**Lab #6: Of Aliens and Heartbeats**
**ENGN/PHYS 207—Fall 2019**
**RC filters: application to audio and biomedical design problems**

## Circuits You'll Build

1. RC high pass filters (1- and 2-stage) to recover a "lost" audio track.
2. Multi-stage bandpass filter for high-quality ECG recordings.

## Lab Skills You'll Learn

1. Designing and building passive RC filters—they are classic and ubiquitous.
2. Understanding the trade-offs in filter design, and making smart engineering judgement choices to balance benefits and limitations thereof.

# 1 Communicating with Aliens


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

Figure 1: Two Toy Story icons: the chosen alien and Buzz Lightyear.

## 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 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 test two RC filter circuits to selectively reduce the rocket's noise of the rockets and make clearly audible the alien's parting words. One of the circuits must be a 1-stage filter. The other must be a 2-stage filter.***

This is open-ended design problem, there is no one single correct answer. However, there are some designs that work better than others. Hints: 1) A previous acoustic analysis of Buzz's jet pack has indicated most of the sound content occurs at frequencies $\leq$ 300 Hz. 2) Feel free to start with designs similar to those briefly viewed at the end of class Wednesday Oct 30. (see course website under Supplemental). Such designs are likely a very good starting point. Revise/iterate upon the design as you wish.

**You must provide a live demonstration of the your circuit to officially complete this lab. You can do this either in person (preferred) or in video format.**

## 1.2 Equipment and Components

You may use any components found in the Circuits lab. The sound file of the alien's recording from the course website AliensTalkingWithRocket.wav

You'll certainly want to make use of some audio equipment to hear the output from your circuit to assess how well the filter is functioning. You'll also want to use the scope to view the input (original sound file signal) and output (filtered output signal). Once you have your filter designed to your liking, be surely to clearly measure the magnitude $|H(f)|$ over a sufficiently wide range of frequencies for both the 1- and 2-stage HPFs. A good rule of thumb is to measure two orders of magnitude above and below the cutoff frequency $f_o$. You will ultimately submit graphics showing the decibel gain $G(f)$ vs. $\log_{10} f$ comparing experiment to theory. (See Section "What to Turn In" at end of this manual)

[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 Listen to Your Heart: Electrocardiogram (ECG)

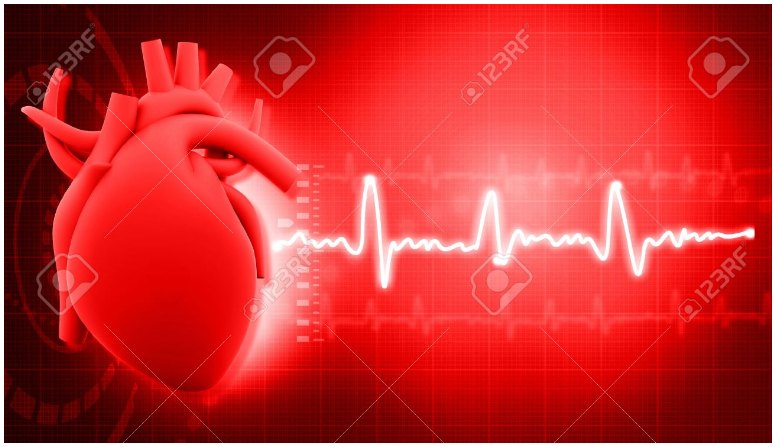

Figure 2: Heart beat muscular contractions produces an electrical signal. Image credit: 123rf.com

## 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 first 4 min of this very well illustrated video by JOVE 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–bueno!

All righty, let's see what we are working with today—it's a synthetically produced ECG signal (generated by a computer, not by an actual human heart). Figure 3 illustrates the component waveforms under consideration in this problem.

The ECG signal $s(t)$ was simulated using fancy biophysics and math techniques[2]. The simulation code was downloaded from Physionet: ECGSYN - A realistic ECG waveform generator. The P wave, QRS complex and T wave are all fairly easy to pick out by human eye. Random, high

[2] c.f. McSharry PE, Clifford GD, Tarassenko L, Smith L. A dynamical model for generating synthetic electrocardiogram signals. IEEE Transactions on Biomedical Engineering 50(3): 289-294; March 2003

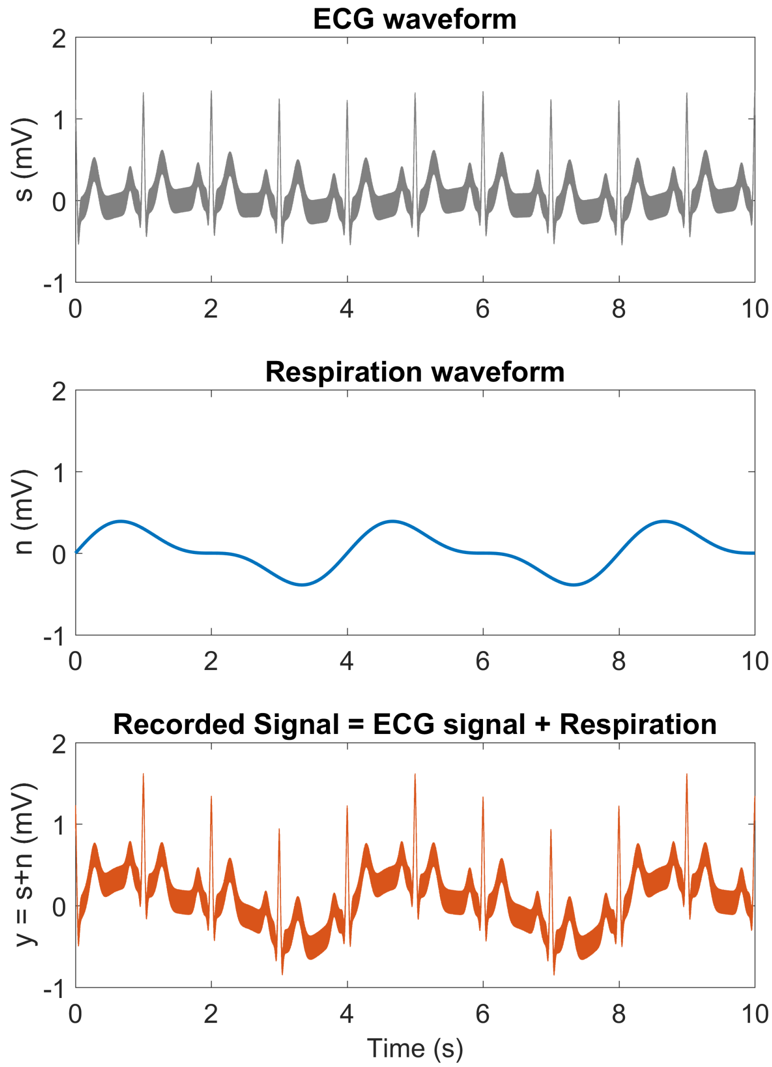


Figure 3: Simulated ECG signal (top), synthetic respiration signal (middle), and electrical signal recorded on skin surface (bottom).

frequency noise was superimposed with a mean amplitude of $A_{noise} = 0.15$ mV. This is seen as a thick band oscillating about the main ECG waveform.

A synthetic respiration signal was generated using the following formula:

$$n(t) = A_{resp}\sin(2\pi f_{resp}\, t) + \frac{A_{resp}}{2}\sin(4\pi f_{resp}\, t) \quad (1)$$

where the amplitude $A_{resp} = 0.3$ mV, and the frequency $f_{resp} = 0.25$ Hz $= 15$ breaths per minute.

The total recorded signal $y(t)$ is the summation of the noisy ECG waveform superposed with the respiration signal:

$$y(t) = s(t) + n(t) \quad (2)$$

The frequency content in the recorded signal $y(t)$ can be visualized per Figure 4. Large spikes indicate frequency components of the periodic heart beat signal. For the math curious, this figure was produced using the Fast Fourier Transform (FFT). You'll hopefully cover this in Math Methods next winter (or possibly you've seen it before!)

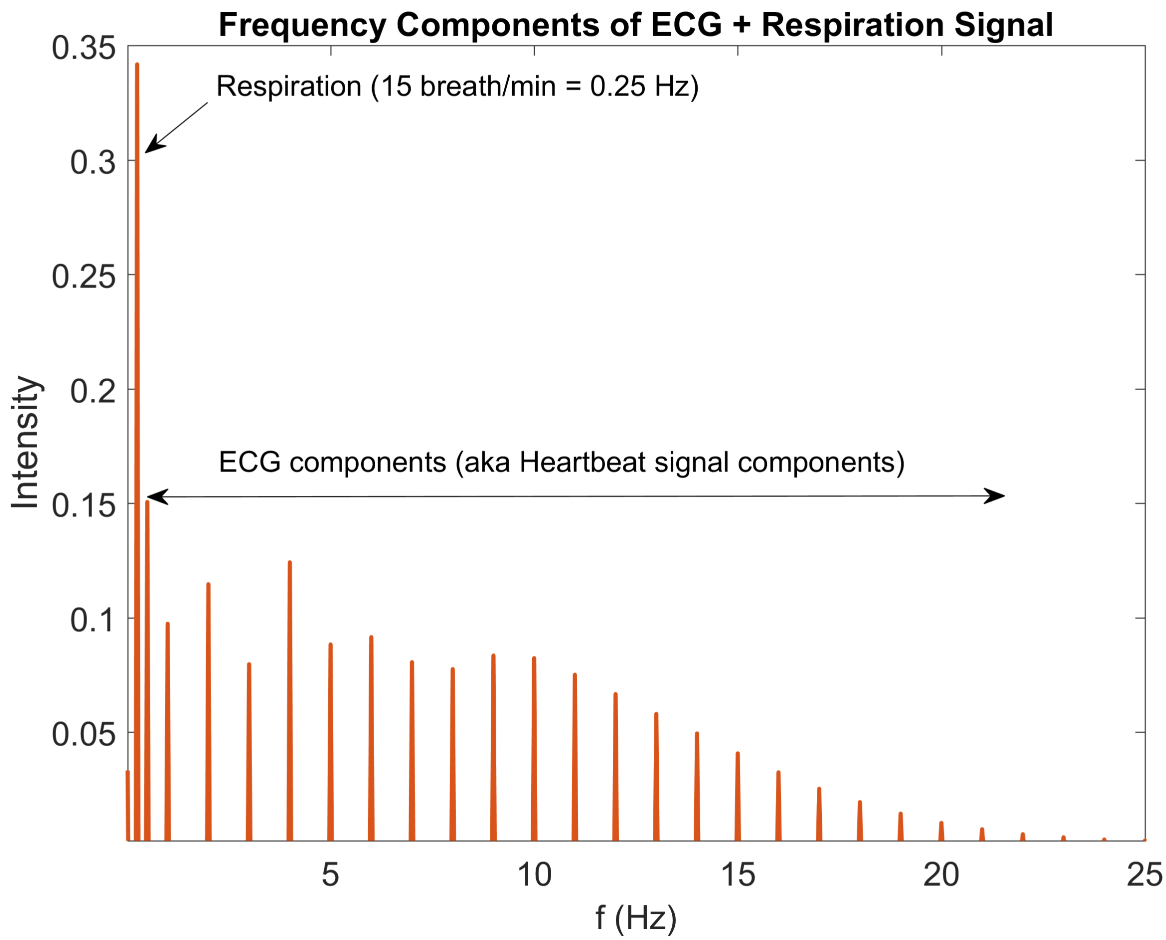


Figure 4: Fast Fourier Transform of the skin surface recording $y(t)$. The components with frequencies between $\approx 0.5 - 25$ Hz correspond to the underlying heartbeat. These are components we want to pass untouched. The respiration component is relatively very strong. Ideally this signal would be strongly filtered out.

### 2.2 Problem Statement: Band Pass Filter Design

We need you, fearless Circuiteers, is to build a band pass filter that will pass the underlying electrical signal generated by the heart, whilst attenuating out-of-band noises sources.

In this case we need a BPF to reject some low- and high-frequency unwanted signal components. As described above, the BPF should pass ECG components in the frequency band of $f = 0.5 - 25$ Hz. The low-frequency respiration ($f \leq 0.25$ Hz) waveform should be rejected (attenuated). Similarly, high frequency noise should also be attenuated. High frequency noise sources arise from other electronic equipment (often computer monitors refreshing in the several kHz range) and from 50/60 Hz power line interference.

***Your task is to design, build, characterize, and perform proof of concept experiments for a BPF that outputs a clean (high signal to noise ratio, SNR) ECG signal.***

The cardiac signal can be input to your circuit as follows:

1. Download the audio file which encodes the cardiac waveform as illustrated in the bottom panel of Figure 3.
2. Play this on repeat through your mobile device.
3. Connect the audio output of your mobile device to your circuit and oscilloscope. Note: If you try listening to this file, you won't hear a heart beat; rather you'll hear a hiss that corresponds to all the high frequency noise components.

For a strong hint of where to get started with your design, check out the BPF designs in the worksheet for RC filters (on the course website under supplemental, sections 4 and 5). Adjust to taste. Once you have your filter designed to your liking, be surely to clearly measure the magnitude $|H(f)|$ and phase response $\phi(f)$ over a sufficiently wide range of frequencies. A good rule of thumb is to measure two orders of magnitude above the high cutoff frequency $f_H$ and two orders of magnitude below the low cutoff frequency $f_L$. As always, plot as you go to make sure you are acquiring sufficient data.

# 3 What to Turn In

Your written report should consist of a single document broken into two chapters of the same book, so to speak—one for the aliens audio portion, and one for the ECG portion. 5-page absolute max limit. Appendices do not count toward the page count

## 3.1 Aliens Audio

1. Clearly labeled circuit schematics labeling all component values used.
2. Design rationale: Explain design decisions made. For example, what factors played into your setting the cutoff frequency for the filters? What were the pros and cons of that choice?
3. Results: Plot of decibel gain vs. frequency ($G(f)$ vs. $\log_{10} f$) comparing BOTH filters on the SAME axes. This means you should have 2 theoretical curves and 2 sets of data points (your experimental values) overlaid, 1 for each filter.
4. Proof of concept: do this either in person or take a brief video.
5. Analysis: How well did theory and experiment align (or not). Was the agreement excellent everywhere? Just in the pass band? In the cutoff region? How did the empirically determined cutoff frequency compare to the theoretical ones? What was the slope in the cutoff region? Did you observe the canonical $m \times 20$ dB/dec ($m$ is the filter order)? Be quantitative!!
6. Discussion: Overall, how well did your circuit accomplish the objective of isolating the alien talking? What are the tradeoffs with the first and second order filters tested. How could the system be improved in the future?

## 3.2 ECG analysis

- Clearly labeled circuit schematic labeling all component values used.
- Design rationale: Explain design decisions made. For example, what factors played into your setting the lower and upper cutoff frequencies? What were the pros and cons of these design decisions? Specifically, address how the filter balanced attenuating unwanted components while passing the actual ECG components. Both magnitude and phase response are important here.
- Results: Plot of theoretical decibel gain vs. frequency ($G(f)$ vs. $\log_{10} f$) with data points overlaid. Use/revise sample matlab code from previous works, as needed.
- Similarly, lot of for phase vs. frequency ($\phi(f)$ vs. $\log_{10} f$) with data points overlaid.
- Proof of concept: Illustrate/visualize the filtering action in photos–perhaps a series of a few oscilloscope screen shots comparing input (unfiltered) and output (filtered) signals would work well here.

- Analysis: How well did theory and experiment align (or not). Was the agreement excellent everywhere? Just in the pass band? In the cutoff regions? How did the empirically determined cutoff frequencies compare to the theoretical ones? What was the slope in the cutoff region? Did you observe the canonical $m \times 20$ dB/dec ($m$ is the filter order)? Be quantitative!!
- Discussion: Overall, how well did your circuit accomplish the objective of isolating the ECG signal while cutting the respiration and high-frequency components? How could the design be improved in the future?

### 3.3 Theory Work

Complete the RC filter worksheet introduced in class. Specifically, complete sections 3 (high pass filter) and 4 (band pass filter). Submit as an appendix.