MRI Signal Properties and Relaxation

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Main Areas Covered in Lecture

- Phase of the magnetization
- Spin echo and refocusing the magnetization
- T2 relaxation and T2-weighting
- T2* relaxation and T2*-weighting
- T1 relaxation and T1-weighting
- Proton density and proton-density weighting

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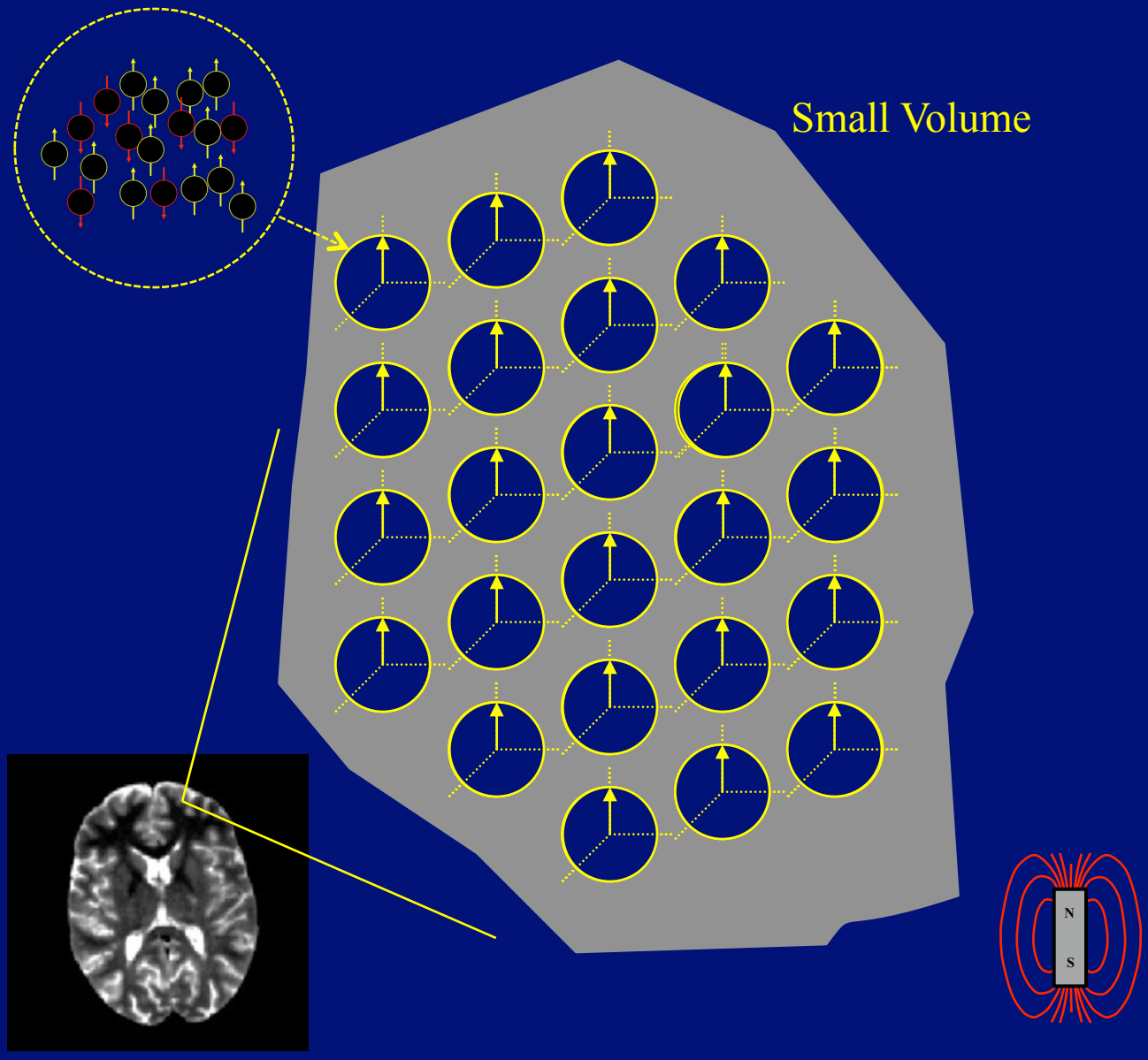
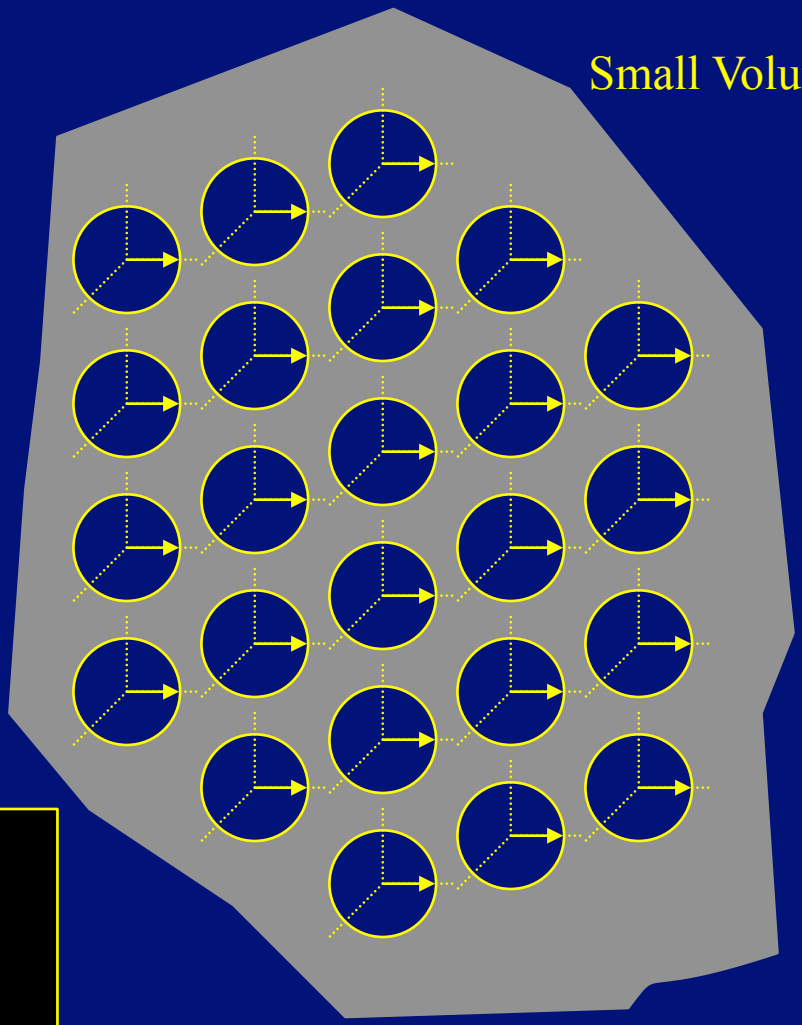
Magnetization Vectors

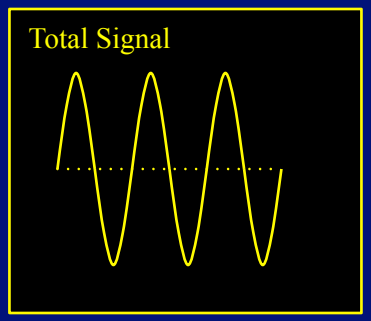


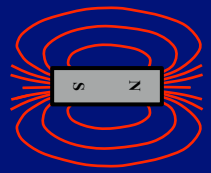
MRI consists of probing the distribution of magnetization vectors (M's). How M's behave in different tissues governs contrast.

Even in a small volume there are huge numbers of local M vectors.

Magnetization Vectors - Phase







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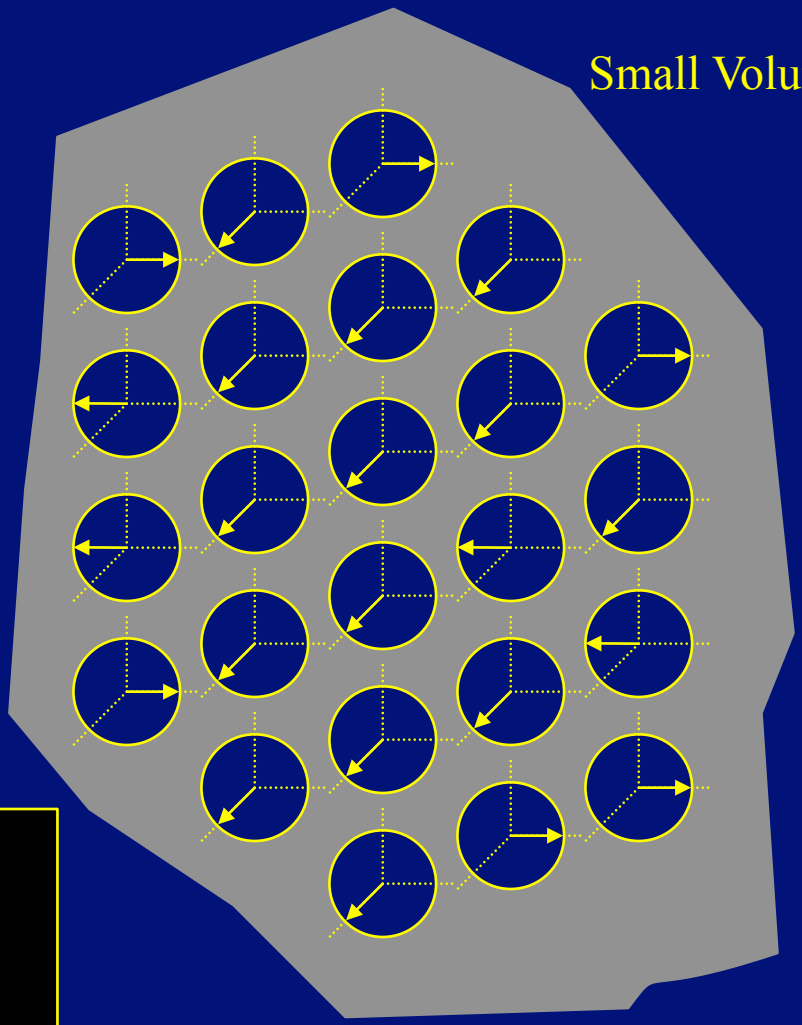
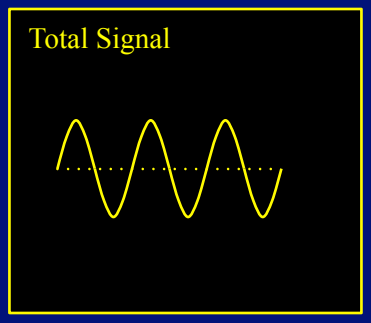
Even in a small volume there are huge numbers of local M vectors.

Immediately after excitation, the M vectors throughout the volume should all be in-phase and signal is at a maximum.

Magnetization Vectors - Phase





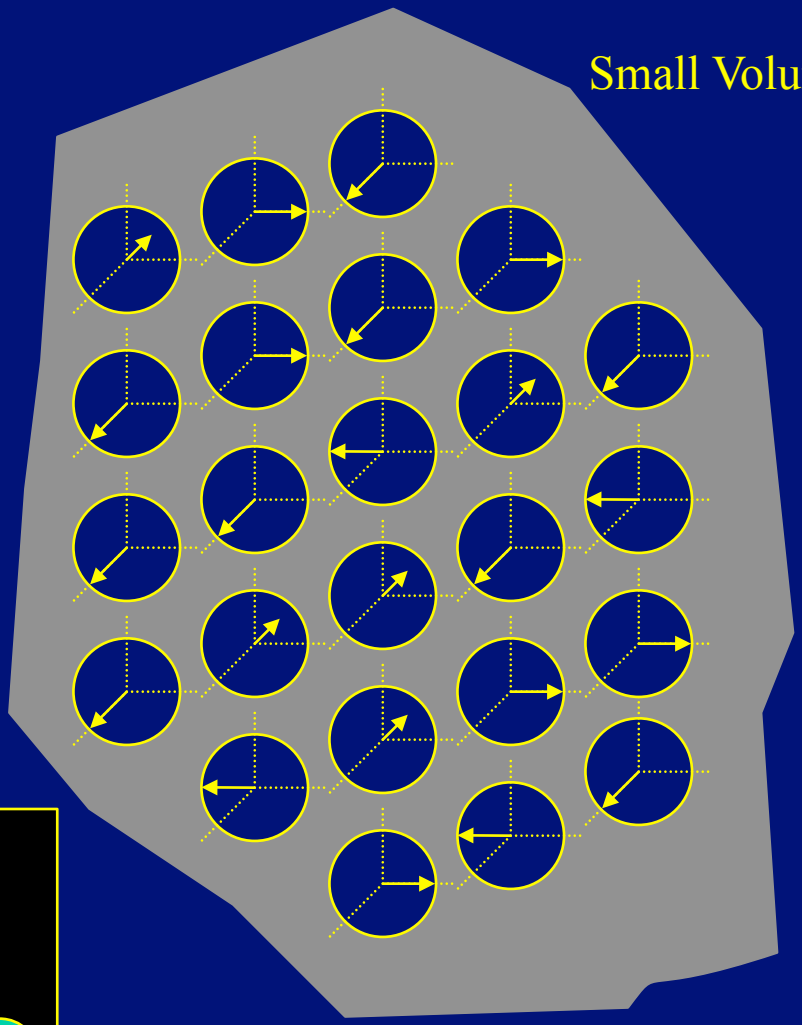
MRI consists of probing the distribution of magnetization vectors (M's). How M's behave in different tissues governs contrast.

Even in a small volume there are huge numbers of local M vectors.

Immediately after excitation, the M vectors throughout the volume should all be in-phase and signal is at a maximum.

Over time, due to small variations in the magnetic field, which cause the magnetization vectors to precess at slightly different frequencies, the vectors will begin to get out of phase with each other resulting in signal reduction.

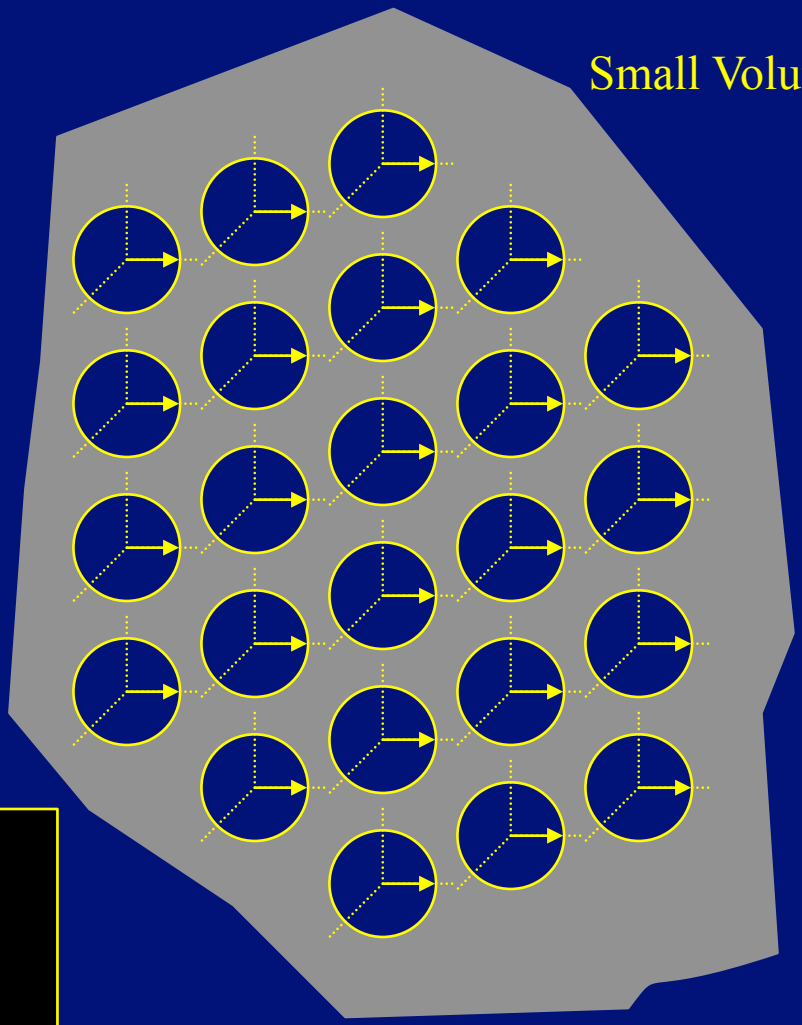
Magnetization Vectors - Dephased

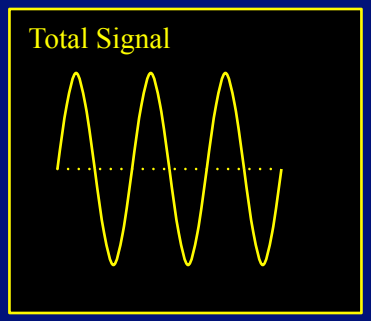


Total Signal

Eventually, there is no net signal from the volume because the magnetization vectors become completely out of phase with each other.

Refocusing the Magnetization





Eventually, there is no net signal from the volume because the magnetization vectors become completely out of phase with each other.

There is a 'trick', however, that enables bringing all the vectors back into phase to refocus the magnetization and bring the signal back.

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- Phase of the magnetization
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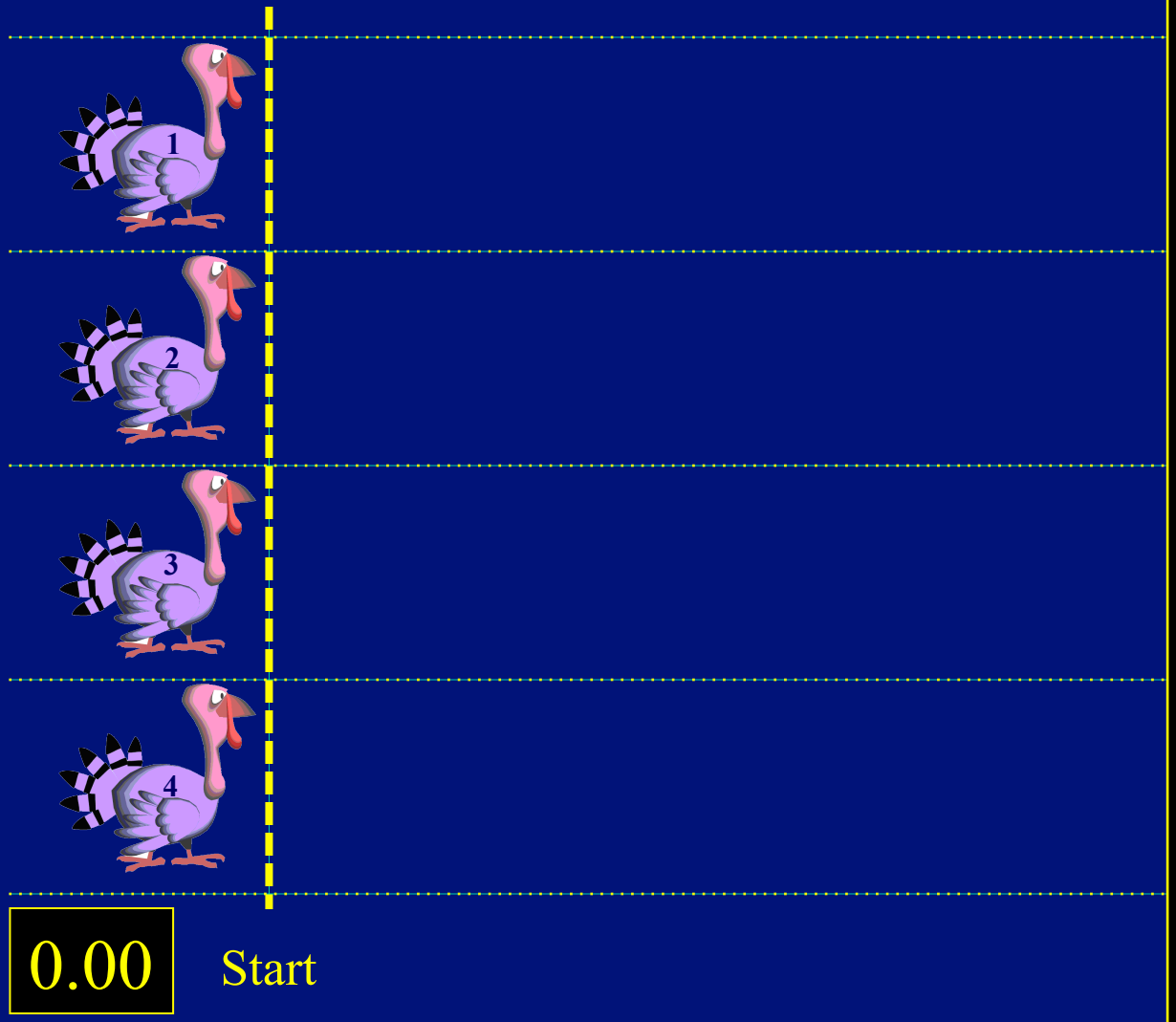
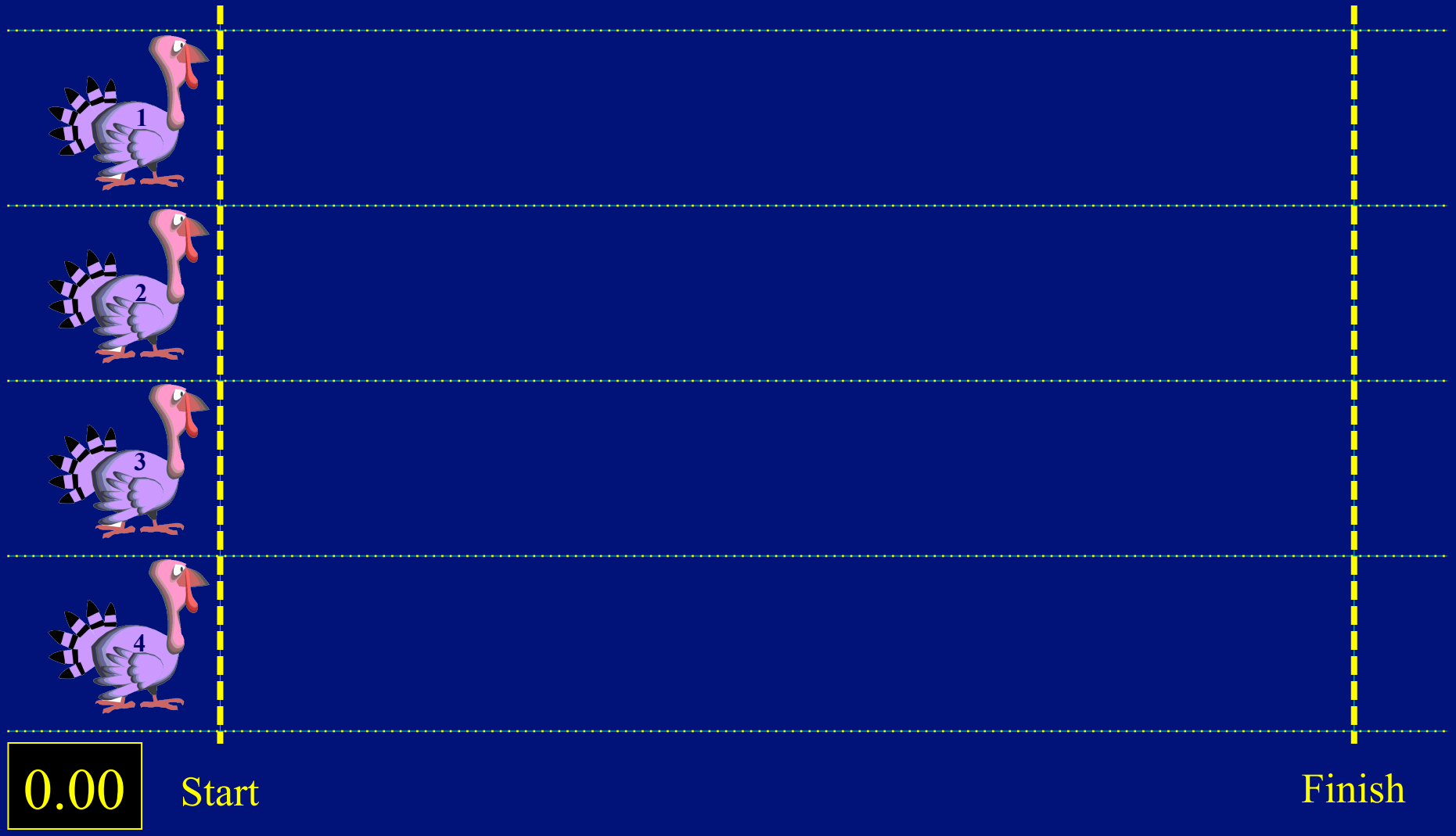
Refocusing the Magnetization



This ‘trick’ to bring all the vectors back into phase involves the use of a 180^{o} refocusing pulse and results in the formation of a spin echo.

Refocusing the Magnetization The Turkey-Race Analogy



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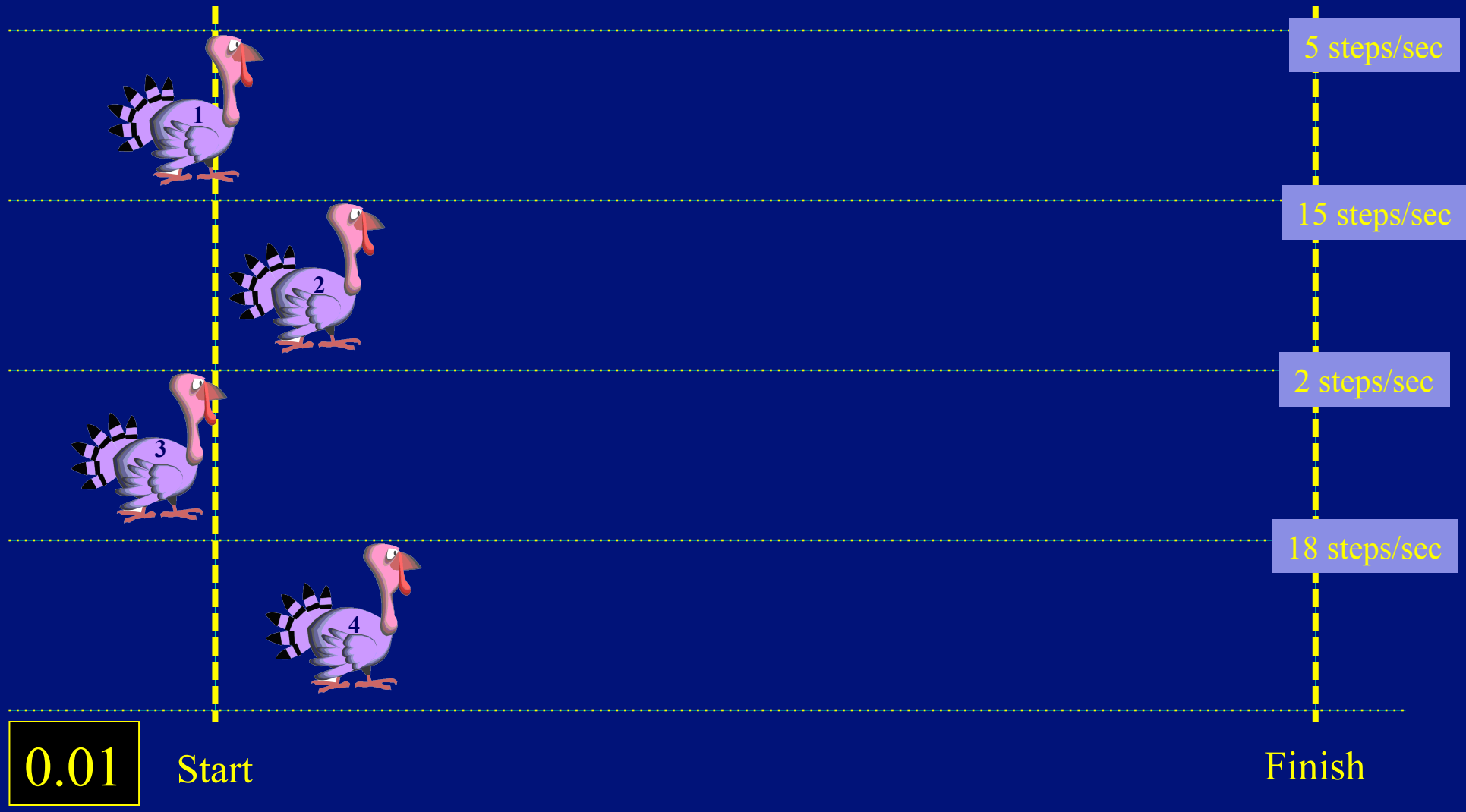

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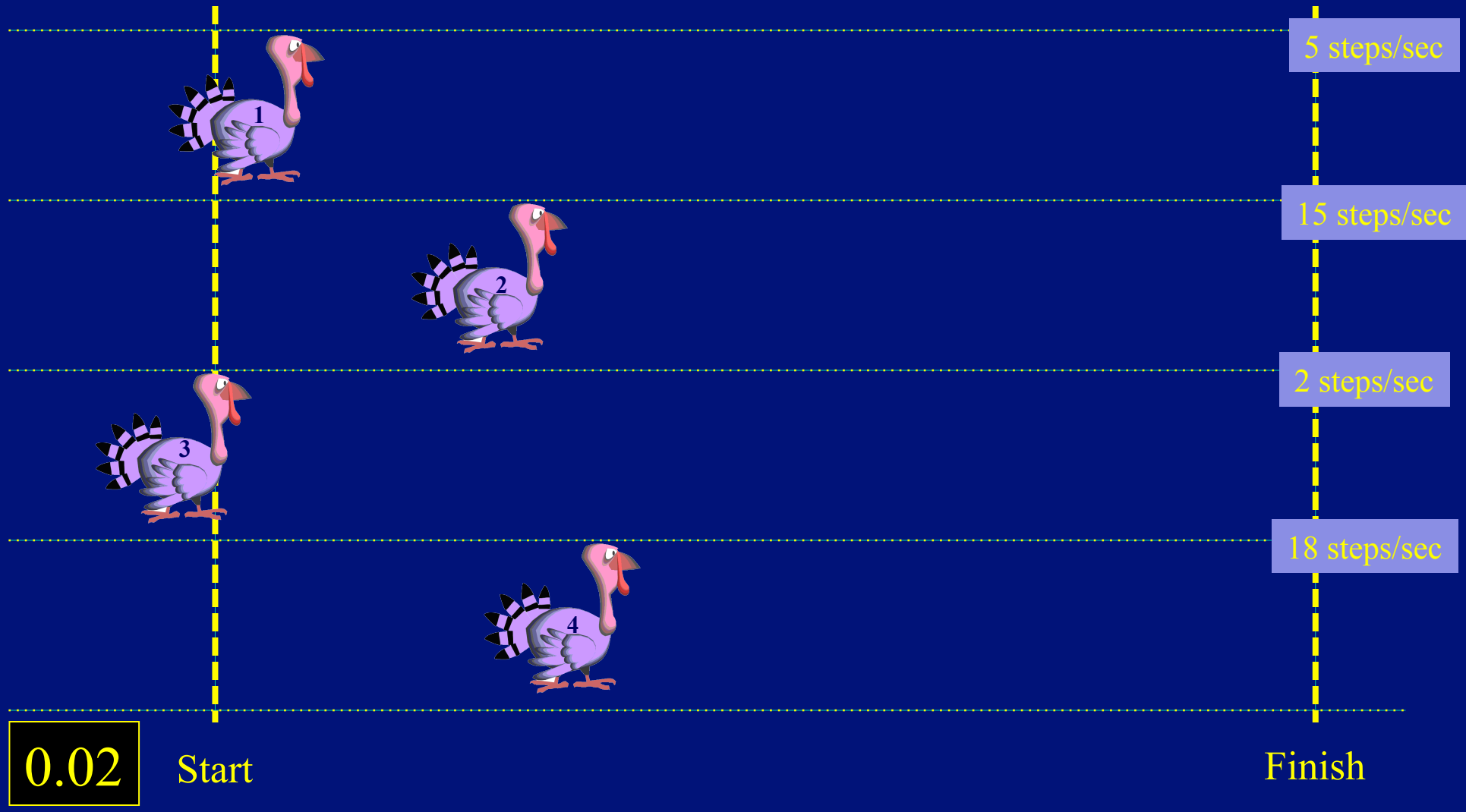

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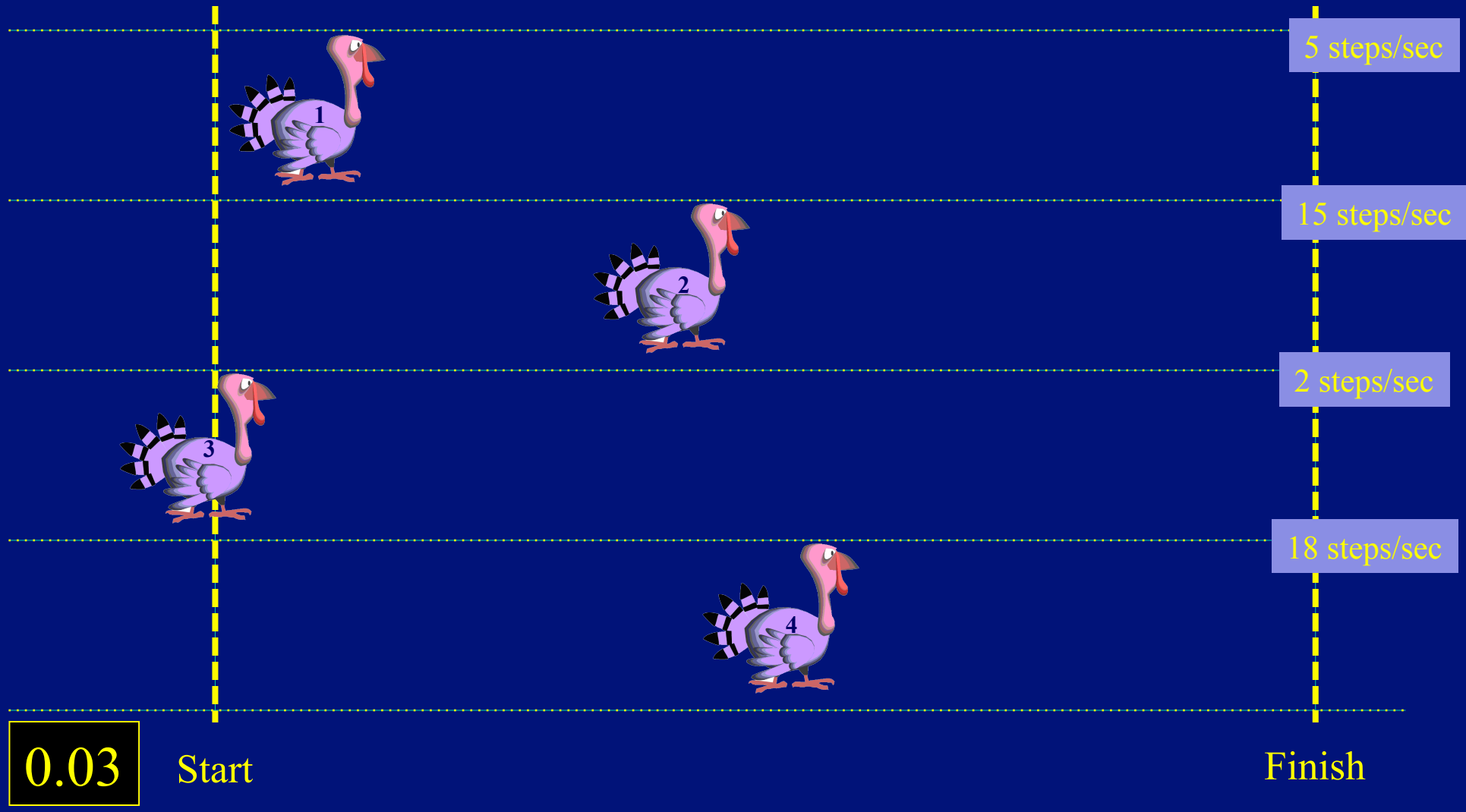

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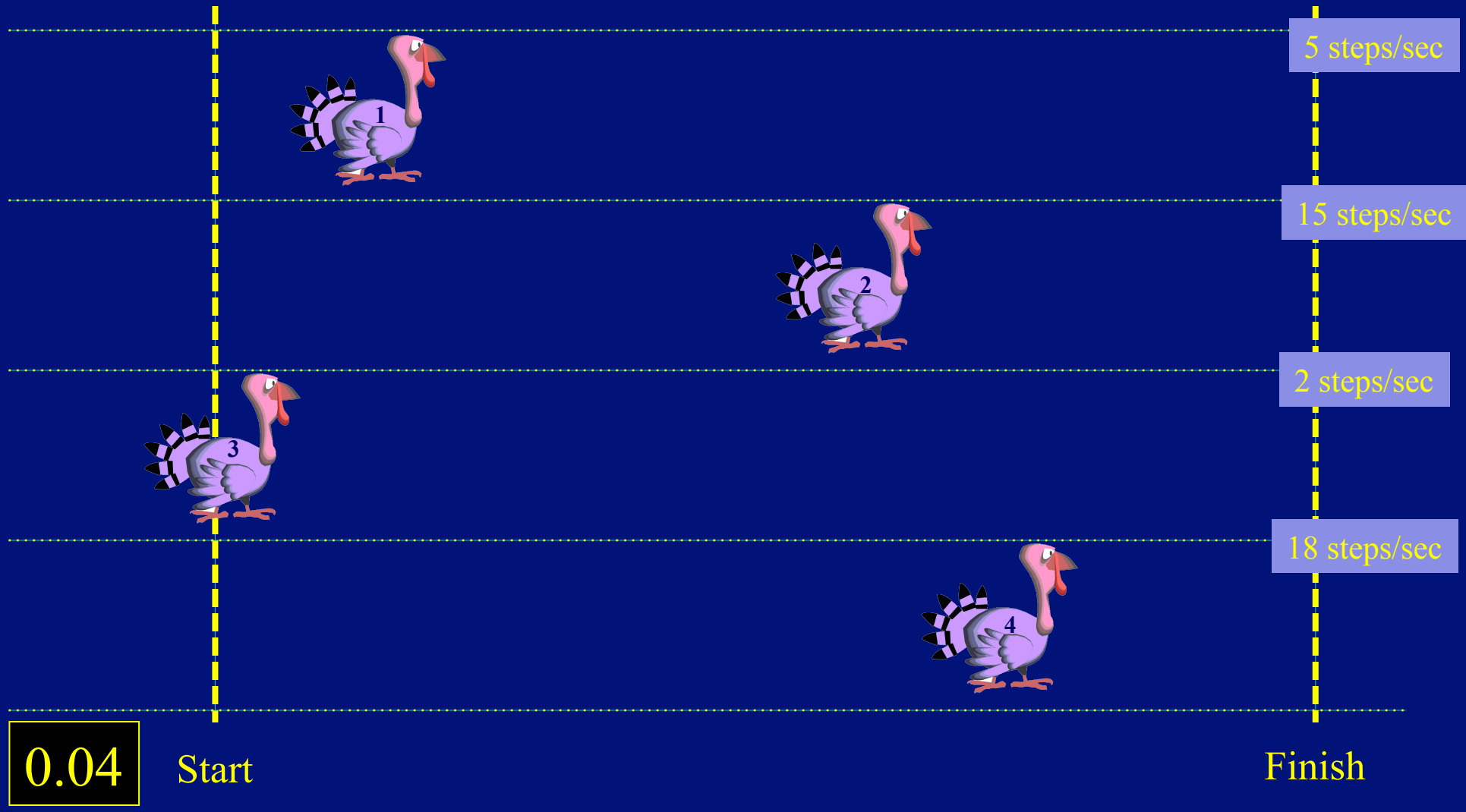

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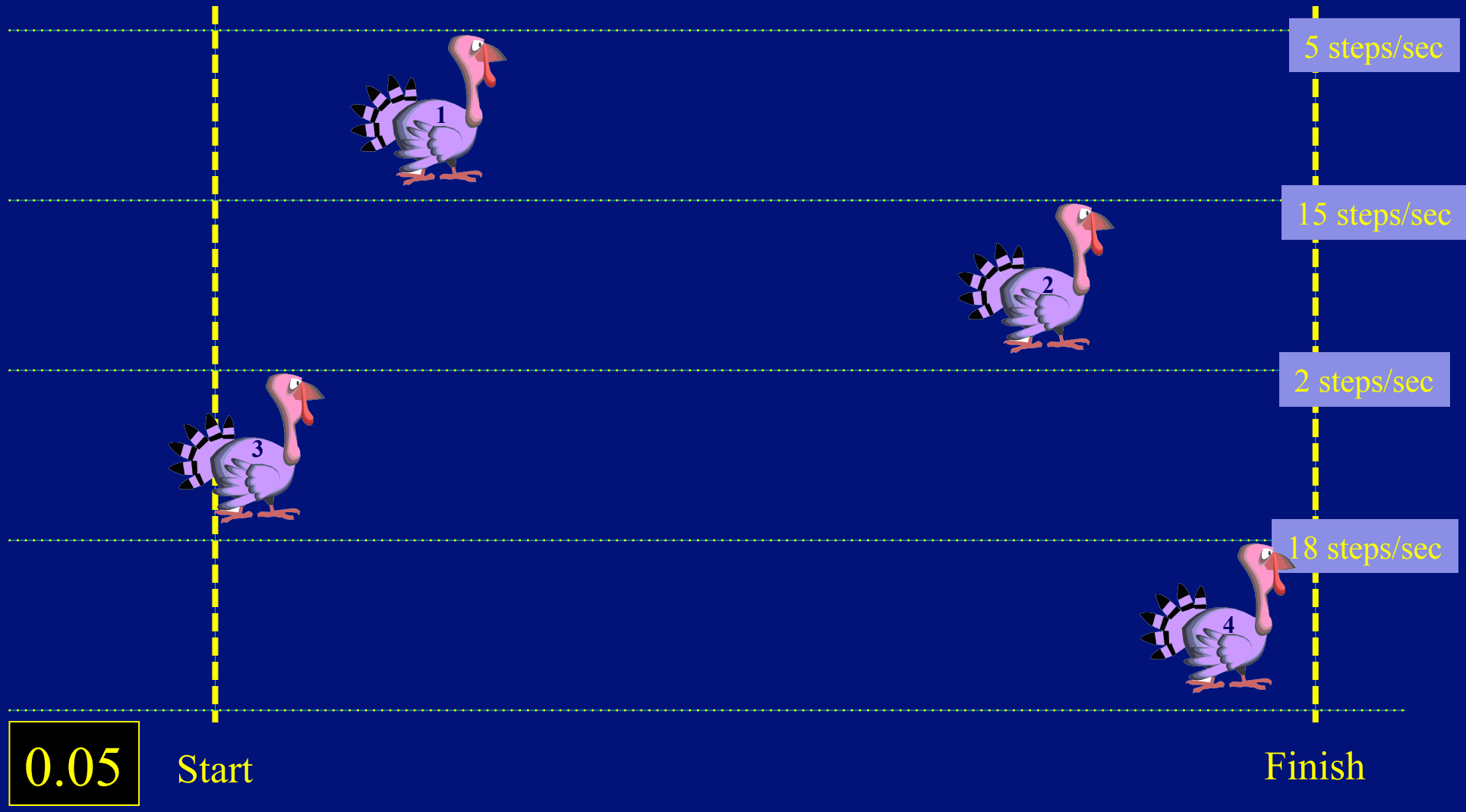

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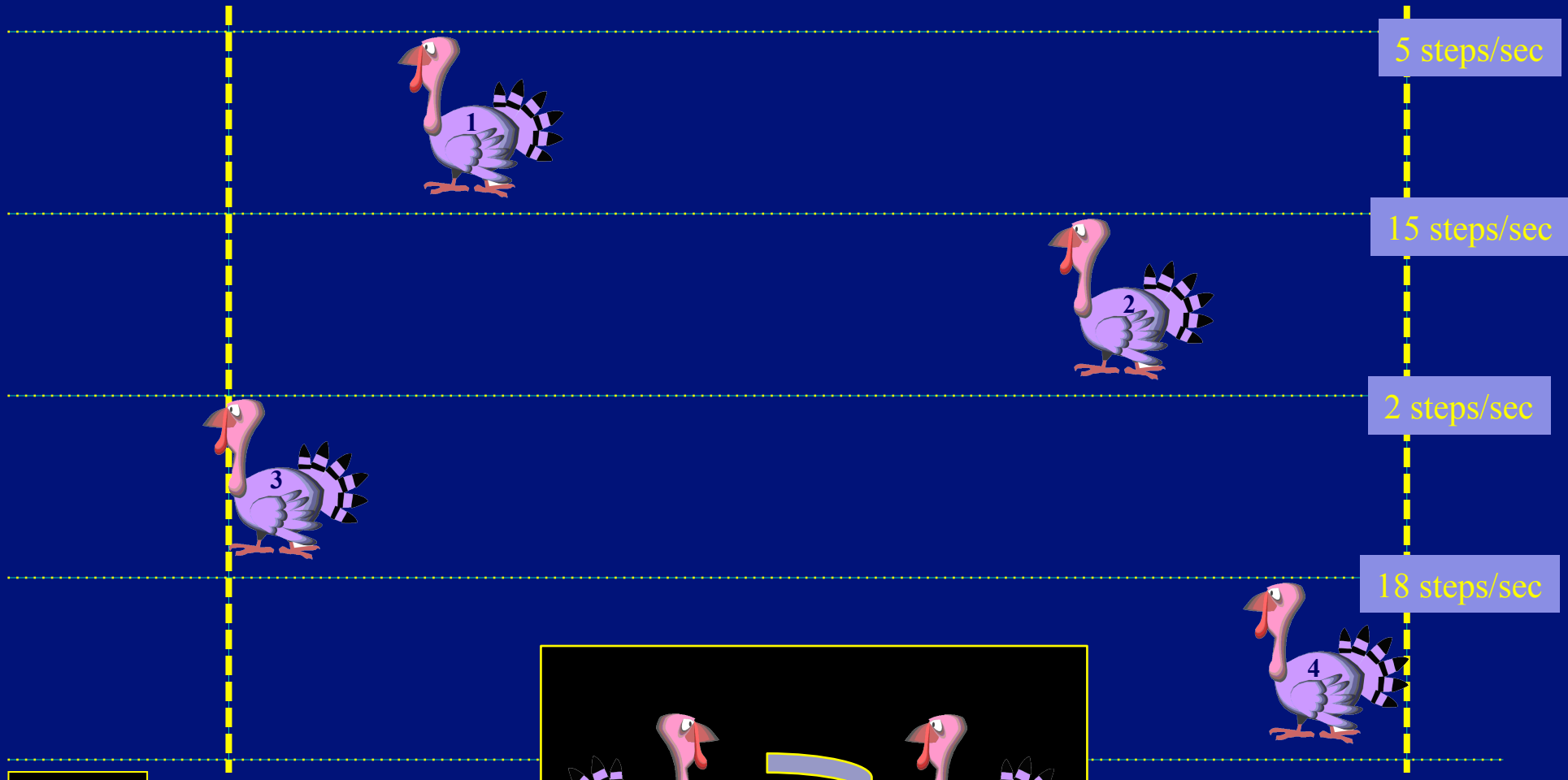

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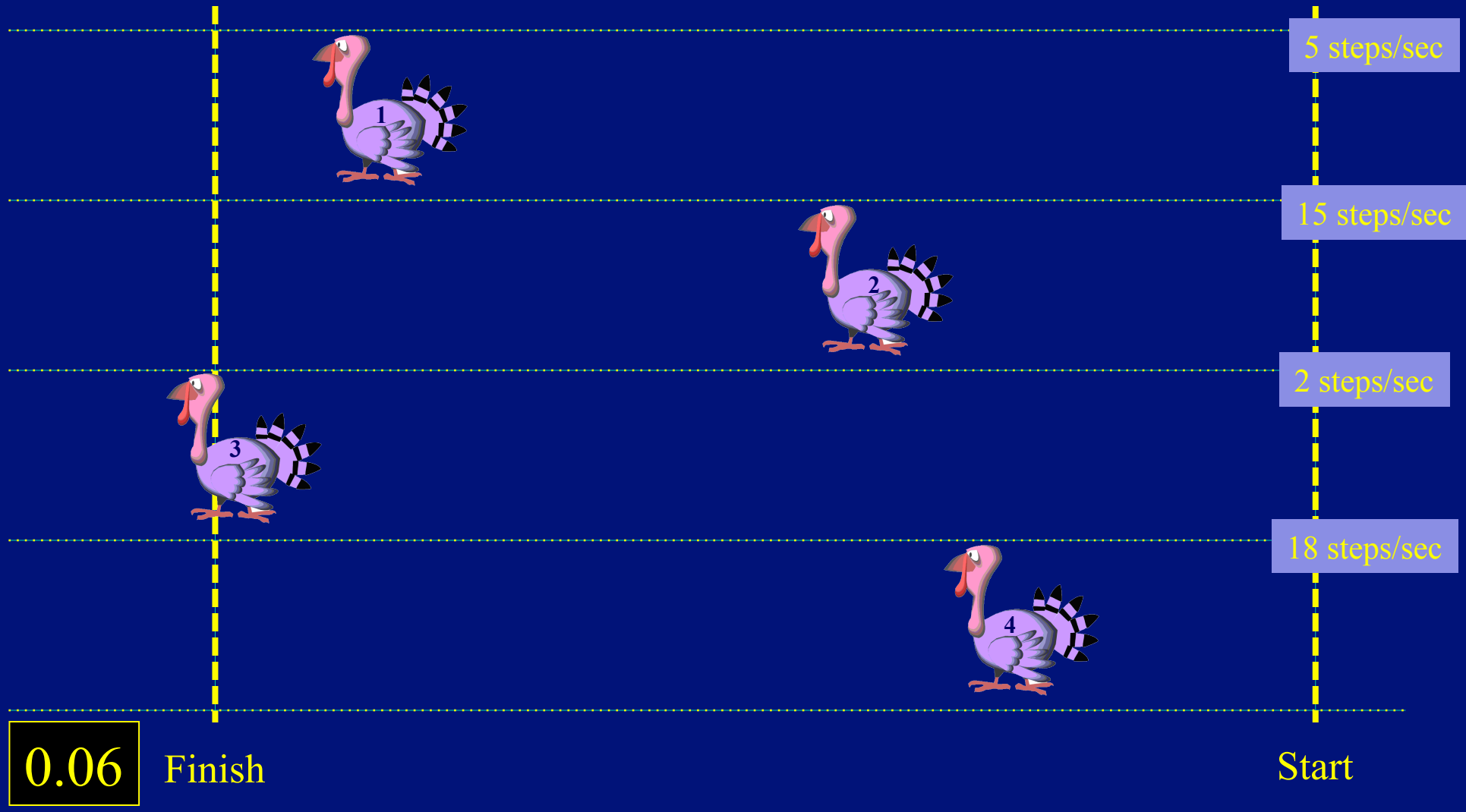

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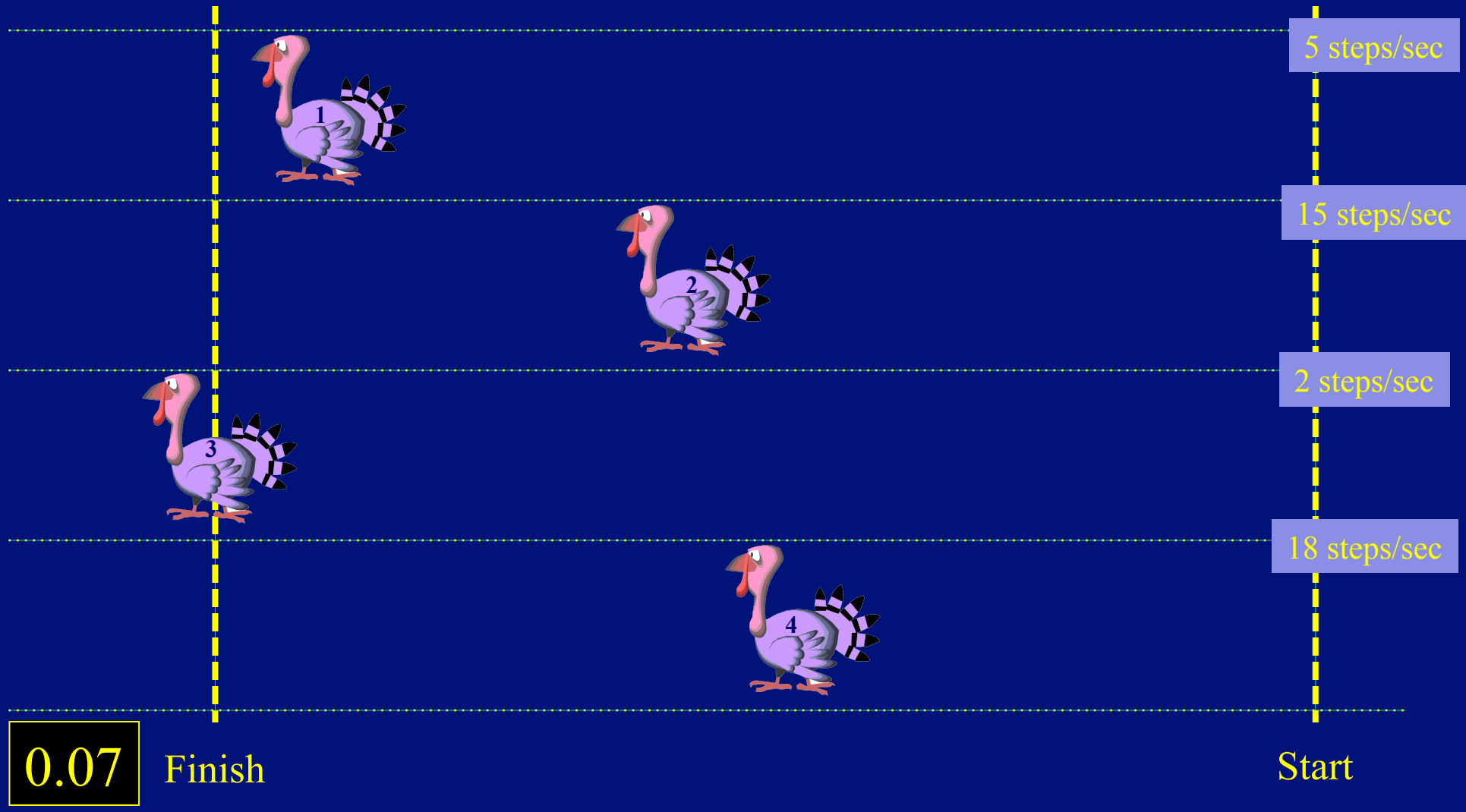

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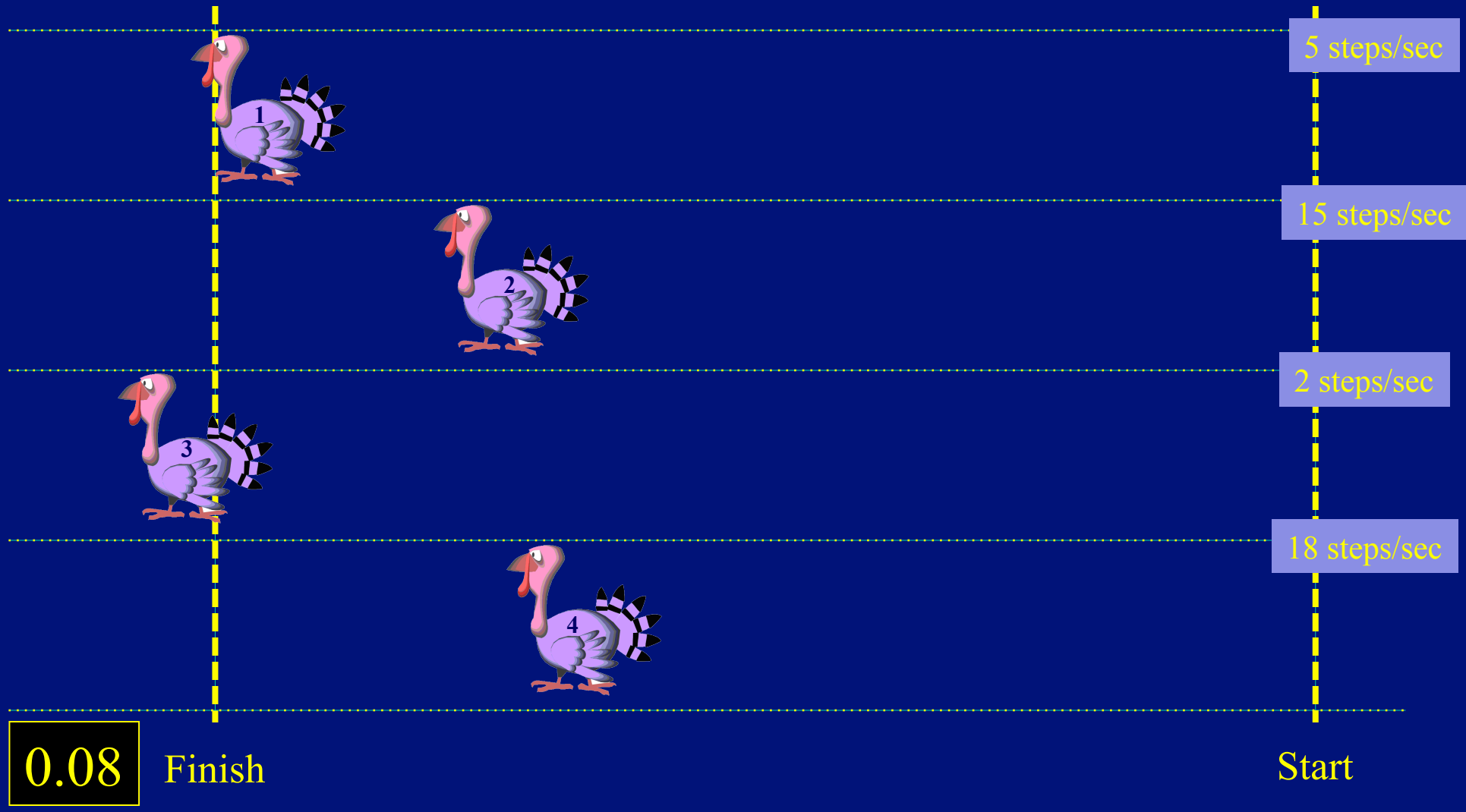

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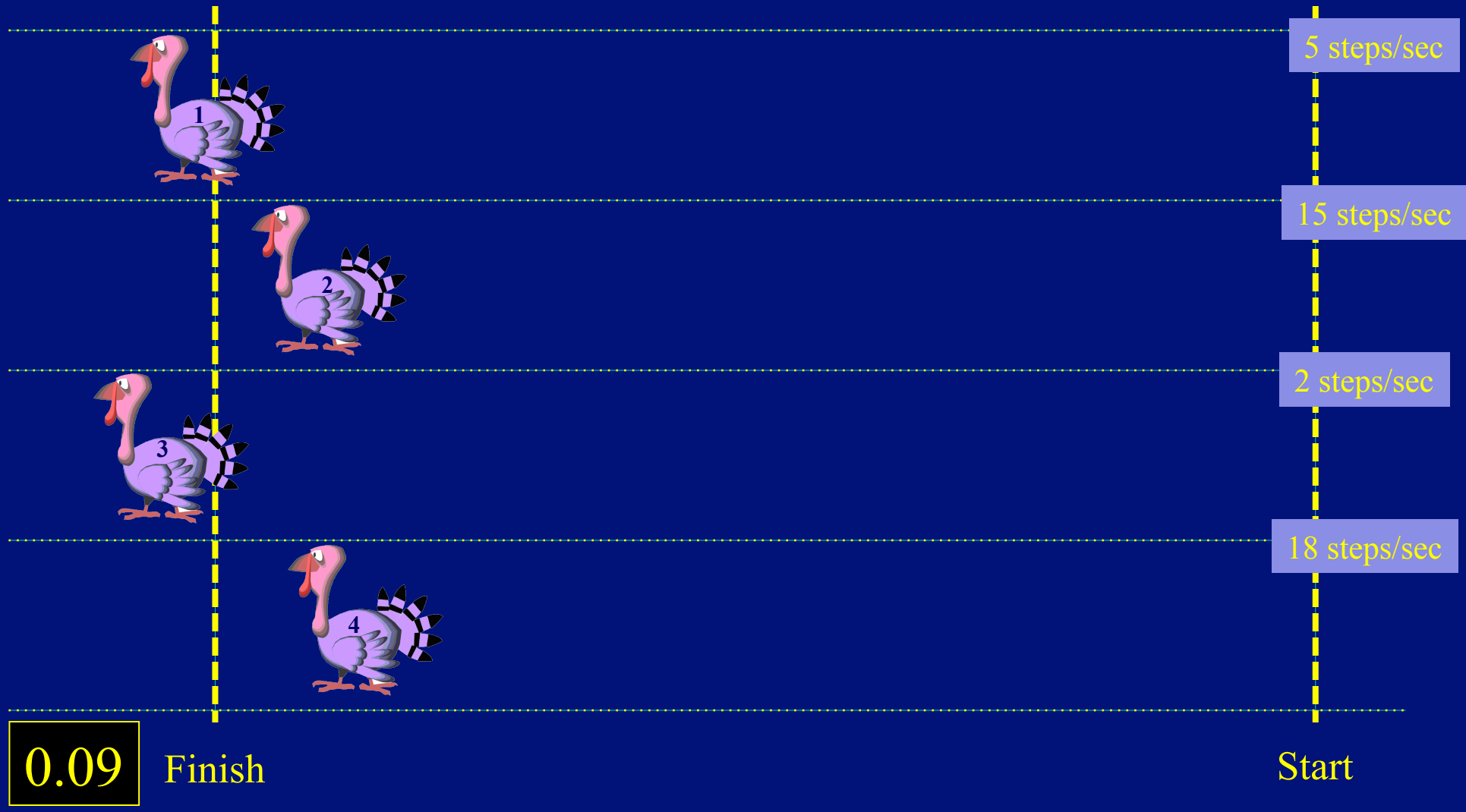

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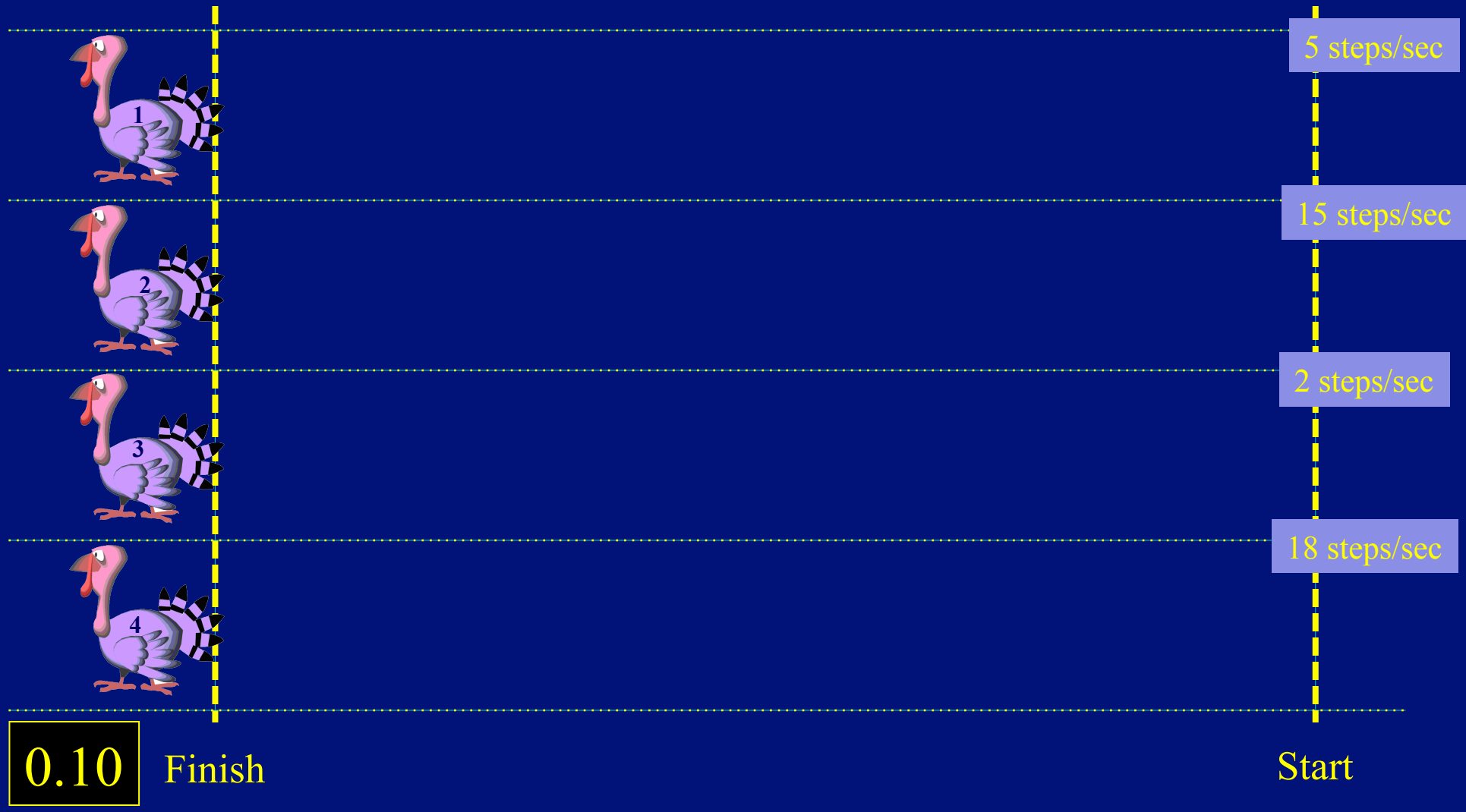

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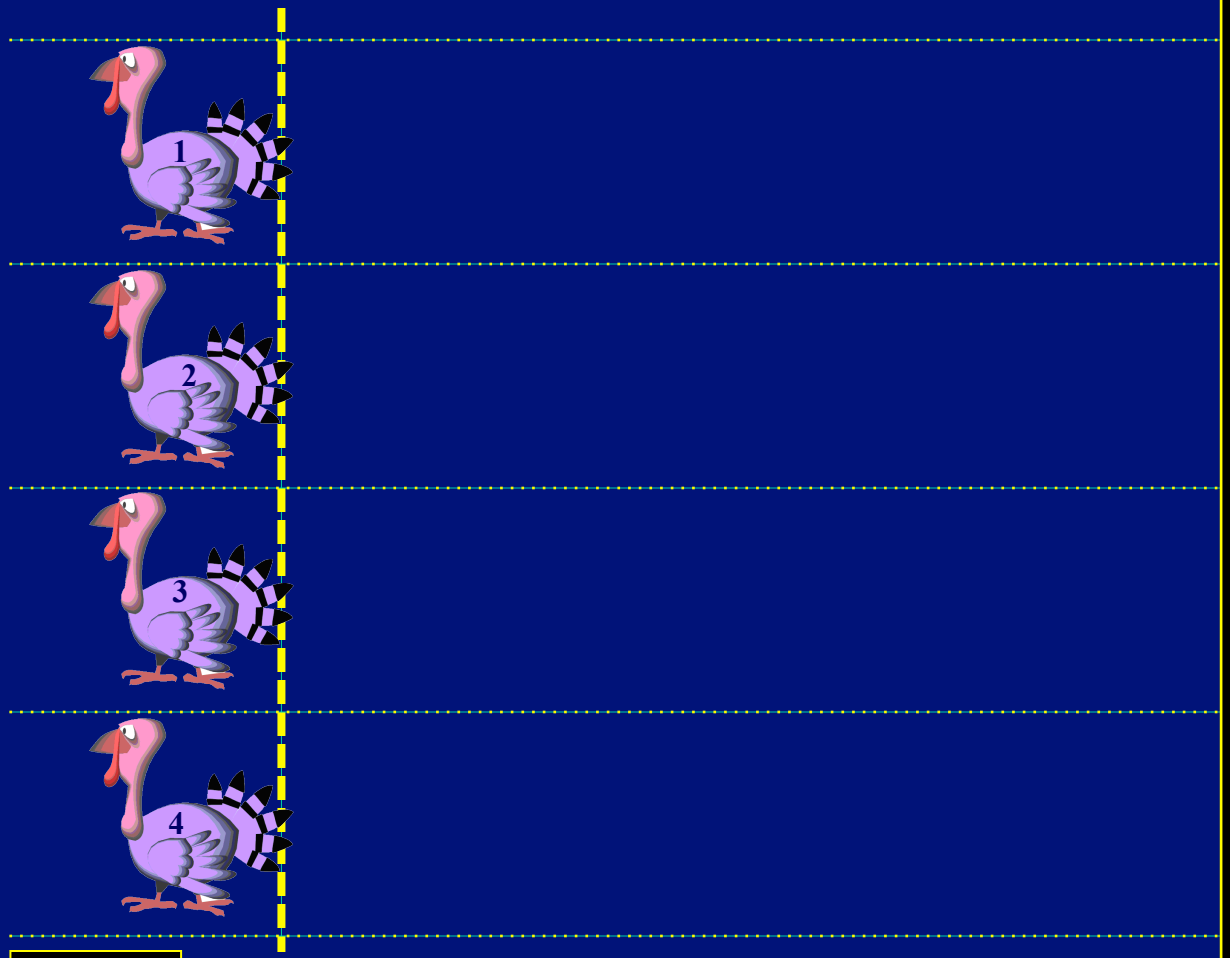
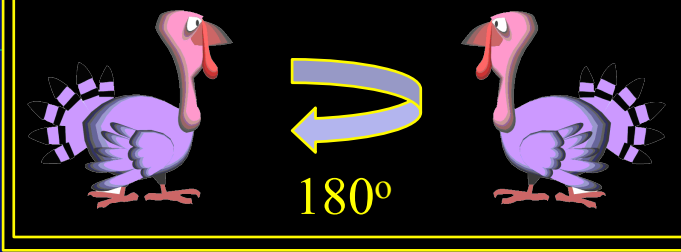


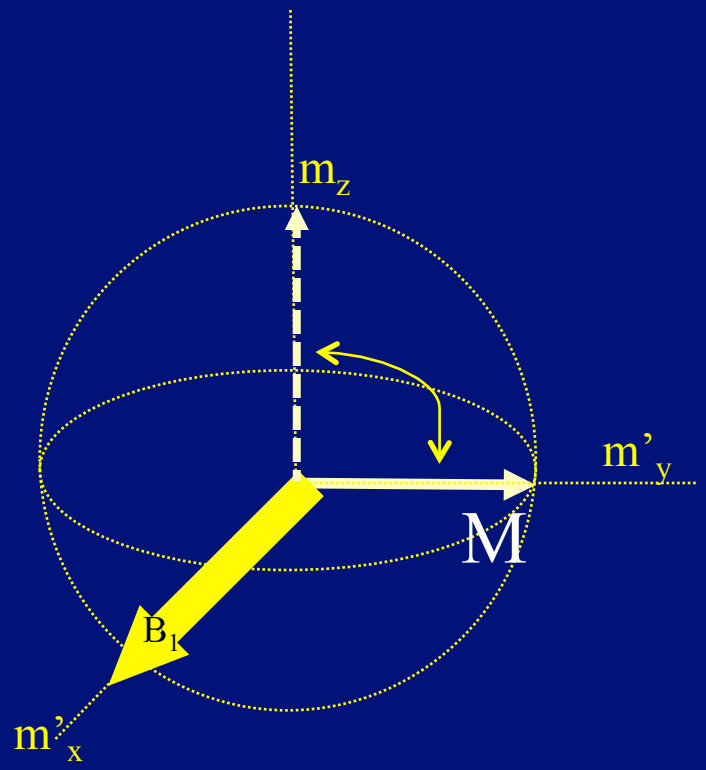
The 'trick' used to bring the racers back to the same location was the 180° reversal.

In MR a similar trick is used on the magnetization vectors.

A 180° RF pulse is used to refocus (rephase) the vectors.

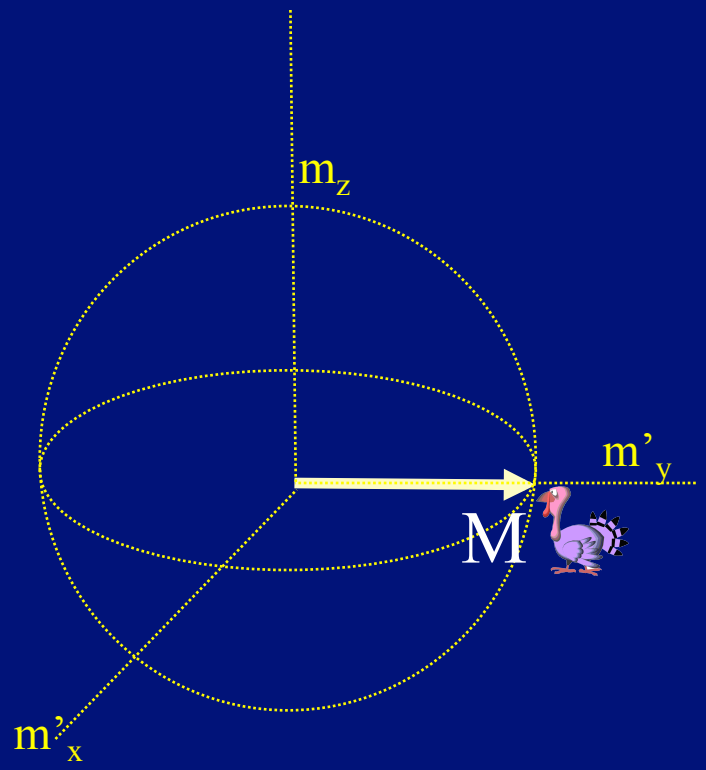


Refocusing (180^{o}) RF Pulse



Recall: Initially, a 90^{o} RF pulse, B_1, is used to 'excite' spins into the transverse plane so that signal detection can proceed.

Refocusing (180^{o}) RF Pulse

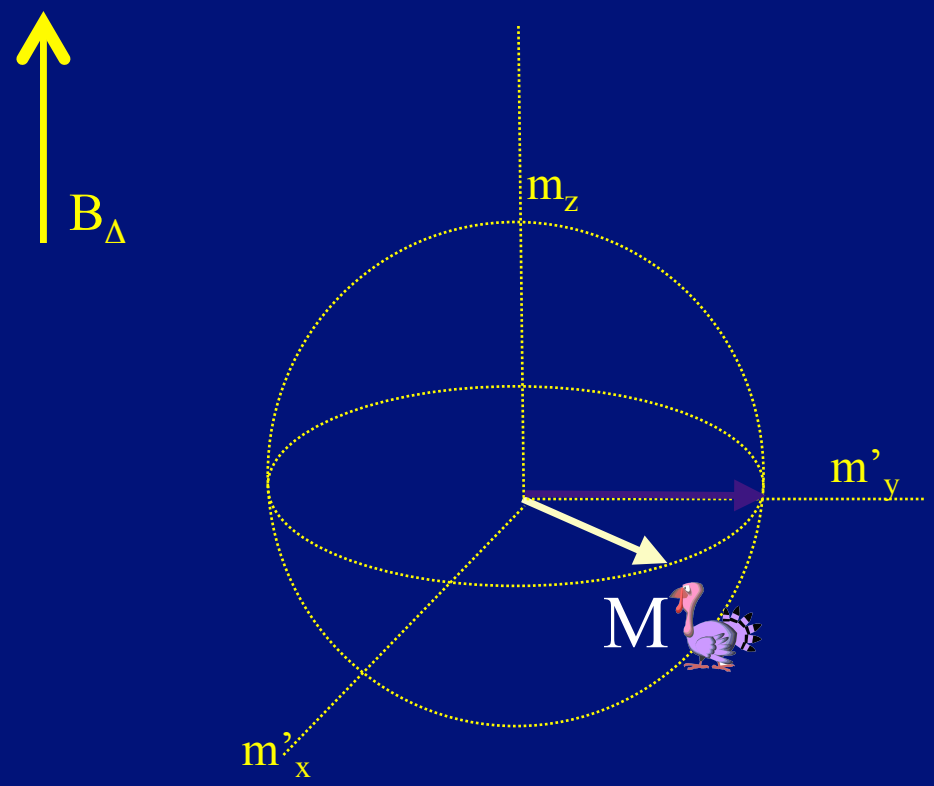


Recall: Initially, a 90^{o} RF pulse, B_1, is used to 'excite' spins into the transverse plane so that signal detection can proceed.

M precesses about the main B_o field direction (m_z), however, in m'_x-m'_y , a frame of reference rotating at the Larmor frequency, M remains stationary.

If B_o is perfectly uniform, all M's in the volume remain stationary and in phase in the rotating frame.

Refocusing (180º) RF Pulse



Position of M after 90º pulse

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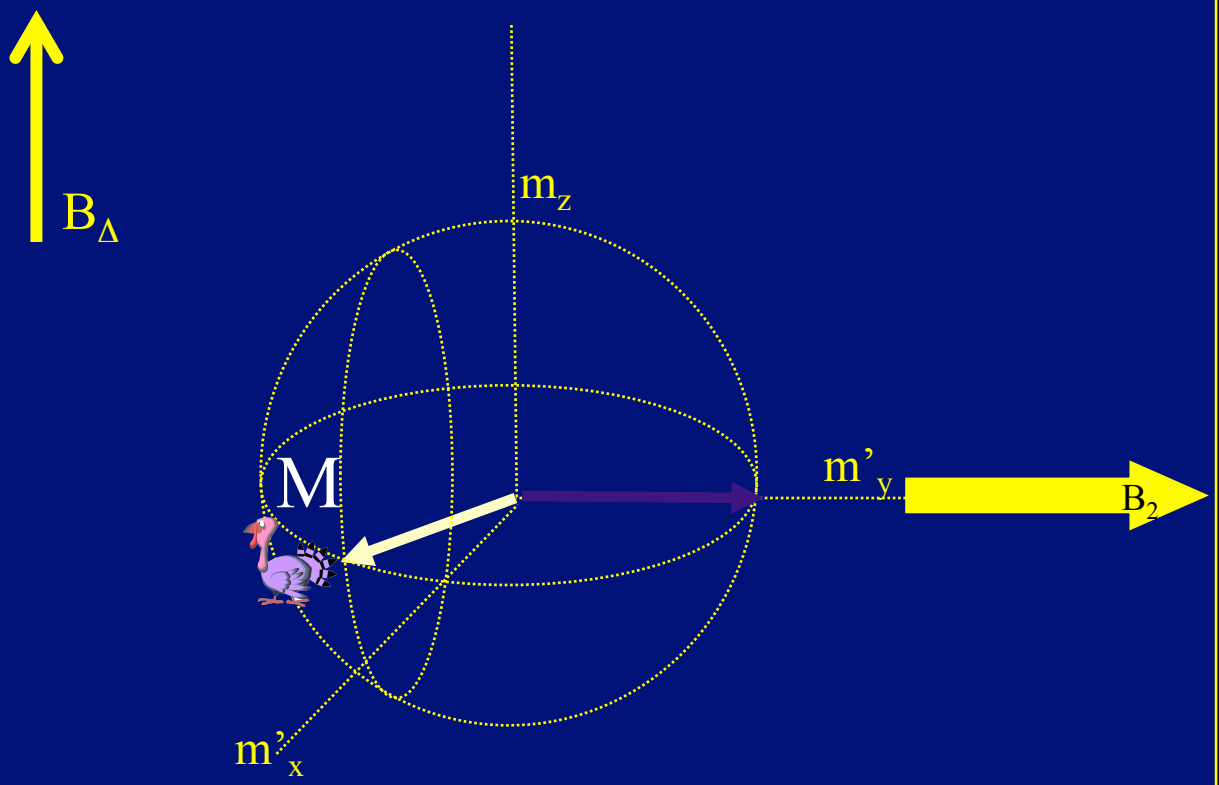
If there is some local variation, B_Δ , in the main field, then M will slowly begin to precess depending of the degree of the variation.

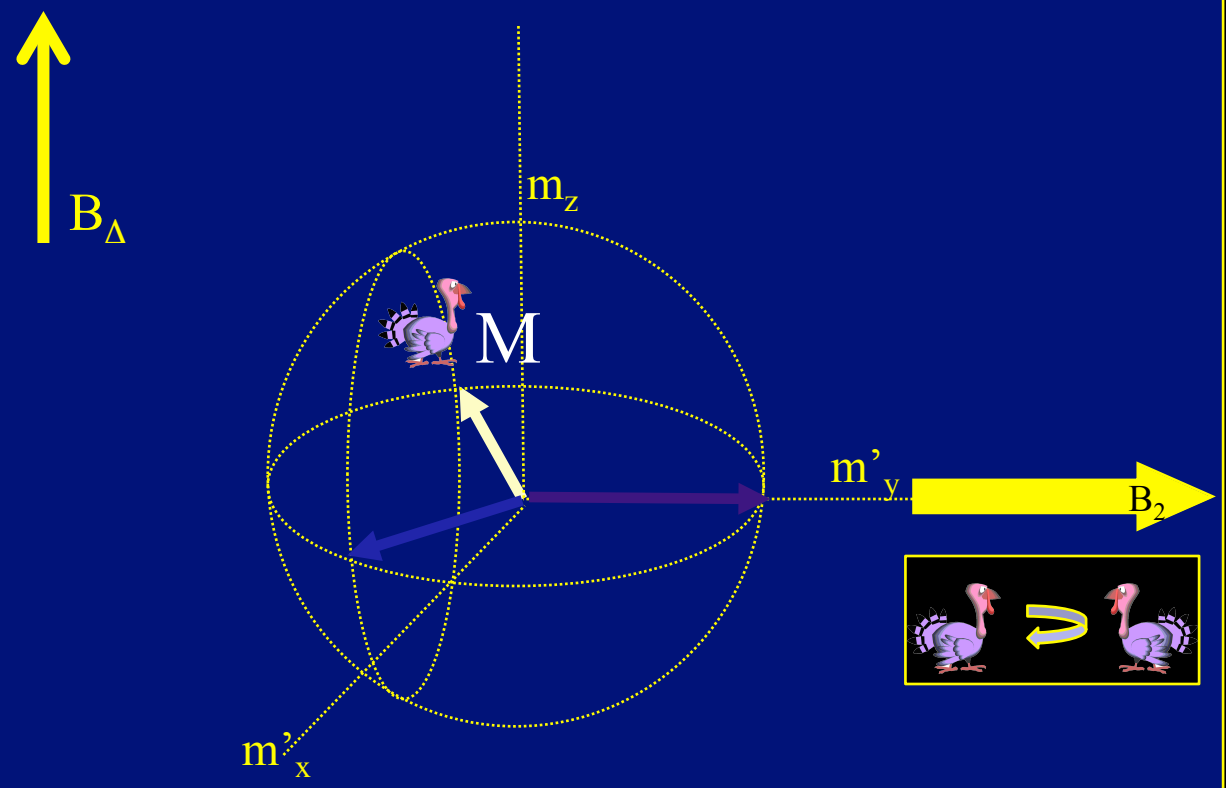
Refocusing (180º) RF Pulse



Position of M after 90º pulse

The Trick: After some time, T, another RF pulse, B2, is applied. This time, the RF pulse is used in order to rotate M about the m'_y axis.

Refocusing (180º) RF Pulse

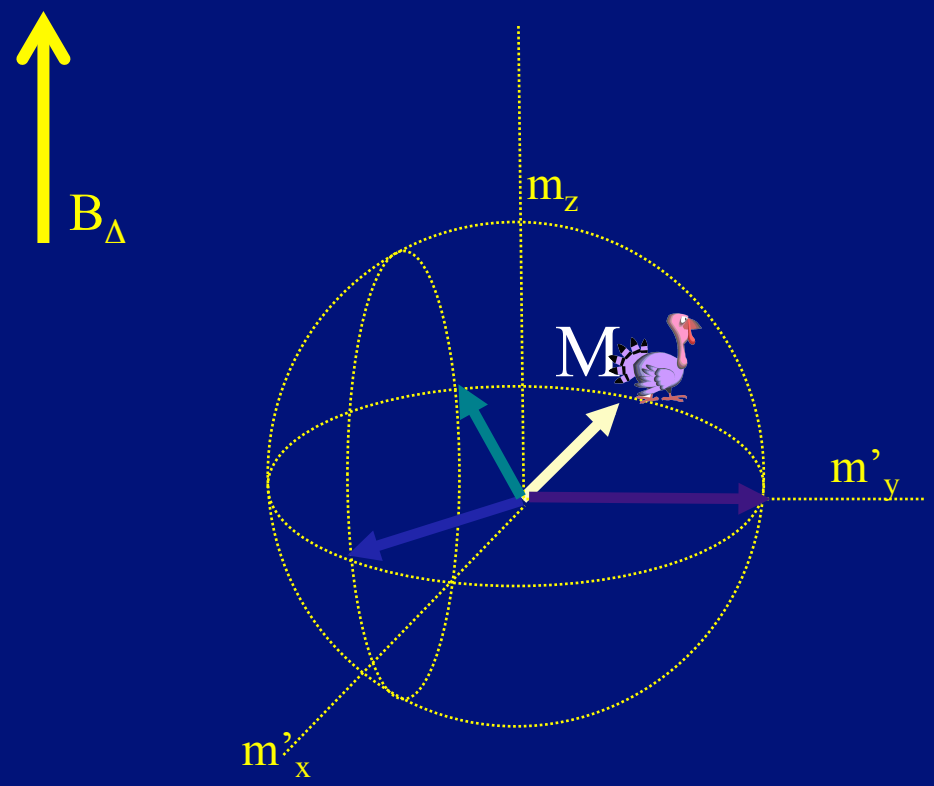


Position of M after 90º pulse
Position of M after time T

The Trick: After some time, T, another RF pulse, B2, is applied. This time, the RF pulse is used in order to rotate M about the m'_y axis.

The B_2 pulse is applied for just enough time to rotate M 180º and bring it back into the opposite side of the transverse plane.

Refocusing (180º) RF Pulse



Position of M after 90º pulse
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Position of M after 180º pulse

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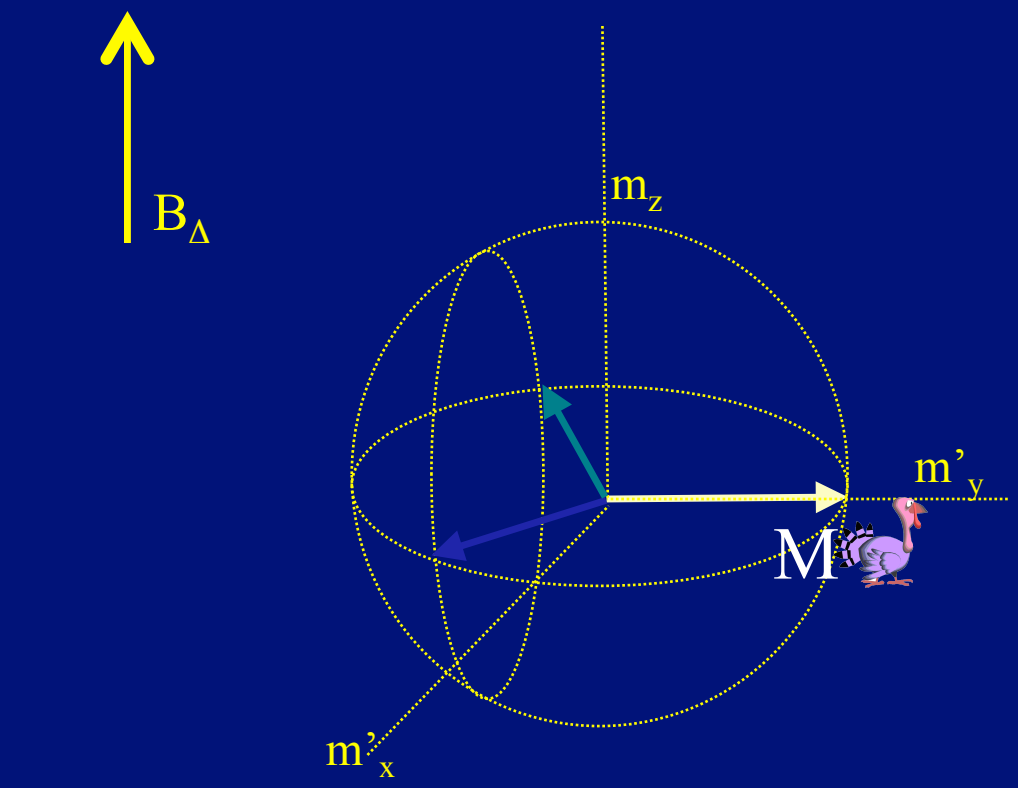
The B_2 pulse is turned off and meanwhile M continues to precess from its new position.

Refocusing (180º) RF Pulse



Position of M after 90º pulse
Position of M after time T
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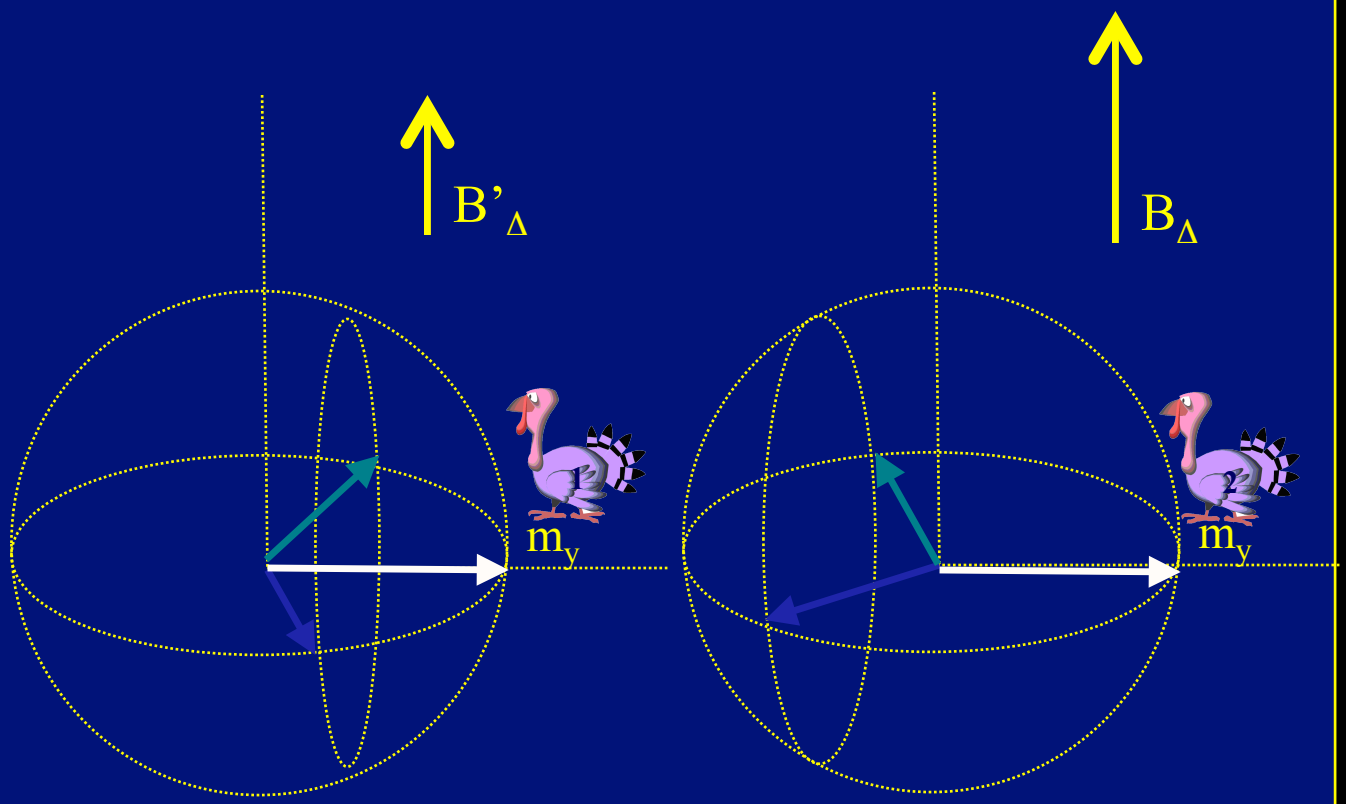
The B_2 pulse is turned off and meanwhile M continues to precess from its new position.

After a second time T (following the application of B_2), M will return to its original position.

Refocusing (180º) RF Pulse

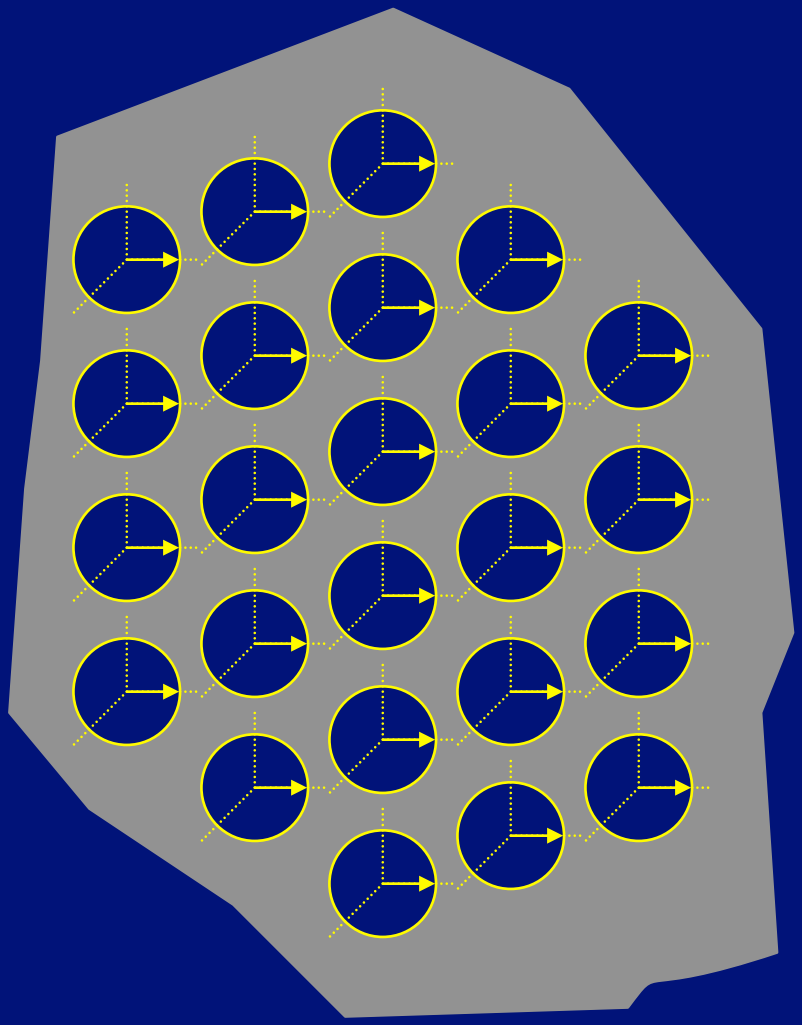


Position of M after 90º pulse
Position of M after time T
Position of M after 180º pulse

The M's in different parts of the volume will precess different amounts depending on the local variation in the main field.

Regardless of the local field variations, however, all M's will return to their original position at time, 2T, after the initial 90º B_1 pulse and time, T, after the B_2 pulse.

Refocusing (180^{o}) RF Pulse



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Regardless of the local field variations, however, all M's will return to their original position at time, 2T, after the initial 90^{o} B_1 pulse and time, T, after the B_2 pulse.

At time 2T, all the M's are back in phase and the magnetization has been completely refocused.

This refocusing of the magnetization by the 180^{o} pulse is referred to as a spin echo.

Main Areas Covered in Lecture

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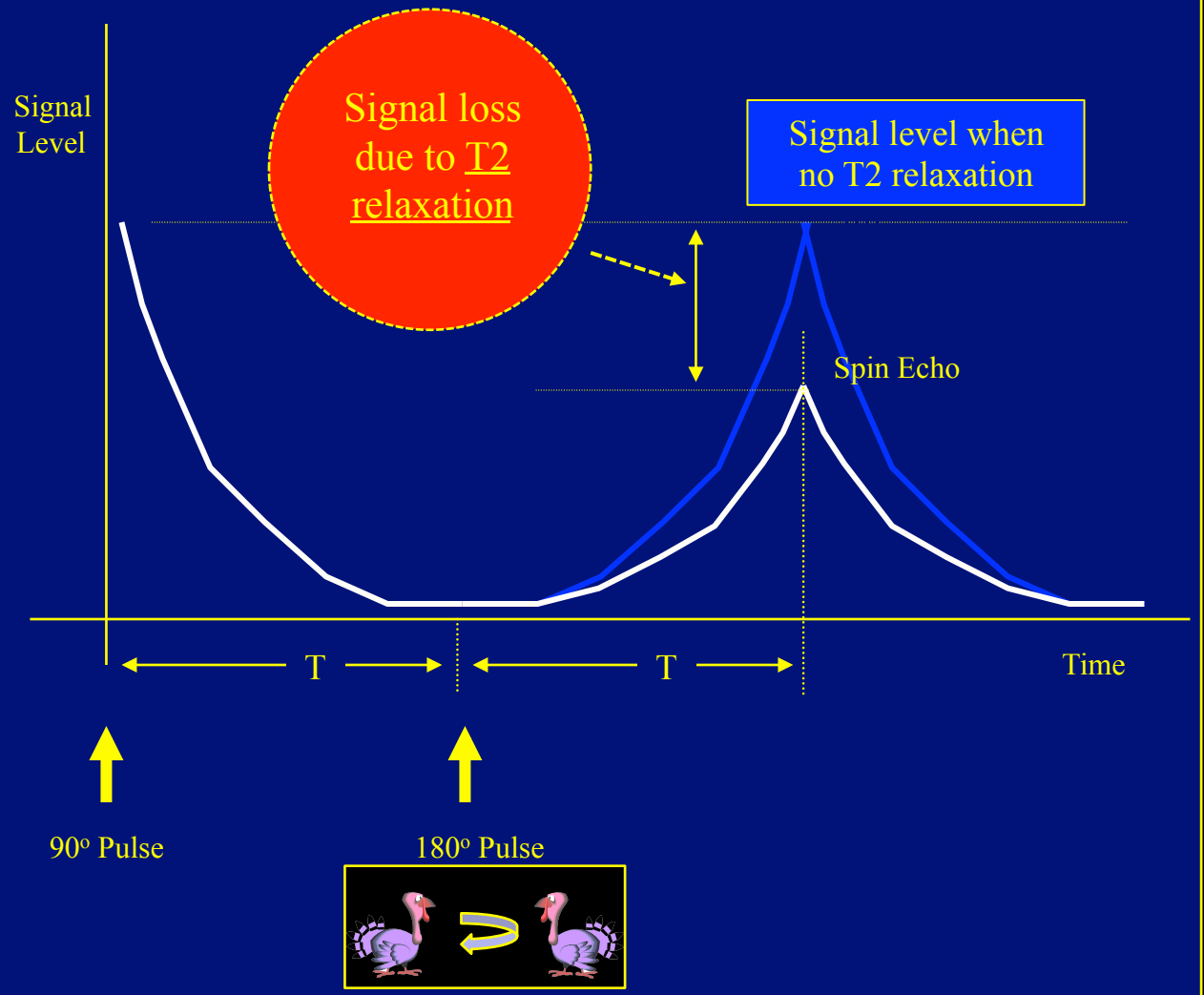
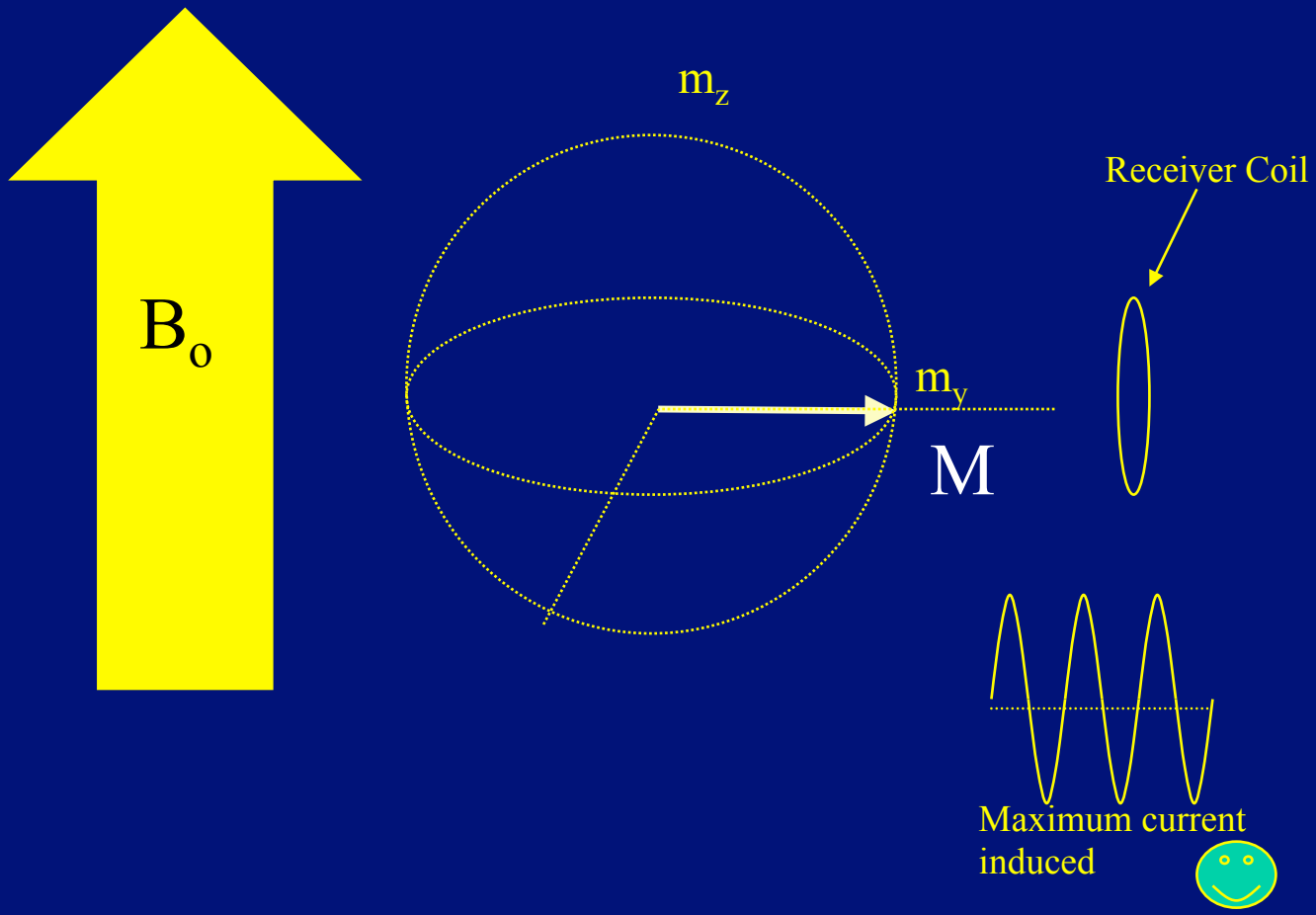
Spin-echo signal: T2 Relaxation



Summary: With the 180° refocusing pulse, applied at time T after the initial excitation, the magnetization vectors throughout the volume will come back into phase after an additional time T.

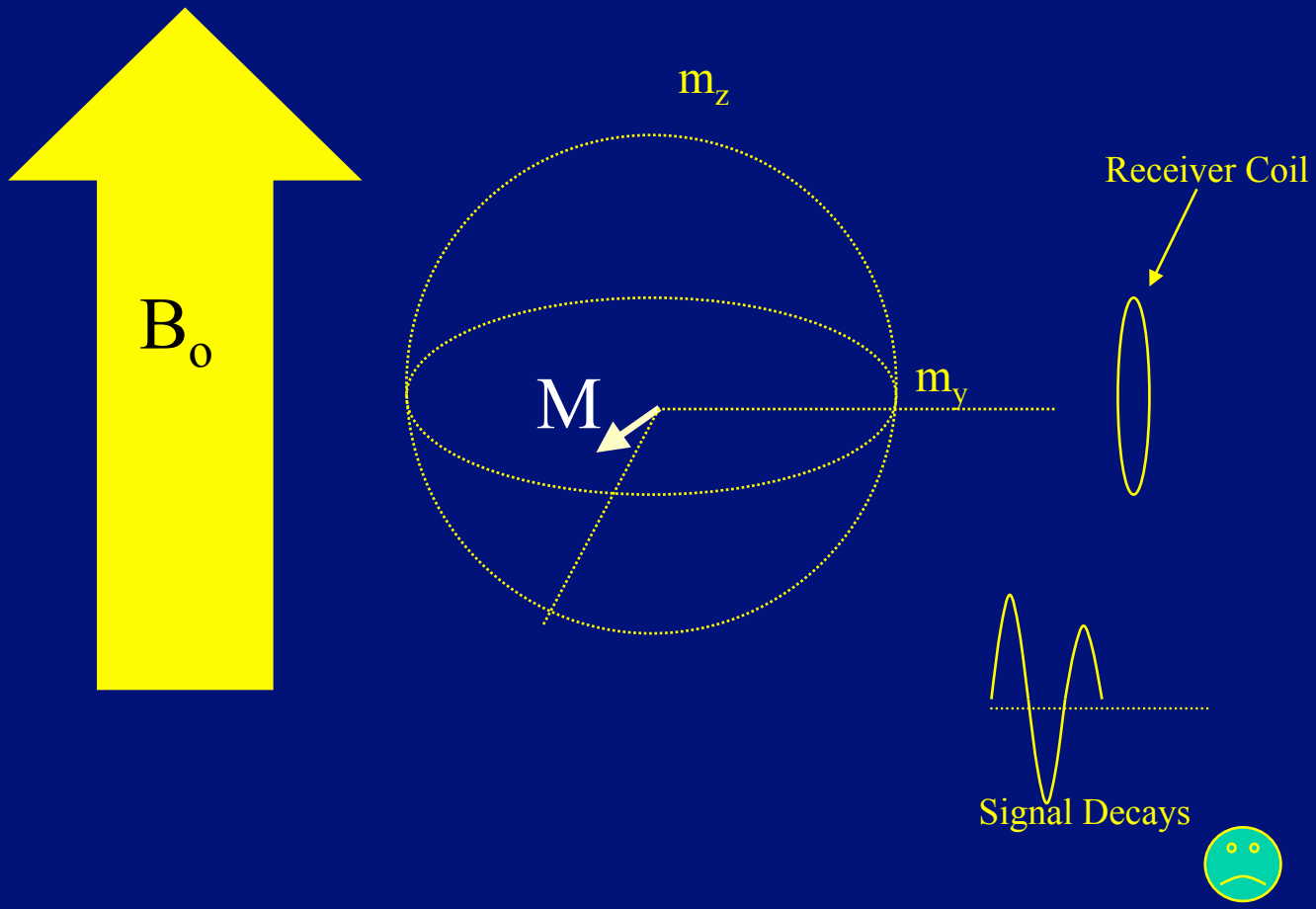
The full signal is not recovered, however, due to T2 relaxation whereby the magnitude of the individual M vectors decay (get shorter) as a result of irreversible processes on a molecular level.

T2 Relaxation



Without dephasing of the M vectors, signal would not decay if it were not for T2 relaxation.

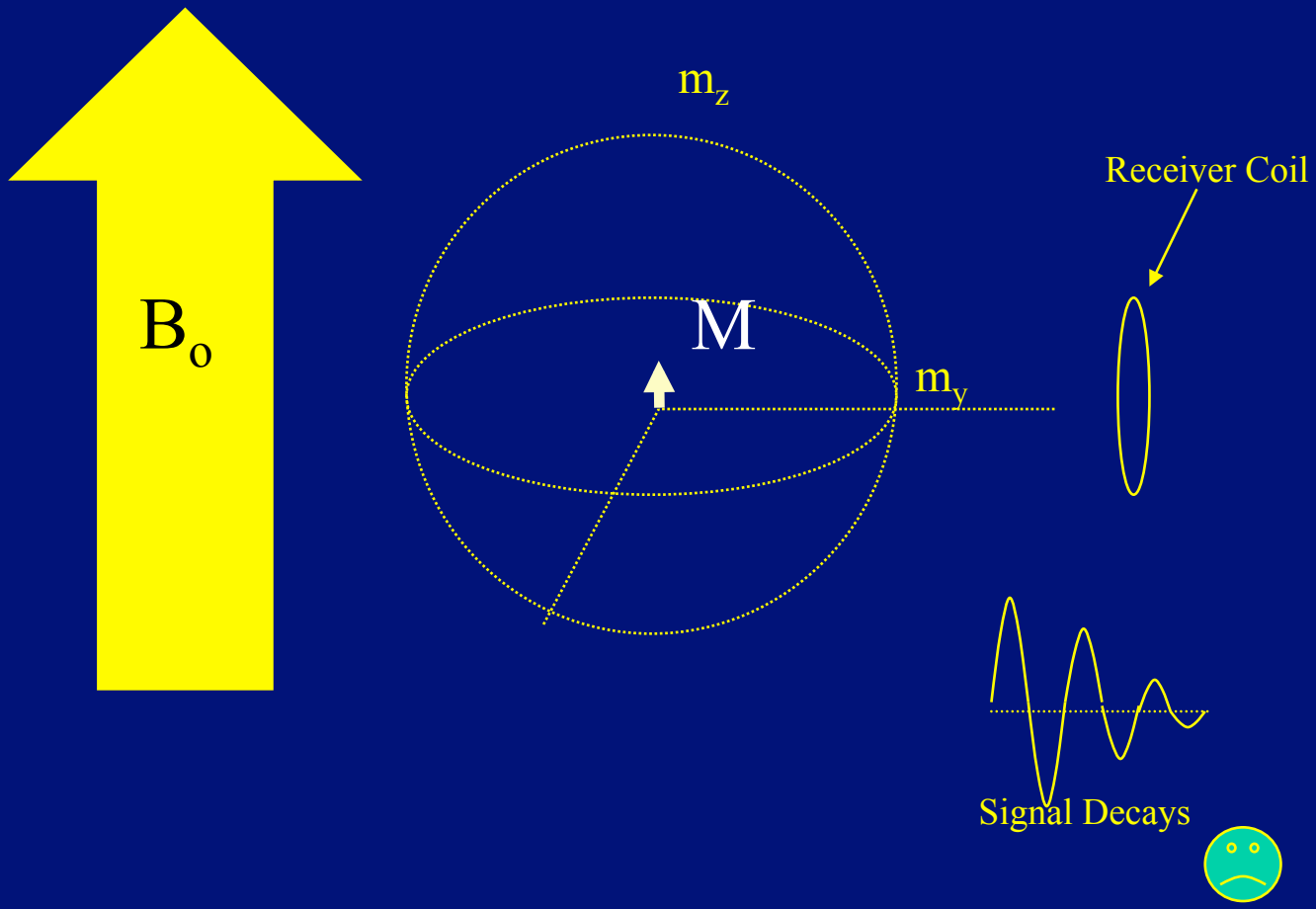
T2 Relaxation



Without dephasing of the M vectors, signal would not decay if it were not for T2 relaxation.

However, M itself decays (becomes shorter) due to destructive signal interference, which is caused by microscopic interactions between neighboring spins.

T2 Relaxation

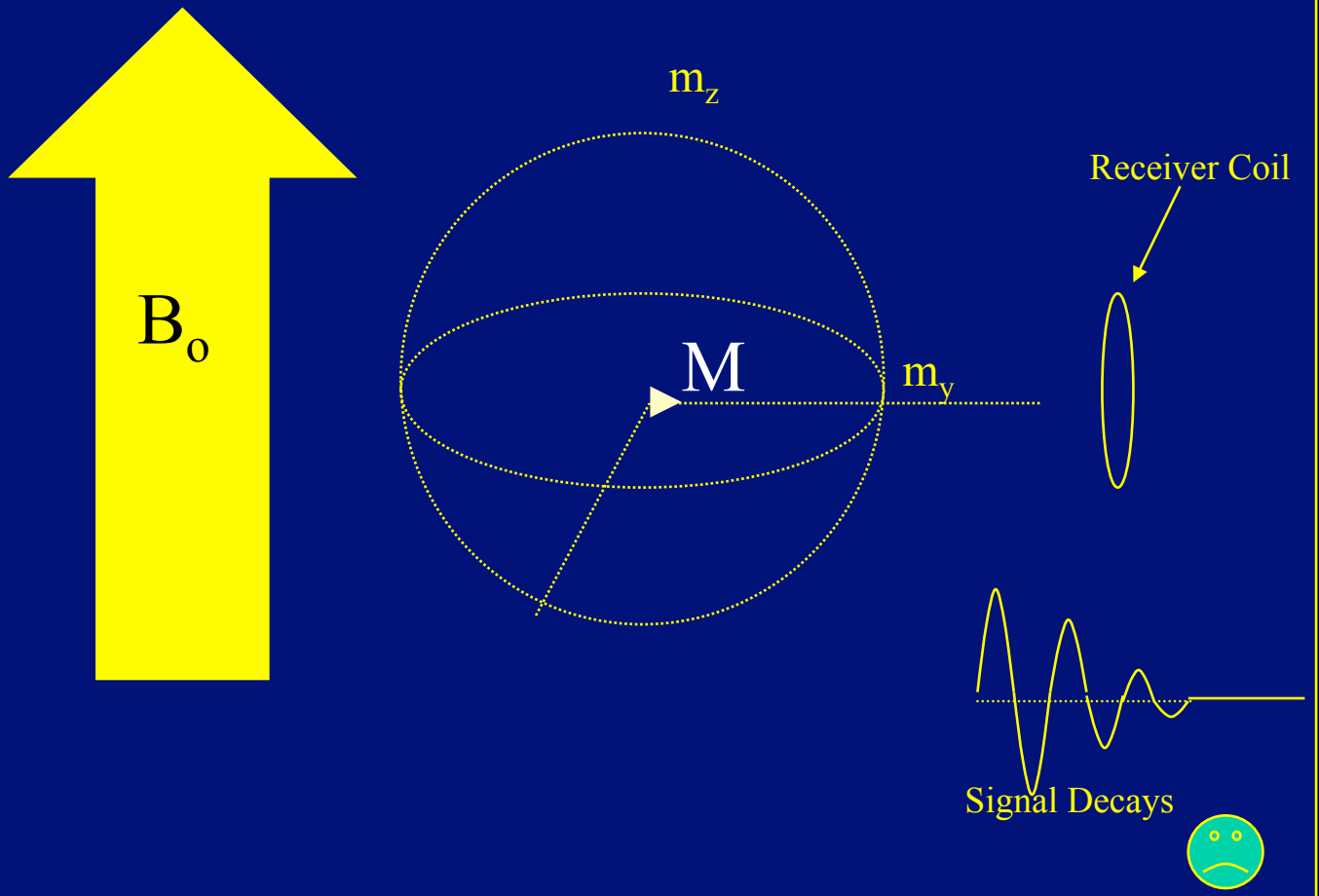


Without dephasing of the M vectors, signal would not decay if it were not for T2 relaxation.

However, M itself decays (becomes shorter) due to destructive signal interference, which is caused by microscopic interactions between neighboring spins.

The signal decays, therefore, due to <u>both</u> the dephasing of the M vectors as well as from the decay of the individual M's.

T2 Relaxation



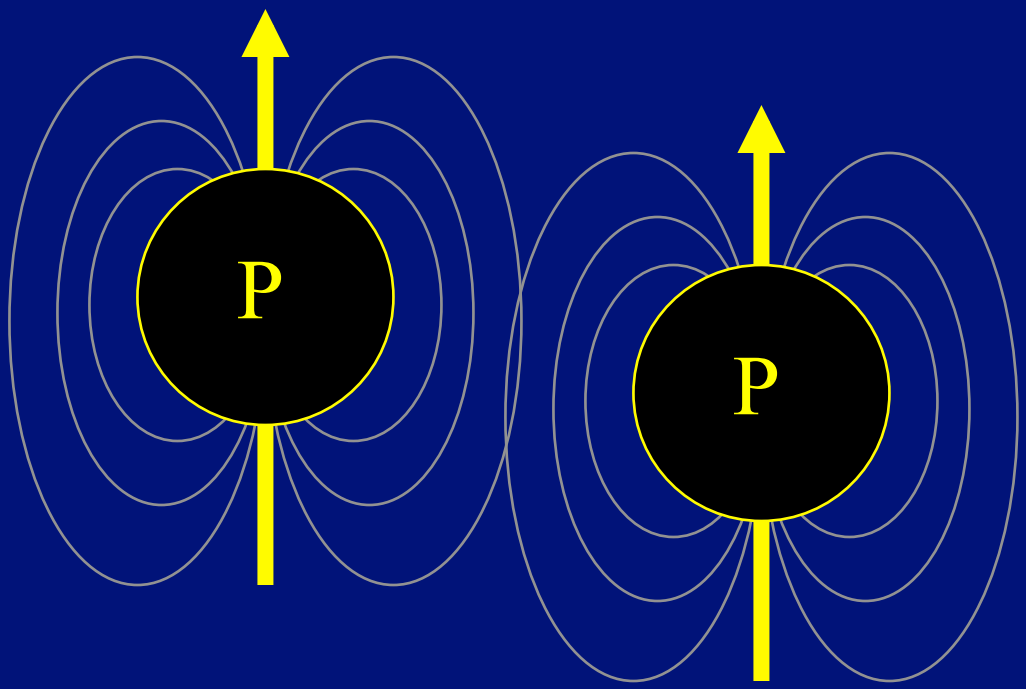
Without dephasing of the M vectors, signal would not decay if it were not for T2 relaxation.

However, M itself decays (becomes shorter) due to destructive signal interference, which is caused by microscopic interactions between neighboring spins.

The signal decays, therefore, due to both the dephasing of the M vectors as well as from the decay of the individual M's.

M decays with a time constant of T2. This process is called T2 relaxation.

T2: Spin-Spin Relaxation

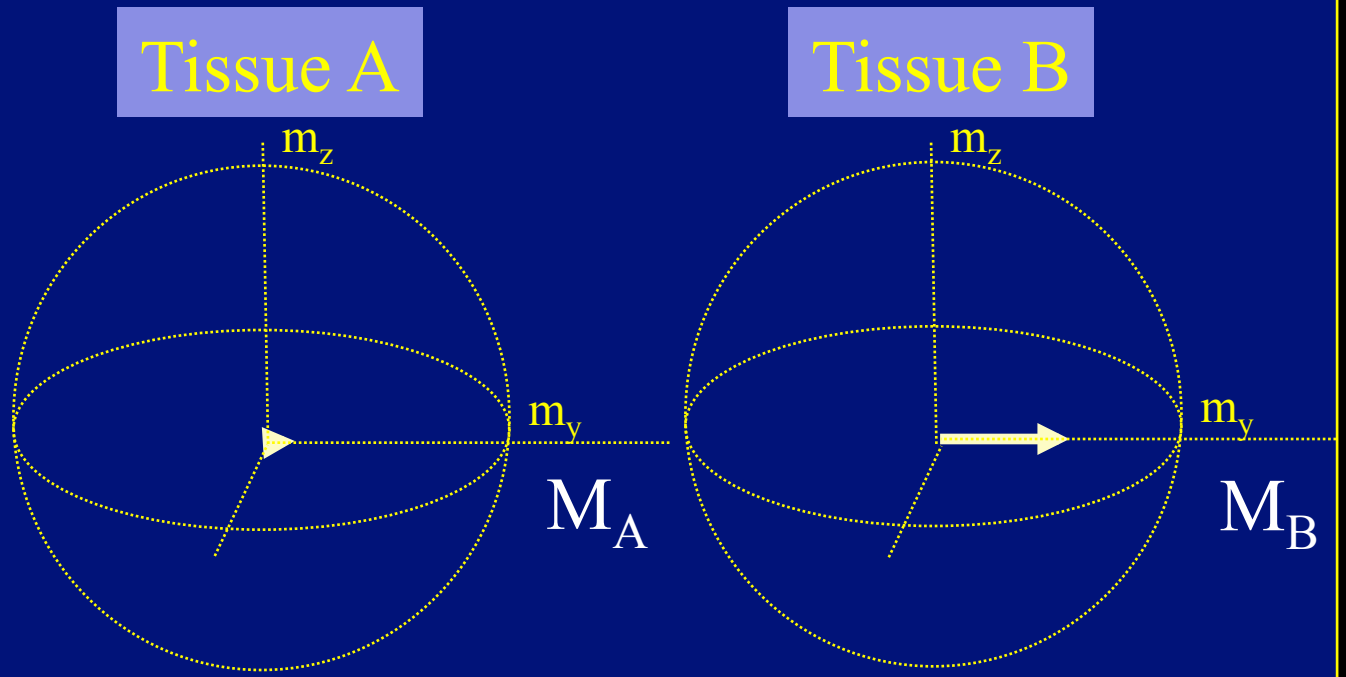


T2 is heavily dependent on the local molecular environment. In general, T2 is shorter for compact tissues and when water is more tightly bound – i.e. when spins are more likely to experience the field of neighboring spins.

T2 is very short in solids. In MRI the signal from solids decays before it can be measured so that solids will be dark in MR images.

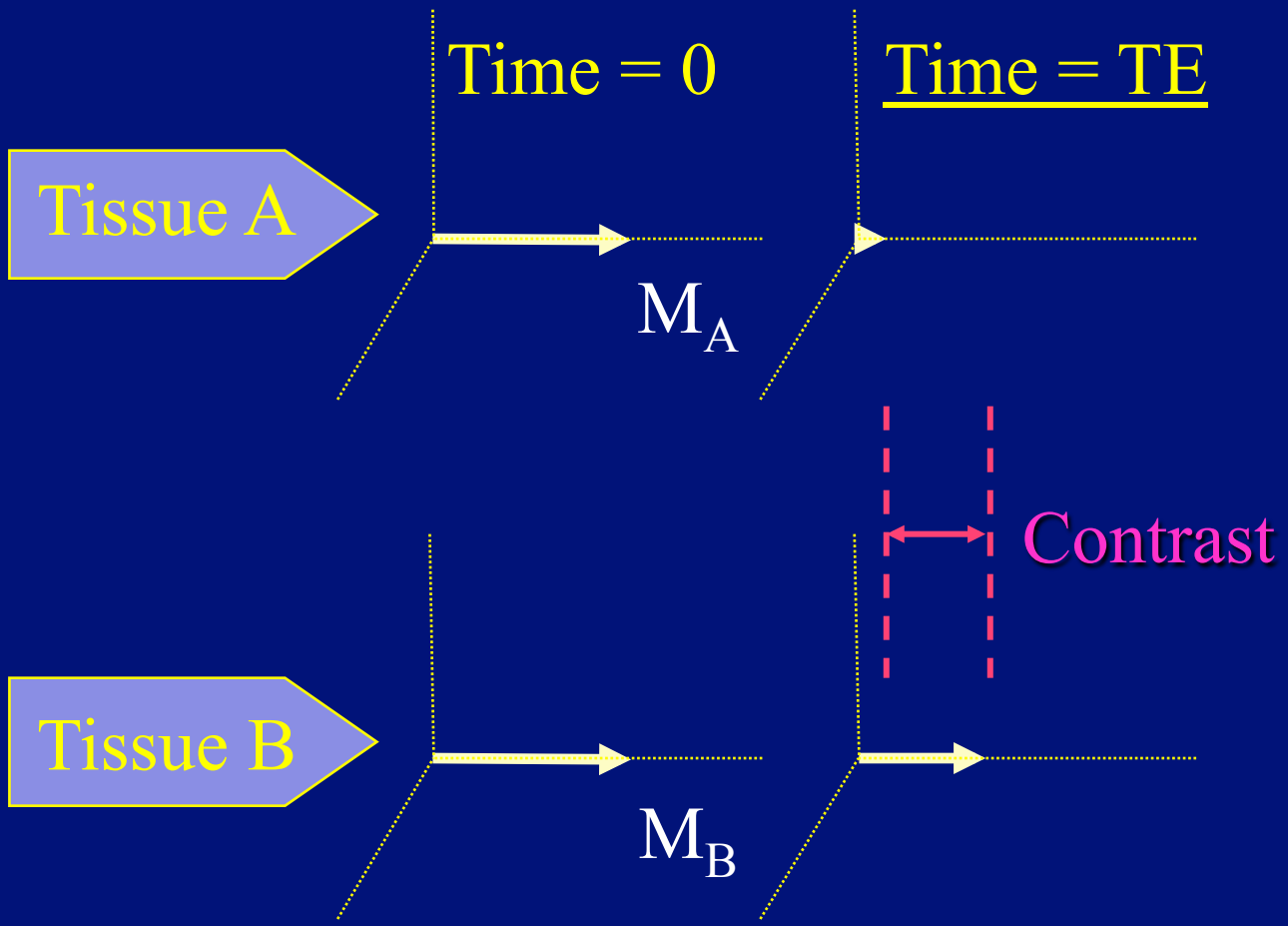
Images can be sensitized to T2 differences – i.e. T2-weighted.

T2 Weighting



The magnetization vectors in tissues with different T2 relaxation times will decay at different rates.

T2 Weighting



The magnetization vectors in tissues with different T2 relaxation times will decay at different rates.

With a long time between RF excitation and signal acquisition time = TE there is contrast between signals from tissues with different T2.

Images acquired this way are called T2-weighted

(Remember: we need a long TE).

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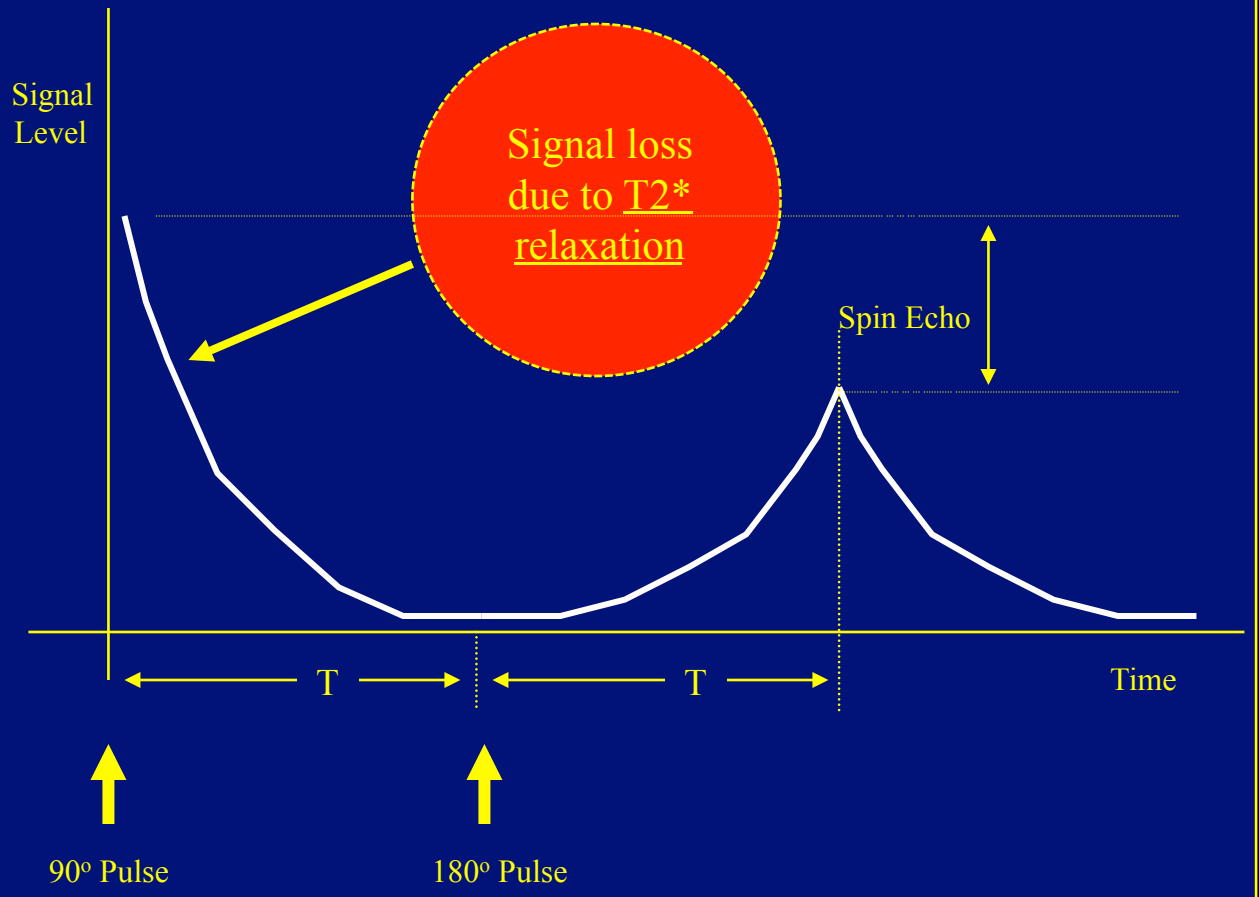
- Proton density and proton-density weighting

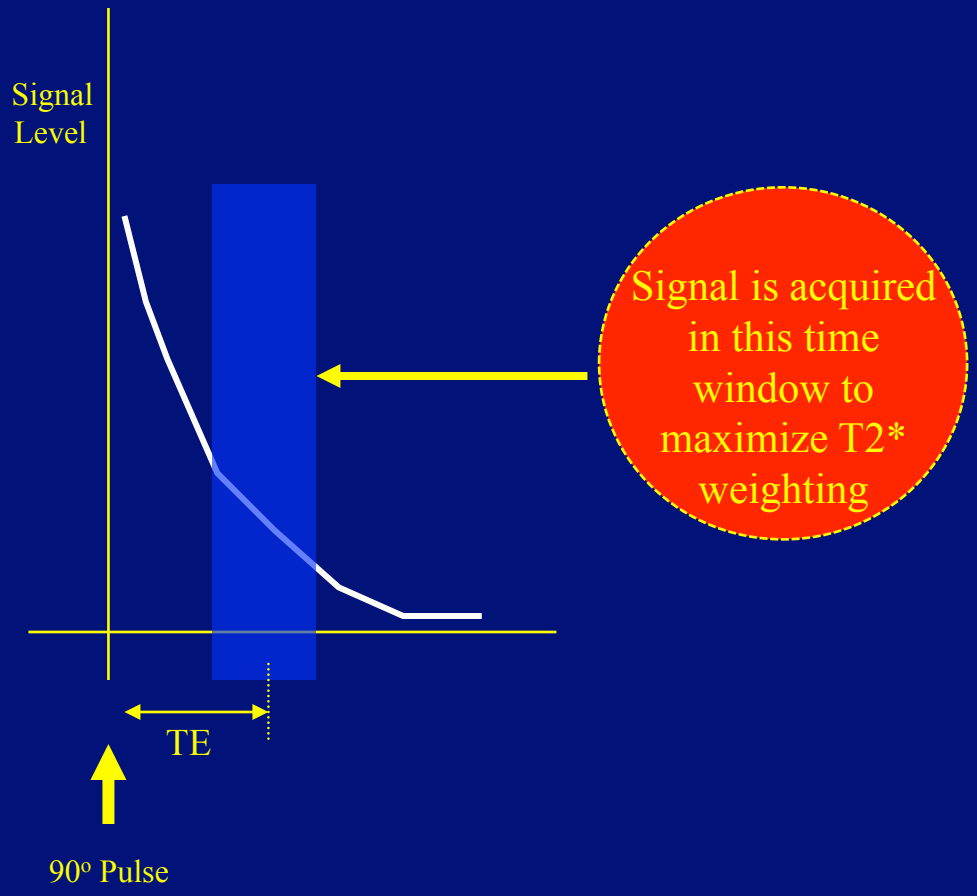
T2* Relaxation



Prior to a 180° pulse, the signal decays due to both T2 relaxation and dephasing of the magnetization.

This initial decay is referred to as T2* relaxation.

T2* Weighting



Prior to a 180° pulse, the signal decays due to both T2 relaxation and dephasing of the magnetization.

This initial decay is referred to as T2* relaxation.

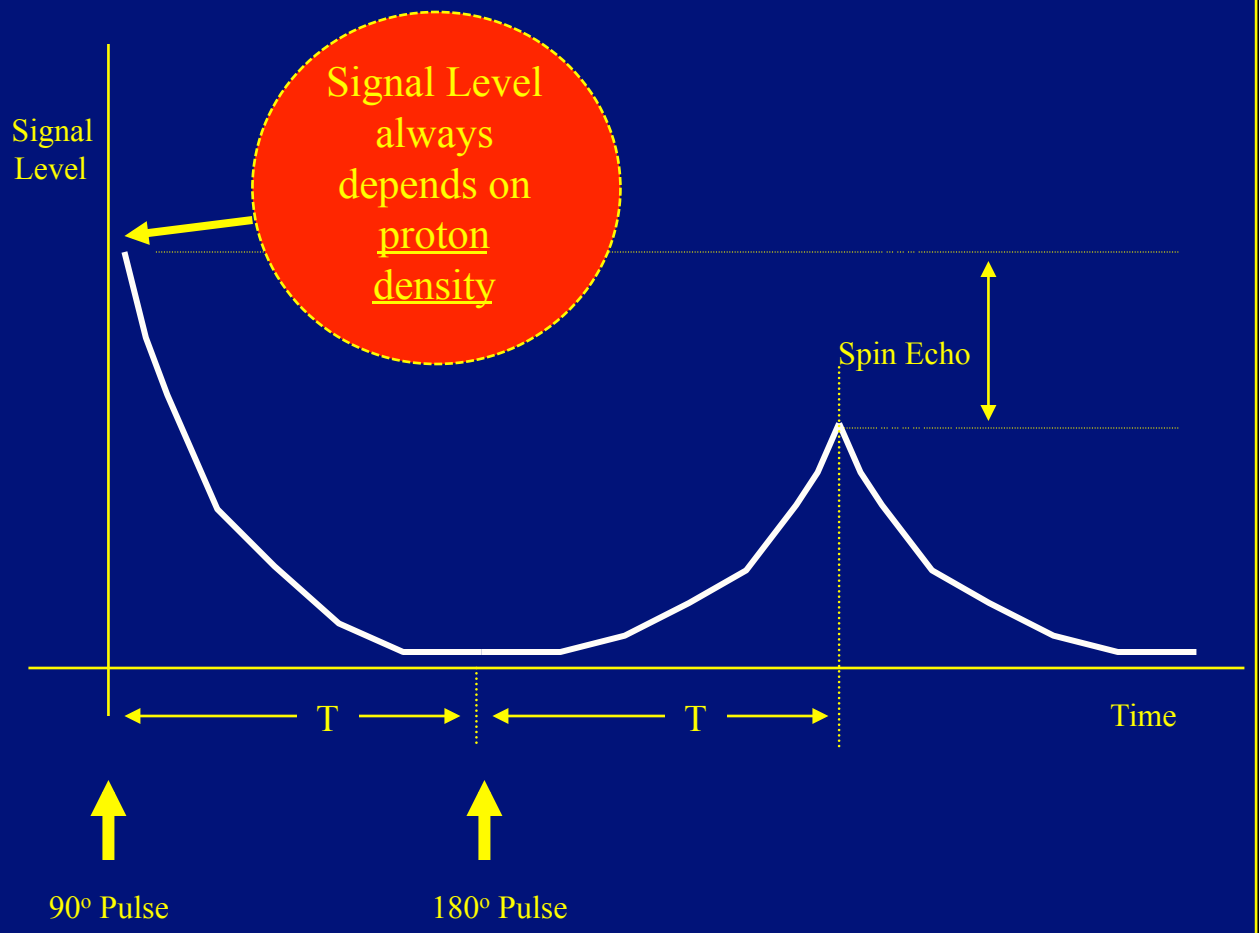
Imaging parameters can be selected to sensitize images to the relative decay of the T2* relaxation.

To do so, a pulse sequence without a 180° pulse is used and the signal is acquired with some significant delay, TE, after the 90° excitation.

Main Areas Covered in Lecture

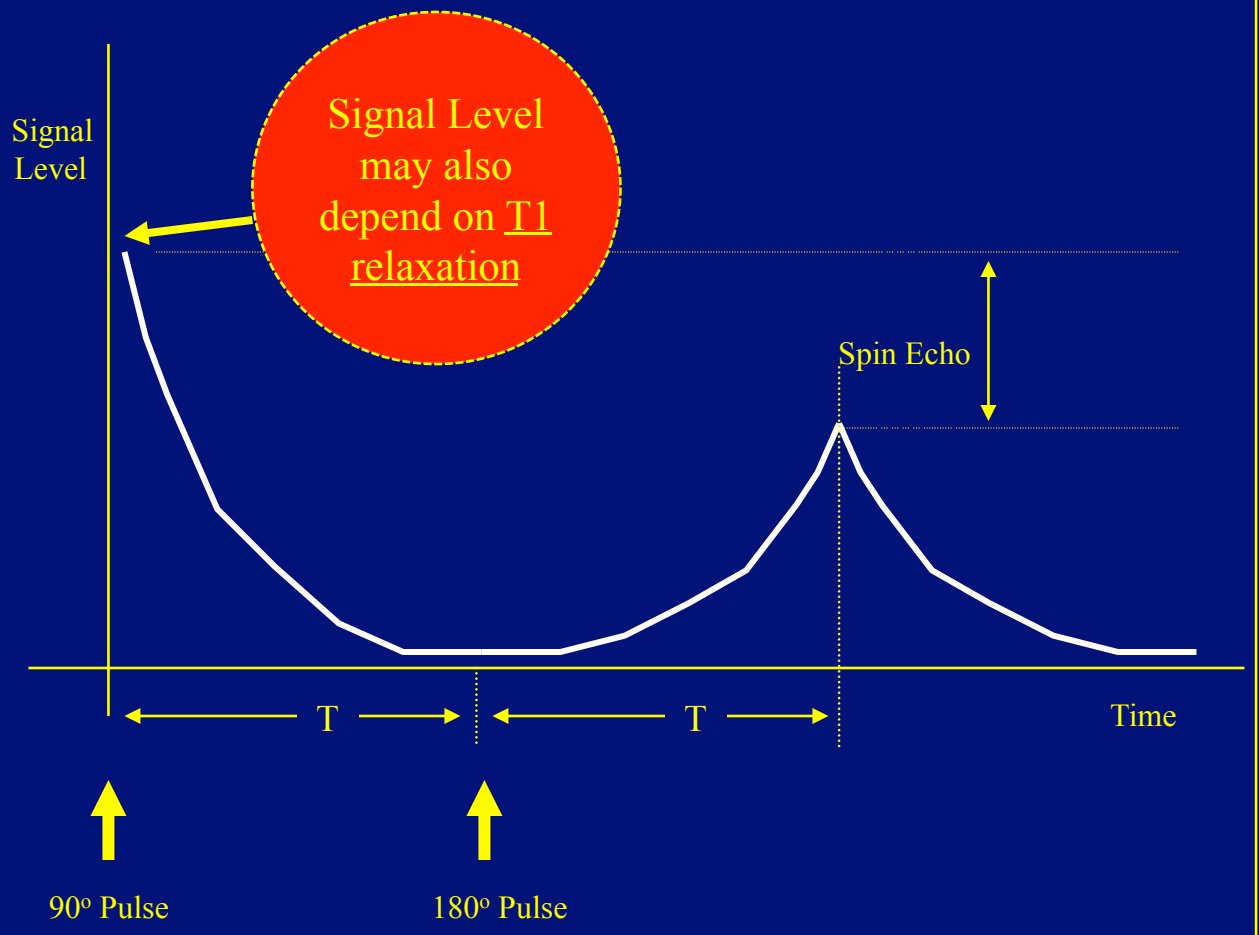
- Phase of the magnetization
- Spin echo and refocusing the magnetization
- T2 relaxation and T2-weighting
- T2* relaxation and T2*-weighting
- T1 relaxation and T1-weighting
- Proton density and proton-density weighting

T1 Relaxation



At equilibrium (in the resting state) the magnitude of the local M vectors is proportional to the proton or spin density – roughly, the amount of (MR visible) material at a location.

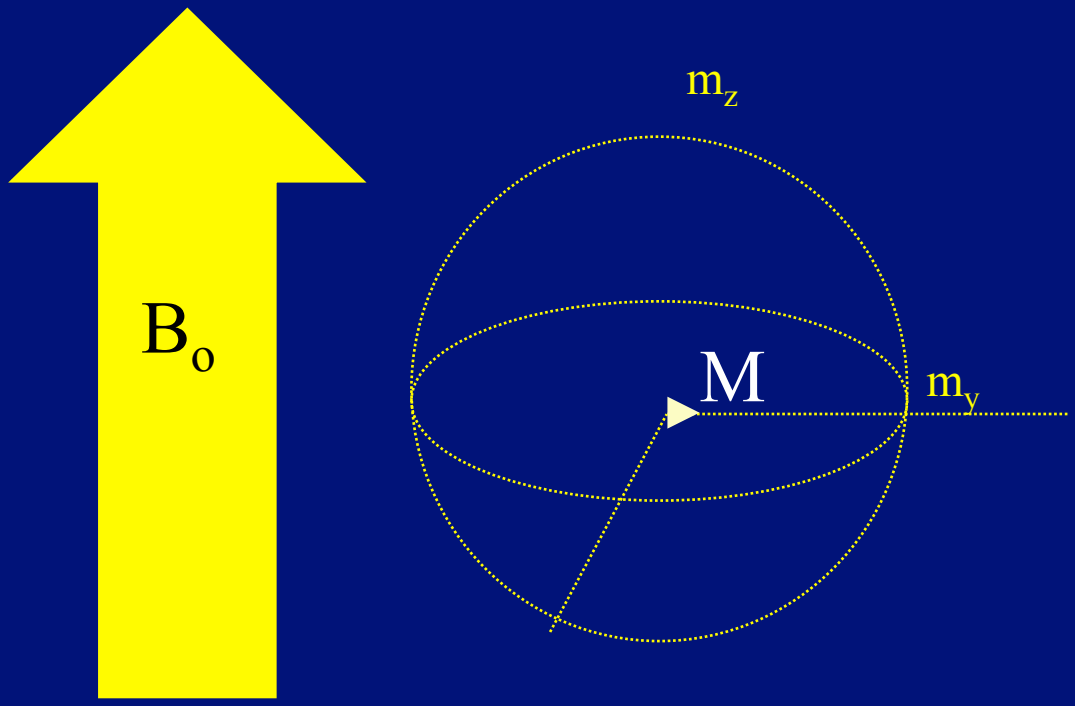
T1 Relaxation



At equilibrium (in the resting state) the magnitude of the local M vectors is proportional to the proton or spin density – roughly, the amount of (MR visible) material at a location.

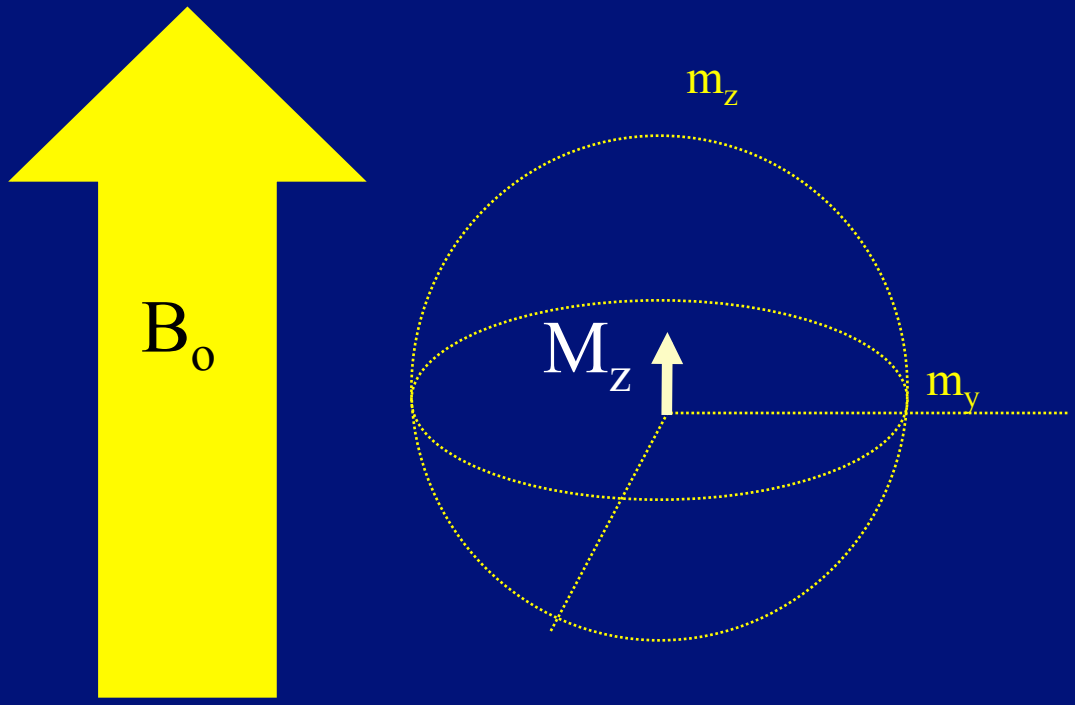
If the magnetization has not fully returned – relaxed - to the equilibrium state from a previous excitation and there is another 90° excitation, then there will be a reduced signal after the next 90° pulse.

T1 Relaxation



After M decays, no more signal can be detected unless there exists a further process that restores the magnetization.

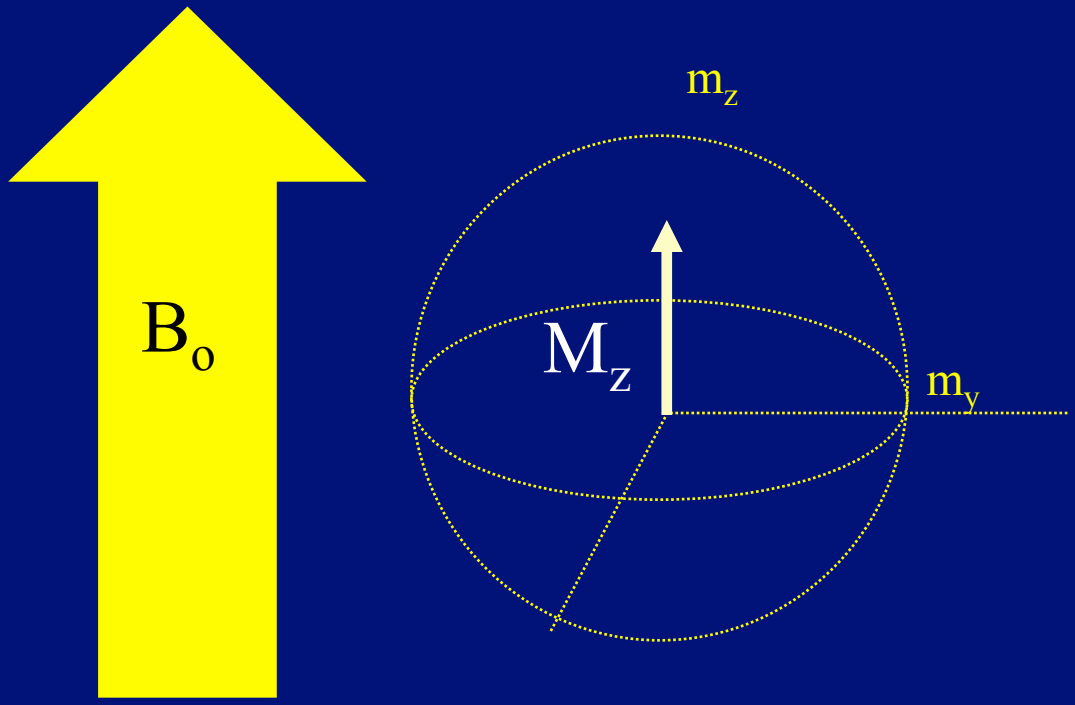
T1 Relaxation



After M decays, no more signal can be detected unless there exists a further process that restores the magnetization.

Fortunately, due to such a process, the magnetization, M_z, eventually begins to reappear along the m_z axis.

T1 Relaxation



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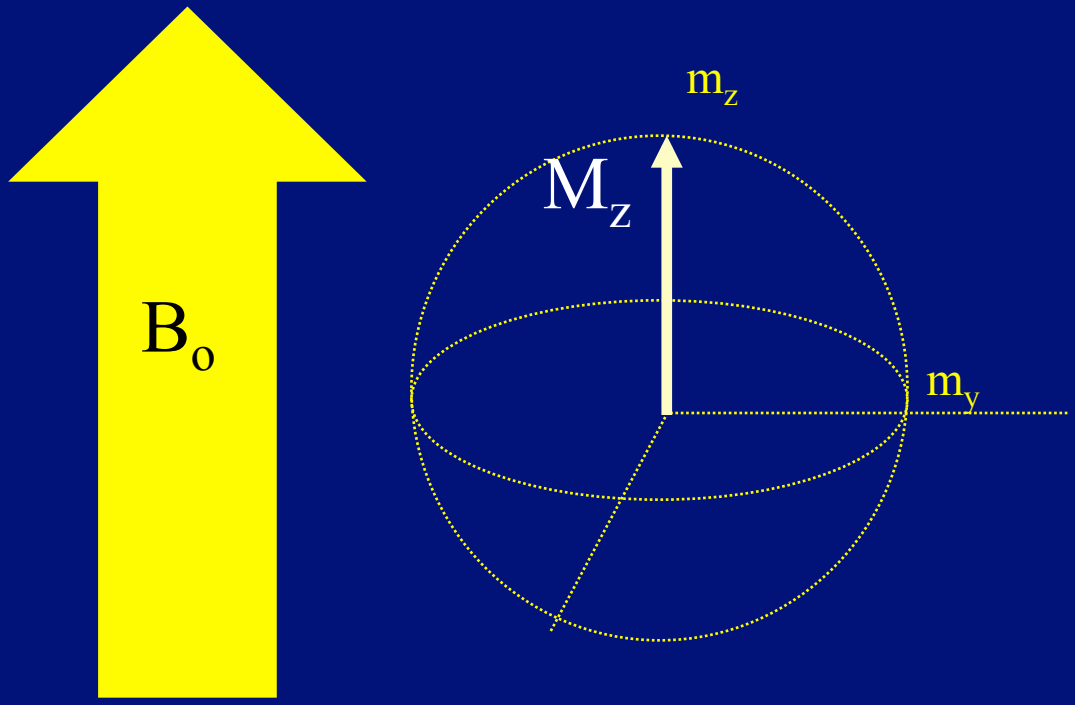
Fortunately, due to such a process, the magnetization, M_z, eventually begins to reappear along the m_z axis.

The magnetization recovers at a rate T1.

T1 Relaxation



$$M_z = M_o (1 - e^{-t/T1})$$

Note: at t=0, $M_z \rightarrow 0$; t>>T1, $M_z \rightarrow$ Mo.

After M decays, no more signal can be detected unless there exists a further process that restores the magnetization.

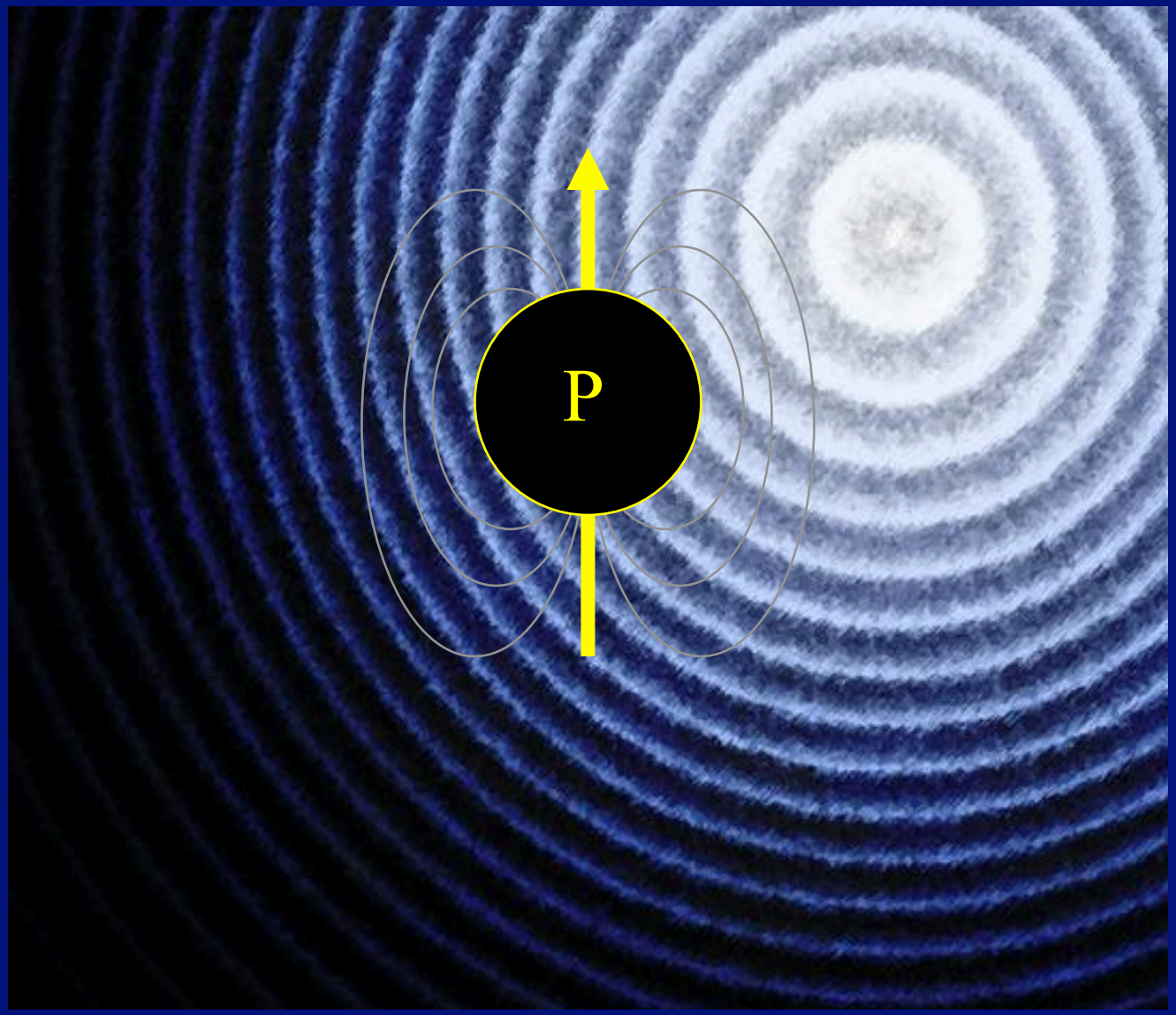
Fortunately, due to such a process, the magnetization, M_z, eventually begins to reappear along the m_z axis.

The magnetization recovers at a rate T1.

When M has fully recovered (after a time >> T1) it reaches its equilibrium value, M_o.

This process is called T1 or Longitudinal Relaxation, although it is really a signal recovery process.

T1: Spin-Lattice Relaxation

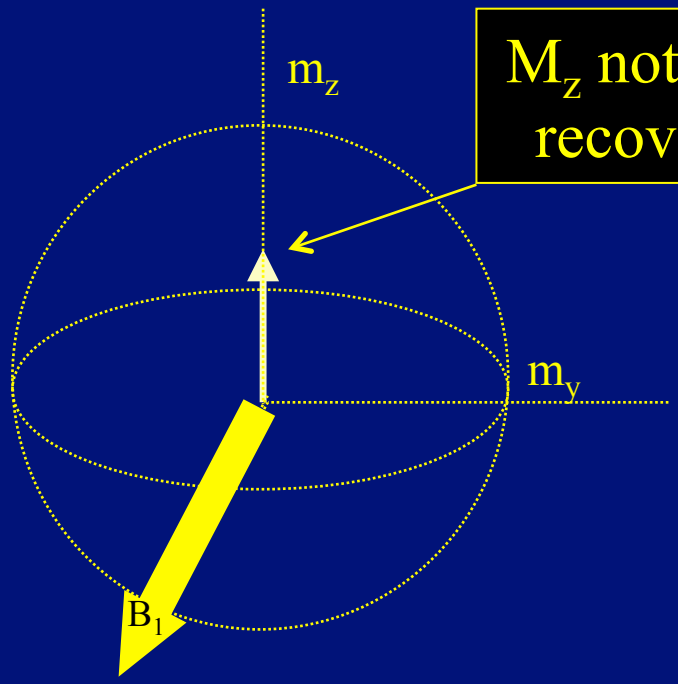


T1 is also dependent on the local molecular environment. Rather than neighboring spin interactions, it depends on the nature of molecular motion in the 'lattice' or environment – specifically motion that is resonant with the Larmor frequency.

T1 is quite dependent on field strength.

Images can be sensitized to T1 differences – i.e. T1-weighted.

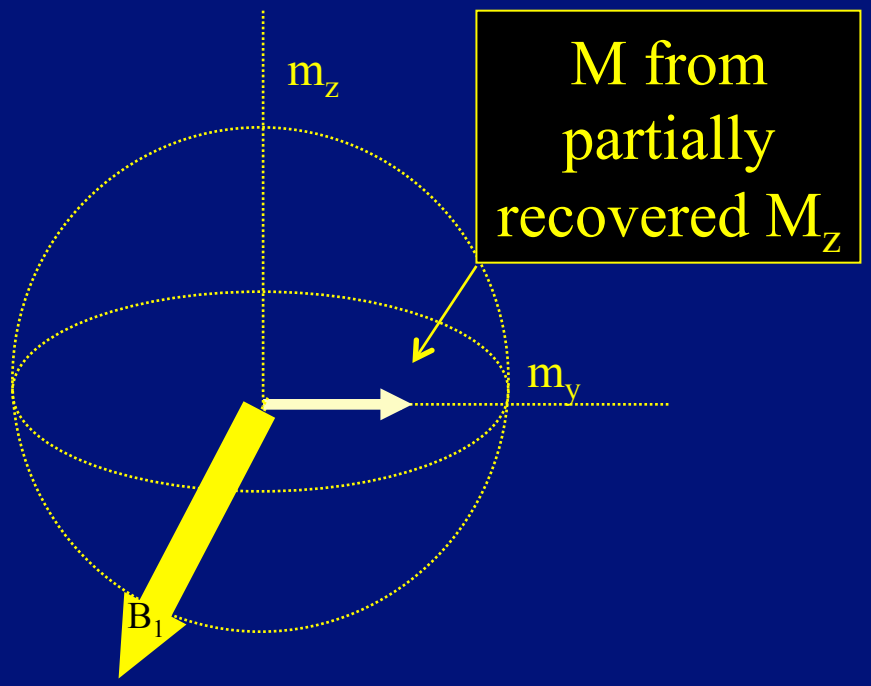
T1 Weighting



$$M_z = M_o (1 - e^{-t/T1}) < M_o$$

T1 weighting occurs when the 90° RF excitation pulse is applied before the longitudinal magnetization has recovered to its full equilibrium value, M_o.

T1 Weighting

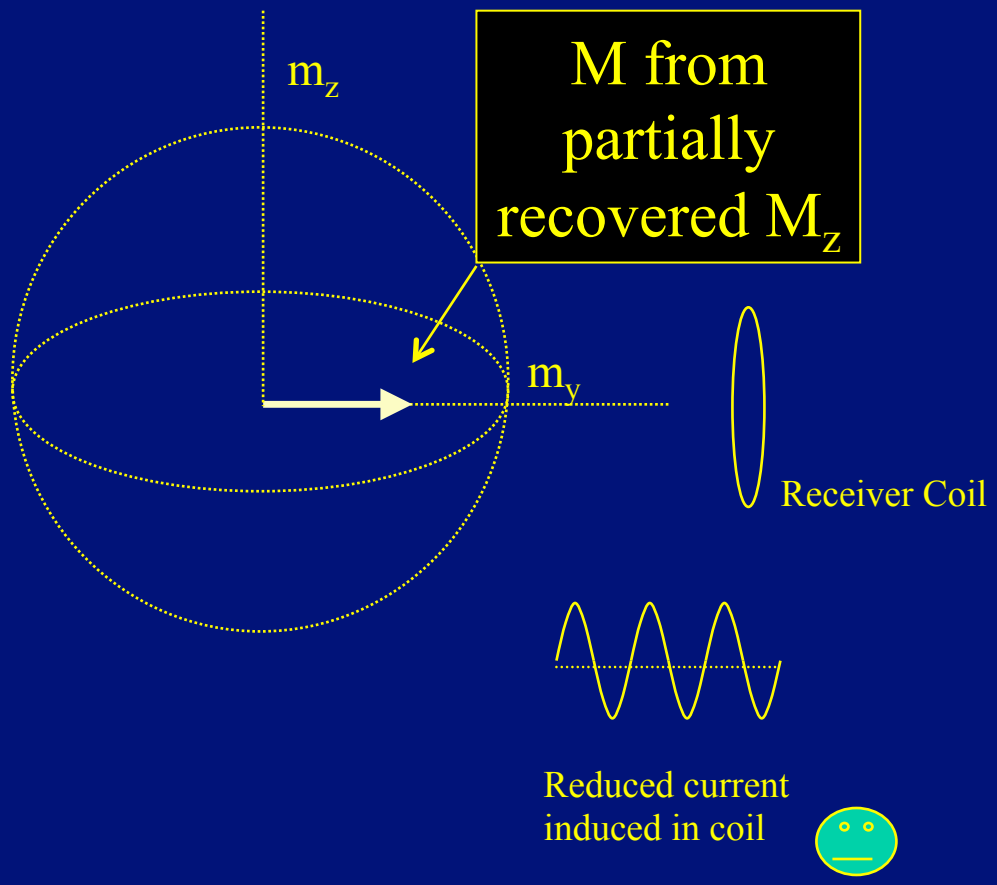


$M<M_o$

T1 weighting occurs when the 90° RF excitation pulse is applied before the longitudinal magnetization has recovered to its full equilibrium value, M_o.

The 90° pulse flips a reduced M into the transverse plane.

T1 Weighting

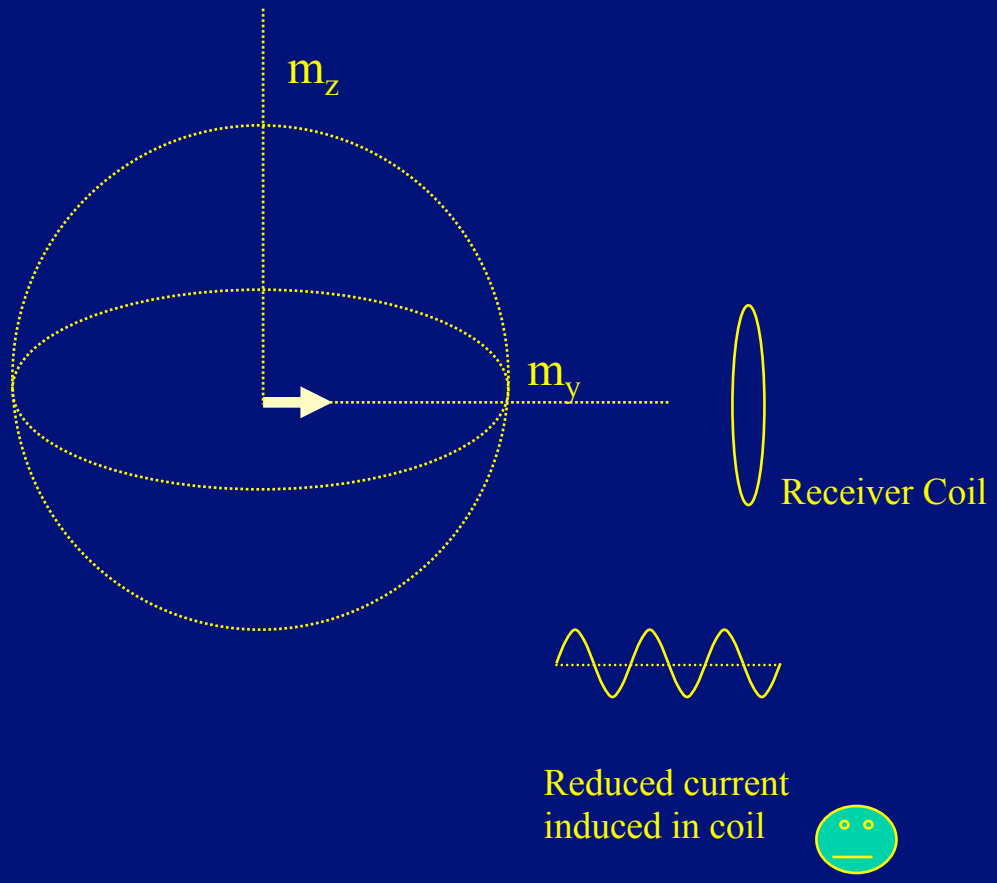


T1 weighting occurs when the 90° RF excitation pulse is applied before the longitudinal magnetization has recovered to its full equilibrium value, M_o.

The 90° pulse flips a reduced M into the transverse plane.

The signal detected is reduced relative to the maximum.

T1 Weighting



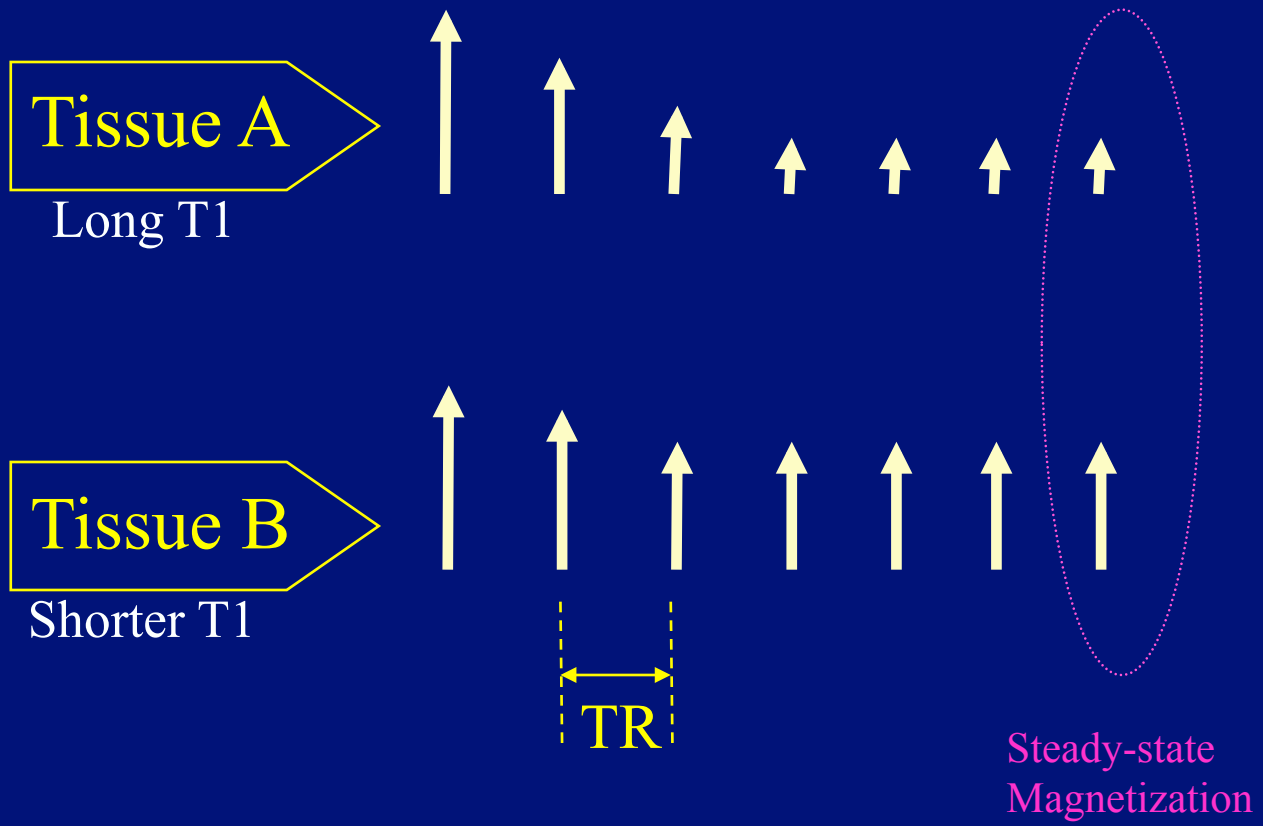
T1 weighting occurs when the 90° RF excitation pulse is applied before the longitudinal magnetization has recovered to its full equilibrium value, M_o.

The 90° pulse flips a reduced M into the transverse plane.

The signal detected is reduced relative to the maximum.

After repeated excitations, M eventually reaches a steady-state level. The signal level depends on T1 and time between repeated excitations = TR.

T1 Weighting



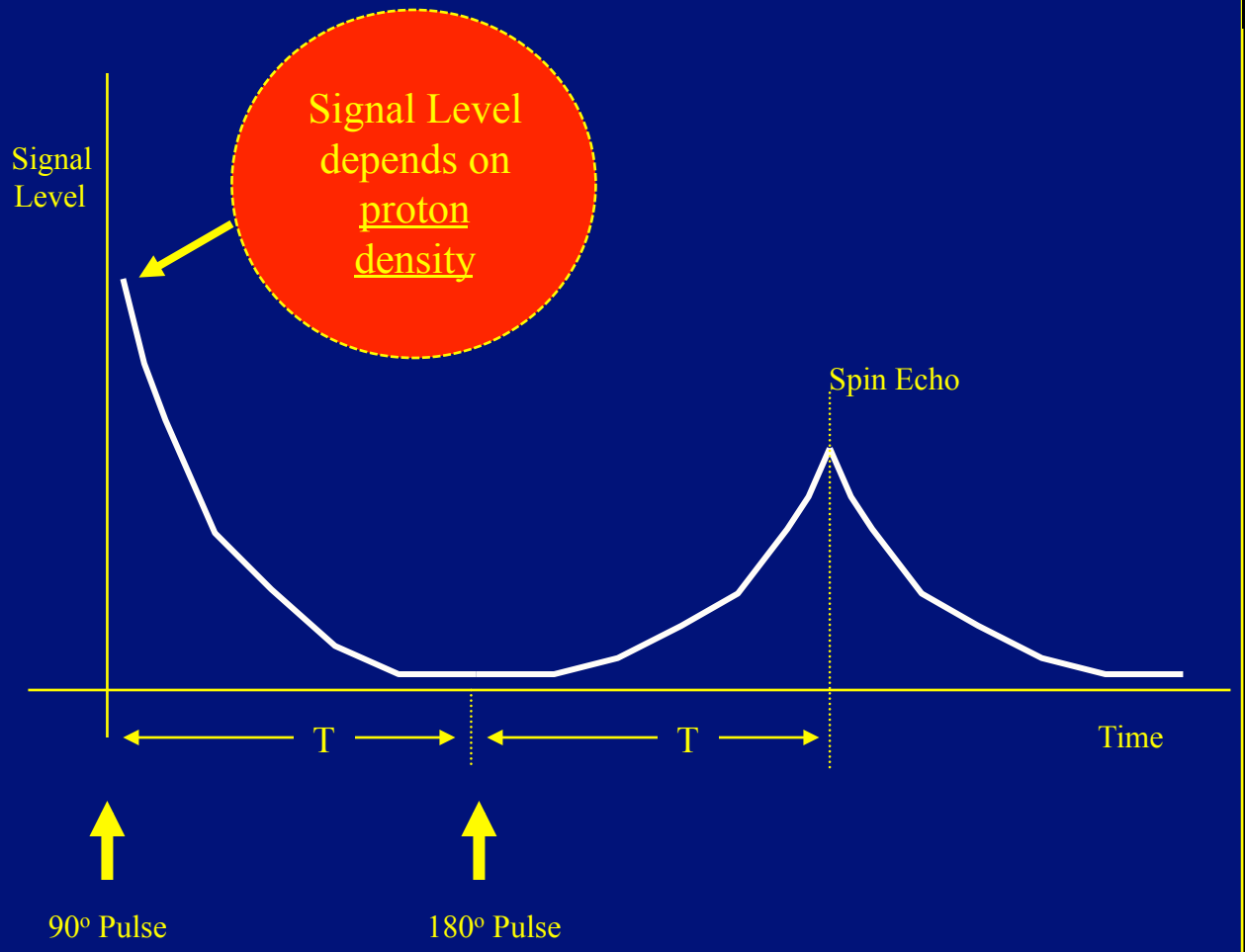
The shorter the time, TR, between excitations, the more M will be reduced relative to its equilibrium (maximum) level – especially when T1 is very long.

With a short TR, there can be a significant difference or contrast between signals from tissues with different T1, resulting in T1-weighted images.

Main Areas Covered in Lecture

- Phase of the magnetization
- Spin echo and refocusing the magnetization
- T2 relaxation and T2-weighting
- T2* relaxation and T2*-weighting
- T1 relaxation and T1-weighting
- Proton density and proton-density weighting

Proton Density

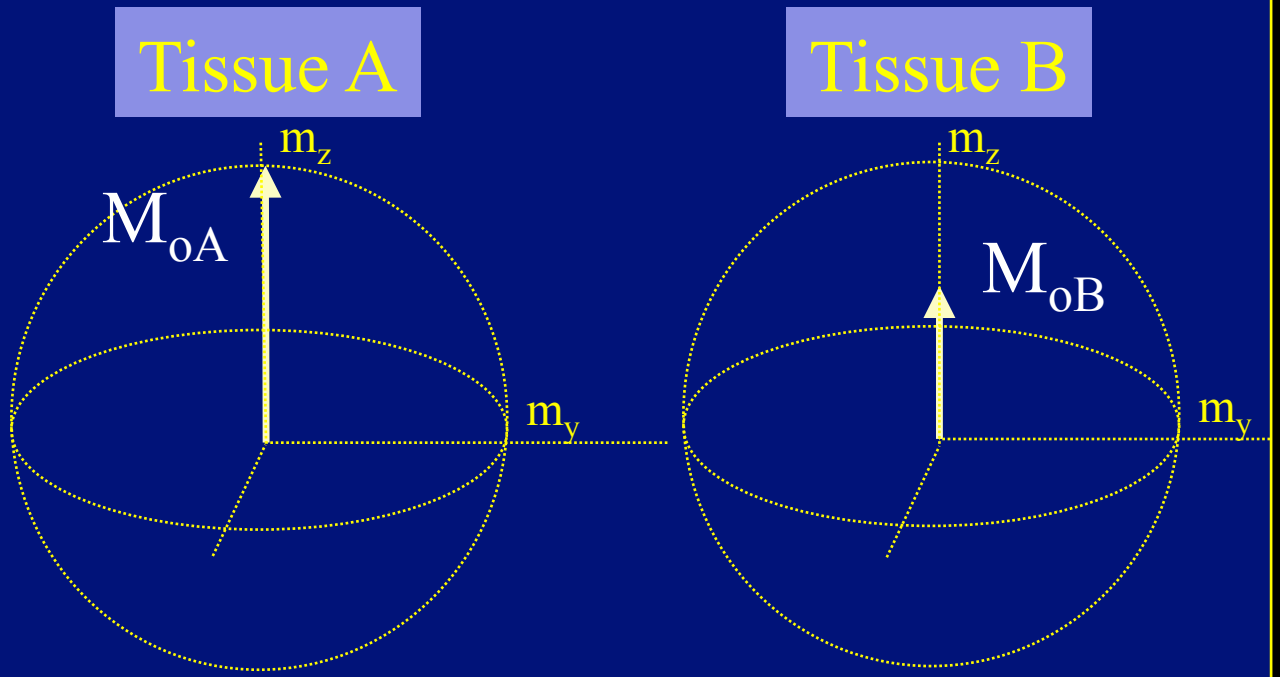


At equilibrium (fully relaxed) the magnitude of the local M vectors is proportional to the proton or spin density – roughly, the amount of (MR visible) material at a location.

The actual value of the equilibrium magnetization is dependent on the density of ^{1}H atoms in the volume, the magnetic field strength, B_o, and the temperature.

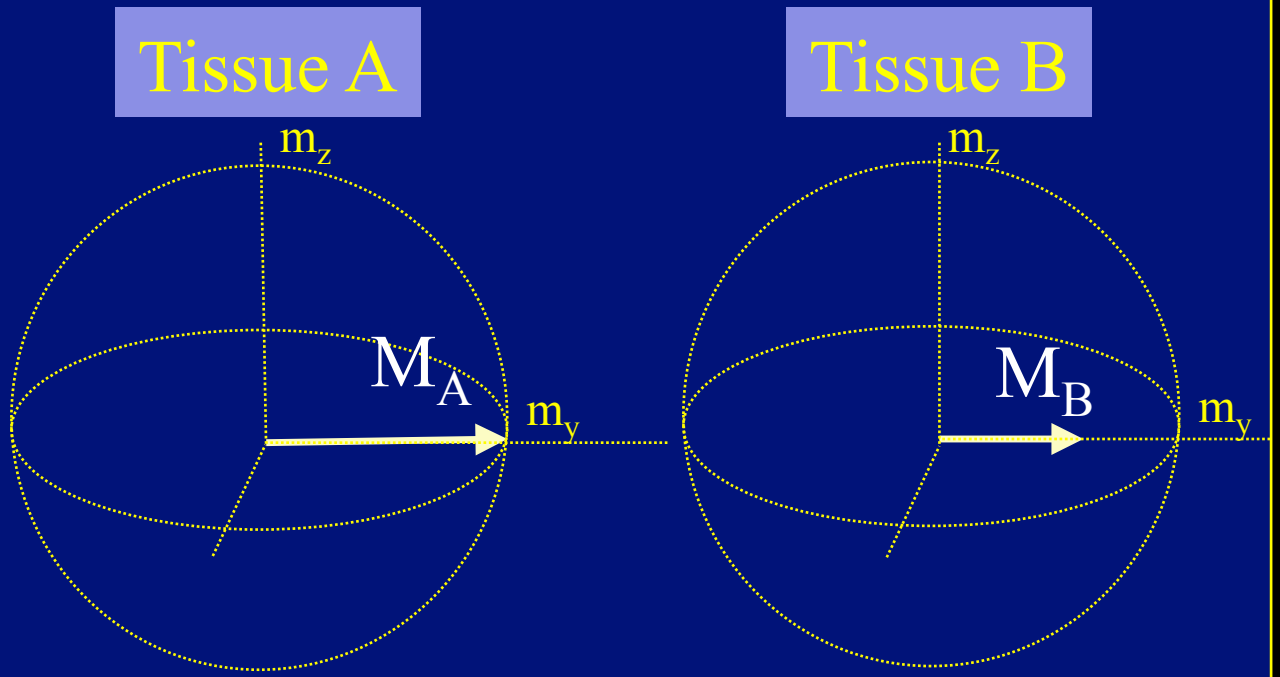
Imaging parameters can be selected to sensitize images to the relative magnitude of the proton density to obtain proton density weighted images.

Proton Density Weighting



Tissues may have different proton densities and thus different equilibrium magnetization, M_o.

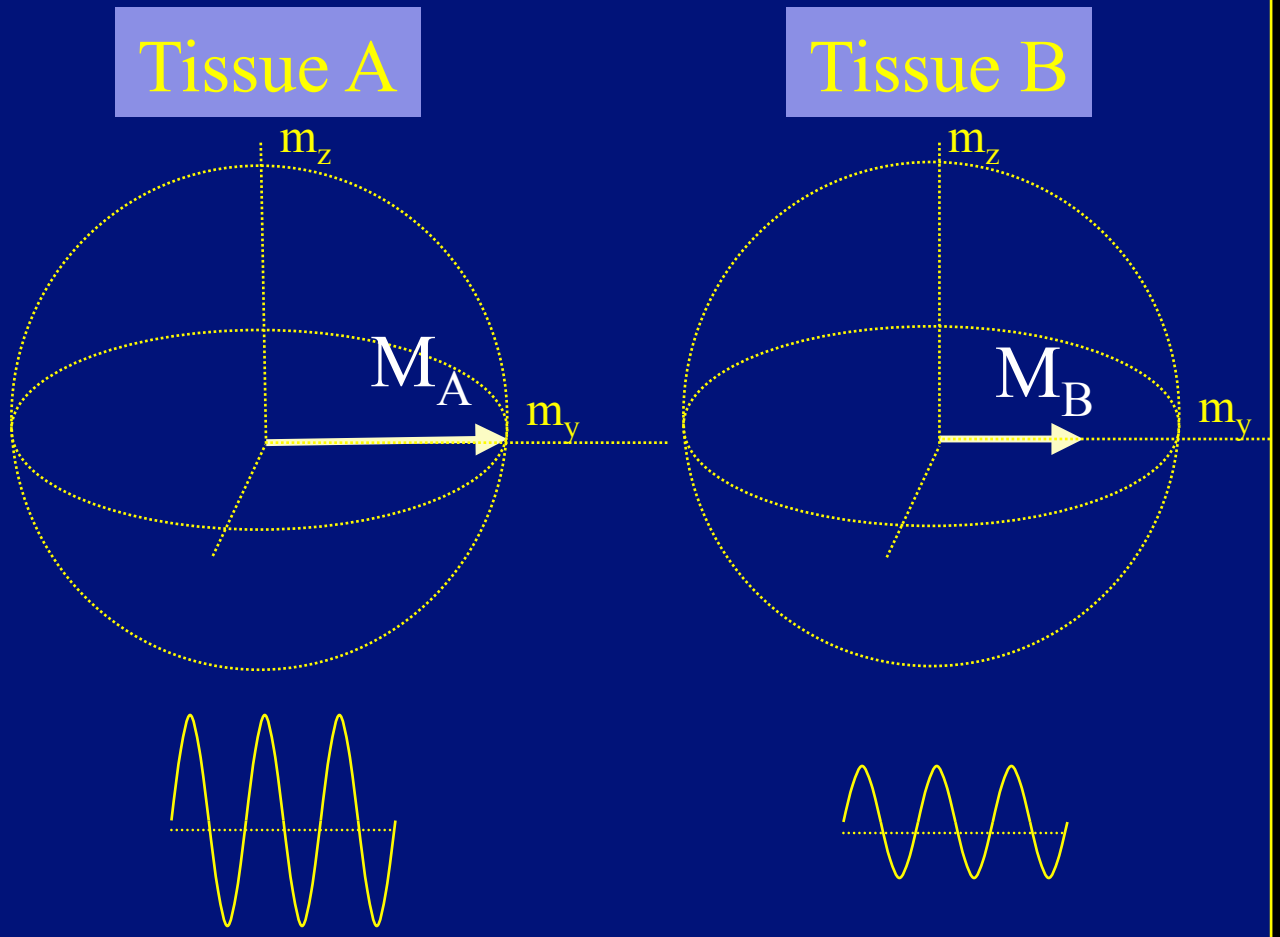
Proton Density Weighting



Tissues may have different proton densities and thus different equilibrium magnetization, M_o.

Different levels of Magnetization reflecting the proton density are flipped following a 90^o pulse.

Proton Density Weighting



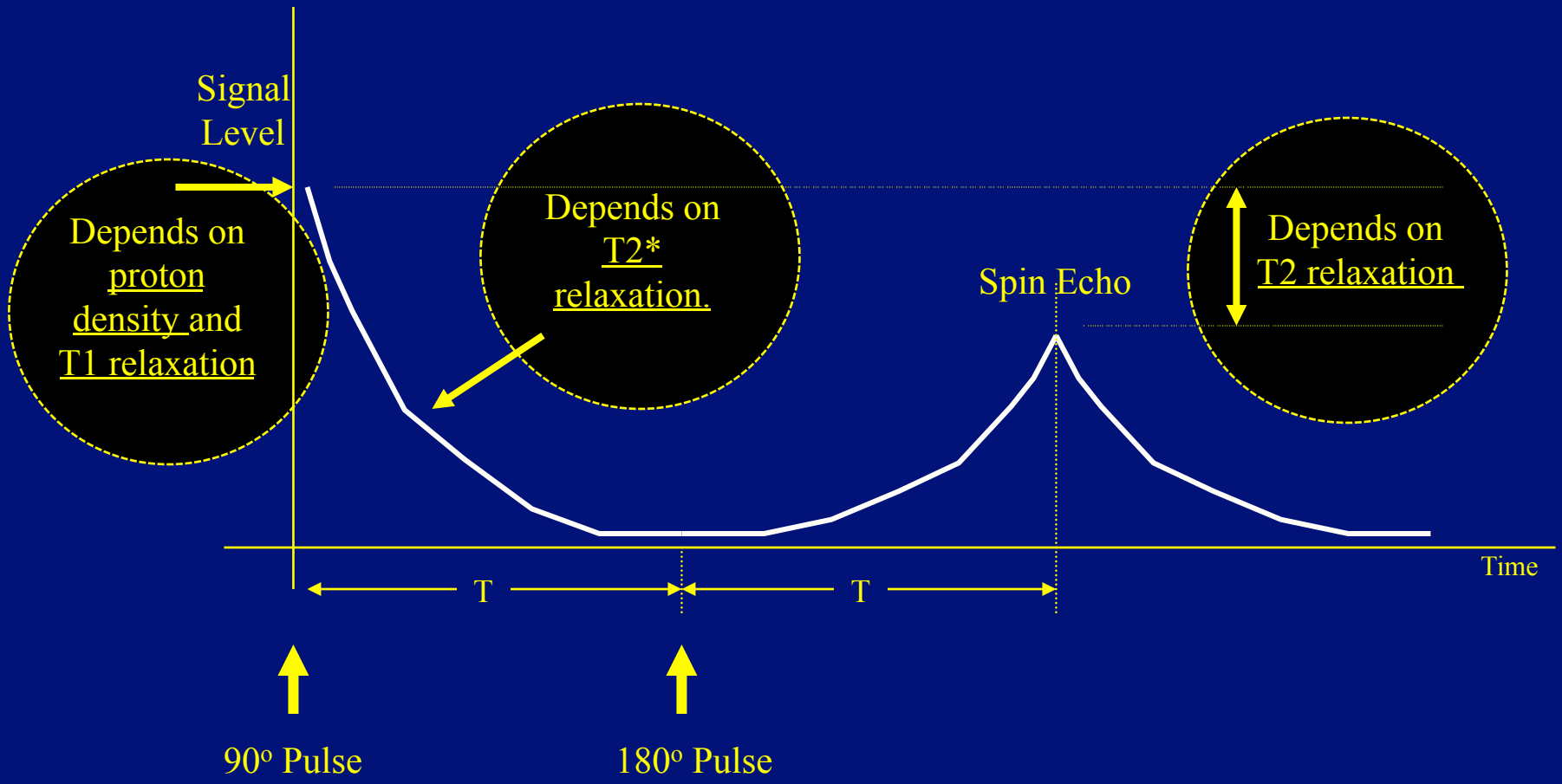
Tissues may have different proton densities and thus different equilibrium magnetization, M_o.

Different levels of Magnetization reflecting the proton density are flipped following a 90° pulse.

The signal acquired after the 90° pulse, signal level will reflect the proton density of the tissue.

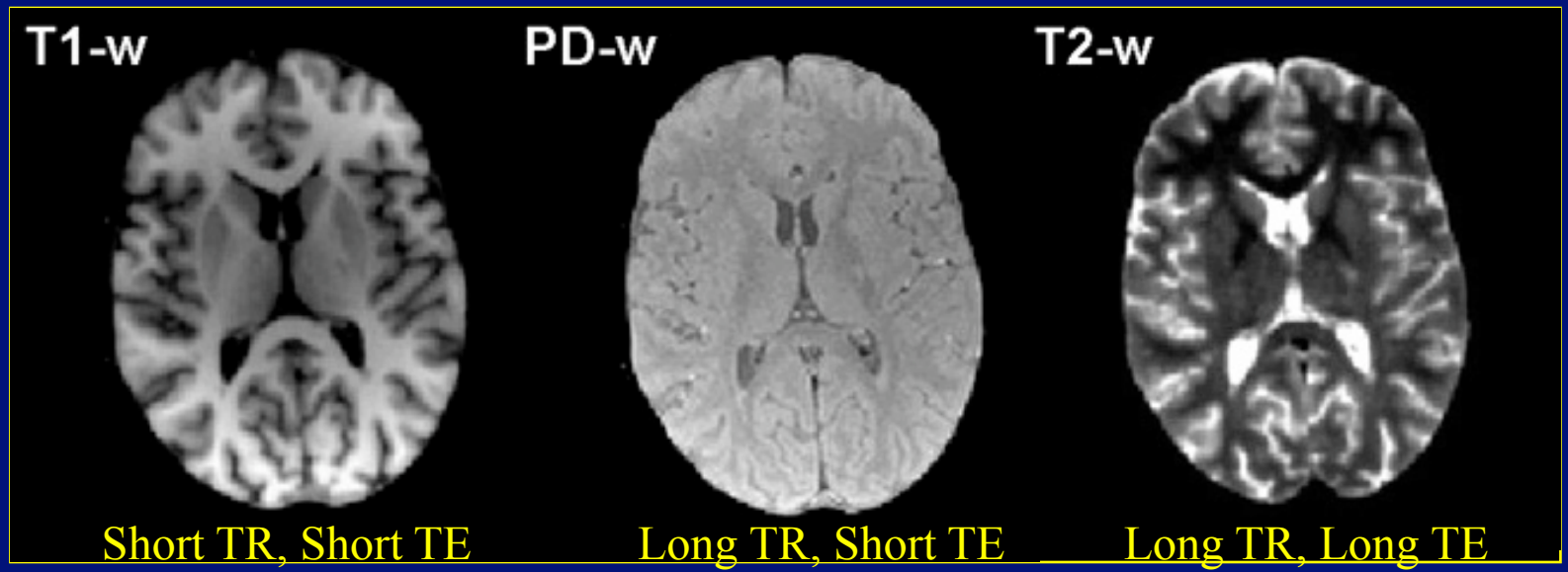
To maximize the proton-density weighting, the signal should be acquired immediately after the 90° pulse (i.e. with a very short TE) and the time between excitations, TR, should be long to minimize the T1 effect.

MRI Signal Weighting: Summary



Contrast due to Relaxation

Tissue Type	T1 (msec)	T2 (msec)
White Matter	510	67
Gray Matter	760	77
CSF	2500	200
Fatty tissue	250	70



Main Areas Covered in Lecture

- ✓Phase of the magnetization
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