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LightWorks Challenge: Hands-On Optics-Focused Games Built by and for ECE Students

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LightWorks Challenge: Hands-On Optics-Focused Games Built by and for ECE Students

Abstract

We developed a hands-on learning experience using six interactive optics-themed games, designed and built by upper-level undergraduate electrical and computer engineering (ECE) students at UC San Diego. The project aimed to introduce incoming ECE students to core optics concepts in an engaging and accessible format while also highlighting the kinds of technical and creative skills they will develop throughout the program. Each game station integrates authentic engineering practices, such as microcontroller programming, embedded systems design, circuit design, sensing, and actuation, within an optics context, allowing new students to explore technical material through play.

During the session, participants rotate through the game stations in a carefully managed sequence that avoids overlap and ensures a smooth flow. The games are fully functional and self-contained, allowing students to engage independently with the material. The games are supported by a complete set of technical documentation, including hardware schematics, embedded code, mechanical designs, and calibration procedures, all of which are openly available for adoption and adaptation.

To evaluate the educational value of the experience, data were collected from both the upper-level student builders and the incoming student players. Builder reflections showed that students not only applied concepts from prior coursework but extended them through self-directed learning, gaining new skills and a deeper understanding of how to translate theoretical knowledge into practical, hands-on experiments. For the players, pre- and post-concept-check surveys indicated short-term improvements in understanding of optics and motivation to pursue further studies in ECE.

The set of experiments developed through this project can be implemented flexibly: each game can stand alone as an individual lab activity within a course, or the full set can be used together as part of a cohesive, game-based learning experience, as detailed in this work. By combining optics concepts with ECE design and prototyping practices, the games offer a practical and engaging model for instruction. Their open-ended, student-built nature makes them well-suited for adaptation by other institutions, whether as part of a first-year introduction, an outreach activity, or an integrated course module.

This is a student-authored paper under the supervision of a faculty member.

Introduction

Engineering education increasingly emphasizes experiential, hands-on learning to bridge theory and practice and to help students connect abstract concepts with real-world problem-solving [1]. Within electrical and computer engineering (ECE), where topics often rely heavily on mathematical abstraction and simulation, many students struggle to see the relevance of early coursework to physical applications and systems. At the same time, industry expectations continue to shift toward multidisciplinary experience, requiring students who can integrate hardware and software thinking in practical contexts. These trends have motivated a growing emphasis on project-based learning and game-based instruction, and vertically integrated experiences that link students across academic levels.

To address this need, we developed the LightWorks Challenge, a hands-on learning experience composed of six optics-focused, hardware-intensive games designed and built by upper-level undergraduate ECE students for incoming students. Each game introduces optical concepts such as reflection, refraction, absorption, scattering, polarization, and interference through fun and interactive stations. The activities integrate microcontrollers, sensors, actuators, and circuits to create systems that invite exploration and support both conceptual learning and engineering practice.

The LightWorks Challenge serves two complementary educational purposes. First, it provides an engaging, low-barrier introduction to optics for new ECE students who may have limited prior technical and hands-on experience. Second, it creates a vertically integrated learning experience for upper-level students, who assume the roles of designers, fabricators, and communicators of educational technologies. This model aligns with the principles of cognitive apprenticeship and "learning by teaching," which have been shown to deepen understanding and foster transferable skills.

This dual-purpose model, supporting both novice learners and student designers, is grounded in well-established research on active learning. Hands-on, project-based approaches in engineering education have been shown to improve engagement, conceptual understanding, and long-term retention [2], [3], [4], [5]. Vertically integrated projects, in particular, create multi-layered ecosystems in which advanced students mentor or create experiences for peers, enhancing the learning of both groups [6]. Game-based learning, too, has gained momentum in ECE education, offering students a framework to experiment, fail safely, and receive immediate feedback, conditions aligned with constructivist learning theory [7]. In ECE contexts, such approaches have been effectively used to teach programming, embedded systems, control theory, and signal analysis [8]. However, relatively few studies examine student-built games as instructional tools.

Optics and photonics education has also benefited from low-cost, hands-on modules designed to make light phenomena accessible to undergraduates. Simplified experiments have been shown to support student understanding when learners actively engage in building and performing the activities. Yet most implementations in optics settings remain instructor-developed rather than student-built [9]. The LightWorks Challenge contributes a novel, student-driven framework for integrating optical education, embedded design, and interactive play. By openly sharing technical blueprints, evaluation data, and implementation strategies, we aim to support replication and adaptation of this approach in other engineering programs seeking to enhance engagement, creativity, and peer-to-peer learning.

Design, Implementation, and Game Mechanics

Game 1: Cosmic Whisper

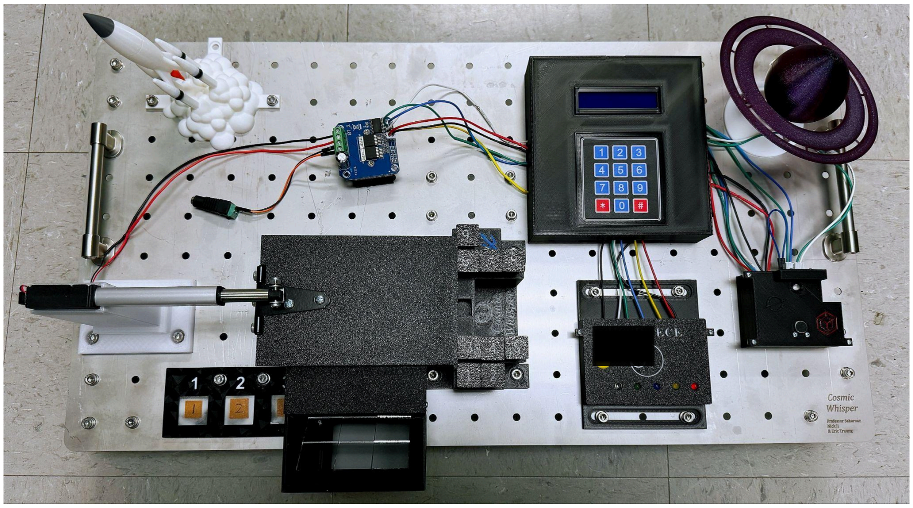

Figure 1. Cosmic Whisper Setup
Counterclockwise from upper right: keypad console, microcontroller, linear actuator, spectrometer, Morse code case, sensor housing

Learning Objectives and Optics Concepts
Cosmic Whisper introduces students to fundamental optics and signal processing concepts through an immersive three-body problem narrative. The game teaches: (1) spectroscopy and wavelength analysis through a custom-made spectrometer and food dye samples, (2) fluorescence and UV excitation via fluorescent powder identification, (3) optical signal encoding through Morse code transmission, and (4) audio frequency-to-light color mapping using real-time audio processing and LED visualization.

Hardware Architecture
The system is built using a FREENOVE ESP32-S3 WROOM microcontroller with PSRAM, housed in a custom laser-cut SAE 304 stainless steel mounting board (24" × 18"). All components are integrated through 3D-printed enclosures designed for durability and user interaction.

Game Mechanics and Technical Challenges
Players progress through three interconnected puzzles requiring different engineering subsystems:

- Stage 1 - Spectroscopy Challenge: Students operate a custom-built spectrometer to analyze how light interacts with food dye solutions, identifying each dye by the spectrum of transmitted light. The spectrometer was constructed using a narrow slit (made from two razor blades), a diffraction grating slide (≈1000 lines/cm) to separate wavelengths, and mirrors to direct the diffracted light toward a viewing window so participants could see the results without opening the enclosure. A standard flashlight served as the light source to illuminate the dye samples placed in cuvettes. The technical challenge involved calibrating sample concentrations (1-1.5 drops per 50 mL) to produce distinguishable spectral signatures while maintaining visual similarity under ambient lighting.

- Stage 2 - Cryptographic Decoding: An embedded Morse code generator transmits signals through LED light sequences. Players decode these signals manually, then apply a Vigenère cipher algorithm. The Vigenère cipher works by adding a keyword to the base word to create a ciphered word. The adding algorithm is the same as adding strings in C/C++. The firmware implements precise timing control for Morse transmission and ASCII-based cipher mapping.
- Stage 3 - Signal Processing: Using the microcontroller, the system performs real-time Fast Fourier Transform (FFT) analysis of the microphone input, mapping audio frequencies to LED colors and amplitudes to brightness. This demonstrates digital signal processing concepts while providing immediate visual feedback. The players use a tone generator to find the hinted correct frequency, then adjust the volume.

Advanced Technical Features
The station incorporates several engineering elements that showcase ECE skills:

- Real-time FFT Implementation: Uses library "arduinoFFT.h" to perform frequency analysis on the ESP32-S3, demonstrating embedded signal processing capabilities.
- Precision Mechanical Integration: Linear actuator provides smooth servo control for signal alignment, with custom 3D-printed mounting hardware.

Game 2: Diffraction Decoder

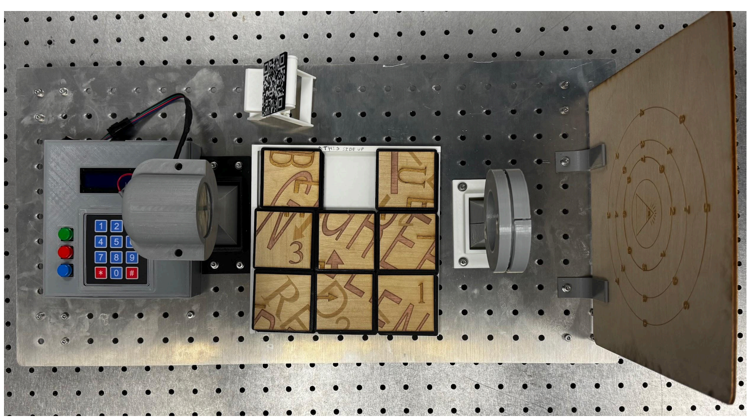

Figure 2. Diffraction Decoder Game Setup
Left to right: keypad console, laser housing, sliding puzzle, rotatable diffraction grating, code observation screen

Learning Objectives and Optics Concepts
Diffraction Decoder teaches fundamentals of wave optics through an engaging hands-on experimentation with diffraction gratings and interference patterns. Students learn: (1) the

relationship between wavelength, grating spacing, and diffraction angles through direct observation, (2) the wave nature of light through visible diffraction phenomena, and (3) systematic experimental methodology by correlating grating orientations with observed patterns.

Hardware Architecture
The system centers on an ESP32 microcontroller with integrated WiFi capabilities, housed within a custom 3D-printed enclosure that combines mechanical puzzle elements with precision optics. The design emphasizes durability and intuitive user interaction.

Game Mechanics and Technical Challenges
The two-stage puzzle structure requires both mechanical problem-solving and optical analysis:

- Stage 1 - Sliding Puzzle Interface: Created in InkScape and laser-cut from plywood at multiple intensities. The puzzle was assembled in a way that students can’t simply take them out and rearrange freely, so they need to actually solve the puzzle. Students manipulate 8 pieces within a 9-slot grid to reveal color-coded numerical sequences and directional arrows. Each combination corresponds to specific diffraction grating orientations for different laser wavelengths.
- Stage 2 - Diffraction Pattern Analysis: Players rotate the grating mount according to puzzle solutions and observe how laser light diffracts into distinct patterns. The technical challenge required calibrating grating angles to produce clearly distinguishable diffraction orders that map to specific digits in the 6-digit password.

<u>Game 3: Sugar Mystery</u>

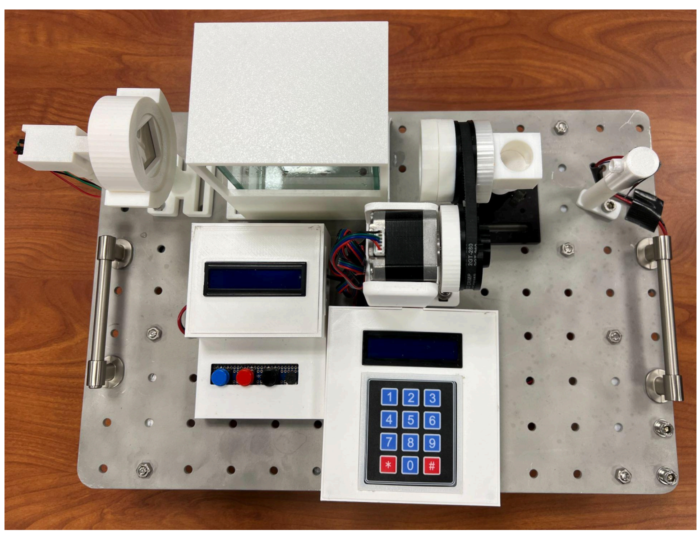

Figure 3. Sugar Mystery Setup
Counterclockwise from upper right: laser diode, motorized rotating polarizer, basin anchor, fixed polarizer, detector, motor control module, keypad console

Learning Objectives and Optics Concepts
The sugar mystery game serves as an introduction to the wave nature of light, demonstrating the fundamental concepts of polarization, phase, and refractive index. In addition, students are

introduced to the field of polarimetry, learning about its applications and core concepts such as chirality and specific rotation.

Hardware Architecture

The game utilizes two ESP32 microcontrollers to manage different functions. One ESP32 handles the core mechanism of the experiment. It receives user inputs via buttons to control a stepper motor, which is calibrated to rotate a polarizer by precisely one degree. A laser diode shines a beam of light through the rotating polarizer, a sugar solution, and a fixed polarizer before its intensity is measured. The intensity and the polarizer angle are then displayed on the screen, from which the user can calculate the sugar concentration of the measured solution.

A second ESP32 interfaces with the game network. After calculating the sugar concentrations, users input their final values into a keypad. Once the correct concentrations are entered, the ESP32 unlocks the next available game in the series.

Game Mechanics and Technical Challenges

For the demonstration, three sugar solutions of different concentrations (180 g/L, 250 g/L, 100 g/L) were prepared. Before beginning, participants received a technical briefing on polarization, chirality, and polarimetry. They were then instructed to determine the unknown concentrations using Eq. 1, given that the specific rotation [α] of D-sucrose is 66.37 $° \cdot mL \cdot dm^{-1} \cdot g^{-1}$.

$$C = \frac{\theta}{\alpha \cdot l} \tag{1}$$

Following the briefing, participants were required to independently configure the setup to characterize the solutions. The experimental protocol was as follows:

- Stage 1 - Identification of Intensity Extremum: While both maximum and minimum transmittance could serve as references, the protocol emphasized the measurement of minimum transmittance by rotating the analyzer's plane of polarization to be orthogonal to that of the fixed polarizer. This approach was dictated by the photodiode sensitivity, which would saturate before reaching the angle of maximum transmittance. Thus, the null point is a more precise metric for determining the polarization angle in this setup.
- Stage 2 & 3 - Polarization Rotation Measurement: Students place the solution in the beam path. Though the laser and diode were pre-aligned, this step served as a practical exercise in optical alignment as participants were required to ensure that the basin's glass surface was positioned perpendicular to the incoming beam to prevent misalignment via refraction. Students must then rotate the analyzer to find the minimum intensity and calculate the concentration based on the shift in the polarization angle.

Advanced Technical Features

The station demonstrates the following engineering solutions:

- Accurate Polarization Control: A stepper motor was programmed and calibrated to rotate the polarizer by precisely one degree of rotation. User inputs were received via buttons, and the corresponding angle and measured output intensity were displayed on the LCD screen.

Game 4: Polarization Patterns

Learning Objectives and Optics Concepts
The Polarization Patterns game serves as a transition from geometric optics to physical optics by characterizing light as a transverse electromagnetic wave with a particular polarization. Students learn the polarization concept by rotating the polarization filter and thus visualizing the learning.

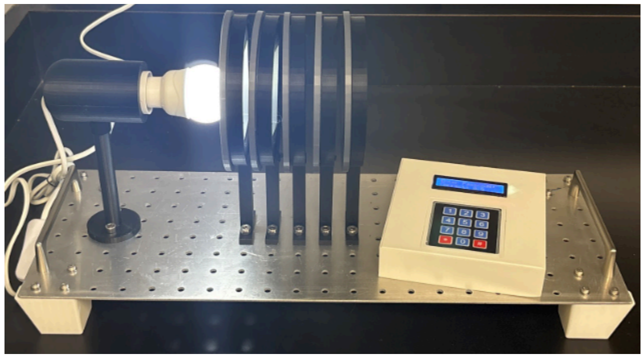

Figure 4. Polarization Patterns Setup
Left to right: LED bulb, rotatable polarization stages, keypad console

Hardware Architecture
The control system is centered on an ESP-32 microcontroller, which manages the user interface and synchronizes the game status with the broader game network. Four rotatable polarizer assemblies were made by clamping a polarizing film onto a transparency film with a code cutout. This was placed within a rotating stand and mounted on the optical table. Each of these films was oriented at a specific axis, while a lamp was hoisted behind the films for illumination.

Game Mechanics and Technical Challenges
After a brief introduction to the concept of polarization, users are instructed to look through the polarizer placed farthest from the light bulb while rotating each of the four polarizers to uncover a set of digits. The game process is as follows:

- Stage 1 - Polarizer Rotation: All digits are initially obscured as users look through the row of polarizers. Users rotate the gray analyzers until a number appears, which occurs when the adjusted analyzers' polarization is crossed with the input polarizer, creating the contrast necessary to decipher the transparency film's cutout number.
- Stage 2 - Code Sequencing: Upon discovering the 4 digits shown by each of the analyzers, the user reads a sequence of riddles to determine the order in which to input the digits. Three riddles must be solved, each yielding a different code from the same set of four numbers. The riddles are ordered in increasing difficulty, and the codes are sequentially entered into the keypad. Once all three codes are entered successfully in the correct riddle sequence, the game is won.

Game 5: Solar Mania

Learning Objectives and Optics Concepts
Solar Mania introduces students to fundamental photovoltaic technology and energy management through an interactive analog charging challenge. The station teaches: (1) solar energy conversion and the relationship between light intensity and power output through direct

manipulation of light sources, (2) capacitive energy storage and charge/discharge dynamics via real-time LED feedback, (3) sequential logic and state management through SR latch-based module enabling, and (4) energy management strategy through time-pressure gameplay requiring balancing charge maintenance across multiple modules.

Hardware Architecture

The system is built using an ESP32 microcontroller for the top module, with analog circuitry controlling four submodules. Each submodule contains independent solar panel charging circuits housed in custom enclosures. All modules are interconnected through standardized 4-pin connectors (carrying +9V, GND, SIGNAL, -9V), enabling modular configuration. A dual-servo gimbal mount provides mechanical control for flashlight positioning via analog potentiometer knobs.

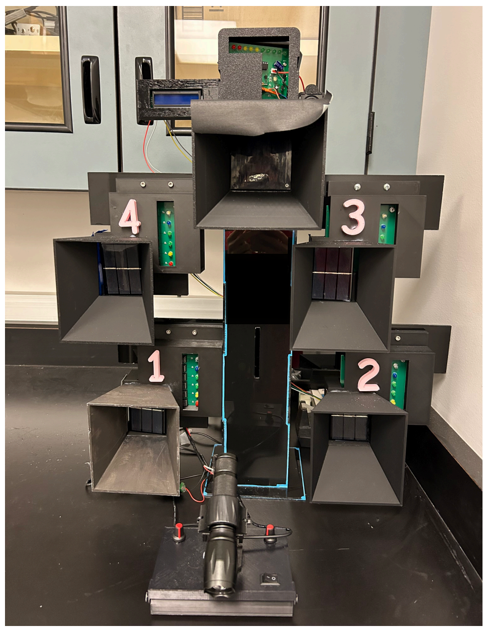

Figure 5. Solar Mania Setup

Flashlight joystick control console at the bottom; solar panel game sequence from bottom to top.

Game Mechanics and Technical Challenges

Players progress through a sequential charging system requiring strategic light management:

- Stage 1-4 - Submodule Charging Sequence: Students operate a flashlight mounted on a dual-axis gimbal to charge solar-powered modules in sequence. Each module features a photovoltaic cell that charges a capacitor (1000 µF for Module 1, varying values for others), with charging rate directly proportional to incident light intensity. The technical challenge involves balancing charge accumulation across modules while managing self-discharge. If light is removed, capacitors discharge and may reset progress. Each module uses five LM741 op-amps configured as comparators to monitor a voltage divider network, illuminating LEDs (RED → YELLOW → GREEN → GREEN → BLUE) as charge increases. When fully charged, an SR latch enables the next module in the chain. Figure 6 shows module LED indicators displaying charge progression.

- Stage 5 - Final Depletion Challenge: After all submodules reach full charge, the top module activates. This module uses an ESP32 microcontroller with an LM3914 LED driver controlling a 10-LED “health bar.” Players must shine light on the top module's solar panel to deplete the health bar completely. The system provides audio feedback via buzzer and visual confirmation through white LED illumination when receiving light.
- Control System: Players manipulate flashlight position using two analog potentiometer knobs controlling servo motors on yaw and pitch axes, providing tactile feedback and requiring steady hand coordination for optimal light coverage.

Figure 6. Final Stage LED Indicator and Integrated Speaker

Advanced Technical Features

The station incorporates several engineering elements that showcase analog circuit design and embedded systems integration:

- Analog Comparator Networks: Each submodule uses five LM741 op-amps as voltage comparators, comparing capacitor voltage against reference levels from a resistor voltage divider network, demonstrating analog signal processing and threshold detection.
- SR Latch State Management: Set-reset flip-flops maintain module state and control signal propagation to subsequent modules, implementing sequential logic without microcontroller overhead.
- PWM-to-Analog Conversion: The top module employs an RC smoothing filter to convert ESP32 PWM output into an analog voltage for the LM3914 input, as the LED driver requires true analog signals rather than digital PWM. LTSpice simulations validated filter performance at 25% and 75% duty cycles (1kHz frequency).
- Amplified Charging Circuit: LF411 op-amps amplify solar panel output to charge capacitors, with NE555 timer ICs providing clock signals for charge level sampling.

Game 6: Chromatic Labyrinth

Learning Objectives and Optics Concepts

The Chromatic Labyrinth serves as a collaborative exercise in geometric optics, demanding a higher level of optical intuition to reconcile multiple beam paths with restricted optical components. The use of prisms and mirrors with translational and rotational degrees of freedom cultivates an intuition for light propagation across non-parallel interfaces. By utilizing a limited inventory of mirrors and prisms, students must account for cumulative angular deviations and the precise alignment of each monochromatic beam to its corresponding photodetector within a time constraint, thereby necessitating team collaboration.

Hardware Architecture
Three laser pointers of different wavelengths (i.e., red, green, blue) and three photodetectors are fixed at a particular position and orientation onto the large optical board, measuring 34 x 22 in. Laser, mirror, and detector mounts were designed to allow for precise adjustment by users with the aid of a 3D-printed iris. Long tubes were printed and attached to the photodetectors to prevent diverging or stray beams from activating the photodetectors.

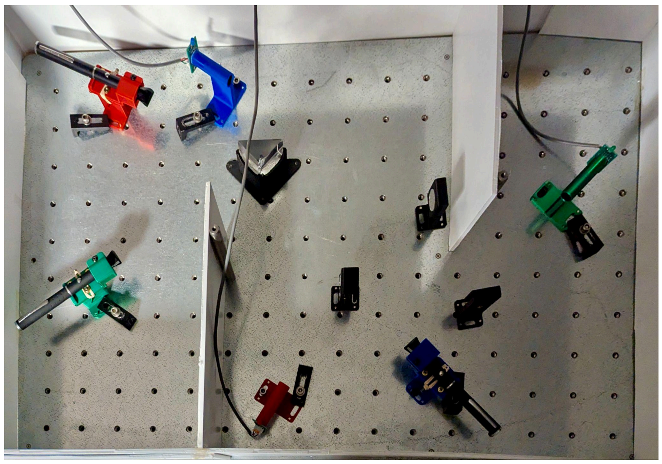

Figure 7. Chromatic Labyrinth Setup
Note that this is an example game solution. The objective is to route each beam so that every fixed laser is correctly aligned with its matching color-detector.

The optical board consists of three layers bolted together. The bottom layer serves as a rigid wooden support with holes drilled. The top layer is a thin sheet of aluminum with laser cut holes. M4 nuts are hammered into the holes of the middle corkboard layer. Cardboard walls were cut and magnetically secured to block stray laser beams. Neutral density filters were taped onto the blue and green laser pointers to attenuate the beam intensity for safety.

The control system is centered on an ESP32 microcontroller, which manages the user interface and detects when all three wavelengths are detected simultaneously. The microcontroller then updates the game network with the completed status.

Game Mechanics and Technical Challenges
Players are briefed on Snell's Law, its application to prisms, and the Law of Reflection before being provided with an iris, a hex key, and a limited set of mirrors and prisms. Accurate and efficient alignment is critical for the successful completion of the challenge. The game is designed such that, ideally, only one solution is possible. Players must activate all lasers simultaneously to trigger all photodetectors and win the game.

Game Station Routing System

Overview and Design Requirements

Managing multiple groups across distributed educational game stations presented significant logistical challenges. During an earlier pilot run, participants were manually assigned to stations according to a fixed schedule, which led to long queues at certain games.

To address these issues, we developed an intelligent routing system that dynamically coordinates game assignments and tracks progress for up to five groups across six or more interactive learning stations. The system is designed to balance station utilization, reduce congestion, and minimize downtime between activities. Since we had six game stations, we set the system for six games.

The routing algorithm operates on three fundamental requirements: (1) ensuring no game station is simultaneously assigned to multiple groups, (2) providing smooth progression through available learning activities, and (3) maintaining real-time visibility into system-wide progress for facilitators. These requirements emerged from preliminary observations of traditional rotation-based systems, which often resulted in bottlenecks at popular stations and suboptimal learning sequences.

System Architecture

Authentication and Group Management
The system employs a distributed authentication mechanism where participant groups are assigned unique three-digit identifiers at the beginning of each session. This approach decentralizes group verification while maintaining centralized tracking capabilities. Groups authenticate at any available station using a 4×3 matrix keypad interface.

Upon successful authentication, the system establishes a bidirectional communication channel between the local ESP32 microcontroller and a cloud-based coordination service implemented using Google Apps Script. This architecture choice utilizes existing institutional Google Workspace infrastructure while providing the scalability and reliability required for real-time multi-station coordination.

State Management and Conflict Resolution

	A	B	C	D	E	F	G
1		Game1	Game2	Game3	Game4	Game5	Game6
2	Group1	0	0	0	0	0	0
3	Group2	0	0	0	0	0	0
4	Group3	0	0	0	0	0	0
5	Group4	0	0	0	0	0	0
6	Group5	0	0	0	0	0	0

Figure 8. Game Assignment Google Sheet

The core routing algorithm maintains a 5×6 status matrix representing all possible group-game combinations, with three discrete states:

- State 0 (Available): Game station is accessible for assignment.
- State 1 (In Progress): Game station is actively occupied by a group.
- State 2 (Completed): Game station has been finished by the specific group.

This state-based approach enables the system to implement sophisticated conflict resolution strategies. When a group completes an activity, the algorithm performs a systematic scan of all available games (State 0) while excluding those currently in progress by other groups (State 1). The next optimal assignment is determined through a sequential availability check, automatically reserving the selected station (transitioning to State 1) to prevent race conditions.

Real-Time Communication Protocol

Station-to-server communication occurs through RESTful HTTP requests with three primary endpoints:

- action=start: Transitions game state from Available to In Progress.
- action=done: Marks completion and requests next assignment.
- action=reset: Administrative function for session initialization.

The communication protocol implements automatic retry mechanisms and connection monitoring to handle network instabilities common in educational environments. Local stations maintain basic functionality during temporary disconnections, displaying appropriate user feedback while attempting reconnection.

Implementation and Performance Characteristics

Hardware Integration

Each game station integrates an ESP32 microcontroller with LCD displays for user feedback and real-time status updates. The distributed processing model reduces server load while providing responsive local interfaces. Wi-Fi connectivity enables seamless integration with institutional networks, while the modular hardware design supports rapid deployment and reconfiguration.

Scalability and Optimization

The current implementation supports up to five concurrent groups across 6+ game stations, with computational complexity of $O(n \times m)$ for next-game assignment, where n represents the number of groups and m represents the number of stations. Both numbers can be increased with correct adjustments and planning.

Educational Impact Assessment

The routing system's ability to eliminate mandatory wait times and enable self-paced progression significantly enhanced participant engagement metrics. Additionally, the system's real-time progress tracking enabled facilitators to provide targeted assistance to groups experiencing difficulties, improving overall learning outcomes.

The completion detection mechanism, which displays "All Games Completed!" upon finishing all available activities, provided clear achievement feedback that contributed to participant satisfaction and sense of accomplishment.

Limitations and Future Development
Current limitations include dependency on stable Wi-Fi and the potential for suboptimal routing when groups have significantly different completion rates. Future enhancements under consideration include predictive assignment algorithms based on historical completion times.

The modular architecture positions the system for expansion to larger-scale implementations, with theoretical support for dozens of concurrent groups across even more games available.

Evaluation and Findings

Participant Post-Game Learning Evaluation & Feedback

To evaluate the educational impact of the various games, a run-through event was organized with 19 participants. 13 of the 19 participants were lower-classmen. Pre- and post-game surveys asking students about their familiarity with the main topics were administered using a 1–5 Likert scale, with 1 indicating no familiarity and 5 indicating high familiarity. The survey questions are included in the Appendix. The results of these surveys and the percent improvement of each concept are tabulated below. The Mann-Whitney U test was used to assess the significance of differences between pre- and post-ratings. The increase in participants' understanding of concepts such as light and sound frequency and wavelength, fluorescence, and photovoltaic cells was statistically significant. The data in the table suggest that students might have already been familiar with concepts such as light absorption and light polarization, while they might have never done an experiment related to a concept like fluorescence.

Table 1. Student Pre- and Post-Game Ratings of Familiarity with Game Concepts

Concepts	**Pre-Game Average**	**Post-Game Average**	**% Improvement**	**P-Value**
Light Absorption	3.38	3.57	5.62%	0.393
Frequency and Wavelength	2.38	3.71	55.88%	0.017
Diffraction	2.85	3.57	25.26%	0.183
Fluorescence	1.85	3.14	69.73%	0.007
Light Polarization	2.62	3.57	36.26%	0.485
Photovoltaic Cells	2.54	4	57.48%	0.024
Polarizers	2.69	3.86	43.49%	0.115

Builder Post-Game Reflections

In what follows, we present the reflections of senior ECE students, referred to as the builders in this paper, on designing and building the games documented after the game session.

Cosmic Whisper - Designing and building required integration of mechanical design (Fusion 360 CAD), electrical schematic capture (KiCAD), embedded programming (Arduino/C++), and signal processing algorithms. The project challenged the senior student to solve real-world engineering problems, including optical calibration and user interface design. The station's complexity demonstrates authentic ECE skills while remaining accessible to incoming students through its game-like interface and progressive difficulty structure. The spectroscopy component introduces fundamental physics concepts, while the signal processing stage showcases advanced digital techniques in an intuitive format. The builder of this game spent approximately 400 hours over the course of 4.5 months to build this game.

Diffraction Decoder - Despite incorporating advanced optics and its complex embedded system, this game remained accessible through its puzzle-based structure and clear cause-and-effect interactions. By combining a physical sliding puzzle with laser diffraction analysis, the game encouraged players to actively explore the relationship between grating orientation, wavelength, and diffraction patterns. The builders of this game spent approximately 100 hours over a span of three months on the game's design and assembly.

Sugar Mystery - Given the handling of liquids with electronics, the development of the sugar mystery game required thoughtful consideration of component and game design. For successful operation, the game demanded the precise measurement of concentrations without relying on commercial optical components. Accurate polarization-angle measurements were achieved by programming a stepper motor and calibrating each rotation increment to equal one degree. Other components, such as the laser and photodetector mounts, were designed for easy and precise adjustment. The design and building process highlighted several undergraduate-level ECE competencies, including analog circuit design, embedded systems integration, and parametric design. The builders invested approximately 48 hours over a span of three months to build this game.

Solar Mania - This game required integration of analog circuit design, embedded systems, mechanical control, and game logic. The project challenged the senior student to design and debug photovoltaic charging circuits, comparator networks, and sequential logic using SR latches, while also implementing servo-based mechanical control and microcontroller-driven feedback. This station emphasized system-level thinking, as reliable gameplay depended on coordinated behavior across analog, digital, and mechanical subsystems. The builder of this game spent approximately 156 hours over a span of three months to build this game.

Polarization Patterns - The game's simplicity makes it an appropriate project for novice builders seeking experience in CAD, assembly, and 3D printing. The builders spent approximately 100 hours over a span of ten weeks to build this game.

Chromatic Labyrinth - A primary factor for the game's popularity among the participants was that the complexity could be readily calibrated for a diverse range of skill levels, while serving as a valuable exercise in optical alignment regardless of skill level. The two builders of this game spent approximately 30 hours over the course of two weeks to build this game.

The challenge with building the chromatic labyrinth was balancing user flexibility and usability with safety, size, and material costs. The three lasers and detectors, two prisms, and four mirrors were placed on a small custom-built optical table, a design that demanded that the builder propose a structure that minimized weight and cost while maximizing rigidity and stability. A creative solution for building a magnetic optical table ended up costing less than $100 in materials, whereas an optical breadboard of comparable dimensions from ThorLabs would cost roughly 10 times as much.

Conclusion

Overall, designing, building, testing, and presenting the games has given builders a deeper understanding of circuits and game design through direct, hands-on experience. At the same time, the games serve as engaging tools for introducing new students to concepts in optics and engineering who may be unfamiliar with these fields. By combining play with visual demonstration, the project creates an enjoyable learning environment that makes engineering topics more accessible and tangible.

Resources

GitHub Repository: https://github.com/UCSD-Optics-Maze-Educational-Games

Acknowledgement

Several undergraduate UC San Diego students, including Chanae Turk, Jordon Worf, Kesler Anderson, Alex Wu, Danny Wu, Giselle Mendoza, James Fleming, Leah Minler, and Virakboth Hang, contributed to the design and building of the games in this project. The Chromatic Labyrinth game was originally developed by the SPIE Student Chapter at UC San Diego for their “Optics Hour” outreach events. Its sustained usage across numerous public engagements prompted its adoption into the LightWorks Challenge suite. Karl Johnson, who is a PhD student and the president of the student chapter, was the primary contributor to the design and manufacturing of the Chromatic Labyrinth game and provided all related figures.

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Appendices / Supplemental Materials

Bill of Materials and Fabrication
Cosmic Whisper
Electronic Components:
- ESP32-S3 ($14.99)
- TCS34725 RGB sensor ($8)
- Linear actuator ($30)
- BTS7960 driver ($3)
- 3×4 matrix keypad and I2C LCD 1602 module ($15)
- MAX4466 mic module ($7)
- LED components ($4)

Optical Elements:
- Diffraction grating slide ($2)
- Flashlight ($5)
- UV light source ($10)
- Mirrors and sample containers ($25)

Mechanical Components:
- Laser-cut stainless steel board ($45)
- 3D-printed enclosures ($30 in material)

Diffraction Decoder
Electronic Components:
- ESP32 Dev Module ($10)
- Keypad and LCD ($15)
- Buzzer ($3)

Optical Elements:
- Diffraction grating slide ($2)
- Laser pointer module ($12)

Mechanical Components:
- Laser-cut stainless steel board ($25)
- 3D-printed enclosures ($20 in material)
- Sliding puzzle board and pieces ($15 in material/fabrication)

Sugar Mystery
- (2x) ESP32-WROOM ($9.99 each)
- Photodiode Sensor Module (10 pcs for $9)
- 42-40 Stepper Motor with Extruder Gear ($14)
- 3×4 matrix keypad (6 pcs for $10)
- (2x) I2C LCD 1602 module ($12)
- (3x) Protoboards (32 pcs for $7)
- Red Laser Diode (10 pcs for $7)
- GT2 Synchronous Wheel Timing Pulleys (2 pcs for $13)
- Laser-cut stainless steel board ($45)
- 3D-printed enclosures ($30 in material)
- (3x) Glass Vase 4” W x 5” H ($10)

Polarization Patterns

- (2x) ESP32-S3 ($14.99 each)
- Photodiode Sensor (10 pcs for $9)
- 3×4 matrix keypad (6 pcs for $10)
- I2C LCD 1602 module ($12)
- Polarizing Film ($12)
- LED Light Source ($20)
- Protoboards (32 pcs for $7)
- Laser-cut stainless steel board ($45)
- 3D-printed enclosures ($15 in material)

Solar Mania

Electronic Components:

- ESP32 Dev Module ($10)
- TCS34725 RGB sensor ($8)
- Capacitors: 1000µF and various values ($1)
- NE555 timer ICs ($5)
- LM741 op-amp ICs ($5)
- LF411 op-amp ICs ($6)
- LM3914 LED driver IC ($5)
- LEDs (Red, Yellow, Green, Blue, White) ($1)
- Buzzer ($3)
- SR latch flip-flops ($3)
- Resistors and filter capacitors ($1)
- Protoboard and connectors ($3)

Mechanical Components:

- Dual-axis servo motors ($15)
- Servo mount bracket and gimbal hardware ($5)
- Potentiometer knobs ($3)
- Flashlight ($5)
- Module enclosures ($20)
- Power supply components ($10)

Chromatic Labyrinth

- ESP32 Dev Module ($10)
- (3x) Photodiode Sensor (10 pcs for $9)
- 3×4 matrix keypad (6 pcs for $10)
- I2C LCD 1602 module ($12)
- Glass Prism(s) ($10 each)
- Red Laser Pointer ($8)
- Green Laser Pointer ($8)
- Blue Laser Pointer ($8)
- Mirrors (25 pcs for $9)
- Laser-cut stainless steel board ($45)
- Wooden Board ($15)

- Small magnets ($6)
- Cork Board ($10)
- 300 M4 Nuts ($7 for 50 pcs)
- 3D-printed enclosures ($20 in material)

Figures

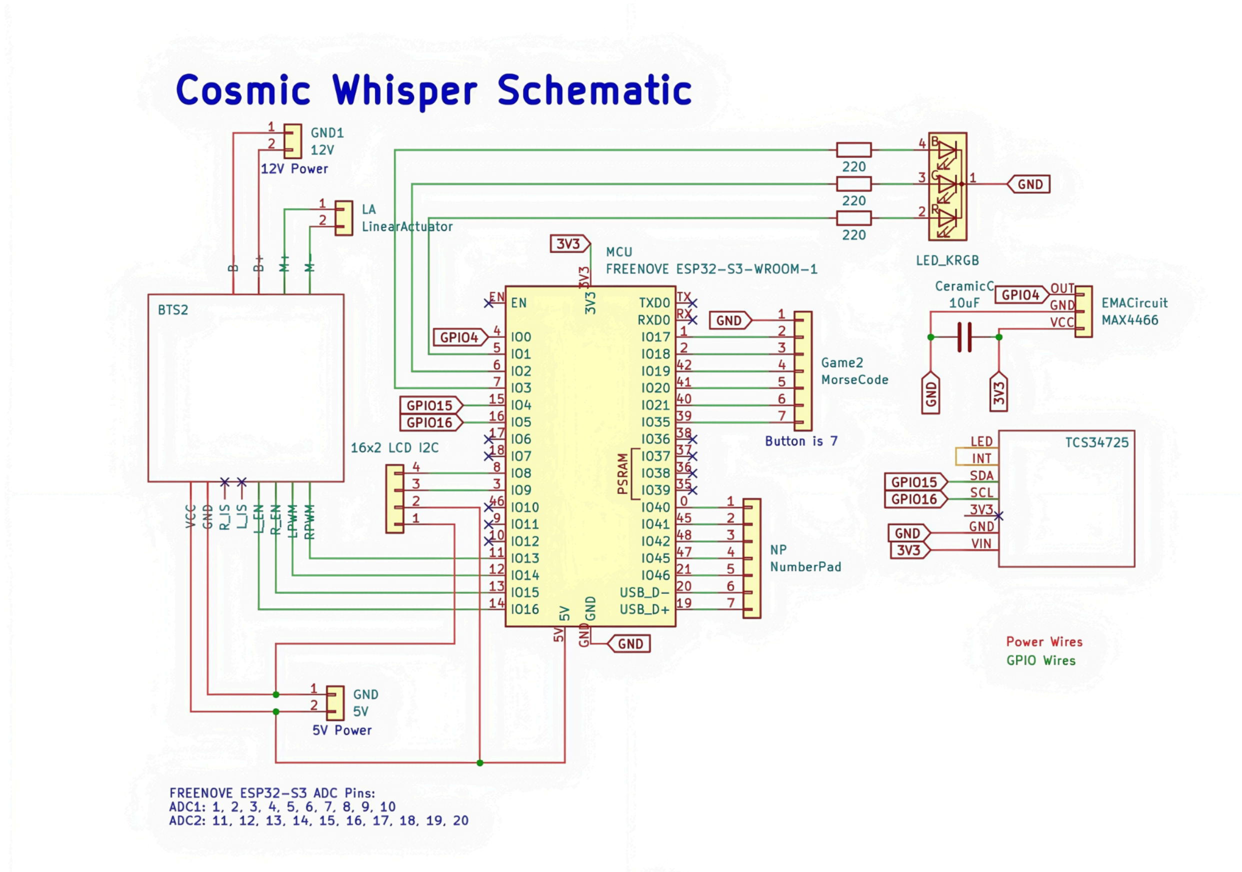


Figure S1. Cosmic Whisper KiCad Schematic

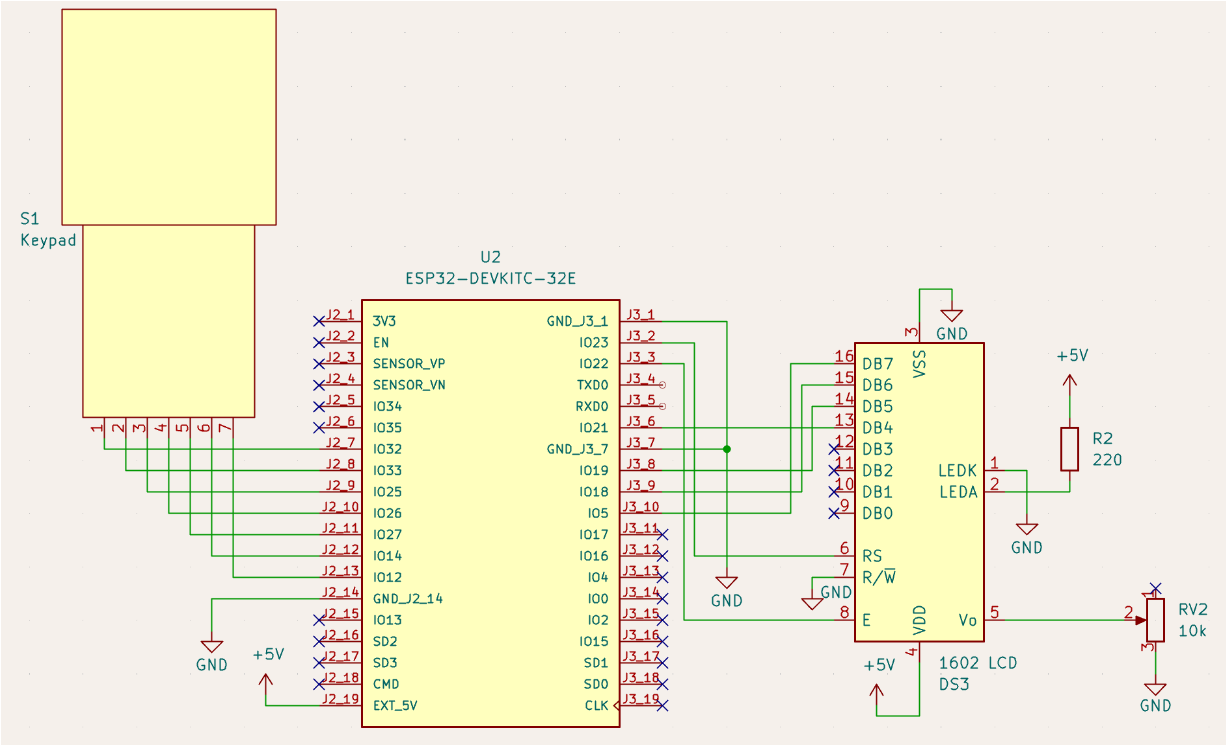


Figure S2. Sugar Mystery: Schematic of Connectivity Console

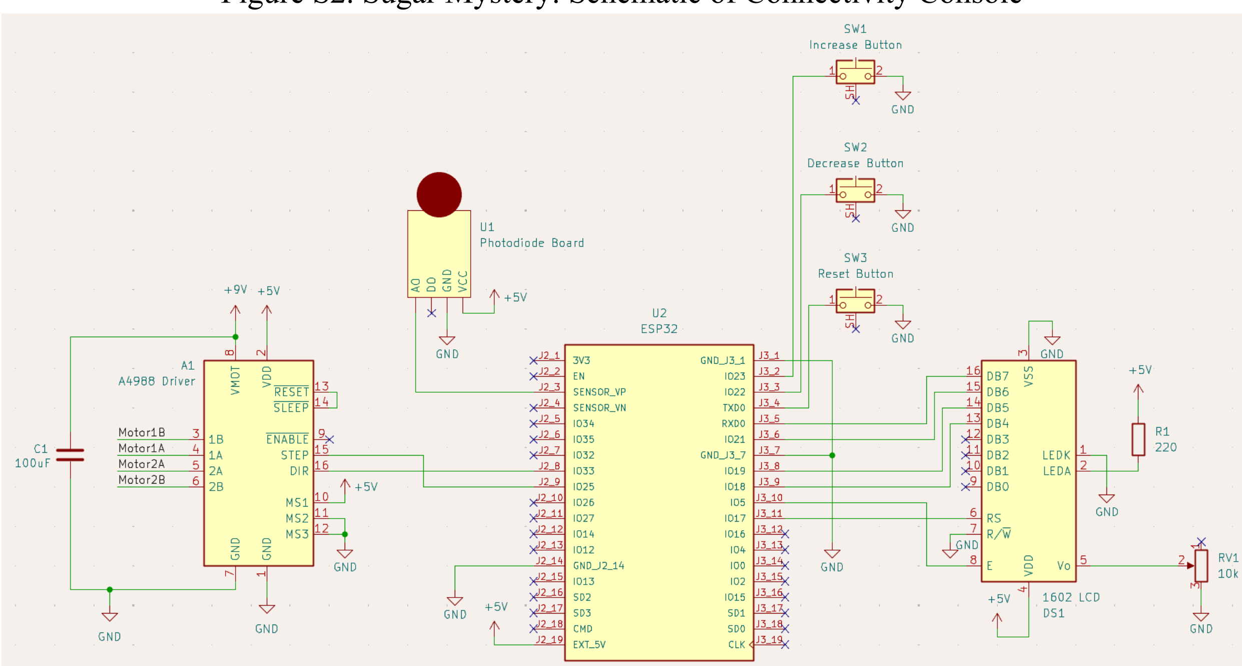


Figure S3. Sugar Mystery: Schematic of Mechanics Module

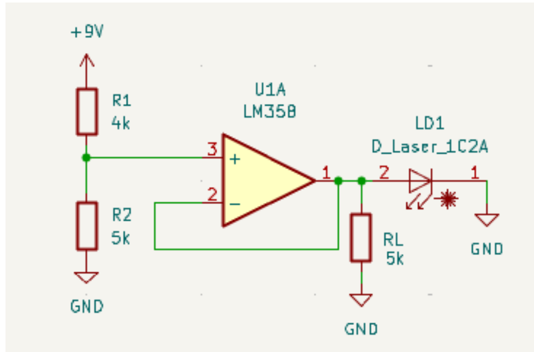


Figure S4. Sugar Mystery: Schematic of Voltage Follower & Laser Diode

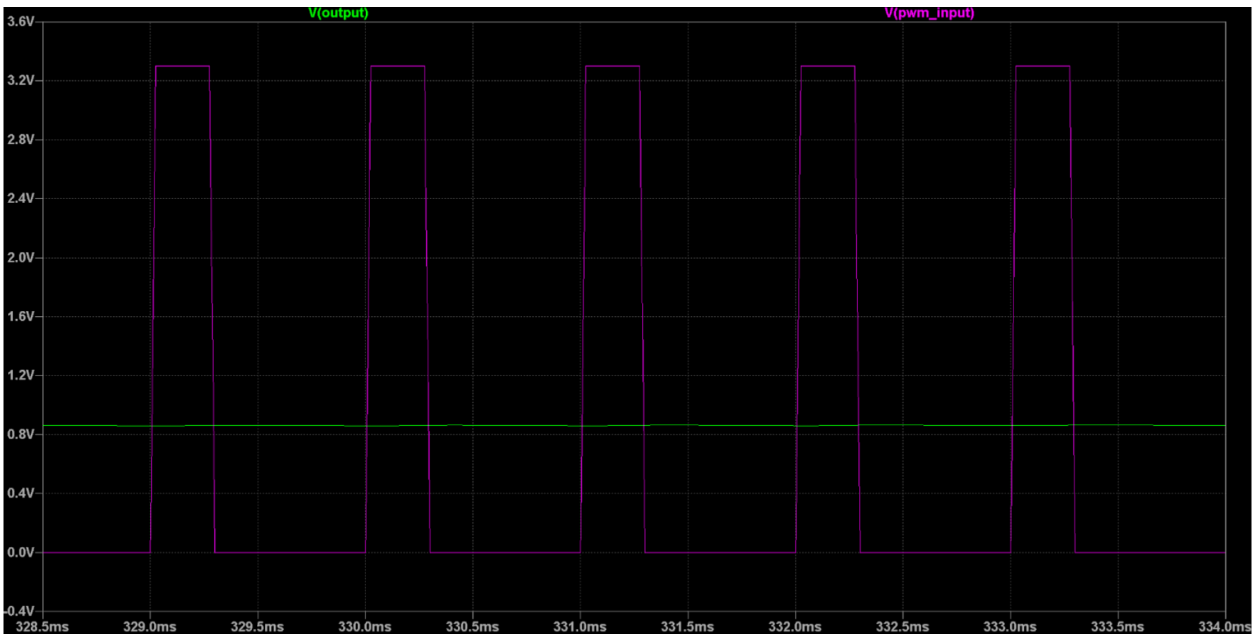


Figure S5. Solar Mania PWM Filter 25%

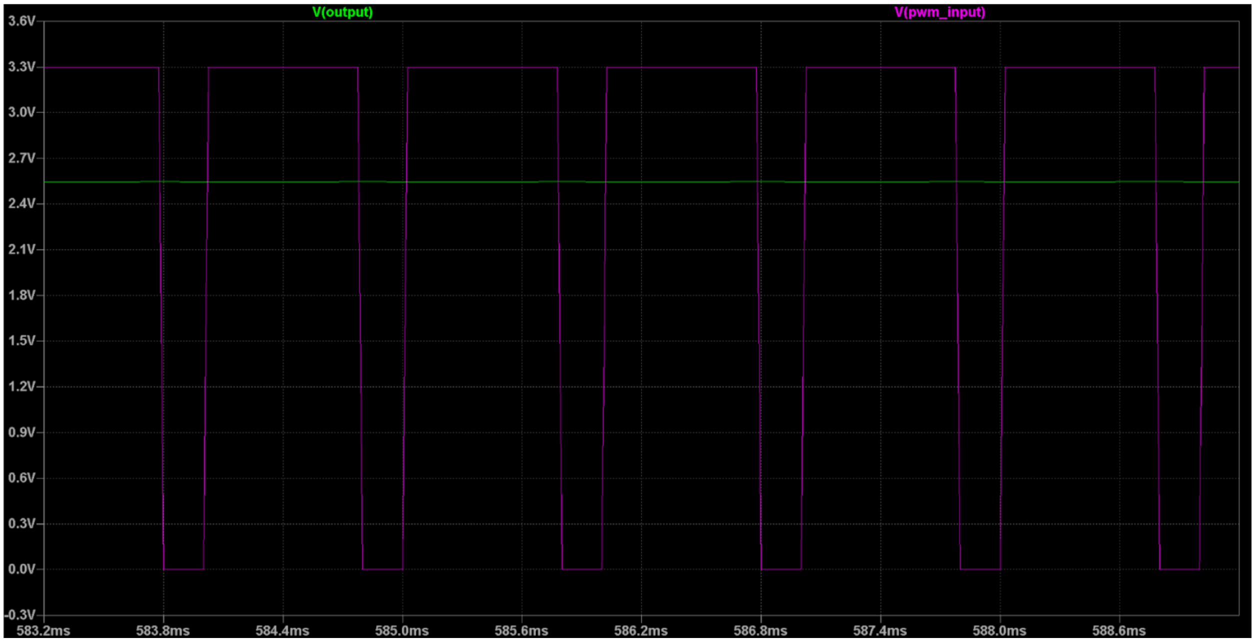


Figure S6. Solar Mania PWM Filter 75%

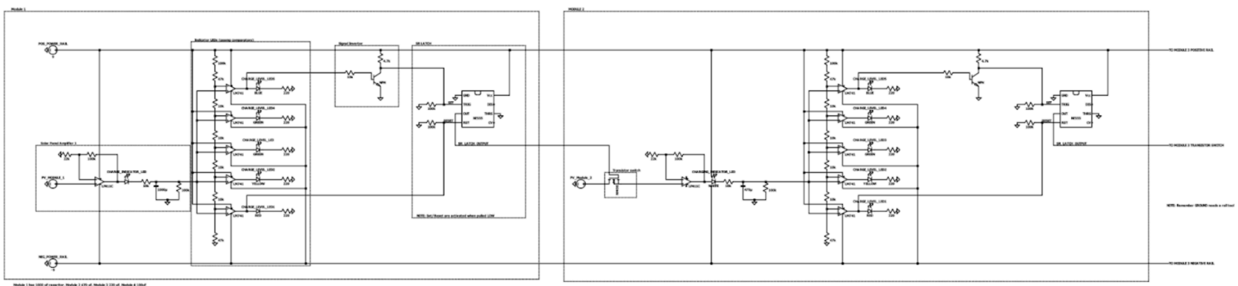


Figure S7. Solar Mania Submodule Circuit

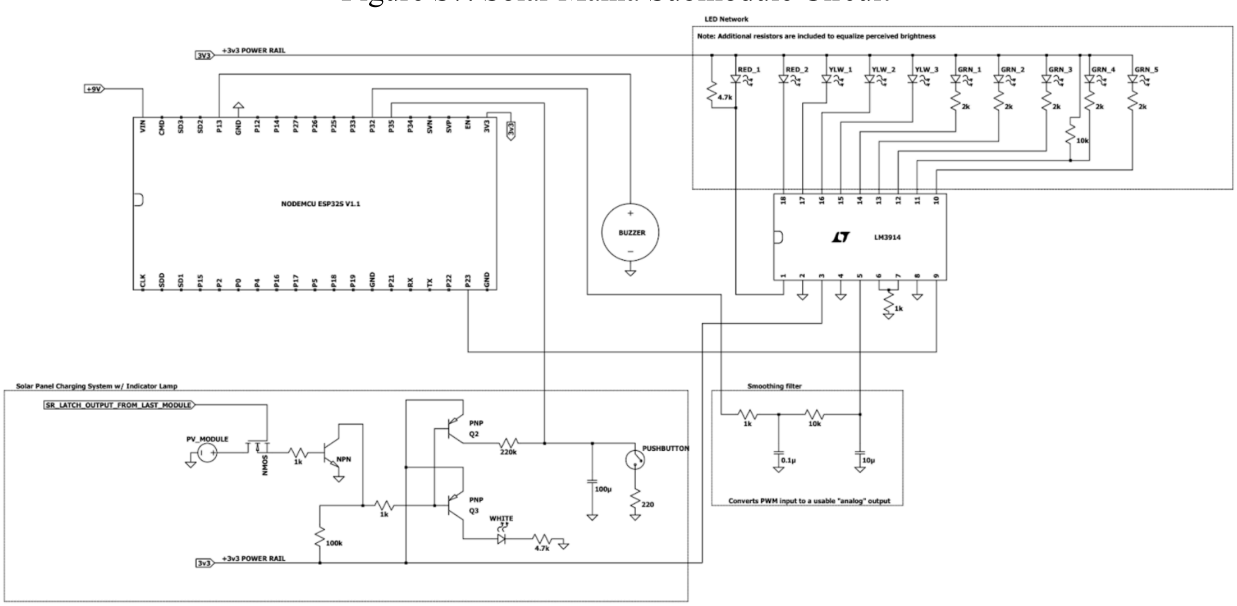


Figure S8. Solar Mania Top Module Circuit

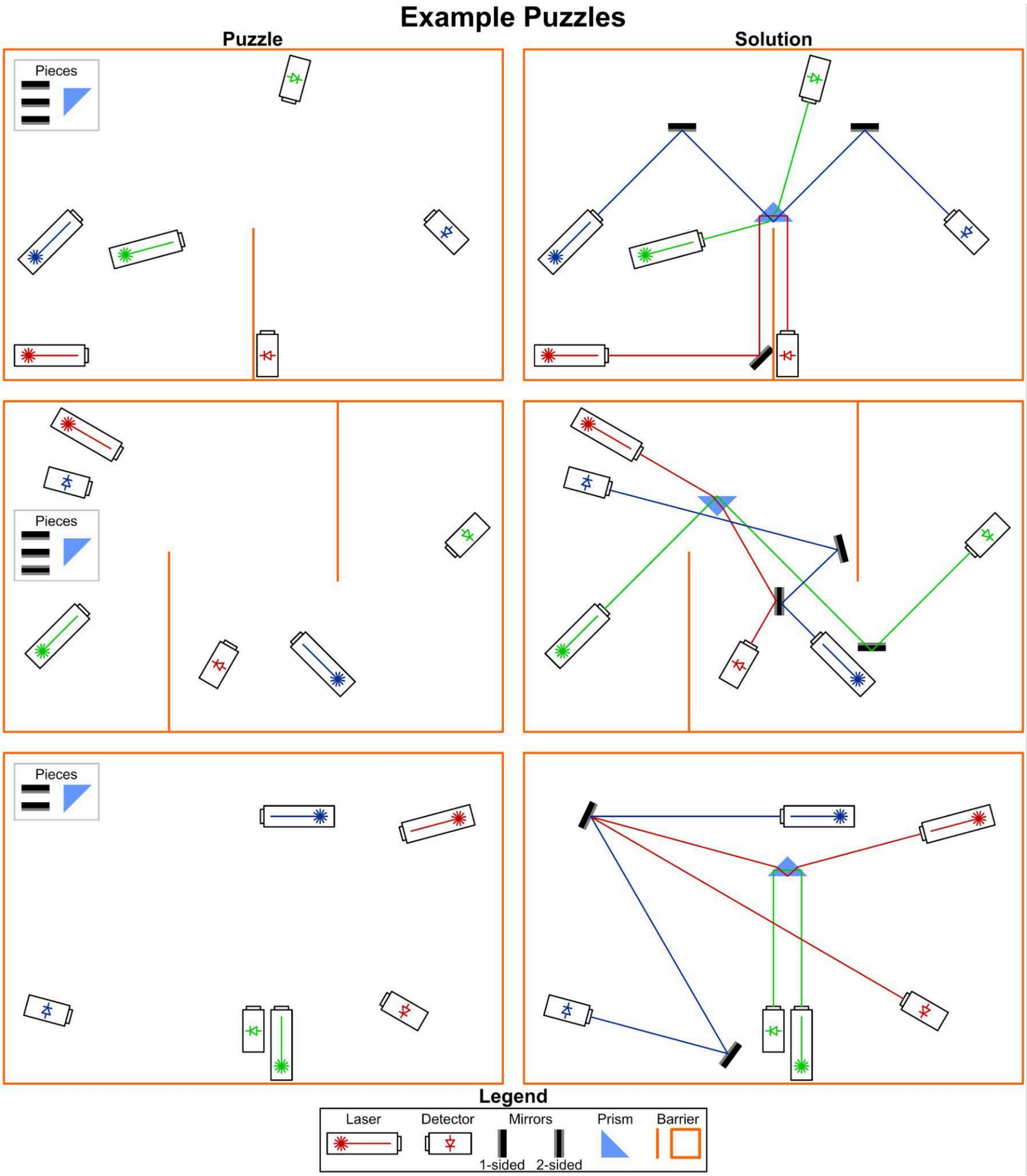
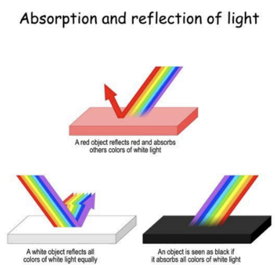


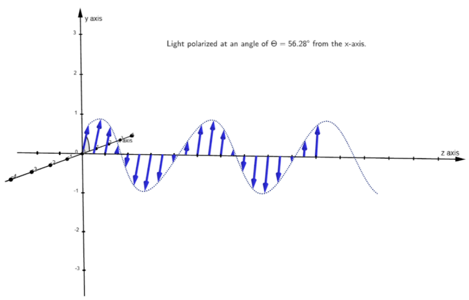
Figure S9. Chromatic Labyrinth Example Puzzles

The Likert scale pre-game survey questions with options from (1) Not at all familiar to (5)Very familiar.

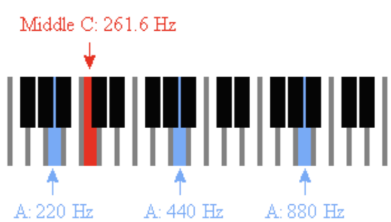
- To what extent are you familiar with the concept of light absorption? Specifically, why do we see everyday objects in certain colors?



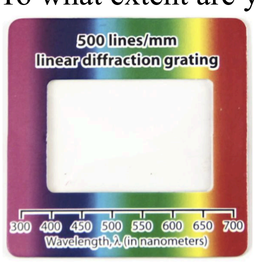
- To what extent are you familiar with the phenomena of light polarization?



- To what extent are you familiar with the concept of sound frequency, and how a microcontroller can change LED colors to reflect changes in nearby sounds?

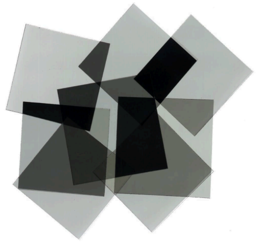


- To what extent are you familiar with the concept of diffraction?



- To what extent are you familiar with the photovoltaic cells, aka solar panels?

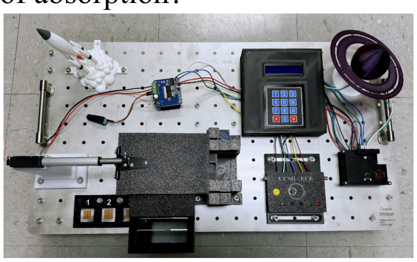
- To what extent are you familiar with polarizers?



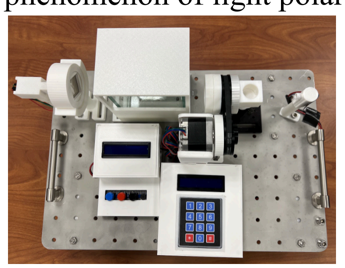
- To what extent are you familiar with the concept of fluorescence?

The Likert scale post-game survey questions with options from (1) Not at all familiar to (5)Very familiar.

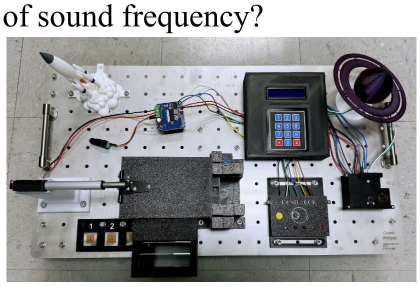
- After playing the Cosmic Whisper game, to what extent are you familiar with the concept of absorption?



- After playing the Sugar Mystery game, to what extent are you familiar with the phenomenon of light polarization?



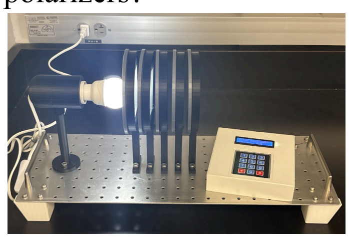
- After playing the Cosmic Whisper game, to what extent are you familiar with the concept of sound frequency?



- After playing the Diffraction Decoder game, to what extent are you familiar with the concept of diffraction?

- After playing the Solar Mania game, to what extent are you familiar with the photovoltaic cells?

- After playing the Polarized Patterns game, to what extent are you familiar with polarizers?



- After playing the Cosmic Whisper game, to what extent are you familiar with the concept of fluorescence?