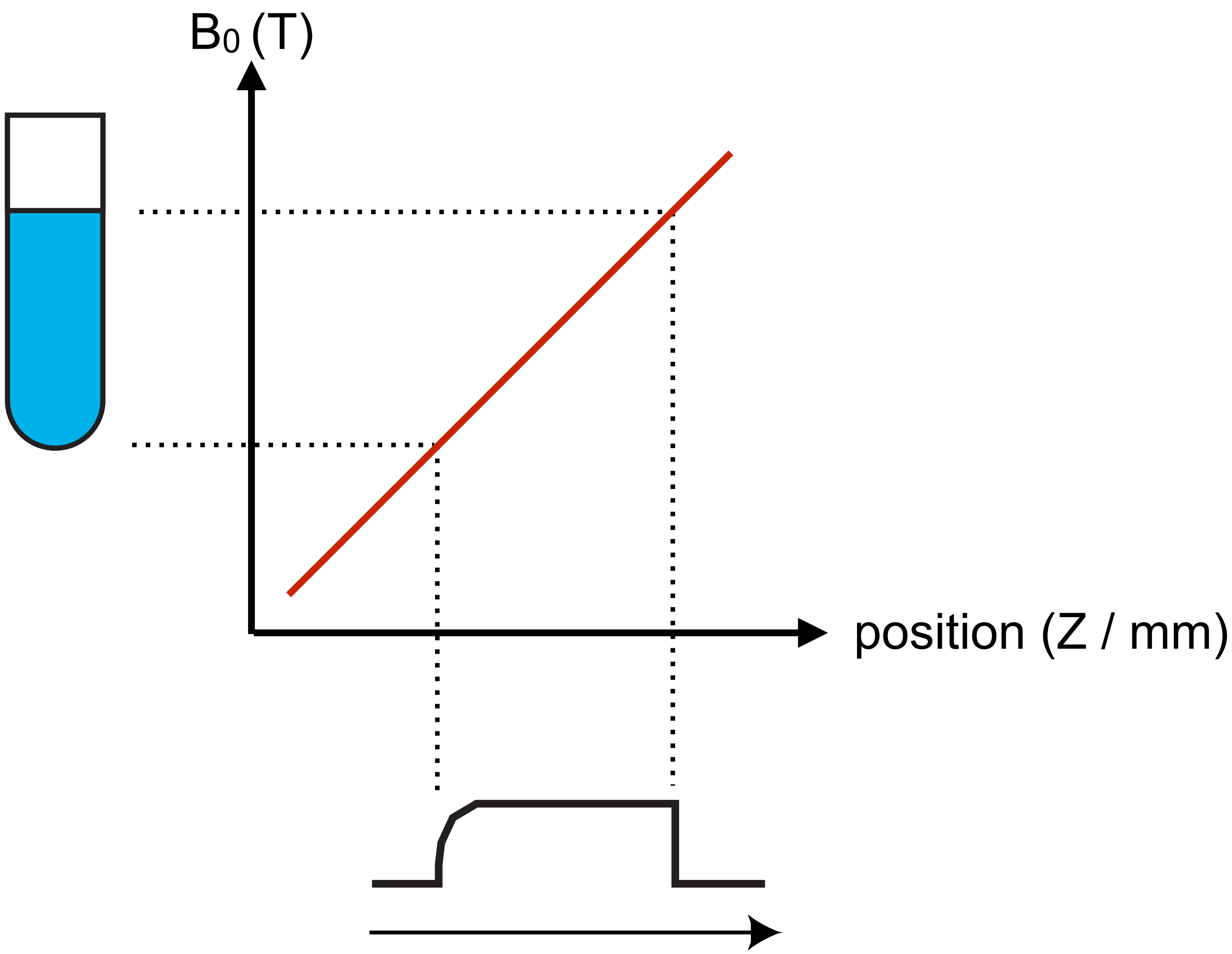
1D-Imaging (profile)



The spatial resolution in MRI depends on the gradient strength.

In imaging, we adjust the applied magnetic field to deliberately create a magnetic field gradient along a given spatial direction so that the molecules in the sample have a resonance frequency that is related to their position.

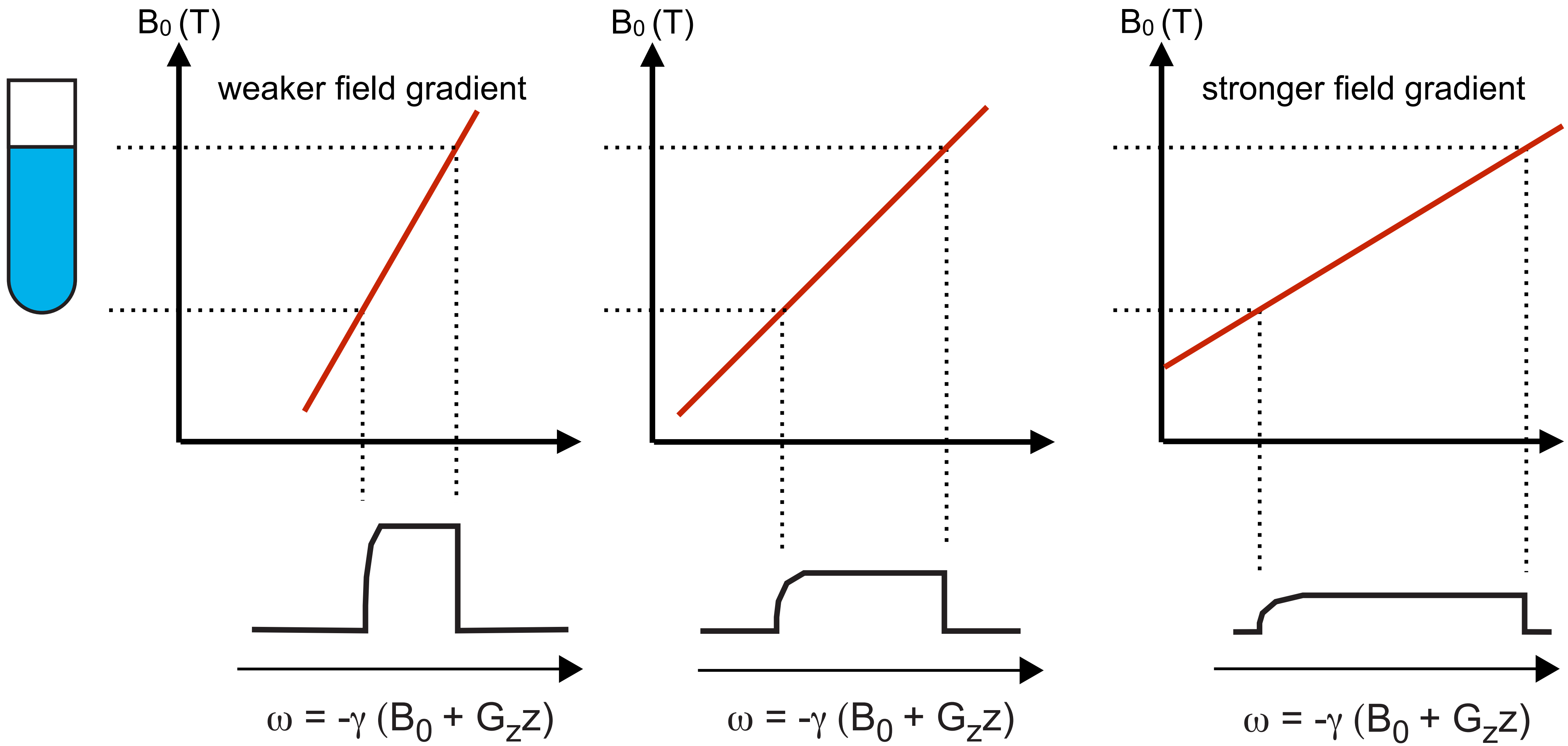
Principles of Magnetic Resonance Imaging



$$\omega = -\gamma B_z$$
$$= -\gamma (B_0 + G_z z)$$

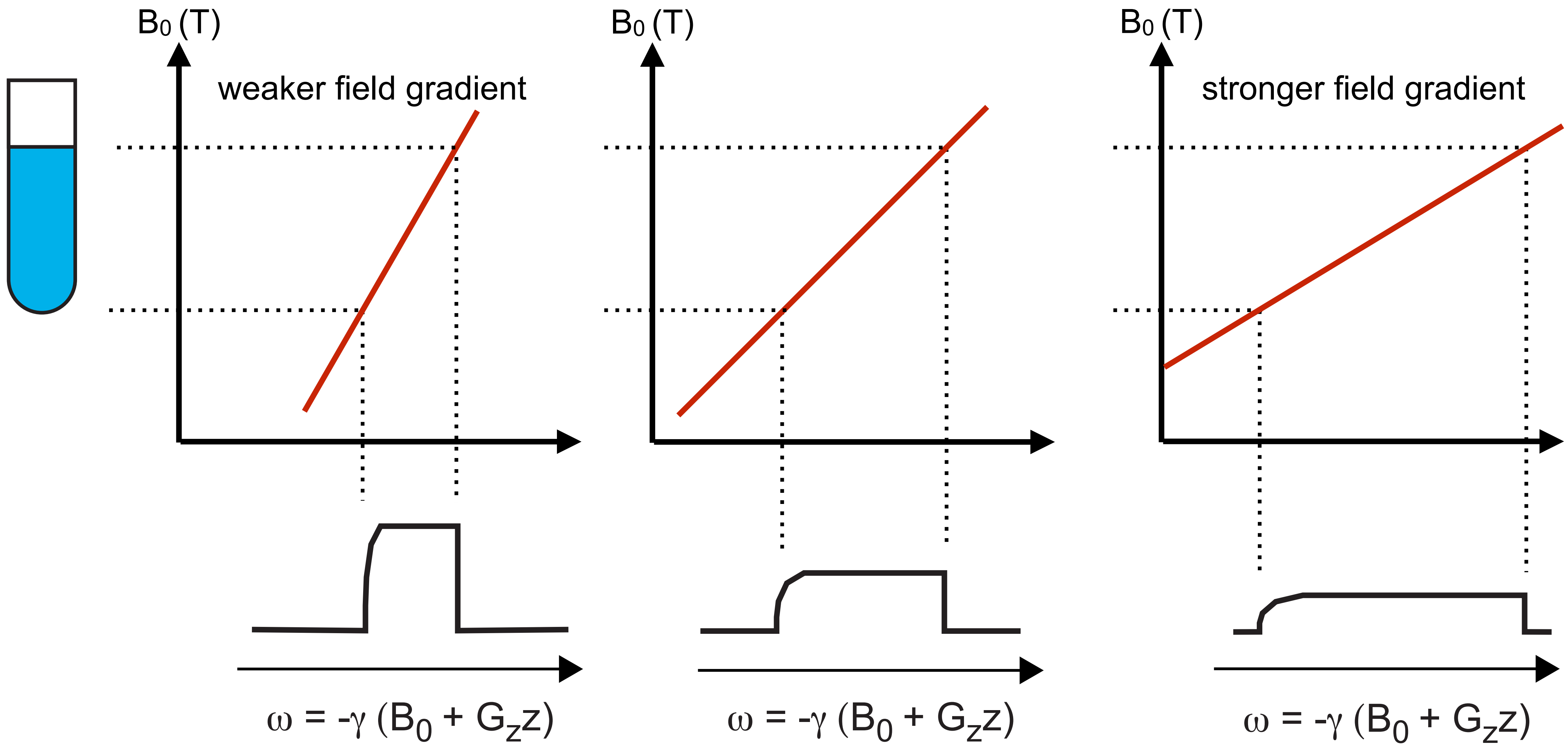
For a constant field gradient, the NMR spectrum for a given species (e.g. the ^{1}H in H_2O) will be the projection of the spin density of that species onto the axis of the gradient.

Principles of Magnetic Resonance Imaging



For a constant field gradient, the NMR spectrum for a given species (e.g. the [1]H in H_2O) will be the projection of the spin density of that species onto the axis of the gradient. The stronger the applied field gradient, the greater the spatial dispersion in Hz/mm. The stronger the applied field gradient, the weaker the signal (the total integrated signal integral is proportional to the number of spins in the sample, and is a constant).

Principles of Magnetic Resonance Imaging

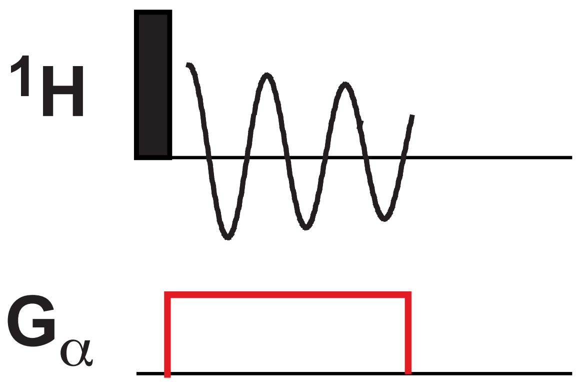


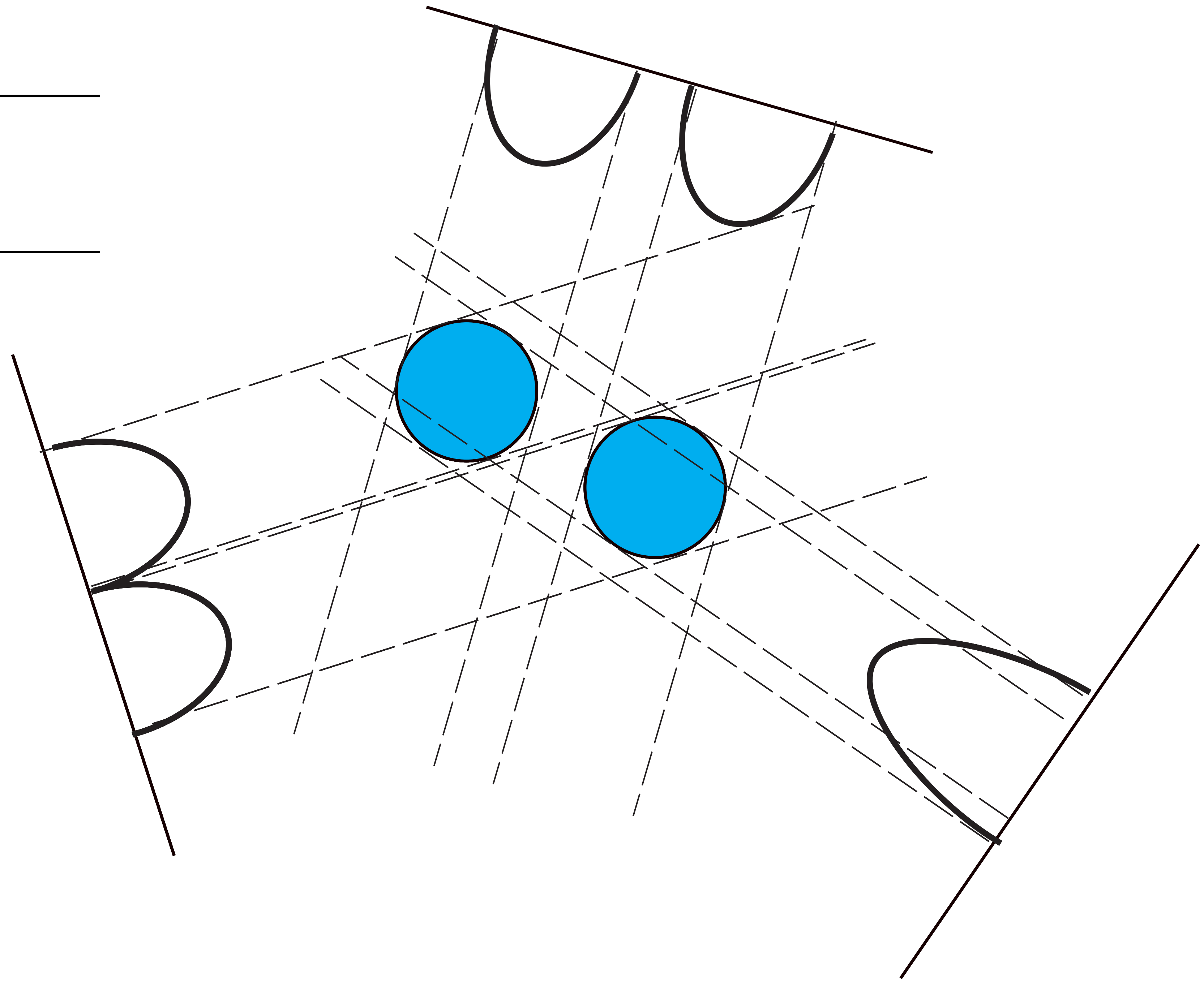
The maximum spatial resolution ρ in the image is given by the ratio between the intrinsic line width of the analyte (e.g. H_2O) Δ* in Hz and the dispersion induced by the gradient in Hz/mm d, $\rho = \Delta^* / d$.

For example, if the applied gradient induces 10 Hz/mm of dispersion, and the intrinsic line width is 1 Hz, then $\rho = 1 / 10 = 0.1$ mm.

Multi-Dimensional Imaging?

change the gradient direction: (i) projection reconstruction



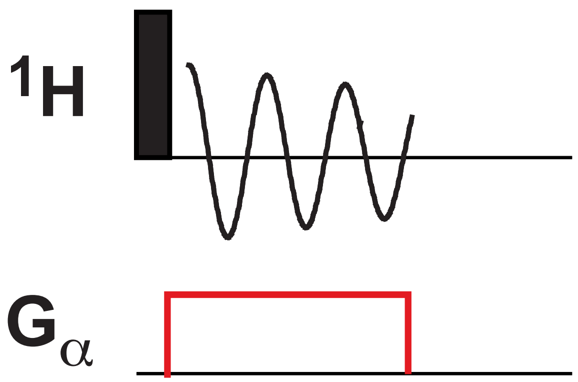


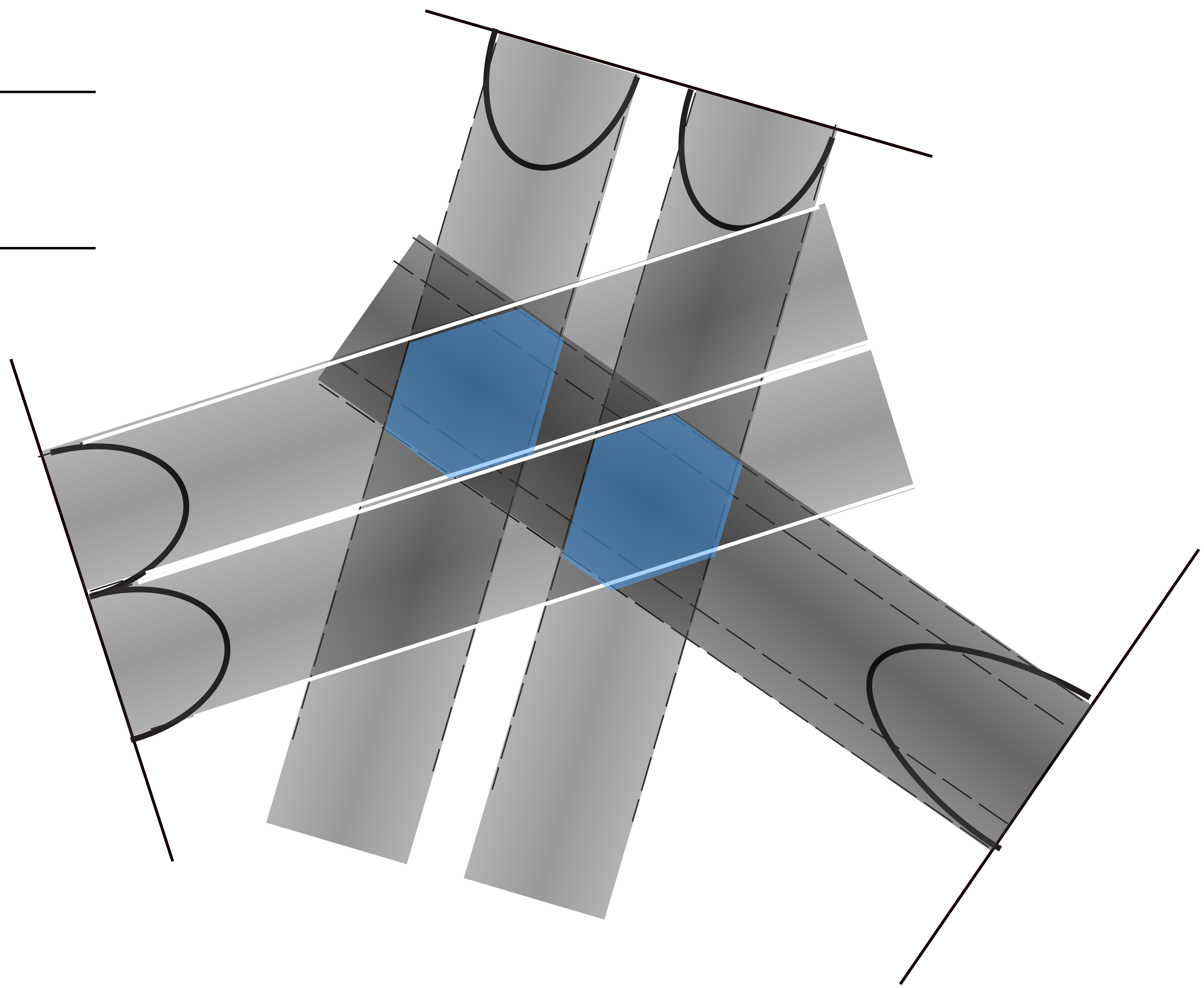
$$\omega = -\gamma B_\alpha$$

$$= -\gamma (B_0 + G_\alpha \alpha)$$

Multi-Dimensional Imaging?

change the gradient direction: (i) projection reconstruction

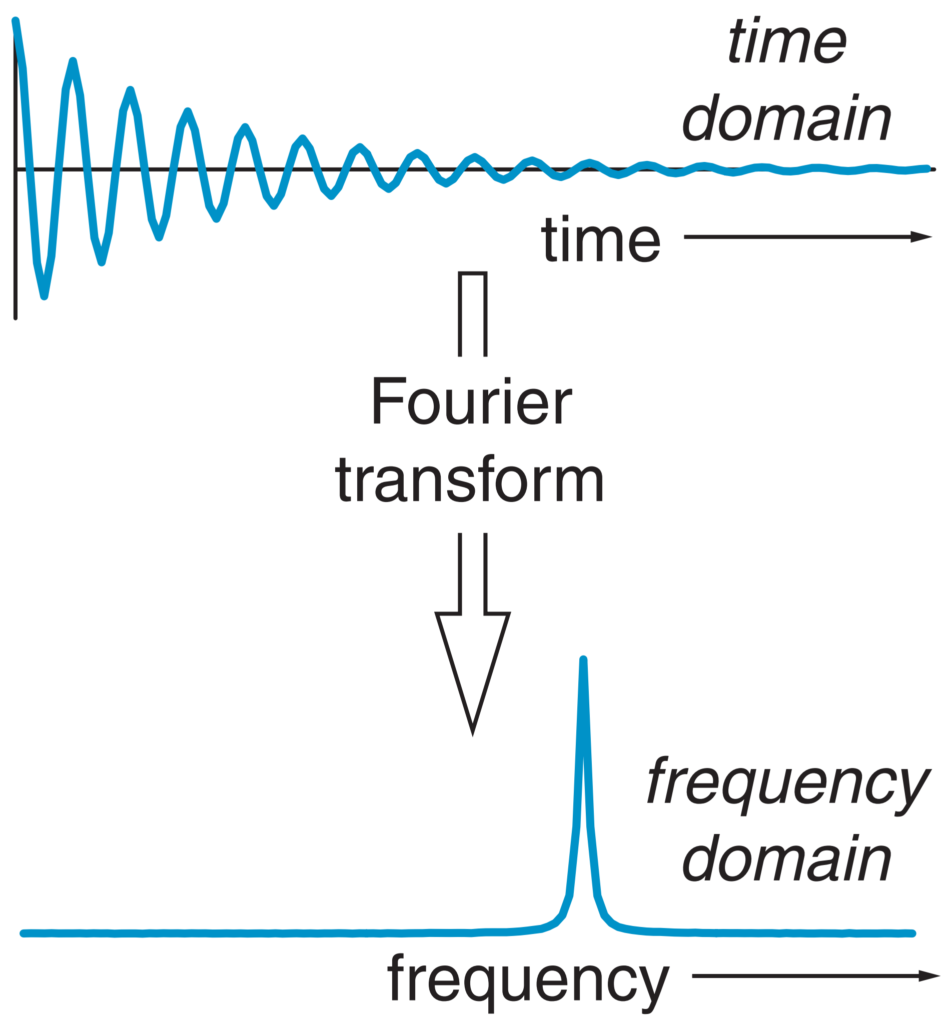




$\omega = -\gamma \, B_\alpha$

$= -\gamma \, (B_0 + G_\alpha \alpha)$

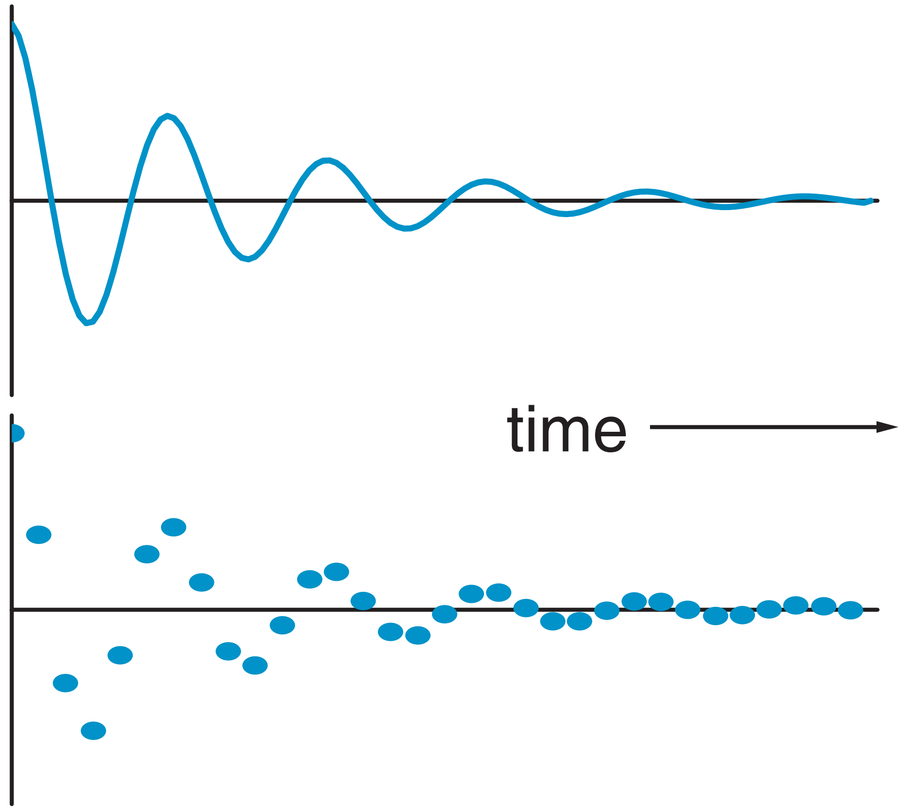
Fourier transform NMR: Time domain signals



$$I(\omega) = \int S(t)\exp\{-i\omega t\}dt$$

The Fourier transform is a mathematical process which turns a time-domain signal, the FID, into a frequency-domain signal, the spectrum.

How does the detection period work in the ordinary experiment?

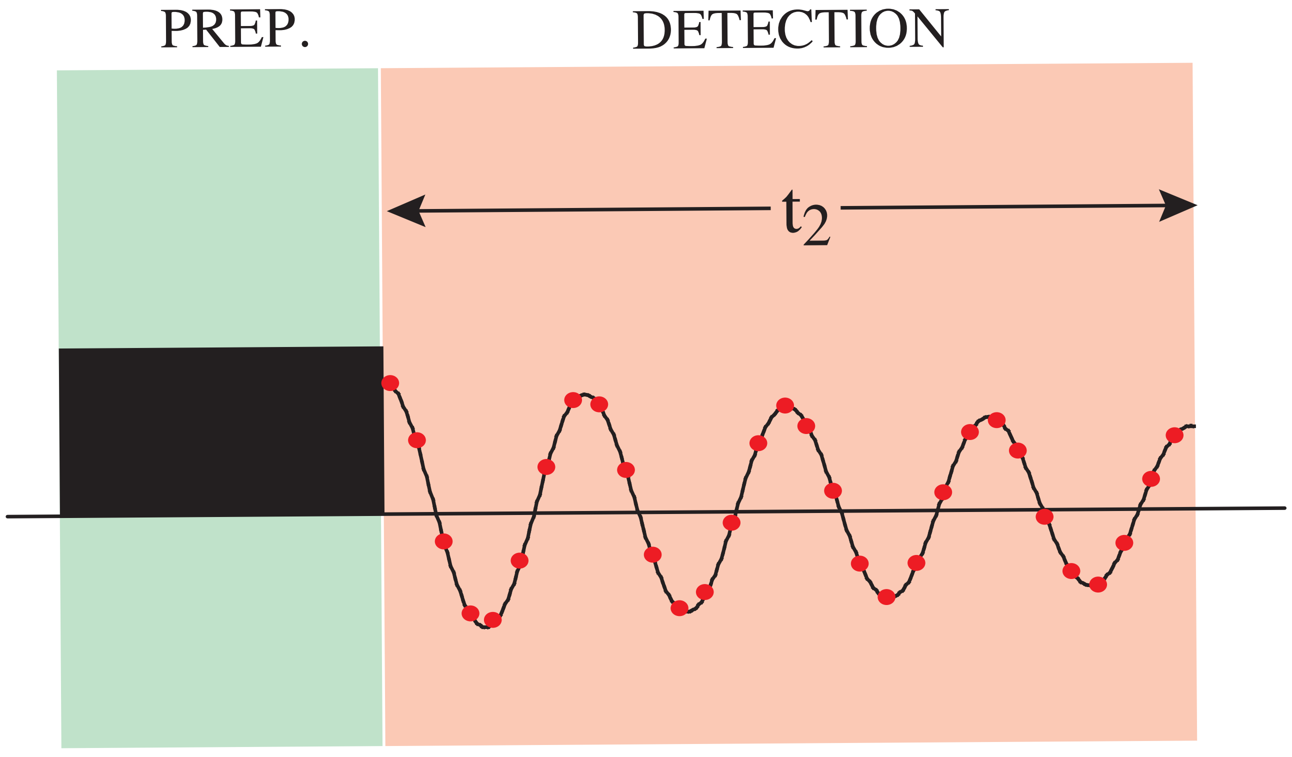


The amplitude of the FID varies as a function of time.

In order to be able to manipulate this time-domain signal in a computer, the signal is digitized at regular intervals.

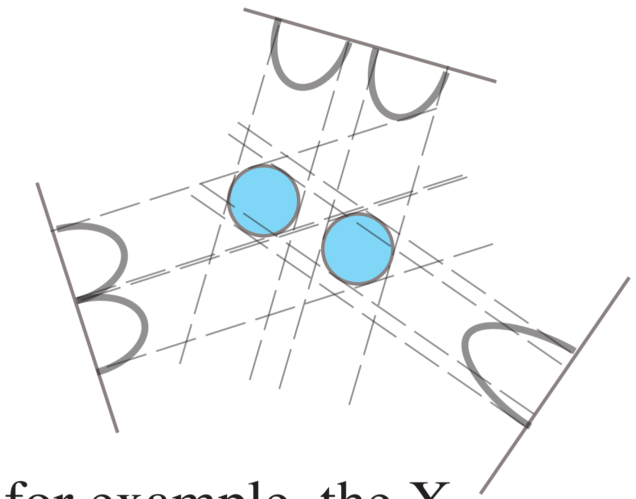
$$I(\omega) = \sum_{i=1}^{N} S(t_i)\exp\{-i\omega t_i\}dt$$

Time Domain Spectroscopy



Multi-Dimensional Imaging?

(i) Projection Reconstruction; k-space



The free induction decay during acquisition in presence of a gradient along, for example, the X direction, is given by

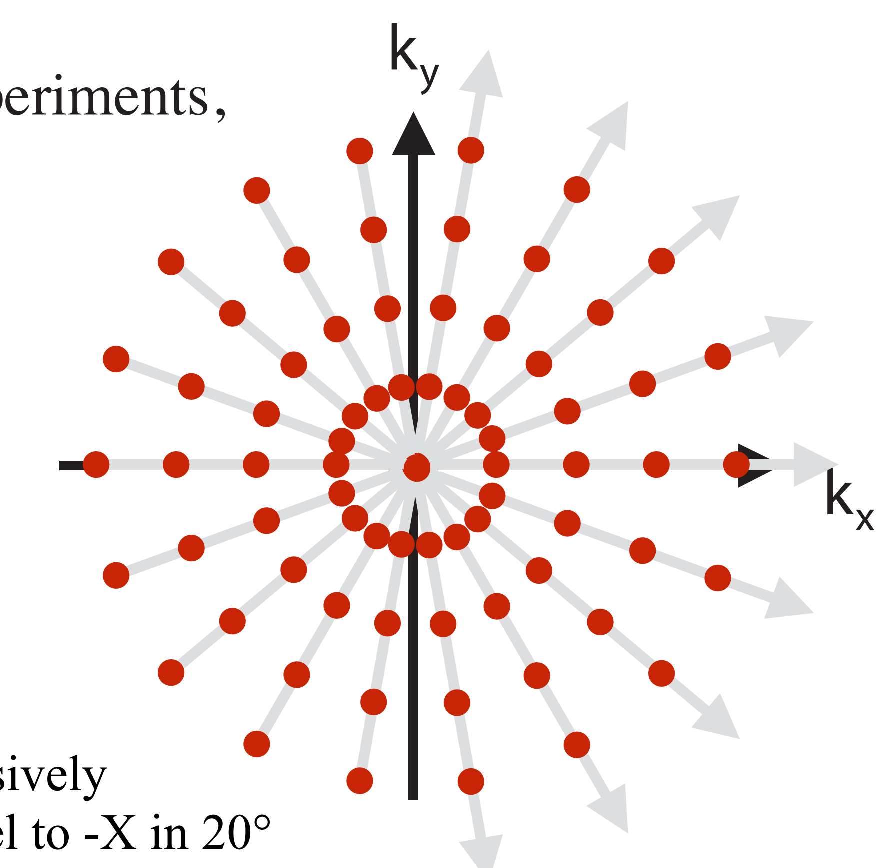
$$s(t_2) = \int \rho(X)\exp\{i\gamma X G_X t_2\}dX$$

where $G_X = dB_z/dX$ and we immediately see that the Fourier transform of the signal leads to a spectrum corresponding to a projection of the spin density onto the X axis.

We often talk about *k*-space (or reciprocal space) in imaging experiments, where the *k*-vector is given by $k_X = \gamma G_X t_2$. Then we have

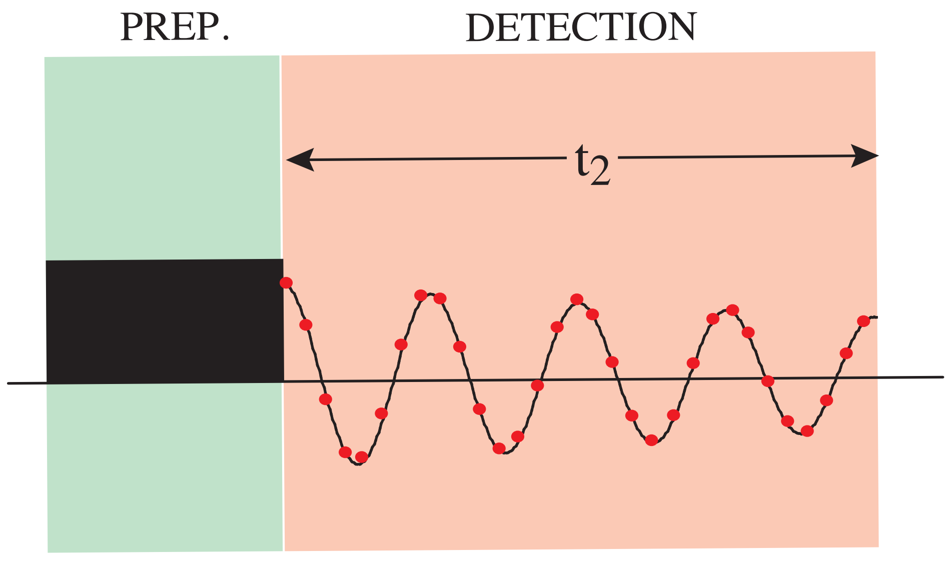
$$s(t_2) = \int \rho(X)\exp\{ik_X X\}dX \, .$$

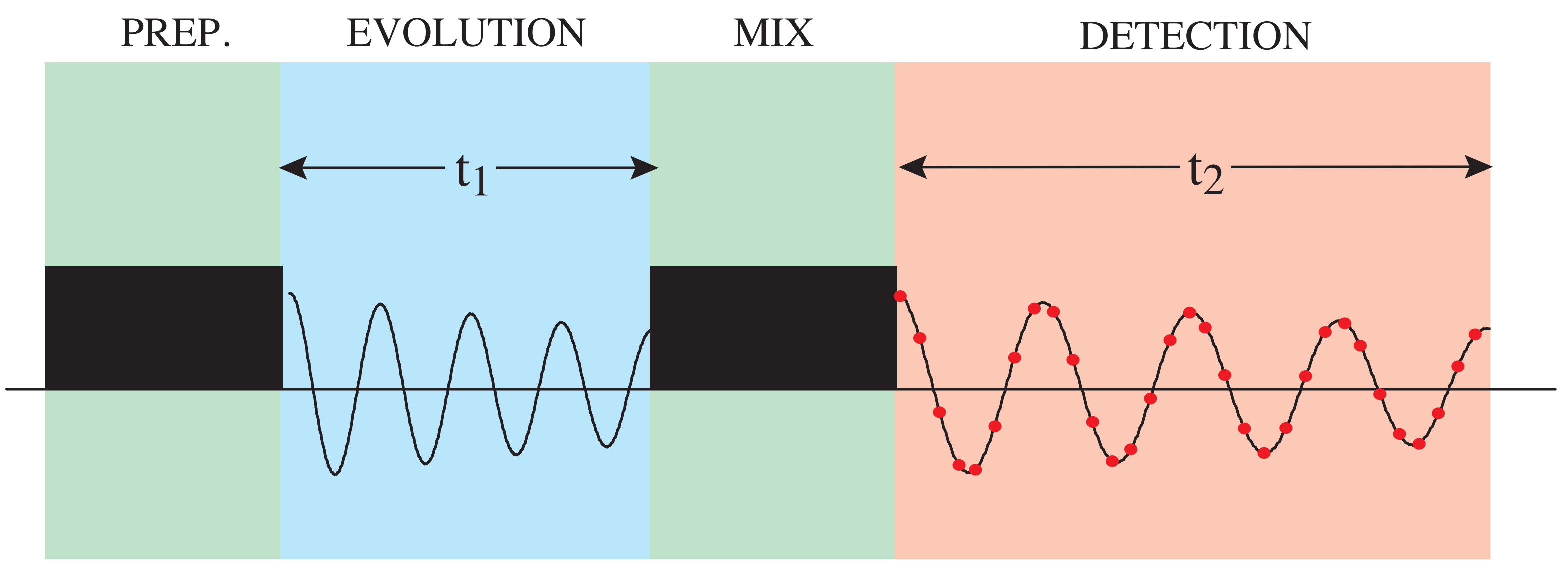
We can now look at the NMR signal in *k*-space. For projection reconstruction we find the following.



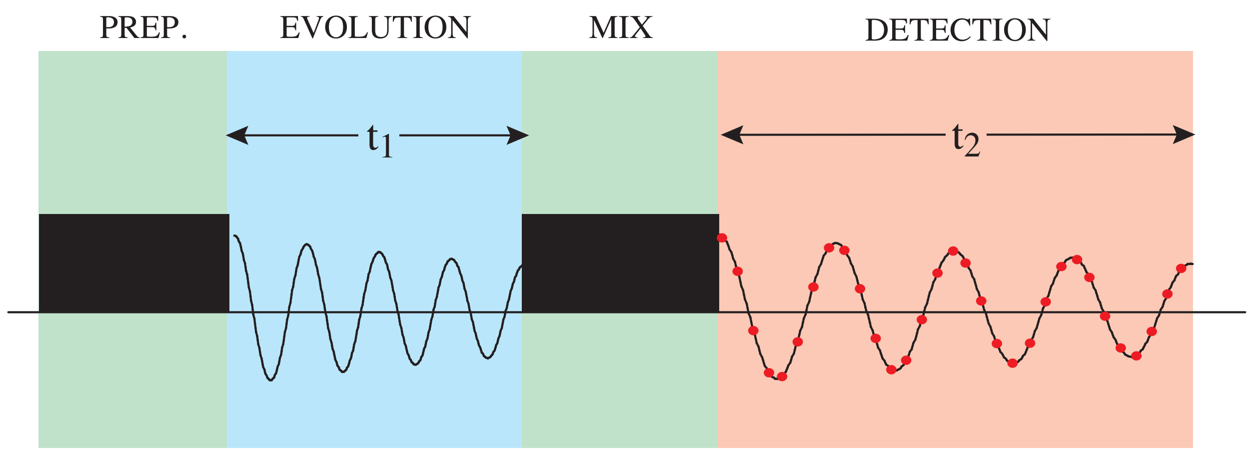
In this example, the experiment consists of acquiring 9 projections, progressively incrementing the gradient direction from being parallel to X to being parallel to -X in 20° steps

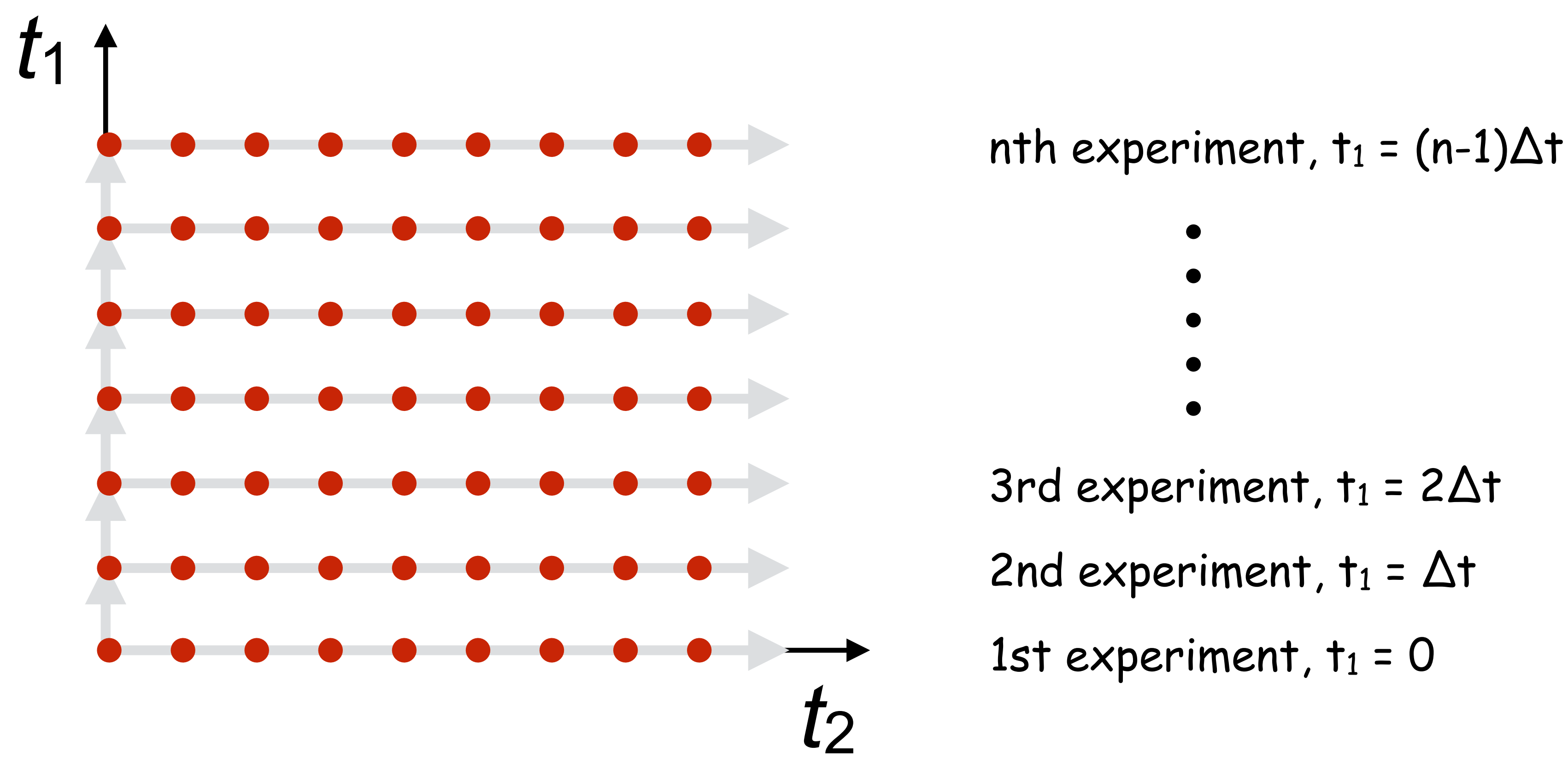
Principles of Multi-Dimensional Spectroscopy





Principles of Multi-Dimensional Spectroscopy

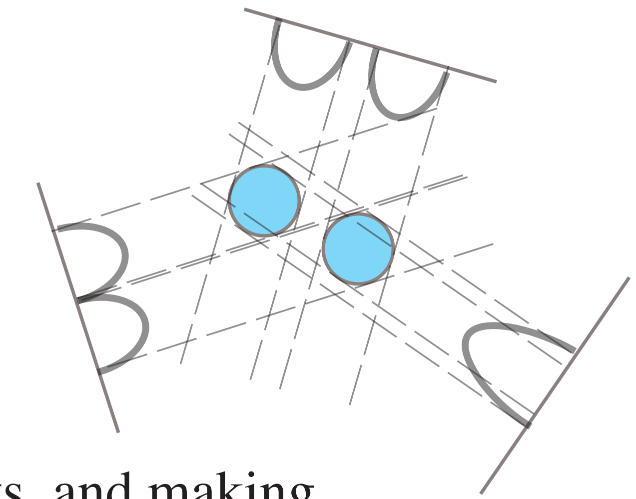




We can fill a two-dimensional time domain with data by repeating the experiment, with acquisition along t_2 in each experiment, and with t_1 being incremented progressively from one experiment to the next.

Multi-Dimensional Imaging?

(ii) Fourier Imaging



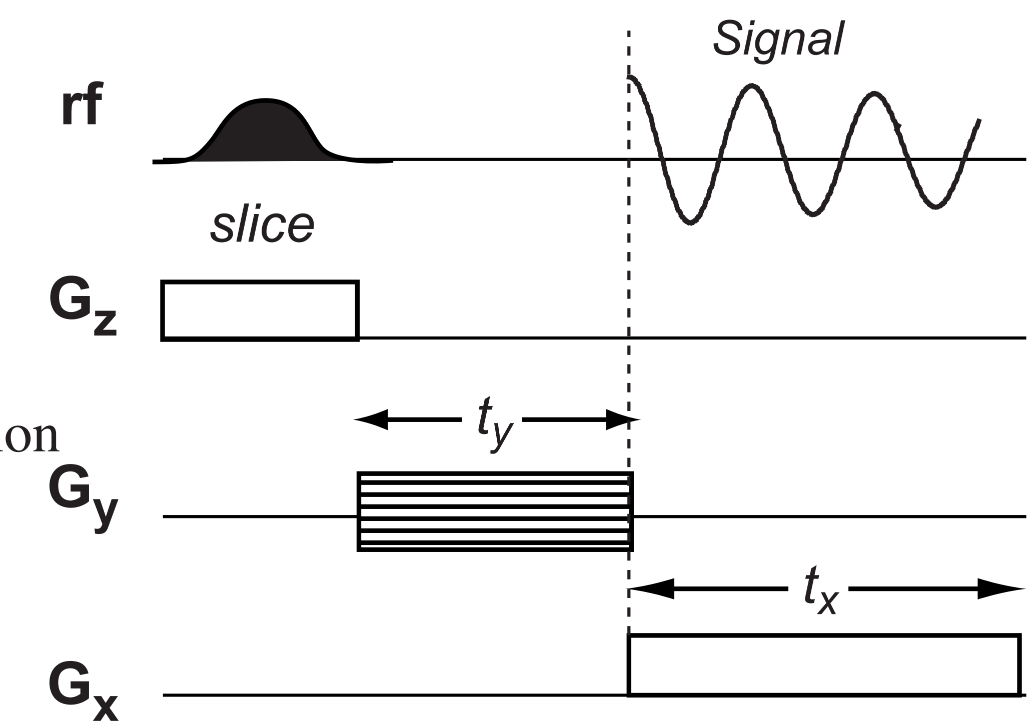
Projection reconstruction over samples the center part of k-space, inducing artifacts, and making processing complicated. However, from our experience of multi-dimensional spectroscopy, we should see that there is a much more straightforward way to sample k-space, which yields the following signal, with $k_X = \gamma G_X t_X$ and $k_Y = \gamma G_Y t_Y$:

$$s(k_X, k_Y) = \int \rho(X,Y) \exp\{i(k_X X + k_Y Y)\} dX dY$$

Double Fourier transform yields a two dimensional image along the gradient directions X and Y.

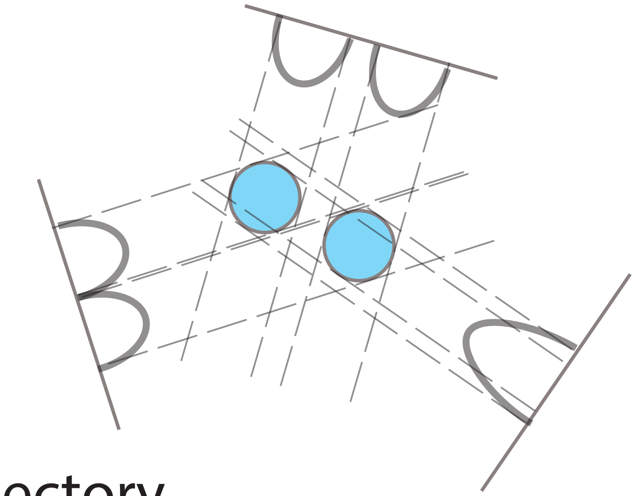
A full three-dimensional image could be obtained by acquisition along three gradient directions, X, Y, and Z, to yield a signal

$$s(k_X, k_Y, k_Z) = \int \rho(X,Y,Z) \exp\{i(k_X X + k_Y Y + k_Z Z)\} dX dY dZ.$$

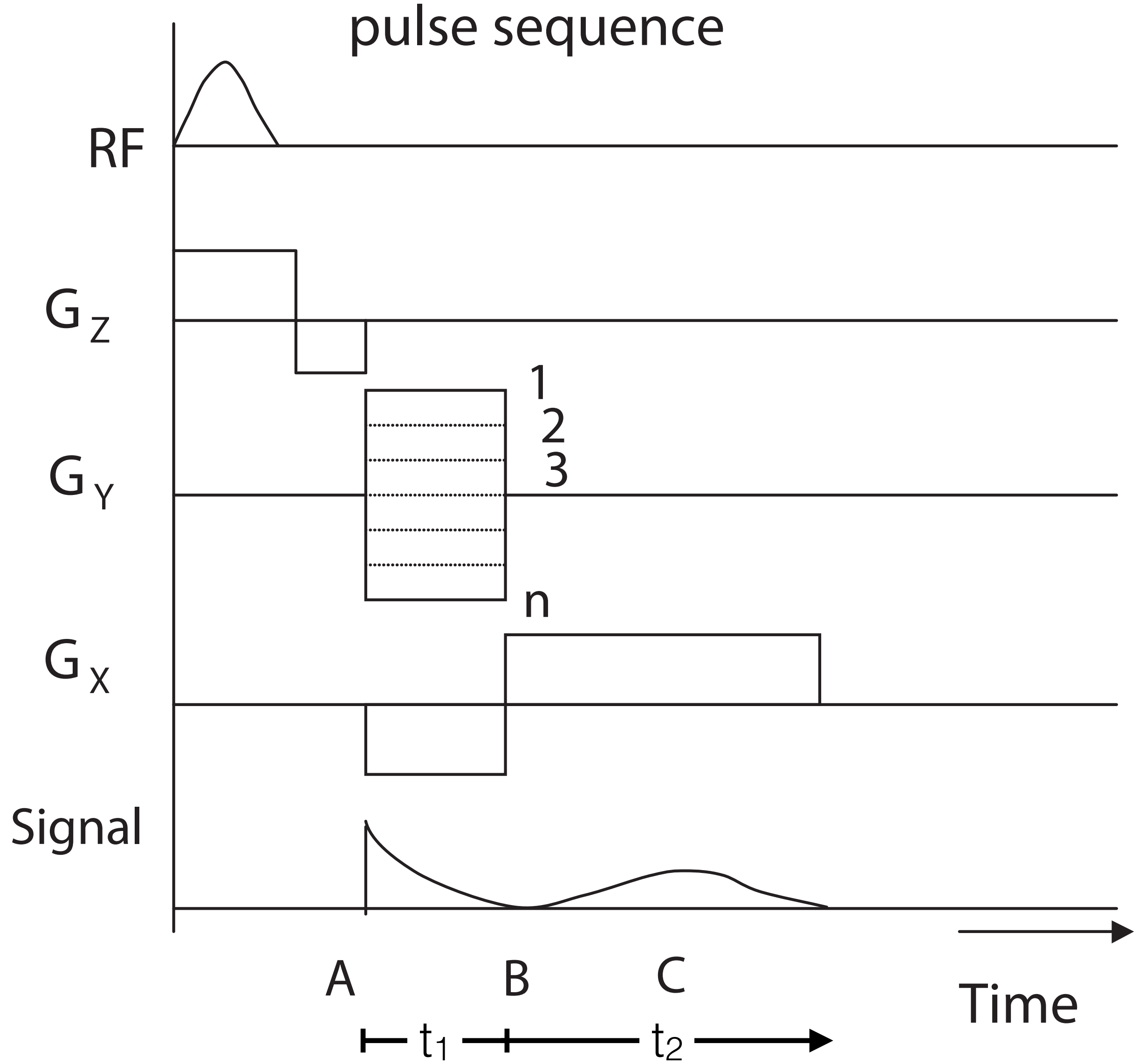


Multi-Dimensional Imaging?

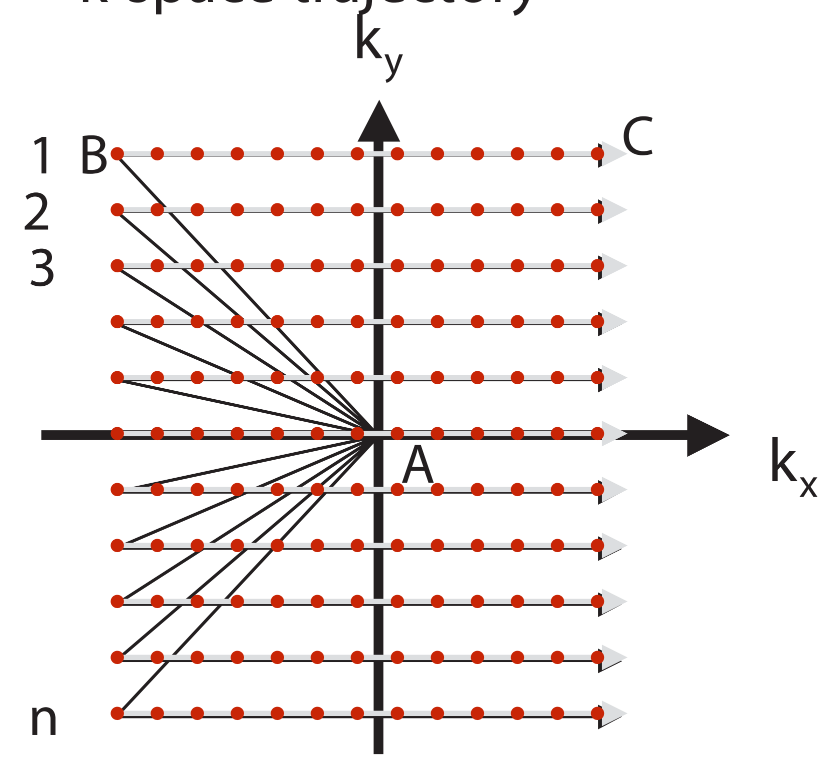
(ii) Fourier Imaging



Spin-warp
pulse sequence



Spin-warp
k-space trajectory



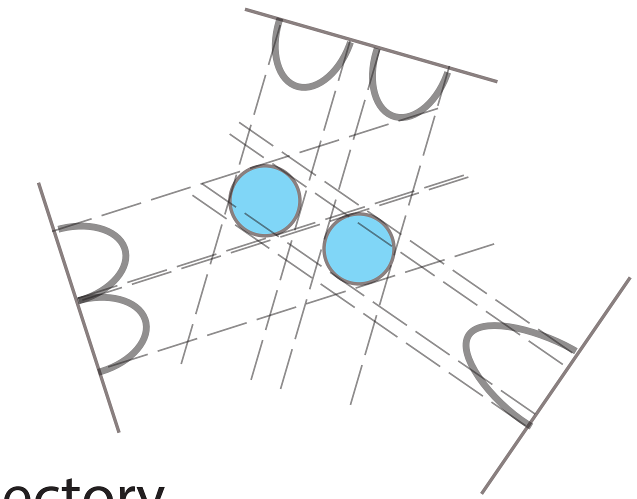
$k_x = \gamma(-G_X^{acq}\, t_1 + G_X^{acq}\, t_2)$

$k_y(n) = \gamma(G_Y^{n}\, t_1)$

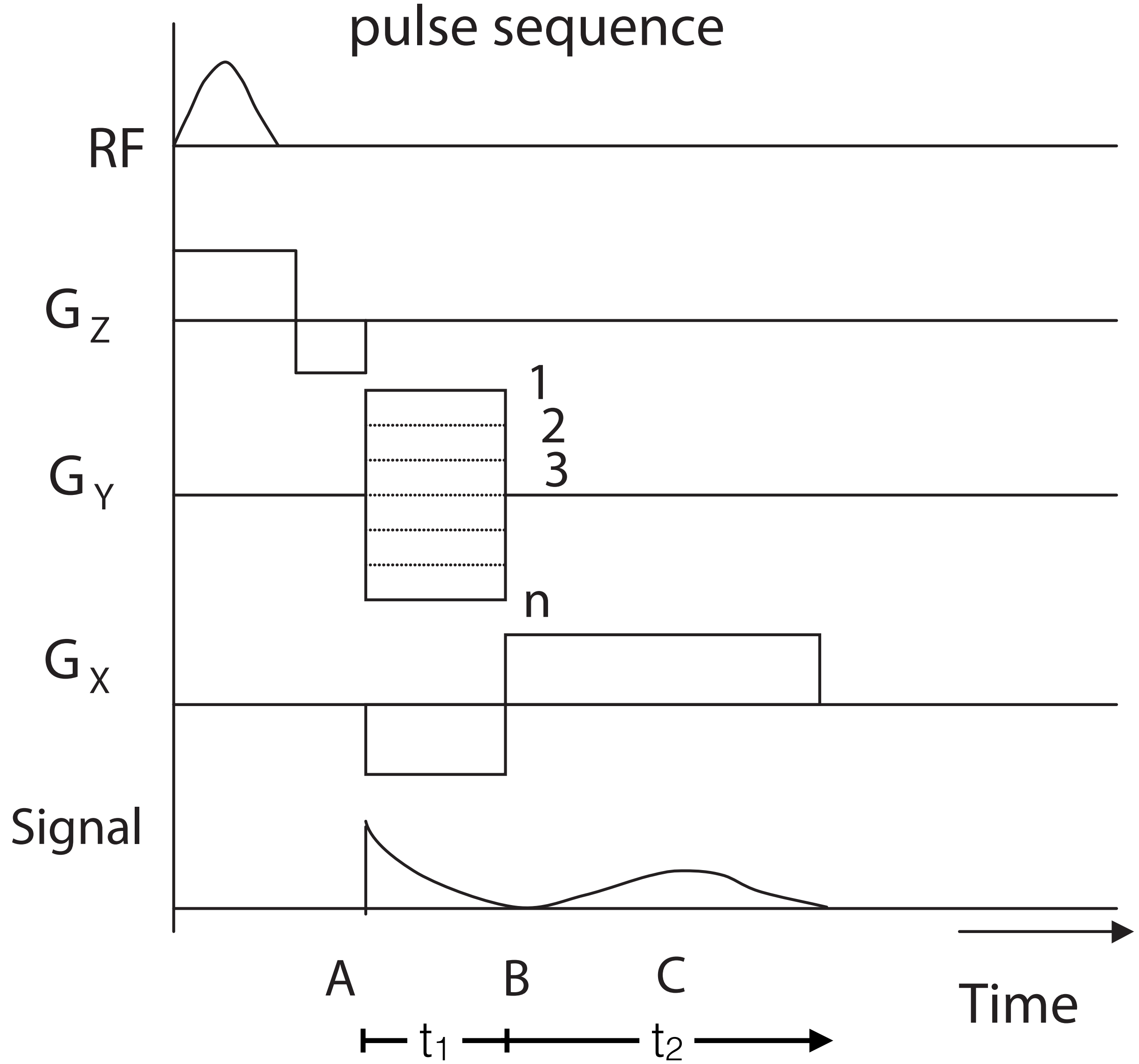
In this example, the signal acquisition as a function of t_2 is always done with the gradient direction being parallel to X, and being constant in amplitude G_X^{acq}. Conversely, from one experiment to another the duration, t_1, of the gradient applied along the Y direction is kept constant, but the amplitude of the gradient along Y is incremented from G_Y^{max} to $-G_Y^{max}$ in 11 steps.

Multi-Dimensional Imaging?

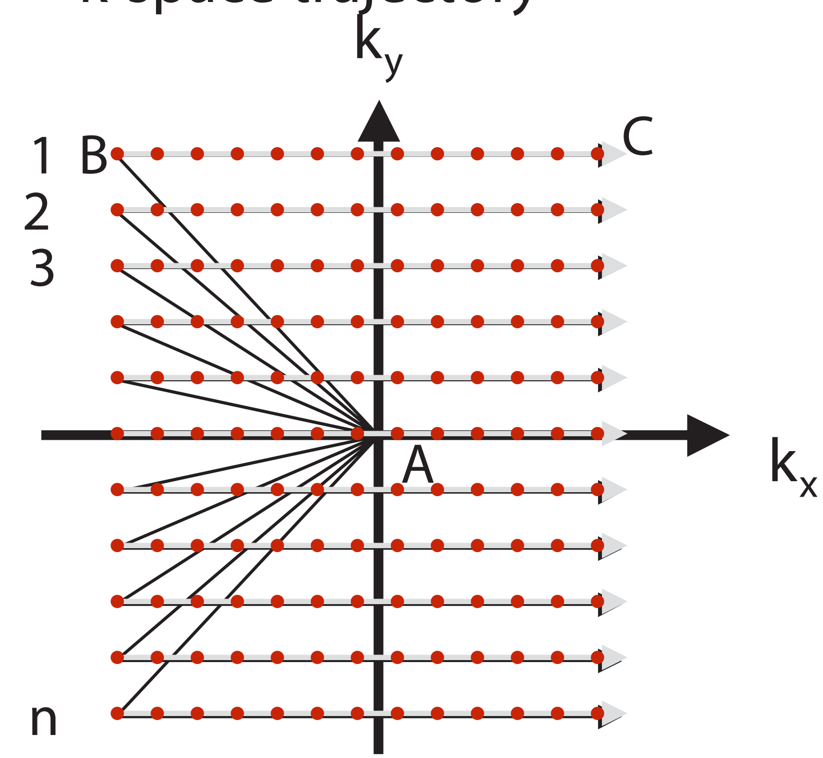
(ii) Fourier Imaging



Spin-warp
pulse sequence



Spin-warp
k-space trajectory

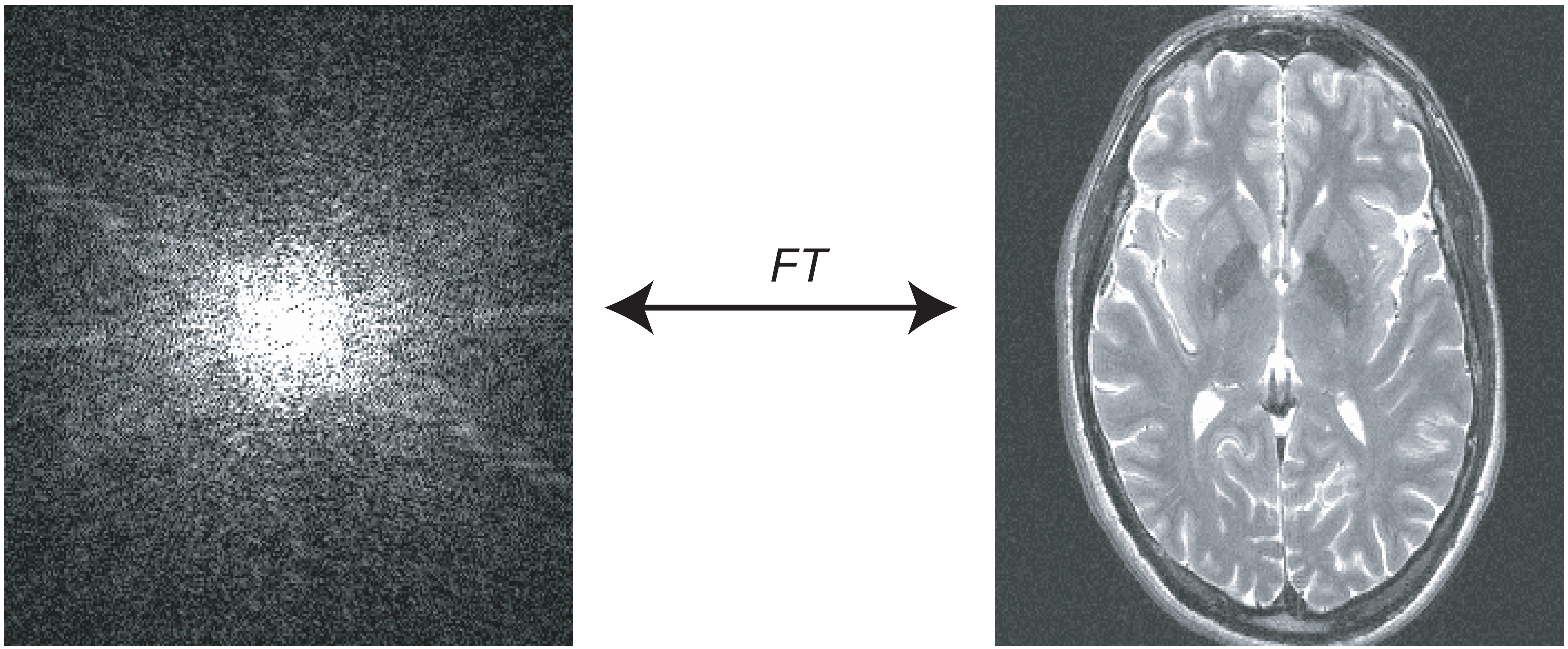


$$k_x = \gamma(-G_X^{acq}\, t_1 + G_X^{acq}\, t_2)$$

$$k_y(n) = \gamma(G_Y^{n}\, t_1)$$

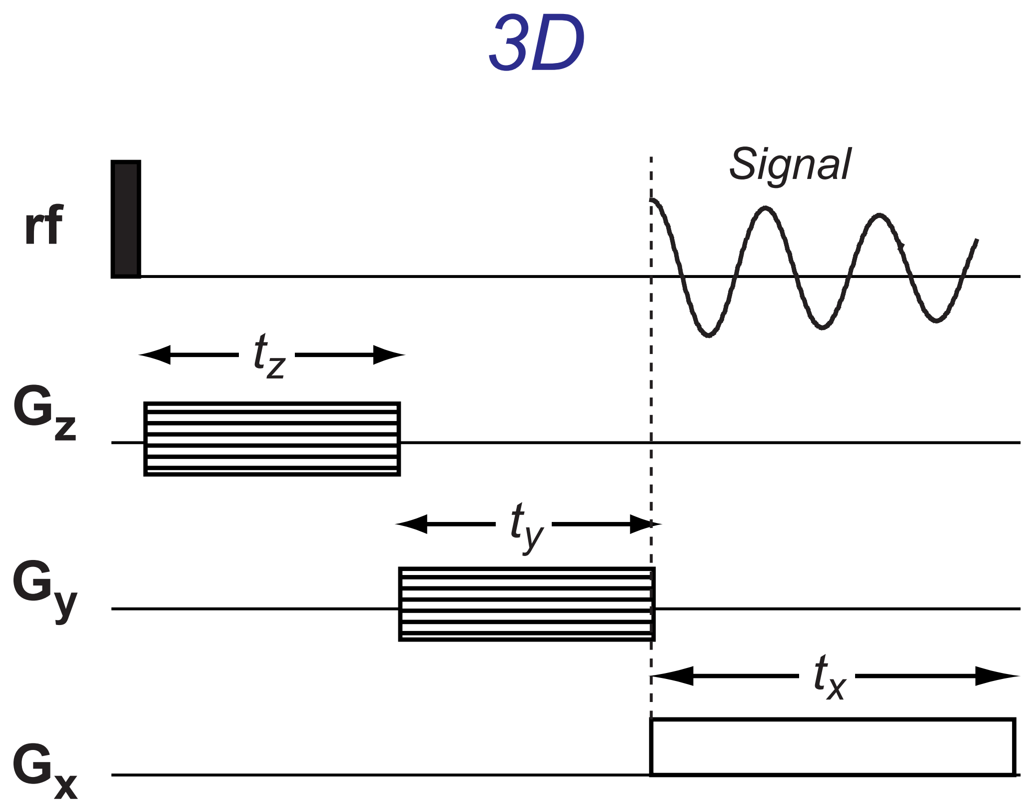
Homework: now draw the pulse sequence that would be used to acquire the projections shown in slide 20.

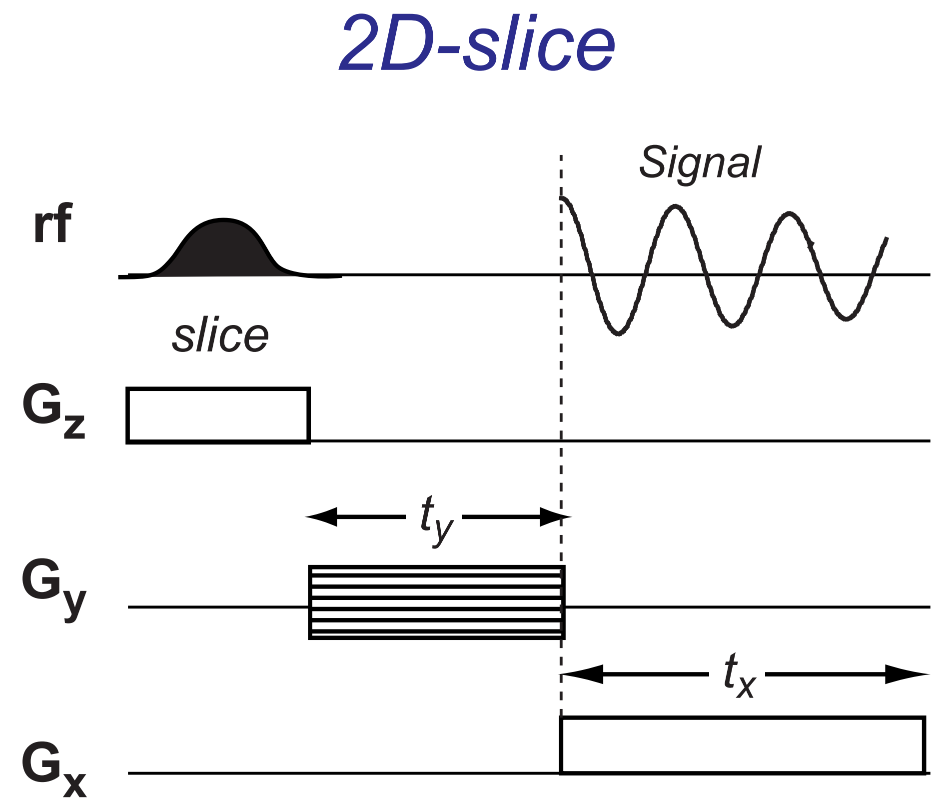
Multi-Dimensional Fourier Imaging



k space *Image space*

Two- and Three-Dimensional Fourier Imaging





Technical limitations for the pulsed field gradients (100 G/cm =1 T/m)

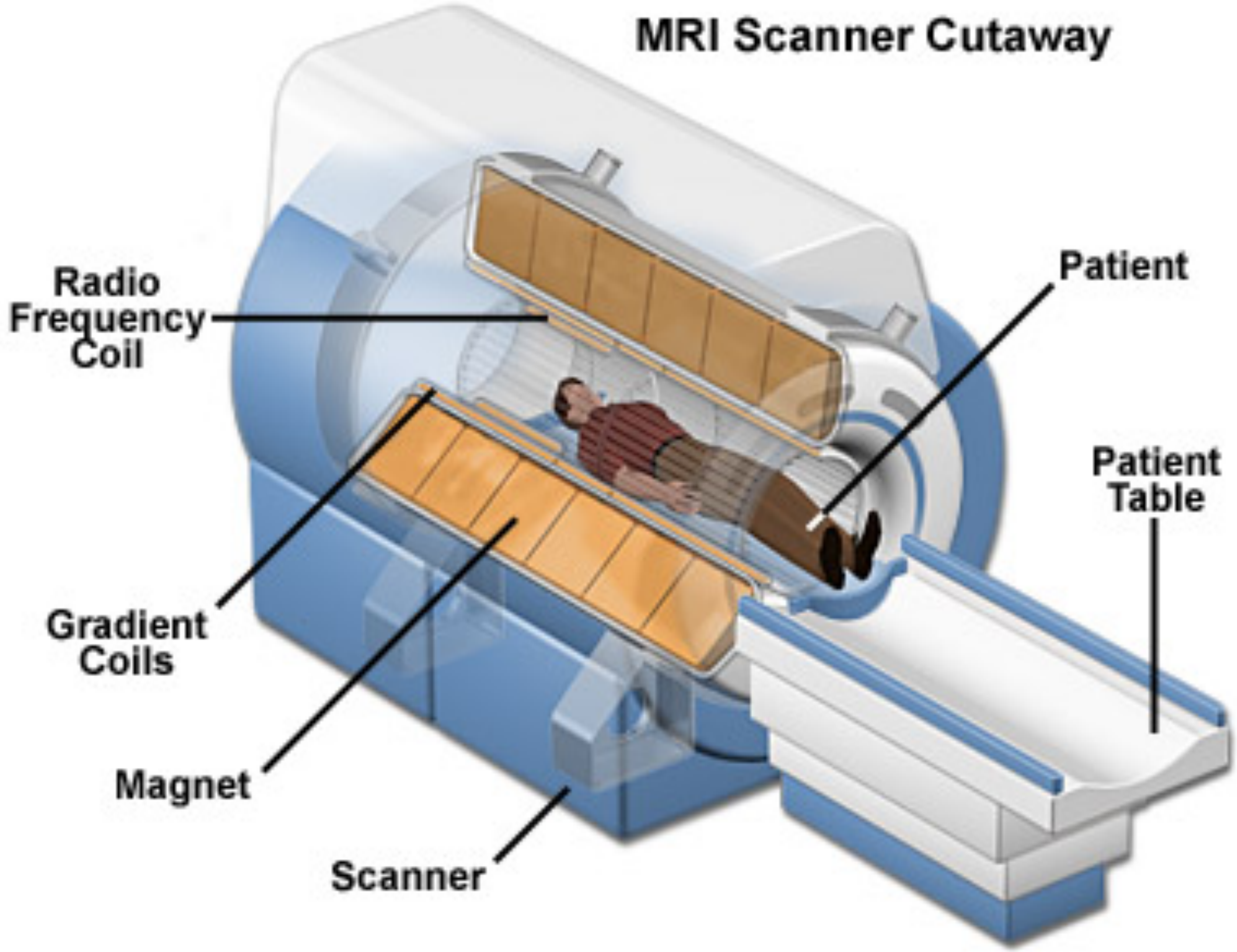
Spatial resolution (~ 50 μm)

Modern MRI

http://health.siemens.com/mr/image-gallery/#/search/scanners:MAGNETOM%20Aera/image/73

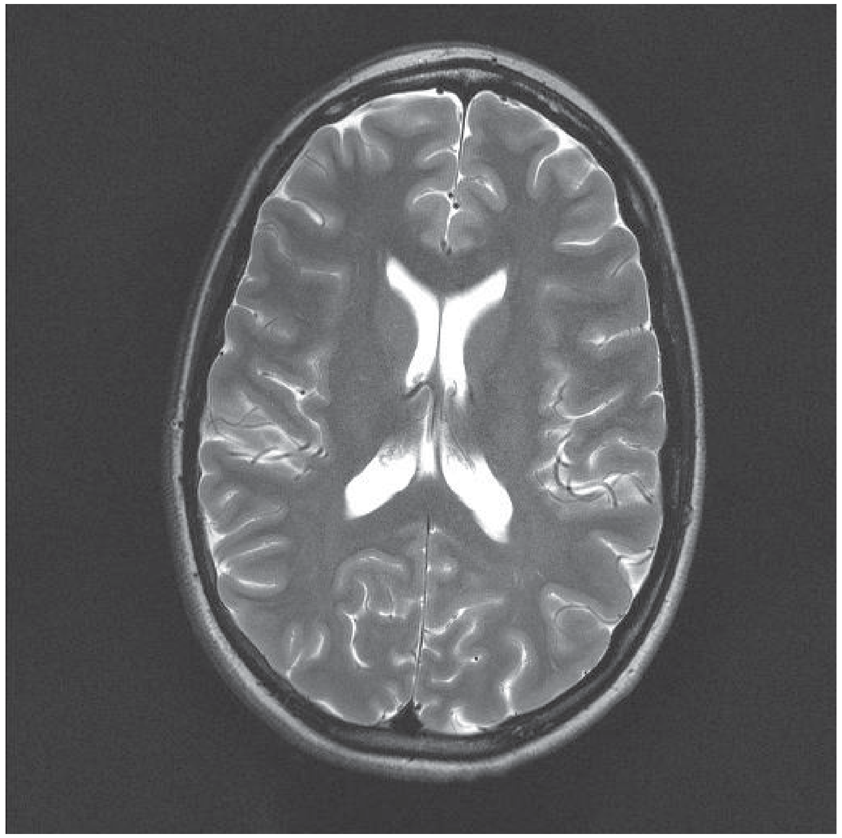
http://www.newscenter.philips.com/pwc_nc/main/shared/assets/nl/Newscenter/2012/philips-en-isala-partnership/digitale-MRI-scanner.jpg

The MRI Scanner



The MRI Scanner

Image contrast?

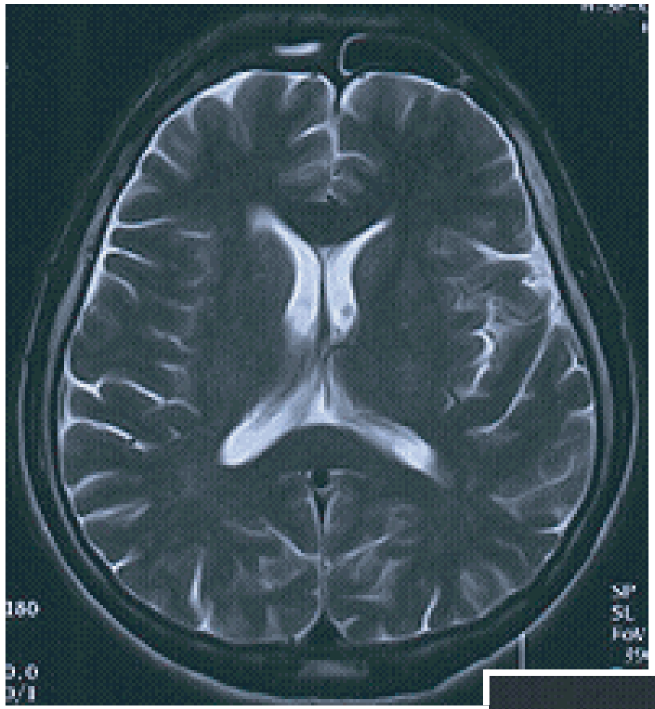


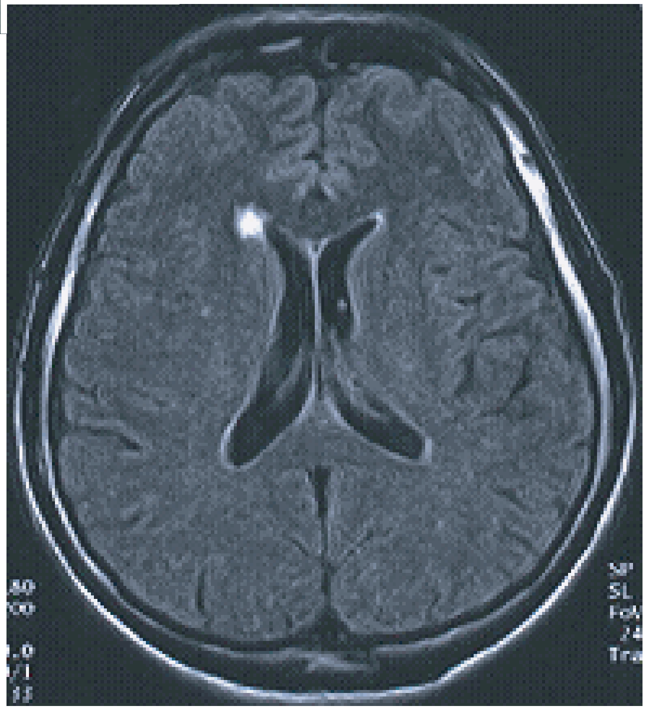
Where does the contrast in this image come from?

Spin (H_2O) density is more or less constant between white and grey matter....

tissue type	***water content***
grey matter	71 %
white matter	84 %
heart	80 %
blood	93 %
bone	12 %

Image contrast?





Worse (!?), these two images are of the same patient, at the same time. In one, CSF is bright. In the other CSF does not appear, and a MS plaque is bright.....

Conclusions

- In the presence of a magnetic field gradient strong enough to obscure other effects, NMR spectra directly reflect spatial concentrations of spins
- The NMR is a projection of the spin density onto the direction of the field gradient.
- A multi-dimensional inverse (*k-space*) space can be defined where $k_\alpha = \gamma G_\alpha t_i$ with α = e.g. *X,Y,Z*
- *k* space is linked to physical space by Fourier transformation. A generalisation of multidimensional spectroscopy.