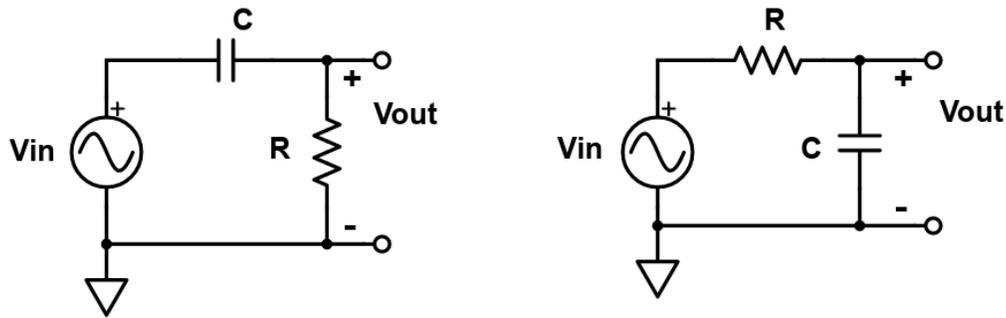# Circuits You'll Build

Figure 1: High and low pass filters. These are the simplest kind of RC filter

1. High pass filters to recover a lost last word from the Toy Story Aliens

2. Low pass filter for better electrocardiogram (ECG) recordings

Lab Skills You'll Learn

1. Designing and building passive RC filters—they are classic and ubiquitous

2. Measuring frequency response: magnitude and phase vs. frequency

3. How to use an oscilloscope and function generator—two classic pieces of test equipment in the circuits lab

1 Communicating with Aliens

1.1 Problem Statement

Did you hear about the recently unearthed "secret" track from the silver screen smash hit, Toy Story? One of the Toy Story aliens has been "chosen by the claw" (c.f.: https://www.youtube.com/watch?v=W9t5ZqeHcYk). The cuddly lil' green guy is peacefully departing with some final words, an oratorical offering of solace to his fellow aliens—in the ever familiar fairly high-pitched Toy Story alien voice. But Buzz Lightyear, ever the proud show-off, will have none of it! He decides

(a) Alien the "claw has chosen", (b) Buzz Lightyear ready for blastoff

Figure 2: Two Toy Story icons: the chosen alien and Buzz Lightyear.

to save the alien from the claw. Immediately, he fires his jet pack, blasts upward and tries to snatch the alien from The Claw. [1] Amidst all of the commotion, another alien was recording for posterity the final words of the dearly departing friend. Houston (Lexington?), we have a problem! The low frequency, dull rumbling noise of Buzz's rockets are so loud that they nearly completely drown out the aliens parting words. Buzz Lightyear to the rescue? Hardly. Circuits students to the rescue? Now we're talking!

Your mission is to design and analyze the performance of an RC filter that selectively reduce the rocket's noise of the rockets and make clearly audible the alien's parting words.

A previous acoustic analysis of Buzz's jet pack (rumor has it SpaceX/NASA did the analysis) indicated most of the sound content occurs at frequencies ≤ 300 Hz. Similarly, the aliens are reported to speak at frequencies concentration in a bandwidth of 500 to 5000 Hz. So let's split this down the middle when choosing an appropriate cutoff frequency $f_o \approx 400$ Hz. Use an $R \approx 5.6$ kΩ resistor in your design[2].

1. Sweep out the frequency response for your circuit. This means you need to gather sufficient information for the magnitude $|\tilde{H}(f)|$ and phase ($\phi(f)$) response vs. frequency. The frequency range you test should be at bare minimum one **_decade_** (factor of 10) above and below the cutoff frequency (40 to 4000 Hz, in this example), better if you can push to 2 decades above and below. Do be aware that 10 kHz is the maximum frequency that can be generated by the Picoscope 2204A AWG (arbitrary waveform generator).

2. Make a plot of the **_decibel gain_** $G(f)$ vs $\log_{10} f$.

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[1]OK, Toy Story aficionados, this is heresy, I know. It's not really how the movie plays out. The original plot line has been modified to fit conveniently into the Circuits pedagogy.

[2]This is a nice mid-range value resistor. Plus, the picoscope has an output impedance of 600 Ω, so we can only "drive" loads that are about 10× larger, e.g. 6 kΩ, without loss of input signal through voltage division becoming too severe

3. Make a plot of the **_phase angle_** $\phi(f)$ vs $\log_{10} f$.

4. For each, overlay the theory curve so that you can instantly compare and contrast with experiment. Highly recommend matlab here, you even have sample code at your disposal. Show the instructor of TA your plot when you are done (BEFORE you walk out of lab).

5. When all looks good and sensible—proof of concept your filter is working properly—we'll connect you into the audio so you can the net result for yourself. The audio file you need is on the course website titled "Aliens Talking with Rockets" linked here.

   In order to complete this lab, provide a live demonstration of the your circuit. After all, we are on the edge of our seats wanting to know what the secret message was!

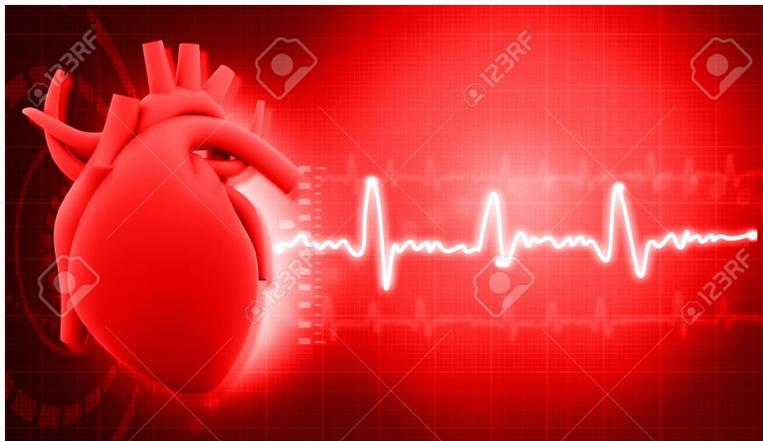# 2 Listen to Your Heart: Electrocardiogram (ECG)

Figure 3: Heart beat muscular contractions produces an electrical signal. Image credit: 123rf.com

2.1 Intro to the ECG

The electrocardiogram (ECG) is a critical diagnostic tool to assess heart health in medical clinics worldwide. In essence, it is an electrical measurement of the heart's muscular activity pumping blood throughout the body.

One basic measure derived from the ECG is heart rate. The cleaner the ECG signal, the easier it is for a computer-automated algorithm to find the peaks of the QRS wave, and thus the more accurate the determination of the heart rate. A more sophisticated analysis of the ECG can reveal abnormal cardiac activity, such as atrial fibrillation (AF). Abnormal heart activity shows up in the ECG as abnormally timed and/or abnormally shaped waveforms. Again, it is absolutely critical to get a high quality ECG for the cardiologist to properly analyze!

Before plunging ahead, let's see how the heart beat generates an electrical signal on the skin surface. Watch the last 2 min of this very well done video that explains how electrical signals arise from muscle contractions. It also explains the origin of some interference signals that should be filtered out in order to recover the true underlying heartbeat signal alone. Good filtering leads to good quality signals. Good quality signals lead to accurate diagnoses–excellent!

All righty, let's see what we are working with today. The "clean" (non-noisy) signal, which we will call $v_{ecg}(t)$ was measured from an actual patient's human heart The ECG signal $v_{ecg}(t)$ was retrieved from the MIT ECG stress test database here. This signal is illustrated in 4, bottom panel.

High frequency noise, $n(t)$, was added synthetically inside a computer (Matlab!). The added noise added mimics real life hospital conditions with power line interference and high frequency medical instruments contaminating the clean ECG signal. Thus the total record signal is:

$$v_{noisy}(t) = v_{ecg}(t) + n(t)$$

The noise was generated using the following sum of cosines:

$$n(t) = a_1 \cos(2\pi f_1 t) + a_2 \cos(2\pi f_2 t) + a_3 \cos(2\pi f_3 t)$$

where the amplitudes are: $a_n = [50, 100, 25]$ mV, and the frequencies are $f_n = [180, 300, 4000]$ Hz.
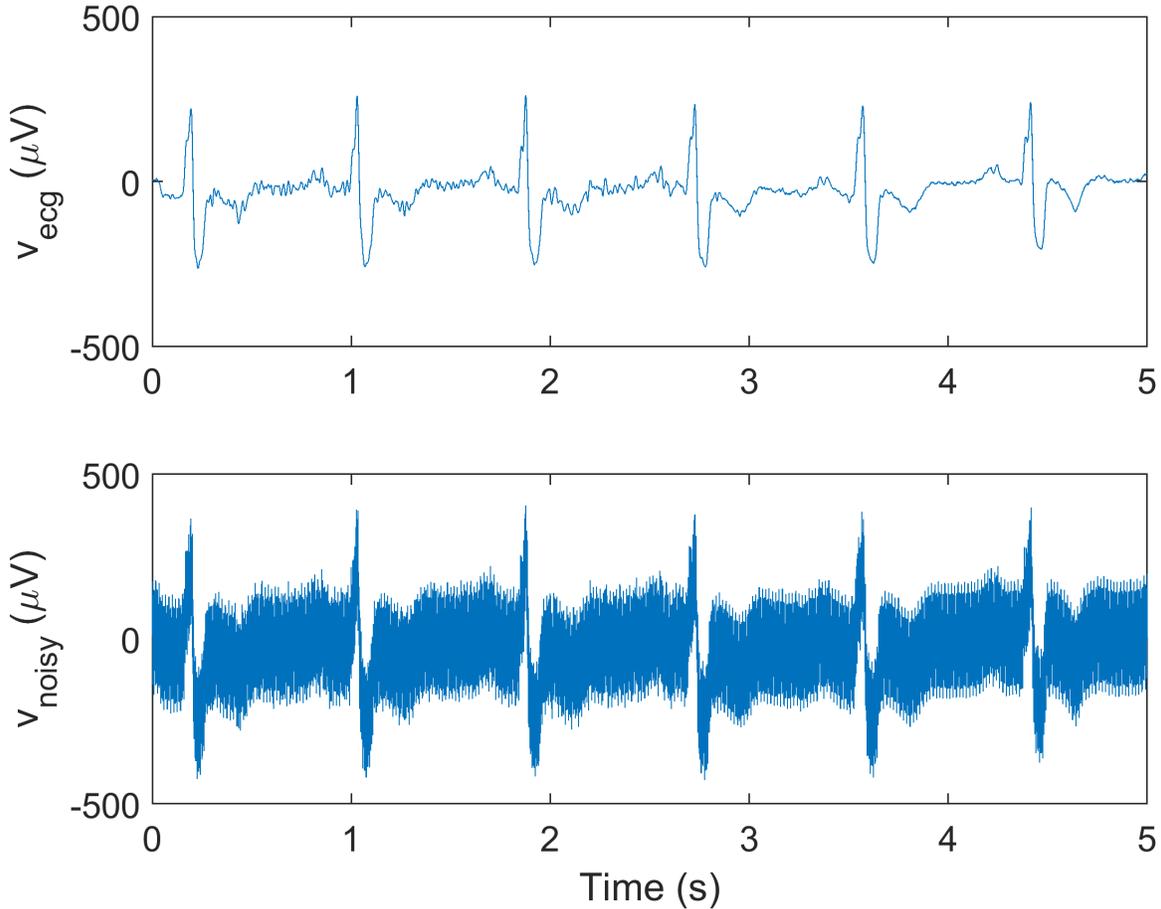

Figure 4: Bottom: clean ECG signal. Top: noisy ECG signal.

The QRS complex can be variable among patients. They typically have a duration of about 50 - 150 ms. You can think of this as the period of the underlying oscillation. Thus, we can also say that the underlying frequency range of interest spans $f = 1/150$ ms to $1/50$ ms. Equivalently, we can say the QRS complex typically is in the frequency range of $f = 6.7$ to 20 Hz.

2.2 Problem Statement: Low Pass Filter Design

Dear fearless Circuiteers, doctors and patients need your help cleaning up the noisy ECG signal. Specifically, they need your new found expertise to build a low pass filter that sufficiently attenuates the noise and interference sources (frequencies of 180 Hz and higher), whilst preserving the underlying ECG signal QRS complex (frequencies of approximately 20 Hz and below).

Your task is to design, build, characterize, and perform proof of concept experiments for a LPF that does just this: ditch the high frequency noise, keep the ecg
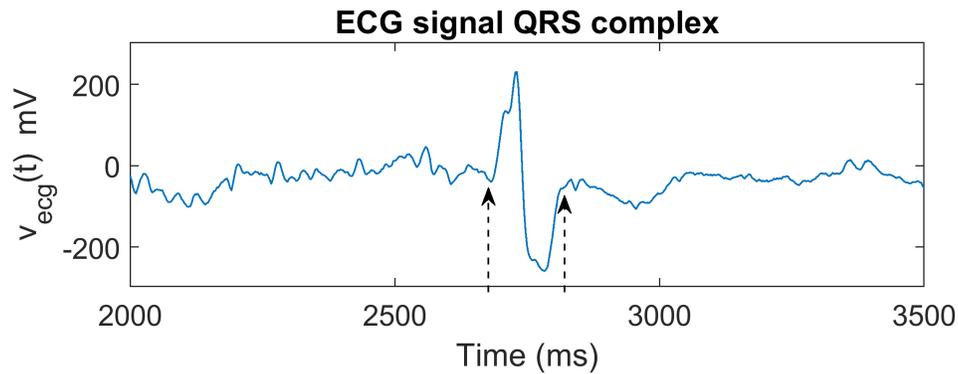
Figure 5: QRS complex timing of ECG signal in today's data set. The duration of the complex (period of underlying oscillation) indicated by the dotted arrows is $\Delta t \approx 130$ ms.

signal. That is, don't throw the proverbial baby out with the bath water!

Steps you should (and must) take are:

1. Select a suitable cutoff frequency. Discuss/verify this with the instructor of TA prior to actually building.

2. Build the LPF on a breadboard. Use resistors, capacitors, potentiometers, anything you find in your kit or in the lab.

3. Pipe in the ECG signal from your computer or mobile device. The ECG signal is formatted as an .wav audio file (easy to play back this way) from the course website called "noisy ecg" linked here. The clean ecg data file is also provided on the course website for reference. Note: If you try listening to these file, you won't hear a heart beat; rather you'll hear a hiss that corresponds to all the high frequency noise components.

4. View the noisy signal (input) and the clean(er) signal (filter output) simultaneously using your scope. Does it look better/cleaner? If so, great. If not, adjust to taste! When you are happy with the result, verify with the instructor or TA before moving on to the next part.

5. Time to fully characterize the frequency response of the filter you designed! This is very similar to what you just did for measuring the filters gain and phase response, just as you did in the aliens portion of this lab. That is, gather sufficiently data for $G(f)$ and $\phi(f)$ that you can plot vs. $\log_{10} f$. Remember to work across decades (powers of 10) in frequency land!

6. Plot your data overlaid on the theoretical curves.

7. Verify all looks sensible—check with the instructor or TA.

6

3 What to Turn In

You should basically be done with this report as you walk out of lab. There is not much writing, the figures should tell the majority of the story. 2 pages max are allowed for the Aliens Audio and ECG filter sections below (4 pages total, max!).

3.1 LPF theory

Turn in your work for section 6 in the RC filters worksheet. Pdf scan or similar is fine, so long as it is legible. Translation: don't spend 23 light years formatting in equation editor or LaTeX.

3.2 Aliens Audio

1. Clearly labeled circuit schematics labeling all component values used

2. Beautiful plot of decibel gain experiment vs. theory

3. Beautiful plot of phase response, experiment vs. theory

4. One sentence explaining your filter design, for example: "I designed a (fill in the blank) filter with a cutoff frequency of X Hz because (supply reason here)." Show any relevant calculations, e.g. cutoff frequency given R and C value

5. Audio demo proof of concept that your filter worked sufficiently well

6. Two sentences discussing pros/cons of the design, for example: "My filter design worked well in that (intelligent comment goes here). One limitation or possible improvement for the design was (some aspect that was suboptimal goes here)"

3.3 ECG analysis

1. Clearly labeled circuit schematic labeling all component values used.

2. Show any relevant calculations, e.g. cutoff frequency.

3. Screenshot or similar of ECG signal input and output. This serves as proof of concept your design worked properly.

4. Beautiful plot of decibel gain experiment vs. theory

5. Beautiful plot of phase response, experiment vs. theory

6. One paragraph of text describing your design rationale: How did you choose your cutoff frequency? What were the pros and cons of these design decision? Specifically, address how your filter design balanced 2 competing factors, attenuating unwanted components while passing the actual ECG components. Both magnitude and phase response are important here. In drafting this paragraph, it may be helpful to refer to the prompts in the Aliens Audio "What to Include" section above.