Al-Mustaqbal University
College of Engineering and Technical Technologies
Biomedical Engineering Department

Subject: Biomedical Instrumentation Design_II.

Class (code): 5th (MU0115103)

Lecture: 3

BMID_II

MRI Design: Resonance and signal generation

Resonance is an energy transition that occurs when an object is subjected to a frequency the same as its own. Resonance is induced by applying a **radiofrequency (RF) pulse**:

- at the same frequency as the precessing magnetic moments hydrogen spins;
- at 90° to B_0.

› This causes the hydrogen spins to resonate (receive energy from the RF pulse), whereas other types of MR active nuclei do not resonate, as their gyromagnetic ratios are different.

› Two things happen to the hydrogen spins at resonance: *energy absorption and phase coherence*.

MRI Design: Resonance and signal generation

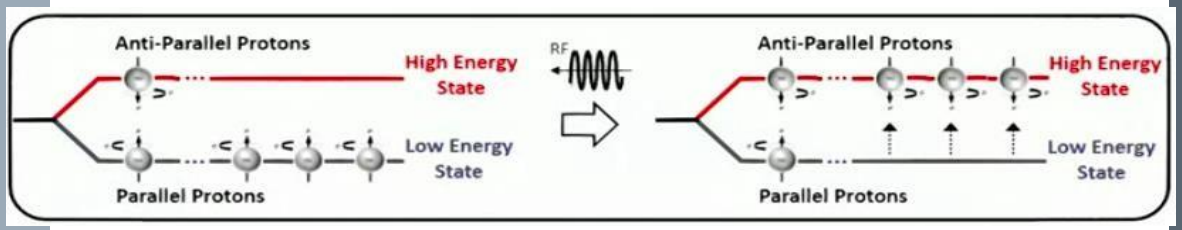
Energy absorption: the energy and frequency of electromagnetic radiation (including RF) are related to each other.

› The frequency required to cause resonance is related to the difference in energy between the high- and low-energy populations and, thus the strength of B_0

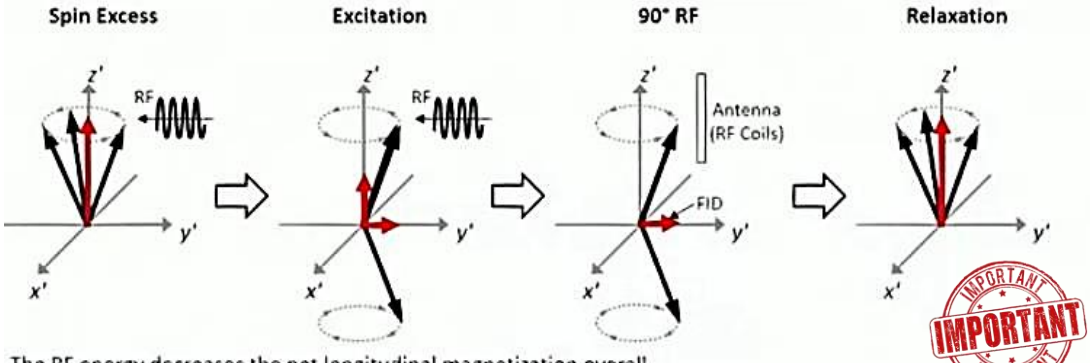
› The spin-up, low-energy hydrogen spins absorb energy from the RF pulse (excitation pulse) and move into the high-energy population.

› At the same time, the spin-down, high-energy spins give energy away and return to the low-energy state.

MRI Design: Resonance and signal generation

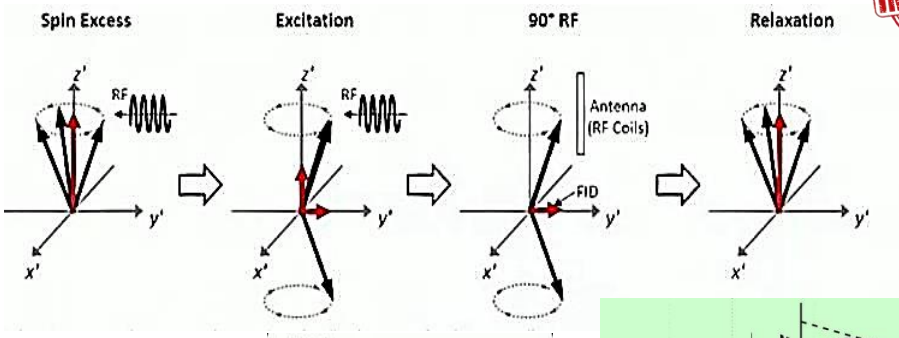


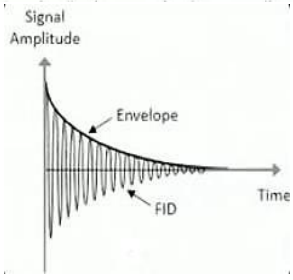
MRI Design: Resonance and signal generation

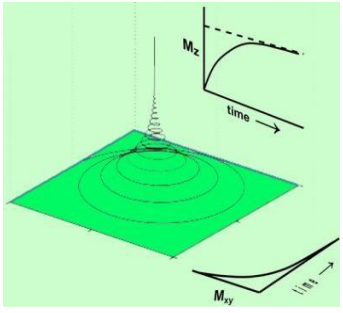


The RF energy decreases the net longitudinal magnetization overall.
The net transverse magnetization starts to appear (i.e., becomes in-phase)
When we stop applying for the RF energy in the transmission RF coil, we can detect a signal in the receiver RF coil, which is called free induction decay (FID).
FID signal can be maximized by stopping application of the RF energy when the longitudinal magnetization becomes zero. This RF pulsing is called 90° RF, since the original longitudinal magnetization is flipped completely toward on the transverse plane.
Only transverse magnetization can be detected and used for imaging. Why?
→ The majority of parallel and anti-parallel spins are aligned along longitudinal direction.
→ The magnetization component orthogonal to the B_0 can be detected as MR signals.
The net magnetization eventually returns back to the original state, which is called "**relaxation**".

MRI Design: Resonance and signal generation







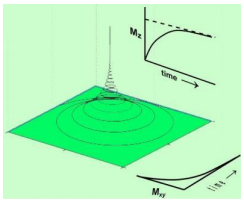
MRI DESIGN: Relaxation, in M_z and M_{xy}

› The MR signal decay occurs because the individual spins that comprise M interact with each other and their environment. As such, M would not precess indefinitely around B_0, but would instead seek to return to its initial alignment parallel to B_o with equilibrium magnitude M_o.

› To do this, the spin system had to release its energy to the environment in a process termed relaxation, with relaxation time constants T1 and T2.

› T1 reflected the regrowth of longitudinal magnetization (Mz), whereas T2 characterized the decay of the transverse components (Mx and My).

› Because T2 is always shorter than T1, the transverse components typically decay completely before the longitudinal magnetization is fully restored. The spiral pattern is sometimes said to resemble a "tent".



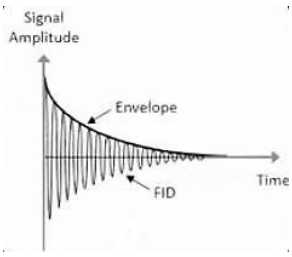
MRI Design: Relaxation Mechanism

› **Relaxation** is the loss of energy that spins have gained via excitation.

› After the RF excitation pulse is removed, the coherent component of NMV in the transverse plane, which is passing across the receiver coil, begins to gradually decrease as an increasingly higher proportion of spins become out of phase with each other. Thus, the signal induced in the receiver coil begins to decrease.

› The amplitude of the voltage induced in the receiver coil therefore gradually decreases.

› This is called **free induction decay** or **FID**



MRI Design: Relaxation Mechanism

› The NMV in the transverse plane decreases due to:

- Relaxation processes and field inhomogeneities and susceptibility effects.
- The cumulative dephasing of spin-spin interactions and inhomogeneities is called T2* decay.

Table 7.1 Common equations of relaxation mechanisms.

Equations		
$1/T2^* = 1/T2 + 1/2\ \gamma\Delta B_0$	T2 and T2* are the tissues' T2 and T2* relaxation times (ms) γ is the gyromagnetic ratio (MHz/T) ΔB_0 is the variation in magnetic field (inhomogeneities) (parts per million, ppm)	This equation shows how T2 and T2* are related to each other. Poor field inhomogeneities result in T2* being much shorter than T2, and fast decaying signal.

MRI Design: Relaxation Mechanism

› The magnetization in each tissue relaxes at different rates, which would largely depend on how tightly the hydrogen atom is bound to the molecule. ***This is one of the factors that create image contrast.***

› Spins emit energy absorbed from the RF pulse through a process known as **spin-lattice energy transfer** and shift their magnetic moments from the *high-energy state* to the *low-energy state*. The NMV recovers and realigns to B_0. This relaxation process is called T1 recovery

› The magnetic moments of the spins lose precessional coherence or dephase and the *NMV decays in the transverse plane*. The dephasing relaxation process is called ***T2 decay.***

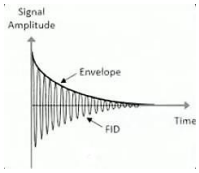
MRI Design: Relaxation Mechanism

Field Inhomogeneity

› Despite attempts to make the main magnetic field as uniform as possible via shimming, inhomogeneities of the external magnetic field are inevitable and slightly alter the magnitude of B_0.

› Since the precessional frequency of the magnetic moment of a spin is proportional to B_0, so spins that pass through inhomogeneities experience a precessional frequency and phase change, and the resulting signal decays exponentially.

› This results in a change in dephasing of the transverse magnetization due to a loss in phase coherence. The resulting signal decays exponentially and is called an FID.



MRI Design: Relaxation Mechanism

Pulse sequence

› In order to produce images where T2 contrast is visualized, ideally, there must be a mechanism to rephase spins and compensate for magnetic field inhomogeneities. That mechanism is ***Pulse sequences***.

› A **pulse sequence** is defined as a series of RF pulses, gradient applications and intervening time periods. They enable control of the way in which the system applies RF pulses and gradients, hence controlling image weighting.

› Pulse sequences are required *because*, without a mechanism of refocusing spins, there is insufficient signal to produce an image. This is because dephasing occurs almost immediately after the RF excitation pulse has been removed.

MRI Design: Relaxation Mechanism

Pulse sequence

› The main purposes of pulse sequences are to:

› rephase spins and remove inhomogeneity effects and therefore produce a signal or echo that contains information about the T2 decay characteristics of tissue alone;

› enable manipulation of the TE and TR to produce different types of contrast. Spins are rephased by using

› a 180° RF pulse (used in all spin echo sequences);

› a gradient (used in all gradient echo sequences).

MRI DESIGN: T1 Recovery

› **T1 recovery** is caused by the exchange of energy from spins to their surrounding environment or lattice and is called **spin-lattice energy transfer**.

› The rate at which spins dissipate their energy and retain their longitudinal magnetization occurs as an **exponential process**, and it takes place at different rates in different tissues.

› **The T1 recovery time** of a particular tissue is an intrinsic contrast parameter that is inherent to the tissue being imaged.

› For a particular tissue, T1 is defined as the time it takes for 63% of the longitudinal magnetization to recover in that tissue. The period of time during which this occurs is the time between one excitation pulse and the next or the **TR**.

› The TR, therefore, determines how much T1 recovery occurs in a particular tissue.

MRI DESIGN: T1 Recovery

› T1 recovery

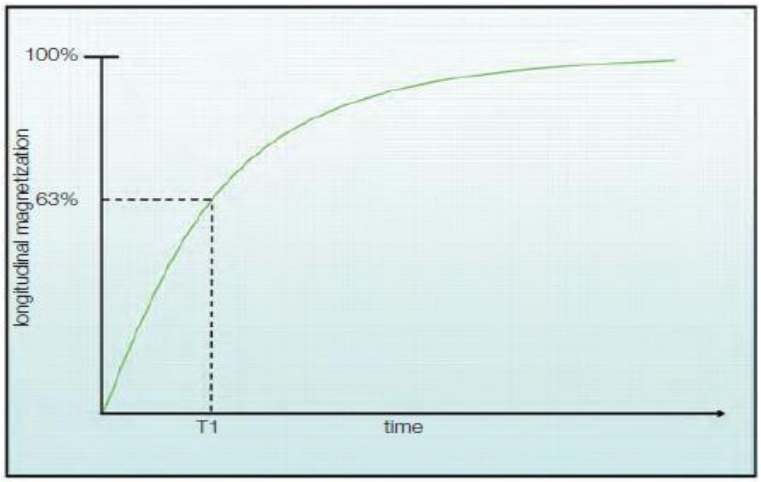


Figure 8.1 The T1 recovery curve.

MRI DESIGN: T1 Recovery

T1 recovery in fat

› Due to the fact that fat is able to absorb energy quickly, the *T1 recovery time of fat is very short*; that is, spins dispose of their energy to the surrounding fat tissue and return to B_0 in a short time.

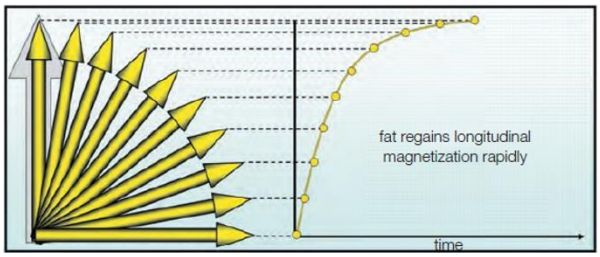


Table 8.2 T1 relaxation times of brain tissue at 1 T.

Tissue	T1 relaxation time (ms)
Water	2500
Fat	200
CSF	2000
White matter	500

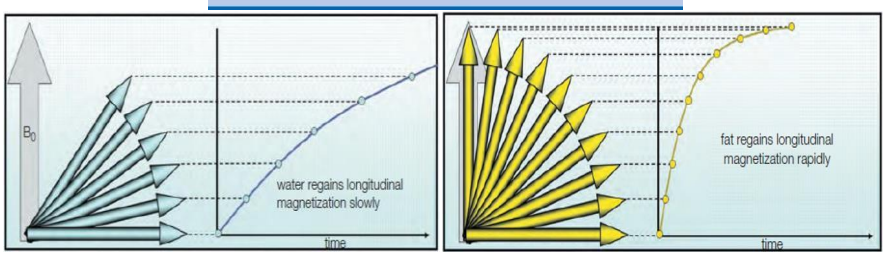
MRI DESIGN: T1 Recovery

T1 recovery in water

› Water is very inefficient at receiving energy from spins, thus *T1 recovery time is quite long*; that is, spins take a lot longer to dispose of their energy to the surrounding water tissue and return to B_0.

Table 8.2 T1 relaxation times of brain tissue at 1 T.

Tissue	T1 relaxation time (ms)
Water	2500
Fat	200
CSF	2000
White matter	500



MRI DESIGN: T1 Recovery

Control of T1 recovery

› Since energy exchange due to molecular motion only occurs at Larmor frequency, and the Larmor frequency is proportional to B_0, **T1 recovery is affected by the strength of the external magnetic field.** *T1 recovery takes longer as B_0 increases.*

› The TR controls how much of the NMV in fat or water recovers before the application of the next RF pulse.

› ***A short TR* does** not permit full longitudinal recovery in most tissues so that there are different longitudinal components in fat and water. These different longitudinal components are converted to different transverse components after the next excitation pulse has been applied.

› As the NMV does not recover completely to the positive longitudinal axis, they are pushed beyond the transverse plane by the succeeding 90° RF pulse. This is called **saturation**. When saturation occurs, there is a contrast difference between fat and water due to differences in their T1 recovery times.

MRI DESIGN: T1 Recovery

Control of T1 recovery

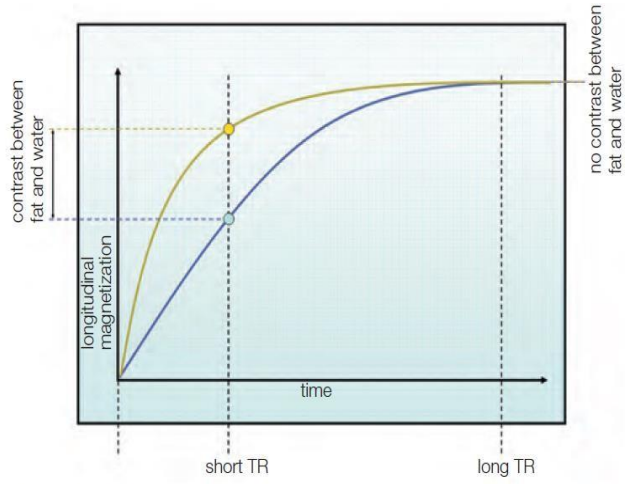


Figure 8.4 T1 recovery of fat and water.

MRI DESIGN: T1 Recovery

Control of T1 recovery

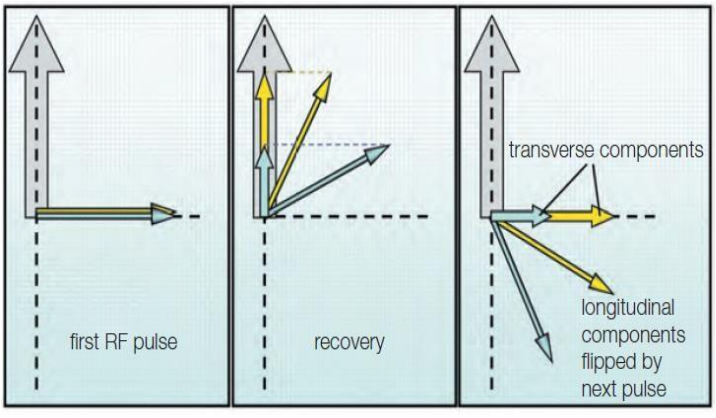


Figure 8.5 T1 contrast generation.

MRI DESIGN: T1 Recovery

Control of T1 recovery

› *A long TR* allows full recovery of the longitudinal components in most tissues. There is no difference in the magnitude of their longitudinal components.

› There is no contrast difference between fat and water due to differences in T1 recovery times when using a long TR.

› Any differences seen in contrast are due to differences in the number of protons or **proton density** of each tissue.

› The proton density of a particular tissue is an intrinsic contrast parameter and is, therefore inherent to the tissue being imaged

MRI DESIGN: T2 Decay

› The interaction between the magnetic fields of neighbouring spins causes ***T2 decay***. It is called **spin-spin interaction**.

› This produces a loss of phase coherence or dephasing and results in the decay of the NMV in the transverse plane.

› It is an exponential process and occurs at different rates in different tissues.

› It is the time it takes for 63% of the transverse magnetization to be lost due to dephasing; that is, transverse magnetization is reduced by 63% of its original value (37% remains).

› The period of time during which this occurs is the time between the excitation pulse and the MR signal or the **TE**. The TE, therefore, determines how much T2 decay occurs in a particular tissue.

MRI DESIGN: T2 Decay

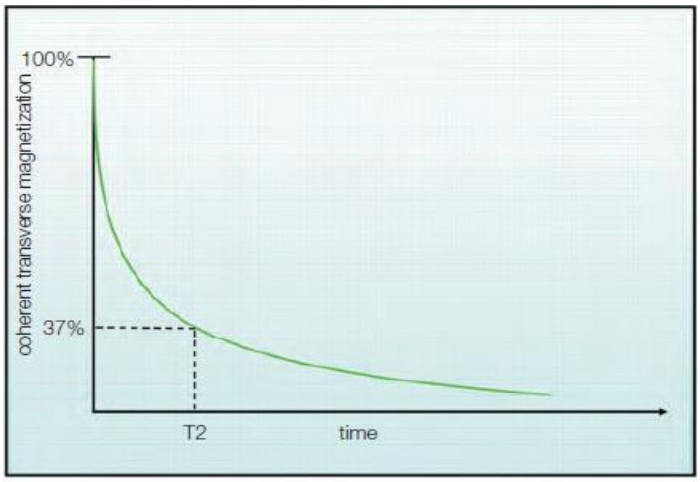


Figure 9.1 The T2 decay curve.

MRI DESIGN: T2 Decay

T2 decay in fat

› T2 relaxation occurs as a result of the spins of adjacent nuclei interacting with each other. The efficiency of this process depends on how closely packed the molecules are to each other.

› In fat, the molecules are closely packed together so that spin-spin is efficient. *The T2 time of fat is, therefore, very short.*

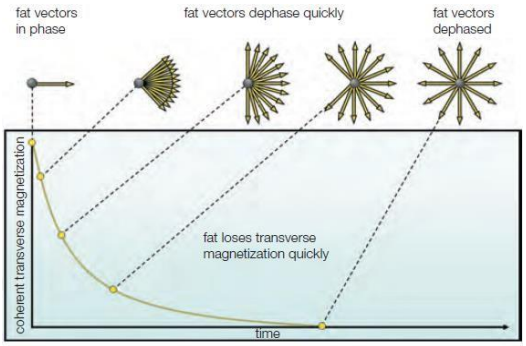


Figure 9.2 T2 decay in fat.

MRI DESIGN: T2 Decay

T2 decay in water

› T2 relaxation In water the molecules are spaced apart so that spin-spin is not efficient.

The T2 time of water is, therefore, very long

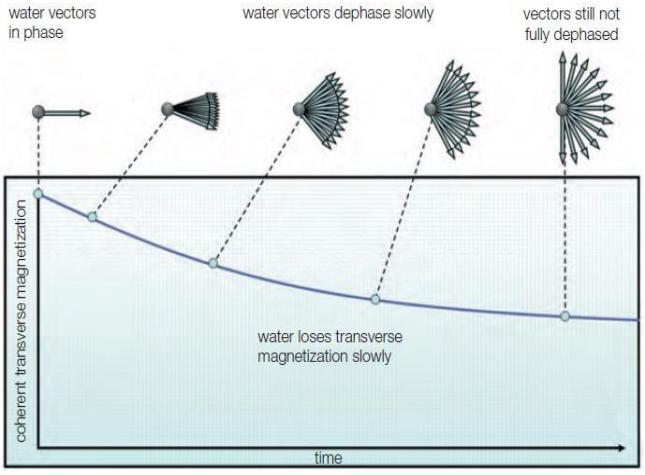


Figure 9.3 T2 decay in water.

MRI DESIGN: T2 Decay

Control of T2 decay

› The **TE** controls how much transverse magnetization has been allowed to decay in fat and water when the signal is read.

› A *short TE* does not permit full dephasing in either fat or water, so their coherent transverse components are similar. There is little contrast difference between fat and water due to differences in T2 decay times using a short TE.

› A *long TE* allows the dephasing of the transverse components in fat and water. There is a contrast difference between fat and water due to differences in T2 decay times when using a long TE

MRI DESIGN: T2 Decay

Control of T2 decay

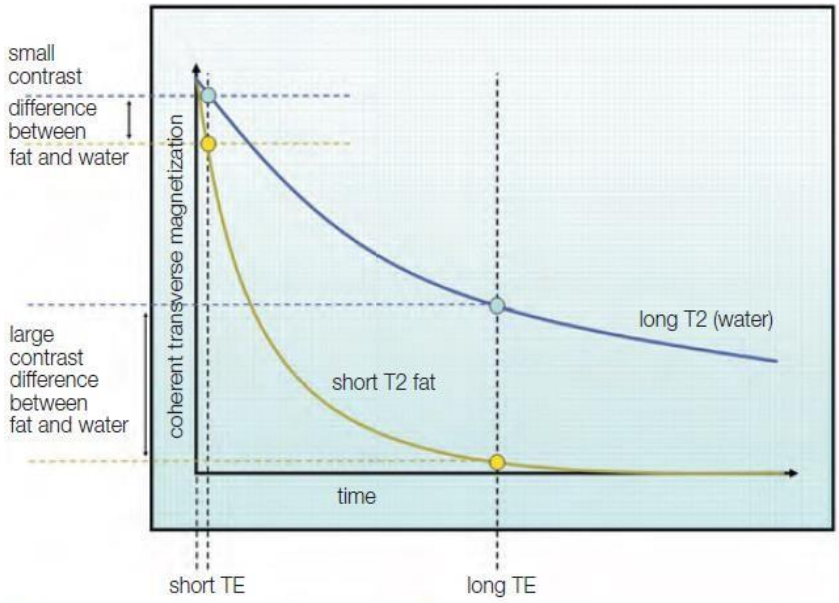


Figure 9.4 T2 decay curves in fat and water.

MRI DESIGN: T2 Decay

Control of T2 decay

› The T2 decay is affected by the strength of the external magnetic field. Spin-spin processes are more efficient when molecular motion occurs at the Larmor frequency.

› The Larmor frequency is proportional to B_0, and therefore T2 decay takes longer as B_0 increases because fewer molecules are moving at relaxation-causing frequencies.

› It should be noted that fat and water represent the extremes in image contrast. Other tissues, such as muscle, grey matter and white matter, have contrast characteristics that fall between fat and water

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