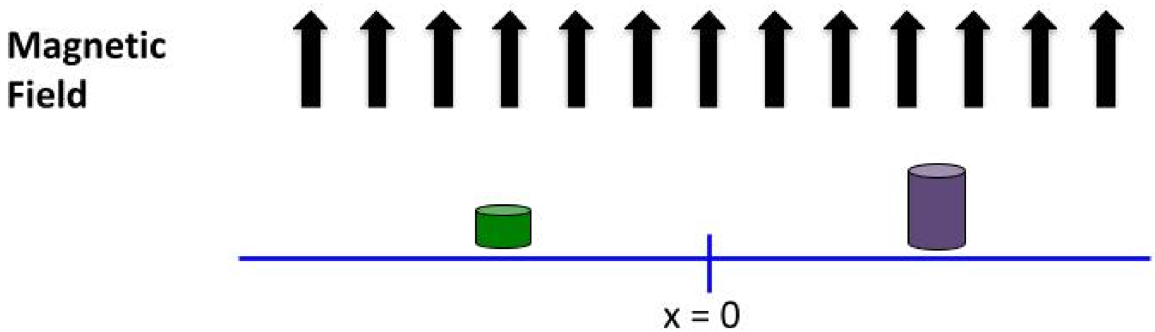
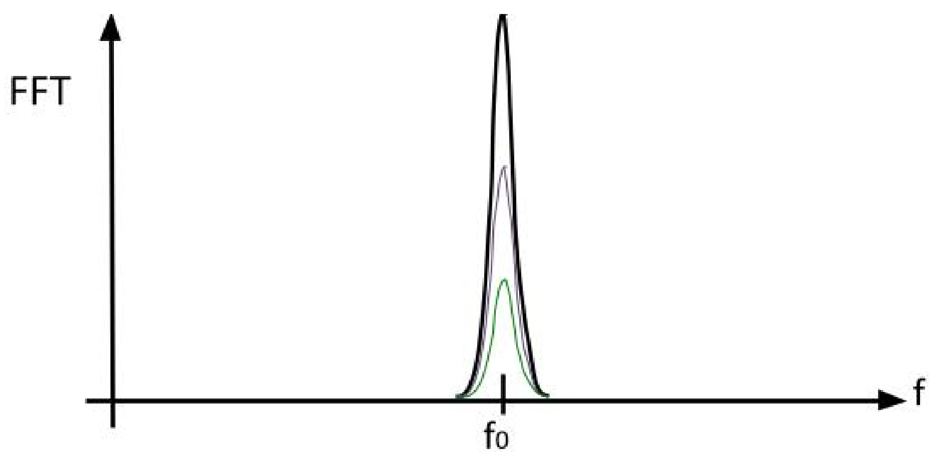
Module 10 Student Questions

Thought Experiments: How Can We Encode Spatial Information into MR Signal? - Guided Inquiry Questions

Thought Experiment 1: Consider a sample that is split between two different locations in space and placed in a uniform magnetic field, like the one shown below.



1. Sketch what you think the MR frequency spectrum of this sample would look like. *Hint: Are the Larmor frequencies different for the different bits of the sample?*



2. Would you be able to determine the spatial distribution of the sample from this frequency spectrum?

No, the spectrum just shows that all the spins precess at approximately the same Larmor frequency since they are seeing the same external magnetic field.

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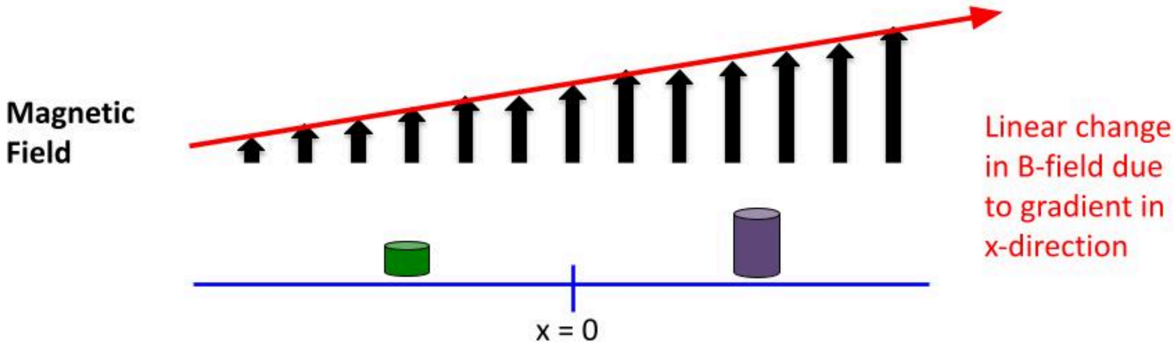
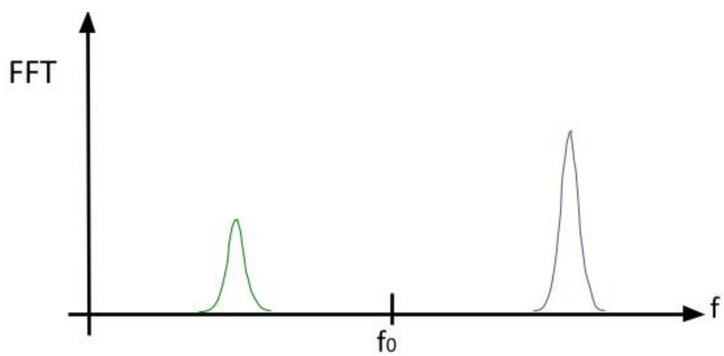
Thought Experiment 2: Consider the same sample, but now placed in a known ***magnetic field gradient*** *- i.e., the magnetic field changes over space (in this case, in a nice linear fashion, as the figure illustrates below).*



3. Sketch what you think the MR frequency spectrum of this sample would look like now. *Hint: Are the Larmor frequencies different for the different bits of the sample?*



4. Would you be able to determine the spatial distribution of the sample from this frequency spectrum?

I would be able to determine that there is a small bit of sample in the region of space with the lower magnetic field (-x direction) and then a larger bit of sample in the region of space with the higher magnetic field (+x direction). If I knew the strength of the applied field gradient, I could map these frequencies directly to positions in space along the x spatial dimension.

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A New Form of Imaging - Guided Inquiry Questions

5. Why do gradients need to be applied in multiple different directions in order to build up a multidimensional image?

> A gradient along a single dimension provides a projection of the object along that single dimension. Presumably, if you want a 2D (or 3D image), you would need at least 2 or 3 gradients, one along each different spatial dimension.

6. If we want higher resolution images, would you want to increase or decrease the magnetic field gradient (e.g., have more or less variation of magnetic field strength over space)?

> If you want higher-resolution images, you would want to increase the magnetic field gradient. The larger the gradient, the more the individual signals spread out at specific locations in space (almost like zooming into the image), so we can then better resolve those images. This also makes sense because, in the limit that we have no magnetic field gradient, you have no spatial resolution at all.

7. A higher resolution image means that each pixel in a 2D image (voxel in a 3D image) contains a signal from a smaller and smaller area (volume) in space. What might be some limiting factors for the spatial resolution in MRI?

> One limiting factor would be the amount of MR signal you can get from smaller and smaller regions in space. At some point, the signal-to-noise ratio will get too small for signal detection.

How Do We Use Gradients to Create Images? - Guided Inquiry Questions

8. Once you open the [PhET MRI Simulation](), you can click on the tab entitled "Simplified MRI" and see something similar to the figure in the margin.

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a. What are the red, blue, and white arrows representing? Why do you think they are represented that way?

They are the atomic nuclei. They look like little bar magnets and spinning tops to represent quantum spin.

b. What do the white block arrows represent? Is the magnetic field being shown homogeneous or inhomogeneous?

The white block arrows represent the magnetic field direction and strength at each location in space. Without any gradients, the magnetic field shown is homogeneous.

9. Check out the "Radiowave Source" control panel at the bottom.

a. What is "Power" controlling?

The “Power” is controlling the strength of the radio wave source (presumably the amplitude of the electromagnetic radiation that is being applied).

b. What is "Frequency" controlling?

The “Frequency” is controlling the frequency of the radiowave source, which you can observe in the simulation by the wavefronts getting closer together (high frequency) or farther apart (lower frequency).

10. Play around with the controls to determine (roughly) the resonant frequency of the system (without changing any of the magnetic field controls on the right).

a. Describe what happens at this resonant frequency.

At the resonant frequency (~31.9 MHz), you start to see lots of waves (or photons) being emitted from the atomic nuclei horizontally and hitting the detector on the right side.

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b. Using the magnetic field strength given on the right side and the table provided in the margin, what nuclei do you think we are detecting?

Since the magnetic field strength is 0.75 T and the resonant frequency is ~31.9 MHz, that suggests a gyromagnetic ratio of 31.9 MHz/0.75 T ~ 42.5 MHz/T. This would suggest the nuclei we are detecting are **hydrogen-1 nuclei**.

11. Check out the control panel on the right side.

a. Describe what happens when you turn up the gradient in the horizontal direction. Where does the magnetic field strength get weaker? Where does it get stronger? Where does it stay the same?

The magnetic field strength gets weaker on the left, stronger on the right, and stays the same right in the middle.

b. Describe what happens when you turn up the gradient in the vertical direction. Where does the magnetic field strength get weaker? Where does it get stronger? Where does it stay the same?

The magnetic field strength gets weaker at the top, stronger at the bottom, and stays the same right in the middle.

12. Set the frequency of the radio wave source to 42.5 MHz, the main magnet to 1.2 T, and the power of the radiowave source to 100%.

a. What can you adjust so that only the atoms at the top of the head resonate?

I can adjust the vertical magnetic field gradient to be 0.04 so that only the atoms at the top of the head resonate.

b. What can you adjust so that only the atoms in the ear on the left resonate?

I can adjust the horizontal magnetic field gradient to be 0.04 so that only the atoms in the ear on the left resonate.

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Now let's go tumor hunting! A "tumor" in this simulation is an area where there is a high density of atomic nuclei. To make this slightly more realistic, unclick "show atomic nuclei". You now only have the frequency, magnetic field, and gradient controls to isolate the location of the tumor by looking at the detected signal.

13. Describe a procedure you can use to identify an approximate location for the tumor.

I will keep the main magnetic field at 1.20 T and the frequency of the radiowave source at 42.4 MHz, and then slowly sweep through vertical gradient values until I get the largest amount of signal. From that info, I can infer the possible vertical location of the tumor. I can then keep the vertical gradient at that value and slowly increase the horizontal gradient to see which region horizontally produces the most signal to infer the possible horizontal position of the tumor.

14. Click the "Add tumor" button in the lower right corner and use your procedure to attempt to find the approximate location of the tumor.

a. Which quadrant of the head do you think the tumor is located?

Upper right quadrant.

b. After you have made your best attempt to find the tumor, reclick “Show atomic nuclei.” Were you correct about its location?

Yes*

*It turned out the horizontal gradient was not much help with the settings used (just added more resonance in the non-tumor region on the left side,) since the spins would be in resonance at slightly lower magnetic field than the main field, that means that any of the horizontal gradient values would make the right side of the head go more and more off-resonance. Ideally would have the option to flip the gradient direction, so then can resonate the right side just as much as the left side to have a fairer comparison. Similarly, for the vertical gradient.

15. Based on what you have seen in the simulation, how might scientists build up an image using the controls provided?

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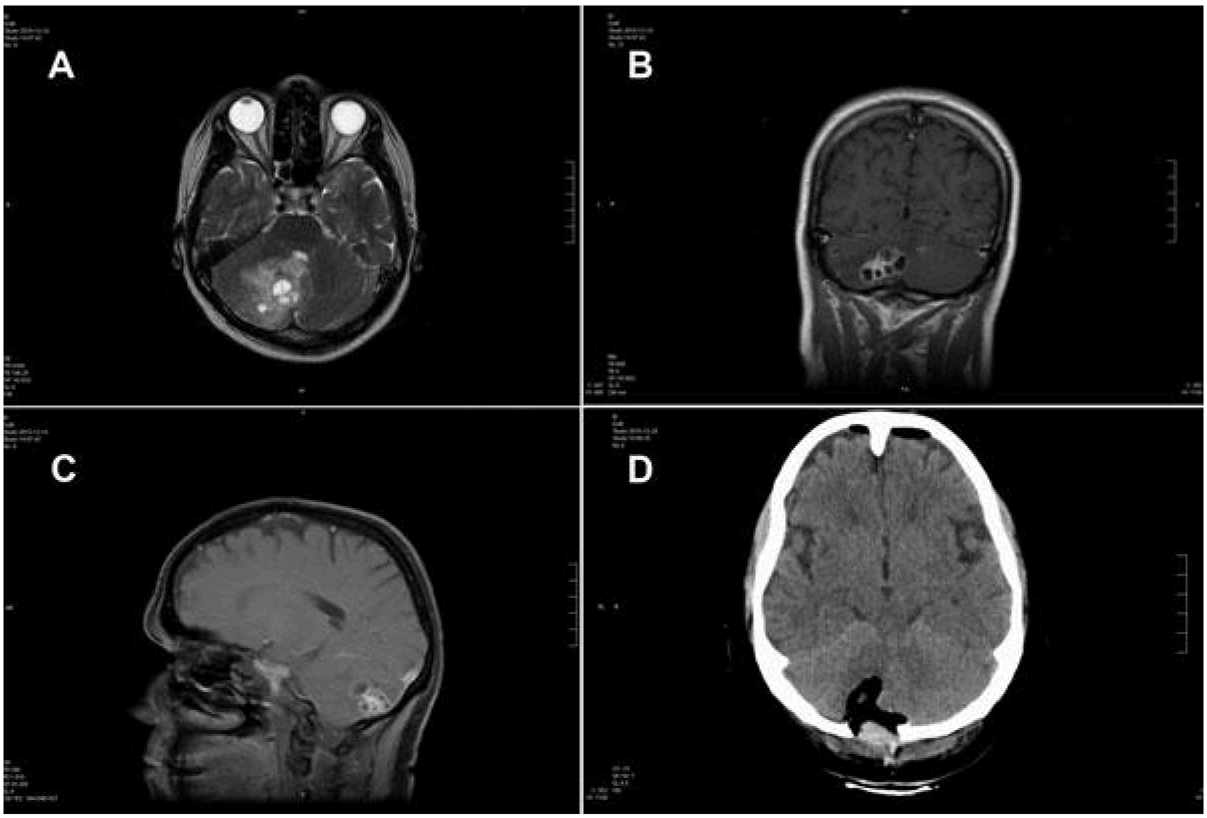
In the simulation, you can see how you might be able to build up an image by using particular horizontal and vertical gradient values to cause a particular region of the head to resonate and then seeing how much signal is detected (which would determine the pixel brightness in the region). Then you can systematically go through different gradient values to resonate different regions of space to build up your image.

Modern-Day Imaging - Guided Inquiry Questions

16. On the MRI (A, B, C) and CT (D) images below, give the name of the specific plane that each image was taken from and suggest which region of the body is shown.



A: Transverse, B: Coronal, C: Sagittal, D: Coronal
Looks to be looking at the head with a focus on the brain.

What Provides Contrast in Imaging? - Guided Inquiry Questions

17. The easiest way to decipher which type of imaging sequence was used in an MRI image of the brain is to look at the signal intensity of cerebrospinal fluid (CSF) in comparison with the gray matter of the brain.

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Tissue	T1 (msec)	T2 (msec)
Water/CSF	4000	2000
Gray matter	900	90
Muscle	900	50
Liver	500	40
Fat	250	70
Tendon	400	5
Proteins	250	0.1- 1.0
Ice	5000	0.001

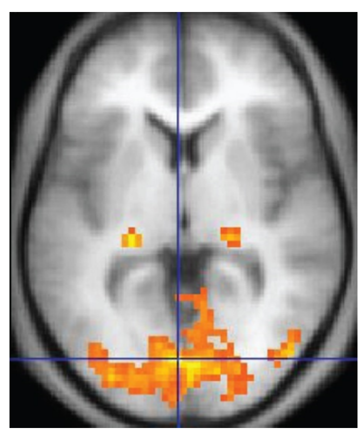
a. The CSF looks much darker than the gray matter in the T_1-weighted image. Why is that the case?

The CSF has a longer T_1 relaxation time, so in a T_1-weighted image, the shorter TR means there are fewer spins in CSF who have equilibrated compared with gray matter when the signal is acquired, so CSF ends up being darker than the gray matter in the image.

b. The CSF looks much brighter than the gray matter in the T_2-weighted image. Why is that the case?

The CSF has a longer T_2 relaxation time, so in a T_2-weighted image, the longer TE means that more of the signal from the gray matter has decayed in comparison with the CSF, so CSF ends up being brighter than the gray matter in the image.

18. Look carefully at the fMRI image shown in the margin.



a. What plane was the image taken from?

Transverse

b. What type of imaging sequence (PD, T_1 weighting, T_2 weighting) do you think was used for the background?

T_1-weighting, since the CSF is darker than the gray matter in that image.

c. Why might different blood oxygenation levels provide contrast in MRI images?

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Oxygen is paramagnetic and acts as a natural contrast medium for MRI. The relative abundance of oxygen in the blood would change the relaxation times, which would be noticeable in T_1- and T_2-weighted images.

19. What are the possible advantages of adding contrast media, compared to the other image contrast mechanisms discussed?

The fact that you can target particular tissues (like tumors) using contrast media is a nice advantage compared with other image contrast mechanisms.

Reflection Questions

1. In the history of MRI given in the text, what were some obstacles that Lauterbur and Mansfield had to overcome for MRI to be widely accepted?

Both Lauterbur and Mansfield faced skepticism from the scientific community for their new ideas regarding MRI. Lauterbur's seminal paper was at first rejected by Nature, and Mansfield had to work for 15 years on building the equipment for EPI before others were convinced it was worthwhile. It took roughly 30 years for their work to be honored with a Nobel Prize.

2. MRI is almost predominantly looking at ^1H in blood, soft tissues, and other bodily fluids. Provide possible MR and biological reasons for using ^1H instead of another nuclear isotope.

Hydrogen-1 is a great isotope for NMR because it is highly abundant naturally and it is a spin-½. Biologically, there is a lot of hydrogen in living organisms - being made mostly of water or organic materials.

3. The images in question 16 are of the brain of a 51-year-old woman infected with tapeworm larvae. The MRI images were taken using T_1 weighting (A), T_2 weighting (B), using a contrast agent (C), and then the final image (D) was made using a CT scan post-operation after the larvae were removed. Why do you think these doctors used these different imaging modalities for diagnosis and post-operation imaging?

Using different MRI contrasts helped locate foreign tissue in the brain, which was highlighted in different ways and suggested some characteristics of the tissue. Using T_1 weighting (shows up brighter than surrounding gray matter, so shorter T_1 than gray matter), T_2 weighting (shows up darker than surrounding gray matter, so shorter T_2 than

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gray matter as well). CT shows overall tissue mass density difference and only provides one potential contrast mechanism, making it potentially less useful for identifying an unknown tissue. However, CT does show very clearly the absence of tissue post-op, so it makes sense to use it there.

4. Using what you understand about MR and have learned about MRI in this module, what are some potential limitations and challenges for MRI?

Challenges would be imaging solids in MRI since they have such short T_2 and long T_1 times in comparison with the soft-solids primarily imaged using MRI. MR imaging time is limited by the T_1 times of the samples, and faster imaging sequences like EPI require fast-changing gradients, which have technical limitations. The resolution limitations are primarily due to the limits of detecting the signal at smaller and smaller scales. Fortunately, many of these limitations and challenges can be addressed by technological advances.

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