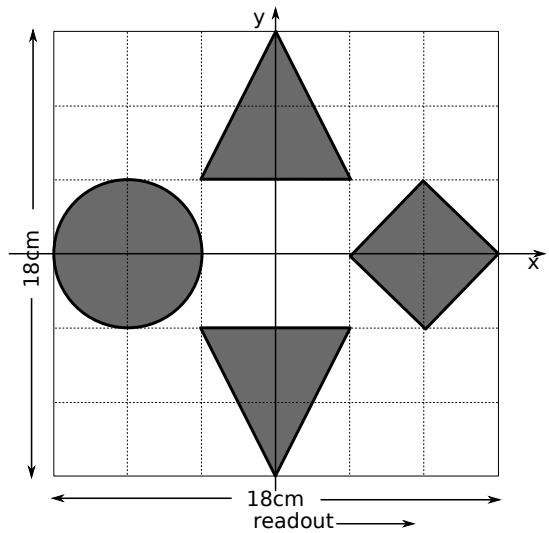
EE225E/BIOE265 Spring 2016 Miki Lustig
Principles of MRI

Assignment 7

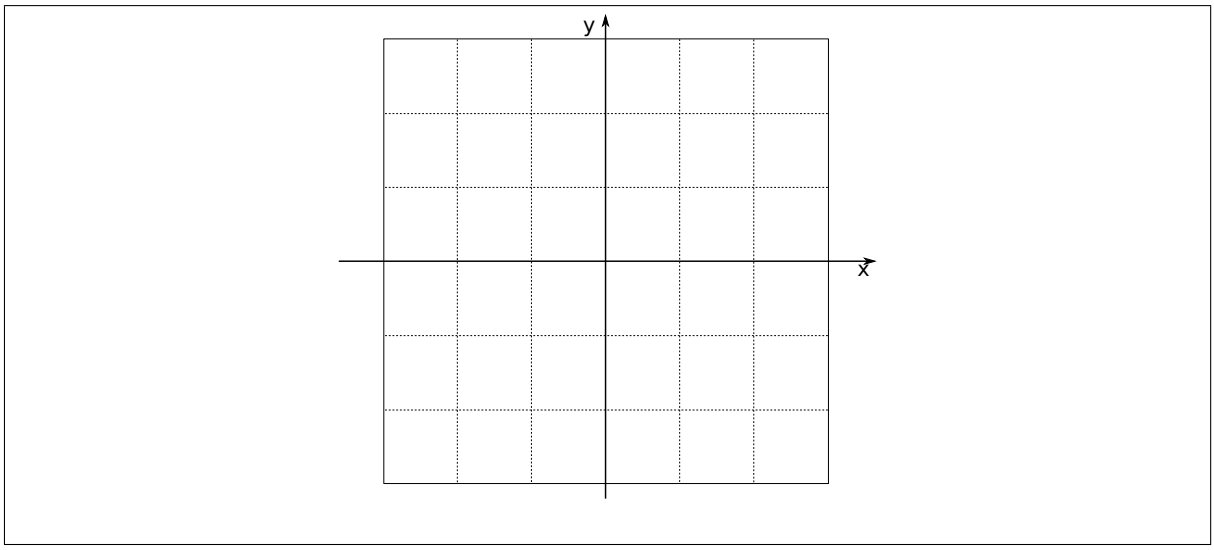
Due March 18th, 2016, Self Grading Due March 21st 2016

1. Read Nishimura Ch. 7

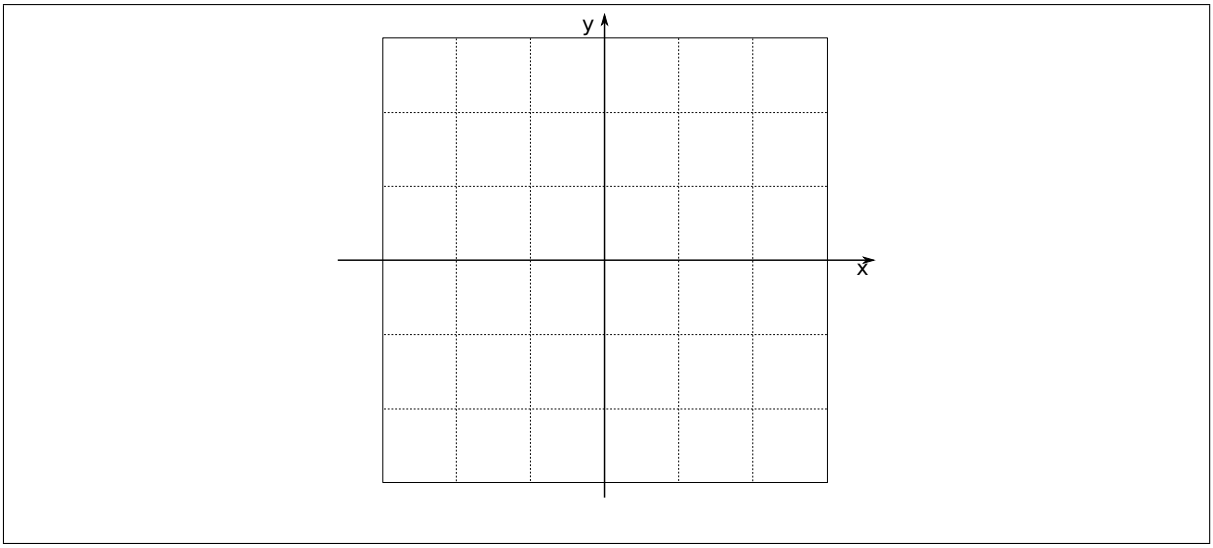
2. Artifacts in 2DFT: From Midterm I 2013:
An object is imaged with a 2DFT sequence to produce the image below. Also assume $\frac{\gamma}{2\pi} = 5$ kHz/G and that the readout gradient amplitude is 1 G/cm, FOV=18 cm, resolution=1 mm.



a) During the pre-scan, the receiver demodulation frequency was set incorrectly to 15kHz **below** the Larmor frequency. Sketch the resulting image if the scan was repeated with the wrong settings. Note that the dumb (inflexible) reconstruction computer blindly takes the inverse FFT of the raw data and displays the image matrix.



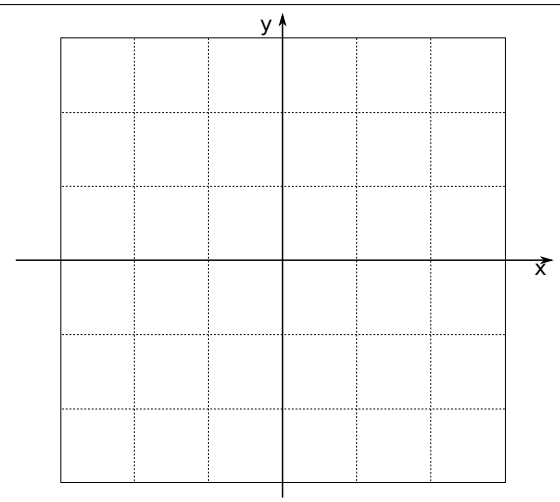
b) During the scan, an error occurred in the receiver A/D and the imaginary channel (Quadrature) was filled with zeros instead of data (Only the real-part of k-space was stored). Sketch the resulting image. Again, assume a dumb reconstruction computer.



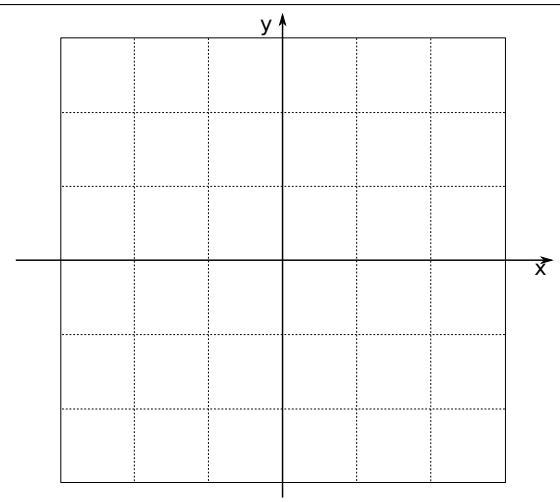
c) You scanned the object, but by mistake you entered a FOV of 6cm instead of 18 on the scanner console. You keep the same number of phase and frequency encodes,N_{pe} and N_{fe} and readout time. For each of the following parameters, comment if it changed and if so, by how much. Comment on: G_x, Δk_x, W_{ky}, δ_x.

G_x:	Δk_x :	W_{ky} :	δ_x :

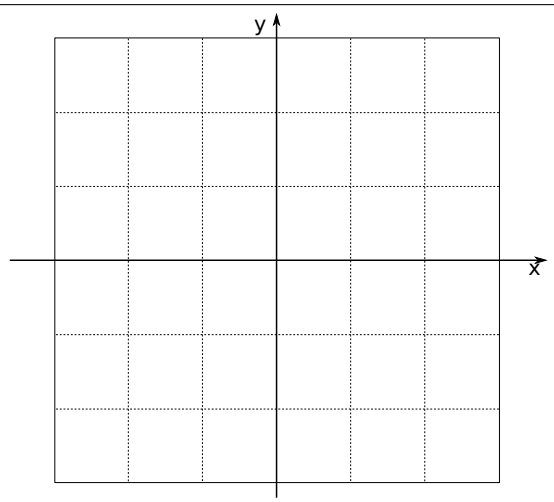
d) Sketch the resulting image from part (c). (Note that here the receiver and the reconstruction computer are aware of the new parameters).



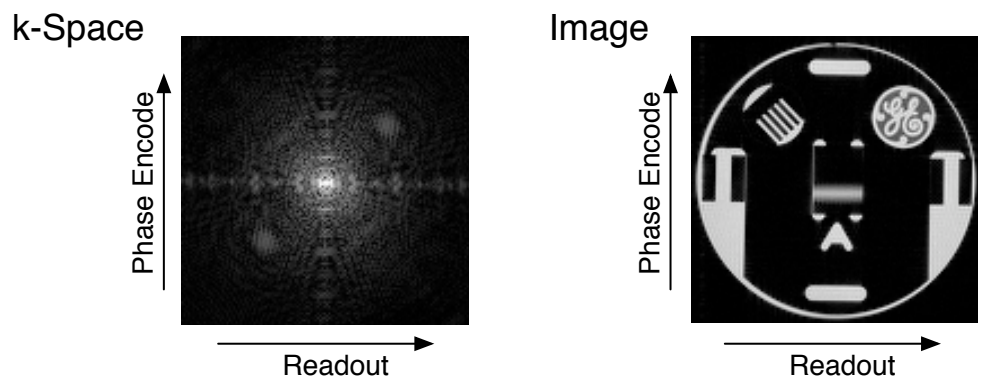
e) You use the exact same gradient waveforms from (c), but now, you fill the object with ^{13}C solution instead of water. For simplicity, assume that ^{13}C has 1/3 the gyromagnetic ratio of proton. Sketch the resulting image.



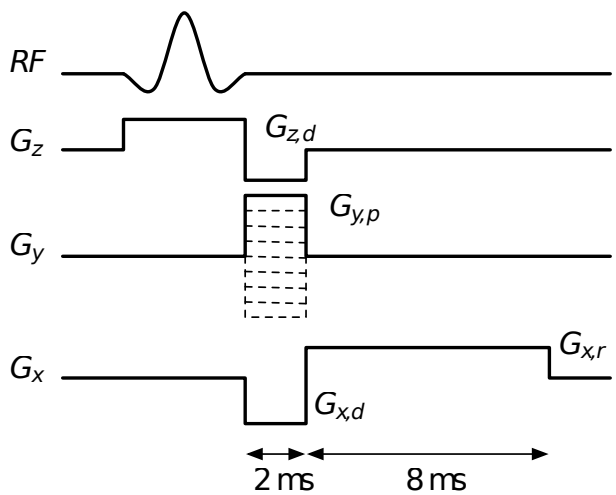
f) You rescan the object with the correct original parameters. But, exactly when the scanner is about to scan the DC phase-encode (line through the center of k-space) someone briefly opens the door to the scanner room. Unfortunately there's a radio station in your area that is transmitting a tone at a frequency of 30KHz above the Larmor frequency, which is also picked up by the receiver. Assuming that only a single phase encode is affected, sketch the resulting image.



3. More artifacts: From Midterm I 2010:
You've just programmed up your first 2DFT pulse sequence, and are trying it out on the scanner. You're pretty sure that the timing of the pulse sequence and the RF pulse amplitude are right, but you **aren't sure you have all the <u>gradient amplitudes</u> correct**. The k-space data and image you expect are shown below:

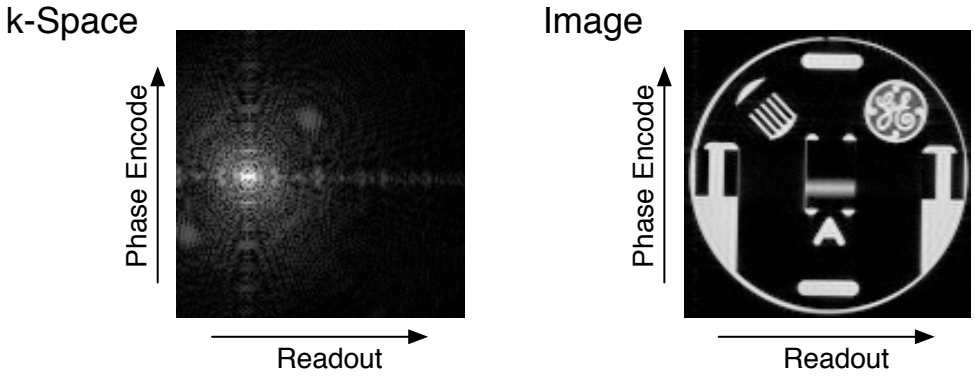


Instead the image has turned out differently, so something is wrong. The pulse sequence you thought you programmed is



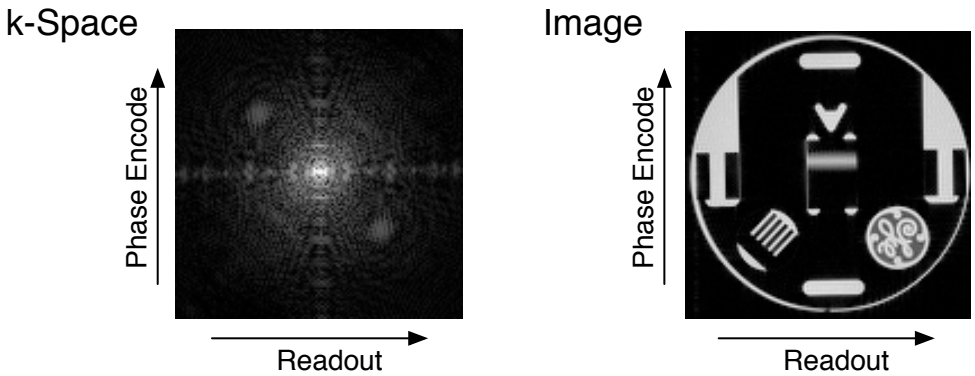
where phase encode gradient amplitude is $G_{y,p} = 1$ G/cm, the readout dephaser amplitude $G_{x,d} = 1$ G/cm, and the readout gradient itself is $G_{x,r} = 0.5$ G/cm. For each of the cases below, describe what pulse sequence programming error could have caused you to get each data set and image. A typical answers might be "the readout gradient was zero," or "the phase encode gradient amplitude is 0.5 G/cm instead of 1 G/cm."

a)



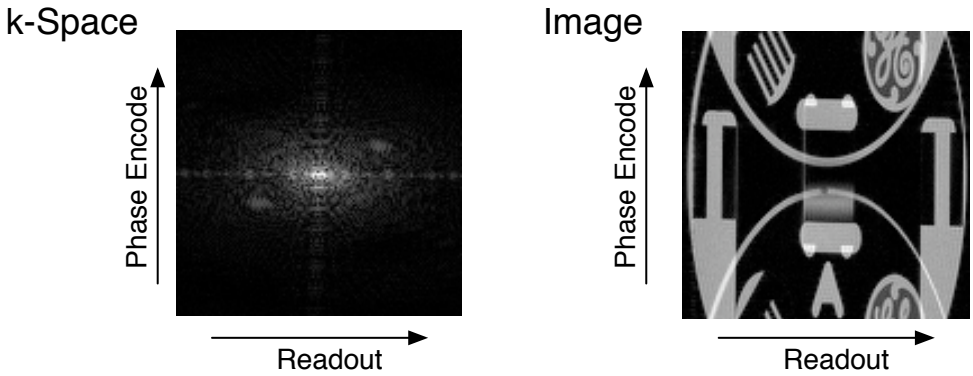
Diagnosis:

b)



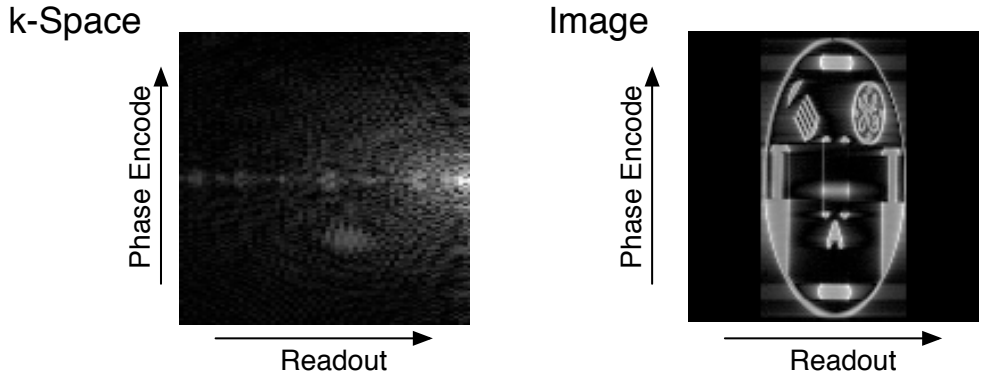
Diagnosis:

c)



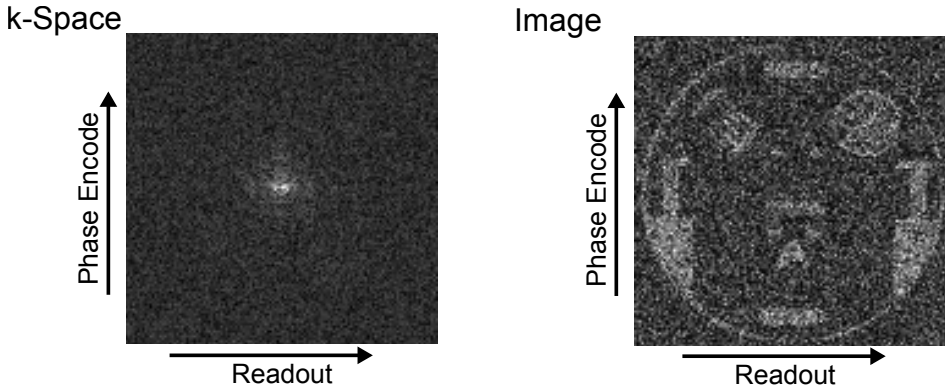
Diagnosis:

d)



Diagnosis:

e)



Diagnosis:

4. Nishimura 7.2

5. Flow Encoding (From midterm II 2010)

In this question we will consider several situations of flowing spins. We are going to make several approximations: 1) The transverse magnetization decays completely between excitations. 2) The displacement of the spins during a scan is much smaller than the imaging resolution, so it can be neglected for the purpose of determining position. 3) The effects of flow on the excitation are negligible. 4) We assume stroboscopic acquisition, e.g, a spin that moved from position y_0 to $y_0 + \Delta y$ during a TR, in the next TR it will also move from y_0 to $y_0 + \Delta y$. 5) Flow in tubes is NEVER turbulent.

a) A spin at position $y = y_0$ is moving in the y direction with velocity v_y, so its position is $y(t) = y + v_y t$. Derive an expression for the phase of the spin $\theta_{[y,v]}(t)$ in the presence of a general time varying $G_y(t)$ gradient.

$\theta_{[y,v]}(t) =$

b) The signal equation of an ensemble of spins at different y positions and y velocities is

$$s(t) = \int_y \int_v m_{xy}(y, v) e^{-i\theta_{[y,v]}(t)} \, dv \, dy.$$

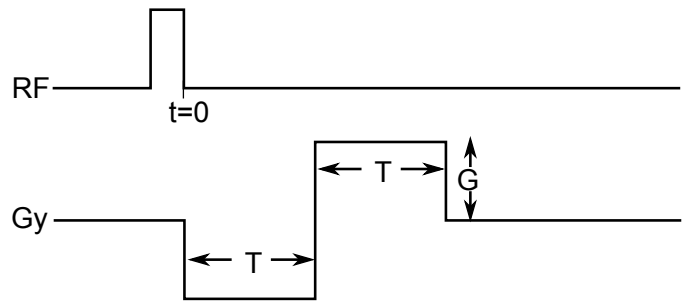
Show that it can be written in the form of

$$s(t) = \int_y \int_v m_{xy}(y, v) e^{-i2\pi[k_y(t)y + k_{vy}(t)v_y]} \, dv \, dy,$$

where $k_y(t) = \frac{\gamma}{2\pi} \int_0^t G_y(\tau) d\tau$ is the usual spatial k-space and $k_{vy}(t)$ is y velocity k-space. Find the expression $k_{vy}(t)$.

$k_{vy}(t) =$

c) Consider the following bipolar gradient pulse:

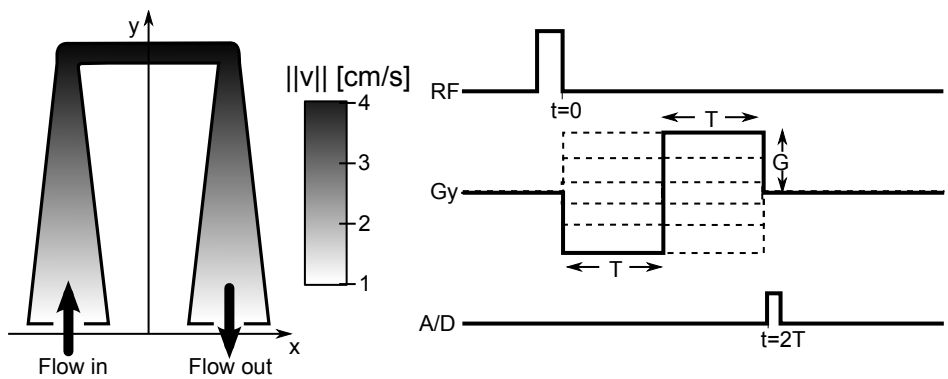


What are k_y and k_{vy} at the end of the pulse ($t = 2T$).

$k_y(2T) =$	$k_{vy}(2T) =$

d) Regardless what you got before, for this question assume that $k_{vy} = \alpha G$, a linear function of G.

You are given the following microfluidic device,



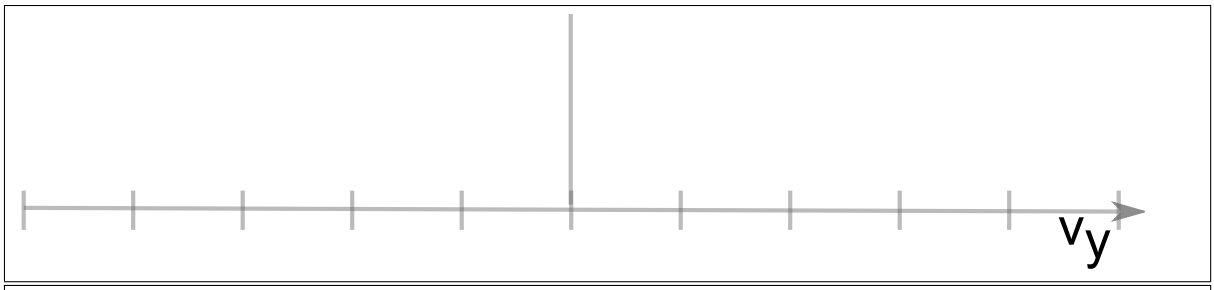
Fluid is injected into the device on the left side and is ejected on the right. The linear narrowing and broadening of the volume of the tubes generates a linear spectrum of velocities which we would like to image using the flow encoding sequence on the right. The flow velocity magnitude (not direction!) is grayscale coded in the image and represents magnitude velocities ranging from 1 cm/s to 4 cm/s.

In a similar way to phase encoding, in each TR the bipolar gradient amplitude is linearly varied from G to $-G$. Every TR we collect a single sample immediately following the bipolar gradient. After N repetitions we get a 1D signal with N samples. We reconstruct a velocity spectrum by computing an inverse 1D Fourier transform.

Qualitatively draw the ideal y-velocity spectrum of the device for this pulse sequence. Annotate, label and explain as much as possible. (You do not need to make calculations in order to do it!)

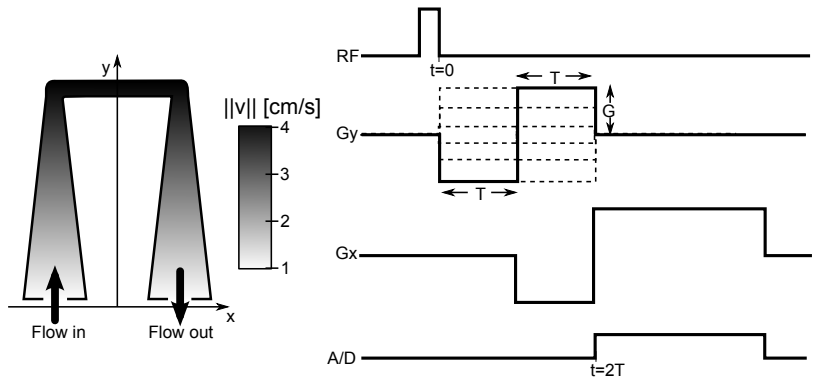
How many velocity encodes N_{kv} are needed to avoid aliasing if $k_{vy_{\max}} = 1$ s/cm?

Ideal Velocity Spectrum:



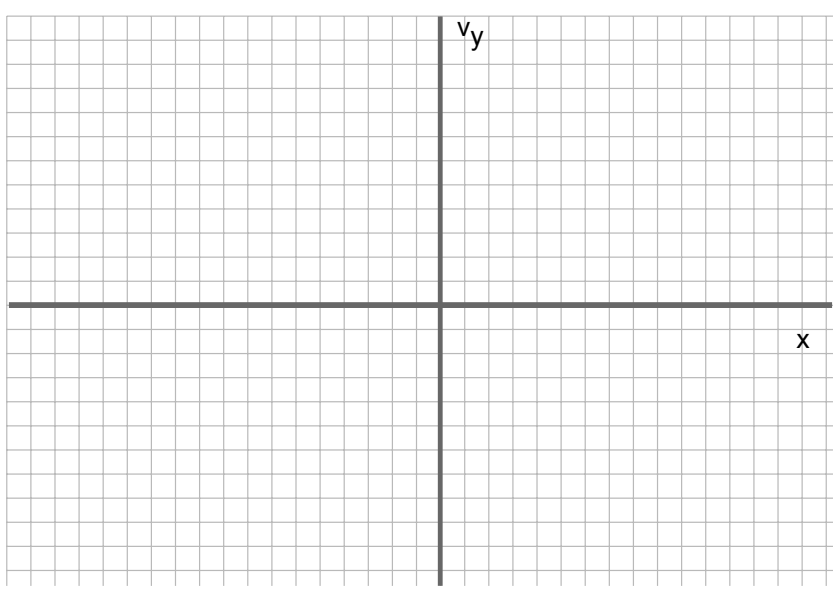
$N_{kv} =$

e) You modify the pulse sequence in d) to include a readout gradient:

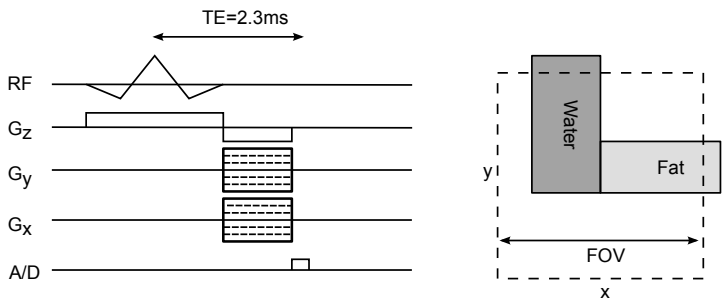


Here we collect M readout samples in each TR, resulting in kv-kx 2D data.

Draw the image that is the result of applying an inverse 2D Fourier transform to the acquired data. Annotate the image to provide intensity information. In the empty space describe in words as clearly as possible your thought process. In your analysis, ignore any flow effects in the x direction due to the readout gradient.



6. Consider the following image and sequence.



This sequence uses phase encoding in two dimensions. This means that for each excitation we read a single point in k-space and there is no gradient on during the readout. The number of phase encodes are enough to support the FOV given in the figure.

a) Re derive the effect of chemical shift (Eqns 7.5-7.10 in the text) for this pulse sequence.

b) Draw the reconstructed image.

c) How would your answer change if you used a regular 2DFT with readout in the x direction. Draw the image qualitatively pointing out the differences. Assume $TE = 11.5$ms.

7. **Matlab Problem: Twinkle Twinkle T_2^***

a.) In this problem we will simulate the effect of T_2^*. In general, T_2^* is an exponential decay approximation signal loss due to intra-voxel dephasing. As you will see in the next questions, this dephasing can be refocused. Again, we will use the Brian Hargreaves Bloch simulator.

First, we will generate a 90° RF pulse:

```
>> dt = 4e-6; % 4 us sampling rate
>> rf_90 = 90/360/(4257*dt);
>> % impulse RF pulse
>> b1 = [rf_90;zeros(100e-3/dt,1)];
>> g = b1*0; % no gradient
```

We will simulate a spin population (512 spins) with a Gaussian distribution of off-resonances:

```
>> % create gaussian distribution of off-resonance
>> % with std 20Hz
>> df = randn(512,1)*20;

>> % All spins at iso-center
>> dp = 0;
>> t1 = 800e-3; % Set T1
>> t2 = 50e-3; % Set T2

>> % start at Mz
>> mx_0 = 0;
>> my_0 = 0;
>> mz_0 = 1;
```

Simulate the the excitation followed by the free induction decay period:

```
>> % Simulate
>> [mx,my,mz] = bloch(b1,g,dt,t1,t2,df,dp,2,mx_0,my_0, mz_0);
```

The signal from an individual spin should exhibit just T_2 decay. Whereas the sum of the signals from all the spins together should exhibit T_2^* decay:

```
>> % for t2 take only 1 spin
>> s_t2 = mx(:,end/2+1)+i*my(:,end/2+1);
>> % for t2* average across off-resonance
>> s_t2star = mean(mx + i*my,2);

>> figure,
>> plot([1:length(s_t2)]*dt,abs(s_t2),[1:length(s_t2star)]*dt,abs(s_t2star));
>> legend('t2','t2^*');
```

Submit the plot that you get.

Low flip angle spin-echoes. Early in the days of NMR (Hann 1950) people observed that when applying two 90° pulses separated by time τ, the FID signal seems to increases at time 2τ.

b.) First, derive an expression (ignoring $T1$ and $T2$) for the transverse magnetization at time $t = 2\tau$. Show that the signal has magnitude $M_0/2$

c.) Validate the result by simulating a sequence with two 90° pulses separated at $\tau = 20ms$. Design the hard 90° RF pulses with maximum $B1_{\max} = 0.16G$. Simulate uniform off resonance ranging $[-600Hz, +600Hz]$. Use at least 512 discrete off-resonance locations! Use $T1 = 1s$, $T2 = 1s$. Plot $s(t)$, the FID of the sequence, for $0 < t < 60ms$. (don't forget to average across the off-resonance!)

d) Repeat the simulation in c), for 45° and 135° refocusing pulses. Do you see a spin-echo? What can you say about the refocusing properties of pulses as a function of flip angle?

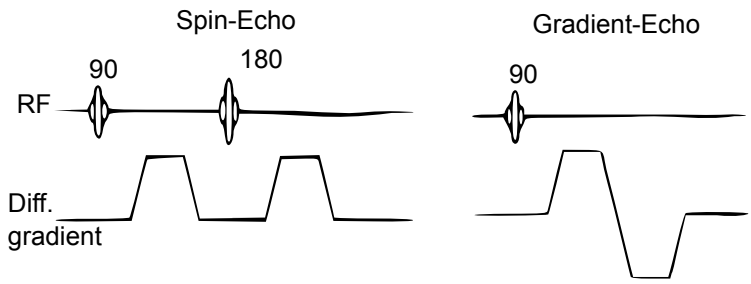
e) Simulate a series with three nonequidistant RF pulses with arbitrary flip angles, e.g. 30°, 90°, and 60°, pulses separated by $8ms$, and $14ms$ apart. Plot the the FID for $0 < t < 80ms$. How many echoes do you see after the last RF pulse? What if you add one more RF pulse (e.g. 45°), separated by $34ms$ from the third pulse? Plot the the FID for $0 < t < 160ms$. Use off-resonance of=linspace(-2600,2600,1024). The echoes you see are called stimulated echoes and are coherence pathways that refocus at different times. Stimulated echoes can often create artifacts in images. But, if used wisely can boost imaging speed, improve signal to noise ratio and more.

8. Matlab Assignment: Diffusion simulation

The MR signal can be sensitized to diffusion. It is in fact the only way in which diffusion of water molecules can be observed *in-vivo*. Diffusion weighting is used clinically very often. for example, stroke often shows much earlier on diffusion weighted images than on T_1 or T_2-weighted images. Diffusion weighting also provides us information on micro-structures. For example, the diffusion of water molecules within axon in white matter fiber is restricted across the axon, and is free along the axon. This allows us to track white matter fibers in the brain non-invasively.

Diffusion weighting is achieved by applying a diffusion sensitizing gradient. The most common approach is to apply two gradient lobes with equal area. In spin echo sequences, the two lobes will

have the same polarity and be placed at either side of the 180 spin-echo pulse. In gradient echo sequences the lobes will have opposite polarity and be often placed next to each other. The gradient amplitude for diffusion weighting is usually the maximum and their duration is usually much longer than imaging gradients.



A population of spins going through brownian motion will exhibit signal attenuation due to dephasing after the application of diffusion gradients. In this assignment we will simulate this effect.

a. Download the script diffSim.m from the class website. In order to run the script you will need the bloch simulator at the same directory. The script simulates the effect of diffusion in a gradient-echo sequence. Familiarize yourself with the script before continuing.

   There are three main parameters in the script. N is the number of spins in the simulation. M is the duration of the diffusion gradient (in samples of dt). D is the diffusion parameter and is the variance of the random motion that the spins exhibit. Run the script with D=0, D=2E-3 and D=3E-3. Submit the result of the simulation. Explain the results.

b. Download the script T2Sim.m from the class website. The script simulates a population of spins in the presence of a gradient, spin-echo train and brownian motion. Here, there is an additional parameter SE which is the interval between spin-echo pulses (in samples). This example can represent a voxel of water molecules next to a vein.

   Run the script with D=0 (no brownian motion) N=500, M = 1000 and SE = 200. You should see 5 spin echoes exhibiting very mild T_2 relaxation.

   Now, run the script with D=3E-3 (N=500, M=1000, SE=200). What happened?

   Run it again with SE=100 and SE=20. Explain.