ENGN/PHYS 207—Fall 2019
Final Project (option B): Feast for the Eyes and Ears
Light and Music Fusion

Initial validation (frequency response curves): must be completed by 5pm Tues, 03 Dec 2019 (firm deadline!)
Final proof of concept (live demo): must be completed by end of your lab period Thurs, O5 Dec 2019 (firm deadline!)
Final Report Due Date: Noon, Tues 10 Dec 2019

Figure 1: 3 sets of illuminated LEDs synced to audio. The bass, mids and treble channels were all outputting a relatively high (suprathreshold) level of energy at the moment this frame was captured. The potentiometer master volume control knob is visible at bottom left. The current limiting resistor is visible for the bank of blue LEDs. Image courtesy of Chris Cotton, Circuits alumni fall 2017.

Fusing Sound and Sight–a brief history

The idea of fusing light with sound, or that these two media could be correlated in meaningful ways to augment the sensory experience, has fascinated humankind for a long-time, including historical heavy hitters such as Aristotle, Pythagoras, and Leonardo da Vinci[1].

Some neuroscience studies suggest that visual and auditory perception seems to be integrated deep in the human brain, suggesting that the Greeks really were on to something. To point, several famous classical composers, including Franz Liszt and Sergei Rachmaninoff were believed to have synaesthesia — a natural state where musical notes are intrinsically associated with seeing colors and/or shapes. So too was Alexander Scriabin, who was completely obsessed with the idea of a color music[2]. Scriabin conceived of the western 12-tone scale as being mapped to the colors of the visible spectrum (see Fig. 2.) You can hear the beginning of Scriabin's mysticism in his Etudes, played spectacularly by Vladimir Horowitz here: `http://www.youtube.com/watch?v=XawgKTDyBcM`.

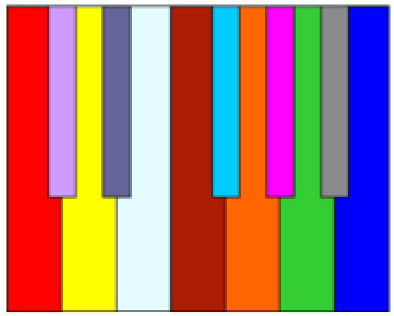

Figure 2: Scriabin's *Color Keyboard*. Image source: wiki commons

As electronic technology developed over a century, especially the past few decades, electromechanical instruments combining visual and auditory perception, such as the Lumigraph, became popular[3]. In more recent times, some very hip party people have designed a bit of electronics that syncs up the flashing of lights to certain musical sounds. A still photo of such a circuit is illustrated in Fig. 1. This device is often referred to as a *light organ*.

You will note that there are multiple colors of lights, and each color group is synced up to a certain bandwidth. For instance, the green lights are essentially the only ones illuminated initially as the low tom-toms are hitting; the greens a blues kick in a little bit when the high toms or snare hit. Then when the rest of the band joins in with the raucous brass, other colors illuminate. A snapshot is nice, but an animated version is really much better. You can admire the handwiwork of a previous Circuits group in living color here and here.

Design Problem Statement

Develop and implement a "light organ" which, in essence, synchronizes a light show to a musical track. Music will be separated into 3 channels: bass, middle, and treble. A corresponding bank of LEDs will illuminate according to the the signal strength within a certain frequency band at that given moment. Figure 3 summarizes the overall functionality of the light organ

Development of the system will come in two phases: **Phase I—Initial Validation**: Your

[1] `http://www.awn.com/mag/issue2.1/articles/moritz2.1.html`
[2] c.f. `http://mnemotechnics.org/forums/alexander-scriabin-and-artificial-synesthesia-1016.html`
[3] `http://www.awn.com/mag/issue2.1/articles/moritz2.1.html`

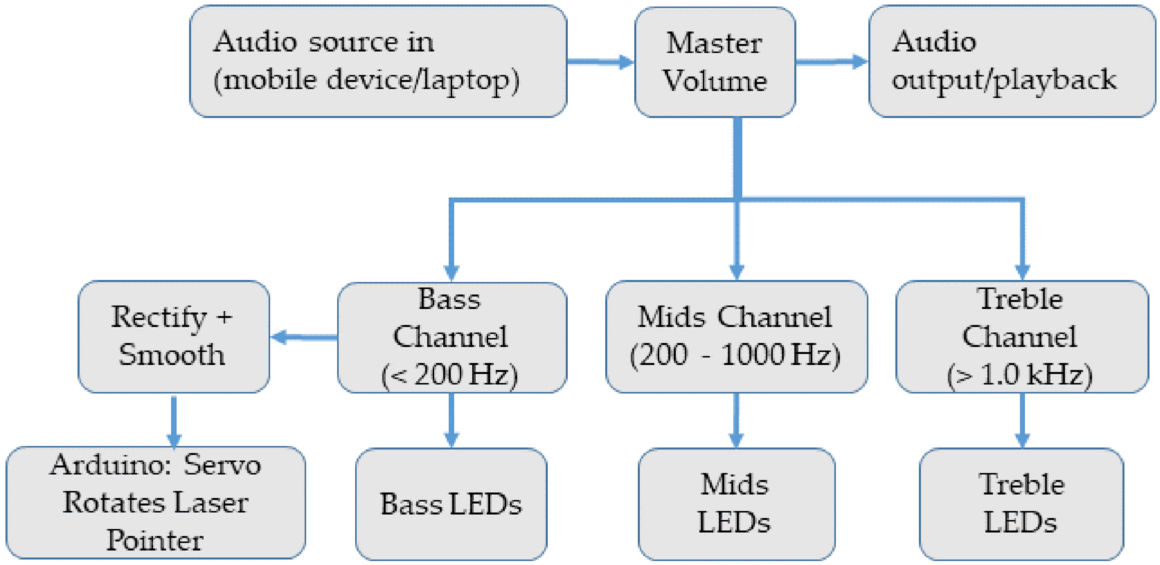

Figure 3: System Overview for Lights + Music.

task is to design, build, characterize, and perform proof of concept experiments for a circuit that is capable of separating a musical track into 3 different frequency channels along with a master volume control.

The net result of Phase I should be sufficient evidence to establish proof-of-concept of: 1) appropriate filtering; 2) appropriate amplification; 3) discrete transistors switch LEDS on and off; 4) Arduino measures and displays rectified and smoothed basss signal envelope. This evidence needs to be presented by showing appropriate decibel gain vs. frequency data, and a quick live-demo with the Arduino serial plotter.

Phase II—Final Proof of Concept: Your system will incorporate an Arduino microcontroller that measures the bass channel envelope. In response, the Arduino will output commands to a servo motor by an angle proportional to the strength bass signal rotating a laser pointer with diffraction grating. This element projects a very cool looking light image onto a display screen.

The net result of this phase should be a live-demo of your fabulous laser + LED + music show!

Design Criteria

Your design must meet the following design criteria and considerations:

1. Master volume control knob. Some devices play audio content with small amplitude ≈ 50 mV pk-pk (newer phones); and strong audio sources output much larger amplitude signals ≈ 1 V pk-pk. Your master volume control will make the light organ compatible with any audio source. For instance, the user can turn a knob to amplify a faint audio source; or turn the knob the other way to deamplify a strong audio source.

2. Must have ≥ 3 distinct frequency bands (e.g., bass, mid, treble). Roughly speaking, bass is defined as frequencies ≤ 200 Hz, mids as $\approx$200 Hz - 1.0 kHz, and treble as ≥ 1 kHz. ***The bass and treble channels must be selective at the 40 dB/dec level.***
3. User must be able to change sensitivity of the LEDs illuminating or not depending on the corresponding energy in a frequency band. For instance, one user might want red LEDs to light up only when the bass is very strong, whereas another might want them to light up even if the bass is less intense. Therefore, each channel (bass, mid, treble) must integrate a sensitivity knob —in essence, you can turn up the volume in the bass, middle, and treble channels independently from one another. Therefore, your system must contain 3 sensitivity knobs.
4. Each frequency band must be synced with ≥ 3 color LEDs (minimum of 9 total LEDs). The LEDs in a group must all turn on and off synchronously (at the same time). You may choose to group the LEDs and geometrically position them any way you want.
5. LEDs must all illuminate brightly for good visual effect. Therefore, use a transistor as digital switch to turn them all on at once, with sufficient power delivered (sufficient current flow) to each.
6. An Arduino will read the rectified and time-averaged bass channel signal. In response, the Arduino must approprioately rotate a servo arm onto which a laser pointer is mounted. This creates an additional visual display synced to the bass pumpin' and thumpin'.

Design Constraints

This section lists various constraints and related considerations:

1. All circuitry must fit on a single breadboard module; the overall footprint on the breadboard should be relatively small and tidy. Wiring should be neat and tidy, kept to a minimum.
2. Your design may incorporate a maximum of three TL082 chips (6 op-amps total = 3 chips $\times$ 2 op-amps/chip).
3. You should design for dual power supply operation at $\pm$ 9V, supplied by the BK precision power supply; or two 9V batteries in series.
4. Arduino ADC input voltages must be strictly unipolar between 0-5 V. Negative voltages can fry the Arduino; ditto for analog inputs > 5 V.
5. You may use any other components you find in the Circuit's lab (Howe 111). If you desire a component or tool which is not present, or you cannot find, please consult with the instructor.

Some Design Tips and Hints

In phase II of this project, you'll interface your bass channel measurement circuitry to an Arduino microcontroller. The Arduino will 1) make an analog measurement the rectified and smoothed bass signal and 2) actuate a motor to rotate according to the strength of the bass signal. There are several considerations to be aware of when interfacing the analog and digital sides.

1. **Filter cutoffs for 2-stage passive design:** You've seen empirically that a 2-stage filter actually shifts the cutoff frequency by a substantial amount away from the canonical $f_o = \frac{1}{2\pi R_1 C_1} = \frac{1}{2\pi R_2 C_2}$. Show that for a high pass filter the actual cutoff frequency is:

$$f_o = \frac{1}{2\pi\tau}\left[\frac{1}{\sqrt{2}-1}\right]^{1/2} \approx 1.55\frac{1}{2\pi\tau}$$

   where $\tau = R_1C_1 = R_2C_2$. In other words, the cutoff frequency has shifted up about 55 % in the 2-stage design compared to 1-stage.

   You can similarly derive the actual cutoff frequency for a low-pass filter.

   Keep such results in mind if and when trying to build circuits with precisely set cutoffs!

2. **Analog signal acquisition:** Analog signals measured by the Arduino must be in the range of 0-5 V. Exceeding either of these limits can fry the Arduino in part or whole. Leave the bbq sauce at home; it doesn't go well on burnt plastic.

3. You must be able to cleanly **view the the raw and time-averaged bass channel analog signals using the Serial Plotter** feature in the Arduino IDE. So your Arduino code needs to be programmed accordingly to output that data in a format suitable for displaying 2 plots in real-time.

4. The **rectified and time-averaged (smoothed) bass signal** will ultimately be used to control servo motor rotation. We've previously implemented a rectifier + RC smoother in our AM radio receiver build. We will modify that circuitry here to prevent sacrificing the $\approx 0.7V$ diode voltage drop (a significant loss/waste in this case). See Figure 4. Notice the diode is now wired in the feedback path of the op-amp, which otherwise looks like a buffer. Show that the input-output relation for this op-amp circuitry is:

$$V_{out} = V_{in} + V_{diode} \approx V_{in} + 0.7\text{V}.$$

   In other words, the output of the op-amp recovers the approximately 0.7V that would otherwise be lost!

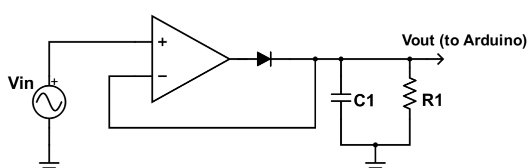

Figure 4: Smoothing Circuit based on diode and RC discharge. The time constant = the smoothing window: $\tau = R_1C_1$.

5. **Servo Motor Control:** The Arduino will be used to rotate servo motors to a desired position based on the strength of the bass signal. The servo motor, in turn, rotates a laser pointer that is mounted to an armature. We have accomplished very similar operation of a servo in labs from earlier this year (e.g. flex-sensor gesture sensing).

6. **Power Supply Considerations:** The Arduino power supply will power your analog circuitry. Its power supply is typically limited to a max current of about 500 mA—-just barely enough power for a standard-ish servo. If needed, we'll use a separate high-current LiPo battery (or lab bench power supply) to power a beefy servo motors, which typically draws ≈ 1 to 2 A max current.

1 Design, Testing, and Proof-of-Concept

Make suitable measurements and do sufficient analysis to demonstrate proof-of-concept that your design meets the criteria described above. In terms of quantifying actual performance measure the magnitude response ($G(f)$ vs. $\log_{10} f$ for all 3 of the sub-circuits servicing each frequency band (1 bass + 1 mid + 1 treble). Remember: the name of the game in any lab is to compare experiment to theory.

For the test-drive, Carefully choose an audio track that has a wide range of frequencies, as well as clearly delineated rhythms. In the instructor's humble experience, electronica tends to work well. For instance, something from Kraak and Smaak, a sort of Dutch doppleganger of the French band Daft Punk: `https://soundcloud.com/kraaksmaak` should work well. Again, the track selection is yours to make.

The design process will probably be an iterative one, especially since there is an aesthetic component to it. You might draw up something on paper, go into the lab to build it, and find it works great. If so, awesome! If not, then modify/tweak your circuit. Keep making purposeful changes until you arrive at a good solution—that's the way real-world actually works. (Of all the circuits I've ever designed of significant complexity, maybe 2% have worked the first time just perfectly. Not that I am particularly poor circuit designer, just the way life works in the lab.)

Once you have in hand convincing evidence that your light organ works works as desired, make a video demo to demonstrate it. Please ***do NOT tear down your circuit until you get the OK to do so***.

2 Final Report—What to Turn In

Your final report must include standard written work plus one illustrative proof-of-concept video. You should present the the following core elements. The full report, including all graphics, must not exceed 8 pages. Figures should be numbered sequentially, with a caption. The Appendix does not count toward the 7 page limit; it may be of any length necessary.

1. **Introduction**:

   (a) What circuit system are you building? What is its intended purpose/application, and why is it relevant/important?

   (b) Brief overview of the system design.

(c) Highlights of main final results achieved

2. **System Design and Rationale**:

   (a) Final circuit diagram(s). You may have one diagram for the analog sensing circuitry; and another for the Arduino + servo digital side of the design. In both cases, clearly label all component values. Delineate individual functional blocks and how they are integrated as a whole (a la Axani's muon detector circuit diagram we have reviewed in class).

   (b) Provide detailed description of what functional block does, and provide quantitative design rationale. For example:

   > Stage [B] is an active band pass filter. We chose to set the gain to 20x because ..., and we set the band pass range to x to y Hz because ... The values for R and C were chosen based on the following principles/equations...."

   (c) Describe how individual functional blocks are integrated into a complete sensing side of system. Justify why you arranged the functional pieces in the manner chosen, tradeoffs involved, etc. For example:

   > For the bass channel, we implemented a 2-stage active low pass filter (block [A]) cascaded to an inverting amplifier (block [B]) to achieve a 40 dB/dec cutoff. We opted for this design strategy for two reasons. Firstly, a (nearly) ideal cascaded passive filter is easy to construct and is overall simpler than implementing an active filter design based around an op-amp. Additionally, this configuration reduces power consumption, prolonging battery life for a portable module. Second, the inverting amp incorporating a potentiometer of x ohms and a static resistor of y ohms allows the user allows quickly and easily boost or cut the bass signal. The range of voltage gain is x to y; any value below 1 means we are cutting the signal, while voltage gain values above 1 mean the signal is boosted. One disadvantage of this desing is (fill in the blank...).

   (d) Digital/servo design and algorithm: Describe how you mapped the measured bass signal onto the servo rotation angle.

3. **System Validation Results**. This section should show quantitative results which describe, illustrate, and quantify the actual behavior of the circuit. It should also provide sufficient analysis of the results: Does the circuit work as intended? How did actual performance compare to theory? Be sure to include:

   (a) Pretty plot of the decibel gain vs. frequency, $G(f)$ vs. $\log_{10} f$ for relevant portions of the system. These plots are crucial to establish proper functionality. This graphic must display and compare both theory and experimental data. Sufficient data should be acquired to establish the system works as designed, and properly performs the required filtering and amplification (sensitivity-to-illuminate control).

   (b) A photograph/screenshot/graphic of similar ilk illustrating this diode + RC smoothing portion of the circuit works as advertised.

   (c) **Proof of concept**. Demonstrate via (pretty) figures that the system works as required. Additionally, post a video of your circuit in action. Video footage is the more natural presentation format here—we love music and lights live (still shots not as much). Provide a live narration and/or descriptive text that walks the user through the demo. This demo video should clearly establish that your design allows you to clearly measure a signal directly related to the strength of muscle contraction.

4. **Conclusion and Future Work**

   How well did your system work overall? What were benefits and limitations of the design? Include at least 2 substantive suggestions for an improved design. Remember to both identify and issue, and propose a concrete solution for it.

5. **Appendix**. The appendix has no page limit and should include:

   (a) Include input-output relations (transfer functions) for each functional block, which are not already fully elucidated in the main text.

   (b) Theoretical work deriving input-output relationships that we have not previously seen in class.

   (c) Arduino code

   (d) Matlab code