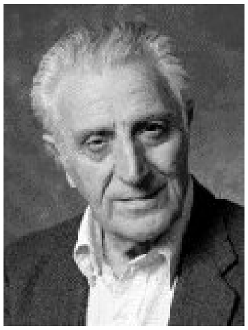
# Spin Echo



Erwin Hahn

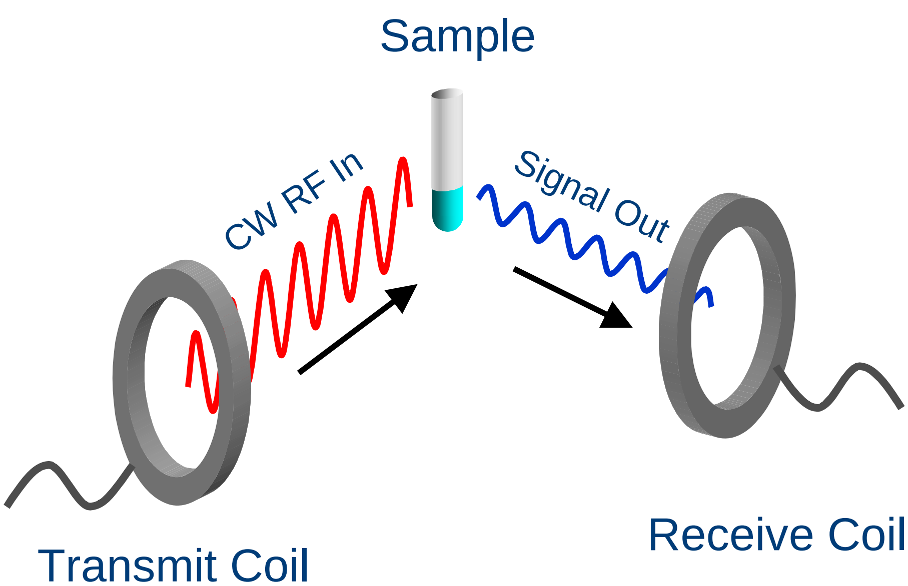
**History:** In **1946**, future Nobel laureates Felix Bloch (Stanford) and Edward Purcell (Harvard) independently observed the NMR phenomena as an RF signal response to a continuous (CW) irradiating RF field applied to a magnetic nuclei in a uniform magnetic field. In **1950**, Erwin Hahn, then a graduate student at the University of Illinois, was experimenting with NMR using pulsed RF energy and observed echo signals, hereafter called “Spin Echo” or “Hahn Echo” signals.

In today’s lecture we will be exploring some of the basics of spin echo including:

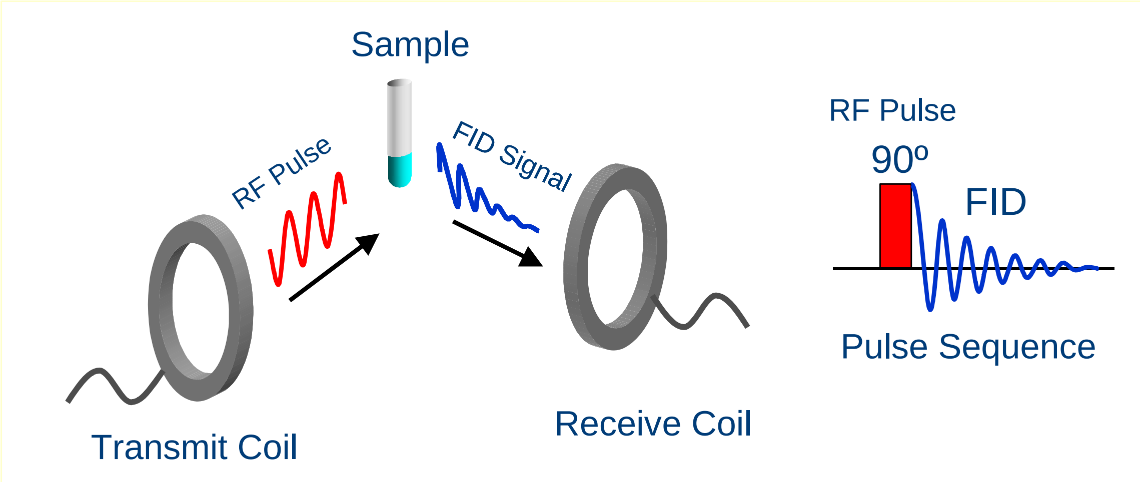
- Generation of spin echo signals from two or more RF pulses
- Signal characteristics of spin echoes
- Reversible and irreversible dephasing
- Spatial encoding with spin echo signal
- Basics of image contrast and pulse sequence considerations

**What are Spin Echoes?** First, look at three types of NMR experiments:

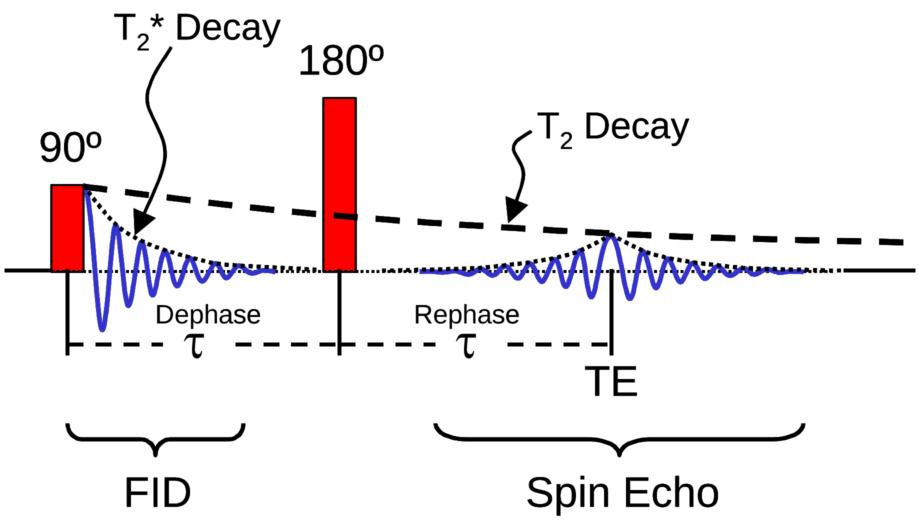
1. **CW (Continuous Wave):** Irradiate a sample with a continuous low level RF and observe the absorption of RF and/or the quadrature broadcast of RF energy.




2. **FID (Free Induction Decay):** Irradiate a sample with a single short pulse of RF energy and observe an NMR signal as it is initially generated and then decays with decay time $T_2$*. This is the basis of all Pulsed NMR (or MR) methods. In the MR Imaging context, single pulse methods are the basis of gradient recalled echoes (GRE).

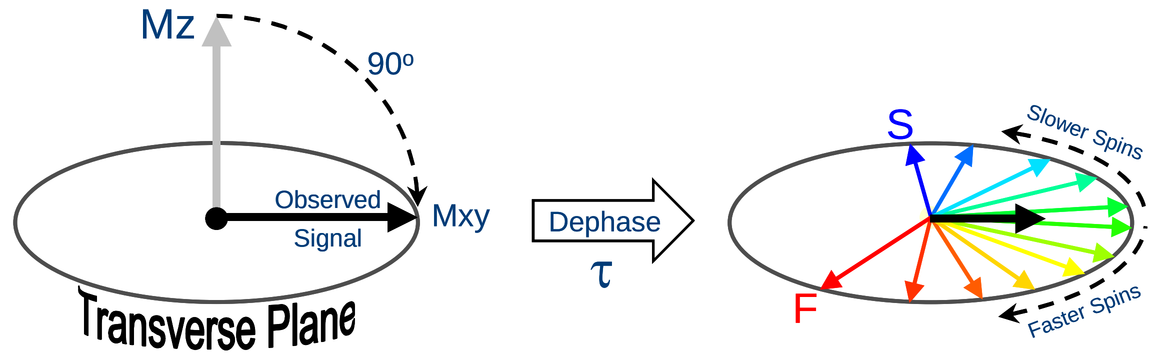



3. **Spin Echo:** Irradiate a sample with two or more RF pulses and observe an echo signal that has its peak energy at some time after the RF pulses. More specifically, start with a 90° excitation pulse, wait a short time period $\tau$, then apply a 180° refocusing pulse, wait another equal time period $\tau$ for the peak of the spin echo signal to occur.

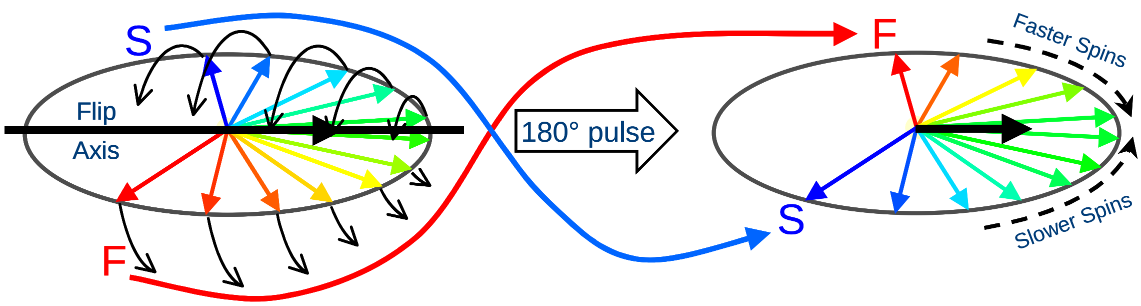



**How are spin echoes generated?** Here we will return to spin diagrams:

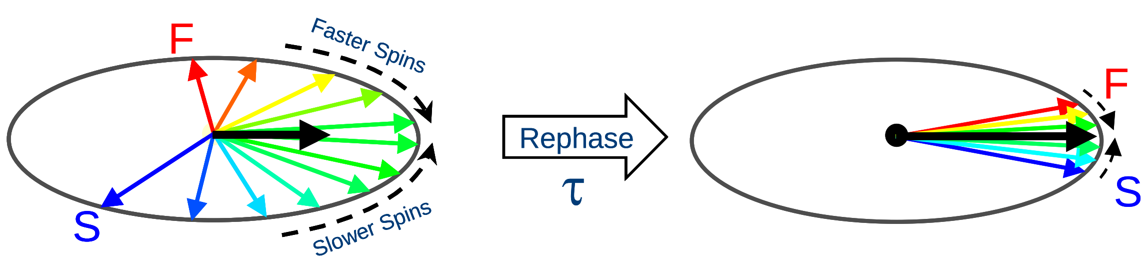
1. **Excitation Pulse and Dephasing:** Individual spins in MR have such low energy that they are not observed independently. Instead, we observe the combined signal of all the spins within the sample (or within the voxel). Immediately after the 90° RF excitation pulse, all the spins are in phase and add coherently to form the maximum signal. In real-life situations these spins start to dephase immediately as some precess faster, and some slower, than the average. As the spins move further out of phase with each other, they don't add together as effectively, and the sum of all the spins starts to decrease (or "decay").




2. **Refocusing RF Pulse:** Application of a 180° pulse "flips" the spins in the transverse plane like flipping a pancake. The spin phases are reversed: now the faster ones are where the slower ones used to be and the slower ones where the faster ones were. From this new starting point the spins continue to precess at their individual rates.




3. **Rephasing and echo formation:** As the spins continue to precess they are now rephasing rather than dephasing. After rephasing for a time $\tau$ equal to the original dephasing time, an echo forms:




Echo forms as spins rephase

Another popular illustration for the spin echo process involves a group of runners who all start off at the same time around the track at the sound of the first starting pistol (or excitation pulse). Rather than letting the race proceed in the normal fashion, however, a second shot of the starting pistol (the refocusing pulse) signals all the runners to instantly stop, turn around, and run back along the track in the opposite direction.

### Echo Terminology

**Spin Echo (SE):** Generally refers to an echo formed after application of two pulses: an excitation pulse and a refocusing pulse, commonly a 90° - 180° sequence. A spin echo is also known as a *Hahn echo*.

**Stimulated Echo (STE):** An echo that is formed by the application of three or more RF pulses, such as the classic STE sequence [90-90-90-echo]. The magnetization that contributes to stimulated echoes spends the time between the second and third RF pulses as "stored" $M_z$ magnetization. During this "storage" time no additional phase accumulates.

**Gradient Echo (GRE):** An echo signal that is intentionally generated by application of a rephasing gradient pulse to counter a previous dephasing gradient pulse on the same physical axis. Normally Gradient Echo also implies the lack of a 180° refocusing pulse and the use of dephasing and rephasing gradient pulses of opposite sign. The underlying RF pulse sequence for the gradient echo is the FID (Free Induction Decay) sequence illustrated above.

### Reversible vs. Irreversible Dephasing: T2* and T2 Decay

**Reversible:** Sources of spin dephasing that are constant with time are refocused with the classic Hahn echo sequence 90° – – 180° – – Echo. Reversible dephasing contributes **$T_2$* decay**. Sources of reversible dephasing include:

- Main magnetic field inhomogeneity
- Local magnetic susceptibility
- Chemical shift

**Irreversible:** Dephasing that relates to *random processes* such as spin-spin interactions or diffusion through magnetic field gradients is not reversible. Irreversible dephasing leads to irreversible signal loss and contributes to **$T_2$ decay**.

### Gradients and dephasing

Hahn's work relates to the underlying NMR signal in the absence of gradient pulses. Many of the same concepts apply regarding signal dephasing and rephasing when gradients are applied. Gradient pulses cause phase accumulation that is proportional to the gradient pulse area and the distance from isocenter. Rephasing occurs when the net gradient area (or *zeroeth moment*) reaches zero. Hence, gradient pulses cause reversible (and intentional) dephasing.

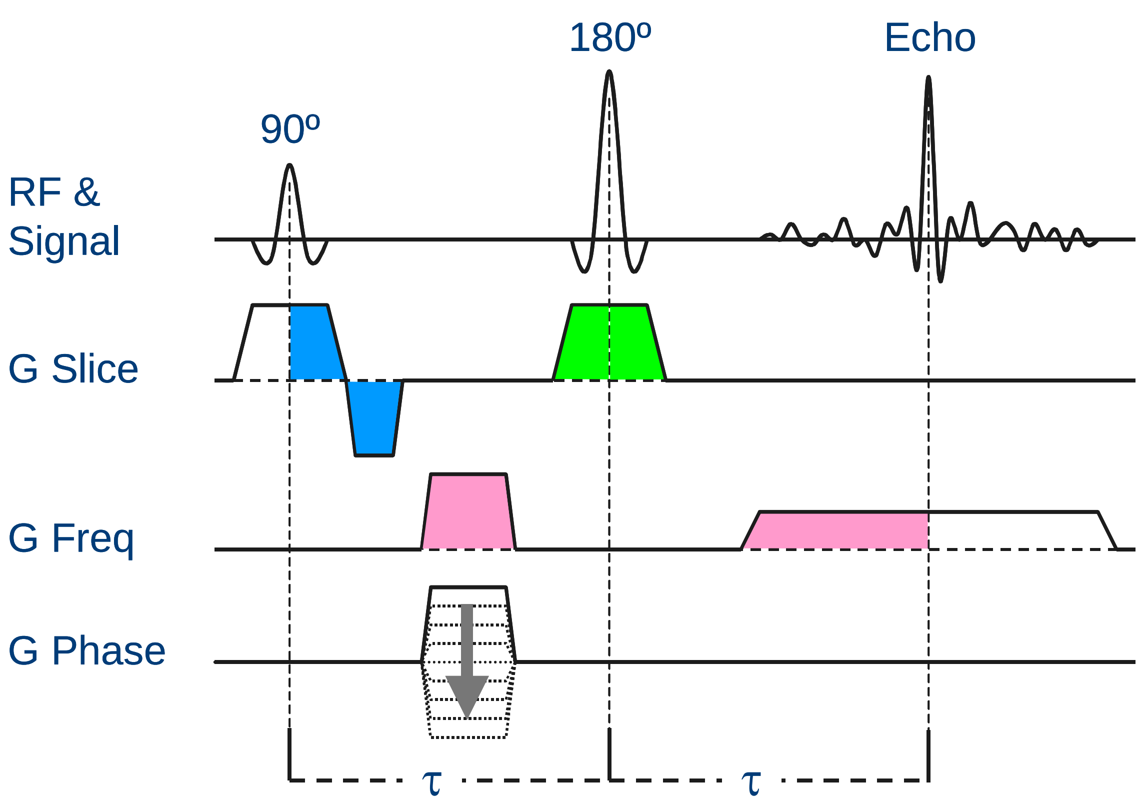
### Slice Selection

When a gradient is turned on, it causes the effective magnetic field to vary in a (nearly) linear fashion across the subject within the imaging volume. The Larmor equation, $\omega = \gamma * B$ tells us that the spin frequency $\omega$ is proportional to the magnetic field B, related by the constant term, the gyromagnetic ratio, $\gamma$. Hence, an applied gradient causes the resonant frequency to vary as a function of slice location. If a frequency-selective RF pulse is applied, spins at the region (or slice) corresponding to that frequency band experience the effect of the RF pulse. Other regions are largely unaffected. This is the basis of slice selection – the combination of specially designed ("shaped") frequency selective RF pulses with slice selection gradient pulses.

**Spin Echo Imaging sequence:** The application of imaging gradients to a spin echo sequence is illustrated below. This sequence, originally presented by Edelstein et al. in 1980 as the Spin Warp sequence, referring to the phase "warping" action caused by the phase encoding gradient. Because the spin echo sequence refocuses the spin dephasing caused by field inhomogeneity, this sequence was ideal for application on early magnets that did not always boast the best homogeneity and was the mainstay of early clinical imaging.

The gradients shown below act in the following way in the spin echo sequence:

- **G Slice** is applied during the selective RF pulses to excite (or refocus) a desired slice
- **G Freq** is applied during the readout of the echo – spatial location relates directly to frequency and is generated with a Fourier transform.
- **G Phase** is applied as a pulsed gradient either before or after the 180° pulse and is incremented in amplitude from view to view. After collecting a complete set of phase encodes a Fourier transform extracts spatial location in the phase direction



A few other points:

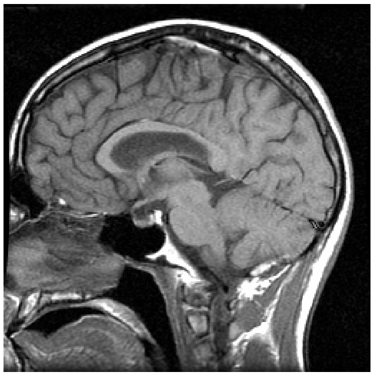
- The dephasing caused by the gradients corresponds to the area under the gradient pulses. An echo is formed when this area on a given axis balances to zero.
- The 180° pulse reverses the accumulated phase up to that point. This is equivalent to negating the gradient area accumulated up to the center of the 180° pulse.
- For purposes of calculating gradient areas before and after RF pulses, the entire RF pulse is assumed to occur "instantaneously" at the center of the RF pulse – a useful and generally good simplification.

**Fundamentals of image contrast with spin echo:** MR image signal intensity (and hence contrast) is a function of many parameters. Pulse sequences can be adjusted to emphasize one or more contrast mechanisms thereby optimizing visualization of one tissue or another. In spin echo imaging the dominant contrast phenomena and the pulse sequence implications are:

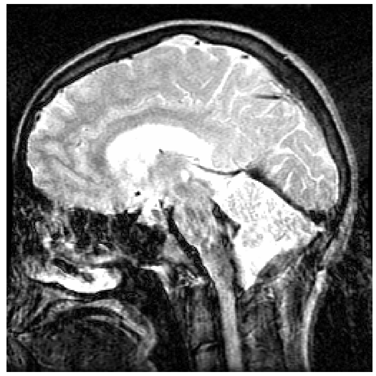
- **T1**, or the *longitudinal relaxation time*, is a tissue parameter represents how quickly magnetization returns to the longitudinal (Mz) axis after an excitation pulse flips it into the transverse (Mxy) plane or after an inverting pulse flips it to the negative Mz axis. Decreasing TR (repetition time, TR < 700 ms) increases the effect of T1 on image contrast. T1-weighting also generally uses a short TE (TE < 20 ms) to minimize T2 contrast.

- **T2**, or the *transverse relaxation time,* is a tissue parameter that represents how quickly transverse (Mxy) magnetization irreversibly dephases. Because spin echo refocuses the reversible decay of T2*, spin echo images are not sensitive to T2*. Changing the TE (echo time) adjusts T2 contrast. Longer TE values (TE > 80 ms) cause longer T2 tissues to appear brighter. Increasing the TE too far, however, can also lead to signal loss so there is an optimal TE that achieves optimal contrast-to-noise ratio (CNR) for two tissues with different T2 values.

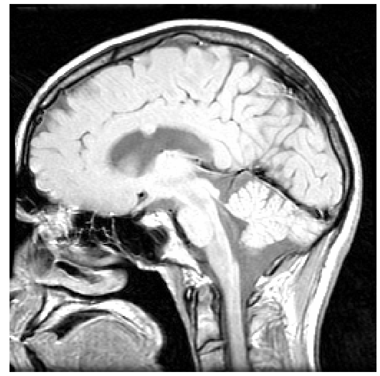
- **Proton density** is the most fundamental contrast parameter. Tissues with few protons such as cortical bone yield little signal while those abundant in protons such as CSF or fat tend to give bright signals. Minimizing T1 contrast with a long TR (TR > 2000ms) and minimizing T2 contrast by using a short TE (TE < 20 ms) results in proton density weighting. Because proton density tends to be similar over a wide range of tissue types, proton density-weighted images often tend to be relatively flat in contrast appearance albeit with very high SNR.



T1 Contrast
TE = 14 ms
TR = 400 ms



T2 Contrast
TE = 100 ms
TR = 1500 ms



Proton Density
TE = 14 ms
TR = 1500 ms

**Other considerations:**

- Spin echo and its variants are relatively insensitive to field inhomogeneity caused by metal such as dental work or MR-compatible implants (hip, knee, etc.).
- Because of the need for a relatively long TR value spin echo is generally considered a slow pulse sequence today. Faster variants would combine SE with parallel imaging and/or with multi-echo sequences such as FSE (Fast Spin Echo).

**References**

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