

AUTOMATIC MUSIC-REACTIVE LIGHTING SYSTEM

By

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Project Proposal for ECE 445, Senior Design, Fall 2026

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September 18, 2026

Project No. 10

1. Introduction

1.1 Problem

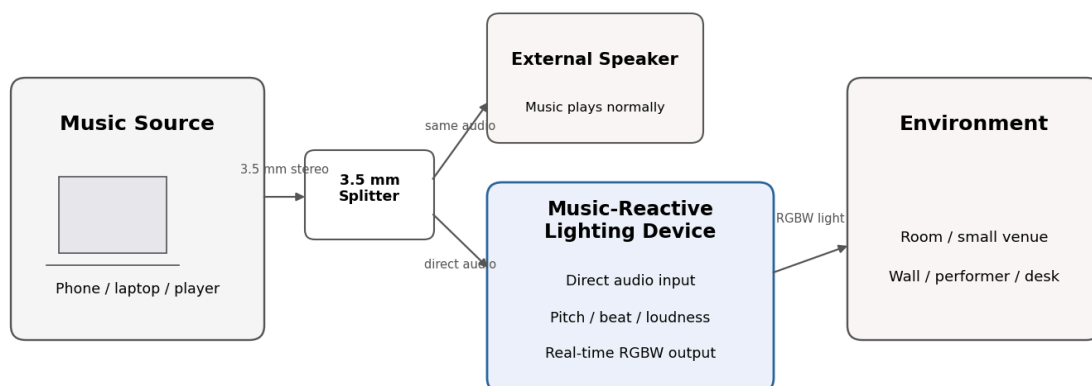
Small venues, student events, home listening spaces, and interactive installations often benefit from lighting that responds to music. Professional show-lighting systems can produce sophisticated effects, but they usually require a separate controller, programmed cues, or a dedicated operator. At the other extreme, inexpensive “sound-active” lights often react only to instantaneous volume and provide limited control over how rhythm, frequency content, and intensity are translated into light. The engineering problem is therefore to build a compact standalone device that can analyze a music signal in real time and generate repeatable RGBW lighting effects without requiring a computer, cloud service, or manually authored light show.

1.2 Solution

The proposed solution is a self-contained automatic music-reactive RGBW lighting device that receives a direct analog audio signal through a 3.5 mm stereo input. During demonstration, a 3.5 mm splitter sends the same source signal to both an external speaker and the lighting device, so the music plays normally while the custom PCB analyzes an electrical copy of the signal. The left and right channels are combined through separate resistors so they are not directly shorted together. The resulting signal is AC-coupled, attenuated as needed, biased near 1.50 V, buffered with an MCP6002 operational amplifier, and low-pass filtered before reaching an ESP32-S3 ADC. A direct electrical input provides a cleaner and more repeatable signal than room audio because it is not affected by microphone placement, background conversations, or room acoustics.

The ESP32-S3 samples the conditioned audio signal and processes short frames in real time. The firmware estimates the dominant frequency of clear tones and maps the nearest musical pitch class to a programmed RGBW color. Changes in short-time audio energy are used to detect beats, inter-beat timing is used to estimate tempo, and signal amplitude controls overall brightness. The ESP32-S3 generates four PWM outputs, one per RGBW channel. Each PWM signal controls an AL8861 constant-current buck LED driver, and a 0.15 ohm sense resistor targets approximately 0.67 A per channel at full scale. The lighting load is a nominal 10 W RGBW emitter mounted to a thermally conductive board and heatsink. A certified 12 V/3 A wall adapter powers the LED stage, while a 3.3 V regulator powers the ESP32-S3 and analog audio-conditioning circuitry.

1.3 Visual Aid



The splitter sends the same source signal to the speaker and the lighting device.

Figure 1. System context. A 3.5 mm splitter sends the same music signal to an external speaker and the lighting device; the device analyzes the direct audio signal and generates synchronized RGBW lighting.

1.4 High-Level Requirements

The project will be considered successful only if the completed prototype satisfies all three of the following quantitative system requirements:

- The system shall correctly classify the pitch class and command the assigned RGBW color in at least 90% of 70 isolated-note trials, consisting of 10 trials each for C4, D4, E4, F4, G4, A4, and B4, using 0.5 Vrms synthesized tones applied directly to the 3.5 mm audio input.
- The system shall estimate tempos from 60 to 180 BPM with an absolute error of no more than 5 BPM after no more than 5 seconds of clearly rhythmic audio applied through the direct input, and each detected beat shall cause a PWM command update within 100 ms of the corresponding input event.
- The system shall independently control all four RGBW channels with at least 8-bit brightness resolution and a PWM carrier frequency of at least 1 kHz, while limiting each channel to no more than 0.75 A and maintaining the measured LED heatsink temperature at or below 60 °C after 15 minutes of the maximum allowed continuous-output test at 25 °C $\pm$ 3 °C ambient.

2. Design

2.1 Block Diagram

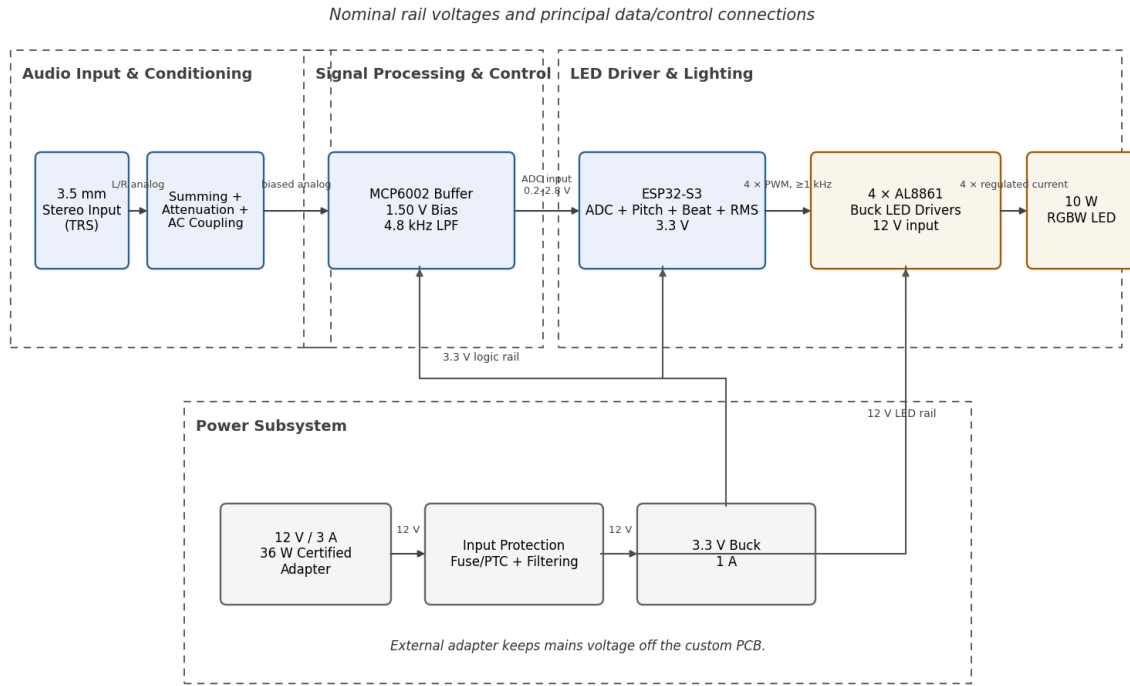


Figure 2. High-level block diagram showing subsystem boundaries, nominal power rails, and principal data/control interfaces.

2.2 Subsystem Overview

The design is divided into four subsystems: Audio Input and Conditioning, Signal Processing and Control, LED Driver and Lighting, and Power. Each subsystem has a measurable interface to the next so that it can be tested independently before full integration.

2.2.1 Audio Input and Conditioning Subsystem

The Audio Input and Conditioning Subsystem receives stereo audio from an external source through a 3.5 mm TRS connector and produces a protected, biased analog signal that the ESP32-S3 ADC can sample. During normal use or demonstration, a passive 3.5 mm splitter can send the same source signal to both a powered speaker and the lighting device. Each left and right input channel is AC-coupled and connected through its own 47 kohm summing resistor so the source channels are never directly shorted together. An 18 kohm resistor to a buffered 1.50 V reference both biases and attenuates the summed signal. One channel of an MCP6002-I/SN generates or buffers the bias reference and the other buffers the conditioned audio. The MCP6002 operates from 1.8 V to 6 V, has rail-to-rail output, and a 1 MHz gain-bandwidth product [3]. A first-order 3.3 kohm/10 nF low-pass network gives a nominal cutoff near 4.8 kHz before the signal reaches the ESP32-S3 ADC. The ADC will use the high-attenuation range and calibration support described by Espressif [14].

This subsystem directly supports the pitch, tempo, and latency requirements because the downstream algorithms can only be repeatable if the input is not clipped, excessively loaded, or contaminated by out-of-band noise. The direct connection removes room acoustics and unrelated sounds from the signal path, while the high input impedance keeps the lighting device from significantly loading the music source. The ESP32-S3 will sample the conditioned signal at least 16 ksample/s, which is sufficient for the intended single-note, beat, and loudness analysis while leaving substantial processing margin.

- With no audio applied, the conditioned ADC input shall be biased to 1.50 V +/- 0.10 V, and for a sine-wave input up to 2.0 Vrms per channel the conditioned signal shall remain between 0.15 V and 2.85 V.
- The left and right stereo channels shall be combined only through resistive isolation, and the effective input impedance seen by either source channel shall be at least 50 kohm over the intended audio band.
- The analog low-pass network shall have a nominal cutoff between 4.0 kHz and 6.0 kHz, and the ESP32-S3 shall sample the conditioned signal at a rate of at least 16 ksample/s.

2.2.2 Signal Processing and Control Subsystem

The Signal Processing and Control Subsystem is implemented on the ESP32-S3. The ADC continuously samples the conditioned direct-audio signal and groups samples into short frames. Each frame produces three feature groups. First, a dominant-frequency estimate is converted to the nearest pitch class when the confidence is high enough; the selected pitch class determines the programmed RGBW color. Second, positive changes in short-time or spectral energy are treated as onset candidates, and inter-onset intervals are accumulated in a rolling history to estimate tempo. Third, RMS or smoothed signal amplitude controls overall brightness. This approach lets the system demonstrate explicit note-to-color mapping on clear tones while still producing useful rhythm and loudness responses on ordinary music.

The control subsystem contributes to all three high-level requirements. Pitch-class accuracy depends on the ADC sampling and pitch estimator, tempo accuracy depends on the onset-history algorithm, latency depends on frame length and processing time, and independent RGBW control requires four deterministic PWM outputs. The direct-input architecture makes algorithm verification repeatable because the same electrical test waveform can be applied for every trial.

- The pitch estimator shall command the correct mapped color for at least 63 of the 70 defined isolated-note trials across C4 through B4.
- The tempo estimator shall report 60–180 BPM values within ± 5 BPM on the defined rhythmic test set after a maximum 5-second acquisition window; on a reference beat track, the onset detector shall detect at least 90% of beats with no more than one extra trigger per 20 reference beats.
- The firmware shall complete ADC frame acquisition, feature extraction, and lighting mapping quickly enough that the measured input-event-to-PWM-command latency remains no more than 100 ms.
- The MCU shall generate four independent PWM outputs with at least 8-bit duty-cycle resolution and a carrier frequency of at least 1 kHz.

2.2.3 LED Driver and Lighting Subsystem

The LED Driver and Lighting Subsystem converts MCU duty-cycle commands into controlled current through the red, green, blue, and white dies of a high-power RGBW emitter. Four AL8861MP-13 buck LED-driver channels are proposed. The AL8861 accepts a 4.5–40 V supply, supports analog or PWM dimming, and regulates LED current using an external sense resistor [5]. Each channel uses a 22 μ H power inductor, a 40 V/2 A Schottky diode, and a 0.15 Ω current-sense resistor. The selected 10 W RGBW module provides separate red, green, blue, and white terminals and is supplied on a thermally conductive metal-core board [6].

This subsystem directly supports the brightness-resolution, current-limit, and thermal high-level requirement. Constant-current drivers prevent channel current from depending strongly on LED forward voltage, while the hardware sense resistor prevents firmware from commanding current above the designed limit. The LED assembly will be mounted to a heatsink and measured with a thermocouple during sustained-output verification. Firmware may reduce the combined channel duty cycle if required to maintain the 60 °C heatsink limit.

- Each LED channel shall use hardware constant-current regulation and shall remain below 0.75 A over component tolerances at full command.

- Each driver shall accept a PWM control signal of at least 1 kHz and reproduce duty-cycle changes from 0% to 100% without visible instability or uncontrolled flicker.
- The LED assembly shall be mechanically mounted to a heatsink or thermally conductive enclosure surface and shall remain at or below 60 °C at the measurement point during the 15-minute maximum-output thermal test.
- The system shall turn all LED channels off if the MCU is reset or if the enable/control lines are intentionally forced low.

2.2.4 Power Subsystem

The Power Subsystem supplies a 12 V high-current rail for the four LED-driver channels and a regulated 3.3 V logic rail for the ESP32-S3 and the audio-conditioning circuitry. A Phihong PYA36A120300 12 V/3 A, 36 W wall adapter is the candidate external supply [7]. The custom PCB therefore handles only low-voltage DC. Input protection includes a fuse or resettable protection element and local bulk/decoupling capacitance. A 1 A LMR50410 buck regulator is the 3.3 V rail device [8].

The Power Subsystem contributes to every high-level requirement because brownouts and switching noise can corrupt ADC samples, reset the processing pipeline, or alter LED output. The 36 W adapter provides margin above the approximately 10 W LED load plus the controller, analog front end, regulators, and conversion losses. PCB layout will keep high-current LED switching paths away from the audio input and bias reference, with local decoupling and controlled return paths to reduce noise coupling.

- The external supply shall provide 12 V nominal at a continuous current rating of at least 3 A and at least 36 W rated output power.
- The regulated logic rail shall remain within 3.3 V $\pm$ 0.1 V while the MCU processes audio and all LED channels are exercised over their programmed range.
- The custom PCB shall include input overcurrent protection and shall contain no exposed mains-voltage circuitry.
- The 3.3 V buck regulator shall be rated for at least 1 A continuous output, providing margin above the expected controller and analog audio-conditioning load.

2.3 Tolerance Analysis

One critical design risk is ADC clipping at high source levels. The proposed input AC-couples the left and right channels through separate 47 kohm $\pm$ 1% resistors into a summing node, with an 18 kohm $\pm$ 1% resistor to a buffered bias reference. The bias is generated from the 3.3 V rail by a 120 kohm/100 kohm divider, both $\pm$ 1%. Using the specified 3.3 V $\pm$ 0.1 V logic rail, the worst-case bias is:

$$V_{\text{bias,min}} = 3.2 \text{ V} \times 99 \text{ kohm} / (121.2 \text{ kohm} + 99 \text{ kohm}) = 1.439 \text{ V}$$

$$V_{\text{bias,max}} = 3.4 \text{ V} \times 101 \text{ kohm} / (118.8 \text{ kohm} + 101 \text{ kohm}) = 1.562 \text{ V}$$

For equal left and right signals, the two 47 kohm input resistors act as 23.5 kohm in parallel. Including 1% resistor tolerance, the small-signal gain from a common stereo input to the summing node ranges from approximately 0.429 to 0.439.

A 2.0 Vrms sine wave has a 2.828 V peak. At the maximum calculated gain of 0.439, the conditioned deviation is about 1.24 V peak. Combined with the worst-case bias, the ADC waveform is approximately 0.20-2.80 V, below the ESP32-S3 effective upper range of about 2.9 V at maximum attenuation [21]. The 3.3 kohm/10 nF output filter has a nominal cutoff of 4.82 kHz and remains about 4.34-5.41 kHz with component tolerances. The front end therefore preserves ADC headroom while passing the frequency range needed for pitch, beat, and loudness processing.

3. Ethics, Safety and Societal Impact

3.1 Ethics and Responsible Use

The project will be developed under the professional principles reflected in the IEEE Code of Ethics, particularly prioritizing public safety, stating technical claims honestly, acknowledging limitations, and accepting and correcting errors [11]. The direct audio input also reduces a privacy concern that would exist with an always-listening room microphone: the device analyzes only the electrical signal intentionally connected to its 3.5 mm input. Audio samples and extracted features will be processed locally on the ESP32-S3 and will not be stored or sent to a cloud service. We will document the tested input-level limits and will not claim reliable pitch recognition for dense chords or highly polyphonic passages outside the demonstrated scope.

We will also avoid presenting the device as universally safe for every viewer. Photosensitive responses depend on flash frequency, brightness, contrast, and viewing conditions [1]. Because the system's highest required beat rate is 180 BPM, or 3 beats per second, the default effect library will limit deliberate full-output high-contrast flashes to no more than 3 per second. Brightness PWM itself will operate at 1 kHz or higher so that low-frequency PWM flicker is not introduced by the dimming carrier. A steady or low-motion mode will be available, and safety-related output limits will not be bypassed by user settings.

3.2 Electrical, Optical and Thermal Safety

Electrical risk is reduced by using a certified external low-voltage 12 V adapter so that the custom PCB does not expose us or the user to mains voltage. UL/CSA 62368-1 is a hazard-based product-safety framework applicable to audio/video and information/communication technology equipment [12], and the selected Phihong adapter references 62368-1 in its product listing [7]. The prototype itself will not be represented as certified, but the standard informs the choice to isolate mains conversion in an approved external adapter and to include low-voltage overcurrent protection.

Optical safety will be considered with reference to IEC 62471, which specifies photobiological-safety evaluation for lamps and lamp systems [2]. During bench testing, we will not stare directly into the high-intensity emitter. The LED will be mounted behind a diffuser or oriented away from eye level during long-duration testing. Thermal verification will measure the heatsink temperature after sustained output, and firmware will reduce maximum combined duty cycle if the 60 °C requirement cannot be met with the selected mechanical cooling.

During development, we will follow ECE 445 laboratory safety requirements, including required training and the course rule against working alone in the laboratory [13]. Soldering, hot components, sharp leads, high-brightness optical output, and accidental short circuits are the primary bench hazards for this project. Eye protection, appropriate ventilation or fume extraction, power-off inspection before rework, and current-limited bench supplies will be used during bring-up.

3.3 Societal, Economic, Environmental and Global Impact

The device is intended to make responsive lighting accessible to small events and personal creative spaces without requiring an operator or expensive show-control infrastructure. The direct wired input provides repeatable behavior across rooms and avoids capturing nearby conversations, although users with phones or computers that lack a 3.5 mm output may need a simple adapter. Because the algorithm relies on pitch, onset timing, and amplitude rather than a fixed song database, it can respond to music from different genres and cultural traditions. Economically, the low-voltage architecture and commonly stocked components keep the prototype parts cost modest. Environmentally, the design favors reusable electronics, a replaceable external supply, and a separable LED/heatsink assembly so that a single failed part does not require discarding the entire device.

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Appendix A. Requirement and Verification Table

This table converts the three high-level requirements into concrete verification procedures. Detailed subsystem-level tests can be expanded during the design-review phase.

Requirement	Verification	Pass Criterion
Pitch-to-color mapping: $\geq 90\%$ correct across 70 isolated-note trials for C4-B4.	Feed 0.5 Vrms synthesized C4, D4, E4, F4, G4, A4, and B4 tones directly into the 3.5 mm input, 10 trials per note. Log the detected pitch class and commanded RGBW color for each trial.	At least 63 of 70 trials identify the correct pitch class and command its assigned color.
Tempo and beat response: 60-180 BPM, ≤ 5 BPM error after ≤ 5 s; input-event-to-PWM command latency ≤ 100 ms.	Feed reference beat tracks at 60, 90, 120, 150, and 180 BPM through the direct audio input. Compare reported BPM with the reference and measure the input event and a PWM output simultaneously with an oscilloscope or logic analyzer.	Steady-state tempo is within ± 5 BPM at every test tempo, and the worst measured event-to-command delay is ≤ 100 ms.
Four-channel RGBW control: ≥ 8 -bit resolution, PWM ≥ 1 kHz, each channel ≤ 0.75 A, heatsink ≤ 60 °C after 15 min.	Measure PWM frequency and duty steps with a logic analyzer, each full-scale channel current with a DMM/current probe, then run the maximum continuous-output pattern for 15 min at 25 °C ± 3 °C ambient and measure the heatsink with a thermocouple.	All four channels meet PWM specifications; no channel exceeds 0.75 A; heatsink remains ≤ 60 °C.

Table A.1. Preliminary high-level requirement and verification matrix.